Wir schaffen Wissen – heute für morgen

Paul Scherrer Institute

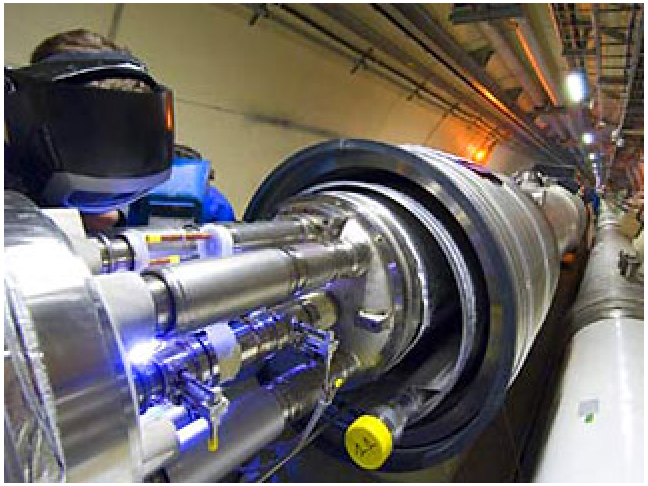
Alexander Gerbershagen

Advantages and challenges of superconducting magnets in gantry design

Content

- Motivation: reduce facility’s
  - Cost
  - Weight
  - Footprint
  - Height

- Use of superconductivity
  - Potential to fulfill the criteria,
  - Advantages result from the strong fields (e.g. high momentum acceptance),
  - Additional costs from cooling,
  - Additional risks from quenching,
  - Challenges dealing with stray fields.



- Examples of existing gantries and designs with SC magnets

Introduction and motivation

Consider changing customer composition
Research centers …

… give way to large hospitals.

⇒ Major interest in treating the maximal number of patients
⇒ Require

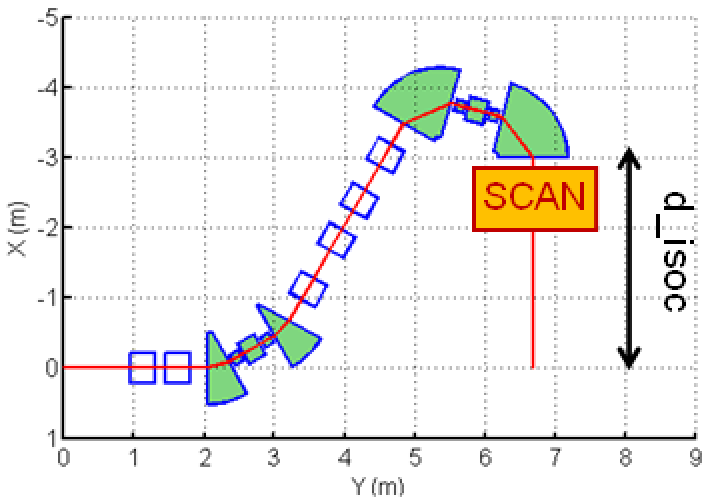
- High reliability of the machines
  - Maximal treatment interruption of couple of days
  - No quenching/good quench protection
- Easiness of service
  - Minimal warm up and cool down times

Advantages of SC magnets in gantries

Proton gantries

Reduction of:
- *power consumption*
- *weight*

Example: ProNova SC360, 25t



250 MeV p: $B\rho = 2.4$ Tm

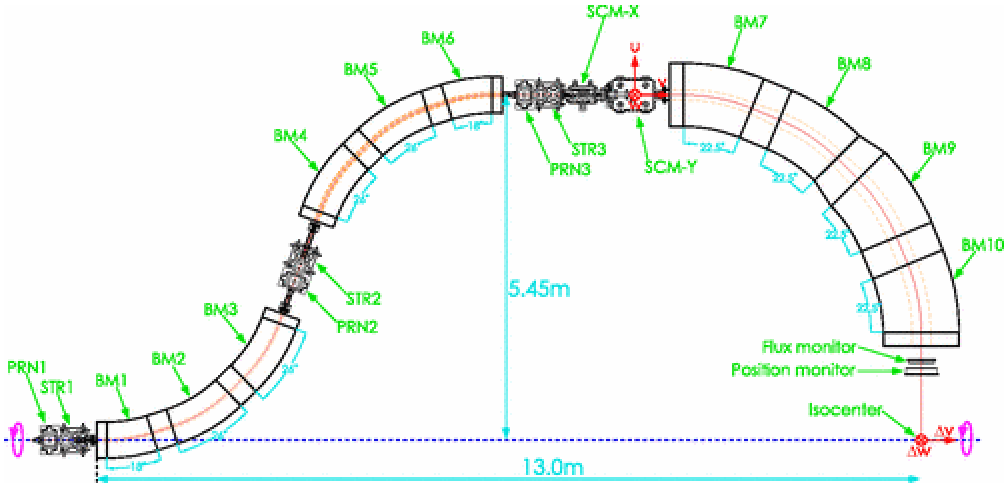
=> Most distances dictated by the purpose of the gantry:

