Huazhong University of Science & Technology

Design considerations of a superconducting gantry with alternating-gradient combined-function magnets

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OUTLINE

I. **Introduction of HUST-PTF**

II. **Design of SC gantry with AG combined-function magnets**

1. *Overall considerations*
2. *Field imperfections of small-curvature AG-CCTs, and its influence*
3. *Design of a hybrid structure degrader*

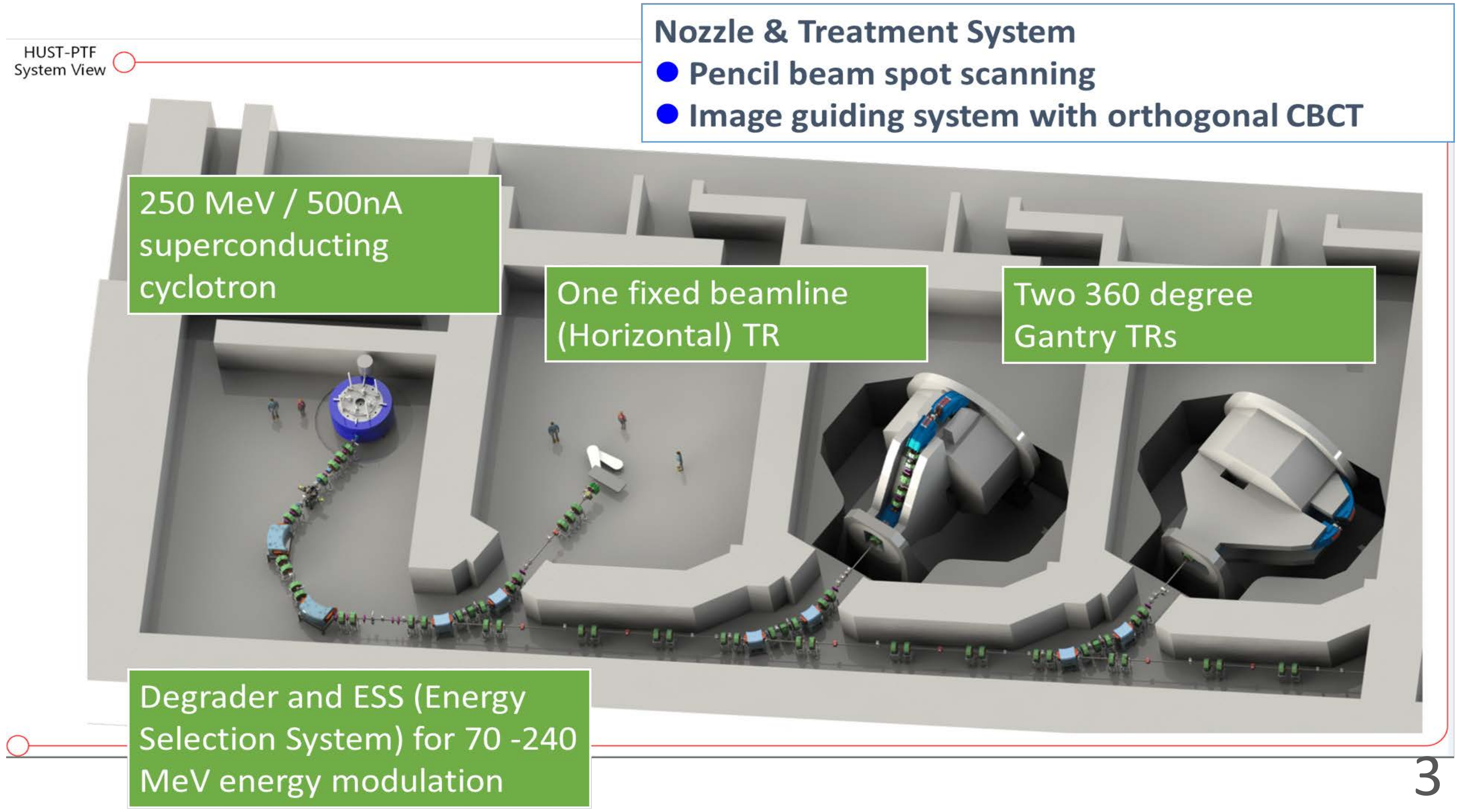
III. **Conclusion**

Introduction of HUST Proton Therapy Facility

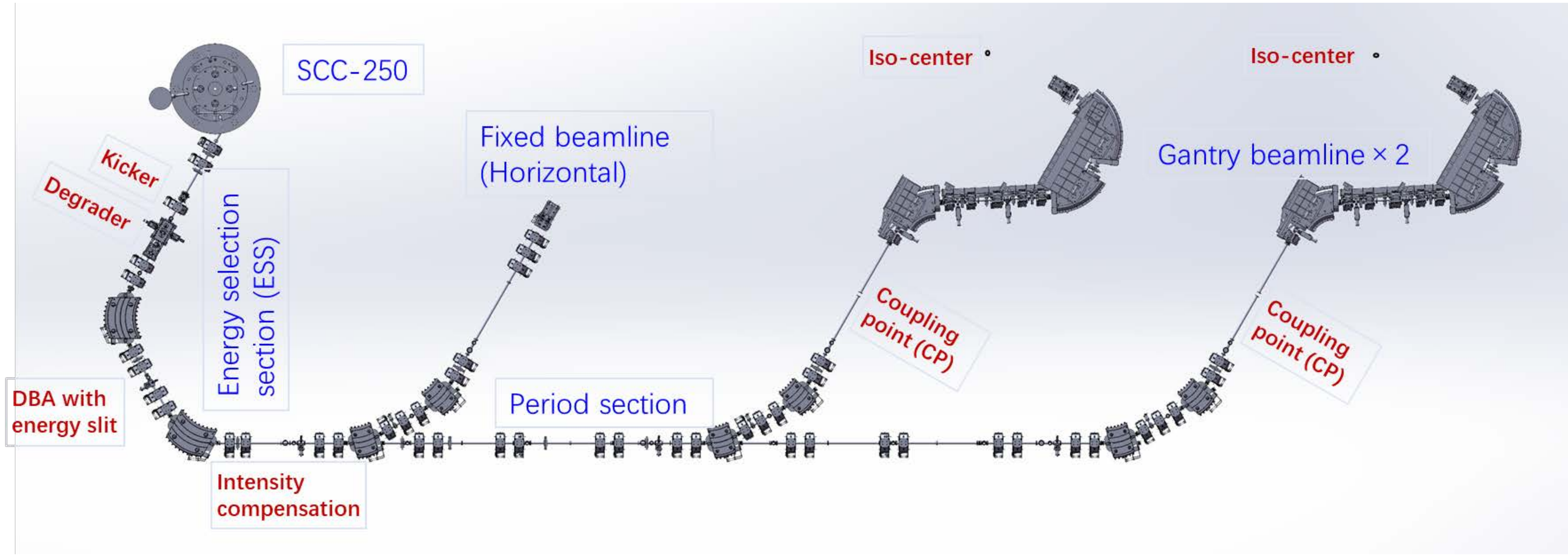
- At HUST (Huazhong University of Science and Technology, Wuhan, China), a multi-rooms proton therapy facility based on superconducting cyclotron, is under development.

Main specifications

Specification	Value
Accelerator type	SC cyclotron (250 MeV)
Energy range of ESS	70-240 MeV
Gantry type	±180 degree, normal conducting
Scanning method	Downstream, pencil beam spot scanning
Virtual SAD	2.6 m
Beam intensity @ Iso-center	0.4 – 5 nA
Field size	30cm×30cm
Image guiding	Cone beam CT



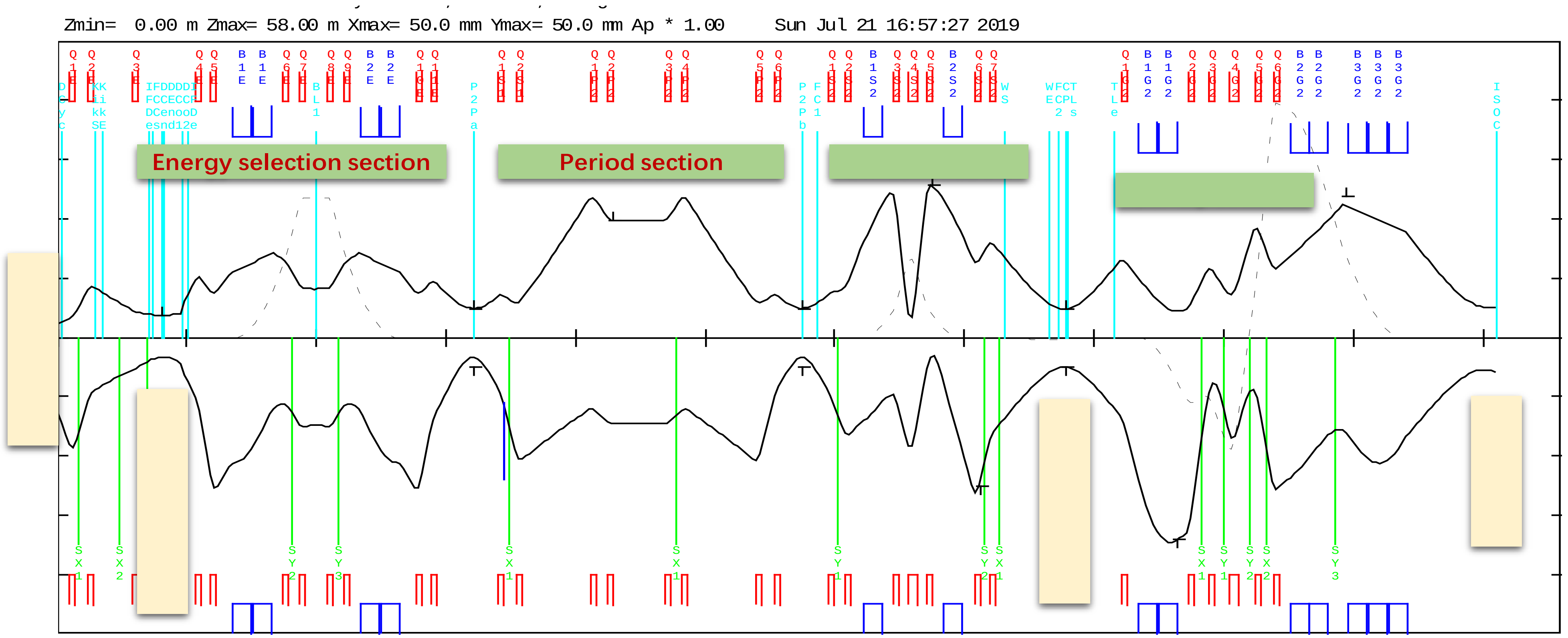
Beamline layout and resistive gantry



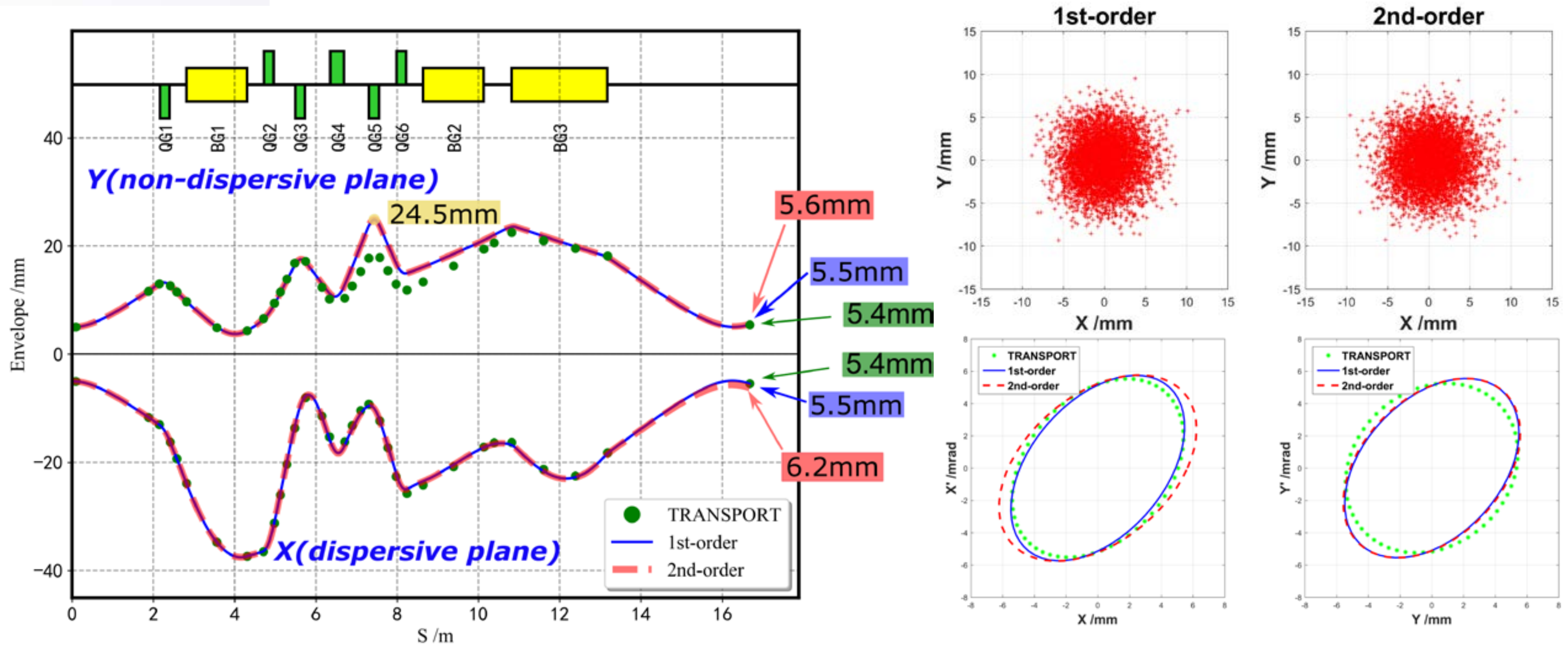
Gantry beamline with downstream scanning:

1.Image optics for better correlation between the iso-center and entrance CP;

2.Beam optics is optimized when considering fringe fields and 2nd order aberrations (COSY INFINITY with ENGE function / FEA-ODE code), and validated by tracking.

