PHYSICS CHALLENGES FOR ERL LIGHT SOURCES*

Lia Merminga#, Jefferson Laboratory, Newport News, VA 23606, USA

Abstract

We present an overview of the physics challenges encountered in the design and operation of Energy Recovering Linac (ERL) based light sources. These challenges include generating a low emittance, high-average current beam, preserving its transverse and longitudinal phase space during acceleration and energy recovery, and dealing with high peak and average current effects in superconducting RF systems. These key R&D issues drive the design and technology choices for future ERL light sources. Simulations and calculations of these processes are presented and compared with experimental data obtained at the Jefferson Lab Free Electron Laser (FEL) Upgrade, a 10 mA ERL light source presently in operation, and during a 1 GeV demonstration of energy recovery at CEBAF.

INTRODUCTION

In an ERL in its most basic configuration (see Fig. 1), the electrons are generated in a high brightness electron source, accelerated through a linear accelerator, transported by a magnetic arc lattice to a photon generating device (which can be either an undulator or an FEL), transported back to the entrance of the linac 180^0 out of phase for deceleration and energy recovery, and then dumped at an energy close to their injection energy. In ERLs, the accelerating and decelerating beams nearly cancel each other and the net current is very small. Therefore ERLs can, in principle, accelerate very high currents with only modest amounts of RF power. This feature makes ERLs an attractive concept for a variety of applications. In this paper we assume that the linac is a superconducting RF (SRF) linac. As energy recovery is much more efficient in an SRF linac, most new ERL proposals are based on SRF linacs.

ERLs can be compared and contrasted with the two traditional types of accelerators, storage rings and linacs. In a storage ring, electrons are stored for hours in an equilibrium state, whereas in an ERL it is the energy of the electrons that is stored. The electrons themselves spend little time in the accelerator (from ~1 to 10ís of μs) thus never reach equilibrium. As a result, in common with linacs, the 6-dimensional phase space in ERLs is largely determined by the electron source properties by design. On the other hand, in common with storage rings, ERLs have high current carrying capability enabled by the energy recovery process, thus promising high efficiencies. The combination of these special characteristics makes ERLs ideally suited as driver accelerators for at least two types of light sources, FELs operating in the oscillator configuration, and multi-GeV synchrotron light sources.

*Supported by US DOE Contract No. DE-AC05-84ER40150
#merminga@jlab.org

THE PROMISE OF ERL LIGHT SOURCES

Free Electron Lasers operating in the oscillator configuration have traditionally been driven by storage rings or linacs, and have been limited either by the quality of the electron beam properties (in the case of storage rings), or by the amount of electron beam current (in the case of linacs). FEL ERLs, however, hold the promise of unprecedented average laser power, high overall system efficiency (since the RF power consumption in the linac is nearly independent of beam current), and low dump activation (since the final energy is relatively low).

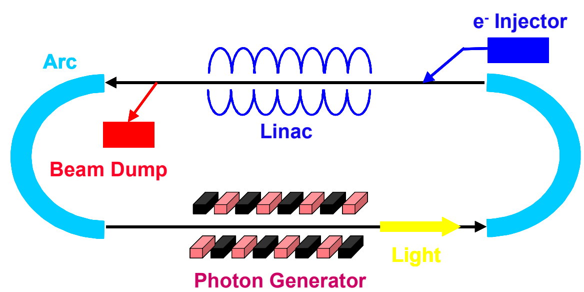

Figure 1. Schematic layout of a generic ERL Light Source

To date there are three oscillator-FEL-ERLs in operation, at Jefferson Lab, JAERI, and BINP, providing confirmation and first glimpses of the unprecedented parameter reach of these devices. The most advanced of these FELs is the Jefferson Lab FEL Upgrade [1], shown schematically in Fig. 2, which recently achieved 10 kW of CW output laser power at 6 μm wavelength. The driver accelerator has accelerated and energy recovered up to 8 mA of average current to 145 MeV, and up to 9 mA to 88 MeV.

