FEL POTENTIAL OF THE HIGH CURRENT ERLS AT BNL *

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Abstract

An ampere class 20 MeV superconducting Energy Recovery Linac (ERL) is under construction at Brookhaven National Laboratory (BNL) [1] for testing concepts for high-energy electron cooling and electron-ion colliders. This ERL prototype will be used as a test bed to study issues relevant for very high current ERLs. High average current and high performance of electron beam with some additional components make this ERL an excellent driver for high power far infrared Free Electron Laser (FEL). A possibility for future up-grade to a two-pass ERL is considered. We present the status and our plans for construction and commissioning of the ERL. We discus a FEL potential based on electron beam provided by BNL ERL.

INTRODUCTION

The R&D ERL facility at BNL aims to demonstrate CW operation of ERL with average beam current in the range of 0.1-1 ampere, combined with very high efficiency of energy recovery. The ERL is being installed in one of the spacious bays in Bldg. 912 of the RHIC/AGS complex.

The ERL R&D program is pursued by the Collider Accelerator Department (C-AD) at BNL as an important stepping-stone for 10-fold increase of the luminosity of the Relativistic Heavy Ion Collider (RHIC) using relativistic electron cooling of gold ion beams with energy of 100 GeV per nucleon. Furthermore, the ERL R&D program extends toward a possibility of using 10-20 GeV ERL for future electron-hadron/heavy ion collider, eRHIC [2].

These projects are the driving force behind the development of ampere-class ERL technology, which will find many applications including light sources and FELs.

The intensive R&D program geared towards the construction of the prototype ERL is under way: from development of high efficiency photo-cathodes [3] to the development of new merging system compatible with emittance compensation [4].

LAYOUT OF THE R&D ERL

Two operating modes are envisaged, namely the high current mode and the high charge mode. The high current (0.5 A) mode will operate electron bunches with lower normalized emittance, 0.7 nC charge per bunch at 703 MHz rep-rate. In this case, the full energy of electrons at gun exit is limited by the available RF power 2.5 MeV. In high charge mode electron beam will consist of bunches with charge up to 5nC per bunch at 10MHz repetition rate, 50 mA average current. The electrons energy at the exit of the gun can be pushed upto 3.0-3.5 MeV by the maximum field attainable in the super-conducting gun itself.

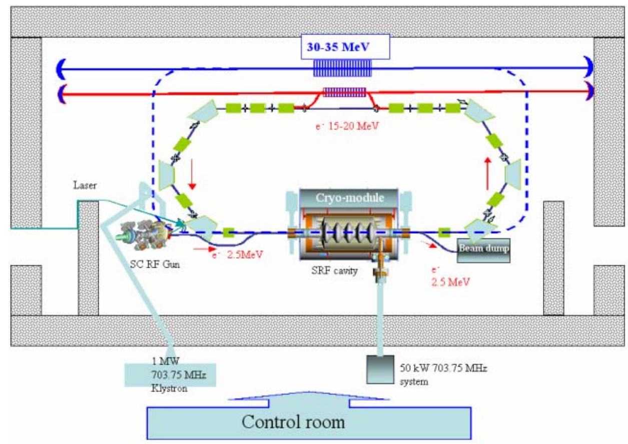

Figure1: Layout of the R&D energy recovery linac in the shielded vault with possible FEL setup. Dashed line shows considered second pass upgrade.

The ERL design (shown in Fig. 1) has one turn: electrons are generated in the superconducting half-cell gun and injected into the main superconductive linac. Linac accelerates electrons 15-20 MeV, which pass through a one turn re-circulating loop with achromatic flexible optics [5].

The photocathode is located in a high electric field for immediate acceleration of the electrons to as high energy as possible, reducing emittance degradation due to strong space charge force. Furthermore, linear part of space charge effects is compensated by applying a suitable external solenoid magnetic field.

In nominal recovery operation regime the path-length of the loop provides for 180 degrees change of the RF phase, causing electron deceleration (hence energy recovery) down to injection energy. The decelerated beam separates from the higher energy beam and goes to the beam-dump.

ERL Injector

The electron injector is a central part of any ERL that has to deliver high brightness electron beam. The BNL R&D ERL injector (see Fig. 2) consist of ½ cell superconducting RF gun with photocathode inside, solenoid, four dipoles and two solenoids turned on in opposite direction (in order to match the electron beam with linac entrance more accurately). The 4^{th} dipole mergers the high and low energy beams.

