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# THE DESIGN OF THE PROTON-EDM INJECTION LINE FROM BNL AGS BOOSTER

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*Abstract*

The proton Electric Dipole Moment (pEDM) storage ring to measure the electric dipole moment of the proton is proposed to be built in the tunnel of the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory (BNL) by storage ring EDM (srEDM) Collaboration. We proposed that the AGS Booster to pEDM ring transfer and injection line (BtP) would use the partial portions of the existing BtA (AGS Booster to AGS) transfer line optics. In this practice, both of BtP Clockwise orientation (CW) and Counter-clockwise orientation (CCW) injection lines are designed and matched using the single turn injection scheme. The injecting beam parameters are matched to pEDM ring Twiss functions.

## INTRODUCTION

We would use single turn injection method for the beam injection to pEDM ring from AGS Booster [1]. The injection scheme is shown in Fig. 1.

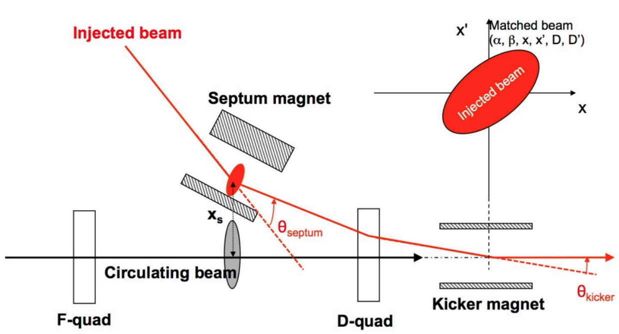



Figure 1: pEDM single turn horizontal injection scheme [2].

The pEDM ring design specifications regard the injection line design that reads as ”the injected beam with spin vector to be vertical in the pEDM ring within ±20 mrad” [3]. In this work, we carried out the BtP CW and CCW horizontal injection scheme injection line design by following the design procedures as shown below:

- Calculation of the beam parameters and dispersion functions, at the starting point of the BtA line (AGS Booster F6 Septum).
- Calculation of the beam parameters, dispersion functions of the circulating beam in pEDM at the injection point of pEDM CW and CCW ring (CW injection septum X and CCW injection septum X2A/X2B).
- Matching of the BtP line to the pEDM CW and CCW ring. In the matching procedure we use a Zgoubi model of the BtP line. The beam parameters of the injected beam $(\alpha(s), \beta(s), x, x', D(s), D'(s))$ are matched to those of the circulating beam at the pEDM CW and CCW injection point.

## PROTON-EDM RING LATTICE

The pEDM ring lattice used the symmetric-hybrid ring design and consisted of 24 FODO cells and its longitudinal length is ~ 800 $m$. [4] The single FODO lattice is given in Fig. 2.

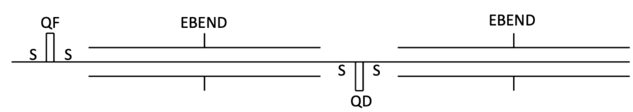
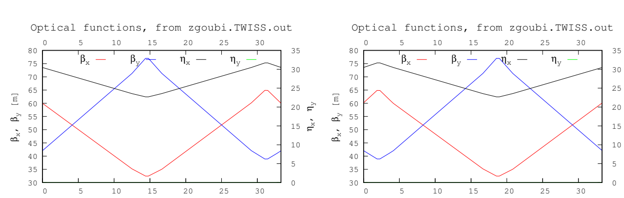



Figure 2: pEDM single FODO cell. QF: focusing quadrupole; QD: defocusing quadrupole; S: straight free drift; EBEND: electric bending [4].

The symmetric-hybrid ring design would allow simultaneous clockwise (CW) and counterclockwise (CCW) beam storage. Those counter-rotating (CR) beams see the opposite focusing effect from magnetic quads.

