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Advantages and challenges of superconducting magnets in gantry design
• 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
Consider changing customer composition
Research centers …

⇒ 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

… give way to large hospitals.
Advantages of SC magnets in gantries

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

Example: ProNova SC360, 25t

250 MeV p: \( B_\rho = 2.4 \text{Tm} \)

=> 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\(^6^+\): \( B_\rho = 6.8 \text{Tm} \)

=> 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 $\mathbf{F}_\text{Lorentz}$
  - Strong and extended stray fields
    Effect of iron in the surroundings
    $B$ must be $< 0.5 \text{ mT}$ at the iso-center
    $\Rightarrow$ Require passive/active shielding

- Beam scattering in magnet
  $\Rightarrow$ 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$_3$Sn**
  - $T_c$ 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$_2$Cu$_3$O$_{7-x}$**
  - $T_c$ of 92 K
  - In form of a tape on a carrier material
Existing sc gantries – Toshiba and NIRS

- Carbon gantry
- Significant size reduction: \( r = 5.45, l = 13 \text{ m} \)
  - compare to HIT in Heidelberg: \( r = 6.5 \text{ m}, l = 25 \text{ m} \)
- 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
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

IN-Beam (2\(\sigma\)): \(x = y = 3.0\) mm, \(x' = y' = 7.0\) mrad

\(\delta = 0\%\)

\(\delta = 3\%\)
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 $\Delta p/p$ (>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 $\pm 10\%$
  - 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.
Thank you very much for your attention!