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Optics and beam transport in energy recovery linacs

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Abstract

Here, we report on the working group ‘‘Optics and Beam Transport’’ of the 2005 Energy-Recovery-Linac Workshop. This workshop also had working groups on ‘‘Electron Guns and Injector Designs’’, ‘‘Superconducting RF and RF Control’’, and ‘‘Synchronization and Diagnostics/Instrumentation’’. Here, we are concerned with the many different ERL proposals that international laboratories have been working on. Subjects of concern are optics, accelerator design and modeling, stability requirements, designs of the merger that connects the conventional injector linac with the Energy Recovery Linac, longitudinal phase space manipulations to produce short pulses, beam dynamics and limitations by beam instabilities, and computational aspects of space-charge and synchrotron radiation effects. A coarse grain overview is given and reference is made to more detailed articles that were presented in this working group. Subjects are identified where collaborations should be encouraged and areas of future R&D are prioritized.

Keywords: ERL; Light source; FEL; Electron cooling; Optics; Beam dynamics

1. Introduction

Energy Recover Linacs (ERLs), proposed already in Ref. [1], have received attentions in recent years since they have the potential to accelerator currents much larger than those of non-recovering linacs, and since they have the potential of providing emittances smaller than those in X-ray storage rings at similar energies and for similar beam currents. The first potential is due to the fact that the current in linacs is limited by the available electric power if the energy of the accelerated particles are not recovered. Accelerating a 100 mA beam to 5 GeV, as approximately required for an X-ray source would require a beam power of 0.5 GW which is technically not feasible, whereas ERLs do have the potential to provide such beam powers. The second potential is due to the fact that the emittances in an ERL is that of the electron source, if emittance increase during acceleration can be avoided. And as described in the working group on ‘‘Electron Guns and Injector Designs’’, simulations indicate that emittances much smaller than those for modern low-emittance storage rings could be produced for currents in the 100 mA regime. Fig. 1 shows how the very small horizontal and longitudinal emittance that can be achieved in an optimized DC photo injector changes with bunch charge and bunch length.

The first international ERL workshop with its about 150 participants in early 2005 has also shown the large interest in ERLs that is prevalent in the accelerator community.

The charge of the working group on ‘‘Optics and Beam Transport’’ was as follows: perform a survey of the present status of optics and beam transport issues in ERLs and make a list of unsolved problems. The ERLs to be covered include those currently in operation, currently under construction, or envisioned as a possibility for the future anywhere in the world. Special emphasis should be placed on the clear identification of the beam physics limits and accelerator technology limits and an examination of the extent that they have been addressed by past research or need to be addressed by future research. These issues should include linear optics design for the main linac section, linear optics for different ERL applications, nonlinear optics, current-dependent effects like BBU and CSR, other sources of emittance growth, halo development

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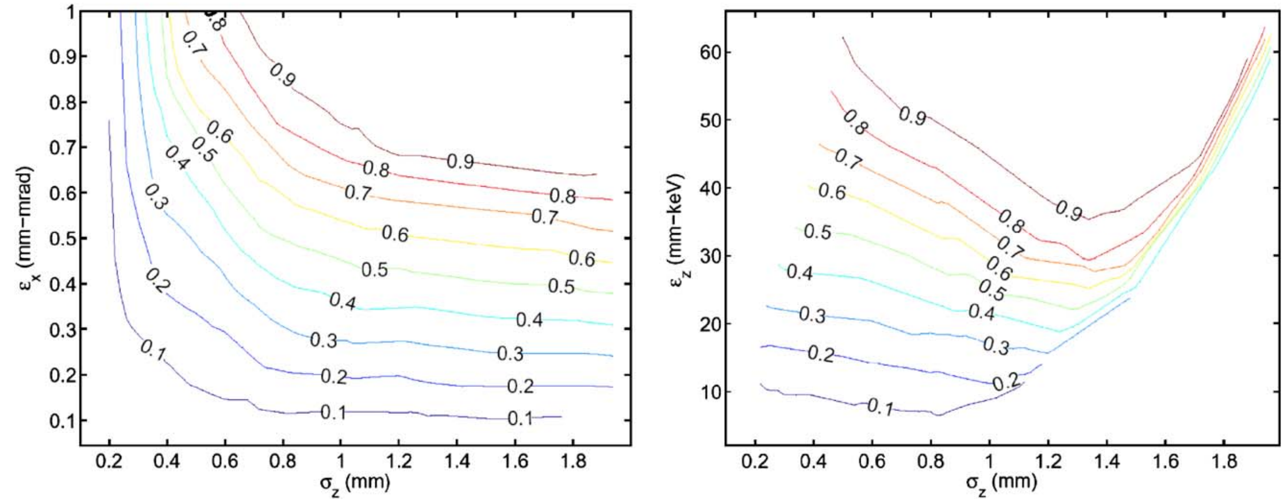

Fig. 1. Simulated small horizontal (ε_x) and longitudinal (ε_z) emittances from DC electron sources as a function of bunch length (σ_z) and bunch charge in nC as indicated at each curve.

