Particle therapy machines

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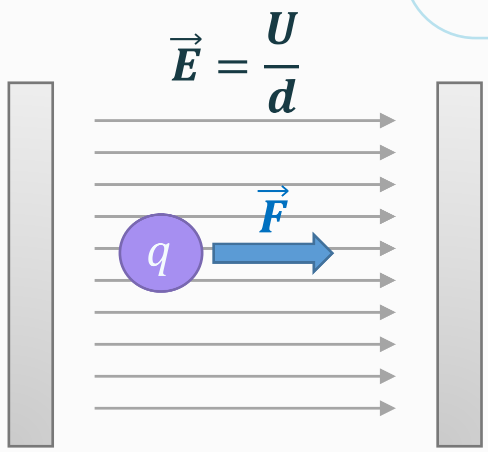
Agenda

- Fundamentals of particle beam production
- Accelerators: Cyclotrons and Synchrotrons
- Beam delivery: active scanning
- Gantries
- Facility examples

Governing forces in ring accelerators

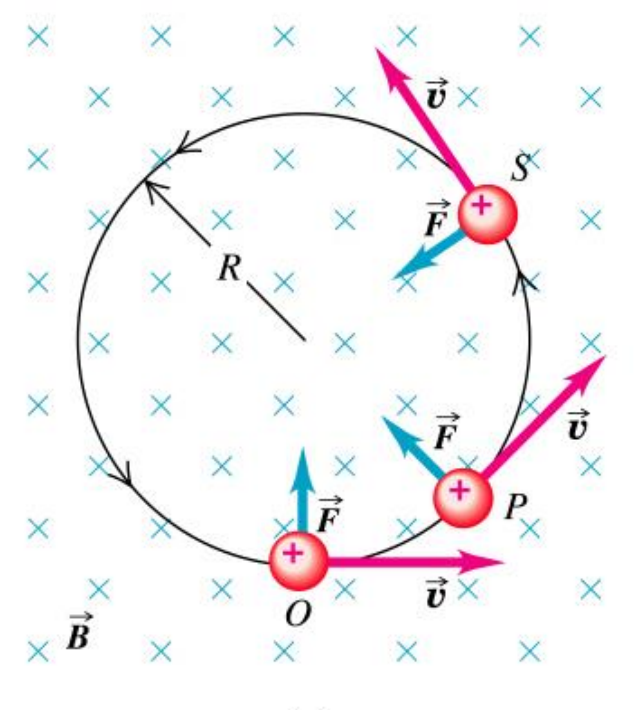
- The Lorentz force: $\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$
- Electrical component $\vec{F} = q\,\vec{E}$
- **Force acts on object with a charge q**
  - **in the direction of the electric field E**
  - **acts on objects at rest ($v = 0$)**
  - **accelerates the object**
  - **independent of the object's mass m**
- **Objects traversing an electric field will gain kinetic Energy $E_{kin} = qU$**

force $\vec{F}$
charge q
electric field $\vec{E}$
voltage U
velocity $\vec{v}$
magnetic field $\vec{B}$



Governing forces in ring accelerators

- The Lorentz force: $\vec{\boldsymbol{F}} = \boldsymbol{q}(\vec{\boldsymbol{E}} + \vec{\boldsymbol{v}} \times \vec{\boldsymbol{B}})$
- Magnetic component $\vec{\boldsymbol{F}} = \boldsymbol{q}(\vec{\boldsymbol{v}} \times \vec{\boldsymbol{B}})$:
- **acts on a moving object ($v > 0$) with a charge q**
  - **perpendicular to both $\vec{v}$ and $\vec{B}$**
  - **does not change the magnitude of $\vec{v}$, but its direction**
  - **independent of the object's mass m**
  - **counteracted by centripetal force $\vec{F} = m \cdot \frac{v^2}{R}$, object turns on a circular track**



(a)

Governing forces in ring accelerators

- Equality of magnetic Lorentz and centripetal force if B and v are perpendicular:

$$q \cdot v \cdot B = m \cdot \frac{v^2}{R}$$

$$\vec{F} = q(\vec{v} \times \vec{B})$$

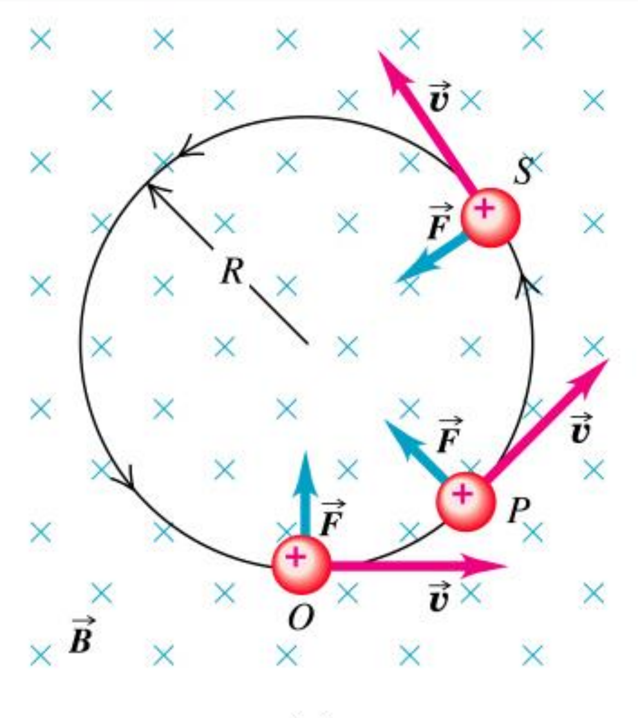
$$\vec{F} = m \cdot \frac{v^2}{r}$$

- allows to derive magnetic rigidity Brho

$$BR = B\rho = \frac{m}{q} v \text{ [magnetic rigidity in Tm]}$$

accelerator properties:
field strength,
bending radius

particle beam properties:
mass,
charge,
speed



(a)

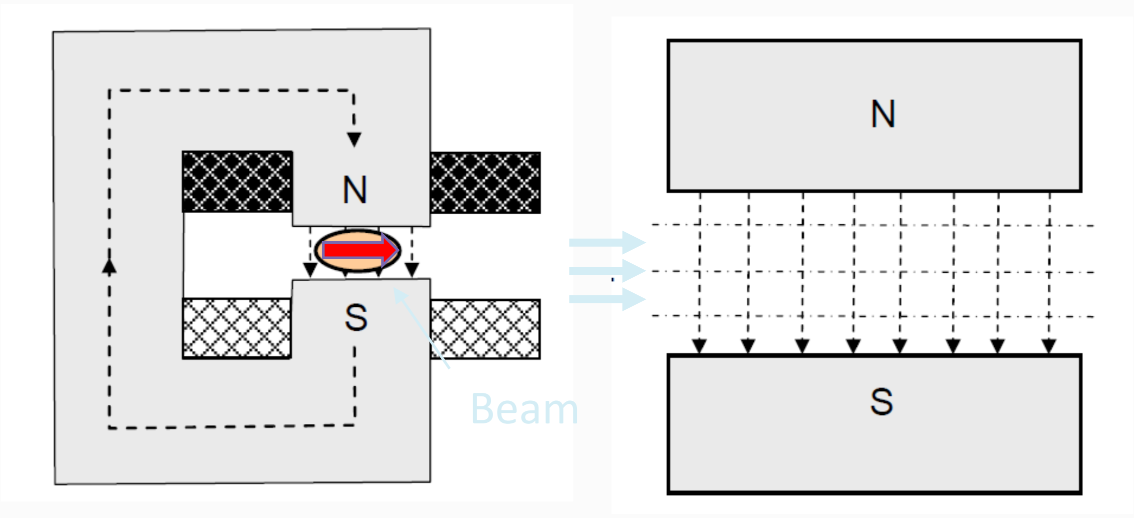
Application of Lorentz forces

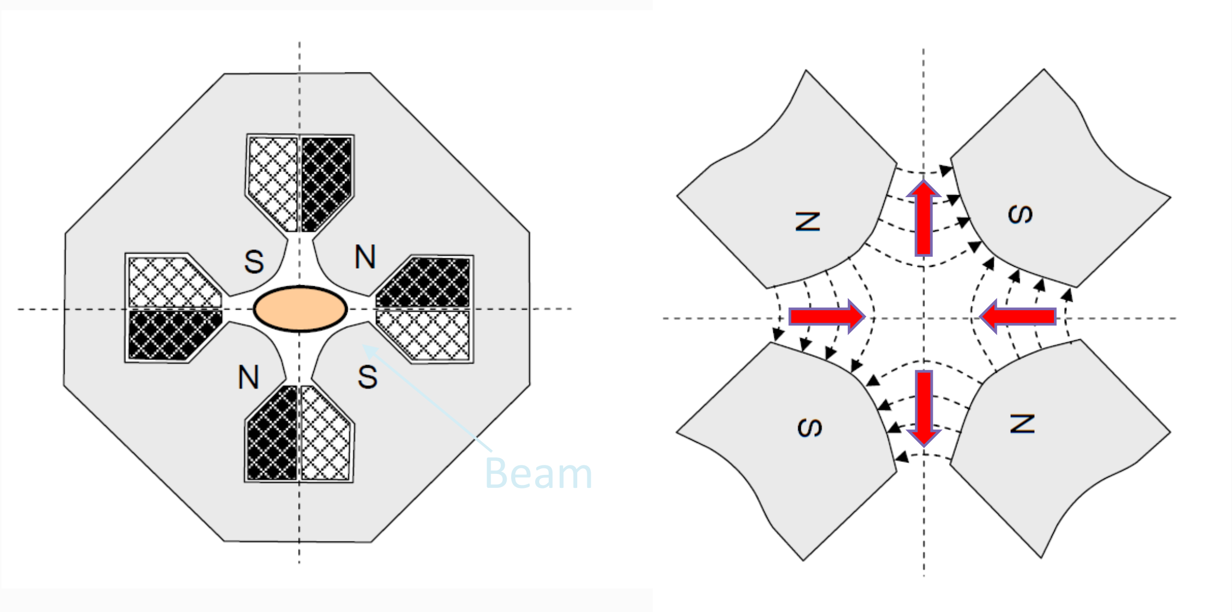
- Electrical component – acceleration
  - can change magnitude of velocity
  - does not scale with velocity
- Magnetic component – steering and focusing
  - changes vector, but not magnitude of velocity
  - scales with velocity – much more effective at high speeds

