ERL UPGRADE OF AN EXISTING X-RAY FACILITY: CHESS AT CESR*

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Abstract

Cornell University has proposed an Energy-Recovery Linac (ERL) based synchrotron-light facility which can provide greatly improved X-ray beams due to the high electron-beam quality that is available from a linac. To provide beam currents competitive with ring-based light sources, the linac must operate with energy recovery, the feasibility of which we plan to demonstrate in a downscaled prototype ERL. Here we present two of several 5 GeV ERL upgrade possibilities for the existing 2nd generation light source CHESS at CESR. This proposed upgrade suggests how existing storage rings can be extended to ERL light sources with much improved beam qualities.

INTRODUCTION

Linear accelerators with a photo-emission electron source can produce transverse emittances and bunch lengths that are significantly smaller than those of storage rings. Since todays ring-based light sources have beam energies of several GeV and beam currents a sizable fraction of an Ampere, we are planning a facility that can deliver 5 GeV beams of 100 mA. Continuous beams of these currents and energies would require klystrons 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.

Energy recovery can be achieved when the high energy electrons after being used for X-ray production are sent through cavities to excite fields, which in turn accelerate new electrons to high energy. Since the high energy electron beam delivers most of the RF power to the cavities, the required klystron power is very much reduced. However, to continuously transfer field energy from electrons to the RF cavities and back to new electrons, it is essential that the cavities are continuously filled with field energy and thus are operated in continuous wave (CW) mode. Only SC cavities can achieve high fields in CW operation.

An injector, which in our case accelerates to 10MeV [1], is needed to send beam into such an ERL, and our efforts on the design of a superconducting injector cryomodule are well under way [2]. 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. [3]. However, the large beam powers and small transverse and longitudinal emittances required for an X-ray ERL have not been achieved anywhere, and we therefore plan to build a prototype facility that can verify the functionality of all essential devices and physical processes before building an ERL based user facility. The high energy physics experiments for which CESR was built will be phased out in about four years. CESR has been also used as the 5 GeV second generation light source CHESS since its construction and it will be available for this purpose alone when CESR stops high energy physics operation. Then we plan to upgrade CHESS to an ERL facility based on the CESR complex.

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

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

This will enlarge the wide range of applications of third generation light sources by producing beams similar to their CW beams, albeit with much higher brilliance due to the much smaller horizontal emittance and possibly smaller energy spread. At the same time, it can serve more specialized experiments that require ultra small emittances for high spacial resolution or ultra short bunches for high temporal resolution [4]. To obtain a photon flux similar to that of third generation light sources, we plan to accelerate a current of 100 mA. 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.

AN ERL UPGRADE TO CESR

The future ERL light source at Cornell University is under investigation. The design should be made cost efficient by reusing much of CESR's infrastructure. The operation of CHESS should be disrupted as little as possible while building and commissioning the ERL, the facility should provide space for a sufficient number of X-ray beamlines,

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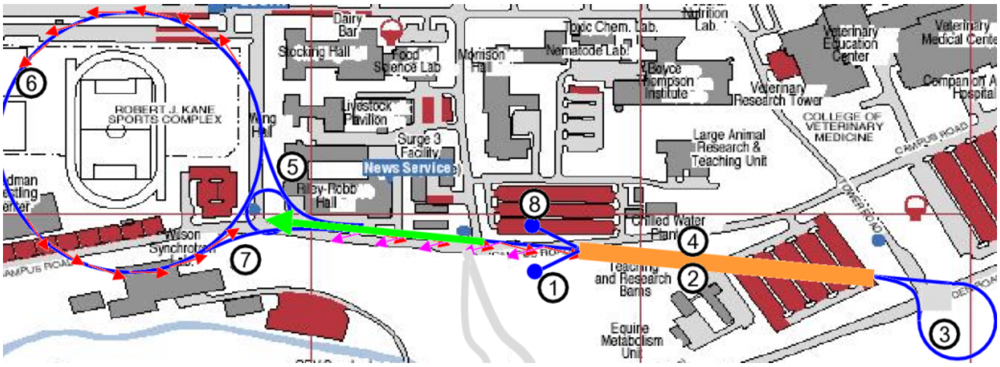

Figure 1: An ERL in an extended CESR tunnel.

and it should have the potential for future upgrades. In [5] we have reported on an optimization which extends the CESR ring to a racetrack shape. 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, and nearly all required magnet strength could be supported by the magnets that are in CESR today. In order to extend the space for cavities, to make space for possible upgrades, and to minimize the impact on CHESS operation, work has been invested in the layout of Fig. 1. It 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 5GeV. 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 2.5GeV. The return loop leads the electrons to the second linac section where deceleration back to 10MeV and leads to the beam dump (8). 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 the figure) 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.

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.

