Superconducting (SC) gantry with large momentum acceptance (LMA) applied to proton therapy

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OUTLINE

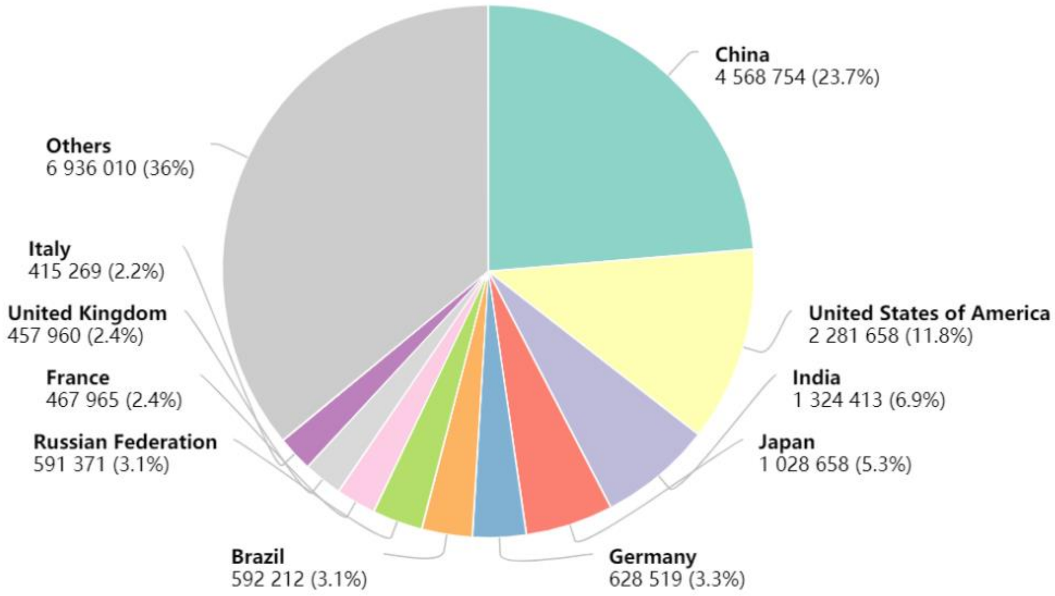
1. SC gantry and motivation of large momentum acceptance design

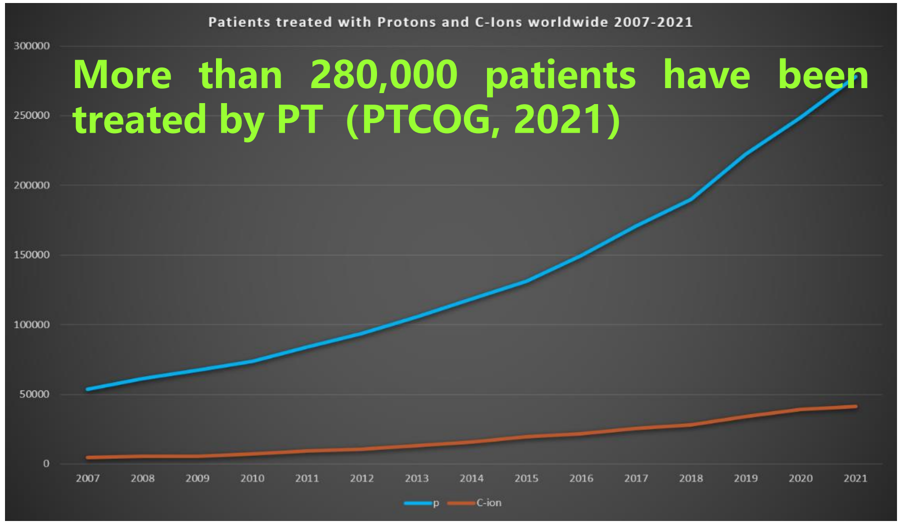
2. Design of a LMA SC gantry based on CCT magnets

3. Potential clinical applications

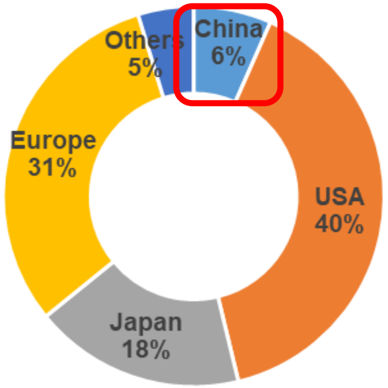
Status of proton therapy – world-wide and China

New cancer cases in 2021

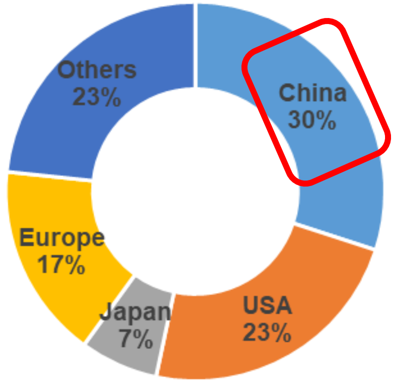




In operation
(China 6%, in 106 sites)



Under construction
(China 30%, in 30 sites)