Dipoles and Quadrupoles

- Basic forms of magnets in acceleration

Forces on a positive charged ion traveling out of the screen

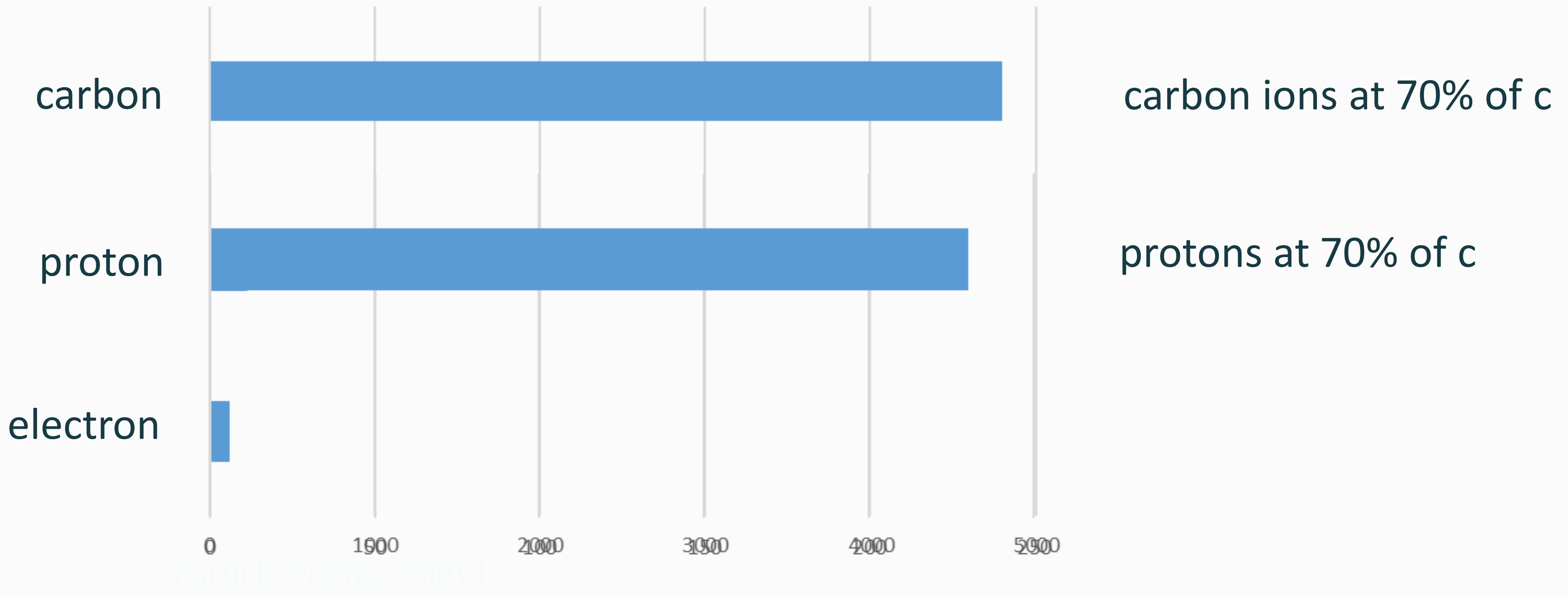




Task: Bending Focusing

Particles need bigger accelerators…

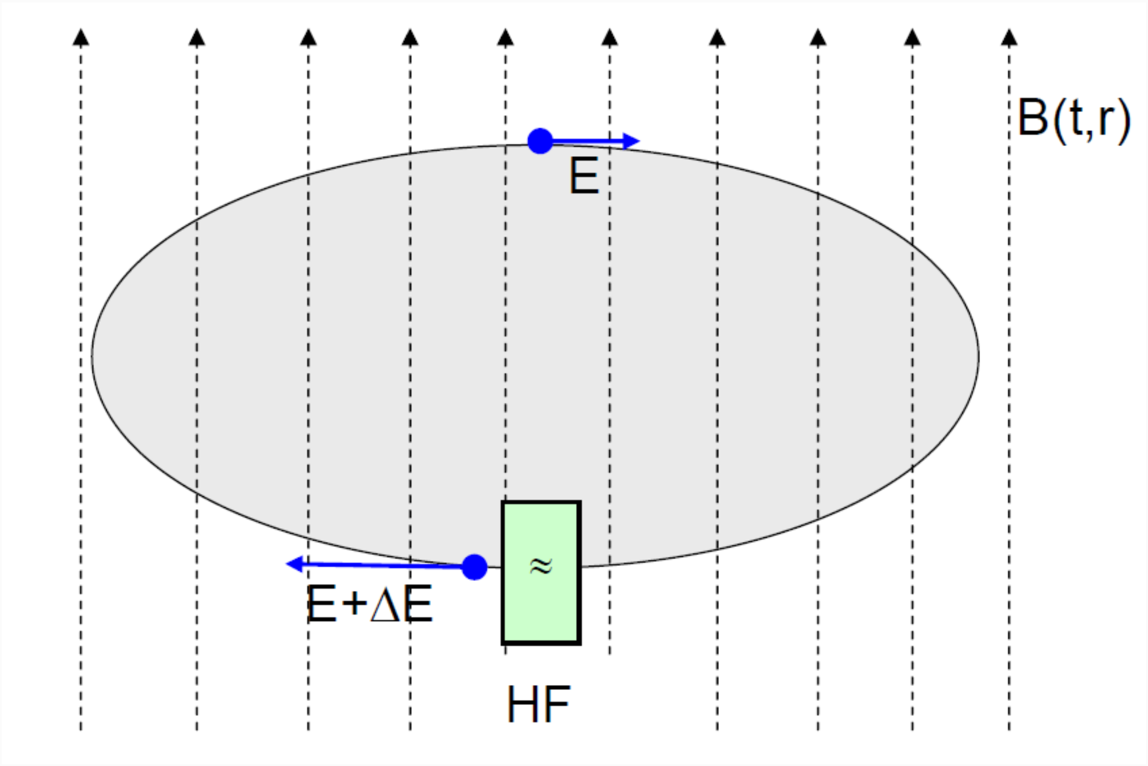
- Protons and ions need much higher energies for sufficient penetration



Magnetic rigidity of this proton beam: 2.2 Tm, of this carbon ion beam: 6.7 Tm

Ring accelerator principle

- To achieve high energies, re-use accelerating cavity
- Requires
  - synchronization of particle rotation and cavity HF
  - some form of magnetic fields to return particles to cavity again and again
- Realizations for particle therapy: cyclotrons and synchrotrons



Nozzle - everybody scans...

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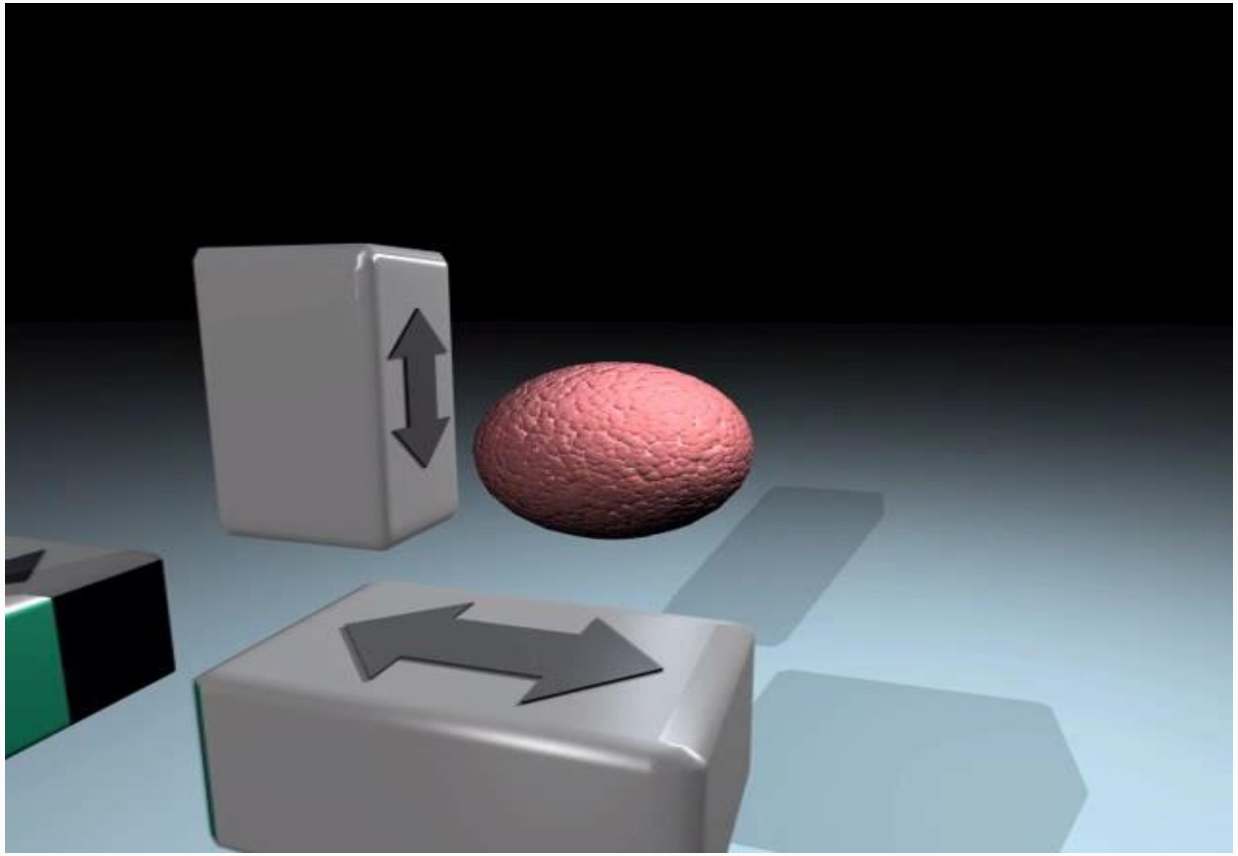
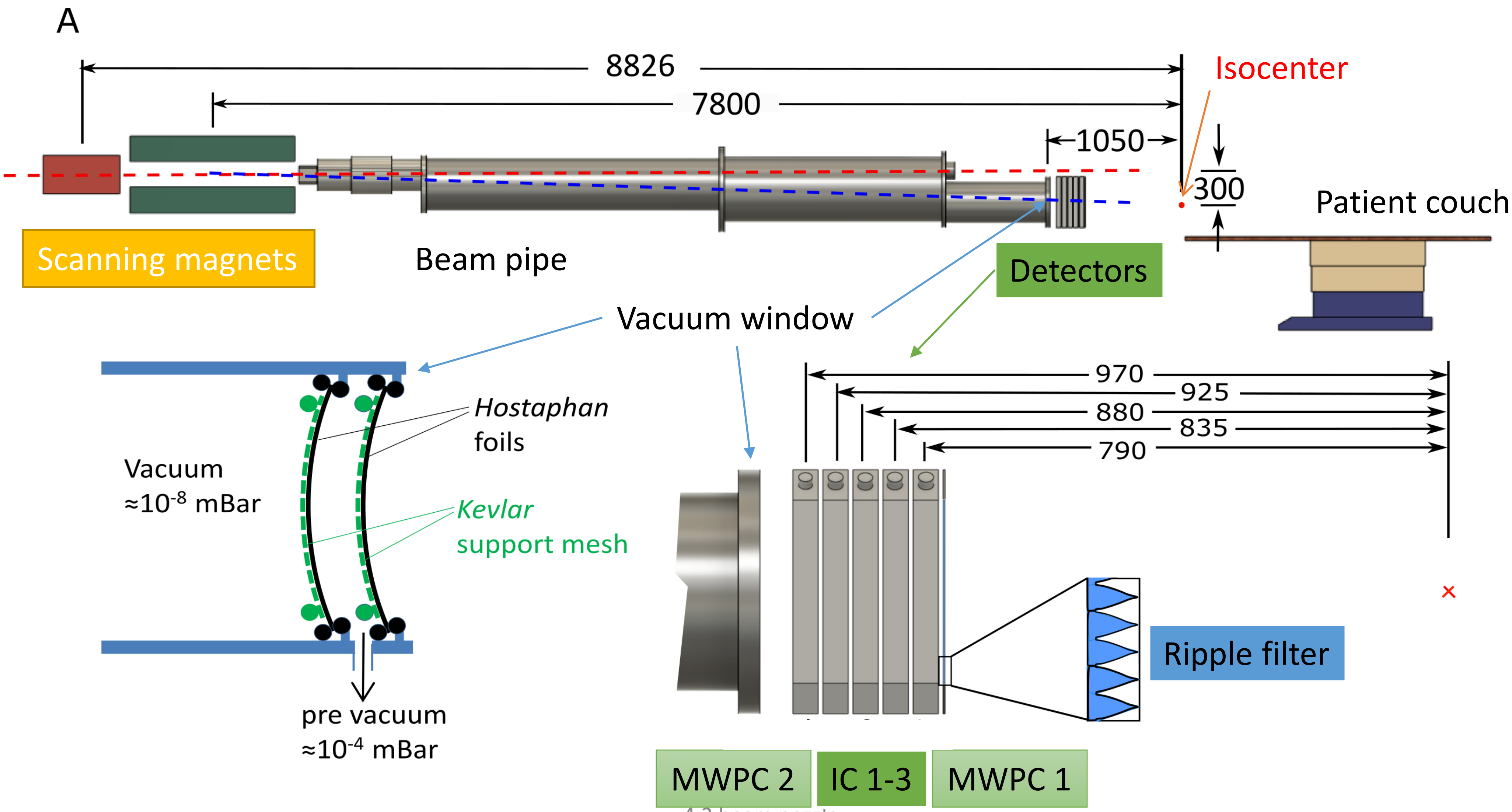
Scanned particle beams

