Superconducting magnets for medical accelerators

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BCMT
BERKELEY CENTER FOR MAGNET TECHNOLOGY

Acknowledgements

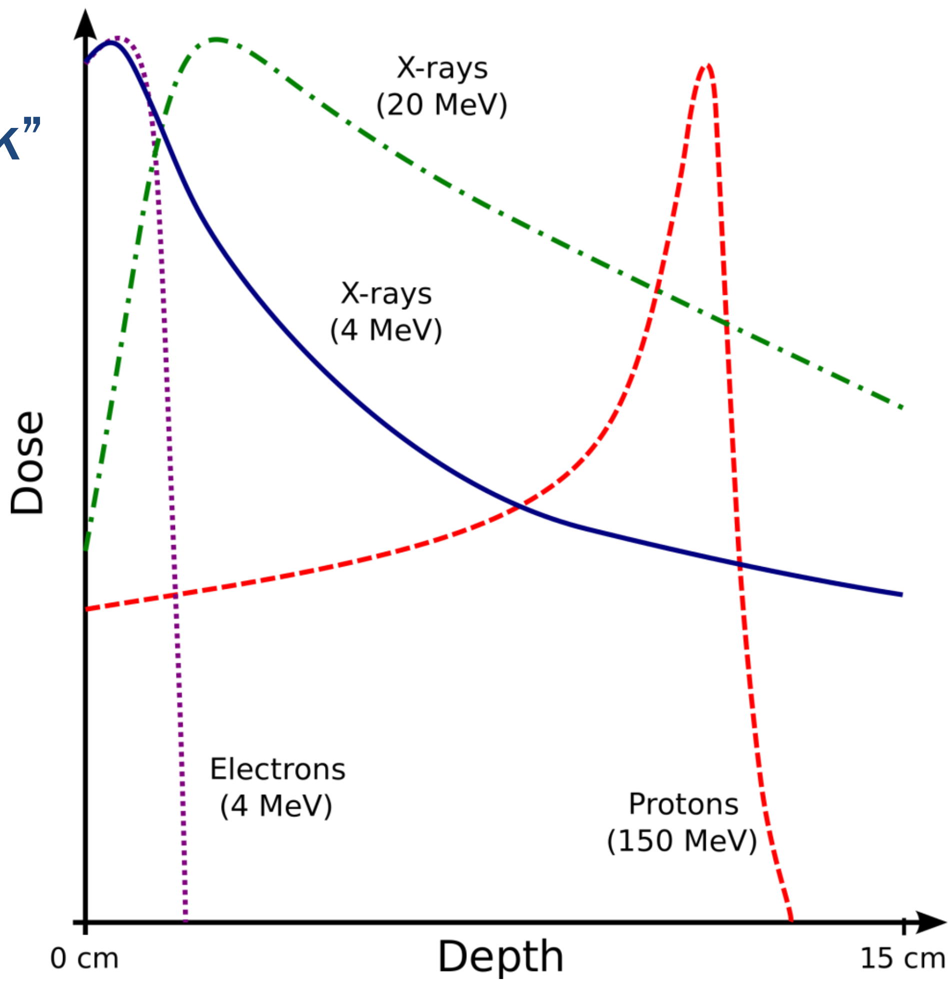
- This presentation was pulled together from a wide range of sources, including (but not limited to)…
  - ”Current Status and Future Vision: Technology”, Sandro Rossi, Ion Beam Therapy Workshop Bethesda, 9 January 2013
  - H. Owen et al., International Journal of Modern Physics A Vol. 29, No. 14 (2014)
  - J. Minervini et al., Beam Dynamics Meets Magnets – II, Dec. 1-4, 2014
  - “Cyclotrons: Magnetic Design and Beam Dynamics”, W. Kleeven and S. Zaremba, Ion Beam Applications, Louvain-La-Neuve, Belgium
  - W. Wan, L. Brouwer, S. Caspi, S. O. Prestemon, A. Gerbershagen, J. M. Schippers, and D. Robin, “Alternating-gradient canted cosine theta superconducting magnets for future compact proton gantries,” Physical Review Special Topics-Accelerators and Beams, vol. 18, no. 10, p. 103501, Oct. 2015.
  - A. Gerbershagen, D. Meer, J. M. Schippers, and M. Seidel, “A novel beam optics concept in a particle therapy gantry utilizing the advantages of superconducting magnets,” Zeitschrift für Medizinische Physik, Apr. 2016.

Outline

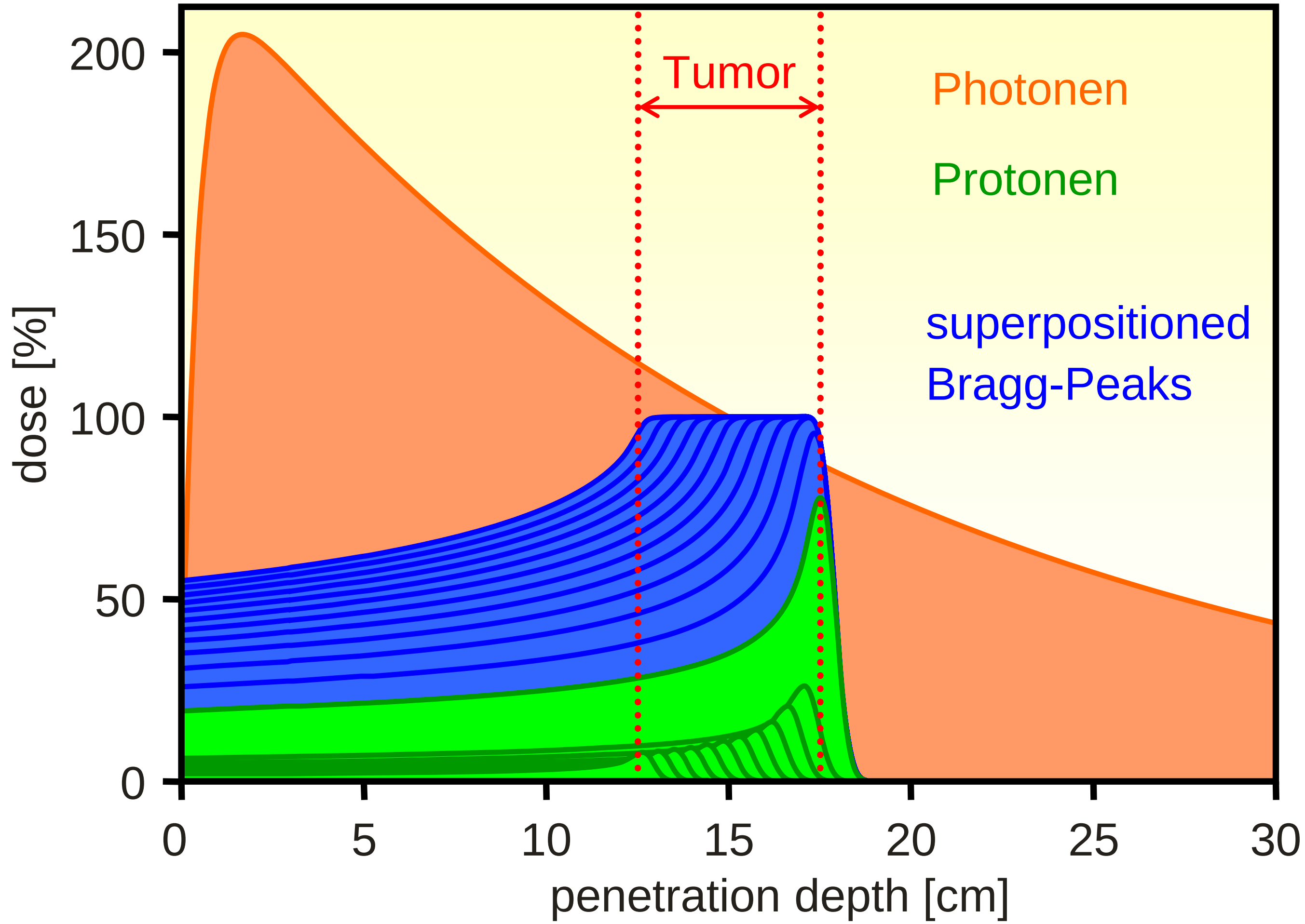
- Intro to medical therapy using Hadrons
- Motivation for superconducting magnets for medical therapy
- Challenges to the implementation of superconducting technology
- Examples: cyclotrons and synchrocyclotrons
- Examples: gantries
- Technical hurdles and opportunities for the broader implementation of superconducting technology
- Summary

Motivation: Hadron therapy has significant advantages

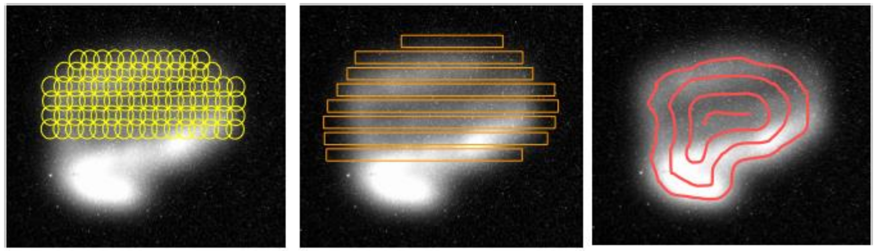
- Hadrons deposit energy primarily at the “Bragg peak”
  - Enables focused energy deposition
  - Reduces damage to peripheral organs
- Deposition depth controlled by beam energy
- Together with beam transvere position control, enables “raster scanning”



