(Review of Medical application for HTS)

HTS for Commercial Proton Therapy

WAMHTS-5 Workshop

Budapest, April 12, 2019

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Varian Medical Systems Particle Therapy GmbH

Medical applications

Potential medical fields for high temperature superconductors

NMR	MRI	Ions
• Nb-Ti / Nb_3Sn – Limited to 1 GHz (23.4 T) • Progress using HTS – NIMS 1.02 GHz (Bi-2223 at 24 T) – Bruker 1.2 GHz (REBCO? at 28 T) – RICKEN 1.3 GHz (Bi-2223 and REBCO at 30 T) – NHMFL 1.3 GHz (Bi2223/REBCO/Bi2212 at 30 T) • **This will go commercial** – But small market	• Competing with decades of Nb-Ti commercialization • Some HTS demo's • "Cheap" MgB_2 for 3rd world MRI? • Conduction-cooled Ho-Hum • **Hard to make a business-case**	• Isotope production – Mostly 10 – 30 MeV H^- – High field not required for compactness – Hard to make a business-case • **Proton / Ion cancer therapy** – Huge systems when NC (cost) – LTS or HTS? – Paradigm change when compact • **Huge potential market** – **If…**

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Vision:
A World Without
Fear of Cancer

Mission:
To combine the ingenuity of people with the power of data and technology to achieve new victories against cancer

Varian – a snapshot

Global Leader In photon and proton therapy	**$2.6B*** FY16 revenues	**7,750** medical linear accelerators	**>25** worldwide training centers

A focused cancer company

4,600+ software installs	**70+** proton therapy rooms	**6,400+** employees	**50%**** international order mix

* Varian FY 16, excluding Imaging Components.

** YTD thru Fiscal 3rd quarter 2017 Gross Orders, excluding North America

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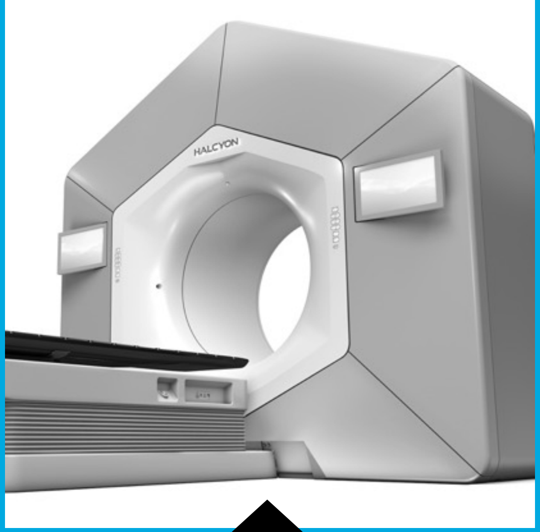
Advanced radiation therapy solutions

ProBeam®

Proton Therapy

VitalBeam™

TrueBeam®



Halcyon™

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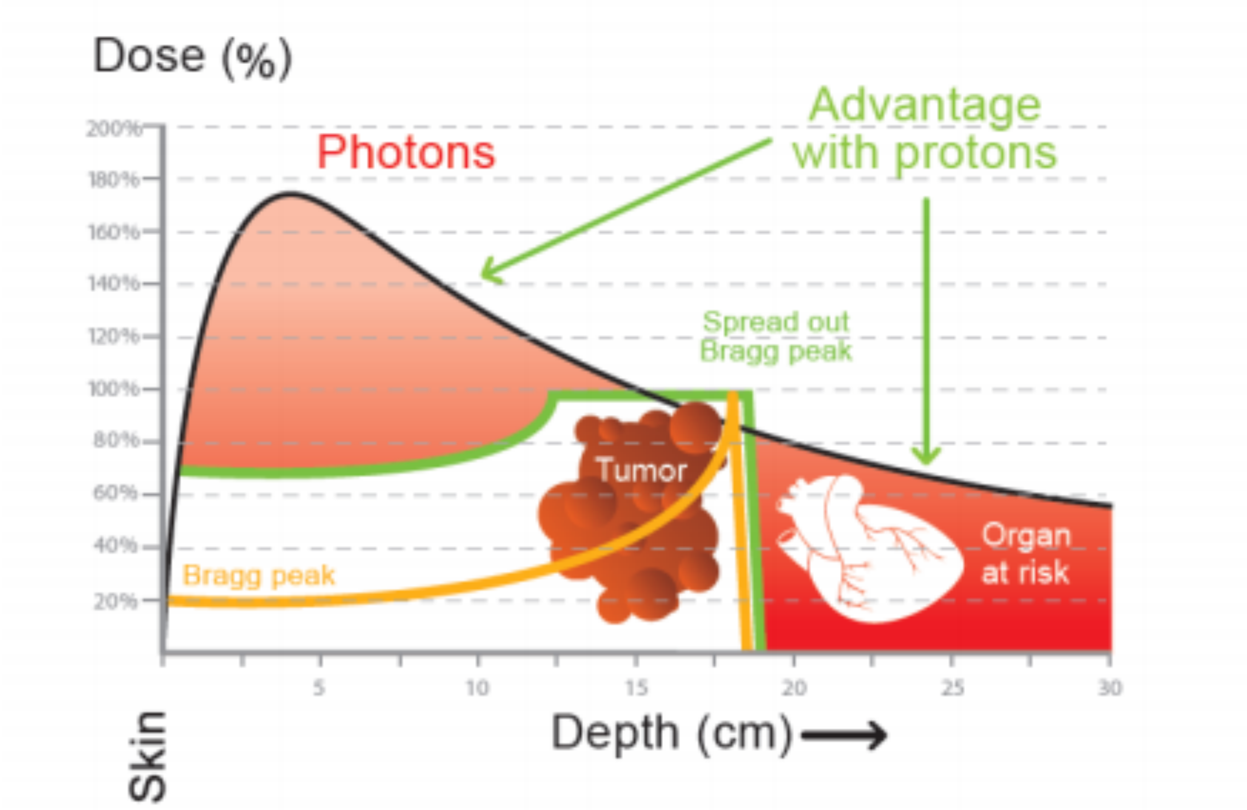
Why Proton Therapy?

Protons stop!



- Proton Therapy allows us to treat the tumor while sparing healthy tissue and other organs at risk

