OPTICS AND BEAM TRANSPORT FOR ENERGY-RECOVERY LINACS SUMMARY OF WORKING GROUP 2 AT ERL07

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Abstract

The 41st Advanced Beam Dynamics Workshop on Energy Recovery Linacs was held at Daresbury Laboratory, May 21-25, 2007. The workshop was organized into four working groups, one of which, WG2, covered optics and beam transport issues relevant to realization of high-brightness and high-average current beams in ERLs both in operation and under proposal. The outcome of the working group discussions is summarised.

INTRODUCTION

Energy recovery linacs now occupy an important position amongst advanced particle accelerators both for exploring uncharted nature of science and for promoting the industrial application of accelerators. Several proposals of future facilities based on ERLs have been put forward and world-wide efforts towards them are being pursued. Holding an international meeting focusing on technological challenges in such ERLs is a good opportunity to resolve the various issues we are facing, and to enhance those proposed ERL projects. The 41st Advanced Beam Dynamics Workshop on Energy Recovery Linacs was held at Daresbury Laboratory from May 21-25, 2007, after a two-year interval from the last workshop, ERL-2005 [1].

Energy-recovery linacs are in principle able to generate an electron beam of extremely small emittance and high average current, which has never been available in storage rings and single-pass linacs. However, we must overcome a number of technological challenges to effectively realise the potential performance of ERLs: the workshop was organized into four working groups to cover the full range of these challenges. Our working group, WG2, focused on issues in electron optics and beam transport. The development of components such as electron guns for small emittance, and superconducting cavities for high average current, both major topics, were dealt with in separate working groups. Our agenda was to encompass all the optics and beam transport issues relevant to realization of high brightness and high average current beams in ERLs, both those in operation and being proposed. Although a large part of the agenda related to theoretical considerations and numerical simulations, we kept a close connection to the practical activities of machine development. Joint sessions with the other working groups were held for this purpose.

Previous international workshops, ERL-2005 [1] and FLS-2006 [2], provided opportunities for discussions of optics and beam transport issues for ERLs. These discussions revealed that some issues can be handled by well-known classical theories in beam optics, whilst others need more research and development of hardware components together with the help of new ideas. Following the outcome of these two workshops and noting recent progress in hardware development, we finalized the agenda of WG2 as follows:

- Session 1. Optics Issues for Ongoing ERL Projects – Joint with WG4 (5 talks)
- Session 2. Beam Loss and Stability Issues – Joint with WG4 (6 talks)
- Session 3. Computational Aspects – Joint with WG1 (6 talks)
- Session 4. Optics Developments (6 talks)
- Session 5. BBU and Cavity Optics – Joint with WG3 (7 talks)

In the rest of this paper we overlook and summarise the working group discussions subject by subject. A complete description of each talk in the working group can be found in these proceedings and other references cited.

LINEAR AND NONLINEAR OPTICS

The beam transport of an ERL can be designed flexibly, with the primary rule that the accelerated beam must be decelerated after use. The design of an ERL beam transport should be started with consideration of linear and nonlinear optics before going on to a deep analysis of electron motion such as collective self-interaction or interaction with the surrounding environment (such as wakefield analysis). We see examples of these linear and nonlinear considerations in the design of ERLs as described below.

The energy-recovery linac planned at Daresbury Laboratory, 4GLS, is a complex of radiation sources, in which two electron beams from two different injectors, one for a high-average current ERL and the other for an XUV-FEL, share a single superconducting accelerator. A dipole separator magnet is used at the exit of the accelerator to separate these two beams, which have different energies of 550 MeV (ERL) and 750 MeV (XUV-FEL). The higher-

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energy beam (separated outward) is transported to an XUV-FEL undulator installed inside the ERL loop. A vertical offset of the outward beam to pass over the ERL loop is established by inclining the outward arc at a small angle, ~ 2 degrees from the horizontal plane. A pair of solenoid magnets is installed at the entrance and exit of the arc to rotate electrons in the x-y plane [3].

Another example of vertical elevation of an electron beam is seen in an e-cooler for eRHIC developed at BNL. In the cooling section, an electron beam from an ERL is transported along an ion beam trajectory to cool the ion beam. Subsequently, the electron beam passes a turn-around arc and is utilized for cooling the other ion beam. This arc has vertical bends to step over the ion beam pipe. The turn-around arc design uses an 'H-V achromat lattice', in which the achromat condition is fulfilled in both the horizontal and vertical planes without any x-y coupling by setting appropriate quadrupole magnets between the vertical bends for beam elevation and horizontal bending for the 180-degree turn [4]. These designs of electron beam transport at 4GLS and eRHIC are good examples of the linear optics design exercise.