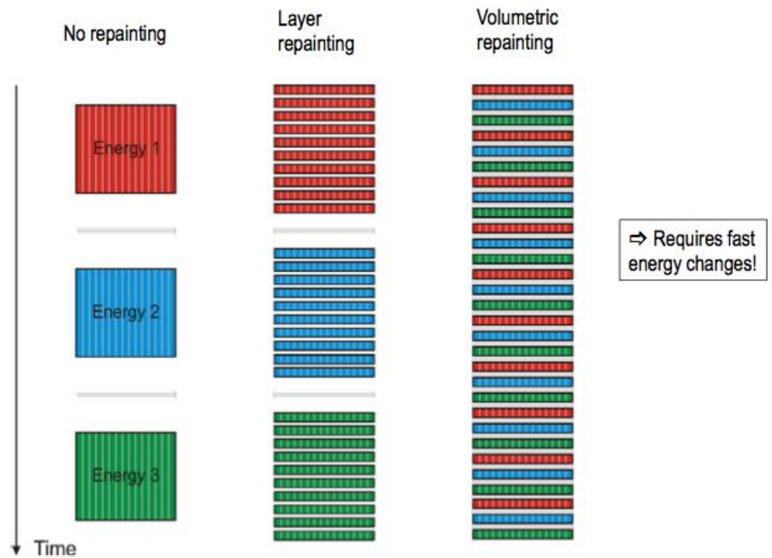
Visualization of the benefit of Hadron therapy, courtesy M. Seidel (Beam Dynamics meets Magnets, PSI, 2014)



Hadron therapy treatment modalities are evolving

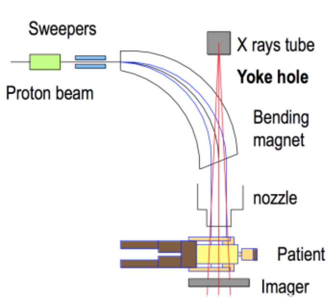


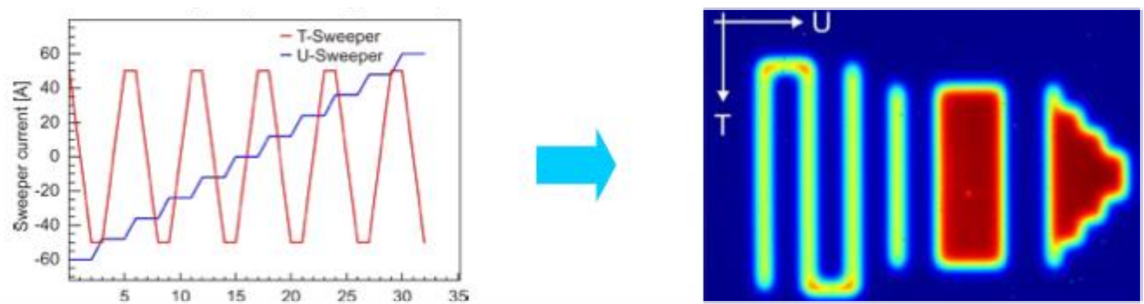
- Discrete spot scanning (Default mode Gantry 1)
  - Switching off the beam after each spot
  - Dead time per spot ~3 ms.
    Typically field: 10'000 spots -> 30 s dead time, scales with number of repaintings!
  - Spot scanning is starting mode for Gantry 2
- [Raster – Scanning]
  - Drag beam from spot to spot, transient dose (?)
- Continuous line scanning
  - Paint lines with beam intensity modulation
  - For maximum repainting number and simulated scattering
  - Example for a 1 liter box:
    Line 10 ms, Layer 200 ms, Volume 6 s
- Contours scanning (?)
  - For optimizing repainting and lateral fall-off (difference Gaussian to error-function)



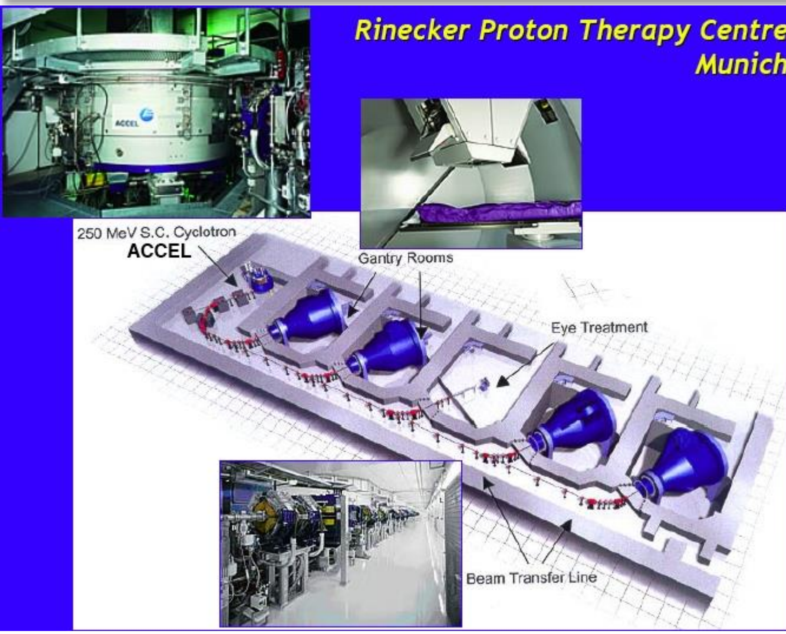
David Meer, Workshop on Modern Hadron Therapy Gantry Developments

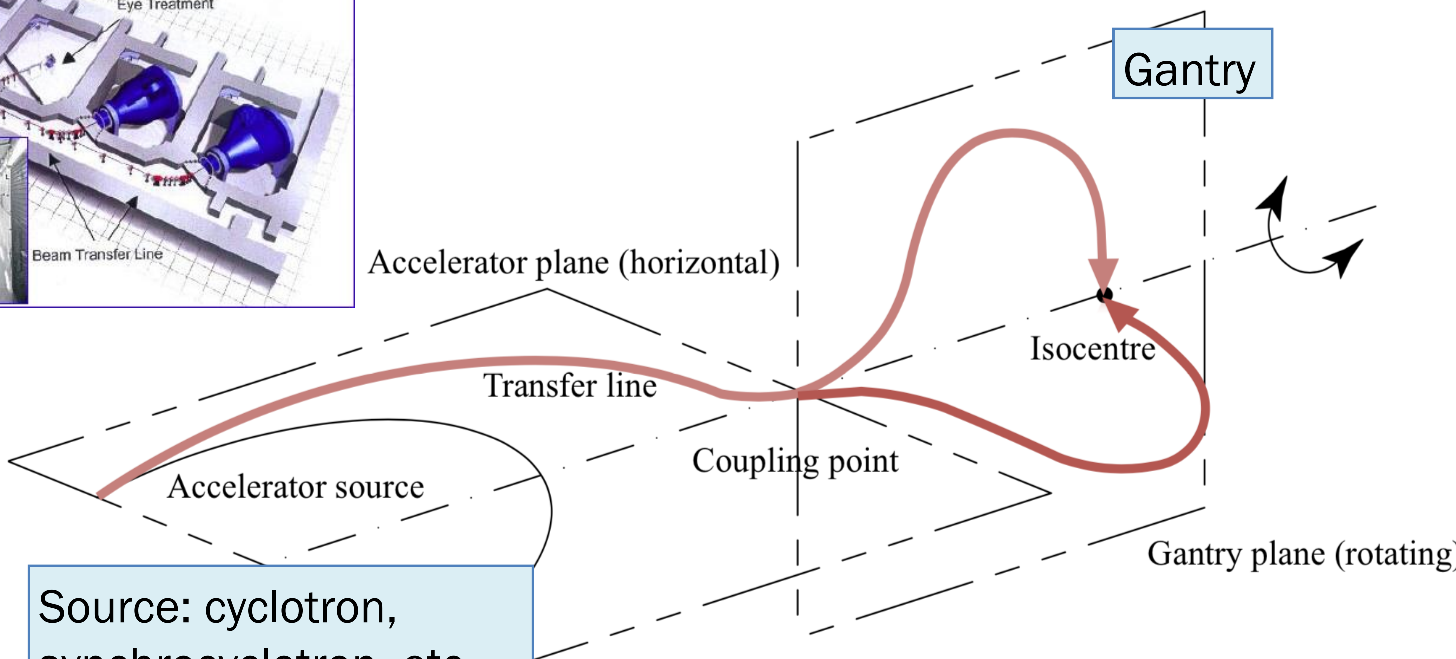
Upstream scanning PSI
Compact gantry





Elements of hadron therapy where superconducting magnets are particularly relevant

