Agenda for a Workshop On Energy Recovery Linac as a Driver for Synchrotron Radiation Sources

380 Wilson Lab, Cornell University, August 11 and 12, 2000

Objective: Examine the feasibility and R&D issues for a high energy (~7 GeV), high current (100 mA) energy recovery linac for high brilliance x-ray production using state of the art, narrow gap insertion devices (ID).

August 11:
8:00 - 8:30 am Intro & limitations of storage ring sources, Sol Gruner (CHESS)

8:30 - 9:30 Overview of a naive concept for a 7 GeV ID driver, Ivan Bazarov (CHESS/LNS), Maury Tigner (LNS)

9:30 - 10:25 Energy Recovery, Lia Merminga (CEBAF)

10:25 - 10:40 Coffee break

10:40 - 11:35 Examples of ERL used as driver for ID's, Geoffrey Krafft (CEBAF)

11:35 - 12:30 Low emittance sources, Charles Sinclair (CEBAF)

12:30 - 2:00 Lunch

2:00 - 3:00 ID Characteristics, Don Bilderback (CHESS)

3:00 - 5:30 Working Groups (WG)
WG 1 Single particle dynamics, transverse and longitudinal quantities
  (Rm 380 W; Conveners: R. Talman (LNS) & G. Krafft (CEBAF).
  Notes: I. Bazarov (CHESS/LNS)
WG 2 Beam stability issues and quantities
  (Rm 380 E; Conveners: J. Rogers (LNS) & L. Merminga (CEBAF).
  Notes: K. Finkelstein (CHESS)
WG 3 Low emittance electron sources
  (Lrg Conf. Rm; Conveners: G. Dugan (LNS) & C. Sinclair (CEBAF).
  Notes: D. Bilderback (CHESS)

5:30 - 6:00 Plenary session (380 Wilson)

6:30 - 8:30 Participants Dinner (Wilson Lab Patio & Common area)

August 12:

8:00 - 12:00 Working Groups convene again to produce work list, R&D plan suggestions

12:00 - 1:00 Lunch

1:00 - 3:00 Plenary session. Summaries of WG's and discussion of next steps.

Participants:

Ivan Bazarov (CHESS; LNS)
Don Bilderback (CHESS)
Joel Brock (A&EP, Cornell)
Gerry Dugan (LNS)
Ken Finkelstein (CHESS)
Ernie Fontes (CHESS)
Alex Gaeta (A&EP, Cornell)
Sol Gruner (CHESS)
Lou Hand (Physics, Cornell)
Don Hartill (LNS)
Randy Headrick (CHESS)
Geoffrey Krafft (Jlab)
Peter Lepage (LNS)
Lia Merminga (Jlab)
Hasan Padamsee (LNS)
Dave Rice (LNS)
Bob Richardson (LASSP)
Joe Rogers (LNS)
Dave Rubin (LNS)
Al Sievers (LASSP)
Charlie Sinclair (Jlab)
Detlef Smilgies (CHESS)
Karl Smolenski (CHESS)
Richard Talman (LNS)
Dan Thiel (MacCHESS)
Maury Tigner (LNS)
Frank Wise (A&EP, Cornell)

WG 1: Lattice and single particle dynamics, transverse and longitudinal quantities

Participants: R. Talman (convener), G. Krafft (convener), I. Bazarov (note taker), D. Rice, D. Hartill.

Objectives: general layout for ERL machine; optics considerations; power budget calculations; single particle dynamics (beam break-up (BBU), vacuum issues, energy spread, transverse emittance); tentative R&D program.

