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MEASURING BEAM ENERGY WITH SOLENOID*

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Abstract

We have developed a method of measuring electron beam energy based on the measurement of the Larmor angle. In this paper, we describe the experimental set-up and obtained results.

INTRODUCTION

Measuring energy of the electron beam with few MeV energy is a challenging task. Conventional approach utilizing energy spectrometer has a disadvantage of low magnetic field in a bending magnet, which is hard to measure accurately and it is affected by the residual magnetic fields. Electron beam is also sensitive to the stray magnetic fields. Time-of-flight technique requires precise measurement of arrival time because the velocity variation is inversely proportional to the square of the relativistic factor.

Low-energy beamlines usually implement solenoids for the focusing of the beam (the usage of the quadrupoles is limited due the same reasons as for the spectrometer dipole). The solenoids are rotating the plane of the betatron oscillations [1] and the rotation angle is directly proportional to the axial field integral, which is usually known with high accuracy, and inversely proportional to the beam rigidity.

The electron beam energy is found from the change in the response matrix with varying excitation current of the solenoid.

MEASUREMENT TECHNIQUE

The transfer matrix of a hard edge solenoid can be represented as multiplication of the rotation matrix M_{rot} and focusing matrix M_f:

$$\begin{pmatrix}\tilde{x}\\ \tilde{x}'\\ \tilde{y}\\ \tilde{y}'\end{pmatrix} = M_{rot}M_f\begin{pmatrix}x\\ x'\\ y\\ y'\end{pmatrix} \tag{1}$$

where rotation matrix is:

$$M_{rot} = \begin{pmatrix}cos\theta & 0 & sin\theta & 0\\ 0 & cos\theta & 0 & sin\theta\\ -sin\theta & 0 & cos\theta & 0\\ 0 & -sin\theta & 0 & cos\theta\end{pmatrix} \tag{2}$$

and $\theta = \int eB_{\parallel}(s)/2p\, ds$, where e is electron charge, p is its momentum, and $B_{\parallel}(s)$ is axial field. The focusing matrix can be calculated from the following equation:

$$M_f = \begin{pmatrix}cos\theta & sin\theta/k & 0 & 0\\ -ksin\theta & cos\theta & 0 & 0\\ 0 & 0 & cos\theta & sin\theta/k\\ 0 & 0 & -ksin\theta & cos\theta\end{pmatrix} \tag{3}$$

where k is $eB_{\parallel}(s)/2p$.

The real solenoid can be represented as series of hard edge solenoids with different magnetic fields. Because rotation and focusing matrices commute and focusing matrix does not mix horizontal and vertical plane the Larmor angle will be sum of the rotation angles for the parts of solenoid and Eq. 2 is valid for any solenoid.

In our experiment, we steered the electron beam with a trim located prior a solenoid and measured the tilt of the beam trajectory in the X-Y plane (see Fig. 1).

