OVERVIEW OF ENERGY RECOVERY LINACS

Ivan V. Bazarov, LEPP/CHESS*, Cornell University, Ithaca, NY 14853, USA

Abstract

Existing Energy Recovery Linacs (ERLs) are successfully operated as kW-class average power infrared Free Electron Lasers (FELs). Various groups worldwide actively pursue ERLs as a technology of choice for a number of new applications. These include high brilliance light sources in a wide range of photon energies utilizing both spontaneous and FEL radiation production techniques, electron cooling of ion beams, and ERL-based electron-ion collider. All of these projects seek in various ways to extend performance parameters possible in ERLs beyond what has been achieved in existing relatively small scale demonstration facilities. The demand is for much higher average currents, significantly larger recirculated beam energies and powers and substantially improved electron sources. An overview of the ongoing ERL projects will be presented along with the summary of the progress that is being made in addressing the outstanding issues in this type of accelerators.

INTRODUCTION

The idea of energy recovery is not new [1]. The first demonstration of energy recovery using superconducting linac took place at HEPL facility nearly two decades ago [2]. However, it was not until successful operation of TJNAF DEMO-FEL [3] that the interest of various groups worldwide was spurred to serious pursuit of ERL technology for new applications.

ERLs seek to obtain much higher average currents than what otherwise is available from linear accelerators. By decelerating the high energy beam in the same (superconducting) RF linac which is used for acceleration, one achieves essentially zero loading from the two beams, leading to dramatic reduction in necessary installed RF power and beam dump energy, as well as much higher average current than what otherwise is available without energy recovery. Unlike the storage rings, ERL does not recycle electrons, but rather their energy, and electrons spend at most few turns ($\leq$ few μs) in ERL. In this respect, ERLs are very much like conventional linacs meaning that the properties of "short-lived" electrons are primarily determined by the electron source and not by lattice equilibrium as in the storage rings.

PARAMETER SPACE

Since there are proposals to use ERLs for very different applications, the goal parameter space is quite diverse. Multi-GeV machines are envisioned for hard x-ray production and electron-ion colliders, while energies of $\leq$ 100 MeV are adequate for long ($\geq$ μm) wavelength oscillator FELs and electron coolers of ions.

Light sources

Here, the important considerations are the wavelength of radiation and light production technique to be employed.

FELs. Lasing on free electrons is an efficient way for light production but also the one that can impose strict demands on electron beam in the 6-dimensional phase space.

In the infrared spectral region, the availability of high reflectivity mirrors allows oscillator FEL configuration. This low-gain regime uses short wigglers, which leads to relaxed energy spread requirement $\Delta E/E \leq 1/4N_p$, while the relatively long wavelength of light makes achieving the diffraction-limited electron beam ($\epsilon_{x,y} \leq \lambda/4\pi$), e.g. 0.25 % rms energy spread and 13 mm-mrad normalized rms emittance was required for 40 MeV TJNAF DEMO-FEL to lase at 3 μm wavelengths and longer [4]. Since the lasing gain is proportional to electron peak current, the FELs benefit from subsequent bunch compression following the injector, making longitudinal emittance an important consideration due to relatively low full to injection energy ratio ($\leq$ 10). High average power FELs ($\sim$100 kW) require beam currents of 100 mA and higher. All of these parameters, with the exception of the high average current, have been already demonstrated by the existing ERL-FELs. 20 mA has been demonstrated at BINP FEL without lasing, and 9.1 mA was achieved at TJNAF FEL upgrade.

As the wavelength of the desired radiation becomes shorter, the requirements on electron beam become correspondingly more stringent. Single pass high-gain operation demands high peak currents ($\sim$kA) simultaneously with low energy spread ($\sim 10^{-4}$) and small transverse emittance [5]. For example, 4GLS at 700 MeV requires 3 mm-mrad or better rms normalized emittance, 1.5 kA peak current and $< 10^3$ rms energy spread to achieve lasing at the proposed 100 eV [6]. These single bunch requirements are no different than those for low repetition rate high-gain FELs. Because of high efficiency of the lasing process, the FELs operating in XUV/soft/hard x-ray regions are less likely to depend on high average current. In short, XUV/soft/hard x-ray ERL-FELs would require high beam energies ($\geq$ GeV) and demanding single bunch qualities, whereas already demonstrated average currents are most likely sufficient for future short wavelength ERL-FELs.