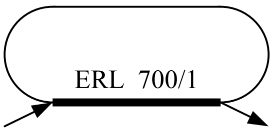
Charges:

- List important design issues that need checking in preliminary design needed for R&D proposal.
- What are limits to energy ratio between injected beam and top energy beam, i.e. 3 – 10 GeV?
- From Jefferson lab experience w. FEL, is there a preferred lattice for the linac and transport lines?
- Comment on the alternative ID distributions – "herringbone" layout or arc trajectory – from accelerator physics and technology point of view. Note probable length of ID's at 25 m.
- Any problem with using DBA (double-bend achromat) or TBA (triple-bend achromat) for turnaround arcs?
- What lattice features are essential for good beam position regulation (micron level)?
- Can optics be flexible enough to handle either flat or round input beam from injector?
- Outline a preliminary optics scheme with quantities.
- Is 7 GeV the optimal beam energy?
- Would it be possible to build an X-ray source with the same characteristics using conventional approach of electron storage ring?

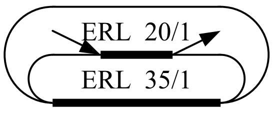
Resolutions.

1. General layout of ERL machine

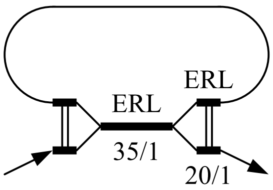
a)



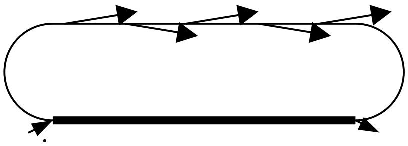
b)



c)



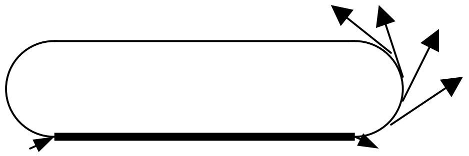
2. Beamline configurations options:



a) Herringbone or zig-zag

- simplifies dispersion suppression;
- favors the lowest emittance lattice (min-H lattice);
- needs achromats between lines.

b) Arrayed around arcs



- favors DBA or TBA lattice;
- first lines have best possible brilliance.

3. Optics tasks:
    a) linac optics;
    b) turnaround arcs;
    c) undulators optics;
    d) matching sections;
    e) longitudinal (bunchers, phase rotators, etc.);

4. Specification setting tasks:
    a) beam quality at exit of ERL after acceleration;
    b) beam quality after once around;
    c) emittance blow-up during deceleration;
    d) general design approach: work back from worst possible beam quality at end of ERL after deceleration.

5. Power budget.

	@ 7 GeV	@ 5 GeV
	P_{AC}	
RF wall losses	3.5 MW	2.5 MW
SR power	2.4 MW	0.7 MW
RF Drive	5.6 MW	4.0 MW
Injector	2.0 MW	2.0 MW
Electromagnets	1.5 MW	0.7 MW
Total	15 MW	10 MW

These numbers can conceivably be reduced by improved microphonics control, recovery of the injector energy, better Q, etc. Needs to be examined in detail.

6. Needed from other R&D groups:
    a) BBU instability check up for linac optics;
    b) joint design team – optics / IDs;
    c) web site for useful papers;
    d) calculation of higher mode power loss in undulator sections;
    e) vacuum issues.

7. Answers to questions posed:

Any problem with DBA/TBA?
- No;

What lattice features are essential for good beam?
- Feedback for every ID;
- generous space allotment;
- X-ray beam as input to feedback loop;
- BMPs (beam position monitors) needed at every quadrupole in acrs.

Can optics be flexible enough for flat/round beam?
- Yes.

Is there a preferred ERL optics?
- Needs further study. See http://www.jlab.org/~douglas/ULTRAFEL/jlabtn00005.pdf

Would it be possible to build an X-ray source with the ERL characteristics using conventional approaches of a storage ring?
- As far as brightness is concerned, the ERL at 100 mA exceeds any existing storage ring if the normalized emittance is of the order of 1 mm-mrad. Other advantages of the ERL, which would be hard to obtain in a conventional storage ring, are the possibility of very short pulses and a flexibility of operation.