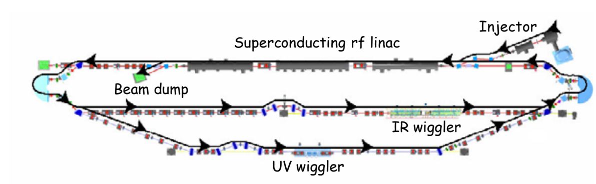

Figure 2. JLab FEL Upgrade

The second type of ERL light sources, the synchrotron light ERLs (SL ERLs), hold the promise of producing radiation with much enhanced average brightness and flux compared to third generation synchrotron radiation sources, very short pulses (from 1 ps to 100 fs), and high coherence. The realization of these promises is made possible by the properties, capabilities and flexibility of ERLs. Specifically, high average brightness is attainable by low electron beam emittance (~1 mm-mrad normalized, rms), high average current (~100 mA) typically made up by relatively low bunch charge and high repetition rate (equal to the RF frequency), and geometry that allows the insertion of long undulators. Full spatial coherence and high temporal coherence are attainable with diffraction-limited round electron beams and small relative energy spread (~10^{-4} rms) respectively, high average flux results from high average beam current and sub-ps X-rays can result from sub-ps electron bunch pulses (~100 fs). Although the possibilities exist, these parameters have yet to be demonstrated simultaneously in an ERL. In the next sections we describe the challenges that might be encountered in designing an ERL light source with the above specifications.

THE REALIZATION OF THE PROMISE

The realization of the promise of ERL light sources necessitates resolving certain physics challenges, centered largely around three areas: achieving high electron source brightness, maintaining high beam brightness through the accelerator transport, and dealing with high peak and average current effects in superconducting RF systems.

Challenge I: Generation and Preservation of Low Emittance, High Average Current Beams

In an ERL light source the highest quality beam must be produced at the source and preserved at the low energy regime, where space charge forces can degrade the beam quality. The challenge for ERL light sources is to minimize the space charge induced emittance growth - which generally requires the use of high accelerating gradients to rapidly accelerate the electrons from the cathode - while operating at high repetition rate. There are 3 basic approaches to high brightness electron sources to date, all of which are based on photocathode guns: DC, RF and SRF photoinjectors.

DC photoinjectors have operated at the highest bunch-to-bunch repetition rates to date. The state of the art in DC photoinjectors is the Jefferson Lab FEL gun operating at a repetition rate of up to 75 MHz, with cathode voltage from 350 to 500 kV. To date it has produced normalized rms emittances between 7 and 15 mm-mrad (measured at the wiggler) [2] for bunch charge between 60 to 135 pC and up to 9 mA of average current. As DC guns typically employ relatively low accelerating gradients, their biggest challenge is to minimize the emittance growth due to space charge. A recent optimization study done for the Cornell ERL prototype injector [3] has concluded that emittance growth as low as 0.1 mm-mrad is possible at the exit of the injector (10-15 MeV), for 80 pC, 3 ps bunches. This study was carried out assuming uniform transverse and longitudinal electron distributions at the photocathode, and did not include any thermal emittance. Nevertheless, such studies lend optimism that DC photoinjectors can meet the source requirements for ERL light sources, and provide a practical procedure for setting the various operating parameters in real injectors self-consistently and optimally.

RF photoinjectors employ extremely high accelerating gradients (~100 MV/m) to minimize the space-charge induced emittance growth in the low energy regime, and have produced the lowest normalized emittances to date (~1 mm-mrad at bunch charge of 0.1-1 nC), although at relatively low bunch-to-bunch repetition rate (10-100 Hz). The challenge for RF photoguns is to balance the high accelerating fields with the high repetition rate, which gives rise to significant thermal effects.

An approach, which promises high gradient CW RF fields, is the SRF photoinjectors. There are presently two major R&D efforts on SRF guns, at Rossendorf and at BNL. The Rossendorf proof-of-principle experiment consists of a 1.3 GHz, 10 MeV injector and has produced 77 pC bunches at 13 MHz and 1 nC bunches at less than 1 MHz [4]. The BNL/AES/JLAB collaboration is developing a high average current, high brightness gun based on 1.3 GHz, 1/2ñcell Nb cavity at 2K and is presently under testing [5]. An interesting recent possible enhancement of this SRF gun is the diamond window amplified cathode, which protects the cathode from contamination, while the secondary emission enhanced photoinjector allows for much higher average currents [6]. Although SRF guns appear to be ideally suited for ERL light sources, significant R&D is required before they can become operational.

Challenge II: Accelerator Transport

Once a high brightness beam is produced at the source, the next challenge is to ensure its 6-dimensional emittance preservation and phase space management during acceleration and energy recovery. There are at least three aspects to this challenge: longitudinal matching, coherent synchrotron radiation effects, and transverse matching.