- d from final bend to the patient
- Scanning system
- Beam focussing
- Dispersion suppression

Carbon ion gantries

Reduction of:
- *power consumption*
- *weight*
- *size*

Example: Toshiba-gantry at NIRS, 300t



450 MeV/nucl C^{6+}: $B\rho = 6.8$ Tm

=> Large share of distances dictated by the beam bending radius

Challenges of SC magnets in gantries

– Strong electromagnetic fields in the magnet

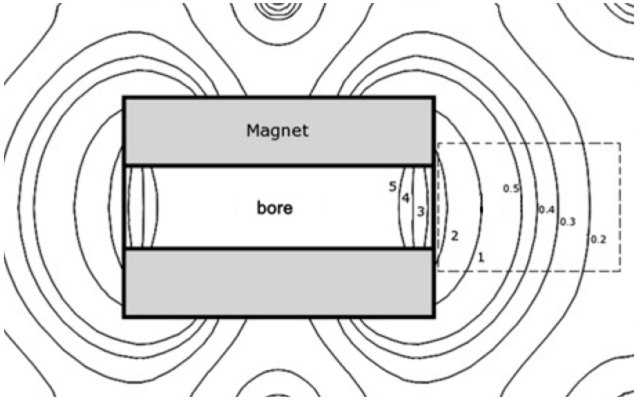
  – Need high mechanical stability to counteract the effects of $\vec{F}_{Lorentz}$

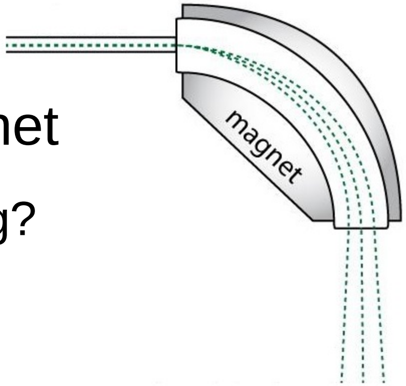
  – Strong and extended stray fields

    Effect of iron in the surroundings

    B must be < 0.5 mT at the iso-center

    => Require passive/active shielding





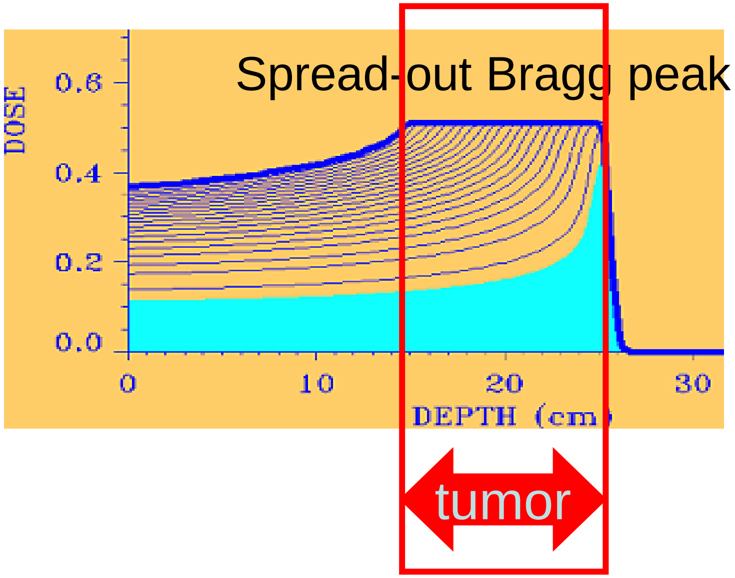
– Beam scattering in magnet

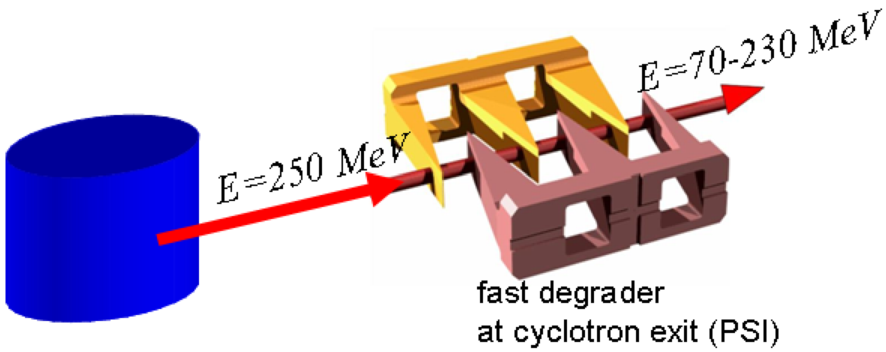
    => Possible quenching?

