

BNL ERL Review Feb 17 & 18, 2010 (DRAFT)

COMMITTEE:

Ivan Bazarov (Cornell), Swapan Chattopadhyay (Chair, Cockcroft Institute), Jens Knobloch (BESSY-II), George Neil (JLab), Vitaly Yakimenko (BNL).

CHARGE:

The committee was charged with:

- (i) technical review of ERL Design and the status of subsystems;
- (ii) observations and comments on possible problem areas;
- (iii) advice and recommendations on improvements to the design and commissioning, with no considerations of cost.

[*Note:* committee commented on the 'quality' and 'quantity' of scheduling/commissioning but not on milestones and deliverables etc.]

EXECUTIVE SUMMARY

The chair had assigned specific task sharing of the review committee members as follows:

- (i) Ivan Bazarov: Beam Dynamics, Parameters, Diagnostics, Photocathode, Focusing and RF Damping;
- (ii) Jens Knobloch: SRF Electron Gun, SRF Cavity and Cryomodule (including HOM damping), LLRF, Cryogenics and Diagnostics;
- (iii) George Neil: Laser, Laser Light Transport, HPRF, Cryogenics, Beam Dump;
- (iv) Vitaly Yakimenko: G5 Test and Commissioning, Magnets and Power Supplies (including HTS Solenoid), Vacuum Systems, Controls, Machine Protection Systems and Beam Dump.

The detailed comments and recommendations of the committee members in all these specific areas are appended following this Executive Summary, which only touches the highlights of the review.

A. GENERAL COMMENTS

The committee was very impressed with the overall BNL ERL R&D effort, the competence, dedication and quality of the assembled ERL R&D team and its leadership.

Overall the program is very well planned and excellent work is underway. This is especially remarkable given the budgetary difficulties which have complicated planning. The team is highly qualified and addressing the important issues in priority order. The progress is excellent and given steady funding they should be able to meet the technical goals.

Photocathode, magnets, HTS solenoid, SRF cavity and cryomodule, HPRF, LLRF and Laser R&D all have made excellent progress. The Safety Systems are well planned for implementation.

The committee has no major recommendations for the project as a whole. Noted below are a few suggestions that might improve performance or operations.

The time-line for commissioning and beam-dynamics studies appears to be very aggressive. Consider relaxing this to ensure that the machine fulfills its "mission" of test-facility for accelerator physics.

B. GENERAL OBSERVATIONS

Coherent Electron Cooling is an innovative promising concept yet to be tested but its requirements for MeRHIC and eRHIC seem to determine all ERL parameters. The parameter set is not based on any demonstrated prototype, requiring future flexibility in adjusting them. (Note: the existing ERL will still be the world's first high current ERL of its kind with a current of 0.5 Amp under superconducting RF environment).

The gun design appears to be rigid : mechanical cathode position, penetrations, RF coupling etc. are not adjustable from zero to full current; once built, they are expected to operate exactly as designed, with no room for adjustments.

The headroom and margin in RF power and beam control appear tight, given the high loaded Q, high current and the limited 80 kW IoT.

The apertures appear to be tight given the very high current demanding beam halo control (lot of scattering);

Elements like bend, focusing, chromatic correction etc. are combined in the innovative and compact vertical Z-bend. The distance from cathode to cavity is 7 meters – quite long. There is no ‘adjustable’ booster energy knob. Though emittance is not critical, the charge/bunch is, so tolerances may be critical as far as beam halo, halo particles etc. are concerned.

No show stoppers for the project as a whole. Noted below are a few suggestions that might bring out critical elements in the program for improved performance or operations.

C. GENERAL RECOMMENDATIONS

(i) Parameters and Commissioning

Flexibility should be kept in mind in the ERL design as much as possible since Coherent Cooling is yet untested and speculative, with the potential need for a very different parameter regime.

It is desirable to decouple the “high-current” aspect from the “Energy Recovery” aspect of the ERL R&D e.g. high current injector gun commissioning is critical and must come before anything else.

An early test of the gun cavity will be critical in view of lack of flexibility in its design.

It is advisable that necessary and sufficient commissioning time be assigned for G5 in order to understand and fix problems as they arise. Commission G5 with high current will be important.