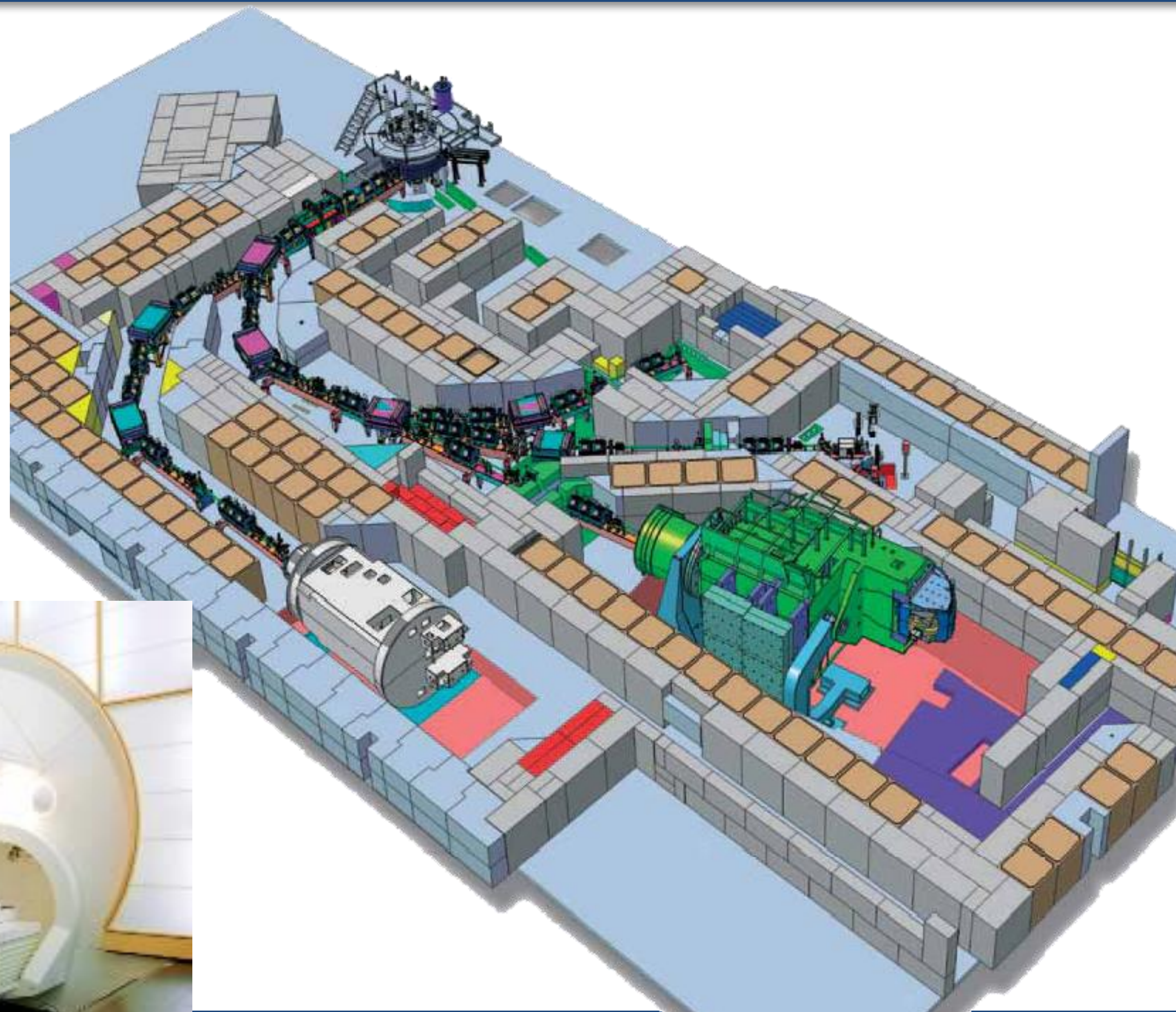




Source: cyclotron, synchrocyclotron, etc.

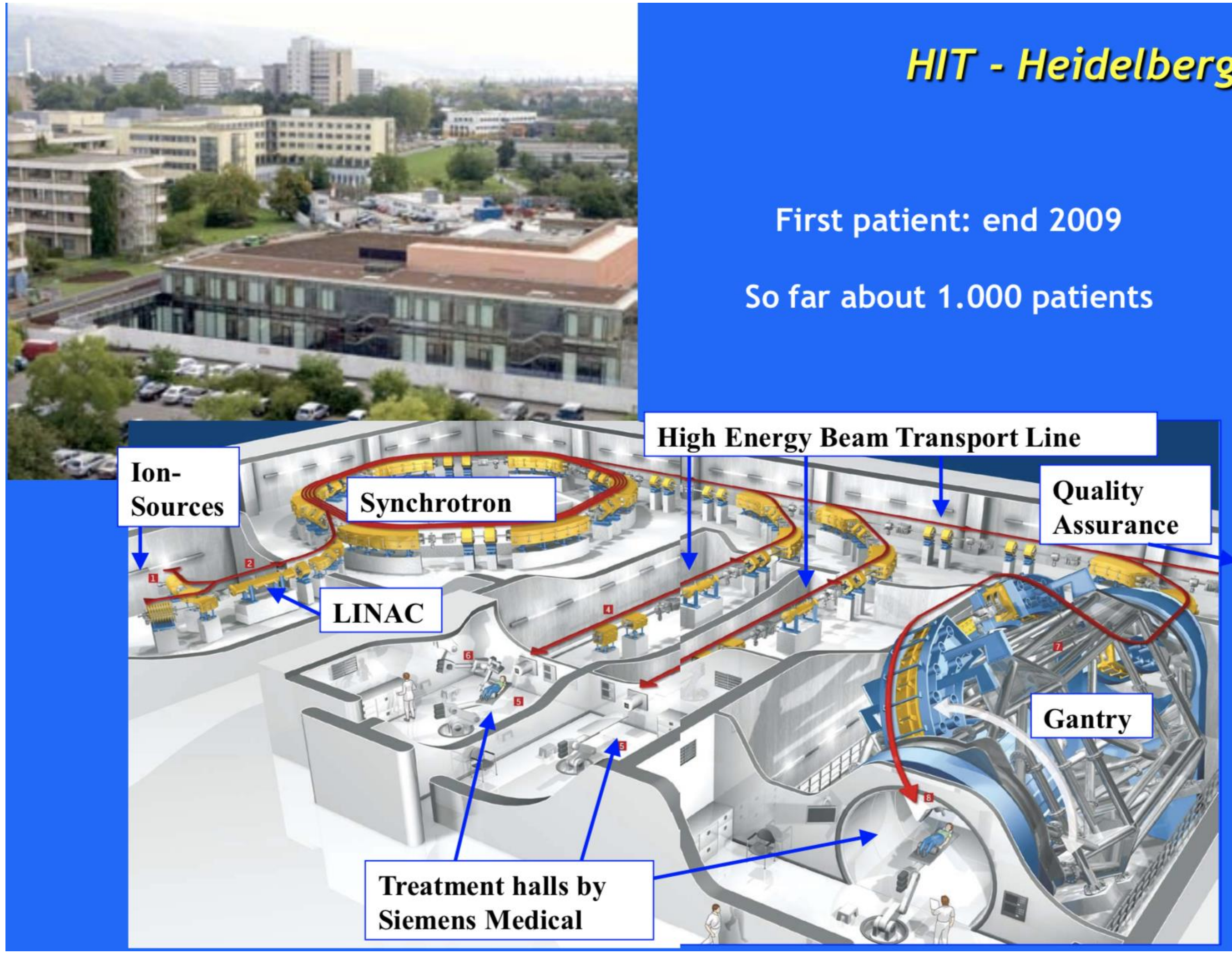
H. Owen et al.

Example: PSI facility



Example: Heidelberg

- Slide from Sandro Rossi



Motivations for superconducting technology: performance enhancement, size and mass reduction

- Performance: Access to higher magnetic field
  - Enabling for sources – the major "players" in proton therapy use superconducting cyclotrons / synchrocyclotrons
  - Enable the Mevion concept – "cyclotron-on-gantry"

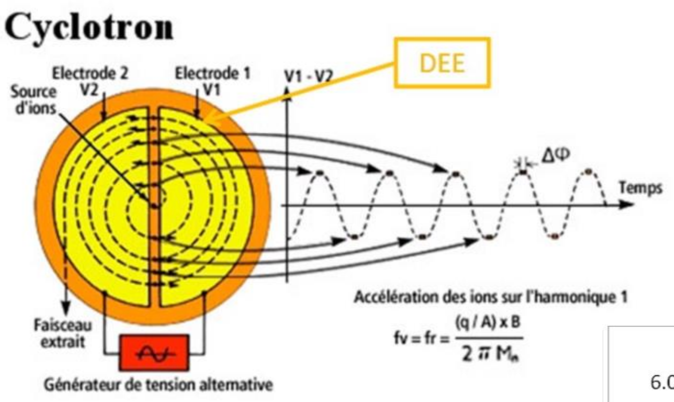
- Size reduction: reduce footprint and weight of gantry
  - In principle order-of-magnitude reduction in weight is possible for protons, more for Carbon
  - Footprint is reduced also
    - Marginal for protons
    - Significantly for Carbon

Challenges to superconducting technology for medical applications: some technical, but primarily cost/complexity

- Technical:
  - Gantries require ramping – AC losses need to be minimized and addressed in design
  - Field quality can be difficult if beyond iron saturation
    - Can no longer use iron scalar potential to control field quality
    - Problem exacerbated if situation involves varying field and iron
  - Stray field needs to be understood and minimized
    - Many peripheral systems are sensitive to field

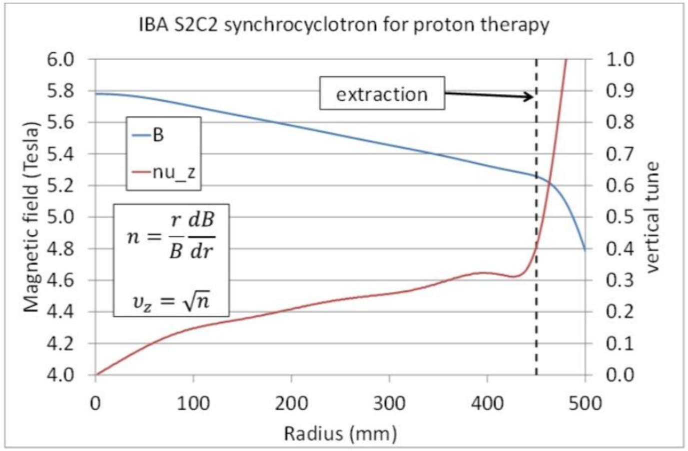
- Cost / complexity:
  - Industry base knowledgeable in SC magnets is “small”
  - Cryogenics add complexity and are anathema to hospitals/users