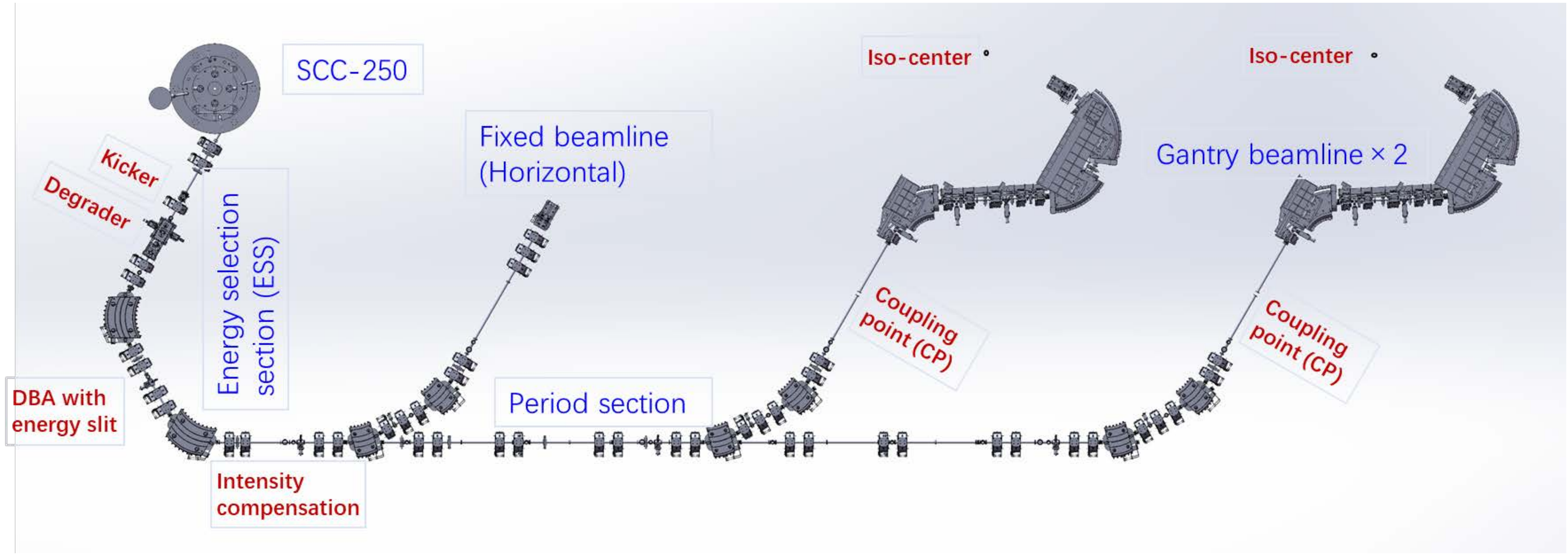


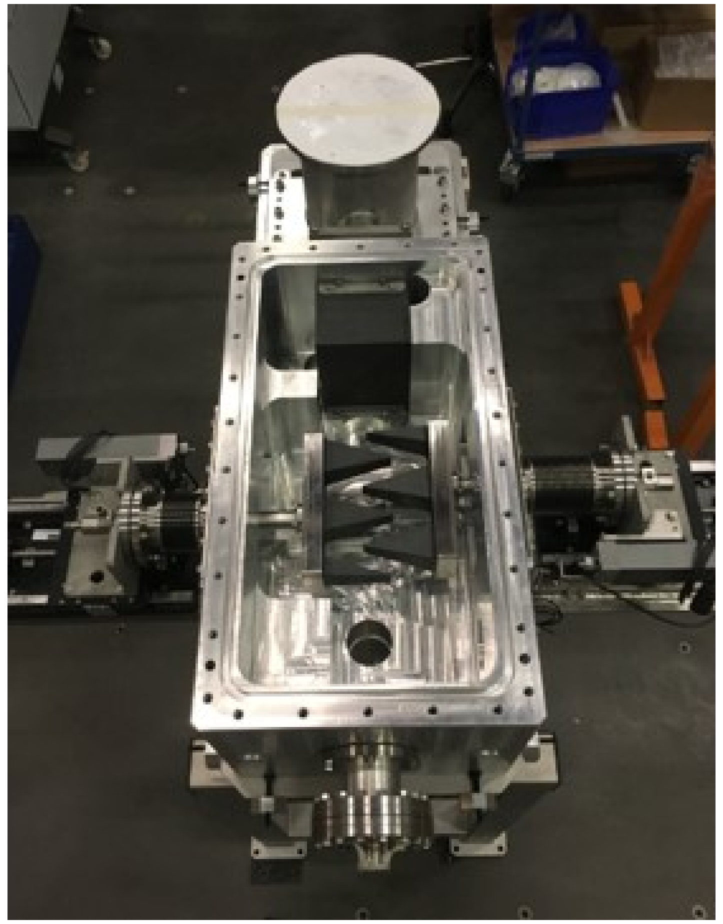
2σ beam ($\epsilon_{x,y} = 28\pi \cdot \mathrm{mm} \cdot \mathrm{mrad}$, $\Delta p/p = \pm 0.6\%$) envelope calculated by Transport

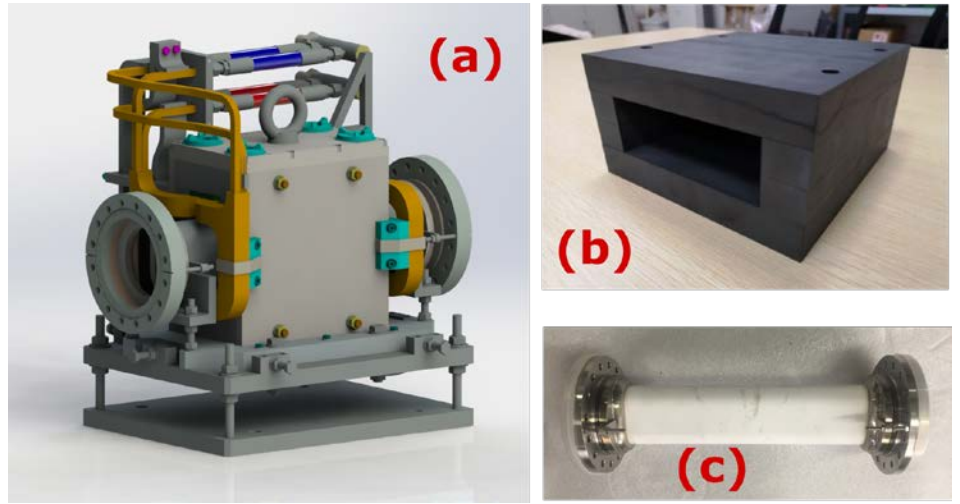


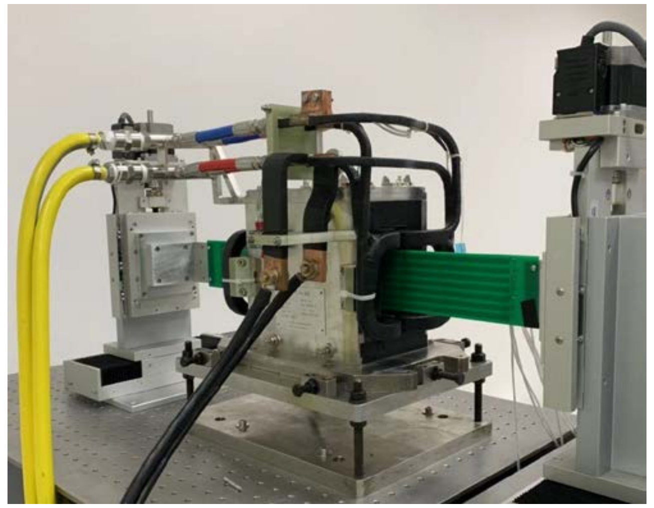
Comparison of 2σ beam envelope with Transport, first / second order results after optimization with COSY Infinity.

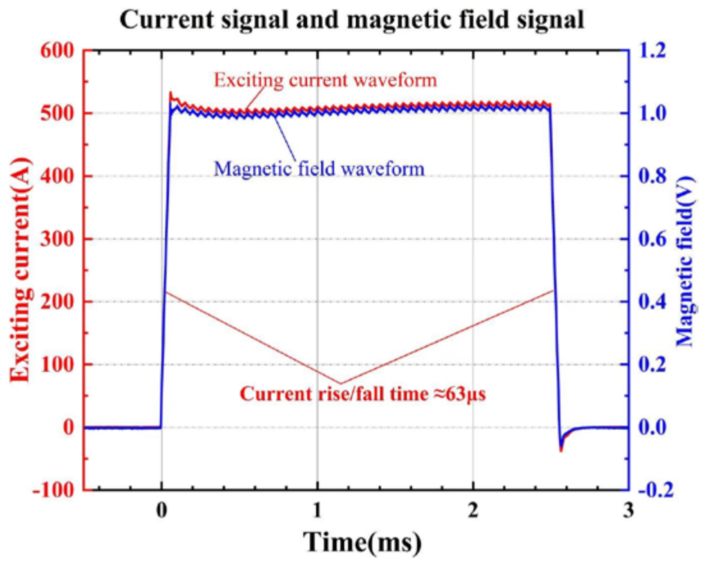
Beamline layout and resistive gantry







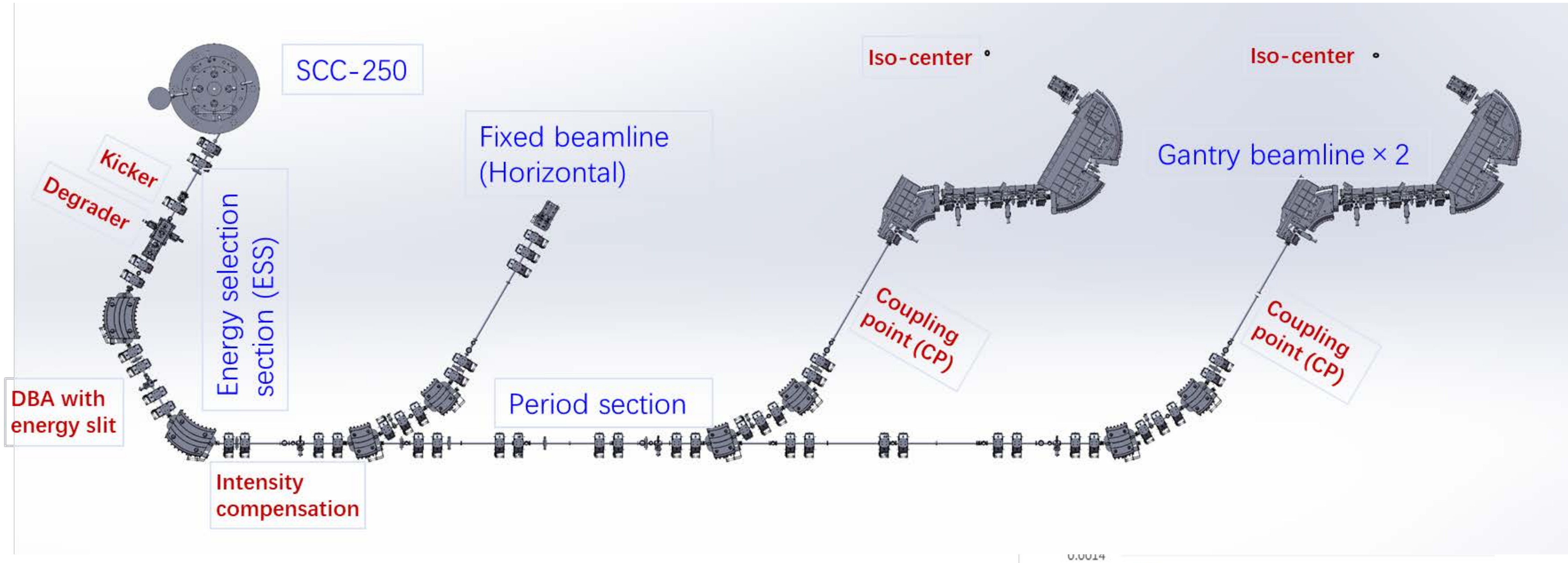




- Energy degrader: multi-wedge type for continuous and fast energy modulation (70 – 240 MeV, 200ms / step)

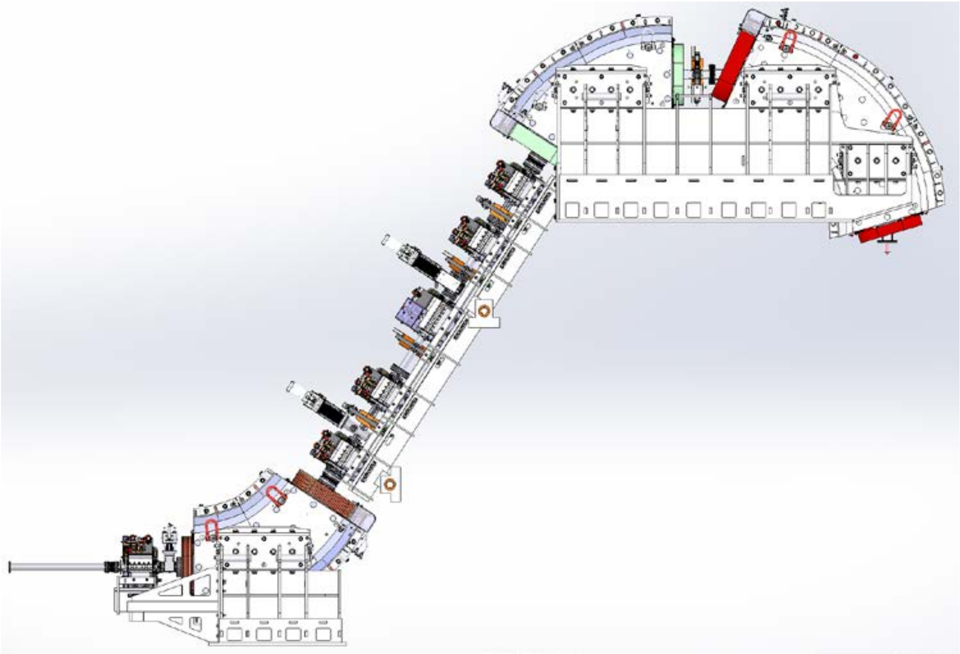
- Kicker magnet for fast beam switch : MnZn ferrite core + Ceramic vacuum chamber; rise / fall time 63 us (measured)
- Central field 1050Gs, field homogeneity 0.5% in GFR (measured)

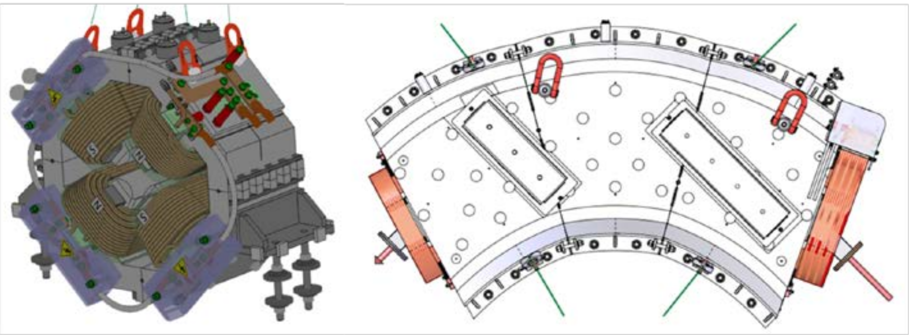
Beamline layout and resistive gantry

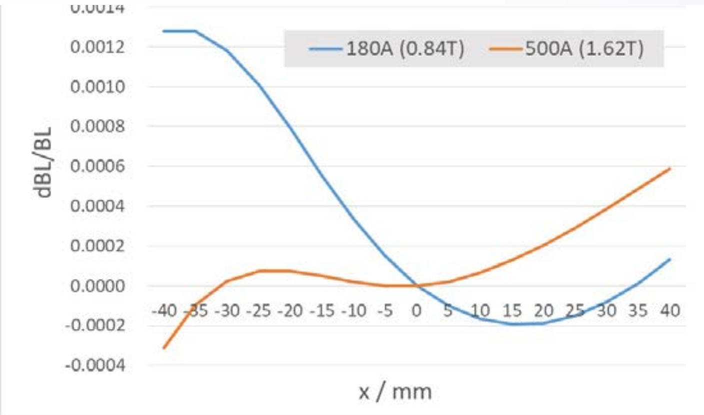


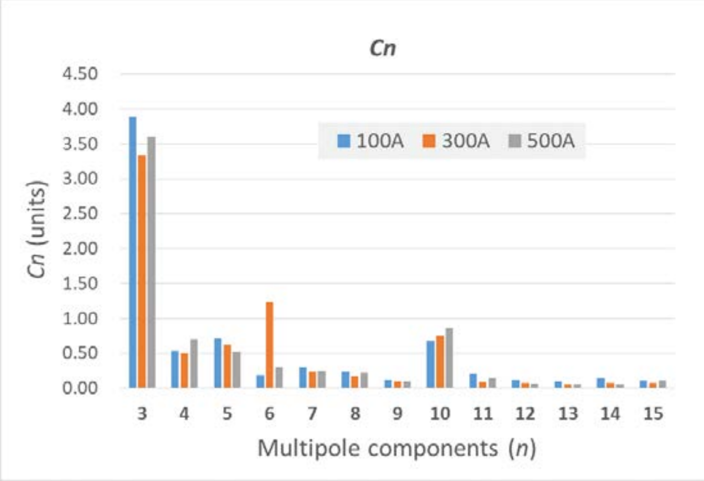
Gantry beamline

- ➢ Downstream scanning with field size 30cm × 30cm
- ➢ **Integrated design** for magnets, vacuum system, diagnostics and girders.
- ➢ **#1 gantry beamline will be manufactured and tested in the end of 2019.**