– Maintenance

  – Requires dedicated know-how

Energy modulation - ramping





- Scanning is performed in layers
- The energy change between two layers should be ideally performed in <100 ms
- The momentum step between two layers is ~1%

=> Two options:

  - Magnet ramping speed of ~1% dB/B in 100 ms
  - Gantry momentum acceptance very large (Δp/p > 10-20%)

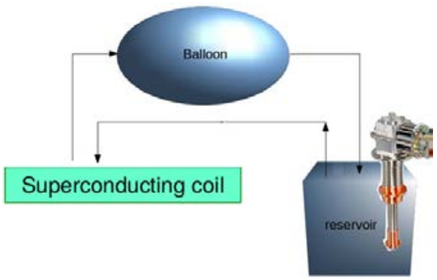
Cooling of the SC magnets

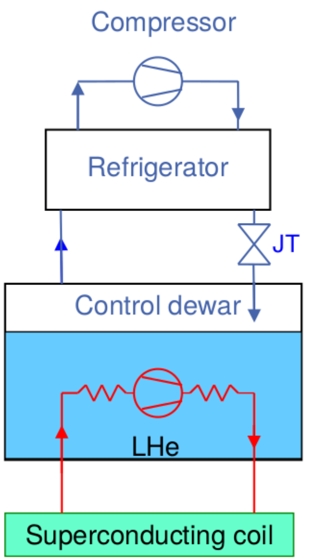
Temperature variation due to magnet ramping

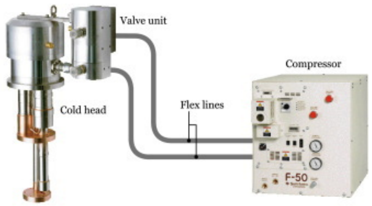
- All energy stored in the magnet is transformed into thermal energy
- AC losses from
  - Hysteresis in the superconductor magnetization
  - Coupling currents among the filaments and strands

Cooling options

- Bath cooling
  - liquid helium (<4.5 K)
  - challenging to manufacture a rotating cryostat
  - helium quench pipelines have to be implemented
- Forced flow cooling
  - supercritical helium at 4.5-5 K and 3-8 bar
  - requires a cooling and pressurizing system
  - vibration in case of turbulent flow
- Cryo-coolers directly coupled to the cold mass
  - no cryogenic fluid in the magnet
  - heat removal is limited (~1.5 W at 4.2 K)
  - loud noise



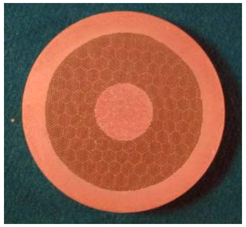




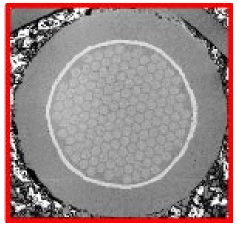
Available superconducting materials

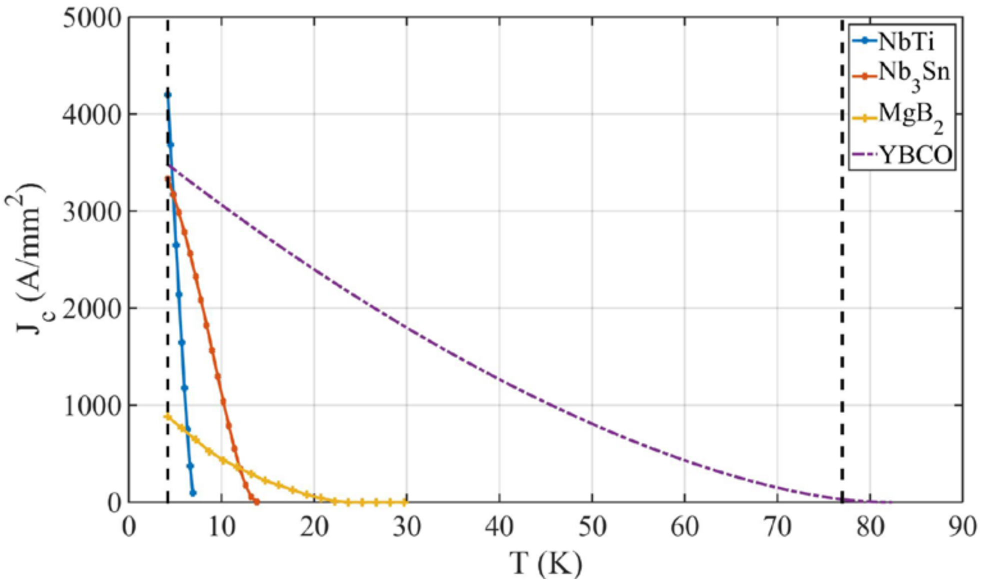
- NbTi
  - Most commonly used, >50 years of experience
  - Ductile material
  - Very thin filaments (<1 μm diameter)