The beta and dispersion functions of the pEDM ring for both CW and CCW beam are shown in Fig. 3. The particle tracking is done by Zgoubi model. In this work, a Serret-Frenet coordinates frame $(\hat{x}, \hat{s}, \hat{y})$ is used (radial, longitudinal, vertical); for both CW and CCW rings, the longitudinal axis $\hat{s}$ is oriented in the beam direction, and the radial axis $\hat{x}$ points outward. Referring to Fig. 3(b), the moving frame has its longitudinal axis $\hat{s}$ in the beam direction (CCW), its radial axis $\hat{x}$ points outward (curvature is negative, dispersion is positive), and its vertical axis $\hat{y}$ points down.




(a) CW (b) CCW

Figure 3: pEDM CW and CCW beam beta function and dispersion function.

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# PROTON-EDM CW/CCW INJECTION KICKER PARAMETERS

The injection kicker angle $\theta_{kicker}$ could be calculated by

$$\theta_{kicker} = \frac{X_s}{\sqrt{\beta_k \beta_s}\sin(\mu)} \quad (1)$$

Where $X_s$ is the beam displacement at the injection septum magnet, $\beta_k$ is the beta function value at the kicker location, and $\beta_s$ is the beta function value at the septum magnet location, $\mu$ is the phase advance between the locations of septum magnet and kicker.

The beam displacement $X_s$ at the location of the injection septum magnet has to be larger than the total sum of several length quantities, such as the injected beam envelope, the radius of beamline vacuum pipe, the thickness of the septum blade, the beam size increase due to energy spread, the closed orbit distortion, the alignment errors, etc.

- *The radius of beamline vacuum pipe:* we assumed the beamline vacuum pipe has the radius as $r_0 = 0.06\ m$.
- *The thickness of the septum blade:* we assume the injection septum thickness as $l_0 = 0.01\ m$ and some clearances $l_c = 0.002\ m$ at both sides of the injection septum.
- *The injected beam envelope:* from the specifications of pEDM ring lattice, we note that injected beam envelope as $\sigma_x = \sqrt{\epsilon_x \beta_x} \cong 0.372\ cm$. Note that $\epsilon_x^{rms} = 0.214\ mm \cdot rad$, $\epsilon_y^{rms} = 0.25\ mm \cdot rad$. [4]
- *The beam size increase due to energy spread:* the momentum spread from the AGS booster is $\sim 1.4 \times 10^{-4}$ [3], the horizontal beam size due to energy spread $\sqrt{\epsilon_x \beta_x + D_x^2 (\Delta p/p)^2}$ was also considered into this calculation.
- *The closed orbit distortion:* ref. [4] gives that for pEDM experiment, the closed orbit distortion caused by field errors would fall into the range of few $\mu m$.
- *The alignment errors:* ref. [4] gives that for pEDM ring lattice, the tolerable alignment errors would be constraint to few hundreds of $\mu m$.

By taking into account of all length quantities mentioned above, we note that the beam displacement $X_s$ at the injection septum magnet should be larger than at least $\sim$ 8 $cm$ to achieve the injection.

The electrode spacing of electrostatic bending plates is 4 $cm$. The 4.16 $m$ straight sections (drift space + QF/QD + drift space) between electrostatic bends accommodate the injection system segment (injection septum magnet and injection kicker), no pEDM lattice optical structure is changed in this design. The injection septum and kicker are placed either side of de-focusing quadrupole (QD) to minimize kicker strength.

In order to easily calculate the kicker angle at the injection point of pEDM lattice, we extracted the beam from pEDM lattice rather than injected the beam. By tuning the injection kicker strength, we achieve the beam displacement $X_s \sim 8.03$ $cm$ at the injection septum location. The beam trajectory for a QD extraction is shown in Fig. 4. The parameters for this type of kicker are shown in Table. 1.