It is advisable to implement a robust Machine Protection System (MPS interface tied to drive laser EO cells and physical laser shutter to cut off beam).

(ii) Laser/Optics

Temperature stability, humidity and air-current control in the drive laser room will be critical, possibly requiring portable Air Conditioning. At underground facilities, temperature controls within 0.5 degree are not uncommon. The committee recommends the team to determine what will be the exact need for the BNL ERL R&D program.

The committee recommends investigating the issue of the ‘slow drift’ of the laser with respect to the RF over time (seconds to minutes) and planning for feedback/feed-forward as necessary.

The committee advises that the team must plan for an ‘optical dump’ near the cathode as stray reflected light could be up to 30% adding to background halo and stray particles.

There is concern about scattered light in optical transport needs because if it lands outside the desired spot on the cathode it will lead to halo generation. This is a particular concern in CW high power operation. The committee advises the team to consider minimizing windows and reflections in transport as well as re-imaging the near aperture on cathode.

(iii) Vacuum and Beam Dump

The committee recommends planning for diagnostics of beam just before dump.

The committee has concerns about ion accumulation and whether a 10^{-9} torr vacuum will be sufficient in the arc transport. The committee advises investigating possibilities of ion trapping and making room for remedial actions.

Isolation of the beam dump from cavity will be important as far as vacuum is concerned in order to eliminate back contamination. The BNL ERL R&D is significant in the international context with unique features such as the highest beam current (0.5 Amps) and all-SRF systems.

There are concerns of Hydrogenation of cooling water by X-rays and the committee recommends planning for removal of generated hydrogen.

(iv) RF, Focusing and Diagnostic Control

It is advised that the overhead margin in RF and beam control power be examined thoroughly.

General Tolerances (e.g. Z-bends; Metrology: detailed survey of ground stability with heavy elements, etc.) should be investigated in detail via full 3D space charge start-to-end simulations with realistic field maps and laser profiles.

A magnetic field survey is highly recommended in order to minimize stray fields.

With regards to the HTS solenoid, the committee recommends checking the saturation of iron between 5 K and 77 K and considering adding temperature sensor to the mu-metal.

Special attention must be paid to timing diagnostics (e.g. fast scope, streak camera or RF deflecting cavity, etc.) as well as halo diagnostics due to tight apertures. The committee recommends retaining all diagnostics from stage-to-stage in the G5 commissioning. The committee also recommends planning for a cathode QE scanner in the real injector and establishing beam-based measurements of phase (timing) and charge whenever possible. More Beam Profile Monitors are desirable in G5 and it may be necessary to add slits upstream of dipole in G5.

(v) Cavity, Cryomodules, HOMs and Cryogenics

Plans for HOM damping are matured. Planned HoM dampers are sufficient for the current prototype; however it is recognized that future extrapolations to long ERLs will require different HoM power extraction in the cold environment.

There is a lot of activity world-wide on high current HOMs. The committee suggests the team to organize a high power HOM damping workshop soon, given the unique high current aspect of the BNL ERL.

The advised the team to consider testing thermal power handling capacity of HOM loads outside of the cryomodule.

For the cavity and cryomodules, the committee recommends that the magnetic shielding for the gun be fitted with temperature sensors.

In the area of cryogenics, the committee advises to insure more cryogenic overhead for extended testing.

D. FINAL REMARKS

The BNL ERL R&D is significant in the international context with unique features such as the highest beam current (0.5 Amps) and all-SRF systems. The BNL ERL R&D is strategically important to eRHIC and it will be important to plan its scientific and technological exploitation beyond the immediate ERL R&D. The committee advises the team to consider the upgrade to 2-passes and the addition of booster cavity control options. Finally, it will be appropriate to begin considering possible accelerator and other scientific experiments for full exploitation of the prototype.

