Fermilab Feasibility Study on a Neutrino Source Based on a Muon Storage Ring

Muon Collider / Neutrino Factory
Collaboration Meeting

David Finley

Witherell Letter

- Insert Witherell 9/22/99 letter to Holtkamp … 2 slides

Witherell 9/22/99 Charge to the Study Group

- Design concept … reasonable assurance … neutrino based research program
- Likely cost drivers
- R&D program
- Specific ESH issues
- Work closely with the Collaboration

Overall Status

- March 1, 2000 is due date (will come close to making it)

- Parameters are: 2E20 50GeV-muon decays per year aimed at “West Coast” and be able to flip sign of muons once a week or so

- Physics study (Geer, Schellman) in parallel

The Muon Collider Collaboration and Contributing Institutions

- Argonne National Laboratory
- Budker Inst. Of Nuclear Physics
- Brookhaven National Laboratory
- UC Berkeley
- UC Davis
- UCLA
- UC Riverside
- CERN, Geneva, Switzerland
- Cornell University
- ETH Zuerich
- Fairfield University
- Fermi National Accelerator Laboratory
- Indiana University
- Illinois Inst. of Technology, IIT
- University of Iowa
- Jefferson Lab.
- Kansas State University
- Research Center Karlsruhe
- KEK
- Lawrence Berkeley National Lab.
- Inst. of Mathematics, Novosibirsk
- Michigan State University
- University of Minnesota
- University of Mississippi
- Nat. High Magnetic Field Lab.
- Northern Illinois Univ.
- SUNY, Stony Brook
- Northwestern University
- Oak Ridge National Lab.
- Princeton University
- Rutherford A. Lab.
- Rockefeller University
- Tel-Aviv University, Israel
- University of Texas Pan American
- University Voctoria
- University Wisconsin

An Artist’s View of a Muon Collider

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Elements of a Neutrino Source

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Consider a Lepton Collider

$$L = \frac{N^2 \cdot f_c}{4p \cdot s^*_x s^*_y} \propto \frac{P_{beam}}{E_{cms}} \times \frac{N_e}{4p s^*_x s^*_y} \times H_D$$

Gain by: $N_e \rightarrow N_\mu$ x $f_{rev}N$
lose by: σ’s

cms Energy	GeV	3000	400	100	
Proton energy	GeV	16	16	16	
Protons/bunch	10^{13}	2.5	2.5	5	
bunches/pulse		4	4	2	
rep rate	Hz	15	15	15	
beam power	MW	4	4	4	
? / bunch	10^{12}	2	2	4	
? beam power	MW	28	4	1	
collider circ.	m	6000	1000	300	
~depth	m	500	50	5	
rms dp/p	%	.16	.14	.12	.003
6D emittance (? m rad)^3	10^{-12}	170	170	170	
transv. Emitt. (? m rad)	10^{-6}	50	50	85	290
? *	cm	0.3	2.3	4	14.1
$?_r$ at spot	? m	3.2	24	82	294
Luminosity 10^{34}	cm^{-2}sec^{-1}	5	0.1	0.012	0.001

This is very different in a neutrino source

Proton Driver Study I

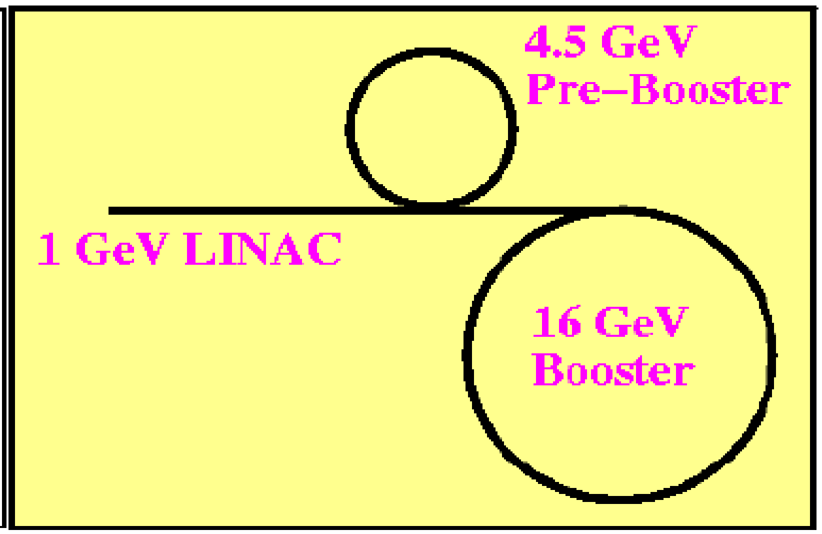
- Benefits for Main Injector Based Program:
  - more intensity for fixed target program (16 + 120 GeV)
  - prepare the basis for a muon storage ring for neutrino beams
    - remember: many bunches is ok, only the total charge counts --> eases the design of cooling and capture channel
  - Main Injector plus upgrades: 5x Intensity
  - maybe: p-bar target -> liquid targets etc
  - maybe: TeV 33
- Benefits for MCNF Collaboration
  - **RF, beam loading, feedback**
  - **Collective effects**
  - **Magnet, power supplies, vacuum**
  - **Lattice**
  - **H^- source and linac / linac upgrade**
  - **Collaboration with KEK/Japan**

Proton Driver Study II

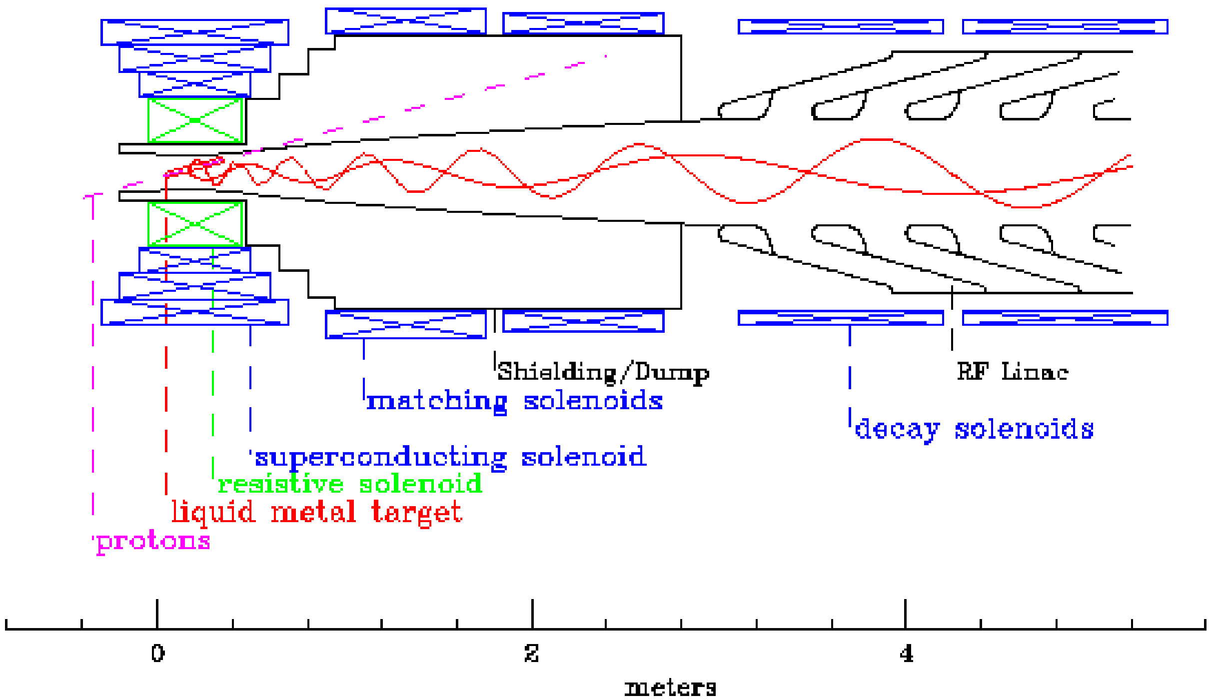
Upgrade 400 MeV Linac –> 1 GeV

Upgrade 8 GeV Booster –> 16 GeV

Add a 4.5 GeV (3 GeV ?) Pre–Booster (facilitates short bunches).



Pion Source and Muon Production



- 16 GeV protons at 5x10^{13}
- 2 bunches per pulse

- 0.6 p+ per proton
- p_z ~ p_t 200 MeV/c with s_E ~ 100 %

Target

- Choices
  - Use solid for 1.5 MWatt
  - Building to support 4 Mwatt
  - Solid not likely for 4 Mwatt
  - other talk

Cooling

- Pions are emitted in a very diffuse phase space

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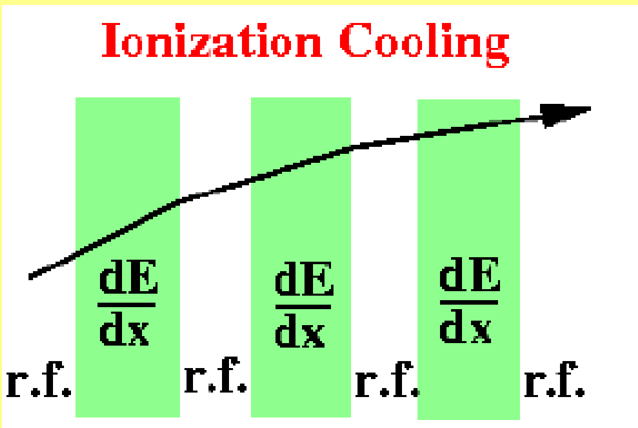
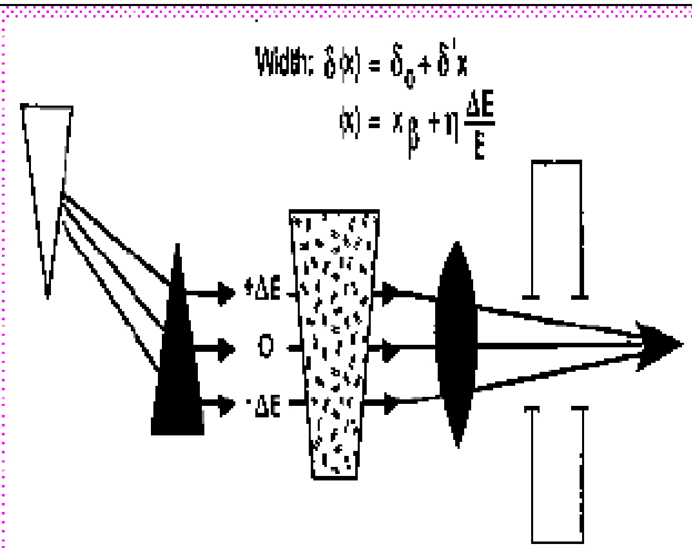
Cooling Principle



Transverse Cooling

Muons lose energy by dE/dx and long–itudinal momentum replaced by r.f.