Longitudinal matching is important in synchrotron light ERLs, as bunching during acceleration is typically required for the production of short X-ray pulses. In oscillator FEL ERLs, longitudinal matching is required to produce high peak current at the FEL, to allow the large energy spread introduced by the FEL interaction to be decompressed during deceleration, and to reduce the energy spread on the transport to the dump so the spent beam is cleanly dumped. Simulations, measurements, and operational experience both at the 10 kW FEL Upgrade and its predecessor, the 2 kW IR DEMO FEL [7], have shown that nonlinear distortions in phase space must be corrected for minimum bunch length and proper energy recovery [8]. In particular, the recirculation optics of the JLab FEL is set up to impart not only a linear position-energy correlation by proper choice of the R_{56}, but in addition, a quadratic dependence of the fractional momentum spread on the longitudinal position upstream from the linac, by proper choice of the T_{566}. In this scenario, the RF-induced curvature is compensated and the fractional momentum spread is greatly reduced. In the JLab FEL these corrections are done with sextupole magnets.

Emittance preservation especially in SL ERLs is very important, therefore one must ensure minimum beam quality degradation due to coherent synchrotron radiation (CSR), as the beam is transported around the bends in a typical ERL configuration. In SL ERLs, the combination of relatively low bunch charge (~0.1 nC) and not exceedingly short bunches (~0.1-1 ps) tends to alleviate CSR-induced problems. Further, optics schemes are being developed to minimize these effects [9].

The next transport issue is related to transverse matching. Transverse matching is not generally an issue for oscillator-FEL-ERLs, which tend to operate at relatively low energy (~100 MeV), but for multi-GeV SL ERLs energy recovery must work up to several GeV. This is a significant extrapolation from the FEL ERL paradigm. The challenge is to demonstrate sufficient operational control of two coupled beams of substantially different energies (especially at the beginning and the end of the linac) going through a common transport channel, in the presence of steering and focusing errors.

To address these issues a 1 GeV experimental demonstration of energy recovery took place at CEBAF [10]. CEBAF is an SRF recirculating linac at Jefferson Lab operating at nearly 6 GeV for Nuclear Physics experiments. For the purposes of this experiment a special chicane was installed at the end of South Linac, which provided $\lambda_{RF}/2$ path length delay. The beam was injected into the North Linac at energies of 50 and later 20 MeV, accelerated up to 500 MeV and transported to the South Linac where it was further accelerated to 1 GeV. After going through the delay chicane, the beam was transported back to the North Linac 180^0 out of RF phase, where it was decelerated to 500 MeV at the end of the North Linac, and close to the injection energy at the end of the South Linac, and it was dumped.

The goals of the CEBAF-Energy Recovery (CEBAF-ER) experiment included: to quantify the evolution of transverse phase space during acceleration and energy recovery, and to test the dynamic range of the system, by determining the largest ratio of final-to-injected beam energies. Clearly, the higher the energy ratio, the higher the overall system efficiency.

Preliminary conclusions of the CEBAF-ER experiment include:

- Demonstration of a significant operational extension of energy recovery to high energy (1 GeV), through a large (~ 1 km circumference), superconducting RF system (40 cryomodules).
- Demonstration of feasibility of energy recovery with ratio of final-to-injected beam energy up to 50:1 (from 20 MeV to 1 GeV).
- Verification of no significant emittance dilution as a result of the energy recovery process, and no unforeseen surprises.

The next step of energy recovery experiments at CEBAF includes energy recovery with current doubling. This experiment requires reconfiguring the $\lambda_{RF}/2$ delay chicane into a $\lambda_{RF}/4$ chicane. In this configuration the beam will be accelerated on the first pass, will coast on the second pass, and will be decelerated on the third pass.

Challenge III: High Current Effects in Superconducting RF Systems

This section addresses challenges in ensuring cryogenic efficiency during the acceleration/deceleration of high average current, short bunch length beams in an SRF environment, and beam stability against multipass instabilities. Two topics will be discussed: efficient extraction of Higher Order Mode (HOM) power and stability against multipass beam breakup (BBU). Longitudinal wakes excited by high average current, short bunch length beams in SRF cavities, in addition to causing beam quality degradation, also give rise to HOM power, which can be of significant magnitude and extends over high frequencies (of order hundreds of GHz). As an example, the monopole mode power excited when a 0.77 mm, 77 pC bunch traverses a 9ñcell TESLA-type cavity is 185 W. Of this power, approximately 80 W are at frequencies below 5 GHz, while the remaining 105 W are at frequencies above 5 GHz and up to 100 GHz. The challenge is to ensure adequate damping of HOMs and the extraction of HOM power with good cryogenic efficiency [11]. The HOM damping scheme that has been adapted for the Cornell ERL includes HOM loop couplers on both sides of an RF cavity to couple out modes below ~5 GHz and bring them to room temperature loads for absorption, and ferrite ring absorbers at 80 K for modes above 5 GHz [12].

