OMA Superconducting gantry for proton therapy and imaging

Ewa Oponowicz, Hywel Owen
The University of Manchester/The Cockcroft Institute

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The Cockcroft Institute
of Accelerator Science and Technology

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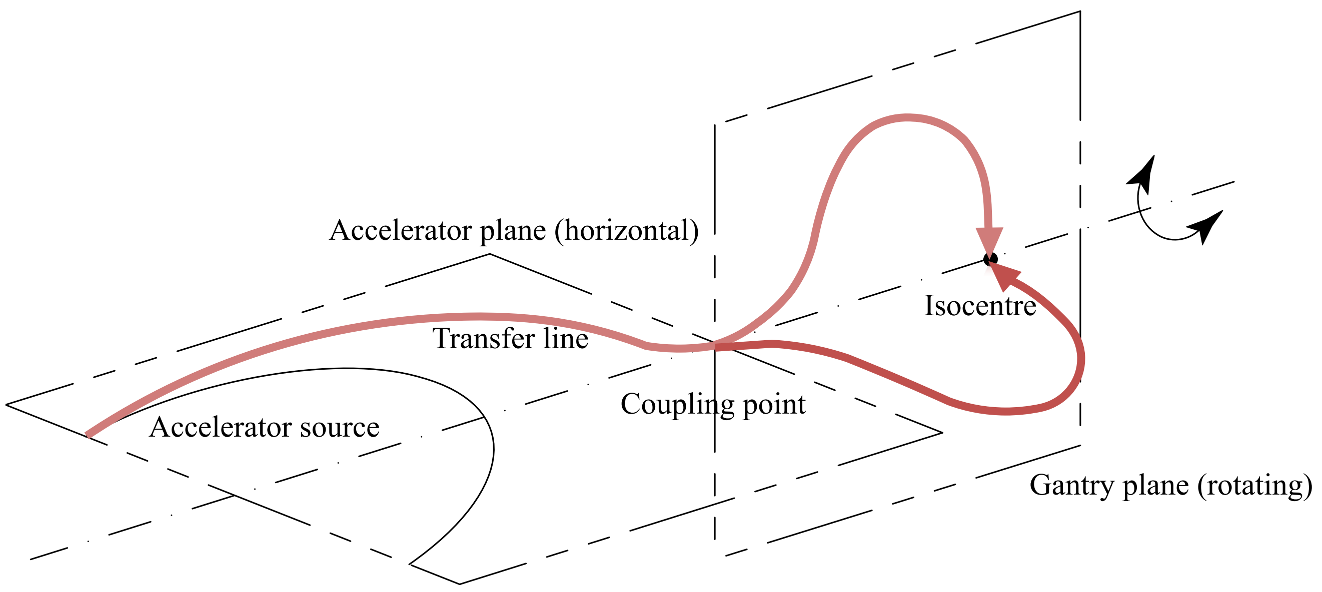
Gantry for proton therapy

Main components:
- Magnets (bending/focusing)
- Beam scanning system (downstream/upstream/combined)
- Beam instrumentation devices
- Vacuum and cooling systems
- Mechanical support system
- Drive mechanism

Typical proton gantry:
- Max. 250 MeV kinetic energy
- Isocentric (centre of min. sphere crossed by beam axis)
- Delivering beam to a supine patient on a rotating table
- 180/360 deg rotation capability
- Normal-conducting
- Occupies volume of 8m x 8m x 8m

Imaging prior to the treatment:
- MRI
- X-ray CT



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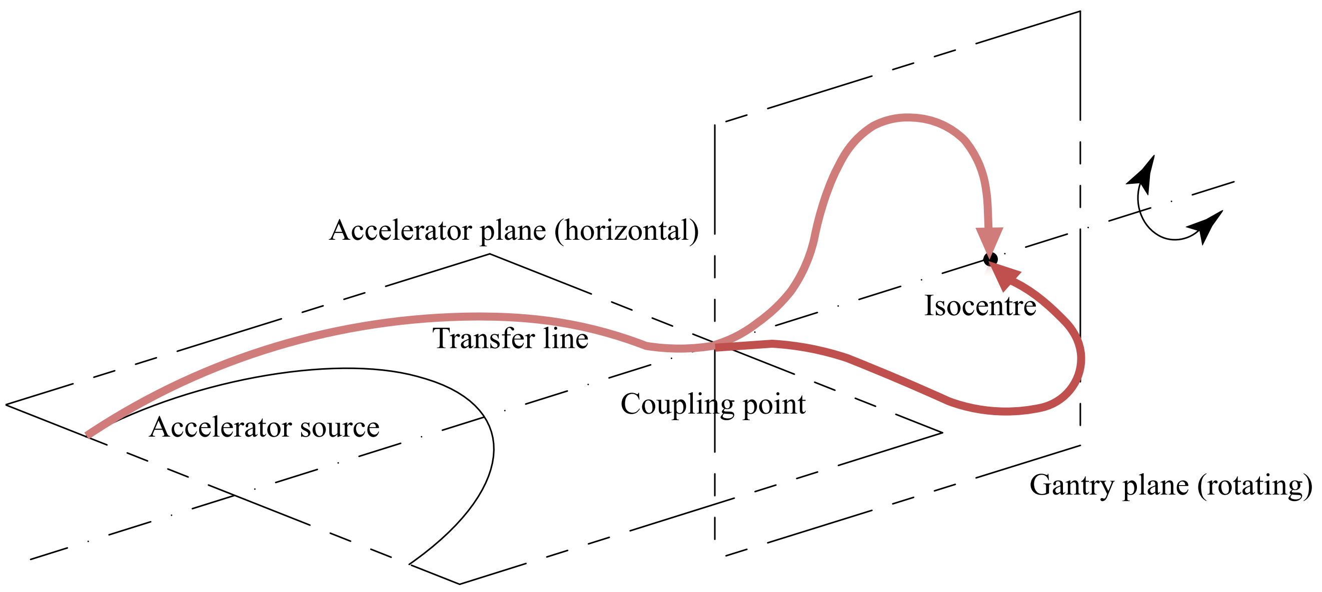

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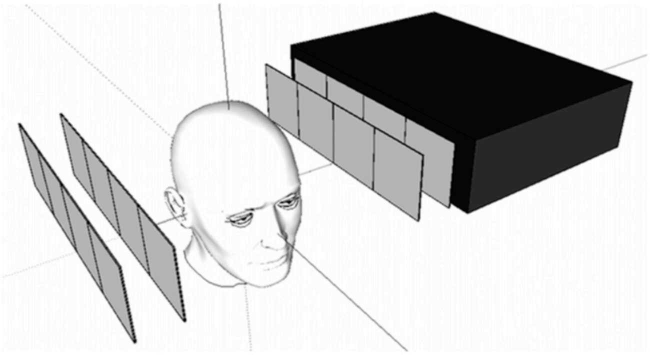
→ **Conversion from HU to effective electron density: proton range uncertainty of up to 3.5%**

Proton computed tomography



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Proton CT:

- Proposed in 1963, not available in clinics yet
- Proton-tracking (detecting energy deposition and trajectories of individual particles)
- Proton-integrating (measuring integrated energy deposition)

Proton CT scan of head:

- 10^8 protons (~0.2 pA) compared to 10^{11} protons for a single treatment fraction
- 1.4 mGy radiological dose compared to 50 mGy for an X-ray CT

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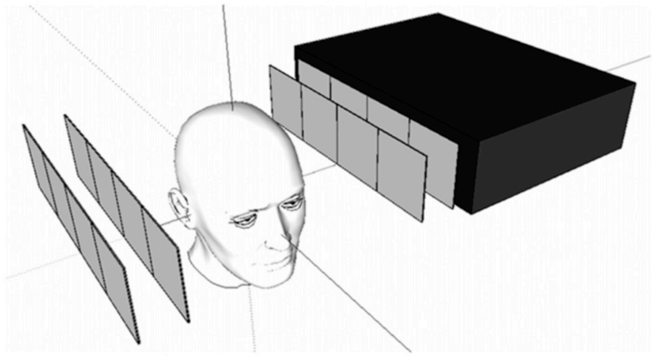

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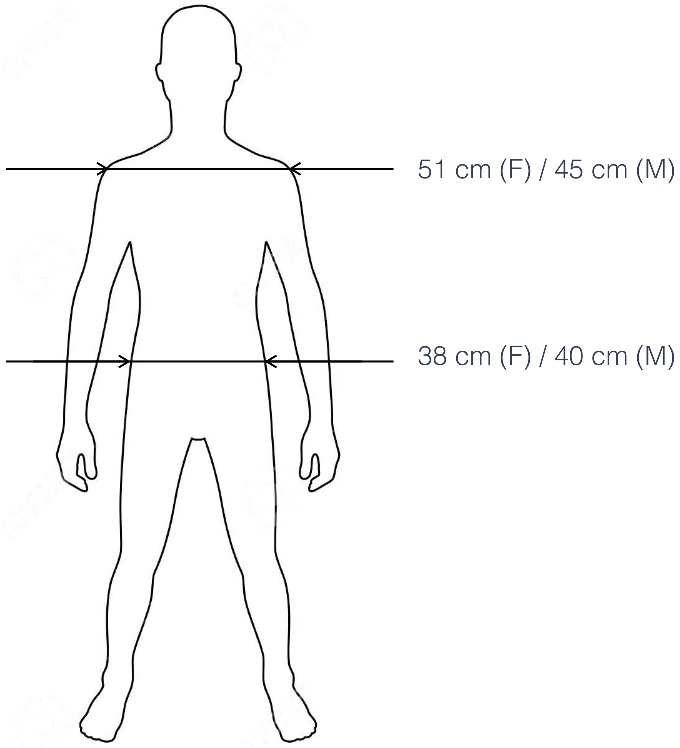
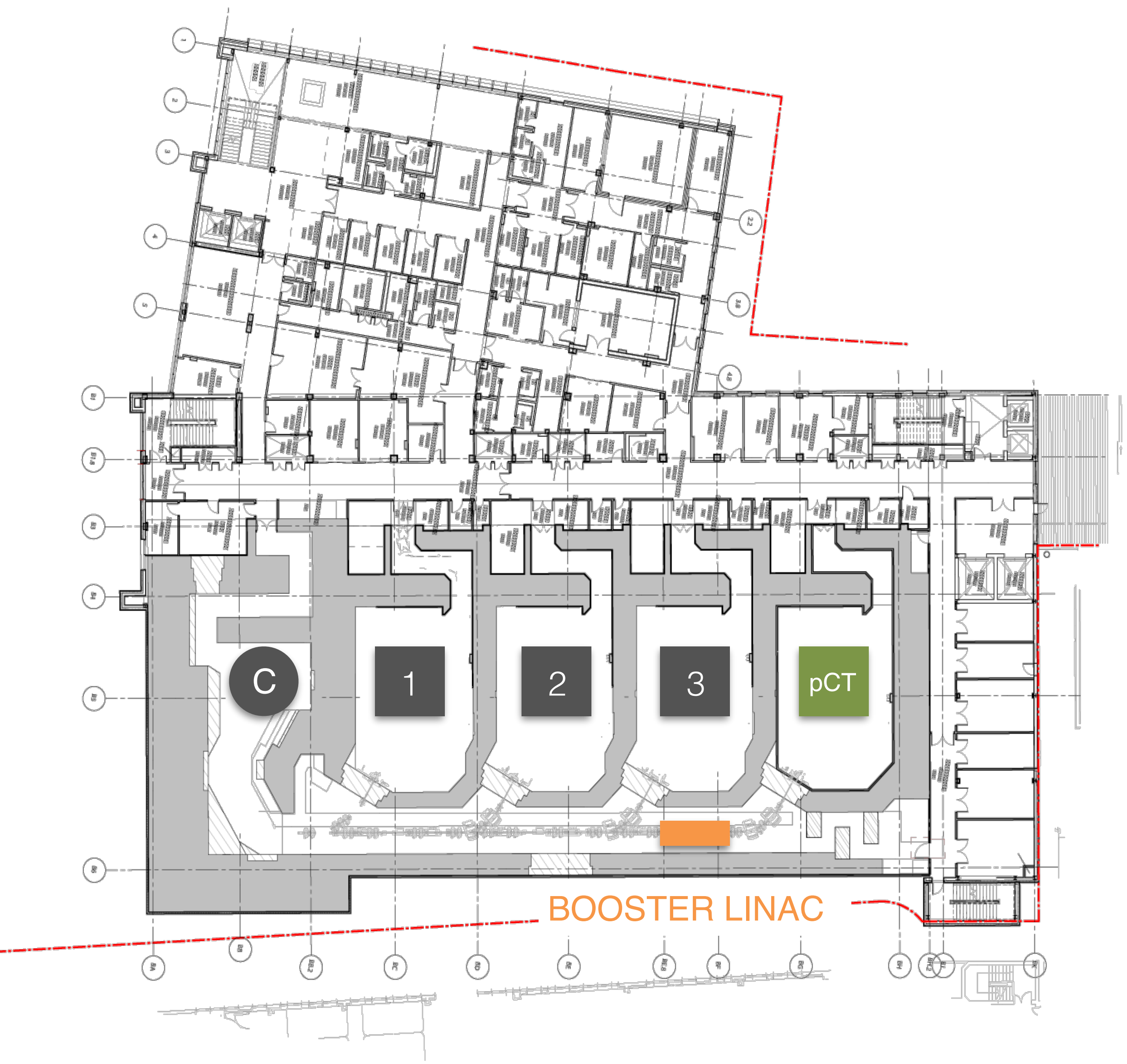


