For Project/Workshop users only

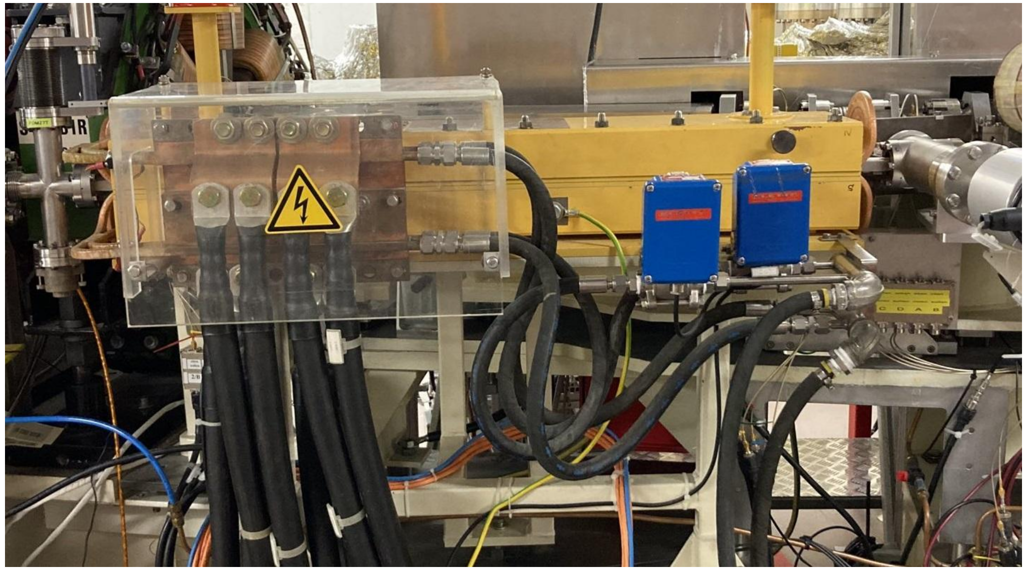
PERMANENT MAGNET DIPOLE FOR BESSYII+

I. Asparuhov 15.09.25

4th PerMaLIC workshop

Berlin, Germany

Permanent-magnet bending triplet as successor to a 30-kW injector-beamline high-current electrodipole



Current B2PT which is a 1-m long 1.6-kA copper-coil 30-kW static C-shaped electro-dipole at end of transfer line upstream of injection septum.

- Provides a field $B_y = 0.78$ T.
- Targeted for replacement by a PM concept in the framework of the BESSYII+ upgrade project.

Context and goal

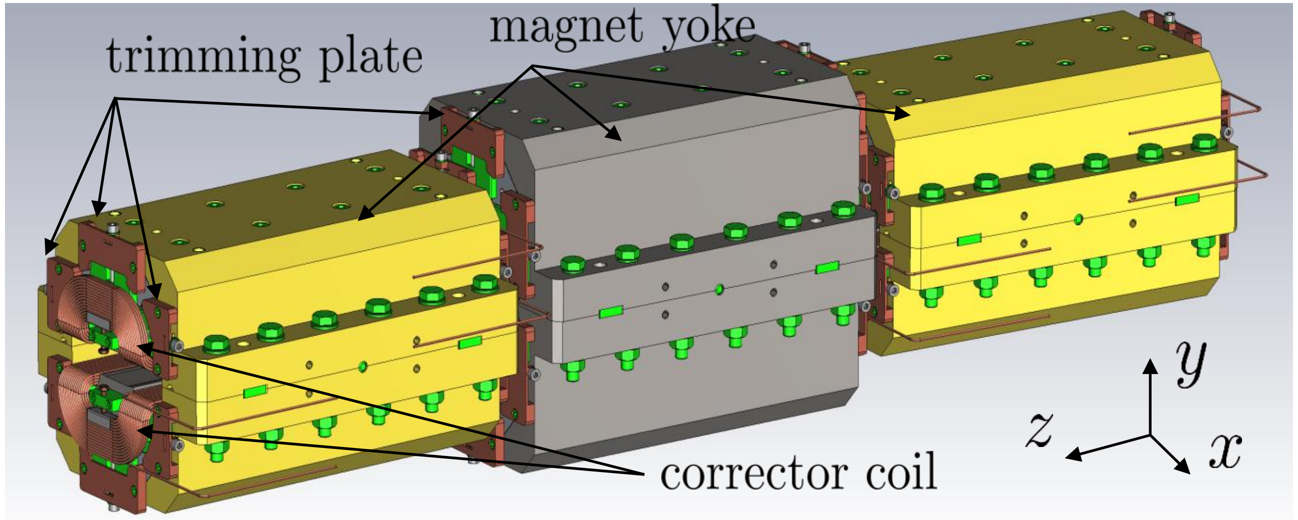
- **Reduction of overall power consumption (0.2 GWh yearly in energy)** of new facility for improved energy efficiency with enhanced magnet operation stability **- elimination of field ripple and vibration sources** (power supplies and cooling channels)**.**
- **First PM-based accelerator magnet at BESSYII**. Further magnet projects planned (BESSYII+ upgrade acting as technology development project):

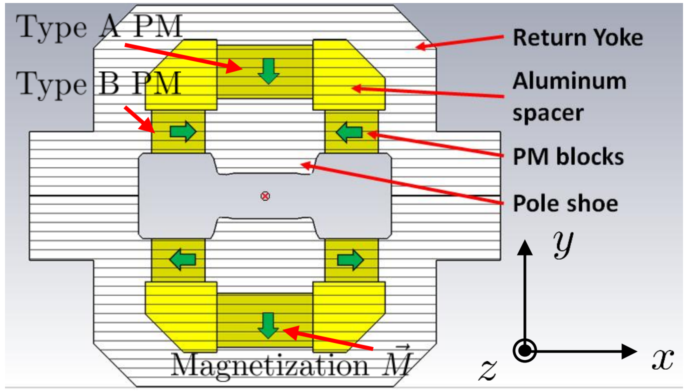
  => PM bending magnets in BESSYII storage ring (homogeneous and longitudinal-gradient bend)
  => 2.5-GeV 4th generation low-emittance BESSYIII.
- B2PT PM dipole triplet to provide **new bend angle of 7.82°** for 1.7-GeV e^- beam trajectory towards septum (reduced from 8.19° due to injection setup and septum optimizations).
- Optimization of triplet PM and geometry configuration for required beam trajectory taking into account technical capabilities for field tuning.