- **To Minimize heating from Coulomb Scattering:**
  - Small $\beta_\perp$ (strong focusing) : High–field solenoids or Lithium Lenses
  - Large L_R (low–Z absorber) : Liquid H_2



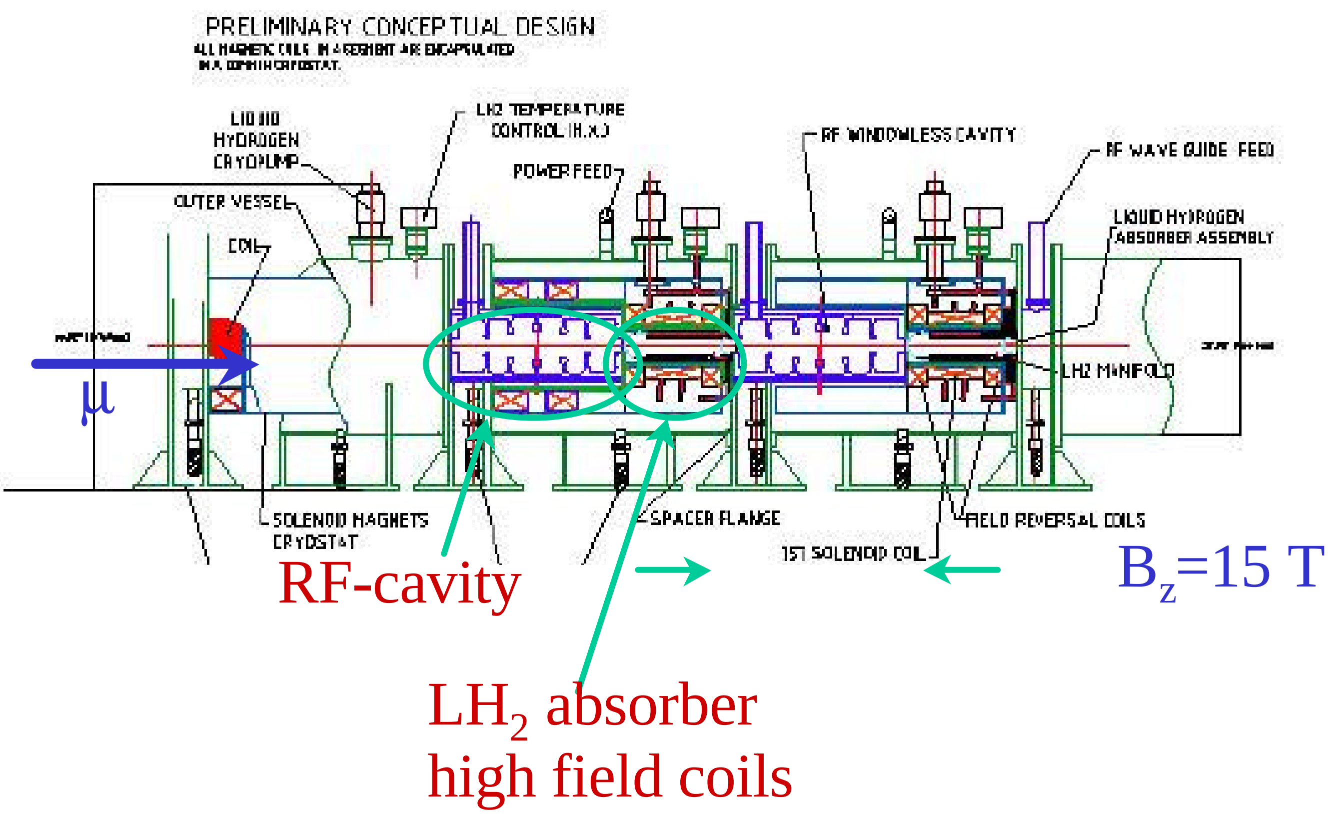
Energy "Cooling"

Ionization cooling using a wedge plus dispersion.

Exchanges emitt–ance between transverse & long–itudinal directions

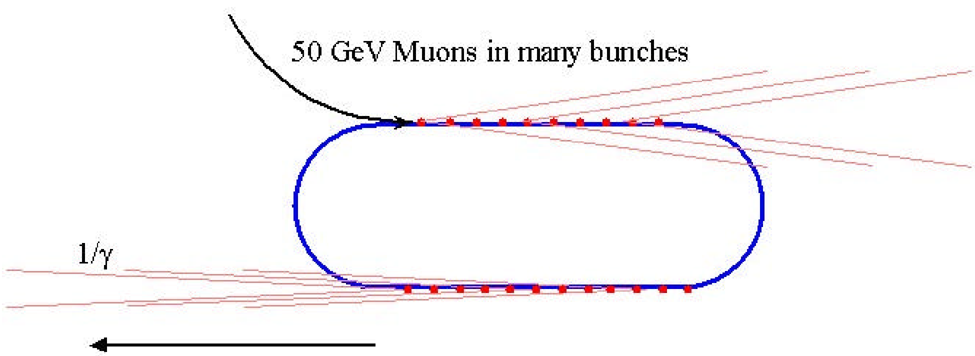
Cooling Channel for Muon Collider

- BNL/ITT/ FNAL/FSU design approach for an integrated cooling channel
  - 42 cm Liquid hydrogen target (D. Kaplan, E. Black)
  - 15 T alternating solenoid channel (P. Lebrun, B. Palmer, J. Miller)
  - 0.96 m x 27 MV/m accelerating structure



Neutrino Source

- First experiment based on an intense muon source
  - small emittance not necessary because divergence is dominated by decay kinematics
  - recognized by S. Geer



Parameters for the Muon Storage Ring		
Energy	GeV	50
decay ratio	%	>40
inv. Emittance	m*rad	**0.0032**
β in straight	m	160
N_μ/pulse	10^{12}	6
typical decay angle of $\mu = 1/\gamma$	mrad	2.0
Beam angle $(\sqrt{\varepsilon}/\beta_o) = (\sqrt{\varepsilon}\,\gamma)$	mrad	0.2
Lifetime $c*\gamma*\tau$	m	3×10^5

$\gamma = (1-\alpha^2)/\beta$

Neutrino Source Study @ FERMI

- Application of a “Generic Neutrino Source” to specific site
- Base the study on specific set of Parameters
- 6 month period of time to define the R&D program and develop a layout to investigate the scope of such a complex

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Generic Layout

↓

collaboration
paper

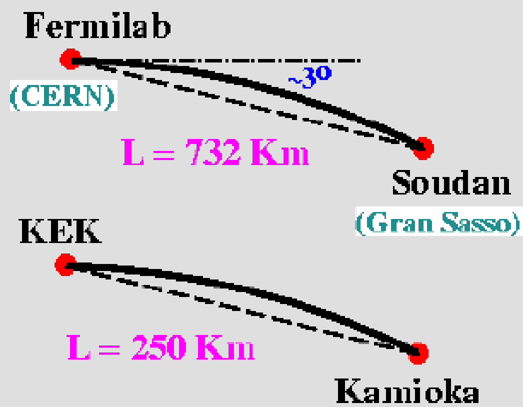
“deviate wherever
necessary or useful”

Physics Study in parallel
H. Schellmann / S. Geer

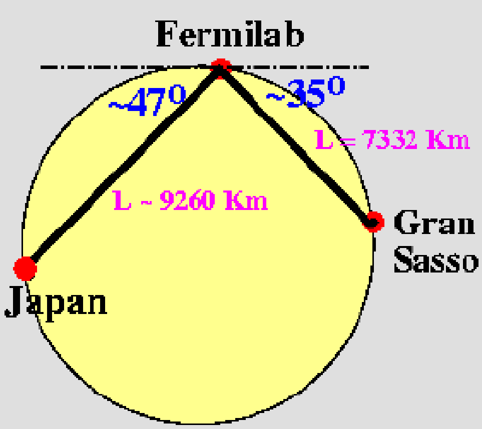
L/E and Other Physics Guidance

- Purity of the beam: μ^+/μ^- -> $e^{+/-}\nu_e/\nu_\mu$
- Kinematics from decay well known
- Polarization -> oscillation of ν_e component

	L (km)	Dip (Deg.)	Heading (Deg.)
FNAL -> Soudan	732	3	336
FNAL -> Gran Sasso	7332	35	50
FNAL -> Kamioka	9263	47	325



E_ν (GeV)	L/E (Km/GeV) FNAL–Soudan	KEK–Kam.
10	73.2	25.0
20	36.6	12.5
30	24.4	8.3
40	18.3	6.3
50	14.6	5.0



E_ν (GeV)	L/E (Km/GeV) Gran S.	Japan
10	~733	~926
20	~367	~463
30	~244	~309
40	~183	~232
50	~145	~185

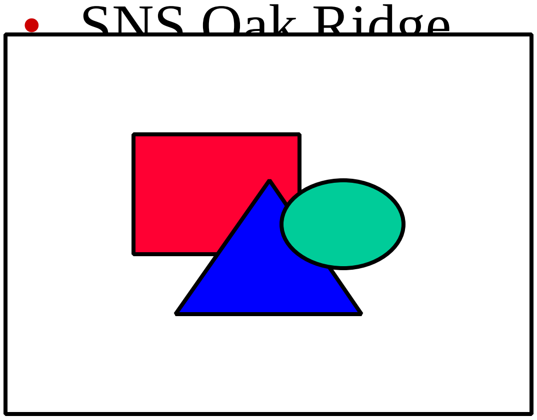
Parameter Choices for Study

Parameters for the Neutrino Source		
- Energy of the ring	GeV	50
- Number of muons decaying in straight section		$2x10^{20}$/y
- no polarization		
- capability to switch between m^+ and m^-		
- Fermilab to SLAC / LBNL		

- Basic Calculation
  - If
    - 1/3 of the muons decay in the straight section
    - 10 protons for 1 μ into the storage ring
    - $2x10^7$ sec (versus $1x10^7$) in a year
  - Then
    - $2x10^{13}$ proton on target per pulse @ 16 GeV and 15 Hz
    - $2x10^{12}$ μ per pulse to be accelerated and injected into the ring
  - Longer bunch in proton driver (1 nsec --> 3 nsec)
  - Ring tilt is 13 degrees (22%)
  - Maximize straight section / circumference

Chose a Target for the Neutrino Factory

- Comparable Targets
  - RAL: Spallation neutron sources
  - CERN/ FNAL: p-Bar production
  - new developments for Muon sources
  - SNS Oak Ridge



