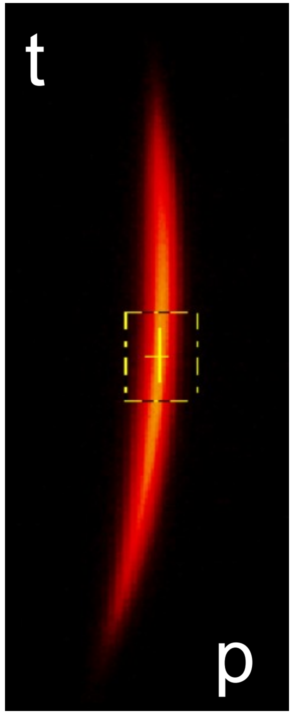
Using slit to extract emittance induced slice energy spread measurement resolution



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Outline

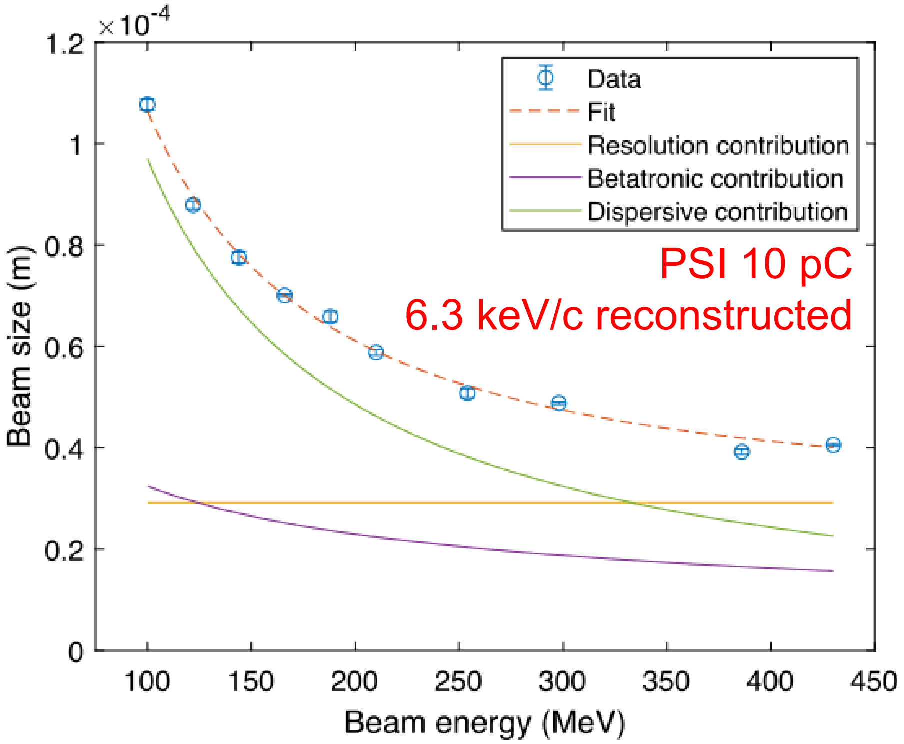
- Slice energy spread measurement with a slit mask at PITZ
- Reference screen analysis for general momentum measurement
- Longitudinal phase advance during booster phase scan for LPS tomography