PT centers in operation and under construction

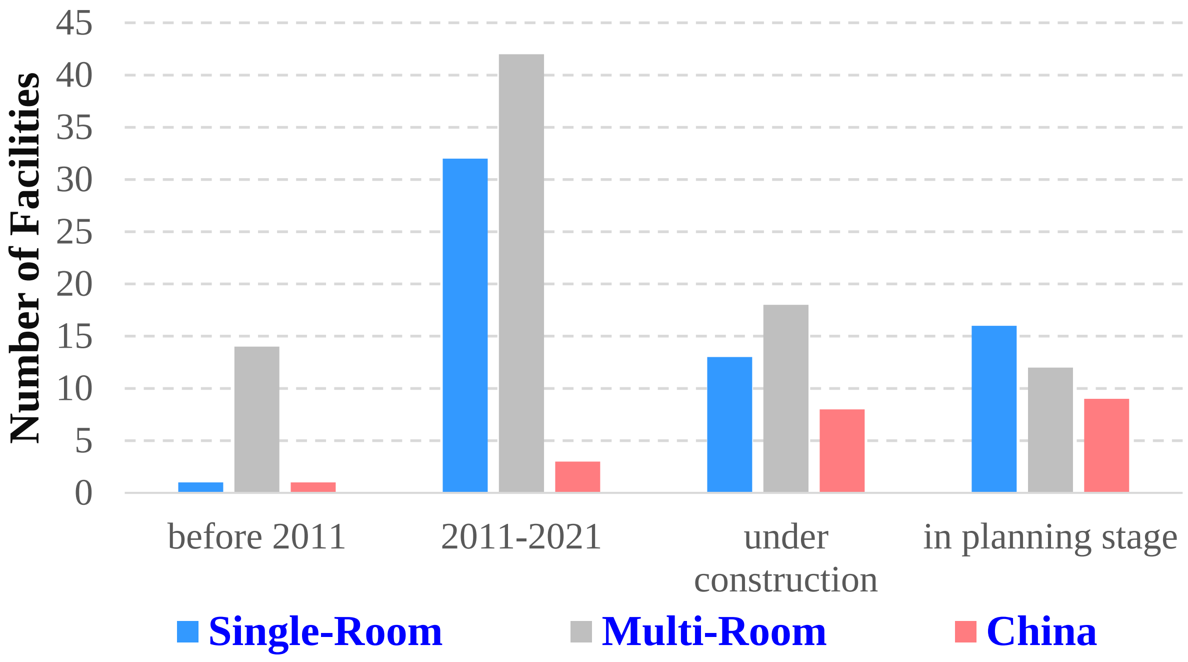
[1] IARC Report(2022)
[2] PTCOG website

3

Challenges and unmet need for PT facilities

- **Shrink the PT infrastructure**
  - ✓ Superconducting technology applied to accelerators and gantries
  - ✓ Compact single-room PT system
  - ✓ Non-rotating gantry
- **Increase the efficiency of beam delivery**
  - ✓ Shortening delivery time
  - ✓ Volumetric scanning
  - ✓ FLASH

Comparison between single-room and multi-room PTs



(Source: www.ptcog.ch)

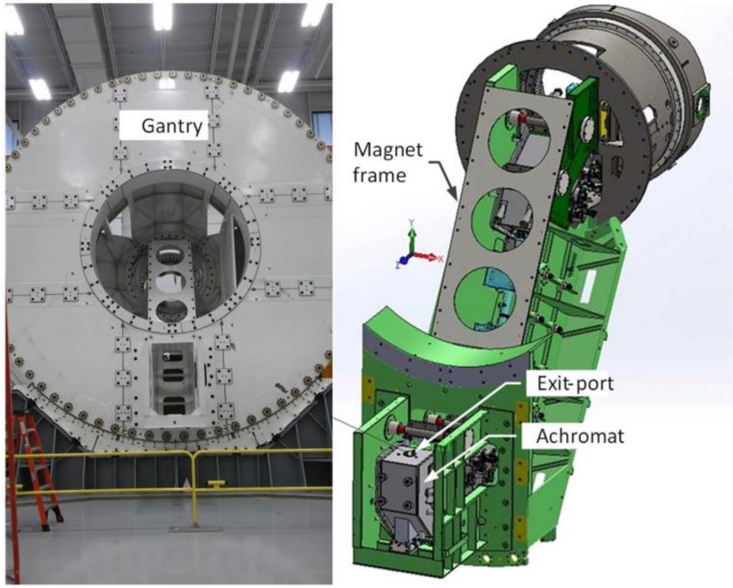
[1] TR. Bortfeld, JS. Loeffler. Nature, 2017, 549(7673): 451-453.
[2] J. Yap, A. De Franco and S. Sheehy, Front. Oncol., 2021, 11:780025

SC gantry → one of solution to shrink the PT facility

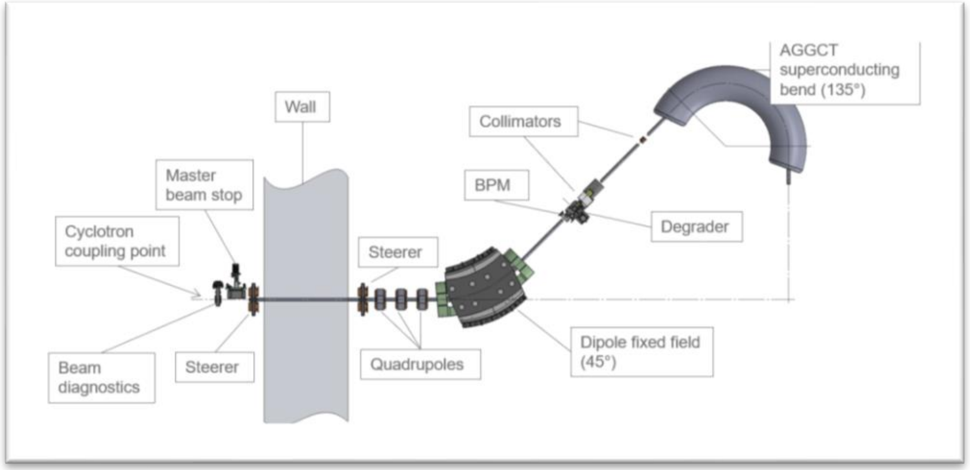
- Applications of SC magnets (Super-ferric / CCT type) can significantly suppress both the footprint and weight of gantries.

Normal-conducting gantry, >200 tons (PSI Gantry 3)

ProNova 360, Superferric magnet gantry, ~30 tons [dp/p=+/-3%]



LBNL / Varian AG-CCT gantry [dp/p = 16.5% @ Bore 210 mm]



H.U. Klein et al., NIMB, 241(1), 2005
P. Hansen and D. Hu, Rev Sci Instrum, 88(12), 2017

W. Wan, L. Brouwer et al., PRSTAB, 18(10), 2015
A. M. HUGGINS, Novel Beam Optics of Achromatic Superconducting Gantries for Proton Therapy, 2021 (Doctoral dissertation).

Ramping limit for SC magnet

- **To avoid quench due to local ‘hot spot’， the ramping of SC magnets is limited to ~ 1% B_{max} / s**

-- AC losses ， hysteresis losses

$$P_{hystersis} = \frac{2}{3\pi} J_c(B)\, d_{eff} \boxed{\frac{dB_t}{dt}} \left(1 + \frac{J^2}{Jc^2}\right),$$