Prototype beamline magnets: 60° dipole; L270 mm quadrupole; 30° dipole

- ➢ Max. dipole field 1.62T, with integral field homogeneity ±0.08%
- ➢ Max. quadrupole gradient 18T/m, high order harmonics < 5 units

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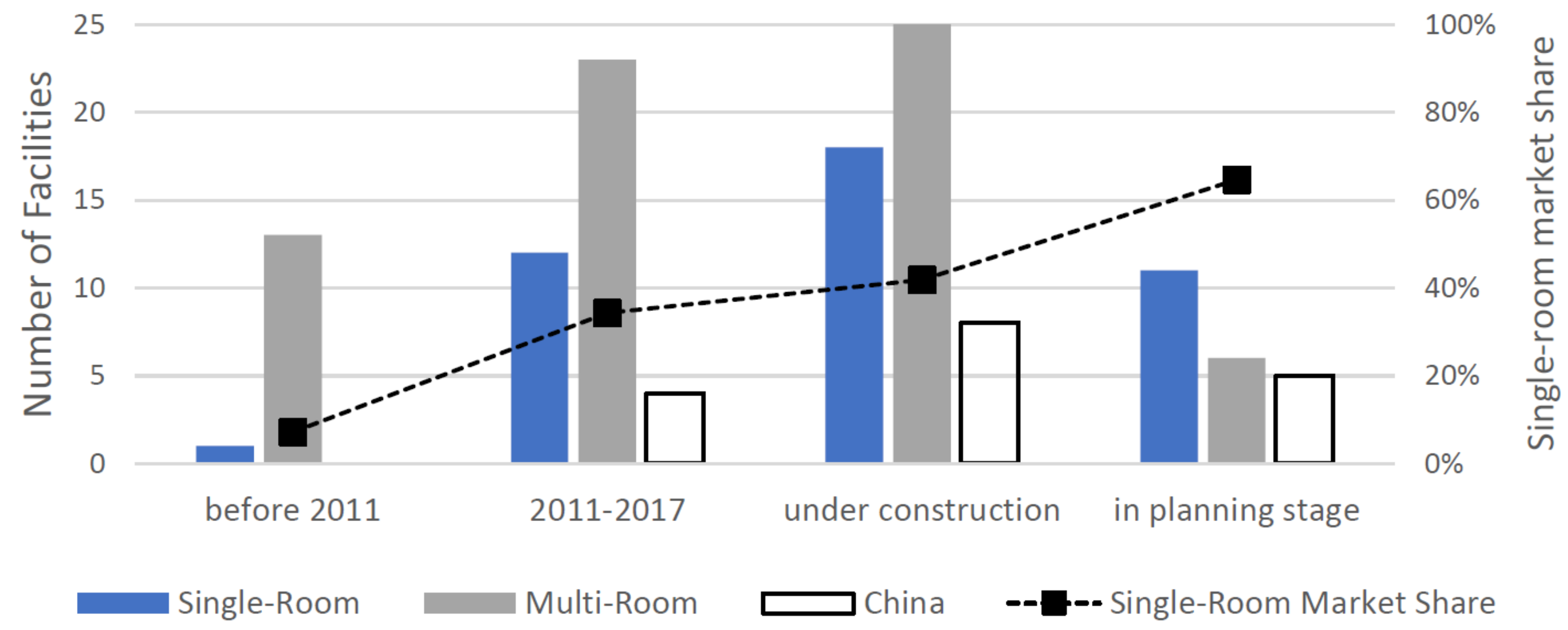
III. Conclusions

Motivation

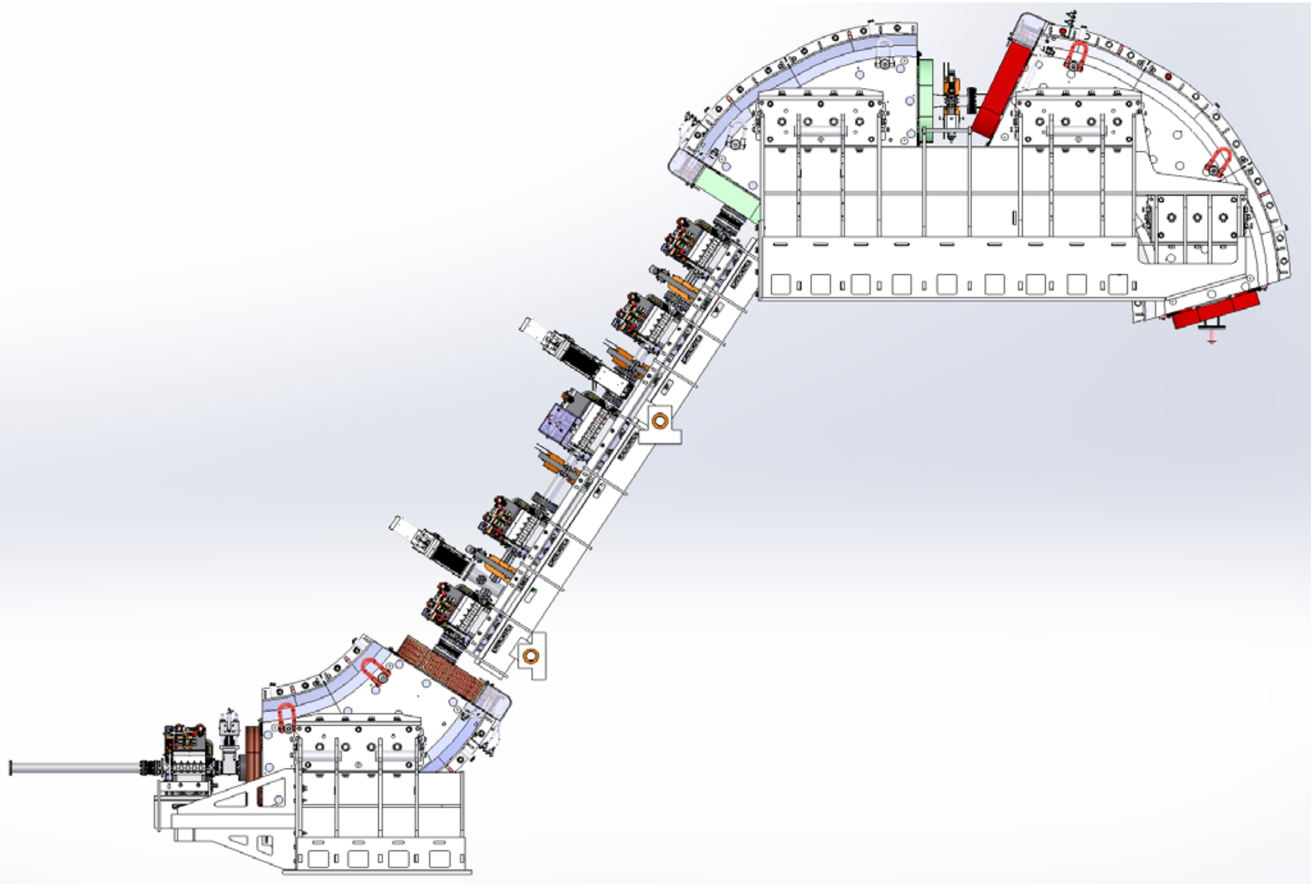
- Single room compact PT system becomes attractive for radiotherapy markets: **16 of 44 PT centers under constructions will adopt single-room solutions** (*from https://www.ptcog.ch*)

Courtesy of Weishi Wan (*"design and simulation of high momentum acceptance gantries for ion beam therapy"*, ICAP'18)



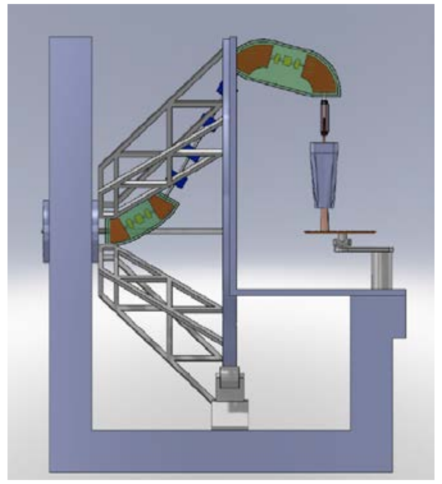
- SC cyclotrons / synchro-cyclotrons have been applied to PT, however, most of single-room and multi-room PTs employs resistive gantries. **SC technology can further suppress both the footprint and weight of gantries.**

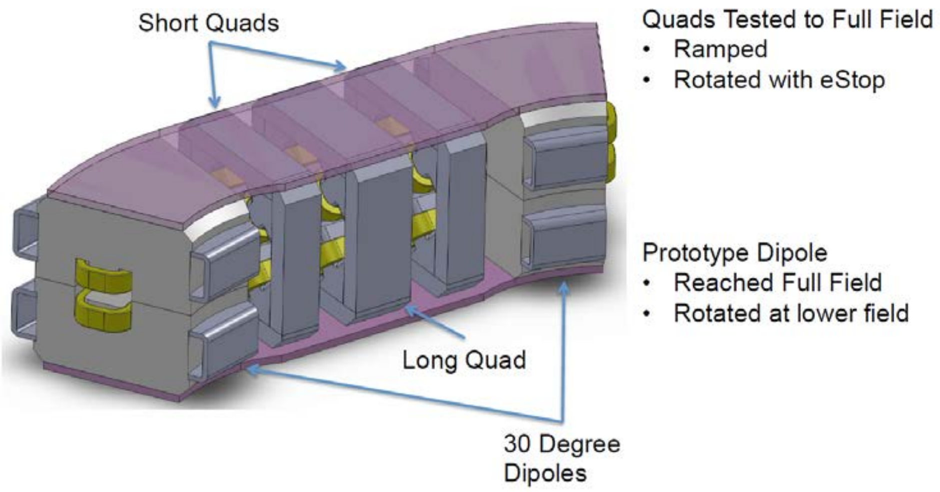
Present resistive gantry beamline of HUST-PTF
-- Weight of beamline (magnets + girders) ~ 35 tons
-- Overall gantry weight: ~ 180 tons
-- Footprint: ~ 5m (R) × 8m (L)



A lightweight gantry is considered for future upgrade

Existing schemes of SC gantries (PT)

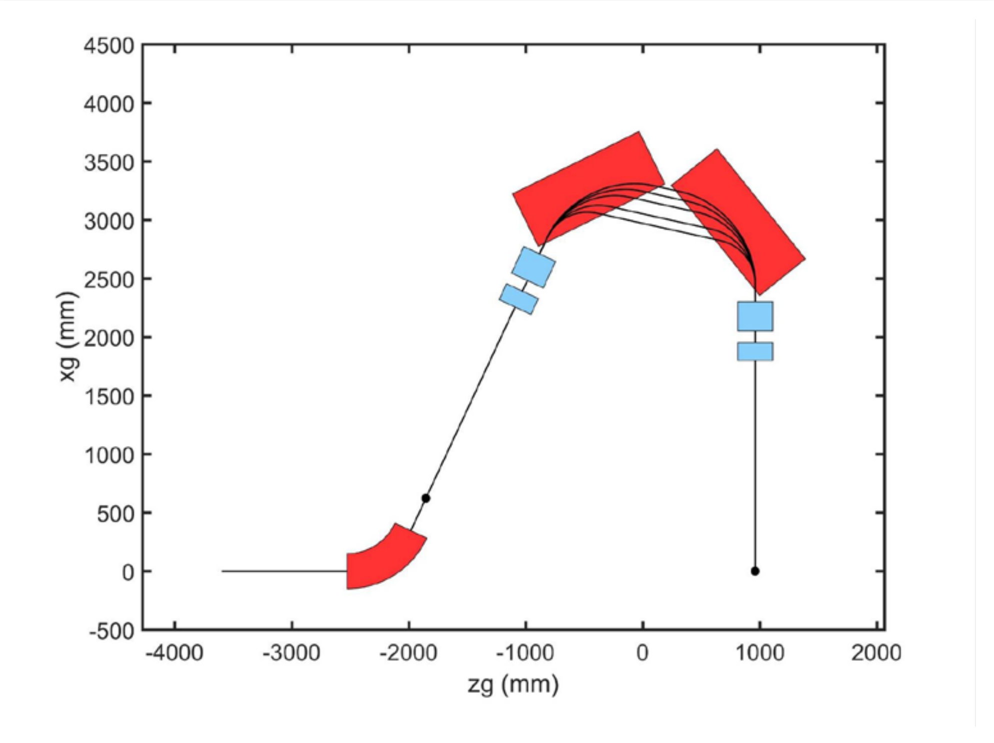




ProNova Super-ferric scheme

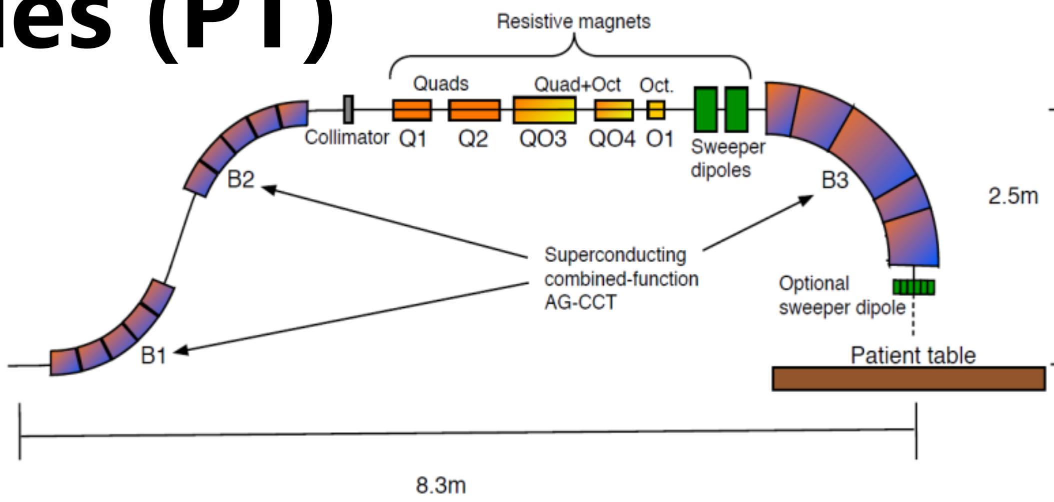
- Combined super-ferric magnets, +/-3% momentum acceptance
- Commercial available, 30 tons lightweight gantry

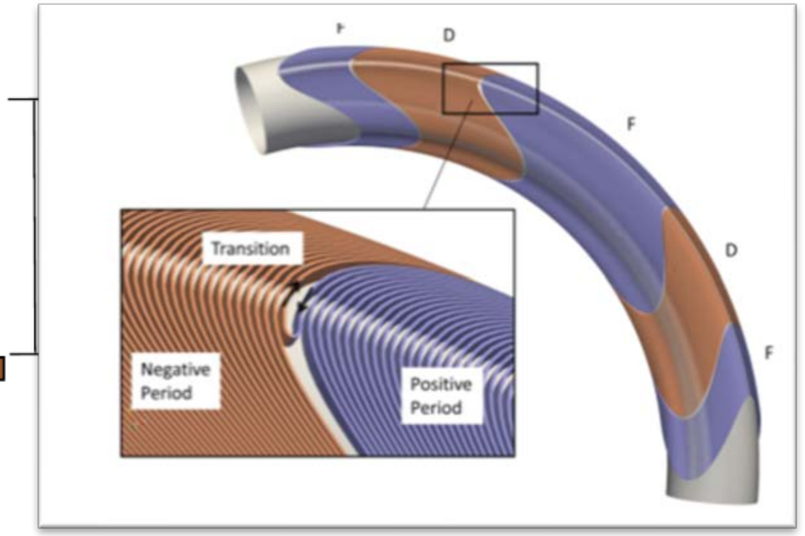
-- L. Derenchuk, The ProNova SC360 Gantry, Modern Hadron Therapy Gantry Workshop, 2014



Fixed field dipole scheme

-- Anthony Huggins, Lucas Brouwer, Weishi Wan, Design and simulation of high momentum acceptance gantries for ion beam therapy, ICAP'18, 2018