Review of slice energy spread measurement at PSI

$$\sigma_{emit}^2 = \frac{\varepsilon_n \beta}{\gamma}$$

$$\left(D\frac{\sigma_{E0}}{E}\right)^2 \sim \frac{1}{\gamma^2}$$

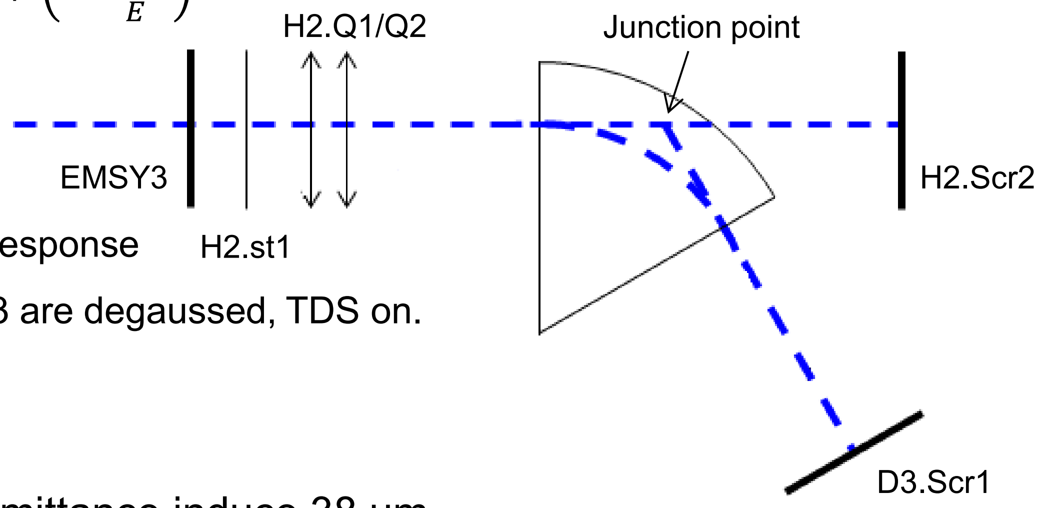
- Without TDS, just a dipole, or assuming TDS effect is removed by TDS scan
  - Beam size on dispersion screen after the dipole, $\sigma_M^2 = \sigma_R^2 + \sigma_{emit}^2 + \left(D\frac{\sigma_{E0}}{E}\right)^2 + \left(D\frac{\sigma_{TDS}}{E}\right)^2$
    - PSI 10 pC case, @400 MeV, screen→33 um, emit→18 um, energy spread→24 um, overestimate by 86%
    - PSI 10 pC case, @100 MeV, screen→33 um, emit→35 um, energy spread→98 um, overestimate by 11%
    - What if the energy drops to 25 MeV
      - assuming same beta function, same emittance, same energy spread
      - screen→33 um, emit→70 um, energy spread→396 um
      - Overestimation by only 2%
  - PITZ case vs PSI case
    - PSI, 100-400 MeV, beta=0.7 m, D=1.5 m, screen 33 um (~2.2 keV)
    - PITZ, ~20 MeV, D=0.905 m, beta ?, screen 132 um/pixel (~3 keV/pixel)
      - Advantage, a factor of 5 lower energy, sensitive to energy spread
      - Disadvantage, twiss parameters unknown, space charge effect



EMSY slit to help slice energy spread measurement

Direct measurement of emittance induced beam size on dispersion screen

- Issues with the current method
  - Beta function measured with EMSY3 is for the full beam, not the central time slice.
  - When we go to high charge (~250 pC), we can't use transport matrix to calculate beta function @D3.Scr1
- Use EMSY3 horizontal 10 um slit to mitigate space charge, assuming slice energy spread is the same
  - Central time slice beam size @D3.scr1, $\sigma_M^2 = \sigma_R^2 + \sigma_{emit}^2 + \left(D\frac{\sigma_{E0}}{E}\right)^2 + \left(D\frac{\sigma_{TDS}}{E}\right)^2$
  - By scanning V_{TDS}, we can extract $\sigma_R^2 + \sigma_{emit}^2 + \left(D\frac{\sigma_{E0}}{E}\right)^2$
    - With horizontal 10 um slit inserted, $\sigma_{emit} = R_{12}^{EMSY3\rightarrow D3.scr1}\sigma_{x\prime}^{EMSY3}$
      - $R_{12}^{EMSY3\rightarrow D3.scr1}$ can be measured from H2.st1 to D3.scr1by trajectory response
      - $\sigma_{x\prime}^{EMSY3}$can be measured from EMSY3 to H2.scr2 when Q1/Q2 and D3 are degaussed, TDS on.
    - σ_R can be approximated by pixel calibration, then we can extract σ_{E0}
    - With Q1/Q2 off, EMSY3 → D3.Scr1, R11=-0.51, R12=0.38
      - Assuming 1 mm.mrad @20 MeV, 0.25 mm before slit, then emittance induce 38 um
  - Possible issues: low SNR due to 10 um slit and only 2 pulse streaking
    - maybe replace 10 um slit or multi-slit to 50-100 um single slit, a factor of 5-10 more signal

