An Advanced Superconducting Cyclotron for Variable Energy Hadron Therapy

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Outline

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- Evolution of Cyclotrons for Proton Radiotherapy
- Technical Innovation
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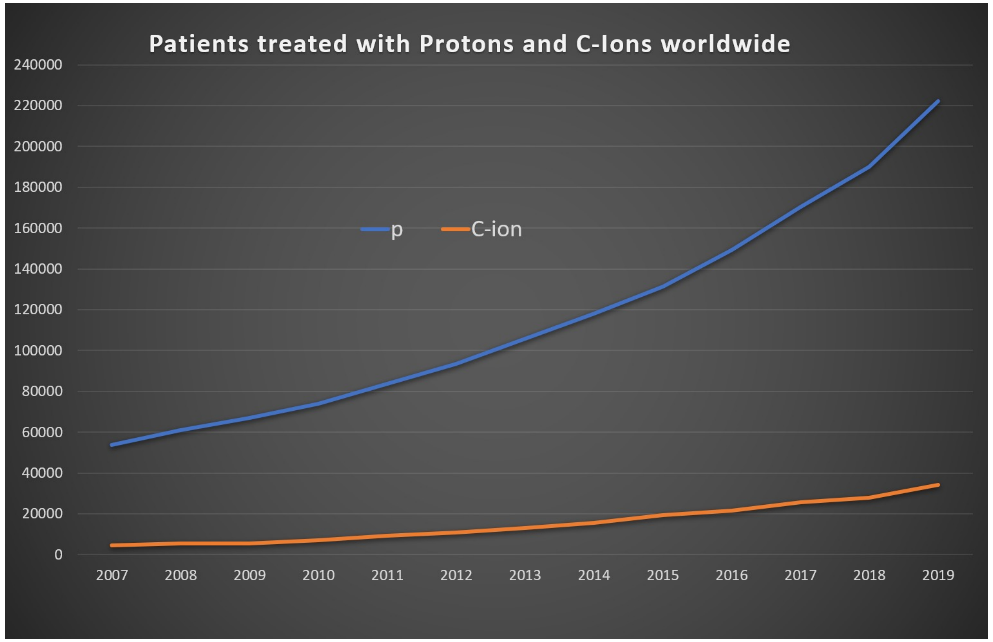
Motivation

- Per end of 2020 more than 290,000 patients have been treated worldwide with Particle Therapy:
  - ~250,000 with protons
  - ~40,000 with C-ions
  - ~3,500 with He, pions and with other ions.

- 89 proton radiotherapy centers operating worldwide
  - 35 in USA
  - 41 proton radiotherapy centers under construction

- 13 carbon radiotherapy centers operating worldwide



Historically hadron radiotherapy centers have been huge installations with multiple treatments rooms costing as much as $200M per facility for protons and even more for carbon.

More recently companies have reduced the number of treatment rooms per facility (1-2) and reduced the accelerator size for protons by using superconducting cyclotrons.