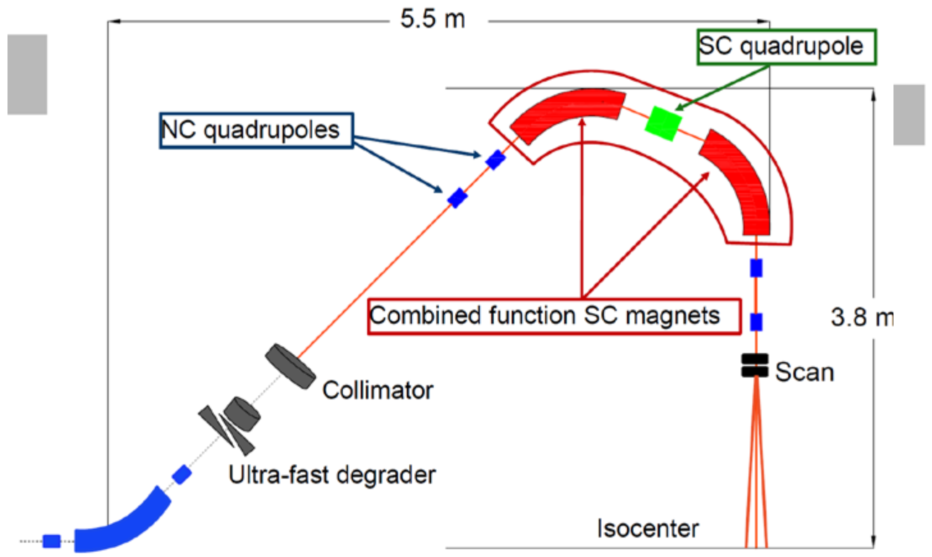


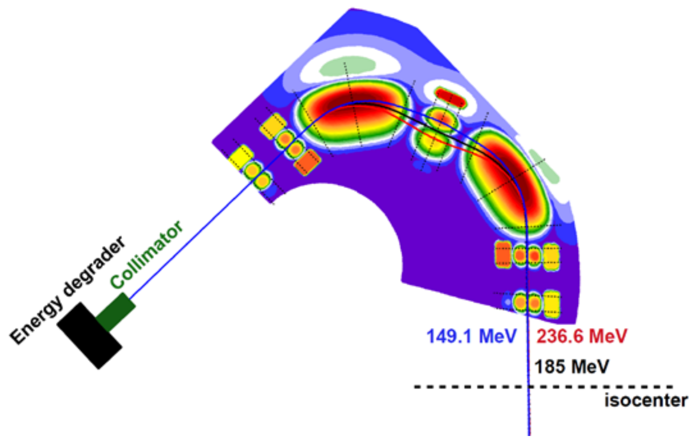


LBNL / PSI: AG-CCT Scheme

- Dipole CCT + AG-CCT, stronger dispersion suppression: +/-10% momentum acceptance;
- Upstream scanning, larger aperture for the final dipole

-- W. Wan et al. Beam Optics in Large Aperture Magnets, EuCARD2, 2015
-- L. Brouwer et al.: Design of an achromatic superconducting magnet for a proton therapy gantry, IEEE TAS, VOL. 27, NO. 4, JUNE 2017

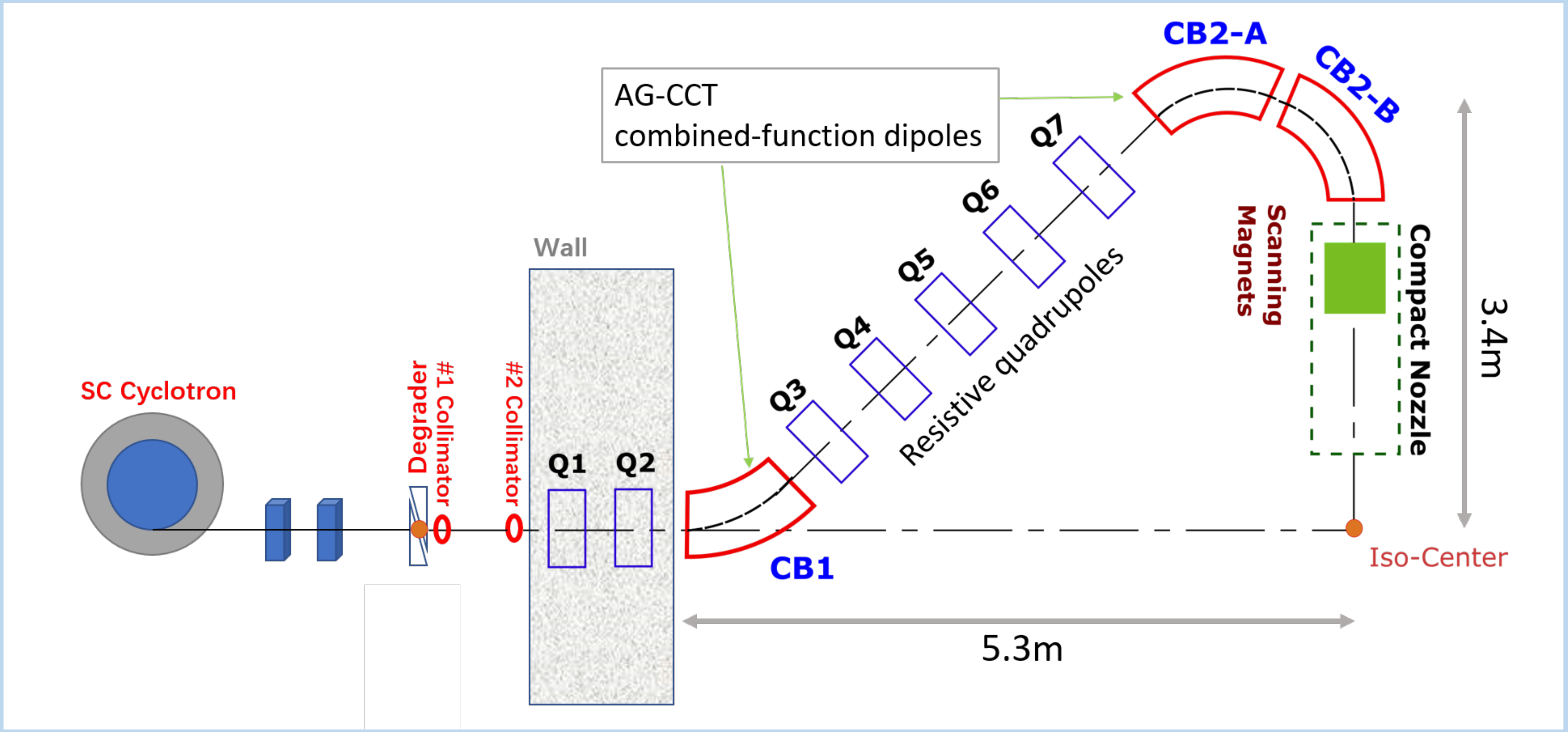




PSI combined-function SC magnet scheme: +/-15% momentum acceptance

-- Konrad P. Nesteruk. Large momentum acceptance beam optics of a superconducting gantry for proton therapy, CPO-10, 2018

Schematic design of the downstream scanning AG-CCT gantry



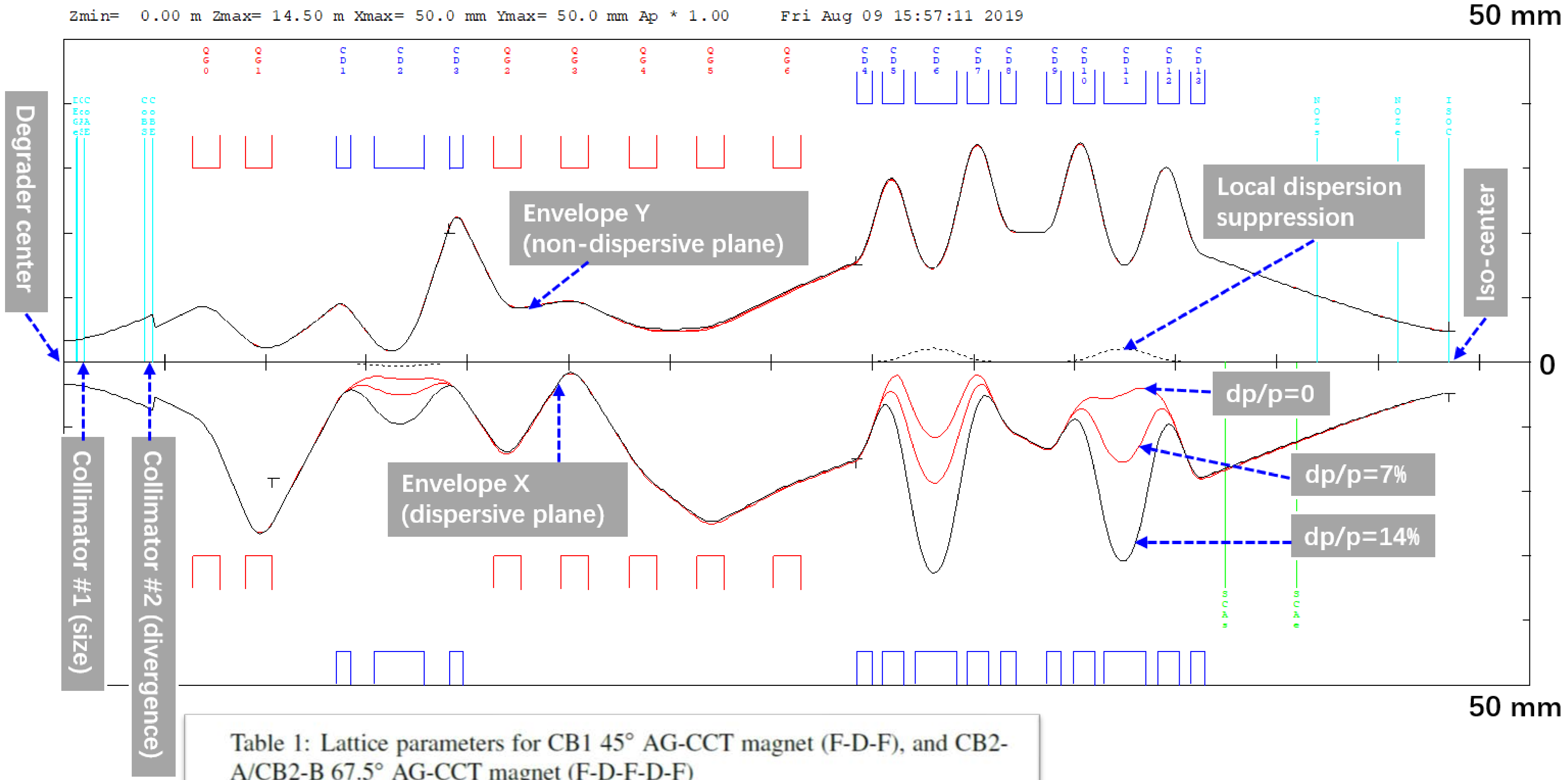
Features:

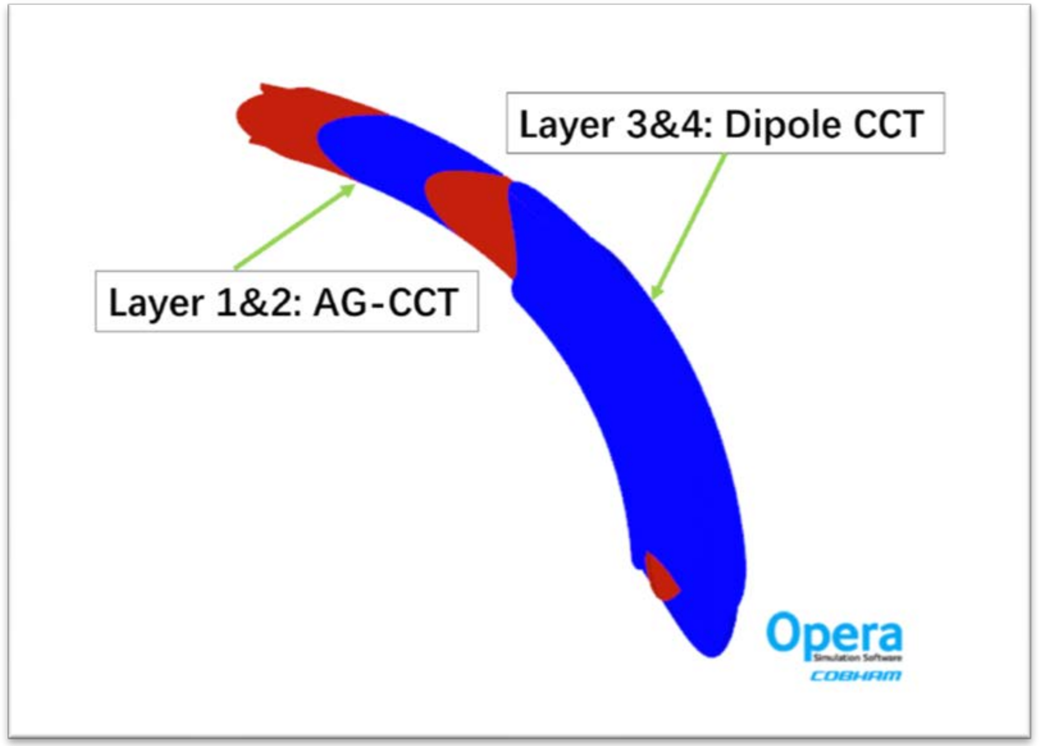
- SC Gantry can be configured as single-room PT or multi-room PT
- **Independent hybrid degrader** installed at the entrance of the gantry (without energy slit, max. 2.6% dp/p @ 70 MeV)
- **Downstream scanning**, avoid large aperture final dipole → reduced fringe field, minor contribution to aberrations.
- **SAD ~ 2.0 m**, with a compact nozzle

Magnets in gantry beamline

- AG-CCT combined function magnets are used for 2 bending sections: CB1 45 deg. ; CB2-A , CB2-B 67.5 deg. **Local dispersion suppression are used to achieve +/-14% momentum acceptance.**
- Q1-Q7 are resistive quadrupoles with small aperture.