Dipole HOMs in ERLs can pose a beam stability challenge. In recirculating linacs in general, the beam and the RF cavities form a feedback loop, which closes when the beam returns to the same cavity on a subsequent pass. The closure of the feedback loop between beam and cavity can give rise to instabilities at sufficiently high currents, driven predominantly by the high quality factor of the superconducting cavities. Energy recovering linacs, in particular, are more susceptible to these instabilities because they can support currents approaching or exceeding the threshold of the instabilities. Instabilities can result from the interaction of the beam with the fundamental accelerating mode (beam loading instabilities), the transverse HOMs (transverse BBU), and the longitudinal HOMs (longitudinal BBU) [13]. In the existing ERL light source designs, transverse BBU appears to be the limiting phenomenon and is described next.

The mechanism of multipass transverse BBU has been understood for a long time. Suppose a beam enters an RF cavity on axis and a previously excited HOM deflects the beam horizontally or vertically. When the beam returns to the same cavity displaced because of the optics of the recirculator, it can exchange energy with the HOM in a way that further excites the mode, deflecting subsequent bunches until they hit the beam pipe.

In the JLab FEL Upgrade the opportunity for experimental investigation of multipass BBU arose when it was discovered that the cavities of the middle cryomodule had insufficiently damped HOMs. The SRF linac of the JLab FEL Upgrade consists of 3 cryomodules, two of which are based on 5-cell Nb cavities, while the third (middle) is based on 7-cell CEBAF Upgrade-style cavities, operating at 1500 MHz. The middle cryomodule was installed at a later point of the commissioning, allowing the beam energy to reach 145 MeV compared to 88 MeV that was possible with only the first and third modules installed.

Beam breakup simulations of the 145 MeV configuration had predicted several HOMs exhibiting threshold currents below the design operating current of 10 mA. The two modes with the lowest thresholds were at 2106 MHz in cavity 7 with predicted threshold of 2.9 mA, and mode 2114 MHz in cavity 4 with predicted threshold of 3.7 mA [14]. These simulations were based on measured HOM parameters (frequencies and Qís) and design optics for the recirculator. In anticipation of the BBU instability, Schottky diodes had been installed at the HOM ports of all the cavities of the middle cryomodule to measure the HOM power at the ports. When the beam current reached 3 mA, the Schottky diode signals of cavity 4 indicated the expected exponential growth of the HOM fields, seen by the red curve of Fig. 3. The green curve of Fig. 3 shows the cavity voltage measured directly at the HOM port. Fourier analysis of the green signal confirmed the frequency of the HOM driving the instability at 2114 MHz, consistent with predicted results.

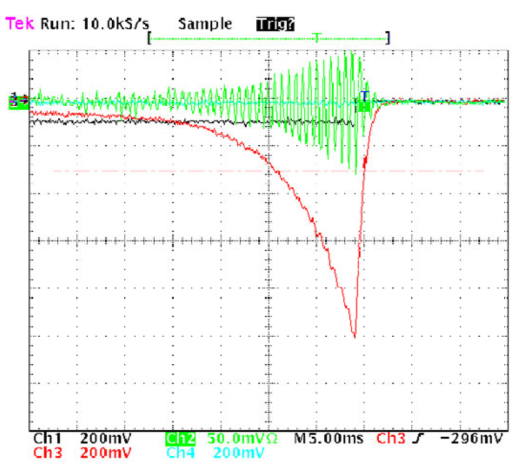

Figure 3. BBU observation at the JLab FEL Upgrade

Another set of experimental observations involved measurements of the growth rate of the instability as function of beam current when beam was run in pulsed mode (Fig. 4). Data were taken for beam currents above the instability threshold, and the threshold was derived from a fit to a simple, single cavity model. The threshold current derived from the pulsed regime data is in excellent agreement with the directly observed threshold of the instability in CW mode. Further, the decay rate of the fields, when the beam is turned off, is consistent with the measured Q of the mode at ~5×10^6 [15].