Nonlinear beam dynamics is also a major subject in the design of ERL beam transport. In the test ERL at the Japan ERL project, it is planned to compress an electron bunch whilst traversing a 180-degree arc of triple-bend achromats. Since an electron bunch prepared for bunch compression has a relatively large energy spread, emittance dilution may occur due to the inherent chromatic aberration of the arc. In the test ERL design, two families of sextupole magnets are installed to compensate for chromatic aberration [5]. These sextupole magnets also have an important role in manipulation of longitudinal beam dynamics: numerical simulations including CSR effects show that sextupole correction is indispensable to obtain an electron bunch with sub-picosecond duration, necessary for the planned utilization of terahertz radiation and for the generation of ultrashort X-ray pulses via laser Compton scattering [6].

Energy spread of electrons induced by the FEL interaction is a matter of concern in ERL-FELs. In a typical FEL oscillator, the exhaust full energy spread ΔE after the FEL is proportional to the FEL conversion efficiency η: $\Delta E/E \simeq 5\eta$. Unlike a normal linac-based FEL facility, the FEL efficiency and output power is therefore limited by the energy acceptance of the return loop and by the beam dump energy. A simple relation of maximum FEL power and the beam power at the dump can be derived as $P_{FEL} \leq P_{dump}(\Delta E/E)$, which becomes a significant limitation especially for a high-energy ERL-FEL such as the VUV-FEL at 4GLS [3].

Keeping a return loop with an appropriate path length is a strict requirement for the ERL operation. A modular path length corrector for this purpose has been proposed for 4GLS. The corrector consists of a final decompressor chicane and girder-mounted movable doglegs connected by expanding bellows. The corrector provides a path length variation of 23 cm (one RF period at 1.3 GHz), which can be used not only for a fine-tuning of the path length around the ideal 180-degree deceleration phase, but also to provide flexible future operation of 4GLS into a 2-loop, 2-pass configuration of acceleration and deceleration [3].

EMITTANCE PRESERVATION

It is well-known that the generation and use of small-emittance beams is one of the most attractive features of and motivation for using ERLs. ERL light sources for hard X-ray radiation require a normalized emittance of as low as 0.1 mm-mrad, which is one order of magnitude smaller than the presently achieved emittance of photocathode RF guns for XFELs. Calculation of X-ray brilliance for the proposed ERL upgrade at APS showed again the importance of small emittance, where an ERL with a normalized emittance of 3 mm-mrad is comparable to the current APS performance and an ERL with 0.1 mm-mrad provides two orders of magnitude improvement in average brilliance compared to the current APS [7]. In order to realize such a small-emittance beam, we need to develop a small-emittance electron source and understand emittance preservation through the entire beam transport, including injector, merger, linac and return loop.

A DC photo-cathode gun to produce a 100-mA beam is under development for the 4GLS high-average current loop. Simulation results for the 4GLS gun show that a 100 mA beam (77 pC, 1.3 GHz) is possible with a transverse emittance of 2.8 mm-mrad and a bunch length of 2.2 ps from a 500 kV DC gun followed by a 10 MeV two-module superconducting linac [8]. Fine-tuning of the drive laser and focusing parameters, beam dynamics including the beam merger, and three-dimensional simulations with an off-center cathode laser spot remain as future work.

Beam parameter simulation of the Rossendorf SRF gun was presented [9]. In this study, the 3.5-cell SRF gun has been applied to three different operation modes: normal ELBE mode (77 pC, 13 MHz), high-charge mode (1 nC, 500 kHz), and a BESSY-FEL mode (2.5 nC, 1 kHz). Effects of cathode retraction, laser spot size and pulse duration on both transverse and longitudinal emittance have been systematically investigated. The cathode retraction successfully reduces the transverse emittance from 7 mm-mrad (without retraction) to 2 mm-mrad (2.6 mm retraction) in the high charge mode. Variation of spot size and pulse duration of the drive laser produces trade-off curves between the transverse and longitudinal emittance at the gun exit, where a smaller transverse emittance means a larger longitudinal emittance, and vice versa.

