

BEAM-BASED CALIBRATION OF THE ELECTRON ENERGY IN THE FERMILAB ELECTRON COOLER*

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Abstract

Electron cooling of 8.9 GeV/c antiprotons in the Fermilab's Recycler ring requires precise matching of electron and antiproton velocities. While the final match can be done by optimisation of the cooling process, for the very first cooling one should rely on the knowledge of absolute values of electron and antiproton energies. The upper limit for the energy uncertainty of both beams is determined by the Recycler's momentum aperture and is equal to 0.3 %. The paper discusses a method of the electron energy calibration that is based on the measurement of the electron's Larmor wavelength in the field of the cooling section solenoid. The method was tested in an 18 m long cooling section prototype with 3.5 MeV electrons. An accuracy of 0.4 % was demonstrated.

INTRODUCTION

The Recycler Electron Cooling (REC) [1] at Fermilab is suggested to be applied to 8 GeV antiprotons and, therefore, requires a DC beam of 4.3 MeV electrons. A general layout of the REC system is shown in Fig. 1. The Pelletron [2] accelerates an electron beam. Then the beam is bent in two planes to bring it into the cooling section (CS). The cooling section is immersed into the 100 G solenoidal field. After the CS, the electrons make a U-bend down the cooler, and finally come back to the Pelletron where they are decelerated and dumped into a collector. The Recycler Electron Cooler has been installed in the Recycler tunnel and is under commissioning now.

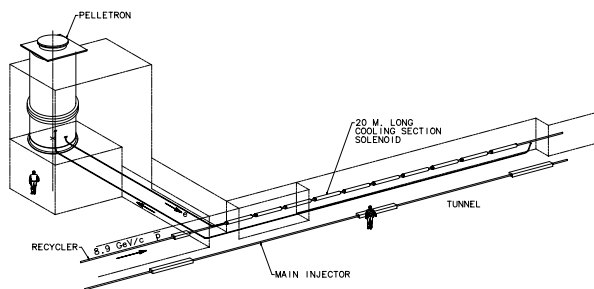


Figure 1: The schematic layout of the Fermilab electron cooler.

A prototype of the actual REC was assembled and tested in the Wideband laboratory at Fermilab for R&D purpose [3]. Some parameters of the REC cooler and the prototype are listed in Table.

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Table 1: Some parameters of the REC

Parameter	REC	Prototype
Terminal voltage	4.3 MV	3.5 MV
Terminal voltage ripple	< 500 V	< 500 V
Electron beam current	0.5 A	0.5 A
Cooling section length	20 m	18 m
Cooling section field	70, 75, 100 G	100, 190 G
Beam radius in the CS	6 mm	6-8 mm

A scenario of the first cooling [4] proposes to fill the entire momentum aperture of the Recycler, which is 0.3%, with antiprotons. To observe cooling, energies of electron and antiproton beams must be matched within this value. The electron energy is determined by the Pelletron high voltage that is measured by a generating voltmeter (GVM). While GVM readings are highly linear, its absolute precision at 4.3 MeV level is estimated to be 2 %. In this paper we propose to measure the electron energy by an independent method, use the obtained data for a precise calibration of GVM and rely on its readings thereafter.

THE ALGORITHM OF THE MEASUREMENTS

General Idea

The proposal for energy measurements consists in the measurement of the wavelength of electron's Larmor precession in the field of the cooling section.

The trajectory of electron beam can be excited by a dipole kicker located upstream of the cooling section. The difference of the initial and excited beam's trajectories (a "differential trajectory") is the Larmor helix in the CS. The wavelength of the helix (λ) is determined by the momentum of the beam (p) and the average value of the CS solenoidal field (B) [5].

$$\lambda = 2\pi \frac{pc}{eB}$$

Here c is the speed of light and e is the electron charge.

The precision of the suggested energy measurement depends on the measurement precisions of B and λ . The dynamics of electron cooling process requires a highly uniform solenoidal field in the cooling section. For this purpose, the value of longitudinal magnetic field in the CS was measured with absolute precision of 0.1 % [6].

The CS is equipped with 10 beam position monitors (BPM). The BPMs are longitudinally positioned with a precision better than 1 mm. For λ approximately equal to 10 m, it gives the possibility to find λ with 0.01 % precision. Therefore, in case of perfectly precise BPMs, the energy can be found with 0.1 % precision.

Theoretical Consideration

Let us consider the motion of an electron in a uniform longitudinal magnetic field taking into account the effect of image charges.

The motion of an electron in electro-magnetic field [5] is described by (1):

$$\frac{d\vec{p}}{dt} = -e \cdot \left(\frac{\vec{v}}{c} \times \vec{B} + \vec{E} \right) \quad (1)$$

Here v is electron's velocity, and E is an electric field.