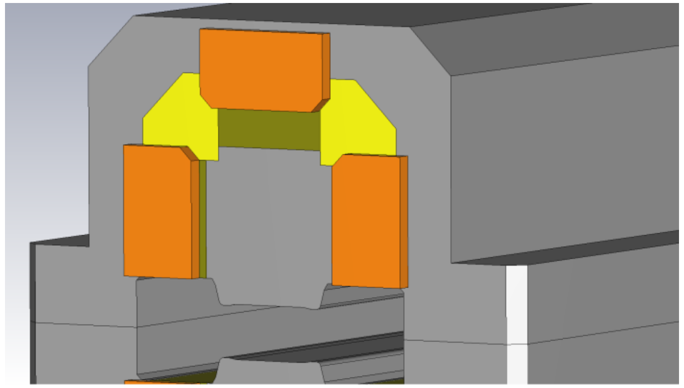
B2PT Dipole Magnet Triplet

New longitudinally symmetric hybrid permanent-magnet triplet assembly B2PT of 3 separate dipole units, 2 identical outer ones and 1 stronger central one. Assembly started in April 2025.

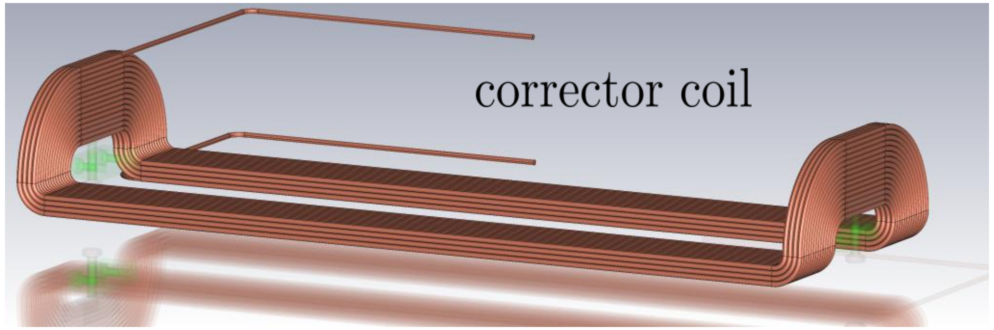
Parameter	central dipole	outer dipoles
length $L_{z\,mag}$	300 mm	300 mm
width	220 mm	220 mm
height	238 mm	178 mm
pole aperture (gap)		
spacing d_{inn}	40 mm	40 mm
dipole angle ν		2.6°
dipole offset Δ	7 mm	
PM type A/B ratio	8/24	10/24
peak field $B_{y\,max}$	0.97 T	0.75 T



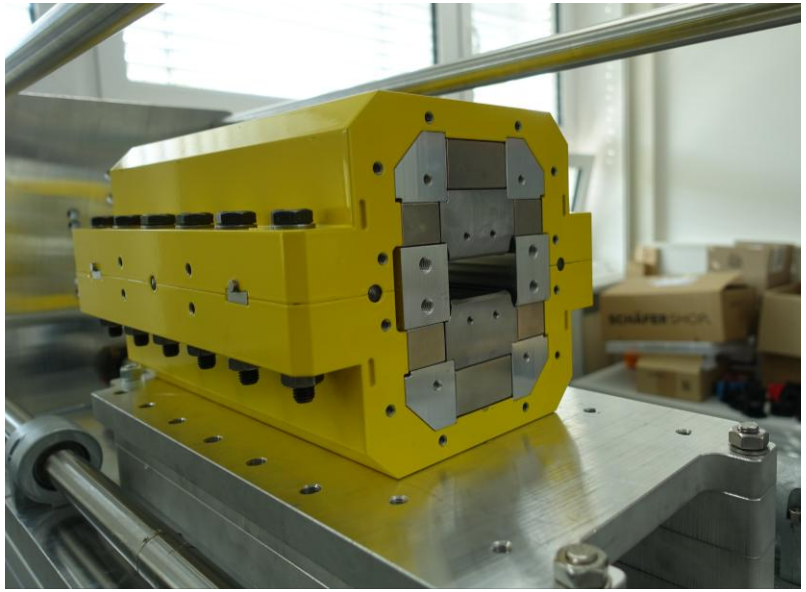




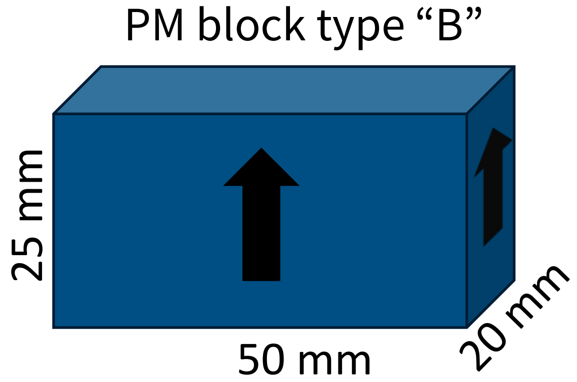
trimming plate (orange)