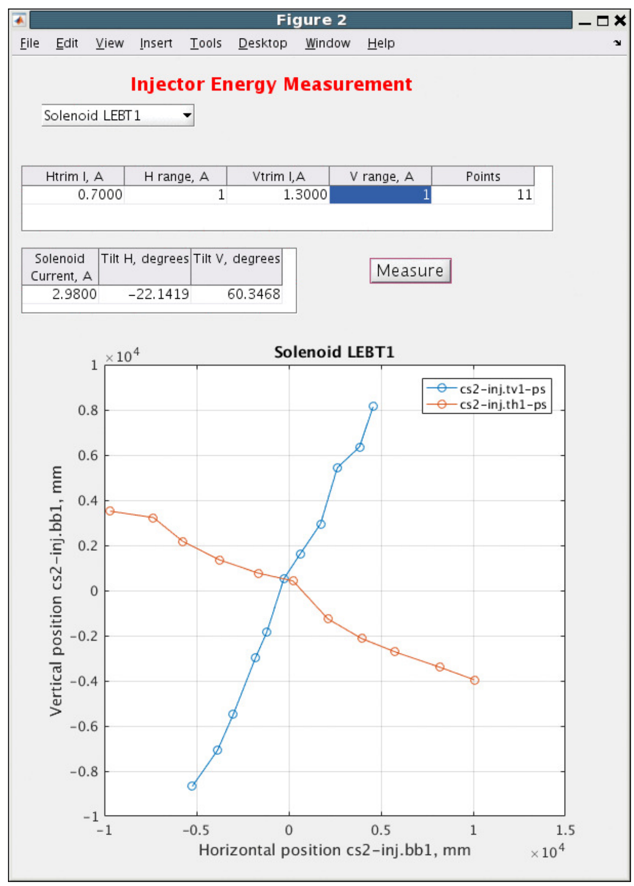

Figure 1: First scan of the orbit tilt in the X-Y plane caused by solenoid's rotation of the orbit. Measured beam position is in microns.

The measurements were performed using an automated MATLAB script. Operator can choose the solenoid (with corresponding beam position monitor (BPM) and trim),

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its current, number of points and trim current range.

First successful attempt was performed on March 24, 2017 (shown in Fig. 1). Two scans with different solenoid settings were done to account for the roll angles of a trim and a BPM. Both vertical and horizontal trims were utilized for the measurement (shown in different color).

The next step improvement was incorporation of two solenoids settings in the same script. For this purpose each trim has individual setting for the middle pf the scan to compensate steering by solenoid and range to account possible reduction in aperture. With this feature the measurement became fully automated. The interface of the upgraded script is shown in Fig. 2.

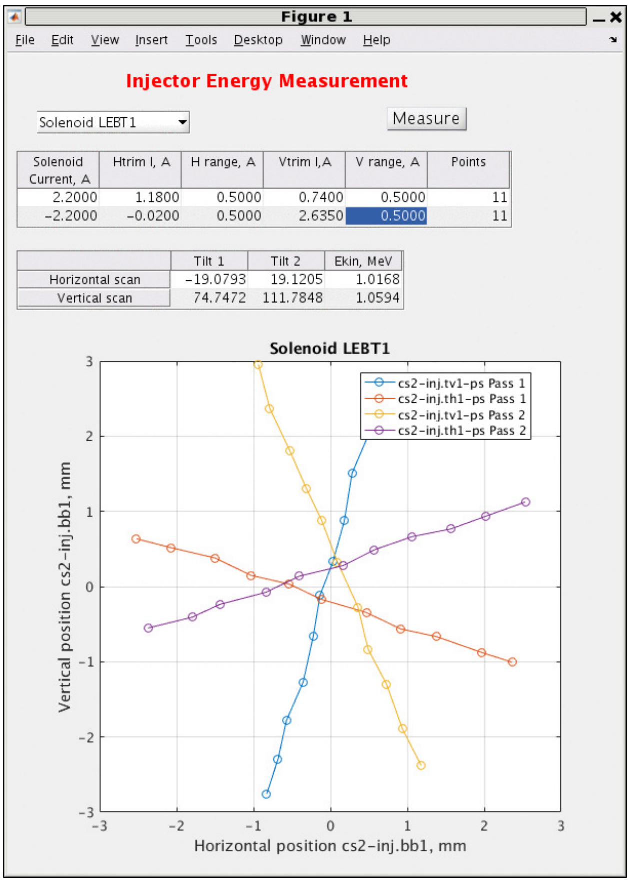

Figure 2: Interface of the MATLAB script with two solenoid settings. There are two lines per setting: one for the horizontal trim and another for the vertical trim.

The script was started being used routinely for the monitoring of the beam energy in the injector beamline and some deficiencies were found. Firstly, the noise in the BPM affected the accuracy of the measurement. Secondly, we observed substantially different tilts changes (up to 30%) for the vertical and horizontal trims, especially with large orbit excursions. We suspected that it was non-linearity of the BPM response. To overcome these difficulties, we decided to use profile monitor to measure beam position.

This allowed significantly improve reproducibility of the measurements and suppress noise in the beam position measurements. The interface for the profile monitor based script is shown in Fig. 3. The improvements are obvious: the points are located on the straight line and tilt change is close for vertical and horizontal trims.