At the last workshop (ERL-2005) we found that multivariate optimization is a quite efficient method for the design of ERL injectors. It was seen that electron beams of 0.1 mm-mrad can be obtained from numerical simulations with optimization of machine parameters: amplitude and phase of a buncher cavity and injector cavities, and strength and position of solenoid and quadrupole magnets [10, 11]. In ERL07, multivariate optimization was applied to the JLAB/AES injector, which consists of a 500 kV gun, 3 single-cell superconducting cavities driven at 750 MHz, and a 3rd-harmonic cavity for linearisation of the fundamental RF curvature [12]. The design goal is to produce an electron beam of 100 mA at 7 MeV (135 pC, 750 MHz) with transverse normalized emittance of 5 mm-mrad and longitudinal emittance of 15 keV-mm. The injector has no buncher cavity in contrast to the injectors for hard X-ray sources in development at Cornell University and in Japan. In this study, a multivariate optimization based on an evolutionary algorithm is employed to determine 10 variables: laser spot size, solenoid strength, and the amplitude and phase for each of 4 cavities. To exclude undesirable folding of the longitudinal phase space, the scanning range of each variable is limited *a priori*. The multivariate optimization for the JLAB/AES injector shows better results than manual optimization, but cannot realize the design goal for the longitudinal emittance. Further calculation suggested that the longitudinal emittance becomes small enough when we allow temporal duration of the electron bunch at the cathode to be a free parameter.

Multivariate optimization thus works efficiently in the practical design of ERL injectors. However, analytical studies of emittance compensation help us to develop real insight into the physics behind the optimization process. In the working group, C-x. Wang presented a beam envelope analysis using a perturbative treatment to study emittance evolution and compensation far from the invariant envelope in a photocathode RF injector [13]. A new condition to achieve favorable emittance compensation is derived. It has been confirmed that the design of the SPARC injector, which gives a quite small emittance of 0.4 mm-mrad for a 1 nC bunch, fulfils this condition. This study stimulates us to develop an analytical theory applicable to an ERL injector with a DC gun obtained from the multivariate optimization.

Asymmetric fields caused by power couplers in a linac are also a potential source of emittance growth [14]. Time-varying asymmetric fields in the coupler region kick an electron bunch transversely and results in emittance growth when the head and tail of bunch suffer different kicks. The emittance growth, however, can be minimized by the following schemes: (1) cancellation of the coupler kicks by rotating couplers around the axis of the linac, or by mounting the couplers alternately at the front and back of the cavities; (2) making the RF field in the coupler region more symmetric by putting a corresponding stub on the inner surface of the beam pipe opposite to the coupler; (3) choosing the coupler position so that an electron bunch feels zero phase of cosine like field. Simulations for the Cornell 5-GeV ERL show that the emittance growth after the above cancellation can be made acceptably small using these schemes.

COHERENT SYNCHROTRON RADIATION

Coherent synchrotron radiation (CSR) during passage of an ERL loop dilutes the transverse emittance and energy spread of an electron bunch. It is known that emittance growth can be compensated by setting cell-to-cell betatron phase advance to an appropriate value or by matching a CSR kick to a beam ellipse in transverse phase space [15, 16]. Emittance growth due to CSR at the ERL test facility in Japan has been examined [6]: numerical simulations for bunch compression in a 180-degree arc show that the emittance growth induced by CSR can be reduced by the envelope-matching technique, and generation of sub-picosecond electron bunches is possible despite CSR emission by tuning the first- and second-order momentum compaction, R_{56} and T_{566}.

CSR can be the dominant source of energy spread in an electron bunch in high-energy ERLs used for X-ray light sources. The Cornell 5-GeV ERL is planned to use electron bunches of 1 nC charge in an ultrafast X-ray pulse mode: in this mode, energy spread induced by CSR in the ERL turn-around loop is estimated to be 1% for 2 ps bunches, which is unacceptable for the ERL operation [17]. A possible solution to relax the growth of energy spread is to make use of the suppression of CSR by the surrounding vacuum chamber walls. The suppression of CSR in the turn-around arc was confirmed by analytic formalism and numerical simulation; further investigation including experimental verification of shielding is needed. Careful reviewing of previous experiments [18] will be helpful to consider future experimental plans.