- protons and ions have a charge, so can be easily steered with magnets
- Targeting is actually much easier than with photons



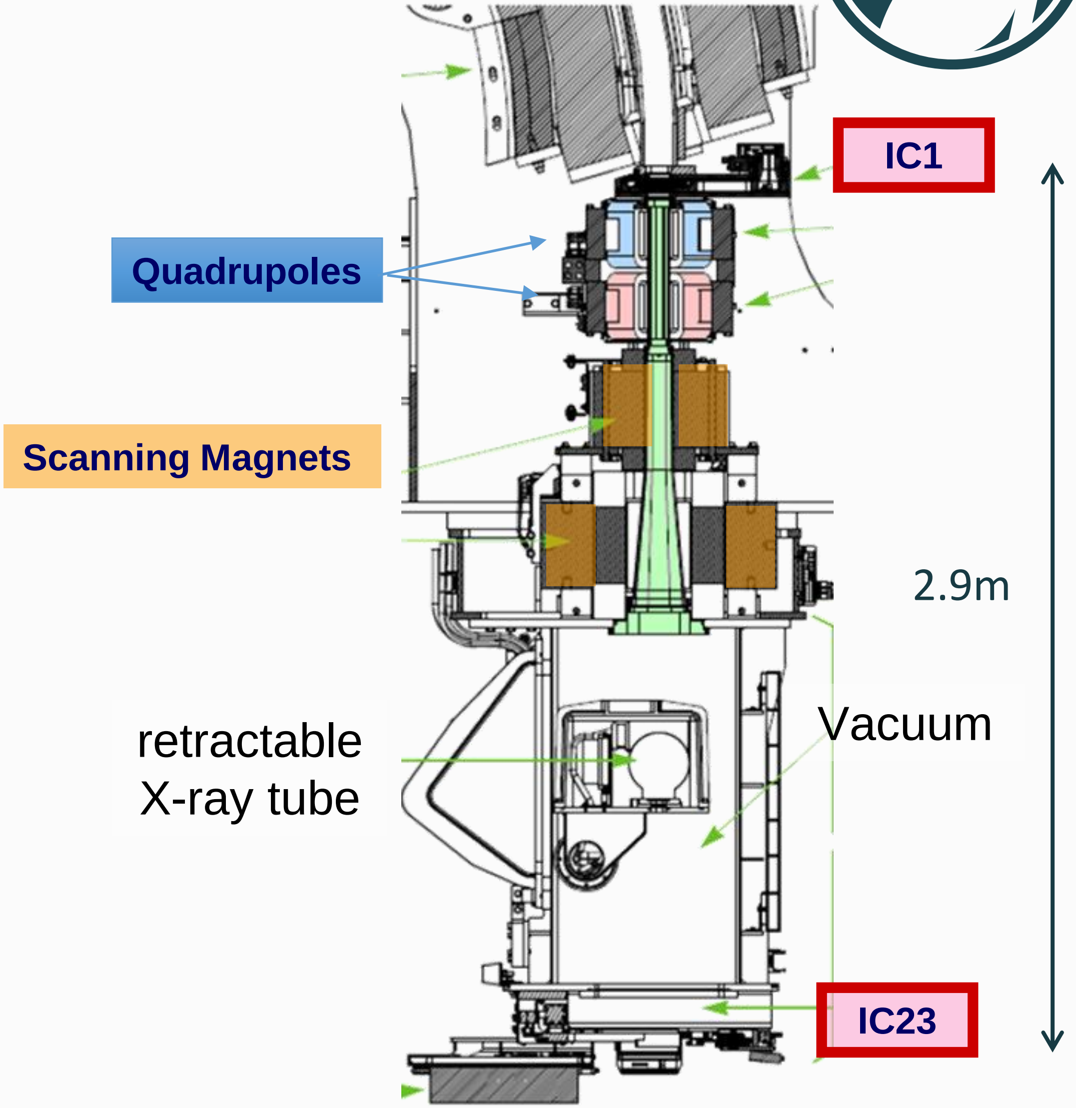
- For precise delivery, tumor is divided into slices of equal beam energy
- a thin beam is scanned over the slice to fill it with dose

GSI's Cave M: the first fully active scanning device



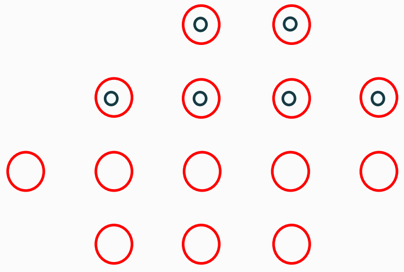
IBA scanning nozzle

- Mounted at gantry exit
- short scan distance for protons
- optimized for PBS
  - quadrupoles, vacuum
- strip IC for intensity and position control



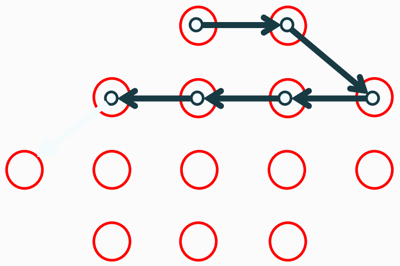
Scanning strategy characteristics

- Spot scanning



- planned spot positions
- delivered spots

- Raster scanning



- Beam turned on/off for each spot
  - requires fast, frequent beam off – technically challenging for synchrotron
  - scanning magnets need to reach position and ‚settle‘ before beam on – fixed minimum spot duration (some ms)
  - synchro-cyclotron: 3+ pulses per spot

- Beam on for transition between spots
  - dose is deposited between spots
  - magnet scan speed and particle rate become highly relevant
  - minimum spot weight to deliver ‚most‘ of the dose on planned position
  - higher min weight in a plan allows for higher particle rate / faster delivery