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. Our analysis, which is based on the 1.3 GHz cavity cell shape of the TESLA design, on four HOM couplers of the TTF type per cavity, and on one ferrite HOM damper of the CESR type per cavity, showed that for a beam tube radius of 39 mm we could not obtain a fill factor larger than 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 [5] 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. To the 14 undulators that could thus be placed in CESR additional undulators could be placed in the section between the linac and CESR, which has been designed with a gentle arc of achromats.

Two linacs and return loop

The loop (3) connecting the two linacs was chosen so as to produce an acceptable emittance increase due to synchrotron radiation. Figure 2 shows an optics with 16 achromatic cells. The magnet in the center of each cell has a negative bend to make the lattice isochronous, it has a horizontally focusing quadrupole which produces a very small average horizontal beta function, and it has a sextupole to correct the second order dispersion. After this correction, nonlinear 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 [6].

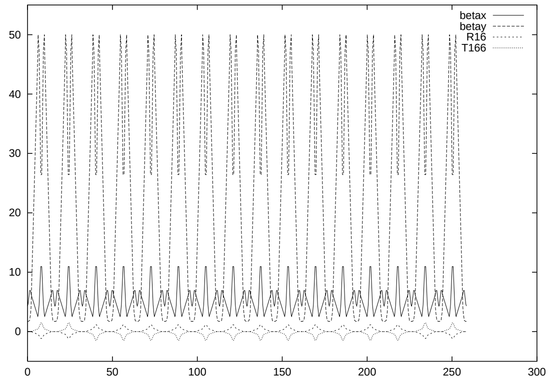

Figure 2: Optics of the return loop.

The emittance growth in this arc 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 [7] is shown in Fig. 3. 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 0.006nm and thus negligible.

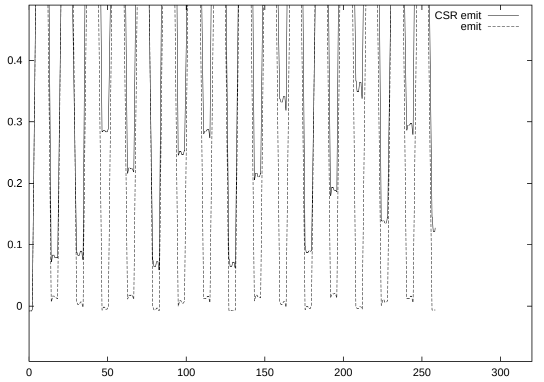

Figure 3: CSR emittance growth in the return loop.

The optics for the linear accelerator is shown in Fig. 4 in x and y for the accelerating beam. The optics for the decelerating beam of the ERL is close to mirror symmetric. The optics of linac and return loop was not well matched and the beta functions are thus not regular from 280 to 540m. Nevertheless, the beta functions are relatively small. The threshold current of the beam breakup (BBU) instability has been calculated for this optics [8]. As in the analysis of a straight linac in [4], the HOM spectrum of TTF cavities was used and a BBU limit between 500 and 600 mA was computed for 10MHz HOM-frequency spread.

Emittance growth due to coherent synchrotron radiation is a phenomenon which is hard to compute accurately.

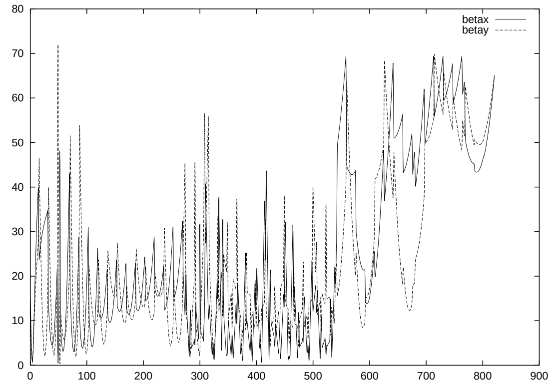

Figure 4: Optics in the two linacs and the return arc.

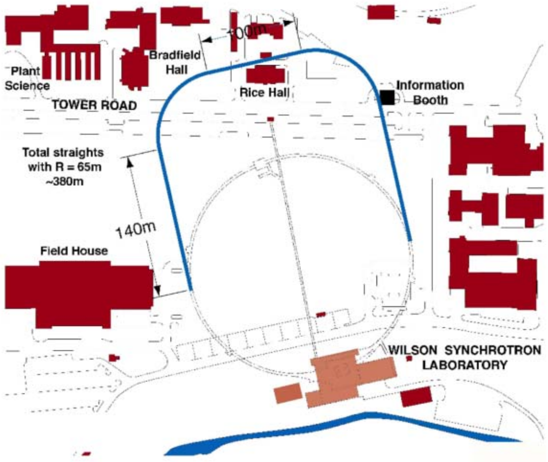

Figure 5: An ERL in the extended CESR tunnel minimizing bend angles.

We are therefore also investigating alternate designs which minimize the total bend angle of the ERL similar to what was presented in [5]. A possible layout that is adjusted to the geography of the Cornell campus is shown in Fig. 5.

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