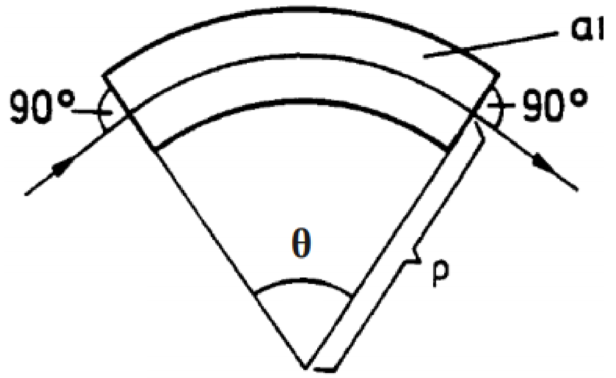


Reference screen for momentum measurement

No space charge model, sector dipole @PITZ

- General transfer matrix from dipole entrance to dispersion screen and to reference screen
  - L is drift from dipole exit to screen, r is bending radius, theta is bending angle

$$\begin{pmatrix} \mathrm{Cos}[\theta] - \frac{L\mathrm{Sin}[\theta]}{r} & L\mathrm{Cos}[\theta] + r\mathrm{Sin}[\theta] \\ -\frac{\mathrm{Sin}[\theta]}{r} & \mathrm{Cos}[\theta] \end{pmatrix} \text{ vs } \begin{pmatrix} 1 & x \\ 0 & 1 \end{pmatrix}$$



- To have a good reference screen, R11=-1

$$\begin{pmatrix} -1 & L \\ -\frac{\mathrm{Sin}[\theta]}{r} & \mathrm{Cos}[\theta] \end{pmatrix} \qquad L = \frac{1+\mathrm{Cos}[\theta]}{\mathrm{Sin}[\theta]} r$$

- A special situation, theta=180 degree, naturally has a reference screen

$$\begin{pmatrix} -1 & -L \\ 0 & 1 \end{pmatrix}$$

Bending plane

$$M_{x,sector} = \begin{pmatrix} \cos\theta & \rho\sin\theta & \rho(1-\cos\theta) \\ -\frac{1}{\rho}\sin\theta & \cos\theta & \sin\theta \\ 0 & 0 & 1 \end{pmatrix}$$

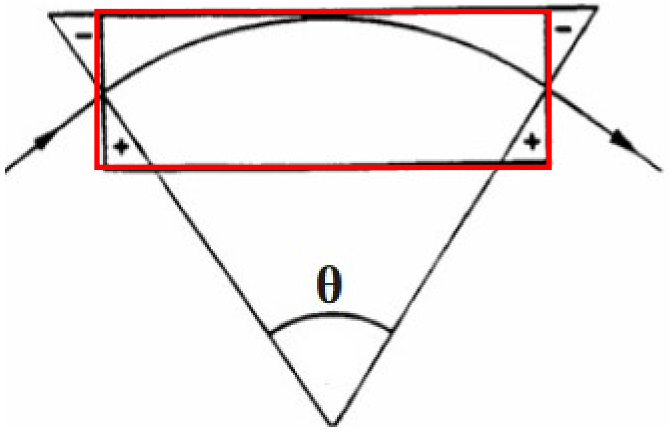
$$M_{y,sector} = \begin{pmatrix} 1 & \rho\theta \\ 0 & 1 \end{pmatrix}$$

Non bending plane

Reference screen for momentum measurement

No space charge model, rectangular dipole

- A rectangular dipole: edge focusing + sector magnet
  - If trajectory is symmetric, i.e. entrance angle equals exit angle
    - Transverse matrix in the bending plane is a pure drift
    - Then reference screen is just $L + r\theta$ from the dipole entrance