•NuMI Target

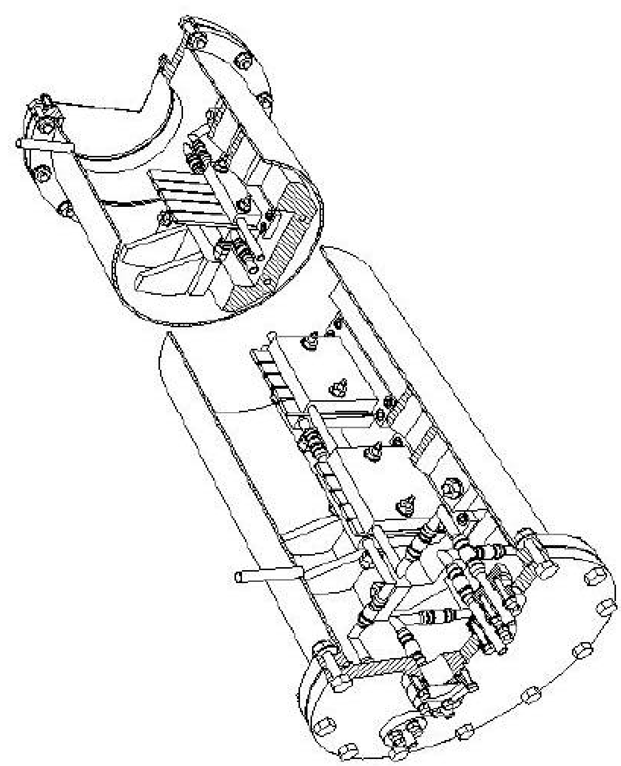
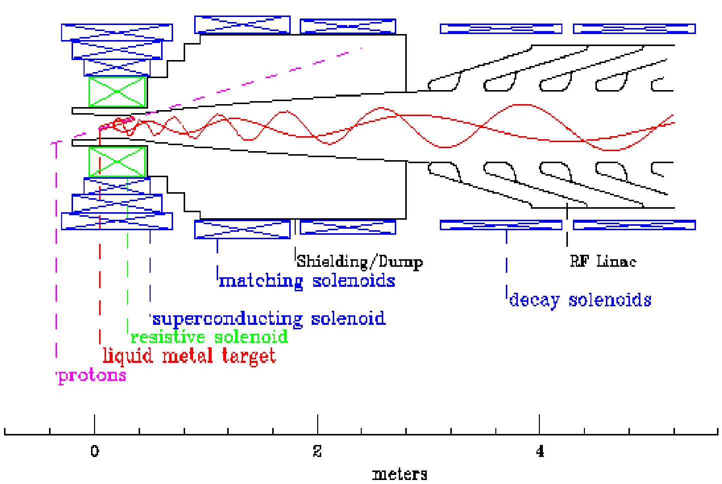


Figure 1.16: Perspective view of the target design.

•Target Experiment



Target Choice for Study

- 1 - 1.5 MW target
- Reduce power in the target -> low Z
- Solid Target

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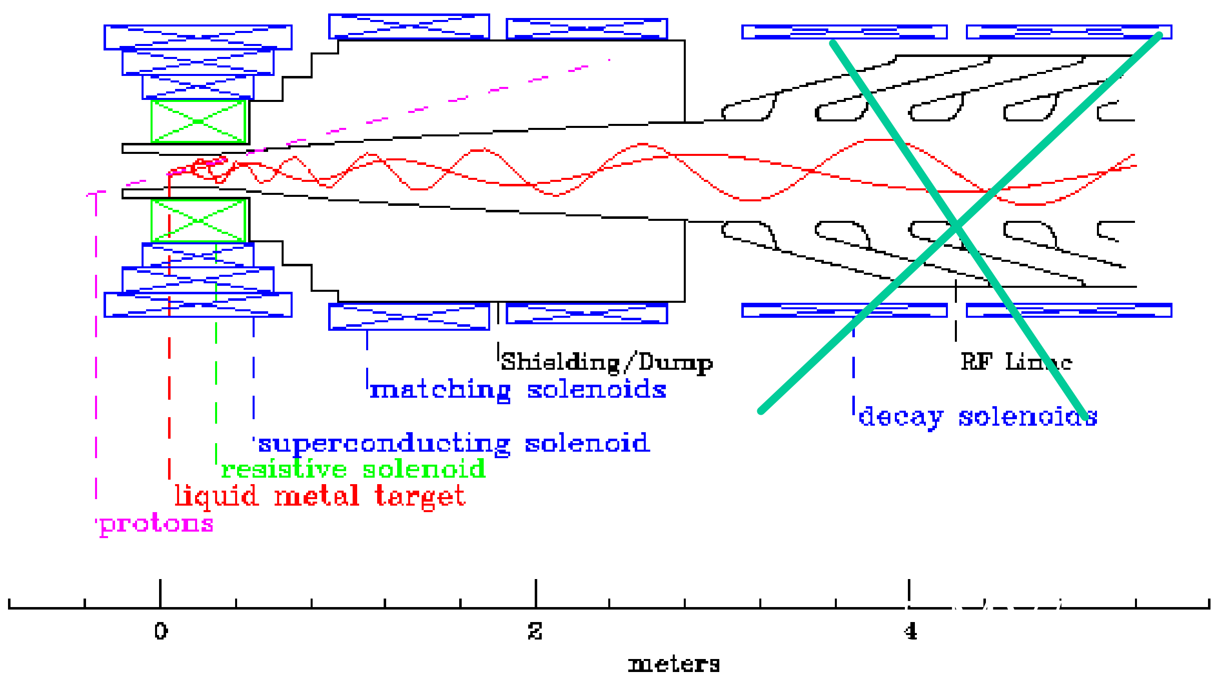
What changes compared to MC

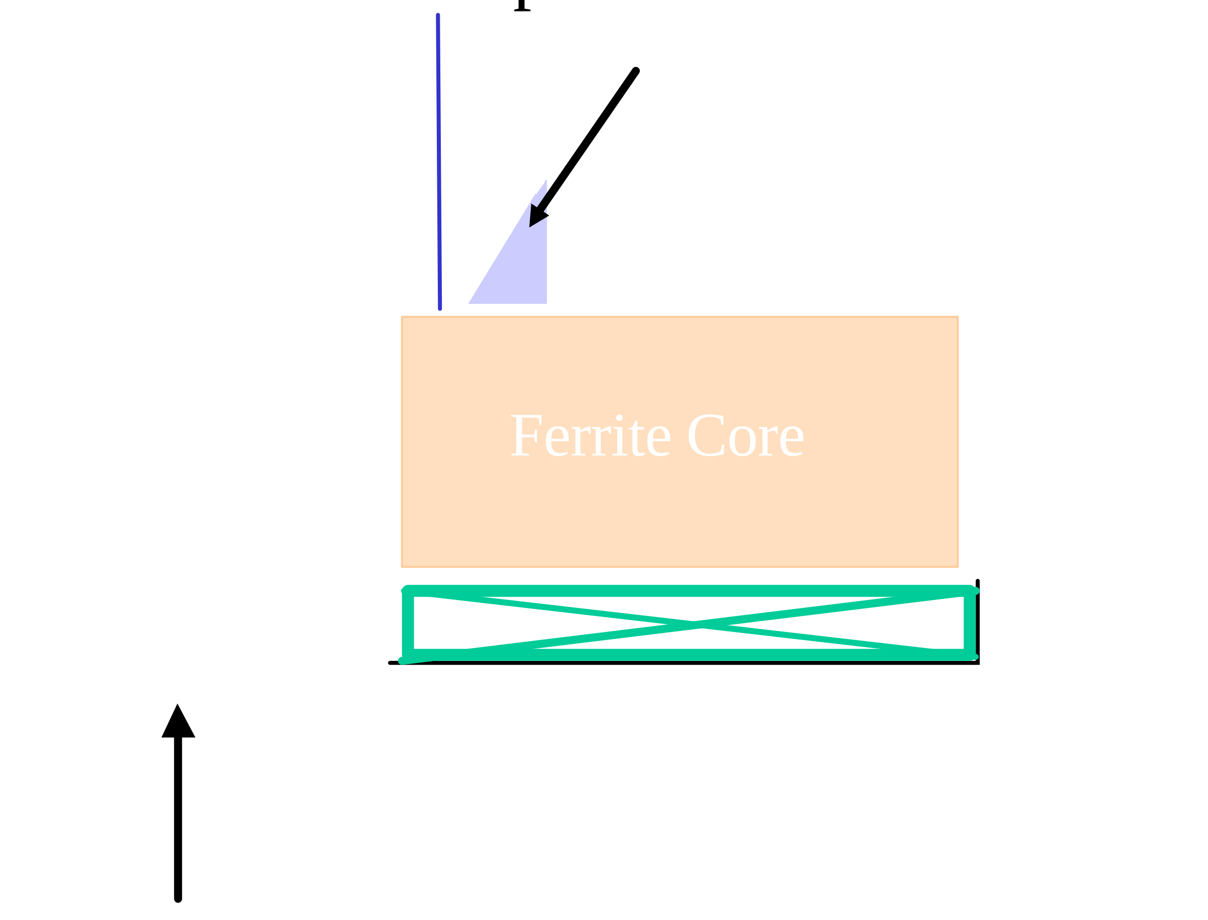
- Proton driver
  - four bunches (and hopefully induction linac)
  - longer bunch (because no polarization)
- Target
  - maybe solid graphite if only 1 MWatt



- 16 GeV protons at $2.5x10^{13}$
- 4 bunches per pulse on target
- solid graphite target (a la NuMI)
- 0.6 π+ per proton
- $p_z \sim p_t$ 200 MeV/c with $\sigma_E \sim$ 100 %

The Induction Linac

- Gradient (1 MV/m)
- Focusing
- Multiple Pulses ⇒ switching system
- Power consumption

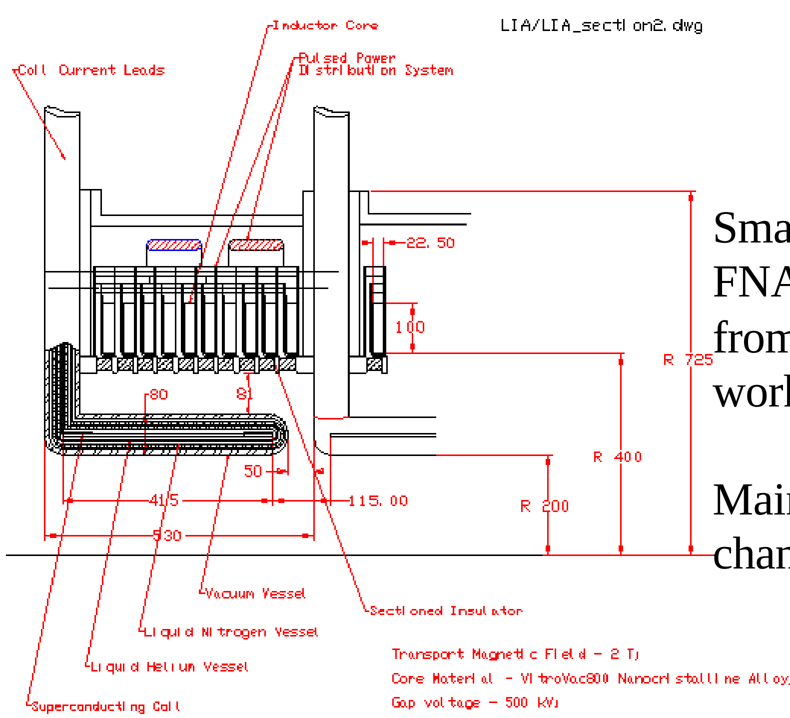


Core Scaling (LBL)