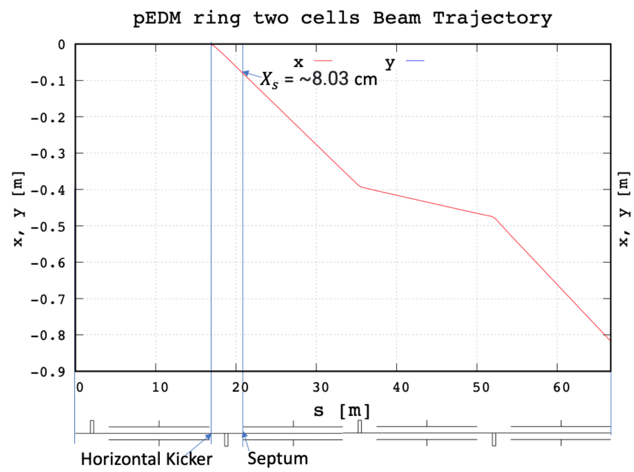


Figure 4: Beam Trajectory for a QD extraction.

Table 1: Horizontal QD Injection Scheme Kicker Parameters

| | | | |
|---|---|---|---|
| Proton P (GeV/c) | 0.707 | Beam Displ. (cm) | 8.03 |
| Kicker Dims. (cm) | 3.2(W)×2.2(H)×50(L) | Bunch Spacing (ns) | 200 [3] |
| Kicker Strength (kG) | 0.947 | Kicker Current (A) | 1658.16 |
| Kicker Angle (mrad) | 22.06 | Kicker Voltage (kV) | 7.58 |

# PROTON-EDM CW/CCW INJECTION LINE DESIGN

*The beam parameters at AGS Booster F6 Septum:* The calculations of the beam parameters and dispersion functions, at the starting point of the BtA line has been well studied. We use a MadX model of the BtA line, and beam parameters at the starting point of the BtA line would be used. [5]

*The beam parameters at pEDM CW/CCW injection septum:* With the knowledge of the locations of injection septum magnet and kicker, we could track and calculate the beam parameters, dispersion functions of the circulating beam in pEDM at the injection point of pEDM CW/CCW ring by Zgoubi model.

## *Matching of The BtP Injection Line To Proton-EDM CW/CCW Ring*

The BtP CW/CCW injection line geometric drawing are shown in Fig. 5.

The BtP CW injection beamline layout is shown in Fig. 6(a), starting from AGS Booster F6 Septum (BtA line starting point), the existing BtA line consists of 3 bending dipole magnets (DH1, DH2, DH3) and 7 focusing/de-focusing

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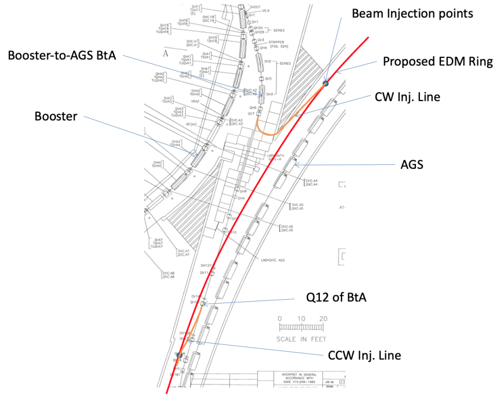
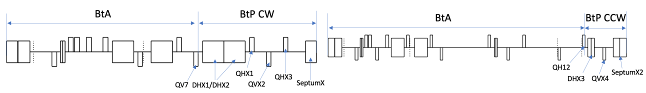



Figure 5: The pEDM CW/CCW injection line geometric drawing.




(a) CW (b) CCW

Figure 6: The pEDM CW/CCW injection beamline layout.

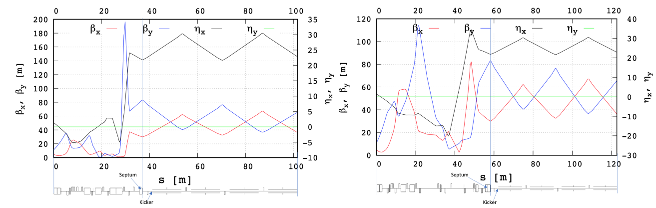
quadrupole magnets (Q1-Q7). Starting from Q7, the BtP CW injection line would have ~ 13.34 *m* in length, consists of two bending magnets (DHX1, DHX2) that provide a total ~ 155° bending angle, and three quadrupoles (QHX1, QVX2, QHX3). The injection angle would be ~ 3°, the injection septum (SeptumX) would provide ~ 1.74°, and the injection kicker would contribute ~ 1.26° to kick the beam into the orbit.