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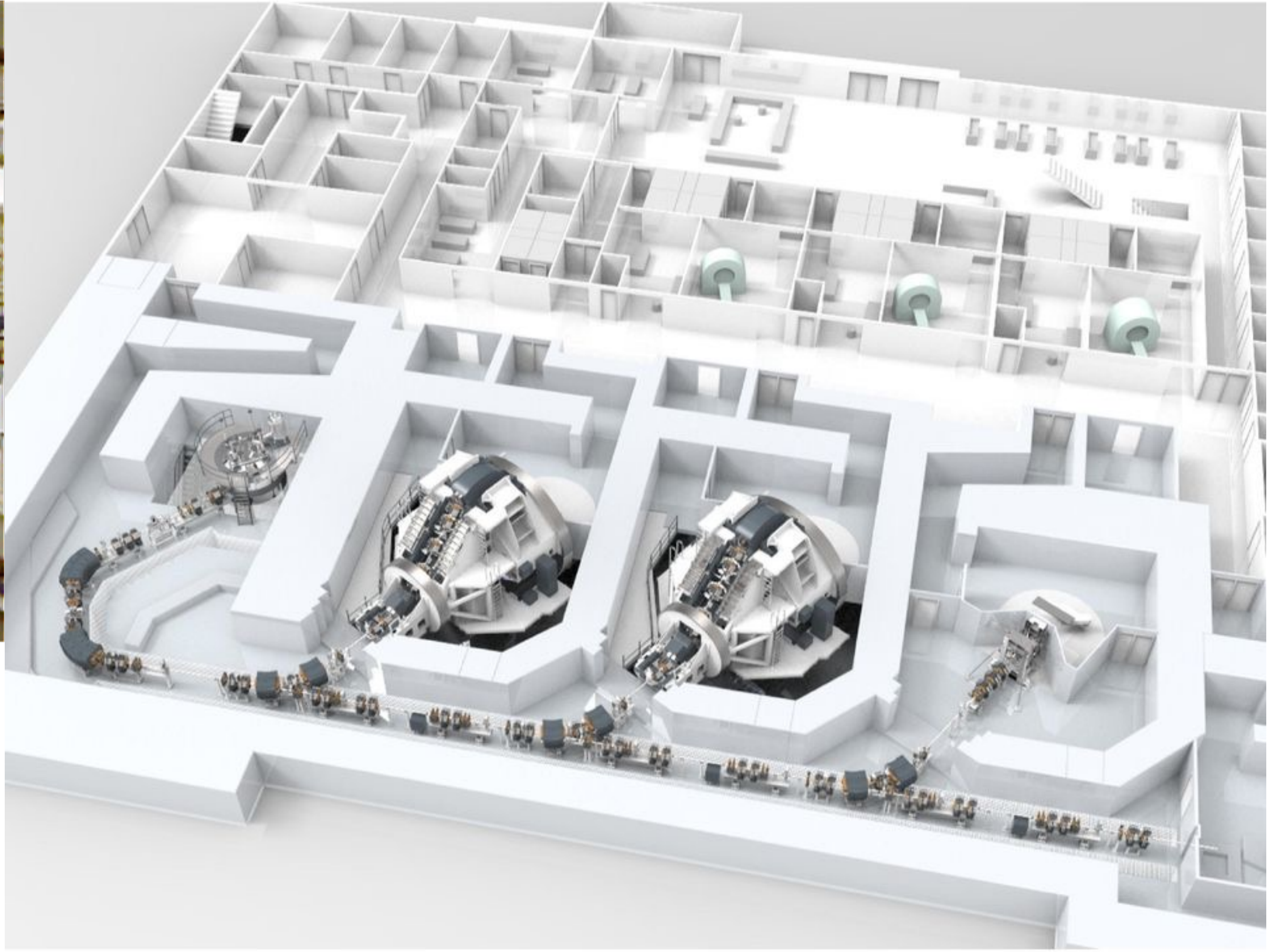
Motivation

- This change in facility size has been driven by the desire to reduce the cost of proton radiotherapy and to increase the availability to the wider population.
- To make the benefits of hadron therapy available to more people we must:
    - Reduce the cost of the system
    - Reduce the footprint
    - Simplify the system
    - Simplify the operation
    - Improve the accuracy and effectiveness of the particle beam

Evolution of cyclotrons for radiotherapy

IBA C230

- 230 MeV protons
- 4.3 m Diameter
- CW beam
- Normal conducting
- Magnet: 200 kW
- RF: 60 kW
- **~240 tons**