- Requirements
  - 2MV quasi-linear ramp for 100 ns => $V\tau$ = 140 mV-s
  - 20 cm bore radius & 25 cm for B_Z magnet & Insulator => R_{inner} = 45 cm
  - < **1.0 MW for 4 pulse burst @ 15 Hz**
- Metglass 2605SC
  - 3.3e-2 m^2 = A_{Met}, 6.7e-2 m^2 = A_{core}
  - 8100 J/m^3 = E_{core}
  - 9.2e-2 m^3 = V_{met} =>746 J per shot = E(2Mev)
  - **4.5 MW system exceeds 1.0 MW allowance**
- Metglass 2714A
  - 0.16 m^2 = A_{Met}, 0.35 m^2 = A_{core}, PF_r = 0.7, PF_a = 0.64 => R_{outer} = 83 cm
  - 188 J/m^3 = E_{core}, 0.9 T out of 1.1 T for I up factor of 2 => H = 219 A/m
  - Rmean = 64 cm => 0.9 kA = I_{core}
  - Use **I_{cell} = 1.5 kA** => 210 J / pulse = E(2MeV)
  - **1.3 MW system**

Induction Linac Layout

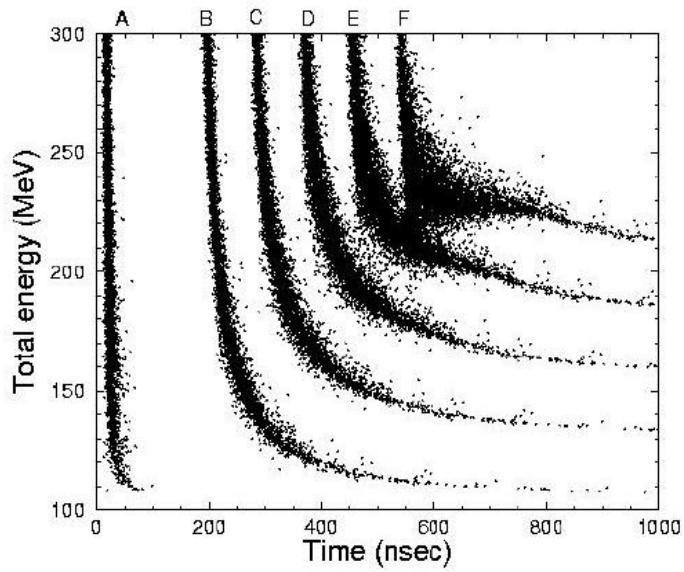
- Strong Effort at LBL for DAHRT
- A little bit of expertise at Fermi
  - higher field 2-3 T and smaller cores is the better solution
  - saturation in the cores is under control
  - switching is the main problem

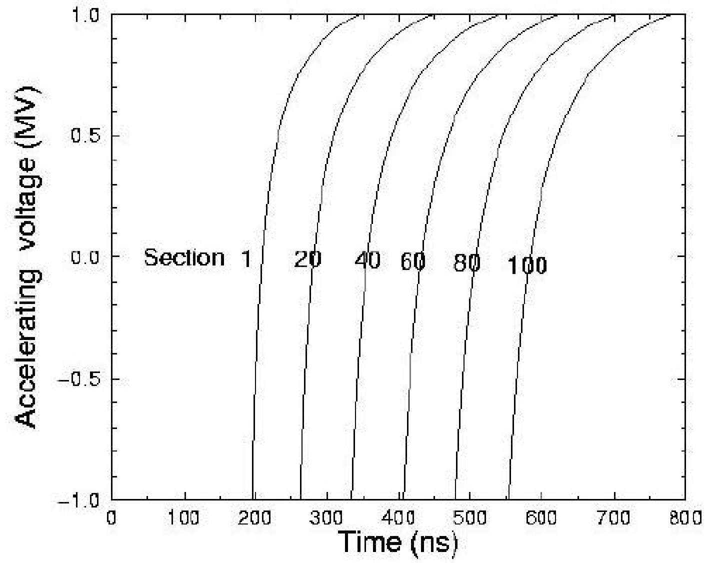


Small effort at FNAL: “old” expert from DUBNA no working in TD.

Mainly on solenoid channel design

Induction Linacs and Long Solenoidal Channels





50 m drift before ϕ rotation

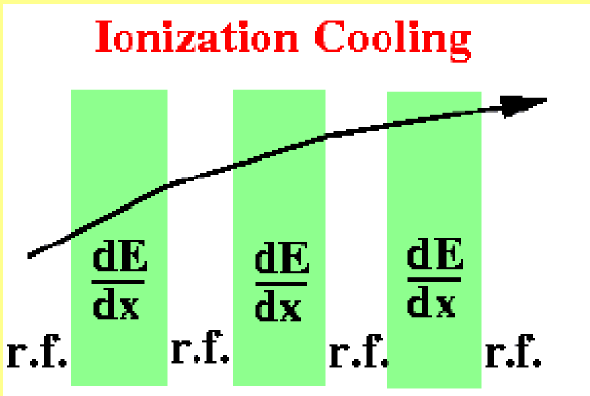
<u>For carbon target</u>:
0.10 μ/p between 225 - 240 MeV
0.13 μ/p between 220 - 250 MeV
0.18 μ/p between 200 - 270 MeV

Trade off:

Energy Spread after rotation⇔ drift channel length [loss]

Particle capture⇔length(voltage) in induction linac

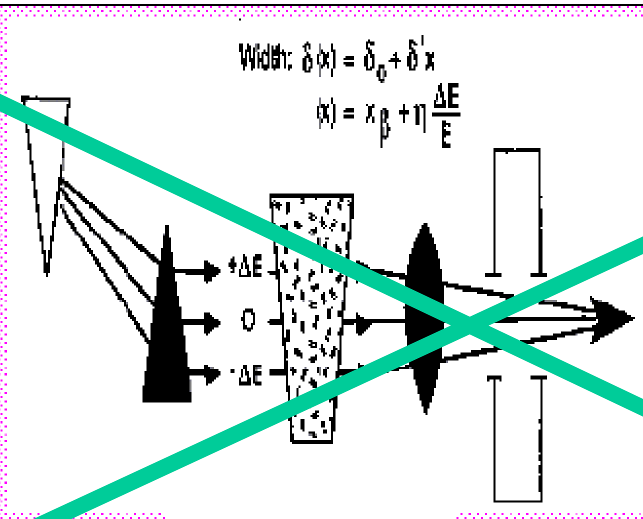
Skip Longitudinal Cooling (. ! ?)



Transverse Cooling

Muons lose energy by dE/dx and long–itudinal momentum replaced by r.f.

- **To Minimize heating from Coulomb Scattering:**
  - **Small $\beta_{\perp}$ (strong focusing) : High–field solenoids or Lithium Lenses**
  - **Large L_R (low–Z absorber) : Liquid H_2**



Energy "Cooling"

Ionization cooling using a wedge plus dispersion.

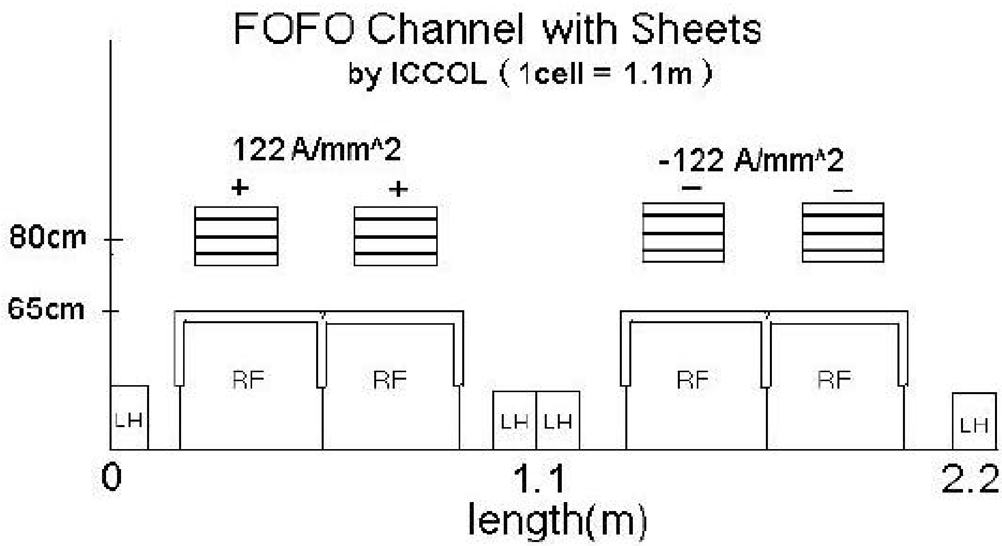
Exchanges emitt–ance between transverse & long–itudinal directions

$\gamma\varepsilon = 0.0015 \times 10\text{-}3\ \pi$ m rad

A Cooling Channel for the Study

- +/- 3.5 T Lattice with 15 MV/m 175 MHz rf

Need about 100 m for cooling channel



RF frequency = 175 MHz   RF Gradient=15MV/m
RF radius = 65cm   RF cell length = 37.2cm

RF window(Be)=125um
RF window raidus= 21cm

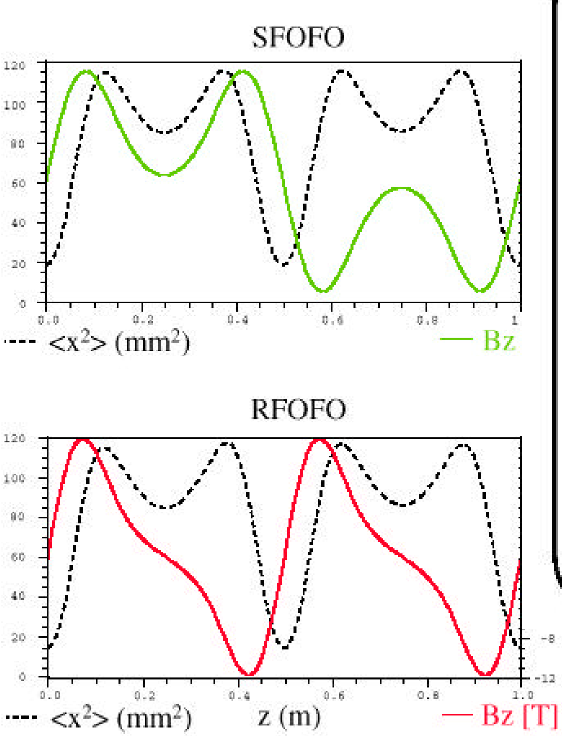
LH length=14cm/cell
LH window(Al) =50 um