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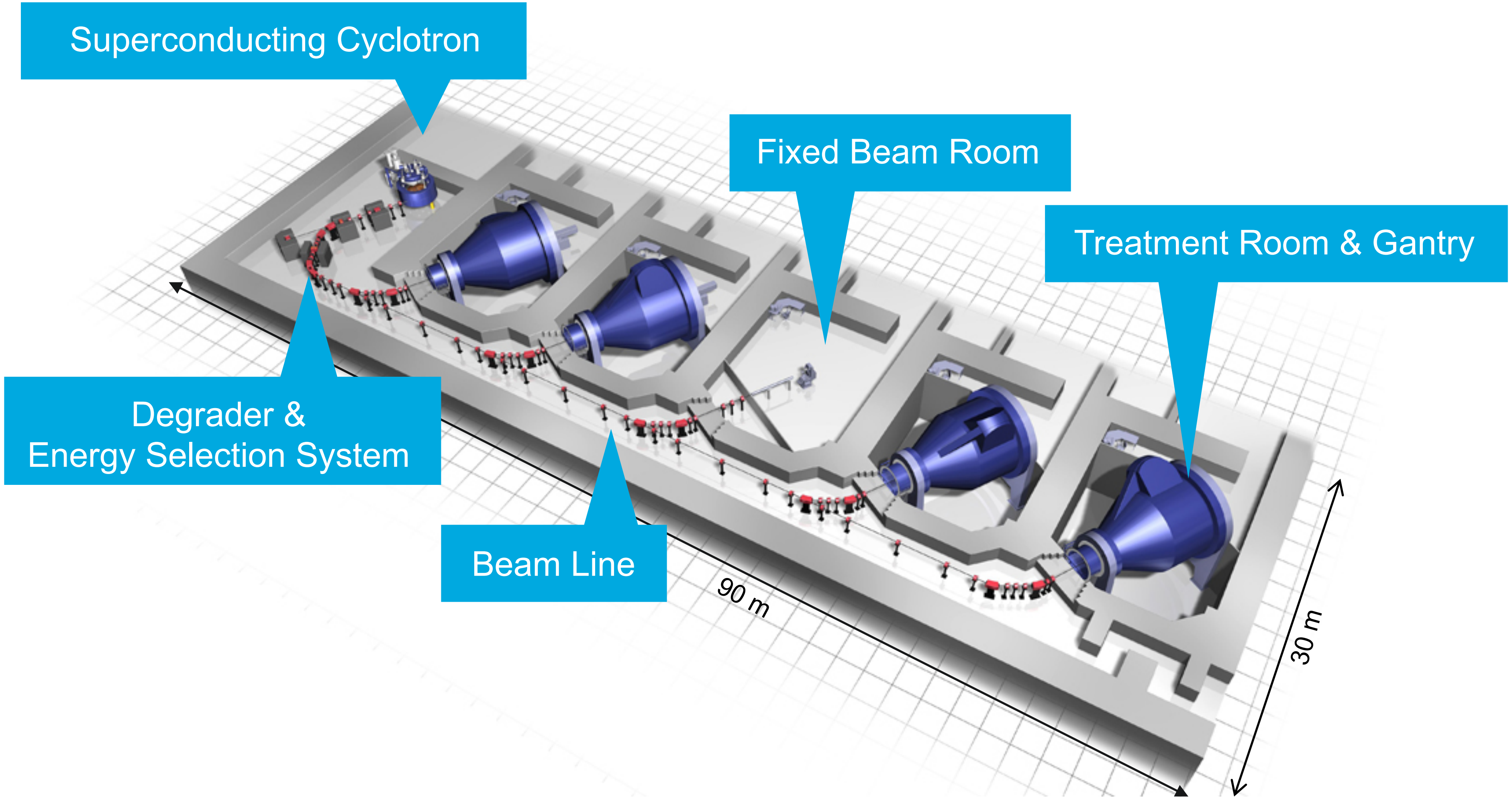
ProBeam®

Proton Platform – Overview



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Proton Therapy

The Varian Range

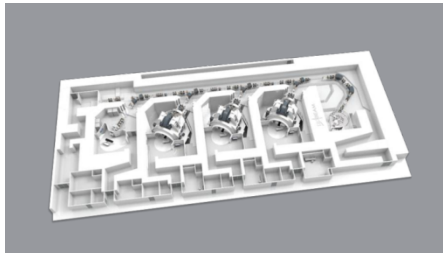
ProBeam® Compact

- 4,500 square feet
- Optimized for compactness
- Fully IMPT capable
- Advanced image guidance

ProBeam® 2-Gantry

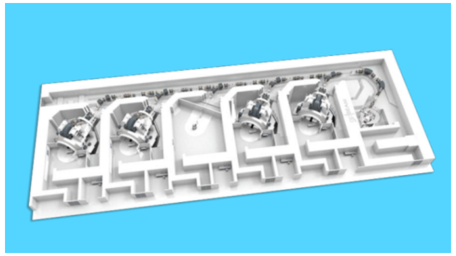
- Matched treatment rooms optional

ProBeam® 3-Gantry + 1 FB



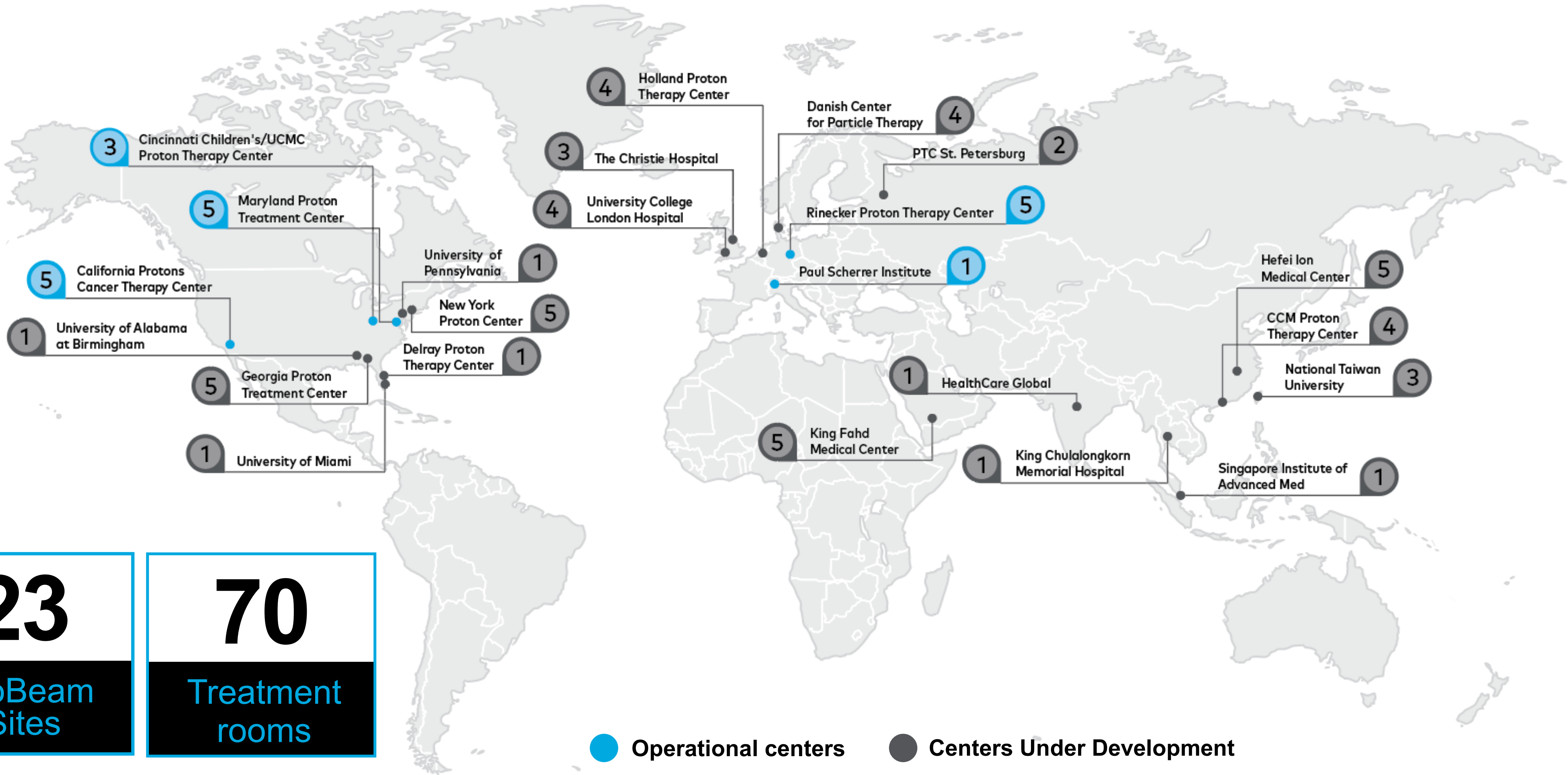
- Horizontal fixed beam room for eye treatment

