Source:

http://icfa-usa.jlab.org/archive/newsletter/icfa_bd_nl_26.pdf

ICFA

International Committee for Future Accelerators
Sponsored by the Particles and Fields Commission of IUPAP

Beam Dynamics Newsletter

No. 26

Editors in chief:
K. Hirata and J.M. Jowett

Editors:
S. Chattopadhyay, W. Chou, S. Ivanov,
H. Mais, J. Wei, and C. Zhang

December 2001

2.3 Cornell/Jefferson Lab ERL Project

Ivan Bazarov, Sergey Belomestnykh, Don Bilderback,
Ken Finkelstein, Ernie Fontes, Steve Gray, Sol M. Gruner,
Hasan Padamsee, Ray Helmke, Qun Shen, Joe Rogers,
Richard Talman, and **Maury Tigner**, Cornell University
Geoff Krafft, Lia Merminga, and **Charles Sinclair**, Jefferson Laboratory

In reference [1] it is proposed that a recirculating linac light source based on closed-loop energy recovery with superconducting linacs offers significant advantages over storage ring sources, both in terms of the possible x-ray beams and, once the technology is developed, cost-effectiveness [2,3]. The basic idea behind an Energy Recovery Linac (ERL) was suggested long ago [4] and the feasibility of operating an ERL has recently been demonstrated with the highly successful infra-red free electron laser (IRFEL) at JLab [5,6]. Our long-term goal is to build a high energy (~5 - 7 GeV) recirculating linac light source at Cornell, both as a development laboratory for ERL technology and as a unique user resource. A high current, high brilliance machine can push ERL technology to new limits.

The advantages of an ERL x-ray source are best understood by first considering storage ring sources. The characteristics of the x-ray beams that may be produced by a storage ring source will always be limited by the qualities of the electron beams used to produce the synchrotron radiation. Specifically, it is desired to have

(1) Low electron beam sixth-dimensional phase space to increase the brilliance and coherence of the resultant synchrotron radiation;
(2) Very short electron bunches to enable fast time-resolved experiments;
(3) Ultra-small round beams;
(4) A radiation output which does not decay over time;
(5) Flexibility of operation to enable easy tailoring of x-ray beams to specific science applications; and
(6) An easy upgrade path as limiting components (e.g., the electron source) improves.

In an ERL machine, the electrons are not stored, constraints of beam equilibrium never become limiting, and the boundaries are different. Photoinjectors can produce bunches with emittances, sizes and lengths which are superior to the equilibrium bunches stored in storage rings. Such bunches are then accelerated to high energy via a superconducting linac (SC linac), which can preserve the salient bunch characteristics. These high energy bunches with superior quality are then passed though undulators to produce SR beams with unprecedented characteristics. For these reasons, ERL sources have recently become the focus of a number of next-generation x-ray source efforts [7-10].

Before committing to specific designs for a large and expensive machine, it is absolutely essential that accelerator and technology issues be explored on a brilliant, high current prototype machine. The reference [1] is a study for construction of the prototype, which is the first step in a two-phase project to build a high-energy ERL light source, and which will provide greater understanding of the process of energy recovery and its limitations. In this contribution we will condense and summarize the findings presented in the study. The discussion will concentrate on beam dynamics and accelerator technology aspects of the project. The full proposal document should be consulted for a more complete discussion of the expected performance of the follow on machine.

2.3.1 Accelerator Physics & Technology Issues

To achieve maximally brilliant x-ray beams, it is important that the ERL be designed so that the photoinjector emittance is as small as possible and that emittance growth during beam acceleration and transport to the undulators is minimized. Another important requirement is that the beam be stable against transverse and longitudinal multibunch instabilities, which are somewhat analogous to the multibunch instabilities that afflict storage rings at high current. It is also required that beam loss be small during beam recirculation, for both cryogenic efficiency and machine protection reasons, and that the RF beam loading from the two beam passes be efficiently compensated to minimize the RF power required. Finally, because the accelerator contains only a few passes, the longitudinal phase space of the accelerated beam can be preserved and manipulated, yielding extra degrees of freedom in design, but also extra degrees of complication. Each of these issues is treated separately and thoroughly in section 3 of [1].