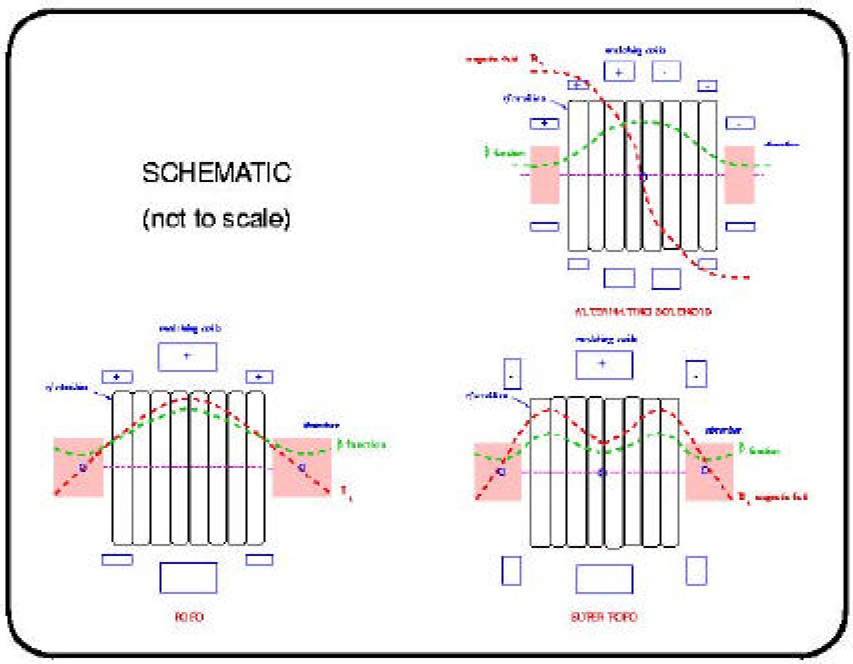
Drift length= 21.44cm/cell   for RF fabrication and assembly
Interval between sheets =30cm   for power supply from klystron

Cooling Simulation Effort led by LBNL

- "From the Target through the Cooling"
  - Participants: BNL, CERN, Fermilab, LBNL
  - Web page : "http://www-afrd.lbl.gov/neutrino/"
    - Target:MARS, ARC, FLUKA
    - Cooling and Beam Tracking: DP-GEANT, ICOOL, Parmela ?
    - Different Lattice types

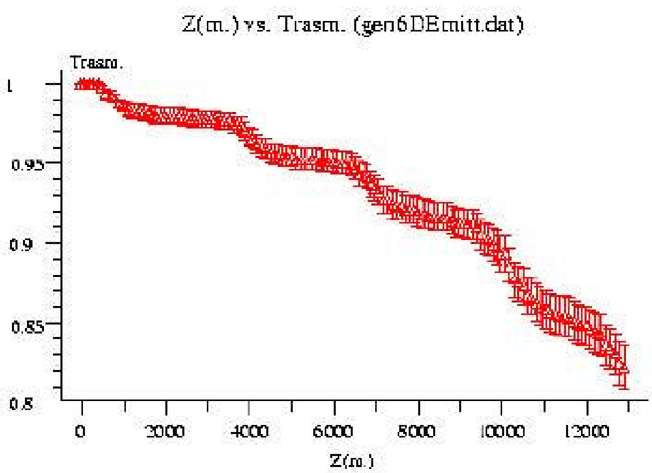
Fields and beta functions: two examples
(note $\langle x^2 \rangle \propto \beta$)

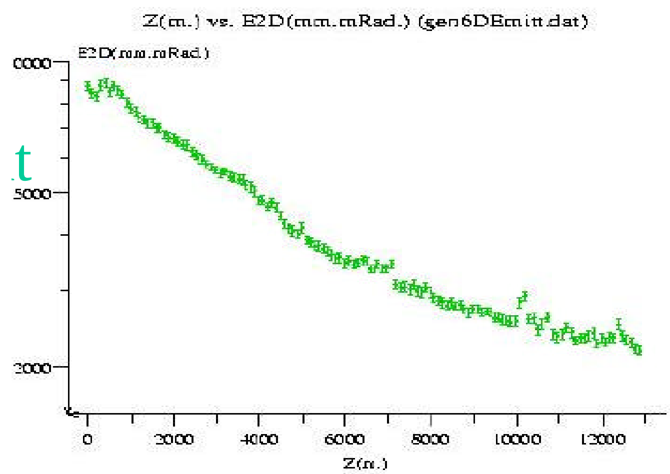


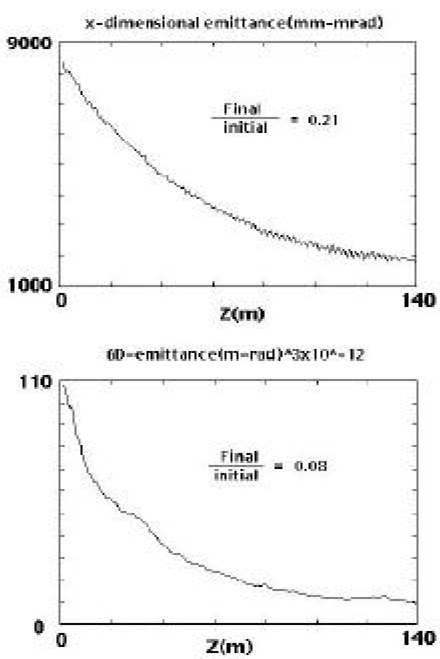


Cooling Simulations Workshop

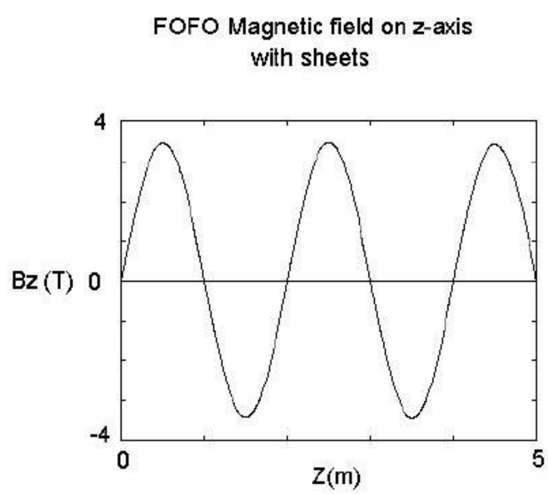
- ICOOL (R. Fernow, BNL)
- DP-Geant (P. LeBrun, Fermi Lab)
- J. Wurtele & A. Sessler +++ Workshop at Berkely







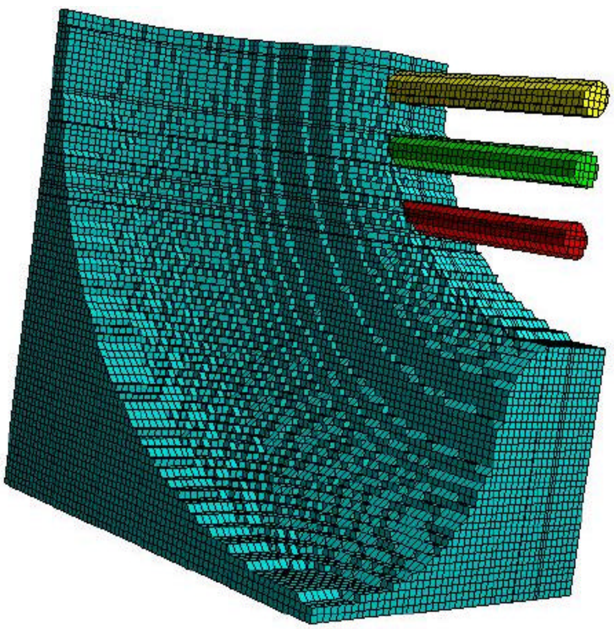
Particle loss =7 % after 140m



Maximum value is located at the center of rf cavities.
Mimimum value is located at thecenter of LH.

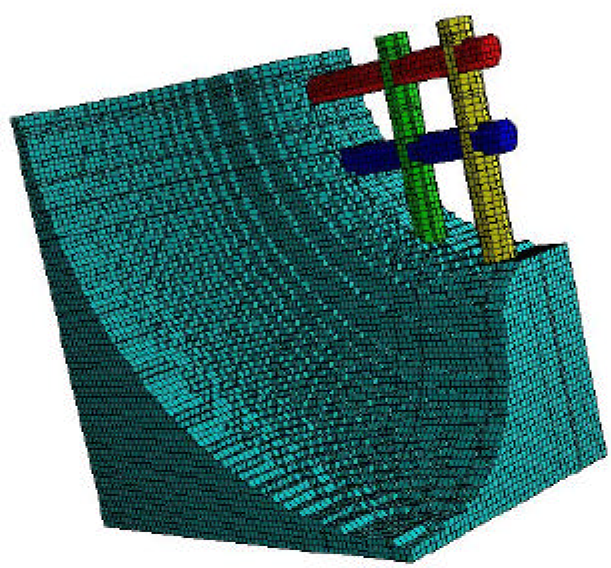
200 MHz Cavity + Power Source

- Engineering Layout required for the study
- Want to build and test it, once study is done



1/8th of the full
accelerating cell

~ 0.65 m



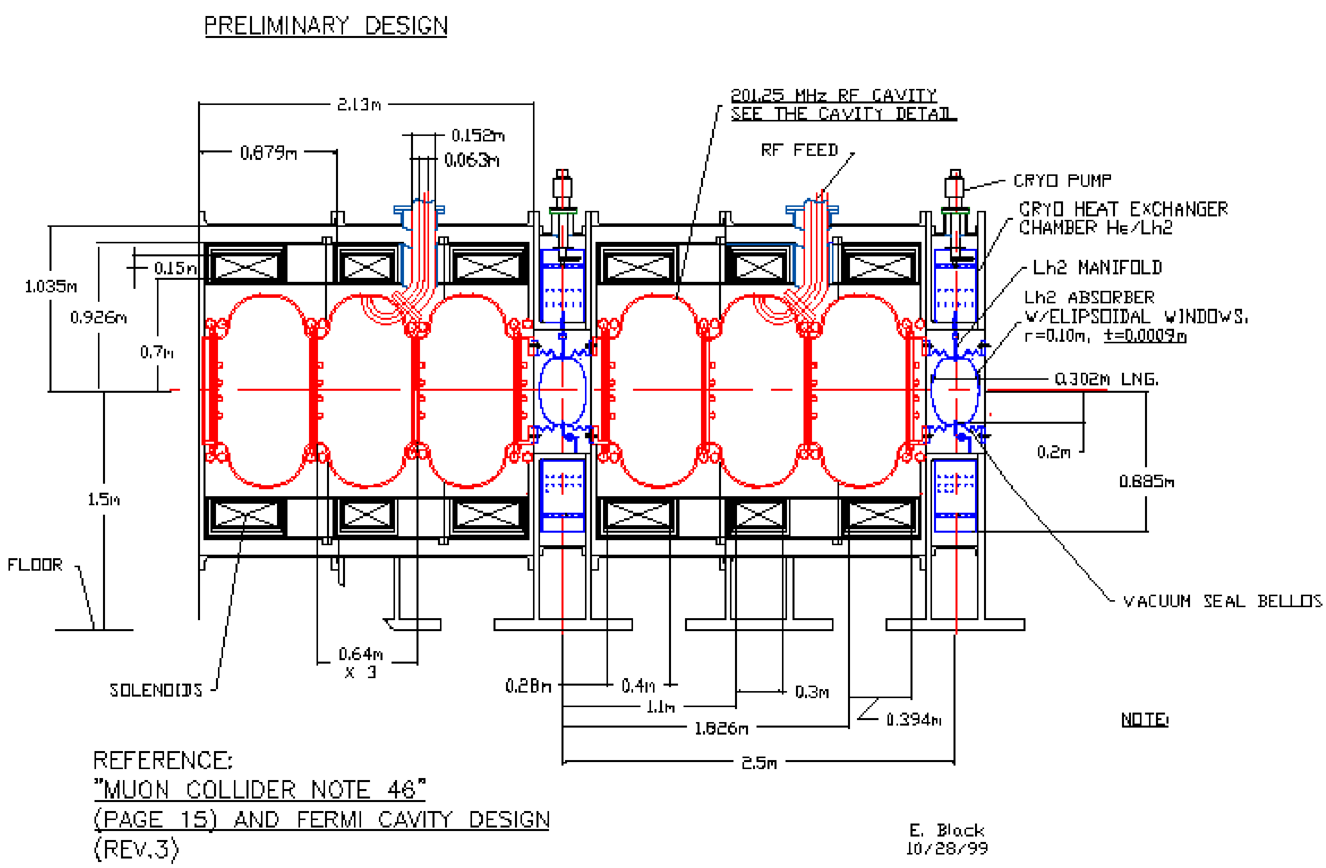
Enhance the E Field
on Axis by using a grid