Cyclotrons

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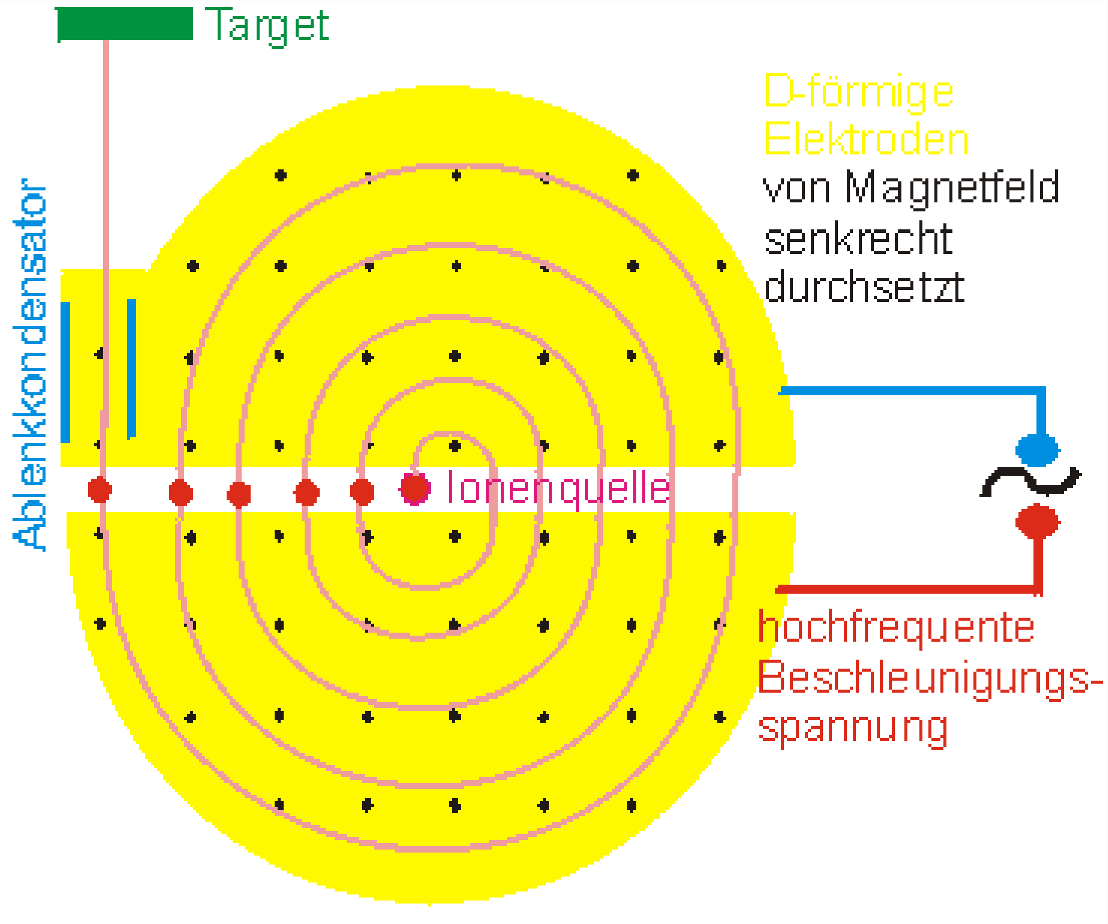
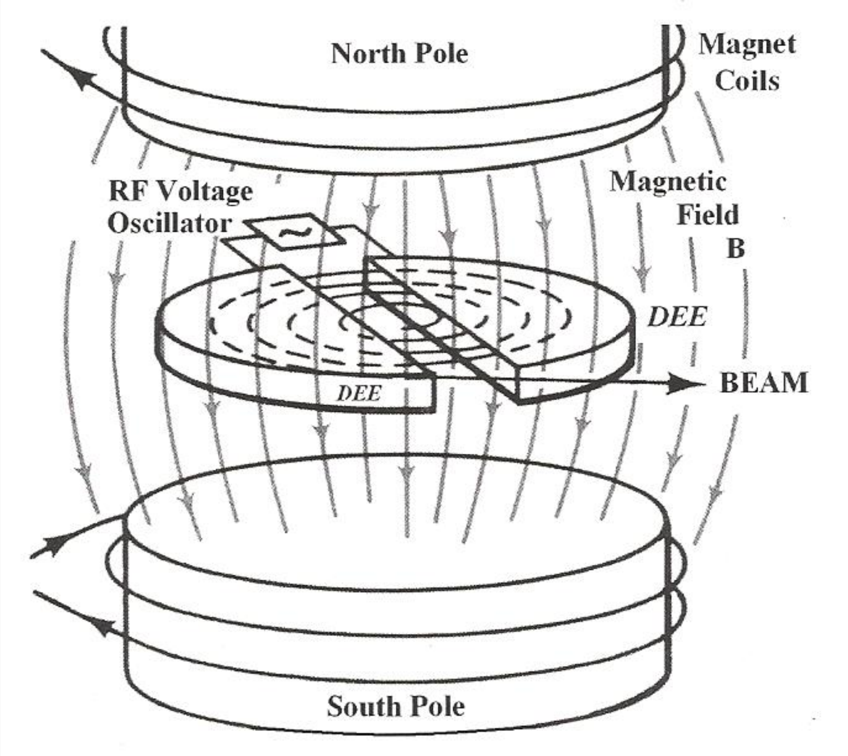
Cyclotron principle





http://www.elsenbruch.info/ph12_b-felder.htm

Cyclotron resonance condition

- Particles bending radius adheres to Lorentz and centripetal force:

$$q \cdot v \cdot B = m \cdot \frac{v^2}{r} \quad \rightarrow \quad q \cdot B = m \cdot \frac{v}{r} = m \cdot \omega$$

$$\boldsymbol{\omega_c} = \frac{\boldsymbol{q \cdot B}}{\boldsymbol{m}} = 2\pi \cdot \boldsymbol{f_c}$$

- For resonance to the accelerating HF with $\boldsymbol{f_{HF}} = \boldsymbol{f_c}$, flight-time
  - has to be constant and energy-independent
  - equal to half the HF period on each half-turn
- For constant HF, B, this condition can be met for constant m/q
- Not possible for relativistic particles, as m will change with increasing velocity!

RF: radio-frequency; HF: high-frequency

Cyclotron for relativistic particles

$$m = \gamma m_0$$

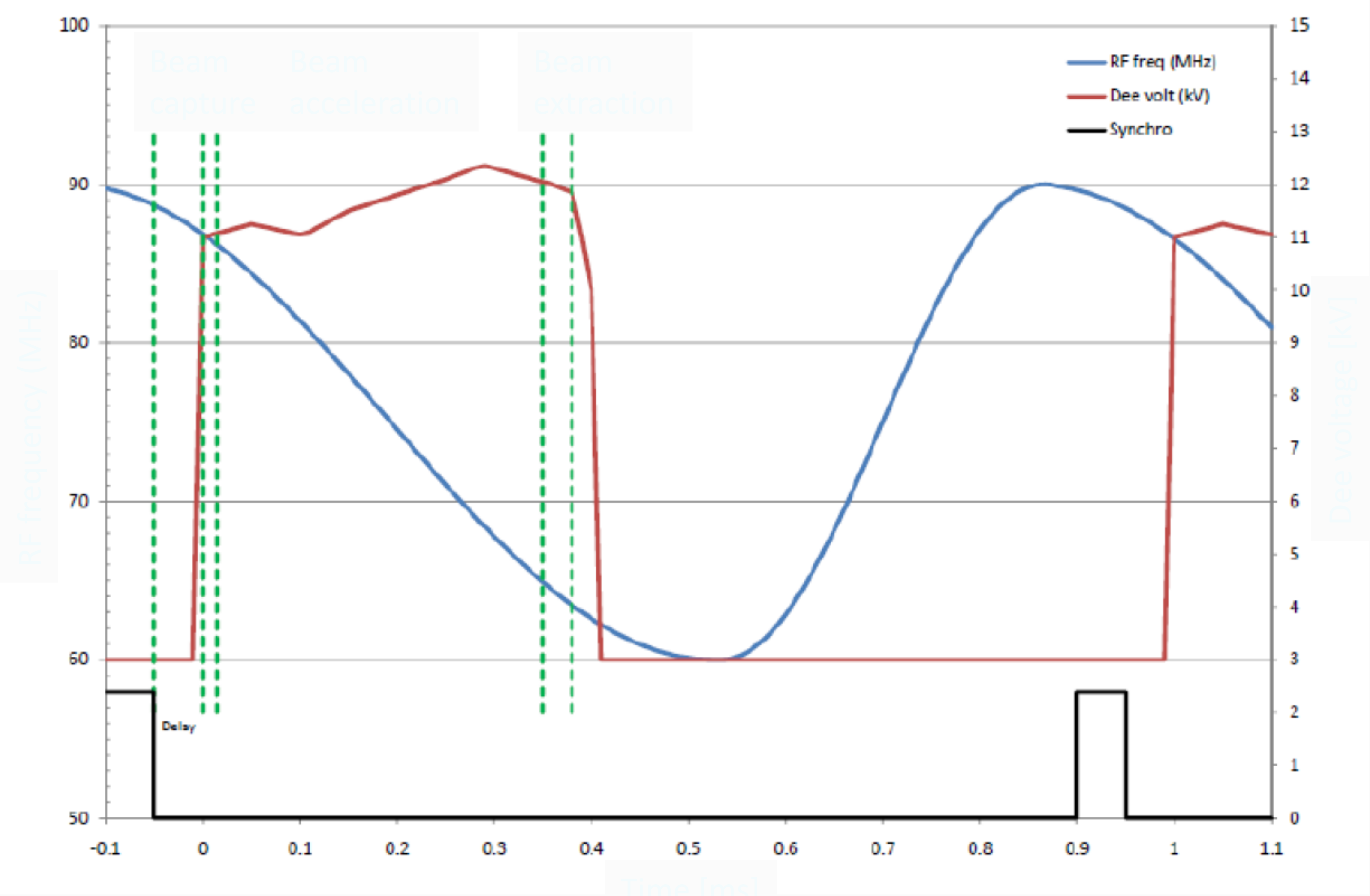
$$\omega_c = \frac{q \cdot B}{\gamma m_0}$$

- Two options:

1. Synchronize HF to particle velocity: **synchro-cyclotron**
   - $\mathrm{B} = \mathrm{const};\ f_{HF} = f_{particle} \downarrow$
2. Increase B field with increasing radius: **isochronous cyclotron**
   - $\mathrm{B} \uparrow;\ f_{HF} = f_{particle} = const$

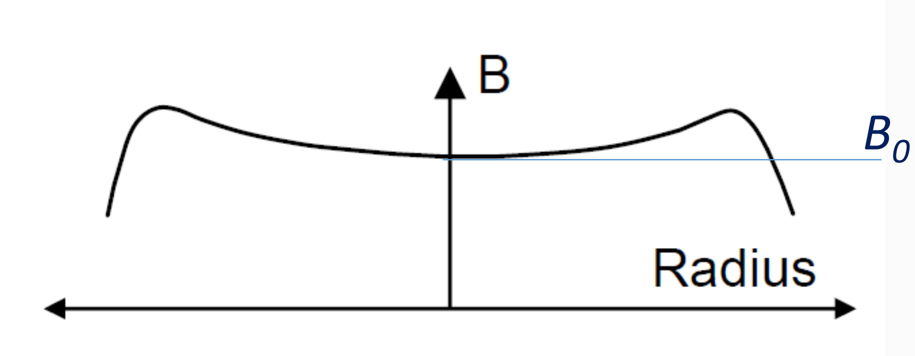
- In both cases, the factor to modify f or B is γ, the relativistic mass increase
- Both are in use for proton therapy
- synchro-cyclotrons can be more compact, as constant high B-field allows smaller radius
- isochronous cyclotrons can produce a quasi-continuous beam: higher duty cycle