ProBeam® 4-Gantry + 1 FB



- Horizontal fixed beam room for eye and H&N

ProBeam® proton therapy system sites



23 ProBeam Sites

70 Treatment rooms

Operational centers

Centers Under Development

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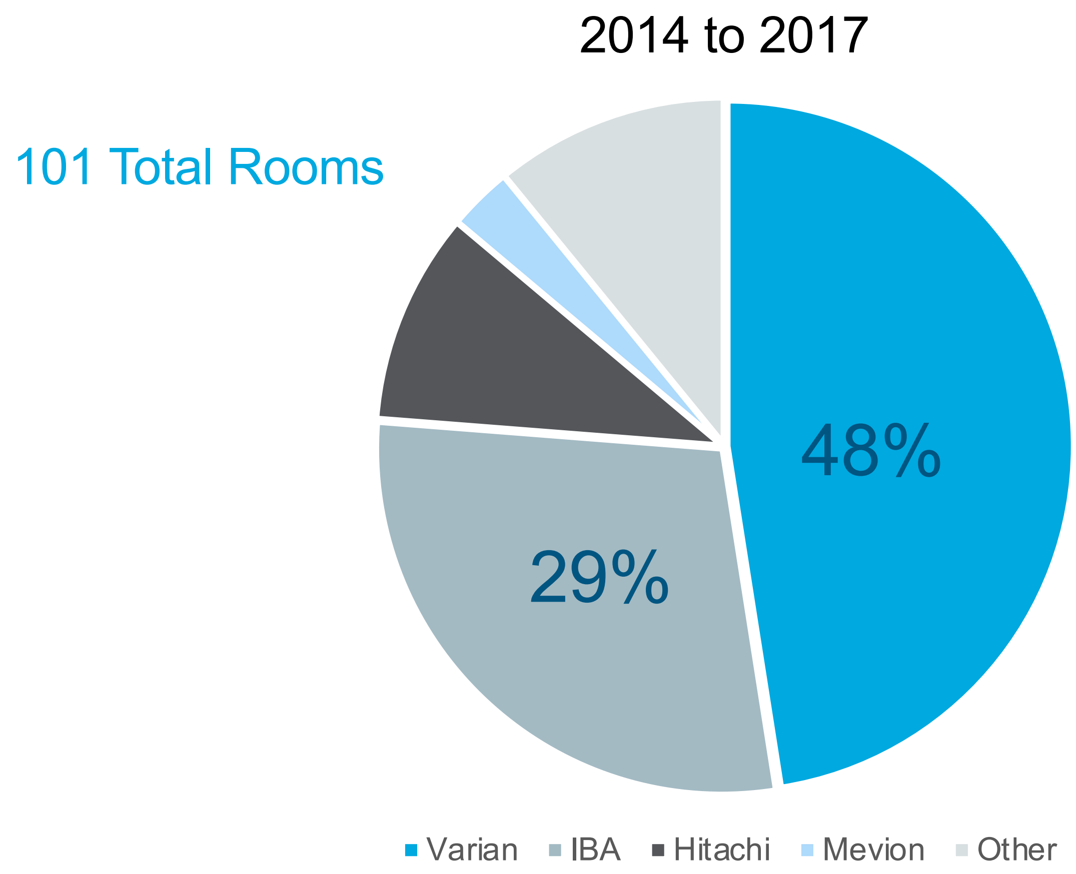
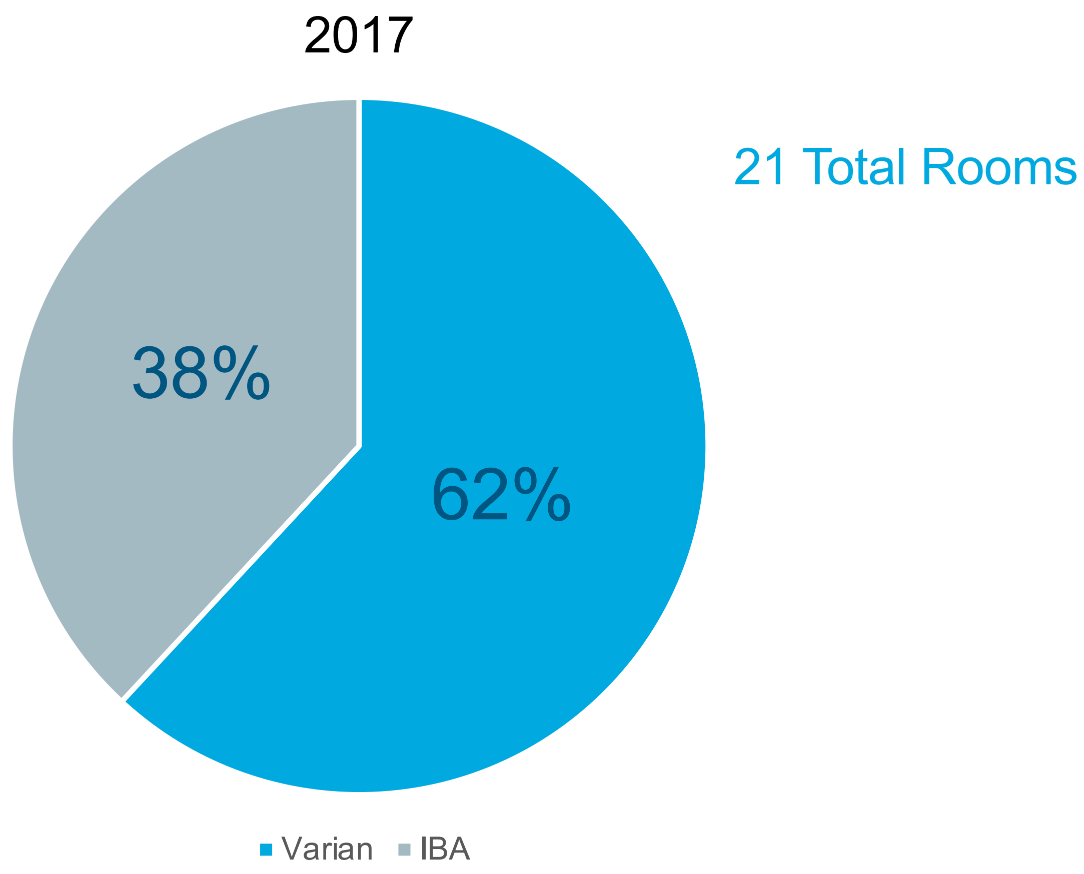
Proton therapy global market share

2014 to 2017 sales by number of rooms





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Increasing global cancer burden…

Expected to grow to 27M new cancer cases in 2050*

Now globally:
- 76 centers
- 203 rooms

3.2M
Proton Therapy Patients

10,700
Treatment Rooms**

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50% market share
assume 2 rooms / system

Implication
90 systems per year
2020 – 2050

Huge potential market, provided systems can be low cost and compact

* American Cancer Society, Global Cancer Facts and Figures, 2007
** Assumes 60% of patients receive radiation, 20% of those are treated with protons, 300 patients per room (current throughput)