Light Sources Using Spontaneous Emission. The 3$^{\rm rd}$ generation light sources demonstrate diffraction-limited vertical emittance, while the horizontal emittance is few

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nm-rad. Further decrease in horizontal emittance is challenging, although new lattice designs that would reduce the emittance to below 1 nm-rad are possible [7]. Comparing a generic state-of-the-art storage ring (SR) light source with 200 mA average current, horizontal emittance of 3 nm-rad, and decoupling of 200 suggests that e.g. a 5-GeV ERL with injector normalized emittance of 1.5 mm-mrad and 100 mA current would perform similarly in terms of x-ray brilliance, assuming undulator with the same number of periods. In addition, ERL is capable of smaller energy spread ($\sim 10^{-4}$ vs. $\sim 10^{-3}$ in the SR), which means a longer undulator will be more efficient due to higher electron monochromaticity. Since the space charge effect in the injector is likely to be the dominant phenomenon in the ERL (e.g. $\epsilon_{x,y} \propto q$), better x-ray brilliance can be expected at somewhat reduced beam current. The ultimate goal for a 5-GeV ERL light source of hard x-rays would be achieving 0.01 nm-rad, or 0.1 mm-mrad normalized rms emittance from the electron source with subsequent emittance preservation downstream of the injector. In short, ERL light source (e.g. 5 GeV) using spontaneous emission needs normalized emittance of ≤ 1 mm-mrad at 100 mA, and ultimately a diffraction-limited emittance (0.1 mm-mrad) at a maximum beam current.

Short pulses (~ 0.1 ps) will be readily available from ERL for pump-probe experiments. This opens new possibilities for time-resolved experiments than what is possible with SR-based light sources. This case, however, will most likely require a special operating mode at a reduced bunch repetition rate (∼MHz) and higher charge per bunch (∼nC) to match the pumping laser pulse frequency and reduce resistive wake heating problems in the insertion devices, and will have an increased energy spread and transverse emittance than in the mode optimized for high brilliance.

Electron-Ion Colliders

Two laboratories (BNL [8] and TJNAF [9]) are seriously looking as an alternative to the ring-ring scenario into a high luminosity electron-ion collider with polarized electrons produced by an ERL with energy between 2 to 10 GeV. There are several advantages to this approach including better handling of electron polarization and potentially higher luminosity due to absence of beam-beam tune shift limit for electron beam. The principle technology challenge to an ERL-based electron-ion collider is in generating high average current polarized electrons (several 100s mA, while the highest demonstrated polarized electron beam current is 1 mA). Introduction of a circulator ring where injected electrons would stay for ∼100 turns seeks to relax this requirement [10].

Electron Cooling

To achieve high luminosity, future electron-ion colliders look into implementing electron cooling of ion species. The reduction in both transverse and longitudinal emittances from electron cooling will also benefit the existing RHIC [11]. While operating at a low beam energy (∼50 MeV) to match velocity of ions, electron coolers require very high charge per bunch ($\geq$ 10 nC) and high average current (100s mA) to achieve the desired cooling rate. Normalized rms emittance is specified to be 50 μm or less.

EXISTING ERLS

All of the existing operational ERLs are (far) infrared FELs. A brief summary of their demonstrated performance and planned upgrades is provided.

TJNAF ERL-FEL

Following successful operation of DEMO-FEL [3], TJNAF has completed an upgrade to their infrared FEL [12]. Installation of an additional cryomodule allowed 160 MeV maximum electron energy. During its operation the FEL has demonstrated over 8.5 kW of continuous power output at 5.7 μm, 10 kW for 1 second long pulses, and CW recirculated electron beam power of 1.1 MW. The photoinjector has delivered up to 9.1 mA of average current at 7 mm-mrad normalized rms emittance from a DC photoemission gun operated at voltage of 350 kV.

Future plans include lasing in UV in the short term as well as construction of new injector capable of producing 100 mA average current.

JAERI ERL-FEL

JAERI FEL has operated with energy recovery at 5 mA beam current in a 1 ms macropulse with 10 Hz repetition rate [13]. The electron injector consists of 230 kV thermionic gun equipped with a grid pulser, providing 0.5 nC, 20 mm-mrad normalized rms emittance bunches with 10 MHz micropulse repetition rate. The injection and full energies of the machine are 2.5 and 17 MeV, respectively.

Several upgrades are underway to allow for long pulse / higher duty cycle operation, which are presently limited by the installed refrigerator capacity. The new improved gun presently allows 10 mA current beams [14].

