THz RADIATION SOURCE POTENTIAL OF THE R&D ERL AT BNL *

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Abstract

An ampere class 20 MeV superconducting Energy Recovery Linac (ERL) is under commissioning at Brookhaven National Laboratory (BNL) for testing concepts for high-energy electron cooling and electron-ion colliders [1-3]. This ERL will be used as a test bed to study issues relevant for very high current ERLs. High repetition rate (9.5 MHz), CW operation and high performance of electron beam with some additional components make this ERL an excellent driver for high power coherent THz radiation source. We present the status and commissioning progress of the ERL. We discuss potential use of BNL ERL as a source of THz radiation and results of the beam dynamics simulation.

INTRODUCTION

The R&D ERL facility at BNL aims to demonstrate CW operation of ERL with average beam current upto 0.3 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 (Fig. 1). The bay is equipped with an overhead crane. The facility has two service rooms and a shielded ERL cave. Its control room is located outside of the bay in a separate building. The single story house is used for a high voltage power supply for 1 MW klystron. The two-story unit houses a laser room, the CW 1 MW klystron with its accessories, most of the power supplies and electronics. The intensive R&D program geared towards the construction of the prototype ERL is under way [2]: from development of high efficiency photo-cathodes [4], design, construction and commissioning SRF gun [5], to the development of new merging system compatible with emittance compensation technic [6]. The R&D ERL will test many generic issues relevant with ultra high current continuously operation ERLs: 1) SRF photo-injector (704 MHz SRF Gun, photocathode, laser) capable of 500 mA. 2) Preservation of low emittance for high-charge, bunches in ERL merger; 3) High current 5-cell SRF linac with efficient HOM absorbers; 4) BBU studies using flexible optics; 5) Stability criteria of amp class CW beams.

Figure 1: Layout of the R&D energy recovery linac in the shielded vault in bldg 912:1-Control Room; 2-diagnostic and control racks; 3-704 MHz 50 kW CW RF transmitter; 4- 704 MHz 1MW CW klystron; 5- 2MW CW HV power supply for the klystron; 6- magnets power supplies and other controls; 7-shielded ERL vault with removable beams; 8- 2 MeV 704 MHz SRF photo-injector; 9- 15-20 MeV 704MHz 5–cell SRF linac; 10 –return loop; 11- beam dump.

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Table 1: Electron Beam Parameters for Different Modes of Operation

	R&D ERL Design	
	High Current	High charge
Charge per bunch, nC	**0.5**	**5**
Energy maximum/injection, MeV	20/2.5	20/3.0
R.m.s. Normalized emittances ex/ey, mm*mrad	1.4/1.4	4.8/5.3
R.m.s. Energy spread, dE/E	$3.5x10^{-3}$	$1x10^{-2}$
R.m.s. Bunch length, ps	18	31
Bunch rep-rate, MHz	700	9.383
Gun/dumped avrg. current, mA	500	50
Average current, mA	**350**	**50**
Injected/ejected beam power, MW	1.0	0.150
Numbers of passes	1	1

GENERAL LAYOUT AND MODES OF ERL OPERATION

Our present 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 to 15-20 MeV, which then traverse a one turn re-circulating loop with achromatic flexible optics [8].

Two operating modes (Tab.1) will be investigated, namely the high current mode and the high charge mode. In the high current (0.35 A) mode ERL will operate electron bunches with lower emittance 0.5 nC bunches with 703 MHz rep-rate. In this case the full energy of electrons at gun exit is limited to 2.5 MeV by the available RF of 1 MW. In a high charge mode, ERL will have electron beam with 5nC per bunch and 10MHz repetition rate, i.e. it will have 50 mA average current. In this mode, the electrons energy at the gun exit could be pushed higher. The limit of 3.0-3.5 MeV most likely will be determined by the maximum field attainable in the super-conducting gun.

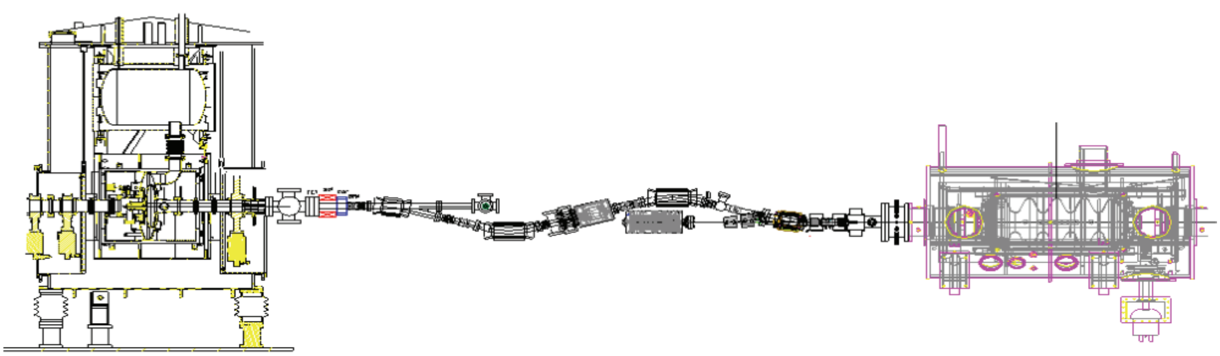

Figure 2: Detailed drawing of SRF Injector for the BNL R&D ERL.