These measurements allow for the first time the direct verification of BBU simulations codes with experimental data. More detailed measurements to characterize the instability are in planning and will be executed in the Fall of 2004.

Soon after the instability was observed the emphasis shifted to mechanisms for its suppression. Several methods were devised and explored to various degrees of completion, including HOM damping schemes, beam-based feedback systems, and optics-based suppression techniques [16]. The latter refers to the concept of using reflecting or rotating optics in the recirculator to rotate the beam phase space such that a horizontal deflection leads to vertical displacement upon return of the beam to the same cavity, and vice-versa, thereby leading to higher instability thresholds [17]. Optics was devised for a reflection and skew quadrupoles were installed in the FEL Upgrade. When the ìreflection was turned onî the BBU instability threshold was raised from 5 mA to at least 8 mA. Operations were limited to 8 mA, however not due to BBU [18].

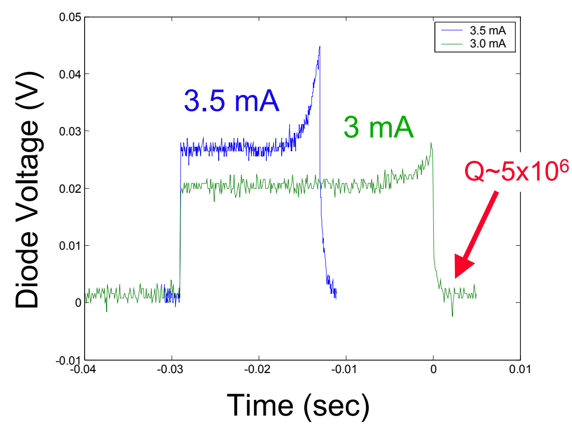

Figure 4. Measurements of the growth rate of beam breakup instability as function of beam current.

In the long-run BBU can be significantly ameliorated by specially designed RF cavities operating at lower frequencies. An example of such a development is the BNL cavity design at 703 MHz, for which the predicted BBU threshold is exceedingly high, above 1 Ampere [19].

ERL LIGHT SOURCE PROJECTS AND PROPOSALS WORLDWIDE

At present there are three operating oscillator-FEL-ERLs, two of which are based on SRF linacs: the JLab FEL Upgrade and the JAERI FEL [20] which uses 500 MHz cavities and is presently preparing for 10 kW laser power operation, initially at reduced duty cycle, and later in CW mode. The third FEL ERL is at BINP [21], uses 180 MHz room temperature RF cavities, and is operating in single pass mode but has plans for a four-orbit racetrack configuration. Table 1 summarizes the parameters of the operating FEL ERLs and their Upgrades. In the future, Daresbury Laboratoryís 4GLS facility will include an IR and VUV oscillator FELs driven by a 600 MeV SRF ERL [22].

The promise of SL ERLs has given rise to several proposals and conceptual designs of multi-GeV ERL light sources. The pioneering BINP MARS proposal [23] emphasizes diffraction limited electron beams with long undulators for the generation of high brightness photon beams, but not high flux. The Cornell [24] and KEK [25] proposals rely on high average currents (~100 mA) for high flux, however they maintain the option of ìhigh-coherenceî mode, where current is reduced leading to reduced emittance for increased brightness. Finally, DESY scientists are exploring the CW energy recovery operation of the XFEL as a potential future upgrade option [26].

Table 1. Operating oscillator FELs and Upgrades

	JLAB	**JAERI** Operating/ Upgrade	**BINP** Operating/ Upgrade
E [MeV]	145	17	12/50
I_{ave} [mA]	9	5/40	20/50
Q_{bunch} [pC]	135	500	900/2200
$\varepsilon_{N, rms}$ [μm]	15	30	20
Rep. Rate [MHz]	75	10/80	22.5
Duty Factor [%]	100	1/100	100

In order to study and resolve the physics and technology challenges of a multi-GeV ERL light source, several proposals for low energy (100-300 MeV), high current (100 mA) prototypes have been developed from Cornell [27], KEK [28], BNL and Daresbury Laboratory. The latter is funded and already under construction [22]. The BNL prototype, which is also funded, aims to address issues related to an ERL-based electron cooler [29], which will be used to counteract the heating of the ions due to intrabeam scattering, and lead to increase of the integrated luminosity of RHIC.