Protons ranges in A-150 tissue equivalent plastic:

250 MeV: ~33.5 cm

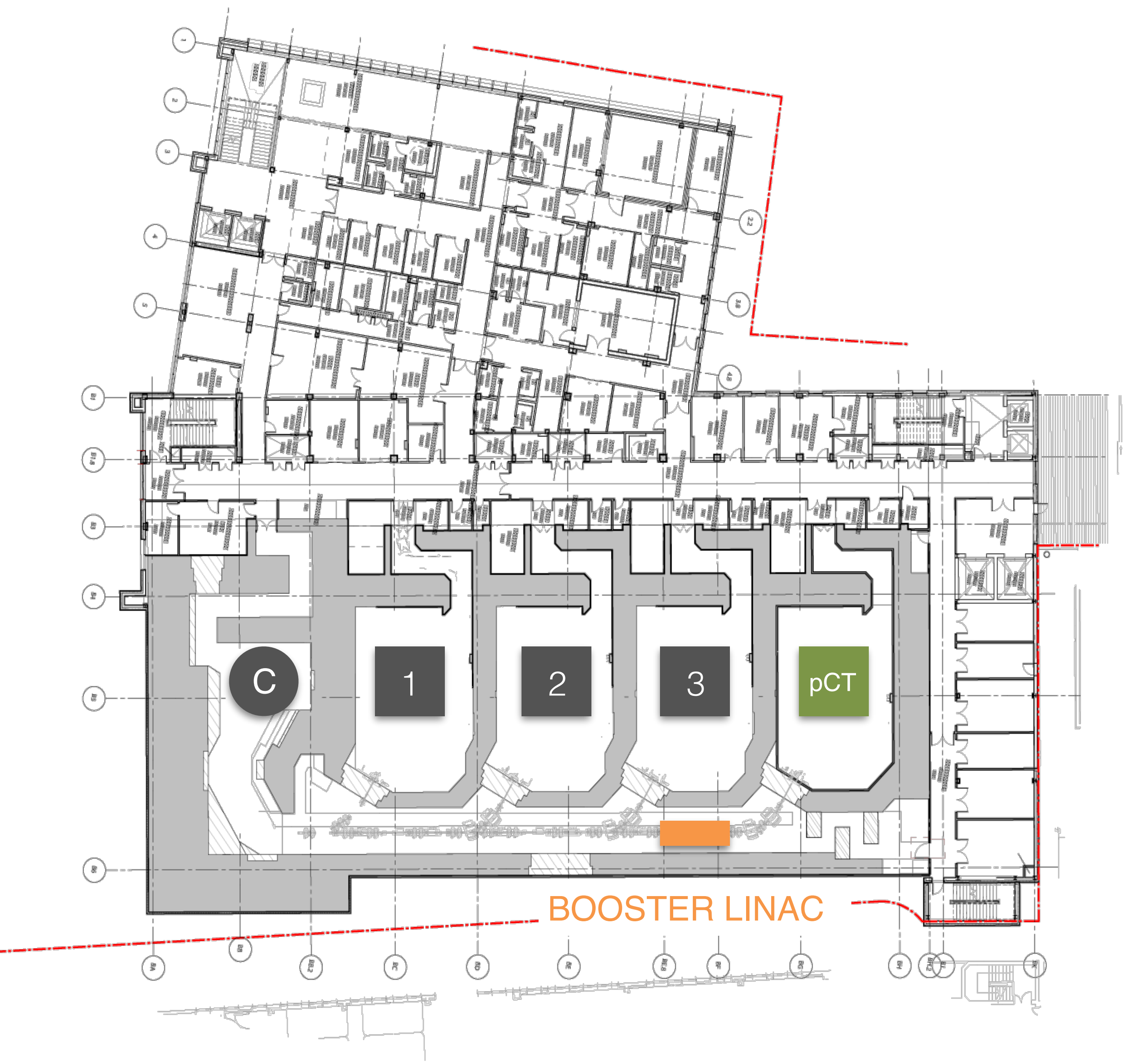
330 MeV: ~53.1 cm

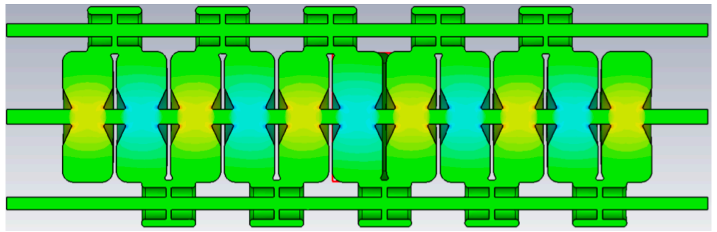
Cyclinac at the Christie Hospital



Proton Therapy Centre at the Christie Hospital in Manchester:

- Opened in 2018
- 80 patients treated
- 3 treatment rooms, 1 research room
- 254 MeV SC Varian cyclotron





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ProBE: Proton Boosting Extension for Imaging and Therapy:

- 250 MeV to 350 MeV
- Two 54 V/m S-band structures
- Less than 3 m long
- Before the research room
- Frequency mismatch between cyclotron/linac RF systems - large beam losses (more than 90%)
- Beam losses not problematic for pCT (low beam currents)

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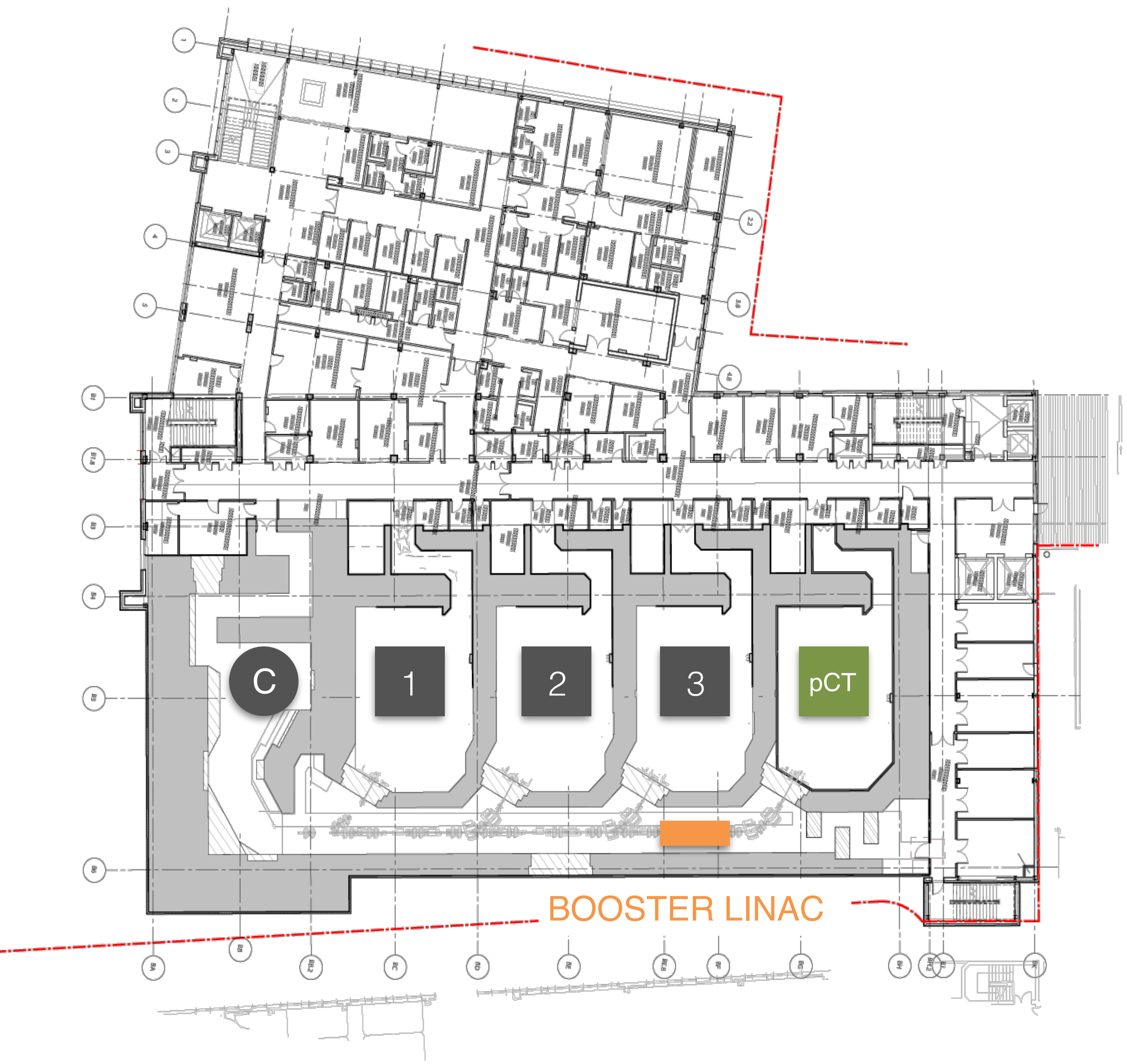

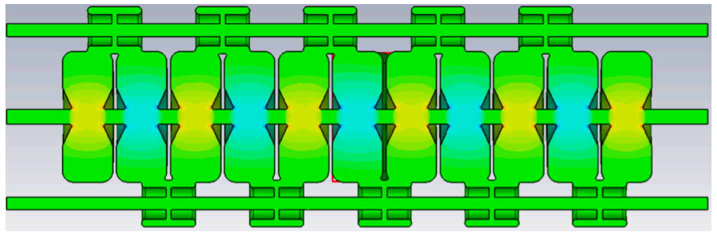

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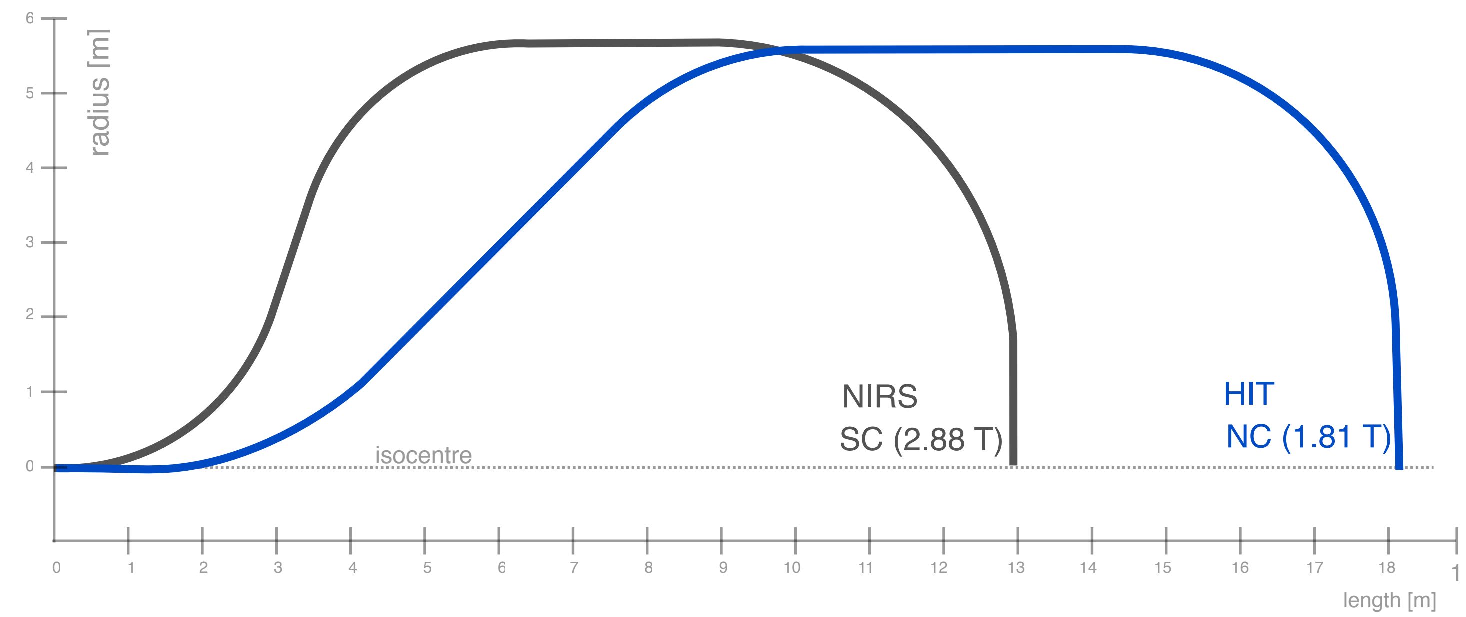
pCT gantry requirements:

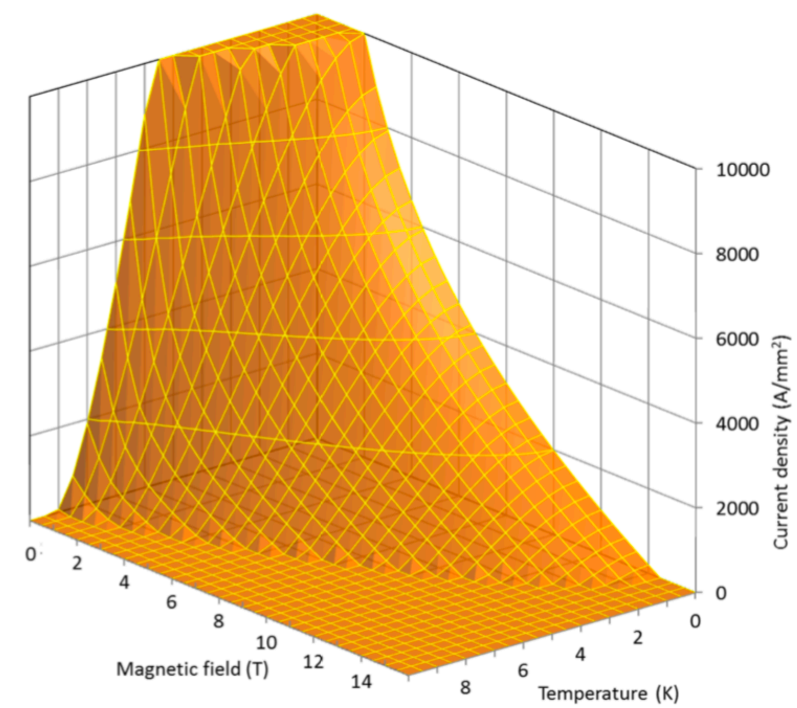
- 2.84 Tm beam rigidity for 330 MeV (2.43 Tm for 250 MeV)
- Source-to-axis distance: min. 2 m
- Downstream pencil beam scanning system
- Occupying the space of a conventional treatment gantry

Superconducting gantry

Advantages:

- **Weight reduction** (300t at NIRS vs 600t at HIT for carbon ions, 25t ProNova vs 200t PSI Gantry 2)
- **Size reduction** for carbon ion therapy / pCT
  (for protons mostly dictated by beam optics and SAD)
- **Footprint and cost reduction**
- **Lower power consumption** (in SC dipoles comes mainly from AC losses, but refrigeration power needed)
- **Combined function magnets**





Critical surface of NbTi (P. Ferracin, JUAS 2017)
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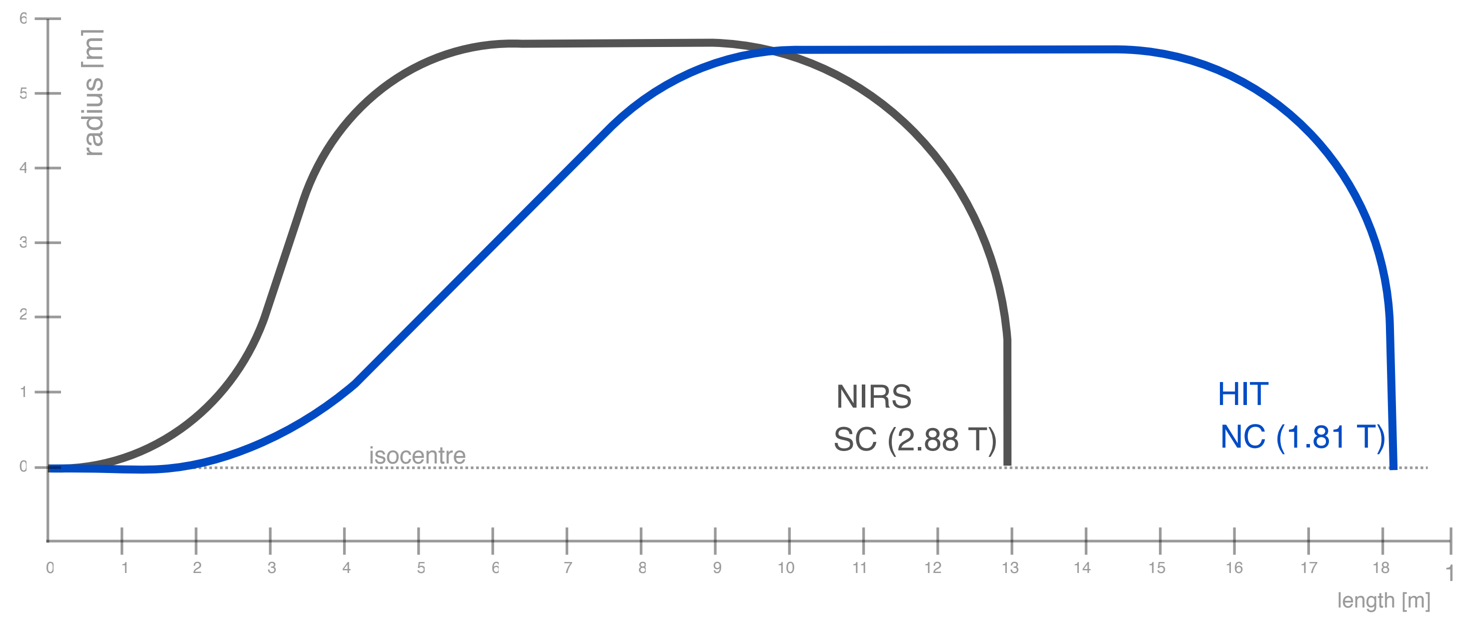
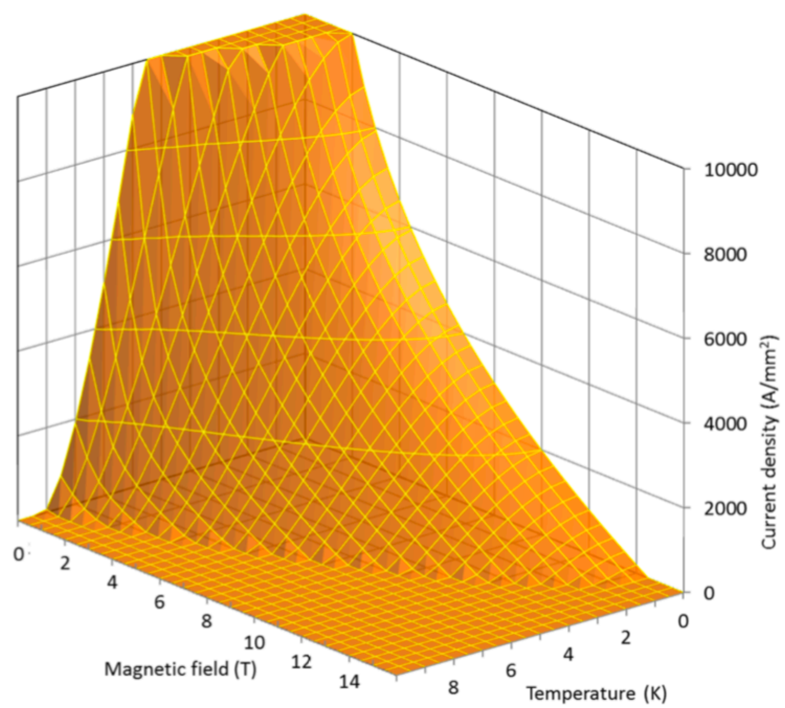


Challenges:

- **Strong magnetic fields** (stray fields, max. 0.5 mT at isocentre)
- **Slower ramping** (high energy acceptance gantries such - fixed field during treatment/imaging)
- **Cryogenics in a rotating system** (cryogen-free cryocoolers)
- **Quenches** (proton therapy facilities require high machine availability, typically more than 95%)



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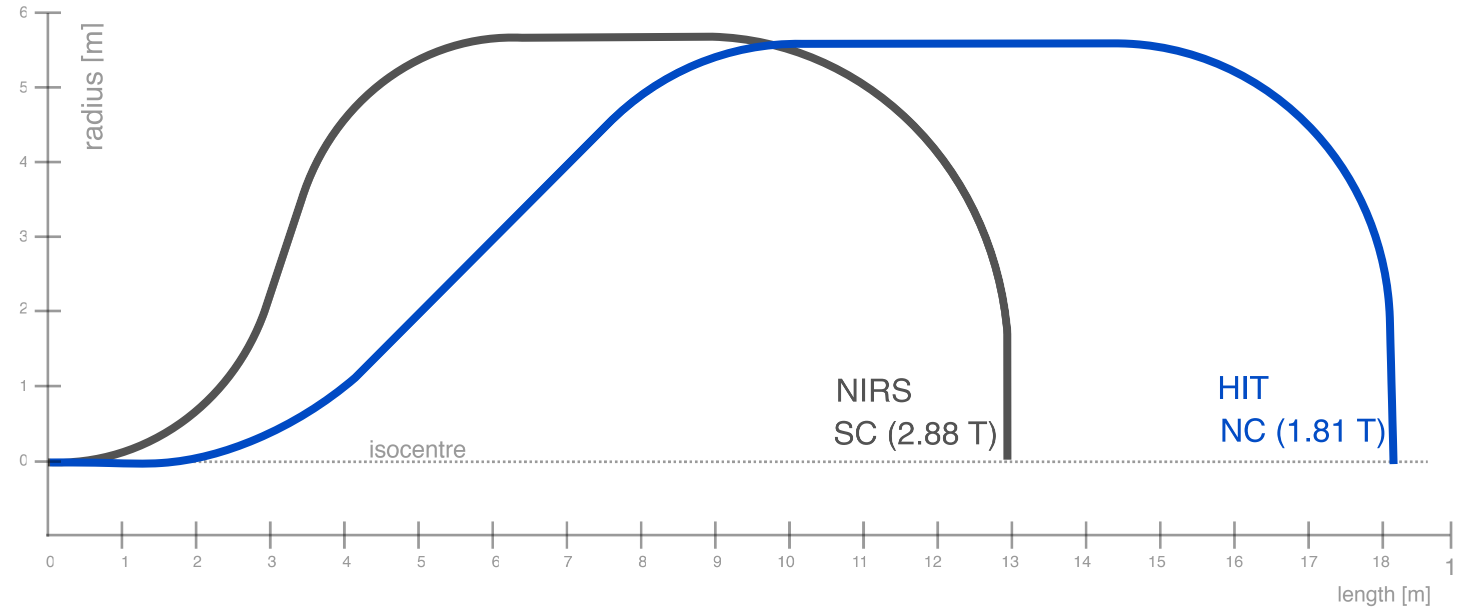

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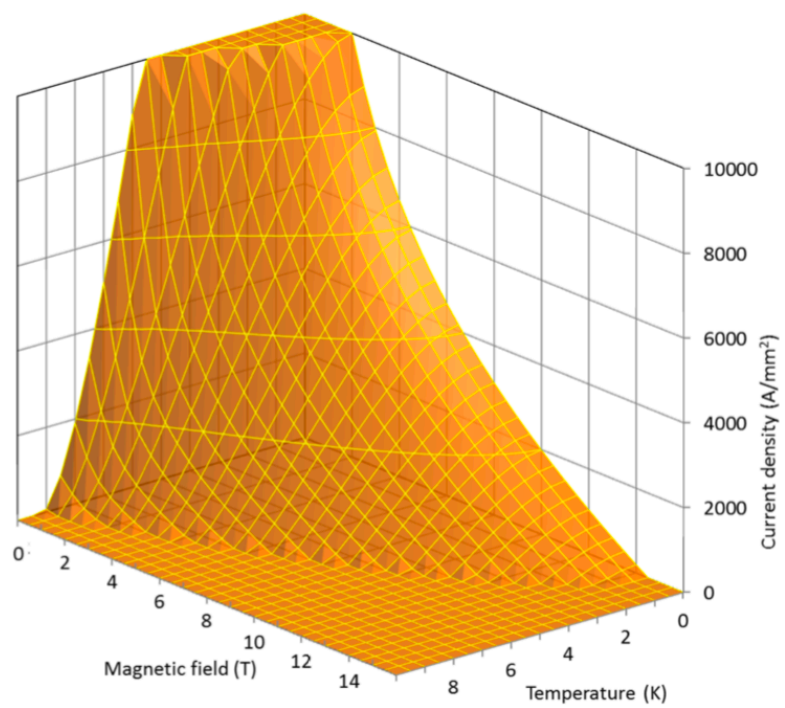
Example in proton therapy: ProNova Solutions SC360

