OPTICS OF THE FERMILAB ELECTRON COOLER

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Abstract

Antiproton electron cooling is a key part of the Run II upgrade plan at Fermilab [1]. A unique parameter of this project is its energy (the relativistic factor is 9.5), which is much higher than for conventional coolers, and requires original solutions for the electron optics.

INTRODUCTION

Recycler is a storage ring of 3.3 km, located in the same tunnel as Main Injector. This ring is to be used for cooling and stacking of 8.9 GeV/c antiprotons coming from the Accumulator, where their stack is limited by IBS and possibilities of the stochastic cooling. The current scenario assumes that $\mathbf{20 \cdot 10^{10}}$ pbars are injected into the Recycler every 30 min. Every pbar batch has to be inside of 10-15 eVs of the longitudinal phase space and 7-10 mm mrad of the transverse normalized 95% emittance. The pbars are to be cooled both by stochastic and electron cooling systems [2-4] to reduce the longitudinal phase space 5-15 times, to counteract gas-driven emittance growth, and, perhaps, some longitudinal IBS. The whole stack is assumed to be up to $\mathbf{6 \cdot 10^{12}}$ within 30-50 eVs and 7-10 mm mrad, when it is extracted into Main Injector, accelerated to 150 GeV, injected in the Tevatron, and used in the proton-antiproton collisions at full energy of 1 TeV.

MAIN FEATURES

The electron cooling occurs due to electron Coulomb scattering on the antiprotons when the two beams are merged in a straight section of the storage ring. It is important that electrons have to be of smaller angles than tail antiprotons in the cooling section; otherwise, the cooling would be slowed down. It is also preferable to have some focusing in the cooler, to prevent drift instability of the electron beam [5]. The last requirement leads to a necessity for some longitudinal magnetic field in the cooler, $\mathbf{\geq 30-50}$ G. To have a parallel electron beam in the cooler, a corresponding field at the cathode is required, so that the magnetic fluxes inside the beam cross-sections are the same at the cathode and in the cooler, according to Generalized Busch's Theorem [6]. An effective emittance of such electron beam is determined by the magnetic flux at the cathode, while the temperature is irrelevant. This angular momentum dominated beam has a rather uniform density inside a well-defined sharp transverse boundary. At Fermilab, the electron beam is accelerated by an electrostatic accelerator Pelletron [7], then it is bended by $\mathbf{90^\circ}$ into the supply line, and bended by $\mathbf{90^\circ}$ in another plane to bring it into the cooling solenoid. After the solenoid, it makes a U-bend down the cooler, and after two $\mathbf{90^\circ}$ bends comes back to the Pelletron, see Fig. 1.

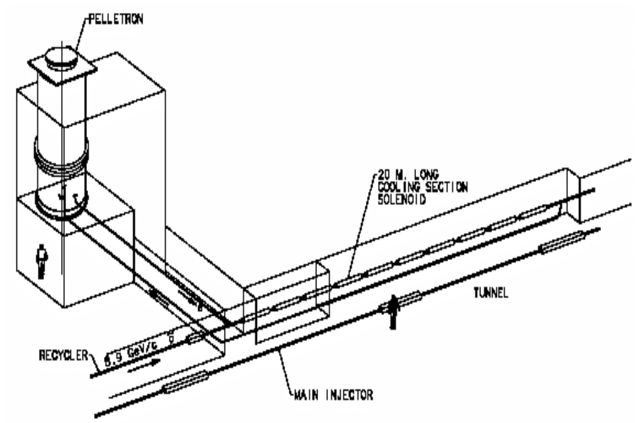

Figure 1: Schematic layout of the Fermilab electron cooler.

Electron cooler is to be installed at Recycler location named MI-31. Currently, its remote prototype is under commissioning at Fermilab [8]. Main parameters of the MI-31 design and the prototype line are presented in Table 1.

Table 1: Cooling System Specifications

Parameter	Cooler	Prototype
Terminal voltage	4.3 MV	3.5 MV
Electron beam current	~0.5 A	same
Terminal voltage ripple	< 500 V	same
Cathode radius	2.5 mm	same
Gun solenoid field	300-600 G	same
Cooling section length	20 m	18 m
Field in the cooler	~100 G	same
Vacuum in the cooler	0.1 nTorr	same
Cooling beam radius	4-6 mm	same
Electron angles	0.1-0.2 mrad	?
Length of the line	97 m	69 m

BEAM ROUNDING

The beam emitted by the round cathode is then accelerated and focused by axially symmetric fields in the Pelletron. Being transported by the supply line, the beam has to be round again in the cooling solenoid. The beam symmetry preservation has to be provided for any settings of the solenoidal lenses upstream the first bend and downstream the last bend in the supply line. From here, it is concluded that the transfer matrix of the supply line has to be rotation-invariant. It is also preferable to have the beam round in as many parts of the return line as possible, especially in the deceleration section.

