Proposal for Accelerator Science at Fermilab
Covering the Period 2009-2011

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I. Introduction and Summary

The Accelerator Science program at Fermilab targets the development of technologies and techniques that support the long term physics mission of the Laboratory and of the Department of Energy's Office of Science. The program emphasizes the development of technology and tools that could support forefront accelerator facilities in the long term, where "long-term" generally refers to beyond-the-next-generation of facilities. These include, but are not limited to, muon storage ring based facilities (Neutrino Factory and Muon Collider) and energy frontier electron-positron colliders. At the same time, the program provides critical support to the ongoing accelerator based programs that form the heart of the near term Fermilab research program (Collider Run II, the neutrino program, and LHC).

The Fermilab Accelerator Science program is aligned with three of the programmatic thrust lines identified by the DOE Office of High Energy Physics:

- Accelerator and Beam Physics

  Activities include beam studies at the Tevatron, Main Injector and Booster accelerators in support of optimizing performance in Collider Run II; development of beam optics and dynamics simulation and modeling tools (including energy deposition simulations); theory of beam instabilities in current and future accelerator facilities; development of new techniques for compensation of beam-beam effects; beam cooling methods; experimental studies of ground motion effects in accelerators and electron cloud effects in high intensity proton beams; theory and experimentation on new collimation and cooling methods; and training of the next generation of accelerator scientists and engineers.

- Muon Collider/Neutrino Factory

  Fermilab provides joint leadership (with BNL and LBNL) of the national Neutrino Factory and Muon Collider Collaboration (NFMCC) and leadership of the Muon Collider Task Force (MCTF). These efforts are developing design concepts, and major subsystem technology simulations/demonstrations for muon-based facilities. This work also features strong cooperation with companies funded by the DOE's Small Business Innovation Research (SBIR) program.

- Beam Sources and Instrumentation

  Activities are centered at the A0 Photoinjector and include high performance electron source and diagnostics development. These activities are conducted in collaboration with a variety of outside laboratories and universities. This program is a significant source of accelerator science PhDs at Fermilab.

Coordination of all Accelerator Science activities at Fermilab is provided by the Accelerator Physics Center (APC). The APC was established in June 2007 to provide integration and coordination of Fermilab's Accelerator Science and Accelerator Development programs aimed at the future. Many activities involve multi-institutional collaborations. The APC also provides support for accelerator operations and for educational initiatives in Accelerator Science. While only the Accelerator Science activities are discussed within this proposal the existence of these other programs provides a positive environment and a multitude of shared tools for support of the accelerator science program.

Principal Achievements of the Fermilab Program

Principal achievements of the Accelerator Science program at Fermilab over the last several years include:

- Development and implementation of optimized beam optics and helical beam separation schemes in the Tevatron, which resulted in significant increases in Collider Run II luminosity
- Development and implementation of instruments for improved beam emittance measurements, orbit stabilization, and beam stabilization in the Tevatron, Main Injector and Booster.
- Experimental studies and parameterization of the effects of proton-antiproton beam-beam effects, development of numerical simulation tools capable of predicting emittance growth and particle losses due to beam-beam interactions.
- Tevatron Electron Lenses - novel instruments for HEP accelerators – have been proposed, designed, built and installed in the Tevatron and used for experimental demonstration of active compensation of beam-beam effects by using low-energy electron beams
- Two-stage collimation systems have been designed, developed and installed in the Tevatron, Booster and Main Injector and demonstrated high halo cleaning efficiency of proton and antiproton beams, in conformance with MARS simulations
- Demonstration of very high efficiency channeling of 980 GeV proton halo particles by bent crystal in Tevatron.
- A systematic program of ground and magnet motion studies has been established which employs several types of detectors covering processes from several-years-long time scales up to kHz frequencies. Results of the studies provided valuable input for the Tevatron Run II operation (continuous monitors of the orbit drift sources) and for future facilities (ILC, NOvA, ProjectX,etc).
- Completion of the first complete feasibility study for a muon storage ring based neutrino factory, in collaboration with the NFMCC.
- Concepts and simulations for several unique advancements in critical muon sub-systems: bunching systems, non-scaling FFAGs, and 6-D cooling schemes (with Muons Inc.)
- Development of an integrated design concept for a multi-TeV muon collider (MCTF, with NFMCC and Muons Inc.)
- Host to the muon cooling technology development (MuCool) program within NFMCC. Construction and initial operations of the MuCool Test Area (MTA).
- Measurement and characterization of 200 MHz accelerating cavity performance in a variety of configurations and within a magnetic field.
- Demonstration (with Muons Inc) of increased gradients with high pressure gas filled cavities.

- First demonstration of the production of a flat electron beam with an emittance ratio of 100:1 via a "flat beam transformer"
- Development of a higher harmonic deflecting mode cavity for utilization in transverse/longitudinal emittance exchange.
- First demonstration of electro-optical techniques for high precision beam measurement.
- Graduation of 16 PhD students over the period 2000-2008.

These achievements provide the base on which the ongoing programs described in this proposal are built.

The 2009-2011 Landscape

This proposal covers FY2009-2011. This period will witness the relocation of the high energy frontier in particle physics from the United States (Fermilab) to Europe (CERN). Following the cessation of operations of the Tevatron at the end of FY2010 the U.S. program in high energy physics will enter a new era. A strategy for this era has been developed by the Particle Physics Project Prioritization Panel (P5), has been adopted by the High Energy Physics Advisory Panel (HEPAP), and forms the framework for the DOE/OHEP strategic plan. This plan is based on forefront programs addressing three frontiers: the energy frontier, the intensity frontier, and the cosmic frontier. The first two of these are reliant on high performance accelerators.

The overriding goal of the Fermilab Accelerator Science program is to support future development of the high energy and intensity frontiers. A confluence of events points to the 2012 time frame as the period of decision on future directions in both areas:

- First physics results based on significant integrated luminosity from LHC will be available and interpreted. These results are expected to provide guidance on the desired energy reach of a future lepton collider.
- The International Linear Collider Technical Design Phase will be complete, providing definitive information on the performance reach and costs of an electron-positron linear collider operation in the range 500-1000 TeV.
- CERN will have completed a conceptual design and cost estimate for a multi-TeV electron-positron linear collider (CLIC – Compact Linear Collider).
- The J-PARC complex will be nearing its full potential with the ability to deliver up to 750 kW of beam power onto a neutrino production target at 30-40 GeV.
- The NOvA long baseline neutrino experiment will be nearing the end of construction, incorporating a 700 kW capability in the Main Injector complex.
- Fermilab and collaborators will have developed complete conceptual designs for a multi-MW proton source and an associated neutrino beamline aimed at a the DUSEL facility.

- Initial results from the upcoming round of neutrino experiments will yield information on whether the mixing parameter $\sin^2 2\theta_{13}$ is greater than or less than ~0.02.

Based on these factors we expect both the international and national communities to be in a position to make decisions in the following areas:

- What is the required energy reach of the lepton collider that will complement the LHC? And what is the preferred technology base for such a collider?
- What is the required reach of the next generation neutrino facility? Is a Neutrino Factory likely to be required to explore CP violation in the neutrino sector?
- What are possible concepts that will support the next generation of HEP facilities beyond the lepton collider and/or Neutrino Factory?

Proposal Goals

The primary goal of this proposal is to assure that the U.S. is in position to answer the above posed questions in the 2012-2013 timeframe. Specific goals include:

- Completion, with international partners, of a Reference Design Report for a muon-storage-ring-based Neutrino Factory.
- Completion, with national partners, of a feasibility study for a Muon Collider with a center of mass energy in excess of 1 TeV.
- Demonstration of a series of novel emittance manipulation techniques at the A0 Photoinjector with potential application to lepton colliders and/or advanced free electron lasers.
- Development of advanced computational and simulation tool, as well as novel accelerator technologies and methods, in support of the above.

Leveraging Fermilab Infrastructure and Resources

The Accelerator Science program is embedded in, and leverages resources and infrastructure from, the much larger operations and general technology development programs at Fermilab. This allows the program to deliver very substantial results at a minimal incremental cost. Among the resources brought to bear on the program are:

- Accelerator infrastructure: Very substantial cryogenics, electrical, and low conductivity water infrastructure are available within the accelerator complex at Fermilab.
- Support functions: Procurement, ESH, QA, accounting, etc. support are available at minimal incremental cost.
- Accelerator facilities: The Fermilab complex is very flexible in its ability to deliver beam at a variety of energies to a variety of locations, simultaneous with ongoing operations. The MuCool Test Area and Meson Area Test Beam are current examples.

- Accelerator personnel: The Fermilab staff possess unique capabilities and skills in accelerator design, construction, and operations, and in advanced accelerator R&D. Personnel are available to support the Accelerator Science program on either temporary or longer term basis via full or part time reassignment.
- Accelerator computation/simulations tools: A variety of advanced computation and simulation tools are available in the APC and via the SciDAC sponsored national accelerator computational program, which is led by Fermilab and closely aligned with APC.

Budget Request

Resources provided to support the Accelerator Science Program as described in this proposal are presented in Table I.1. Costs include both Materials and Services (M&S), Salaries, Wages, and Fringe Benefits (SWF) for participating staff, and all relevant indirect costs. Please note the following:

- The column labeled FY09 IFP corresponds to the Accelerator Science allocation at Fermilab based on the IFP corresponding to the President's FY2009 Budget Request.
- The columns labeled FY09-11 correspond to the resources requirements of this proposal as summarized in the various sub-sections.
- Beam Sources and Instrumentation in FY12 will support the relocated photoinjector in the New Muon Lab (NML). These cost are not yet determined.

	All amounts in $K, fully burdened				
		Proposal Request Amounts			
	FY09 IFP Total	**FY09 Total**	**FY10 Total**	**FY11 Total**	**FY12 Total**
Fermilab Accelerator Science Program	**6,432**	**9,876**	**12,702**	**14,620**	**TBD**
Beam Sources and Instrumentation	1,700	2,782	3,948	4,885	TBD
Muon Collider and Neutrino Factory	3,325	5,697	7,015	7,622	8,087
Accelerator and Beam Physics	1,407	1,397	1,739	2,113	2,095

Table I.1: Resource requirements for the Fermilab Accelerator Science Proposal. All figures are in then-year thousands of dollars and are fully burdened.

II. Accelerator and Beam Physics

II.1 APC background: Rationale and goals for creating Accelerator Physics Center

The Accelerator Physics Center (APC) was established in June 2007 to provide integration and coordination of Fermilab's Accelerator Science and Accelerator Development programs aimed at the future. The APC also provides support for accelerator operations and for educational initiatives in Accelerator Science.

Rationale for creating APC: Traditionally the majority of accelerator research at Fermilab has been centered on developing and operating the present accelerator complex, and designing the direct follow-on facilities. That has been very effective for the purpose of operating the world's most complicated accelerator complex at the ultimate performance levels for more than three decades. However, the Lab is entering a period of drastic changes in the near future, which – after shutdown of the Tevatron Run II - will be dependent upon the renewal of the complex via the construction of new accelerators. For this to happen there is a great need to expand the number of scientists that can contribute to development of new technologies and Fermilab, as the de-facto centerpiece of the US High Energy Physics, must take on a greater share of training people in Accelerator Science.

The role of the APC is to provide a place where any accelerator scientist or engineer, either at Fermilab or in the university community, can contribute to the accelerator research programs at Fermilab. An additional goal is to assist in planning and bringing into existence the facilities that are necessary for a broad Accelerator R&D program. One of the responsibilities of the APC is to identify facilities available for R&D work and assist anyone who wishes to propose or participate in experiments involving these resources. APC also provides a place where theorists and simulators are in close contact and can work on broad classes of problems. Last, but not least, APC supports the critical need for enhanced effort in the education of accelerator scientists and engineers. Fig. II.1 below shows statistics of the PhD production in the field of accelerators in the US since 1980s' (data from DoE Advanced Technology R&D Yearbook (2005).

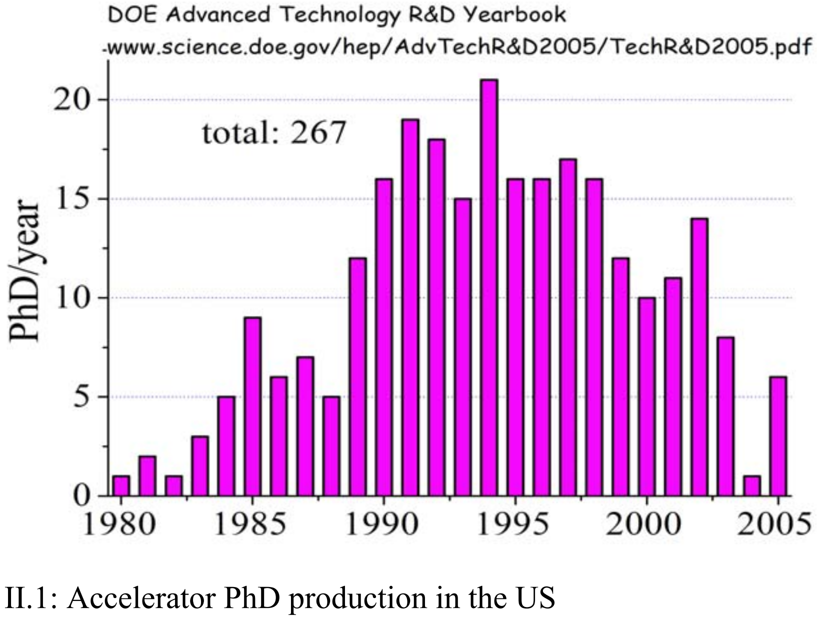
DOE Advanced Technology R&D Yearbook
-www.science.doe.gov/hep/AdvTechR&D2005/TechR&D2005.pdf

Fig. II.1: Accelerator PhD production in the US

The decline of the PhD production in the past decade is of concern. To have a sustainable future for the accelerator based HEP in the US, it will be necessary to have a broad range of experiments and facilities that are available to both the in-house and university groups. It takes a dedicated effort to accomplish this task which is centered at the APC.

Mission, goals and responsibilities of the APC are outlined below:

Mission:

1. Coordinate and conduct accelerator R&D aimed at next-generation and beyond accelerator facilities;
2. Provide accelerator physics support for existing operational programs and the evolution thereof;
3. Train accelerator scientists and engineers;
4. Provide leadership and coordination in establishing the necessary experimental programs for a broad range of accelerator R&D that can be accessed by both Fermilab staff and the world HEP community.

Goals and Connections to Future Accelerators:

The goal of the Accelerator Physics Center is to provide enhanced emphasis on, and support of, accelerator R&D activities aimed at Fermilab's future beyond the end of the current decade. The APC provides both a physical location and an organizational structure that can accommodate accelerator scientists and engineers, either from Fermilab or outside institutions. The APC contributes to the improvement of performance of the existing accelerator complex, and the development of new technologies and accelerator concepts that could enable new forefront facilities beyond the current decade. The scope of activities conducted within APC includes support for Run II and the accelerator based neutrino program at Fermilab, the International Linear Collider (ILC), the Large Hadron Collider (LHC), the High Intensity Neutrino Source (HINS), Project X, Muon Colliders/Neutrino Factories, and long-term research in novel acceleration and instrumentation techniques. In support of this primary goal the APC also increases Fermilab involvement in the education of accelerator scientists and engineers.

II.2 APC Organization and Personnel

The APC Director is appointed by FNAL Director and reports to Associate Director for Accelerators. Along with the Accelerator and Technical Divisions the APC comprises the Accelerator Organization at Fermilab.

The APC is comprised of a core of directly assigned persons, augmented by significant numbers of participating staff from the Accelerator, Technical, Particle Physics, and Computing Divisions. The number of direct assignments will grow as Run II ends. The APC does not have direct operational responsibilities for beam-based test facilities—these are the responsibility of Accelerator Division. In the event that an R&D program evolves into a full-fledged facility construction project, responsibility for the project will be retained by Accelerator Division. The

APC retains responsibility for coordination of inter-institutional collaborations in the advanced accelerator R&D. In particular, the APC works closely with the Argonne Accelerator Institute to coordinate mutual undertakings in accelerator research.

The APC org-chart is presented below:

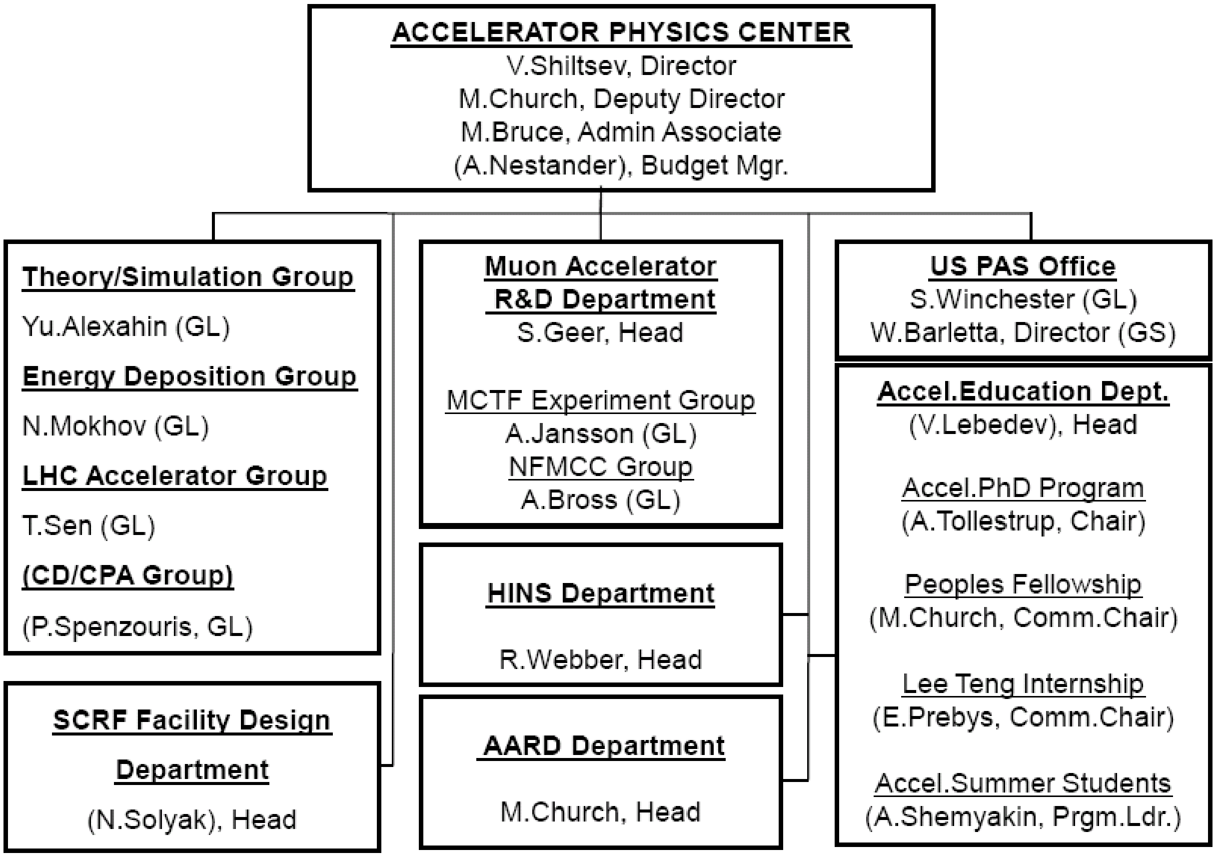

Fig.II.2: Organization Chart of Fermilab Accelerator Physics Center.

As of October 1, 2008, the APC has 42 directly assigned staff members with an additional 12 FTEs represented by 40 scientists and engineers for all Fermilab Divisions participating in APC-led programs. Of these 14 FTE are supported by Accelerator Science (KA15 01 02) funds. In addition there are five PhD students doing thesis research work in APC, AD and TD as part of the APC's Accelerator PhD program. Of the PhD students, three are supported by Accelerator Science funds.

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II.3 Recent Accomplishments

The three major areas of APC activities are: a) accelerator physics design and modeling, b) an experimental R&D program focused on development advanced accelerator concepts, and c) accelerator education programs which attract graduate and undergraduate students, train and develop them into the accelerator scientists. Goals and past accomplishments of all the APC groups are outlined below. Significant recent refereed publications are listed in Appendix I.

II.3.a Accelerator Physics Design and Modeling Groups

The mission of the groups listed below is to advance beam physics understanding both through theoretical and experimental programs, to provide accelerator physics and design support to various Fermilab's projects, and to develop new modeling tools.

Theory and Modeling Group:

This group takes the lead at Fermilab in carrying out theoretical beam dynamics calculations and development of accelerator physics tools and models. It participates in beam studies and provides accelerator physics support to the Accelerator Division on the Tevatron Collider Run II, NOvA and Project X, and programs, including beam-beam compensation studies and simulations, beam optics measurements, optimizations, beam instabilities and other studies as required to support Fermilab accelerator operations and improvements. The group provides modeling and calculational support for other accelerator R&D activities within the APC including support for education and training activities.

Accomplishments in 2007-2008:

a) Tevatron Electron Lens (TEL): new smooth edge with flat top (SEFT) guns designed and installed at TEL1 and TEL2; two-fold proton-lifetime improvement demonstrated with both TEL1 and TEL2; numerical simulations showed significant LHC lifetime improvements with electron lenses;

b) Beam optics: Optimization of helical orbits in Tevatron resulted in improvements of the Tevatron beam efficiencies at 150 GeV , ramp, squeeze and low-beta; MCR console applications for coupling correction at injection and acceleration are routinely used for Tevatron tune-up; a new method is developed for coupled optics reconstruction from TBT data; methods developed for Tevatron are applied to Booster and MI, particularly, MI impedance determined from phase advance and orbit dependence of beam intensity (and found to be in a good agreement with theoretical expectations)

c) Tevatron Digital Tune Monitor (DTM) is developed for fast bunch-by-bunch tune measurements needed for optimization of the beam-beam effects on Collider performance;

d) Analysis and correction of Tevatron orbit and tune drifts concluded in finding the source of the drifts in the distribution of the sextupole field components along the dipole magnet length

e) Space Charge effects in Booster, Recycler and MI: using Mathematica and MAD, the SC effects in Booster were analyzed and shown to be particularly harmful in the presence of large optical irregularities; SC simulations code ORBIT has been set for simulations for the Recycler and Main Injector; TBT optics measurement and correction; analytical study of transverse instability of rigid and non-rigid modes in space charge dominated beam

f) Coherent instabilities in high intensity proton beams: ORBIT simulations of the electron cloud in MI are undertaken, for this purpose, ORBIT was augmented with multibunch option; a series of electron cloud measurements carried out in Main Injector (beam diagnostics and DAQ system developed) , data on dependence of the electron density on proton beam parameters collected and analyzed.

Energy Deposition Group:

The ED group provides its expertise to all Fermilab accelerator based projects. It also develops corresponding software tools to simulation beam induced radiation doses and provides assistance to the US and foreign community of users of these tools. In addition, the ED group develops parallel processor capabilities for advanced scientific simulations.

Accomplishments in 2007-2008:

a) Main Injector two stage collimation system design

b) Tevatron crystal collimation experiment T980 prepared and approved

c) LHC SC magnets and detector backgrounds simulations performed for several IR configurations at luminosity 10^35 cm-2 sec-1

d) Numerical studies of the ILC Beam Delivery System (collimation and muons); 0.15 to 5 GeV transfer line collimation; dark current beam loss in Main Linac; ILC Test Accelerator beam dumps and shielding design

e) Simulations of particle yields, energy deposition, beam loss, shielding for various experiments: MTBF, MuCool, HINS, Booster, MERIT, kaon experiments, muon collider

f) MARS Code: Development of advanced physics models and extension of capabilities

g) Accelerator Physics computer server has been upgraded and relocated to a larger room

LHC Accelerator Research Group:

The group engages in studies that will provide more luminosity to the LHC and benefit present and future US accelerators. The work includes at present developing new layouts for beam optics in the LHC interaction regions, demonstrating the effectiveness of compensation schemes for mitigating beam degradation from colliding beam interactions, building new diagnostic devices for measuring beam parameters and developing new tools for theoretical analysis of beam behavior. This effort is carried out as part of the US-LARP collaboration which includes four national laboratories: Brookhaven, Fermilab, Lawrence Berkeley and SLAC.

Accomplishments in 2007-2008:

a) Accelerator Physics: Beam-beam simulations and wire compensation simulations results compared to experiments in RHIC and a good agreement with single beam data found

b) Electron Lens compensation: a Gaussian e-gun for head-on beam-beam compensation built for possible use in the Tevatron and/or RHIC experiments.

c) Schottky Monitor: four monitors installed in the LHC, controls interface developed and delivered to CERN.

d) AC Dipole was installed in the Tevatron and linear and nonlinear Tevatron optics measurement performed which allowed to measure beta* at B0 and D0.

e) Joint LHC IR Upgrade studies(with TD) has been undertaken, beam optics layout with Nb3Sn magnets in the inner triplet for the Phase I and Phase II upgrades and with crab cavities are developed

SCRF Facility Beam Physics Design Group:

This group provides beam physics support to the design of future SC RF based facilities at Fermilab, like the ILC and Project X. It carries out beam dynamics simulations for the SC RF linacs, supports the New Muon Lab ILC Test Area experiments, and supports the Illinois ground motion measurement program for the ILC, Project X and DUSEL. The group coordinates related activities in Fermilab's Accelerator, Technical and Computing Divisions.