inter-filament coupling losses $\propto (dBt/dt)^2$

-- Eddy current, lamination of mandrel is required

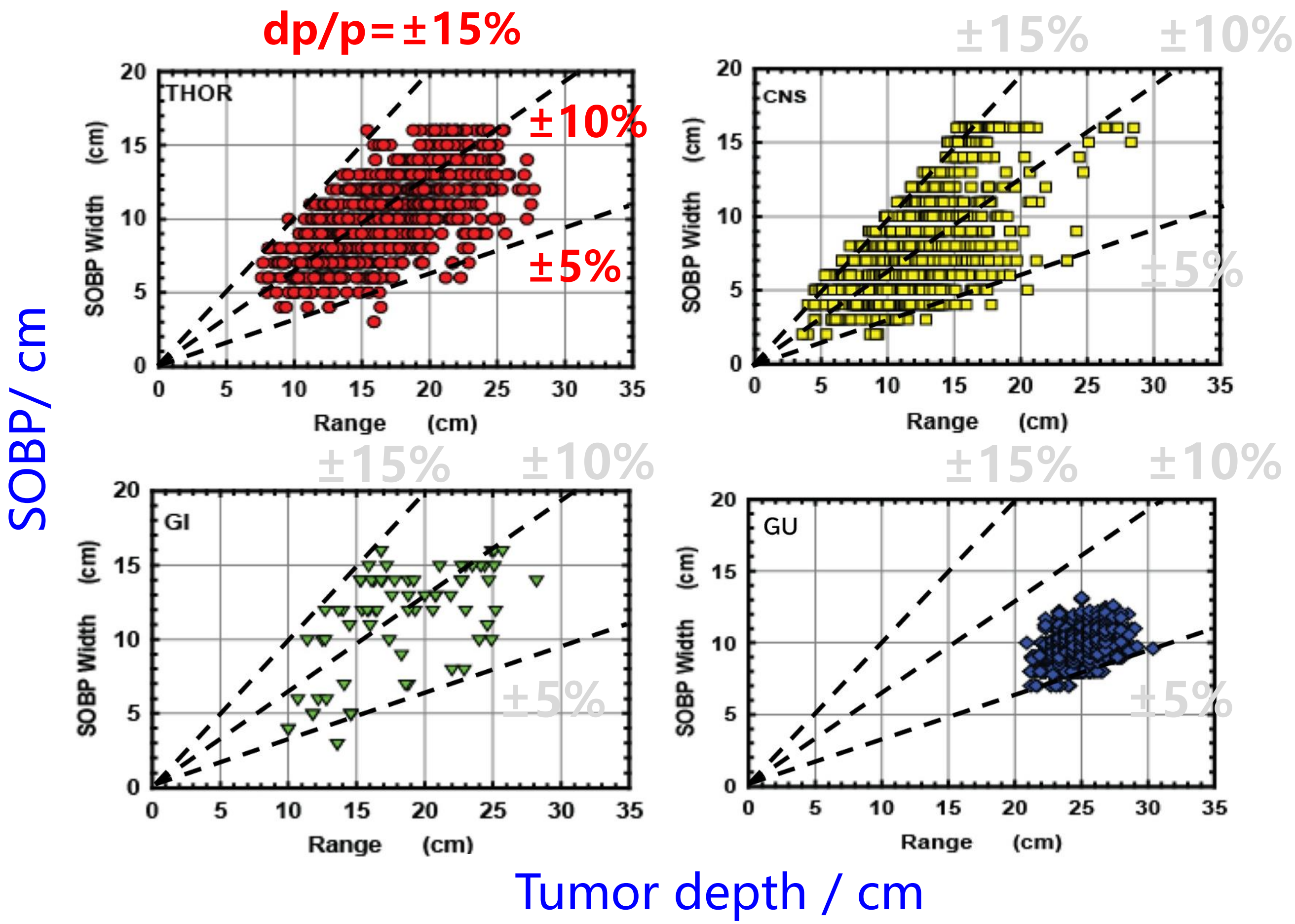
Δ LBNL 90° AG-CCT prototype using laminated mandrel (anodized aluminum)

Due to very slow ramping speed, the magnetic field need be constant or have reduced ramping times.

→ **From beam optics design, large momentum acceptance is required.**

Δ L. Brouwer et al., "Design of an Achromatic Superconducting Magnet for a Proton Therapy Gantry," in IEEE Transactions on Applied Superconductivity, vol. 27, no. 4, pp. 1-6, June 2017, Art no. 4400106, doi: 10.1109/TASC.2016.2628305.

Momentum (energy) range for proton beams from 4 types of tumors



- From MD Anderson Cancer Center statistics[Δ], dp/p = ±10% can treat ~60% of tumors without changing magnetic fields (**THOR**: thoracic; **CNS**: central nervous system; **GI**: gastrointestinal; **GU**: genitourinary); **dp/p = ±15% can treat almost all cases.**
- **For most tumors, with a 15% momentum range beam, only one magnetic field change is required during treatment.**

[Δ] K. Suzuki et al., Quantitative analysis of beam delivery parameters and treatment process time for proton beam therapy, Medical Physics, 2011, 38(7)

OUTLINE

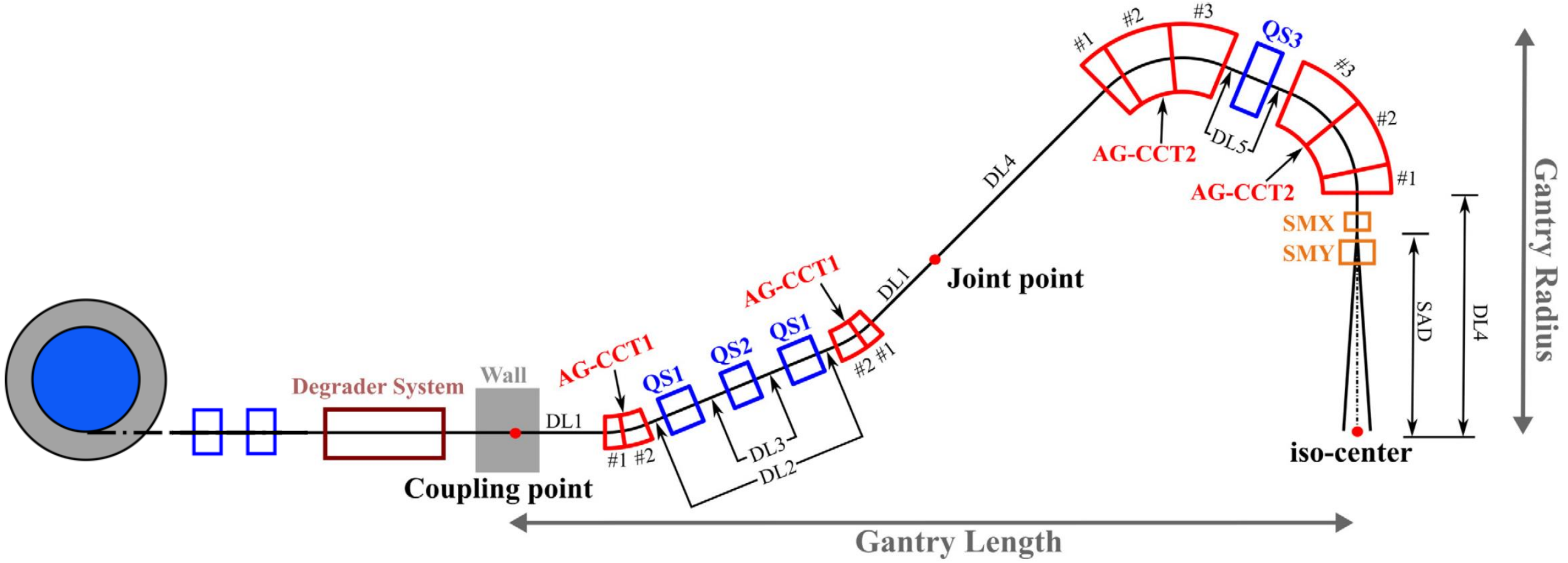
1. SC gantry and motivation of large momentum acceptance design