Detailed Comments and Recommendations

Project goals and parameters

- 1) Overall goals of the project are to demonstrate high average current, charge per bunch and beam emittance. The high charge mode is set by coherent cooling needs though the exact plans are uncertain at this stage and may change in the future. Justification for the list of parameters is found not only in the arena of coherent cooling, but additionally in a more general and challenging R&D needs for a variety of high-average current ERL applications. As such, the particular choice of specific parameters is not to be viewed as “cast in concrete”, but ought to be approached as a good generic set of goals in the challenging R&D task.
- 2) The ERL is designed primarily for accelerator studies and must therefore be flexible. Possible modifications and upgrades should therefore be considered at least in general terms to ensure that these are not precluded by construction measures (or are only possible with major effort). These include, e.g., multiturn operation, inclusion of bunch compression and the later retrofit of a booster.
- 3) In particular, the need for the small energy spread is underlined by the coherent cooling, but the required energy spread cannot be achieved in this ERL prototype, nor simultaneously with the long bunches unless a 3rd (or higher) harmonic linearizer is employed. The current prototype has no plans to address this issue.
- 4) On the longitudinal emittance: it was unclear what sets this particular spec in the accelerator. It was my impression that the longitudinal emittance was not a critical spec and therefore it was unclear e.g. why a particular choice of the photocathode position in the SRF gun should be preferred in the tradeoff shown between the transverse and longitudinal emittances versus the photocathode position. It can (should?) be emphasized that since the key goals of this project are to perform R&D in the area of high current high brightness sources and ERLs, the plans should include maximum exploration of the available parameter space as no machine has ever operated in this parameter range previously.

Upgradeability

- 1) While the machine is designed to focus on parameters of interest for coherent cooling, the international appeal of this demonstration facility would increase if other applications of ERLs can also be studied. In particular, some important aspects of ERLs for light sources are not addressed, including low-emittance, low-energy spread and short pulse operation. Here, additional beam manipulation would be required (e.g., bunch compressor, booster module for flexible acceleration in the injector). Consider these as future upgrades.
- 2) R&D machine such as this one requires flexible installations.

Project Planning

- 1) The Experimental Facility appeared neat and clean with excellent attention to safety and housekeeping.
- 2) Documentation for ARR is well developed and appropriate for this stage.

G5 test

- 1) G5-test is an important and critical phase of the ERL prototype project. The plan presented is sensible and reasonably thought through. The diagnostics beamline after the 5-cell cavity looks very useful, and it is strongly encouraged that it should be retained for future operations even with the energy recover.

- 2) It was a potential concern of this committee that there may be not enough time to finish the tests envisioned. Don't rush the G5 test. It is strongly recommended that as much time as needed is taken in order to complete all G5-tests including expansions mentioned below. Be sure measurements are done before shutting down for installation of ERL because once ERL is installed you won't be able to get same quality of data.
- 3) We recommend to enlarge the scope of G5-tests. The SRF gun, planned to be operational within one year, remains the most critical item in the project. The gun itself may require substantial beam commissioning effort and it should be done without additional complication of energy recover. Consider the possibility of pushing for high current out of the gun in G5-like beamline configuration equipped with the appropriate beam dump *without* the energy recovery (the main cryomodule cavity being detuned).
- 4) The G5 test is to start in Feb. 2011. It should prove to be an important milestone in commissioning the injection system and should point to potential problems with the SRF gun at an early stage. Because the gun represents a critical component for the entire project, its operation should commence as soon as possible. G5 should be used for extensive beam studies and should therefore extended to high current operation before recovery is implemented. The 5-cell cavity can be detuned, while still enabling interesting HOM studies.
- 5) Prioritized measurements list in G5 would be useful (must, like to, what is of interest for the community, workshop to organize discussion).
- 6) Single pulse operations with an additional YAG laser amplifier for a higher charge from metal cathode?

Diagnositics

- 1) Beam diagnositics is reasonably complete. Please ensure that the BPM electronics supports beam phase (time of arrival) measurements as these prove indispensable during beam commissioning and trouble-shooting. It is unclear whether the wire-scanner in the recirculating arc will actually be useful with high charge pulsed beams. Operational experience at DESY suggests that the signal from the beam is overwhelmed by the induced wakefields.

G5 diagnositics & suggestions

- 1) The diagnositics of the G5 test should include timing (BPM beam phases to <1 RF deg accuracy), the RF deflecting cavity, as well as the possibility to perform the emittance measurement after the 5-cell SRF cavity without relying solely on quadrupole scan for these space charge dominated beams.
- 2) More BPMs after cavity to better measure emittance.
- 3) Measurement tools (fast scope, streak camera, ...)