The BtP CCW injection beamline layout is shown in Fig. 6(b), starting from AGS Booster F6 Septum (BtA line starting point), the existing BtA line consists of 4 bending dipole magnets (DH1, DH2, DH3, DH4) and 12 focusing/defocusing quadrupole magnets (Q1-Q12). Starting from Q12, the BtP CCW injection line would have ~ 7.76 *m* in length, consists of one bending magnet (DHX3) that provide a ~ 8° bending angle, and one quadrupole (QVX4). The injection angle would be ~ 7°, the injection septum (SeptumX2A&B) would provide ~ 5.74°, and the injection kicker would contribute ~ 1.26° to kick the beam into the orbit.

The beam parameters of the injected beam ($\alpha(s)$, $\beta(s)$, $x$, $x'$, $D(s)$, $D'(s)$) are matched to those of the circulating beam at the pEDM CW and CCW injection point. The matched optical functions are shown in Fig. 7.

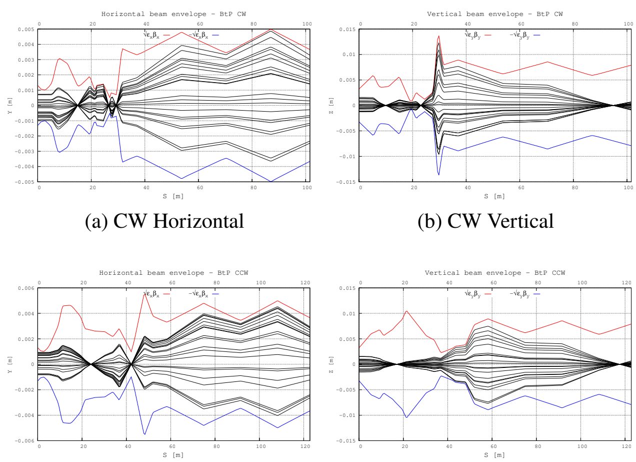
## PARTICLE AND SPIN TRACKING WITH THE MATCHED PROTON-EDM INJECTION LINES

We tracked 20 particles with random initial coordinates in either horizontal or vertical phase space for both pEDM CW and CCW matched injection line. The beam envelopes are shown in Fig. 8.



(a) CW (b) CCW

Figure 7: The pEDM CW/CCW injection line matched optical functions.

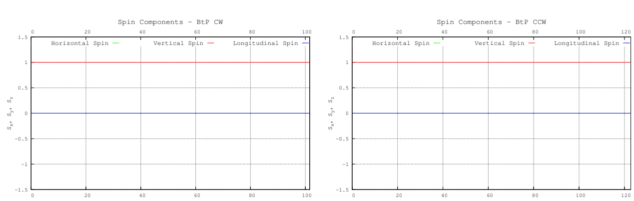


(a) CW Horizontal (b) CW Vertical

(c) CCW Horizontal (d) CCW Vertical

Figure 8: The matched pEDM CW/CCW injection line beam envelopes.

We also tracked spin vector behaviors along both pEDM CW and CCW injection line when injection kicker is ON. The spin components for both pEDM CW and CCW injection line are shown in Fig. 9. Note the injected particle has initial spin along the vertical direction +1.



(a) CW (b) CCW

Figure 9: The matched pEDM CW/CCW injection line spin components with injection kicker ON.

## CONCLUSION

In this work, both of BtP Clockwise orientation (CW) and Counter-clockwise orientation (CCW) injection line are designed and matched in the hypothesis of a single turn horizontal injection scheme. For the future work, we may explore the single turn vertical injection scheme.

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