Goal: 15 MV/m
nc cavities

~ 0.65 m

Cooling Channel for a Neutrino Factory

- IIT, BNL, LBNL, Fermilab: go through an engineering design
- Goal: Do all the cooling with one set of hardware

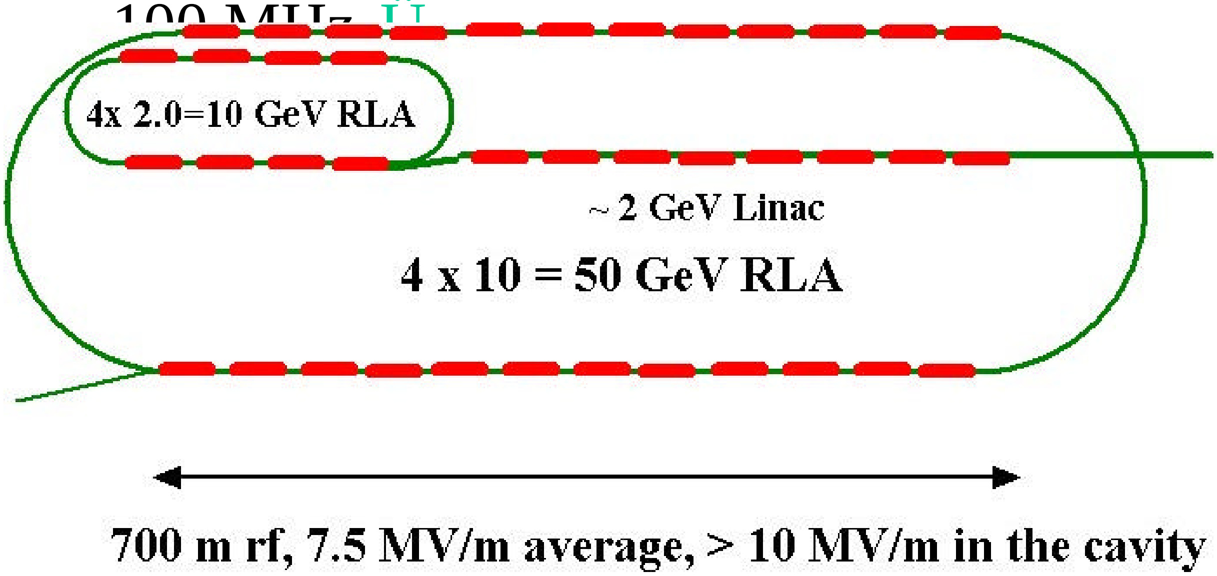


B_z ~ 5 T max

E_{acc} ~ 15 MV/m @ 200 MHz

Acceleration

- Low Frequency Linacs and RLAS (BNL, FNAL especially Jefferson Lab)
  - RF systems at 200 MHz (175)
  - at present emittance -> linac and first RLA at 100 MHz



Acceleration of the Muon Beam II

Based on cooling assumption		
incoming norm.emittance $\varepsilon_{x,y}$	π mm rad	1.5
outgoing emittance at 30 GeV	π mm rad	3.2
energy spread at 50 GeV (95%)	%	+/- 2
incoming momentum	MeV/c	190
incoming norm. emittance ε_{long}	π mm	28
bunch length	mm	120
momentum spread (rms)	%	11
$\beta\gamma$ at start	~	2
pulse length	~	150 nsec (4x(150+250))
number of bunches in one pulse	~	30 (4x30)
number muons per pulse	10^{12}	2.5
repetition rate	Hz	15
acceleration I (linac)	GeV	2 or more
RLA_1 + RLA_2	GeV	50

Acceleration based on RLA

- Why not nc?
  - Peak power limited already
  - in normal conducting cavity: too much power required to build up the gradient
  - gradient is not a free parameter for optimization:
    - muon decay +longitudinal acceptance
- SC structures at 200 MHz (100 MHz) and 10 MV/m (7,5 MV/m real estate)
  - almost no power to build up gradient --> beam
  - loaded Q's are similar to nc structures ->fill time short but coupler ? -> <u>comparatively efficient</u> !
  - 4 x 30 bunches per RLA, 2.5×10^{12} total
  - P_{linac} ~ 6 MW, P_{RLA1} ~ 2 MW, P_{RLA2} ~ 12 MW
  - ~20 MW power for RF acceleration at ~25 % overall efficiency (AC $\rightarrow$ RF)
  - Problem is the required peak power not average power !

RLA Energy	L_{tot} m	L_{linac} m	I_{beam} mA	R_{loaded} MW/m	Q_{loaded}	Nr of turns	$T_{pulse} = T_{fill} + T_{acc}$ /ms	Peak Power MW/m
2-10	800	2x135	120	83	80×10^3	4	132+10	1.2
10-50	2400	2x700	40	252	240×10^3	4	400+32	0.4

Limits for Peak Power and Frequency

- What determines the physical size of a klystron?

ideal situation with no space charge:

$$z_{opt} = 1.84 \cdot \frac{u_o(V)}{2p \cdot f} \cdot \frac{2}{a \cdot b}$$

u_o := velocity of electrons = β*c = $(1-1/\gamma^2)^{0.5}$ *c
α := modulation gap voltage/beam voltage
β:= transit time

f = 200 MHz, U_{gun} = 175kV , uP=1.2 , 15 MW Beam power ->
10 MW rf power,

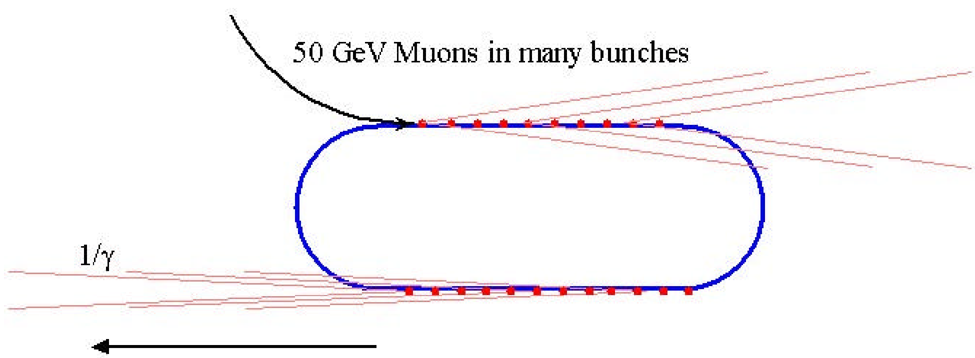
z_{opt} := 10 meter only for the rf part
+ gun + collector ---> easily a 11-12 meter long klystron with a standard approach.

- scaling shows : $z_{opt} \sim 1/f$ klystron becomes longer
- infrastructure in industry can not mechanically accommodate this easily
- test stands are not available

Klystrons as high peak power sources are only feasible below 200 MHz if multi beam tube is used
SLAC and CPI: preliminary discussion going on

A Neutrino Source

- First experiment based on an intense muon source
  - small emittance not necessary because divergence is dominated by decay kinematics
  - recognized by S. Geer



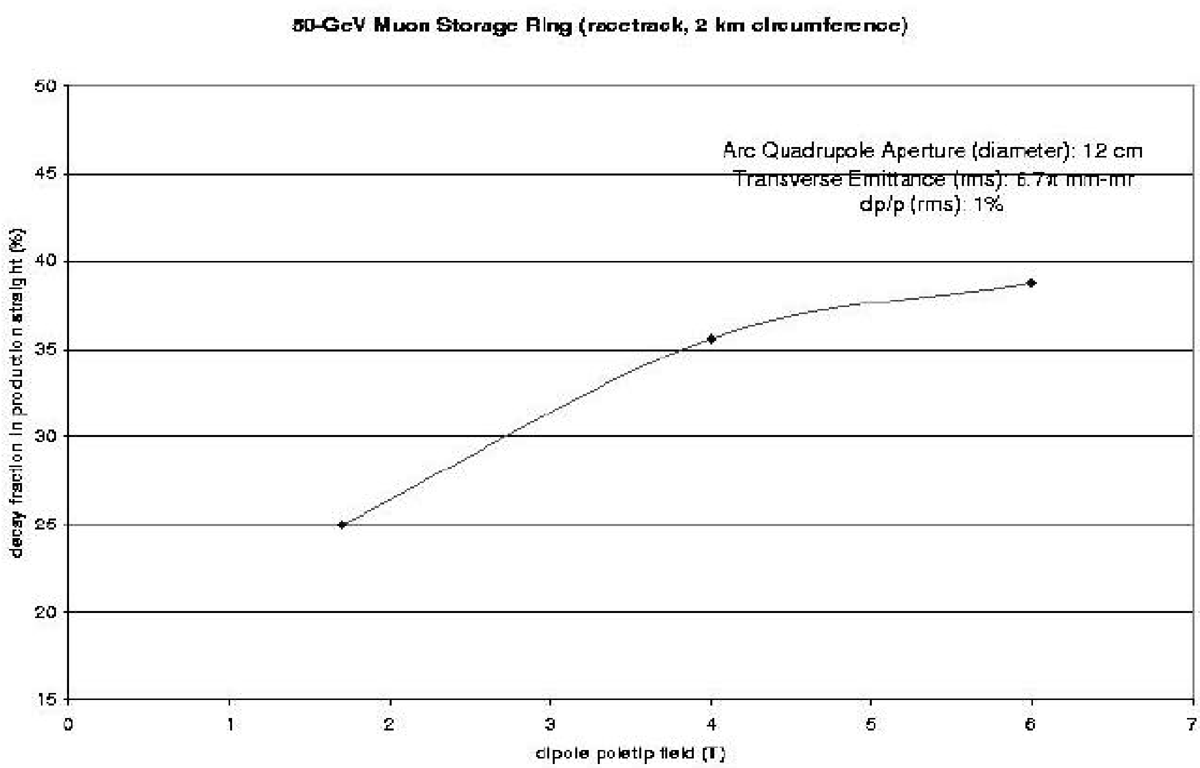
Parameters for the Muon Storage Ring		
Energy	GeV	50
decay ratio	%	>40
inv. Emittance	m*rad	**0.0032**
β in straight	m	160
N_μ/pulse	10^{12}	6
typical decay angle of $\mu = 1/\gamma$	mrad	2.0
Beam angle $(\sqrt{\varepsilon}/\beta_o) = (\sqrt{\varepsilon}\,\gamma)$	mrad	0.2
Lifetime $c*\gamma*\tau$	m	$3x10^5$

$\gamma = (1-\alpha^2)/\beta$

Optimization of the Storage Ring

- Rule: The cheapest way to produce muons decaying in the straight section is to make the straight sections as long as possible compared to the circumference.