Beam Dynamics

- 1) The emittance in this experiment is not so critical but the charge per bunch must be high. To relax the space charge effects, very long bunches must be employed. Hence the energy spread is huge due to RF curvature when compared to more "standard" ERL parameters. It would be nice if the experimental program could also include low charge operation with lower energy spread. Having a booster module (or even just a single cavity) would provide important flexibility in this respect.
- 2) Large emittance case will be dominated by tails, from laser, alignment, etc. Need better understanding of:
 - a. non-Gaussian nature of the beam
 - b. Loss on vacuum chamber.

It is important to quantify how parameters such as emittance are defined. E.g. for some applications 80% of the beam will define the goal, for other 99.99%. Is slice emittance important?

- 3) The zig-zag merger is innovative and needs to be pursued. If successful, it may be beneficial to other ERL projects. The use of "combined-function" magnets (bend, quad, sextupole) saves significant space. Still, the distance from the cathode to the 5-cell cavity is 7 m, which is quite large in light of the low injection

energy (no booster) and the space charge dominated beam propagation in this section. One also notes unconventional vertical bending in the merger.

- 4) Sextupole and higher order components in the magnets: Opera3D simulations for a single magnet with very large beam diameter (2cm diameter) show 0.6 mm-mrad growth, establishing the need for sextupole correction, which is implemented in all magnets. The approach is sensible, but it does raise few potentially important points. Parmela simulations did not include the real fields, so they did not capture the emittance growth due to the sextupole component. The combination of aberrations due to sextupoles and space charge may lead to qualitatively different behavior in the phase space and may be important to understanding of the beam halo formed as a result. Depending on available resources, it is desirable to perform 3D space charge simulations including realistic field maps. Secondly, one needs to come up with a method to set all these sextupoles. What diagnostics is going to be used for that? The tune-up procedure?
- 5) For a better understanding of the machine and beam loss/halo, S2E tolerance studies using the measured field profiles and laser profile should be performed. Jitter from the laser and RF can also be included in these studies.
- 6) The beam aperture (4.6 cm) appears to be quite small given the large beam size (0.5 cm) in the injection line. Careful management of beam loss must be implemented.
- 7) There was no discussion of alignment/survey; the fragmented floor may create uncertainty.

Vacuum & hardware

- 1) Ion accumulation needs to be estimated and mitigating measures envisioned. This is particularly significant for the low energy operation in the space charge dominated regime as beam neutralization will lead to slowly changing beam envelope changes and potential beam losses. The problem is likely to manifest itself only in the high current every-RF-bucket-filled regime of operation. At the highest current (0.5 A) every bucket is filled and no ion clearing gaps exist. Given the low beam energy, ion accumulation may lead to beam degradation. If problems are anticipated, room for countermeasures should be included in the machine layout.
- 2) Vacuum chamber in dipoles does not have straight view vacuum ports (useful for laser alignment).

Drive Laser/Optical Transport

- 1) Drift of laser is as important as jitter. It would be good to develop a diagnostic means and if possible active feedback to hold drive laser pulse timing wrt rf phase.
- 2) The aperture of the merger and dipole chambers is tight for such large charges and average currents. This will place a premium on having a very clean beam produced from the gun. This drives the need for the next two bullets
- 3) It was pointed out that the optical dump for the specularly reflected from the photocathode light is absolutely critical for high current operation. Optical transport needs to be concerned with scattered light because if it lands outside the desired spot on the cathode it will lead to halo. This is a particular concern in CW high power operation. Consider minimizing windows and reflections in transport. Re-image near aperture on cathode.
- 4) It is necessary to have optical beam dump for reflected light or it will lead to beam halo.
- 5) It wasn't mentioned and maybe it is already part of the plan but it is necessary to have a cathode QE scanner in the real injector.
- 6) Temperature, humidity, and air current control in the drive laser room appears marginal to the casual observer.

