ABSOLUTE ENERGY MEASUREMENT OF THE LEReC ELECTRON BEAM *

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Abstract

The goal of future operation of the low energy RHIC Electron Cooling (LEReC) accelerator is to cool the RHIC ion beams. To provide successful cooling, the velocities of the RHIC ion beam and the LEReC electron beam must be matched with 1E-4 accuracy. While the energy of ions will be known with the required accuracy, the e-beam energy can have an initial offset as large as 5%. The final setting of the e-beam energy will be performed by observing either the Schottky spectrum of debunched ions co-traveling with the e-beam or the recombination signal. Yet, to start observing such signals one has to set the absolute energy of the electron beam with an accuracy better than 1E-2, preferably better than 5E-3. In this paper we discuss how such accuracy can be reached by utilizing the LEReC 180 degree bend as a spectrometer.

LEREC LAYOUT

The LEReC accelerator [1, 2] consists of a 400 keV photo-gun followed by the SRF Booster, which accelerates the beam to 1.6-2.4 MeV, the transport beamline, the merger that brings the beam to the two cooling sections (in the Yellow and in the Blue RHIC rings), the cooling sections separated by the 180^o bending magnet and the extraction to the beam dump. The LEReC also includes two dedicated diagnostic beamlines: the DC gun test line and the RF diagnostic beamline.

The LEReC layout is schematically shown in Fig. 1.

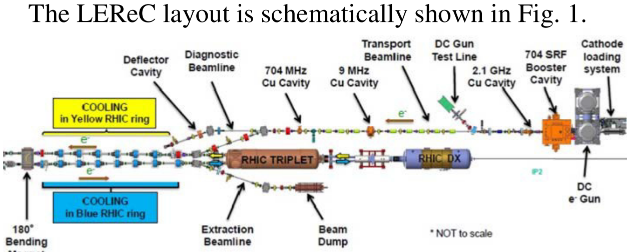

Figure 1: LEReC layout.

To set the absolute energy of the electron beam with an accuracy better than $5\cdot10^{-3}$ we plan to utilize the 180^o bending magnet as a spectrometer.

The 180^o bend setup is schematically shown in Fig. 2.

The 180^o bend is located between the first and the second LEReC cooling sections. It is designed to have a bending radius $\rho_0 = 0.35$ m. The entrance to the magnet is equipped with two BPMs (one of them hybrid [3]) and its exit is equipped with one hybrid BPM. BPM-to-BPM distances are defined by precision requirements of the energy regulation and were set in dedicated optical simulations.

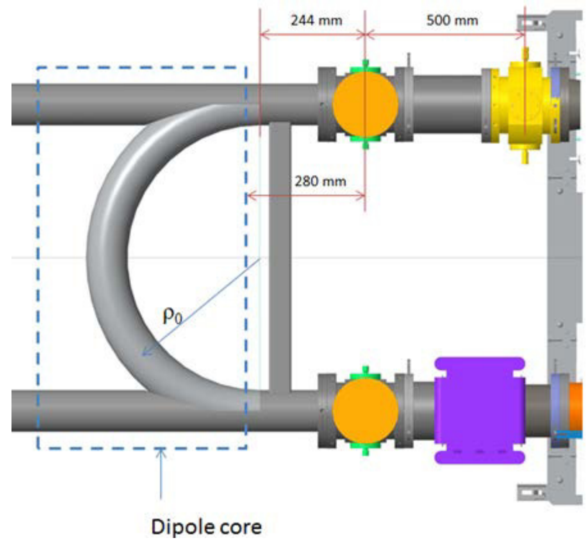

Figure 2: Schematics of 180^o bend.

HARD EDGE APPROXIMATION OF THE 180^O BEND

In the hard-edge approximation the horizontal e-beam displacement (x_{out}) at the exit of 180^o bend is given by:

$$x_{out} = -x_{in} + 2\rho_0 - 2\rho\cos\theta_{in} \qquad (1)$$

The notation used in (1) is explained in Fig. 3.

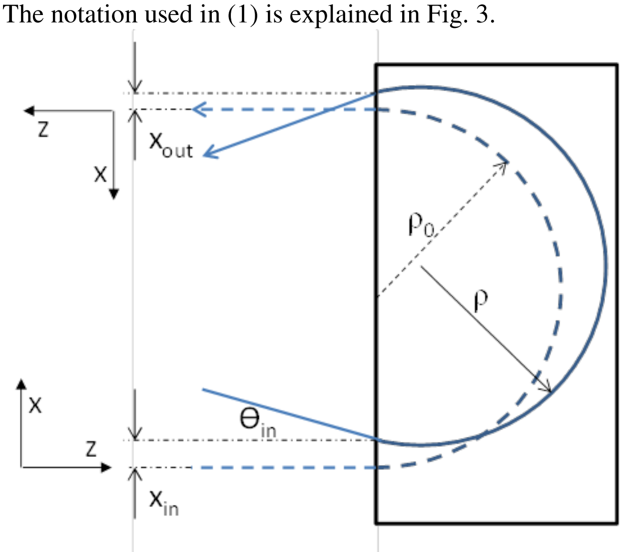

Figure 3: Beam trajectory in 180^o bend.