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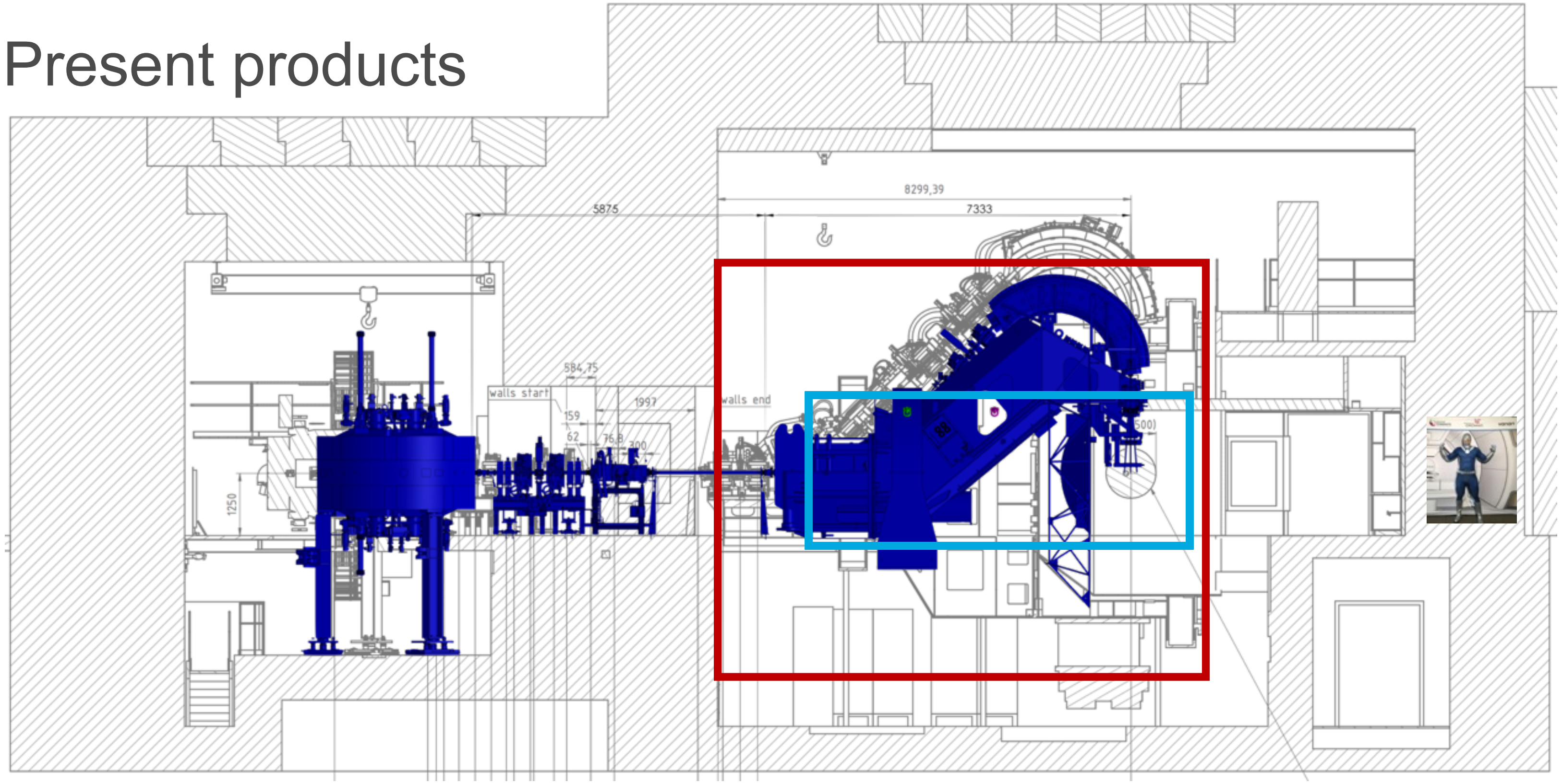
ProBeam® Systems

Size and Cost Complicates Market Penetration

Present products



70+
rooms sold

Varian ProBeam®
- SC accelerator, NC beamline
- Status-of-Art clinical quality

Varian ProBeam® 360°
- SC accelerator, NC beamline
- Limit of Normal Conducting solutions

Mevion H8.5m x L10m
- SC accelerator on Gantry
- Trade-off of size versus beam quality

Varian TrueBeam® H3.2m x L8m
- Photon treatment
- Very compact in comparison

> 7,750 systems installed base

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Potential for size reduction

Using superconducting technology

ProBeam® Compact

- 4,500 square feet
- Optimized for compactness
- Fully IMPT capable
- Advanced image guidance

Potential use of superconductivity

Cyclotron
- Main field coils
- “Flutter” coils

Gantry
- Main bend magnets
- …

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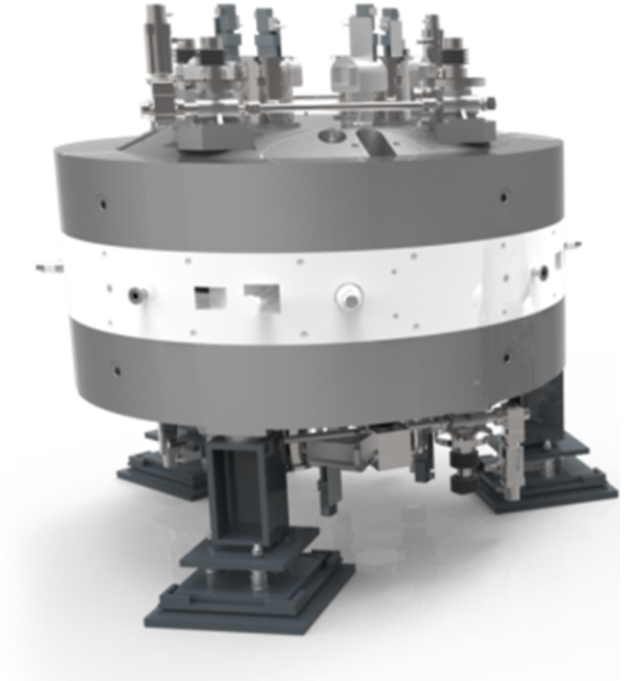
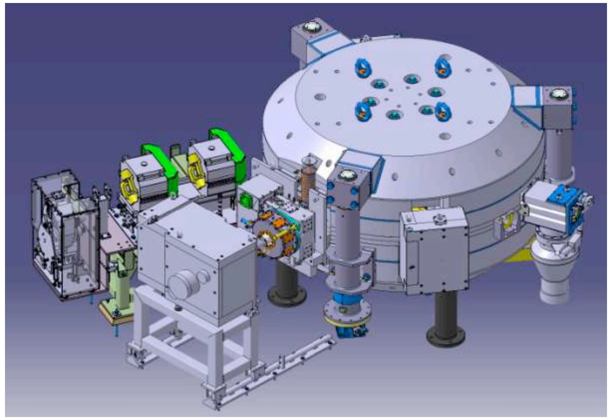
What has been done?

All closed LHe bath + cryocoolers

Varian AC250

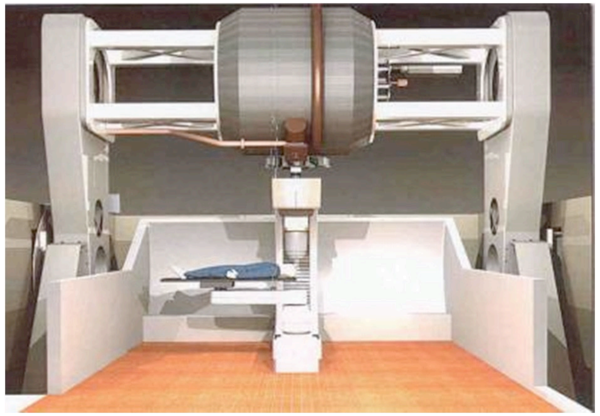
Type:	Isochronous cyclotron
B-field:	2.4 Tesla (Nb-Ti)
Weight:	90 tons
Beam energy:	250 MeV
Avg. current:	800 nA continuous