In the Cartesian coordinate system (x, y, z) with z coinciding with the CS axis, we introduce the following notations: $\theta = \theta_x + i\theta_y$, and $\xi = x + iy$, where i is the imaginary unit, θ_x and θ_y are the x and y components of the transverse angle of an electron. One can show that from equation (1) follows:

$$\begin{cases} \xi' = \theta \\ \theta' = ik\theta + \Lambda\xi \end{cases} \quad (2)$$

Here $\xi' = d\xi/dz$, $\theta' = d\theta/dz$, $k = 2\pi/\lambda$, and $\Lambda = (2Ir_e)/(b^2\gamma\beta^3ce)$ present the effects of image charges in case of a DC beam. Here I is the electron current, b is the radius of the vacuum chamber, γ and β are the standard relativistic parameters. In some measurements the pulsed electron beam (instead of DC) was used. The length of the pulse (2 μ s) is significantly smaller than the time of magnetic diffusion in the wall of the vacuum chamber (about 300 μ s), thus Λ for the pulsed beam is suppressed by the additional factor of γ^2 .

The solution of equation (2) is:

$$\xi(z) = e^{i\frac{k+K}{2}z} \cdot \frac{\xi_0(K-k) - 2i\theta_0}{2K} + e^{i\frac{k-K}{2}z} \cdot \frac{\xi_0(K+k) + 2i\theta_0}{2K} \quad (3)$$

Here $K = \sqrt{k^2 - 4\Lambda}$, θ_0 and ξ_0 are the beam's angle and displacement after the entrance into the cooling solenoid respectively.

So far we have not been taking the nonuniformity of the real solenoidal field into account. The effect of nonuniform magnetic field on the electrons trajectory can be calculated from the comparison of the simulated trajectories in the measured magnetic field and in the uniform field (equal to the integral average of the measured field). With this amendment the readings of BPM # n in the cooling section are given by:

$$\xi_n(\xi_0, \theta_0, k) = \xi(z_n, \xi_0, \theta_0, k) + d\xi_{n,sol}(\xi_0, \theta_0, k) \quad (4)$$

Where z_n is the position of the particular BPM, $d\xi_{n,sol}$ is an additional trajectory's displacement in the BPM, caused by the nonuniformity of the CS magnetic field, and $d\xi_{n,sol}$ is the linear function of θ_0 and ξ_0 .

Measurement Algorithm

We find the fit of a differential trajectory in the least-squares sense by minimisation of the goal function:

$$\chi^2 = \frac{1}{\eta} \sum_n \frac{(\Xi_n - \xi_n)(\Xi_n^* - \xi_n^*)}{\sigma_{\Xi_n} \sigma_{\xi_n}} \quad (5)$$

Here $\Xi_n = X_n + iY_n$, where X_n and Y_n are the readings of BPM # n , σ_{Ξ_n} is the respective error, and * means the complex conjugation; the sum is taken over all BPMs. In all the calculus we used standard deviations instead of the statistical errors. The fact is that the systematic non-linear effects (not taken into account in (3)) are of the value of standard deviations. The number of degrees of freedom η is equal to the number of measured points (N) minus the number of parameters of the fit (M); in the prototype set-up the number of BPMs was 9, thus $N=18$, there are 5 parameters of the fit $(x_0, y_0, \theta_{x0}, \theta_{y0}, k)$, so $\eta=13$. The errors of the found fit parameters are given by:

$$\sigma_{a_m} = \left\{ H^{-1} \right\}_{m,m}, \quad \left\{ H \right\}_{m,n} = \frac{1}{2} \frac{\partial^2 (\chi^2)}{\partial a_m \partial a_n} \quad (6)$$

where a_m is the parameter number m [7].

Ergo, substituting (4) into (5) and minimizing (5) one can find the Larmor wave number k , and from it the energy of the electron beam. The error of the found energy is given by (6).

THE RESULTS OF THE MEASUREMENTS

Table 2: The results of energy measurements

#	B [G]	Beam current [mA]	Dipole kicker	Nominal & measured energy (E) [MeV]	Error [MeV]
	100	160		3.525	
1			XS02	3.467	0.002
2			XS04	3.474	0.008
3			YS04	3.470	0.006
4			YC00	3.470	0.005
	100	puls.		3.525	
5			YS02	3.463	0.006
6			YS04	3.470	0.012
	70	160		3.525, 3.575	
7, 8			XS04	3.455, 3.503	0.004
	75.2	22		3.530	
9			XS04	3.475	0.002
	75.2	22		3.530, 3.540	
10, 11			XS04	3.476, 3.485	0.002

The typical results of the application of the derived algorithm are shown in Fig. 2. The two upper plots show the differential trajectories of BPMs (error bars) and the fitting functions (solid lines) for x and y coordinates. Two lower plots show the corresponding residuals (dots) and the standard deviations of BPM readings (error bars).