SRF COMPONENTS

The electron injector is a central part of any ERL that has to deliver high brightness electron beam. The BNL R&D ERL injector (Fig. 2) consist of 1⁄2 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). 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 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. SRF Gun is under commissioning the voltage of 2 MV has been achieved without cathode stalk during the CETs last year [5] the most recent results 0.9 MV with cathode installed achieved in August 2013. More details on the SRF gun and its photocathode system can be found elsewhere [9].

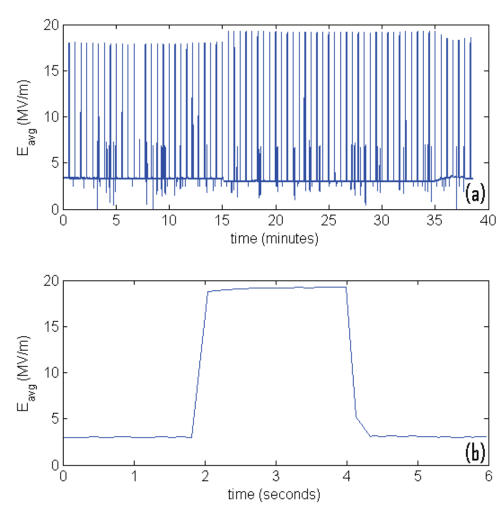

Figure 4: 5 cell cavity performance during horizontal test. Pulses are 2 seconds long with a 30 second interval.

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The heart of the ERL facility is 5-cell SRF linac (Fig. 4), 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.

The 5cell cavity has been commissioned in 2010. In cold emission tests high gradients are achieved for short period of time (Fig. 4). A thermal problem has been discovered during commissioning SRF 5-cell cavity, which prevents CW operation at gradients above ~12 MV/m. However, the prototype program can still be pursued if the cavity can be operated in a pulsed "quasi-cw' mode up to 20 MV/m, in which the cavity is on, with stable gradient, for a time long compared with the transit time through the ERL loop (10 nsec) [6].

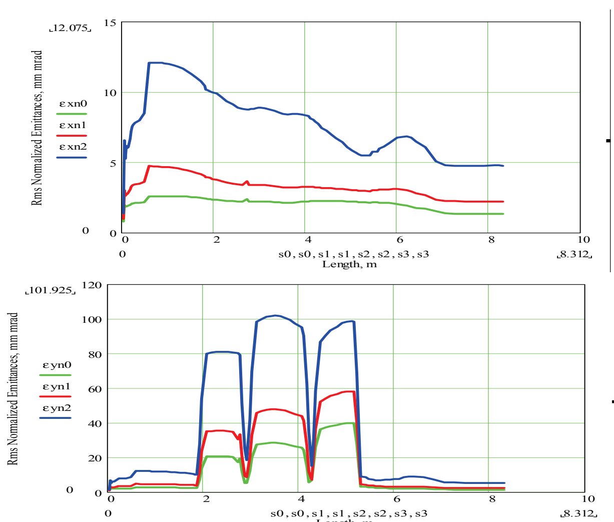

Figure 5: Evolution of normalized beam emittances in ERL injector (top figure – horizontal, bottom figure- vertical). Bunch charge: 0.7 nC-GREEN, 1.4 nC- RED, 5nC –BLUE.

MERGER

Any ERL required a merging system the place there low energy (injected) beam merging with high energy (already accelerated) one. 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]. 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 with equal focusing strength in x- and y- direction is necessary. Fig. 5 shows result of PARMELA 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.

THZ POTENTIAL OF THE R&D ERL

The availability of high quality CW electron beam with low emittance (see Tab. 1) opens new perspective of using BNL R&D ERL as a THz radiation device.

The minimum set of beam requirements for THz mode operation listed in Table 2.

Table 2: Required Parameters for THz Mode Operation

Charge per Bunch:	~100 pC
Beam Energy:	20 MeV
Normalize emittance	~10e-6
Bunch length:	~100um
Energy spread on crest	0.1%
Peak current:	200 A
Max. Rep Rate:	10 MHz

Beam dynamic simulation of ERL injector for low charges is shown on Fig 6.

The long injection line and low gun energy creates significant difficulties to keep bunch short at 100 pC. On of the possible improvement, which we plan to try, increasing the gun energy and adjust the cathode longitudinal position inside the gun.

The results of linear bunch compressing after the linac at 20 MeV: the linac phase 29 degree and bunch compressor with M56=15cm without space charge and CSR effects shown at Fig 7.