8. Some tentative parameters for future machine:

Energy	7 GeV
Current	100 mA
Normalized gun emittance	2 mm-mrad
Emittance at the exit of linac	0.16 nm-rad
Linac RF frequency	1.3 GHz
Interbunch spacing	770 ps
Bunch width	3 ps
Charge per bunch	77 pC
Linac length	~ 400 m
Linac accelerating gradient	20 MV/m
Energy recovery efficiency	> 99 %
Maximum dimensions	500 × 100 m
Total circumference	~ 1000 m
Turnaround arc bend radius	~ 50 m
Lattice type for arcs	Minimum H or Chasman-Green
Maximum beta function in linac	~ 70 m
Average beta function in IDs	~ 10 m
Number of undulators	10 – 12
Emittance increase after once around	15 – 20 %
Energy spread increase ($\sigma_{\Delta E}$)	~ 500 keV
Radiated energy loss (total)	~ 10 MeV

Conclusions:

1. From our point of view, a high brightness X-ray source based on an Energy Recovery Linac seems to be feasible.

2. The next step to be taken is to design linac optics and have it checked for BBU instability using CEBAF code for 2-D BBU calculations.
3. It is important to compare ERL performance and cost at all stages of planning to conventional storage ring approaches.
4. Attention to details of the linac will be needed to reduce power consumption. There are plausible routes to be investigated (e.g., microphonics control).

WG 2: Beam Stability Issues and Quantities

Participants: L. Merminga (convener), J. Rogers (convener), H. Padamsee, J. Welch, D. Hartill, K.D. Finkelstein (note taker).

Objectives: Address the following charges, identify specific questions for future work, and outline an R&D program to investigate beam stability issues for an ERL-based synchrotron radiation source.

Charges:

- What important considerations determine ultimate ERL beam current?
- What collective wake effects limit the ratio of extraction to top energy of the linac?
- What are the R/Q and Q specs needed for a 100 mA ERL?
- Is it likely that CEBAF or TESLA cavity hardware –as is– could support 100 mA?
- Outline an R&D program that could, if successful, demonstrate stability aspects of ERL feasibility.
- Are there emittance dilution issues peculiar to the ERL which might limit the minimum achievable emittance?

Parameters and information needed/received from other groups

- Define desired bunch length:

  Some experimenters may benefit from sub-picosecond bunch lengths, but CHESS participants indicate that 1 ps is a good target.
- What are scaling laws relating the longitudinal and transverse emittance at the source to bunch charge and bunch length?

  It is not clear that any such scaling laws are generally valid.

  Bunch length σ_l at the cathode is the optical pulse length, independently of charge. It grows with distance travelled from the cathode. The amount it grows depends on the gun voltage and the drift distance. How much this can be reversed without significant transverse emittance growth is unclear, and very likely depends on the details of how it is done.

  Transverse emittance at the source might not depend on the bunch charge, but again, it grows with drift distance from the gun. We know that some of the transverse emittance growth can be compensated by proper solenoid settings (which likely have to be determined quasi-empirically for our conditions), but we don't know how much. Finally it's not clear that there is a code which is adequately "bench-marked" to allow us to believe the results at a level which matters for the ERL.
- How much emittance dilution can be tolerated?

  The emittance dilution in the RF cavities should match the emittance dilution expected in the undulators, about 0.007 mm-mrad.
- How much energy spread can be tolerated?

To make use of the narrow spectral width of the long undulators, the energy spread should be limited to $\sigma_E/E < 10^{-3}$.

- How small can beam losses be made?
  Jefferson Lab FEL is protected against 1 μA losses, but it's not known how small the losses can be made.

Beam Current Limitations and Wakefield Effects

Our present understanding is that the most important beam current limiting phenomena in an ERL are: beam loss and collective instabilities. HOM (higher order modes) power dissipation, although not a show stopper, also needs to be analyzed carefully, as it may impose engineering requirements on the superconducting rf cavity design.

The limiting instability is expected to be multibunch, multipass beam breakup (BBU). All multibunch BBU mechanisms must be investigated:

- cumulative (long linac);
- regenerative; and
- multipass.