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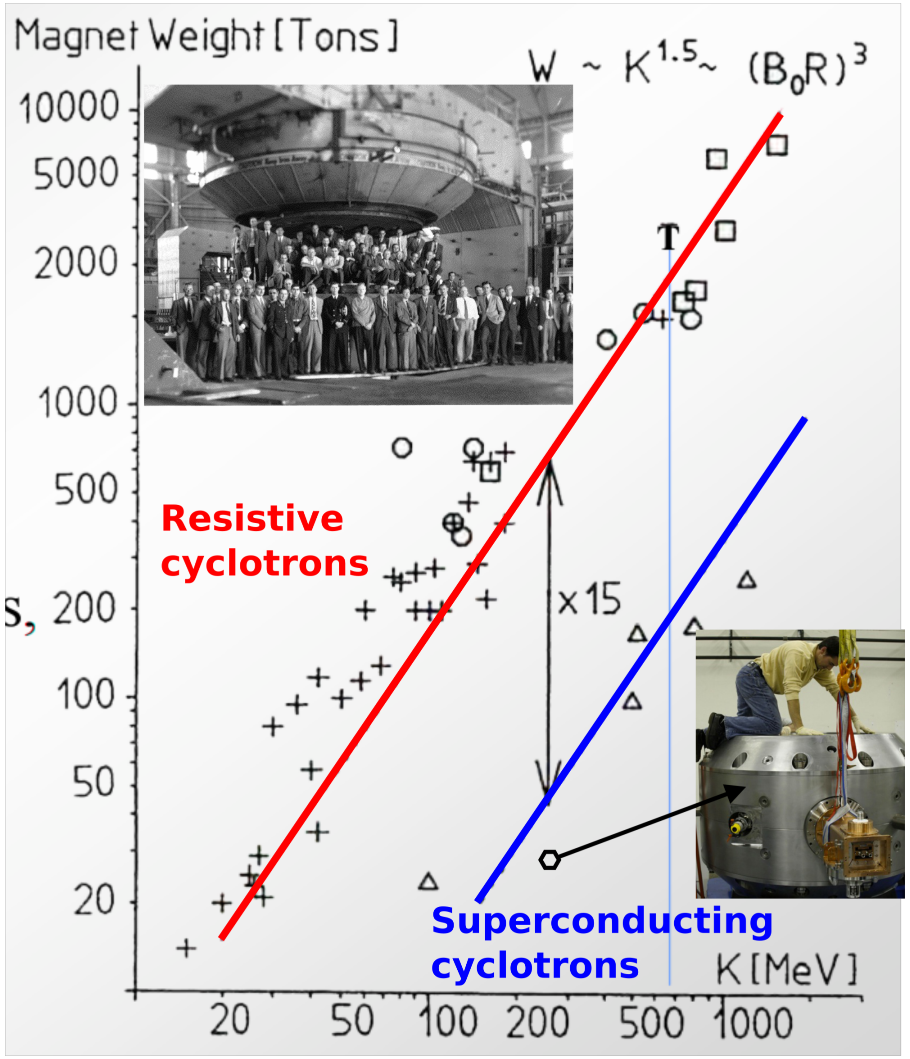
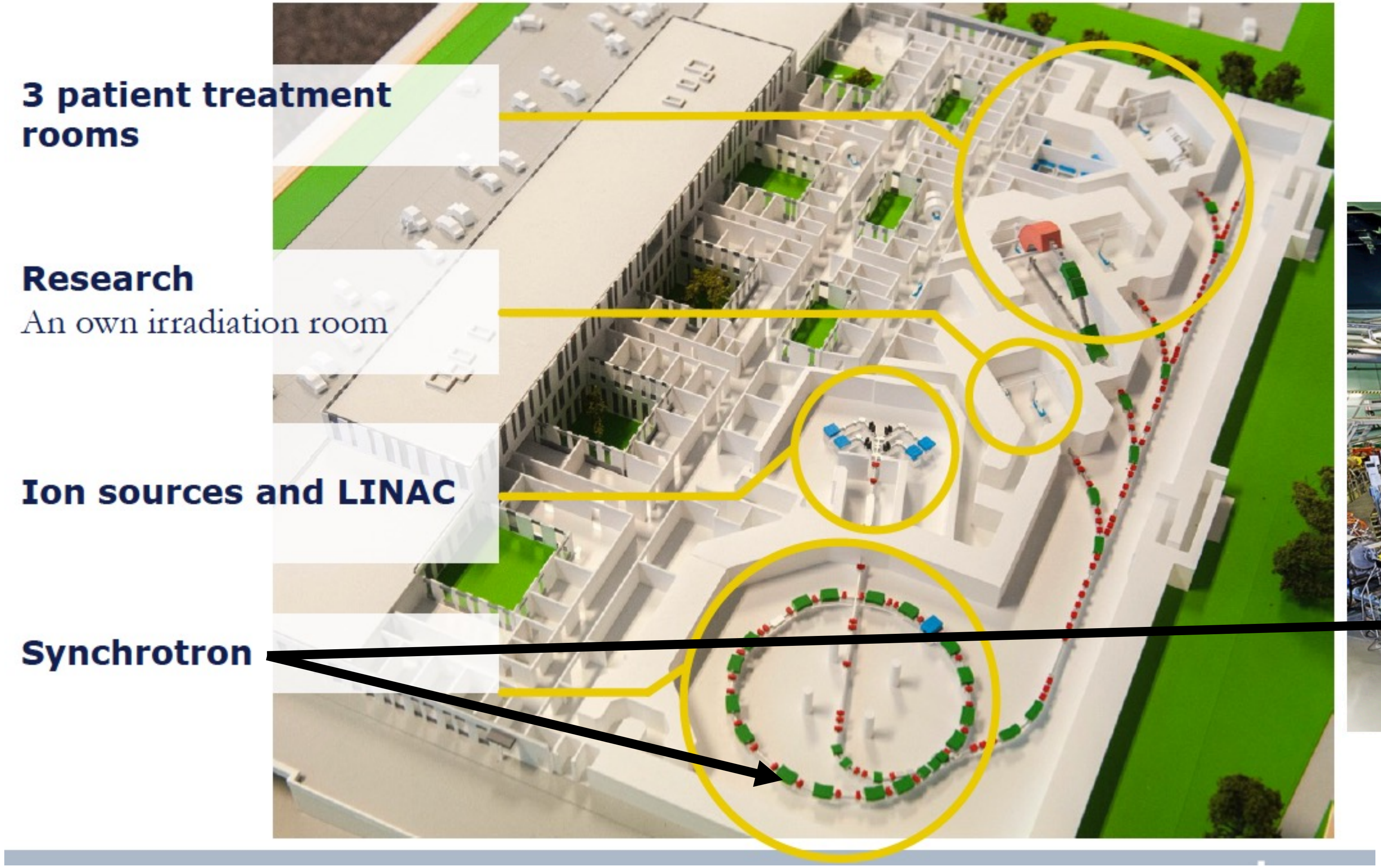
Evolution of Cyclotrons for Radiotherapy

