HIGH CURRENT ENERGY RECOVERY LINAC AT BNL*

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Abstract

We present the design and the parameters of a small Energy Recovery Linac (ERL) facility, which is under construction at Collider-Accelerator Department, BNL. This R&D facility has goals 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 possibility for future up-grade to a two-pass ERL is being considered. The heart of the facility is a 5-cell 703.75 MHz super-conducting RF linac with HOM damping. Flexible lattice of ERL provides a test-bed for testing issues of transverse and longitudinal instabilities and diagnostics of intense CW e-beam. ERL is also perfectly suited for a far-IR FEL. We present the status and plans for construction and commissioning of this facility.

GOALS OF ERL R&D PROGRAM AT BNL

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) [1] using relativistic electron cooling [2] of gold ion beams with energy of 100 GeV per nucleon. The system with increased luminosity and electron cooling, called RHIC II, is sketched below.

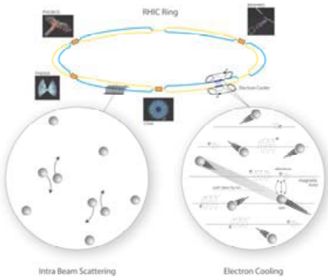

Figure 1. Electron cooling of RHIC, pictorial diagram. Electron cooling is used to reduce the emittance of an ion beam circulating in a storage ring by transferring the transverse motion (the heat) from a high emittance (hot) ion beam to a low emittance (cold) electron beam.

Furthermore, the ERL R&D program extends toward a possibility of using 10-20 GeV ERL for future electron-hadron/heavy ion collider, eRHIC [3].

The 10-fold increase of luminosity in RHIC II will extend the studies of quark-gluon plasma and QCD vacuum beyond the discovery phase towards their full characterization [1]. The ERL-based eRHIC with luminosity of 10^{34} $cm^{-2}sec^{-1}$ per nucleon will extend the capability of RHIC even further using polarized electrons to probe Colour Glass Condensate and spin structure of nuclear, to mention a few. These projects are the driving force behind the development of ampere-class ERL technology [4], which will find many applications including light sources and FELs, These programs also define the goals for the R&D ERL development:

- ❑ Test the key components of the RHIC II electron cooler
- ❑ Test the key components of the High Current Energy Recovery Linac based solely on SRF technology
  - o 703.75 MHz SRF gun test with 500 mA
  - o High current 5-cell SRF linac test with HOM absorbers (one turn - 500 mA, two turns - 1 A)
  - o Test the beam current stability criteria for CW beam currents ~ 1 A
- ❑ Test the key components and scalability for future linac-ring collider eRHIC with
  - o 10-25 GeV SRF ERL for eRHIC
  - o SRF ERL based an FEL-driver for high current polarized electron gun
  - o Test the attainable ranges of electron beam parameters in SRF ERL

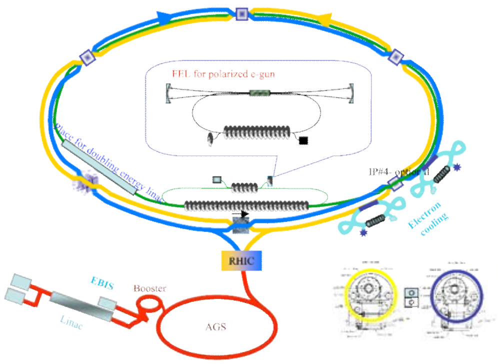

Figure 2. Layout of eRHIC with 10-20 GeV ERL in the RHIC tunnel and with circularly polarized FEL-driver for polarized electron photo-injector [3].

The plans call for construction and commissioning of the prototype ERL within 3 years. The ERL will be located in one of the spacious bays in Bldg. 912 of the RHIC/AGS complex.

Fig.3 The layout of the facility (top) and the photograph of the shielded vault for R&D ERL under construction in the bay of Bldg. 912. The bay is equipped with an overhead crane. The control room is located outside of the bay in a separate building.