Triplet Design and Field Adjustment

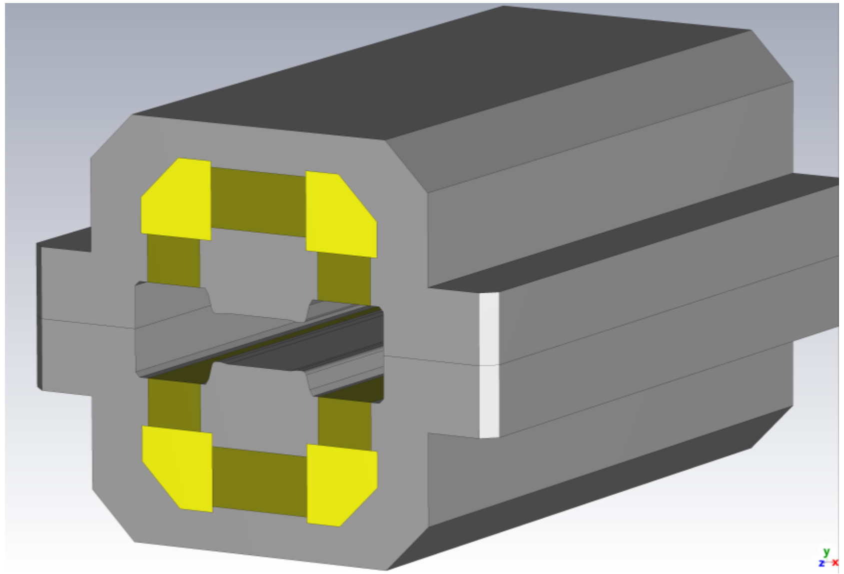


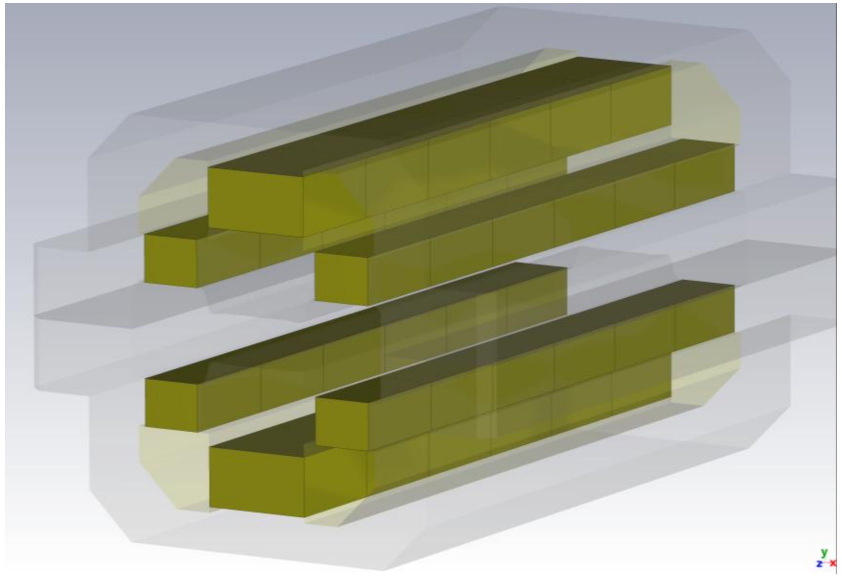
- **Magnetic field driven by PM blocks** nested in symmetric steel structure => return yoke + pole pieces.
- 6 rows of permanent magnets in each dipole => possible total of 6 magnet blocks per row => **resulting maximum 36 magnets per dipole**.
- 2 types of PM blocks, "A": (length × width × height) 50 × 45 ×25 [mm] and "B" (50 × 20 × 25 [mm]).
- **NdFeB N42** PM material of remanent field $B_{\mathrm{r}} = 1.3\ \mathrm{T}$ along easy magnetization with linear relative permeability $\mu_{\mathrm{r}} = 1.05$ used in CST magnetic simulations.
- ≈ **2.6 % field variation** expected with **low-current** (≈ 2.5 A/mm^2**) convection-cooled coils** on outer dipoles.
  => Total available triplet **field tuning range** $\boldsymbol{\theta_{tun} = d\theta_{\max}/\theta_{\mathrm{trgt}} \approx 5.6\%}$**.**
- Additional **tuning with steel trimming plates**, 12 /dipole in 2 end groups of 6.
  => symmetric **adjustment for field tuning ≈** $\boldsymbol{\pm 3}$ %
  => correction of differences among **PM-row average fluxes.**
- PM block positioning with dedicated **press-in tool**.

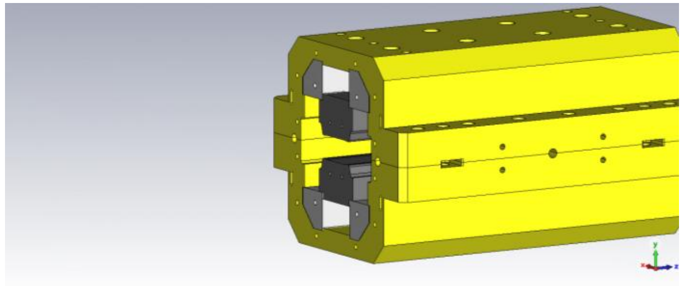


- PM blocks tested in Helmholtz Coil-Setup and Hall-Array.
- Costs of material, equipment and assambly tools amortized in 1.5 years of operation.

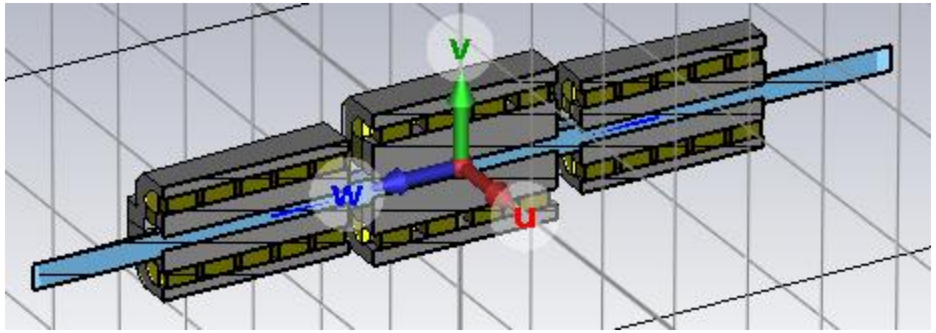
PM block row nesting in dipole yoke structure