BINP Accelerator-Recuperator FEL

Unlike the previous two accelerators, BINP's accelerator-recuperator FEL is using normal conducting RF with low frequency of 180 MHz and accelerating voltage of 0.7 MV per cavity. Thermionic gun injector produces 1.5 nC bunches with normalized rms emittance of 30 mm-mrad. Injection energy is 2 MeV and the full energy is 12 MeV. The accelerator has demonstrated 20 mA average current with energy recovery, while routine operations with lasing occur at 5 mA. 0.2 kW of radiation 0.12-0.18 mm wavelength has been measured [15].

Future upgrade plans include 4-orbit accelerator-recuperator with a maximum energy of 50 MeV and average current of 150 mA. The estimated power of FEL radiation is 10 kW at 3-20 μm wavelength.

NEW ONGOING PROJECTS

In addition to the planned upgrades to the existing ERL-FELs, several laboratories have begun addressing various outstanding issues by constructing new demonstration facilities. The new applications for ERLs being carefully looked into include hard x-ray light source (Cornell University), electron cooling of ions (BNL) and high-power VUV/XUV spontaneous and FEL light production (Daresbury).

Cornell Prototype

Realizing that the beam quality from the injector is the key factor to a future ERL-based x-ray light source, Cornell University, in collaboration with TJNAF, is building a high average current high brightness electron source. The project consists of very high voltage (500-750 kV) photoemission gun, which is a part of the injector capable of accelerating the beam to 15 MeV maximum energy through five 2-cell SRF cavities [16], merger section and the beam dump [17]. Maximum average current will be 100 mA. The project emphasizes very low emittance beam (1 to 0.1 mm-mrad) at a moderate bunch charge (0.1 to 0.01 nC).

BNL Prototype ERL

To address the R&D issues of the RHIC-cooler project, BNL is constructing a high current (up to 0.5 A) low energy ERL (20 MeV) [18, 19]. BNL Prototype ERL emphasizes high average current, high bunch charge (up to 20 nC) – a requirement for efficient cooling of ions. The accelerator will consist of 2 MV SRF gun, a cryomodule containing 703.75 MHz 5-cell SRF cavity optimized for high average current operation, recirculating loop and the beam dump. Since the single bunch parameter needs are dictated by electron cooling considerations, the bunch length is relatively long (5 cm rms for 20 nC) and normalized rms emittance is ∼30 mm-mrad (∼3 mm-mrad for 1.3 nC bunches).

Daresbury ERL-P

ERL-P at Daresbury is a 35 MeV demonstration facility with a primary goal of developing in-house expertise in several important to ERLs areas, such as superconducting RF, high average current photoinjectors, FEL operation, prior to developing technical design report for the 4GLS light source. For details of the project, refer to [20].

ACCELERATOR PHYSICS AND TECHNOLOGY CHALLENGES

While the interest in ERLs as a technology of choice for various future applications is clearly on the rise [22], a number of important accelerator physics challenges must be addressed before many of the proposed ERLs can be realized. This section goes through several of these challenges emphasizing most promising solutions and recently made progress.

High Current Low Emittance Injector

At the moment, it is widely believed that photoemission guns hold the best promise as low emittance high current sources. Three different gun types (DC, RF and SRF) and their variations are being pursued for ERL applications. All three gun types share a common challenge of demonstrating sufficient lifetime robust operation of the photocathode. High quantum efficiency materials, such as Cs:GaAs and $\mathrm{CsK_2Sb}$, will be used. While previous experience with these photocathodes suggests that sufficiently long operational lifetimes with high current operation are possible, care to many technical details is necessary to realize this in practice [23]. A possibility of using secondary emission from diamond as a means of amplifying photoemitted electrons to ease laser system requirements and photocathode lifetime issues is also being explored [24].

Emittance compensation in the injector is of critical importance in a wide range of bunch charges for future ERLs. Very promising results have been recently obtained through computer optimizations of Cornell DC gun photoinjector [25], showing that very high degree of space charge emittance compensation is possible in this type of injector in a wide range of bunch charges (e.g. 0.1 mm-mrad emittance for 0.1 nC charge, 0.7 mm-mrad for 1 nC).

ERLs benefit from having as small injection energy as practically possible to minimize the amount of power going to the beam dump. Thus, the space charge remains important in the section of ERL that merges the high and low energy beams. A merger design was shown to be possible, which is compatible with emittance compensation in the presence of dipole magnets required to inject the beam into the main linac [26].