Accomplishments in 2007-2008:

a) Main Linac: lattice designed with matching to Ring-To-Main-Linac and Beam Delivery System, static tuning and emittance growth simulated with taking into account the effects of dispersion, wakefields and global bumps on emittance dilution; CHEF code development continued

b) Dynamic tuning: adaptive alignment technique in presence of errors and ground motion is developed; LIAR algorithms and tools for multi-loop feed-back system explored

c) Short-range wakefield studies in the 1.3 GHz ILC SRF cavity: effects of asymmetry due to HOM and main couplers and RF Kick from accelerating field are evaluated numerically

d) Ground motion and vibration studies performed in the MINOS hall and the LaFarge mine in North Aurora (IL), model for FNAL site developed

e) Study of dark current dynamic and amplification in ILC linac: developed a model of generation dark current in SRF cavity and its propagation thru the main linac

II.3.b Experimental Accelerator Physics R&D programs

The mission of these Departments is to lead an experimental R&D program focused on development advanced accelerator concepts related to Fermilab's future.

HINS Department:

This department is responsible for accelerator physics and associated R&D required for development of an advanced concept, high intensity, high beam-quality H- Linac to support a future multi-megawatt neutrino facility, a Neutrino Factory, or a muon collider. This includes responsibility for the facility layout, design, and execution of the experimental program at the Meson test facility. The group will study high intensity phenomena of the Main Injector and Recycler rings, including electron cloud and resistive wall instabilities, which might impact the ability to deliver beams demanded by present and future neutrino experimental programs. The group also participates in particle tracking code development and investigates transport considerations and injection designs for high intensity multi-GeV H- beams.

Accomplishments in 2007-2008:

a) Test facility at the Meson Detector Building (MDB) is established; power, cryo, RF and safety requirements satisfied

b) First 325 MHz room temperature cavities designed, fabricated and tested at full power, specification gradient achieved

c) First 325 MHz single spoke SC RF cavities designed, fabricated and tested in a vertical test cryostat, the specification gradient exceeded (18MV/m)

d) 40mA H+ source developed and tested, moved to MDB and made operational

e) New instrument for vector signal modulations based on ferrite phase shifters is developed and successfully tested at the design RF power level

Muon Accelerator R&D Department:

The group leads an AARD program at Fermilab to develop, in collaboration with the NFMCC, Muons Inc., BNL, and LBNL, the Muon Collider concept. The focus of the R&D is, by year 2013, to develop a practical Feasibility Study for a Muon Collider; design, prototype and bench test a complete set of components needed for 6D cooling channel, design and carry out muon cooling demonstration experiment with beam of muons.

Accomplishments in 2007-2008:
(reported separately in Section III)

Experimental AAR&D Group:

The group is responsible for the development, organization, and execution of AARD activities associated with the A0 Photoinjector and NML facilities. The group is also responsible for the establishment of experimental AARD programs at outside facilities as appropriate.

Accomplishments in 2007-2008:
(reported separately in Section IV)

II.3.c Accelerator Physics Education Programs

APC consolidates various accelerator education programs which currently exist at Fermilab, to attract graduate and undergraduate students, train and develop them into the accelerator scientists and technologists who will carry our field forward in the future and enhance Fermilab's capabilities in accelerator science and related technologies.

Accelerator PhD Program:

The PhD program provides dedicated training for accelerator physicists at the Fermilab's beam facilities. The Ph.D. Program works in a joint agreement with participated universities. Fermilab provides the research facilities and mentors to guide students through their research, while the students maintain relationships with their home institution's advisers who oversee the student's progress toward their degree. The program has funds to support up to 8-10 PhD students. As of October 1, 2008, there are 5 students in the program.

Accomplishments in 2007-2008, PhD graduates: (see also Appendix II)

a) R. Miyamoto (University of Texas, Austin)

b) A. Poklonsky (Michigan State University)

c) P. Yoon (Rochester University)

d) P. Snopok (Michigan State University)

US Particle Accelerator School:

The US Particle Accelerator School provides educational programs in the field of beams and their associated accelerator technologies not otherwise available to the community of science and technology. The school conducts graduate and undergraduate level courses at U.S. universities, holding two such programs per year, one in June and one in January. Regular courses to be organized at Fermilab for the Accelerator Physics summer student program and for the PhD program. By successfully completing the courses students earn certain (3) semester hours of university credit.

Accomplishments in 2007-2008:

a) Four US Particle Accelerator Schools organized – at Texas AMU (2007, attended by 130 students), at Michigan State University (2007, 117), at UC Santa Cruz (2008, 147) and University of Maryland (2008, 147)
b) USPAS office selected the site venue, prepared the budget, and laid the administrative foundation for the 2008 Linear Collider School to be held in Chicago in October 2008.

Peoples Fellowship Program:

The APC co-hosts Fermilab's Peoples Fellowship program. The goal of the Fellowship is to attract outstanding accelerator scientists early in their careers, both to enhance Fermilab's capabilities in accelerator science and related technologies, and to train and develop the accelerator scientists and technologists who will carry our field forward in the future. As of October 1, 2008, there are 5 People Fellows in the program.

Accomplishments in 2007-2008:

a) three Fellows selected – A. Latina (2008, APC), Y. Sun (2008, APC), K. Yonehara (2007, APC)

Lee Teng Internship Program:

The Lee Teng Undergraduate Internship in Accelerator Science and Engineering has been established by the Fermilab, Argonne and US PAS to attract undergraduate students into the exciting and challenging world of particle accelerator physics and technology. As a rule, ten highly qualified students are selected into this program – 5 to work at ANL and 5 at FNAL. Successful candidates attend the Summer Session of the U.S. Particle Accelerator School (USPAS) take the *Fundamentals of Accelerator Physics and Technology with Simulations and Measurements Lab* for which undergraduate credit is available. For the remainder of the summer they will work closely with a mentor and a project at either Argonne National Laboratory or Fermilab.

Accomplishments in 2007-2008:

a) the Internship program established in Dec 2007, selection committee organized and selected the first Lee Teng Interns which worked at ANL and FNAL in Summer 2008

Summer Student Program: Physics of Accelerators and Related Technology for International students (PARTI)

The PARTI internship program has been developed to familiarize students with opportunities at the frontier of scientific research in physics and technology of particle accelerators. The PARTI Committee, consisting of Fermilab scientists and engineers, selects the best candidates from the pool of applicants. A Fermilab staff member mentors the intern on some scientific, engineering or computer task to carry out experiments, to improve the operation of the particle accelerator or to support and develop specialized research. The 10-12 week program consists of an assignment, an academic lecture series, weekly meetings, and a final report that each intern presents orally to the Fermilab staff.

Accomplishments in 2007-2008:

a) 8 students from universities of the former Soviet Union majoring in Physics, Engineering, and Computer Sciences have been selected for the 2008 PARTI.

II.4 Proposal for the Period 2010-2012

In the period of 2010-2012, major goals of the General Accelerator R&D programs to be supported under KA 15.01.02 "Future Physics – Accelerator Science" B&R category are:

1. Hardware development and experimental studies to introduce Tevatron Electron Lenses into the Tevatron operation for the purpose of routine compensation of long-range beam-beam effects; relocation of the TELs to BNL after the end of Tevatron Run II and employment of the electron lenses for the head-on beam-beam compensation in the BNL RHIC as the first step toward such compensation in the LHC; numerical and experimental studies of beam dynamics with electron columns for space-charge compensation in Main Injector and Tevatron.

2. Development of the HTS conductor and magnets for a low cost technical solutions for rapid cycling accelerators needed for future energy and intensity frontier machines.
3. Detailed exploration of the physics of the electron cloud instabilities, development of new instrumentation for analyzing the cloud, and development of the most effective mitigations by means of experimental studies of the electron cloud beam dynamics for the Fermilab's high intensity proton accelerators (including participation in the CESR-TA and CERN experiments) together with corresponding simulation program.
4. Experimental studies and data analysis of slow ground motion at Fermilab accelerators and experiments and at the DUSEL site (Homestake gold mine, South Dakota) with a goal to provide reliable input for future facilities design
5. Organization of two USPAS sessions each year, annual support of the Lee Teng Internship program in accelerator science and technology.
6. Beam theory research of the outstanding beam dynamics issues relevant to the energy and intensity frontier accelerators, including integrable solutions for beam-beam effects suppression, fast ionization cooling, optical stochastic cooling, noise spectra in high intensity bunched beams at the very high frequencies (dozens of GHz to optical).
7. Development of new methods of particle collimation for colliding and high intensity beam facilities including bent crystal collimators and hollow electron beam collimators.

To achieve these goals, the developed proposal has following technical goals and milestones for 2010-2012:

1. Electron lenses and columns:
    a. FY2009: Commissioning fast HV modulators for TEL-2; electron columns studies in Tevatron complete
    b. FY2010: Operational compensation long-range of the beam-beam effects in Tevatron;
    c. FY2011: relocation of the TELs to BNL after the end of Tevatron Run II; numerical and experimental studies of beam dynamics with electron columns complete; design of prototype electron column for SCC in MI complete;
    d. FY2012: first round of head-on beam-beam compensation experiments in RHIC; MI electron column SC magnet built and tests began.

2. Rapid cycling proton accelerator magnets:
    a. FY2009: test facility established in E4R; first HTS conductor tests in external 2T/s magnetic field complete;
    b. FY2010: fabrication of the 40-80 mm gap prototype transmission line HTS magnet and AC test at E4R; design of 120mm bore 2T/s magnet complete;
    c. FY2011: development of 5Hz PS with elements of quench protection complete; 120 mm gap prototype transmission line HTS magnet fabricated;
    d. FY2012: 120 mm gap prototype transmission line HTS magnet fully tested at max ramping rate (>5Hz, >2T/s)

3. Electron cloud:

   a. FY2009: RF waveguide electron cloud diagnostics developed and tested in MI. Coatings and new electron cloud analyzers tested in MI. Participation in the CESR-TA, including delivery of electron cloud suppression electrode;
   b. FY2010: Participate in CESR-TA electron cloud measurement and analysis, including results of the suppression electrode. New simulation codes are able to produce beam feedback results. MI measurements continue;
   c. FY2011: SLAC ECLOUD system moved to Fermilab from CESR-TA and installed in MI. Measurements of ECLOUD now made with higher intensity NOvA beams in Recycler and MI, results used to benchmark simulation codes.
   d. FY2012: MI and Recycler electron cloud studies continue at the highest proton bunch intensities for application to buncher rings. If available, measurements will be extended to the Accumulator and Debuncher rings.
4. Ground Motion:
   a. FY2009: installation and commissioning of a system of new type hydrostatic level sensors (HLS) on CDF quadrupoles; few sensor system tests for DUSEL GM studies complete;
   b. FY2010: installation and commissioning of the HLS system on the prospective Project X linac construction site; the first data analysis presented; installation and commissioning of the HLS system at the DUSEL site;
   c. FY2011: extension of the DUSEL site system by the HLSs from the Tevatron tunnel becoming available after the Tevatron shutdown;
   d. FY2012: data taking from full scale systems of HLSs and analysis of slow ground motion at Fermilab Project-X and at the DUSEL site complete;
5. Accelerator Education:
   a. FY2009: two sessions of US PAS; Lee Teng Internship program in the summer
   b. FY2010: two sessions of US PAS; Lee Teng Internship program in the summer
   c. FY2011: two sessions of US PAS; Lee Teng Internship program in the summer
   d. FY2012: two sessions of US PAS; Lee Teng Internship program in the summer
6. Beam theory and experimental advanced accelerator R&D:
   a. FY2009: bent crystal collimator experiment (T980) data taking at Fermilab's Tevatron; theoretical analysis started on feasibility of i) optical stochastic cooling (OSC) test experiment at FNAL NML test facility or at CESR-TA or at the CTF-3 at CERN, ii) measurements of the HF longitudinal fluctuations spectra in high intensity bunched proton beams with optical diffraction radiation monitors (ODRs); iii) experimental test of space-charge effects in resonant half-integer linear focusing optics channels.
   b. FY2010: bent crystal collimator experiment (T980) data taking and analysis finished; theoretical analysis and computer modeling of the three feasibility studies complete; noise spectra ODRs experiments performed in the Tevatron

and/or RHIC; computer simulations of the hollow electron beam collimator complete for MI and RHIC;

c. FY2011: design and construction of the OSC test ring starts (if proven feasible in FY2009-10) ; design and construction of a low energy half-integer resonance test beam line test ring starts (if proven feasible in FY2009-10); prototype ring cathode electron gun built and tested on a bench for hollow electron beam collimation.

II.5 Budget Request

Table II.1: Present (FY08) SWF and M&S for the R&D carried out at the APC under the Accelerator Science B&D and the requested level of support over the next 5 years. (Note, that beginning in FY09, the US PAS is supported out of KA150102 funds while in prior years it was included in KA140104).

		FY09	FY10	FY11	FY12
Electron Lenses/Columns					
	SWF	162	172	180	192
	M&S	72	44	140	180
Rapid Cyclyng Accelerators					
	SWF	142	180	240	184
	M&S	110	270	250	100
Electron Cloud R&D					
	SWF	54	58	62	42
	M&S	25	26	35	30
Ground Motion Studies					
	SWF	42	64	68	68
	M&S	5	22	48	37
Accelerator Education					
	SWF	593	622	647	678
	M&S	94	97	99	102
Beam Theory/AARD					
	SWF	82	142	184	242
	M&S	16	42	160	240
TOTAL		1397	1739	2113	2095
	SWF	1075	1238	1381	1406
	M&S	322	501	732	689

III. Muon Collider/Neutrino Factory

Note: A complete 5-year proposal has been prepared and submitted jointly by the national Neutrino Factory and Muon Collider Collaboration (NFMCC) and the Fermilab Muon Collider Task Force (MCTF). The Executive Summary of that proposal is included in Appendix III. Here we summarize the Fermilab contribution to the full program.

Connection to Future HEP Facilities

The physics program that could be pursued at a high-energy lepton collider has captured the imagination of the world high energy physics community. A lepton collider with sufficient energy and luminosity would facilitate (a) understanding the mechanism behind mass generation and electroweak symmetry breaking, (b) searching for and perhaps discovering supersymmetric particles and confirming their supersymmetric nature, and (c) hunting for signs of extra space-time dimensions and quantum gravity. The Particle Physics Project Prioritization Panel (P5), which was reconstituted by the High Energy Physics Advisory Panel (HEPAP) at the request of the Office of High Energy Physics of the Department of Energy and the National Science Foundation in May 2008, recommended *"…R&D for alternative accelerator technologies, to permit an informed choice when the lepton collider energy is established."* It is expected that this choice is likely to be made around 2012-2013.

The muon collider provides a promising path to multi-TeV lepton collisions with significant advantages compared to e+e- schemes. Since muons are much heavier particles, they do not radiate as readily as electrons. This facilitates using a ring to store and collide TeV-scale muons – in contrast to a single collision per shot in a linear e+e- collider. Correspondingly, the muon collider complex size is smaller and fits the footprint of, e.g., Fermilab. Moreover, the radiation emitted by the muon bunches in collision is also orders of magnitude lower, which assures monochromatic collisions. The long-term Muon Collider development plan, presented to P5, comprises of three important steps toward bringing high energy physics frontier back to the United States: 1) a study to demonstrate the Muon Collider feasibility by 2013; 2) a program of muon beam demonstration experiments and components tests and prototyping over the following 7-10 years; 3) start of the MC construction in early-mid 2020's.

Past physics studies have shown that multi-TeV lepton colliders will need to achieve luminosities of the order of 10^{34} cm^{-2} s^{-1}. To obtain this luminosity a muon collider will need a muon source generating O(10^{21}) muons per year within the acceptance of an accelerator. A muon source with this intensity would also facilitate a "Neutrino Factory" in which the muons are accelerated to a few GeV and stored in a ring with long straight sections. The muons decaying in the straight sections generate neutrino beams with unique properties. The neutrino factory concept has captured the imagination of the neutrino community, and the neutrino factory is considered to be the ultimate tool for studying neutrino oscillations, particularly if the unknown mixing angle θ_{13} turns out to be very small.

Organization and Personnel

Since muon collider and neutrino factory accelerator complexes have similar (possibly identical) front-ends, much of the R&D is in common. Neutrino Factory and Muon Collider R&D has been pursued in the U.S. since 1997 by the Neutrino Factory and Muon Collider Collaboration

(NFMCC), which consists of about 130 scientists and engineers from national laboratories and universities. The collaboration is led by two co-spokespeople, and managed by a project manager. This leadership reports to the Muon Collaboration Oversight Group (MCOG) which consists of members of the directorates of the three sponsoring laboratories (Fermilab, BNL and LBNL) that support the NFMCC. MCOG appoints the Muon Technical Advisory Committee (MUTAC) which reviews the NFMCC program annually, and provides a report which is transmitted, by MCOG, to the DOE. In 2006 the NFMCC program was enhanced by the formation of the Muon Collider Task Force (MCTF) at Fermilab, which is pursuing muon collider specific R&D that complements the NFMCC activities. To ensure the NFMCC and MCTF R&D is coordinated to maximize the impact of the overall muon collider and neutrino factory R&D, the Muon Collider Coordinating Committee (MCCC) was formed, comprising of the three NFMCC and two MCTF leaders.

The Muon effort at Fermilab is organized within the Accelerator Physics Center. As shown in the APC organization chart (Figure II.2), Steve Geer provides overall leadership of the department with Alan Bross and Andreas Jansson as group leaders. Fermilab also provides leadership within the national program where Bross serves as co-spokesperson of the NFMCC, and Geer and Shiltsev jointly lead the MCTF. As shown in Table III.1, a total of roughly 21 FTE's are currently assigned within this program.

Recent Accomplishments

During the last ten years there has been significant progress towards both a NF and a MC. In particular, NF R&D can be considered to be at an advanced stage. Accomplishments to date include (a) the successful completion of an international proof-of-principle MC/NF proton target experiment (MERIT), (b) the launching of an international muon transverse cooling experiment (MICE), and (c) a series of NF design and simulation studies that have progressively improved the performance and cost-effectiveness of the simulated design and culminated in the recent "International Scoping Study" (ISS) which established an internationally agreed upon initial baseline design. The ISS has prepared the way for a NF International Design Study (IDS-NF) which aspires to deliver a Reference Design Report (NF-RDR) for an updated baseline design by 2012. After the NF-RDR, following a final phase of pre-construction R&D, the NF would be an option for a future facility in the U.S. at Fermilab, or elsewhere in Europe or Asia.

Muon Collider R&D has also progressed. Recently, design concepts have been developed for a complete MC accelerator complex capable of producing multi-TeV collisions with the required luminosity. However, the present designs of the required muon 6D cooling channel employ components with assumed performances which in some cases have not yet been achieved. Further design work is required, together with component studies and demonstration tests, before a credible end-to-end simulation and cost estimate for a muon collider accelerator complex can be made.

Specific accomplishments by Fermilab within this program include:

- Host to the muon cooling technology development (MuCool) program within NFMCC. Construction and initial operations of the MuCool Test Area (MTA). The MTA has the capability to test normal conducting RF at high power and in the near future with high-intensity beam. In addition the MTA can test LH_2 and LiH absorber technology.

- Measurement and characterization of 805 MHz NCRF in high magnetic field. Investigation of material effects on operating gradient utilizing 805 MHz test cell.
- Measurement and characterization of 201 MHz accelerating cavity performance in a variety of configurations and within a magnetic field. Demonstration of operation of 201 MHz cavity at gradients above 19MV/m.
- Measurement and characterization of 805 MHz high pressure gas filled cells, up to 65MV/m (with Muons Inc.)
- Performed first tests of a convectively cooled LH_2 absorber for muon cooling.
- Developed concepts for LiH absorbers for muon cooling.
- Participated in the International Design Study for a Neutrino Factory. Contributed to the design, simulation and specifications for muon capture and phase rotation, muon cooling and acceleration. Also developed concepts for the neutrino detector for the NF facility.
- Provided beam instrumentation and particle tracking detector systems for the Muon Ionization Cooling Experiment.

A list of Fermilab generated refereed publications relating to the Muon Program is included in Appendix I.

Research Proposal through 2012

In April 2008 MUTAC reviewed both NFMCC and MCTF programs, and noted that although having two organizations is not optimal in the long term, the present organization (NFMCC and MCTF coordinated by the MCCC) is working well. MUTAC recommended the NFMCC and MCTF *"... create a 5 year integrated NFMCC and MCTF R&D plan*". This 5-year plan has now been created, and the executive summary is attached to this document as an appendix. The NFMCC and MCTF together propose a joint national muon accelerator R&D program through 2013. The proposed main deliverables of the national Muon Accelerator R&D program by 2013 are:

1. A design feasibility study report (DFSR) for a multi-TeV Muon Collider, which will be based on (*a*) a physics and detector study that refines the understanding of the required performance and documents the associated physics reach, and (*b*) an end-to-end simulation of the Muon Collider accelerator complex based on demonstrated technologies or technologies that we can anticipate will be demonstrated after a specified R&D program. The DFS will also deliver the first defensible cost estimate, and identify areas of further technology R&D that should be pursued to improve the performance and/or the cost effectiveness of the design.

2. Component development and experiments that are needed to inform the Muon Collider DFS, and enable a down-selection of candidate technologies for the required ionization cooling channel and acceleration system.

3. Participation in the International Neutrino Factory Design Study (IDS-NF) which aspires to produce a Reference Design Report (RDR) for a Neutrino Factory by 2012. The emphasis of the proposed U.S. participation is on (*a*) studying how the evolving Fermilab proton source can be used for the Neutrino Factory RDR design, (*b*) studying how the resulting Neutrino Factory would fit on the Fermilab site, and (*c*) the design, simulation and cost estimates for those parts of the Neutrino Factory front-end that are (or could be) in common with a Muon Collider.

Fermilab plays a pivotal role in the present neutrino factory and muon collider R&D program. Over the years, Fermilab personnel have contributed to every aspect of the R&D, but in particular have contributed to the leadership of the program, design and simulation studies, and to hosting and leading the muon ionization cooling R&D sub-program (MUCOOL). This has included the construction of a dedicated test area at the end of the FNAL linac to support MUCOOL component developing and testing. Demonstrating and developing the cooling channel technology for a muon collider is considered the most challenging part of the proposed 5 year plan and, to succeed, Fermilab must necessarily play a major role. The main proposed Fermilab contributions to the program are:

(i) Testing the operation of RF cavities in magnetic fields, performed at the MUCOOL test area at the end of the Femilab Linac, and studying how to build very high field solenoids using High Temperature Superconductor (HTS). These activities are crucial to provide the information needed to select a credible muon collider cooling channel design before end-to-end simulation studies can be begun.

(ii) Building and bench-testing a short cooling channel section in the second half of the 5 year period. This is crucial to inform the DFS.

(iii) Making central contributions to the simulation studies. A significantly expanded simulation effort will be required for a credible muon collider DFSR, and it is desirable that the small existing core simulation group at Fermilab be enhanced to efficiently make the required key contributions to the overall simulation effort.

(iv) Making Fermilab site-specific studies for the IDS neutrino factory, and in particular investigating how Project X could drive a neutrino factory.

Budget Request

To succeed with this plan it is proposed that the present Fermilab muon accelerator R&D effort (19 FTE) would ramp up to about 30 FTE over the next 3 years. The required effort is summarized in Table III.1. The overall Fermilab funding request is contained in Table III.2.

Table III.1: Effort (FTE) needed to support Fermilab contributions to the Muon Accelerator R&D 5 year plan activities.

	Present	FY09	FY10	FY11	FY12	FY13
Design, Simulations, Report	2.5	3.65	8	10	12	16
MC-DFS Costing	0	0	0	0	0	0

NF-RDR	0	1.5	1.5	1.5	1	0
MICE	5	6	6	6	4	1
RF R&D	8.3	6	4	3	3	3
Magnet Studies	2	4	4	4	3	3
6D Cooling Sections & Tests	3	0	3	4	7	7
Other R&D	0	0	0	0	0	0
Management	0	1.5	1.5	2	3	3
TOTAL	**20.8**	**22.65**	**28**	**30.5**	**33**	**33**

Table III.2: Budget request for the Fermilab contribution to the Muon R&D Program

	(Amounts are fully burdened $K)			
	FY09	FY10	FY11	FY12
Muon Collider and Neutrino Factory				
M&S	1656	2354	2621	2285
SWF	4041	4661	5001	5802
Total	5697	7015	7622	8087

IV. Beam Sources and Instrumentation

Note: A more extensively detailed version of this proposal is included in Appendix IV.

IV.1 Introduction and Connection to Future Facilities

The Fermilab A0 photoinjector (A0PI) is a 16 MeV electron linac injector located in the A0 service building above the Tevatron beam enclosure. Design work began on this (and for its twin at DESY) in ~1994-5. First beam was attained in 1998. It has been used for beam experiments, research, and training in the development and operation of electron injectors, lasers, advanced instrumentation, and superconducting RF systems.

The photoinjector consists of a 1.3 GHz normal conducting RF gun with a Cs_2Te photocathode, a 12MV/m 1.3 GHz TESLA "capture" cavity, a transport channel for experiments and diagnostics, a 45° bend to a dump, and a user experimental area. The injector can be configured to provide both compressed and uncompressed beam. At present two lines are configured, one straight ahead and a second with two dogleg bends configured for an emittance exchange experiment. The bunch structure of the beam is similar to the TESLA Test Facility at DESY, with 1 μs bunch spacing and bunch trains up to 200 μs duration. Bunch charge up to 10 nC is available.