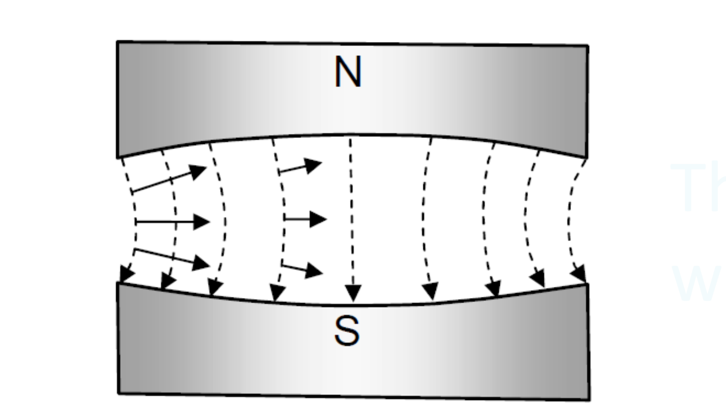
IBA synchro-cyclotron cycle



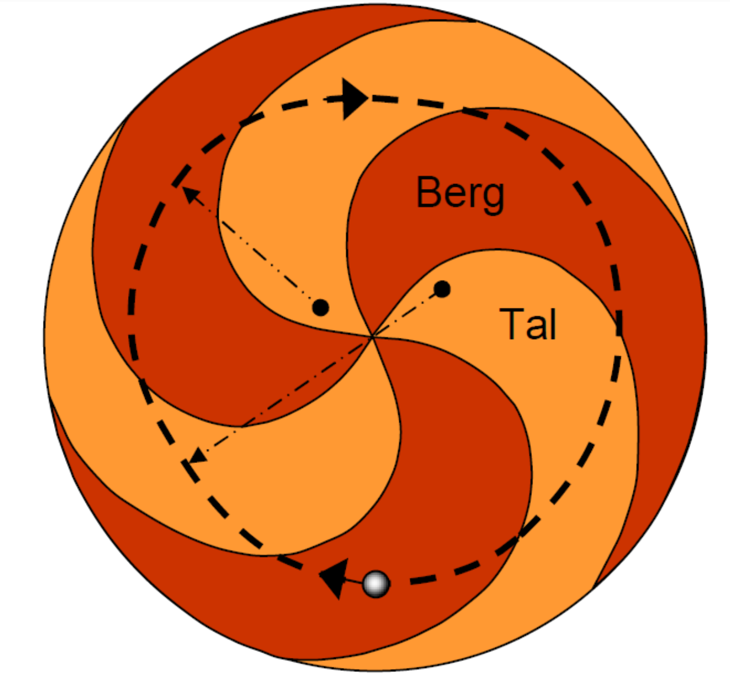
source: IBA,
courtesy of
C. Richter, OncoRay

Isochronous cyclotrons

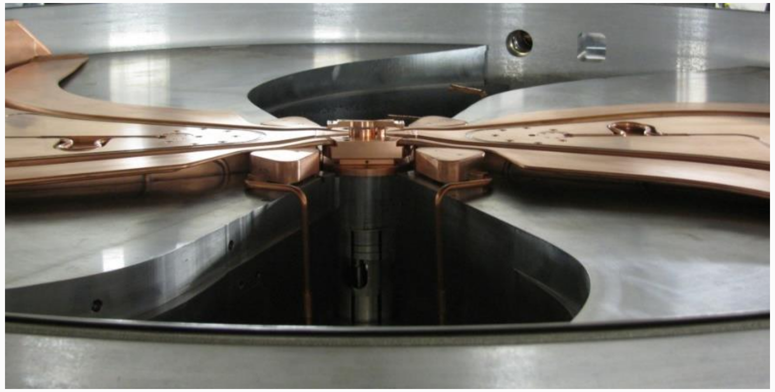




The magnetic field will disperse the beam!



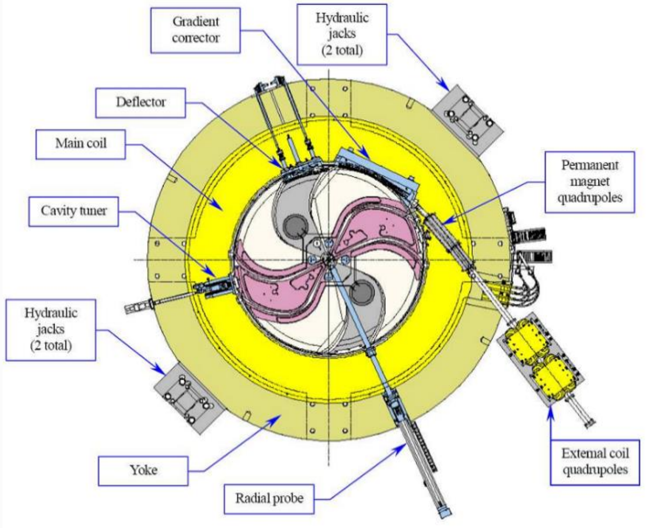
Counteracted by structuring of the magnetic field, spiral hills & valleys



Isochronous (IBA)

C230 isochronous cyclotron

- Diameter: 4.34m
- Weight: 210 tons
- Conventional magnets
- *Bavg*: 1.74T to 2.2T
- Dee voltage: 55kV to 150kV peak
- Rf frequency: 106MHz
- Quasi continuous beam
- Average beam current: 300nA
- Energy: 230MeV (0.6MeV @2σ)

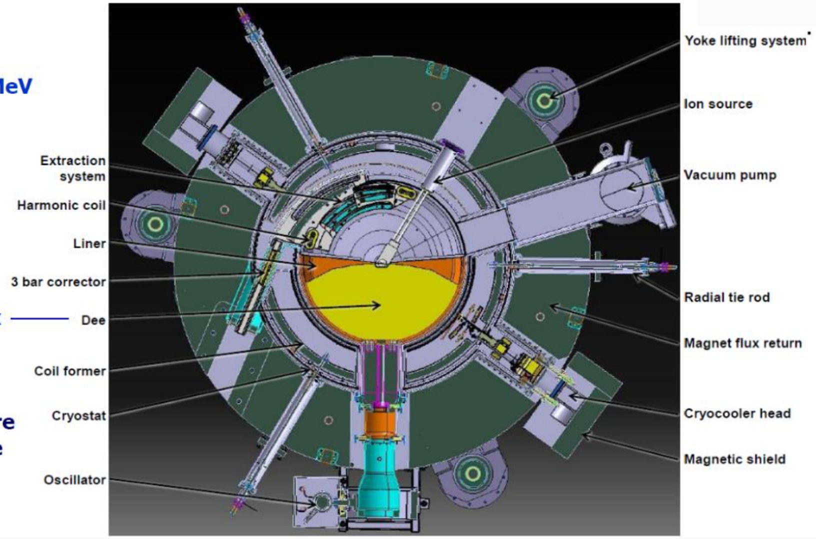


super-conducting synchro-cyclotron (IBA)

S2C2 synchrocyclotron

- Diameter: 2.30m
- Weight: <50 tons
- Superconducting magnets
- *Bavg*: 5.64T to 5.24T
- Dee voltage: 14kV peak
- Rf frequency: 90MHz to 60MHz - 33%
- Pulsed beam at 1kHz rep rate 1 ms
- Average beam current: 150nA
- Energy: 230MeV (2.5MeV @2σ)

Protons 230 MeV



Notice:

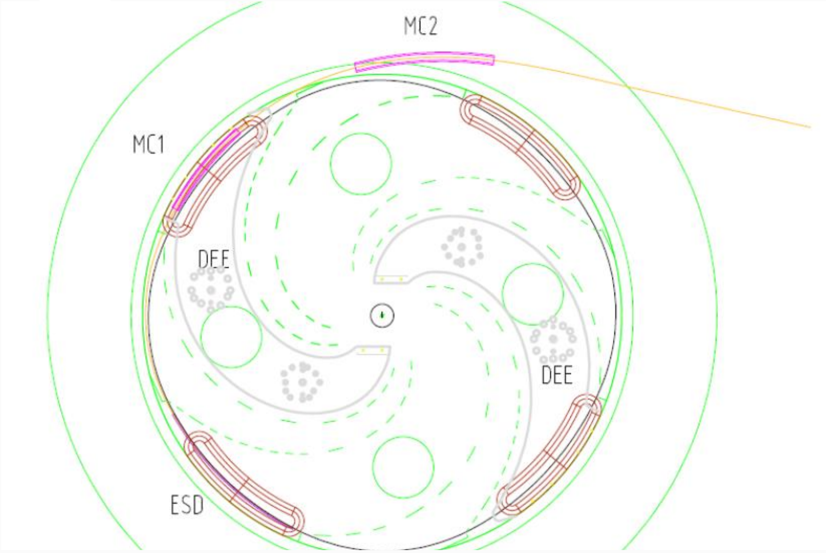
only 1 Dee box

the ground potential of the enclosure constitutes the other Dee

super-conducting isochronous (Sumitomo)

SC230 isochronous cyclotron

- Diameter: 2.8m
- Weight: 63t
- Superconducting magnets
- *Bavg:* 3.2T to 4T
- Dee voltage: 50 – 93 kV
- Rf frequency: 95.2 MHz
- Quasi continuous beam
- Average beam current: 1000nA
- Energy: 230MeV (<0.5MeV @2σ)