Examples: cyclotrons and synchrocyclotrons (see W. Kleeven and S. Zaremba, Ion Beam Applications, Louvain-La-Neuve, Belgium)

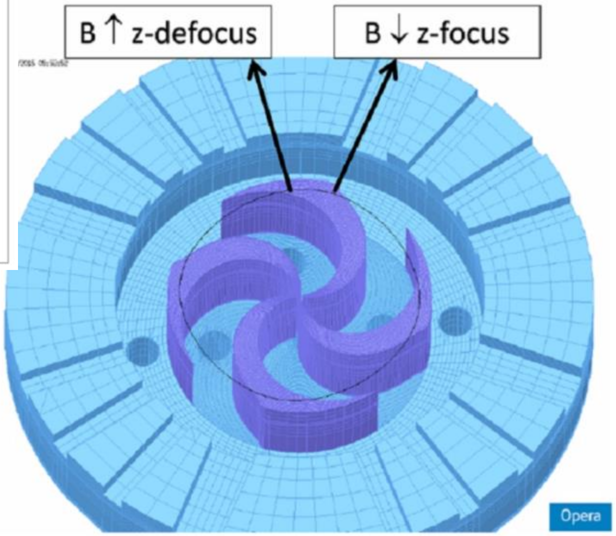


Classical cyclotron:
Lawrence and Livingston, Phys. Rev. 40 (1932) 9

Synchrocyclotron
(time-varying RF)



Azimuthally varying field cyclotrons (isochronous)



Comparison of proton-beam Cyclotrons

	Mevion S250	**Varian Proscan**	**IBA C230**
R pole (m)	0.34	0.80	1.05
D Yoke (m)	1.80	3.10	4.30
Height (m)	1.20	1.60	2.10
B_o (T)	8.90	2.40	2.20
B_f (T)	8.20	3.10	2.90
Mass (tonnes)	*25*	*100*	*250*
T_f (MeV)	254	250	235

MEVION S250

- Many units installed and in operation, or currently being installed…

Examples: gantries

The promise of superconducting magnets for gantries is in size and weight

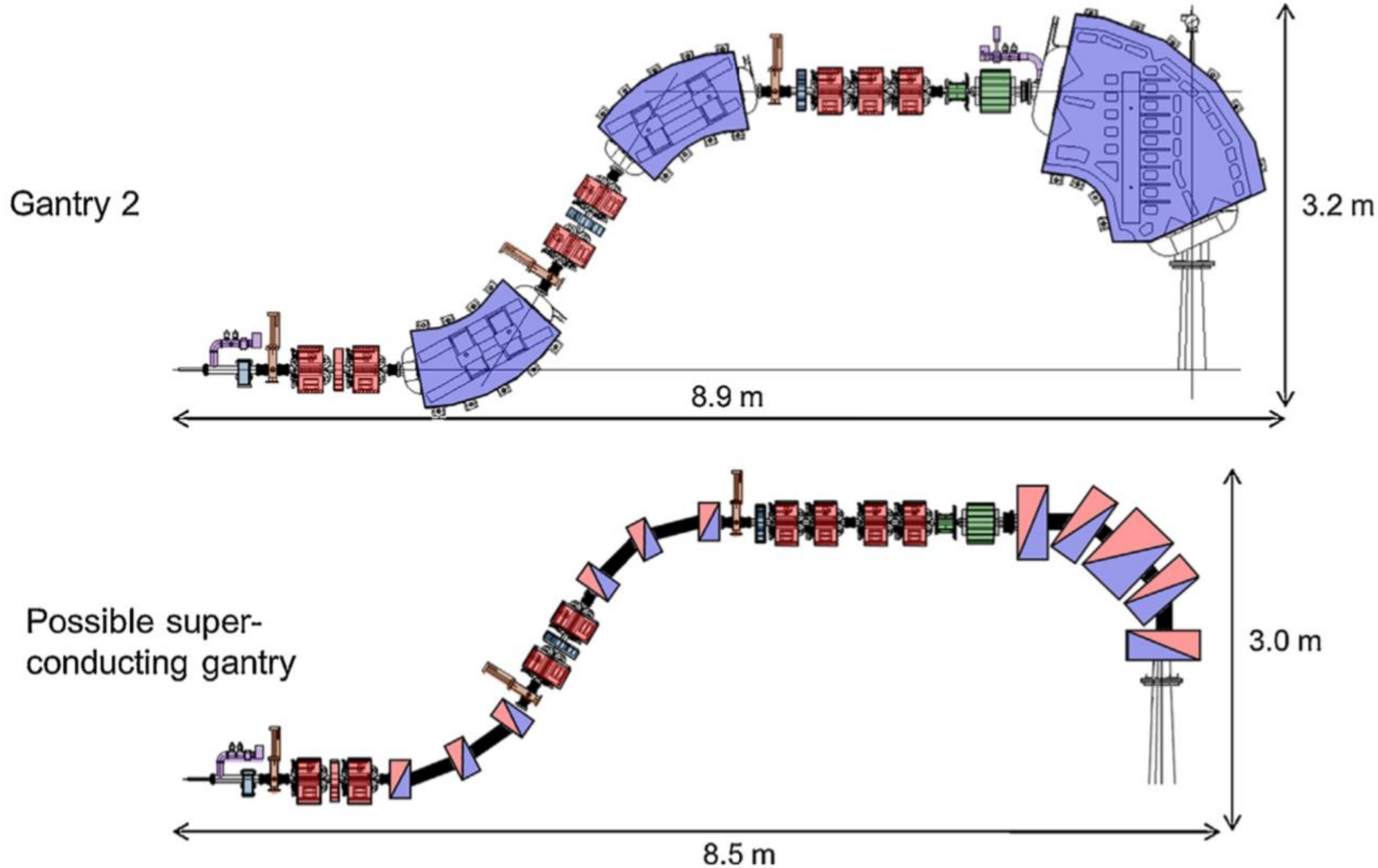
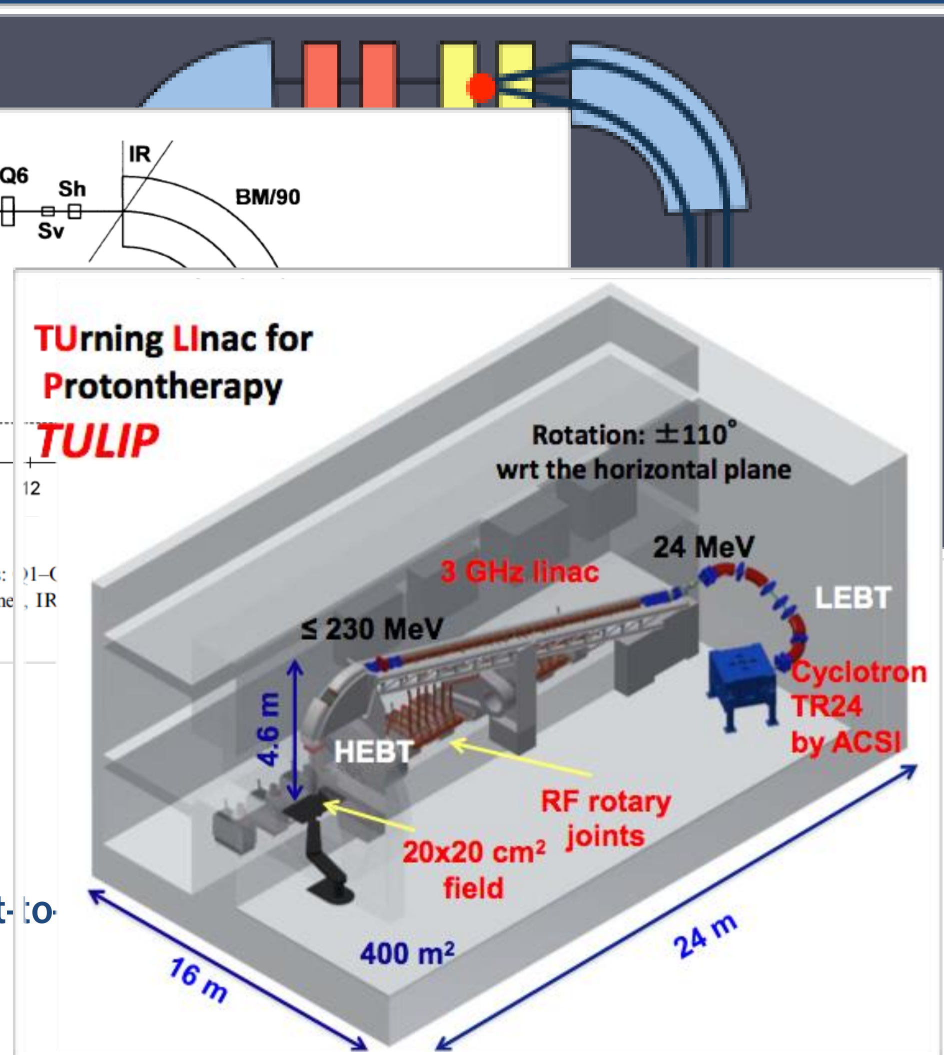


Fig. 4. Schematic illustration of Gantry 2 (top) and proposed superconducting gantry (bottom) with their dimensions. The dipole magnets are shown in blue, the quadrupoles in red, the combined function magnets (dipole and quadrupole) as a combination of blue and red and the scanning magnets in green.