SC Gantry optics





➢ **Demonstration of a four-layer AG-CCT magnet**

Table 1: Lattice parameters for CB1 45° AG-CCT magnet (F-D-F), and CB2-A/CB2-B 67.5° AG-CCT magnet (F-D-F-D-F)

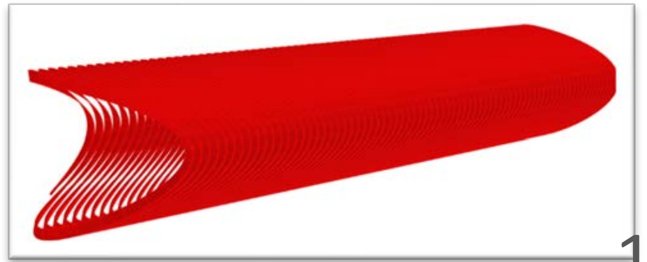
Type	No.	Bending angle	Field index n
45° AG-CCT	#1 (D)	8.2°	25
	#2 (F)	28.6°	-25
	#3 (D)	8.2°	25
67.5° AG-CCT	#1 (F)	9.0°	17.7
	#2 (D)	12.9°	-17.7
	#3 (F)	23.7°	17.7
	#4 (D)	12.9°	-17.7
	#5 (F)	9.0°	17.7

Dipole CCT Path

$$\vec{p}(\theta) = r\hat{r} + [r\cot(\alpha)\sin(\theta) + \frac{\omega}{2\pi}\theta]\hat{z}$$

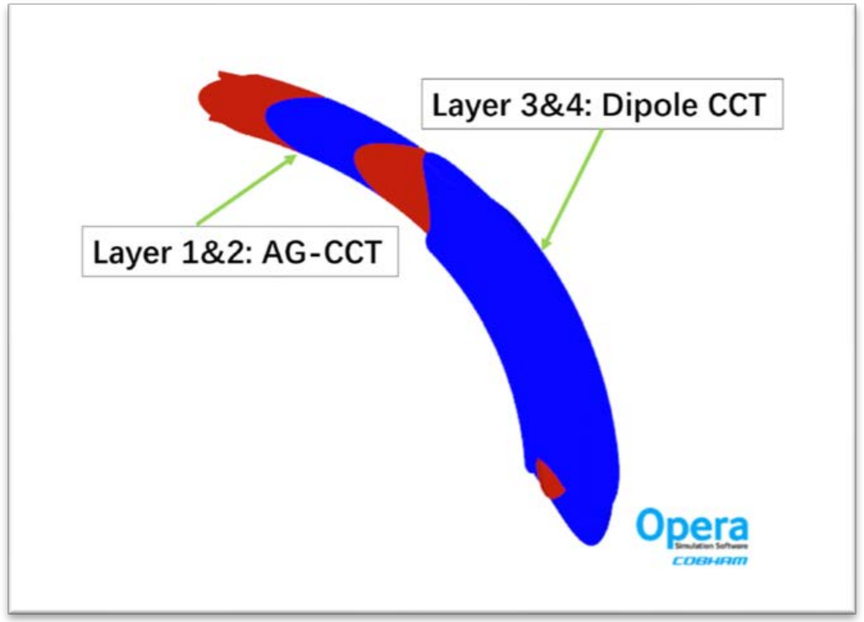
Quadrupole CCT Path

$$\vec{p}(\theta) = r\hat{r} + [\frac{r\cot(\alpha)}{2}\sin(2\theta) + \frac{\omega}{2\pi}\theta]\hat{z}$$

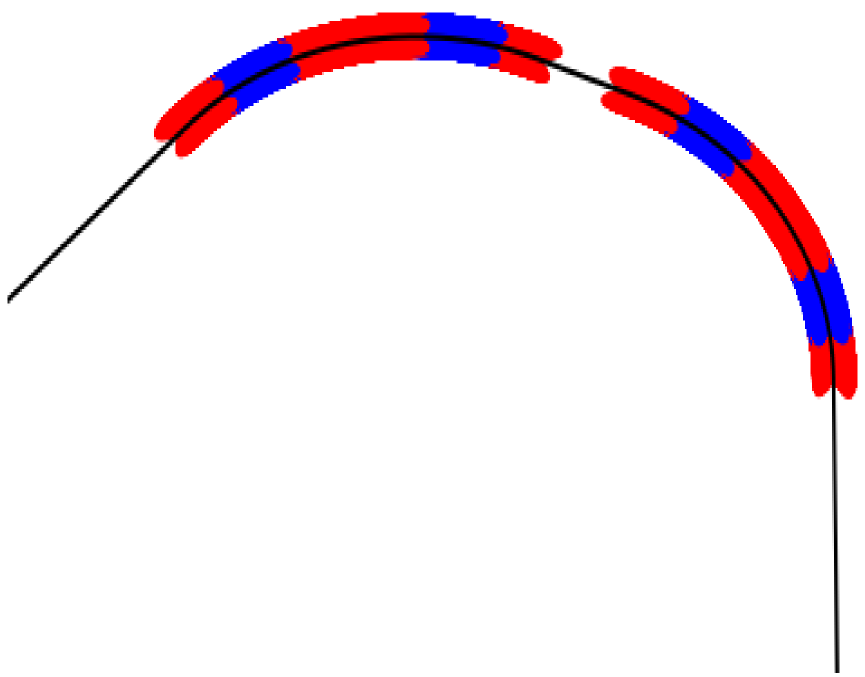


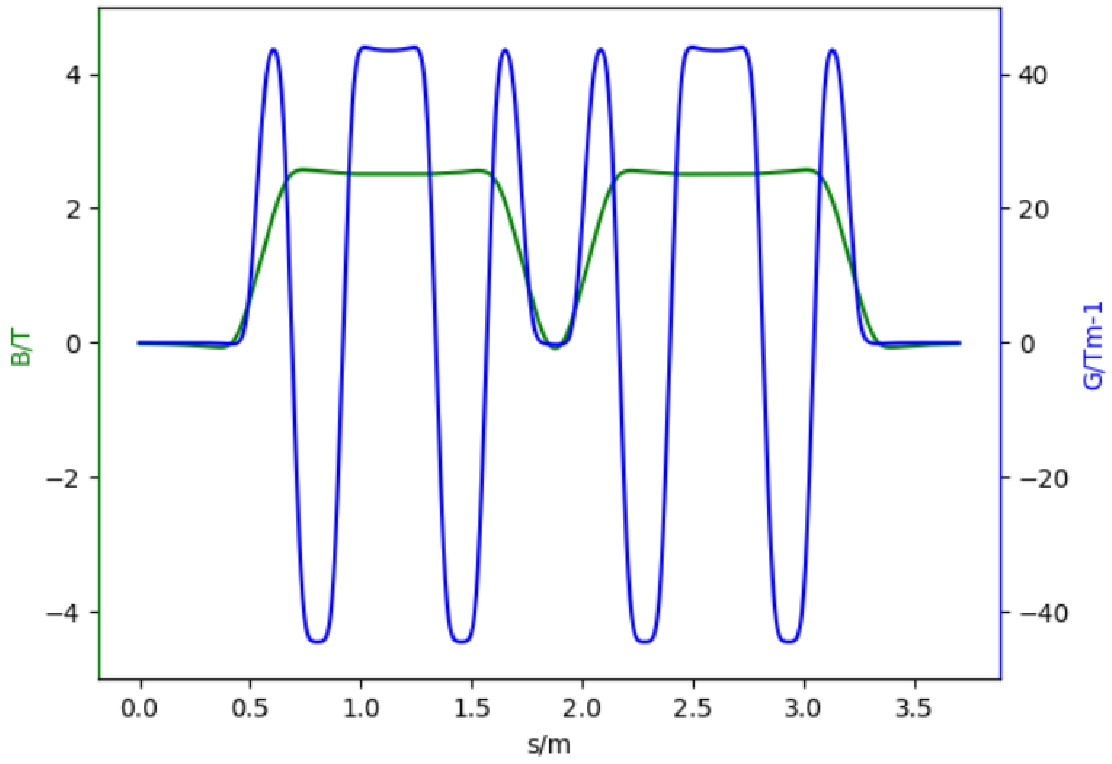
Combined-function multipoles CCT modelling and field calculation

- OPERA-3D: time-consuming for complex multi-layers AG-CCT magnets, based on FEM (finite elements method)



- Due to pure coil induced magnetic fields without iron (ignoring stray field shielding and cross-talk effect), **a self-developed code based on Biot-Savart Law** was written for:
  - ✓ Parametric modelling of combined-function CCT magnets (dipole, quadrupole, sextuple CCTs).
  - ✓ Fast magnetic field calculation according to various precision requirement.
  - ✓ Runge-Kutta particle tracking, Visualization.





Dipole and quadrupole field distortion in curved CCTs

Curvature of curved CCT will break field symmetry along the radius in cross section, and lead to

(1) Small inherent quadrupole field, from dipole CCT

$$b_2^{inh} \approx b_1/(2 \cdot \rho)$$

(2) For quadrupole field of AG-CCT → center deviation & focusing difference in outside and inside radius → nonlinear distortion on beam phase space

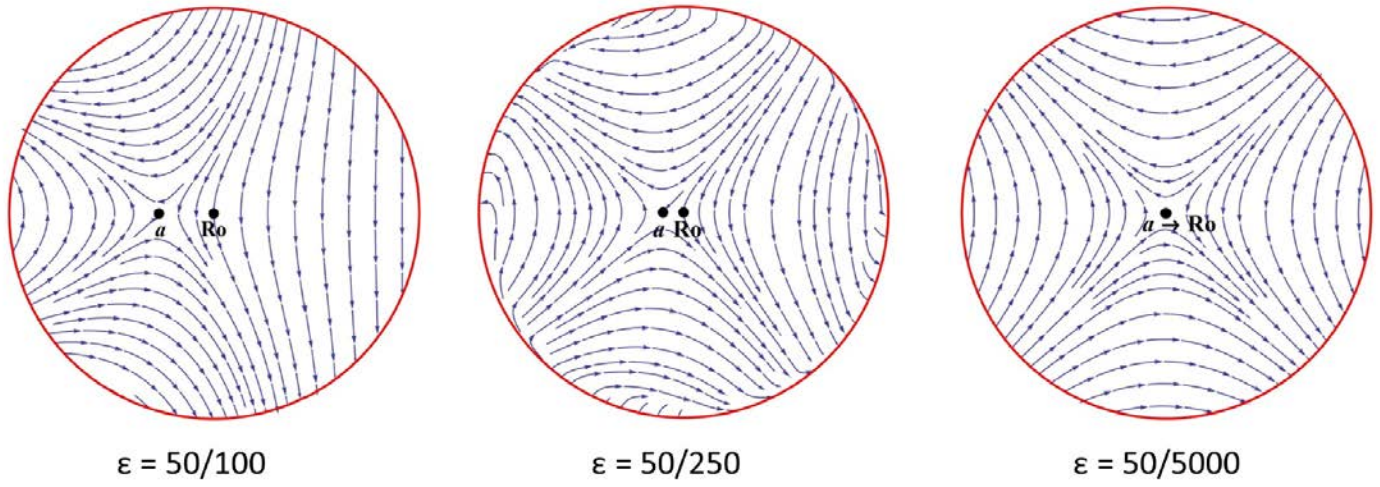
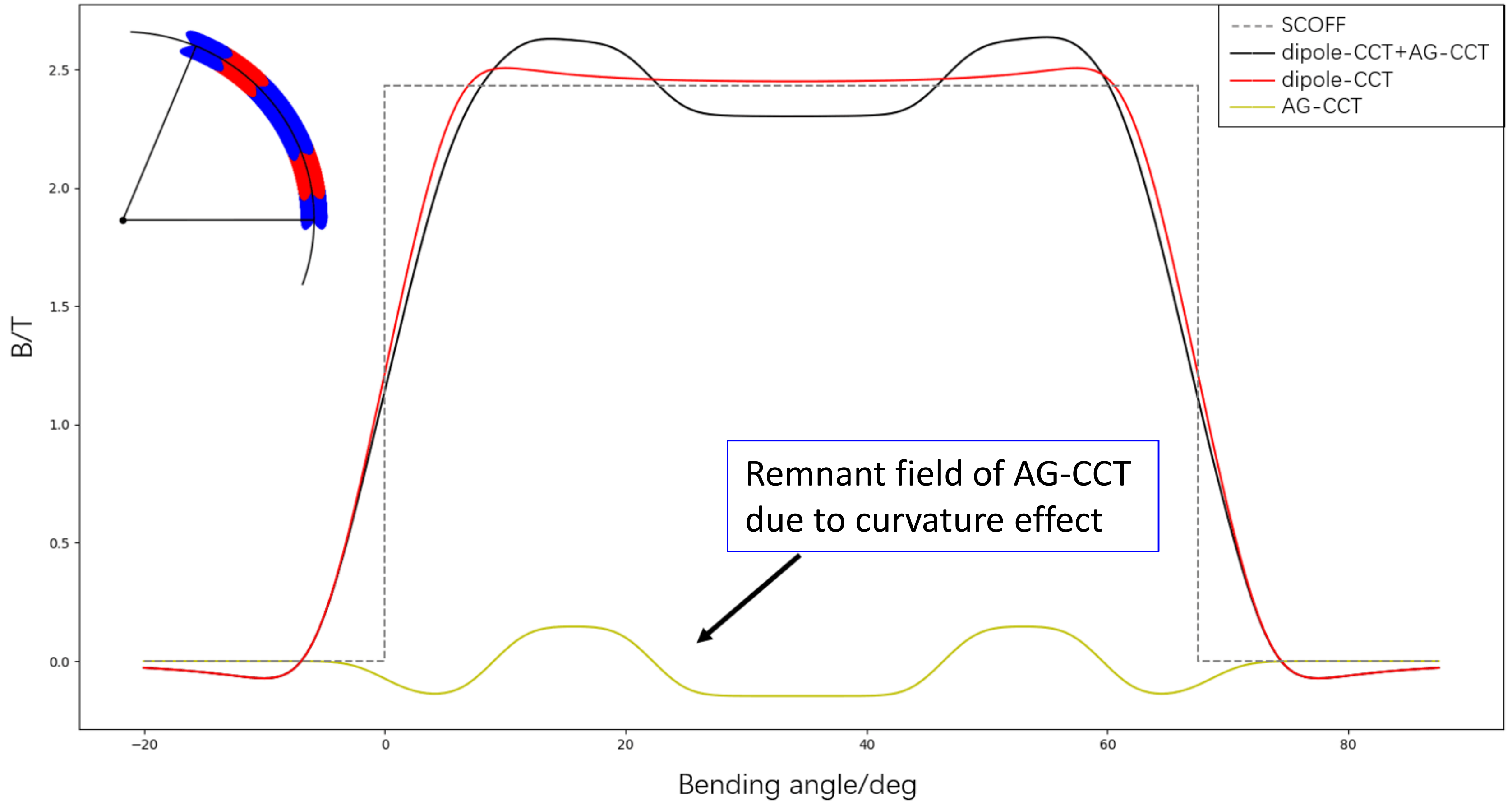


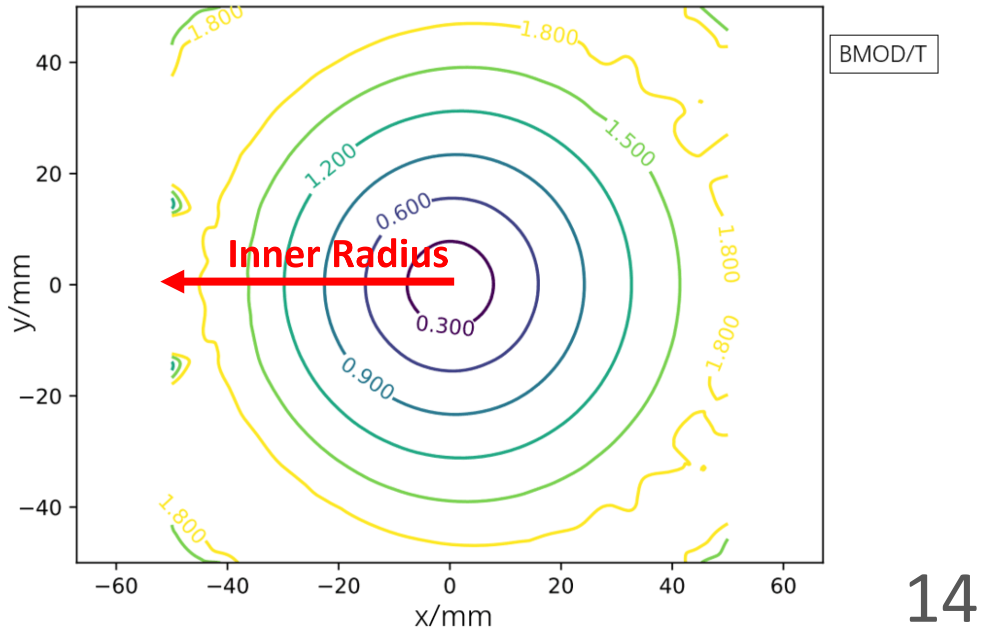
Figure 8.5: The quadrupole-like toroidal harmonic (n=2) is shown for a fixed bore radius R and increasing major radius R_0. The Legendre polynomials needed for the fields were evaluated using the DTOR algorithm [108]. As the aspect ratio of the torus $\epsilon = R/R_0$ tends to zero, the fields are seen approaching those of a straight cylindrical quadrupole.

Lucas Nathan Brouwer, Canted-Cosine-Theta Superconducting Accelerator Magnets for High Energy Physics and Ion Beam Cancer Therapy, PhD Dissertation, UC Berkeley, 2015.