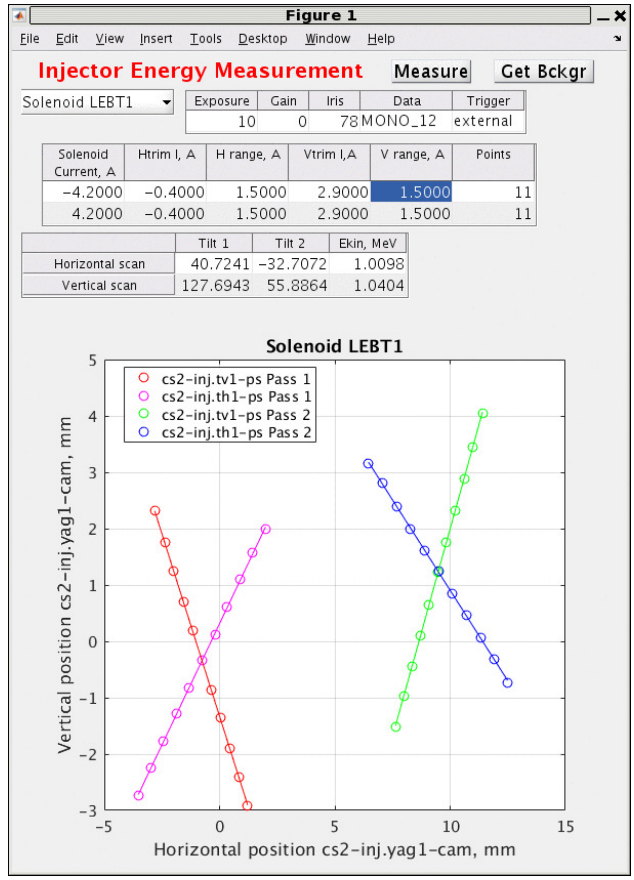

Figure 3: Scan with profile monitor as position measurement device.

The usage of the profile monitor allowed to tightly focus the beam and perform measurement with low charge, where BPMs have significant noise.

Another advantage of the proposed method is insensitivity to the energy spread. We have used it to measure and phase bunching cavities (see Fig. 4).

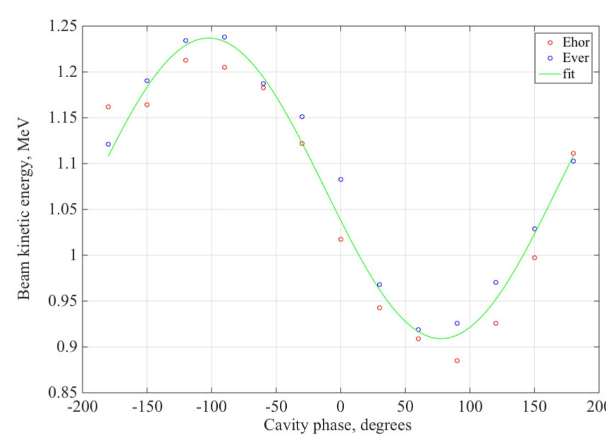

Figure 4: Measurement of the buncher cavities voltage and phase. Beam energy from the gun is 1.073 MeV and buncher voltage is 164 kV.

The maximal induced energy spread of the measurement shown in Fig. 4 was about 4%. Nevertheless, the

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obtained data have a good fit allowing straightforward calculation of the cavity voltage and phase.

For the guns with photocathodes one can employ the scanning of the laser spot on the cathode to provide beam motion instead of the using the trims. This measurement can be combined with quantum efficiency map scan of the cathode surface.

CONCLUSION

We have developed a method of measuring energy utilizing measurement of the solenoid Larmor angle. It is robust and applicable for very low charges. It is also insensitive to the energy spread of the beam. The device is rather compact and utilizes elements readily available.

REFERENCES

[1] S.Y. Lee, “Linear Coupling”, in ***Accelerator Physics***, World Scientific, 1999