Technical details of R&D ERL constitute a significant part of the 260-page ZDR (Zero's-order Design Report), for the RHIC II electron cooler, which is undergoing final polishing. The intensive R&D program geared towards the construction of the prototype ERL is under way: from development of high efficiency photo-cathodes [4] to the development of new merging system compatible with emittance compensation.

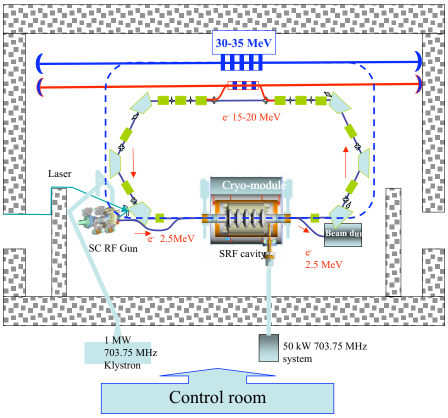

Fig. 4 Layout of the R&D linac in the shielded vault

The SRF gun is currently under design at Advanced Energy Systems with the participation of BNL. The 703.75 MHz, 1 MW CW RF system for the SRF gun is under procurement. The 5-cell SRF linac is under construction at Advanced Energy Systems and is planned to be installed and tested in Bldg. 912 in the middle of 2005. The 50 KW 703.75 MHz RF transmitter for the linac has been installed at the site and is undergoing commissioning.

The lattice of the ERL is designed and needs some final refinements to fit with the SRF injector. The main feature of the lattice is that it provides a wide range of transport matrix parameters to study both longitudinal and transverse beam break-up instability (BBU), while remaining achromatic.

In this paper we describe the current design, the main component and the expected performance of the R&D ERL.

LAYOUT AND MAIN COMPONENTS OF THE ERL

The base-line design has one turn: electrons are generated in the superconducting half-cell gun to about 2.5 MeV and injected through the merging system with emittance compensation (see below) into the main linac. Linac accelerates electrons 15-20 MeV, which pass through a one turn re-circulating loop with achromatic flexible optics (see below). The path-length of the loop provides for 180 degrees change of the RF phase, causing electron deceleration (hence energy recovery) down to 2.5 MeV. The decelerated beam separates from the higher energy beam and goes to the beam-dump. The main expected parameters of this system are listed in Table I.

Table I. Parameters of the R&D ERL in Bldg. 912

	High charge	High current
Injection energy, MeV	2.5	2.5
Maximum beam energy, MeV	20	20
Average beam current, A, up to	0.2	0.5
Bunch rep-rate, MHz	9.4	703.75
Charge per bunch, nC	~20	1.3
Normalized emittance, mm*mrad	~ 30	~1-3
Efficiency of current recovery, >	99.95%	99.95%

A description of the SRF gun and its photocathode system can be found elsewhere [4]. The maximum current from this gun will be limited to a maximum value of about 0.5 A by the RF power of 1 MW 703.75 MHz CW klystron.

Zigzag merging system

One of the novel systems we plan to use for the R&D ERL is a merging system providing achromatic conditions for the space charge dominated beam and compatible with the emittance compensation scheme [6].

The idea of the Z-system is to provide achromatic conditions for electron whose energy is changing while it propagates through the merging system. A detailed description of this mechanism will be published elsewhere [6]. Fig. 6 shows results of Parmela simulations for the R&D ERL injection system. In contrast with traditional chicane, where horizontal emittance suffers a significant growth as result of the bending trajectory, with the Z-system the emittances are equal to each other and are very close to attainable for the straight pass.