IBA S2C2

Synchro cyclotron
5.7 Tesla (Nb-Ti (+Nb_3Sn?))
55 tons
230 MeV
130 nA pulsed



Mevion SC250

Synchro cyclotron
9 Tesla (Nb_3Sn)
25 tons
250 MeV
19 nA pulsed

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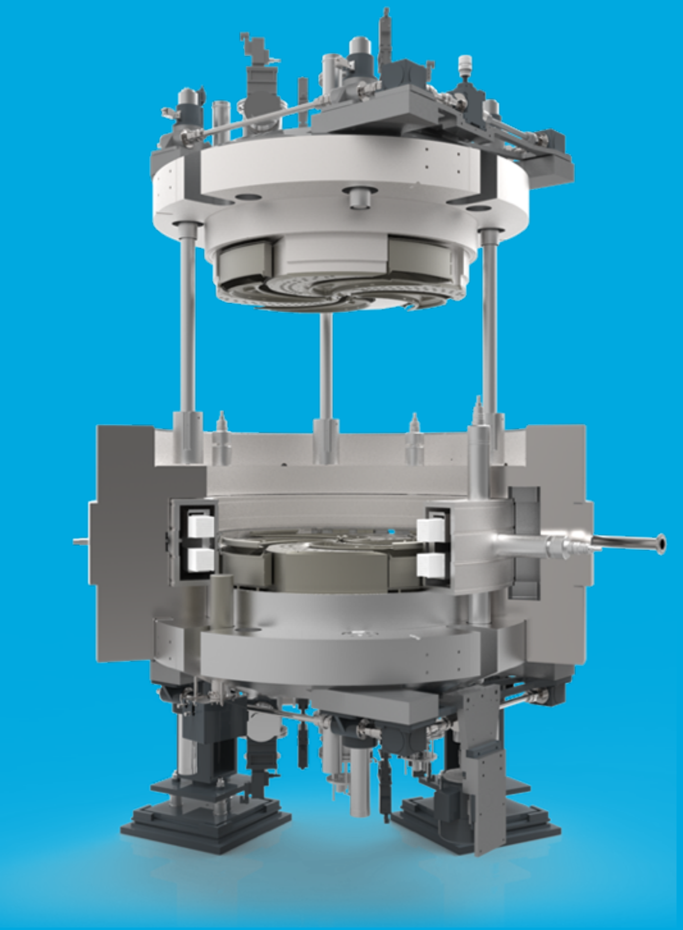
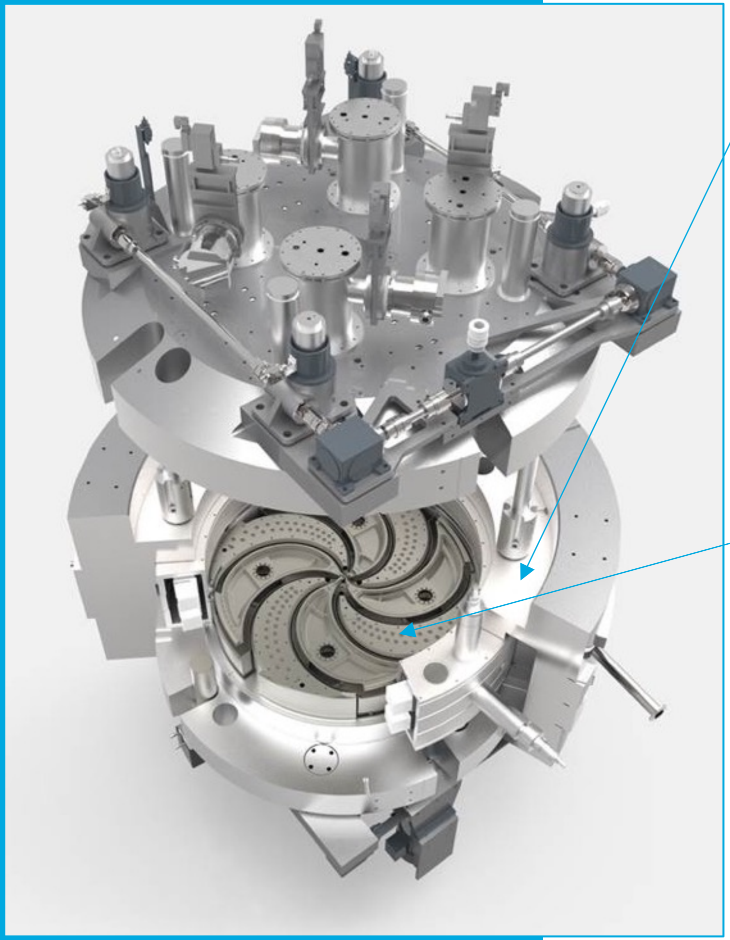
Varian AC250 → Isochronous

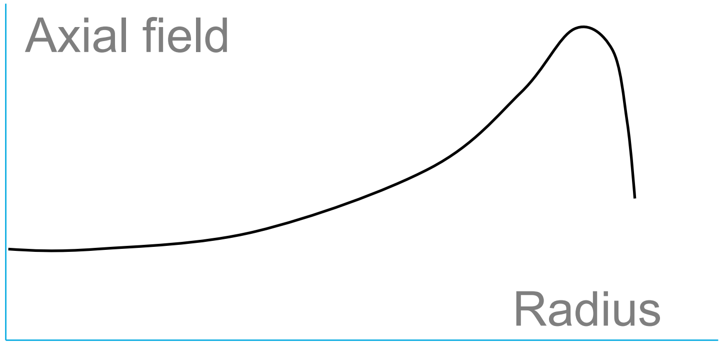
More difficult to make small than synchro-cyclotron



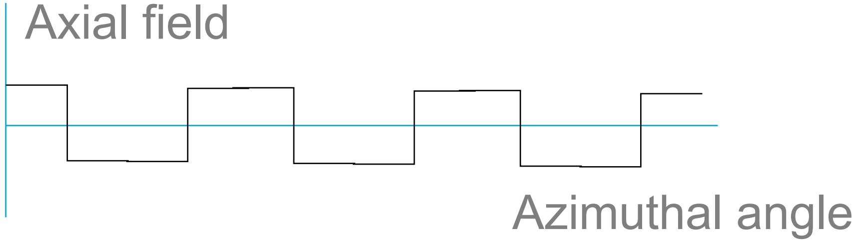


Magnetic field profiles (sketches)

- Nb-Ti main coils
  - Isochronism at high energies



- Iron poles pieces “flutter”
  - Beam stability (focusing)



- Smaller diameter → Higher field
  - **SC “flutter” coils**

What can superconductivity do?

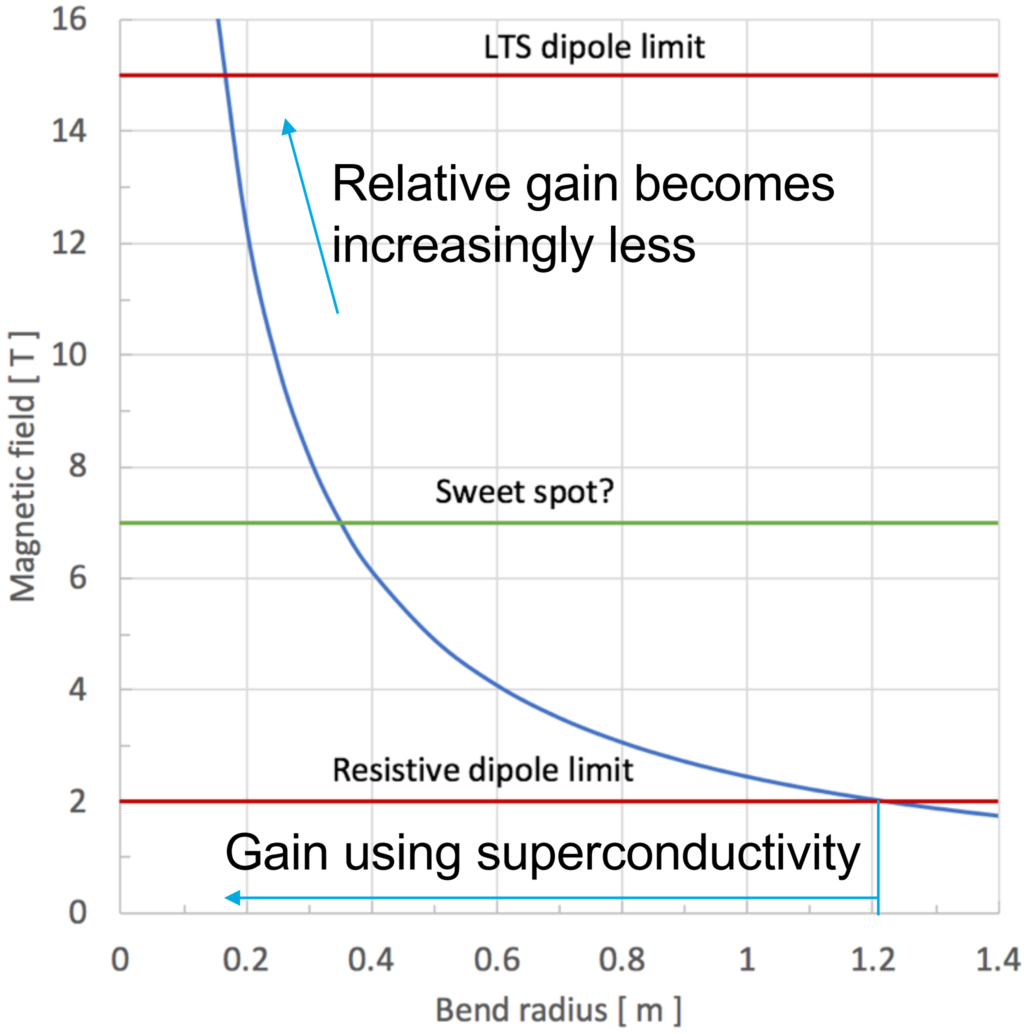
Basics: Particle moving in a magnetic field