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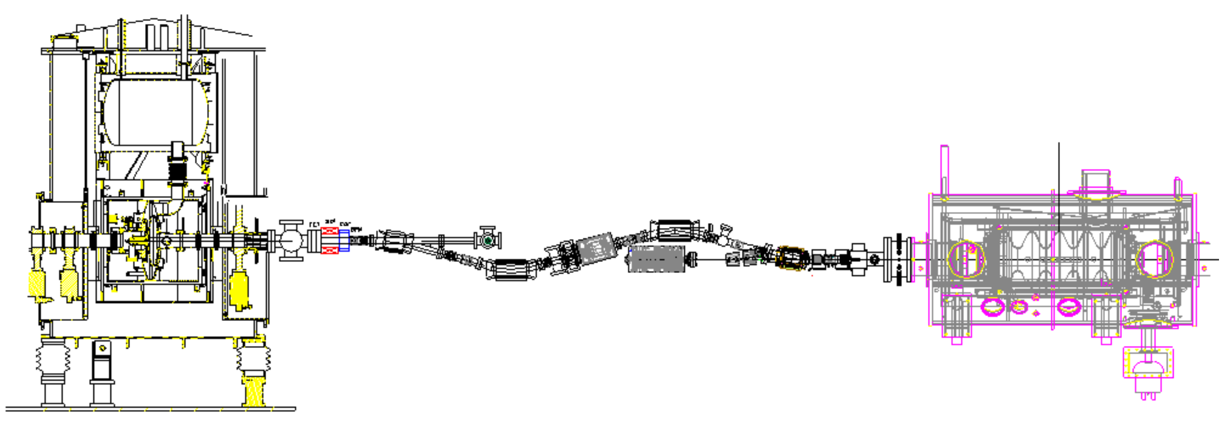

Figure 2: Detailed drawing of SRF Injector for the BNL R&D ERL.

For R&D ERL the superconducting 703.75 MHz RF (SRF) gun was selected (Fig.3). The gun design with a short 8.5 cm cell was chosen in order to provide reasonably high electric field at the cathode at this low accelerating voltage. To provide effective damping of high order mode (HOM) this gun has rather large iris radius of 5 cm. More details on the SRF gun and its photocathode system can be found elsewhere [6].

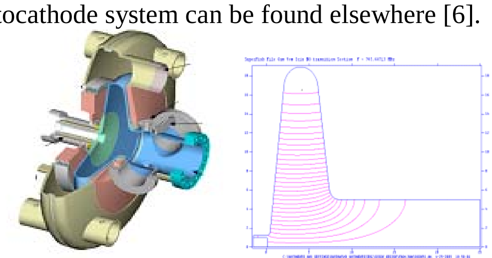

Figure 3: The SRF gun, in helium vessel (cartesy Advance Energy System) and SUPERFISH electric field profile simulation.

Merger

One of the novel systems we plan to use for the R&D ERL is a merging system providing achromatic condition for space charge dominated beam and compatible with the emittance compensation scheme [4].

Table 1: Electron beam parameters of the R&D ERL injector.

Charge per bunch, nC	0.7	1.4	5
Injection energy, MeV	2.5	2.5	3
Max. beam energy, MeV	20	20	20
Average beam current, A	0.5	0.5	0.05
Bunch rep-rate, MHz	700	350	9.38
Normalized emittance ex/ey, µm	1.4/1.4	2.2/2.3	4.8/5.3
Rms energy spread, %	0.35	0.5	0.97
Rms bunch length ps	18.5	21	31

Focusing of the bending magnets in the merging section has significant effect on the low energy electrons. Different focusing in vertical and horizontal planes (astigmatism) makes impossible simultaneous emittance compensation. Hence, the use of combined function magnets [7] with equal focusing strength in x- and y-direction is necessary.

Fig. 4 shows result of PARMELA [8] simulations of the ERL injector for different charge per bunch. Due to the bends in vertical direction the effect of vertical emittance growth is clear. But at the exit of Z-merger both: vertical and horizontal emittances become almost equal. In case of 5 nC per bunch this equality is broken, the next order nonlinearity start playing a role.

The main expected electron beam parameters of this system obtained by PARMELA simulations are listed in Table 1.