- 250 MeV protons
- Radius: more than 4 m, length: less than 5 m
- No considerable size reduction (235 m^3 compared to 250 m^3 Gantry 2 at PSI)
- Max. magnetic field 4 T in superconducting dipoles



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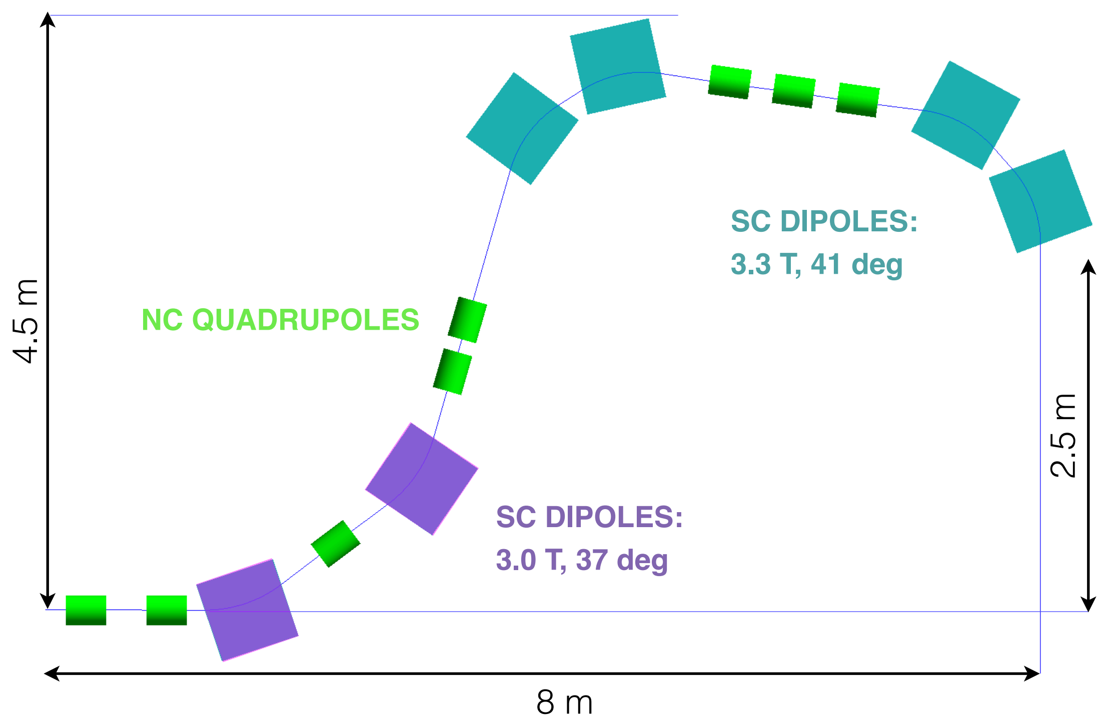
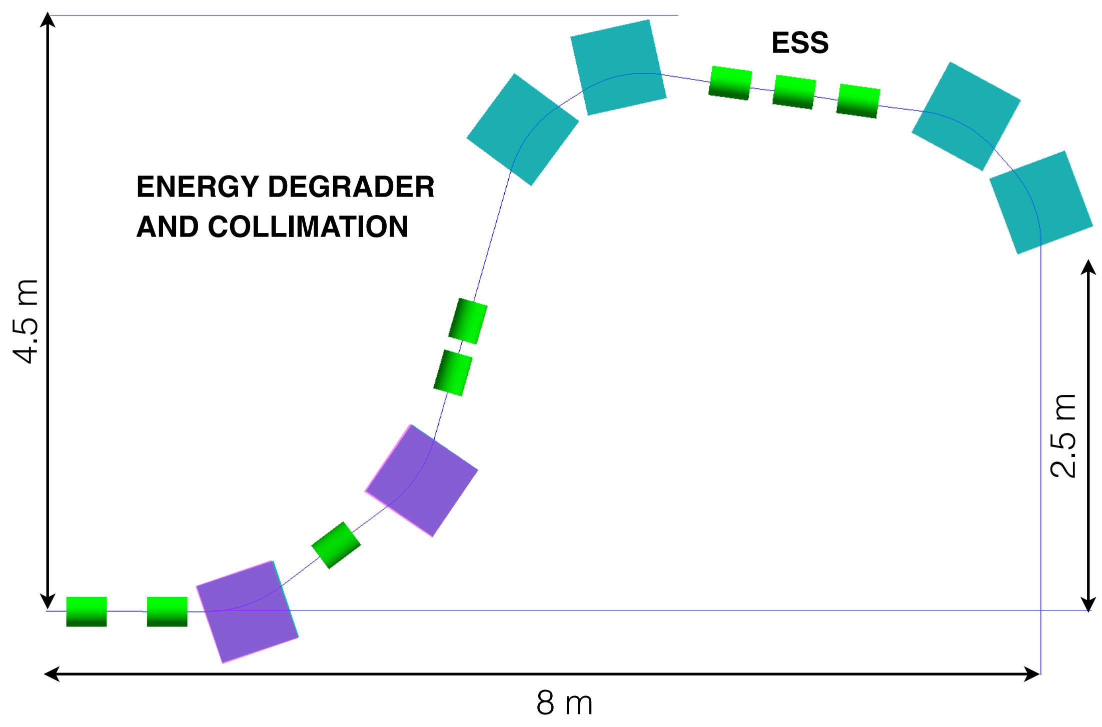
Beam optics design

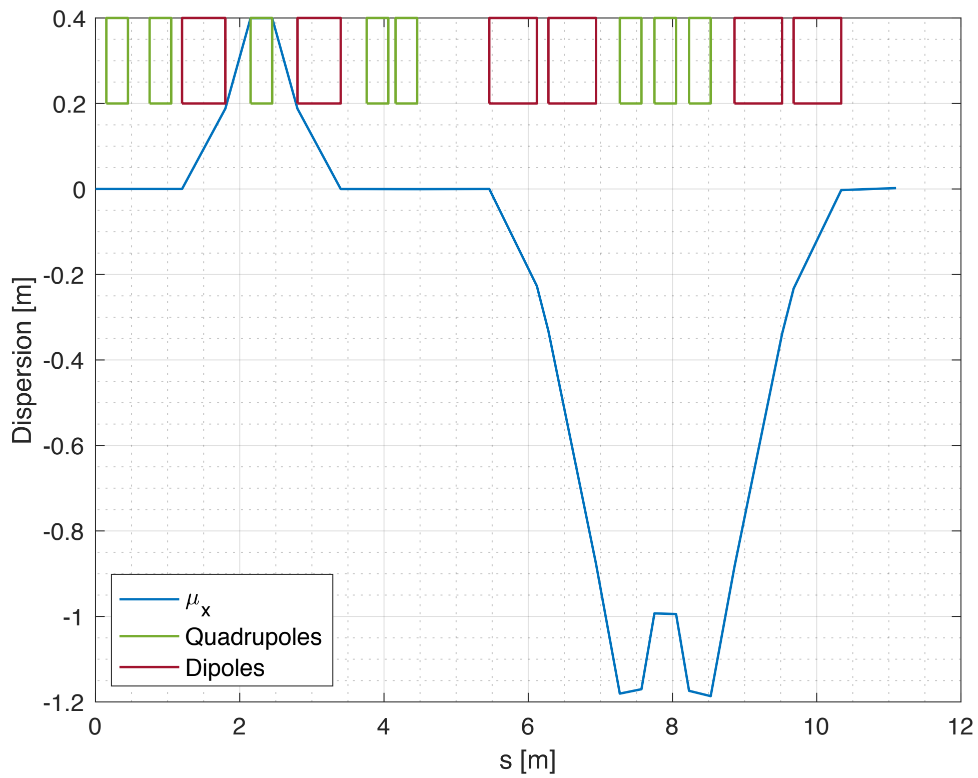


Basic gantry parameters

Length of dipole Type A	0.6 m
Integrated field over physical length (A)	3.0 T
Length of dipole Type B	0.66 m
Integrated field over physical length (B)	3.3 T
Maximum quadrupole coefficient	27 T/m
Gantry length	8 m
Gantry radius	4.5 m
Source-to-axis distance	> 2 m

Beam optics design

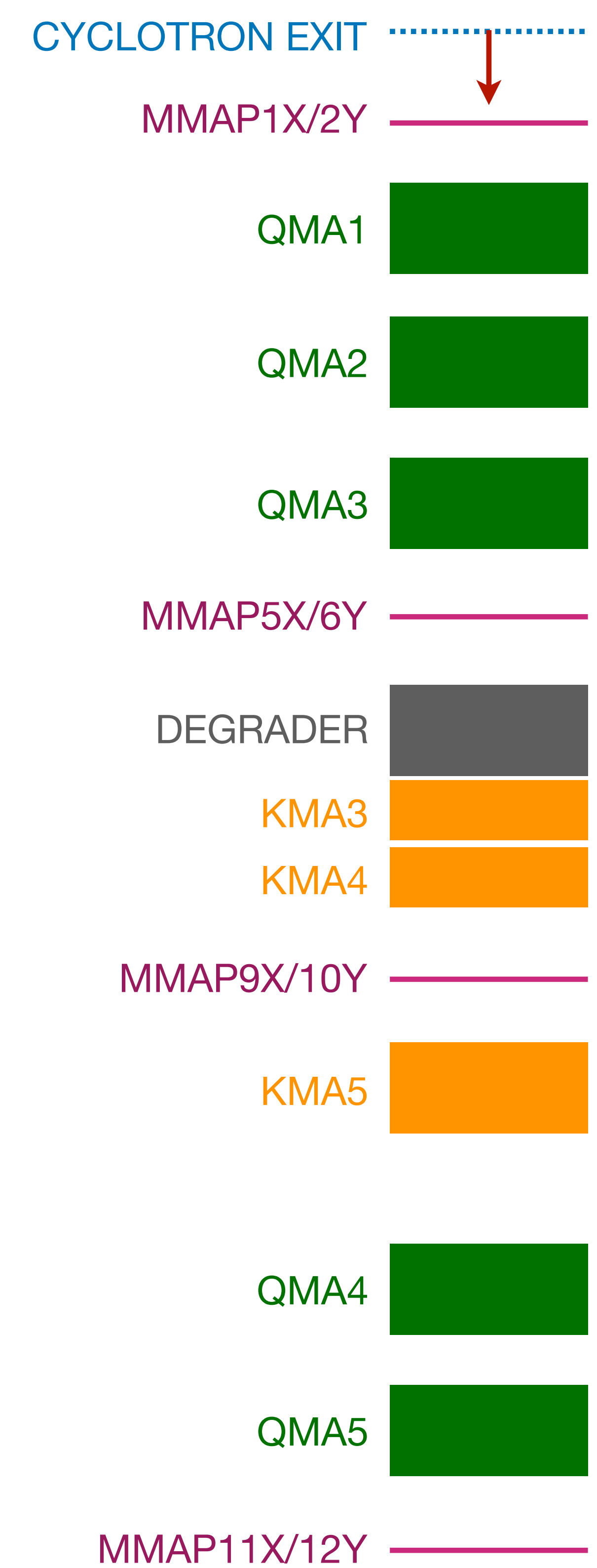




pCT gantry:

- Double achromat design
- Local and global achromaticity
- Beam degrader and collimation system integration