    => reduce AC losses



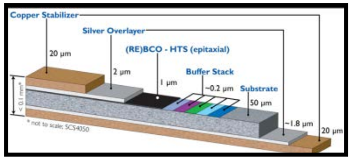
- Nb_3Sn
  - T_c of 18 K
  - 10x price of NbTi
  - Brittle, strain sensitive





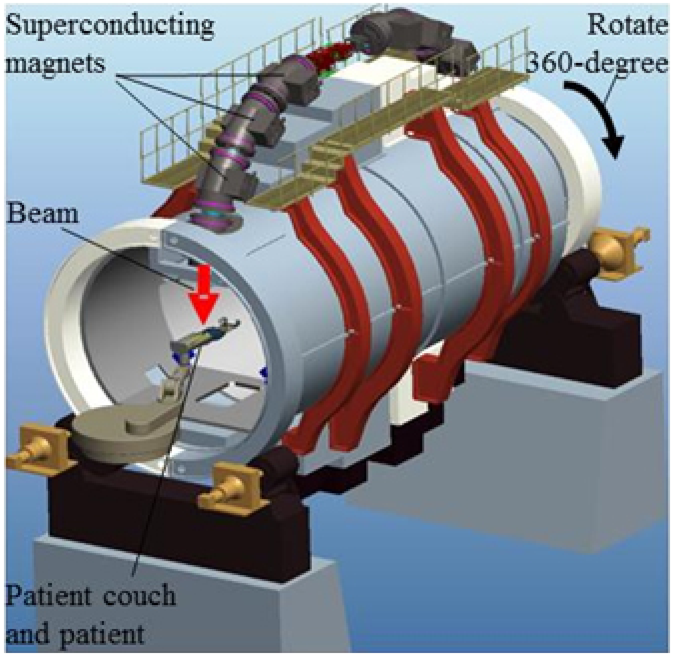
- MgB_2
  - T_c of 39 K
  - Low I_C even at low B
  - Low strain tolerance

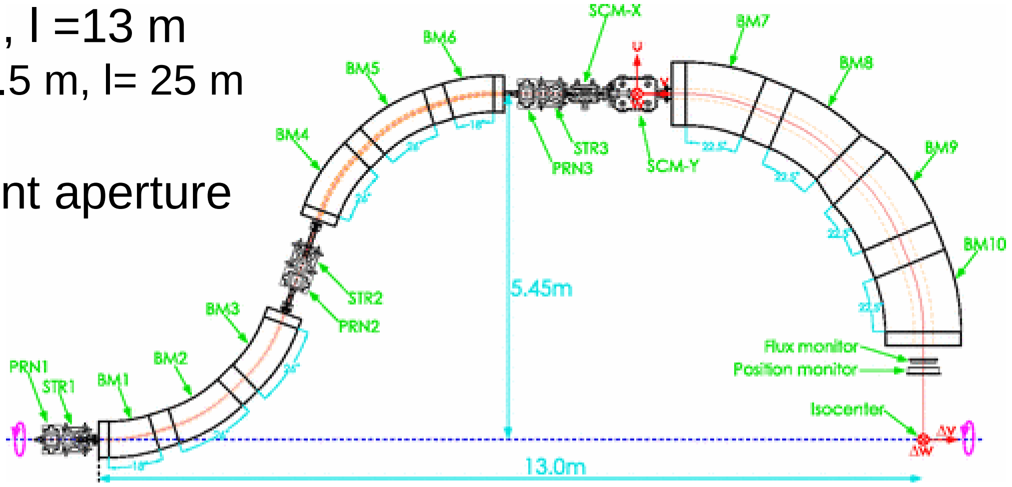
- $YBa_2Cu_3O_{7-x}$
  - T_c of 92 K
  - In form of a tape on a carrier material