Bending plane

$$M_{x,rect} = \begin{pmatrix} 1 & \rho \sin\theta & \rho(1-\cos\theta) \\ 0 & 1 & 2\tan\frac{\theta}{2} \\ 0 & 0 & 1 \end{pmatrix}$$

Drift

Non bending plane

$$M_{y,rect} = \begin{pmatrix} 1-\theta\tan\frac{\theta}{2} & \rho\theta \\ -\frac{1}{\rho}\left(2-\theta\tan\frac{\theta}{2}\right)\tan\frac{\theta}{2} & 1-\theta\tan\frac{\theta}{2} \end{pmatrix}$$

Focusing

Reference screen for momentum measurement

Current situation

- HEDA2 has no good reference screen
  - X transfer matrix from dipole entrance to D3.scr1

$$\begin{pmatrix} -0.51 & 0.87 \\ -1.44 & 0.5 \end{pmatrix}$$

  - X transfer matrix from dipole entrance to H2.scr2

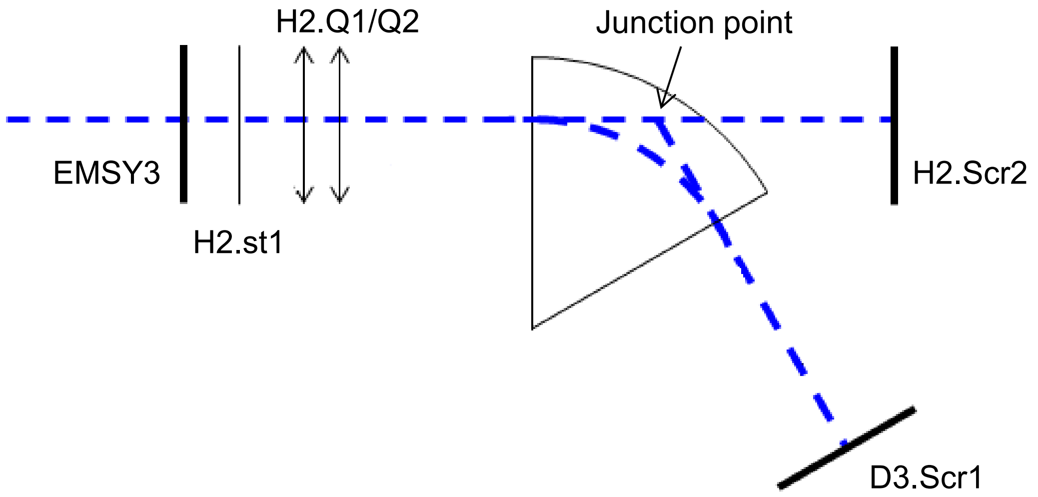
$$\begin{pmatrix} 1 & 0.994 \\ 0 & 1 \end{pmatrix}$$

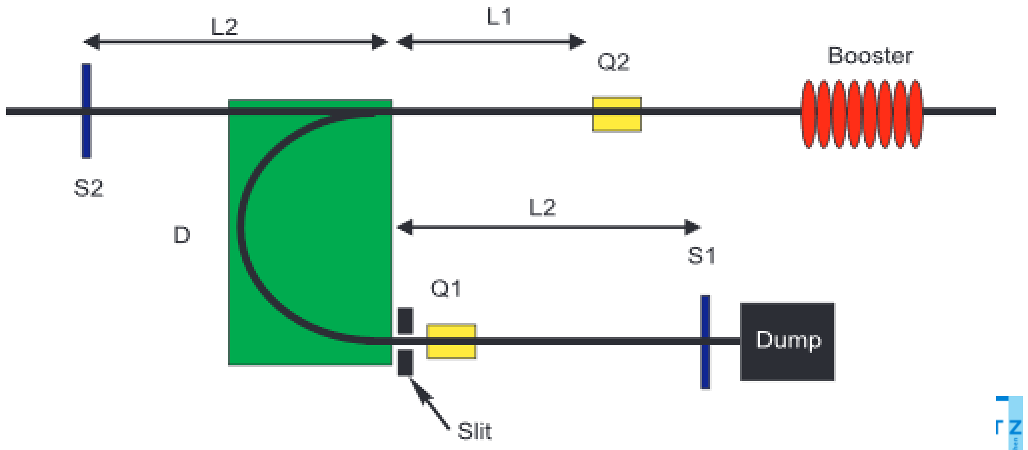
- HEDA1 has good reference screen
  - Y transfer matrix from dipole entrance to D2.scr1