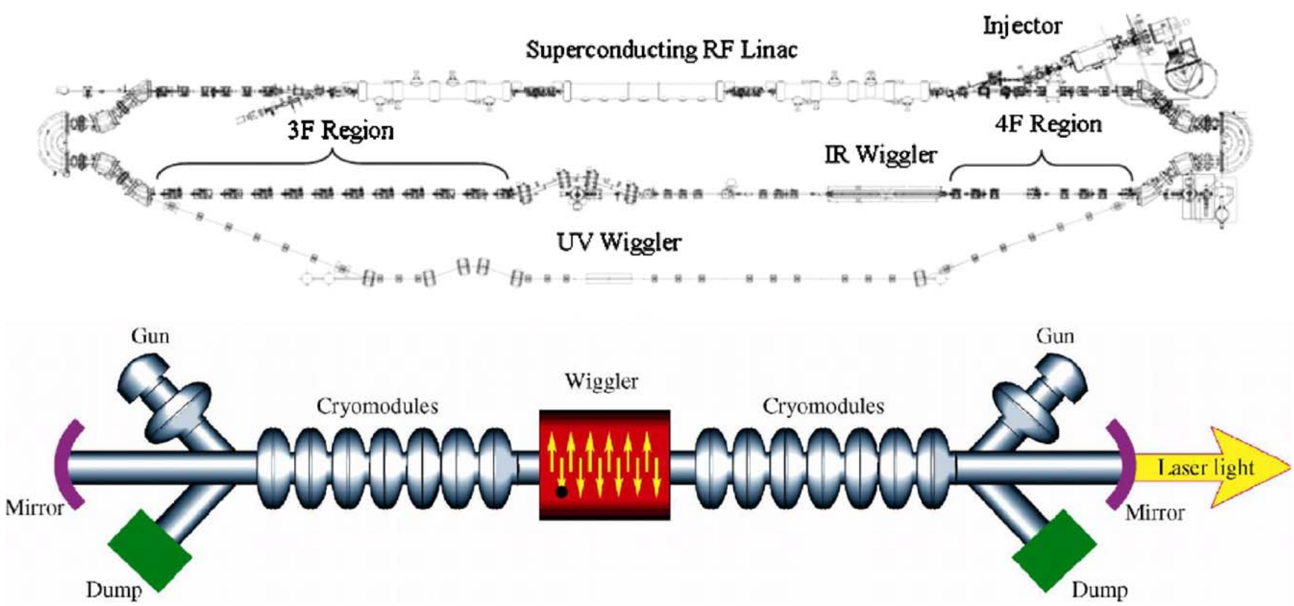

Fig. 2. Layout of the existing JLAB ERL–FEL and the proposed push–pull FEL.

and collimation, instrumentation and commissioning techniques. Identify new and promising ideas even though they may need additional work. Finally, the group should summarize in a brief report the highest priority research topics for beam transport in ERLs and provide a list of key experiments and R&D developments. The group is also asked to provide a comprehensive presentation in plenary sessions during the workshop.

2. Ongoing ERL projects

The ERL projects that were developed in recent years worldwide fall into four classes: ERLs, light sources, electron coolers, and colliding beam accelerators.

ERL–FELs: The only ERLs in operation provide beams for Free Electron Lasers (FELs). A 10 kW light beam has been produced at JLAB [2] (see Fig. 2), more than 2 kW have been produced at JAERI [3], both using superconducting RF systems. And at Novosibirsk an ERL–FEL has been constructed with normal conducting cavities. Also from JLAB comes the proposal of the push–pull FEL [4] depicted in Fig. 2 where two linacs are used, one recovering the energy of the beam that the other has accelerated and vice versa.