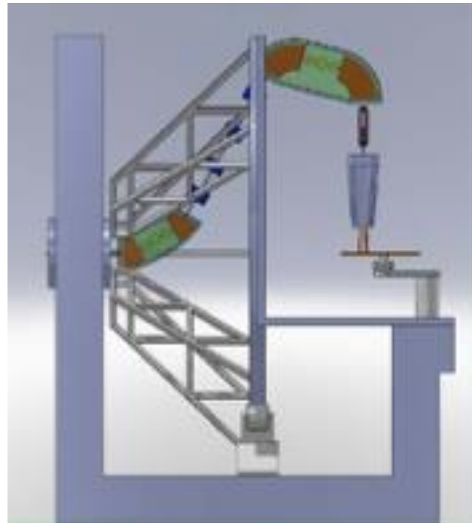
Gantry concepts abound…

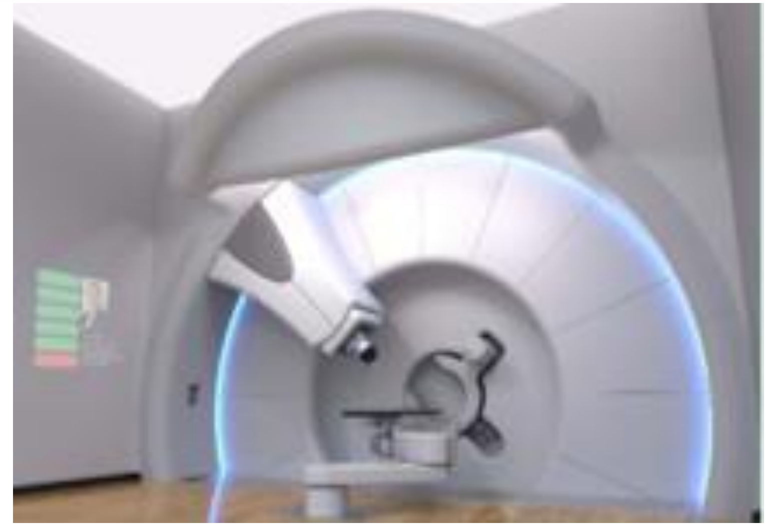


- Pavlovic design:
  - Radially compact; parallel scanning (“point-to-
  - large, large-aperture final bending magnet

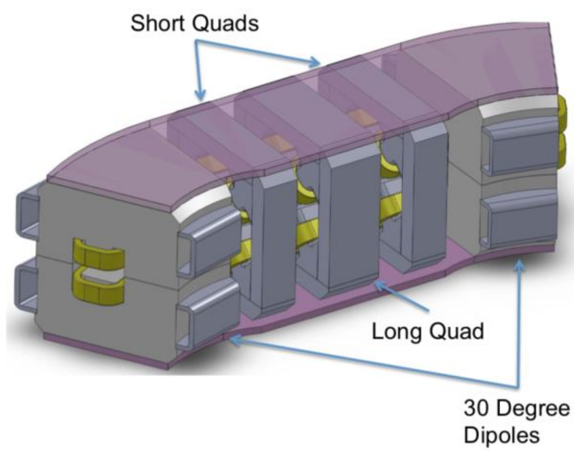
ProNova - introducing superconducting magnets to reduce the size and weight of the gantry

- Achromat pairs of bending magnets
- 3% energy bandwidth

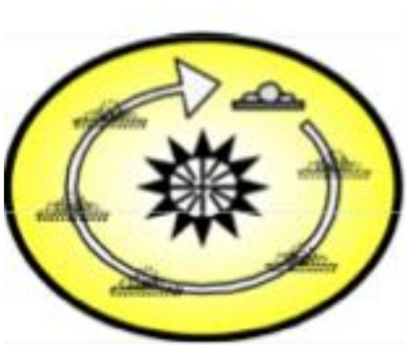


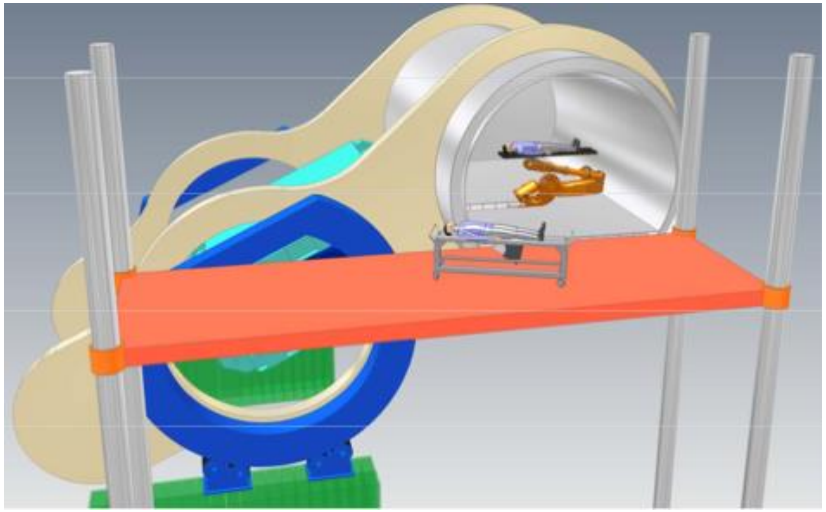


Vladimir Anferov et al, “The ProNova SC360 Gantry”, Modern Hadron Therapy Gantry Developments, Cockcroft Institute, Jan 2014

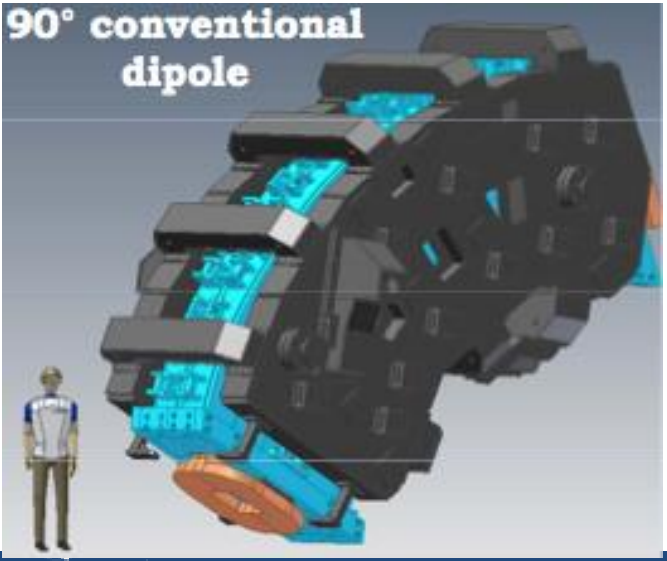


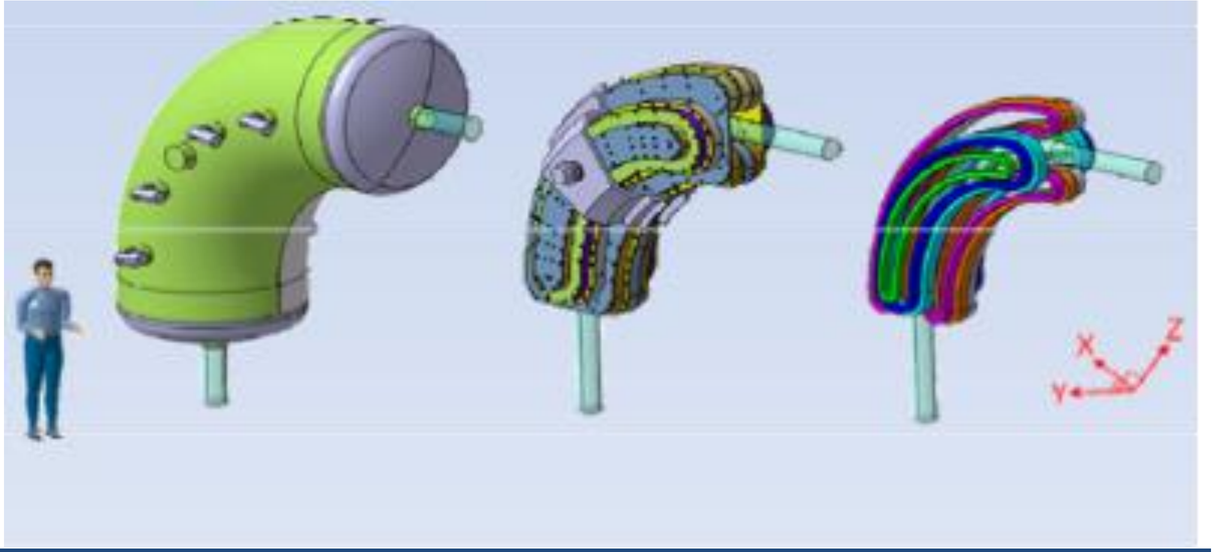
The ULICE gantry of CNAO in Italy takes a different approach to the gantry-patient rotation