Unique and Important Elements

The photoinjector initiative has brought to Fermilab not only a vehicle for growing competency in high brightness electron beam generation and manipulation and in laser and SRF technology, but it also brought a strong collaboration between Fermilab and DESY and has been key in setting at Fermilab a direction toward future SRF accelerator applications (proton or electron).

The photoinjector has over the years played a significant training and development test bed role. Students have complete access to injector that is not compromised by the pressures of operation that strongly limit studies in the accelerators of the Tevatron complex. Similarly it provides ready access and test for engineering developments such as low level RF (llrf), instrumentation, and devices such as high speed kickers. It is planned that the injector and personnel move to the NML-SRF module test area so that these activities can continue and are coupled strongly with future linear collider development. Thus the A0PI though not unique in the world of low energy photoinjectors, serves and should continue to serve a very important role at Fermilab.

The photoinjector as originally designed provides high brightness ~10nC bunch charge. Early accelerator physics experiments made use of this in pioneering plasma wakefield experiments, both acceleration and focusing. Initial electro optical beam sampling measurements have been pursued and will be returned to in the future. The technique of exploring the details of bunch compression with two macroparticles has been developed. Fast kicker systems focused on the needs of ILC have been tested. And considerable work has gone into development and test of llrf systems suitable for future linac control be it electron or proton.

In the past few years scientific emphasis has turned to developing techniques for the manipulation of the 6D beam emittance. For years people have been treating the three 2D phase spaces as separately conserved variables. However a growing number of accelerator theorists have been emphasizing that it is really the 6D emittance that is conserved and that not only is this the property that counts, but that the 2D beam properties can be transformed or exchanged to best meet the performance demands of the accelerator in question. Thus transverse beam phase space can be repartitioned between x and y emittances using the "flat beam transformation" and the transverse and longitudinal beam emittances can be exchanged using "Emittance Exchange". It is these 6D manipulations that we are focusing our efforts on at present. It is one thing to show on paper the simple linear transformations. It is another to actually realize and measure them in the laboratory with a beam that has other forces at play on it. The degree of success and difficulty will impact use in future practical application. These potential applications exist both in FELs and linear colliders. It is very possible that others will emerge as further ideas on 6D manipulations and experiments develop. Recently we have investigated the concept of transverse adiabatic capture (similar in principal to longitudinal adiabatic capture) as a potential way to ameliorate space charge effects.

Collaboration with outside groups.

Collaboration with outside groups has been mostly through student and their advisor involvement. This brings new ideas and knowledge to the effort. We are expanding our efforts to encourage more outside Fermilab participation. We have good connection with ANL and NIU and plan to enlarge the participation with other groups such as the University of Maryland and the University of Wisconsin.

IV.2 Recent Accomplishments

Significant accomplishments include:

- Plasma wakefield experiments with high charge beams
- Measurement of beam transverse wakefields with electro-optical sampling
- Characterization of bunch compression with two macroparticles
- Round-to-flat beam transformation attaining an emittance ratio of 100:1
- Emittance exchange experiments (ongoing), including development of a normal conducting 3.9 GHz deflecting mode cavity.
- 9 graduate student PhD's (past and current students); Yin-e Sun won 1st place for Beam Dynamics Thesis at PAC05; Mike Fitch won the URA thesis award in 2001

Significant refereed publications over the last several years are included in Appendix I.

IV.3 Research Proposal

Proposed research outline

The schedule for A0 Photoinjector over the next few years is broken into 3 components.

- Continued operation at the A0 location till the end of FY2010 when the TEVATRON is scheduled to turn off.
- The move of the injector to NML and its incorporation into the NML test facility and recommissioning in 2011.
- Operation of the photoinjector in 2012 and beyond, in order to support both testing of SRF modules with beam and to support accelerator science beam study activities (Mid-West AARD Center) both at the injector energy level (~40MeV) and at the higher energies provided by the SRF accelerating modules.

The move to NML is driven both by the need for electron beam at NML in order to carry out realistic systems tests and by the fact that the A0PI relies upon TeV operation for its cryogens infrastructure. It does not appear cost effective either to operate A0PI stand alone in its present dewar fed configuration or to install a stand alone refrigerator for its support.
Additionally it is felt to be much more productive and resource efficient to combine activities at NML rather than to try to support two separate activities of a very similar nature at two locations.

Research activities FY09, FY10 at A0PI: Beam Physics/Novel Accelerator Concepts

6D Emittance Manipulations

1.0 Continued work on transverse to longitudinal emittance exchange (EEX).
The next generation of the emittance exchange experiment will focus on emittance measurements after the exchange for different initial transverse and longitudinal phase space configurations and bunch charges. Emittance exchange in combination with flat beam transforms can possibly be a path to providing matched 6D beams for high gain FELs and for long term research toward HEP-ILC injector without damping ring matched to final linac emittance parameters. The focus will include investigations into collective effects (CSR and space charge), which we expect are present and into perfecting the exchange without excessive emittance growth. An understanding on our part of these effects and how to deal with them is necessary for our beamline designs for NML.

We will also investigate the possibility of bunch train generation at the sub ps level from single bunches by inserting a mask slit in the transverse plane and by EEX converting a bunch to a bunch train. Success in this area could point to mini or mirco bunch pre seeding of undulators. We expect strong collaboration with ANL and NIU on these experiments and are collaborating with them on the realization of the EEX.

2.0 Short pulse drive laser and ellipsoidal low emittance bunch generation

Three-dimensional ellipsoidal charge distributions produce linear space charge fields within the distribution and are in principle free of space-charge-induced phase space dilution. With the development of a short pulse drive laser, beam conditions necessary for ellipsoidal bunch generation can be achieved at the A0PI. The generation of ellipsoidal bunches from magnesium and copper cathodes has been recently demonstrated, however generating such a distribution out of a high quantum efficiency semiconductor cathode such as Cs_2Te would be an important proof-of-principle experiment, which we propose to do. This technique may prove to be the best way to generate high brightness, low emittance electron bunches by photocathodes, and several current FEL projects might benefit from it. A recent trend in FEL thoughts is toward very high brightness 6D beams which may be best achieved at low bunch charge. We can explore this phase space. NIU will provide components of the short pulse TiSa laser.

3.0 Microbunching Investigation

Microbunching of high intensity compressed beams from (presumably) a combination of CSR and space charge effects has recently been identified as a source of error in emittance diagnostics of such beams at a number of electron beam facilities. These effects severely limit the use of many standard beam size diagnostics over a wide range of relevant beam parameters. We are considering a series of experiments to study whether we observe this effect, to further understand it and possibly mitigate it. This study is likely to be related to the mini bunch generation discussed in 1.0 above.

4.0 Investigation of the feasibility of an image charge undulator

A possible longer term theme of emittance manipulation includes the improvement of the round-to-flat beam transformation and its adaptation for use in an image charge undulator. Round-to-flat beam experiments have attained a ratio of 100:1 in the transverse emittance ratio. We are interested in exploring the practical difficulties of handling a beam passing through a two plate grating and in trying to push the flat beam ratio even higher.

5.0 Other emittance manipulations

We are open to exploring other possible emittance and beam manipulations as the concepts emerge. Recently we preformed an initial investigation of the idea of "transverse adiabatic capture", reported above. It does not seem feasible to pursue this direction further at this time as the benefit seemed marginal with respect to the investment in developing a small ring.

Recently it was pointed out to us that a skew quad may be used as a diagnostic to provide bunch slice information under certain circumstances. We intend to explore this technique.

Beam Sources and Instrumentation

Our investigations of low emittance beams and emittance manipulations have driven us in the direction of diagnostic developments necessary or of valuable potential for understand in our beams. These efforts are not necessarily unique but are of core value in the measurement of high brightness beams and give us the necessary expertise.

There are a number of beam diagnostic instruments that we are currently developing and will continue to develop in the near time scale. In particular, we are developing several promising techniques for bunch length monitoring for very short beams: a non-intercepting technique using electro-optical (EO) sampling; a more standard technique using a deflecting mode cavity; a technique using coherent transition radiation (CTR) from a flat screen radiator; and a technique using Martin-Puplett interferometry.

Diagnostics under use and development:

- Streak camera
- Pyro detector
- Martin-Puplett interferometer
- Electro-optical modulator, time of flight monitor
- Optical transition radiation interferometry (OTRI)
- Schottky Detector

Diagnostics that will be developed:

- Electro optical Sampling
- Flat screen radiator coherent transition radiation bunch length diagnostic (in conjunction with Univ Maryland)
- HOM Signal Processing

- Cold Cavity BPM

Injector configuration improvements

- During the time scale FY09-FY10 we will be reconfiguring the injector. The main elements of this reconfiguration are:
- new gun system and cathode chamber
- replacement of the TESLA “capture cavity” with one of better gradient performance
- installation of a chicane compressor in addition to the double dogleg

Technology

Technology R&D has always been an important part of the A0PI activities. This has included the initial photoinjector, laser and SRF cavity installation. It has evolved toward instrumentation developments, plasma sources, laser improvements, SRF 3.9GHz development, and low level RF (llrf) control.

llrf

LLRF is core for many plans at Fermilab. Improvements and characterization of the llrf systems will continue at A0. The fact that there are three systems with different requirements and a beam to study beamloading makes A0 a very valuable test bed.

laser

Development and improvement of the photocathode drive laser continues with conversion to diode pumped amplifiers. A TiSa laser will be assembled for the ellipsoidal beam test. A laser is being developed for EO sampling and research into fiber laser technology will be initiated.

3.9GHz SRF

Extensive effort has gone into developing 3.9 GHz SRF cavities at Fermilab. Cavities will be provided to FLASH at DESY for optimization of the bunch compression. The study of the benefits of these cavities to the SASE process will be important accelerator science. At Fermilab we can benefit from the use of both accelerating and deflecting mode cavities in bunch compression and streak-crab capability respectively. Though 3.9 SRF one cavity modules are expensive to fabricate and install, the development is essentially done and installation at NML would allow for benefit of this effort and study with beam. The deflecting mode cavity has potential generic application at ILC final focus.

Other

The A0PI group is interested in developments of photocathodes and of polarized RF guns. This interest is driven by the potential to use 6D emittance manipulations to try to provide linear collider like beams. Low emittance polarized electron guns would be key. These could be normal or SRF. At present this activity is more of a dream than an effort.

SRF guns are of interest for many applications. Others are actively working in this area.

Research activities FY11

During this time the Photoinjector will be moved and reinstalled at NML It will be recommissioned and characterized. A branch beamline off the injection line to the linac modules is planned. This line parallel to the injector would allow for continuation of accelerator science experiments like those at A0 to continue at the higher injector energy. 3.9 GHz SRF accelerating and deflecting mode cavities will be developed for energy linearization and beam streak diagnostics or beam crabbing. Design and development of the line will take place in FY11.

Research activities FY12

By FY12 accelerator science activities now carried out at A0PI will have migrated to NML. Both the injector area and the high energy beam will be available for experiments, student support, and technology development and testing. Initial research areas were discussed in a workshop held in the fall of 2006 (http://home.fnal.gov/~piot/ILCTA_AARD/index.html).

IV.4 Schedule and Budget Request

The requested budget for FY09-11 is presented in Table IV.1. Supported activities and required manpower are as follows:

FY09

A goal in FY09 is to prepare for installation of the new gun system, the improved 9 cell TESLA cavity (capture cavity), a chicane compressor and downstream beamline elements in both the chicane and dogleg lines. The funding uncertainties of the continuing resolution make it difficult to predict when M&S will be available for fabrication and procurement of new parts. We believe that at best parts would be available near the end of FY09, but possibly could not delayed until FY10. Operation will continue throughout the year until a shutdown for installation is possible.

Parts associated with the new gun system will be provided by the NML SRF infrastructure group (contingent on funding) as this allows both of us to gain experience with the new gun before its move to NML. The capture cavity exists and will be tested soon. the chicane, vacuum and beamline elements are the responsibility of the A0PI.

The A0 group has four directly assigned staff. The balance of personnel support is heavily matrixed, primarily from the Accelerator Division and APC. A total of 11 FTE are supported by the budget in Table IV.1. This is an increase of 3-4 over FY08 and recognizes the need to bring the group to critical mass. Not included are two participating students from Northern Illinois University.

FY10

The budget request for FY10 is similar to the higher level of FY09 and reflects the probability of beamline fabrication in FY10 and increased funds for 3.9 SRF cavity and module development. The level of effort is expected to remain about the same. More students will be sought.

FY11

The move to NML will take place. The main responsibility for new components for the injector to the linac modules will be handled by the NML-SRF infrastructure group. However laser and instrumentation improvements will continue and the injector experimental line will need design and initiation of fabrication and installation. Fabrication of a 3.9 GHz SRF module will be undertaken. During the move to NML the mix of matrixed support may shift more toward mechanical and electrical installation. Much of this will be covered by NML-SRF infrastructure. However planning, design, and development of the parallel Accelerator Science injector beam line and the planning of experimental utilization of it and the high energy area will take place.

Table IV.1: Budget request for the Fermilab Beam Sources and Instrumentation Program

		All amounts are fully burdened $K		
		FY09	FY10	FY11
A0 Operations				
	M&S	335	235	305
	SWF	1591	2316	3097
A0 Upgrade				
	M&S	114	625	680
	SWF	742	772	803
TOTAL Beam Sources & Instrumentation		2782	3948	4885

Appendix I: Selected Recent Fermilab Accelerator Science Referreed Publications (2005-2008)

Beam Sources and Instrumentation

(1)*Transverse and longitudinal beam dynamics studies at the Fermilab photoinjector*
J.-P. Carneiro, N. Barov, H. Edwards, M. Fitch, W. Hartung, K. Floettmann, S. Schreiber, M. Ferrario, **Phys. Rev. ST Accel. Beams** 8: 040101 (2005)

(2) *Photoinjector generation of a flat electron beam with transverse emittance ratio of 100*
P. Piot, Y.-E Sun, and K.-J. Kim, **Phys. Rev. ST Accel. Beams** 9, 031001 (2006).

(3) *Experimental investigation of the longitudinal beam dynamics in a photoinjector using a two-macroparticle bunch*, P. Piot, R. Tikhoplav, D. Mihalcea1, and N. Barov
Phys. Rev. ST Accel. Beams 9, 053501 (2006).

(4) *Longitudinal electron bunch diagnostics using coherent transition radiation*
D. Mihalcea, C. L. Bohn, U. Happek, and P. Piot,
Phys. Rev. ST Accel. Beams 9, 082801 (2006).

(5) *Performance of the upgraded laser system for the Fermilab-NIU photoinjector*
Jianliang Li, Rodion Tikhoplav and Adrian C. Melissinos
Nuclear Instruments and Methods in Physics Research Section A **564**, 57-65 (2006).

(6) *Results from the UCLA/FNPL underdense plasma lens experiment*
M. C. Thompson, H. Badakov, J. B. Rosenzweig, G.Travish, H. Edwards, R. Fliller, G. M. Kazakevich, P. Piot, J. Santucci, J. Li and R. Tikhoplav
International Journal of Modern Physics A, Vol. 22, No. 22 (2007) 3979-3987.

Muon Collider/Neutrino Factory

(1) *Optimizing the adiabatic buncher and phase-energy rotator for neutrino factories.*
A.A. Poklonsky, D. Neuffer, M. Berz, D.A. Ovsyannikov, A.D. Ovsyannikov
Nucl.Instrum.Meth.A558:135-141,2006.

(2) *A Cost-effective design for a neutrino factory.*
J.S. Berg *et al.* **Phys.Rev.ST Accel.Beams** 9:011001,2006.

(3) *Near detector at a neutrino factory.*
M. Ellis, F.J.P. Soler, **Nucl.Instrum.Meth.**A569:127-131,2006.

(4) *The Scattering of muons in low Z materials.*
By MuScat Collaboration (D. Attwood *et al.*).
Nucl.Instrum.Meth.B251:41-55,2006.

(5) *The effects of surface damage on RF cavity operation.*
By Neutrino Factory and Muon Collider Collaborations (A. Hassanein *et al.*).
Phys.Rev.ST Accel.Beams 9:062001,2006.

(6) *A Low energy neutrino factory for large theta(13).*
S.Geer, O.Mena, Silvia Pascoli, **Phys.Rev.D**75:093001,2007.

(7) *Neutrino factories: realization and physics potential.*
S. Geer, M.S. Zisman, **Prog.Part.Nucl.Phys.**59:631-693,2007.

(8) *Low-energy ionization cooling of ions for beta beam sources.*
By Neutrino Factory and Muon Collider Collaborations (D.Neuffer *for the collaboration*).
Nucl.Instrum.Meth.A585:109-116,2008.

(9) *A Neutrino factory for both large and small theta(13).*
A.Bross, M.Ellis, S.Geer, O.Mena, S.Pascoli, **Phys.Rev.D77:**093012,2008.

(10) *Accelerator design concept for future neutrino facilities.*
by ISS Accelerator Working Group (J.S. Berg *et al.*). RAL-TR-2007-23, FERMILAB-APC, Feb 2008. **arXiv:0802.4023** [physics.acc-ph]

(11) *Detectors and flux instrumentation for future neutrino facilities.*
By ISS Detector Working Group (T. Abe *et al.*). RAL-TR-2007-24, Dec 2007.
arXiv:0712.4129 [physics.ins-det]

(12) *Muon Collider Task Force Report.*
C. Ankenbrandt *et al.* FERMILAB-TM-2399-APC, FERMILAB-APC, Dec 2007.

Accelerator and Beam Physics

(1) *Parametrization of the driven betatron oscillation.*
R. Miyamoto, S.E. Kopp, A. Jansson, M.J. Syphers,
Phys.Rev.ST Accel.Beams 11:084002,2008.

(2) *A test of a 2 Tesla Superconducting Transmission Line Magnet System,* H. Piekarz et al., **IEEE Transaction on Applied Superconductivity,** Vol. 16, No 2, p 342, 2006

(3) *Design Considerations for Fast-Cycling Superconducting Accelerator Magnets of 2 T B-field Generated by Transmission Line Conductor of up to 100 kA Current,* H. Piekarz et al., **IEEE Transactions on Applied Superconductivity,** Vol.18, No 2, p 256 (2008)

(4) *Beam-Based Alignment of the NuMI Target Station Components at FNAL.* R. Zwaska, et al., **Nucl.Instrum.Meth.A568**:548-560,2006.

(5) *Secondary beam monitors for the NuMI facility at FNAL.* S. Kopp, et al., **Nucl.Instrum.Meth.A568**:503-519,2006.

(6) *Transverse coherent instability of a bunch in a rectangular potential well.*
V. Balbekov. **Phys.Rev.ST Accel.Beams** 9:064401,2006

(7) *Beam-Beam Effects in Tevatron*
V. Shiltsev, et al.,, **Phys. Rev. ST Accel. Beams** 8: 101001 (2005)

(8) *Experimental demonstration of colliding beam lifetime improvement by electron lenses*
V.Shiltsev, et al., **Phys.Rev.Lett.99:**244801,2007.

(9) *The Origination and Diagnostics of Uncaptured Beam in the Tevatron and Its Control by Electron Lenses.*
X.-L.Zhang, et al., **Phys.Rev.ST Accel.Beams** 11:051002,2008.

(10) *Experimental Studies of Compensation of Beam-Beam Effects with Tevatron Electron Lenses.*
V. Shiltsev, et al., **New J.Phys.**10:043042,2008.

(11) *Tevatron Electron Lenses: Design and Operation*
V. Shiltsev, et al.,, **Phys. Rev. ST Accel. Beams** 11: 103501 (2008)

(12*) Applications of parallel computational methods to charged-particle beam dynamics.*
A. Kabel, Y. Cai, M. Dohlus, T. Sen, R. Uplenchwar, **Nucl.Instrum.Meth.A558**:163-167,2006.

(13) *Mitigating radiation loads in Nb(3)Sn quadrupoles for LHC upgrades.*
N.V. Mokhov, I.L. Rakhno, **Phys.Rev.ST Accel. Beams** 9:101001,2006.

(14) *Machine-Related Backgrounds in the SiD Detector at ILC.*
D.S. Denisov, N.V. Mokhov, S.I. Striganov, M.A. Kostin, I.S. Tropin, , **JINST 1:**P12003,2006

(15) *High-Efficiency Volume Reflection of an Ultrarelativistic Proton Beam with a Bent Silicon Crystal* , W.Scandale et al. **Phys. Rev. Lett. 98**, 154801 (2007)

Appendix II: Joint Fermilab-University Accelerator PhD Program Graduates (2000-2008)

Michael Fitch (2000) , University of Rochester
"Electrooptic Sampling of Transient Electric Fields from Charged Particle Beams"

Jean-Paul Carneiro (2001), Paris XI (France)
"Etude Experimentale du Photo-injecteur de Fermilab"

Vadim Kashikhin (2001), Efremov Institute (Russia)
"Design and Optimization of Superconducting Accelerator Magnets"

Vincent Wu(2002), Cincinnati University
"Design and Testing of a High Gradient Radio Frequency Cavity for the Muon Collider"

Linda Imbasciati (2003), TU-Vienna (Austria)
"Studies of Quench Protection in Nb3Sn Superconducting Magnets for Future Particle Accelerators"

Mohammad Alsharoa (2004), Illinois Institute of Technology
"Electromagnetic and Mechanical Design of Gridded Radio-frequency Cavity Windows"

Kip Bishofberger (2005) UCLA
"Tevatron Beam-Beam Compensation"

Ludovic Nicolas (2005), Glasgow (UK)
"Radiation environment simulations at the Tevatron, studies of the beam profile and measurement of the Bc meson mass"

Sergei Seletskiy (2005), Rochester University
"Attainment of Electron Beam Suitable for Medium Energy Electron Cooling"

Robert Zwaska (2005), University of Texas, Austin
"Accelerator systems and instrumentation for the NuMI neutrino beam"

Xiaobiao Huang (2005), Indiana University
"Beam Diagnosis and Lattice Modeling of the Fermilab Booster"

Bernardo Bordini (2006), University of Pisa (Italy)
"*Thermo-magnetic instabilities in Nb3Sn superconducting accelerator magnets"*

Pavel Snopok (2007), Michigan State University
"Capture of a Large Phase Space Beam"

Phil Yoon (2007), University of Rochester
"Error-Induced Beam Degradation in Fermilab's Accelerators"

Alexei Poklonsky (2008), Michigan State University
"Optimization and Control of Tevatron Parameters"

Ryoichi Miyamoto (2008), University of Texas, Austin

Appendix III: Muon Accelerator R&D 5-Year Plan (2009–2013)

Executive Summary

The physics program that could be pursued at a high-energy lepton collider has captured the imagination of the world high energy physics community. A lepton collider with sufficient energy and luminosity would facilitate:

- understanding the mechanism behind mass generation and electroweak symmetry breaking
- searching for, and perhaps discovering, supersymmetric particles and confirming their nature
- hunting for signs of extra space-time dimensions and quantum gravity.

Past studies have motivated lepton colliders with multi-TeV center-of-mass energies and luminosities of the order of 10^{34} $cm^{-2}s^{-1}$. Physics results obtained from CERN's Large Hadron Collider on the time scale of ~2013 are expected to establish the desired energy for the next lepton collider and refine our knowledge of the required luminosity. The Particle Physics Project Prioritization Panel (P5) has recommended *"...R&D for alternative accelerator technologies, to permit an informed choice when the lepton collider energy is established."* At present, the alternatives for a multi-TeV collider are: *a*) a $\mu^+\mu^-$ collider (MC); *b*) a normal-conducting RF e^+e^- linear accelerator (X-band NLC-type or two-beam CLIC-type); or *c*) a plasma wakefield e^+e^- linear accelerator driven either by lasers or by short electron bunches. Since muons—being much heavier particles than electrons—emit negligible synchrotron radiation, the MC promises superior attributes in a number of areas compared with either e^+e^- scheme. The absence of synchrotron radiation allows high-energy muon bunches to be stored in a compact collider ring, so a MC complex would fit conveniently on the site of an existing laboratory, e.g., Fermilab. Moreover, the radiation of particles in the collision of muon bunches is orders of magnitude lower than in e^+e^- collisions, and hence the $\mu^+\mu^-$ collisions would be more monochromatic. These attributes could well prove decisive in selecting the technology of the lepton collider to follow LHC.

To achieve the desired luminosity, a MC will need a muon source capable of delivering $O(10^{21})$ muons per year within the acceptance of an accelerator. In addition to facilitating a MC, a muon source with this capability[1] would also enable a new type of neutrino facility in which muons decaying in a storage ring with long straight sections produce a neutrino beam with unique properties. It has been shown that the resulting Neutrino Factory (NF) would deliver unparalleled performance in studying neutrino mixing and provide tremendous sensitivity to new physics in the neutrino sector. Both the MC and NF require similar—perhaps identical—front ends, and hence much of their associated R&D is in common.

Muon Collider and Neutrino Factory R&D has been supported in the U.S. for the last decade. The main R&D accomplishments include: *a*) the construction and successful completion of an

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[1] Prospects for a MC and/or a NF in the U.S. have recently improved due to the possibility of launching an 8 GeV SC RF proton linac project (Project-X) at Fermilab, since the upgraded linac could serve as the required proton driver.

international proof-of-principle MC/NF high-power target experiment (MERIT); *b*) the launching of an international muon ionization cooling experiment (MICE); and *c*) a series of MC and NF design and simulation studies that have progressively improved the performance and cost-effectiveness of the simulated NF design and prepared the way for a corresponding MC end-to-end design and initial cost estimate. Neutrino Factory R&D is now being pursued by an international community that has launched the "International Design Study of a Neutrino Factory (IDS-NF)", and aspires to deliver a Reference Design Report (NF-RDR) for a baseline design by 2012. The U.S. MC and NF R&D community is making key contributions to many aspects of the IDS-NF, with an emphasis on those common to both MC and NF designs. Since a MC requires a much more ambitious muon cooling scheme, MC R&D is less advanced. Present MC cooling channel designs employ components with assumed performance that in some cases has not yet been achieved.