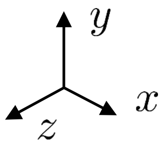




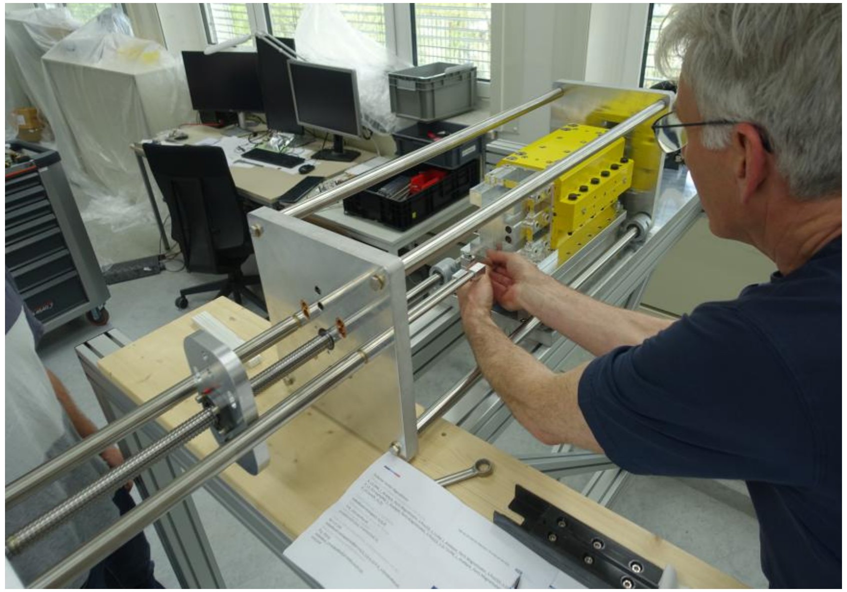


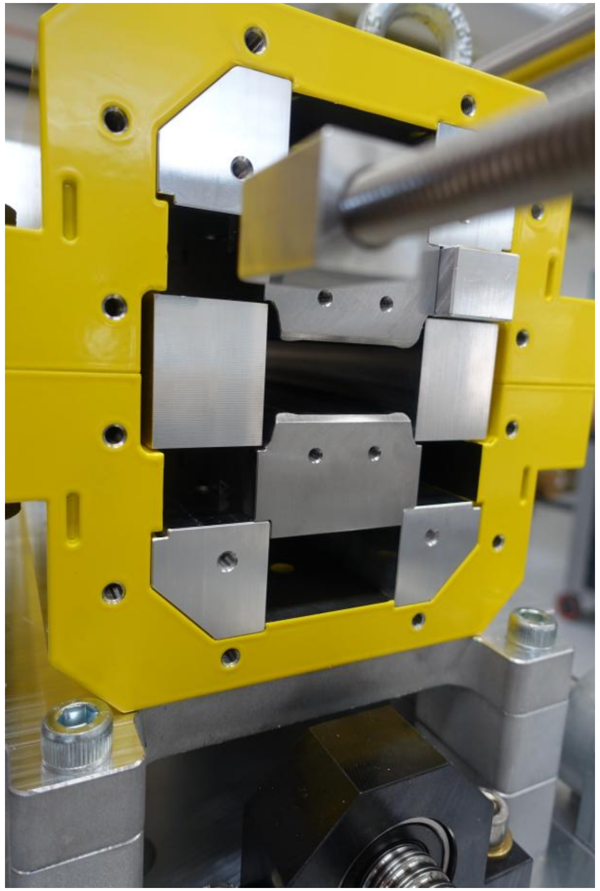
Courtesy: J. Völker

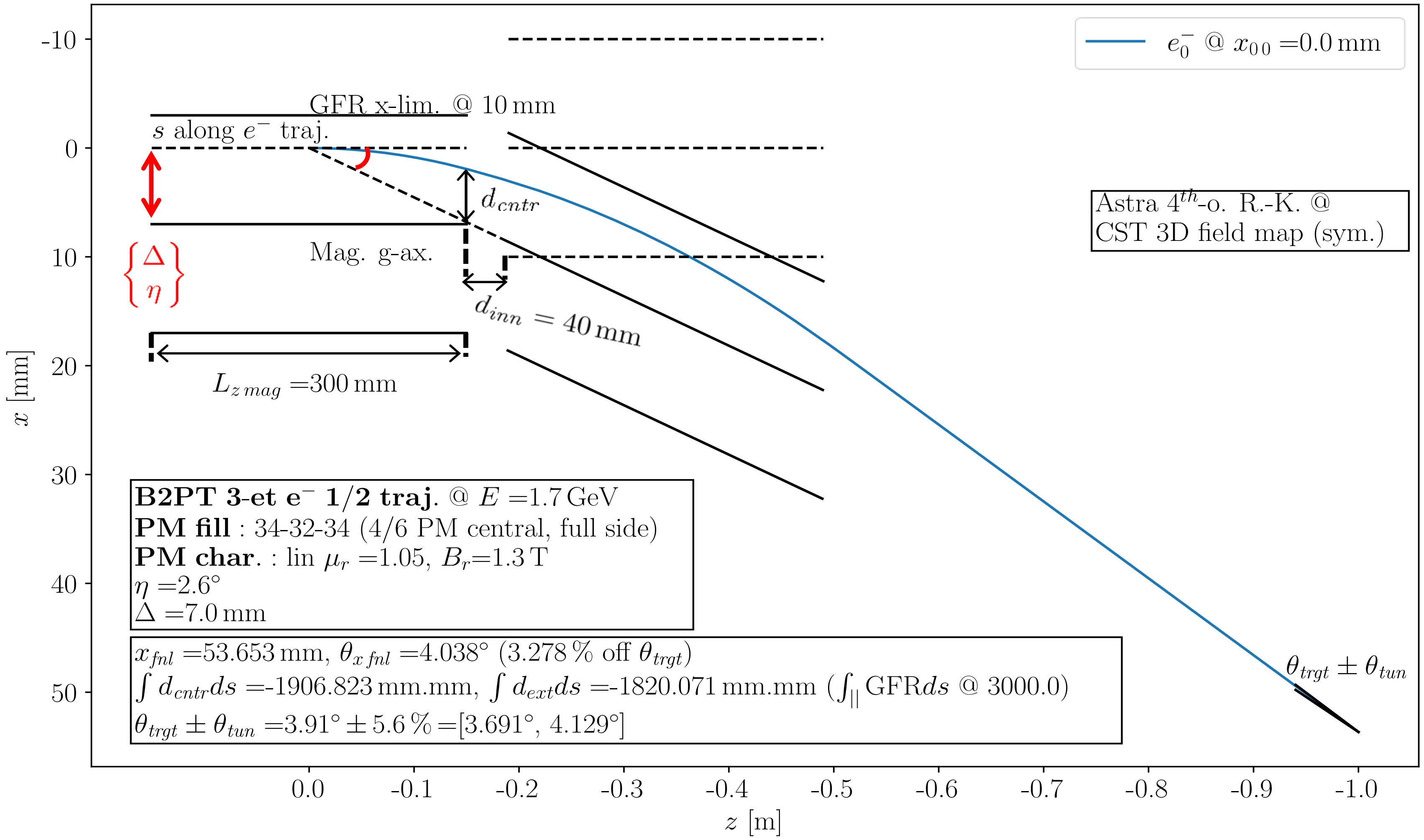




PM insertion in dipole (yellow) via mechanical press-in tool in real life.







Triplet PM fill patterns and geometries

=> outer-magnet angle η and central-magnet horizontal offset Δ for required bend angle $\theta_{x\,fnl}$.

Full 3D triplet field map

=> crosstalk regions + fringe fields computed with CST magnetic solver input in ASTRA Runge-Kutta single-particle tracker for beam trajectory calculation.