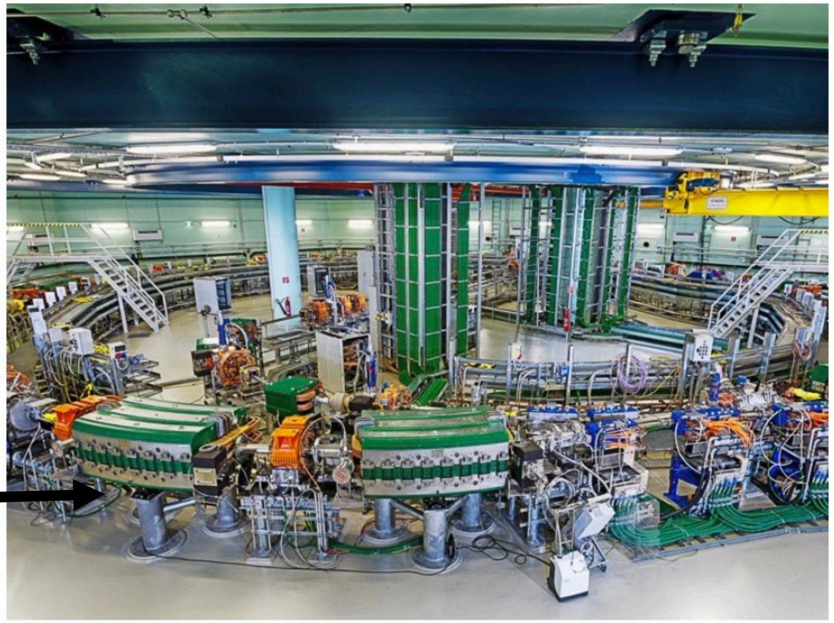


	Mevion S250	IBA S2C2	Varian Proscan	IBA C230
Magnet Type	Superconducting	Superconducting	Superconducting	Copper
R pole (m)	0.34	0.50	0.80	1.05
D Yoke (m)	1.80	2.50	3.10	4.30
Height (m)	1.20	1.50	1.60	2.10
B_o (T)	8.9	5.7	2.4	2.2
B_f (T)	8.2	5.0	3.1	2.9
Mass (mt)	***25***	***46***	***90***	***240***
T_f (MeV)	254	230/250	250	235