ION TRAPPING

Ions generated from the collision of high-energy electrons with residual gases are trapped along the beam trajectory by the steep electric potential well of the electron beam, and induce undesirable effects on beam dynamics such as fast ion instability and large tune shift by charge neutralization. These effects from ions are of interest in ERLs as well as in storage rings, where ion trapping is a well-known issue [19]. In fact, the smaller transverse emittance typical in ERL proposals means that ion trapping may be more problematic than in storage rings used as 2nd- and 3rd-generation light sources.

In the working group discussions, two approaches were proposed for the elimination of trapped ion effects: the first is the use of clearing electrodes, whilst the second is to introduce gaps into the bunch train. Clearing electrodes apply transverse electric field to repel ions trapped along an electron beam trajectory. However, the short bunches typical in ERLs mean that care should be taken of induced wakefields in the design of the electrodes—Cornell University is developing a clearing electrode compatible with a short bunch. Simulations have shown, for the Cornell 5-GeV ERL, that we can almost eliminate the ion effects by installing clearing electrodes every 10 m along the beam path [20].

Gaps in the bunch train are widely employed in storage rings to interrupt the periodic focusing from each bunch, and thereby to make trapping of ions unstable and so remove them. It is, however, not easy to use train gaps in ERLs, since the gap results in variation of beam loading in the electron gun and injection cavities, and beam loading in the main ERL linac itself. The variation of beam loading in the ERL linac can be avoided by ensuring that the interval between the gap ends is an integer fraction of the ERL revolution time.

To investigate the stability of trapped ions for various patterns of bunch gaps, a linear optics calculation has been carried out [21]. It has been found that we can eliminate ions even with high-repetition, short bunch gaps, for instance 10% of bunches absent at a repetition rate of 2 MHz. Note that the influence of beam load variation by bunch gaps becomes moderate when the bunch gap interval is much shorter than the cavity filling time. Moreover, the fluctuation of RF amplitude and phase in the injection cavities may be stabilized by a feed-forward technique or by utilizing a combined RF generator with a large bandwidth.

Ion trapping is an old problem in storage rings, but some new aspects have been added in ERLs. We must investigate carefully ion behaviors in ERLs, and develop methods to exclude their effects. Experiments at test facilities are indispensable for the demonstration of ion elimination methods.

BEAM LOSSES

Beam loss is a tough enemy of successful ERL operation due to the high average beam power associated with such accelerators. Loss of electrons during an ERL return loop means reduction of the recovered beam power and may result in a significant increase in the running cost. Also, even a small percentage of beam loss causes a high radiation hazard to undulators and other equipment along the beam path. This radiation is also a problem for access management of an experiment hall, and for the overall shielding policy of the accelerator. There are several significant sources of beam loss in ERLs: beam halo, gas scattering, and intra-beam scattering.

Beam loss due to the Touschek effect was studied for the APS-ERL upgrade [22]. It was found that Touschek losses are not an issue in the APS ring and the turn-around arc after optimization of energy acceptance. Loss in the linac at low energy is, however, a critical subject. Management of beam loss at APS-ERL is also discussed in terms of energy aperture optimization by sextupoles, collimation strategies, a beam abort system, beam loss monitoring, and shielding consideration [23]. It has been pointed out that radiation dose in the APS and the turn-around arc area, and the energy deposit on the linac SRF cavities due to beam loss are the main concerns.

BEAM BREAKUP

HOM BBU

Higher-order modes (HOM) excited in a superconducting cavity, which do not contribute to electron acceleration, may cause instabilities in the motion of the electron bunch train. Multi-pass beam breakup (BBU) caused by HOMs in superconducting cavities is one of the most critical of these instabilities in an ERL for high-average current. So far, many studies have been conducted for suppression of HOM-BBU, which include beam optics optimization, x-y coupling in a return loop, and polarized cavities [24, 25]. Although these procedures indeed increase the BBU threshold current to some greater or lesser degree, a straightforward solution to the HOM-BBU problem is the development of ERL-oriented cavities with strong damping of the problematic HOMs: pioneering work on HOM-damped ERL cavities by Cornell and BNL [26, 27] were presented at the last workshop.