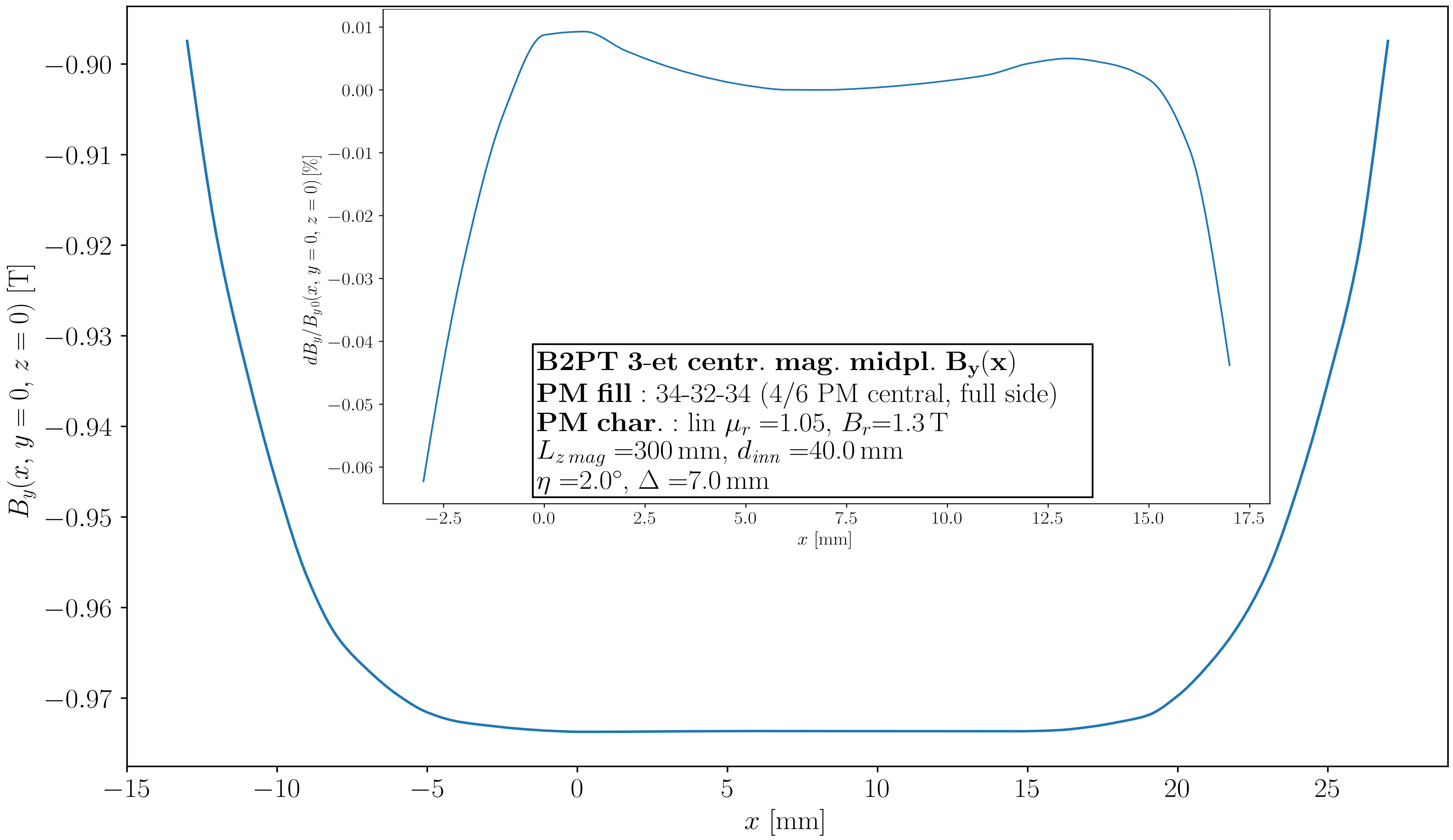
1.7 GeV electron symmetric half-trajectory from ASTRA for **34-32-34 PM block pattern** in triplet dipoles.

=> **3.28 % overbent trajectory in GFR (± 10 mm)** wrt to target half-angle of 3.91°.

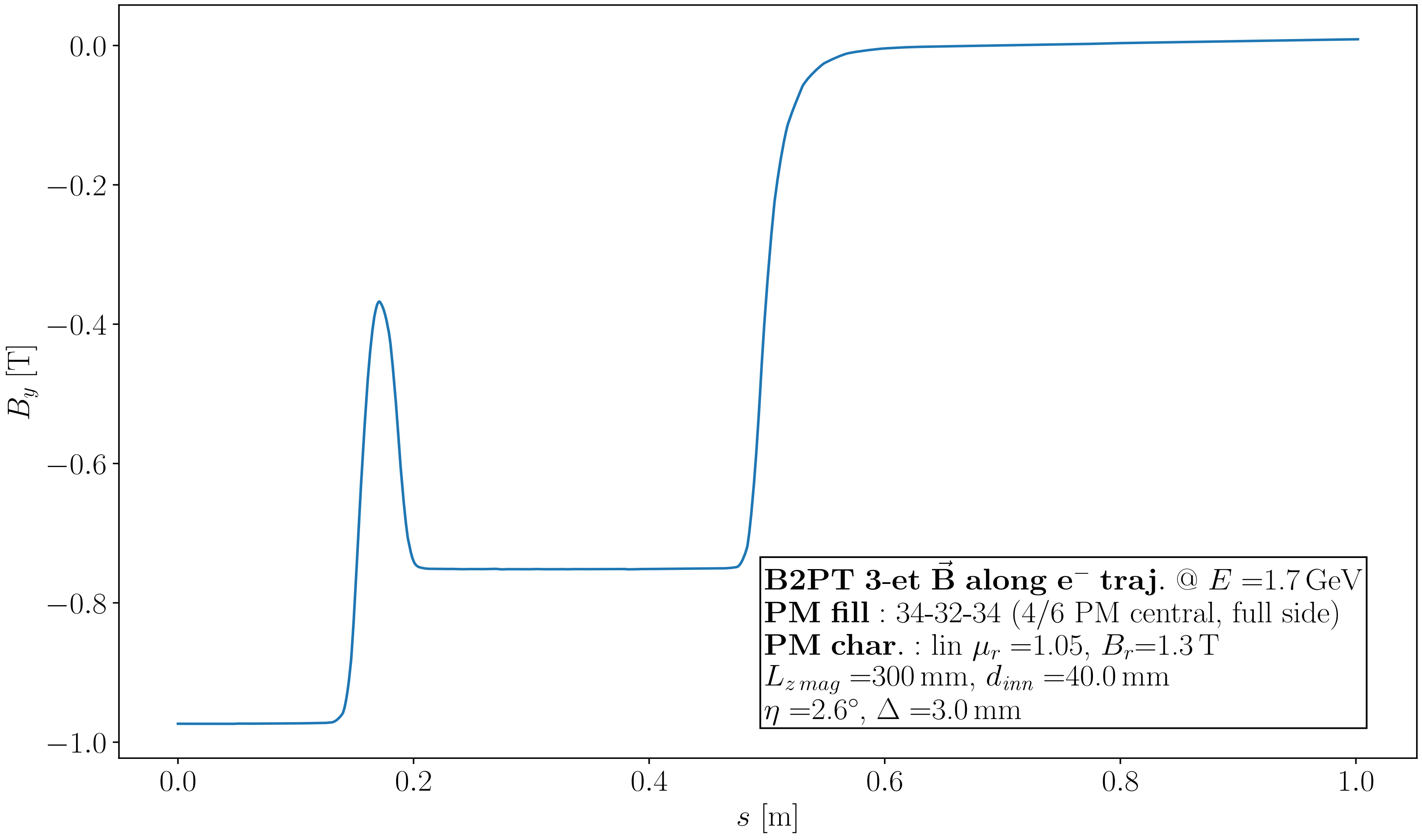
- **Technically down-tunable (trimmable)** to target value, largely with steel trimming plates.
- **Suitable for further optimization** of trajectory wrt to magnet axes
  => **initial beam offset x_0** used as free parameter for this.
- Relatively **reasonable use of PM blocks** wrt full fill 36-36-36
  (2/4 Type A spared in outer/central dipole upper and bottom rows).