Isocenter moves according to the beam direction – only one 90° bending magnet

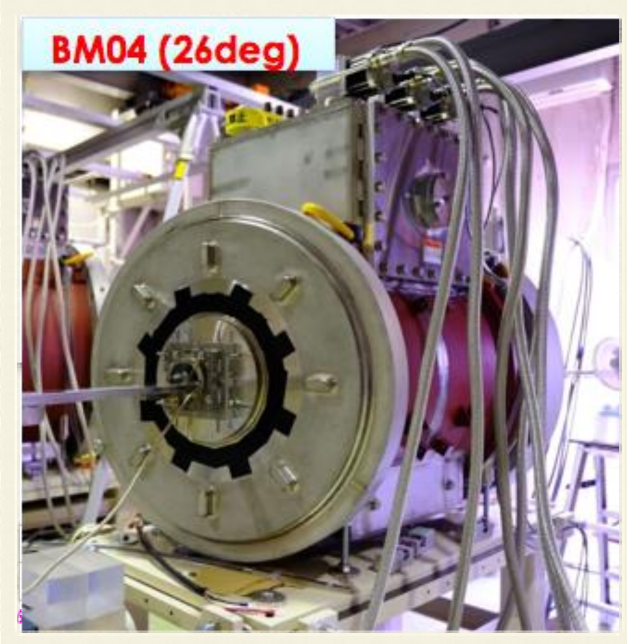


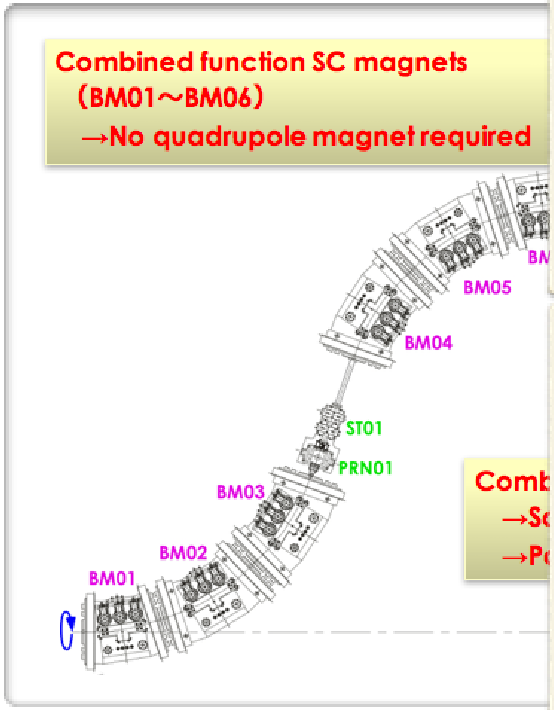


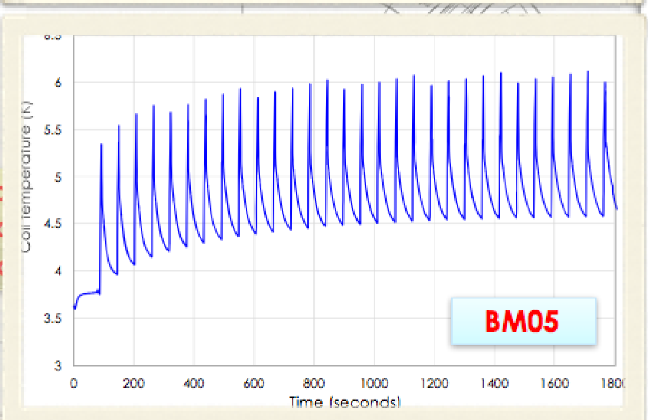
NIRS is developing a heavy ion medical therapy center in Chiba, utilizing superconducting magnet technology for the gantry

Ion kind	: ^{12}C
Irradiation method	: 3D Scanning
Beam energy	: 430 MeV/n
Maximum range	: 30 cm in water
Scan size	: □200×200 mm²
Beam orbit radius	: 5.45 m
Length	: 13 m

Already treating patients!





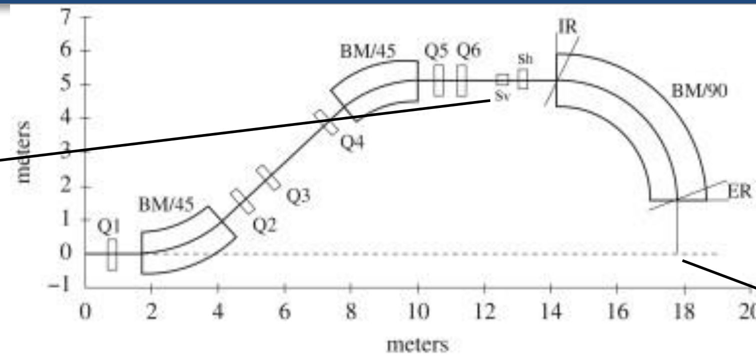


Technical hurdles and opportunities: Perceived and real

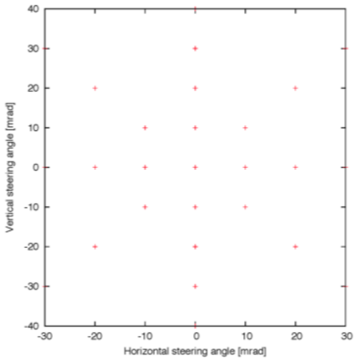
Time-varying fields induce "losses" (heat) that impacts superconducting magnet performance

- Number of considerations when using superconductors:
  - ***"Hysteresis":*** work associated with flux penetration into superconductor
    - Results in heat deposition through field cycle
  - ***"Persistent currents":*** induced currents in superconductor that do not decay
    - *May* result in unwanted field perturbations
  - ***"Coupling losses":*** resistive coupling between filaments resulting in a Joule-heating term
    - Results in heat load during ramp
  - ***"Eddy currents":*** Joule heating from currents induced by changing flux in a conductive media, e.g. mandrels, iron, etc.
    - Results in heat load during ramping
- These can be addressed via cryogenics design and/or by minimizing ramping

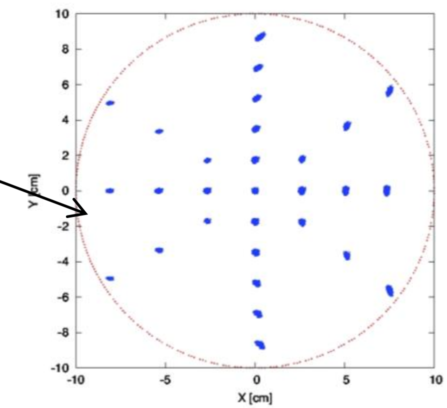
Multipoles for a Final Bending Gantry Magnet



Upstream angle (kick)



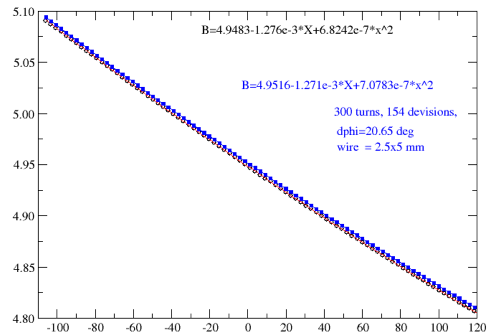
Isocenter position

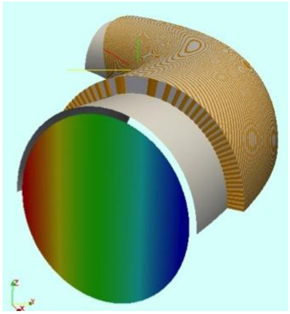


Requires Combined Function Fields

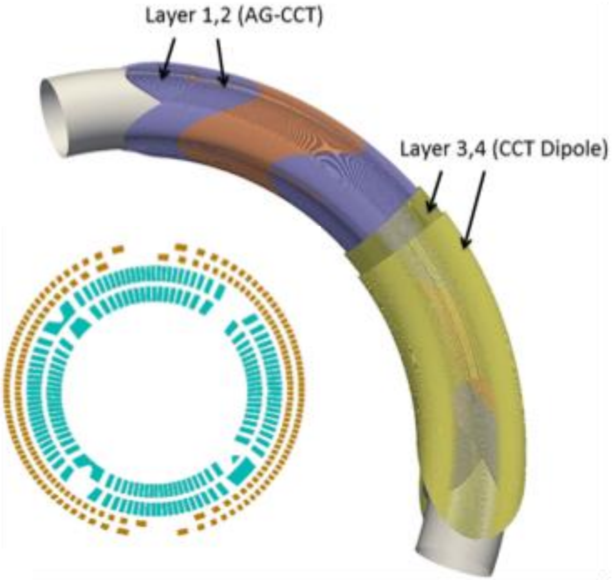
- Dipole component (main)
  - bending
- Quadrupole component
  - focusing in both planes
- Sextupole component
  - minimizing spot distortion

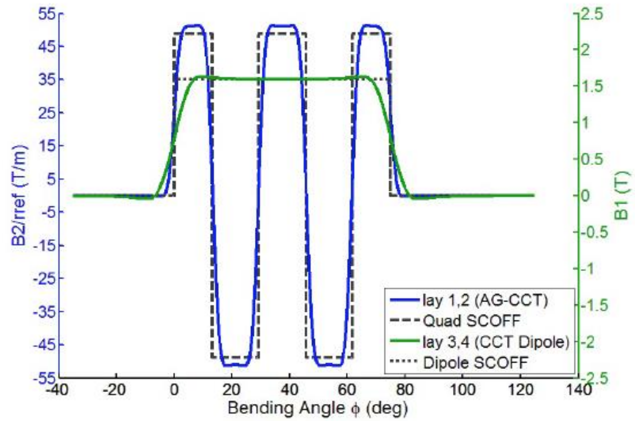
The proper conductor layout produces the desired dipole, quadrupole, and sextupole