SUMMARY AND OUTLOOK

Energy recovering linacs provide a powerful and elegant paradigm for high average brightness, short pulse length radiation sources. The pioneering oscillator-FEL-ERLs, presently in operation, have established the fundamental principles of ERLs. It is encouraging to note that in the recent few years much progress has been made towards achieving the required specifications for an ERL light source. In the most fundamental parameters, we are but an order of magnitude or less away from these specifications: a factor of 5-7 in energy (for 5-7 GeV of final energy), a factor of 10 in current (for 100 mA average beam current), a factor of 5-10 in emittance (for normalized rms emittance of 1-2 mm-mrad at full energy), a factor of 4 in bunch length (for 1 to 0.1 ps rms). It is worth noting that the required charge per bunch has already been demonstrated.

Challenges and R&D opportunities exist for the realization of the next generation of ERL light sources. These challenges center around three major topics: source brightness, emittance preservation and phase space manipulation, and high peak and average current effects in an SRF environment. Vigorous R&D activities in many laboratories around the world promise to resolve the outstanding physics and technology issues. The multitude of ERL projects and proposals worldwide promises an exciting next decade for ERL physics, as existing ERL light sources will be upgraded to higher performance yet, key R&D issues will be resolved and new ERL light sources will begin construction.

The author is grateful to the following colleagues for generously sharing information and data for the preparation of this paper: I. Bazarov, G. Hoffstaetter, M. Liepe and C. Sinclair from Cornell University, I. Ben-Zvi and J. Murphy from Brookhaven National Lab, E. Minehara and R. Hajima from JAERI, M. Poole from Daresbury Laboratory, J. Sekutowicz and S. Simrock from DESY, T. Smith from Stanford University, T. Suwada and K. Yokoya from KEK, N. Vinokurov from BINP, and S. Benson, S. Chattopadhyay, J. Delayen, D. Douglas, A. Hutton, K. Jordan, G. Krafft, C. Leemann, G. Neil, E. Pozdeyev and C. Tennant from Jefferson Lab.

REFERENCES

[1] S.V. Benson, et al., Proceedings FEL Conf. (2004)
[2] T. Siggins, et al., NIM A 475 (2001) 549
[3] I. Bazarov and C.K. Sinclair, in preparation (2004)
[4] D. Janssen, et al., NIM A 507 (2003) 314
[5] T. Srinivasan-Rao, et al. Proceedings PAC 2003, p. 92 and H. Bluem, et al., these proceedings (2004)
[6] I. Ben-Zvi, et al. BNL Report C-A/AP/#149 (2004)
[7] G.R. Neil, et al., PRL Vol. 84, No 4 (2000)
[8] P. Piot, D.R. Douglas, G.A. Krafft, *Phys. Rev. ST-AB* 6:030702 (2003)
[9] R. Hajima, Jpn. J. Appl. Phys. 42 (2003) p. L974
[10] A. Freyberger, et al., these proceedings (2004)
[11] L. Merminga, et al., Proc. Linac Conf. (2000) p. 860
[12] M. Liepe, Proc. SRF Workshop (2003)
[13] L. Merminga, D.R. Douglas and G.A. Krafft, *Annu. Rev. Nucl. Part. Sci.* 53:387-429 (2003)
[14] C. Tennant, et al., JLAB-TN-04-008 (2004)
[15] E. Pozdeyev, et al., in preparation (2004)
[16] C. Tennant, et al., Proceedings LINAC Conf. (2004)
[17] R. Rand and T. Smith, Particle Accelerators 1980, Vol. II, pp. 1-13.
[18] C. Tennant, et al., Proceedings FEL Conf. (2004)
[19] R. Calaga, et al., these proceedings (2004)
[20] Sawamura, et al., these proceedings (2004)
[21] G. Kulipanov et al., Proc. APAC (2004)
[22] M. Poole and E. Seddon, these proceedings (2004)
[23] G. Kulipanov, A.N. Skrinsky, N. Vinokurov, J. Synchrotron Rad. 5, 176-178 (1998)
[24] G. Hoffstaetter, et al., these proceedings (2004)
[25] K. Yokoya, Proc. APAC (2004)
[26] J. Sekutowicz, et al., Proc. SRF Workshop (2003)
[27] G. Hoffstaetter, et al. Proceedings PAC 2003, p. 192
[28] E.-S. Kim and K. Yokoya, these proceedings (2004)
[29] I. Ben-Zvi, et al. Proceedings PAC 2003, p. 39