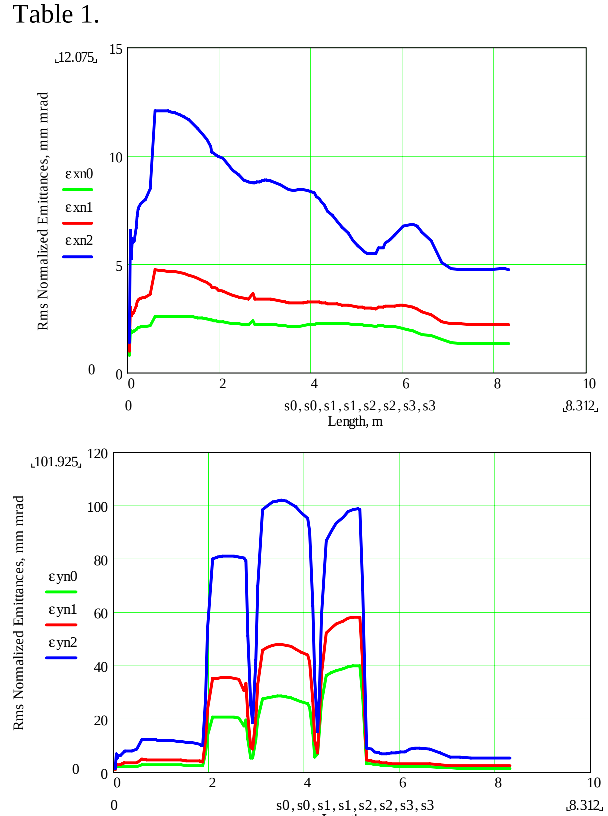

Figure 4: Evolution of normalized beam emittances (top figure – horizontal, bottom figure- vertical) in the ERL injector. Bunch charge: 0.7 nC-GREEN, 1.4 nC- RED, 5nC –BLUE.

5-cell SRF linac

The heart of the ERL facility is 5-cell SRF linac, which is designed for operating with ampere-class CW beam current [9]. The cavity was designed as a “single-mode” cavity, in which all Higher Order Modes (HOMs) propagate to HOM ferrite absorbers through the large beam pipe. This design provides for very low Q’s for HOMs and hence very high ERL stability. Measurements of the damped Q and R/Q of the HOMs and simulations show that in nominal operation regime the cavity is stable to over 20 amperes in a one pass ERL and over 2 amperes for two passes ERL.

Figure 5: The ERL cavity following BCP at JLab.

We plan to intentionally tune the lattice of the ERL to a special mode to test the TDBBU predictions for our SRF linac with current limited only to few hundreds of milliamps.

The cavity was built by AES and is undergoing chemistry at Jefferson Laboratory. Figure 5 shows the cavity at JLab after the first BCP. The 5-cell SRF linac built by AES and is planned to be installed and tested in Bldg. 912 this year.

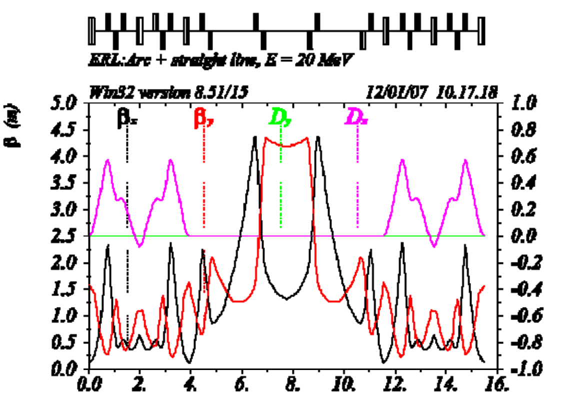

Figure 6: Lattice β and D functions of the R&D ERL for the case of zero longitudinal dispersion $D_s = m_{56}$. The m_{12} and m_{34} elements are controlled independently using quadrupoles in the dispersion-free straight section.

Loop lattice

The lattice of the ERL loop controls the parameters of a symplectic transport matrix, which affect the stability and operation conditions of the ERL. The lattice of the loop is intentionally chosen to be very flexible for the R&D ERL to be a test-bed of new ampere-range of beam currents in ERL technology [10]. The adjustable part of the lattice has two arcs and a straight section. Each arc is an achromat with adjustable longitudinal dispersion. Quadrupoles in the dispersion-free straight section provides for matching of the β-function and for choosing the desirable phase advances independently in horizontal and vertical planes. The lattice functions for isohronus operation regime are shown in Fig.6. The PARMELA tracking result for 0.7 nC per bunch from the cathode to the dump are shown in Fig.7 and Fig. 8.

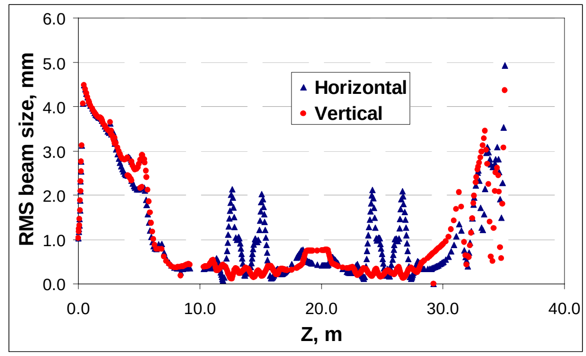

Figure 7: RMS beam size evolution from the cathode to the beam dump as a PARMELA tracking (Q=0.7 nC per bunch).

