A Lattice for a 5 GeV ERL in the CESR Tunnel*

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Abstract

It has been proposed to build an Energy-Recovery LINAC (ERL) based synchrotron-light facility at Cornell. Due to the high beam quality of a LINAC with photo injector, such a facility has the potential to provide better X-ray radiation than ring-based sources. To take advantage of the existing Cornell circular accelerator CESR for this 5 GeV ERL, it has been suggested that the LINAC should be split in sections that are at angles to each other and that half the CESR ring should be used as a return arc to connect the end of the LINAC back to the beginning of the LINAC. Here we specify the minimum optical requirements on such a layout and show a possible lattice for an ERL that uses CESR.

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. To build a light source that profits from this better beam, one has to accelerate to energies (several GeV) and use currents (several 100mA) that are typical for storage ring based light sources. This requires a power of order 1 GW to be delivered to the beam. Without somehow recovering this energy after the beam has been used, such a LINAC would be practically unfeasible.

Energy recovery can be achieved when the high energy electrons are used to generate cavity fields which in turn accelerate new electrons to high energy. Since the high energy electron beam then 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 a continuous wave (CW) mode. Therefore, the cavities of an ERL should be super conducting (SC) since only SC cavities can, in CW operation, achieve the high fields required.

Since neither an electron source, nor an injector system, nor an ERL, has ever been built for the required large beam powers and small transverse and longitudinal emittances, the Wilson laboratory at Cornell University plans to build a prototype facility [1] that can verify the functionality of all essential devices and physical processes before endeavoring to construct a large user facility.

While serving high-energy experiments, CESR has been used as the second generation synchrotron light source CHESS at 5 GeV. As a future light source for this laboratory, an ERL seems ideal. It can enlarge the wide range of applications of third generation light sources by producing beams similar to their CW beams, albeit with 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 [2]. After a successful prototype operation, it is planed to build a large scale ERL light source at Cornell University. The CESR ERL design uses SC TESLA type cavities with 20 MV/m gradiants to produce a 100 mA, 5 GeV electron beam with a 1.3 GHz repetition rate (equivalent to 77 pC/bunch) and a normalized emittance of 2μm. Two operational modes are envisioned: One with a 2 ps bunch–length and a short–bunch mode with bunch-lengths of less than 100fs.

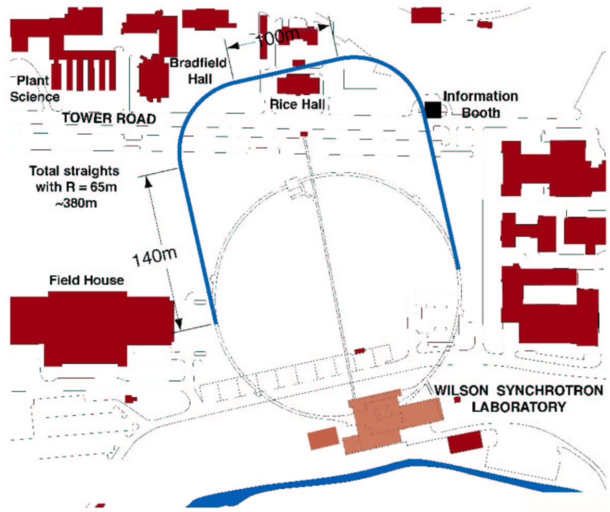

Figure 1: An ERL in an extended CESR tunnel

AN ERL IN THE CESR TUNNEL

How the future light source at Cornell should be constructed is currently under investigation. Here we present an option that takes advantage of CESR, which will no longer be needed for high energy physics experiments after the CESR-c/CLEO-c project is phased down in about 5 years [3]. We have made a design that tries to reuse as much as possible of CESR. The proposed ERL would reuse halp the CESR tunnel, some CESR components, and the infrastructure of CESR. The required extension of the tunnel is shown in Fig. 1. The three straight sections of the tunnel extension would house SC LINACs of 140m, 100m, and 140m length. They are separated by arcs of 65m radius.

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A 10 MeV injector would send electrons Northward into the West straight section. These electrons would emerge from the third straight section with an energy of 5 GeV. The South half of the CESR tunnel would contain undulators and would return the electrons to the first LINAC section. There they enter the LINAC on the decelerating phase, thus each electron transfers its energy back to the cavities and emerges after the third straight section with 10 MeV into a dump.