Horizontal field profile $B_y(x, y = 0, z = 0)$ in the central magnet of the triplet.

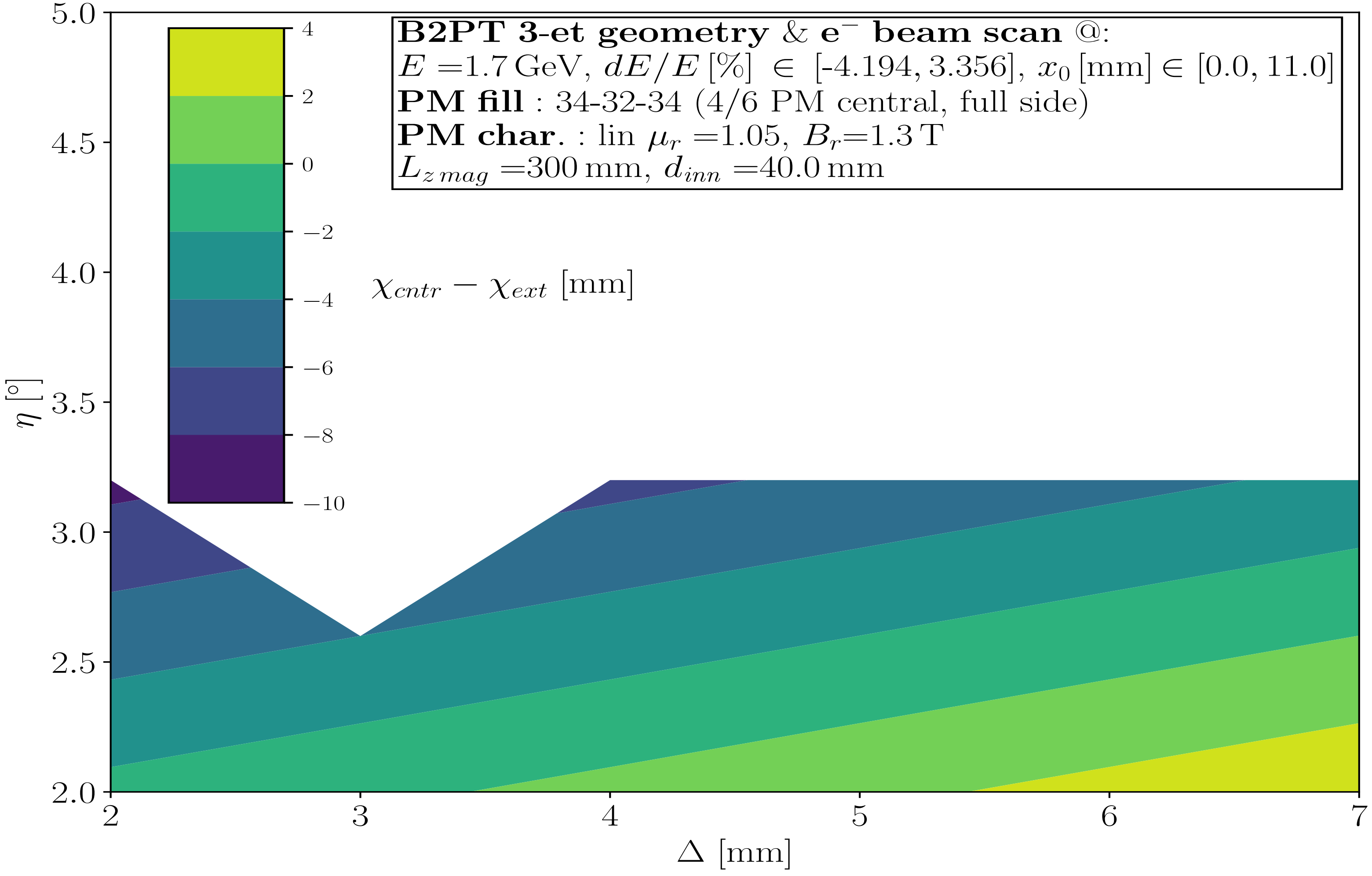
Field quality over GFR (inset).



Typical triplet right-half field profile $B_y(s)$ along the beam trajectory through for a 34-32-34 PM filling pattern.



Zero-crossing difference $\chi_{\text{cntr}} - \chi_{\text{ext}}$ **of beam offset integrals** $\int d_{\text{cntr}} ds(x_0), \int d_{\text{ext}} ds(x0)$ over **triplet geometry space** $\left[\boldsymbol{\Delta} \in {}_{[}\mathbf{2,7}_{]}\ [\mathbf{mm}]\right] \times \left[\boldsymbol{\eta} \in {}_{[}\mathbf{2,5}_{]}\ [°]\right]$ with bend-angle error $\theta_{\text{off}} = (\theta_{\text{x fnl}} - \theta_{\text{trgt}})/\theta_{\text{trgt}}$ **@ 1.7 GeV** $\in [-4.19, 3.36][\%]$.



$$\chi_{\text{cntr}} = x_0\left(\min\left(\left|\int d_{\text{cntr}} ds\right|\right)\right.$$

$$\chi_{\text{ext}} = x_0\left(\min\left(\left|\int d_{\text{ext}} ds\right|\right)\right)$$