ERL-Light sources: Several laboratories have proposed high-power ERLs for the production of high-brightness electromagnetic radiation. Accelerators for different parameter sets and various applications are being worked on by Cornell University [5–7] (see Fig. 3), Daresbury [5,8], Argonne National Laboratory [9] (see Fig. 3), Novosibirsk [10], and KEK [11]. All of these projects had representation at the 2005 ERL workshop. Further there is a project at

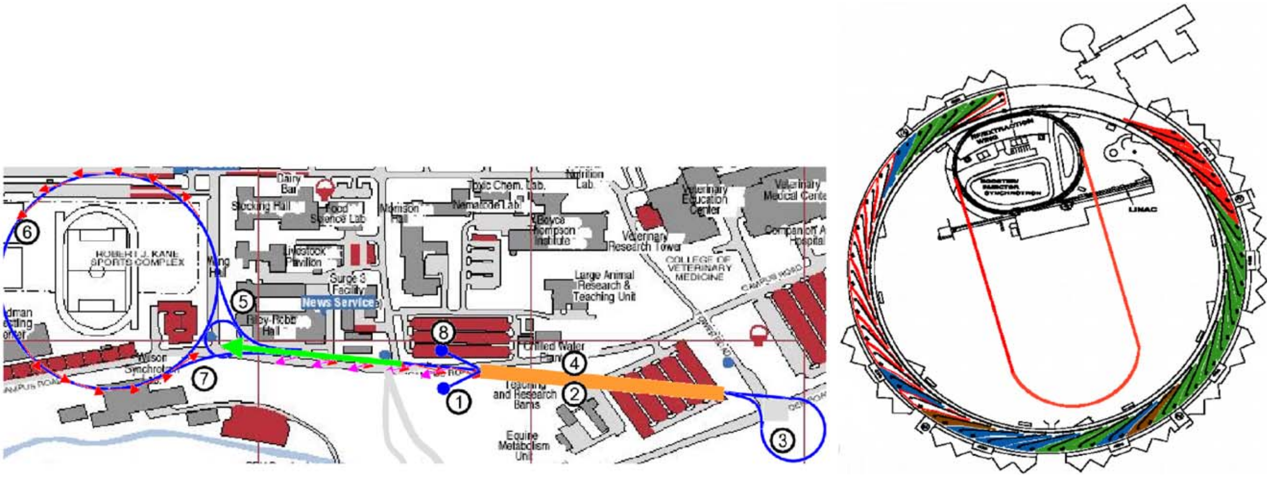

Fig. 3. Layout of the Cornell X-ray ERL, upgrading CESR, and an ERL upgrading the APS.

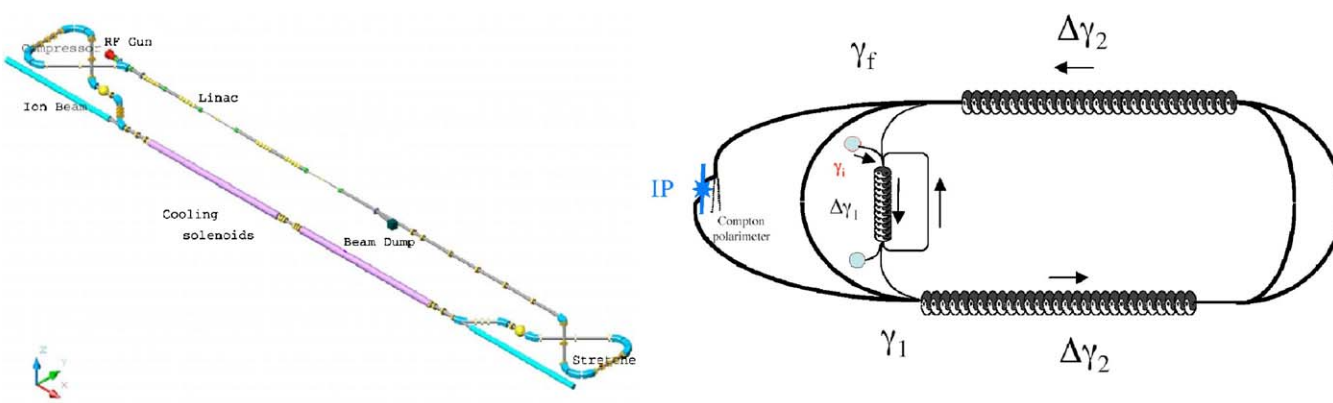

Fig. 4. Layout of an ERL for electron cooling of RHIC's ion beam and of the ERL that would provide electrons for collisions with the RHIC polarized proton and ion beams.

Saclay [12], and projects had been worked on at BNL [13] and at the University of Erlangen [14].

The Cornell and the Argonne proposals are upgrades to existing light sources. The Advanced Photon Source (APS) is a 7-GeV, third-generation synchrotron radiation facility supplying X-ray beams to approximately 50 experimental stations, which is a costly complex of facilities and equipment. In fact, the expenditure for X-ray beamlines and facilities is nearly as large as that for the accelerator itself in such modern light sources. Similarly, though on a smaller scale, CHESS at Cornell is equipped with expensive equipment and facilities which should be included in an ERL project if possible.