Main Linac: SRF Technology

The SRF linac will be at the heart of most future ERLs. Despite much progress in the SRF technology over the last decade, much remains to be done to make efficient, turn-key, high current multi-GeV ERLs a reality.

Since the power bill of a large SRF ERL will be dominated by cryogenic requirements, reliably achieving as high Q_0 as possible for medium gradients (15-20 MV/m) in field emission free cavities is desirable. A potential increase in Q_0 from 10^{10} to 2×10^{10} would result in several MW power savings for 2 K refrigerator. This issue also touches on the choice of optimal cryogenic temperature, good magnetic shielding, appropriate cavity treatment, etc. TJNAF is working on *Renascence* cryomodule for CEBAF 12 GeV upgrade [27] that will come closest in terms of average gradient and Q_0 requirements for efficient CW operation desired for ERLs.

In the main linac, the required peak drive power is proportional to the peak microphonic detuning, Δf, for optimized loaded $Q_{\mathrm{L,opt}} = f_0/2\Delta f$, which makes the design of low microphonics stiff cavities an important priority. When microphonics is sufficiently low, however, one's ability to operate at high Q_{L} will depend on high performance of RF control system. Such control system was developed by Cornell University and has been tested at TJNAF ERL-FEL [28]. An SRF cavity was operated with $Q_{\rm L}$ of 1.2×10^8 with 2×5.5 mA average current in energy recovery mode, with the beam taking and returning 47 kW RF power, while the required klystron power remained at about 200 W level. This important demonstration shows that it is possible to dramatically reduce capital and operational cost in ERLs through a combination of low microphonics and high performance RF control system.

Achieving adequate higher order modes (HOMs) damping is another critical requirement in ERLs. Primary dipole modes need Q's of less than 10^4, and to avoid excessive heat deposition of resonant excitation the primary monopole modes need Q's of $\sim 10^3$. Furthermore, with HOM power per cavity integrated over all frequencies easily exceeding 100 W for most proposed ERLs, one cannot afford uncontrolled dissipation of this power in the cryogenic environment. HOM ferrite absorbers that intercept this undesired power and remove it from liquid He temperature environment are being implemented with SRF cavities to address this issue [29, 30].

Emittance Preservation

Quantum excitation due to spontaneous synchrotron radiation emission at multi-GeV energies is well understood and does not appear to be a limiting phenomenon in ERLs, although requires a certain degree of attention for high energy ($\geq$5 GeV) ERLs [31].

Single bunch effects, such as coherent synchrotron radiation, wake fields, RF input coupler kicks, emittance growth due to misalignments, are common challenges for both ERLs and low average current linacs. An important consideration here is that in certain cases, such as x-ray ERL light source, there will be no need to push for fs pulses when maximizing brilliance of the radiation. The peak currents then are on the order of 10 A, similar to SR values, minimizing the coherent single bunch effects. The short bunch mode with magnetic compression, on the other hand, makes coherent single bunch effects an important concern. It should also be noted that when significant energy spread is present (either correlated for bunch compression or uncorrelated e.g. due to FEL interaction), higher than the linear order optics becomes important for successful energy recovery [32], as well as to minimize chromatic blow up to the beam effective emittance [33].

Beam Stability

BBU. Multipass regenerative beam break-up (BBU) has been identified for a long time as a potential limiting phenomena in recirculating accelerators [34]. Several laboratories have developed new codes to simulate the instability [35] and excellent agreement exists between the theory and simulations [36]. An important series of measurements have been recently carried out at TJNAF ERL-FEL [37], and a few percent agreement between simulations and actual beam measurements was demonstrated. Several ways to increase the threshold have been experimentally verified. In particular, optical coupling was found [38] to be very effective to substantially increase (factor of $\sim$200) the threshold for poorly damped ($Q > 10^6$) polarized HOMs [39]. It is shown, however, that the effectiveness of coupling is reduced as Q of the modes becomes lower ($I_{\rm th,coupled} \propto 1/\sqrt{Q}$); e.g. an increase in the threshold for large ERLs (multiple GeV) with well damped HOMs ($Q < 10^4$) is only a factor of 2-4 larger due to introduction of coupling in the lattice, as compared to the decoupled case [40]. Nonetheless, it is now established by simulations that through a combination of better HOM damping, proper focusing optics in the linac, and coupling, it is possible to design a single-recirculation multi-GeV ERL with BBU threshold in the vicinity of 1 Ampere.