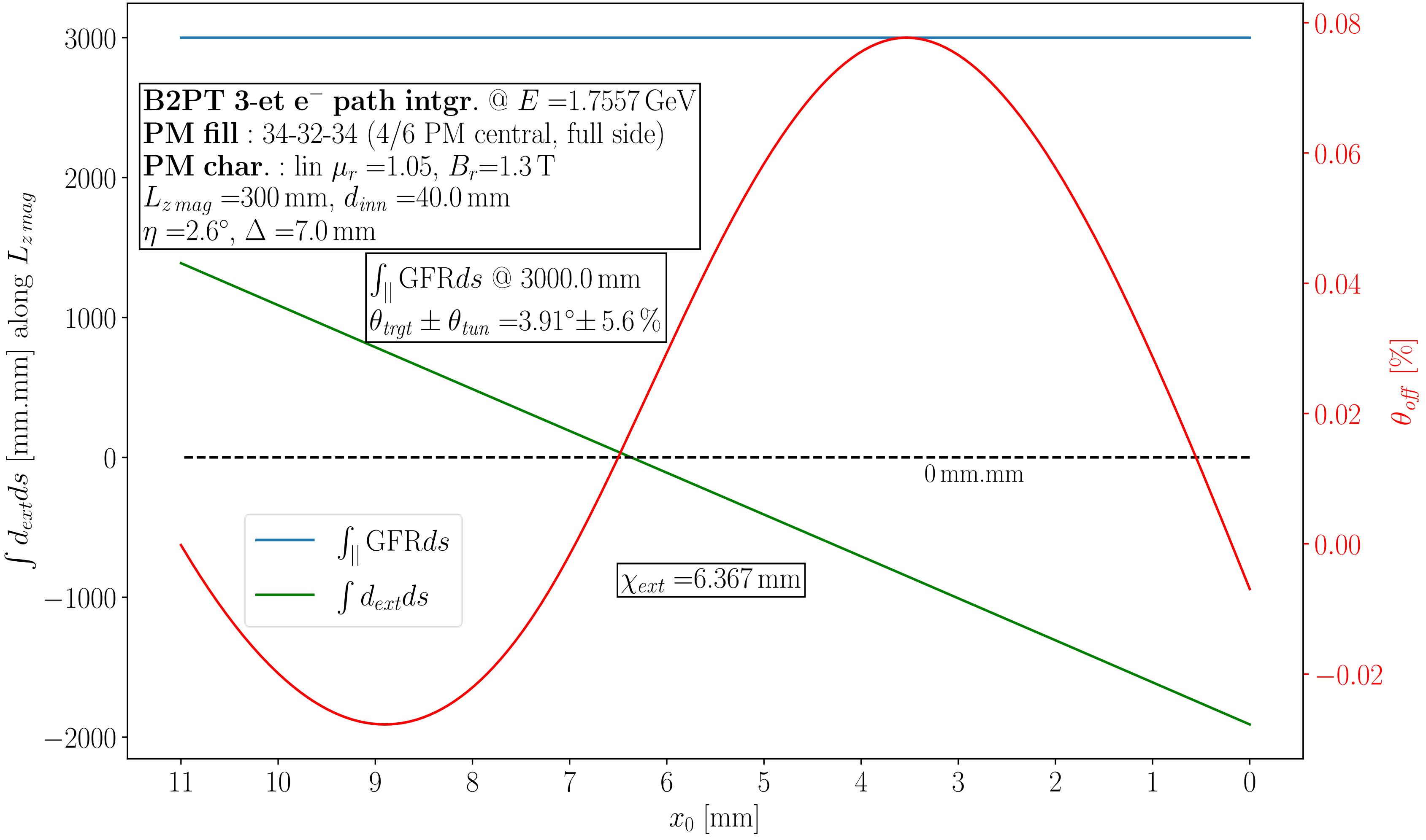
$\Rightarrow$ **In range of expected field tuning capacity**.

=> **Simultaneous minimization of offsets** $\int d_{\text{cntr}} ds(x_0), \int d_{\text{ext}} ds(x0)$ following **prior beam energy adjustment** to nominal 1.7 GeV for BESSYII in ASTRA **equivalent to $\boldsymbol{B_y}$ tune for bend angle correction**.

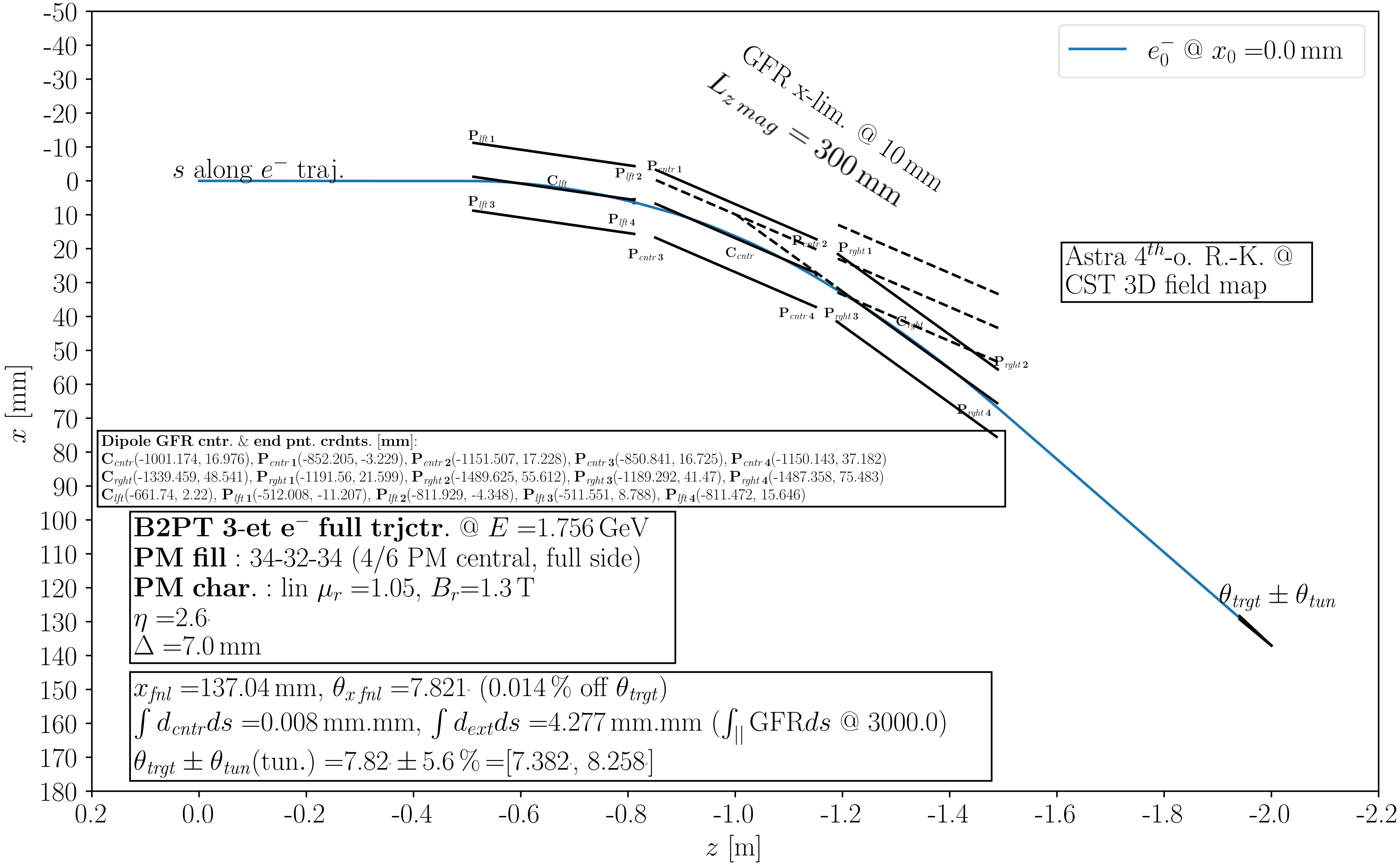
Example of optimal initial beam offset (wrt nominal magnet axis @ $x = 0$) $\chi_{ext} = x_0(\min(|\int d_{ext} ds|) \approx 6.37$ mm for **integral offset cancellation @ in outer dipole triplet setup** $\{\boldsymbol{\Delta = 7}$ **mm**$, \boldsymbol{\eta = 2.6°}\}$.