The long-term MC development plan presented to P5 comprises three important steps toward bringing the high-energy physics frontier back to the U.S.: *i*) a study to demonstrate MC feasibility by 2013; *ii*) a subsequent program of muon beam demonstration experiments, component tests, and prototyping over the following 7–10 years; and *iii*) the start of MC construction in the early to mid 2020s. In parallel with this MC effort, the medium-term Neutrino Factory development plan presented to P5 comprises: *i*) completing the MICE experiment and participating in the IDS-NF to deliver a NF-RDR by 2012; and (assuming the community wishes to proceed) *ii*) pre-construction R&D for the next few years with an option to begin construction in the late 2010s. This document describes a proposal for a unified, national Muon Accelerator R&D program for the coming 5 years (2009–2013)—the first step in the plan presented to P5.

The main deliverables of the national Muon Accelerator R&D program will be:

4. A Design Feasibility Study Report (DFSR) for a multi-TeV MC including a physics and detector study that refines our understanding of the required performance and documents the associated physics reach, an end-to-end simulation of the MC accelerator complex using demonstrated, or likely soon-to-be demonstrated, technologies, a defensible cost estimate, and an identification of further technology R&D that should be pursued to improve the performance and/or the cost effectiveness of the design.

5. Component development and experiments that are needed to inform the MC-DFSR studies, and enable an initial down-selection of candidate technologies for the required ionization cooling and acceleration systems.

6. Participation in the International Neutrino Factory Design Study (IDS-NF) to produce a Reference Design Report (RDR) for a NF by 2012. The emphasis of the proposed U.S. participation is on: *a*) design, simulation and cost estimates for those parts of the NF front-end that are (or could be) in common with a MC; *b*) studying how the evolving Fermilab proton source can be used for the Neutrino Factory RDR design; and *c*) studying how the resulting NF would fit on the Fermilab site.

The present annual level of support for all MC- and NF-related R&D in the U.S. is about $7.5M. The projected funding for the 5-year program proposed here is about $21M/yr, i.e., a threefold increase (see table below). With this increased support[2], we expect to demonstrate feasibility of the MC based on a credible design, an end-to-end simulation of the full accelerator complex, and a first cost estimate. We will also accomplish sufficient hardware R&D (RF, magnets, and cooling section prototyping) to guide, and give confidence in, our simulation studies.

Current-year (FY08) support for the NF and MC R&D, and the requested level of support*) for the unified national 5-year plan of the Muon Accelerator R&D program.

	FY08	FY09	FY10	FY11	FY12	FY13
Effort (FTE)	32	50	58	72	83	87
M&S ($M)	1.8	2.1	4.8	5.5	5.6	5.0
Total ($M)	7.5	11.1	15.3	18.6	20.6	20.8

*) FY09-13 numbers are preliminary. Estimates will be refined for the final proposal.

The program is foreseen to comprise participants from the three sponsoring U.S. laboratories (BNL, FNAL, LBNL) and a number of other U.S. laboratories, universities and SBIR companies. Significant international collaboration with the UK, and with other countries, to understand, develop and exploit the accelerator science and technology of muon accelerators is also anticipated. Most of the support is envisioned to come from the DOE/OHEP Accelerator Science budget, with small (~12%) contributions from the DOE/OHEP Detector R&D budget and from the DOE SBIR/STTR and University grants.

By ~2013 we expect that new physics results from the LHC and from the next generation of neutrino experiments (Double Chooz, Daya Bay, T2K, and Nova) will be available. These will provide the worldwide HEP community with the knowledge it needs to identify which types of facilities are best suited to fully exploit the exciting new physics opportunities that will undoubtedly arise. In particular, we expect that the physics cases for both a multi-TeV lepton collider and a Neutrino Factory will be more fully understood in this time frame. Our proposed work will give clear answers to the questions of expected capabilities and performance of muon-based facilities, and will provide defensible estimates for their cost. This information will allow the HEP community to make well-informed decisions regarding the optimal choice of new facilities. We believe that this work is an absolutely critical part of any broad strategic program in accelerator R&D and, as the P5 panel has recently indicated, is essential for the long-term health of high-energy physics.

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[2] The present level of support will only suffice to enable us to meet our existing commitments to the international R&D program, namely MICE and the IDS-NF, and to pursue a reduced-scope version of the RF R&D program described in our proposal.

Appendix IV: A0 Photoinjector Complete Proposal

Beams-doc-3248

Proposal for Experiments and Upgrades at the A0 Photoinjector

Editor: Mike Church

Contributors: Leo Bellantoni, Nathan Eddy, Don Edwards, Helen Edwards, Ralph Fiorito, Ray Fliller, Elvin Harms, Grigory Kazakevich, Tim Koeth, Alex Lumpkin, Sergei Nagaitsev, Philippe Piot, Jinhao Ruan, Vic Scarpine, Bill Soyars, Yin-e Sun, Mike Syphers, Randy Thurman-Keup, Manfred Wendt

November 10, 2008

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1 Introduction

The Fermilab A0 photoinjector (A0PI) is a 16 MeV electron linac located in the A0 service building above the Tevatron beam enclosure. Since 1992 it has been used for accelerator research and training in the development and operation of electron injectors, lasers, and superconducting RF systems [1]. The photoinjector consists of a 1.3 GHz normal conducting RF gun with a Cs_2Te photocathode, a low gradient 1.3 GHz TESLA technology "capture" cavity, a transport channel for experiments and diagnostics, a 45° bend to a dump, and a user experimental area. The beam parameters and the current beamline layout are shown in Appendices 6.1 and 6.2, respectively.

The injector can be configured to provide both compressed and uncompressed beam. The bunch structure of the beam is similar to the TESLA Test Facility at DESY, with 1 μs bunch spacing and bunch trains up to 200 μs duration. Bunch charge up to 10 nC has been available, and such high charge bunches have been used in successful plasma wakefield experiments [2].

Another area of focus has been round-to-flat beam transformation experiments in which equal emittances in the two transverse planes are repartitioned to give a very large relative ratio of 100:1. This experiment required the addition of a three quadrupole "transformer" and the ability to provide magnetic field (B_z) on the cathode. It was completed in 2005 [3]. Other experiments at this time included the characterization of the bunch compression with two macroparticles [4]. The present ongoing experiment attempts to perform efficient emittance exchange between the longitudinal plane and one transverse plane. This experiment has required a reconfiguration of the beam line. The magnetic chicane was removed and reconfigured into a two dogleg arrangement with a deflecting mode cavity after the first dogleg. The deflecting mode cavity was previously developed in a superconducting version for an HEP experiment [5]. The emittance exchange experiment, with its very short bunch lengths, has reemphasized the need for developing better methods of bunch length measurement. Present experiments typically use 1 nC bunch charge, and at this intensity coherent synchrotron radiation (CSR) can be important. This proposal addresses the following experimental themes.

Theme 1: Generation, transport, and manipulation of high-brightness electron beams

The next generation of the emittance exchange experiment will focus on emittance measurements after the exchange for different initial transverse and longitudinal phase space configurations and bunch charges. Emittance exchange in combination with flat beam transforms can possibly be a path to providing matched beams for high gain FELs and other applications [6]. The focus will include some investigations into collective effects, which we expect are present. We will also investigate the possibility of bunch train generation at the sub ps level from single bunches. We expect strong collaboration with ANL and NIU on these experiments.

Thee-dimensional ellipsoidal charge distributions produce linear space charge fields within the distribution and are in principle free of space-charge-induced phase space dilution. Beam conditions necessary for ellipsoidal bunch generation can in principle be achieved at the A0PI. The generation of ellipsoidal bunches from magnesium and copper cathodes has been recently demonstrated [7][8], however generating such a distribution out of a high quantum efficiency semiconductor cathode such as Cs_2Te would be an important proof-of-principle experiment, which we are proposing to do. This technique of generating high brightness electron bunches by photocathodes could benefit several projects [9].

Microbunching of high intensity compressed beams from (presumably) a combination of CSR and space charge effects has recently been identified as a source of error in emittance diagnostics of such beams at a number of electron beam facilities [10]. These effects severely limit the use of many standard beam size diagnostics over a wide range of relevant beam parameters. We are considering a series of experiments to study this effect to further understand it and possibly mitigate it.

A possible longer term theme of emittance manipulation includes the improvement of the round-to-flat beam transformation and its adaptation for use in an image charge undulator. Round-to-flat beam experiments have attained a ratio of 100:1 in the transverse emittance ratio, and we are interested in pushing this ratio even higher.

Transverse adiabatic capture of a ring beam is an accelerator physics concept that has been developed by Y. Derbenev [11] and requires a proof-of-principle experiment. This concept incorporates the flat beam transformation and possibly the emittance exchange. It may provide a path toward developing lower emittance beams at high charge density, and it may help in the goal of developing ILC-like injector parameters. We plan to study how it could be implemented but don't expect to be able to complete this experiment until the photoinjector is moved to the new test accelerator at the New Muon Lab (NML) building.

Theme 2: Diagnostic experiments

There are a number of beam diagnostic instruments that we are currently developing and will continue to develop in the near time scale. In particular, we are developing several promising techniques for bunch length monitoring for very short beams: a non-intercepting technique using electro-optical (EO) sampling; a more standard technique using a deflecting mode cavity; a technique using coherent transition radiation (CTR) from a flat screen radiator; and a technique using Martin-Puplett interferometry.

Theme 3: Technology development

The A0PI group has also been interested in developing a spin polarized RF gun using a GaAs photocathode. This photocathode is extremely sensitive to vacuum conditions in the gun, and to date has only been successfully used in DC guns. Fermilab is collaborating with DULY Research Inc. to produce a Plane Wave Transformer (PWT) gun which has an open RF structure which will allow for greater pumping via a sputtered non-evaporate getter (SNEG) coating. To this end, A0 has a cathode preparation chamber for GaAs photocathodes which has yet to be commissioned. DULY Research Inc is building the gun, and is funded by a Phase II SBIR.

Another technology that may prove useful for a spin polarized electron RF gun is a superconducting RF gun. Such a gun will have excellent vacuum and may support such a cathode. BNL is already pursuing this course, and we hope to leverage our SRF infrastructure to collaborate with them on this project.

LLRF development is a core development for many plans at FNAL. The A0PI with its different cavity systems and beam is an ideal and unique test bed at FNAL for this development.

In addition to near term work on the cathode drive laser and the development of a laser for an EO system, we have plans to become knowledgeable in fiber laser technology as this technology may provide better and less costly alternatives to today's solutions.

It is worth noting that with a higher energy beam the laser acceleration experiment proposed by Melissinos [12][13] using a ring structure laser would be possible. We are not at this time considering this experiment. Also with our large bunch charge capability (~10 nC), plasma experiments are possible and have been done at the A0PI in the past. We do not plan to pursue these experiments at present as very competitive work is being done elsewhere.

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2 Beam physics experiments

2.1 Emittance exchange experiments

Transverse to longitudinal emittance exchange was proposed by Y. Orlov et al. in 1991 [1]. In 2002, Cornacchia and Emma proposed an approximate exchange which consists of a dipole mode cavity flanked by two doglegs of opposite sign [2]. K.–J. Kim modified the optics to achieve exact emittance exchange [3]. Based on Kim's optics, a transverse to longitudinal emittance exchange experiment is currently being performed at the A0PI. The goals of the experiment are: demonstrate proof-of-principle, study the dynamics of the exchange, understand emittance diluting effects in the exchange, and develop mitigating strategies for the dilution. This experiment uses two doglegs with a deflecting mode cavity between them to exchange the horizontal and longitudinal emittances. This is followed by a short diagnostics section and a vertical spectrometer before the beam dump.

The 4x4 transverse/longitudinal transport matrix is of the form

$$R = \begin{pmatrix} A_{11} & A_{12} & B_{11} & B_{12} \\ A_{21} & A_{22} & B_{21} & B_{22} \\ C_{11} & C_{12} & D_{11} & D_{12} \\ C_{21} & C_{22} & D_{21} & D_{22} \end{pmatrix}.$$

Following the notation of D. Edwards [4], let α be the bend of each magnet in a dogleg and L_1 the distance between bends, then the dog leg matrix is given by

$$M_{dog} = \begin{pmatrix} 1 & L_1 & 0 & \alpha L_1 \\ 0 & 1 & 0 & 0 \\ 0 & \alpha L_1 & 1 & \alpha^2 L_1 \\ 0 & 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} 1 & D/\alpha & 0 & D \\ 0 & 1 & 0 & 0 \\ 0 & D & 1 & \alpha D \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

where D is the dispersion. Let this be followed by a drift, L_2, to a thin lens deflection mode cavity. The cavity matrix is given by

$$M_{cav} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & T & 0 \\ 0 & 0 & 1 & 0 \\ T & 0 & 0 & 1 \end{pmatrix}.$$

Where for exchange $T = -1/D = \frac{-1}{\alpha L_1} = \frac{\omega}{c}\frac{eV_{cav}}{E_{beam}}$ and V_{cav} is the deflection strength of the cavity and E_{beam} is the beam energy.

The total exchange is

$$M_{dog}L_2M_{cav}L_2M_{dog}=\begin{pmatrix} 0 & 0 & -\frac{1}{\alpha}-\frac{L_2}{D} & -L_2\alpha \\ 0 & 0 & \frac{-1}{D} & -\alpha \\ -\alpha & -\alpha L_2 & 0 & 0 \\ \frac{-1}{D} & \frac{-1}{\alpha}-\frac{L_2}{D} & 0 & 0 \end{pmatrix}.$$

In our geometry D=0.33 m and α = 22.5°.
For a finite length cavity, the (4,3) element of M_{cav} enters and the on-diagonal (coupling) blocks start to show nonzero values and will dilute the 2D emittances, especially the smaller one. The finite length cavity also causes the equilibrium orbit to follow a staircase trajectory through the cavity. These effects can be compensated to some extent by suitable choices of beam and cavity parameters.
The A0PI experiment attempts to exchange a 6 mm-rad normalized transverse emittance with a 120 mm-rad (204 keV-ps) normalized longitudinal emittance. The beamline was commissioned in the summer of 2007 and measurements of the transport matrix are underway. Preliminary data has been taken of the beam emittances before and after the exchange, and analysis of that data is ongoing and will be the Ph.D. thesis of Tim Koeth. (The layout of the current beamline is shown in Figure 6.1 in Appendix 6.2.)

After initial evidence that the emittance exchange was occurring, our experimental program has concentrated on measuring the 6-D emittance exchange transport matrix. Figure 2.1 shows preliminary results of the transport matrix measurements as a function of cavity strength T. The circles represent the data and the red lines are what is expected from the model. The agreement is quite good for 12 of the 16 elements. We believe the discrepancy in the remaining elements is due to errors in the model, in particular how the dipoles are handled.

These measurements have shown a need for improved diagnostics. In particular, we are preparing a Martin-Puplett interferometer for measuring sub-picosecond bunch lengths and larger OTR screens to image the resulting large transverse beam spot. Additionally we have begun to measure the synchrotron and coherent synchrotron radiation that is a consequence of the beam parameters and beamline geometry.

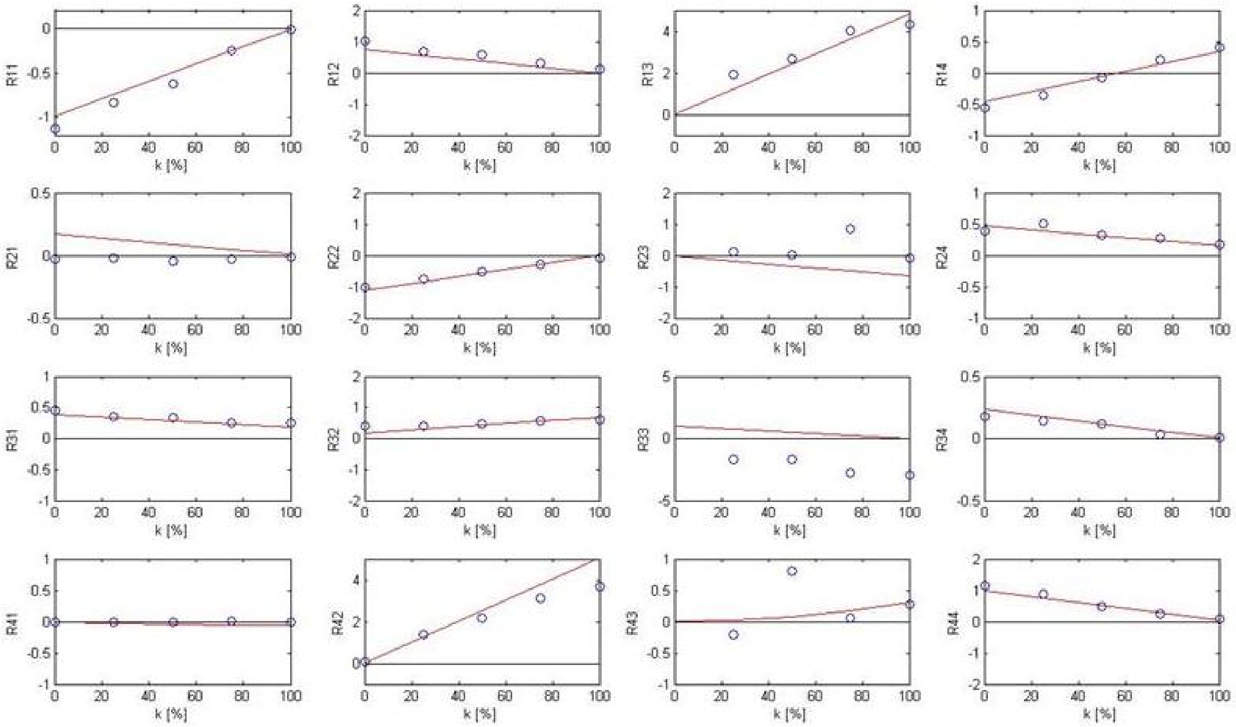

Figure 2.1: The transport matrix as a function of k (= T in the text). The circles are the measurements. The red lines are derived from the ELEGANT model.

We are proposing to continue and expand this experiment with the following program.

Step 1: Measure the emittance exchange

The transverse emittances are measured with a multislit screen which gives a complete picture of the transverse phase space ellipse. The longitudinal emittance measurements are currently limited to separate energy spread and bunch length measurements which provide an upper bound on the longitudinal emittance. Energy spread is measured with a beam screen after a spectrometer, and the bunch length is measured using a streak camera for bunches longer than 1 ps, and a Martin-Puplett interferometer for bunches shorter than 1 ps. Currently the instrumentation is not configured to measure the energy-time correlation of the bunch either at the input or the output of the exchanger. However, it may be possible to transport the light from the screen after the spectrometer to the streak camera, which would give us the energy-time correlation.

These measurements will be done at the low charge of 100 pC/bunch to reduce effects of space charge (SC) and coherent synchrotron radiation (CSR). These two effects increase the beam emittance and distort the phase space. This will require longer bunch trains to increase the signal/noise from the available diagnostics – in particular the bunch length measurements. A deflecting mode cavity would be advantageous for these measurements since a YAG screen could be used to image the beam with single bunches and achieve a higher resolution than can be obtained with the interferometer or streak camera.

Step 2: Measure a reversed exchange

Most suggested applications of the emittance exchange require exchanging a small longitudinal emittance with a large transverse emittance. The experiment proposed in Section 2.2 of this proposal will use a femtosecond laser to produce an ellipsoidal beam. Such a laser can produce a beam with a normalized transverse emittance of 1 mm-mrad and 5 mm-mrad longitudinal emittance with 200 pC of charge. By detuning the emittance compensation in the gun, it will be possible to detune the transverse emittance to 10 mm-mrad [5]. This beam can then be used to do the more interesting exchange of a small longitudinal emittance with a large transverse emittance.

Step 3: Manipulate the input phase space ellipse to tune the output phase space ellipse

Tuning the input transverse phase space ellipse will modify the output longitudinal phase space ellipse and vice versa. We can tune the beam for short bunches, or low momentum spread, by adjusting the spot size prior to the exchange. Adjusting the input energy chirp of the beam will adjust the output transverse phase space ellipse. The reason to study the effect of the input phase space ellipses is to look for different output conditions like shorter bunches and for the effects of non-zero elements in the A and D blocks of the transport matrix due to the finite length cavity. These elements will lead to coupling of the emittances and increase the measured emittances after the exchange. This effect is most dramatic in the longitudinal emittance after the exchange since it is the smaller of the two. These measurements will be done at the low charge of 100 pC/bunch to reduce effects of SC and CSR, which increase the beam emittance and distort the phase space.

Step 4: Arbitrary tailoring of the current distribution of a relativistic electron bunch.

Very recently a scheme to arbitrarily shape the current profile of an electron beam was proposed [6]. The technique relies on the emittance exchanger in the following way. An incoming beam is first transversely shaped upstream of the exchanger; then the emittance exchanger maps the transverse profile into the time profile thereby resulting in a tailored time distribution. Tailoring the longitudinal profile of an electron beam has tremendous applications ranging from super-radiant operation of a free-electron laser (by using a beam consisting of microbunches) to several advanced accelerator concepts. Linearly ramped bunches are known to increase the transformer ratio in beam-driven acceleration techniques (such as dielectric and plasma wakefield acceleration). Preliminary calculations indicate the possibility to generate bunch trains with 80 fs spacing at 15 MeV (see Figure 2.2). At the A0PI the generation of sub-picosecond bunch trains could be directly observed downstream of the emittance exchanger by a suitable choice of slits parameters. The main diagnostics would be a sensitive THz detector to measure the coherent transition radiation produced by such a train of bunches.

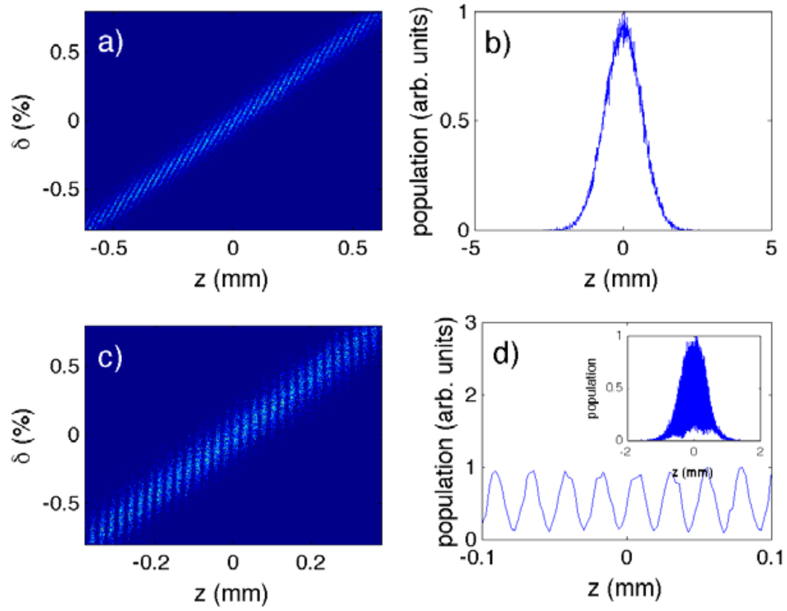

Figure 2.2: Simulation of pulse train generation using a transverse-to-longitudinal emittance exchanger. Zoomed longitudinal phase space (a) and corresponding longitudinal projection (b) downstream of the exchanger. Zoomed longitudinal phase space (c) and associated projection (d) downstream of a small magnetic chicane (R56=0.03 m). The beam upstream of the exchanger was passed through a series of horizontal slits with 0.1 mm width and 0.2 mm spacing (edge-to-edge). The inset in plot (d) correspond to the profile over the full bunch extent while the main plot is a zoom for -0.1 < z (mm) < 0.1.

2.2 Generation of ellipsoidal bunches from Cs_2Te cathodes

Thee-dimensional ellipsoidal charge distributions produce linear space charge fields within the distribution and are in principle free of space-charge-induced phase space dilution. Schemes to generate such a distribution using a photo-emission electron source were proposed by Serafini [7] and more recently by Luiten, *et al.* [8]. In the proposed method a short laser impinges a prompt photo-emitter. The operating parameters of the electron source are chosen such that the distribution evolution is dominated by the linear space charge force. This space-charge-dominated expansion can be achieved provided

$$\frac{eE_0 c\tau_l}{mc^2} << \frac{\sigma_0}{\varepsilon_0 E_0} << 1,$$

where E_0, τ_l are respectively the peak electric field on the photocathode and the time duration of the photoemission process, and $\sigma_0 \approx Q/(\pi r^2)$ is the charge density (Q the bunch charge and r the radius of the laser on the photocathode). For a prompt photocathode τ_l is comparable to the laser pulse duration. Using the A0PI nominal operating parameters E_0=35 MV/m, for charge Q~0.1 pC and assuming a laser pulse length τ_l = 50 fs we have $eE_0 c\tau_l/(mc^2) \approx 0.001$ and $\sigma_0/(\varepsilon_0 E_0) \approx 0.1$ so the condition for ellipsoidal bunch generation can in principle be achieved. However, this requires a photocathode drive laser capable of producing a ~50 fs laser pulse, e.g. a Ti:Sapphire oscillator and regenerative amplifier. The generation of ellipsoidal bunches from magnesium [9] and copper [10] cathodes was recently demonstrated, however generating such a distribution out of a high quantum efficiency semiconductor cathode such as Cs_2Te would be an important proof-of-principle experiment. Several projects based on such cathodes rely on, or would benefit from, ellipsoidal bunches [11]. Using the A0PI as a test bed for such an experiment would present significant improvements and complement the recent experiments performed at UCLA and TU-Eindhoven.