In general, it is necessary to decrease the electron beam emittance as much as possible to maximize the brilliance from the undulators. Because 3rd generation storage ring sources already have very bright beams, the first requirement is to design the machine with an average beam brightness that exceeds that possible in an equivalent energy storage ring. This requirement places a severe limit on the parameter choices possible in the machine. In particular, the requirement tends to drive one to a design with low charge-per-bunch and more frequent bunches, just the opposite of the case with fourth generation sources. One would like the normalized emittance at the undulator to remain as close to the emittance generated at the injector as possible. The emittance from the injector should be minimized by space charge compensation techniques [7,11].

Assume that an injector can be designed with an average brightness better than an equivalent ring. One must then take steps to assure that the beam emittance is not degraded on acceleration and delivery to the undulators. The approach taken in the study involves:

(1) Choosing the single bunch charge low enough that typical single bunch emittance growth mechanisms (e.g. transverse single bunch beam breakup, wakes, non-inertial space charge, and coherent synchrotron radiation), do not result in much emittance growth. This is helped by the fact that superconducting accelerating cavities are being used, thereby permitting large apertures.

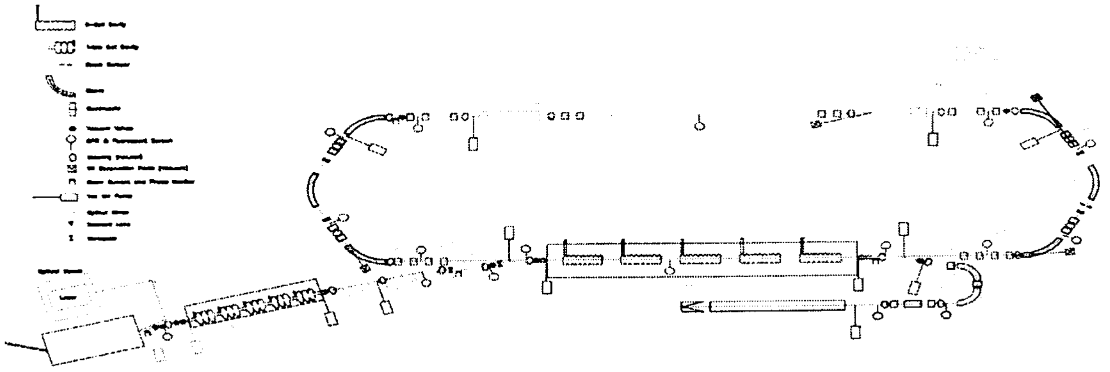
(2) Designing the beam optics such that the single particle sources of emittance growth, in particular that generated by the synchrotron emission in the turn-around arcs, are minimized. The approach is very similar to that taken in storage rings where a minimum emittance lattice design is employed (see section 3.1.5 in the proposal document).

(3) Because the beam average current in the ERL will be high, it is necessary to take care that the beam is stable against multibunch instabilities. The threshold for instability depends strongly on two design parameters, the beam optics of the recirculation loop and the properties of the High Order Modes (HOMs) of the accelerating cavities. Using linac and arc beam optics designs that keep the beta functions small (60 m and smaller) throughout the linac, we have performed simulations that show that a 5 GeV accelerator should be stable at an operating current of 100 mA, assuming the HOMs are damped as well as they have been for the TESLA test facility cavities at DESY [12].