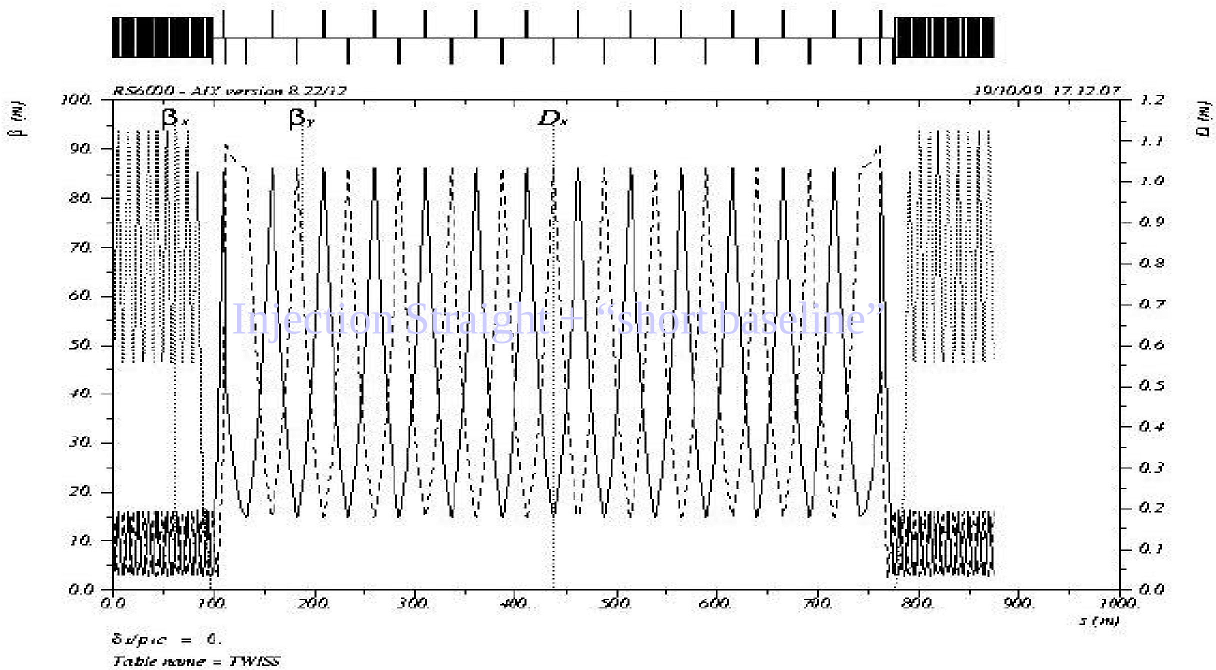
- Efficiency = straight section / circumference
- = Length of straight / (2 π ρ + 2 x Length of straight)



B (Tesla)

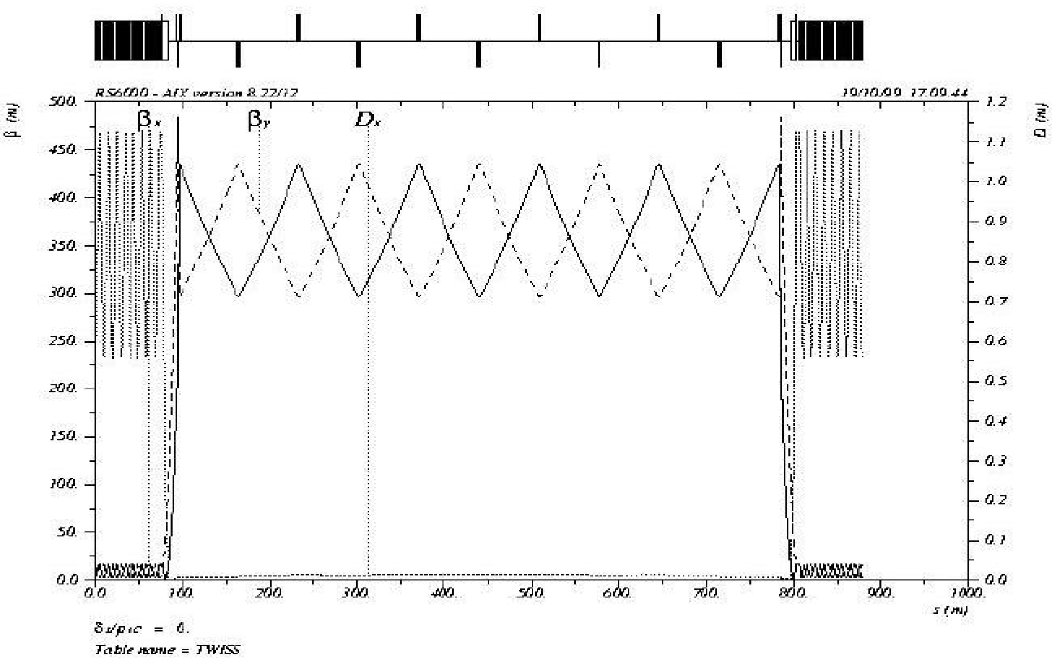
Storage Ring Lattice: First Shot I

- Injection Straight + “short baseline”

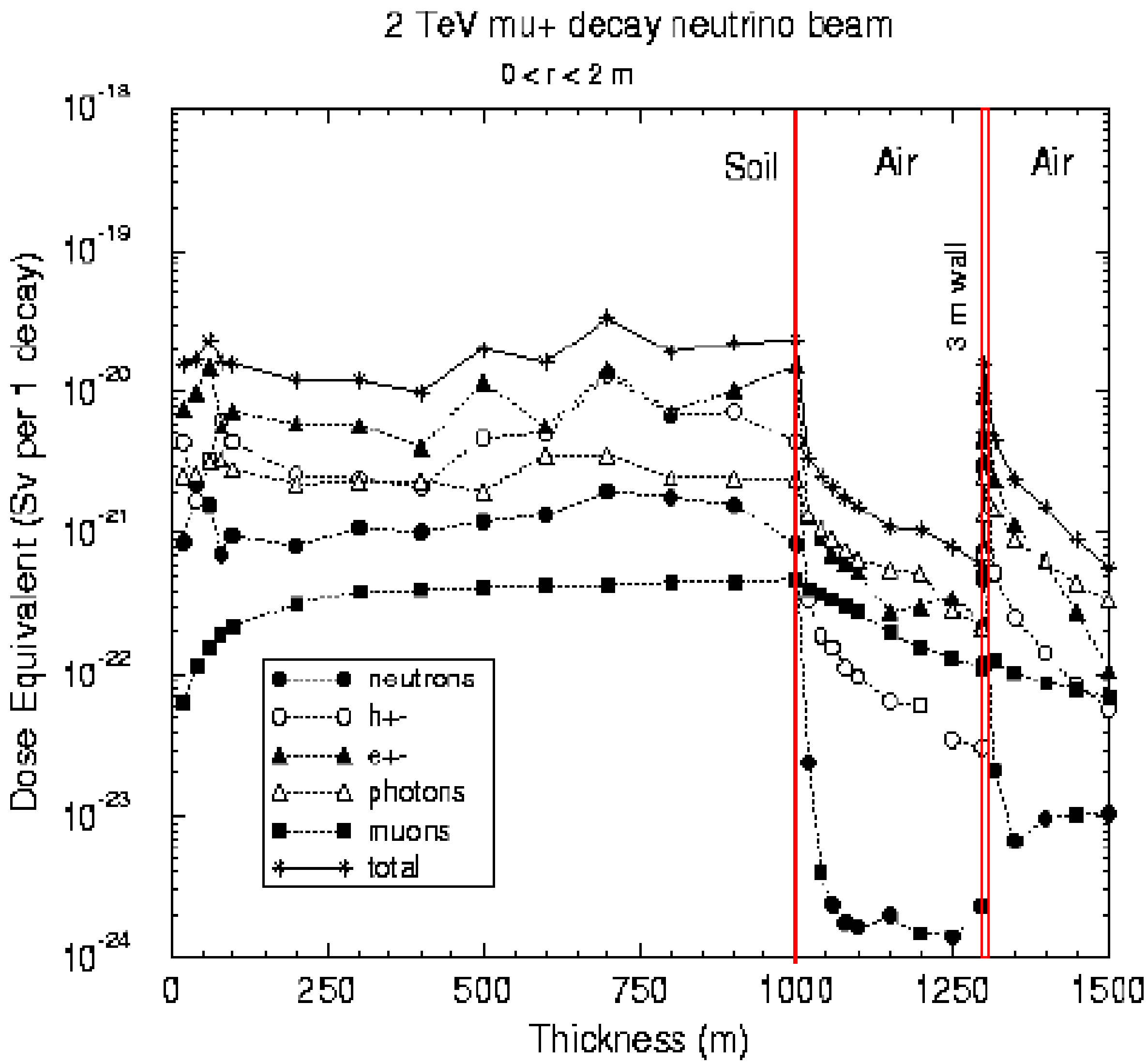


Storage Ring Lattice: First shot II

- Neutrino Production Straight "long baseline"



Upgoing Neutrino Radiation II



MuSR Status

- Insert Finley’s 11/11/99 talk with 6 slides

How Steep is 22%?

•17 % into a quarry

•there is water !