Electron cooling: The electron cooler that BNL is currently developing [5,15] for cooling of the ion emittances in RHIC is based on an ERL (see Fig. 4) since it would be extremely hard to provide the required current by a conventional linac. The DC electron cooler for the Recycler at FNAL was also presented during the 2005 ERL workshop since it recovers the electron energy, albeit not in a linac but in a constant voltage Pelletron, which just recently demonstrated first high-energy electron cooling results [16].

Nuclear physics ERLs: JLAB has incorporated an ERL into its design of an electron–ion collider (EIC) [17] for medium energy physics. And one version of the eRHIC collider, that is to collide 10 GeV electrons with the polarized protons and ions in RHIC is also based on an ERL (see Fig. 4) [5].

3. Emittance growth

When ERLs provide ultra-low emittances in the sub 1 mm mrad range for insertion devices that are located in the ERL's return loop, the incoherent radiation in these bends can lead to significant emittance increase. In the Cornell ERL design this emittance increase is about 100% for the ultra-low initial emittance of 0.1 mm mrad. It is therefore desirable to equip the return loop with lattices that provide for very little emittance increase. The lattices

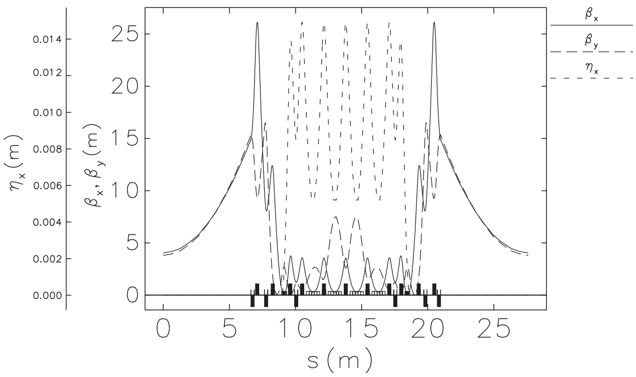

Fig. 5. Lattice functions for the XPS7 design.

of ultra-low emittance storage ring ideas are good candidates for such designs.

One such lattice was presented [18] which uses very strong permanent magnets with superimposed multipoles and correction coils to produce a very small dispersion in bends (see Fig. 5). The quadrupoles are very strong but not so high as to be obviously impossible. However, the dynamical aperture is as of yet far to small to be feasible. Furthermore, there may be stability and radiation protection issues with permanent magnets. However, such strategies would be useful to limit emittance growth when ultra-low emittances from an ERL should be transported for one turn around a return loop.

The list of other contributors to emittance growth contains alignment errors [19], coupler kicks in the linac, wake fields, ion accumulation, space-charge effects, and coherent synchrotron radiation [20].

4. Stability issues

Third-generation storage rings have reduced their emittances and therefore beam-sizes very successfully in recent years. Due to vertical beam sizes of only several micrometers, the stability requirements for these facilities are very strict. In Ref. [19] it is reported that the tolerable orbit jitter within insertion devices is only 1 μm at the SSLS. If ERLs are to be used as X-ray sources, similar stability requirements will apply, since the beams in these sources have similar dimensions, not only in the vertical, but additionally in the horizontal direction.

The electron beam that the JLAB linac supplies to its Nuclear Physics users also has to be very stable. A stabilization of routinely to 10 μm has been reported during the ERL workshop [21]. Improvements of the feedback system could however lead to a stability of about 1 μm. This has not been tested, however, since such a stability has not been required for this facility. Furthermore, while the stability at the CEBAF end-stations has been achieved, the electron beam might have significantly less stability in the recirculating linac itself. However, the stability that can be routinely achieved at the end-station should be reproducible at most locations of the accelerator. For a light source with its many insertion devices, beam stability has to be guaranteed at nearly all of the return loop. Since transverse beam oscillation stability is an essential requirement for a future X-ray beam, studies should be initiated that show that the stability requirements can be met.

5. Longitudinal phase space manipulations

In contrast to storage rings, the bunch length that ERLs can provide is quite flexible and can be below 100 fs. For FEL applications, a very high-peak current and therefore a short bunchlength is needed. Some light source applications require very short bunches to provide high time resolution in pump probe experiments. However, short bunches should be avoided within the linac to reduce higher order mode (HOM) heating. Longitudinal optics manipulations are therefore needed to obtain short pulses in the ERL return loop where the undulators are located. Fig. 6 shows this schematically for the JLAB ERL–FEL.

Longitudinal phase space manipulation uses bends as bunch compressors, or at low energy it uses drift spaces and the fact that particles with different velocities have different speeds. In Ref. [22] it is shown that even for a high-energy ERL, velocity bunching in the linac can be applied so that the bunch leaves the linac with sub ps length. Since the residual energy spread after velocity bunching can be smaller than the correlated energy spread required for magnetic compression through a recirculating loop, velocity bunching is useful to realize short pulse and high-brightness X-ray ERLs where the current is low enough so that HOM heating is not limiting.