The site

In order to limit the cost of cooling, the accelerating gradient of the SC cavities should not exceed 20 MV/m. Thus, 250m of cavities would lead to 5 GeV of beam energy. However, much more space is required for the LINAC since higher order mode (HOM) dampers and connecting tubes have to be places after each cavity. Additionally, 2 quadrupoles have to be placed after each cryomodule of 8 cavities. The LINAC fill factor (ratio of cavity length to LINAC length) is estimated to be less than 67% based upon using a beam tube radius of 39mm with 1.3 GHz TESLA type cavities along with four TTF type HOM couplers and one CESR type ferrite HOM damper per cavity. The total LINAC length would therefore have to be at least 373m. The tunnel extension shown in Fig. 1 has three straight sections with a total length of 380m. A survey of the proposed tunnel extension showed that at the closest point the top of the tunnel was 9.8 m from any steam line and 11.3 m from any foundation wall which is more than an adequite clearance.

X-ray Needs

Before an ERL design could be made, it had to be determined how many undulators the X-ray users need and what types of undulator should be chosen. Together with the CHESS laboratory, it was decided that an initial design should contain two short undulators of 2m length, four with 5m length, and one 25m long undulator made of 5 modules. There should be no dispersion in the undulators and the beta functions should be 1m, 2.5m, and 12.5m in the center of these undulators respectively. The 1m beta function is designed for the production of micro beams, but a flexible lattice can produce larger beta functions easily. A facility with 7 undulators is relatively small, but considering that Cornell is a university and not a large national laboratory, this size might be favorable. Furthermore, it had to be decided how many undulators should be served with bunch length below 100fs. In this initial study only the 25m long undulator was required to have bunches with 100fs length. In short-bunch operation, the bunch–length in the other undulators would be between 140 fs and 600 fs.

LINAC with bends

While the necessity of segmenting the LINAC by bend sections initially seems unfortunate, it can have unexpected advantages for an ERL. The LINAC in an ERL contains one accelerating and one decelerating beam simultaneously, and these beams will have different paths in the bend sections. The two beams therefore will be separated after the first bending magnet, and they have to be guided in two separate beam lines to be finally recombined in the last bending magnet. The advantage that such an arrangement can have over a 380m long LINAC is that the particle optics of the two different beams can be influenced separately in the two beam lines. While the two beams with initially very different energies (5 GeV vs. 10 MeV at injection) have to be guided by a common optical system for 380m in a single LINAC, in our design only 140m long sections are common to both beams. Consequently, it is more difficult to find an acceptable optics for a straight LINAC, and in an initial design [2] a quadrupole triplet was needed after every cryomodule. In the design for the CESR extension that is shown in Fig. 2, only quadrupole doublets of the TTF type are used. The first 50m are shown for the low energy (top) and the high energy (bottom) beam. Here, the second, third, and fourth cavity are operated 90° off crest, so that they only influence the longitudinal phase space but do not accelerate. This allows the low energy beam to pass its focus at 4m without being over-focused by the RF field.

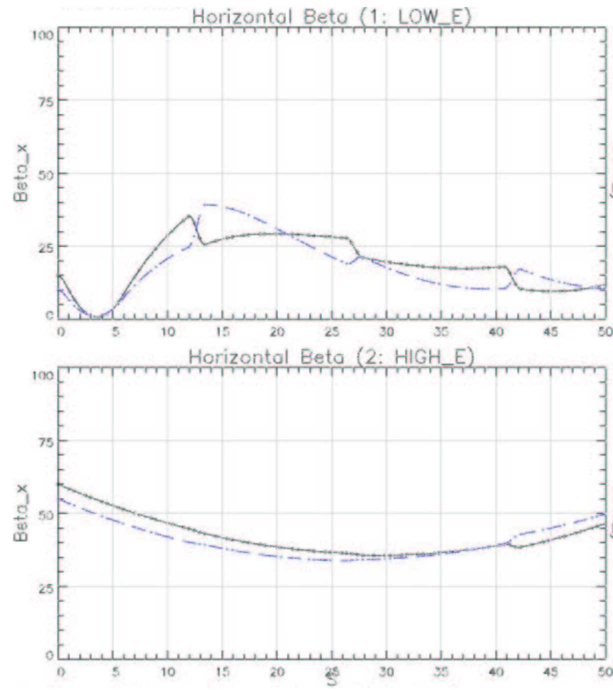

Figure 2: Beta functions at the start of the LINAC

The threshold current of the beam breakup (BBU) instability has been calculated for this optics [5]. As in the analysis of a straight LINAC in [2], the HOM spectrum of TTF cavities was used and a BBU limit between 100 and 200mA was computed.