Besides generating ellipsoidal bunches, the A0PI also incorporates an accelerating cavity which could be used to further accelerate and/or manipulate the bunch. For instance the cavity could be used to remove the large correlated energy spread thereby providing insight on the origin of slice energy spread. Furthermore the first dogleg used in the emittance exchange experiment could be modified to be achromatic and would therefore act as a bunch compressor enabling the generation of ~kA peak current.

Preliminary simulations of the generation and transport of ellipsoidal bunches at the A0PI were performed using the particle tracking code ASTRA. An example of distributions at z=3.77 m from the cathode (downstream of the accelerating cavity) are presented in Figure 2.3. For these simulations the charge is 50 pC and all the accelerator settings are identical to the ones presently achieved at the A0PI (the current A0PI setup is used for these simulations). The simulation supports the generation of ellipsoidal bunches as inferred from the (z,x) configuration space. The normalized transverse emittance obtained in these simulations is 0.8 μm (this number includes the thermal emittance using an excess kinetic energy of 0.55 eV at the photocathode). Thorough numerical optimization of the ellipsoidal production and transport scheme still remain to be done.

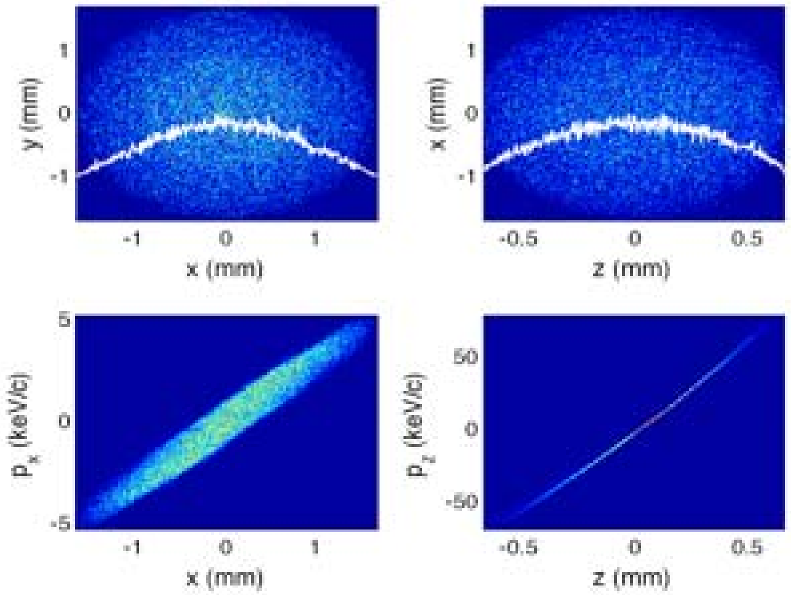

Figure 2.3: Transverse (top right), side (top left) configuration spaces and transverse and longitudinal phase spaces at z=3.77 m obtained by impinging a 50 fs (rms) laser on a Cs_2Te cathode. The simulations are for Q=50 pC and all parameters except laser pulse length are similar to the ones presently achieved at the A0PI.

We have also peformed a simulation of a possible bunch length and time distribution diagnostic using the currently used 5-cell 3.9 GHz copper cavity. The setup includes a set of quadrupoles, the deflecting cavity and a YaG screen 1.2 m downstream (Figure 2.4). The quadrupoles are used to focus the beam on the YaG screen when the cavity is off. When the cavity is turned on the ellipsoidal character of the distribution can be inferred (see Figure 2.5), e.g., from the top right picture (which is representative of the (*z,y*) distribution) along with the associated (parabolic) distribution.

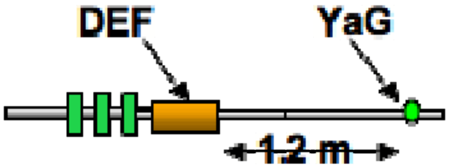

Figure 2.4: Experimental setup to measure the time distribution of the 15 MeV ellipsoidal bunch using the current copper deflecting cavity.

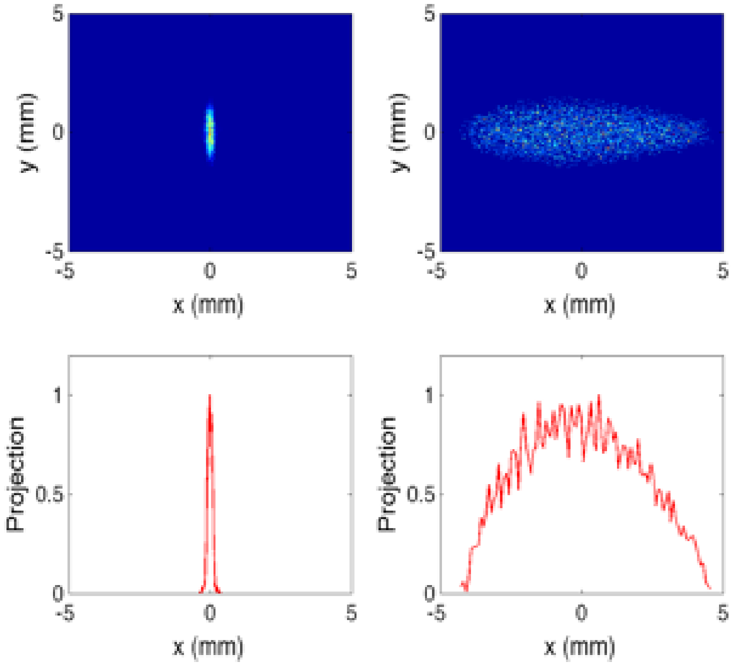

Figure 2.5: Simulation of bunch length measurement using the present copper deflecting cavity. The top images are the beam spots downstream of the cavity on a YaG screen, the bottom plot are the corresponding projection along the horizontal axis (the cavity is horizontally deflecting the beam). The right and left columns respectively correspond to cavity on and off.

2.3 Other experiments under consideration

2.3.1 Round-to-flat beam transformation and image charge undulator

High intensity x-rays can be generated from large synchrotron radiation or FEL facilities using electron beams at GeV energies. The image charge undulator (ICU) [12][13] offers an opportunity to generate high intensity x-rays using electron beams of much lower energy generated by a much more compact and less expensive electron source. With sub-millimeter gratings, the radiation produced by an ICU can be in the hard x-ray regime for an electron beam energy less than 200 MeV. Currently, there has not been an experimental demonstration of the image charge undulator. At the A0PI we have the experience of producing flat electron beams with emittance ratio 100:1 [14] with normalized rms beam emittance of 0.4 and 40 μm. This experience provides an advantage to pursue a proof-of-principle image charge undulator experiment using planar gratings.

An ICU will require a flat electron beam with a transverse emittance smaller than what has been achieved in round-to-flat beam transformation experiments to date. This program provides additional motivation for extending those experiments.

As shown in Figure 2.6, the ICU consists of two identical metal gratings on either side of the beam vacuum. The electron beam induces its image charge on the metal gratings which apply a Lorentz force (wake field) on the electron beam. Due to the periodic geometry of the gratings, the image charge wake field alternates just like in a conventional magnetic undulator. This process leads to the undulating motion of the electron beam.

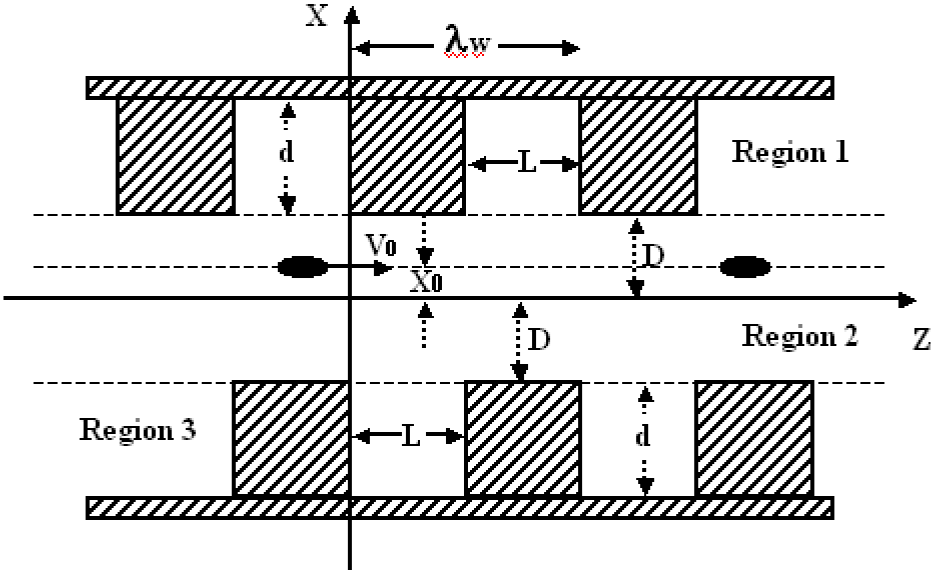

Figure 2.6: Schematic of a 2-D image charge undulator (from ref. [13]).

For a uniform sheet beam and infinitely long undulator, the magnetic field of the image charge wake field has only a non-alternating component which is parallel to the grating groove direction (i.e., B_y only). The vertical electric field near the undulator center is given by

$$E_x(z) = E_0 \sum_{n=1}^{\infty} N_{2n+1} \sin(2n+1)k_w z, \quad E_0 = \frac{\sigma}{2\varepsilon_0},$$

where σ is the surface charge density of the sheet beam, ε_0 is the permittivity of free space, and $k_w=2\pi/\lambda_w$ is the wave number. The dimensionless coefficients N_{2n+1} depend only on the geometry of the image charge undulator and are given by

$$N_{2n+1}=-\frac{a_n\tanh(2n+1)\pi\frac{d}{L}}{(n+\frac{1}{2})\pi\sinh(2n+1)\pi\frac{D}{L}}.$$

The strength of the transverse electric field is determined by the electron beam charge and size (E_0), as well as the grating geometry (N_{2n+1}). As d approaches 0 (no grating) the image charge force vanishes, and as D decreases the image charge force becomes larger. Keeping only the first term of the transverse electric field, the equation of motion in the vertical direction is

$$v_x(z)\approx\frac{cK}{\gamma}\cos(k_wz);\qquad K=\frac{eE_0N_1}{mc^2k_w}.$$

where v_x is the vertical particle velocity. The radiation mechanism follows as in a magnetic undulator, so one may borrow the formulae for the radiation wavelength, spectral and angular distribution of the photons, etc. For example, the radiation wavelength is given by

$$\lambda=\frac{\lambda_w}{2\gamma^2}\left(1+\frac{K^2}{2}\right).$$

For a bunch charge of 1 nC, beam (hardedge) thickness, width, and length of 10 μm, 150 μm, 100 μm, respectively, undulator period of 50 μm, and D/L = 0.5, d/L = 1, the image charge undulator parameter K is about 1.06×10^{-2}. The photon angular density of nth harmonic in the central cone N_p^n (in units of photons per second per mrad per 0.1% bandwidth) is given by [15]

$$\left.\frac{dN_p^{\ n}}{d\Omega d(\Delta\omega/\omega)}\right|_{\theta=0}=1.74\times10^{14}N_g^{\ 2}E_e^{\ 2}[\text{GeV}]I[\text{A}]F_n(K).$$

where N_g is the number of grating period, E_e the beam energy, I the current, and $F_n(K)$ is given by

$$F_n(K)=\frac{K^2n^2}{(1+K^2/2)}\left\{J_{\frac{n-1}{2}}[\frac{nK^2}{4(1+K^2/2)}]-J_{\frac{n+1}{2}}[\frac{nK^2}{4(1+K^2/2)}]\right\}^2$$

Integrating the angular density over the solid angle, we have the number of the photons per second per 0.1% bandwidth given by

$$\frac{dN_p^{\ n}}{d(\Delta\omega/\omega)}=1.34\times10^{14}N_gQ_nI(A)\text{, where }Q_n(K)=(1+K^2/2)F_n(K)/n.$$

The bandwidth near the nth harmonic is given by

$$\frac{\Delta\omega}{\omega} = \frac{2.8}{n\pi N_g}.$$

Now consider the first harmonic of the radiation. For an electron beam energy of 30 MeV, a bunch train of 1 nC separated by 1 μs (current = 1 mA), $F_1(K) = 1.1 \times 10^{-4}$, a 3.4 cm long ICU will produce 8×10^9 photons per second per mrad per 0.1% bandwidth in the central cone at 7.3 nm radiation wavelength, which is about 1×10^{10} photons per second per 0.1% bandwidth integrated over the solid angle. The bandwidth is about 0.1%.

The ICU will require a flat electron beam of suitably small emittance. Over the grating length of 3.4 cm, the beam thickness cannot exceed 2•D, which corresponds to a maximum divergence of about 0.3 mrad. Given a thickness of 10 μm at the ICU center (waist), this corresponds to a normalized emittance of about 0.05 μm for a $\beta_0 \sim 1$ cm. This is ~1/8 of the normalized emittance achieved in round-to-flat beam transformation experiments to date, which were performed at half the charge proposed here. This set of numerical calculations is listed in the "Soft-X" column in Table 2.1, as well as other numerical examples of undulator, beam and photon parameters.

Table 2.1: Numerical examples of the image charge undulator experiment parameters

		Green	far UV	Soft-X
Grating tooth width (L)	μm	500	250	25
Grating tooth depth (d)	μm	500	250	25
Grating separation (2D)	μm	500	250	25
Grating period	μm	1000	500	50
Bunch charge	nC	1	1	1
Beam energy	MeV	16	30	30
Beam length	μm	1000	500	100
Beam width	μm	500	250	150
Beam thickness	μm	100	50	10
Radiation wavelength	nm	510.01	72.54	7.25
Undulator parameter K		6.33e-3	1.27e-2	1.06e-2
Gain length	cm	47.91	22.46	3.40
Grating period in a gain length		479	449	679
Norm. rms vertical emittance	μm	0.40	0.40	0.05
Norm. rms horizontal emittance	μm	3.53	3.53	8.42
Norm. rms round beam emittance	μm	1.19	1.19	0.65
emittance ratio		9	9	170

There are several upgrades that can improve the performance of the round-to-flat beam transformation [16]. This includes the upgrade of the RF gun to one with an axial symmetric coupler – which reduces the degradation of the flat beam transformation from the gun asymmetry. More importantly, if the upgraded RF gun can be operated at higher gradient, this will help mitigate the space charge force, which is the major degrading factor in the round-to-flat beam transformation. With an additional acceleration cavity the beam energy can be increased to

~50 MeV. Apart from further reducing the space charge force, this upgrade will also make it possible to obtain higher photon energy and larger photon flux. Furthermore, if the flat beam can be compressed through a magnetic bunch compressor, the higher peak current can give rise to a larger image charge force, which will enhance the image charge undulator strength. In this case, the addition of a new dipole mode cavity will provide an improved bunch length measurement.

The numerical example for an ICU given here is a 2-D model with an infinitely long sheet electron beam. In fact, the beam transverse and longitudinal distributions will influence the process. There are other theoretical models [17] that treat an axially symmetric wake field undulator that can be adapted to study our planar case.

Contrary to the conventional undulator, the wiggling strength in an ICU is not uniform. The beam has a finite emittance and a certain longitudinal distribution, which will influence the radiation process. Numerical simulations need to be performed to understand how these factors will affect the radiation process. Furthermore, there will be other types of significant longitudinal and transverse wakes such as those induced by the Smith-Purcell process. We will identify a proper simulation tool to study these issues.

Experimentally, due to the very small gap between the two gratings, it will be a technical challenge to send the beam through the ICU. One of the first things one can explore is to simply arrange two pieces of flat metal surfaces without any gratings on them, and try to gain some experiences by transporting the electron beam through the small opening between these simple metal surfaces [18].

2.3.2 Ring beam generation

The generation of ring beams has several potential applications in beam physics. First, ring beams can be used in beam-driven collinear acceleration such as dielectric wakefield based on a cylindrical symmetric structure [19][20]. In this scheme a high charge drive hollow beam excites the wakefield in the dielectric structure and a probe beam propagating on the structure axis is accelerated. In the past, such attempts at low energy resulted in an instability that prevented the scheme from properly working. Therefore the generation and transport of high charge hollow beams is an interesting topic that could be pursued at the A0PI.

On the other hand such ring beams, if properly manipulated, might result in very bright beams since for the same charge, a ring beam has a lower charge density than its counterpart uniform cylindrical beam. We therefore conjecture that the transverse phase space dilution due to space charge would be mitigated and if a proper transformation capable of converting this hollow beam into a uniform beam would be implemented at high energies, the final beam could have higher brightness than otherwise achievable. A possible manipulation consists of producing a magnetized ring beam (by immersing the cathode in an axial magnetic field) and using the round-to-flat beam transform to create a beam with a hollowed transverse phase space in one degree of freedom. A method to coalesce this hollow phase space into a single-peaked phase space distribution was first suggested by Derbenev [21], and one implementation was recently worked out [22][23]. The scheme as envisioned today requires a lengthy focusing channel or a small isochronous ring to perform the transformation, but with further design study could be pursued as a possible future addition to the A0PI or NML facility.

2.3.3 Microbunching Diagnostics and Experiments

Over recent years there has been considerable study of possible microbunching processes in linacs that provide short bunches with high peak current for FEL application. These linacs have magnetic bunch compression that can convert energy modulation to charge density modulation after the compressor. High frequency components in the beam can result from coherent synchrotron radiation (CSR), wakefields, and longitudinal space charge (LSC) effects. In particular, modulations in bunch charge can provide energy modulation through space charge that can then be amplified in the compressor resulting in further charge modulation at higher frequency due to compression. Such an effect was initially hinted by start-to-end simulation of LCLS and a theory was developed in Reference [24]. Because of the possibility of this effect, the XFEL has incorporated a “laser heater” to be able to increase the uncorrelated energy spread. This beam microbunching has caused unexpected enhancements of the beam images from optical transition radiation (OTR) beam profiling screens. This has been observed at LCLS [25], APS [26], and FLASH. The ultra low emittance beams at a small focus exceed the threshold for YAG:Ce scintillator linearity, so OTR screens are indicated. However, following bunch compression there seems to be a combination of LSC and CSR induced microbunching that results in these coherent OTR (COTR) emissions nonuniformly fluctuating over the beam image. The LCLS is presently precluded from using their OTR screens from 135 MeV to 14.3 GeV to perform reliable beam profile and hence emittance measurements. Besides the diagnostics complication there may be a contribution to the emittance degradation in the chicane bends from COSR and FIR CTR. Examples of the data taken at APS at 150 MeV in collaboration with staff there are shown in Figure 2.7 where the almost 10 times more intense spikes show up near maximum compression in the image and profile at the right.

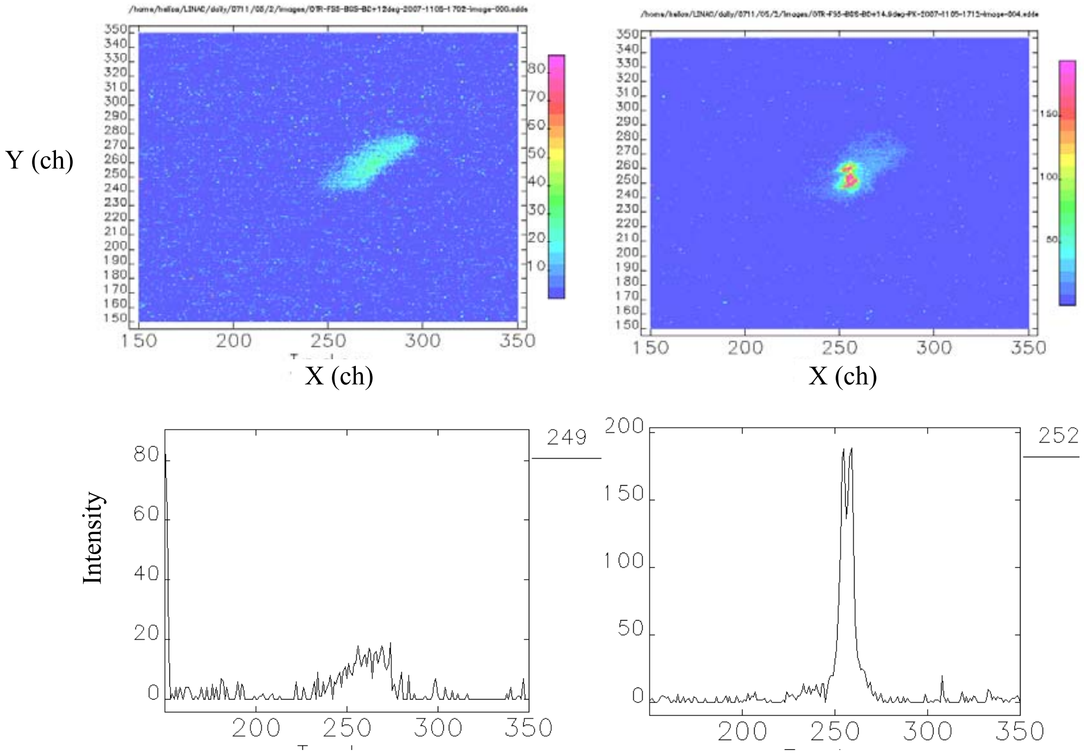

Figure 2.7: Comparison of the OTR images obtained after the chicane at low compression (top left) and high compression (top right). The corresponding x profiles through the images are shown in the two lower plots. The enhancement is about a factor of ten in the profile on the right.

What seems to surprise people is that this coherent effect shows up in optical frequencies, and there is speculation as to the generation mechanism [27]. It is not known if these fundamental LSC effects will be evident at 15 - 50 MeV following bunch compression of the bunches to sub-500 fs FWHM bunch lengths. There is speculation by J. Rosenzweig that freezing space charge is important and that we may not be at high enough energy. However, there is known to be a strong charge dependence of LSC so the use of 4-6 nC per bunch rather than 0.5 nC could compensate for the lower energy. There is also the possibility of looking in the near IR where the effects could be larger. Currently, we only compress in the dogleg configuration at A0, and we have not yet seen the effect in our brief inspections of the beam images. We plan to reinstall a compressor in the straight ahead line that will make possible observation easier. Initial measurements and modeling would look for the effect and how to possibly generate it by inducing bunch modulation. We suspect that the emittance exchange experiment at A0 will also be an interesting test on the microbunching effect. It is possible that the x-z exchange would mitigate the effect. If the effect can be observed, further studies and modeling of it and its mitigation would be warranted. The understanding and mitigation of this effect has become a critical task for LCLS, Elettra, and other advanced accelerators. It has been one topic of this year’s Zeuthen CHBB Workshop in May 2008, and there is now a second Microbunching Instability Workshop devoted to this topic planned at LBNL in October 2008. The A0PI and NML facilities could be used to uniquely explore high charge and lower energy parameter space in the USA and also uniquely compare the results of bunch compression by a chicane and by EEX. If a LSC instability effect is found at 3 nC per micropulse at γ=60, we could then consider the option of a laser heater operating on the third harmonic of the resonant wavelength to mitigate the effect at A0 and NML.

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3 Advanced beam instrumentation

Besides the measurement of fundamental beam parameters (intensity, position, transverse size and emittance), the experiments proposed at the A0PI require advanced instrumentation to observe in detail the longitudinal characteristics of the bunches. The requirements will be even more stringent when shorter bunches are generated with the Ti:Sapphire laser and EEX. Therefore most of the proposed plans for advanced beam instrumentation focus on longitudinal beam parameter characterization: bunch length, bunch profile, and bunch time-of-arrival. Each of the presented methods has its particular strengths and weaknesses; none is able to fully characterize the complete range of longitudinal bunch parameters adequately in a single shot, non-invasive manner. The instrumentation capabilities are summarized in Table 3.1.

Table 3.1: Bunch length measurement devices with the applicable ranges and features of each.

Device	**Applicable Bunch Lengths**	**Comments**
Deflecting Mode Cavity	100 fs – 2 ps	well understood; expensive; measure single or a few bunches (warm cavity) or many bunches (cold cavity)
Streak Camera	> 1-2 ps to 40 ps	well understood; expensive; measures single bunch; commercial device; dispersion effects dominate short bunch measurements; provides arrival times and jitter
Martin-Puplett Interferometer	< few ps	slow response; scanned over many macropulses; susceptible to upstream CSR and wakefields; missing phase makes details of bunch profile difficult to obtain
CTR angular distribution	< few ps	parametric measurement of bunch profile; must input assumed shape; scanned over many macropulses; susceptible to upstream CSR and wakefields
Electro-optical Sampling	100 fs – 2 ps	single shot measurement; expensive; must understand behavior of electro-optical crystal in frequency regime corresponding to expected bunch lengths; usceptible to upstream CSR and wakefields (less so than CTR and M-P Int.)
Waveguide Pickup	200 fs – 2 ps	inexpensive and simple, but absolute calibration is very difficult; does not give shape, just rough bunch length

3.1 Deflecting mode cavity

Deflecting mode cavities provide a method of measuring the longitudinal bunch distribution and have been used for many years at SLAC and DESY for this purpose[1][2]. The method relies on the transverse kick as a function of beam arrival time in the deflecting cavity. This kick maps the bunch length into the deflecting plane. If the beam is imaged at a suitable location downstream of the deflecting cavity then the longitudinal bunch profile can be determined. If this device is coupled with a spectrometer magnet bending in the other plane, then a complete picture of longitudinal phase space may be obtained.