6. BBU instability and linac optics

One important limitation to the current that can be accelerated in ERLs or recirculating linear accelerators in general is the multipass beam-breakup (BBU) instability. The size and cost of all new ERL accelerators certainly justifies a very detailed understanding of this limitation. In Ref. [23] a BBU theory for particle motion in one degree of freedom for recirculating linacs with arbitrary recirculating RF phase, i.e. also for ERLs, has been described in detail. This theory determines above what threshold current I_{th} the transverse bunch position x displays an exponential growth of oscillations. This is due to an unstable feedback from a HOM that kicks a beam so that it in turn excites that very HOM after passing around the ERL. If there is only one HOM with angular frequency ω_λ, with $(R/Q)_\lambda$ in the circuit definition (0.5 times the linac definition, units of $\Omega\mathrm{m}^{-2}$), with the quality factor Q_λ, the return time t_{r} for one turn around the ERL, and the optical matrix element T_{12} transporting transverse momenta into offsets after one turn, then this theory leads to the following approximations which are applicable in three different regimes. The number of bunches that fill the return loop is n_{r} and we use $\varepsilon_\lambda = \omega_\lambda t_b / 2Q_\lambda$.

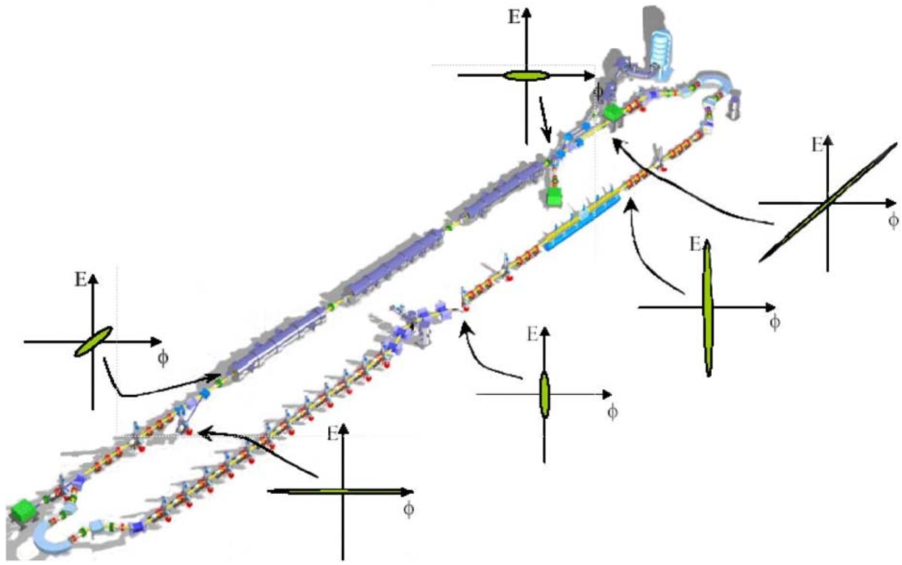

Fig. 6. Longitudinal phase-space manipulations in the JLAB FEL.

For $n_r \ll 1/\varepsilon_\lambda$ one obtains

$$I_{th} \approx \begin{cases} -\frac{\omega_\lambda}{eQ_\lambda (R/Q)_\lambda T_{12}} \frac{1}{\sin(\omega_\lambda t_r)} & \text{for } T_{12}\sin(\omega_\lambda) < 0 \\ \frac{\omega_\lambda}{eQ_\lambda (R/Q)_\lambda |T_{12}|} \sqrt{1 + \left(\frac{\mathrm{mod}\,(\omega_\lambda t_r, \pi)}{\varepsilon_\lambda n_r}\right)^2} & \text{else.} \end{cases} \quad (1)$$

For $n_r \gg 1/\varepsilon_\lambda$ but $\varepsilon_\lambda \ll 1$ the approximation derived in Ref. [23] is

$$I_{th} \approx \frac{\omega_\lambda}{eQ_\lambda \left(\frac{R}{Q}\right)_\lambda} \frac{1}{|T_{12}|}. \quad (2)$$

A theory of BBU instability in recirculating linacs, where the energy is not recovered but added in each pass through the linac was presented in Ref. [24] and lead to the first of the three specified approximation. A corresponding formula had already been presented in Ref. [25]. In Ref. [26] this first approximation has been generalized to the case of one polarized HOM with a coupled optics in 2 degrees of freedom. Occasionally, additional factors are found when this equation is stated [27–29] which would suggest that the threshold current becomes very large for long return times t_r. Since this first equation is not applicable for large t_r this suggestion is not correct, but rather Eq. (2) has to be applied which also does not have an exponential factor and which does not become large for large t_r.