However, not all the elements in the beam transport line preserve the rotation invariance. To kill the dispersion, the **90°** bends are cut in halves with a pair of opposite-field solenoidal lenses in between, which makes the bend matrix uncoupled. For technical reasons, the **45°** dipoles are with zero gradient; thus, they do not preserve the rotation symmetry. Another non-invariant element in the beam line is a dispersion-killing quadrupole inside the U-bend following the cooling section. Due to geometry restrictions, the solenoidal doublets cannot be used here. Thus, both **90°** and **180°** bends are non-invariant elements, i. e. do not preserve the beam symmetry. That is why a problem of the invariance restoration appears.

Any rotation-invariant matrix can be presented in the canonical phase space as a product of an arbitrary rotation in the transverse plane and a block-identical matrix [6]:

$$\boldsymbol{M}_{4\otimes 4} = \boldsymbol{R}(\theta)\begin{pmatrix} \boldsymbol{M}_{2\otimes 2} & \boldsymbol{0}_{2\otimes 2} \\ \boldsymbol{0}_{2\otimes 2} & \pm \boldsymbol{M}_{2\otimes 2} \end{pmatrix}.$$

This 4-parametric group of transformations preserves an absolute value of the canonical angular momentum. Taking into account that an arbitrary symplectic matrix is of 10 independent parameters, it follows that 6 free parameters are required to transform it into an invariant. In a special case of an arbitrary uncoupled matrix, the number of additional free parameters is only 3; for instance, 3 quadrupols at given positions and with free gradients are sufficient to transform the matrix into an invariant.

Invariance restoration by means of the quad triplet was used after the U-bend at the prototype electron line. When the quads are set properly, any round beam state at the bend entrance is transformed into a round state again after the triplet. An example of this transformation is presented in Fig. 2.

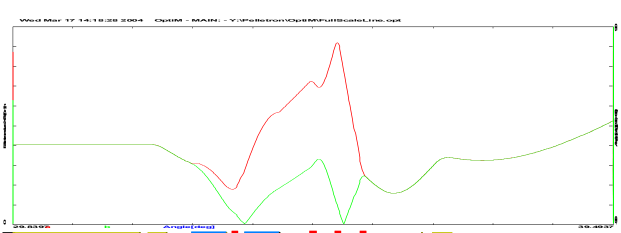

Figure 2: Beam rounding after U-bend by means of quad triplet. Green and red lines depict the 2 half-axes of the beam ellipse. The vertical scale is 1 cm, horizontal – 10 m.

All optical simulations were done with the code OptiM [9], which provides a wide range of possibilities for a fully-coupled optical analysis with a convenient GUI. Fig. 2 and other similar figures have a graphics at the bottom showing the lattice segment. Black color relates to acceleration / deceleration, yellow is for solenoids, blue – for dipoles and red – for quads. The green and red lines show two half-axes of the beam elliptical cross-section.

The U-bend consists of dipoles with the index 0.5. If the fringe fields of these dipoles are corrected with weak quads to make them invariance-preserving as well, the whole dipole is invariant. Thus, the only non-invariant element would be the central dispersion-killing quad. In this case the symmetry can be restored by means either of a ± solenoidal doublet and a single quad, or by a single solenoid and a pair of a normal and skew quad. Rounding quad used for this solution is significantly weaker than for the triplet case, so it could be ironless, which removes the hysteresis problems. That is why a current design for the cooler assumes a single-quad solution, illustrated in Fig. 3.

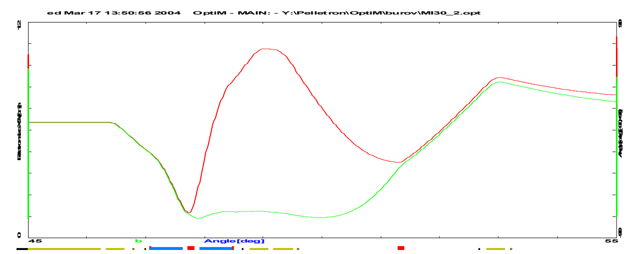

Figure 3: Beam rounding at U-bend by means of a solenoidal doublet and a single quad. The vertical scale is 1.2 cm, horizontal – 10 m.

Another special solution for the invariant optics has been found for the horizontal segments of the supply and return lines. This solution assumes that the beam is round at the entrance and exit of these segments only; inside them the beam is elliptical. Remember that the symmetry is broken by the dipoles of the **90°** bends. It is interesting that there is a special possibility to make the optics of these segments invariant without a single quad used. This special solution assumes mirror symmetry for a lattice of these segments; in this case, their matrices can be invariant for specific settings of their solenoids. This solution for the supply segment is shown in Fig. 4. The quads depicted at the bottom of the figure are zeroed for the design; they are going to be used for correction of a stray quadrupolarity in the supply line only.

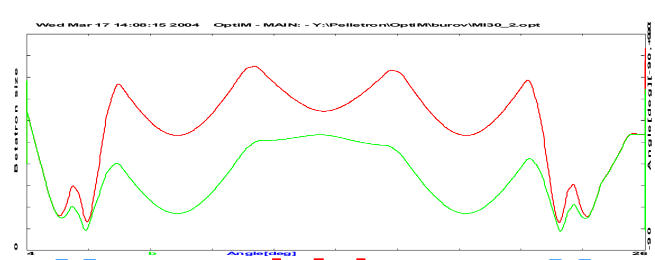

Figure 4: Invariant optics of the supply line is provided by the lattice symmetry; all the depicted quads are zeroed. The vertical scale is 1.2 cm, horizontal – 22 m.