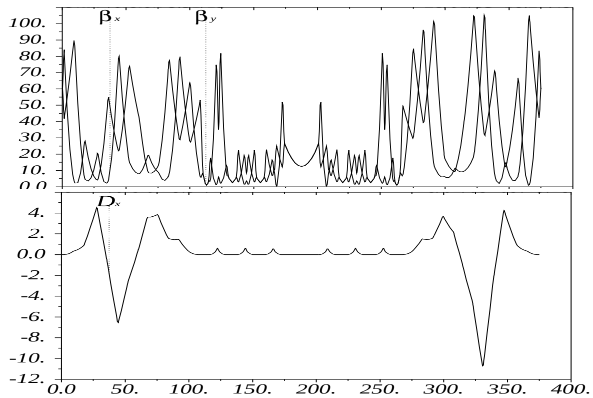

Figure 3: Beta functions and dispersion in the arc

Arc optics

We studied whether a favorable optics can be found for the CESR South arc in spite of the constraints imposed by the existing tunnel. To reuse as much as possible from CESR, we maintained the bending magnets and quadrupoles in their current positions and only replaced the regions where the undulators would be installed. Each undulator has two matching quadrupoles at each side and is separated from the next undulator by a three-bend achromate. Finding an optics for the operation with 2ps bunch length turned out to be relatively simple. The matching constraint were: $\beta =$1m, 2.5m, 2.5m, 12.5m, 2.5m, 2.5m, 1m in the seven successive undulators, and $\alpha = 0$, $D = 0$, $D' = 0$ in these seven places.

The optics for an rms bunch length of 100fs has to fulfill several additional requirements. The RF acceleration phase ϕ and the first and second order time of flight terms R_{56} and T_{566} of the first half of the arc have to be chosen to yield the desired bunch length in the central undulator [4]. For the second half of the return arc, R_{56} and T_{566} are determined by minimizing the energy spread after deceleration. The beta function and the dispersion for the return arc are shown in Fig. 3. Even though the magnet arrangement is symmetric around the center of the arc, the optics functions are not symmetric since the conditions for R_{56} and T_{566} are different for the two halves.

The second order time of flight term T_{566} is influenced by sextupoles and has to have the same sign as R_{56}. This is hard to achieve in the achromatic arrangements that have been proposed for this purpose. However, with the FODO like optics of the CESR arc this can be achieved with relatively weak sextupoles. This advantage is due to the large dispersion after the LINAC.

The nonlinear dynamics due to the sextupoles can increase the emittance. However, due to the weak sextupoles and the small transverse beam size, the dynamics is so weakly nonlinear that only the second order dispersion T_{166} and its slope T_{266} had to be eliminated in the center of the return arc. The second order conditions on T_{566}, T_{166} and T_{266} were satisfied by three sextupoles on each side of the arc close to the three maxima of the dispersion in Fig. 3.

For short-bunch operation, coherent synchrotron radiation (CSR) can also increase the emittance. The emittance growth was computed with the code ELEGANT and is shown in Fig. 4. Since the beam dilution due to the nonlinear dispersion is included, the emittance is shown to decrease where the second order dispersion is corrected. In the central undulator, the emittance for 100fs bunch length has only increased by a factor of 1.8. To limit the emittance growth, it was found prohibitive to compress the bunch length to its minimum since this creates a spike in the longitudinal density and strongly enhances CSR. We therefore increased ϕ to obtain 100fs bunches without full compression.

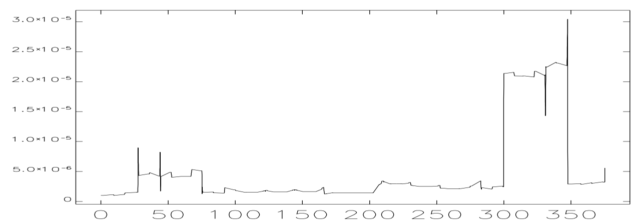

Figure 4: Effective emittance along the arc

CONCLUSION

The possibility of extending the CESR tunnel to include an ERL has been investigated. Geographically such an extension is possible. Furthermore, a suitable optics for the LINAC and for the return arc has been found that supports sub 100fs bunch lengths. The required dipole, quadrupole, and sextupole magnets are about as strong as the magnets of CESR.

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