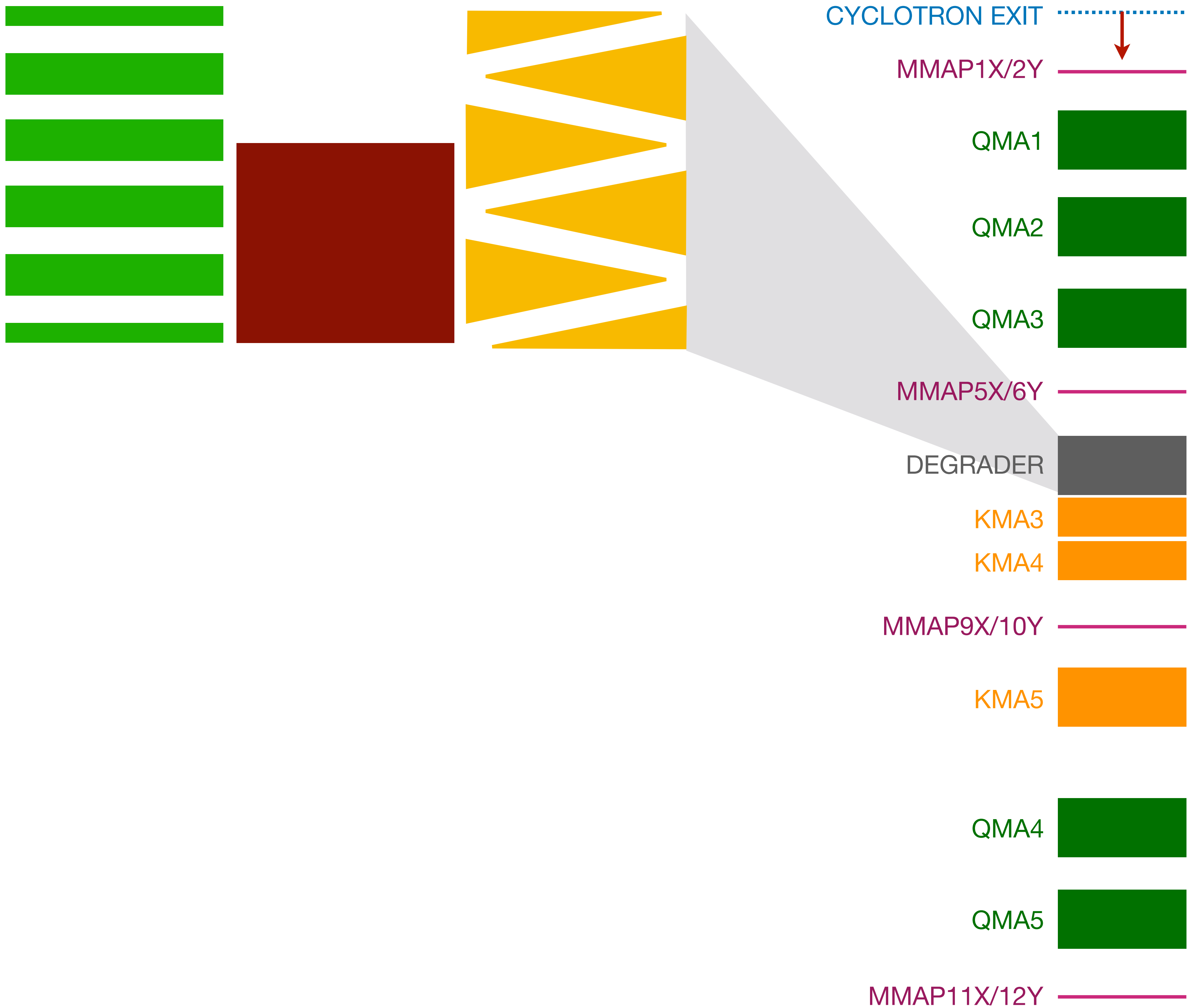
Energy degrader



Energy degrader

Degrader properties

Material	Graphite
Density	1.87 g/cm^3
Ionisation potential	81 eV
A	12.02
Z	6
Full wedge angle	23 deg



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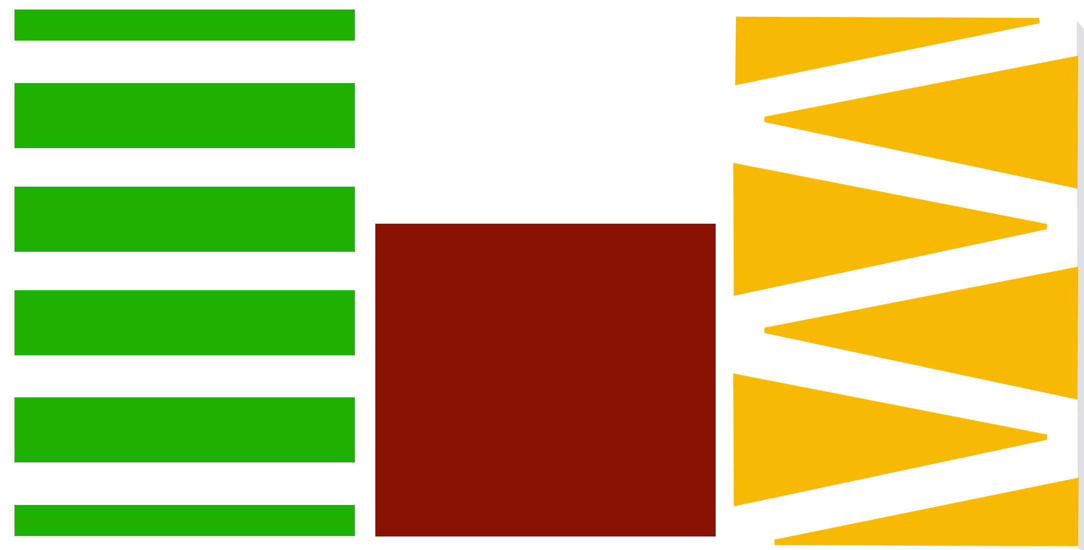