The residuals are too high, and as a result χ^2 is about 20 instead of 1. An additional analysis shown that the residuals are linear functions of θ_0 and ξ_0 . Therefore, the most probable reason for the high value of the residuals is unsatisfactory precision of BPM calibration and BPM tilts that were not taken into account in the fit (4).

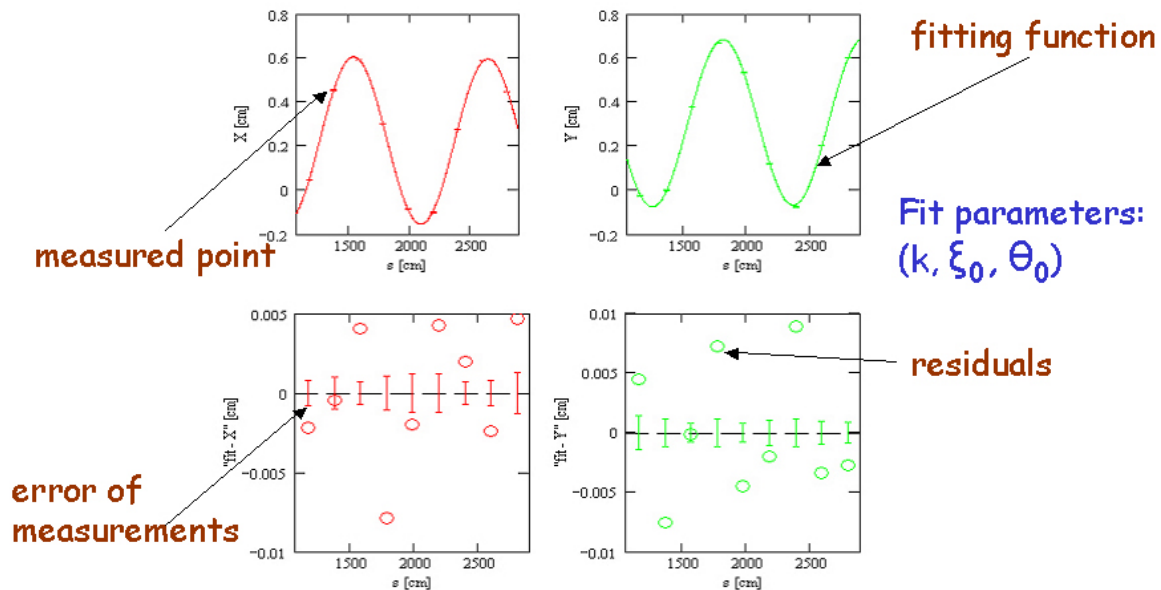


Figure 2: The typical result of the applied fitting algorithm. $B = 75.7$ G, nominal energy = 3.530 MeV, $I = 22$ mA. The standard deviations (error bars in the lower plot) were calculated from 20 consecutive BPM readings. The scatter of the readings is caused by the beam's oscillations.

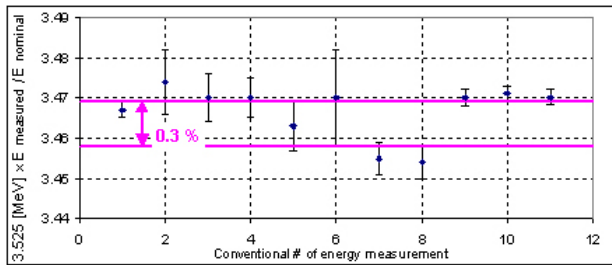


Figure 3: The spread of measured energies.

The differential trajectories were taken for different CS fields, at the different energies and beam currents, and were excited by the different dipole kickers. The results of the measurements are summarized in Table 2. The fourth column in the table gives the conventional names of the dipole kickers, used to excite the differential trajectories. The nominal energy (printed in the bold font) was measured by the generating voltmeter. The error of the energy measurement was calculated from (6) and represents a statistical error only. The same data are shown in Fig. 3 after normalization. All points fit to 0.4% range.

CONCLUSION

We have devised and tested the algorithm of beam-based energy measurements. The obtained precision of the measurements of electrons' energy is better than 0.4%. The measurements were done in the prototype of the Recycler Electron Cooler.

By the present time the electron cooler has been moved into the Recycler tunnel. We will repeat the same measurements and hope to improve the precision of the energy measurements to 0.1 % (the precision of magnetic field measurements). Improvements of BPM calibration

are planned to be done by measuring the trajectory of the antiproton beam, which is a straight line inside the cooling section.

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