Recently, the Japanese group also started cavity development for their future X-ray ERL facility. They chose a 9-cell 1.3-GHz structure and optimized cell shapes and diameter of beam pipes to achieve strong damping of the HOMs; design of cavity shape has been completed and fabrication of a prototype is underway [28]. Numerical simulations of HOM-BBU with this newly-designed cavity show that the threshold current for 5-GeV ERL is 600 mA without HOM frequency randomization, and exceeds 1.5 A when HOM frequency randomization of 1 MHz is included (1 MHz is considered a typical lower-bound on the frequency accuracy of such cavities in any case—see below). The threshold current for this newly-designed cavity is 10 times larger than previous TESLA cavities and completely fulfils the requirement of future ERL light sources [29]. This result strongly encourages us to continue our efforts towards future ERL light sources, although on-axis absorbers to extract high-power HOMs are yet to be satisfactorily demonstrated.

Deliberate randomization of HOM frequency is effective in increasing the BBU threshold current. Also, experience of TESLA cavity production leads us to expect a frequency randomization of several MHz introduced naturally by the manufacturing process. Artificial deformation of cavities is also a promising approach to increase the threshold current [30].

The improvement in cavity performance seen above allows the possibility of multi-turn ERL configurations. Estimation of BBU threshold current with the 9-cell cavities developed by the Japanese group suggests that a 5-GeV ERL with 2-turn configuration is a practical design from the viewpoint of HOM-BBUs [29]. The e-cooler developed at BNL is also based on a 2-turn design [4]. Since multi-turn configuration significantly reduces construction and operation costs of the ERL linac and its associated cryoplant, we need to examine beam dynamics issues in multi-turn ERLs further in cooperation with cavity development.

Resistive-Wall BBU

Long-range transverse wakefields arising from a resistive vacuum vessel may induce beam breakup: it is therefore useful to study resistive-wall beam breakup (RWBBU) in a general sense. Since the analytic asymptotic expressions are valid only for limited parameter ranges and initial conditions, a simulation program for transverse beam breakup has been developed [31]; this simulation program was applied to the Japanese test ERL. The RWBBU grows in proportion to the square root of the duration of a bunch train. The maximum orbit distortion due to the RW wake is evaluated to be about 1% of the injection error at 77μs after the beam is turned on. Installation of a small-gap vessel for an insertion device significantly increases the orbit distortion in the beam path downstream of the device. Orbit correction and a copper-coating of a small-gap ID vessel may reduce the RWBBU growth.

The above simulation of resistive wall BBU is based on a simple assumption of the wake potential, which does not include the property that the skin depth at low frequencies may exceed the pipe thickness. Future work should therefore examine simulations with realistic pipe thickness, pipe radius and conductivity as well as validation of numerical results by using existing machine parameters such as for the JLAB ERL.

LIGHT SOURCES

Light sources are the most promising target of future ERL applications: synchrotron light sources based on ERLs are now under development at various laboratories around the world.

For high-power free-electron lasers, three facilities (JLAB, JAEA, BINP) are operating their own ERLs and carrying on R&D efforts [32]. At Daresbury Laboratory, a 35-MeV ERL is soon to be commissioned and used to drive an IR-FEL [33].

There are also several IR-FEL projects under proposal. The National High Magnetic Field Laboratory (NHMFL) in Florida recently started the concept and engineering design of an ERL-FEL in collaboration with JLAB [34]. In Peking University, they plan to build a 30-MeV ERL-FEL and a DC-SC injector is under development [35]. A superconducting linac facility at the Korean Atomic Energy Research Institute (KAERI) is proposed to extend into an ERL-FEL at 10-22 MeV electron energy [36].

As light sources for VUV, XUV and X-rays, ARC-EN-CIEL in France [37], 4GLS at Daresbury [3], the CESR upgrade at Cornell [39], and Japanese ERL project [38] are all in the proposal stage. These proposals have been well-described in previous papers, and we do not repeat the detail of them. However, we do emphasize these high-energy, high-average-current light sources are flagships of future ERLs, and provide a strong motivation to improve the key components of ERLs.

In the following subsections, we see some new proposals of light sources presented during the working group discussion.