Bz along the central trajectory (67.5 deg. combined-function CCT)



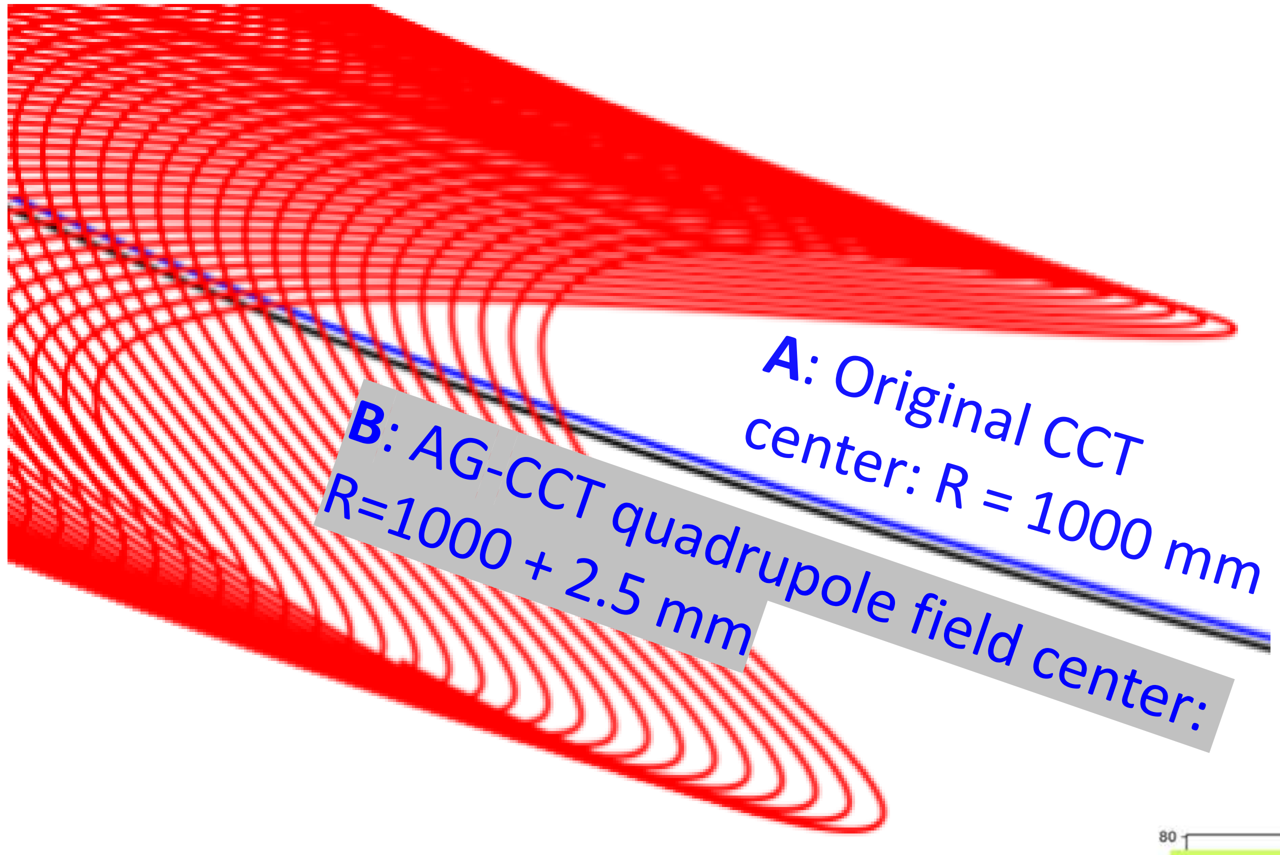
A compromise between the larger curvature (ρ) and higher dipole field is needed.
For our case: ρ = 1 m, bore radius = 50 mm, b1 = 2.43 T
Off center = 2.5 mm

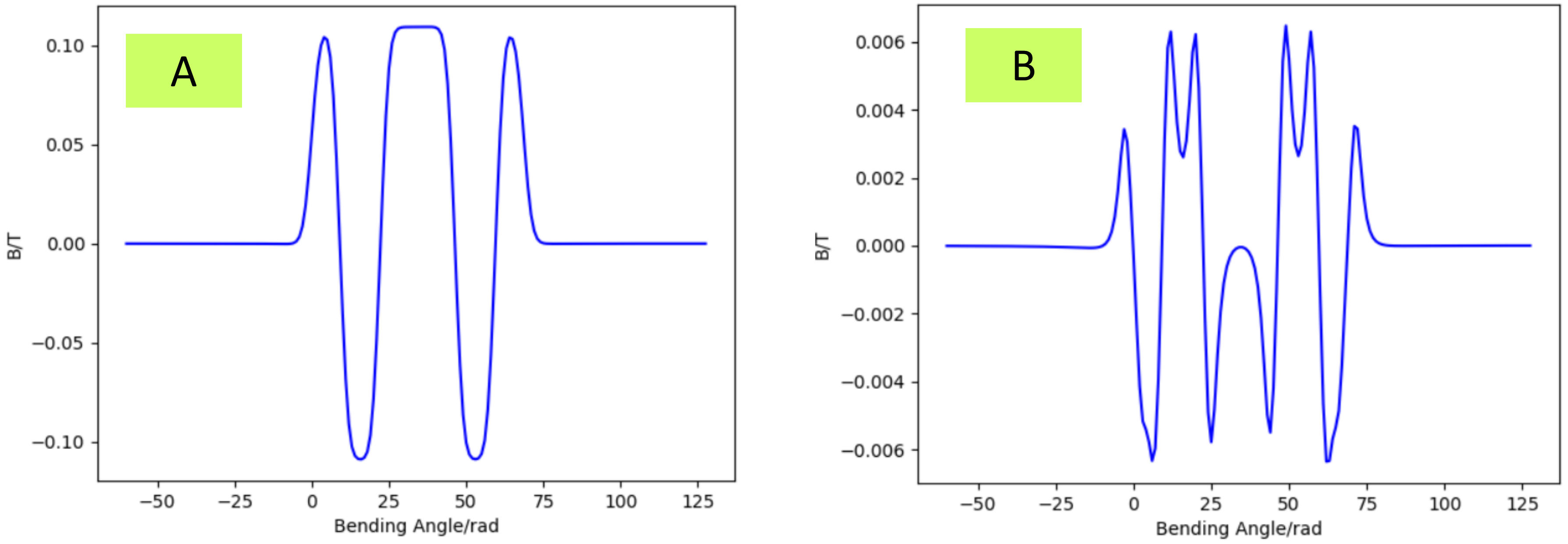


Isometric line of B_{mod} @ cross section of AG-CCT

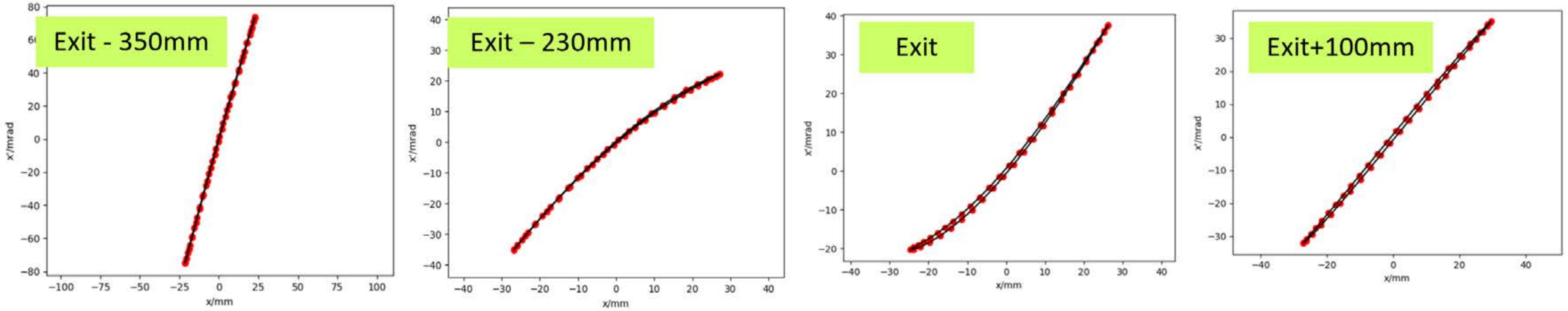
Nonlinear effect on beam phase space

- One solution is to set a deviation for the central beam trajectory to the distorted quadrupole field center;
- However, due to the gradient distortion, the beam will have nonlinear focusing effect





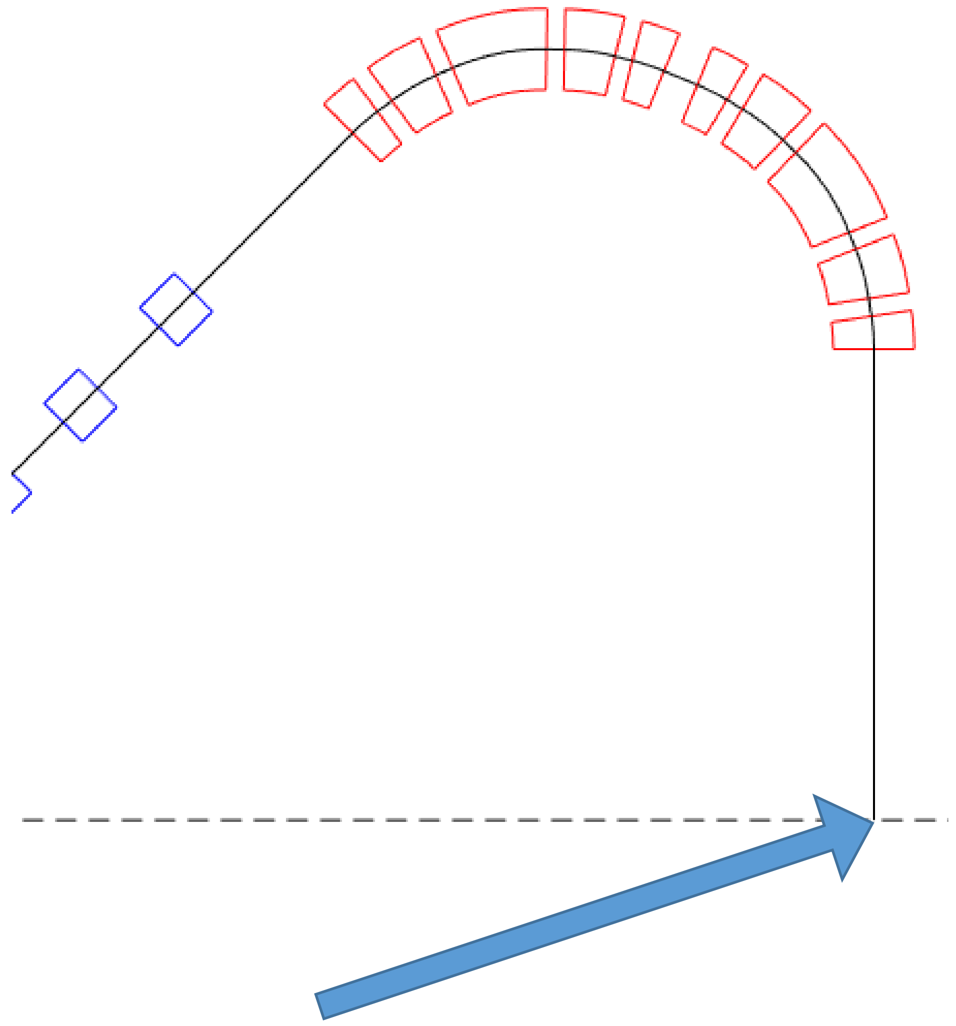
Remnant dipole field distribution due to quadrupole field distortion in AG-CCT



Phase ellipse evolution with nonlinear focusing effect, when passing one 67.5 deg. AG-CCT

Parameters of 67.5 deg. AG-CCT

For 67.5 deg. AG-CCT:
Max. dipole field: 2.43T; Max. gradient: 43T/m



@Isocenter: Stray field 5.3Gs
(safety limit 5Gs)

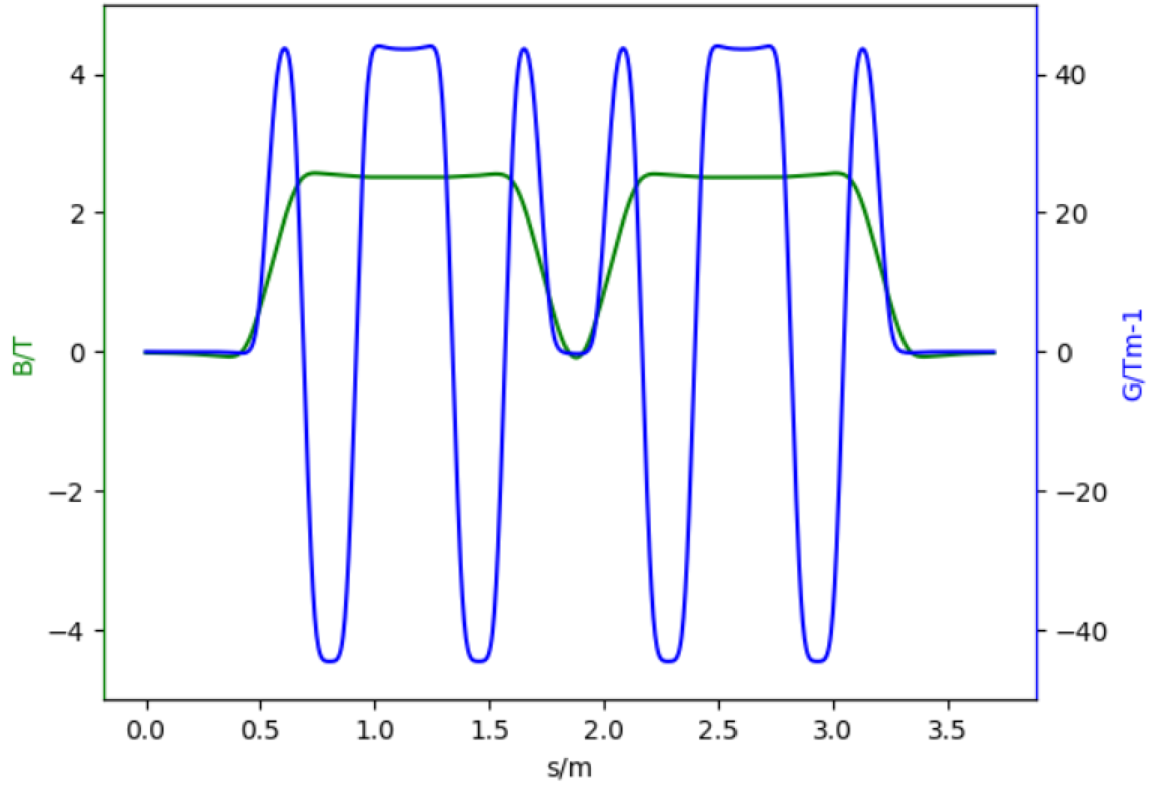
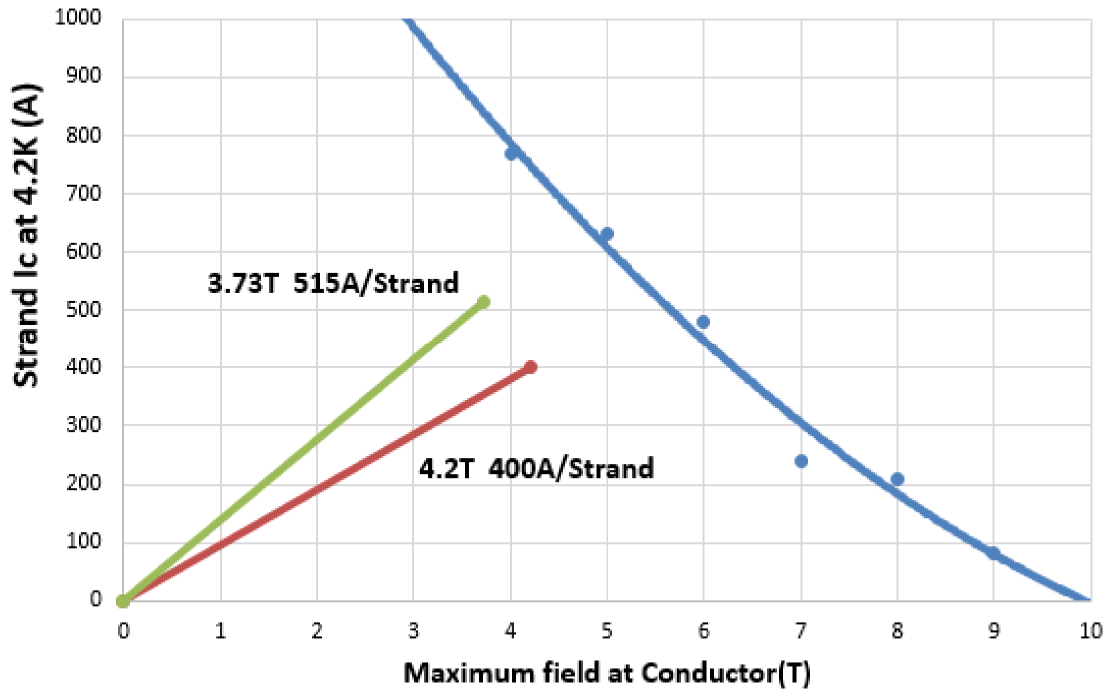