The whole picture of the designed beam envelopes for nearly 100 m of the electron beam line is presented in Fig. 5. Note that the beam is round inside the accelerator, in the cooling section and the tunnel segment of the return line. The beam is parallel (no angles) in the cooler. The dispersion is zeroed everywhere outside the bends.

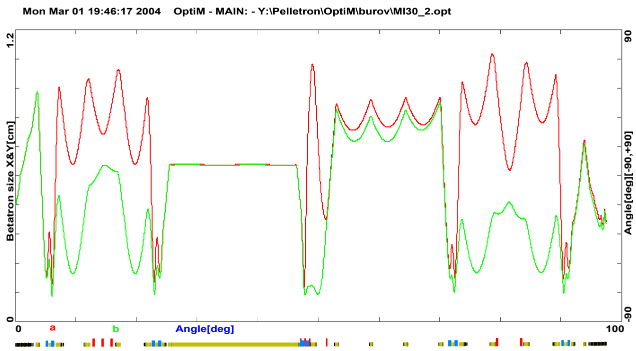

Figure 5: The beam half-axes for the whole line. The scale is 1.2 cm and 100 m.

TOUSCHEK EFFECT

Due to the Coulomb scattering, some electrons transfer their transverse energy into longitudinal one in the beam frame. Large angle scattering leads to growing of non-Gaussian tails in the longitudinal distribution (Touschek effect or single IBS). When the energy deviation exceeds the gun-collector potential, the electron is rejected from the collector area and is lost. To minimize losses, the angular momentum flips have to be avoided, as it is seen in the design envelope plot. The Touschek losses are calculated according to Ref. [6] and shown in Fig. 6 as a function of the gun-collector cut-off potential. The figure shows that the effect is not negligible and has to be taken into account in the collector design.

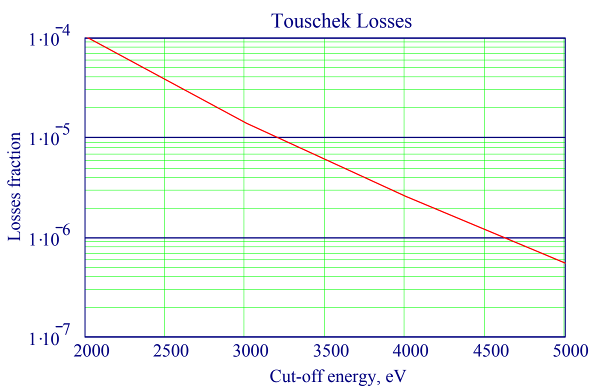

Figure 6: Touschek losses as function of the cut-off gun-collector energy, eV.

MEASUREMENTS AT PROTOTYPE

Optics of the prototype line [8] mainly repeats the cooler design, some differences are reflected in Table 1. Several kinds of optical measurements have been done, and this work is in progress.

Differential measurements of the beam trajectory show how the beam deflects at BPM positions when one or another upstream corrector is used. These measurements allow to correct calibration of the optical elements, to find fudge factors and stray forces, which requires sufficient number of BPMs and correctors. This program is only partly realized for the prototype line because of the insufficient BPM density.

Beam energy has been calculated from the wavelength of Larmor helix in the main solenoid (9 x-y bpms are equidistantly located there). The energy is found with an error ~ 1%, mainly limited by the BPM resolution.

Beam sizes have been measured by means of the multi-wire scanner, located 2.5 m below the last lens inside the accelerator tank. Measured as a function of this lens (A5) current, this allows to calculate the beam radius and divergence at the acceleration exit, as well as to check the magnetic field at the cathode. Fig. 7 shows the multi-wire data for the 2 transverse directions and the best fit of the calculated function. From this fit, the envelope at the acceleration exit is 4.5 mm and -0.3 mrad. Processing of the multi-wire data is a subject to be improved.

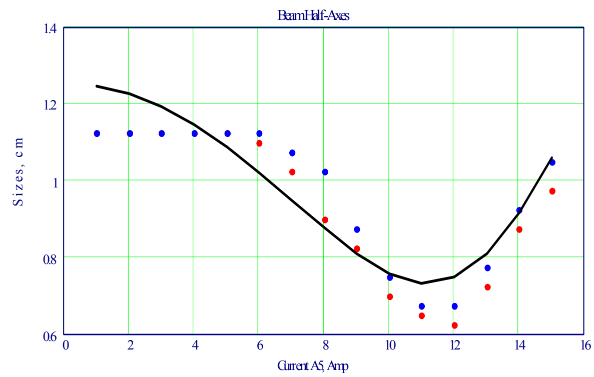

Figure 7: Beam envelope measurements (dots) and calculated best fit (line). The vertical scale is 0.6 – 1.4 cm, the horizontal – up to maximal current for the lens.

Commissioning of the prototype line is in progress.

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