A collaboration between JLAB and Cornell university has led to a comparison of beam-breakup measurements and computer simulations. The measurements are described in Ref. [30]. It has been observed that the threshold current can be predicted in cases where the accelerator is limited to currents below threshold for technical reasons. When the ERL is accelerating a current I, and a beam oscillation is excited close to a HOM frequency ω_λ, then the beam oscillates more freely if I is closer to I_{th}. It turns out that the damping of this oscillation decreases approximately linearly with $I_{th} - I$ and extrapolating the damping to zero yields the threshold current.

Similarly, if one can try to store more currant than the I_{th}, a transverse beam oscillation immediately develops. The rise-time of this oscillation is zero exactly at threshold and increases about linearly with $I - I_{th}$. Therefore, extrapolating the rise-time to zero also yields the threshold current. Both effects were observed at the JLAB FEL and modeled reasonably well, considering that the optics of the accelerator had not been measured with high precision.

Experiences with raising the threshold current of the BBU instability by stabilizing measures is reported in Ref. [30]. Fig. 7 shows four different methods that have been investigated. An active feedback on BBU, where transverse oscillations are measured at one location and minimized by a kicker at another location in the ERL, is also a feasible option that is worth further analysis and study. Some aspects of this option are mentioned in Ref. [30].

Since the beam-breakup instability is a significant thread for high-current ERLs, computer codes to determine the threshold current have been developed at several labs. Most programs are mentioned in Ref. [30]. These codes fall into two classes. Those in the first class perform tracking of charged bunches with transverse oscillations and find the current above which beam oscillations grow exponentially. For the second class of codes, the HOM fields that successive bunches excite in HOMs are summed up analytically. When the beam oscillates at a frequency ω, this leads to an analytical dispersion relation $I = f(\omega)$. The threshold current is given by the smallest real value that $f(\omega)$ can assume for real frequencies ω. This dispersion relation is solved numerically.

During the ERL workshop it was shown [30] that all of these programs agree remarkably well for cases where they are mutually applicable. While work on stabilizing BBU

		Effect on 2106 MHz HOM	Considerations for Implementation
Q-Damping	Damping Circuit	$5 \times I_{th}$	• Works for only *1 mode per cavity* • Not as effective at raising the threshold as beam optical methods
	3-Stub Tuner	$1.5 \times I_{th}$	• Long term stability of system • Does **not** effect beam optics
Beam Optics	Phase Trombone	*Stabilized*	• Can *stabilize* the mode against BBU • What are the effects on other HOMs?
	Pseudo-Reflector	*Stabilized*	• Do they prevent reaching the requirements needed for a suitable lasing configuration?

Fig. 7. Experience with methods of BBU stabilization.

and optimizations of optics for large threshold currents is to be encouraged, the state of codes is quite satisfactory already. However, it should be noted that the optics at the lower energy sections of the ERL determines the BBU threshold most strongly. At low energies the cavity focusing is most relevant and therefore has to be understood completely. Currently, computed and measured optics within low-energy cavities do not seem to agree sufficiently well.

7. Accelerator modeling

In high-energy and nuclear physics accelerators as well as in light source facilities, accelerator modeling has developed to a very high level in recent years. Programs are available that perform optics simulations to various degrees of accuracy, simulate orbit and magnetic field errors, and take into account various beam dynamics effects like coherent synchrotron radiation and space-charge forces. Some of these accelerators have control systems that are closely connected to the accelerator modeling software. A similar step has been taken for the JLAB FEL–ERL, where the simulation program that controls CESR at Cornell University [33] has been adopted to automatically read out the accelerator state of the FEL and to simulate its optics, and its beam-breakup instability current. Beam position data measured at the ERL–FEL are used to refine the optics model and consistency checks allow to locate monitor errors. With this model of the coupled optics, high-precision beam-breakup instability studies including the polarization direction of each HOM become possible.

8. Merger design

Every ERL needs a merger between the injection linac and the ERL, and each project has its own proposal. These proposal fall into two classes: a three bend achromat that puts the injector linac at an angle with the ERL [31], and a four bend achromat that puts the injection linac in line with the ERL [32]. The four bend achromat has the advantage that it is not only achromatic but compensates the part of the phase space focusing that is linear in the longitudinal coordinate τ. The space-charge-driven emittance increase is therefore reported to be significantly smaller in this layout. Since the four bend merger requires the injector to be in line with the ERL, it is hard to bring the high-energy beam into the linac without infringing on the injector linac. Further analysis is needed to decide which merger design is best for each proposed ERL application.