Orbit and Energy Stability. To utilize ultra-small beam emittance in ERLs, it will be necessary to stabilize beam position with remarkable precision. E.g. for a future hard x-ray light source, one is looking into having a diffraction-limited electron beam, or 0.01 nm-rad emittance in *both* vertical and horizontal planes. This translates into a sub-micron stability requirement. As an example, the fast feedback on the beam at CEBAF routinely achieves 20 μm rms [41], which is limited by BPM noise. Implementation of fast orbit feedback in SR light sources has resulted in sub-micron level stability in a frequency range up to 100 Hz [42]. Similar or better performance will be needed in the ERL light source, which will require careful tolerance management and implementation of slow and fast feedbacks.

In addition, high stability in RF field amplitude and phase is desired. The newly developed Cornell low level RF control system has demonstrated 10^{-4} field and $0.02°$ phase stability in the presence of 5.5 mA energy recovered beam [28].

Diagnostics and Instrumentation

Diagnostics and instrumentation poses several challenges unique to ERLs. One such example is a development of robust and easily read out non-interceptive beam profile (transverse and longitudinal) measuring techniques in the context of very low emittances, short duration pulses at high average beam power.

Machine protection in the presence of continuously replenished high power beam also poses specific challenges: good characterization of beam halo, its source, and its minimization will be critical [43].

SUMMARY

The next few years will witness a considerable progress in the field of ERLs, as both existing and new projects continue to expand the parameter space and improve the performance of this class of accelerators. Following the demonstration stage, one ought to expect proposals for im-

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proved / larger scale ERLs to meet new kinds of applications in addition to already existing ERL-FELs.

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REFERENCES

[1] M. Tigner, "A Possible Apparatus for Electron-Clashing Experiments", Nuovo Cimento, Vol 37 (1965) 1228-1231

[2] T.I. Smith et al., "Development of the SCA/FEL for Use in Biomedical and Materials Science Research", NIM A, Vol 259 (1987) 1-7

[3] G.R. Neil et al., "Sustained Kilowatt Lasing in a Free-Electron Laser with Same-Cell Energy Recovery", PRL, Vol 84 (2000) 662-665

[4] D.D Douglas, "The Jefferson Lab 1 kW IR FEL", Proc. of LINAC 2000, pp. 716-720

[5] e.g. see A. Renieri, "Linac-Based Short Wavelength FELs", Proc. of EPAC 1996, pp. 105-109

[6] T. Neil (Daresbury), private communication

[7] e.g. see A. Ropert, "Prospects for a Long-Term Lattice Upgrade at the ESRF", Proc. of EPAC 2004, pp. 2344-2346

[8] V. Ptitsyn et al., "eRHIC, a Future Electron-Ion Collider at BNL", Proc. of EPAC 2004, pp. 923-925

[9] Ya. Derbenev et al., "Electron-Ion Collider at CEBAF: New Insights and Conceptual Progress", Proc. of EPAC 2004, pp. 893-895

[10] L. Merminga et al., "ELIC: an Electron-Light Ion Collider Based at CEBAF", Proc. of EPAC 2002, pp. 203-205

[11] I. Ben-Zvi et al., "R&D Towards Cooling of the RHIC Collider", NIM A, Vol 532 (2004) 177-183

[12] S.V. Benson et al., "High Power Lasing in the IR Upgrade FEL at Jefferson Lab", Proc. of FEL 2004, pp. 229-232

[13] M. Sawamura et al., "Status and Development for the JAERI ERL-FEL for High-Power and Long-Pulse operation", Proc. of EPAC 2004, pp. 1723-1725

[14] R. Hajima et al., "Recent Results of the JAERI Energy-Recovery Linac FEL", Proc. of FEL 2004, pp. 301-303

[15] N.A. Vinokurov et al., "Status of the Novosibirsk Terahertz FEL", Proc. of FEL 2004, pp. 226-228

[16] M. Liepe et al., "Design of the CW Cornell ERL Injector Cryomodule", these proceedings

[17] C.K. Sinclair et al., "Design for a 1.3 MW, 13 MeV Beam Dump for an Energy Recovery Linac", these proceedings

[18] V.N. Litvinenko et al., "High Current Energy Recovery Linac at BNL", Proc. of FEL 2004, pp. 570-573

[19] V.N. Litvinenko et al., "High Current Energy Recovery Linac at BNL", these proceedings

[20] M.W. Poole and E. Seddon, "4GLS and the Energy Recovery Linac Prototype Project at Daresbury Laboratory", these proceedings

[21] 1st International ERL ICFA Workshop, Newport News, VA (2005) http://www.jlab.org/intralab/calendar/archive04/erl/

[22] In support of this claim, the author points out that the 1st International ERL ICFA Workshop [21] has reflected high level of interest towards the subject in the accelerator physics community with over 150 participants from more than 20 laboratories worldwide.