Carbon Systems are Even Larger

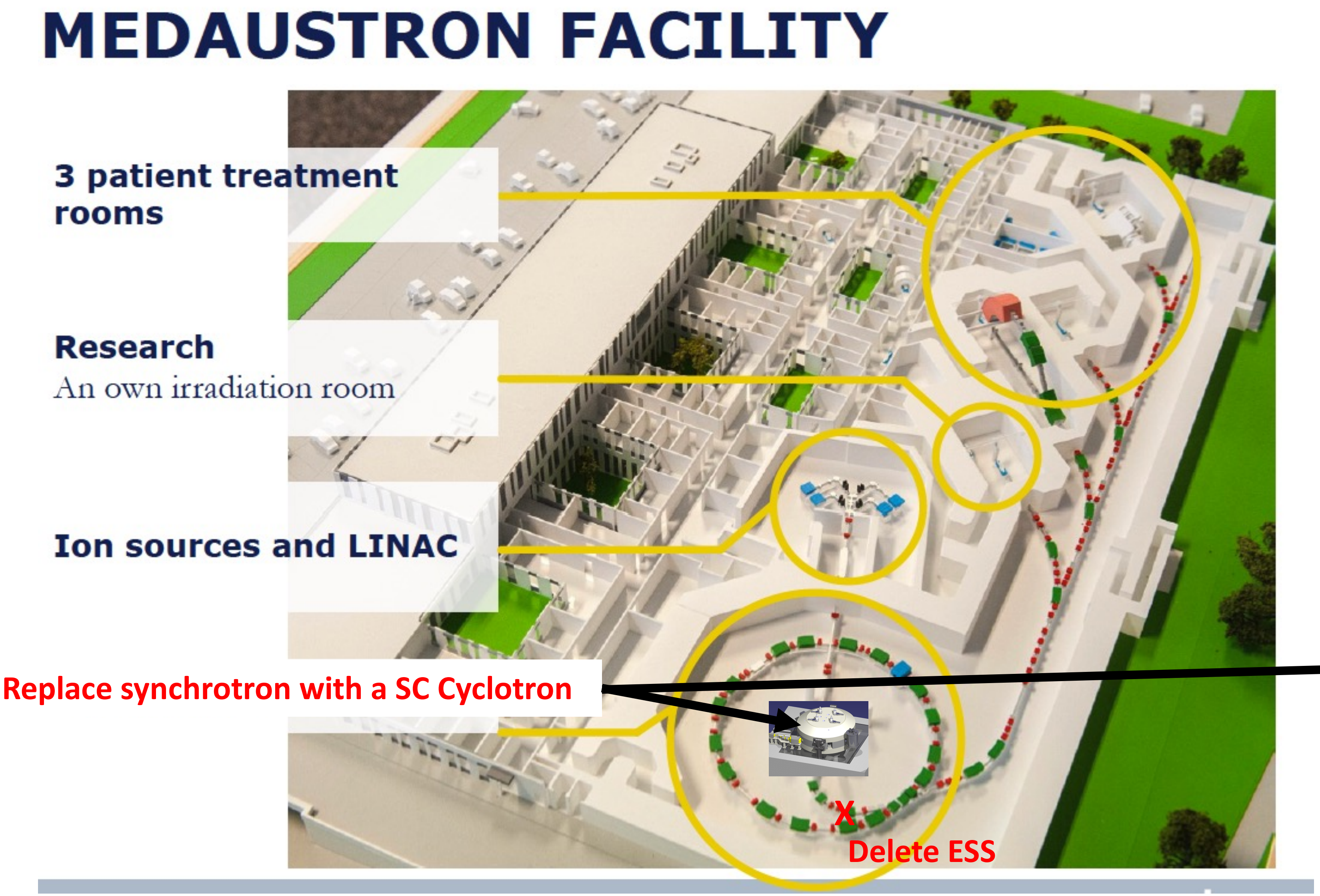
MEDAUSTRON FACILITY



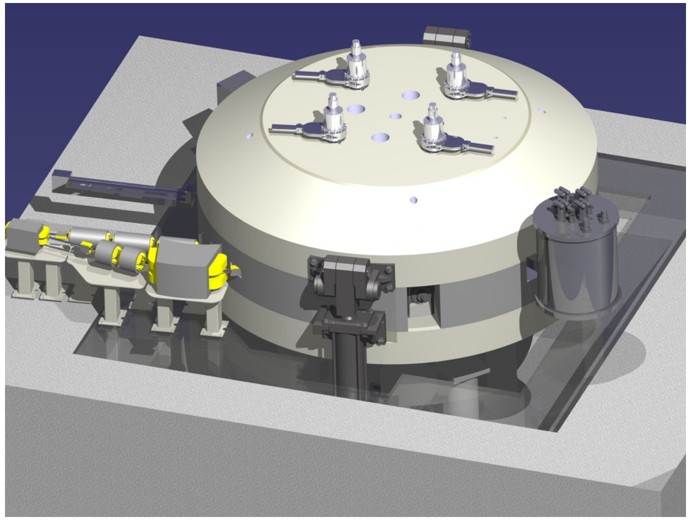


Dia. = ~24m

Carbon Systems are Even Larger



IBA SC400 SC IsoCyclotron