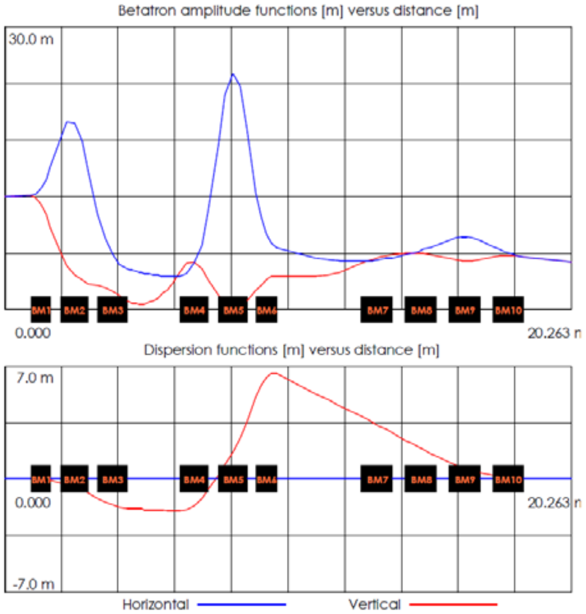


Existing sc gantries – Toshiba and NIRS

- Carbon gantry
- Significant size reduction: r = 5.45, l =13 m
  - compare to HIT in Heidelberg: r= 6.5 m, l= 25 m
- Upstream scanning
- Final bend: 4 magnets with different aperture