9. Halo formation

The formation of a large amplitude beam halo in a high-current ERL poses several severe problems. It can create dark current, it can radiate, activate and heat material, notably superconducting structures, it can lead to background radiation in the experiments, and it can produce emittance dilution. In Ref. [34] mechanisms that lead to halo formation in hadron beams are described and it is analyzed which of these mechanisms will also apply to electron ERLs. It is pointed out that in ERLs there are two different regions. The first contains the photo injector where the beam is initially fully space-charge dominated, but resonances which for proton beams lead to halo formation do not have time to build up due to rapid acceleration. An effect that remains in this region is the dynamics due to nonlinear time-dependent RF fields.

The second region contains the rest of the ERL which has emittance dominated beam dynamics, where halo formation is usually small. But for the high beam densities of a ultra-low emittance beam, Coulomb scattering becomes relevant. This leads to particle loss in the energy phase space due to single and multiple scattering events, i.e. the Touschek effect and intrabeam scattering. Furthermore, the nonlinear forces from Coherent synchrotron radiation could transport particles to large amplitudes.

This field of halo formation due to beam dynamics clearly needs more study. However, there are other sources of beam halo that are not related to beam dynamics. Examples are a defocused laser spot on the cathode due to light scattering in the laser optics or diffusion of electrons in the cathode's conduction band. Experiments and analysis is needed here in collaboration with laboratories that operate photo-cathode sources.

10. Space charge and CSR calculations

Space-charge effects are strongest in the source and injector region and have been stressed in the working group on "Electron Guns and Injector designs". However, longitudinal space charge (LSC) can be important up to energies of many 10 MeV and it is therefore an effect that should be understood in existing FELs and should be analyzed for every new design.

Coherent synchrotron radiation is an effect that also stems from the charge distribution of the bunch and is therefore a form of space charge. Accurate computer codes should therefore take both effects into account. In Ref. [9] a simulation of CSR is described for a bunch that travels from an ERL once around the APS. The evolution of the longitudinal phase space is shown in Fig. 8. A classic CSR-wake shape can be seen, where the head of the bunch is accelerated while the center and tail are decelerated. Due to the momentum compaction of the lattice, the head falls back and the tail moves forward, creating a region of higher current near the center of the bunch. This leads to even stronger CSR effects, resulting in a folded longitudinal distribution and in the appearance of charge lumps. It seems likely that if the initial phase space were not Gaussian, much more serious effects would arise, including the micro-bunching instability.

Coherent synchrotron radiation has been a field of intense study in recent years since bunch compressors for FEL and SASE FEL projects require very short bunches which can produce a destructive amount of coherent synchrotron radiation. In Ref. [20] the major codes that treat CSR are compared and their approximations are mentioned. In Fig. 9 from [35] the energy loss and the energy spread as well as the transverse emittance growth after a bunch compressor is compared for different codes. The agreement is very reasonable, considering that all codes use very different formalisms and approximations. However, since the approximations are either very severe, or only very few particles are used to create the CSR fields,