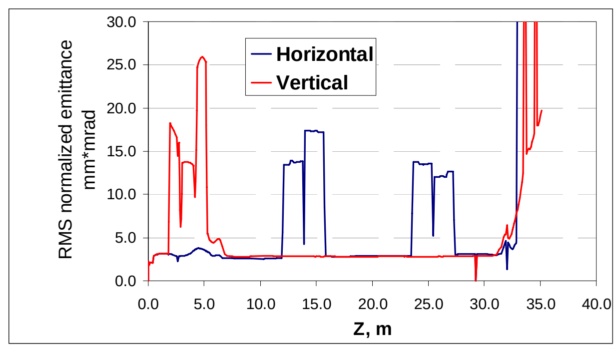

Figure 8: RMS normalized emittances evolution from the cathode to the beam dump as a PARMELA tracking (Q=0.7 nC per bunch).

The PARMELA simulation demonstrates what after the acceleration to 20 MeV the emitances are preserved (Fig. 8). There are effective horizontal emittance jumps due to nonzero dispersion inside the banding arcs. However in dispersion free straight section vertical and horizontal emittances are equal again.

Beam dump

After a cycle of acceleration and deceleration back to the injection energy 2.5 MeV electron beam goes to beam dump. The beam dump has bullet like shape inside with full water cooled jacket around. This beam dump is an exact copy of that is used for 1MW klystron water cooled collector and this beam dump can accept electron upto 2 MW avrage power CW. In order to avoid very hot spots on a surface of the beam dump the electron beam is over focused by short focal length solenoid. The result of simulation shows on Fig 9 what maximum power density is less 200 W/cm^2.

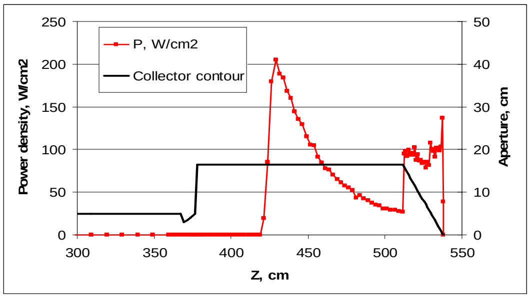

Figure 9: Power density distribution of 1 MW electron beam in the beam dump.

FEL POTENTIAL OF THE R&D ERL

The availability of high current electron beam with low emittance (see Tab. 1) opens new perspective of using BNL R&D ERL as an electron beam provider for free electron laser. The simplest upgrade is to install in the dispersion free straight section bypass with one undulator and mirrors from both side. For shorter wavelength we consider the potential extension of this facility into two turn configuration and installation of IR FEL. The shielded vault is designed for ERL with maximum energy of 54 MeV to accommodate these future up-grades. The loop of the ERL is designed to accommodate large energy spread of electron beam in the case of operating a 100 kW CW FEL [10].

An other option to use the high power electron beam in optics-free (ring [11]) FEL. The simple schematic of such type of FEL layout is shown in Fig. 10. There are two undulators in straight section and isochronous 360 degrees bend. Radiation from the second undulator (amplifier) produces energy modulation of the new coming beam inside the first undulator (modulator). The isochronous bend delivers the modulated electron beam in the amplifier. One of the big issues is to preserve microbunching structure of the electron beam during the 360 degrees turn.

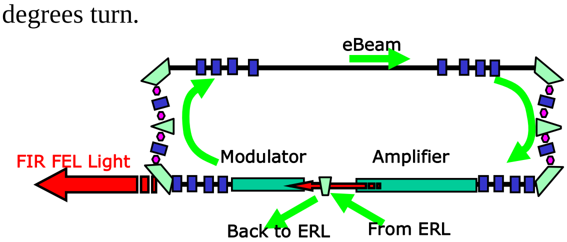

Figure 10: Schematic layout of optics free FEL

For 5 cm undulators period and 0.7 nC electron beam (Tab. 1) at rep. frequency 9.38 MHz the GENESIS [12] simulation gives: wavelength 29 microns, peak power 2 MW and average power 400 W. For full current mode operation rep. rate 703.75 MHz we obtain 30 kW far infrared in CW mode.

CONCLUSSIONS

We are designing, constructing, and commissioning a small (about 20 meters in circumference) R&D ERL to test the key issues of amp-class CW electron accelerator with high brightness beams, required for future nuclear physics experiments at RHIC-II and eRHIC. Extensive R&D program on many novel components to be used in the ERL is under way. The prototype ERL will demonstrate the main parameters of the electron beam required for electron cooling.

This facility, planned to be commissioned in 2009, will serve as the test-bet for new range of beam parameters whose application will extend well beyond the goals set forward by Collider Accelerator Department at BNL.

The high avrage current and nice performance of the electron beam makes BNL R&D ERL opens the potential of using this machine as an electron source for kilowatts class FELs.

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