2.3.2 Prototype Design

The prototype, as shown schematically in Fig. 2.3.1, consists of a DC photocathode gun, a superconducting capture section that accelerates the beam to 5 MeV for injection, and a main linac within the recirculation loop that takes the beam to 100 MeV. To achieve the goal of 2 μm or smaller normalized emittance in the undulators, it will be necessary to achieve 1.5 μm or less out of the injector and less than that from the gun. Thus, very good space charge emittance compensation [11] must be achieved and the effects of RF focusing, non-inertial space charge and coherent synchrotron radiation emittance dilution [13-15] must be strictly minimized. Measuring these effects and benchmarking codes will be an essential feature of the accelerator physics program of the prototype. Wake fields in the cavities and beam lines will also present a challenge to emittance preservation and are to be explored in the prototype.

The photoinjector source is at the heart of the facility since it determines the maximum achievable flux and brilliance. Various source technologies are being studied for their potential suitability for an ERL aimed ultimately at x-ray production. Initial surveys and calculations (see section 2.6) convince us that the DC, laser excited photocathode is likely to be successful. Selecting the optimum cathode material and assuring adequate operating life under high current operating conditions present significant challenges that must be surmounted early on.



Beam Energy	100 MeV	Charge per bunch	77 pC
Injection Energy	5 MeV	Emittance, norm.	2* μm
Beam current	100 mA	Shortest bunch length	100* fs

Figure 2.3.1 ERL Prototype Schematic, * values are rms

The superconducting capture section of the photoinjector will require development. The need to minimize emittance-diluting asymmetries while coupling 500 kW to the beam in a flexible way so that RF focusing and RF bunching can be accomplished without destroying space charge compensation is far more demanding than in any existing system. The ERL prototype must demonstrate robust operation of this element of the system.

The main linac posited for the ERL light source will operate at levels beyond existing technology. The economic optimum indicates that 20 MV/m or less is a desirable operating gradient. This gradient has been routinely achieved in pulsed operation with relatively small average beam currents. It must be demonstrated that the required high gradients and Q values can be obtained under the necessary CW, high current operating conditions. Not only must the higher modes be heavily damped for transverse stability but, because of the CW operation and the consequent significant power in these modes, they must be extracted from the low temperature with high efficiency. Careful measurements, using the prototype, will be needed to assure that these criteria can be met and maintained under operating conditions.

To provide sub-picosecond bunches to the undulators while avoiding the severe wake field consequences of such short bunches in the injector and linac, requires that the short bunches be obtained at the highest energy by magnetic compression. The accelerator physics and technology of effecting such compressions without undue damage to the beam properties is beyond today's state-of-the-art and will require exploration on the prototype before one can design the needed system for a full scale facility with confidence.

Measuring the beam properties with the accuracy needed in the face of the enormous circulating beam power will require non-intercepting methods that are robust and easily read out for tuning and feedback control. Optical methods analyzing incoherent and coherent synchrotron radiation originating at various stations around the loop are promising but will need demonstration in this very low normalized emittance context. Likewise, measuring halo in the presence of such high circulating beam power will be difficult. Easily repeated methods for doing so must be developed as tuning and diagnostic tools.

To summarize, we plan to prototype the source and other injector components at full scale. Demonstration of acceptable energy recovery efficiency requires a full ERL configuration. Beyond that, one must be able to probe the instability thresholds for the type of cavities planned for the final facility. This requires sufficient length of cavity that buildup of any instability can be seen. With these considerations in mind the ERL prototype will have high beam power from the injector, 100 mA CW at 5 MeV. A 100 MeV energy for the main linac of the prototype appears adequate for a good evaluation of the beam breakup. Magnetic compression and de-compression sections are a feature of the design. Achievement of 20 MV/m gradient continuously and possible periodic restoration of the gradient capability are essential results to be demonstrated in the prototype.