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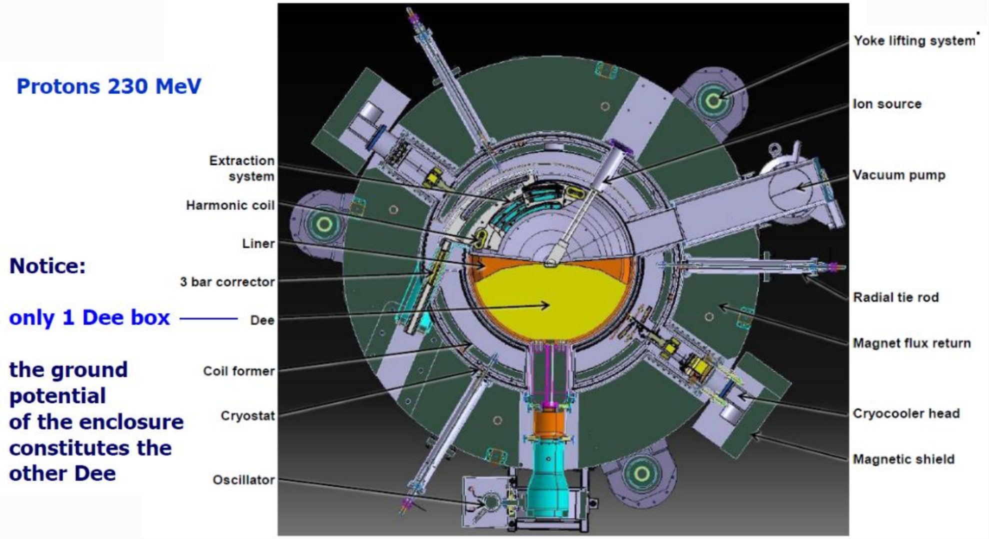
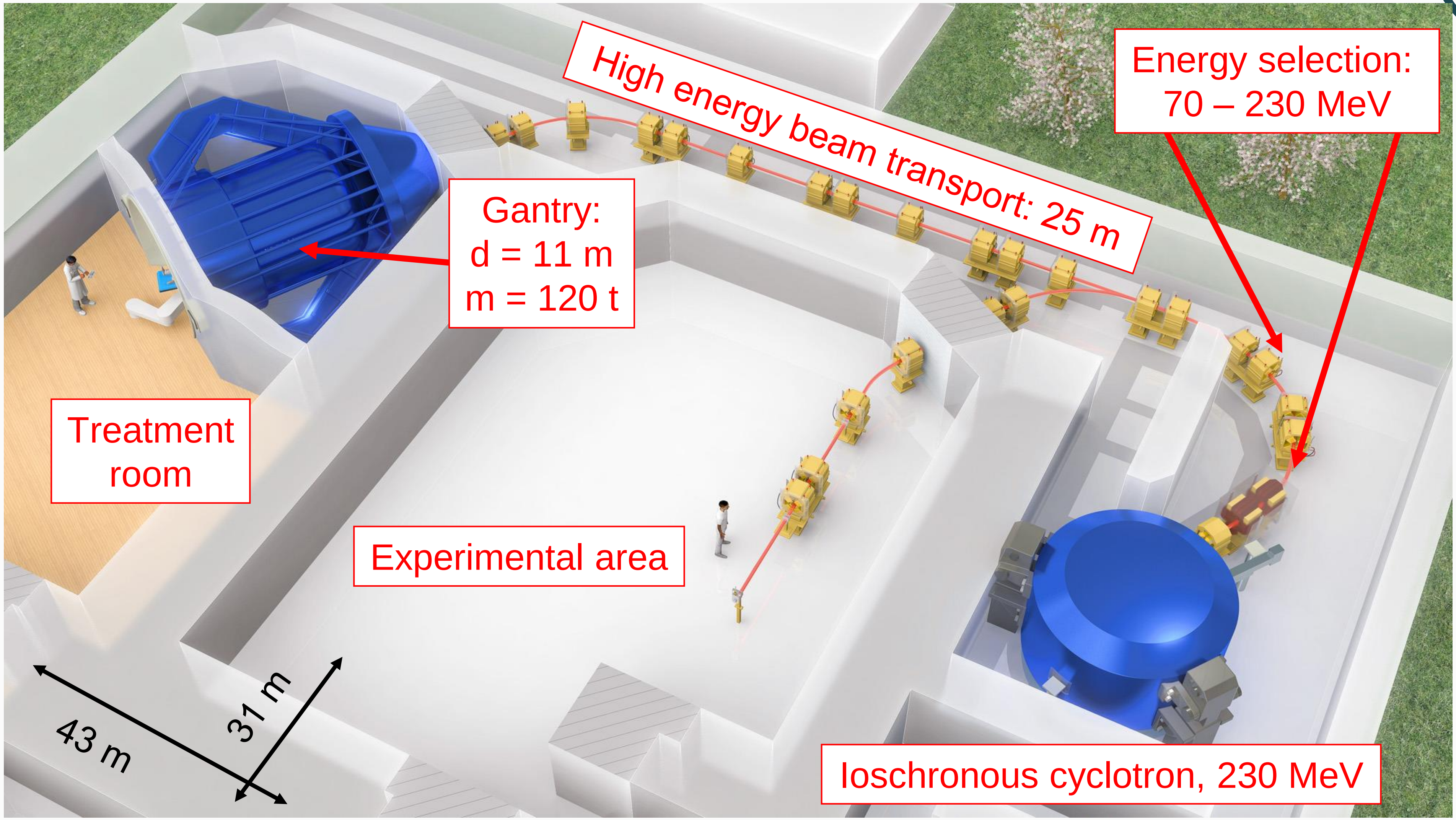


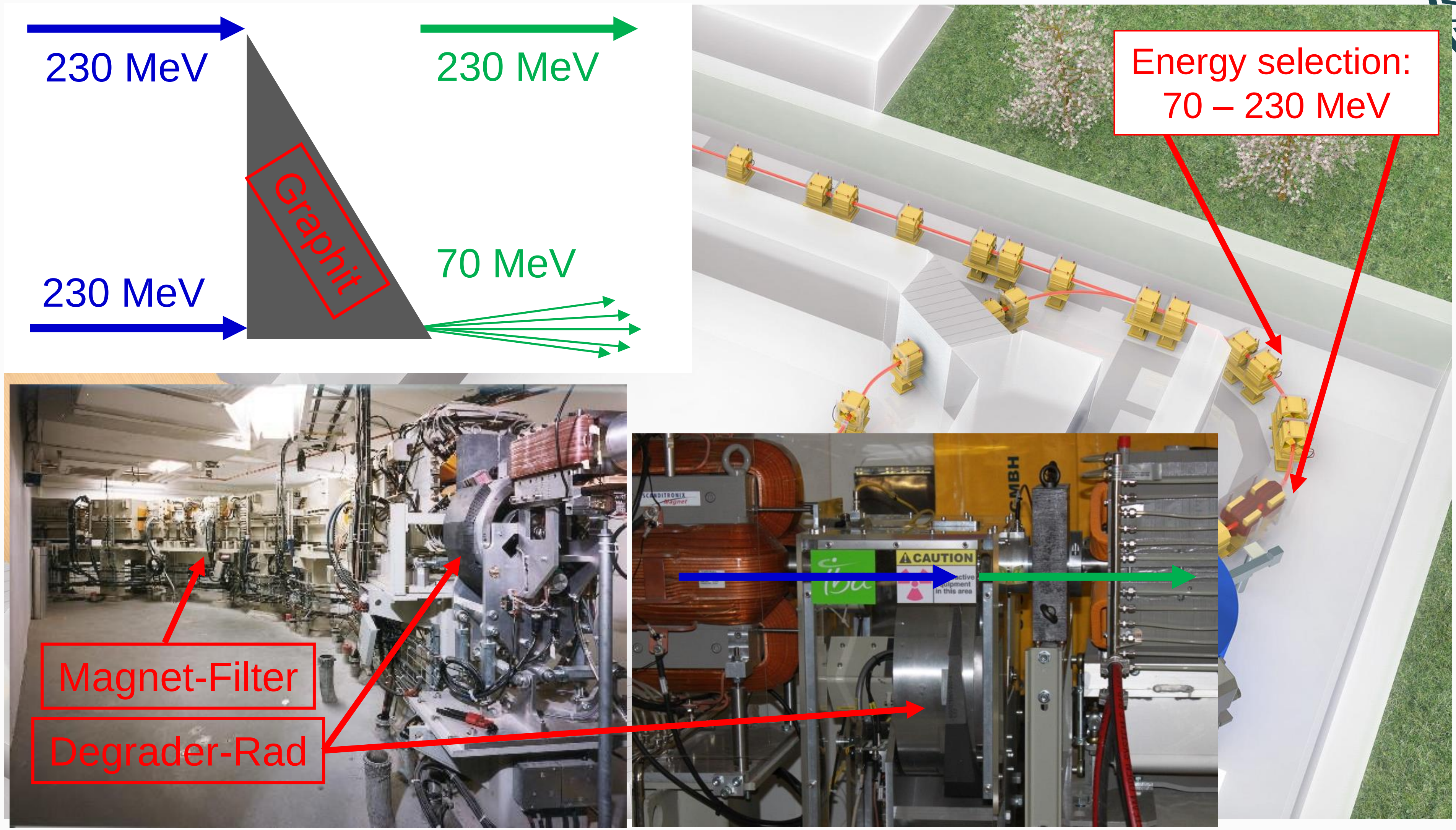
Cyclotron facility example: OncoRay Dresden



IBA cyclotron

- mass: 210 t
- diameter: 4.34 m
- proton energy: 230 MeV
- beam current: < 500 nA
- beam power: < 100 W
- electrical power uptake: 1,5 MW