Dia. = 6.6m

Weight = ~700 tons

~ 1/3 diameter of synchrotron

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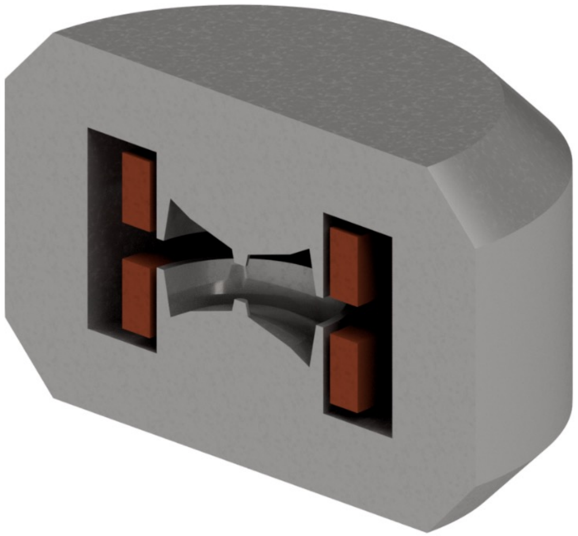
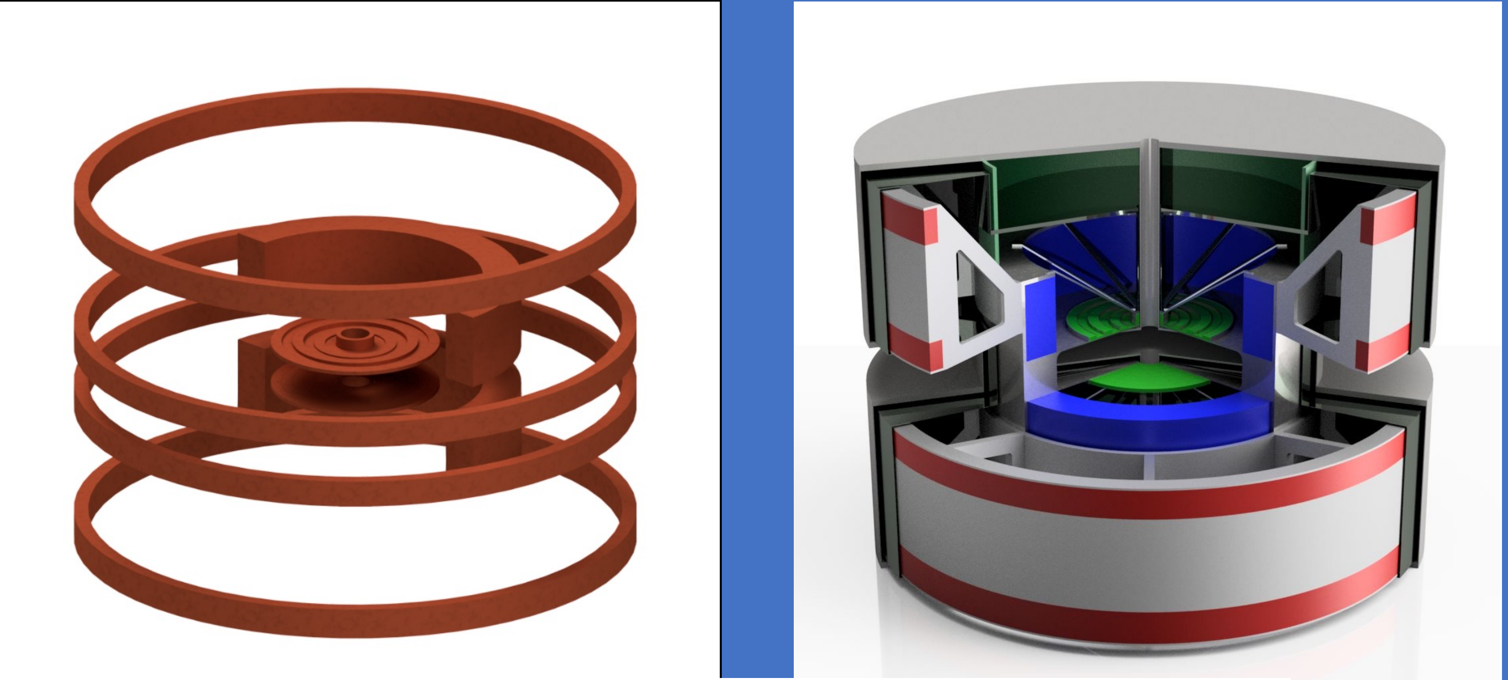
Technical Innovation