Estimating multibunch beam breakup is a short term R&D project. L. Merminga has simulated a similar case (acceleration from 100 MeV to 1 GeV in TESLA cavities) and has found an instability threshold of order 100 mA, with the instability threshold scaling as $I_{\mathrm{threshold}} \propto \sqrt{E_{\mathrm{injection}} E_{\mathrm{final}}}$. This is in the current range of interest for the ERL, and indicates that improvement in the damping of higher order modes (HOMs) by an order of magnitude over the present TESLA cavities may be needed.

The only practical method of estimating the multibunch BBU thresholds is through simulation with codes such as TDBBU (Krafft, Bisognano, and Yunn). This can be done fairly rapidly. The effect of rf focusing from the cavities appears to be significant, especially at low energies, and should be taken into account in the BBU simulations. A small modification of TDBBU is required and is being pursued.

It should be investigated whether active fast feedback systems can be effective in damping the multibunch BBU, as the BBU risetime near the instability threshold is quite long (comparable to the damping time of the cavity HOMs). The short spacing between bunches would require a feedback system similar to those in use at B-factories. It may not be possible to feed back on the bunch being sensed because of cable and processing delays, but feedback could be implemented by feeding back on a later bunch.

The Jefferson Lab FEL accelerated and recovered energy with Q_b = 60 pC, (close to the 77 pC target of the ERL) but with a much shorter linac.

A loss factor of 10 V/pC per cavity, typical of CEBAF and TESLA cavities for ~ps long bunch, was used to estimate the head-tail energy spread due to the linac. The total loss factor in 350 m of cavities is $k_{\|}$ = 3.5 kV/pC. The energy spread due to this loss factor is

$\sigma_E = 0.27$ MeV, and $\sigma_E/E = 3.9\times10^{-5}$ at the end of the linac. There may be a doubling of this number with two beams (accelerating and decelerating) in the linac. This energy spread is not problematic at the undulators, and although larger at the beam dump, σ_E/E = 2.7%, it is not expected to be a problem there either. If it is a problem, the energy spread can be reduced by appropriately phasing the RF voltage.

Emittance Dilution and Limitations

Emittance dilution may come from:

- beams which are off-center in the cavities;
- non-axisymmetric wakefields from asymmetries in the cavities (from, *e.g.*, couplers)
- single bunch BBU

For the JLab FEL emittance growth due to single bunch BBU is not a problem even at 135 pC/bunch, however the ERL emittance tolerance is tighter, therefore the calculation should be done and combined with the emittance growth due to the other effects.

The Jefferson Lab FEL emittance grows from 1 to 7 mm-mrad from the electron source to the end of the linac. Much of this growth is in the region between source and linac entrance. The source of this emittance growth has not been determined, as the final emittance is adequate for the Jefferson Lab FEL.

A number of other effects could degrade the beam quality and should be evaluated. They include emittance growth due to coherent synchrotron radiation (CSR) in bends, ion trapping, fast beam-ion instability and resistive wall effects in the undulators.

R/*Q* and *Q* specifications

Dynamic losses from the accelerating RF can be estimated as power dissipated per unit length by $P_{\text{dynamic}} = \dfrac{V^2}{(R/Q)Q_0} = \dfrac{(20\ \text{MV/m})^2}{(10^3\ \Omega/\text{m})2\times10^{10}} = 20\ \text{W/m}$ at 2 Kelvin (based on the best recent Q_0 in TESLA cavities). Total losses in 350 m of cavities are 7 kW. If the efficiency of the refrigerator is 1/500 at 2 K (specification for LHC plant is 1/700, but larger efficiency is possible in principle), then the refrigerator wallplug power is 3.5 MW. The static heat leak at 2 K is estimated at 5 W/m.