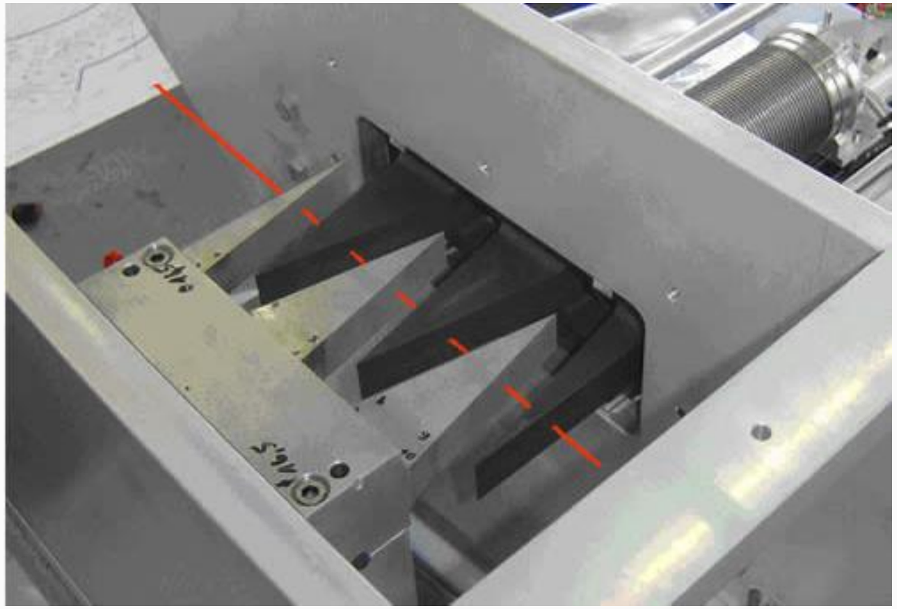
Energy selection system

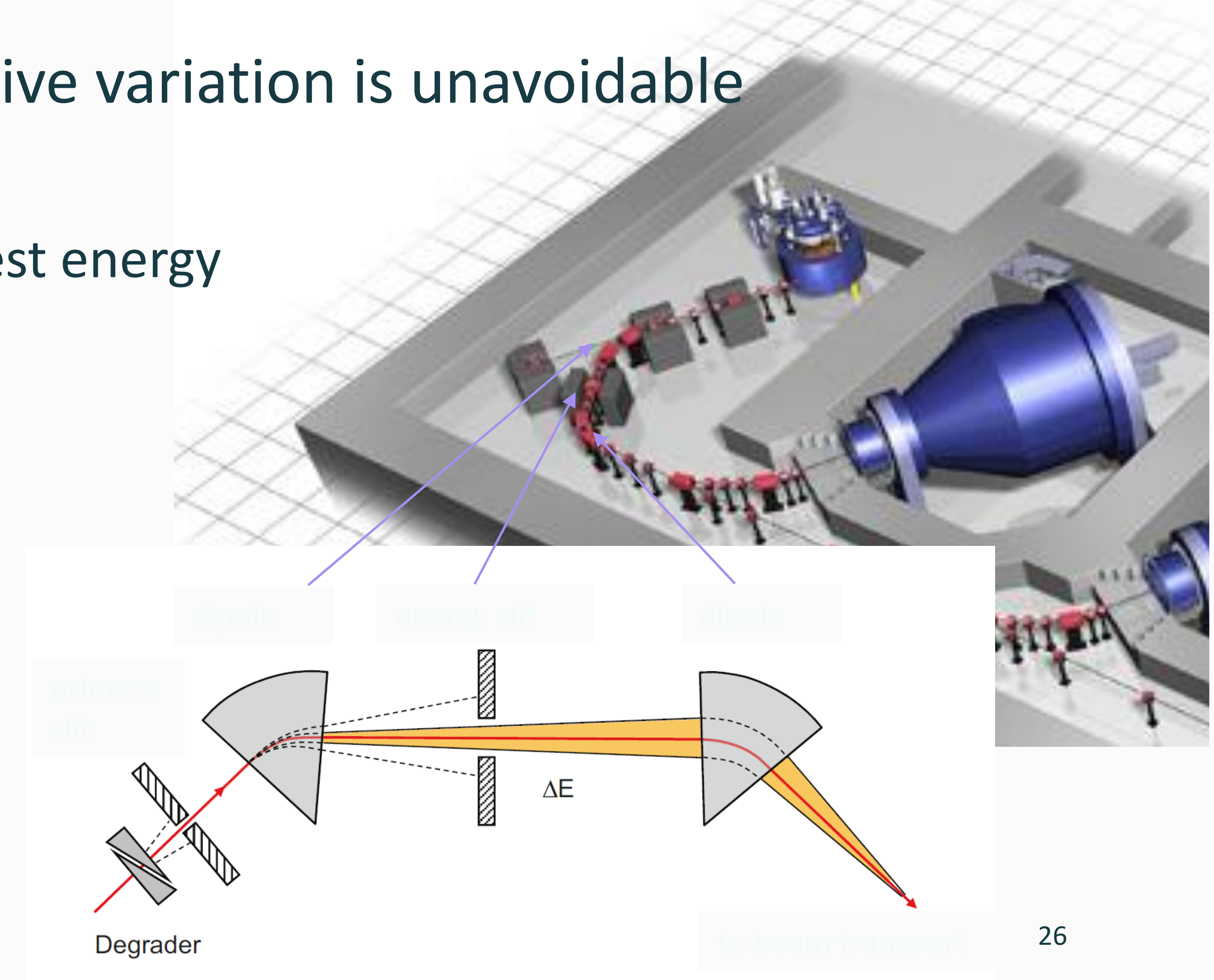


Problem 3.3.: Man berechne die maximale Dicke des Graphitkeiles.

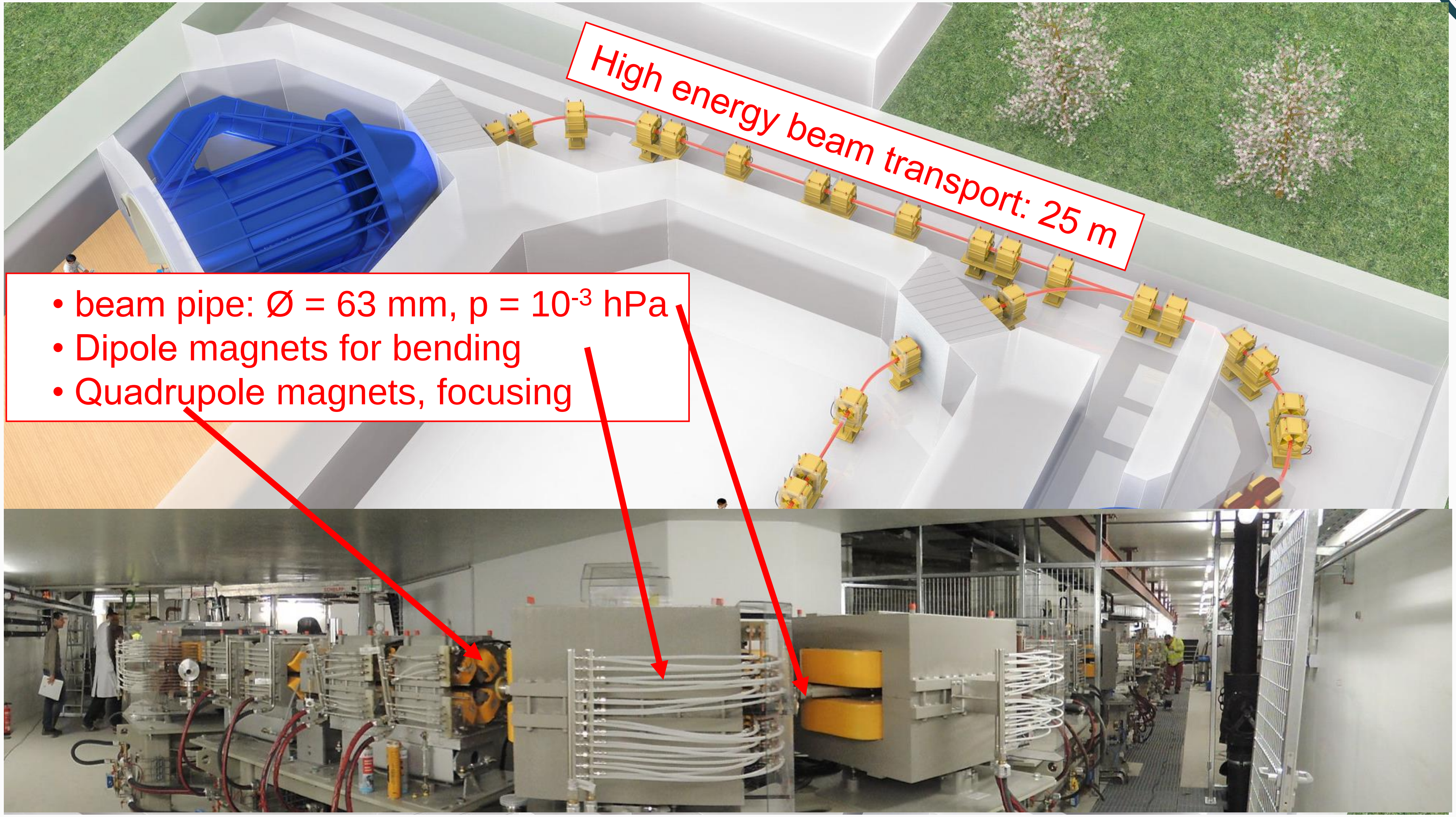
Energy selection: Varian / PSI

- Cyclotron energy is fixed – passive variation is unavoidable
- ‘Energy-selection system’
  - loss of >95% of particles for lowest energy
  - ‘hot’ region – both emissions & long-term activation