$$Bqv = \frac{mv^2}{r} \rightarrow B = \frac{mv}{q} = \frac{p}{qr}$$

$$E_{\text{kin}} = \frac{1}{2}mv^2 \text{ and } m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$\rightarrow m = m_0\left(1 + \frac{E_{\text{kin}}}{m_0 c^2}\right) \text{ and } v = \sqrt{\frac{2E_{\text{kin}}}{m}}$$

$$\rightarrow B = \frac{2.445}{r} \text{ for protons at 230 MeV}$$



Superconducting Gantry final bend → At most a 1 meter radius reduction
Compact accelerators also ~7 T → But SC flutter coils when isochronous

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Conductor options

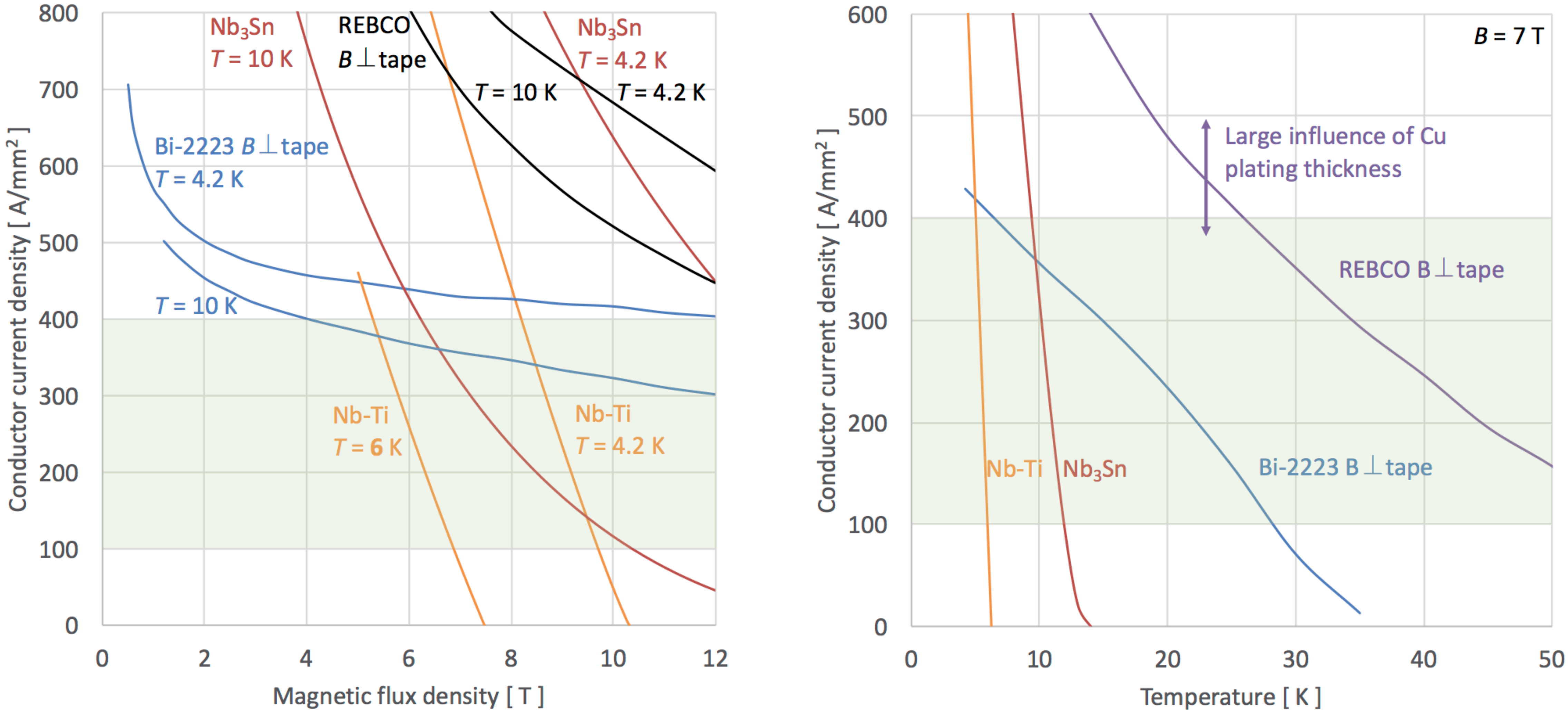
HTS compared to LTS: Ideally cryogen-free systems

- **Nb-Ti** (~ $1.50 / m)
  - Cheap and ductile, but 0.5 to 1 K margin at 4 K (risk)
- **Nb_3Sn** (~ $3.50 / m)
  - Wind-and-React – difficult insulation + heat-treatment adds risk and cost
  - Pre-reacted – more costly than W&R + still requires 4 K cryogenics
- **Bi-2223** (~ $20 – $30 / m)
  - Cost competitive with W&R Nb_3Sn and cost has downside potential
  - Mature conductor, medium magnetization, 10 K cryogenics, cheap cable
- **Bi-2212** (~ $20 – $30 / m)?
  - Isotropic round wire with separated filaments, high Je when reacted under pressure
  - Reaction (under high pressure?) at 900 °C in oxidizing environment
- **REBCO** (~ $30 – $100 / m)
  - High Je, high cost, large magnetization, expensive cables, and single crystal conductor (risk)

Conductor performance

Ideally cryogen-free, conduction-cooled with cryocoolers

Nb-Ti: Record dipole quality
Nb_3Sn: ITER bronze quality
Bi-2223: DI-BSCCO Type HT-NX, B//c
REBCO: 32 T quality (Abraimov), B//c



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High temperature superconducting cable developments

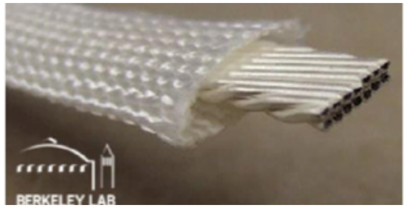
Cyclotron main coils and Gantry magnets likely will need cables