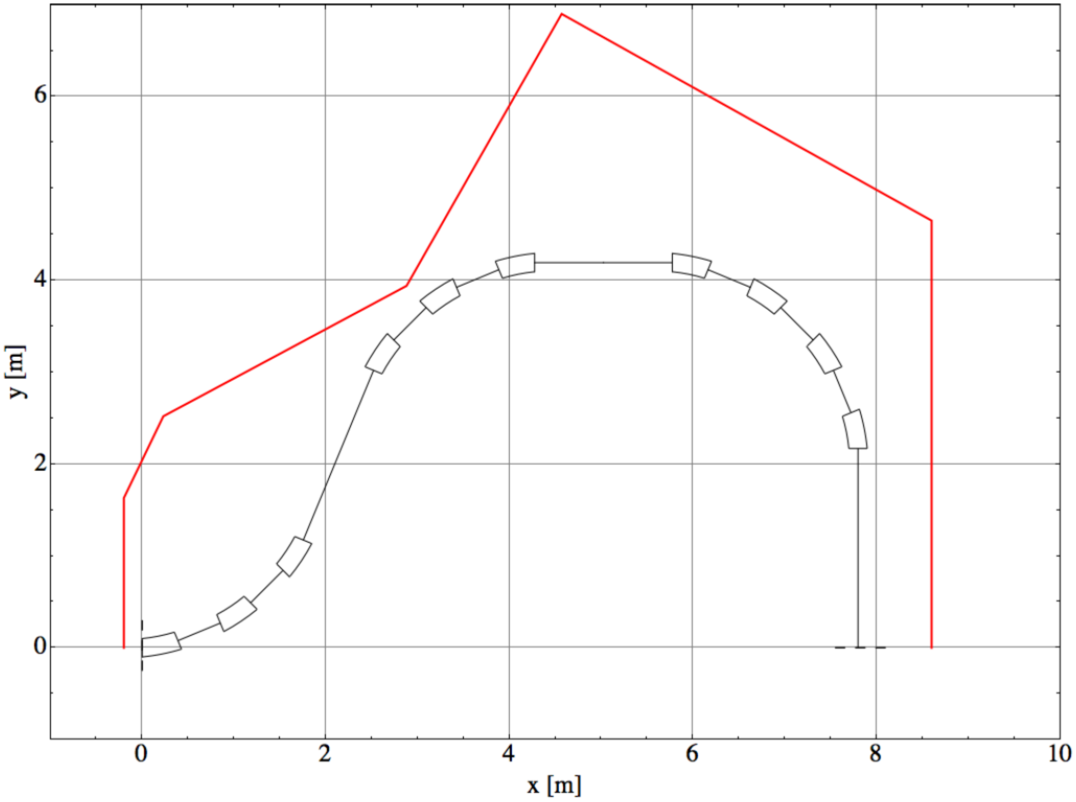






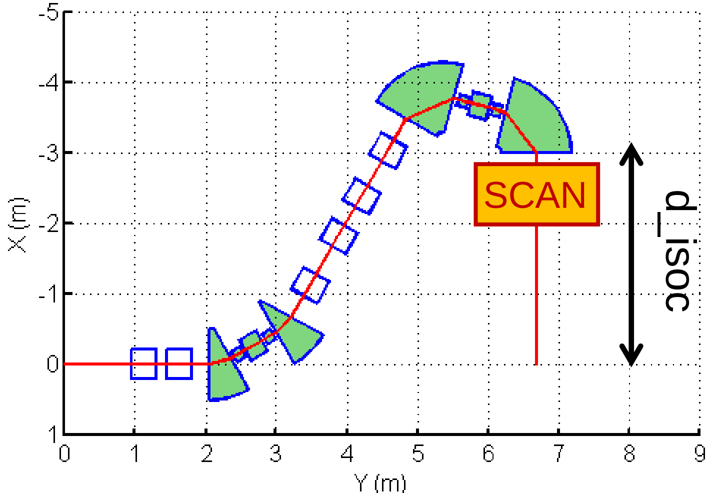
SC gantry design – Cockcroft Institute

- 330 MeV proton beam required for pCT
- 10 identical superconducting magnets
- Size comparable with existing nc gantries



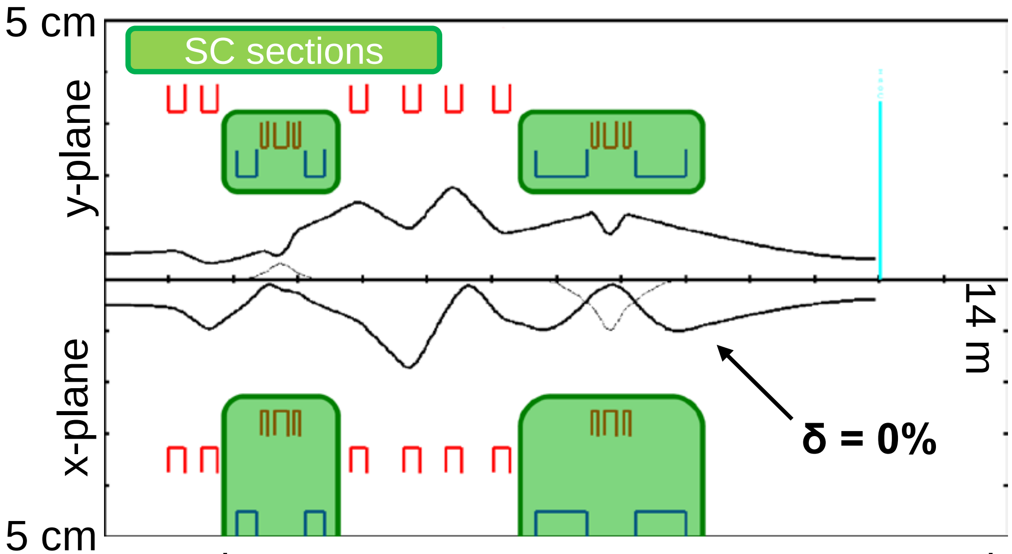
SC gantry design – ProNova

ProNova Gantry design

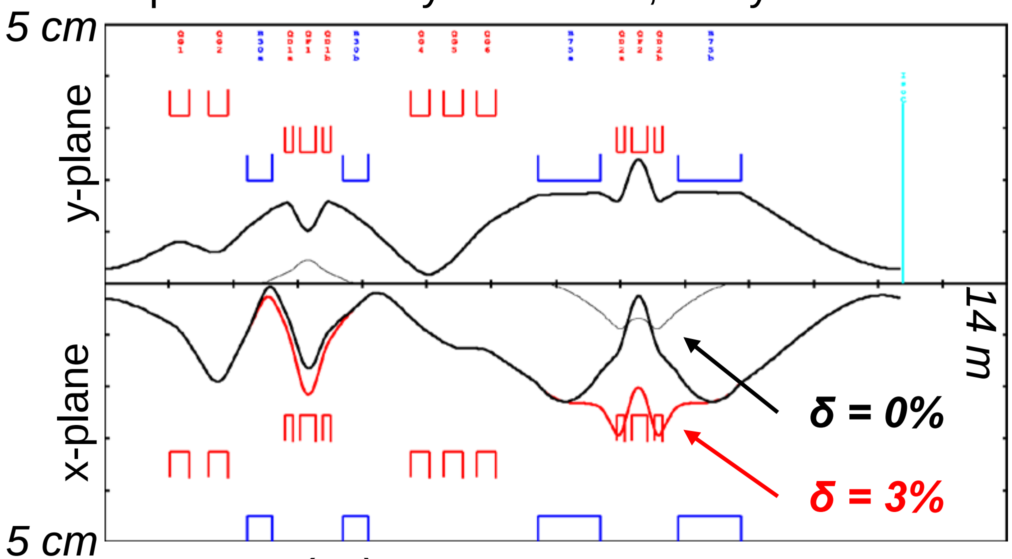


Two achromatic sc bends, each with
- 2 dipoles
- and 3 quadrupoles between them.

