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Status of a Plan for an ERL Extension to CESR *

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Abstract

We describe the status of plans to build an Energy-Recovery Linac (ERL) X-ray facility at Cornell University. This 5 GeV ERL is an upgrade of the CESR ring that currently powers the Cornell High Energy Synchrotron Source (CHESS) [1]. Due to its very small electron-beam emittances, it would dramatically improve the capabilities of the light source and result in X-ray beams orders of magnitude better than any existing storage-ring light source. The emittances are based upon simulations for currents that are competitive with ring-based sources [2, 4]. The ERL design that is presented has to allow for non-destructive transport of these small emittances. The design includes a series of X-ray beamlines for specific areas of research. As an upgrade of the existing storage ring, special attention is given to reuse of many of the existing ring components. Bunch compression, tolerances for emittance growth, simulations of the beam-breakup instability and methods of increasing its threshold current are mentioned. This planned upgrade illustrates how other existing storage rings could be upgraded as ERL light sources with vastly improved beam qualities.

INTRODUCTION

Cornell University is currently prototyping a DC photo-emission electron source and a 10 MeV injector linac for low emittance beams of high CW currents [5]. The bunches that this injector is designed to produce could be accelerated in a CW linac to energies and with beam currents that are comparable to those of storage-ring based light sources. However, the transverse emittance and the bunch length at the end of the linac could be significantly smaller than for a ring-based source, so that X-ray beams of higher brilliance, higher coherence fraction, smaller cross-section and smaller bunch length could be produced.

Since todays ring-based light sources have beam energies of several GeV and beam currents a sizable fraction of an Ampere, Cornell is planning a facility that can deliver 5 GeV beams of 100mA. The production of a continuous beam of this current and energy by a one-pass linac would require delivering a power of the order of a GW to the beam. Without recovering this energy after the beam has been used, such a linac is impractical.

The energy recovery process that is to be used works as follows: After high-energy electrons have been used for X-ray production they are sent through cavities to excite fields, which in turn accelerate new electrons to high energy. Superconducting RF cavities will be used since normal conducting cavities cannot achieve high fields in CW operation.

Current (mA)	100	10	1
Charge/b (nC)	0.08	0.008	1.0
$\epsilon_{x/y}$(nm)	0.1	0.015	1
Energy (GeV)	5.3	5.3	5.3
Rep. rate (GHz)	1.3	1.3	0.001
Av. flux ($\frac{\mathrm{ph}}{0.1\%\ \mathrm{s}}$)	$9\ 10^{15}$	$9\ 10^{14}$	$9\ 10^{12}$
Av. brilliance ($\frac{\mathrm{ph}}{0.1\%\ \mathrm{s\ mm^2\ mrad^2}}$)	$1.6\ 10^{22}$	$3.0\ 10^{22}$	$2.0\ 10^{17}$
Bunch length (ps)	2	2	0.1

Table 1: Parameters for an ERL at Cornell University for three different running modes: for high flux, for high coherence and for short pulses. We show initial target emittance figures, simulations suggest that lower values may be possible.

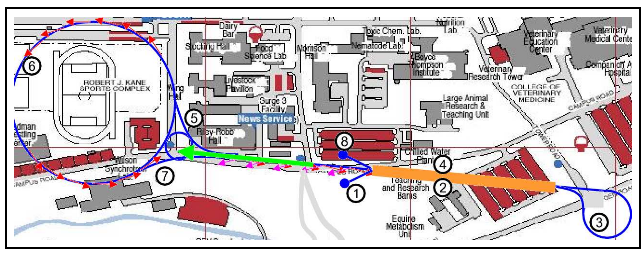

Figure 1: An ERL in an extended CESR tunnel.

DC photo-emission sources with negative electron affinity cathodes have been simulated to give less than 0.4πmm mrad for a 100mA beam current in a continuous beam at 1.3 GHz [2]. Contrary to storage rings, the transverse emittance in a linac can be reduced by using smaller bunch charges. Therefore a high coherence option with reduced average current is planned as well. Furthermore we plan for a short pulse option with reduced repetition rate and higher bunch charge for pump probe experiments with high time resolution. Parameters for the current scheme, not containing the smallest simulated emittances, are shown in Tab. 1. Construction of a prototype electron source and of a 10 MeV superconducting injection linac [6, 7, 8] that should together provide such beams is progressing well. With this facility we want to verify that the functionality of all essential devices and physical processes before proposing and building an ERL based user facility.