Available high Je HTS Cables	Recent Bi-2223 Cable

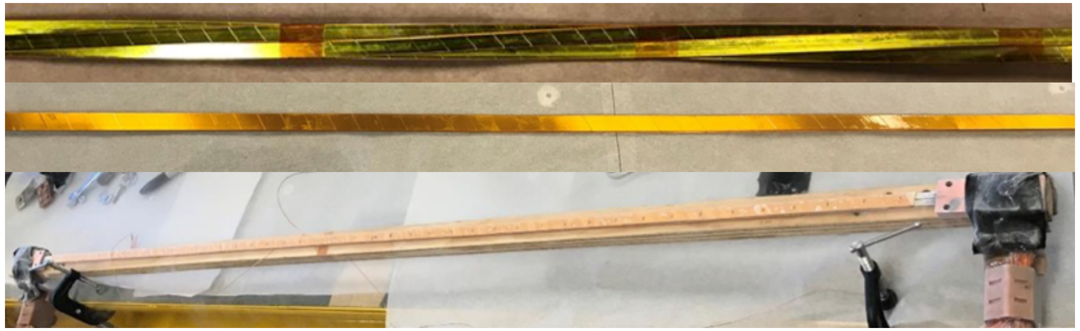
- Pre-reacted REBCO (**several k$ per m**)
  - Roebel (CERN)

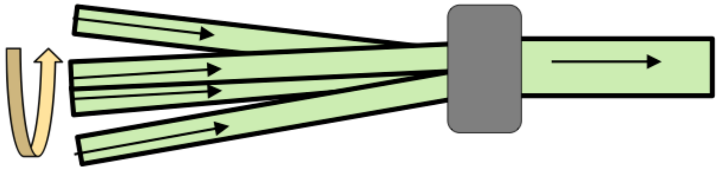
  - Cable on Round Core (Advanced Conductor Technologies)

- LBNL / OST Bi-2212
  - Needs **900°C in O_2** heat treatment

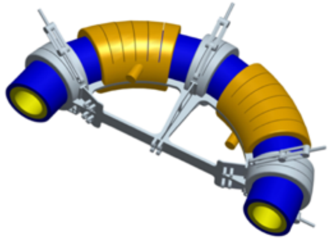


- DI-BSCCO HT-NX Roebel (**≪ $500 per m**)
  - Solid Material Solutions' Transposed Tape Cable



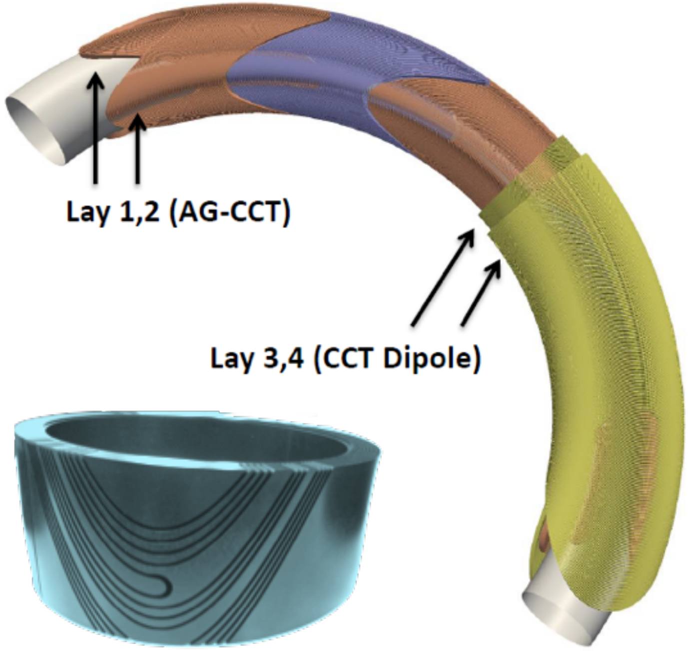


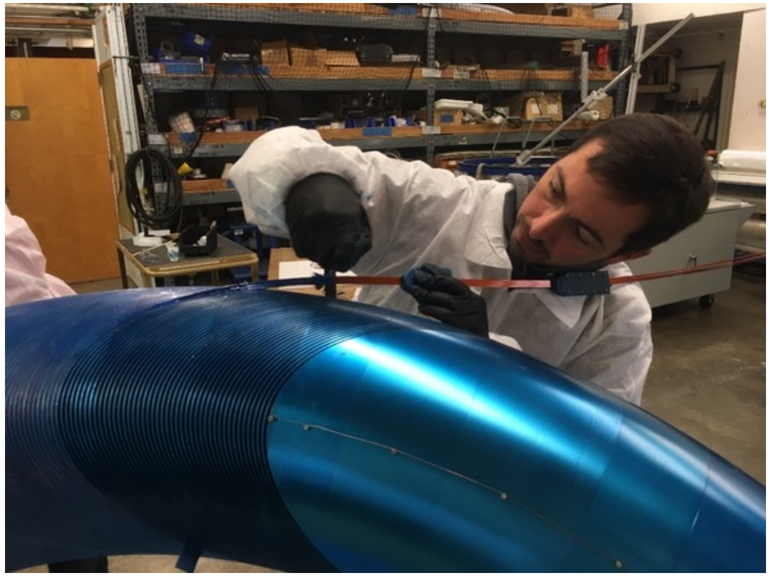
Probing studies on superconducting Gantry magnets



Nb-Ti Combined Function Magnet with *Large Momentum Acceptance*

Combined function magnet built from curved sections	Superconductor insertion into machined grooves	Assembly of second dipole layer over finished first





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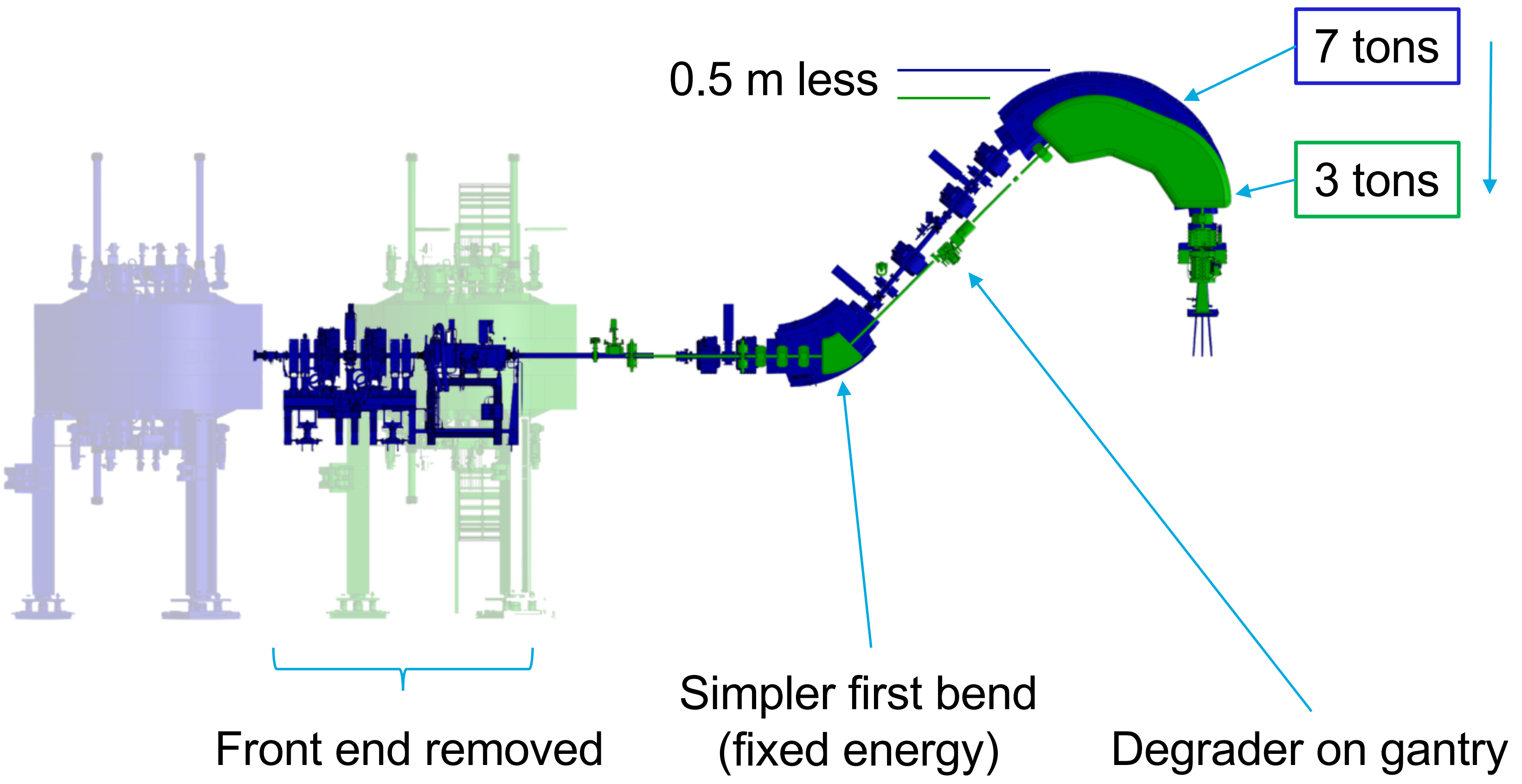
ProBeam® 360 with SC final bend magnet