HOM losses are $P_{\text{HOM}} = 2Q_b^2 k_{\|} f_{\text{bunch}}$ = 150 W per cavity. This is an unacceptable loss at liquid helium temperature, however preliminary analysis shows that, with a carefully chosen Q_{ext}, most of the power can be extracted and only a small fraction is dissipated in the cavity walls. There is still however the power flow issue, implicit in the Q_{ext} of the beam pipe openings, which must be thought through because it could impose design requirements on TESLA or CEBAF cavities, such as placing cooled absorbers in the warm section of the beam line.

Can CEBAF or TESLA cavity hardware –as is– support 100 mA in this application?

The answer is a qualified *no*. The structure itself is fundamentally adequate, but a redesign is required for better HOM damping of some modes, for HOM extraction to a room temperature load, and modifying the RF couplers for a higher Q_{external}. Redesign of rf couplers and windows might also be required for the injector cavities if the beam power is ~1 MW at 1.3 GHz.

The necessary RF power is determined by a compromise between insensitivity to microphonics (which pushes Q_{external} down and P up) and economics (which pushes P down and Q_{external} up). Our estimate was $P = 5$ kW, $Q_{\text{external}} = 2\times10^7$. Even with a 5° imbalance between accelerating and decelerating beams, and 25 Hz of microphonics noise, the required power per cavity is 12.5 kW (Figure 1), still a modest amount.

An R&D program to address beam stability

- MAFIA calculation to determine whether chicanes or asymmetric cavity structures (coupler on one side) are responsible for emittance dilution as observed in Jefferson Lab FEL.
- Simulate BBU with code such as TDBBU. Need to coordinate with optics design to minimize M_{12} / M_{34} from one pass through the cavities to the next.
- Particle tracking to simulate emittance growth from HOMs.
- Modification of TESLA or CEBAF cavity design to improve damping of worst HOMs by an order of magnitude, and to remove the HOM power to a room temperature load, followed by prototype construction and test.
- Develop tools, both experimental and theoretical, to understand and characterize beam halo generation and loss.
- Prototype accelerator:
- 100 mA, 1.3 GHz source
- energy recovery
- 6-D phase space diagnostics (intercepting profile monitors and streak camera)
- measure HOMs (ideally, one unpowered cavity would be available)
- benchmark BBU codes
- demonstrate reliable operation of srf cavities and rf control system at:
    a. high gradients (20 MV/m) and high average current (in the Injector)
    b. high gradients and almost zero beam loading (in the ERL)
- room for installation of feedback transducers
- investigate and minimize beam loss

Conclusions:

Continuing with an R&D study toward producing an energy recovery linac for synchrotron radiation seems well warranted, as this working group discovered no fundamental obstacles. Some modification of existing RF cavities is needed, but these changes are technically straightforward. The large total refrigeration power (similar to CEBAF) is a concern, and requires very high Q_0 and very efficient refrigeration. Simulation of beam breakup is a high priority. A low energy ERL should be constructed to demonstrate energy recovery at high average current, benchmark the BBU codes, measure emittance growth, and investigate and minimize beam loss.