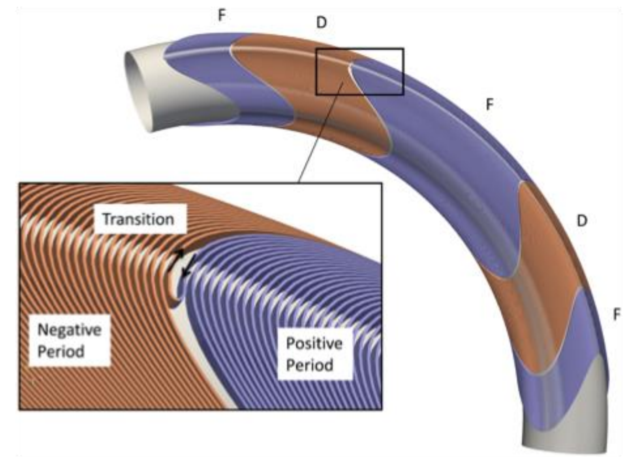




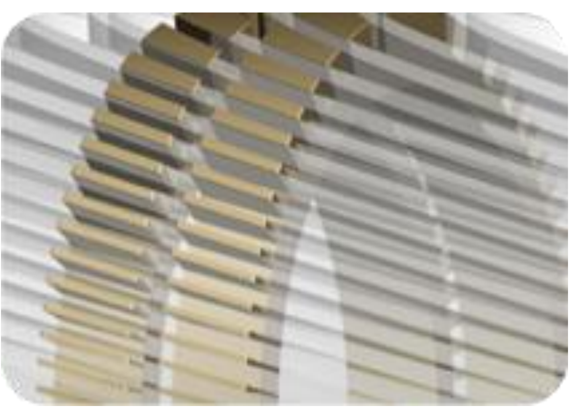
One possible approach: minimize ramping via novel achromatic optics, and minimize eddy currents via laminations

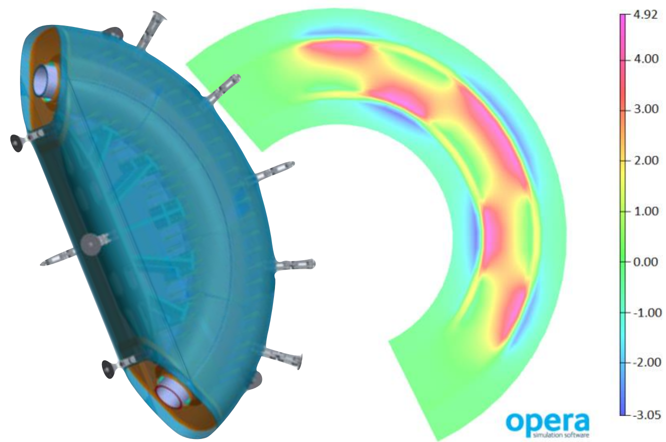


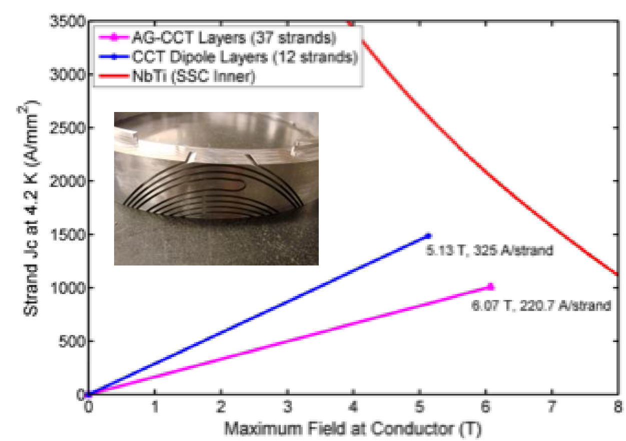




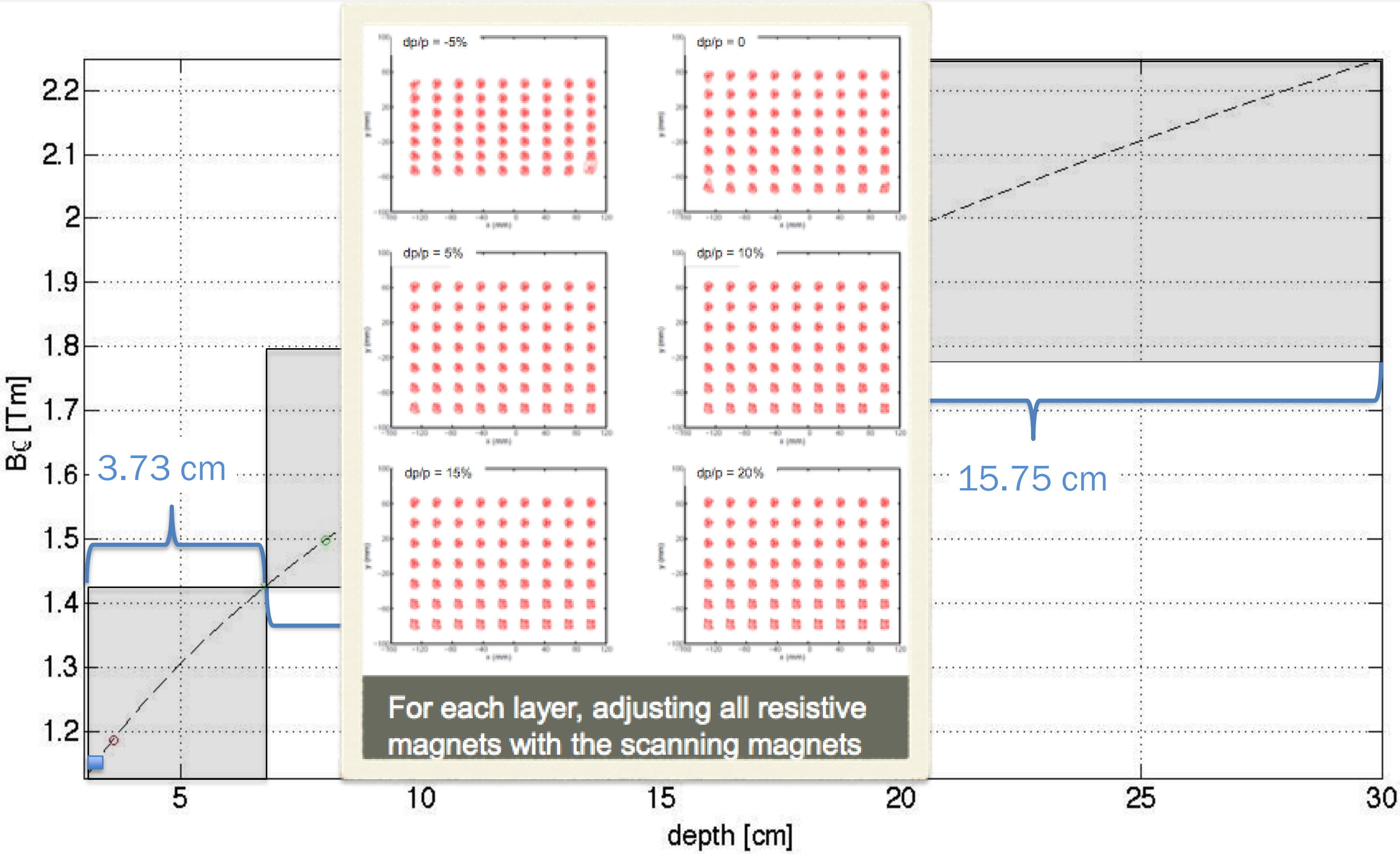
W. Wan et al., PRSTAB 18, 2015







Depth versus Momentum:
Example 1% versus 25% momentum range



Characteristics of the ideal therapy facility

- Fast, tunable control of beam energy
- Low beam emittance
- Fully achromatic transport
- Access to a variety of hadrons – protons, Carbon, …and others?

- The dream is arbitrary, fast raster scanning of the tumor
- There is furthermore interest in single-shot treatment
  - Ideally with tunable single-pulse current

Summary

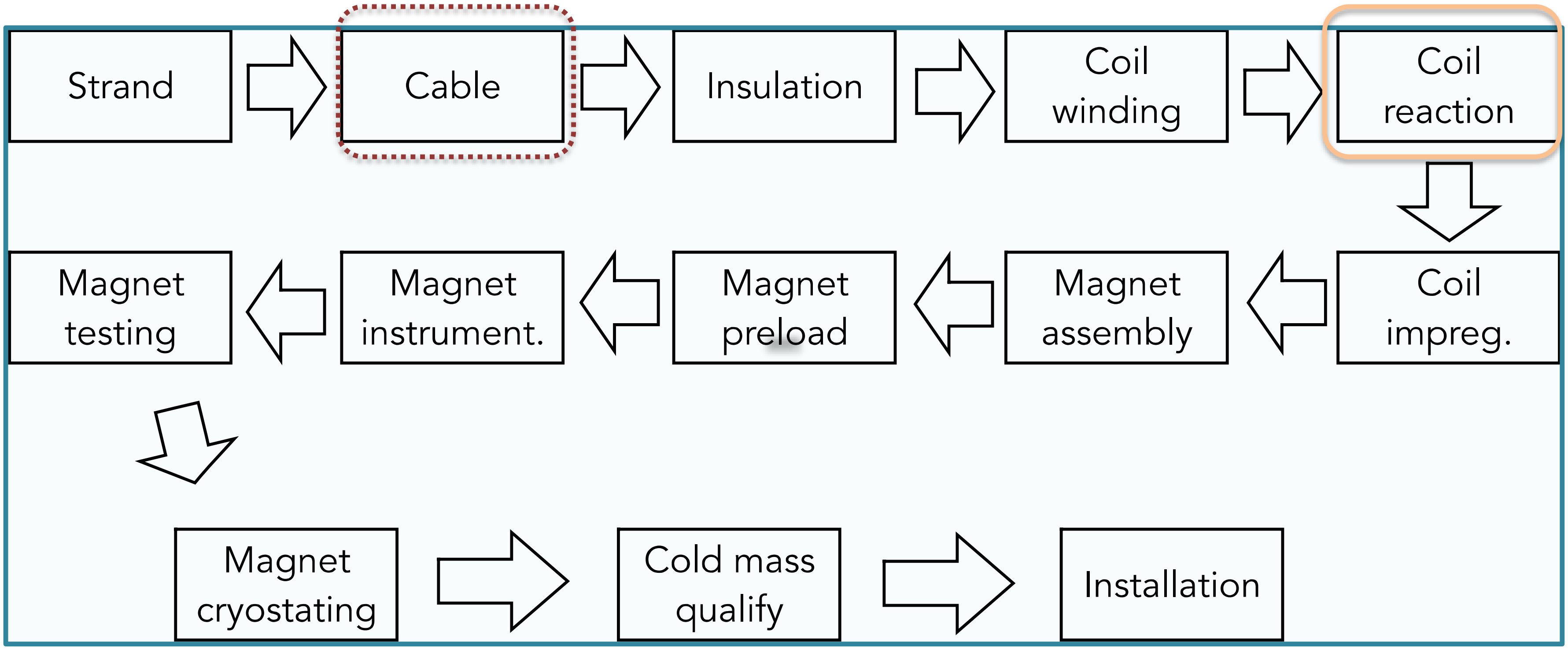
- The implementation of superconducting technology for medical therapy systems is well underway…
  - Particularly in cyclotrons/synchrocyclotrons
  - But also in first gantries