At the A0PI a streak camera is currently used to measure bunch lengths, and it has a single bunch resolution of ~1.5 ps rms. At bunch lengths shorter than 1 ps, a Martin-Puplett interferometer is used, but this method requires multiple bunches per train and many minutes of data taking to obtain an accurate measurement. The analysis relies on certain assumptions of the bunch shape and frequency response of the detector in order to reconstruct the shape of the bunch and also loses information about the head-tail orientation of the bunch.

We wish to improve our method of measuring short bunch lengths by using a superconducting deflecting mode cavity operating at 3.9 GHz. Extensive design work has already been committed to such a cavity, and much of the technology and design will be based on 3.9 GHz acceleration mode superconducting cavities being built by FNAL for DESY. In addition, a 3.9 GHz acceleration mode cavity will be required at NML for generating very short bunches. Our goal for a deflecting mode cavity is to have a system that can measure the bunch length of a single bunch with a resolution ~50 fs rms over a large range of bunch lengths, at a beam energy up to 50 MeV which will be available at NML.

Currently at the A0PI there is a 3.9 GHz 5-cell normal-conducting copper cavity based on a superconducting deflecting cavity design for a separated kaon beam experiment. This cavity is cooled with liquid nitrogen to increase the Q and separate the modes. It is powered by an 80 kW klystron, and the integrated deflecting field is 550 kV. It is currently used for the emittance exchange experiment at the A0PI. It does not have sufficient voltage for measuring bunch length with the required accuracy at 50 MeV beam energy. A superconducting cavity constructed with 9 cells will provide approximately 2.5 MV integrated deflecting field.

Figure 3.1 shows the beamline with a matching section prior to the cavity, the deflecting cavity, a drift length and a flag to image the beam. The purpose of the matching section is to focus the beam at the flag when the cavity is turned off. We shall assume that the beam can be focused to a 0.1 mm rms spot at the flag, and the flag has a pixel resolution of 28 μm.

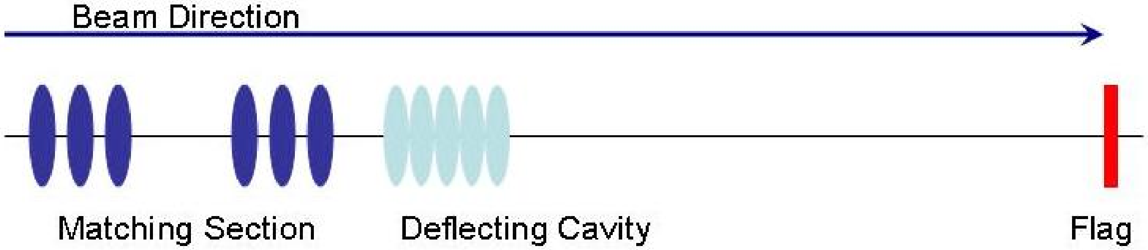


Figure 3.1: Schematic drawing of a bunch length measurement using a deflecting cavity.

The deflecting cavity is operated at the zero crossing of the deflecting field which will give no net deflection to the bunch, and kick the head and tail in opposite directions. The beam spot at the flag, with the deflecting cavity on, is then

$$\sigma^2_{x-flag} = \sigma^2_{x-cavoff} + \sigma_z^2 k^2 \left(L + \frac{L_c}{2}\right)^2$$

where $\sigma_{x\text{-flag}}$ is the beam spot at the flag location, $\sigma_{x\text{-cavoff}}$ is the beam spot at the flag when the cavity is turned off, σ_z is the bunch length at the deflecting cavity, L_c is the deflecting cavity length, and L is the drift length from the downstream end of the cavity to the flag. k is given by

$$k = \frac{eV\omega}{Ec},$$

where eV is the integrated transverse kick, c is the speed of light, ω is the angular frequency and beam energy is E. For the 9-cell superconducting cavity, k=4.1 m^{-1} at 50 MeV, and, for comparison, the 5-cell copper cavity currently in use at the A0PI has k=0.9 m^{-1} at 50 MeV. To measure a 100 fs bunch with a resolution of 50 fs will require a lever arm (L) of only 0.9m using a 9-cell superconducting cavity. For comparison, the 5-cell normal conducting cavity will require a lever arm of 4.8 m.

Over the years considerable development work has been done on the design of a deflecting mode cavity. Prototypes have been built and a 3-cell cavity tested in a vertical dewar. It achieved 7.5 MeV/m deflecting gradient (Figure 3.2).

At the A0PI all the cavity ancillaries will use the designs developed for the 3.9 GHz accelerating mode “3rd harmonic cavities”. These include input coupler, HOM coupler designs, helium vessel, and tuner. Outstanding design issues are associated with the lower order mode (LOM) and other polarization mode damping. These will be the real R&D developments for this design and are related to future applications such as crab cavities for the ILC interaction region. For the application at the A0PI we will be running short bunch trains and mode damping will not be that much of an issue. Even so, this is an opportunity to try various LOM designs.

The cryogen insulating vacuum module will be designed to accommodate one 9-cell cavity of either accelerating or deflecting variety. It will interface to the standard cryogen feed “top hat” design used both at the A0PI and in the Meson Lab SRF test areas. The length and diameter of the vessel will be ~ 1.1 m and 0.5 m, respectively.

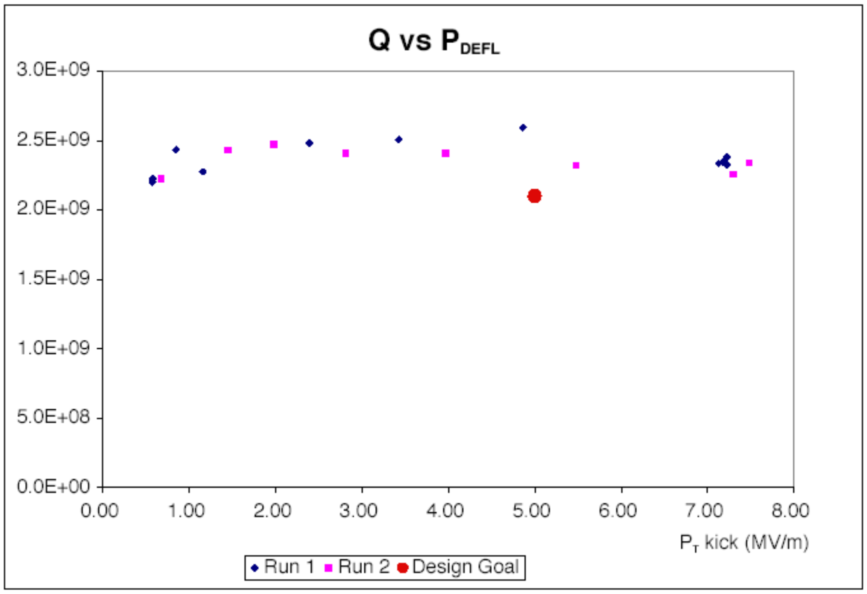


Figure 3.2: Results from a 3-cell TM110 deflecting mode cavity. Large red dot is design value; pink and blue dots are measurements. 7.5 MV/m corresponds to 120 mT maximum surface field.

3.2 Electro-optical sampling

Electro-optical (EO) sampling has been proven to be a very effective non-intercepting technique for measuring longitudinal bunch information [3]. We propose that EO sampling be studied with the present A0PI and integrated into the upgraded A0PI. The goals of EO sampling at the A0PI are to develop methods not explored at other accelerators and to provide a fully operational diagnostic tool for other A0PI experiments. Presently, the unique EO sampling opportunities at the A0PI are: (1) measure longitudinal bunch information of low energy electron beams; (2) measure longitudinal bunch distribution for bunch lengths up to a few ps; and (3) investigate the use of alternate laser wavelengths via fiber lasers. As cross-checks, longitudinal bunch information from EO sampling will be compared with streak camera measurements (see section 3.3.1), Martin-Puplett interferometer measurements (see section 3.3.2), and with the future deflecting mode cavity (see section 3.1).

Currently, most single–shot EO sampling experiments are carried out using spectral decoding, temporal decoding, or spatial decoding [4]. Each technique has unique properties that must be evaluated in terms of the bunch measurement requirements. Among the three methods, temporal decoding is able to measure the shortest bunches, spatial decoding has been used as a fs resolution clock at advanced light sources [5], and spectral decoding has been effective in measuring longer pulses.

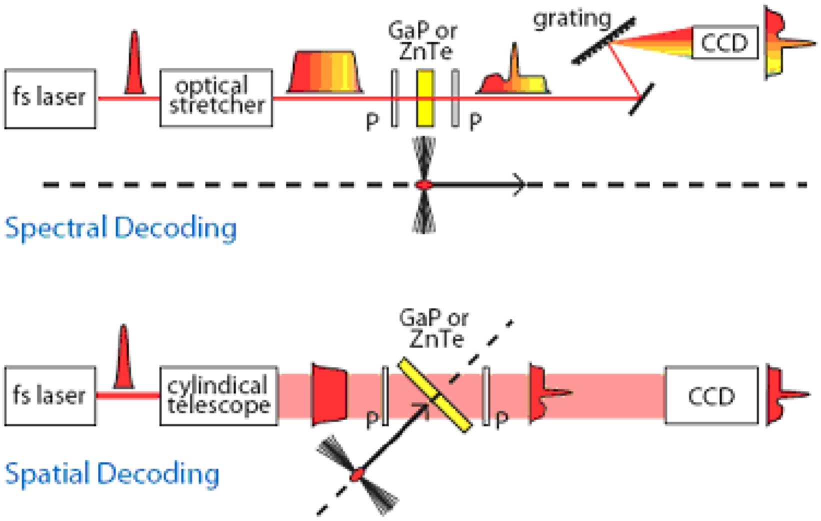


Figure3.3: Schematic representations of the 3 common single shot EO detection techniques for investigation at A0PI [4].

Our efforts and plans at the A0PI will concentrate on developing single-shot EO sampling based on the spectral decoding and spatial decoding techniques to investigate low energy electron beams with bunch lengths 200 to 2000 fs (rms). Figure 3.3 shows schematics of both spectral and spatial decoding methods. In addition, current EO studies are focused on high energy beams (few hundred MeV and higher). EO sampling of low energy electron beams has not been studied, and our proposed research will address this low energy gap.

We will also concentrate on developing a suitable fiber laser system for EO sampling. Present EO sampling methods utilize expensive Ti:Sapphire lasers. In addition, transport of the Ti:Sapphire beam to the beamline is problematic. Fiber lasers may solve these problems and make EO methods more convenient and affordable for multiple locations in a large accelerator facility.

Current A0PI Laser System

The bandwidth of our current Nd:YAG laser system is too small to do an optimal EO experiment, however, this laser can still be used to begin our EO sampling efforts. Because of the longer bunches and limited bandwidth of the Nd:YAG laser, it will difficult to chirp the laser pulses enough to perform spectral decoding, therefore we will do an initial experiment with spatial decoding using the current laser system on long bunches up to a few ps. We expect to accomplish two things in this experiment. First we will learn more detail of the uncompressed A0PI electron beam longitudinal structure and compare it to our streak camera measurement. Second we will have in place a suitable optical path and EO beamline device for a future fs laser system (Ti-sapphire or fiber laser).

Ti:Sapphire laser system

A Ti:Sapphire laser is used to generate ultrashort pulses (down to 10's of fs) because of its large bandwidth. To date most EO experiments have used commercial Ti:Sapphire systems, and we also plan to use a commercial system. We have formed a collaboration with Argonne National Laboratory (ANL) and Northern Illinois University (NIU) to study EO sampling

Because of the availability of an amplified Ti:Sapphire laser at ANL, initial EO experiments have been carried out at the Advanced Wakefield Accelerator at ANL. At ANL we have already used a ps laser pulse to focus on a ZnTe crystal to generate terahertz radiation as measured with a LN_2-cooled Golay cell. In the next stage, an EO setup with a spatial decoding technique will be assembled using parts already purchased. After this stage the setup will be moved into the AWA beamline and experiments with beam will be carried out.

At NIU, a new Ti:Sapphire and amplifying system has been purchased. One graduate student has been assigned to carry out bench-top studies in the NIU laboratory. After these bench-top measurements, the laser setup will be moved to the A0PI and experiments with the electron beam will be conducted. Both spectral and spatial decoding will be investigated. This work will be a major component of the student’s Ph.D. thesis project. In addition, advanced EO studies, such as real-time beam structure and position monitoring, will be carried out using this setup.

Fiber laser system

Although a Ti:Sapphire laser system is the laser of choice in current EO studies, it is expensive and difficult to distribute to several accelerator positions. A fiber laser of appropriate wavelength and power will alleviate these difficulties.

There are two approaches we are pursuing. First, we will use an Er-doped fiber laser (1530 nm) which has already been purchased for time-of-arrival EOM measurements (see section 3.1.3), to investigate both spectral and spatial decoding techniques. One difficulty with this approach is that the group velocity mismatch inside the commonly used EO crystal (such as ZnTe or GaP) between the THz wave and 1530 nm is larger than the Ti:Sapphire case. This is a severe problem for measurements of very short bunches (<200 fs). This will not be an issue in our measurements of 200-2000 fs bunches. At the same time we will also investigate the possibility of using frequency doubling of the 1530 nm as our EO probe. Second we will construct in-house a fs fiber laser based on Yb-doped fiber (1030 nm). This wavelength would greatly reduce the mismatch caused by the longer wavelength Erbium laser. Figure 3.4 is a simulation of EO sampling for different laser wavelengths and shows that the change in measured bunch length is small for a 1 ps bunch. This indicates that EO sampling with fiber lasers is a viable option for the intermediate bunch lengths proposed at the A0PI.

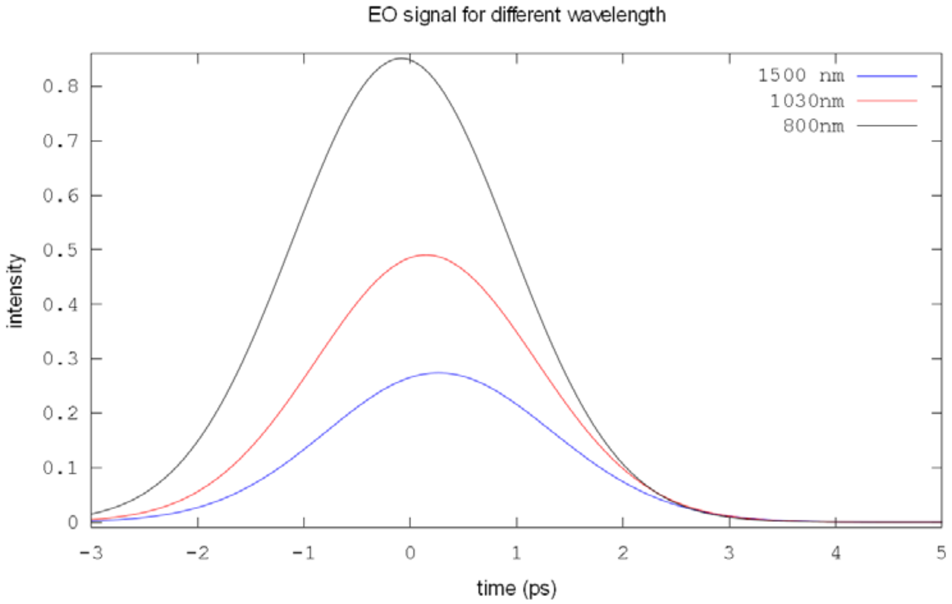


Figure 3.4: Simulated EO signal using 3 different laser wavelengths. Electron beam bunch length is 1 ps rms with a bunch charge of 1 nC. The EO sampling crystal is 1 mm thick ZnTe and 5 mm away from the beam center. Gaussian fits of these curves give rms values of 1.025 ps, 1.032 ps and 1.06 ps for 800 nm, 1030 nm and 1500nm respectively.

3.3 Other instrumentation development

3.3.1 Streak camera

The opportunity for a new series of streak camera experiments at the A0PI was recognized in the last year. The enabling upgrade was adding the synchroscan option to the existing C5680 Hamamatsu streak camera mainframe. By locking this module to the 81.25 MHz subharmonic of the RF system, the synchronous summing of bunches could be done with a trigger jitter of <1.5 ps (FWHM) for both the UV drive laser harmonic and the e-beam via optical transition radiation (OTR). This summing allowed the needed bandpass filters to be utilized to reduce the chromatic temporal dispersion effects inherent to the use of the broadband OTR source and the transmissive optics components. In addition, the C6768 delay module with phase feedback was also acquired, and this stabilized the streak camera sweep relative to the master oscillator so that the camera phase drift was reduced to the picosecond level over tens of minutes. This latter feature allowed a series of experiments to be done on the bandwidth effects and transit time effects in the respective transport lines, including evaluation of the matrix elements of the emittance exchange line.

In the course of our experiments, we have done a series of tests on the chromatic temporal dispersion effects for this particular input optics barrel with UV transmitting optics and our optical transport lines. Our effects are less than that reported at SSRL with optical synchrotron radiation and their transport [6], but ours still needed to be characterized carefully to allow accurate bunch length measurements using the OTR. We now use a 550-nm longpass filter as a compromise on effective bandwidth and the reduced variation in group velocity with wavelength in the red end of the spectrum. This results in a contribution to system time resolution of about 2.6 ps (FWHM) due to this bandwidth effect including a quartz window, one quartz lens, and the input optics barrel. The optics barrel lens set is the largest contributor. The intrinsic tube resolution for a single wavelength is 1.5 ps FWHM (0.6 ps σ). At the shortest bunch lengths the sensitivity to changes becomes reduced as one works near the system resolution value.

After characterizing the UV laser bunch length, a series of e-beam experiments on the A0PI beamlines was performed [7]. We have measured a significant bunch length elongation versus bunch charge for the present conditions in the uncompressed line and showed that this is consistent with ASTRA calculations. We also observed a time-dependent transverse focusing effect at 4 nC/bunch as shown in Figure 3.5. Such a “self-pinching” effect is observed in typical high charge bunch simulations. Our experiments indicate the bunch head and tail to have 50% larger transverse size than the bunch central slices. The bunch length is 28 ps (FWHM). This topic merits further study in FY09. Detailed beam dynamics simulations using particle-in-cell calculation will be performed and the evolution of the (x,t) configuration pattern will be studied for different electron source settings (solenoids, and laser (flat top versus Gaussian distribution)

One of our more critical measurements this year was the verification of the x-z emittance exchange process by graphically showing the reduction in the bunch length when the 5-cell cavity is at 100% power compared to power off. This is shown in Figure 3.6 where the horizontal axis is in seconds, or shot number, for each state of the cavity power, and the vertical axis is the corrected bunch length. The FWHM length reduction from 5.2 ± 0.7 ps to 1.4 ± 0.9 ps is clear. Note however that the 1.4 ps number is below the resolution band width limit so its absolute value includes some systematic error.

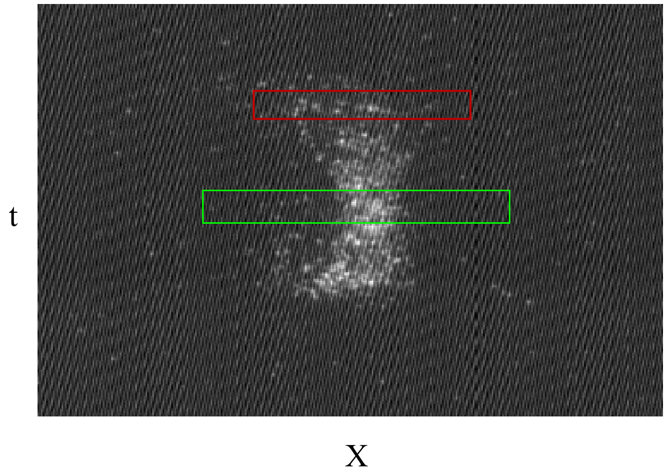


Figure 3.5: Evidence of time-dependent transverse focusing effects in a 4-nC bunch.

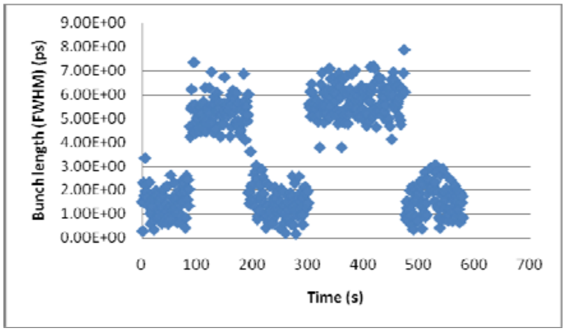


Figure 3.6: Direct measurement of the x-z emittance exchange and the bunch-length reduction with the 5-cell cavity power on versus 5-cell cavity power off.

Plans

We have just started our dual-sweep streak camera experiments to look for phase jitter and slew within the laser and e-beam bunches. We expect to continue our efforts to reduce the chromatic temporal dispersion effects by testing a grating pair as a compensator or by acquiring a commercial mirror-input-optics assembly for the camera. If either is successfully employed, we can reduce the effective system resolution limit by a factor of ~2 and be able to use 4 times more bandwidth of broadband OTR to improve image statistics. We are also evaluating purchase of a new 12-bit digital readout camera for the streak camera. The combination of these features will bring us closer to single-`bunch longitudinal profile measurements at the 1 nC level at A0PI upgrade energies and will enable slice-emittance tests. This system would support any future x-z emittance exchange experiments, laser/e-beam relative phase tests, and bunch compression tests in FY09 and later. We also could support qualification of the Martin-Puplett interferometer and the CTR angular distribution bunch length measurement methods that are just underway or planned.

The optical transport line will be redesigned to increase OTR signal collection efficiency and allow us to observe the drive laser in the same streak image with the OTR. The direct relative phase information (peak centroid positions) should be obtainable at the 300 fs level or one camera system pixel. With dual-sweep mode, we should be able to investigate sub-bunch transients and accelerator phase feedback loop issues.

The streak camera system is currently used routinely for beam characterizations and in the x-z emittance exchange experiments. With the proposed upgrades, it can continue to be the reference longitudinal profile and phase measurement device at the 1-2 ps level. It can be used in the development and commissioning of the other techniques that will push measurement capabilities further towards the 100-300 fs level.

3.3.2 Martin-Puplett interferometer

One method for determining the bunch length of an electron beam is autocorrelation interferometry. Interferometric bunch length measurements are possible because of the relationship between the magnitude of the spatial spectrum of the bunch and the spectral content of Coherent Transition Radiation (CTR) from the bunch. Since the spectrum of CTR is a function of only the magnitude of the bunch spectrum (no phase dependence), an exact determination of the longitudinal charge distribution cannot generally be obtained. However, for certain simple shapes, such as Gaussians, the approximations necessary to obtain phase information do a fairly good job of preserving the main parameters of the bunch, such as width. At the A0PI we have installed a Martin-Puplett interferometer [8], borrowed from DESY (Fig. 3.7). A Martin-Puplett interferometer is a polarizing type interferometer which in this case uses closely spaced wire grids for the polarizers and splitters. The grids consist of 15 μm diameter gold-plated tungsten wires spaced by 45 μm.

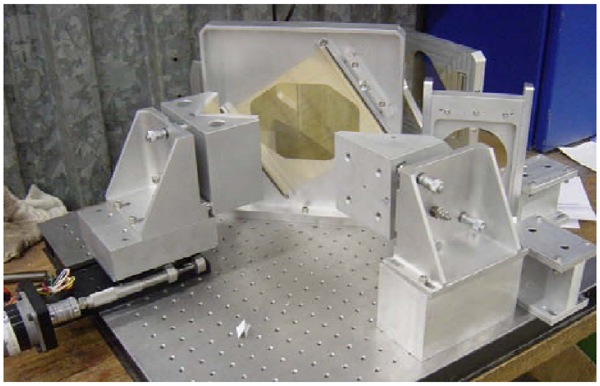


Figure 3.7: Photograph of the interferometer. The gold-colored portion is the wire grid beam splitter.

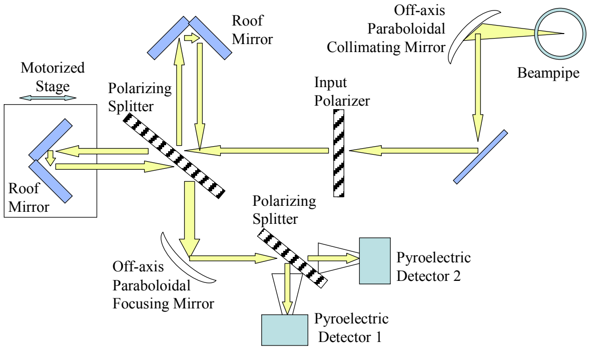


Figure 3.8: Schematic of the interferometer.

The CTR exits the beamline through a quartz window and is immediately collimated by a 200 mm focal length off-axis parabolic mirror (Fig. 3.8) to prevent loss of light through the interferometer.

A complication in this technique is the fact that due to the small size of the CTR screen (1.25 cm radius), there is a strong diffraction effect which in turn introduces a frequency-dependence (broadening) of the angular distribution. The extent of this broadening depends on $\gamma\lambda$. Combined with a finite aperture, this leads to a reduction in long wavelengths in the interferogram. We have a plan to replace the existing radiator with a simpler shape to facilitate correcting the interferogram.