=> < **10 µm difference** wrt to equivalent χ_{cntr} in central dipole.

$\theta_{off} = (\theta_{x\ fnl} - \theta_{trgt})/\theta_{trgt}$



Full trajectory from above steps + after final triplet position adjustment .



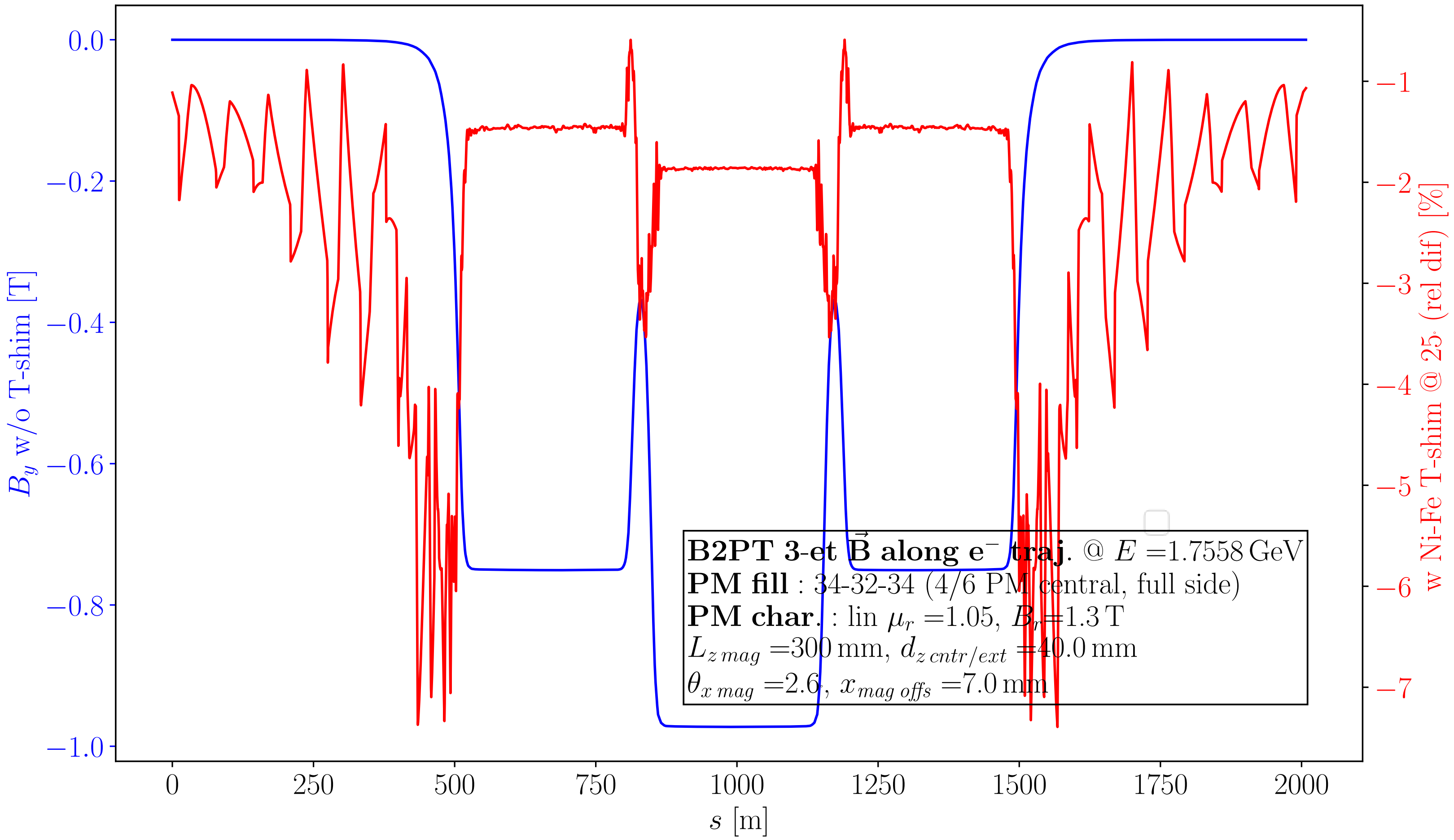
Conclusion - Outlook

- New B2PT PM dipole triplet studies build on previous investigations following BESSYII -> BESSYII+ injection setup modification.
- Investigated parameter set allowing to select convenient triplet geometries for fulfillment of new beam-bending angle requirement between booster and storage ring at end of BESSYII transfer line for BESSYII+ upgrades.
- Efficient use of permanent-magnet triplet dipole design in terms of PM fill pattern found.
- First PM-based magnet at BESSYII ready for follow-up full assembly with yokes and PM blocks delivered and individual dipole assembly tested – installation foreseen in 2026.
- Corrector coil production and tests started in house.
- Possibility to use NiFe thermal shims – effect on integrated triplet field during temperature excursion.

Acknowledgements

Daniel Böhlick, Volker Dürr, Marc Dirsat, Andreas Jankowiak, Nina Ohm, Fabian Pflocksch, Jens Völker, Nora Wunderer

Bundesministerium für Bildung und Forschung (BMBF), Land Berlin



Preliminary result for longitudinal triplet dipole field profile along beam trajectory $\boldsymbol{B_y(s)}$ with and without NiFe shims (pink in image)

=> relative effect @ RT.