- But faces significant hurdles for implementation in commercial proton therapy systems
  - cost-effectiveness – systems remain complex
  - cultural – lack of familiarity/comfort with cryogenic technology

- Value/impact is more clear with Carbon/heavy ion systems;
  - For protons the benefit exists, but faces bigger commercial challenges

Backup slides

An example process flow in superconducting (Nb_3Sn) high-field magnets

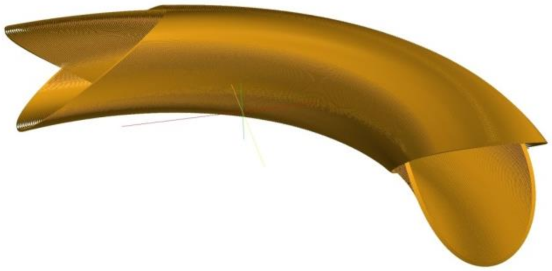


Every element has requirements and QC; in every case examples of issues exist!
Start to end time not a critical parameter <u>if</u> the process flow is reliable

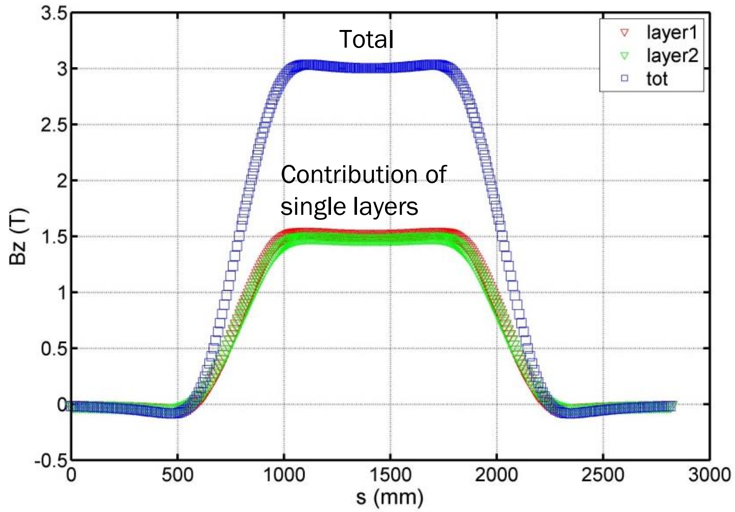
Example: 3T Proton Gantry (Magnetics)

Example: 90º bending magnet 3T

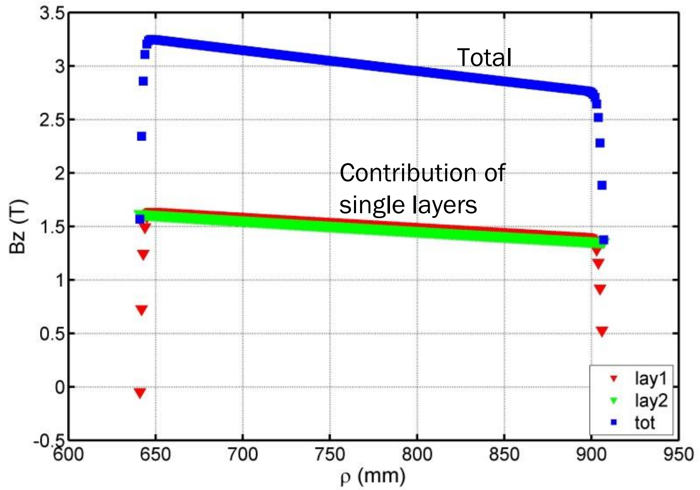
1. Magnetics
2. Structural
3. Ramping losses



Dipole Field Along the Central Path



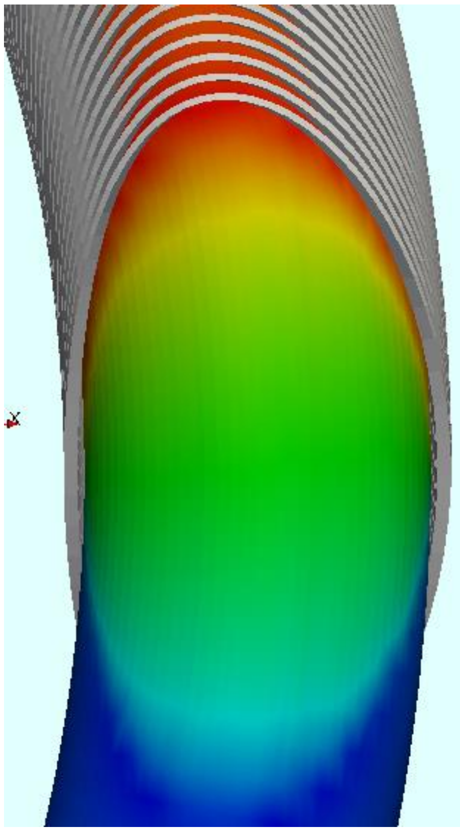
Vertical Field Across Bore on Midplane



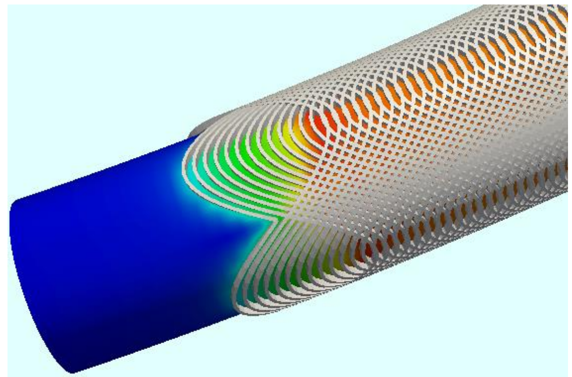
3T dipole, -1.9 T/m gradient

Generating Multipoles in the Curved Geometry

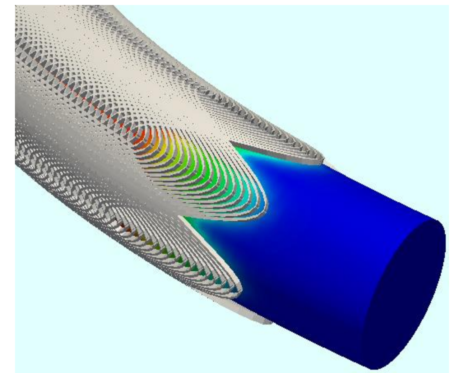
Dipole

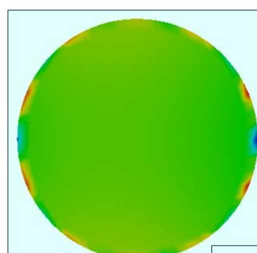


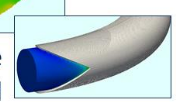
Quadrupole



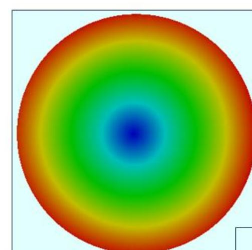
Sextupole

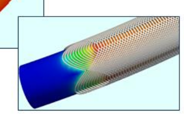




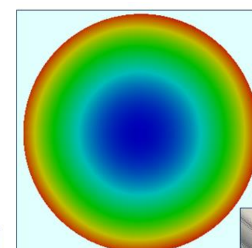


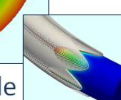
Uniform dipole field





Uniform quadrupole field





Uniform sextupole field

The ultimate “FFAG-like” magnetic structure is a continuously rotating quadruple field (akin to a helical undulator)

- *Morita and Iwashita, PRSTAB Vol.6, 2003*
- *Brouwer et al, “3D Toroidal Field Multipoles For Curved Accelerator Magnets”, PAC2013*

- Helical focussing channels
  - “The focusing power of a HQFC is twice as large as that of a FODO lattice with same K, because a HQFC can be considered as a superposition of a conventional FODO and a skewed FODO with longitudinal displacement.”
  - Requires matching sections at entrance and exit