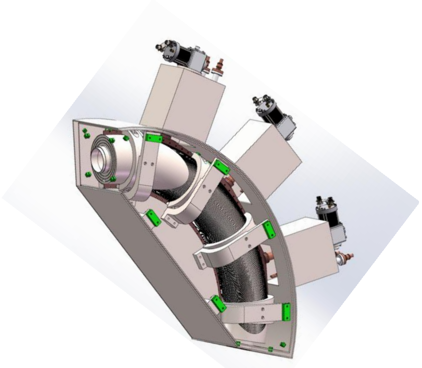
2. **Design of a LMA SC gantry based on CCT magnets**

3. Potential clinical applications

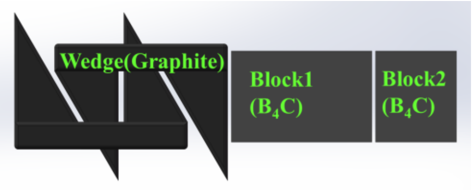
SC gantry using AG-CCT magnets

- We proposed a SC gantry using **AG-CCT (Alternating-Gradient Canted-Cosine-Theta)** magnet.
- **Local dispersion suppression** is realized by symmetrical optical structure and AG-CCT strong focusing.
- Downstream scanning with small SAD

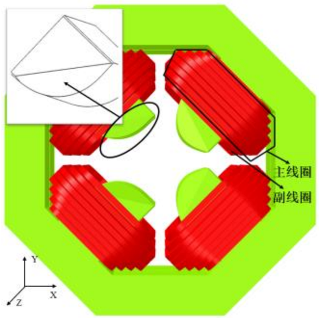




(A) AG-CCT magnet



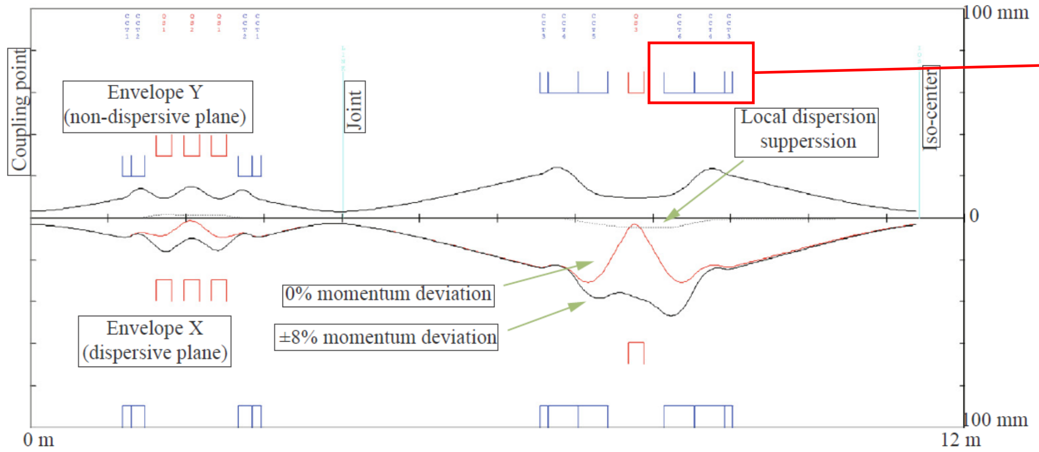
(B) Graphite+B_4C compact degrader



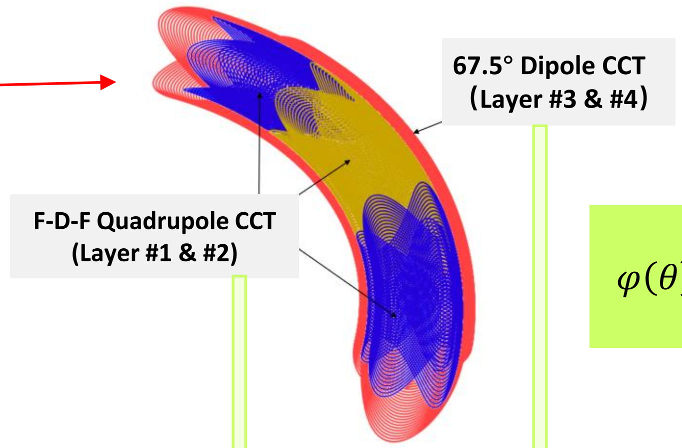
(C) Combined function Quad-Sextupole magnet

[1] R.X. Zhao, B. Qin*, X. Liu et al., Physica Medica, 73 (2020)
[2] X. Liu, B. Qin et al., Physica Medica, 73 (2020)

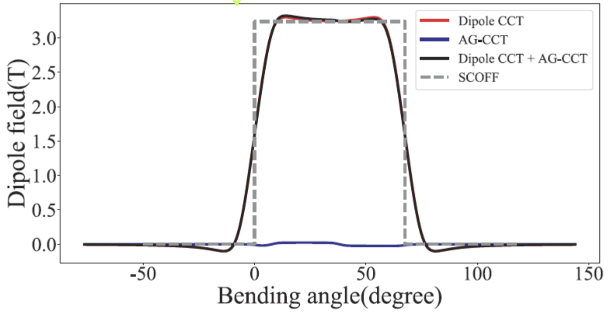
SC gantry using AG-CCT magnets

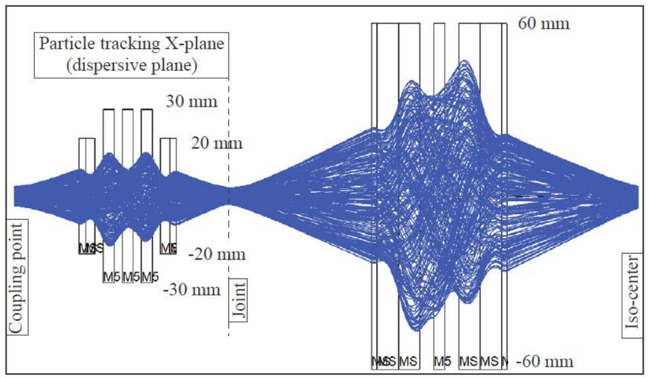


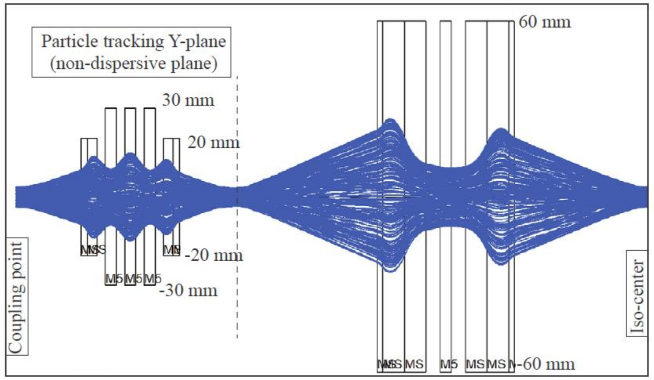
First order beam envelope with dp/p=±8% (Transport calculation),
max. dispersion ~ 2 mm / %