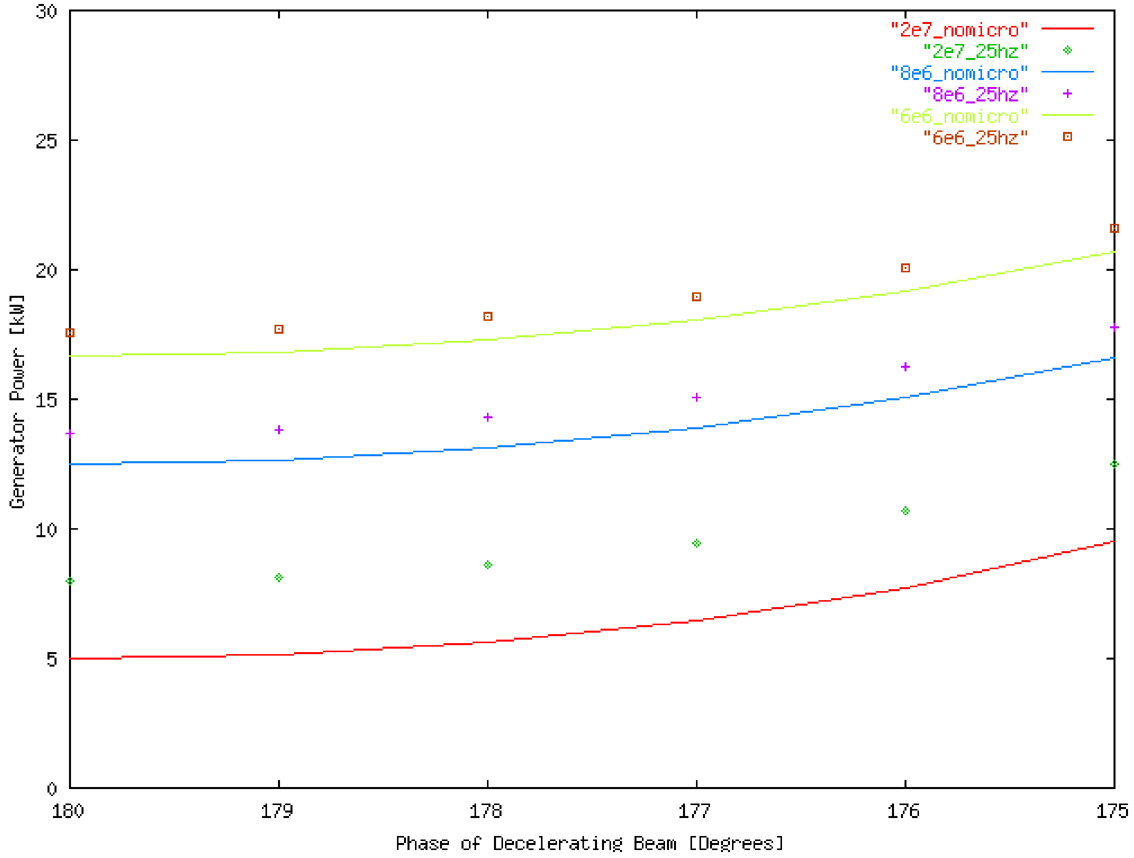


Figure 1. Generator power vs. phase of the decelerating beam, assuming the accelerating beam is on crest of the rf wave. The 3 solid curves correspond to loaded Q's of 2x10^7, 8x10^6 and 6x10^6, and the data points correspond to power required if the microphonic noise is 25 Hz.

WG 3: Low emittance electron sources

Participants: Charlie Sinclair (convener), Gerry Dugan (convener), Don Bilderback (note taker), Alex Gaeta, Sol Gruner, Maury Tigner

Objective: Assess the present and future methods of making low emittance sources of electrons that can yield 80 pC per bunch charge with RF of 1.3 GHz (100 mA) and with normalized emittance below 2 mm-mr.

Questions for study:

- What are today's best performance expectations in terms of charge per bunch per micrometer normalized emittance with every bucket filled at ~1.3 GHz?
- What performance might be reasonable to expect in 5 years?
- What is the ultimate performance potential from today's frame of reference?
- What are the limiting phenomena?
- If we give up current, is there a limit on the minimum emittance achievable?
- Are there alternatives to photocathodes?
- What bunch lengths might one reasonably achieve at 100 mA and every bucket filled?
- What constraints apply with very short bunches? How short can the bunches be?
- Outline an R&D program for source development that would result in a source suitable to drive a proof of principal ERL to be turned on 3 years hence.

