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UNIQUE FEATURES IN MAGNET DESIGNS FOR R&D ENERGY RECOVERY LINAC AT BNL *

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Abstract

In this paper we describe the unique features and analysis techniques used on the magnets for a R&D Energy Recovery Linac (ERL) [1] under construction at the Collider Accelerator Department at BNL. The R&D ERL serves as a test-bed for future BNL ERLs, such as an electron-cooler–ERL at RHIC [2] and a future 20 GeV ERL electron-hadron at eRHIC [3]. Here we present select designs of various dipole and quadrupole magnets which are used in Z-bend merging systems [4] and the returning loop, 3-D simulations of the fields in aforementioned magnets, particle tracking analysis, and the magnet's influence on beam parameters. We discuss an unconventional method of setting requirements on the quality of magnetic field and transferring them into measurable parameters as well as into manufacturing tolerances. We compare selected simulation with results of magnetic measurements.

R&D ERL

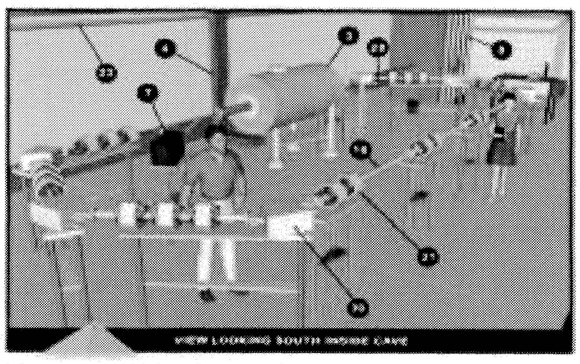

Figure 1. A side-view rendering of the R&D ERL at BNL: (3) is the 20 MeV 5-cell SRF linac, the return loop has six 60° dipoles (30) and twenty-five quadrupoles (31). The 2 MeV SRF gun is shown in the upper-left corner of the shielded cave.

A 20 MeV R&D ERL (Fig. 1) is in an advanced phase of construction at the Collider-Accelerator Department at BNL, with commissioning planned for early 2009. In the R&D ERL, an electron beam is generated in a 2 MeV superconducting RF photo-gun, next is accelerated to 20 MeV in a 5 cell SRF linac, subsequently passed through a return loop, then decelerated to 2 MeV in the SRF linac, and finally is sent to a beam dump. The lattice of the R&D ERL is designed with a large degree of flexibility to enable the covering of a vast operational parameter space: from non-achromatic lattices to achromatic with positive, zero and negative R_{56} parameter. It also allows for large range tunability of R_{12} and lattice R_{34} parameters (which are important for transverse beam-break-up instability). Further details of the R&D ERL can be found elsewhere in these proceedings [5].

Table 1: Main parameters of R&D ERL

Parameter	High average current	High charge per bunch
Charge (nC/bunch)	1.4	5
Ave. current (mA)	500	50
ε_n (mm-mrad)	< 5	< 10

R&D ERL MAGNETS

The return loop magnets are of traditional design with the following exceptions:

a) The bending radius of the 60° dipole magnets is 20 cm, which is rather small. We use 15° edges on both sides of the dipoles to split very strong focusing evenly between the horizontal and vertical planes (so-called chevron-magnet).
b) The requirements on field quality of the loop's quadrupoles had been determined by the requirement to preserve a very low normalized transverse slice emittance of electron beam ($\varepsilon_n \sim 1$ mm-mrad). We used direct tracking of a sample electron beam to verify a high degree of the emittance preservation.
c) Each quadrupole is equipped with a dipole trim coil, which can be also used to excite a sextupole component, if required, for emittance preservation of e-beam with a large energy spread.

One of the unique features of all ERLs is the necessity for merging low and high energy electron beams. In the R&D ERL, 2 MeV from the SRF gun merges with the 20 MeV electron beam coming around the return loop into the same trajectory at a position within the SRF linac. In the linac, injected bunch is accelerated to 20 MeV, while the returned or "used" bunch is decelerated to 2 MeV. The challenge for a merger design is to provide conditions for emittance compensation [5] and also for achromatic conditions of a low energy, space-charge dominated e-beam [4,6]. The scheme which satisfies these requirements (called Z-bend [4]) is used on the R&D ERL. The Z-bend is approximately 4-meter long. It bends

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the beam trajectory in the vertical plane. It is comprised of four dipole magnets designed to be equally focusing in both planes, with bending radius ~ 60 cm, and bending angles of: +15°, –30°, +30° and –15°. The beam dynamics in the Z-bend results in a large-size (centimeters) near-laminar electron beam [7].