PSI design of 350 MeV gantry was based on this layout



Input beam: x = y = 5.0 mm , x' = y' = 2.4 mrad



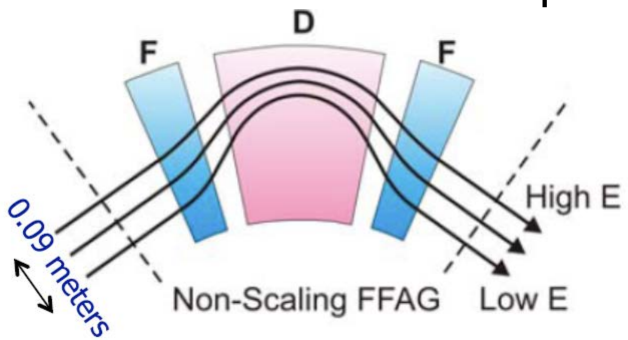
IN-Beam (2σ): x = y = 3.0 mm , x' = y' = 7.0 mr

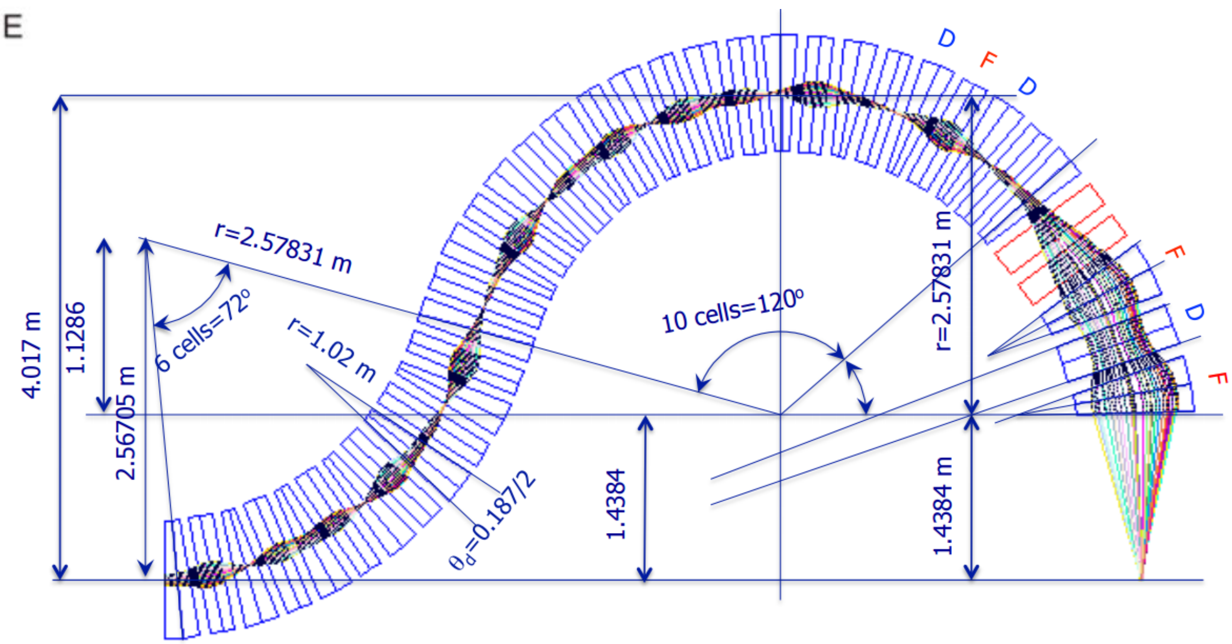
Fixed-Field Alternating Gradient (FFAG)

- Cells consist of focusing, defocusing and focusing quadrupoles.
- Orbit offsets for the required energy range are relatively small