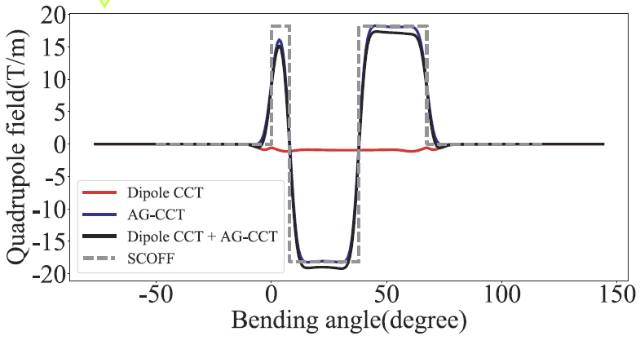


$$\varphi(\theta) = \frac{\varphi_0}{2\pi} + \sum_{i}^{n} \frac{co\,t(\alpha_i)}{i \cdot sh(\eta_0)} sin(i\theta)$$









Particle tracing in 2nd order, with dp/p=±8%
(Cosy Infinity calculation)

High order optics optimization with Generic Algorithm

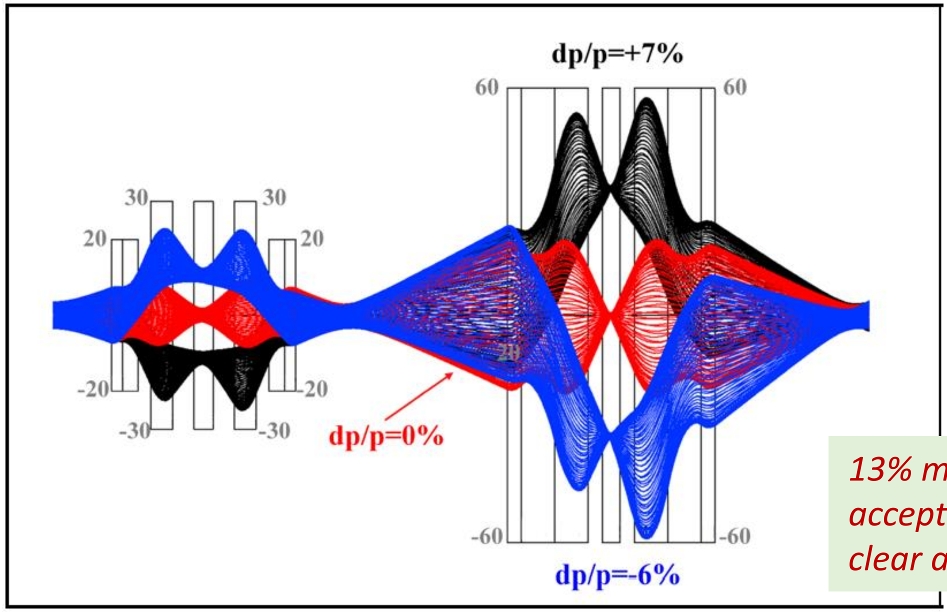
- High order aberrations (up to 5th order) have significant influence on beam optics , for large momentum offset;
- Multi-object optimization using **NSGA-III genetic algorithm** was applied to search optimal parameters.

Optimization objectives

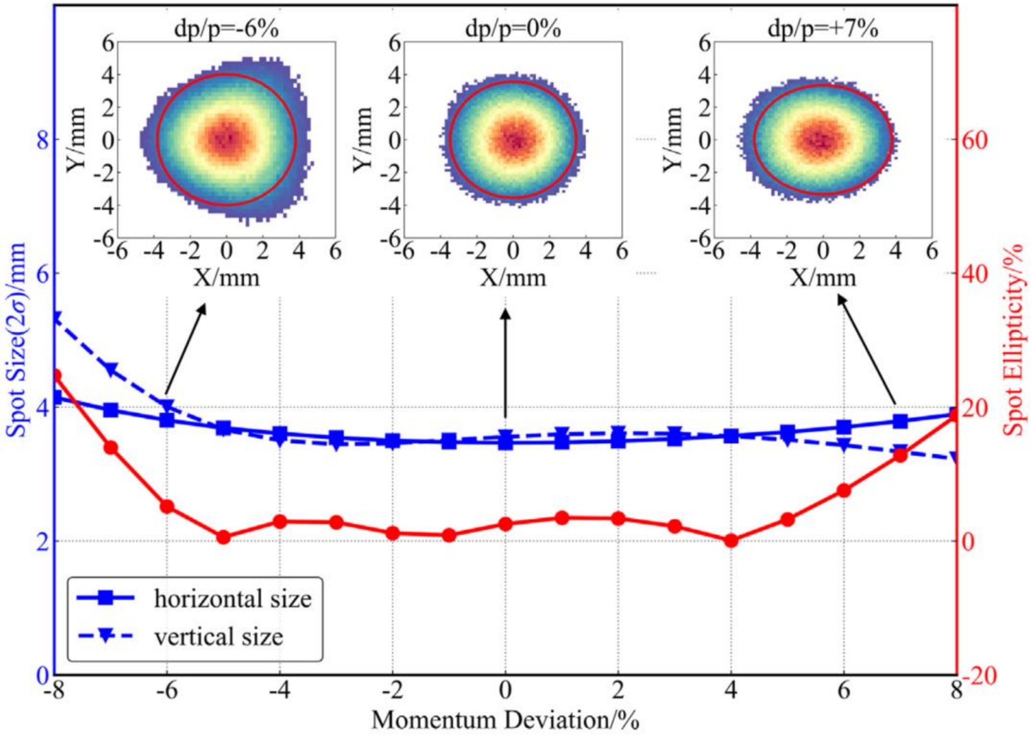
- Beam size: $1.5 \leq \sigma_x, \sigma_y \leq 3.0$ mm;
- Beam spot ellipticity: $\epsilon \leq 10\%$;
- Beam size fluctuation: $\Delta\sigma_x, \Delta\sigma_y \leq 0.3$ mm;
- Beam position fluctuation: $\Delta X, \Delta Y \leq 1$ mm.

Table 1
Hyperparameter settings of NSGA-III.