Photocathode deposition and transport system

- 1) The BNL group has put a substantial effort into photocathode R&D and continuation of this work is strongly encouraged. Provided that the 3rd generation of the preparation chamber for the growth of the multi-alkali photocathodes and their transport to the gun is shown to be a success, the stage of commissioning in the G5 configuration using a metallic photocathode should be skipped in favor of the higher QE photocathode operation.

Radiation & Safety Issues

- 1) 1 uA total beam losses set the radiation safety envelope. While certainly not unreasonable, no realistic 3D simulations of the beam with the actual vacuum apertures all the way to the dump including realistic field maps and the measured laser spatio-temporal distributions were presented to establish that such loss rate will not be surpassed while at the same time allowing a substantial margin for tolerance and alignment errors. A concern was voiced that clearance for some of the apertures may be marginal for 0.5 Ampere beam.
- 2) 50V might be important threshold for safety to access experimental hall with magnets ON

Machine protection

- 1) More interlocked gate valves needed to protect in accidental loss of vacuum.
- 2) Make sure MPS interface is tied to drive laser EO cells and physical laser shutter to cut off beam. Verify shutoff times are consistent with no beamline damage.
- 3) Institute some means of ensuring state of MPS masking is always known by machine operator.

Magnets

- 1) Consider PLC or real time computer control for hysteresis loop of major dipole for reproducibility. Degauss of main dipoles loop, timing or mercury relay.
- 2) Quadrupole temperature stability at full current.

Gun and Solenoid

- 1) The gun represents a critical component of the accelerator with the greatest risk factor. To ensure that it is field emission free at the operating point it should be commissioned at the earliest possible time, even if beam operation is not yet enabled.
- 2) Since the gun will likely be temperature cycled to room temperature or intermediate cryogenic temperatures, it should be checked how the (often sudden) evolution of gases that previously were cryopumped on the cavity surface affect the performance of the cathode. It may be necessary to remove the cathode prior to significant temperature cycles.
- 3) The cathode position is only adjustable by changing the stalk. More flexible adjustability may be desirable to provide flexible RF focusing (further “knob”) independent of the RF phase. For short pulse operation this may prove to be particularly important. Indexing of the cathode position relative to the cavity surface should be possible to compare measurements with simulations.
- 4) The coupler is not adjustable and therefore cannot respond to changes in beam loading. Zero current operation will thus require about 125 kW of applied power per coupler.
- 5) The tuner motor is in the cold vacuum, increasing the risk of failure. However, given the large bandwidth of the cavity little tuning should be required.
- 6) The existing plan calls for use of mu-metal in the SRF gun at low temperatures to shield from the HTS fields. This also excludes the ambient earth’s field. The permeability at a particular temperature should be (re)checked and the use of cryoperm instead ought to be considered. It was not clear to the committee, which material was being used. The shield should be compatible with cold operation (note that regular a

mu metal has a significantly reduced permeability at cryogenic temperatures). Other materials (e.g., cryoperm) must be annealed for a specific operating temperature. Hence the shield should be heat stationed to a well defined temperature. The shield should reach this temperature when the cavity transitions to the superconducting state to provide effective shielding against the earth's field, which otherwise will be trapped in the niobium. A temperature sensor on the shield is important to confirm the operating temperature.

- 7) Since the shield temperature may not be 77 K during cryomodule operation, the planned LN2 test of the solenoid shielding may not yield accurate results. HTC solenoid iron saturation at low temperature. Magnet shield efficiency at low temperature needs to be rechecked.
- 8) No details were provided for the tuner, coupler and gun-cavity HOM design. The committee therefore cannot make any recommendations in this respect. Especially coupler operation at 500 kW each will be critical and extensive off-line conditioning studies should be performed to validate the power limit and thermal management.