  => very large Δp/p (>50%) for a fixed magnetic field

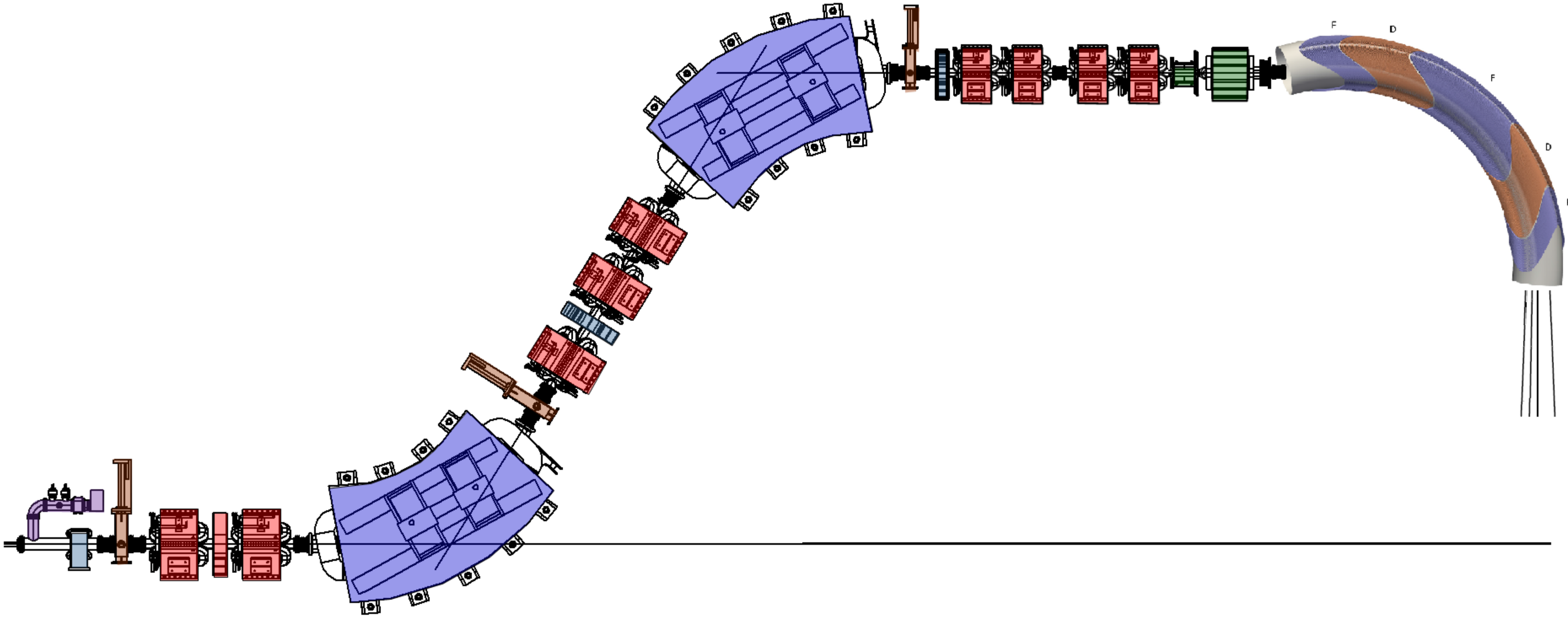
  => potentially allows treatment without change of B





SC gantry design – PSI & LBNL

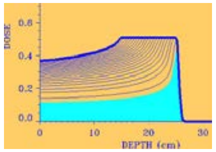
- Combined function CCT magnets with alternating gradient
- Upstream scanning
- Momentum acceptance of over ±10%
  - Treatment of the small tumors without change of the SC magnet field
  - Treatment of large tumors with only one or two of such changes
  - Can be used i.e. for volumetric rescanning on a very fast time scale

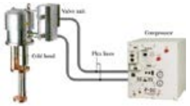


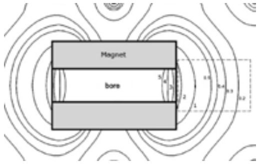
Summary

- The weight and, for the heavy ions, the size advantage of SC gantries promises significant cost and footprint reduction
  => particularly important for the commercial particle therapy

- Some challenges remain
  - Fast ramping of the magnetic field,
  - Most common superconducting material (NiTi) has a limited T-margin,
  - Cooling options are restricted due to gantry rotation,
  - Patient located near the strong magnetic fields,
  - Need to keep high reliability and availability.







- Use of SC magnets gains popularity among the particle therapy research centers and companies and promises to give this treatment method a big push in development regarding
  - Cost efficiency,
  - Practicality of such facilities,
  - Better accuracy via new treatment and diagnostic techniques.

PAUL SCHERRER INSTITUT

PSI

Thank you very much for your attention!