Hyperparameter	1st Section	2nd Section
Number of knobs	11	7
Population size	500	300
Maximum generation	1000	
Crossover operator	Simulated Binary Crossover	
Crossover rate	100%	
Mutation operator	Polynomial Mutation	
Mutation rate	9%	12.5%



13% momentum acceptance for 120 mm clear aperture

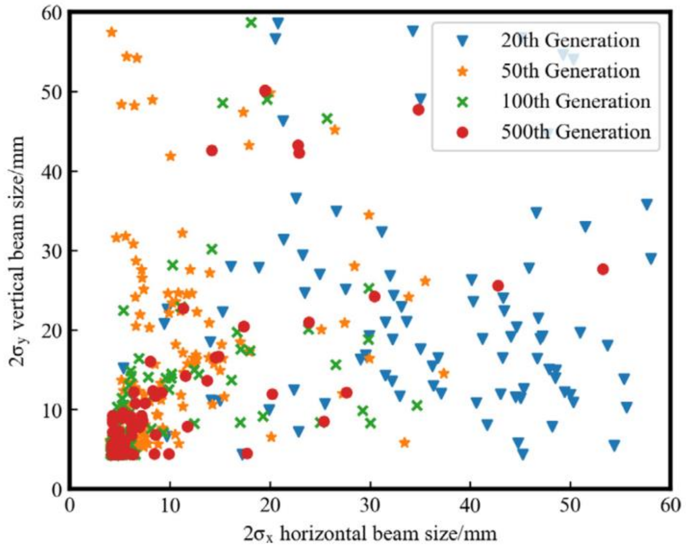


Beam size & spot ellipticity at dp/p = -6% ~ +7%

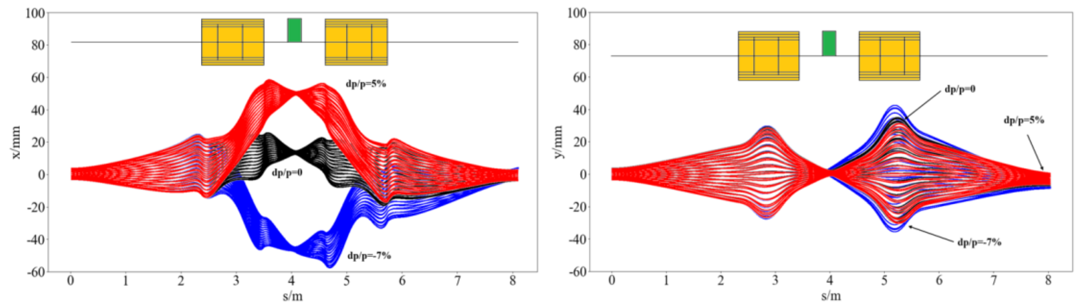
[1] Y.C. Liao, X. Liu*, B. Qin, High order beam optics optimization for a superconducting gantry applied to proton therapy based on NSGA-III, NIM, A 1014 (2021) 165727

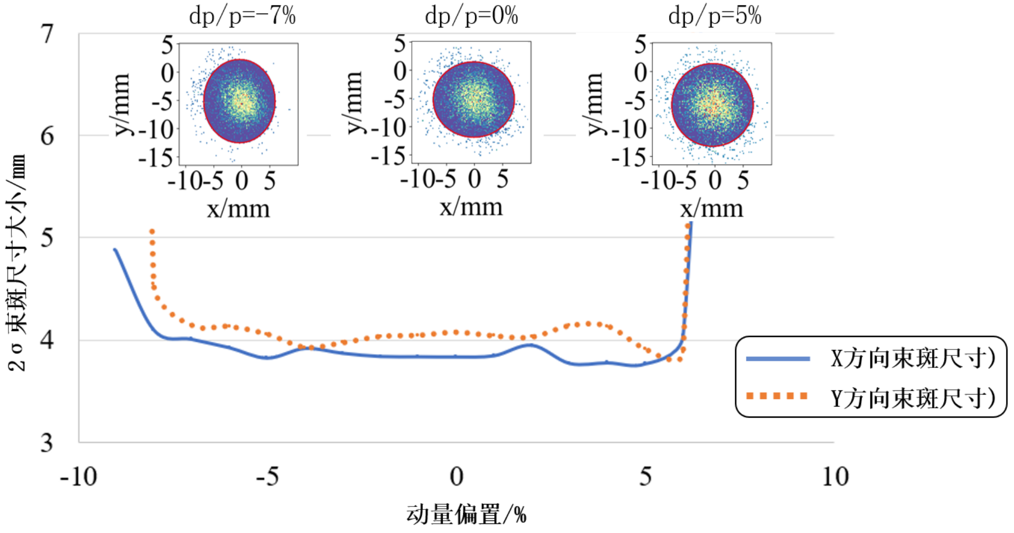
Validation using realistic magnetic fields

- Enge function can’ t be applied to AG-CCT, realistic AG-CCT field is required;
- AG-CCT magnetic fields calculated by Biot-Savart law (in the absence of ferric material)
- Parallel computation with CUDA adopted to shorten the optimization time (speed-up ratio ~ 200)



Pareto for objectives (NSGA-III)



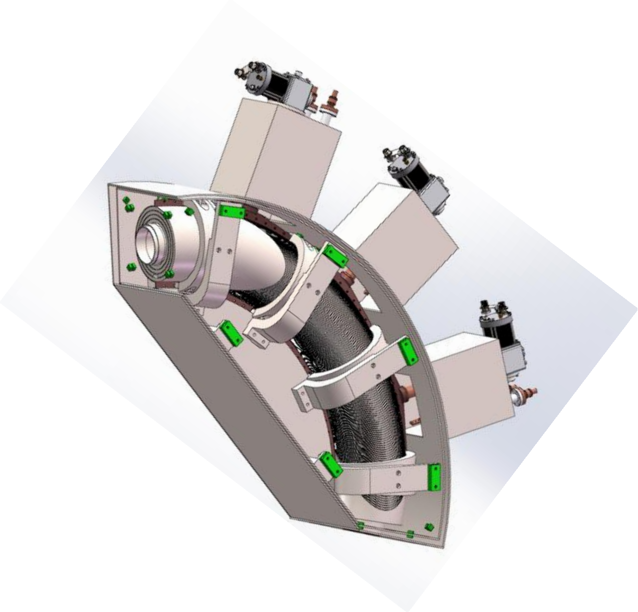


Particle tracking @ iso-center, with realistic fields

[1] R.X. Zhao, B. Qin*, Y.C. Liao et al., NIM, A 1015 (2021) 165773

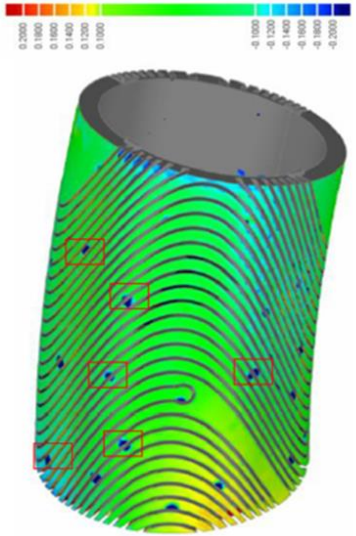
R&D of AG-CCT prototype magnet

- R&D of a **67.5° / 4 layers** AG-CCT prototype magnet was initiated;
- 3 GM cryocoolers for direct cooling，NbTi superconductors;
- Laminated Aluminum alloy mandrel