The large beam size and very low slice emittance of the e-beam dictates the tolerances on the magnetic field to be very tight. The integrated nonlinear kicks (see details below) should not exceed ~20 micro-radian per magnet at a typical radius ~ 1 cm. The magnets in the Z-bend are rather short (15 cm effective length for the 15° magnet) and have a rather large aperture of 6 cm. Analysis predicts that the influence of various field components on the emittance growth are complicated by the fact that the beam trajectory bends significantly in the fringe fields. Hence, we decided to use direct tracking in the calculated fields extracted from Opera3d of test beam to evaluate and to minimize influence of magnetic field on the beam emittance (see description below).

In addition, we used predictions of Opera3d and compared them with results of magnetic measurements for the return loop dipole and quadrupole. One of the features of the loop magnets is that they are fabricated with a very high geometric tolerance, allowing them to be an excellent test bed for bench-marking our predictions. Agreement with the prediction provides us with sufficient confidence that Z-bend magnets will preserve beam emittance.

R&D ERL MAGNET DESIGNS

Table 2: Main parameters of ERL magnets

Magnet	Field or Gradient	Gap (cm)	Magnetic length (cm)
60° dipole	3.3 kGs	3	19
Quadrupole	0.3 kGs/cm	6	16.
30° dipole (Z-bend)	0.145 kGs	6	20
15° dipole (Z-bend)	0.145 kGs	6	8
Solenoid	0.25 kGs	6	8

All R&D ERL magnets were designed using Opera3d [8] for 3D magnetic field calculations as well as the influence of geometric tolerances on the field quality. Main parameters of the magnets are listed in Table 2. A typical ERL-loop elements are shown in figure 2. Figure 3 shows the 15 degree magnet used at the merger. This rather complex window-frame magnet has parallel edges and is to be constructed with four coil sets (vertical dipole -pink, main quadrupole -gold, sextupole -small coils in the corner, and horizontal correction dipole -wound with quadrupole coils). The quadrupole coil is used to split focusing equally between the planes, while main dipole coil is designed to create both dipole and sextupole components of the field which is necessary for emittance preservation. The amount of the sextupole component is controlled by the gap between the yoke and the main dipole coil. A small additional coil in the corners is a sextupole trim coil, intended for use if the magnetic measurements indicate need to change sextupole component. The ERL solenoids have a very standard design and we skip their description in this paper.

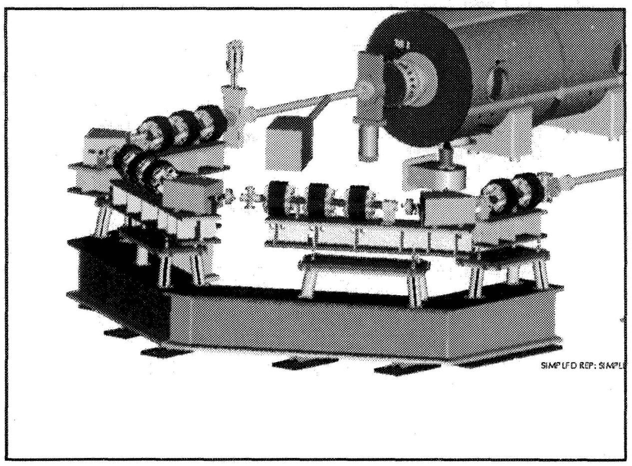

Figure 2. Depicts a standard ERL segment comprised of a CNC-machined girder with a precisely located 60° dipole and a triplet of quadrupoles. Relative location accuracy of magnetic elements and BPM (yellow) is ± 100 μm. Magnets are locked into position by high precision pins located in the CNC-machined girder.

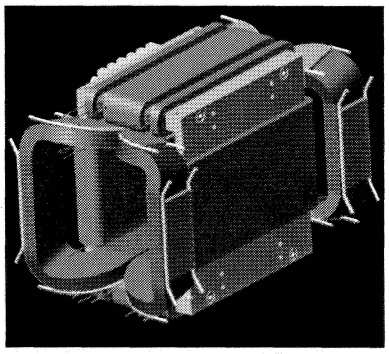

Figure 3. Window-frame dipole for Z-bend with bend trajectory in vertical plane.

MAGNETIC MEASUREMENTS

Magnetic measurements of the ERL magnets employs both rotating coil and Hall probe array mapping (Fig. 4). Hall probe array comprises of four Group3 Hall probes [9] spaced by 10 mm. Relative centers of the probes are measured in a quadrupole with accuracy of few micrometers. The hall probe array is cross-calibrated versus an NMR probe in a test dipole. Overall expected accuracy of magnetic field measurements is ~ 0.03%, while relative accuracy of the rotating coil measurements is better than 50 ppm. First set of measurements with loop dipole showed excellent agreement between predictions of Opera3d and actual magnetic measurements (Fig. 5).