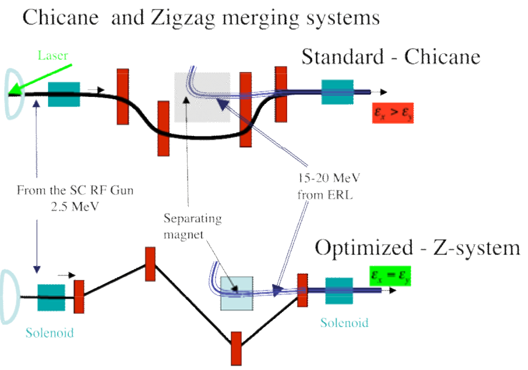

Fig. 5. Schematics of traditional chicane and Zigzag-system (Z-system) for merging system of low and high energy beams in an ERL. In contrast with chicane, which provides achromatic conditions and emittance preservation only for low-charge beams, the Z-system provide for emittance preservation and emittance compensation of e-beams with a high charge.

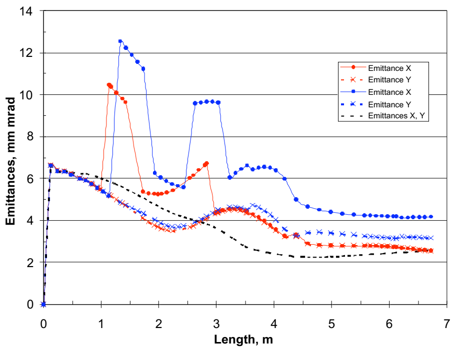

Fig. 6. Results of Parmela simulation for 1 nC e-bunch from the cathode to the end of the linac in R&D ERL: black dashed curve is for a round beam passing without bends (the baseline); blue curves are for that with a compensated chicane, red curves are for that with the Zigzag merging system.

5-cell SRF linac

The heart of the ERL facility is 5-cell SRF linac, which is designed for operating with ampere-class CW e-beams [4,5]. The main feature of this design is very large apertures of the structure which effectively couples all Higher Order Modes (HOMs) to two ferrite absorbers, which is located on both sides of the cryo-module (see Fig.7). This design provides for very low Q's for HOMs and hence very high ERL stability. Thresholds of the transverse beam break-up instability (TBBU) for ERL with one 5-cell linacs is measured in amperes (see example in Fig. 8). We plan to intentionally tune the lattice of the ERL to a special mode (see below) to test the TDBBU predictions for our SRF linac with current limited only to few hundreds of milliamps.

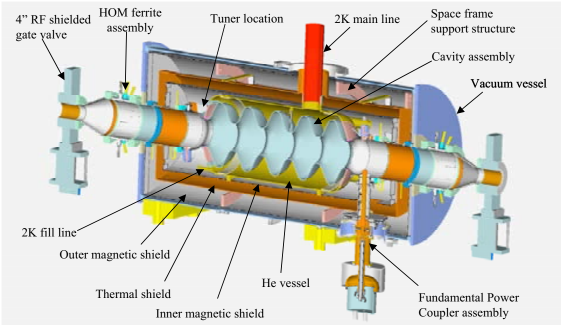

Fig. 7. The 5-cell SRF linac with HOM absorbers
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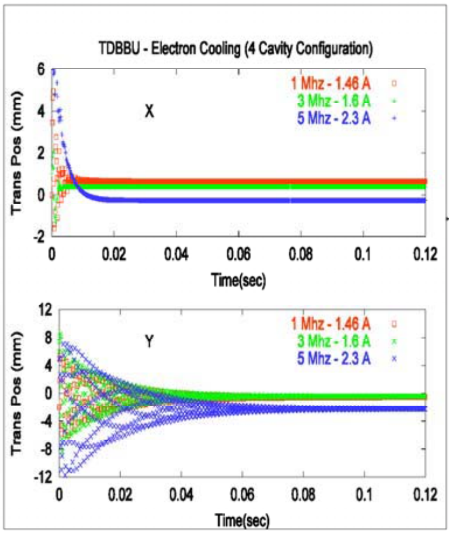

Fig. 8. Results of TBBU simulations for ERL with four 5-cell linacs [5].