2.3.3 References

1. Gruner, S. M. and Tigner, M. (Eds) Bazarov, I., Belomestnykh, S., Bilderback, D., Finkelstein, K., Fontes, E., Gray, S., Gruner, S. M., Krafft, G., Merminga, L., Padamsee, H., Helmke, R., Shen, Q., Rogers, J., Sinclair, C., Talman, R., and Tigner, M. "Study for a Proposed Phase I Energy Recovery Linac (ERL) Synchrotron Light Source at Cornell University", CHESS Technical Memo 01-003 and JLAB-ACT-01-04
   http://erl.chess.cornell.edu/papers/ERL_Study.pdf, or
   http://casa.jlab.org/publications/manuscripts/casa01045.pdf

2. Bilderback, D., Bazarov, I., Finkelstein, K., Gruner, S., Krafft, G., Merminga, L., Padamsee, H., Shen, Q., Sinclair. C., Tigner, M., and Talman, R. "New energy recovery linac source of synchrotron x-rays", Synchrotron Radiation News **14**(3): 12-21.

3. Gruner, S., Bilderback, D. and Tigner, M. "Synchrotron radiation sources for the future", Sept. 2000, CHESS, Cornell University, Ithaca, NY,

http://erl.chess.cornell.edu/papers/WhitePaper_v41.pdf.

4. Tigner, M. "A Possible Apparatus for Electron Clashing-Beam Experiments", Nuovo Cimento **37**: 1228-1231.

5. Benson, S., Biallas, G., Bohn, C., Douglas, D., Dylla, H.F., Evans, R., Fugitt, J., Hill, R., Jordan, K., Krafft, G., Legg, R., Li, R., Merminga, L., Neil, G.R., Oepts, D., Piot, P., Preble, J., Shinn, M., Siggins, T., Walker, R., Yunn, B. "First lasing of the Jefferson Lab IR Demo FEL", Nuclear Instruments and Methods in Physics Research A, **429**: 27-32

6. Neil, G. R., Bohn, C.L., Benson, S.V., Biallas, G., Douglas, D., Dylla, H.F., Evans, R., Fugitt, J., Grippo, A., Gubeli, J., Hill, R., Jordan, K., Krafft, G. A., Li, R., Merminga, L., Piot, P., Preble, J., Shinn, M., Siggins, T., Walker, R., Yunn, B. "Sustained Kilowatt Lasing in a Free-Electron Laser with Same-Cell Energy Recovery", Phys. Rev. Lett. **84**(4): 662.

7. Bazarov, I. V., Bilderback, D.H., Gruner, S.M., Padamsee, H.S., Talman, R., Tigner, M., Krafft, G.A., Merminga, L. and Sinclair, C. "The energy recovery linac (ERL) as a driver for x-ray producing insertion devices" 2001 PAC, Argonne Nat. Lab, Argonne, IL: (submitted).

8. Ben-Zvi, I., and Krinsky, S. "Future light sources based upon photo-injected energy recovery linacs", Synchrotron Radiation News **14**(2): 20-24.

9. CHESS Energy Recovery Linac (ERL) Machine Workshop, Cornell Univ., Ithaca, NY, 11-12 Aug 2000 http://erl.chess.cornell.edu/papers/ERLMachineWorkshopAgenda.htm.

10. Padmore, H. A., Schoenlein, R.W., Zholents, A.A "A recirculating linac for ultrafast x-ray science", Synchrotron Radiation News **14**(2): 26-31.

11. Carlsten, B. E. "New photoelectric injector design for the Los Alamos National Laboratory XUV FEL accelerator", Nuc. Instr. Meth. Phys. Res. A **285**: 313-319.

12. Bazarov, I. V., Krafft, G.A., and Merminga, L. "Linac optics for energy recovery linac" 2001 PAC, Argonne Nat. Lab, Argonne, IL: (submitted).

13. Braun, H., F. Chautard, R. Corsini, T. O. Raubenheimer and P. Tenenbaum "Emittance growth during bunch compression in the CTF-II.", Phys. Rev. Lett. **84**: 658-661.

14. Carlsten, B. E. "Calculation of the noninertial space-charge force and the coherent synchrotron radiation force for short electron bunches in circular motion using the retarded Green's function technique", Phys. Rev. E. **54**: 838-845.

15. Rosenzweig, J., Serafini, L. "Transverse particle motion in radio-frequency linear accelerators", Phys. Rev. E **49**: 1599-1602.