•incremental cost small compared making more ν

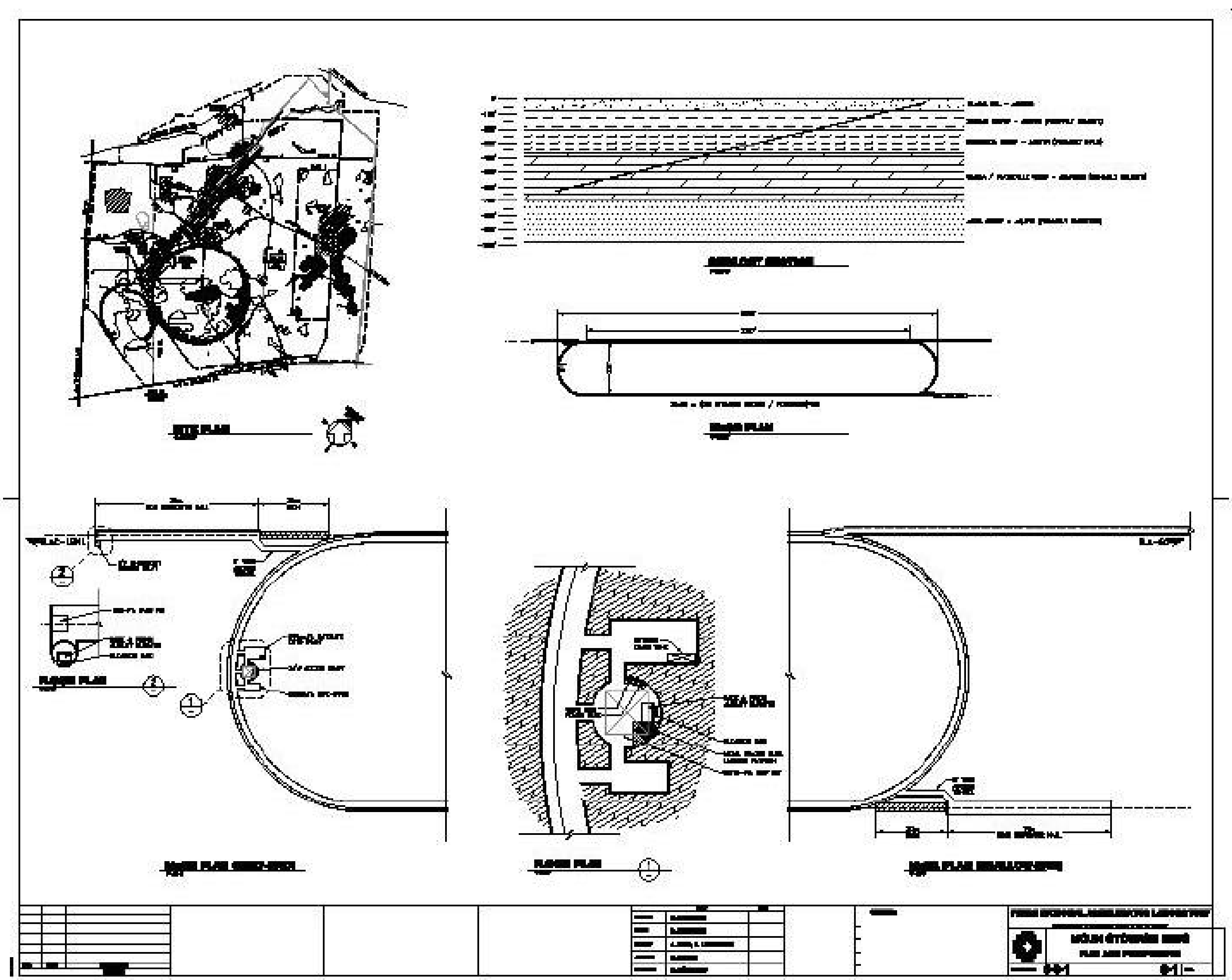
•extend the ring up to the surface

Further down the ramp

Use vehicles

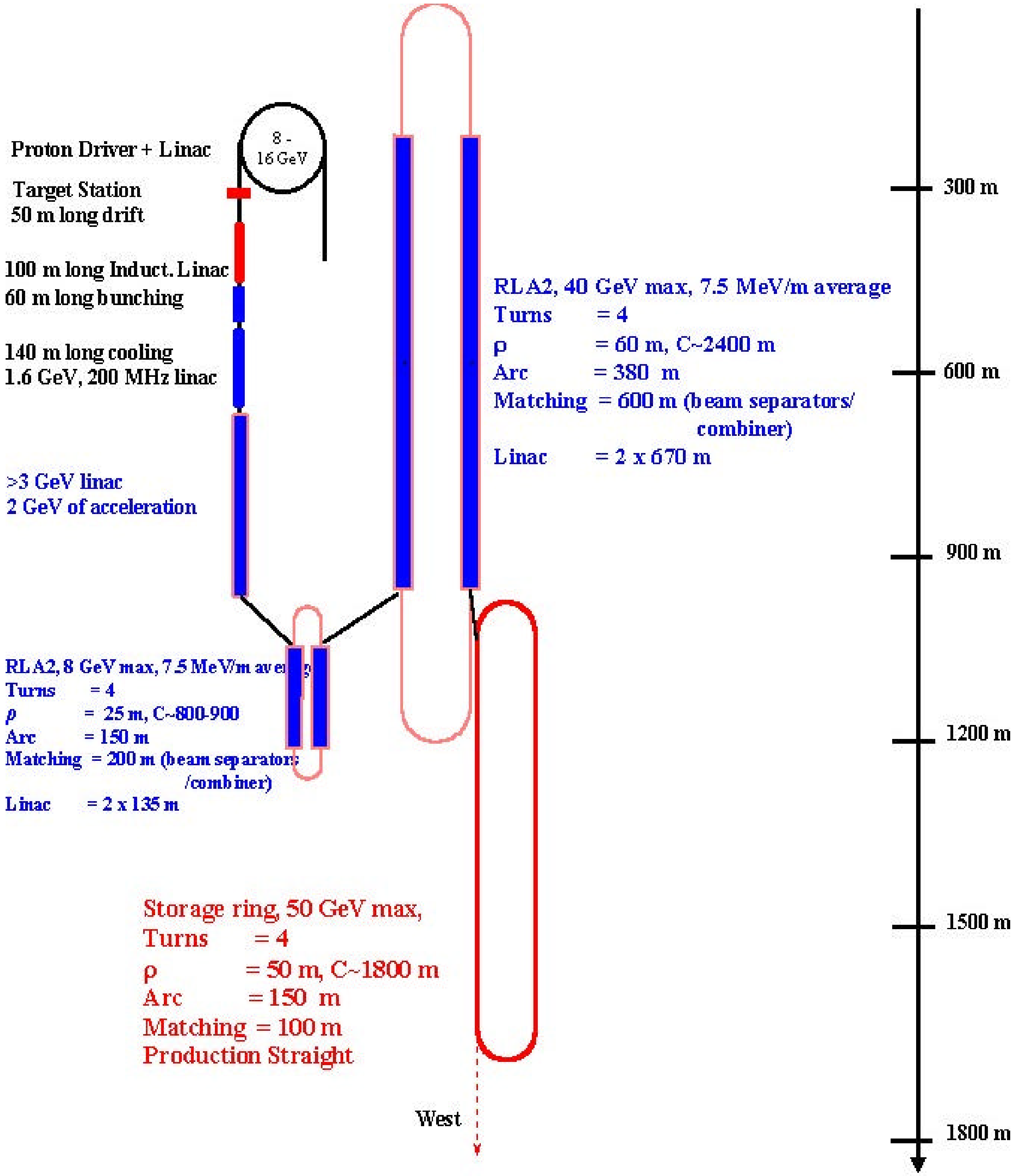
Storage Ring Layout

- Site layout for the Storage Ring and the Arcs
- Experimental beam lines and halls
- Cryo space requirement



Footprint for a 50 GeV Neutrino Source

- Infrastructure is very close together ...



Strategy of Study

- Approach (only have six months … so …)
  - Go more conventional where ever possible
    - Target (solid), longer bunch in proton driver, remove (~30MHz) rf -> use induction linac ...
    - Get outside expertise where necessary and/or useful (target, acceleration, induction linacs, sc solenoids)
      - Oak Ridge, FHML, Brookhaven ⇒ the target
      - Jefferson Lab / Cornell ⇒ sc rf and re-circulating linacs
      - LBNL ⇒ induction linacs
      - IHEP Protvino ⇒ sc solenoid channels
  - Squeeze Fermilab for resources or site specifics
    - General engineering (large scale rf systems, sc magnets, sc solenoid channels, ps, vacuum, beam lines, tunnel, water → comes out of BD / TD (whichever division can help)
    - Site Layout, ESH Issues → Fermilab specific

“Six Month Study” Overview

- “6 Month study Goals”
  - Text
    - 10 pages per subsystem
    - + 1 page R&D program / schedule
    - + 1 page cost drivers
    - + 1 page ESH issues for Director
  - Milestones
    - Internal Review Mid January to align the different contributions (might not make it)
    - Documents in by mid February
    - Report to Witherell by March 1, 2000
- Collaborate as much as possible
- Develop Alternatives for the most risky parts
  - induction linac
  - cooling channel design and performance
  - acceleration: ($\rightarrow$ probably largest cost driver)
    - Jefferson Lab $\Leftrightarrow$ Cornell $\Leftrightarrow$ Fermilab

Timeline for Study

- Accelerator Physics Design
  - Conceptual design has started for all of the subsystems, and iterated for some
  - Preliminary designs ready by mid-December (?)
  - Specifications on web for all subsystems
- Engineering designs
  - Have started for all of the subsystems
  - Should fully start over the period from now to mid December (learning curve)
  - ready by mid - end January
- Pre Review (internal) within this group end of January
- 10 pages per subsystem written by mid-February
- Aiming for: Report to Witherell by March 1, 2000.

Questions (aka Blood Pressure Check)

- What comes after the study?
- Review the results, of course … and BP should rise ...

- ***Does "the lab" want to do "this"?***
- Assume **"Yes".**
- Then: (BP should go down and …)

  - Define the Neutrino Factory R&D program:
    - MCNF: Leading role for the Muon Cooling experiment
    - MCNF: Develop efficient and cost effective accelerating systems at low frequency
    - Fermilab: Continue participation in the ongoing site study
    - HEP: Continue advancing the particle physics studies

Director's Office

How to get more information?

- Web Page:
  - http://www.fnal.gov/projects/muon_collider/nu-factory/nu-factory.html
  - Holtkamp talk at: /afs/fnal.gov/files/wwwdocs/projects/muon_collider/nu_factory/holtkamp
  - web master = T. Jurgens (tjurgens@fnal.gov)

- Information Available:
  - Subsystem Specifications (Postscript)
  - Drawings, pictures, sketches, specs, tables, (nearly) everything you can think of
  - Nothing is final, all is preliminary.
  - Growing weekly

Summary I: My Own Worries and Opinions

- Conceptual Feasibility:
  - Cooling channel design
  - Phase rotation scheme
  - Credible acceleration scenario and simulation
- Technical Feasibility:
  - induction linac
  - power sources
  - high gradient and low frequency
- What does such a complex look like?
- There is plenty of further R&D needed
- Note: Not worried AS MUCH about the ring
- Travel restrictions have prevented most Fermilab collaboration members from presenting their own work to this collaboration meeting. But same for NLC.

Summary II: Status of Witherell 9/22/99 Charge to the Study Group

- Design concept … reasonable assurance … neutrino based research program
  - Is it an intense enough muon / neutrino beam?
  - Probably will estimate scaling of costs with energy and intensity
  - (Remember … no polarization)
- Likely cost driver
  - Acceleration of muon beam to 50 GeV
- R&D program (includes … no surprise …)
  - Make an intense muon beam
  - Accelerate to 2 GeV … and beyond to higher and higher GeV
  - Revive longitudinal cooling?
- Specific ESH issues
  - Target station (even at 1 Mwatt, an issue for Fermilab)
  - Neutrino radiation: Fermilab or Federal limit?
- Work closely with the Collaboration
  - Ongoing and going and going and going ...