Possible ERL Upgrade to APS

Recently, a research group from the Advanced Photon Source (APS) at Argonne National Laboratory has joined in participation with the ERL community [7]. APS is a mature 3rd-generation facility that will eventually need an upgrade to stay competitive. The emittance of the APS cannot be made significantly smaller using existing hardware, giving two options: replacing the storage ring or adding an ERL injector. A replacement storage ring was considered, but is only calculated to give a 3-fold decrease in emittance, leading to $\sim$40-fold greater brightness assuming a doubling of the current and 3-fold longer undulators. Using a simulation code `elegant`, they designed an ERL that incorporates the APS ring, and modeled transport from 10 MeV to 7 GeV and back. The "ultimate" configuration is a 7 GeV straight linac pointing away from APS, since this gives a short-pulse upgrade path with an FEL or spontaneous radiation facility. This configuration features a large new turn-around arc with 48 straight sections, which could accommodate new beamlines with 8 m-long insertion devices. Using Cornell's high-coherence mode parameters [39] (2 ps rms bunch length, 0.02% rms energy spread, and 0.1 mm-mrad normalized emittance), we see only $\sim$2-fold emittance growth in the horizontal plane by the end of the APS ring. This provides more than 2 orders of magnitude increase in brightness and coherent radiation fraction for a 3.3 cm period undulator (the most common period length presently employed at APS). No significant performance reduction results from use of the APS ring as part of the system—performance is even better for undulators with optimized period and/or operation at 8 GeV.

In terms of minimum injector requirements, we need 20 pC/bunch, 25 mA average current, and $\sim$0.3 mm-mrad normalized emittance for a 10-fold brightness increase. A straight 7-GeV linac will require approximately 45 MW of wall-plug power for the cryogenic systems; mitigating approaches include using a multi-pass linac, developing cavities with higher Q_0, and building a longer, lower-gradient linac.

X-Ray FEL Oscillator

In the last century two kinds of bright light sources — lasers and synchrotron radiation sources — have been developed more or less independently. Now, we are facing a new generation of light sources using a marriage of these two technologies. The first laser in the hard X-ray region will be realized as a free-electron laser based on self-amplified spontaneous emission (SASE), at the Linac Coherent Light Source in California. An X-ray pulse from a SASE-XFEL, however, differs considerably from conventional lasers operated in the visible and infrared region. X-ray pulses in a SASE-XFEL consist of a number of optical spikes having no correlation to one another, while an optical pulse from a laser oscillator is usually a single pulse with full temporal coherence. In addition, a SASE-FEL suffers from an inherently limited pulse-to-pulse energy and wavelength stability.

In this workshop, K-J. Kim et al. presented a novel idea for an X-ray FEL oscillator (X-FEL-O) driven by an ERL, for the generation of hard X-ray pulses with full coherence both in spatial and temporal properties, and which is a genuine laser in the hard X-ray region [40]. They have studied a 1 Å FEL using electron beam properties extrapolated from the high-coherence mode of the proposed Cornell ERL, scaled to 7 GeV: a bunch duration of 2 ps (rms), un-normalized emittance of 6 pm (rms), bunch charge of 19 pC, and energy spread of 0.02% (rms). The undulator parameter and period length are chosen to be K=1.4 and 1.88 cm respectively. With a 30 m undulator the small signal gain is about 20%, sufficient for lasing if one round trip reflectivity is greater than 90%.

The gain will be higher for a higher bunch charge, up to 60 pC, achievable with further optimization of the gun [41]. The peak power of the circulating optical beam at saturation is about 20 MW and its bandwidth 10^{-6}. The average brightness of the output will be in the range of $10^{28} - 10^{30}$ photons / (sec) (mm-mr)^2(0.1%BW), higher by four to six orders of magnitudes than the ERL-based spontaneous X-ray sources. The increased energy spread of the electron beam due to the FEL interaction is not thought to pose a problem for the recirculation optics. Two possible schemes for the optical cavity were presented. One is a triangular-shaped optical cavity with three crystal reflectors similar to a previous study of an X-ray regenerative amplifier [42]. The other is to use a cavity consisting of two Bragg reflectors in a near-backscattering configuration and a grazing incidence mirror in-between; parasitic diffraction in the backscattering from a cubic crystal provides a convenient out-coupling mechanism. The fraction of parasitic diffraction can be set to a small desired value by suitably orienting the crystals away from the exact backscattering geometry; the mirror serves also the function of focusing the x-ray beam.

The photon performance of the XFEL oscillator is complementary to SASE-FELs. Less raw power of X-ray pulses from the XFEL oscillator is beneficial to many applications. In the XFEL oscillator, critical requirements for an electron beam are transverse emittance as small as diffraction limit of the X-ray and CW operation with high-repetition rate, both of which are promising features of the multi-GeV ERLs under proposal.