$$\begin{pmatrix} -1 & -1.405 \\ 0 & -1 \end{pmatrix}$$

  - X transfer matrix from dipole entrance to H1.scr5

$$\begin{pmatrix} 1 & 1.418 \\ 0 & 1 \end{pmatrix}$$





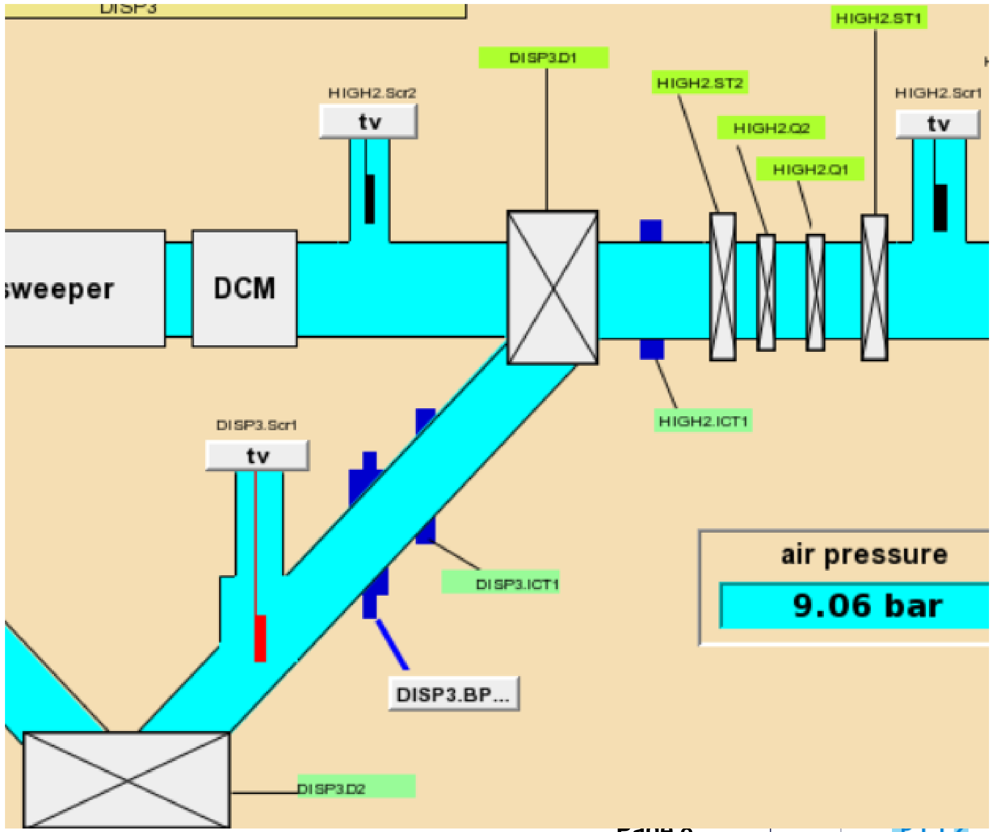
Reference screen for HEDA2

Need some changes

- Plug the numbers for D3 to design a reference screen
  - Theta = 60 degree, r=0.6 m, then L=1.039 m
    - Currently L=0.7 m, too short
      - Near the perfect position has the element ‘Driftrohr DN100’
    - Reference screen is 1.039 m upstream of D3 entrance
      - 74 mm upstream of H2.scr1
      - Still within the range of EMSY3 station

$$\begin{pmatrix} -1 & L \\ -\frac{\mathrm{Sin}[\theta]}{r} & \mathrm{Cos}[\theta] \end{pmatrix} \qquad L = \frac{1+\mathrm{Cos}[\theta]}{\mathrm{Sin}[\theta]} r$$