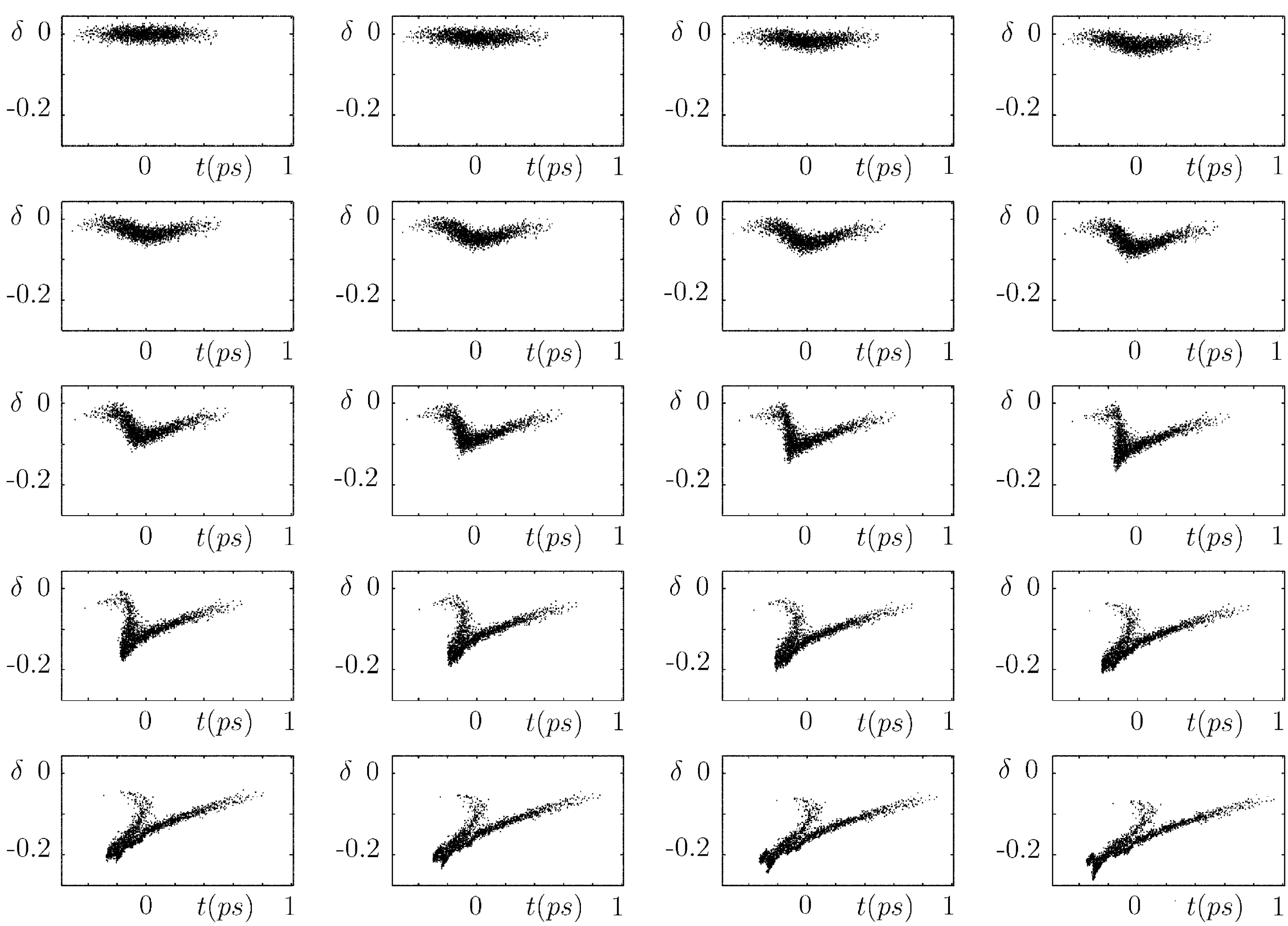

Fig. 8. Longitudinal phase space at the center of every other straight section in an APS lattice, assuming 100 pC, 50-μm initial rms bunch length, 0.01% initial rms momentum spread, and 1-μm initial normalized emittance [9].

	3D	δE	σE	ε
3D	TRAFIC4	-0.058	-0.002	1.4
	TREDI	-0.018	-0.001	1.85
2D	Program by R.LI	-0.056	-0.006	1.32
1D	Elegant	-0.045	-0.0043	1.55
	CSR_CALC	-0.043	-0.004	1.52
	Program by M. Dohlus	-0.045	-0.011	1.62

Fig. 9. Results obtained with different CSR codes for the same bunch compressor.

work on more accurate computational tools would still be very welcome.

11. Collaborations

Since the many mentioned laboratories are working on ERL projects, a strong synergy of collaborations can be expected. In Ref. [36] the EUROFEL collaboration is described and some aspects of it can inspire collaboration on ERL-related issues.

The areas of collaboration for several different FEL projects between 18 European laboratories lead by DESY in Hamburg are:

- DS 1: Photo-Guns and Injectors;
- DS 2: Beam Dynamics;
- DS 3: Synchronization;
- DS 4: Seeding and Harmonic Generation;
- DS 5: Superconducting CW and Near-CW linacs;
- DS 6: Cryomodules Technology Transfer.

As a start of collaboration on optics and beam transport in ERLs one can mention the JLAB/Cornell work on BBU, and the preparation of articles for the ERL05 workshop. The following papers were prepared as a multi-lab collaboration, rather than as individual contributions corresponding to individual talks: on the optics of different ERL projects [5], on BBU theory and observations [30], on all major CSR codes [20], and on ion clearing in ERLs [37]. For light-source ERLs, ion gaps are problematic since users want to avoid gaps in the beam and since problematic transient RF effects in the main linac, the injector linac, and the electron source can be dangerous.

12. Summary of recommended studies

As mentioned throughout this article, the working group on "Optics and Beam transport" in the 2005 ERL workshop encouraged further research in the following initial areas:

- transverse beam stability;
- beam loss and halo formation in ERLs;
- CSR and LSC suppressing designs;
- completion of beam-breakup instability tests;
- ion clearing in ERLs;
- experimental verification of RF optics;
- studies of limits to multi-turn ERLs.

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