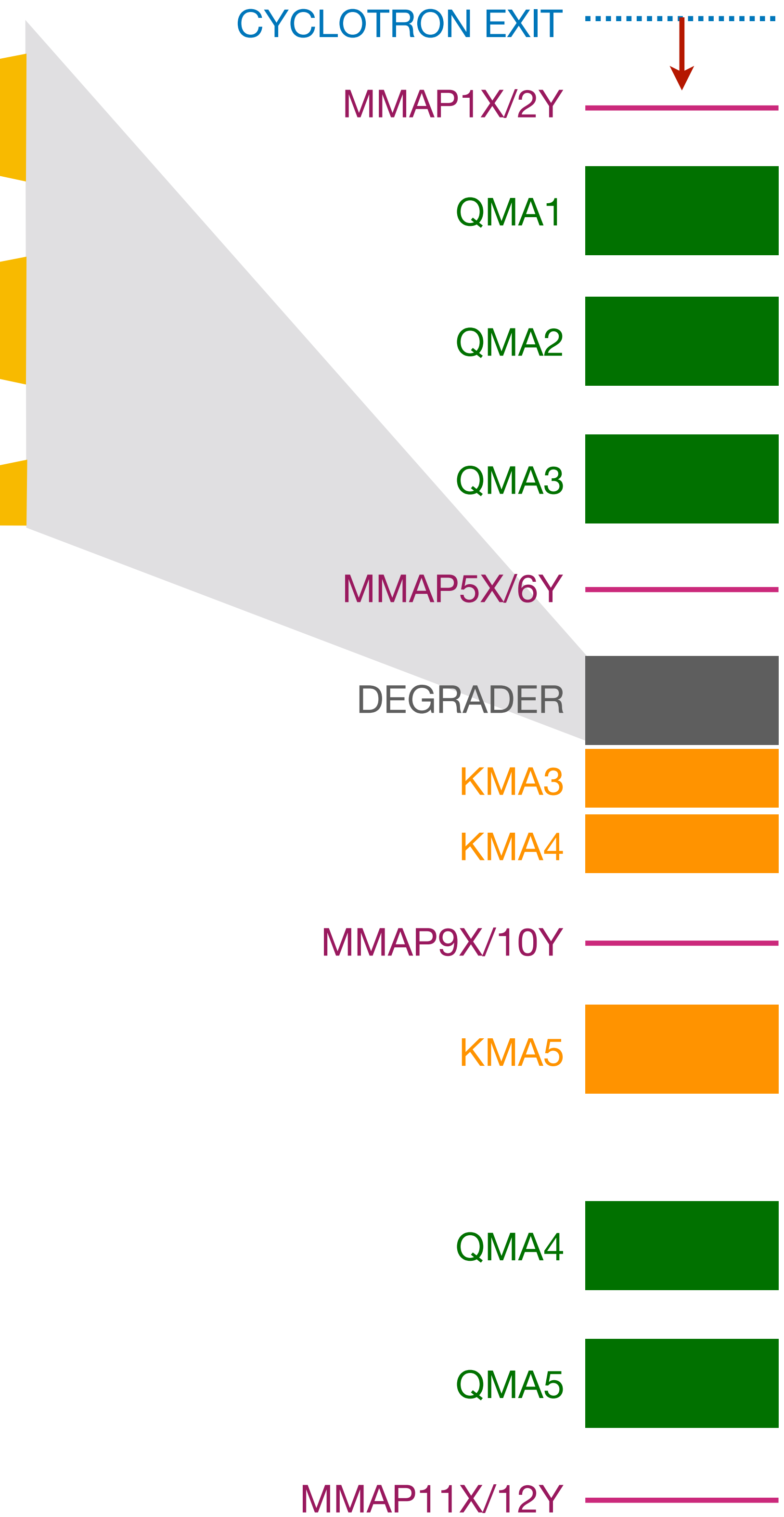

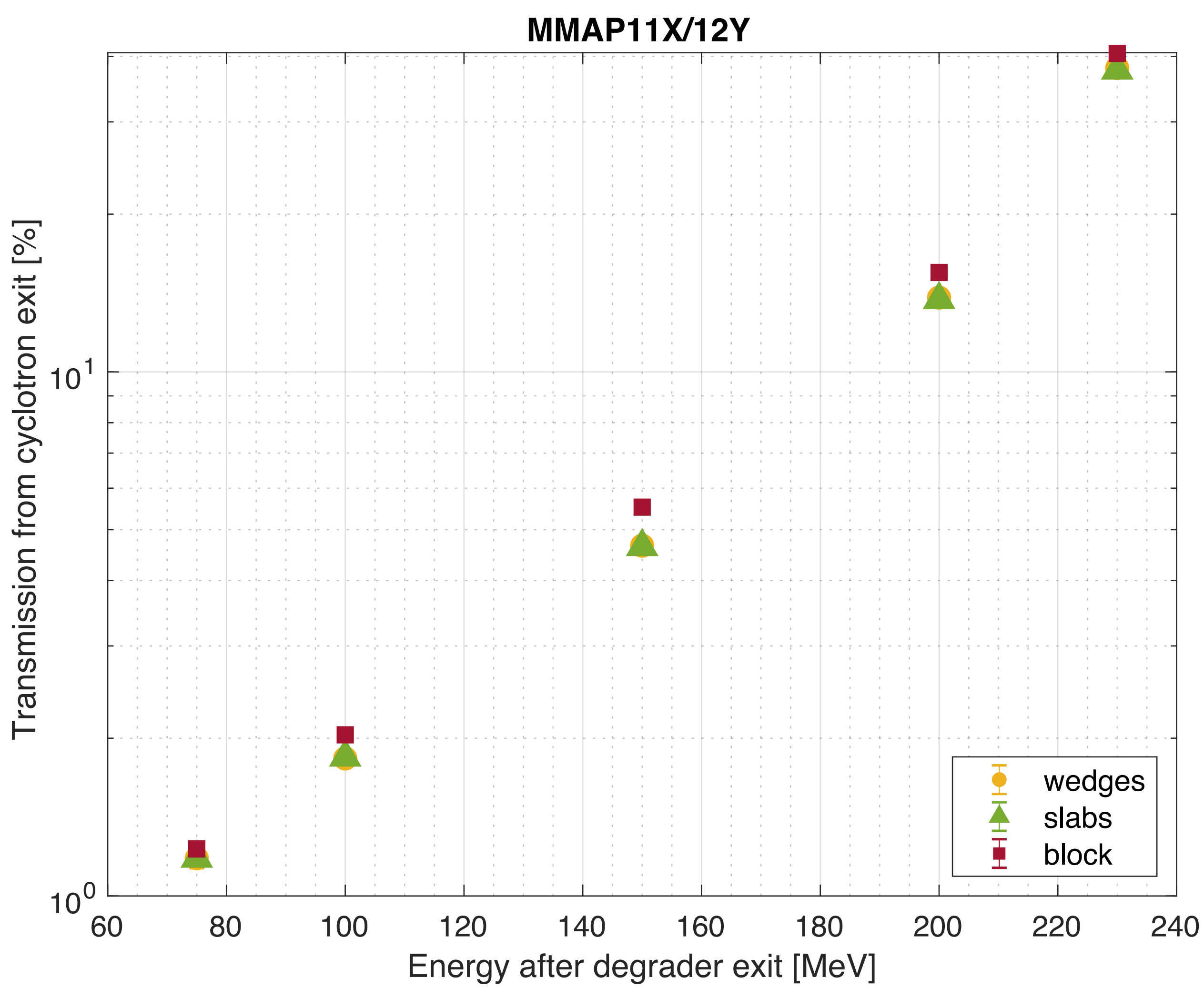

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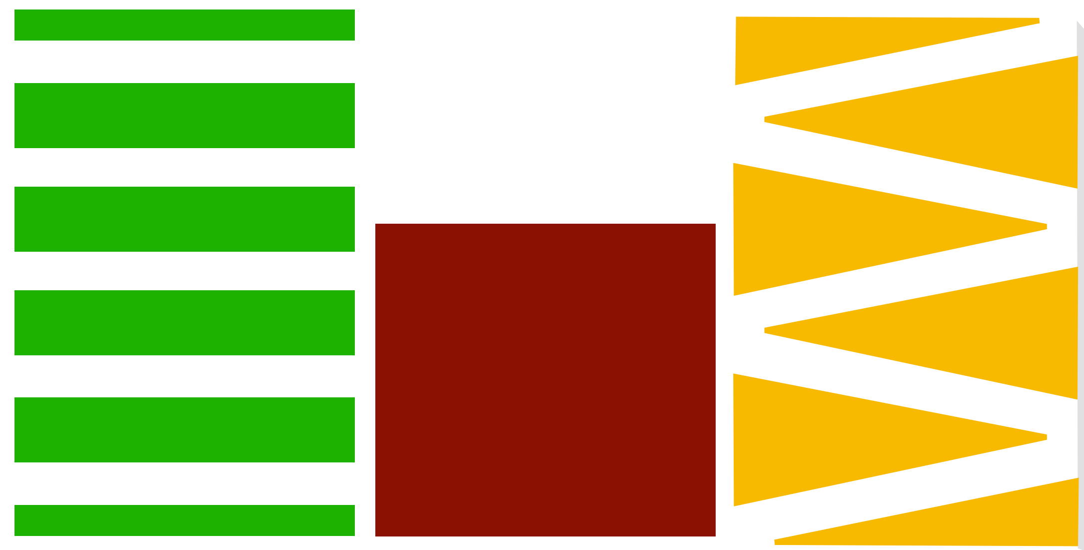

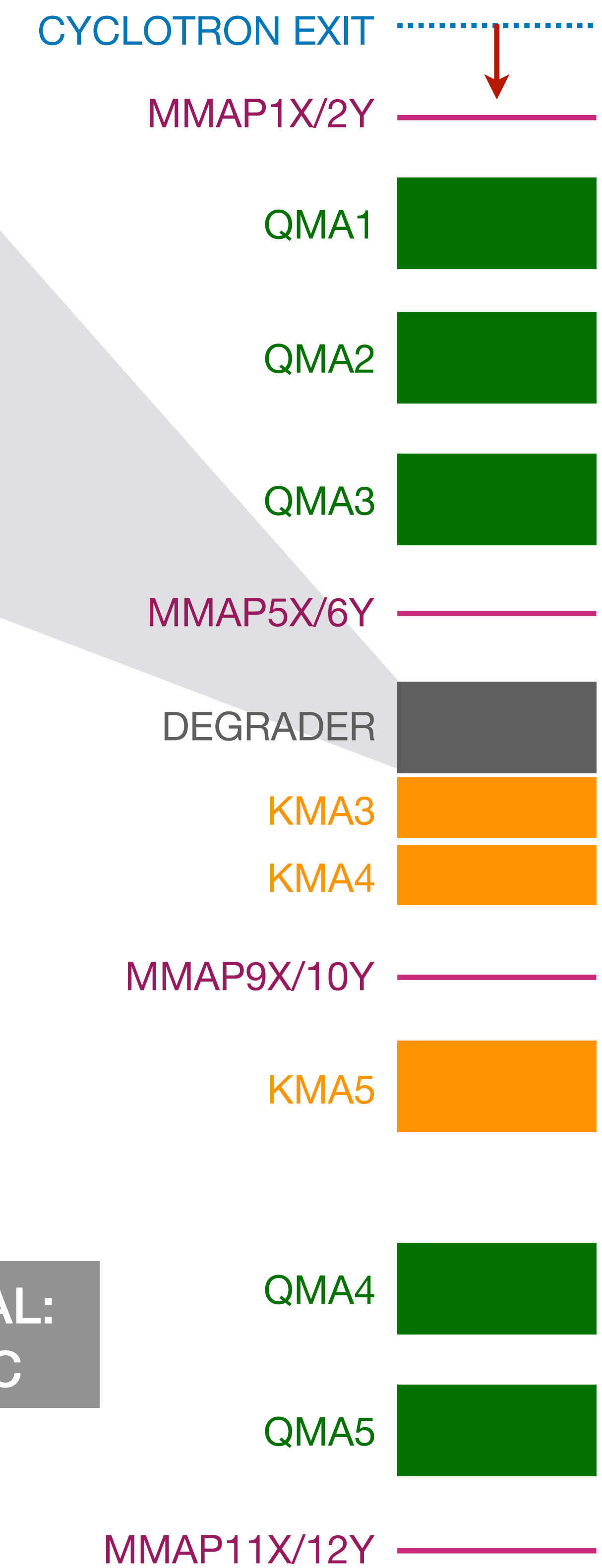

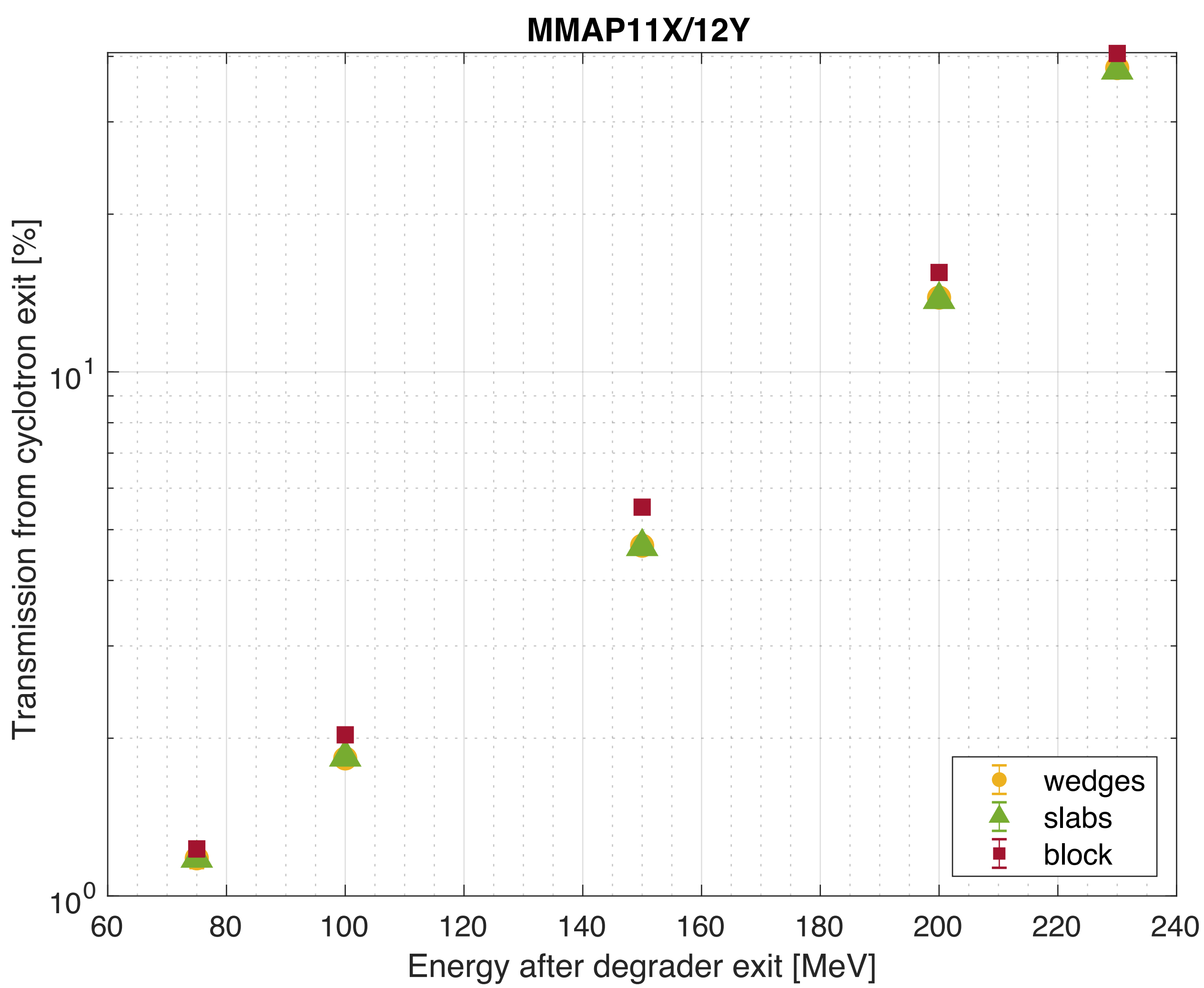

ALTERNATIVE MATERIAL: BORON CARBIDE B4C

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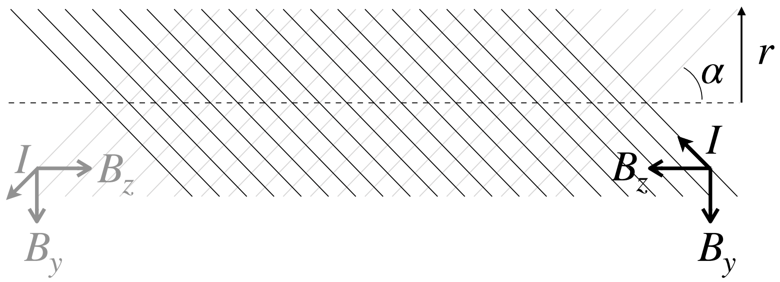
PAUL SCHERRER INSTITUT PSI

Canted cosine theta magnet

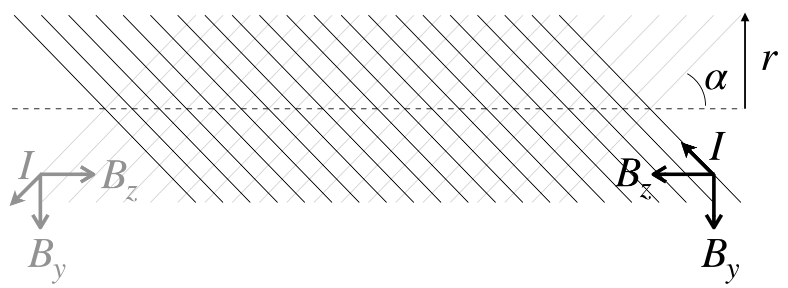


Conductor layers are wound such that:

- Transverse field components sum
- Solenoidal field components cancel

S. Caspi, A 16T Canted-Cosine-Theta (CCT) An option for the FCC, 2015

Canted cosine theta magnet



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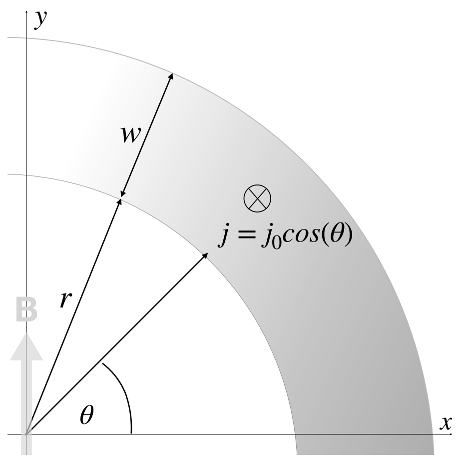

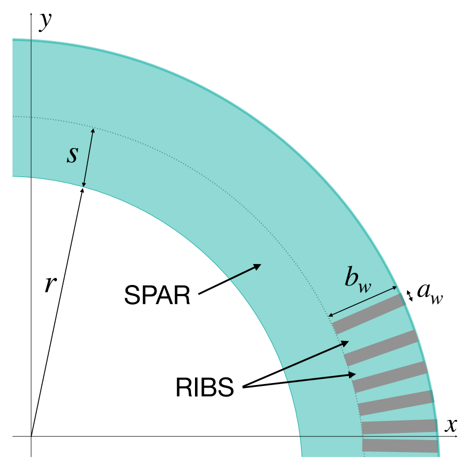

CCT cross section:

- Each conductor sits in its own channel;
- Channels separated by the ribs (transferring Lorentz forces to the spar)