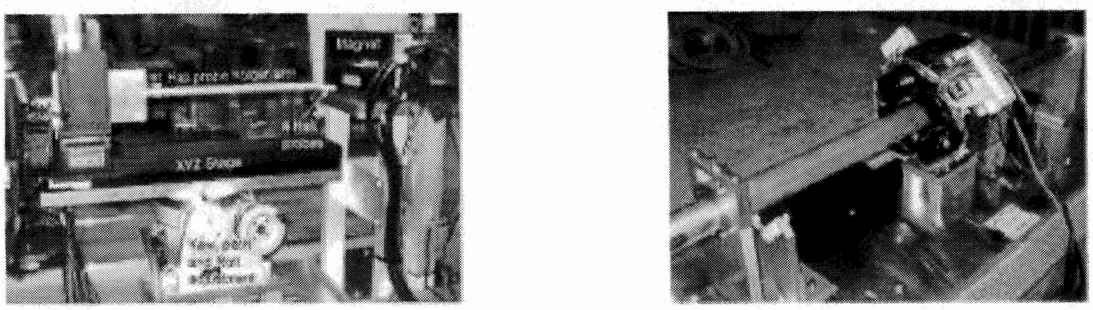

Figure 4. Magnetic measurements with rotating coil and Hall Probe array at Superconducting Magnet Division, BNL.

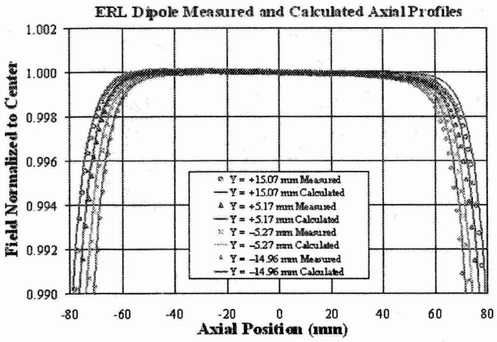

Figure 5. Comparison of measurement and simulation.

TRACKING

We used direct tracking of 2,000 particles in the 3D-magnetic field, which calculated by Opera3d/Tosca. For the Z-chicane dipoles we used initial distribution of electron with kinetic energy of 2.77 MeV and transverse radius of 1 cm. These particles were tracked from the center of the magnet to far (0.5 m to be exact) outside the magnet using Opera-3d Post-processor with the step of 1 mm. The output file contains all 3D position and velocity components at each step. Another program was used to translate these components to a local coordinate system, which was defined by the final position and momentum of the central ray. These results led to the extraction of the final phase space distribution (x, x', y, y').

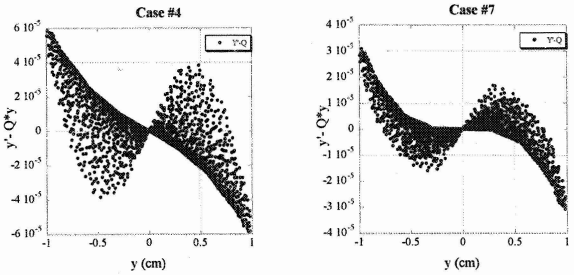

Figure. 6. Tracking in 30° Z-bend magnet: vertical axis is vertical angle at the exit of the magnet with linear term subtracted.

This data was then analyzed using various programs and the next iteration of the magnet design was processed. One of the tools used was the expansion of angles of the trajectory $(x',y')_{out}$ far from the magnet exit as function of initial coordinates $(x,y)_{in}$. Since the trajectories are strongly curved, these expansions do not have clear harmonic content (for example x^2 and y^2 terms have different coefficients). Therefore we had used the increase of the beam emittance as a figure of merit, while using coefficients in second and third order expansions as guidance.

Figure 6 shows samples of vertical phase space plot (y, y') for two of seven cases studied for 30° Z-bend dipole. In case #4, the integrated sextupole component along the trajectory was zeroed, while case #7 was optimized to minimize emittance by adding sextupole component in the main part of the dipole. Such contra-intuitive optimization allowed reducing normalized emittance growth from 0.35 mm-mrad to 0.23 mm-mrad. It is worth mentioning that Z-bend geometry provides for reversal of a significant part of this emittance growth.

CONCLUSSIONS

We intensively used Opera-3d/Tosca for 3-D magnetic design of ERL magnets and tracking in these fields for evaluation of their influence on electron beam dynamics and emittance growth in the R&D ERL. Results obtained by this approach are very encouraging.

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