Loop-Shaped FEL

The Budker Institute propose a new type of FEL, a loop-shaped FEL [43, 44]. In this FEL device, lasing is established as a result of successive growth of microbunching in an electron bunch passing through several undulators installed in a recirculation loop, where bending arcs are designed to be exactly isochronous to keep the microbunching at the optical wavelength. After each circulation of an electron bunch, radiation from the bunch is used as a seed light to initiate FEL interaction of the next electron bunch. An ERL is employed as a driver of the loop-shaped FEL, which requires a continuous bunch train with a high repetition rate. Two examples of a conceptual design were presented: a soft X-ray FEL at $\lambda = 50$ nm and an IR FEL at $\lambda = 6\mu$m. Although the loop-shaped FEL has no optical cavity, it shows better temporal coherence than SASE-FELs thanks to the feedback of the radiation signal after every circulation.

COMPUTATIONAL ASPECTS

A large part of the studies seen above rely on computer simulation tools such as beam optics codes, particle tracking codes, BBU codes, CSR codes, and so on. A computer code, `elegant`, which has been developed by M. Borland and his colleagues at APS, is one of the most popular simulation tools in our community. In the working group, we had a chance to hear an up-to-date status of the code, including parallelization and other new features.

The program `elegant` is widely used in the ERL and FEL communities. The philosophy of the program is to use a tool-based approach, relying on self-describing files and a generic toolkit of programs (the ‘SDDS Toolkit’) for pre- and post-processing. This makes `elegant` well suited to high-throughput computing using scripting and computing clusters. Basic element types include single particle dynamics, time-dependent elements, and collective effects. Commands include tracking and optimization of almost any computed quantity.

A multi-year program to parallelize `elegant` is in progress. The parallelization strategy allows gradual parallelization, also necessitated by the on-going development of the serial version. It also allows use of parallel features during development, since the program automatically switches between parallel and serial mode as needed. At this time, about 80% of the elements are parallelized, and parallelism may be used for both tracking and optimization. Benchmarking shows 85% parallel efficiency on 1024 processors using an IBM BlueGene computer to model deflecting cavities in the APS storage ring.

Other new features in the past three years include deflecting cavities, fast chromatic matrix tracking, and calculation of coupled lattice functions. They also distribute an accelerator physics toolkit that cooperates with `elegant` for lifetime, undulator, and related computations. The future development plan includes parallelization of longitudinal space charge, addition of Touschek scattering, true multi-bunch simulation for BBU and electron cloud and ion effect calculations.

Computer simulations are also indispensable for designing RF structures with electron beams inside. J.-H. Han presented a numerical experiment on an RF photocathode gun. It was shown that tuning the 1st half-cell length is effective for reducing dark current, which is one of the most critical issues in the design of such guns. With the help of `ASTRA`, the cell-length tuning has been applied to the FLASH gun driven at 1.3 GHz frequency. The transverse emittance does not change dramatically over the range 64 to 70 mm half-cell length; dark-current reduction for a longer cell length has been demonstrated. The reduction of the dark current is explained by separation of photoemission and field emission [46].

CONCLUDING REMARKS

We have overviewed the discussion of Working Group 2, which was concerned with optics and beam transport issues for ERLs. There is no doubt that the energy recovery linac is a valuable and promising device, which will cover an unexplored area of accelerator technology: simultaneous realization of high-brightness and high-power beams. In the first meeting of the series of ERL workshops, ERL-2005, we made a list of optics and beam transport issues to resolve for exploiting full potential of ERLs. After two years of intensive efforts, we see a steady improvement on these issues, some of which will soon be demonstrated on test stands.

Development of components essential for successful ERLs has also settled into shape since the last workshop and optics and beam transport considerations should be performed in conjunction with developments in this area. The joint sessions we had in the workshop served as a good seed for such collaborations: future items in optics and beam transport which relate to the components development include simulations of a DC photo-injector with finite (more realistic) time response of a photocathode, injector optimization including trapped ions, and detailed investigation of multi-turn ERLs. The discussions we had at ERL07 give some basis for this work.

It is worth mentioning that 13 talks out of 30 in the WG2 discussions were given by the APS group and the Japanese group, who launched their ERL plans within the last two years. There are many interesting subjects in ERLs, and new entrants to the ERL community are truly welcome.

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