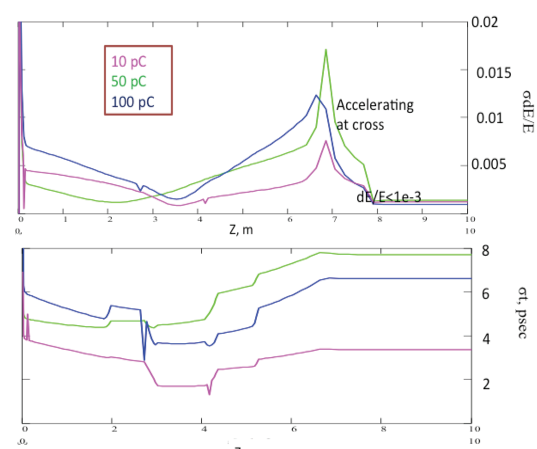

Figure 6: Longitudinal beam dynamics for low charge operation: Evolution of energy spread (top figure – rms energy spread, bottom figure- rms bunch length) in the ERL injector. Bunch charge: 10 pC -magenta, 50 pC -green, 100pC –blue.)

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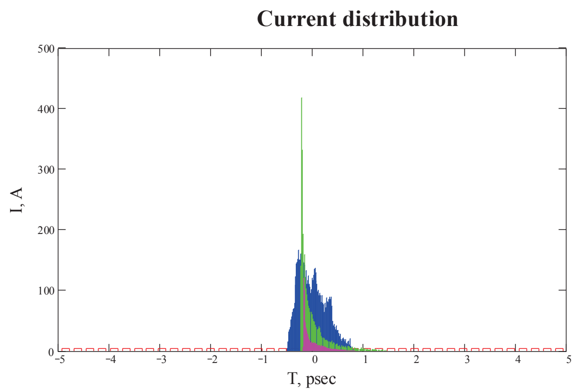

Figure 7: Current distribution after compression: magenta Q=10 pC, σz= 59um, Imax=120 A, green Q=50 pC, σz=89um, Imax=418 A, blue Q =100 pC, σz=83um Imax=167 A.

The expected enhancement N^2 of coherent component of bunched beam radiation (where N is number of particles in the bunch)

$$\left.\frac{\mathrm{d}^2 I}{\mathrm{d}\omega \mathrm{d}\Omega}\right|_{\text{bunch}} = N\left[1+(N-1)\,F(\omega)\right] \left.\frac{\mathrm{d}^2 I}{\mathrm{d}\omega \mathrm{d}\Omega}\right|_{\text{single}},$$

will be significantly reduced by the form factor

$$F(\omega) \equiv \left| \int \rho(\boldsymbol{x})\, \mathrm{e}^{\mathrm{i}\omega \hat{\boldsymbol{n}}\cdot \boldsymbol{r}/c} \mathrm{d}^3 x \right|^2$$

The results of radiation spectrum calculation in THz from different inserting devices are shown at Fig 8.

PLANS AND CONCLUSION

We have designed and start 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.

The R&D ERL will demonstrate the main parameters of the electron beam required for high energy electron cooling and for electron ion colliders.

We are in commissioning SRF Gun stage. After high power RF conditioning, the gun cavity is now able to operate at 2 MV in CW mode. The first beam test is scheduled next month.

Then the injection merger will be installed in order to test the concept of emittance preservation in a beam merger.

Then the recirculation loop will be completed to demonstrate energy recovery with high charge per bunch and high beam current. ERL will be operation next summer.

We started explore the possible use of BNL ERL beyond of initial goals. Parameters that can be achieved at ERL looks promising for THz application. The system needs additional tuning in order to reach reasonable power in THz mode. Work is in progress.

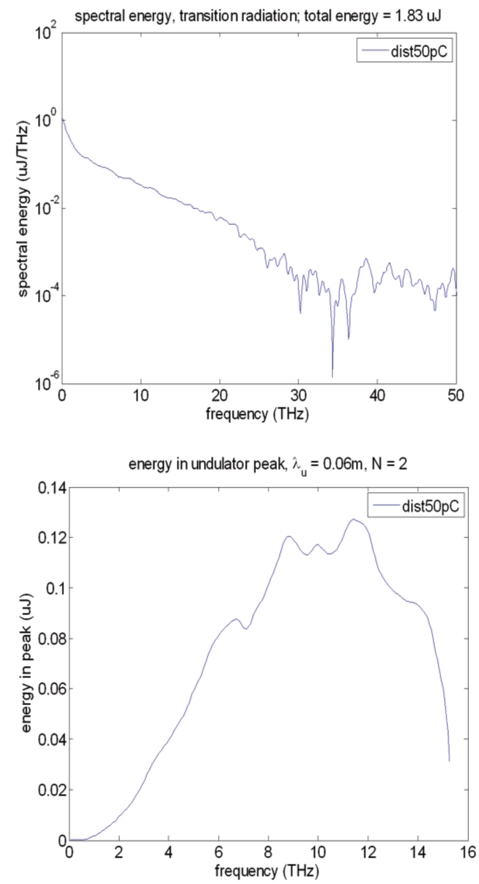

Figure 8: Radiation spectrum for 50 pC charge per bunch. (top) aluminium foil transition radiation, (bottom) 2 periods of undulator radiation.

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