To measure beam energy (E) in the 1.6-2.6 MeV range with the accuracy required for LEReC one must perform proper Taylor expansion of the exact expression for magnetic rigidity:

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$$B\rho = \frac{mc}{e}\sqrt{\left(\frac{E_0(1+\delta)}{mc^2}+1\right)^2 - 1} \approx B_0\rho_0\left(1+\frac{E_0+mc^2}{E_0+2mc^2}\delta\right) \quad (2)$$

where e is the charge of the electron, m is the electron mass, c is the speed of light and $\delta = E/E_0 - 1$.

Defining the fractional error in setting the dipole field as $\Delta \equiv B/B_0 - 1$, from (1) and (2) we get:

$$x_{out} = -x_{in} - 2\rho_0 \frac{E_0+mc^2}{E_0+2mc^2}\delta + 2\rho_0\Delta \quad (3)$$

Equation (3) solves the problem of the dependence of accuracy of energy measurements on accuracies of BPM settings and magnetic field measurements. Indeed, x_{in} and x_{out} correspond to BPM readings (x_1, x_2, x_3) as:

$$x_{in} = x_2 + S_b \frac{x_2 - x_1}{S_{12}} \quad (4)$$

$$x_{out} = x_3 + S_b \frac{x_2 - x_1}{S_{12}} \quad (5)$$

Here S_{12} is the distance between the first and the second entrance BPMs, S_b is the distance from the second BPM to the hard edge dipole entrance and from the dipole exit to the exit BPM, x_1 and x_2 are the horizontal readings of two entrance BPMs and x_3 is the exit BPM reading.

Then the accuracy of energy measurement ($\tilde{\delta} \equiv (E_{measured} - E_{real})/E_0$) is given by:

$$\tilde{\delta} = \frac{E_0+2mc^2}{E_0+mc^2}\left(\Delta + \frac{\sigma_{BPM}}{\rho_0}\left(1+2\frac{S_b}{S_{12}}\right)\right) \quad (6)$$

Here σ_{BPM} is the absolute error of BPM readings, which includes accuracy of each BPM alignment with respect to the other BPM and with respect to the dipole and the reading accuracy per se.

Assuming 1.6 MeV nominal energy of the beam (the worst case), the accuracy of magnetic field measurement/setting $=10^{-3}$ and $\sigma_{BPM} = 0.1$ mm, we get the accuracy of energy measurement $\tilde{\delta} = 2 \cdot 10^{-3}$. For the case of relaxed requirements on BPM error ($\sigma_{BPM} = 0.5$ mm) we get $\tilde{\delta} = 5 \cdot 10^{-3}$.

DIPOLE WITH SOFT EDGE FIELD

While formulas (3-6) might be a good approximation of beam dynamics in the 180° bend, it is worth to simulate the beam trajectory in the actual soft-edge dipole, introduce the errors in the BPM readings and the field settings and see with what accuracy we can measure the beam energy.

The algorithm of beam dynamics simulations in non-uniform dipole fields is discussed in [4]. Here we will consider the results of these simulations for the case of a 1.6 MeV beam.

We choose the strength of the realistic dipole field sych that the resulting dispersion downstream of the bend is equal to the nominal 70 cm. Figure 4 shows the field along the beam trajectory and the actual beam trajectory between BPMs 2 and 3 along with the field and trajectory in the equivalent hard-edge dipole.

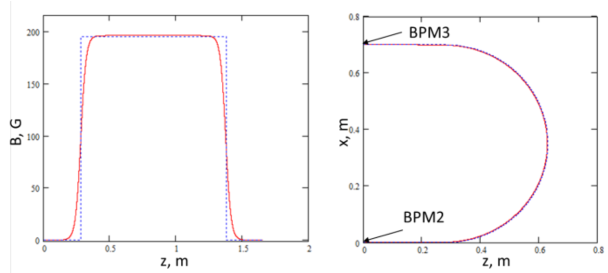

Figure 4: Dipole magnetic field along e-beam trajectory (left) and e-beam trajectory from BPM 2 to BPM 3 (right). The solid red line represents simulation results for the realistic soft-edge dipole. The dotted blue line represents simulation results for equivalent the hard-edge approximation.

There are various measurement and setting errors, which affect the accuracy of energy measurement:

1. The dipole field will be mapped in the region covering possible trajectories of the electron beam with an NMR probe in the homogeneous field region and a Hall probe in the edges. For the NMR probe typical measurement accuracy is 10^{-4} or 0.02 G for ~200 G filed. We believe that since the Hall probe is installed together with NMR in the same holder and can be calibrated vs. NMR in homogeneous field, the accuracy of edge field measurement also will be 0.02 G. We also consider the worst case scenario assuming 0.1 G accuracy of the field measurements. Therefore, in our simulations we introduce 0.02 G (0.1 G for the worst case scenario) of systematic “shift” in the realistic dipole field.
2. If the magnetic probe axis is inclined with respect to the dipole field by angle α then the measured field is reduced by cos(α). In simulations we will assume this angle to be 1° (2° for the worst case scenario).
3. The dipole power supply provides $3 \cdot 10^{-5}$ accuracy. We also will develop and implement an automated hysteresis cycling system to set the dipole operating point. In simulations we assume overall accuracy of field setting to be 10^{-4}.
4. While an ideal 180° bend is a magnetic mirror, the real dipole field is not ideally symmetric. In principle, if this asymmetry is properly measured, then one can account for it in simulations and adjust the dipole current accordingly. In such a scenario one still gets nominal dispersion D in BPM3. Yet, there also is nonzero D’ downstream of the dipole. For simulations we will assume that a possible misbalance in edge fields is not higher than 0.5 G and that we are not “compensating” the resulting dispersion change.
5. There is an ambient magnetic field present in the RHIC tunnel. It is possible that the dipole will be measured in the magnetic lab only and that this measurement will not be repeated inside the tunnel. The ambient field shall be well shielded inside the

dipole and not that well shielded around dipole entrance and exit. The transverse field at the dipole location inside the RHIC tunnel was measured to be about 0.35 G. For our simulations we assume that the unaccounted for dipole field of 0.4 G is present in 35 cm long regions downstream of BPM 2 and upstream of BPM 3.

6. Finally, there are errors in BPM readings due to reading accuracy (cable length, electronics noise etc.) and due to the errors in BPMs positioning both with respect to each other and with respect to the mapped dipole field. In our simulations we assume that all these errors result in BPM readings accuracy to be 0.1 mm (0.5 mm in the worst case scenario).We also suggest, for the sake of simplicity, to perform energy measurements for zeroed entrance angle of the beam trajectory. Assuming that BPMs 1 and 2 are set with 0.1 mm accuracy we get the entrance angle with 0.4 mrad accuracy (2 mrad for the worst case scenario).

We introduce all the described errors in our simulations in such a fashion that the total resulting measurement error is maximized.

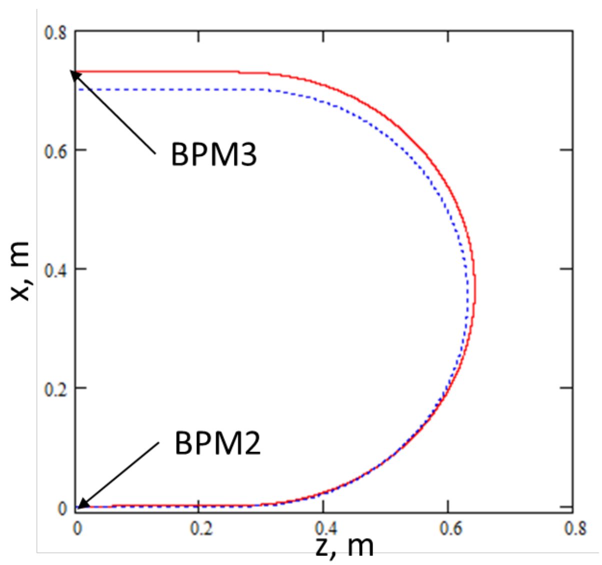

Figure 5: 5% off energy beam trajectory (solid red line) and reference on-energy beam trajectory (dotted blue line) in the realistic soft-edge dipole. The simulations of the off-energy beam trajectory include all the errors listed above.

Next, we simulate beam trajectory with various energy offsets in the dipole (Fig. 5) [4], record the simulated BPM readings and calculate the measured energy according to (3) with $x_{in} = x_2 = 0$ and $x_{out} = x_3$, assuming 0.1 mm accuracy of BPM readings. The result of these simulations is that for the worst considered case of 5%-off-energy beam we expect measuring the real beam energy with $2.6 \cdot 10^{-3}$ accuracy. With the worst case parameters described above the measurement accuracy becomes $6.7 \cdot 10^{-3}$. Results of our studies are summarized in Table 1.

Table 1: Various errors affecting accuracy of energy measurement and resulting measurement accuracy.

Magnetic probe accuracy	0.02 G	0.1 G
Magnetic probe inclination	1^{o}	2^{o}
Dipole field accuracy	10^{-4}	10^{-4}
Edge field asymmetry	0.5 G	0.5 G
Ambient field	0.4 G	0.4 G
BPM accuracy	0.1 mm	0.5 mm
Energy error (simulations)	2.6E-3	6.7E-3
Energy error (analytic)	2E-3	5E-3

CONCLUSION

In this paper we estimated the accuracy of the absolute energy measurement performed with the LEReC 180^{o} dipole magnet. We performed both analytical estimates in the hard edge bend approximation and simulations of the beam trajectory in realistic soft-edge dipole field. We conclude that assuming realistic value for various measurement and setting errors we can expect measuring beam energy with $2.6 \cdot 10^{-3}$ accuracy. Assuming the worst case scenario errors we can measure beam energy with $6.7 \cdot 10^{-3}$ accuracy. Such an accuracy will be adequate to start fine-tuning of the LEReC beam energy using either the Schottky spectrum of debunched ions co-traveling with the e-beam or the recombination signal.

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