- Start with a superconducting synchrocyclotron and then remove all iron from the flux circuit (iron yoke).
- Shield external field with superconducting coils as is done in present MRI magnets.



Superconducting synchrocyclotron with iron yoke



Superconducting synchrocyclotron with shielding coils

Technical Innovation

- Beam energy is quadratically proportional to magnetic field and radius at extraction (synchrocyclotron):

$$T_{ex} = \frac{q^2 B_{ex}^2 R_{ex}^2}{2m}$$

- Removing all magnetic material from the magnetic circuit makes the field magnitude *linearly* proportion to the operating current at all radii:

$$B \propto I$$

- ***Thus, beam energy can be varied directly by changing the magnet operating current.***

Benefits

- Variable Beam Energy by controlling magnet current
- Elimination of degraders for energy variation
  - Greatly reduced secondary radiation, material activation, and need for large shielding
  - Significantly reduced beam dispersion, no loss of beam current, easier focusing

  } Next slide
- Significantly reduced weight – increases transportability
- Reduced fringe field
- Larger mid-plane and axial bore clear spaces –
  - use interchangeable (Ion Source/RF/Extraction) cassettes for different Ions (protons, lithium, carbon)
- Plenty of space inside the cryostat – can be used for efficient low density radiation shields
- No need to shim the iron – big advantage for mass production and commissioning
- No external iron – no positive magnetic stiffness, simpler cold mass support
- No cold iron – less load on cryogenics
- Scaling laws ease magnetic design process

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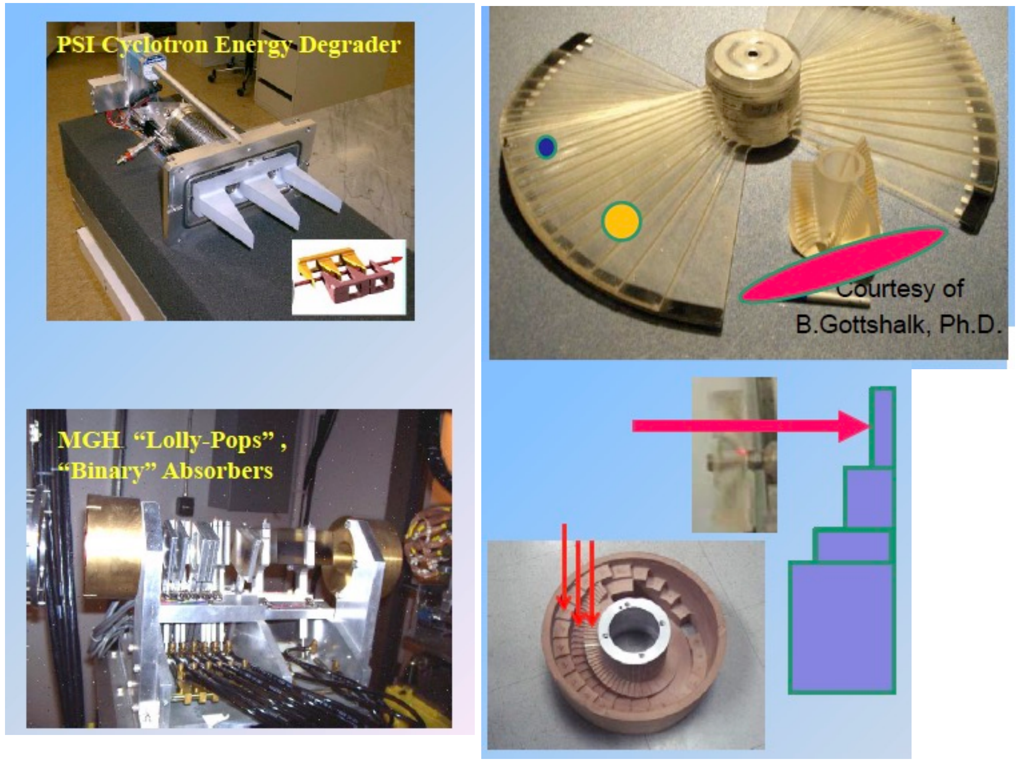