Utilizing the Larger Momentum Acceptance Provided by superconductivity



- Pros
  - Smaller radius
  - Lighter magnet
  - Smaller building
  - *Energy variation*
- Cons
  - More complex (risk, cost,…)
  - Cryogenics
  - *Energy variation*
  - Ho-Hum diameter reduction

Larger gains require more than just superconductivity

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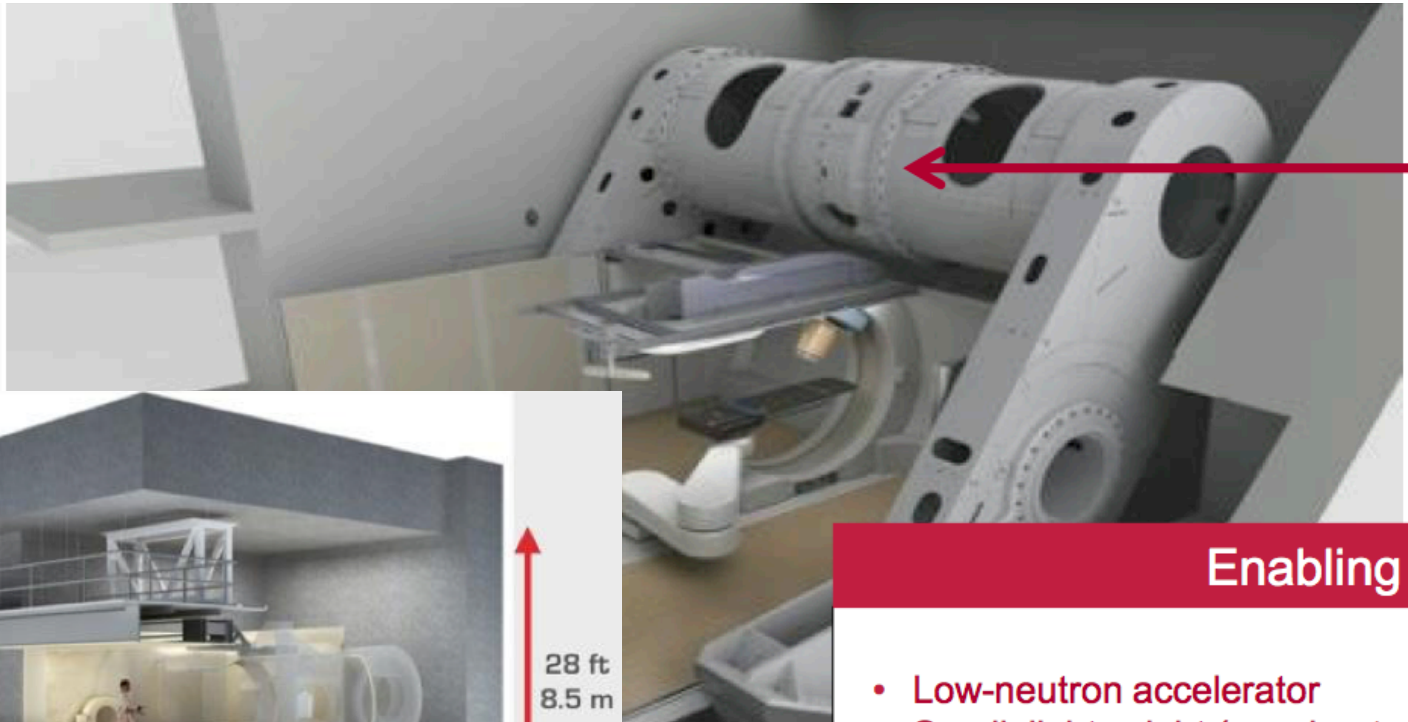
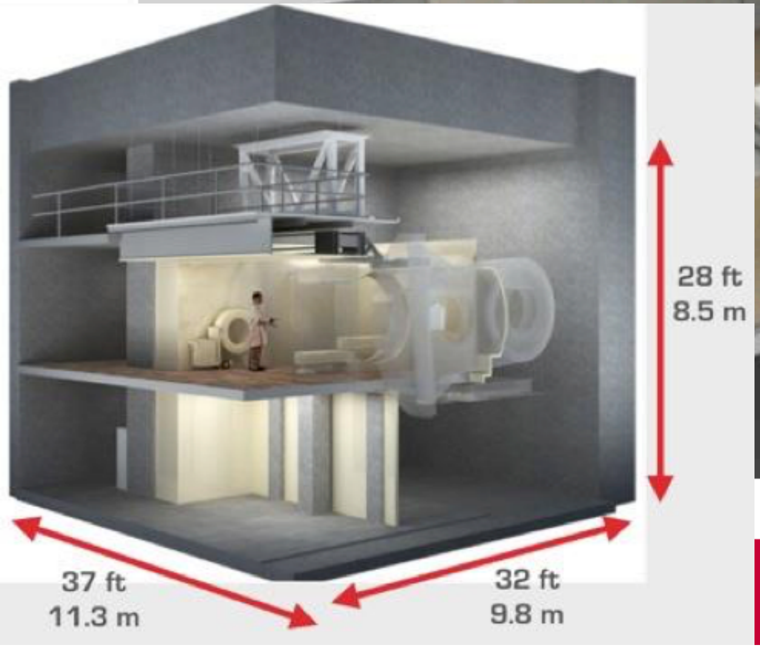
Mevion Gantry-mounted accelerator

System diameter and weight driven by the accelerator

Compact synchro-cyclotron enabled by Nb_3Sn main coils





Enabling Technology

- Low-neutron accelerator
- Small, lightweight (accelerator 17 tons)
- “Direct Beam” – no beam transport
- Pulse width modulated intensity control (Dynamic Range 20)

Summary

Does HTS have a future in medical applications?

- NMR → Beyond 1 GHz
  - Clear market potential due to lack of alternatives
  - Small market
- MRI and isotope production
  - Unlikely, due to high cost, but drive for cryogen-free could help
- Proton and heavier ion therapy → Yes, if business case for HTS in favor of LTS can be made
  - HTS is attractive; but **cost**, maturity, magnetization, length, quench, experience, reliability, strain…
  - Nb-Ti has only about 1 K temperature margin at 7 T
  - Nb_3Sn carries a lot of current but requires reaction for small radii
  - Huge potential market, *but* systems need to become more compact, simpler, and much lower cost

Only 1% of cancer patients receive proton therapy when 20% would benefit

(Thank You)