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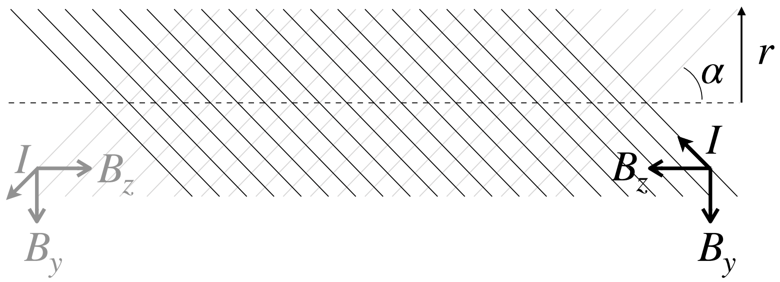
Canted cosine theta magnet



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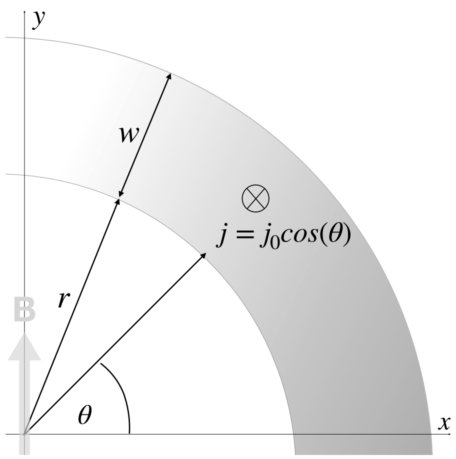

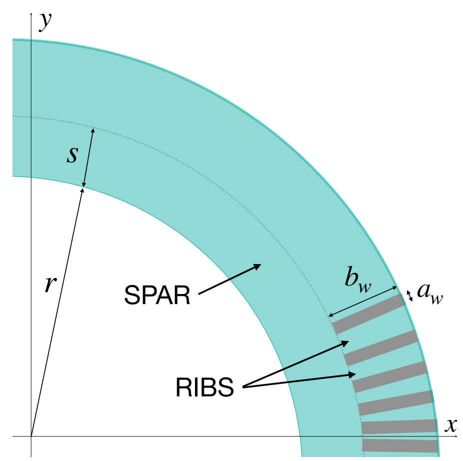

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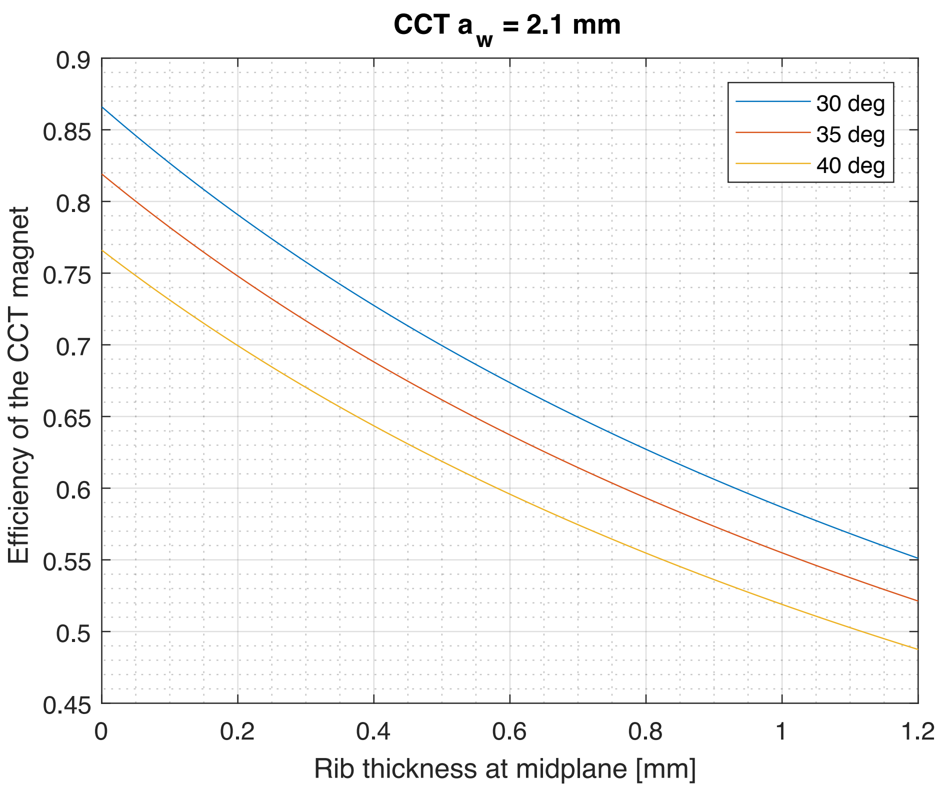
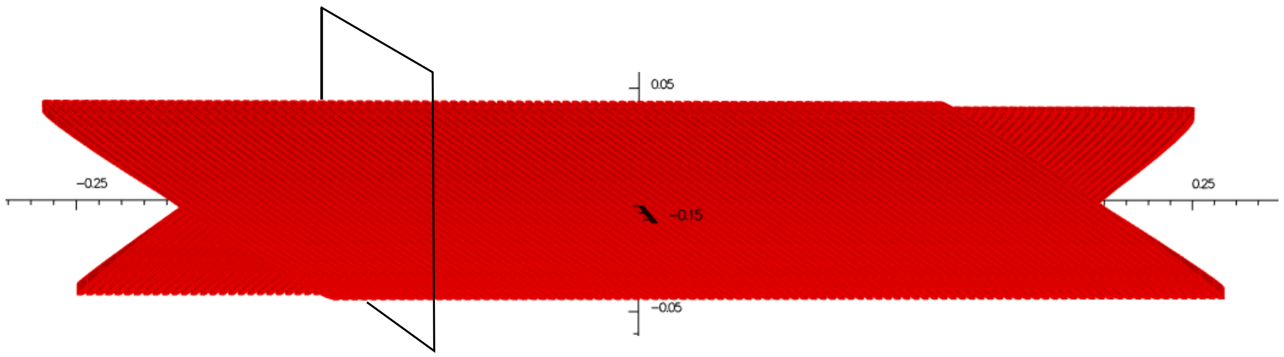
Advantages of a CCT magnet:

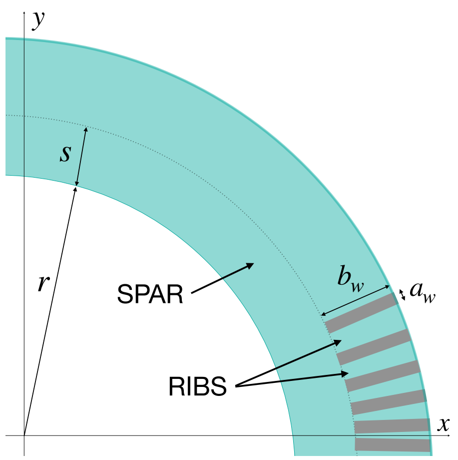
- No or little pre-stress required (no coil movement)
- Any harmonics or superposition of harmonics (combined-function)
- Lower number of components compared to i.e. sector magnet
- Lower cost

Design parameters:

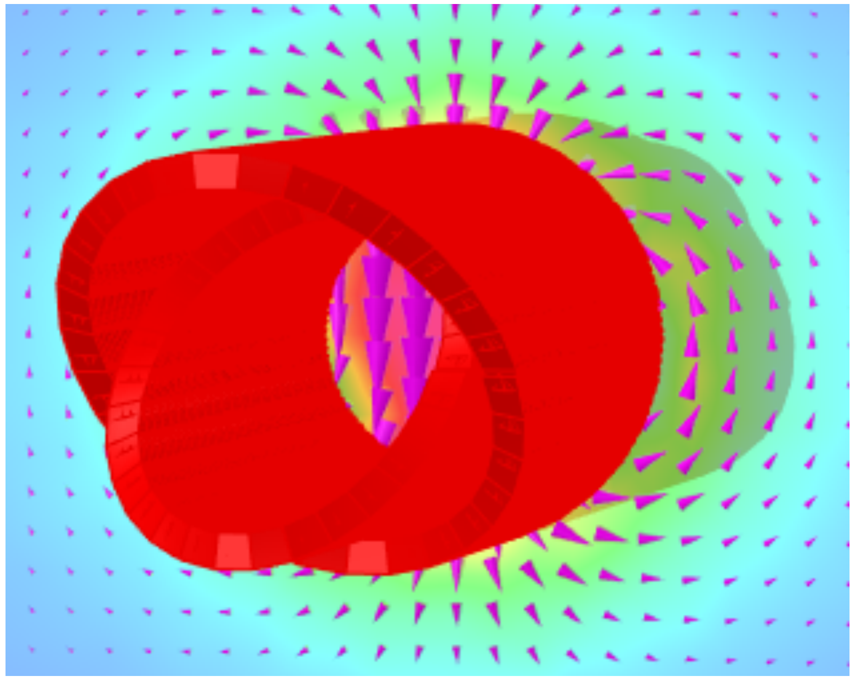
- Bore radius
- Physical length
- Magnetic field
- Rib thickness in the midplane
- Wire: material, dimensions, number of wires in the channel
- Number of layers
- Current density
- Skew angle







CCT dipole main coils

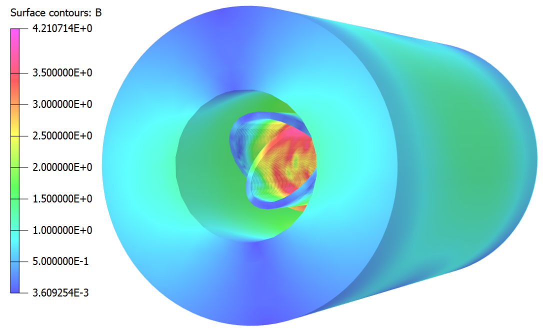


Dipole parameters

Tilt angle of the coil	31.8 deg
Length of the magnet	0.52 m
Midplane rib thickness	0.3 mm
Wire material	NbTi
Wire non-Cu/Cu ratio	0.51
Wire diameter	0.825 mm

CCT dipole shielding

PASSIVE SHIELDING



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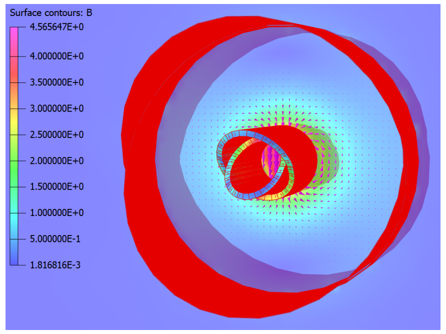

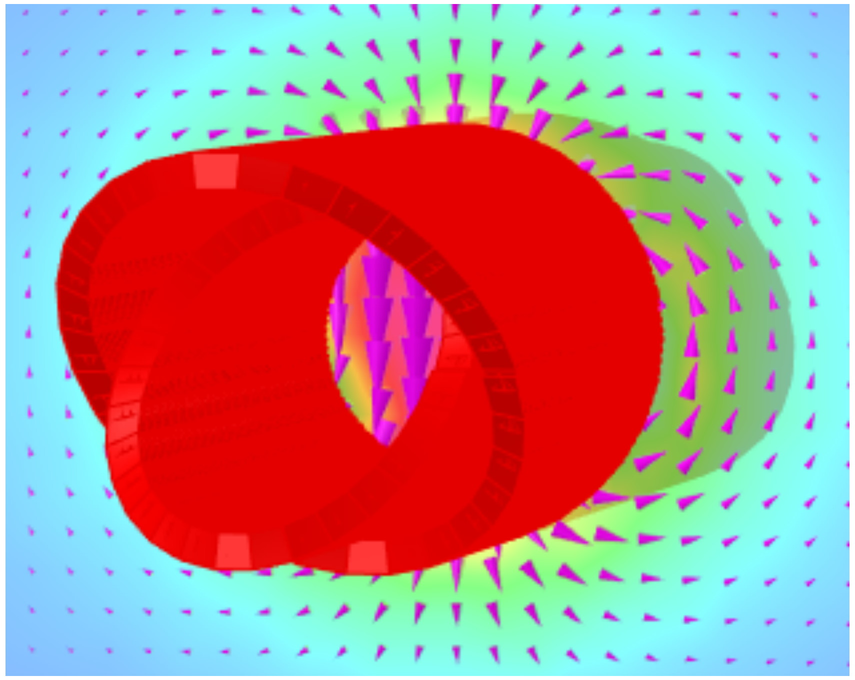

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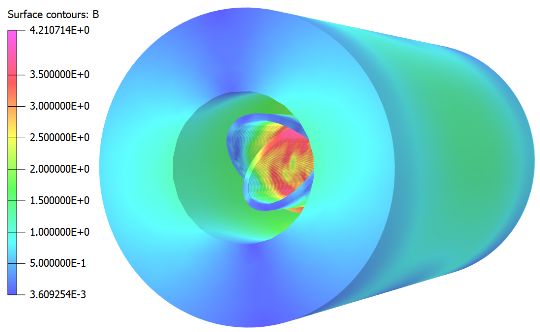