Lattice of the loop

The lattice of the ERL loop controls the parameters of a symplectic transport matrix:

$$\begin{bmatrix} x \\ x' \\ y \\ y' \\ -c\delta t \\ \delta E/E \end{bmatrix}_{s2} = \begin{bmatrix} m11 & \boldsymbol{m12} & \dots & \dots & \dots & D_x \\ m21 & m22 & \dots & \dots & \dots & D_x' \\ \dots & \dots & m33 & \boldsymbol{m34} & \dots & D_y \\ \dots & \dots & m43 & m44 & \dots & D_y' \\ \dots & \dots & \dots & \dots & m55 & \boldsymbol{m56} \\ \dots & \dots & \dots & \dots & \dots & m66 \end{bmatrix} \cdot \begin{bmatrix} x \\ x' \\ y \\ y' \\ -c\delta t \\ \delta E/E \end{bmatrix}_{s1}$$

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. The adjustable part of the lattice has two arcs and a straight section. Each arc is a three-bend achromat with adjustable longitudinal dispersion. Twelve 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.

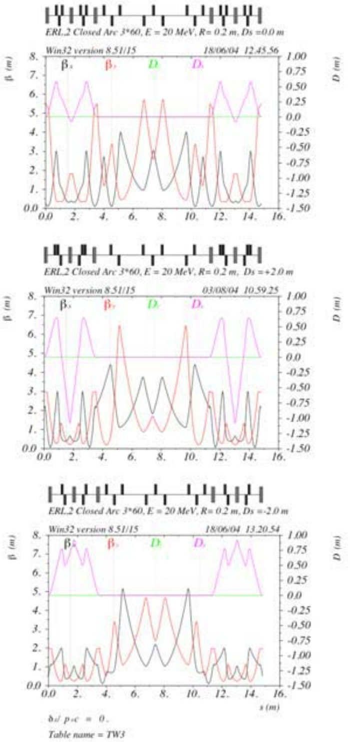

Fig. 9. Lattice β- and D- functions of the R&D ERL for the case of zero, positive (+2m) and negative (-2m) longitudinal dispersion D_s = m_{56}. The m_{12} and m_{34} elements are controlled independently using twelve quadrupoles in the dispersion-free straight section.

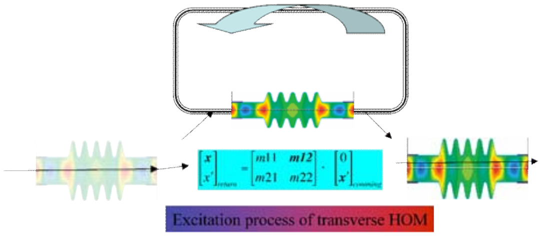

Fig. 10 A sketch of TBBU interaction in R&D ERL: injected electron beam kicked transversely by HOM passes the loop and comes to the cavity with a displacement proportional to m_{12} (for vertical - m_{34}) element of the loop matrix. The displaced beam excites the HOM, which closes the excitation loop of TBBU process.

As shown in a simple sketch below, the threshold of TBBU instability will depend on the values of m_{12} and m_{34}. Hence, we plan to increase these elements to the level of few hundreds of mA, required to observe or to reliably measure TBBU instability threshold and to compare it with the prediction based on the cavity model.

Potential up-grade of the R&D

We consider the potential extension of this facility into two turn configuration and installation of IR FEL, if funds are available. 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 high power FEL.

Table 2. Parameters of a test FEL for R&D ERL

Energy [MeV]	20	40
Wavelength [μm]	10	2.5
with micro-wiggler	*5*	*1*
Beam Power (MW)	10	20
FEL ext. efficiency	1%	1%
FEL power (kW)	100	200
Charge/bunch (nC)	1.3	1.3

CONCLUSIONS

We are designing, constructing, and commissioning a small (about 20 meters in circumference) R&D ERL to test the key issues of an amp-class CW electron accelerator with high brightness beams, required for future nuclear physics experiments at RHIC-II and eRHIC. An extensive R&D program on many novel components to be used in the ERL is under way. This facility, planned to be commissioned in 2007, will serve as the test-bet for new ranges of beam parameters whose application will extend well beyond the goals set forward by the Collider Accelerator Department at BNL.

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