Another issue with this system is the lack of knowledge of the spectral response of the detectors and possible interference effects. We are currently testing a broadband Schottky diode detector as a possible replacement for the pyroelectric detectors and plan to have the pyroelectric detector spectrum measured.

Comparison of Streak Camera and M-P Interferometer Results

Initial comparisons of the Martin–Puplett Interferometer with the streak camera were made on 6/18/08 (Figure 3.9). The streak camera data used a 40 bunch synchronous sum, and the interferometer scans were done over tens of minutes. The data involved the power cycling of the 5-cell cavity which, because of the x-z exchange, compresses the bunch length, but increases the horizontal transverse beam size and divergence. This change in the horizontal emittance may have an impact on the measurement. The ratio of 5-cell on/off measurements was 0.66 for the bunch length from the streak camera, 0.69 for the interferometer autocorrelation peak width, and 0.43 for the reconstructed interferometer bunch lengths.

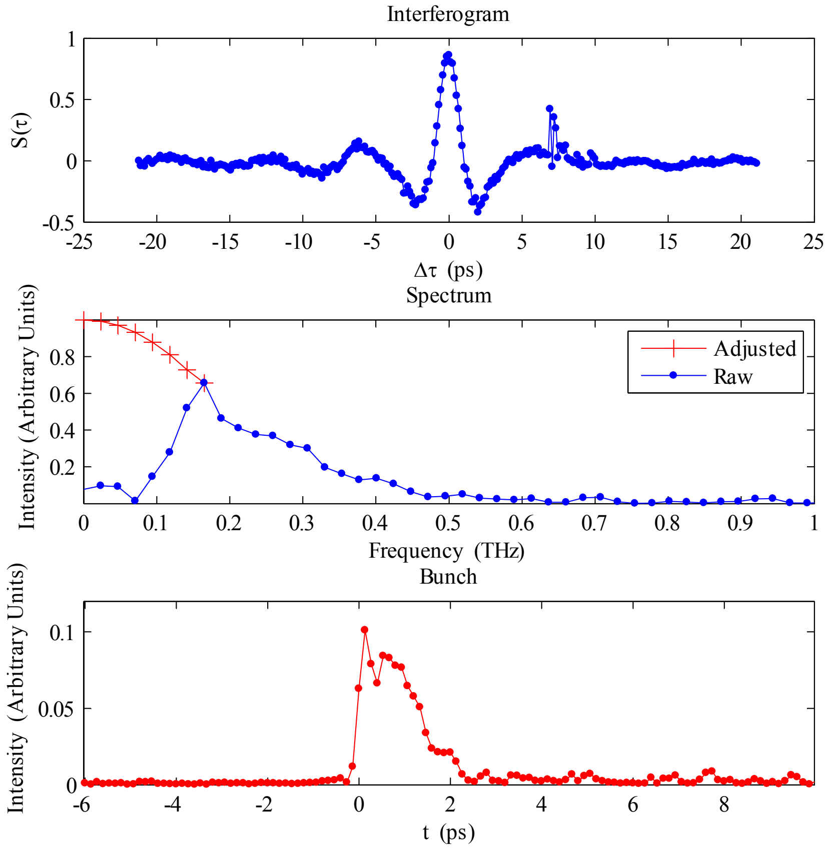


Figure 3.9: Autocorrelation trace (top), raw spectrum (middle blue), corrected spectrum (middle red), and reconstructed bunch (bottom) from 5-cell on/off data.

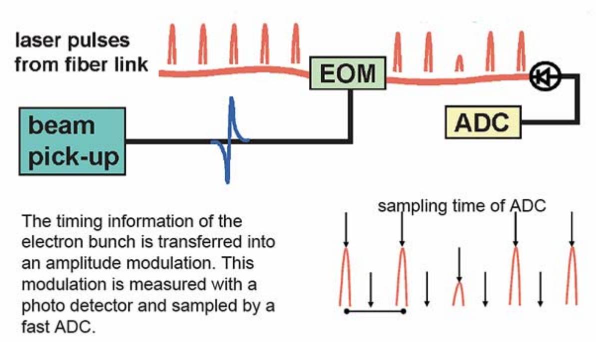
Plans for the Future

We plan to replicate this interferometer since it is borrowed from DESY. We also plan to replace the existing radiator with a simpler shape to facilitate correcting the interferogram for diffractive effects. Another issue with the current system is the lack of knowledge of the spectral response and possible interference effects in the pyroelectric detectors. We are currently testing a broadband Schottky diode detector and a golay cell as possible replacements for the pyroelectric detectors and we also plan to have the pyroelectric detector spectrum measured.

3.3.3 Electro-optical modulator for time-of-flight measurement

The stability of accelerators depends on the synchronization between the beam, low-level RF, and other accelerator components. A precise measure of the bunch time-of-arrival (TOA) with respect to the master oscillator clock signal is important. Operation of future accelerators places a requirement of measuring the bunch TOA to an accuracy of better than 1/10th of a degree of the RF. This results in a need to measure TOA at a resolution better than a few 100 fs. Precision measurement experiments at the A0PI require bunch TOA measurements to the same resolution.

A bunch TOA monitor with a few 100 fs resolution is in development at the A0PI and is based on a system developed at DESY [9]. The monitor is based on conversion of time to voltage for amplitude modulation of a pulsed laser via Electro-Optical Modulation (EOM). Figure 3.10 shows the basic principle of the bunch TOA monitor. The zero-crossing voltage of a broadband beam pickup is used to amplitude modulate a single 100 fs wide laser pulse. Figure 3.11 shows how the zero-crossing voltage changes as a function of the bunch arrival time.



The timing information of the electron bunch is transferred into an amplitude modulation. This modulation is measured with a photo detector and sampled by a fast ADC.

Figure 3.10: Basic principal of the bunch time-of-arrival monitor

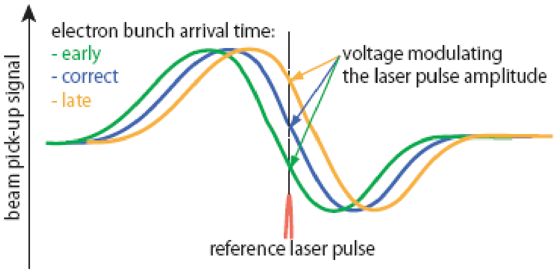


Figure 3.11: Relation between the modulation voltage signal to the bunch arrival time.

Figure 3.12 shows a block diagram of the A0PI TOA monitor. A wide bandwidth beam pickup, needed to permit femtosecond TOA measurements, acquires the bunch electric field. Using a precision variable delay line, the pickup signal is timed to arrive at the electro-optical modulator in coincidence with the laser pulse. The zero-crossing of the RF signal is used to modulate the amplitude of a 100 fs wide laser pulse. The photodiode converts the laser pulse into a voltage which is sampled by an ADC.

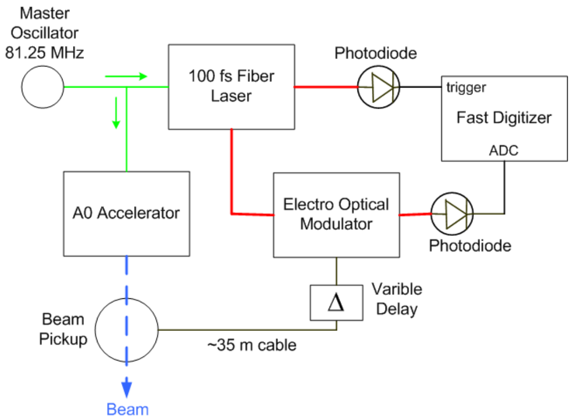


Figure 3.12: Schematic of the TOA at the A0PI.

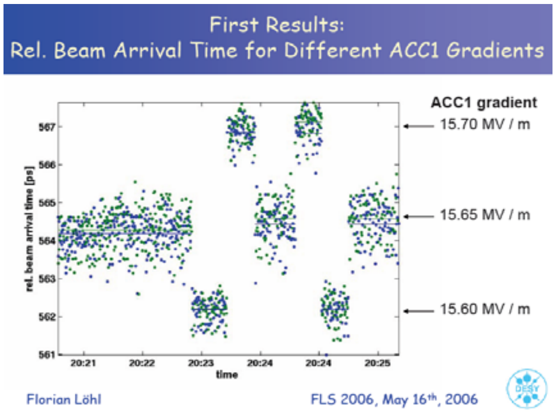


Figure 3.13: First results from DESY FLASH: time-of-arrival vs. accelerating gradient.

A similar monitor has been developed at DESY as a sub-100 fs bunch arrival monitor for the FEL accelerators. Figure 3.13 show the first results from the DESY bunch arrival monitor [10]. These initial results illustrate the potential resolution ability of an EOM bunch time-of-arrival monitor at the A0PI.

3.3.4 Optical transition radiation interferometry

The use of optical transition radiation interferometry (OTRI) to determine the rms beam divergence of electron beams is a well-established technique for electron linac applications [11].

The technique uses imaging-at-infinity optics to obtain the angular distribution of the OTR. In this case an interference pattern is generated by electrons passing through two thin foils separated by a distance comparable to $\gamma^2\lambda$, where γ is the Lorentz factor and λ is the wavelength of the OTR. The photon phase difference from the two sources determines the interference pattern which contains information about energy and angular spread or divergence in the beam at the given λ. The energy of the beam and the foil separation determine the angular width of the fringes. At lower gamma, the multiple scattering of the electrons in the first foil is one of the issues for measuring an actual beam divergence of less than 2 mrad (σ). Also at low gamma the foil spacing is typically sub-mm so one must image the OTR through the first foil. The scattering term, the actual beam divergence, and the imaging system effective resolution term can be treated as a quadrature sum to obtain the observed divergence value. In FY08 the techniques were developed for having the thin-foil planes normal to the beam rather than at 45 degrees to the beam to reduce the effective first-foil thickness by 0.707. This configuration involved imaging the OTRI pattern from a back angle. In addition the MCP was lens coupled instead of fiber-optically coupled to the CCD to improve the imaging angular resolution. This layout and optical scheme are shown schematically in Fig. 3.14. In this geometry the first foil also must be transparent to visible light. By choosing a 2.5-µm thick Mylar film for the first foil, the basic criteria are met of low scattering and visible-light transparency. As can be seen in Fig. 3.15, the modulation of the fringes is different experimentally and calculationally for the total beam divergences of 1.8 and 3.3 mrad. The data and the calculation are in good agreement except at the inner edge of the first fringe for each case.

In the context of the key x-z emittance exchange experiments at A0PI in FY09-10, such an OTRI setup will be used to verify directly the larger x divergence of 3-4 mrad expected after the exchange has occurred. At the same time it would show the vertical divergence unchanged (although limited in sensitivity by the first-foil scattering term). A linear polarizer will also be used to cleanly access the theta-x and theta-y axes of the angular distribution pattern.

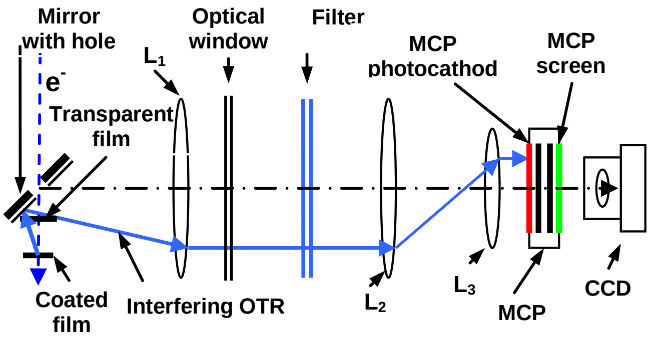


Figure 3.14: The OTRI setup with normal incidence of the electron beam.

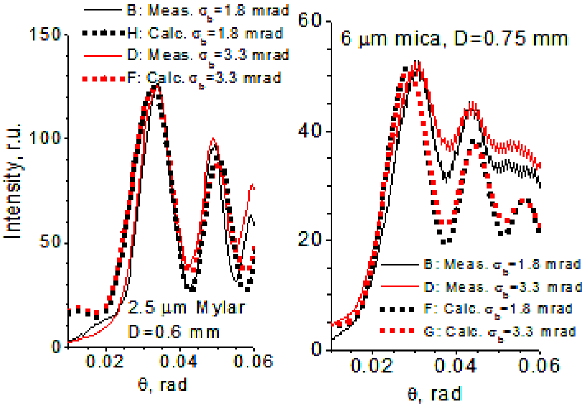


Figure 3.15: Measured (solid lines) and simulated (dotted lines) for a Mylar-based interferometer at normal incidence.

3.3.5 Longitudinal diagnostics via coherent radiation angular distribution

Coherent transition radiation (TR) and diffractive radiation (DR) spectra have been used to measure bunch lengths of picosecond electron bunches. However the angular distribution of this radiation also contains information on the longitudinal distribution of the bunch. When the size of the radiator, r, satisfies the condition $\lambda \sim 2\pi r/\gamma$ and radiation wavelength, λ, is on the order of the bunch length then the angular distribution of the radiation is very sensitive to the longitudinal distribution of the bunch [12]. Therefore by properly choosing the size of the radiator, for a given beam operating point, one can use the shape of the TR or DR angular distribution pattern to determine longitudinal information.

A flat screen radiator experiment has been proposed by Ralph Fiorito (University of Maryland) for the A0PI for making such angular distribution measurements. Theoretical models show that a well-defined radiator size allows for a bunch length measurement based on the angular distribution of the coherent TR at the A0PI. The coherent TR angular distribution will be measured using a highly sensitive Golay cell and a Schottky diode and compared to other A0PI longitudinal detectors such as the streak camera (see section 3.1.1) and the Martin-Puplett interferometer (see section 3.1.2).

Figure 3.16 shows the calculated angular distribution of coherent TR, using a radiator optimized for current A0PI beam parameters, for two different bunch lengths. The simulation shows the clear effect on the angular distribution due to change in bunch length. As part of the A0PI upgrade, a radiator optimized for these parameters will be installed.

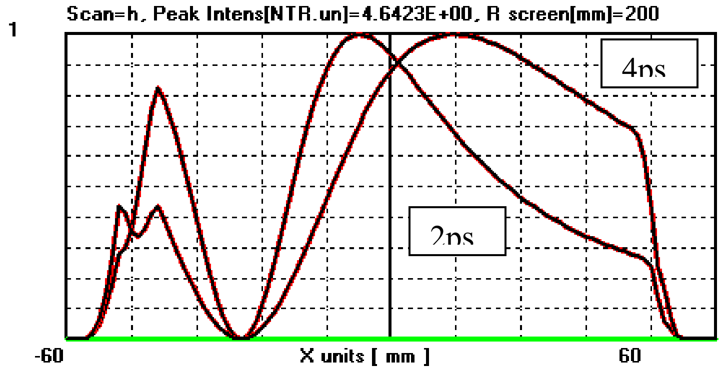


Figure 3.16: Calculated distribution of coherent TR observed from a flat detector plane at distance to source of 200 mm. The simulation is for 16 MeV electrons and Gaussian bunches of 2 and 4 ps width. The distribution is a horizontal scan from an optimized radiator size of 16 X 25 mm at 41 degrees to beam.

The advantages of this technique over other longitudinal measurements is that it is simple to experimentally implement, it can be performed at any transition radiation detector location and it can be tuned to measure sub-picosecond bunches. Presently, the measurements will be made with a scanning detector but an array of detectors could be developed to improve the time required for the measurement.

Measurements of the angular distribution of coherent TR and DR have been performed at the Swiss Light Source (SLS) at the end of the 100 MeV pre-injector [13]. Figure 3.17a shows the angular distribution of coherent TR with the theoretical best fit of a single Gaussian bunch shape with a width of 0.69 ps. Figure 3.17b shows the same angular distribution but with a double Gaussian bunch shape fit. The best fit occurs for Gaussians widths of 0.57 and 2.84 ps with the second Gaussian shifted by 1.5 ps.

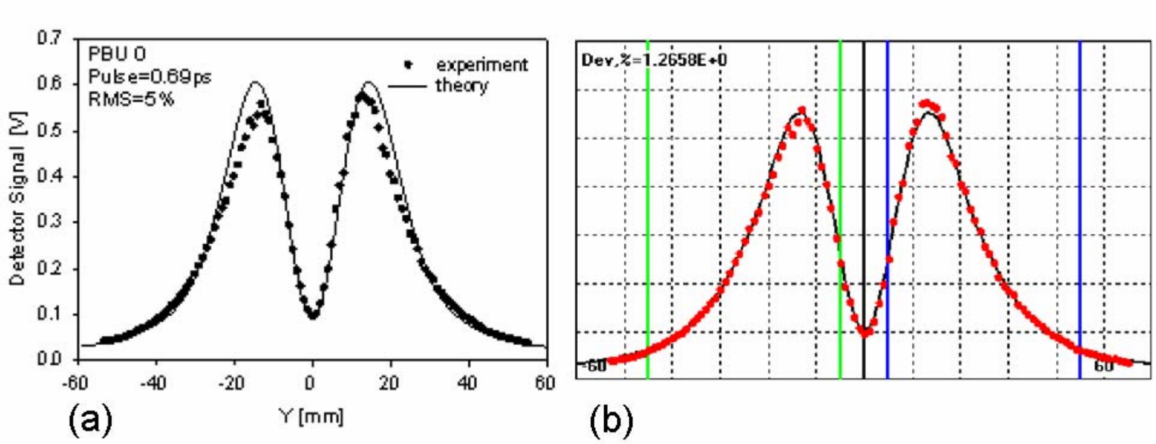


Figure 3.17: Measured coherent TR from 100 MeV electrons at SLS. (a) Theory curve is best fit model based on single Gaussian longitudinal bunch shape with a width of 0.69 ps. (b) Theory curve is best fit model based on double Gaussian longitudinal bunch shape with widths of 0.57 and 2.84 ps.

3.3.6 HOM signal processing

RF accelerating cavities can support, apart from the accelerating mode, a multitude of resonant modes, the so-called higher order modes (HOM). These modes are excited by the charged particle beams and can lead to an increase of the beam emittance or even to beam break-up in large accelerators. However, the HOMs can be useful for beam diagnostics [14,15]. The dipole modes have a linear dependency of their amplitude and phase with the beam offset and angle. Therefore they can be used for position monitoring, similarly to cavity beam position monitors (BPM). By measuring the phase of monopole modes excited by the beam with respect to the injected fundamental mode, one obtains the phase of the beam relative to the RF. The monopole and dipole modes are shown in Figure 3.18.

Broadband HOM-based beam phase detection

The HOM coupler, designed to absorb all higher order modes, except the fundamental acceleration RF is not perfect, thus some of the 1.3 GHz RF drive leaks through. This allows direct measurement of the beam excited phase of higher monopole modes with respect to the 1.3 GHz RF. A simple test system has been implemented in the FLASH linac at DESY which simply digitizes a single HOM coupler signal with a fast 20 GS/s, 5 GHz bandwidth scope and then uses Fourier analysis to measure the relative phase. This system has demonstrated a 0.1° (@ 1.3 GHz) measurement RMS over a couple of hours and has reproduced requested phase changes to the drive RF. In principle this measurement can be improved by implementing dedicated electronics to split the HOM signal and downmix the fundamental and a selected monopole to a convenient IF (~20 MHz) and then digitize. This should greatly improve the signal to noise but does introduce potential phase shifts which need to be understood. This system is very useful to monitor the phase of the RF system and could be used to provide slow feedback for phase stability.

Narrowband HOM-based BPM and cavity alignment observation

The dipole modes behave exactly like a cavity BPM with very high Q. The system implemented at FLASH uses analog downmix electronics to downmix electronics shown in Figure 3.19 to select a dipole mode which couples strongly to the beam. Tests at FLASH have demonstrated resolutions of less than 10 µm for a single bunch and the ability to provide bunch-by-bunch measurements for 1 MHz bunch trains. The system requires calibration by moving the beam through known trajectories in the cavity which is typically done with other BPMs. The narrowband system is very timing sensitive and requires good stability between the RF, LO, and trigger.

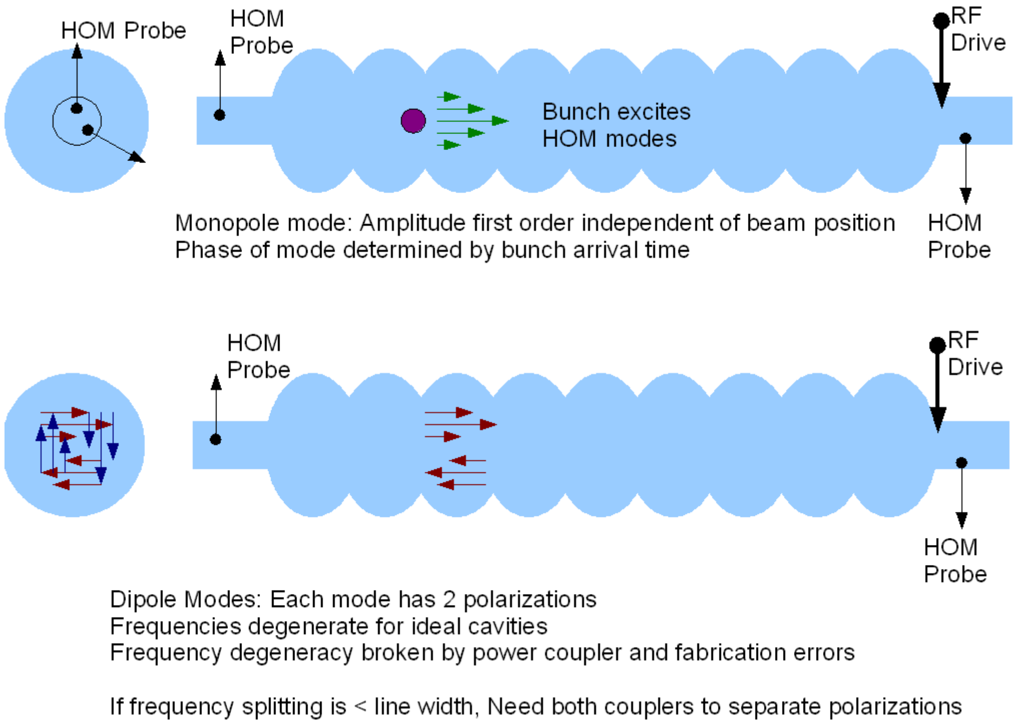


Figure 3.18: Monopole and dipole modes in a Tesla 9-cell cavity.

The HOM signals also are a very useful tool for studying the superconducting cavities under operating conditions. The observed modes can be compared to predicted modes from simulations and test stand measurements. For this reason, a narrowband system capable of measuring different modes is very attractive. This makes implementing the LO, trigger, and downmix electronics challenging given the phase stability which is required.

Plans

In the current A0PI accelerating cavity setup both HOM coupler signals are buried in the cryostat and are unfortunately not accessible. With a new or modified SCRF module these signals will be ported to the outside, allowing analysis of these HOM signals. We plan to investigate both techniques, broadband HOM signal analysis using our (to be upgraded) fast oscilloscope (12 GHz realtime BW), as well as a narrowband read-out system based on a 125 MSPS VME digitizer currently under development.

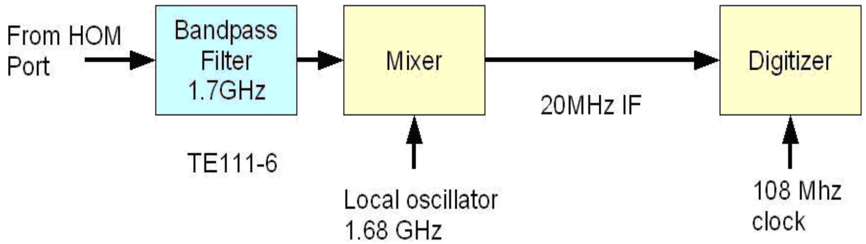
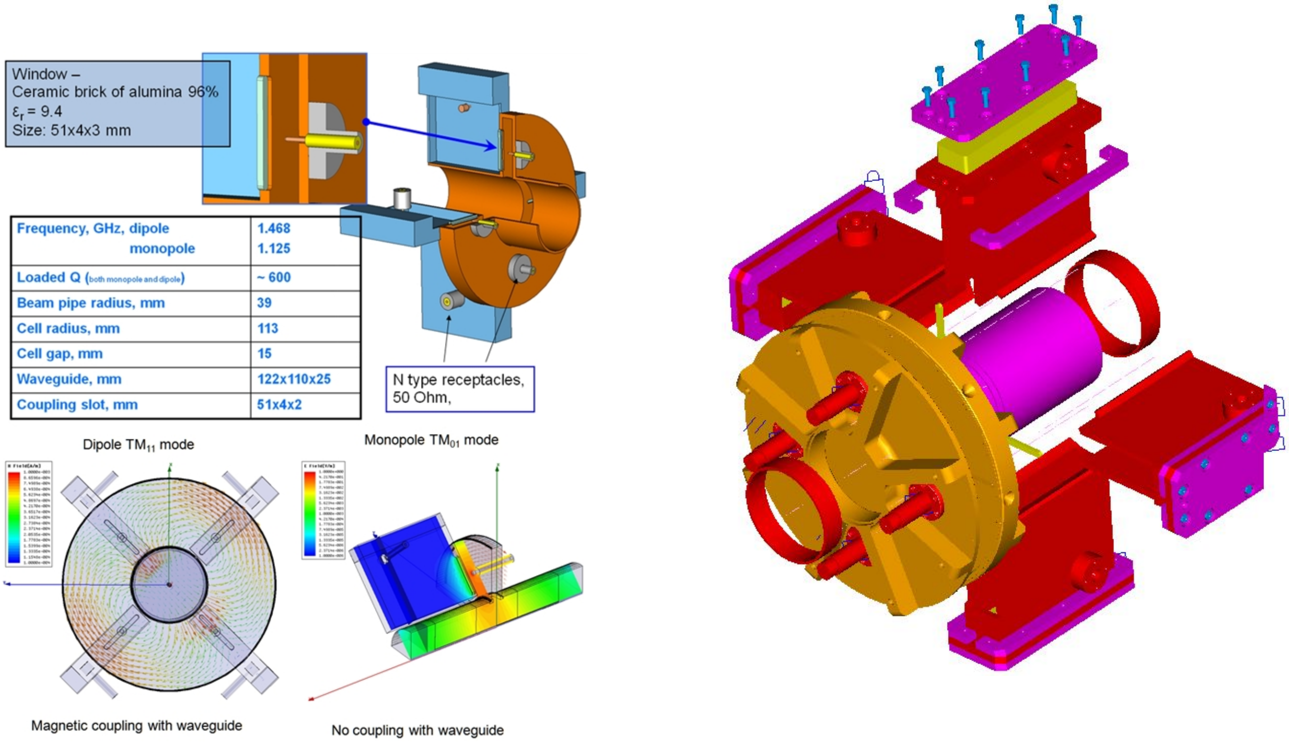


Figure 3.19: Narrowband downmix electronics scheme.