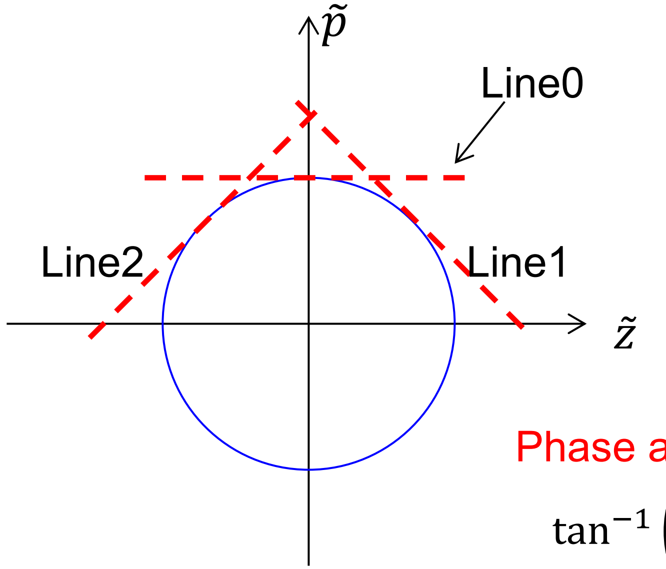
$$\begin{pmatrix} -1 & 1.039 \\ -1.443 & 0.5 \end{pmatrix}$$



Phase advance in HEDA scan

A simple model

- Assuming the input beam has no chirp, so the RMS ellipse of the beam is,
  - $\left(\frac{z_0}{\sigma_z}\right)^2 + \left(\frac{\delta p_0}{\sigma_{p_0}}\right)^2 = 1$
- Simplify the booster into, $p = p_0 + \Delta p_{booster} + kz_0$, $\delta p = \delta p_0 + kz_0$
  - Measured rms energy spread after booster: $\sigma_p = \delta p_0 + kz_0$
  - Rewrite the equation by using $\tilde{p} = \frac{\delta p_0}{\sigma_{p_0}}$, $\tilde{z} = \frac{z_0}{\sigma_z}$, they are unitless
    - Original phase ellipse is $\tilde{p}^2 + \tilde{z}^2 = 1$
    - Measurement $\sigma_p = \sigma_{p_0}\tilde{p} + k\sigma_z\tilde{z}$
      - When k=0, line0 (use this as phase advance 0, min energy spread during HEDA scan)
      - When $k\sigma_z = \sigma_{p_0}$, line1 (phase advance -pi/4, energy spread increase by sqrt(2) w.r.t. min)
      - When $k\sigma_z = -\sigma_{p_0}$, line2 (phase advance pi/4, energy spread increase by sqrt(2) w.r.t. min on the other side)
    - Similar to transverse emittance measurement by quad scan
      - measurement points within +/-pi/4 should be dense, phase advance is very fast, especially near min energy spread, maybe ~10 steps total within +/-pi/4
      - then add a few scan points outside this range to cover more phase advance, e.g. until energy spread increases by a factor of 2
      - more measurements outside this range does not help anymore, because phase advance is very slow, then it only reflecting z dimension, like booster chirping for time profile measurement.
      - To get a detailed scan near min energy spread, booster gradient can't be too big