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OUTLINE

The high energy physics experiments for which CESR was built will be phased out in 2008. CESR will be available for CHESS operation alone when CESR stops high energy physics operation. Then we plan to upgrade CHESS to an ERL facility based on the CESR complex.

The design of such a facility should be made cost efficient by reusing much of CESR's infrastructure. The operating CHESS X-ray facility should be disrupted as little as possible while building and commissioning the ERL and there should be a sufficient number of X-ray beamlines. Furthermore, there should be potential for future upgrades. While it could have turned out that reusing CESR imposes too many constraints, quite contrary it has been found that the flexibility of CESR's magnet arrangement holds several advantages for an ERL design. First and second order electron optics have been found for bunch compression down to at least 100 fs with the code TAO [9, 10], and nearly all required magnet strength could be supported by the magnets that are in CESR today.

In [11] we have reported on an optimization which extends the CESR ring to a racetrack shape. Figure 1 shows the CESR tunnel and the layout of a possible linear ERL extension. Electrons from a 10 MeV injector (1) would be accelerated to the East in a 2.5 GeV linac (2). A return loop (3) would send them into a second linac which is located in the same straight tunnel (4) and accelerates to 5 GeV. An arc (5) injects the electrons into the CESR ring (6) where they travel counterclockwise until another arc (7) injects them back into the first linac, where they are decelerated to 2.5 GeV. The return loop leads the electrons to the second linac section where deceleration back to 10 MeV leads to the beam dump (8) [12].

A return arc is also shown which connects the arcs (5) and (7) so that electrons can return to the linacs after acceleration without passing through CESR. This connection has been chosen so that the ERL could be built and commissioned while CESR is still used as a storage-ring light source. Other advantages of this upgrade plan are that all of the CESR tunnel is reused, which creates space for a large number of insertion devices. The straight tunnel houses two linacs, which reduces tunnel cost as well as the required length of cryogenic lines and cables. The tunnel is laid out longer than required for the two linacs, so that an extension of the facility by extra undulators or by an FEL is possible.

BEAMLINES

The South half of the CESR tunnel would contain undulators and would reuse the current facilities of CHESS. Additionally, new user areas could be created in the North section of CESR (at the top of Fig. 1) and in straight sections of the linac tunnel. The location of the linac at a hillside is chosen in such a way that no existing building foundations interfere and that X-ray beamlines with easy access can be added between the linac and CESR. The outline and the optics for this section is shown in Figs. 2 and 3.

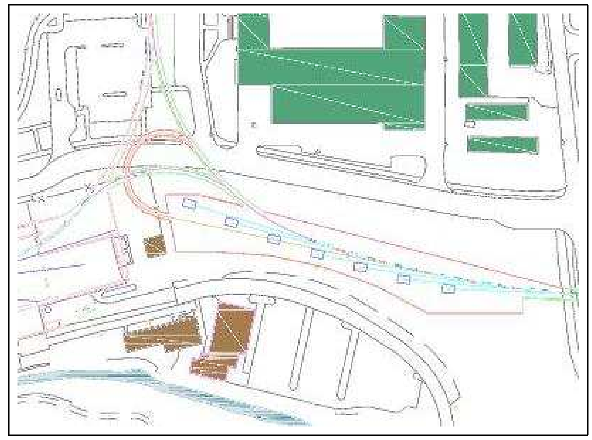

Figure 2: The beamline connecting the linac an the CESR ring. undulator beam lines are shown, but a CW FEL could also be operated in this region.

To limit the cost of cooling, the accelerating gradient of the SC cavities should not exceed 20MV/m. Thus, 250 m of cavities would lead to 5 GeV beam energy. However, much more space is required for the linac, since higher order mode (HOM) dampers and connecting tubes have to be placed after each cavity and 2 quadrupoles have to be placed after each cryomodule of ten 7-cell cavities. With TESLA type cavities and a beam pipe of 39 mm, the fill factor is about 53%. The total linac length would therefore have to be about 500 m. The tunnel extension shown in Fig. 1 has a section of 250 m with two linacs side by side.

In [11] a possible optics was presented which modified CESR as little as possible. It contains four undulators of 5 m length, two undulators of 2 m length and one 25 m long undulator in the South, and an equivalent arrangement could be added in the North. The beta functions are 1 m, 2.5 m and 12.5 m in the center of these undulators respectively but a flexible lattice can produce larger beta functions easily. Currently 18 beamlines and their science case are being investigated. The undulator length are: 25 m for 2, 5 m for 9, 2 m for 2, 1 m for 1, 2 m for 3 undulators in the 2.5 GeV loop in the East, and one diagnostic undulator. These studies cover the areas of: phase imaging and topography, coherent diffraction and XPCS microscopy on the nm scale, nanoscope and nanoprobe TXM and STXM to nm resolution, protein crystalography, inelastic X-ray scattering, femtosecond timing, resonant scattering, SAX and XPCS for mesoscopic science, and general material science, e.g. at high pressures. The undulators at 2.5 GeV would be for soft X-ray studies.