[23] e.g. for technical challenges of DC guns see C.K. Sinclair, "Very High Voltage Photoemission Electron Guns", Proc. of PAC 2003, pp. 76-80

[24] I. Ben-Zvi et al., "Secondary Emission Enhanced Photoinjector", Accelerator Physics Note C-A/AP/149, BNL 2004

[25] I.V. Bazarov and C.K. Sinclair, "Multivariate Optimization of a High Brightness DC Gun Photoinjector", PRST-AB, Vol 8 (2005) 034202

[26] D. Kayran et al., "Optics for High Brightness and High Current ERL Project at BNL", these proceedings

[27] C.E. Reece et al., "Fabrication and Testing of the SRF Cavities for the CEBAF 12 GeV Upgrade Prototype Cryomodule Renascence", these proceedings

[28] M. Liepe et al., "Pushing the Limits: RF Field Control at High Loaded Q", these proceedings

[29] M. Liepe et al., "Design of the CW Cornell ERL Injector Cryomodule", these proceedings

[30] R. Calaga et al., "High Current Superconducting Cavities at RHIC", Proc. of EPAC 2004, pp. 1120-1122

[31] e.g. see Eds. S.M. Gruner, M. Tigner, "Study for a proposed Phase I ERL synchrotron light source at Cornell University", CHESS Tech.Mem. 01-003, 2001

[32] P. Piot, et al., "Longitudinal Phase Space Manipulation in Energy Recovering Linac-Driven Free-Electron Lasers", PRST-AB, Vol 6 (2003) 030702; I.V. Bazarov and G.H. Hoffstaetter, "Lattice Options for a 5 GeV Light Source at Cornel", Proc. of PAC 2003, pp. 842-844

[33] G. Hoffstaetter, et al., "Status of a Plan for an ERL Extension to CESR", these proceedings

[34] J.J. Bisognano and R.L. Gluckstern, "Multipass Beam Breakup in Recirculating Linacs", Proc. of PAC 1987, pp. 1078-1080; G.A. Krafft and J.J. Bisognano, "Two Dimensional Simulations of Multipass Beam Breakup", Proc. of PAC 1987, pp. 1356-1358

[35] M. Sawamura, "BBU Codes Overview", Proc. of ERL 2005 ICFA Workshop [21]

[36] B.C. Yunn, "Beam Breakup in Recirculating Linacs", Proc. of PAC 1991, pp. 1785-1787; G.H. Hoffstaetter and I.V. Bazarov, "Beam-breakup Instability Theory for Energy Recovery Linacs", PRST-AB, Vol 7 (2004) 054401

[37] C. Tennant et al., "Experimental Investigation of Beam Breakup in the Jefferson Laboratory 10 kW FEL Upgrade", these proceedings

[38] Rand R., Smith T., "Beam Optical Control of Beam Breakup in a Recirculating Electron Accelerator", Particle Accelerators , Vol II (1980) pp. 1-13

[39] C. Tennant et al., "Suppression of Multipass, Multibunch Beam Breakup in Two Pass Recirculating Accelerators", Proc. of FEL 2004, pp. 590-593

[40] G.H. Hoffstaetter et al., "Recirculating BBU Thresholds for Polarized HOMs with Optical Coupling", to be submitted to PRST-AB

[41] G.A. Krafft et al., "Measuring and Controlling Energy Spread in CEBAF", Proc. of LINAC 2000, pp. 721-725

[42] T. Schilcher et al., "Commissioning and Operation of the SLS Fast Orbit Feedback", Proc. of EPAC 2004, pp. 2523-2525

[43] W. Graves et al., "Synchronization, Diagnostics and Instrumentation Working Group Summary", Proc. of ERL 2005 ICFA Workshop [21]; P. Piot, "Diagnostics and Synchronization: Emphasis on ERL", ibid.