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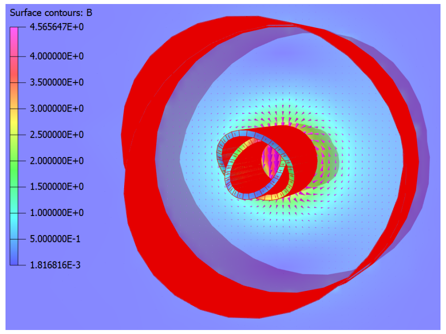

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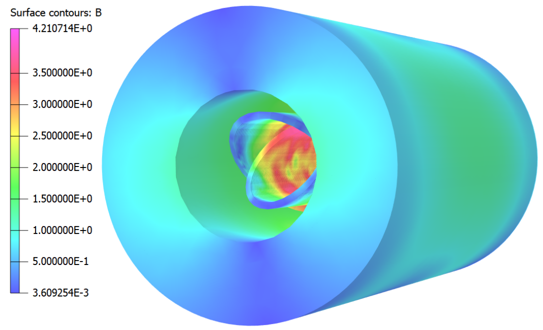

Passive shielding dipole parameters

Eng. current [A]	268 A
Peak field in the conductor	4.2 T
Number of wires	8x2
Yoke inner radius	74 mm
Yoke weight	270 kg
Total length of SC strand	1.14 km

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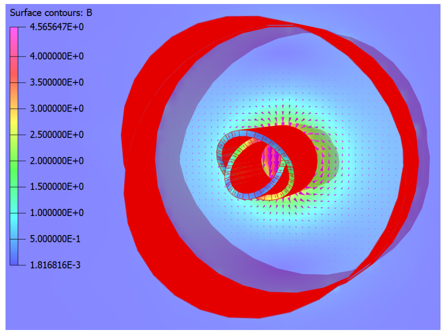

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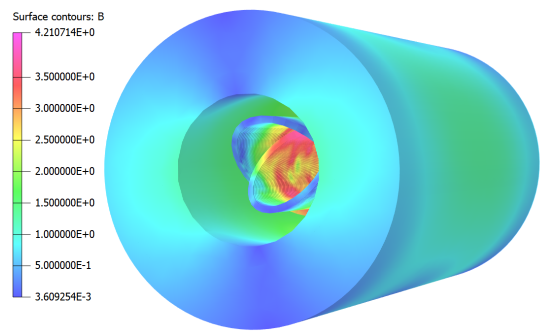

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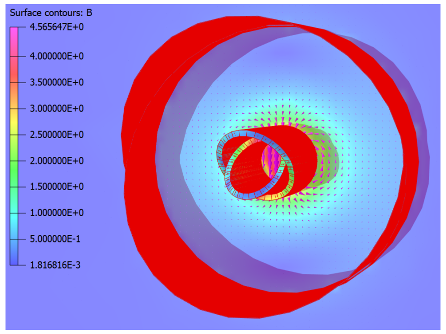
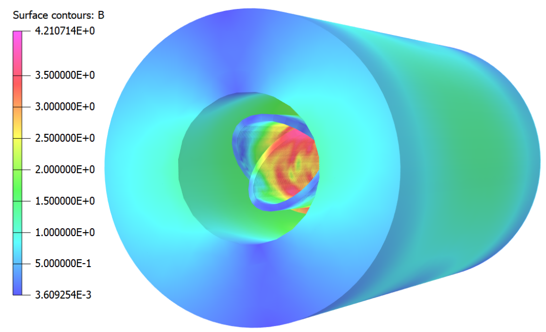


Active shielding dipole parameters

Eng. current [A]	283 A
Peak field in the conductor	5.0 T
Number of wires	11x2
Inner radius of the sh. coil	220 mm
Tilt angle of sh. coil	62.2 deg
Total length of SC strand	2.74 km

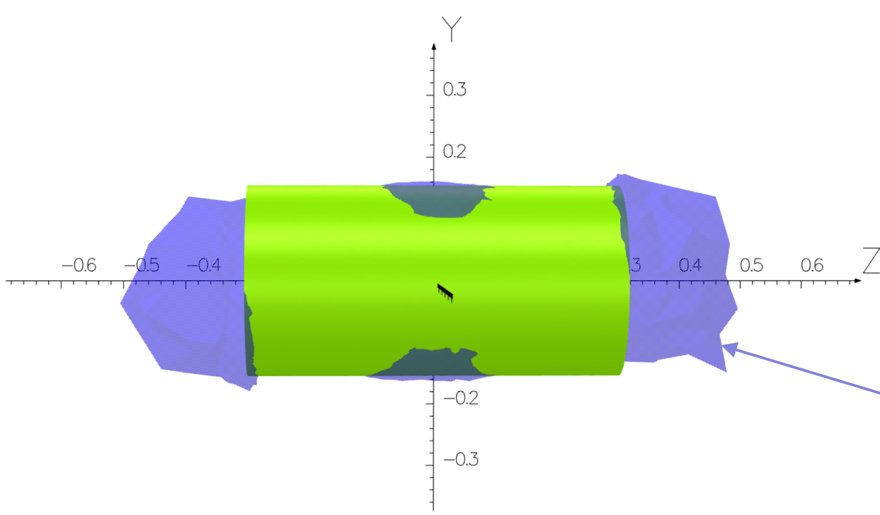
CCT dipole shielding

PASSIVE SHIELDING



Passive shielding dipole parameters

Eng. current [A]	268 A
Peak field in the conductor	4.2 T
Number of wires	8x2
Yoke inner radius	74 mm
Yoke weight	270 kg
Total length of SC strand	1.14 km



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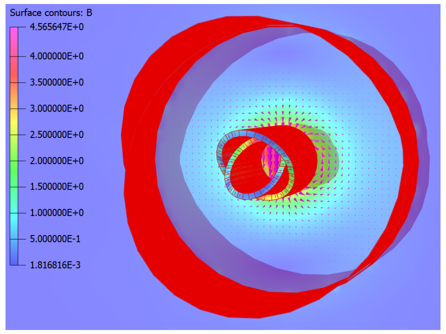

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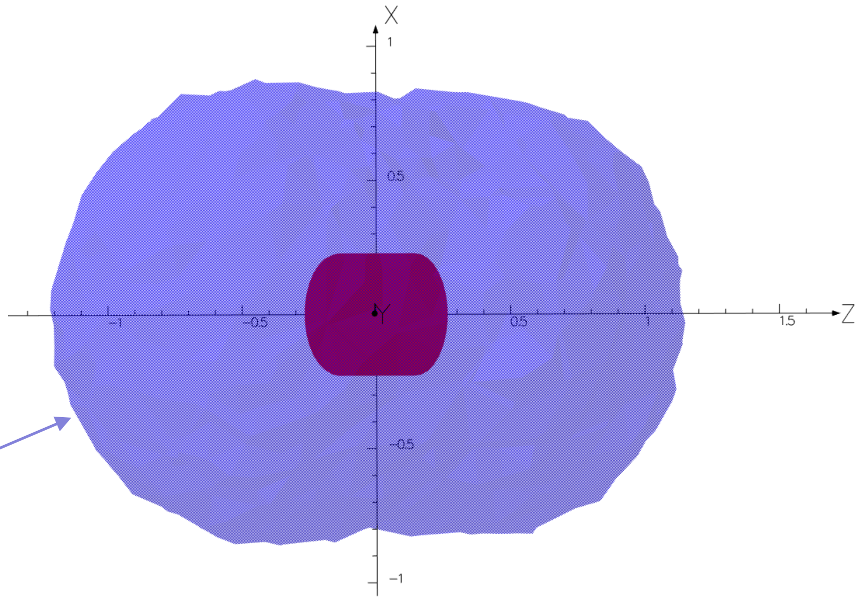

0.5 mT iso-valued surface

CCT dipole shielding

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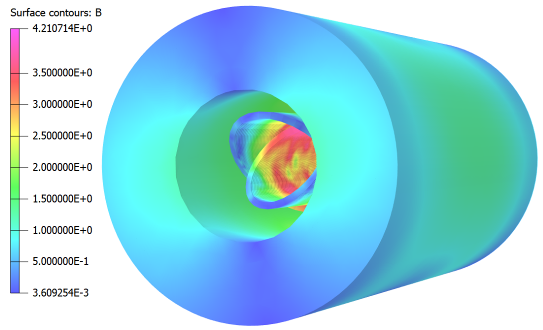

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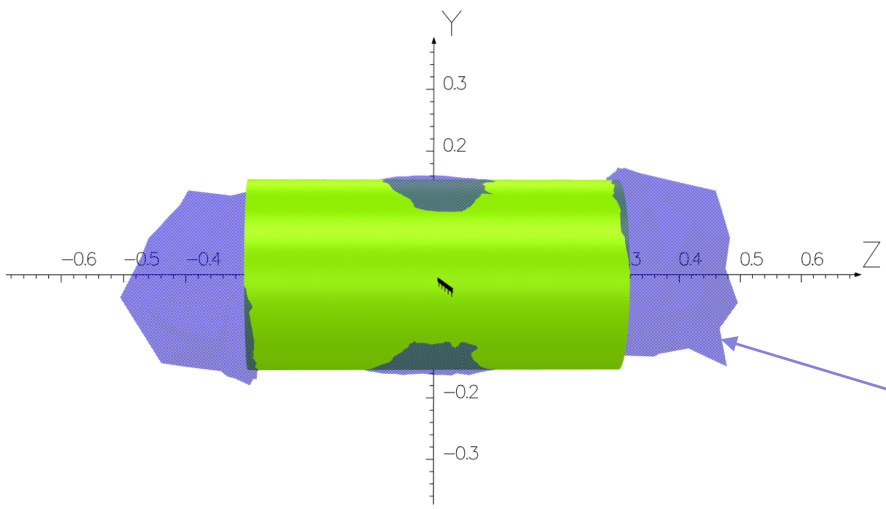
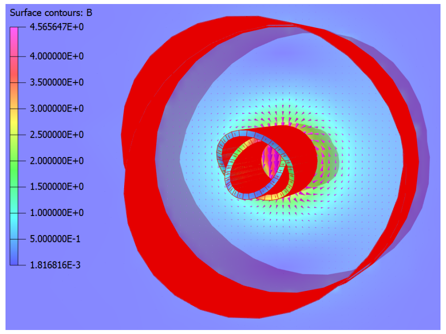


- Heavier
- More efficient stray fields shielding

ACTIVE SHIELDING



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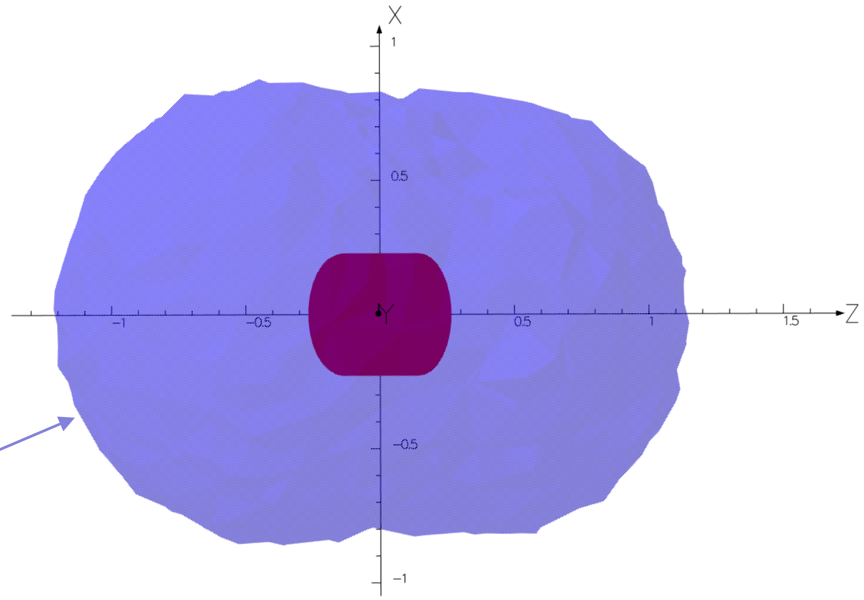

- Larger cryostat, larger cold mass
- More conductor
- Worse stray fields cancellation

Summary

Conclusions:

- Compact gantry capable of transporting protons for therapy and imaging
- Superconducting NbTi CCT dipoles with passive shielding (iron yoke)
- Single block boron carbide energy degrader for higher particle transmission

Next steps:

- Energy degrader integration into the gantry
- Collimation system
- Lower dispersion - larger energy acceptance of the system
- Quadrupole gradient incorporation to the final bending section dipoles

The Cockcroft Institute of Accelerator Science and Technology

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Thank you!

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