Phase advance
$\tan^{-1}\left(\frac{k\sigma_z}{\sigma_{p_0}}\right)$

A recent LPS tomography test

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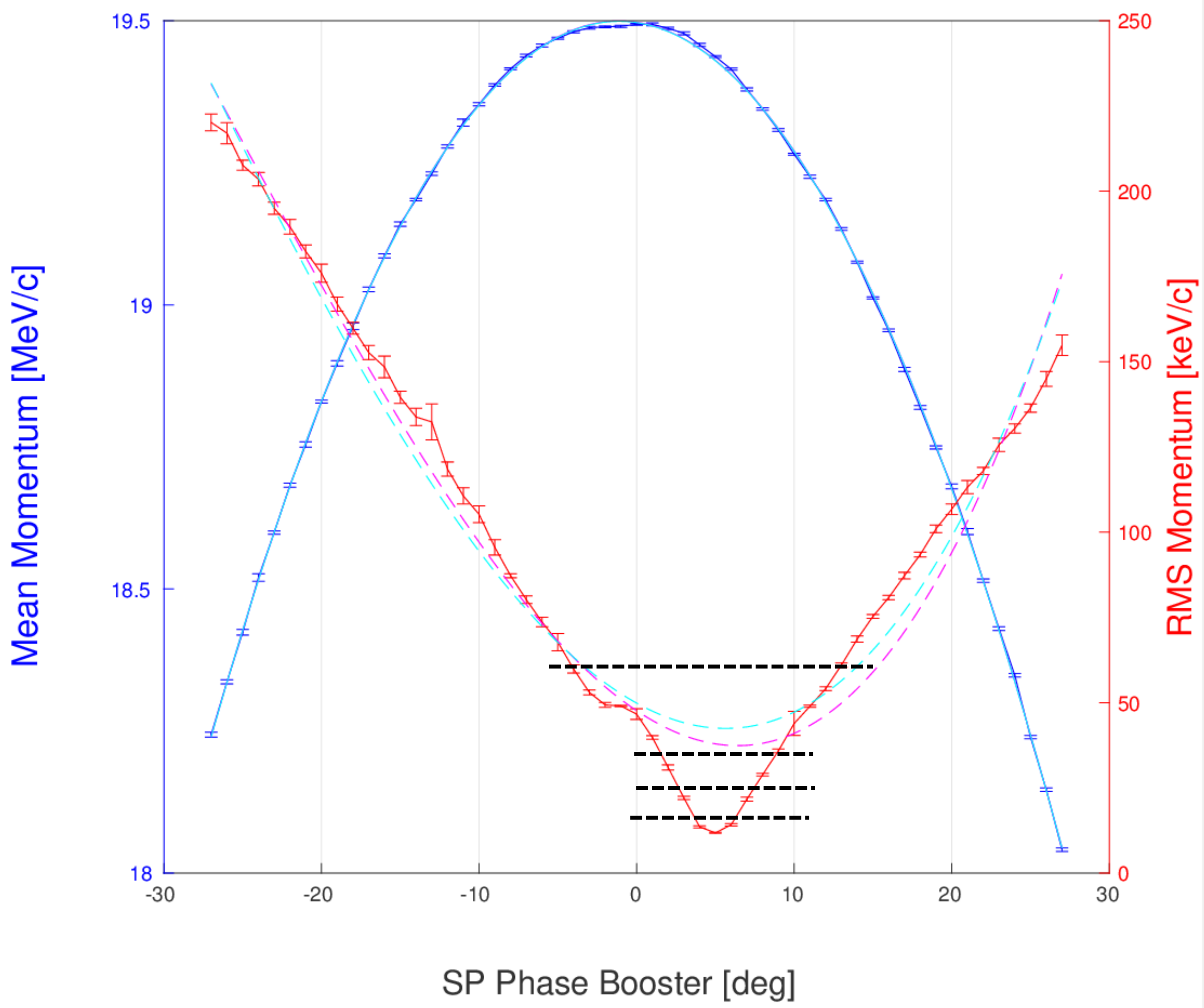

- Minimum energy spread ~12 keV
  - Within +/-45 degree phase advance, 3 points
  - Within +/-60 degree phase advance, 5 points
  - Within +/-70 degree phase advance, 7 points
  - Within +/-80 degree phase advance, 15 points
- Improvements
  - reduce booster gradient for the scan
  - Finer scan within the right range