OPTICS

The loop (3) connecting the two linacs was chosen so as to produce an acceptable emittance increase due to synchrotron radiation. After appropriate nonlinear correction, the dynamics does not lead to emittance growth for a 0.2% energy spread beam that one obtains for 6° off-crest acceleration, as required for compressing a 2 ps long bunch to 100 fs after the linac. This loop could also be used for energy spread reduction by running the second linac -6° off-crest as discussed in [13].

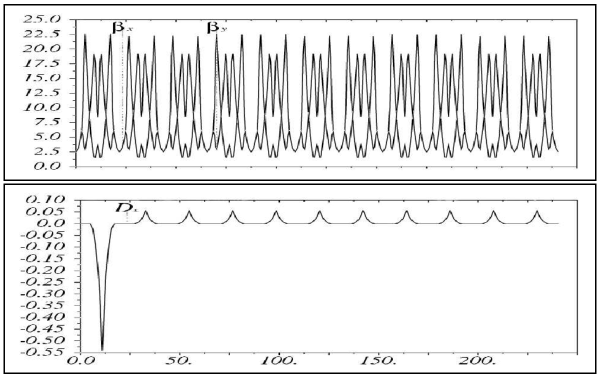

Figure 3: Beta functions and dispersion for the region between linac and CESR (units are m).

The emittance growth for a 100mA beam due to incoherent synchrotron radiation for the high flux option in Tab. 1 is 0.04 nm and therefore acceptable. The emittance growth due to coherent synchrotron radiation as computed by ELEGANT [14] is shown in Fig. 4. The fluctuations are due to second order dispersion, but the difference between the two curves shows the influence of coherent synchrotron radiation. It is approximately 0.0004nm and thus negligible.

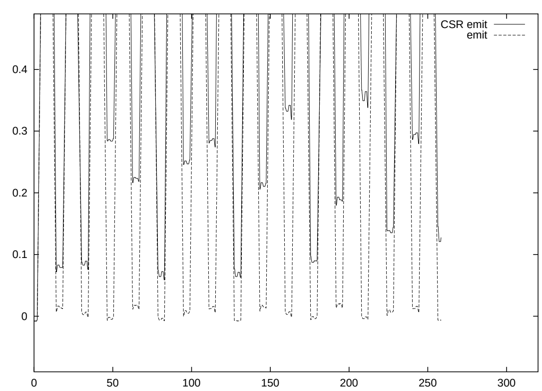

Figure 4: CSR emittance growth in the return loop. Solid: with CSR, dashed: without radiation. Units are % of 0.1nm along the linac (in m).

The optics for the linear accelerator is shown in Fig. 5 in x and y for the accelerating beam. The optics for the decelerating beam of the ERL is mirror symmetric. The beta functions are relatively small. The threshold current of the beam breakup (BBU) instability has been calculated for a similar optics. For quite pessimistic assumptions (HOMs with R/Q of 100 Ω and $Q = 10^4$) the threshold current is about 200mA for a HOM frequency randomization of 1.3 MHz. When the modes are polarized and an optics is

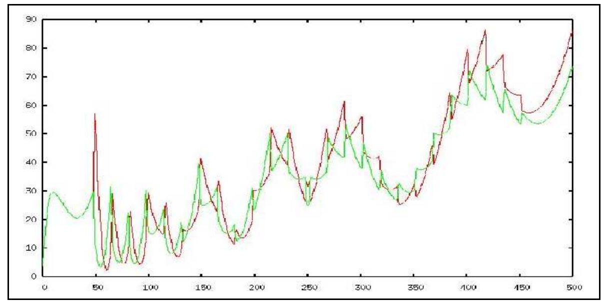

Figure 5: Optics in the two linacs (units are m).

chosen that couples horizontal oscillations to the vertical and vice versa [15], the threshold current is about 650mA.

Emittance growth due to coherent synchrotron radiation is a phenomenon which is hard to compute accurately. We are therefore also investigating alternate designs which minimize the total bend angle as in [11]. Which option is chosen will be decided by a mix of the number of beam lines available, the achievable beam properties, and the total cost of the project.

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