Results of Inquiry:

1. Best performance expectations today: 80 pC per bunch, from photocathode gun (527 nm laser onto a Negative Electron Affinity (NEA) GaAs photocathode), 1.65 micron (mm-mr) RMS normalized emittance achieved at Jefferson Laboratory (Engwall's measurements at 250 keV). The Jefferson Laboratory FEL has operated with 65 pC bunches at a 75 MHz repetition rate for an average current about 5 mA. The 100 mA requirement for the ERL is only a factor of 20 away from what has been already demonstrated and the issue is mostly running the repetition rate up from 75 to 1300 MHz.
2. Ultimate performance potential & reasonable expectation in 5 years: DC gun working at 500 kV; 1.3 GHz operation; 5 watt, 780 nm laser; GaAs single crystal photocathode with 2.25 mm spot size; 20 ps bunch length. For these conditions could expect 0.18 micron emittance (0 mA bunch current); at 80 pC/bunch (100 mA), the emittance might be of order 1 micron depending on the gun design, space charge compensation, etc. (The limits of space charge compensation are not well known). These numbers most likely could be pushed 2x lower with a liquid nitrogen cooled cathode.
3. Limiting phenomena: space charge emittance growth and emittance compensation, wakes, vacuum (breakdown, cathode lifetime). Reasonable photocathode lifetimes before in-situ regeneration is needed are probably feasible by working hard on the vacuum and step-scanning the illuminated area.

4. Emittance vs. current tradeoff: scaling is not well known and needs further research work
5. Alternative Cathodes: alkali tellurides, antimonides - require more difficult lasers, but may have better vacuum tolerance. These materials are sensitive to both chemical poisoning and ion back bombardment, may have worse lifetimes, and are essentially untested at the really low vacuum level where the Jlab gun presently operates.
6. Bunch length at gun: 20 ps. Energy spread at gun: ~0.8 keV @ 300 kV operation. Bunch lengths $\leq$ 1 ps possible by post-gun bunchers.
7. Bunching should be done at high energy to avoid space charge problems. Ultimate bunch length might be expected to be $\propto$ longitudinal emittance $\propto$ Q.
8. R & D program: Develop and benchmark codes for prototype design. Make prototype gun/buncher/accelerator for 10 MeV, 100 mA test. Focus on DC gun @ 500 kV, using 780 nm, 1.3 GHz, 5 W laser with GaAs cathode. Follow gun with prebuncher and accelerate to 5 – 10 MeV as soon as possible. Develop design (full simulation) which employs space charge compensation, rapid acceleration after gun to limit space charge emittance growth. Investigate post-gun bunchers if very short bunches are desired. Appropriate beam diagnostics need to be identified to verify the required beam characteristics.
9. Principal issues for R & D program: 1) limit emittance growth 2) vacuum design which allows 500 kV operation to be reached in gun and provides good cathode lifetime.
10. Backup plan: RF gun, using SC RF at 1.3 GHz for rapid acceleration and bunching after GaAs cathode.

Conclusions:

1. A DC gun with a room temperature semiconductor photocathode, operated at high voltage, can almost certainly produce 80 pC bunches of short duration and 1 micron normalized emittance. The HV operation will require care, but can be done.
2. Operation at 100 mA average current is only an issue of cathode lifetime. For semiconductor cathodes, this lifetime is limited only by ion back bombardment. Demonstrated lifetimes are marginal for 100 mA operation (example of 11 hour lifetime in one spot was given), but improvements are clearly possible. The illuminated spot is small compared to the full photocathode area, so by occasionally stepping the point of illumination across the photocathode, practical lifetimes (weeks) are possible before regeneration is needed. In-situ regeneration of the photocathode is a matter of hours and is already done at Jlab. The addition of a load lock would allow for easy replacement, if needed.
3. Lowering the cathode temperature is very likely to lower the emittance from a semiconductor cathode.

A diffraction limited light source can probably be achieved for 1 Angstrom x-rays at lower beam current. As a first approximation, the current, and flux scale with the illuminated area, (emittance with the square root of the area), so switching to a diffraction limited mode is likely to be mostly a matter of focusing the photocathode laser to a smaller spot. Extrapolating from the projected flux curves in the White Paper suggests that even in a diffraction limited mode, the flux will be extraordinary.