3.3.7 Cavity BPM

In frame of the ILC global design effort, a high resolution (0.5-1 μm) beam position monitor, based on a common-mode free L-Band cavity is under development for application in the SRF cryostat (quad-BPM package) (Figure 3.20) [16]. The manufacturing of a warm prototype is currently underway, it has dipole-mode read-out ports (f_{110}~1.5 GHz) for the displacement signals, as well as monopole-mode ports (f_{010}~1.1 GHz) for beam intensity normalization. The loaded Q is Q_l~500-700, which allows single bunch beam position measurements (>300 ns bunch-to-bunch spacing). After tuning and characterization on an RF test stand, we are planning to analyze the cavity BPM in detail under realistic beam conditions at the A0PI. It is necessary to understand how well the tuning suppresses the x-y coupling, CM rejection in the dipole mode signals, single bunch behavior, signal processing, noise figures, etc. to fully characterize resolution and dynamic range under real world conditions.



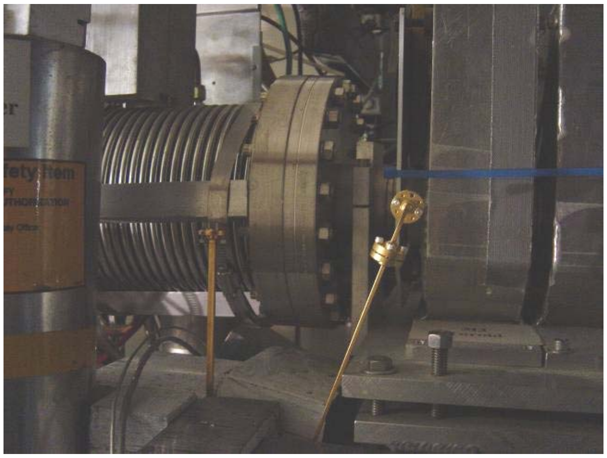
Frequency, GHz, dipole monopole	1.468 1.125
Loaded Q (both monopole and dipole)	~ 600
Beam pipe radius, mm	39
Cell radius, mm	113
Cell gap, mm	15
Waveguide, mm	122x110x25
Coupling slot, mm	51x4x2

Figure 3.20: CM-free L-Band cavity BPM for the SRF cryostat.

3.3.8 Waveguide pickup

We propose this technique, as it is a quite simple and inexpensive technique to estimate the bunch length and verify the bunch compression.

The frequency domain magnitude spectrum of the beam is observed at a radiating ceramic gap at several (2-4) frequencies. Horn-antennas, waveguides, and detector elements are commercially available in a range 90-900 GHz. Similar experiments were executed at the SLAC Endstation-A [17] (Figure 3.21) and at the CERN CLIC Test Facility [18]. The response time of the detector elements is <<1 ns and the noise characteristics are excellent, thus allowing single bunch measurements. The setup is very simple and straightforward, however an absolute calibration of the bunch length is extremely difficult (no phase information, unknown insertion loss, and unknown sensitivity among the different frequency channels). However, this simple, inexpensive method gives a non-invasive, relative observation of the length of each single bunch.



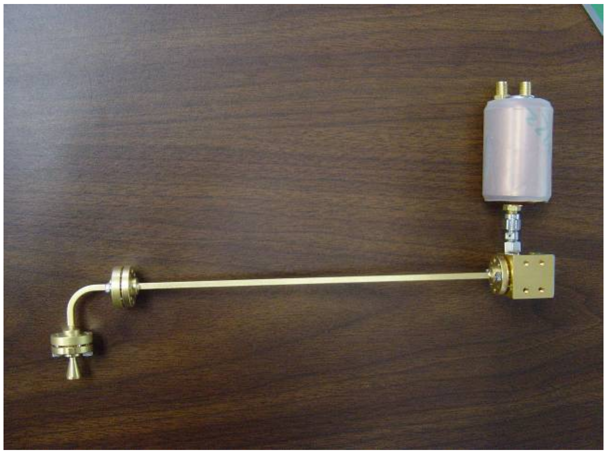


Figure 3.21: 300 GHz waveguide pickup system tested at SLAC ESA.

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4 Facility upgrades

4.1 RF gun

The gun and cathode chamber will be replaced by newer versions from DESY and INFN Milano, respectively. The new cathode chamber will allow for easier changing of the cathodes and the ability to prepare cathodes outside of the beamline cave. The new gun with its on-axis coaxial input coupler will improve gun operation, and reduce dark current, breakdown, and emittance. In conjunction with the TESLA collaboration, Fermilab has constructed and operated several L-band (1.3 GHz) photo-cathode RF guns. One of these guns is presently installed at the A0PI, while another gun was installed at the DESY TTF. Both these Fermilab-built guns have exhibited deficiencies, most notable RF break-downs at long pulses caused by excessive heating at the input coupler slot. Dark current has also been an issue but this is more likely a feature of the cathode than of the gun. The gun at the DESY TTF was later upgraded with a new RF gun, while the Fermilab gun has remained in operation. Fermilab has recently obtained all documentation needed to produce this new upgraded RF gun. This DESY-type RF gun will be procured, commissioned and installed at the A0PI as part of the upgrade. It is schematically shown in Figure 4.1. The DESY-type gun has been characterized at DESY Zeuthen PITZ [1] where they measured normalized 90% emittances of ~1.5 mm-mrad at 1 nC. The normalized 90% emittance measured at the end of the 120 MeV injector at DESY is ~2 - 2.5 mm-mrad with 3MW gun rf power. These measurements give us some expectation that we may improve our beam emittance after the new gun (and, possibly, capture cavity) are installed. RF power for the gun will remain the same as at present (3 MW) and limit the gradient on the cathode to about 35 MV/m. Table 4.1 summarizes the main parameters of the RF gun.

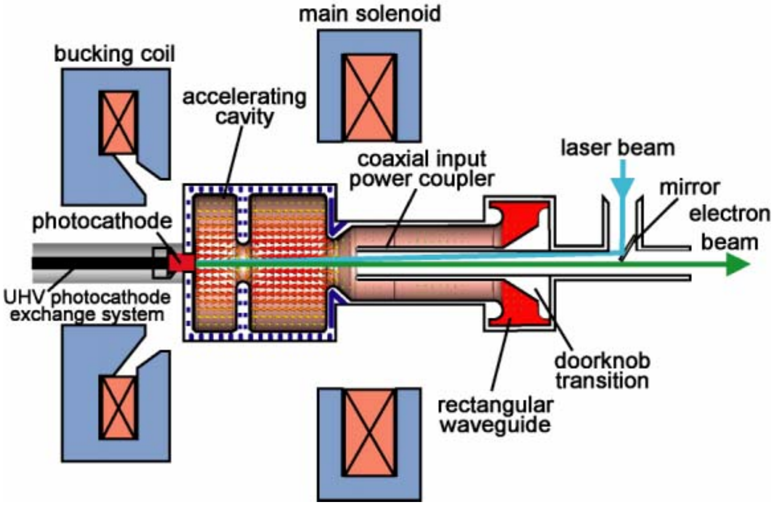

Figure 4.1: Schematic of the DESY-type RF photo gun.

Table 4.1**:** The main RF gun parameters

electrons/bunch	2×10^{10}
bunches/pulse	up to 3000
bunch repetition rate	3 MHz
pulse repetition rate	up to 5 Hz
average current	50 µA
beam energy	4.5 MeV
RMS bunch length	1 – 6 mm
RMS normalized emittance	4-5 µm

The difference in design between the Fermilab and the DESY guns will require the following other components to be replaced at the A0PI: (1) the gun cavity itself, (2) the focusing solenoids, (3) the coaxial RF coupler, (4) the laser mirror cross, and (5) the cathode exchange system. The current drive laser system will be replaced by a Ti:Sapphire based system, as discussed in Sections 2.2 and 3.2 of this proposal.

4.2 SRF acceleration cavity

At the current beam energy of 16 MeV space charge effects play a significant role in the beam dynamics. Increasing the beam energy to ~30 MeV will reduce space charge effects by a factor ~4. The current accelerating cavity has a low quench threshold and is limited to ~12 MV/m. There exists an additional, similar accelerating cavity and cryomodule which is being installed at NML solely to provide a cryogenic load to commission the new cryogenic system there. This cavity is capable of a gradient of ~25 MV/m. After the NML cryogenic system is commissioned, there will be the opportunity to move this higher gradient cavity to the A0PI, replacing the current low-gradient cavity and accomplishing the energy upgrade to ~30 MeV. This replacement would also provide the opportunity to repair the low-gradient cavity before it is installed at NML. Preliminary simulations indicate that reasonable transverse beam emittance is achievable at ~30 MeV with a single accelerating cavity (Figure 4.2).

Implementation of this upgrade is still under consideration, but would take place at the same time the RF gun is replaced. Most likely this will be in early Summer of 2009.

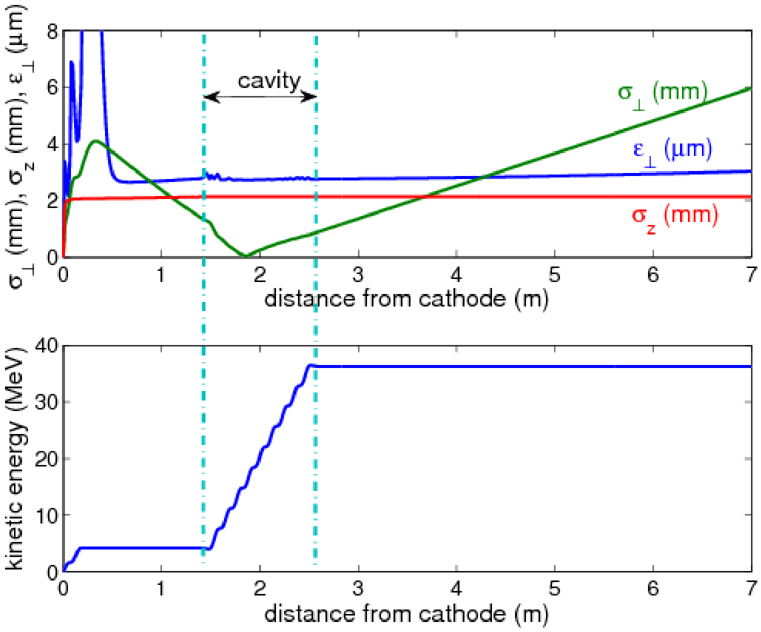

Figure 4.2**:** Beam parameters evolution with a 25 MV/m accelerating cavity. Beam transverse rms size, emittance and bunch length (top) and kinetic energy (bottom) are shown. Egun peak E-field is 40 MV/m and charge per bunch is 1 nC.

4.3 Other components

Beamline reconfiguration

The accelerating cavity is followed by a round-to-flat beam transformer composed of three quadrupoles, a set of normal quadrupoles, and is then split into two lines. One line has a double dogleg configuration, and the other line currently is open. We will reconfigur this 2nd line as a magnetic chicane. Both lines have spectrometer dumps. (The current layout is shown in Figure 6.1.)

Low Level RF system

The present LLRF system coordinates and regulates the timing, RF phases and amplitudes of the three RF cavities and the laser. The systems are state-of-the-art FPGA-based regulation systems for each cavity. The approach is based on the developments at the DESY FLASH and XFEL facilities. Additional R&D and improvements to the system and controls interface are being implemented at Fermilab.

The A0PI provides a unique test bed for this ongoing development and improvement program as it is currently the only place at Fermilab where the systems and feedback algorithms can be rigorously tested with beam, as an integrated multi-cavity system.

Controls

The control and data acquisition system for the A0PI is based on the DOOCS (Distributed Object Oriented Control System) package from DESY. This package includes a framework for writing front-ends and a client for creating and displaying virtual control panels for operators. The client package is currently unsupported and a replacement is currently under development at DESY. We will upgrade to this replacement package if it proves suitable for A0PI operations.

Beam Monitor Read-out Systems

The read-out electronics systems for most basic beam monitors (e.g., toroids and beam position monitors) are outdated or temporary installations, unable to deliver the required performance and reproducibility of the beam parameters to be characterized. A new, low-cost 100 MS/s 8-channel VME digitizer, recently developed in-house, will replace old analog signal processing installations for beam position and intensity measurements. The BPMs will be equipped with a downconverter/calibration unit, already successfully tested at the ATF damping ring at KEK.

Radiation & Shielding

The radiation limit outside the cave is set to 1 mrem/hr and on the roof of the cave to 5 mrem/h. At the present 16 MeV operating energy an administrative beam current limit of 300 nC/sec applies. The existing enclosure shielding thickness is 320 gm/cm^2. At the higher energy of 30 MeV, we will have to determine the allowable pulse length and bunch charge to stay within the above limits. Minor improvements in shielding may be required.

SRF R&D

The A0 building supports an ongoing SRF research area with clean room, clean assembly area, high pressure rinse system and vertical dewar testing. Continued research and testing is planned for the area and the A0 technicians support both this activity and A0PI operations. The A0 area is the ideal place to test small special research cavities such as special coatings, single crystal special cavities, alternative processing, etc. Tests of both 1.3 and 3.9 GHz cavities take place here.

4.4 Collaborations and students

The A0PI has an extensive history of collaboration with other groups and institutions. Much of the hardware that makes up the photoinjector has come from other groups, and people from other institutions have spearheaded or been involved with both the specific projects and the hardware or equipment that make up the photoinjector. These collaborative activities are summarized in Table 4.2.

At present Argonne, Northern Illinois University, Fermilab, and University of Chicago are collaborating in a partnership-like arrangement where we try to supplement each of the other's activities and build on the interchange of both ideas and utilization of equipment and resources. We are hoping to enlarge this group to include participation from others such as University of Maryland, University of Wisconsin, and MIT. At present, discussions of possible mutual interest are in initial phases. We believe we have a facility that well complements that at Maryland and student studies of photoinjector issues and diagnostic development of short bunches could complement their activities. Both Wisconsin and MIT are interested in participating in the ellipsoidal beam experiment and have also expressed interest in electron-laser interactions. Collaboration continues with DESY and INFN Milano on RF gun development.

Table 4.2: Collaborating and participating institutions, past and present.

institution	equipment	projects/people
Argonne		emittance exchange, EOS
Cornell	4 MW klystron, SRF equipment	ILC fast kicker and tests
DESY	TESLA SRF cavities CC1 and CC2, 300 kW klystrons, RF guns, LLRF, DOOCS controls, Martin-Puplett interferometer	Flat beam
Fermilab		all
LBNL		Flat beam
INFN Frascati	intensified camera (loan)	student and use of camera
INFN Milano	cathode preparation chambers	commissioning of cathode systems
NIU	helium gas recovery system, laser oscillator	electro-optical imaging
Rutgers		emittance exchange, CC2 install and test
Saclay/Orsay	SRF cavity cryostats, tuner	injector characterization
UCLA	plasma chamber, magnets	plasma wakefield acceleration and focusing, photoinjector design
Univ. of Chicago		Flat beam
Univ. of Illinois		ILC fast kicker, students and tests
Univ. of Rochester	drive gun laser and additional equipment	Laser assembly, commissioning, EOS, laser acceleration, two macrobunch compression

Students and their supervision are a specific issue for the A0PI. A list of past and present PhD students is given in Table 4.3. For the activities at A0 to be effective there must be a critical mass including both staff and students. We must find stable student sources in order to have a viable program. In the past many of the students have come from University of Rochester and UCLA. We look forward to students from NIU and Chicago, but we must establish other strong university connections.

Table 4.3: Past and current graduate students at the A0PI.

name	institution	date of PhD	thesis topic	current institution
Eric Colby	UCLA	1997	RF photoinjector gun	SLAC
Alan Fry	Univ. of Rochester	1998	laser development	
Mike Fitch	Univ. of Rochester	2000	electro-optical sampling	
Jean-Paul Carneiro	Universite Paris XI	2001	experimental studies of photoinjector	Fermilab
Yin-e Sun	Univ. of Chicago	2005	flat beam transform	Fermilab
Matt Thompson	UCLA	2005	plasma acceleration	
Rodion Tikhoplav	Univ. of Rochester	2006	laser acceleration	UCLA
Tim Koeth	Rutgers Univ.	current	emittance exchange	
Artur Paytyan	Yerevan Univ.	current	SC RF controls	
Timothy Maxwell	NIU	current	EO imaging	

<u>References</u>

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5 Transition to Mid-West AARD Center (NML)

The Tesla Test Facility at DESY has provided a valuable system test for many elements of the TESLA SRF technology. However, several important changes to the TESLA RF cavity and cryomodule design are being planned for the ILC and for Project X at Fermilab. These will include a higher cavity gradient, relocation of the quad, shortening of the cavity end-group, and a new tuner design. Such changes will likely be introduced in several steps, with the first one being called a Type-IV cryomodule design. Also under discussion are different modulators, klystrons, cavity shapes, and other devices related to cryomodule operation. The minimum size system test needed to confirm the performance of such a new design for Project X is 2 cryomodules with 9 mA beam current per pulse.

Presently, Fermilab is building an ILC / Project X test facility, called NML, at the existing New Muon Lab building (Figure 5.1). NML will be the only U.S. facility capable of testing completed cryomodules, and this facility will be capable of testing cryomodules at high accelerating gradients with an ILC-like beam. NML will perform the initial tests of Type-IV cryomodules, and the goal is to produce and test 2 full cryomodules by the end of FY11. This facility will be invaluable to the SRF R&D program leading up to and most likely through the Project X construction. It will allow for a dedicated study of dark currents, HOM extraction, alignment, LLRF and control issues, cryogenic issues, RF power distribution, reliability and system recovery issues. Although the SRF program will be the first user of this facility, it will not be the only user. As the need for SRF-related tests diminishes, the facility will increase service to other users, such as the Advanced Accelerator R&D projects and experiments.

Figure 5.1: Photograph of interior of NML building, looking towards future high energy end. Visible is a single cryomodule (yellow).

The NML test facility will consist of the injector area comprised of the electron gun, acceleration cavities, and low energy beamlines (~24 m), the accelerator area comprised of 2 cryomodules (~27 m), and the high energy beamlines and dump area (~22 m). A schematic layout is shown in Figure 5.2. Currently, a temporary cryogenics system is being installed in the building, but a new cryogenics plant will be added to the facility in the future in order to accommodate the correct fluid temperatures and to provide higher cryogenic capacities.

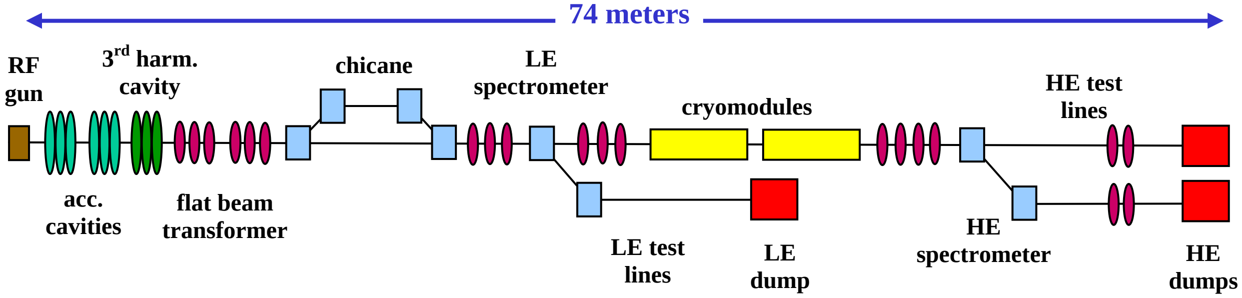

Figure 5.2: Approximate layout of NML beamlines.

Eventually the NML building may be extended so that additional cryomodules can be accomodated and also to add additional space for an enlarged AARD program in the high energy beamlines. The injector will provide beam energies up to 50 MeV and the high energy beamlines will provide energy >500 MeV (with 2 cryomodules). The experiments presented in this proposal can be continued at NML, and in addition, the following experiments have been discussed:

- ILC crab cavity tests
- Optical stochastic cooling
- in-vacuum laser acceleration
- beam driven acceleration in slab dielectric structures
- development of optical diffractive radiation diagnostics.

6 Appendices

6.1 Parameters

Table 6.1: Current A0PI beam parameters

parameter	units	value
gun gradient @ cathode	MV/m	35-40
9-cell cavity accelerating gradient	MV/m	12
bunch spacing	μs	1
# of bunches/pulse		10 - 200
RF pulse length	μs	30 - 300
pulse repetition rate	Hz	1
cathode efficiency	%	0.5 -2.0
laser UV energy	μJ/bunch	16
FWHM laser pulse length, unstacked/stacked	ps	5/21
bunch charge	nC	1 - 10 typ.
kinetic energy after gun	MeV	4.0
kinetic energy after 9-cell cavity	MeV	16
gun solenoid peak field	Gauss	1200
laser spot radius @ cathode	mm	0.7 - 1.6
RMS normalized emittance @ 1 nC	10^{-6}m	4-6
RMS normalized emittance @ 8 nC	10^{-6}m	12.6
uncompressed beam		
RMS momentum spread @ 16 MeV @ 1 nC	%	0.25 - 0.38
RMS bunch length @ 1 nC	mm	1.6
RMS bunch length @ 8 nC	mm	2.9
peak bunch current	A	75 - 330
bunch compressor		
Compressor R56	cm	8
Compressor Max. Dispersion	cm	14
Compression Phase	degrees off crest	-39
Chirped Energy spread	%	1.32
Compressed Bunch Length @ 1nC	mm	0.21
peak bunch current	A	1400
double dogleg compressor		
Compressor R56	cm	24
Compressor Max. Dispersion	cm	66
Compression Phase	degrees off crest	-20
Compressed Bunch Length @ 1nC	mm	0.19
peak bunch current	A	1570
emittance exchange		
CC1 Phase	degrees off crest	-20
Beam Energy	MeV	14.3
Energy Spread	%	0.8
Bunch Length	mm	0.45

Table 6.2 Current A0PI drive laser parameters

parameter	units	value
oscillator frequency	MHz	81.25
oscillator wavelength	nm	1054
oscillator energy/pulse	nJ	5.5
energy/pulse after multi-pass	μJ	6
energy/pulse after two-pass	μJ	100
UV energy/pulse after crystals	μJ	20
UV energy/pulse on cathode	μJ	10
UV pulse length (FWHM)	ps	5
pulse separation	μs	1
length of pulse train		up to 800 bunches
train repetition rate	Hz	1

6.2 Facility layout

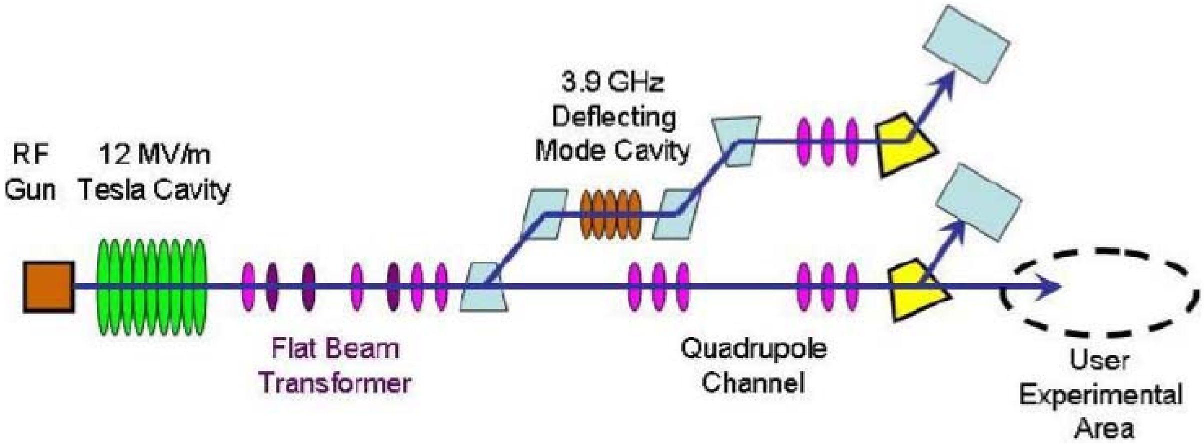

Figure 6.1: Current A0PI layout.