Table 5 Parameters of the NbTi/Cu strand

Superconducting wire	Parameter
Wire type	Monolith
Insulating material	Formvar
Bare dimensions/mm	1.04
Insulated dimensions/mm	1.10
Cu:Sc	2.3
RRR(273K/10K)	≥100
I_c(5T，4.2K)/A	≥630

Table 6 Current margin at the maximum operating point

Type	I/str.(A)	Str.	B_{cond}	Margin
AG-CCT (L1)	400	14	4.2T	24%
AG-CCT (L2)	400	14	4.2T	24%
Dipole CCT (L3)	515	12	3.73T	21%
Dipole CCT (L4)	515	12	3.36T	26%



Characteristic line of monolith NbTi strands

High order aberrations

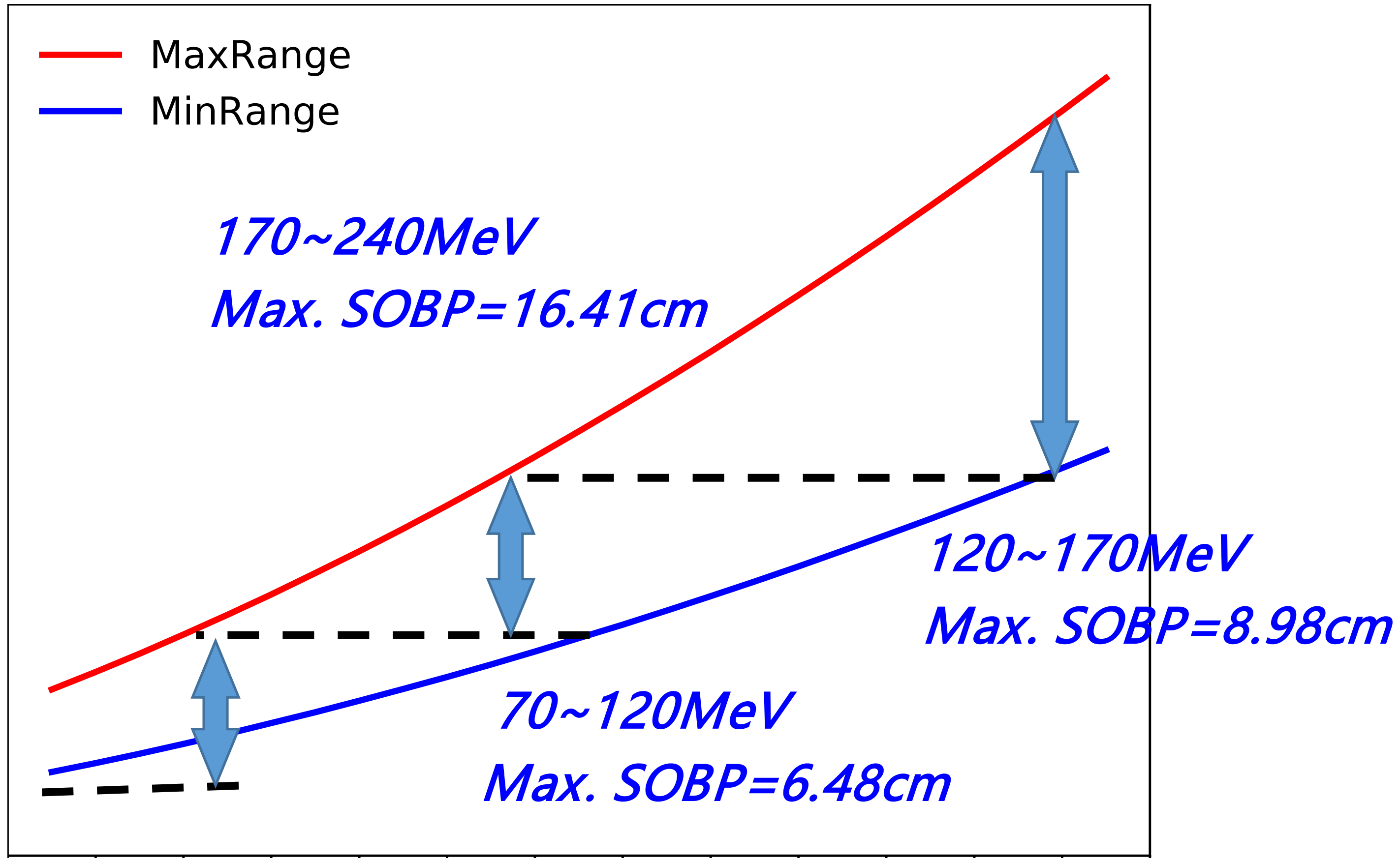
- 2nd order aberrations has been studied using COSY Infinity. Present results show that aberrations have significant infulence on beam optics, especially for large momementum offset situation.

- The original linear optics need be re-optimized in high order situation, and sextupole components will be introduced to minimize the aberrations.

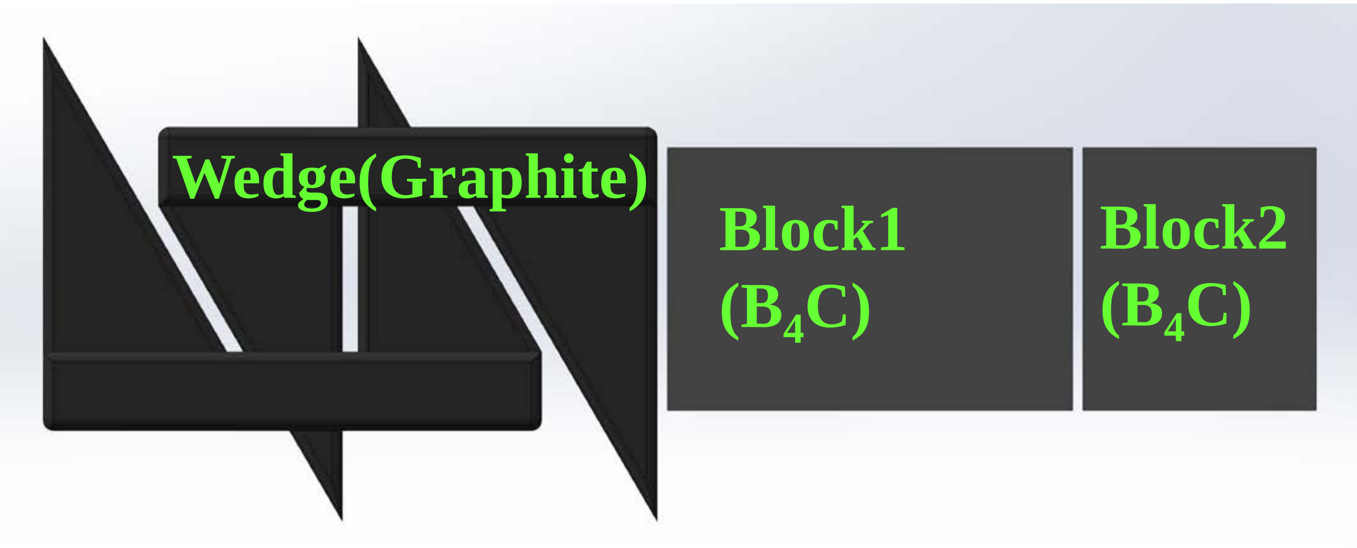
Hybrid structure degrader

- ◻ dp/p=±14% with linear optics; final dp/p=±10% is assumed → 4 central energy for CCTs

Set Energy/MeV	dP/P	dE/E	Emin/MeV	Emax/MeV
75	10.00%	19.26%	60.56	89.44
105	10.00%	18.99%	85.06	124.94
145	10.00%	18.66%	117.94	172.06
205	10.00%	18.21%	167.68	242.32



Energy Degrader in 3 stages:



- ◻ 170~240MeV: Wedge
- ◻ 120~170MeV: Wedge + Block1
- ◻ 70~120MeV: Wedge + Block1 +Block2

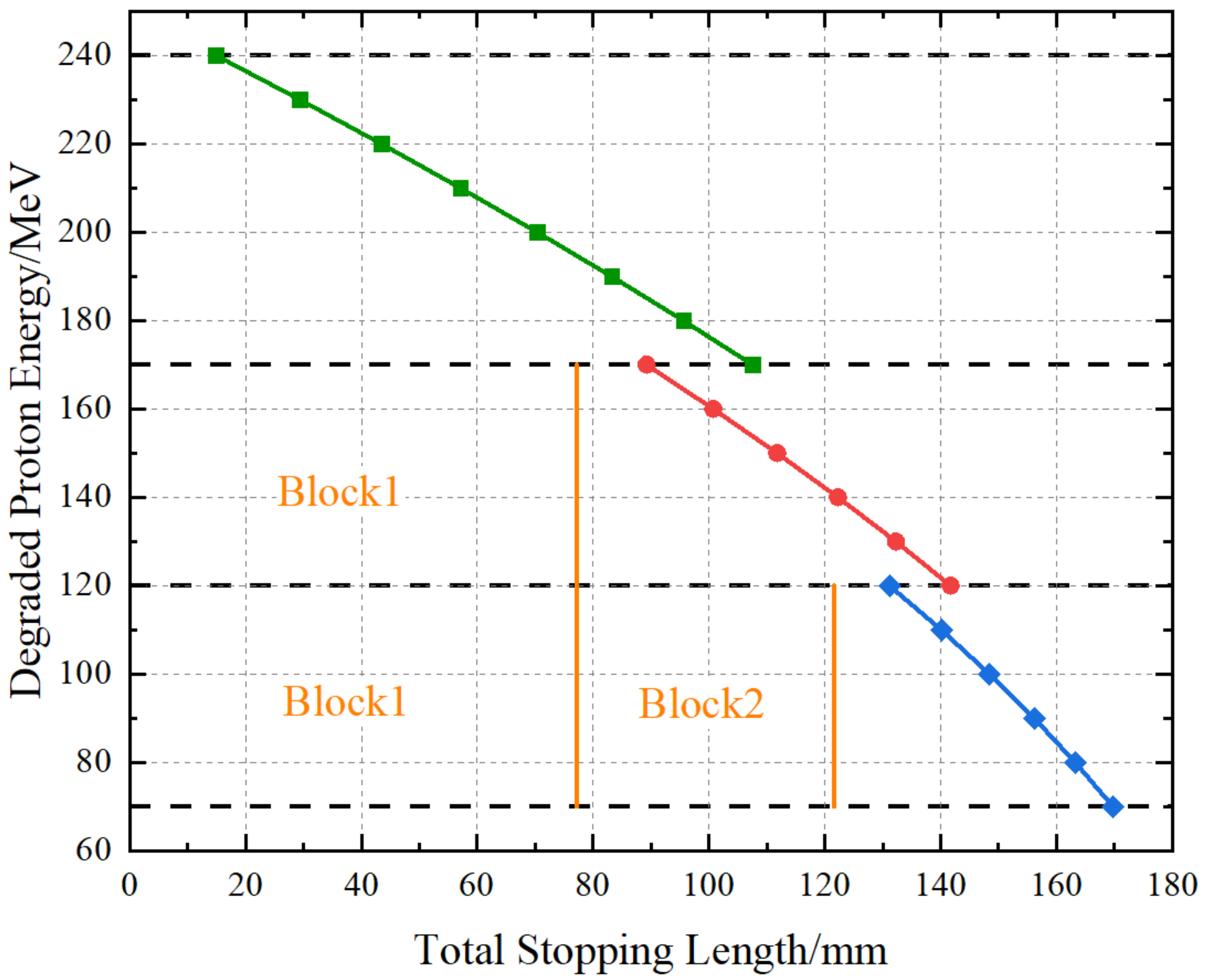
Beneficial:

- ◻ Higher transmission, for low-z materials usage of B1,B2 (B4C, Be)
- ◻ Lighter wedge (~1/4 of full wedge), higher motion speed

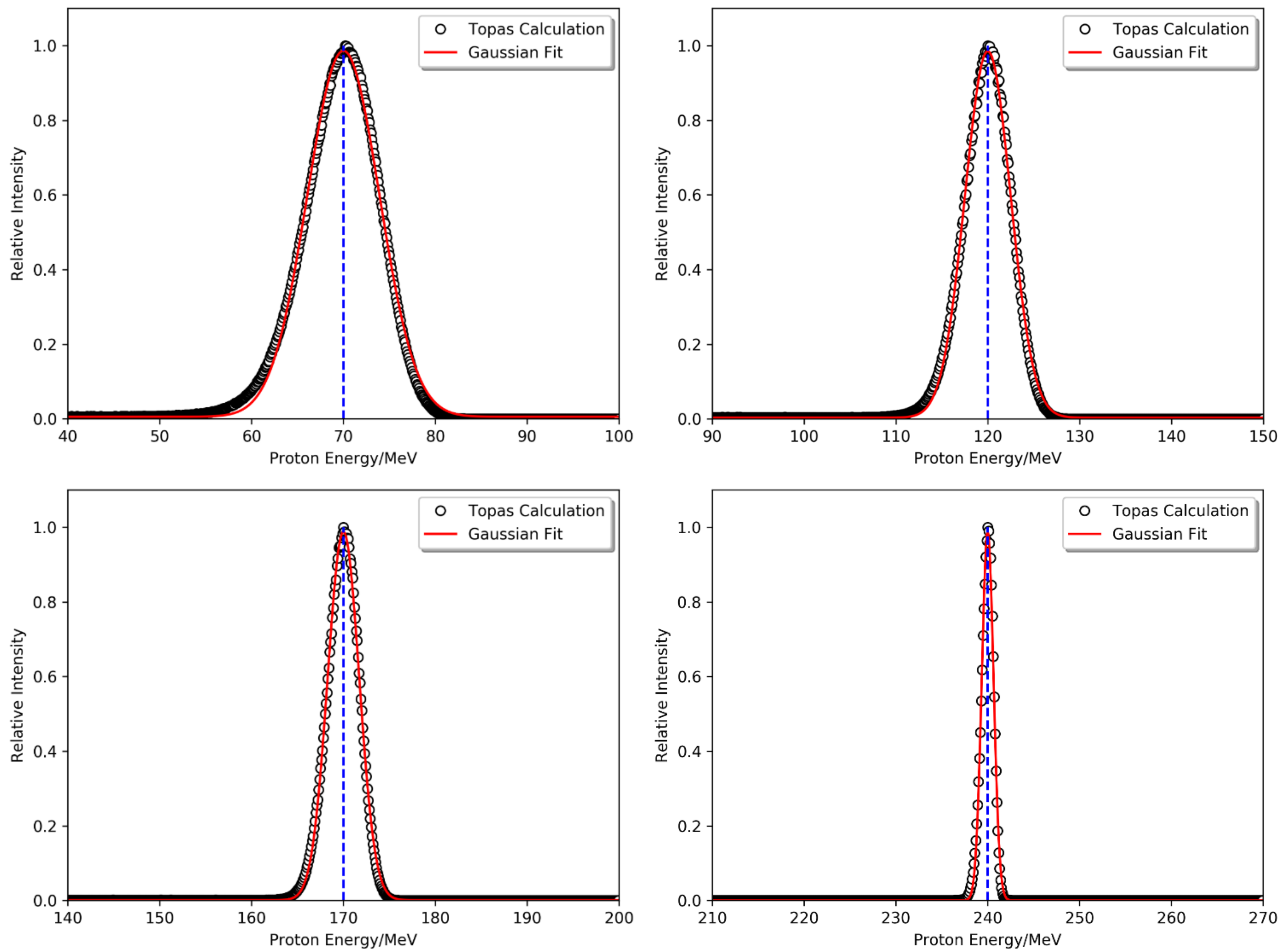
Hybrid structure degrader

For continuous energy degrading:

- **Block1(B4C): 250MeV→180MeV**
- **Block1+Block2: 250MeV→130MeV**



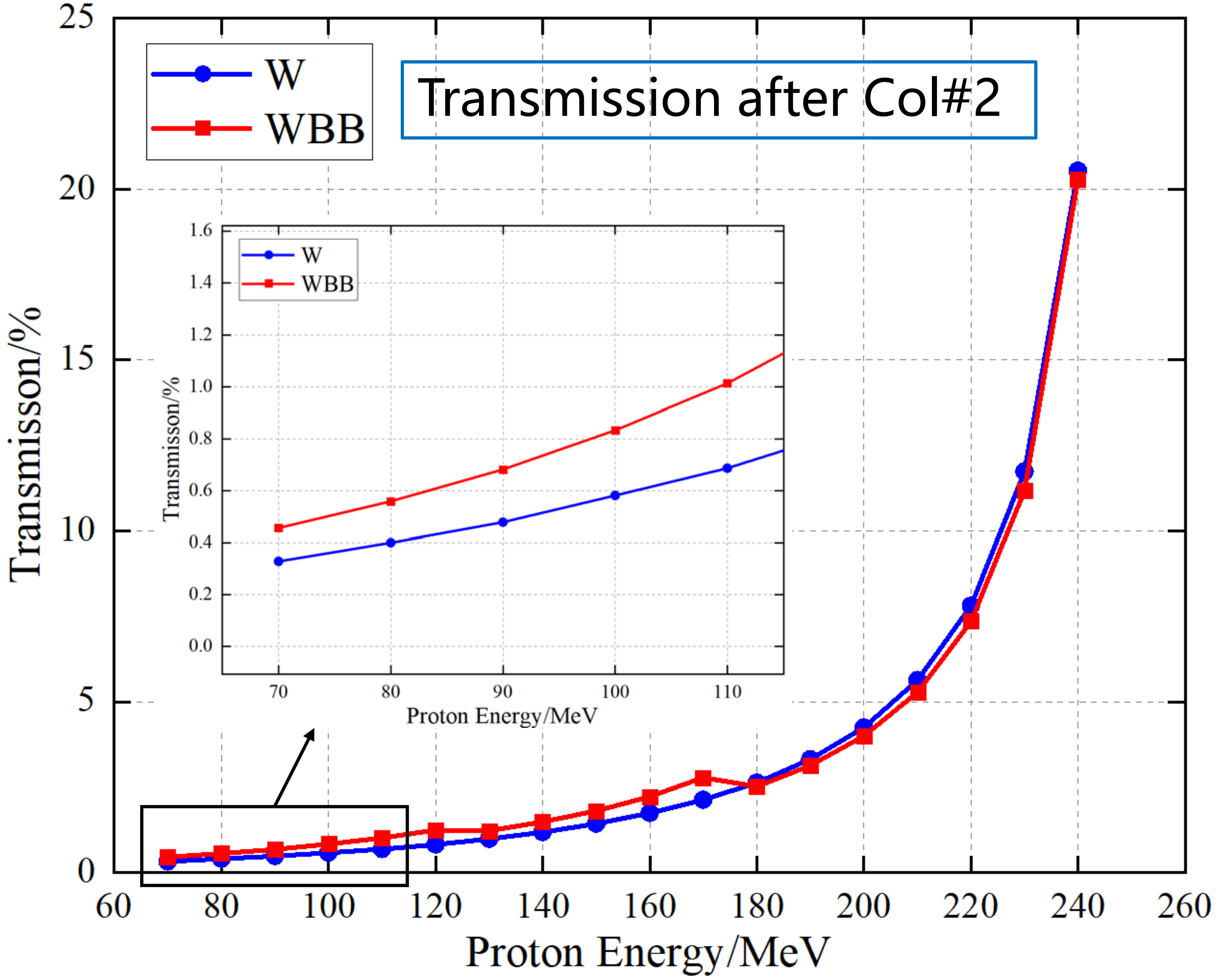
Energy Spread After Degrader: 70, 120, 170, 240 MeV



Transmission optimization of the hybrid degrader

After Collimator #2:

- Beam energy: 70-240MeV
- r.m.s. beam emittance: 7pi mm*mrad



Compared to multi-wedge case:

□ 39~50% increase(relatively) for 70-120MeV

□ 24~30% increase(relatively) for 130-170MeV

Beneficial from natural large energy spread

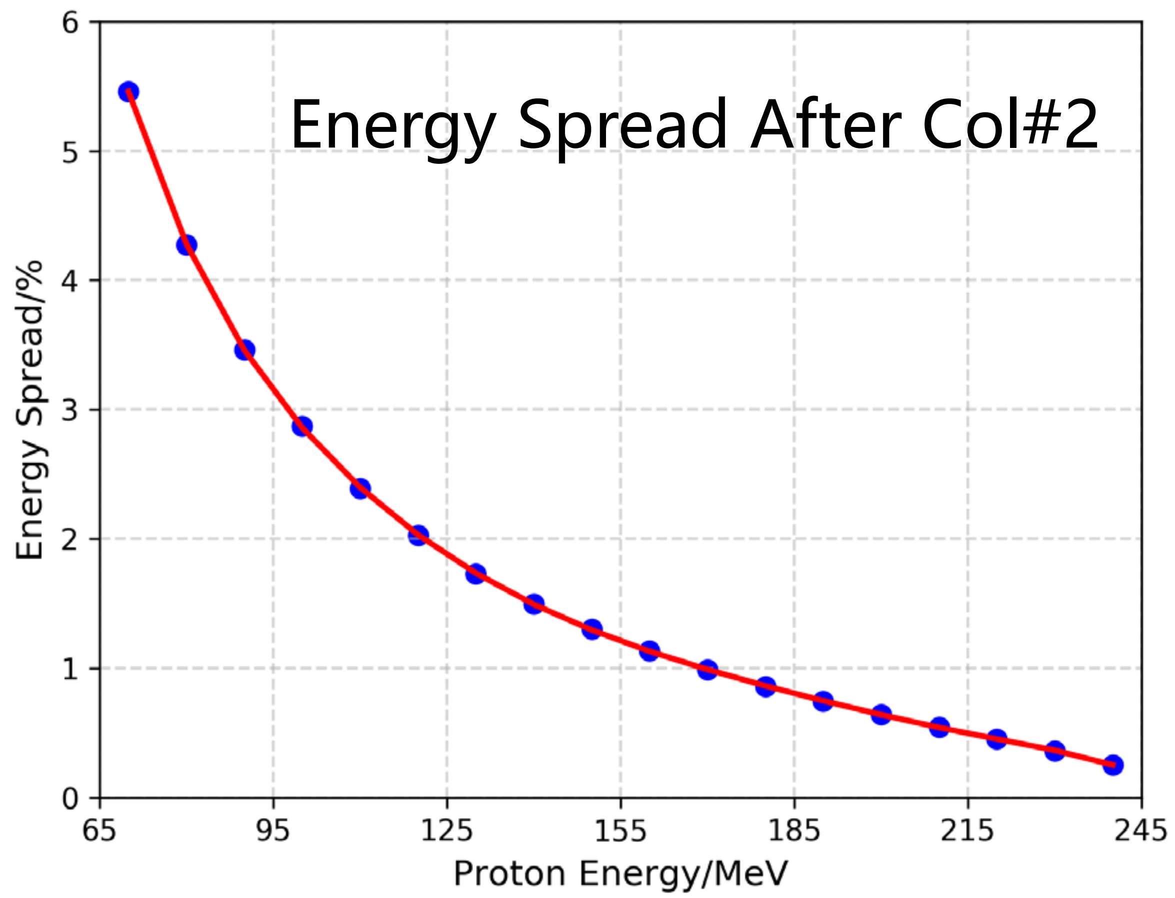
Larger energy spread ⇨ **Larger distal fall-off** ⇨ **Range straggling:** $\frac{dR}{R} = 3.3\frac{dE}{E}$

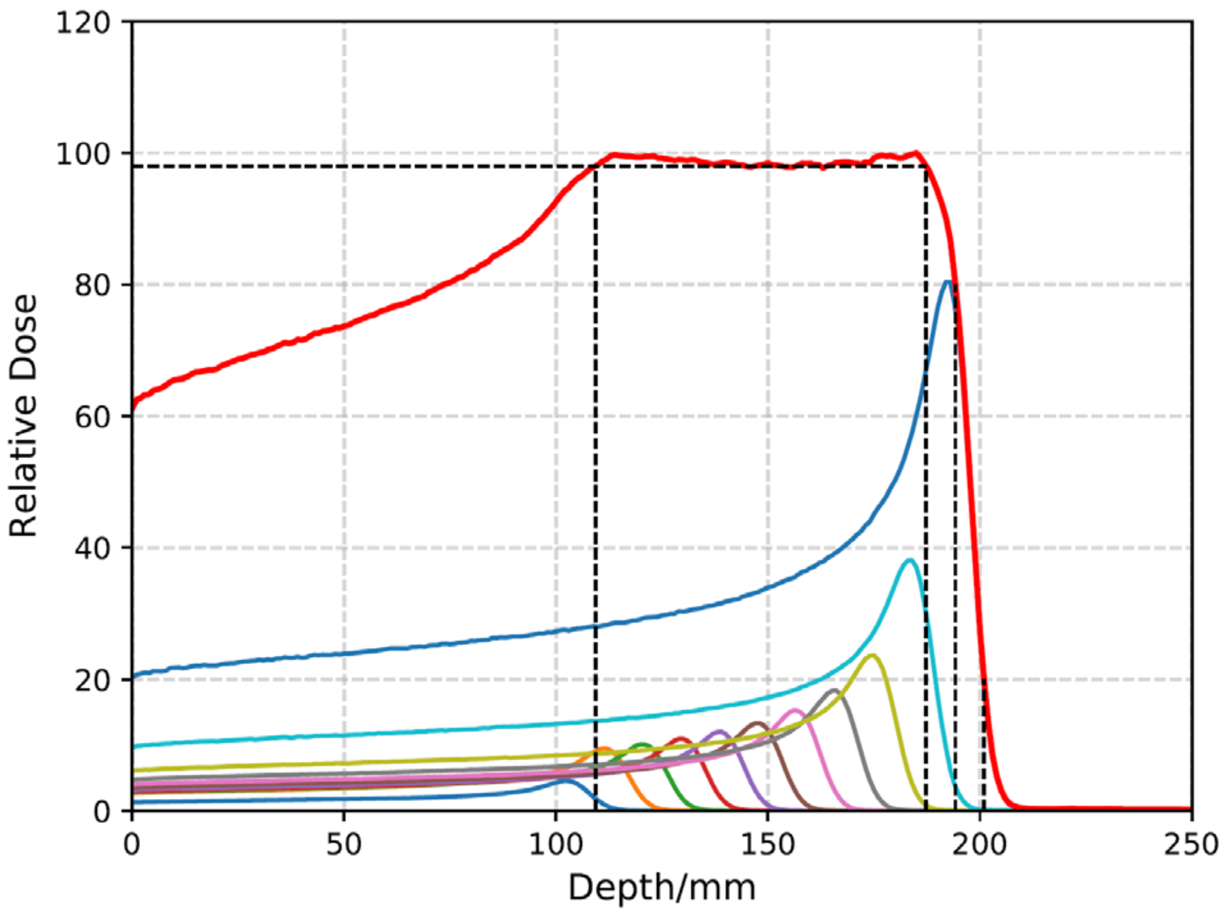
⇩

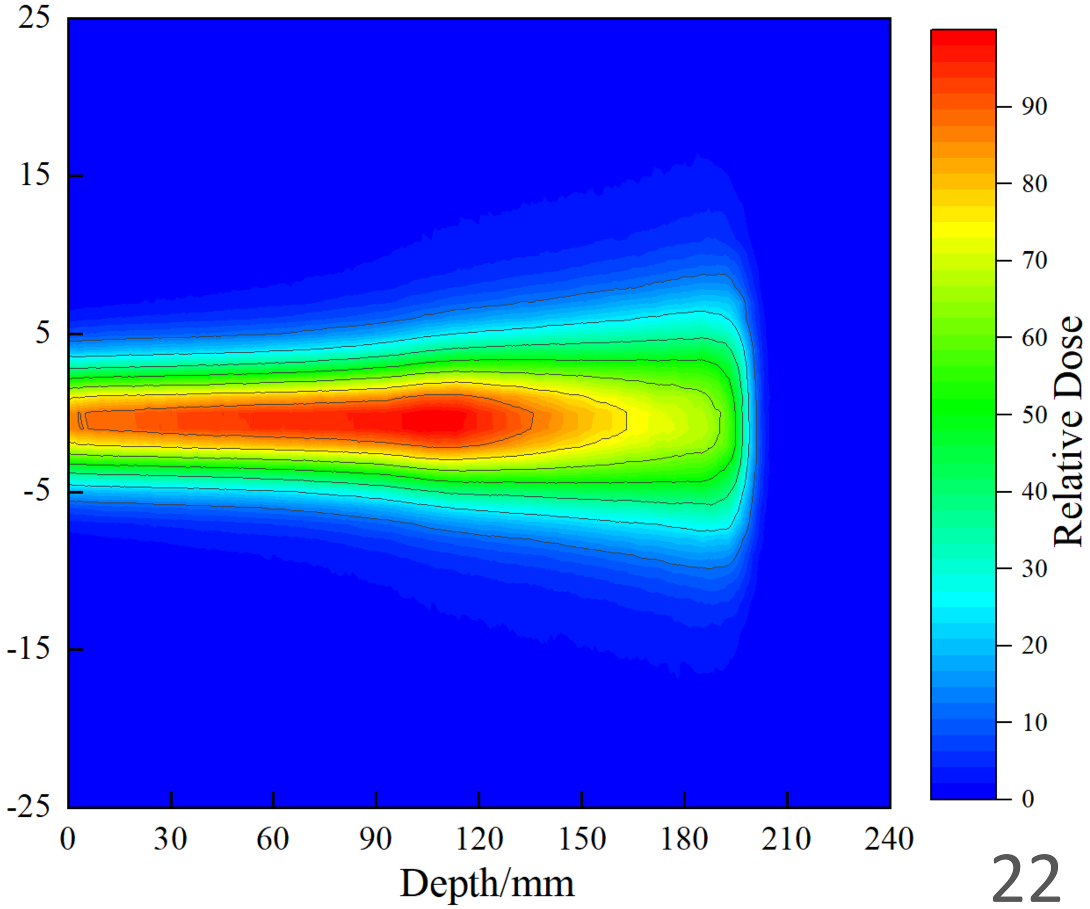
- ✓ Larger distance between successive energy layers is possible
- ✓ Reduce overall energy change time

SOBP Simulation (using TOPAS)

- ☐ Proton Energy: 120MeV -170 MeV ~ Range(10.5cm - 19.5cm)
- ☐ Depth of Energy Layers: 10mm → Energy Step: 11
- ☐ W98=78mm W(d80→d20)=6.62mm







Conclusion

- For future research and development, we proposed a combined function AG-CCT gantry beamline, with large momentum acceptance and smaller footprint.
- Linear optics and influence of field imperfection from small-curvature AG-CCTs were studied. Considering field complexity and large momentum offset, high order aberrations with fringe field effect need be investigated and optimized.
- Combination of large momentum acceptance and natural energy spread during degrading (without energy slit), may lead to potential applications on fast 3D scanning.

Thank you for your attention!

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Posters, this conference

Xu Liu et al., Design of a fast energy degrader for a compact superconducting gantry with large momentum acceptance
Runxiao Zhao et al., Design and optimization of beam optics for a superconducting gantry