67.5° AG-CCT specifications

Parameter	Values
Bore aperture	166 mm
Bending radius	950 mm
Bending angle	67.5°
Dipole field	2.36 T
Gradient field	17.0 T/m
Max. field @ coil	4.5 T



CCT mandrel (Al alloy) and manufacture precision

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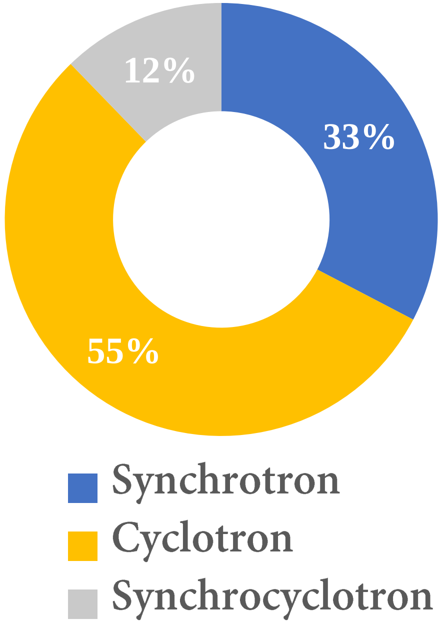
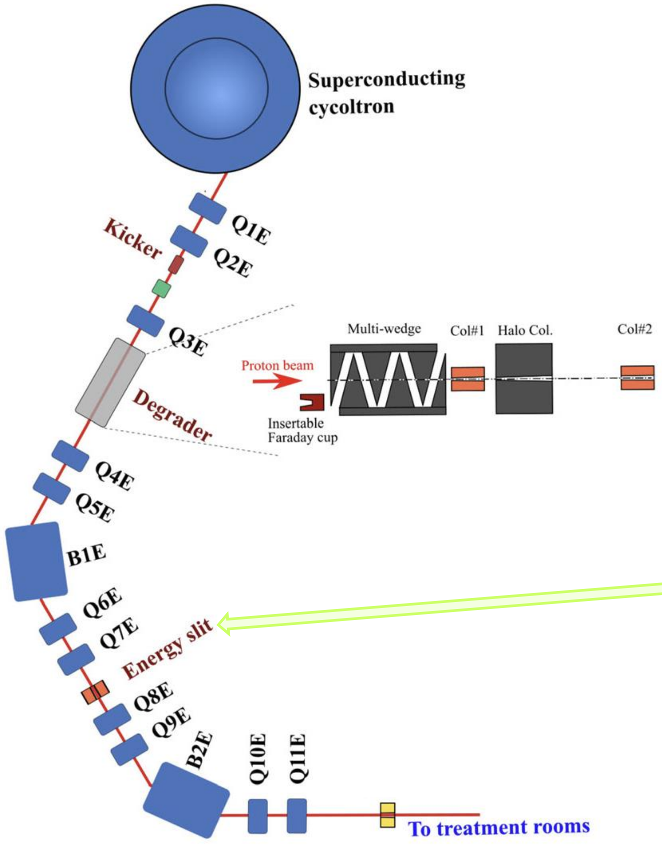
-- Towards improving delivery efficiency using LMA beamline

Large momentum acceptance → higher transmission

- For PT centers in world wide, cyclotron schemes possess around 55%
- Due to Multiple Coulomb scattering in the energy degrader， the transmission is quite low in low energy region (70-100 MeV)： <0.2% @ 70 MeV
- Utilizing the **natural momentum spread** can enhance the transmission by a ratio ~ 5.

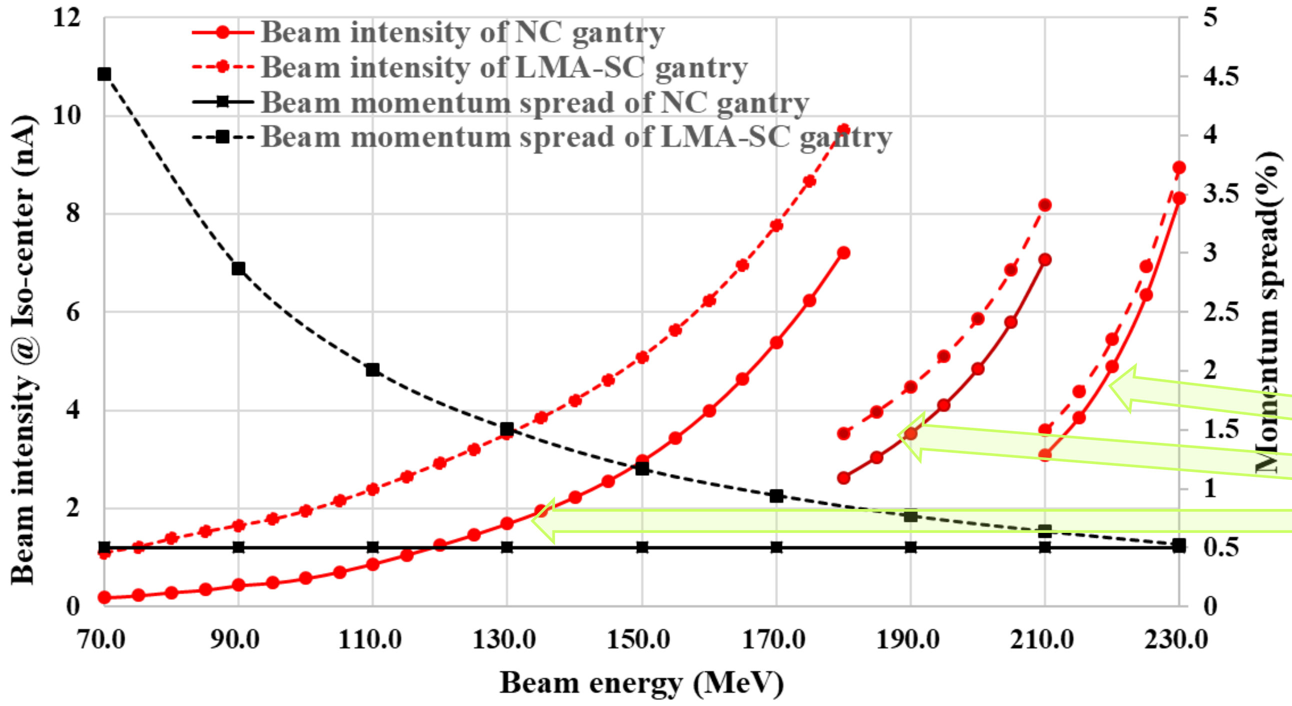




After degrader (with emittance shaping), transmission: ~ 1% @ 70 MeV

After energy slit at DBA (with momentum cut), transmission: <0.2% @ 70 MeV

Improved beam transmission in LMA-SC gantry



NC gantry: Normal-conducting gantry

LMA-SC gantry: Large momentum acceptance SC gantry

Three extracted beam current:

220 nA : 70-180 MeV

80 nA : 180-210 MeV

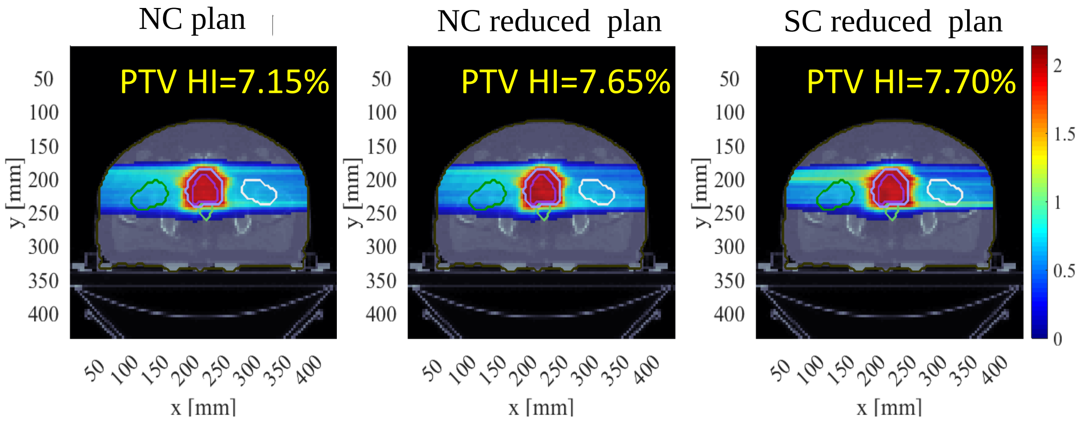
35 nA : 210-230 MeV

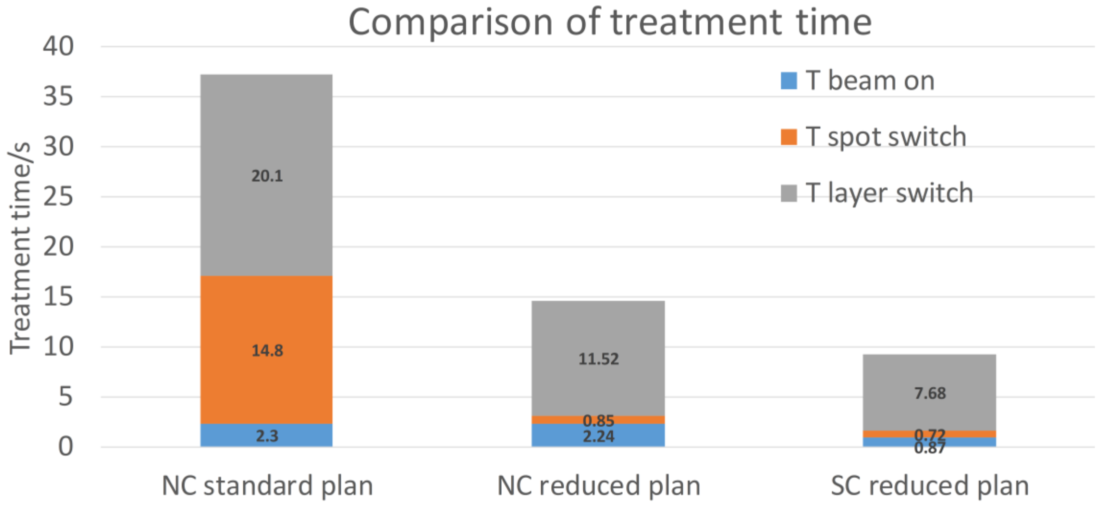
Setup for comparison

- For NC gantry, momentum spread is set to constant +/-0.5% **with energy slit**
- For LMA-SC gantry, momentum spread is 'natural' after energy degrader (**without cut from energy slit**)
- Significant transmission increase at lower energy (70 -130 MeV)

Reduction of energy layers and spots, case study : prostate cancer

- Two fields with angle: 90° and 270° ; **less layers become possible due to larger momentum spread**
- We used an optimizer to concentrate on minimizing spot weights in low-weighted energy layers and then redistributes them to adjacent energy layers → **Spots can be reduced by 95% for LMA SC scheme**
- Balance between the **dose delivery time** and **treatment plan quality** (homogeneity index PTV HI < 10%)

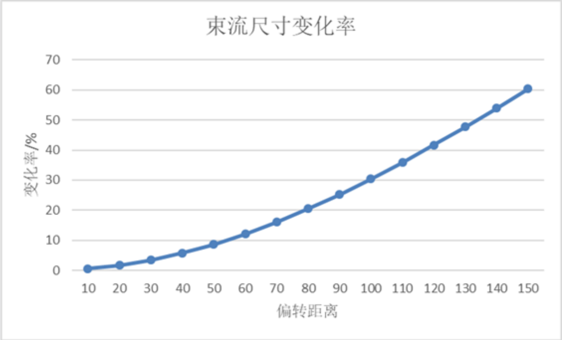


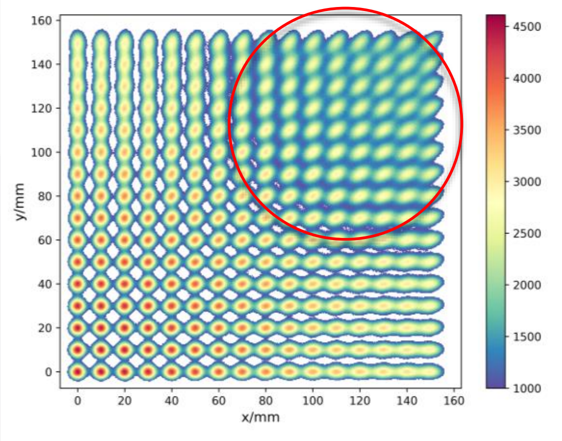


Layer switch time – 250 ms
Spot switch time – 1 ms

Challenge of large momentum acceptance SC Gantry

1. With large momentum beam, the dispersion due to scanning magnets is non-neglectable and need be compensated;
2. Custom-made TPS should be developed for 3D planning of large momentum beam features;
3. Due to the technical complexity of CCTs with large aperture, the cost is not low. Potential clinical applications of large momentum beams need be explored.
4. The LMA gantry could be an attractive solution for PT using laser-driven accelerators and carbon therapy.





Dispersive effect after scanning magnet for large momentum spread beam (e.g. dp/p=±2.4%)

Research group

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Thank you