HOMs & HOM loads

- 1) There has been substantial thinking in the Brookhaven group about the HOM loads given very high currents from the BNL prototype. The HOM load in the SRF gun will have a coated ceramic window separating the ferrites from the beam. There are many questions about the design, many of which can only be addressed through constructing and operating the dampers. The committee encourages BNL to host a workshop on HOM damping and involve experts from other laboratories pursuing high average current bunched beams and efficient HOM damping schemes.
- 2) The five cell cavity has undergone extensive design work and measurements with a network analyzer. Such measurements may not catch trapped modes but given the strong cell-to-cell coupling and the small number of cells, unforeseen trapped modes are not very likely.
- 3) The HOM loads are based on the existing Cornell design (ferrites). These have operated successfully for many years with the CESR 500-MHz system, albeit with a cavity with a Q-factor of $1e9$ rather than the required $1e10$ at BNL. Hence ferrite contamination of the cavity may not be apparent in the Cornell cavity but may still affect the BNL cavity.
- 4) The Cornell design was for a thermal load of 15 W/cm^2 . BNL should calculate the expected heat density in their ERL ferrite tiles. Ideally all tile assemblies should undergo an acceptance test to above this value to validate proper soldering/cooling of the ferrite tiles. Since the 5-cell already has the load attached, additional assemblies may be tested under assumption that these are a representative sample.
- 5) The HOM damping of the gun is performed by a combination of ceramic break and ferrites outside the beamline vacuum. Few details were provided. This load appears to be a fair distance from the gun cell and it should be verified that the damping is sufficient.
- 6) The current HOM loads cannot be used for multi-cavity modules because (a) they reduce the filling fraction significantly and (b) they have to be integrated in the cold. BNL is examining alternative scenarios based on capacitive coupling. It must be ascertained whether these can handle the total HOM power of 2.4 kW without thermal issues. Another promising option not currently being examined is waveguide couplers which potentially can handle a lot of HOM power.

SRF Cavity

- 1) The SRF cavity is very stiff and tuning is difficult. Since Piezo blocking forces are ca. 10x lower at cryogenic temperature, the available tuning range may decrease. Has this fact been included in the quoted value (9 kHz)? If not, the range will decrease to 900 Hz, uncomfortably close to the expected LF detuning (480 Hz). The piezo tuner may be required for cavity start up when performed in generator-driven configuration.
- 2) The quoted cavity performance following cryomodule integration is worrisome (significant field emission, low Q). Conditioning (e.g., Helium conditioning) should be performed to ascertain if performance can be recovered or a whether re-clean is necessary. The large dynamic heat load may be due to thermal transition heating and insufficient cooling at 4 K. This issue must be resolved quickly, otherwise the

cryogenic plant will not enable longer runs. Repeated interruptions for re-liquefaction will hinder the beam dynamics measurements. The time spent re-establishing thermal equilibrium of the cryogenics after refills may be significant.

- 3) The large amount of heating of the normal conducting beam pipe by the fundamental is a concern. This should be re-examined when the next-generation cavities are being designed to avoid cross-talk between cavities and joint losses. A smaller beam-tube and/or large neck-down may be required. The adopted HOM-damping scheme will impact the final solution.
- 4) Significant microphonics were observed at 15 Hz (?), possibly due to the steam system. The source must be identified and mitigated soon.

RF power

- 1) The cryogenic capacity should provide substantial overhead even when relatively high levels of field emission are encountered. The available overhead seemed marginal. A similar statement applies to the required RF power installation.
- 2) The combination of high loaded Q in the ERL cavity, a high average current of 0.5A, and only 50 kW available from the IOT suggests that the ability to vary the relative accelerator/decelerator phase will be limited during such high current operation. This is not a concern for steady state set up but should be re-visited in the case before adding an FEL or other such system is contemplated. It would be good to review the rf loading phasor diagrams under various tunings with microphonics if that hasn't been done.

Control room

- 1) Consider lay out of work stations in "concert stage" style (all facing one wall) instead of facing out to walls. This allows all operators to view a standard large screen with health/safety monitoring hanging on one wall instead of operators working back to back and not knowing what each other is doing.

Beam dump

- 1) The beam dump beamline requires (additional) diagnostics to properly set the dump for high current operation, and should allow setting the beam envelope to ensure proper spreading of the beam.
- 2) Hydrogen radiolysis needs to be estimated and provisions for disposing/neutralizing of gaseous hydrogen made. The rate of H₂ radiolysis is provided in SLAC-TN-67-029 technical note and is on the level of 0.3 liters per MJ of deposited energy into water. Either hydrogen catalytic recombiners or mere venting of H₂ if it is produced in small enough quantities could be an option.