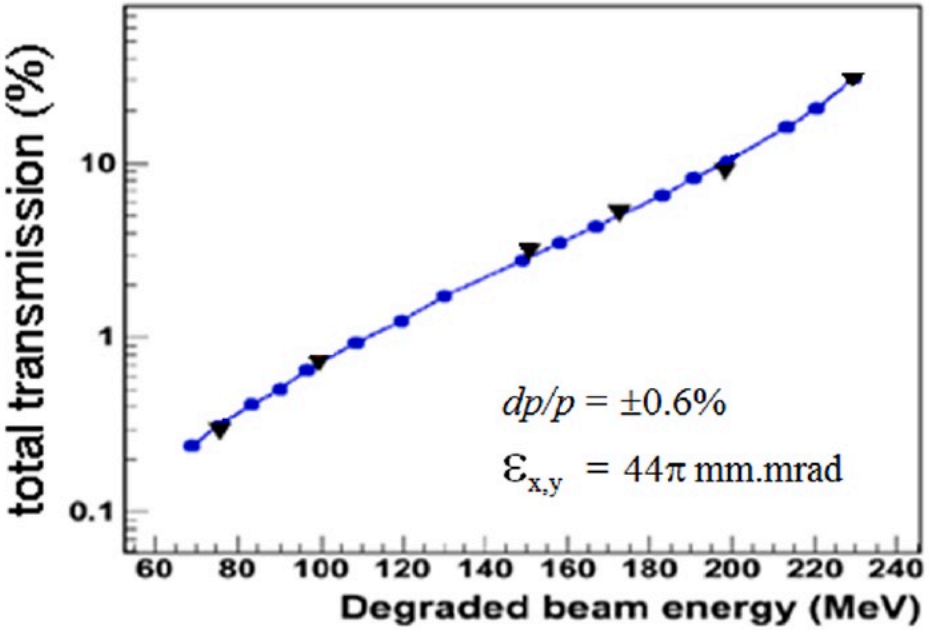

Fig. 4. Example of typical transmission with energy through a cyclotron degrader and ESS: the Paul Scherrer Institute PROSCAN facility; figure reproduced from [60].

[60] Gerbershagen A, Baumgarten C, Kiselev D, van der Meer R, Risters Y, Schippers M. Measurements and simulations of boron carbide as degrader material for proton therapy. Phys Med Biol 2016;61(14):N337–48. https://doi.org/10.1088/0031-9155/61/14/n337.

Transformational Features

- Ability to deliver full beam intensity at all beam energies enables FLASH treatment
  - If proven effective, will have a huge reduction of treatment costs by an order of magnitude reduction in required treatment cycles.
- Scalability to heavier ions all the way to carbon will have high impact on size of accelerator and the space required.
- The radiation oncologist would be able to optimize treatment for each individual and type of cancer suited to ion radiotherapy.
- Will increase access to critical ion beam therapy to serve a larger population of patients and treat a wider range of cancer types.

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Summary

- Superconducting cyclotrons are replacing restive cyclotrons for PBRT.
- New developments in superconducting magnet technology can be used to to design *variable energy cyclotrons* rather than fixed energy cyclotrons required and remove the wasteful energy degrader.
- This opens up new treatment methods such as FLASH therapy.
- The technology can be extrapolated to reduce the size, cost, and complexity of heavy ion systems up to carbon.
- These innovations will lead to much wider acceptance of hardon radiotherapy and significantly expanded patient access to this critical medical technology.