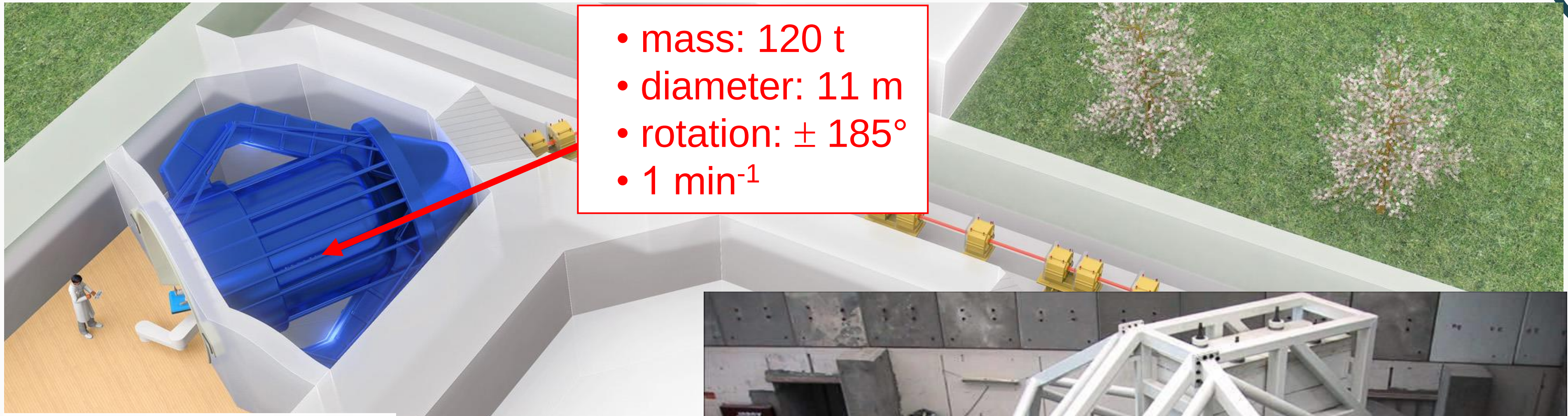




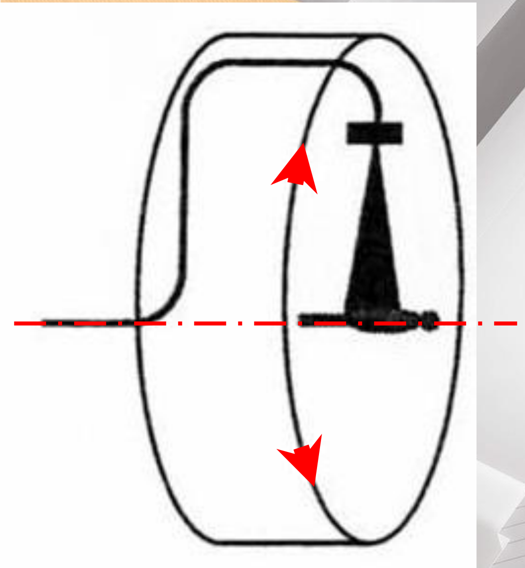
Beam transport to the patient

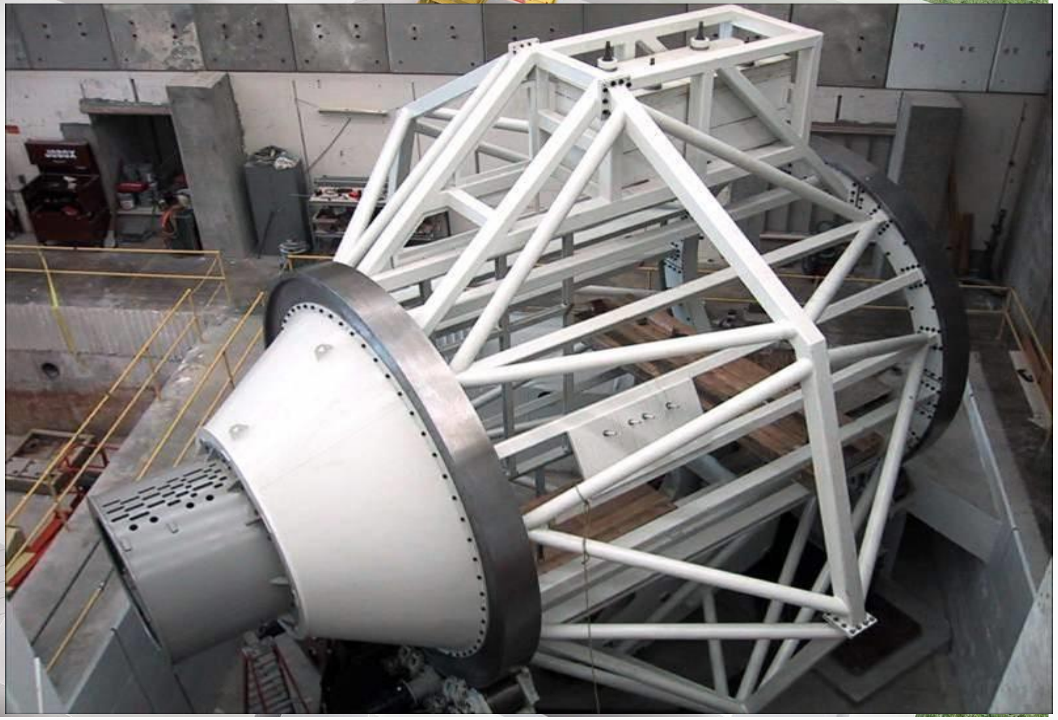


Gantry for patient treatment



- mass: 120 t
- diameter: 11 m
- rotation: ± 185°
- 1 min^{-1}





U. Linz (Ed.): Ion Beams in Tumor Therapy, Chapman & Hall 1995

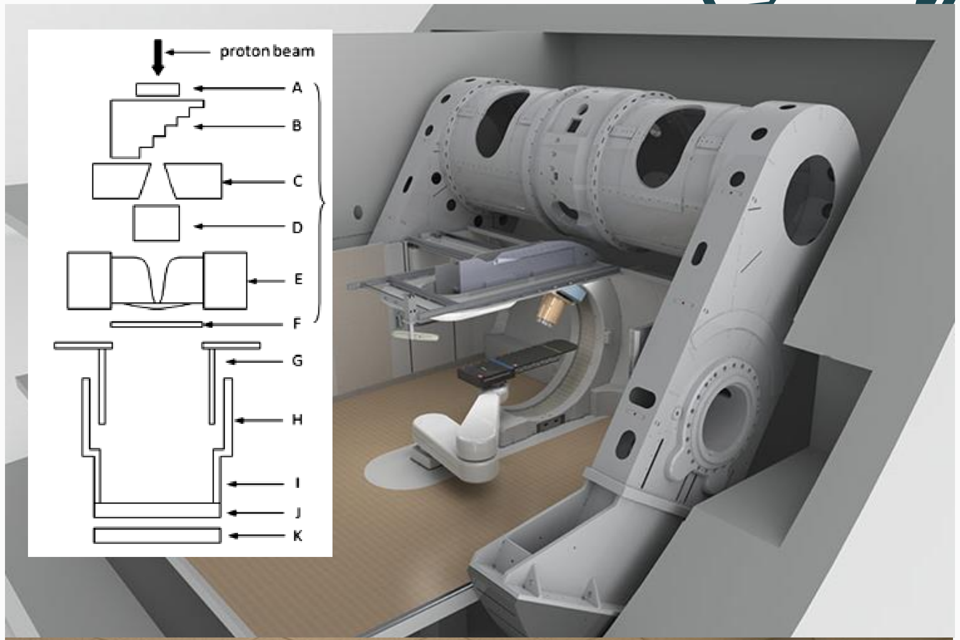
Treatment room

One-room facility example: Mevion

Mevion Monarch 250

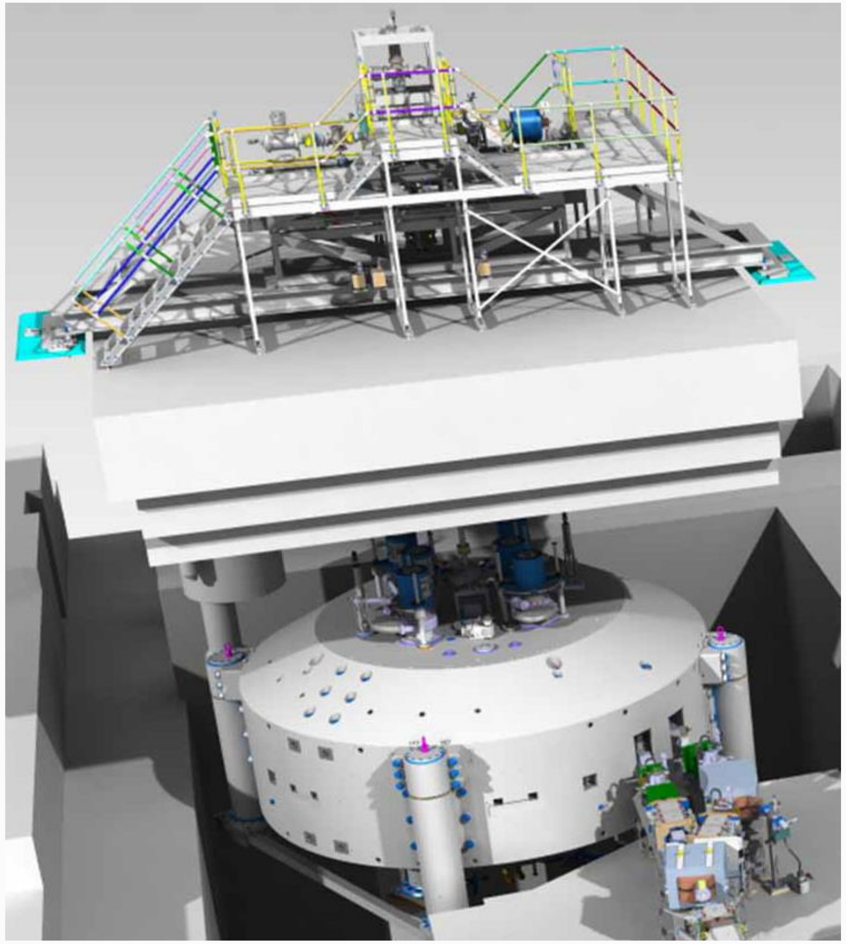
- Clinical since 2013
  - active scanning since 2018
- Synchro-cylcotron @ 9T
  - E_{max} = 250 MeV, r_{extr}= 0.31 m
  - Mass only 20t
  - mounted on isocentric gantry
- Practically no beam transport
- Beam energy ‚selection' directly in front of patient
  - secondary neutrons?

  ≤3.5mSv/Gy (Chen et al. Med Phys 2013)



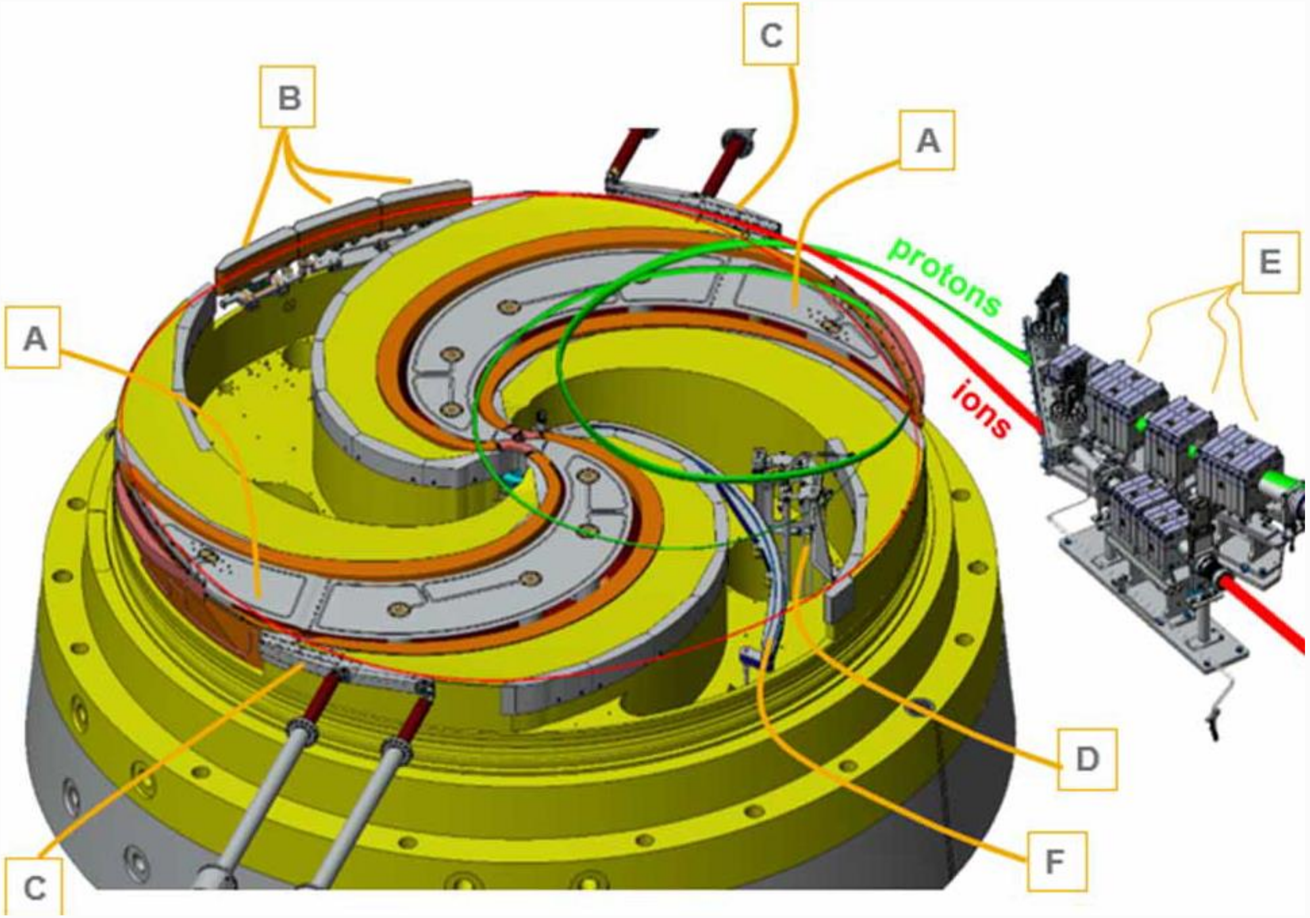
C400 Carbon ion cyclotron: Caen, France

- Iso-chronous cyclotron for H_2, He, C
  - all with A/Q=2, but still different frequencies f=75 MHz (12C), 75.6 MHz (H_2)
- 7m super-conducting magnet > 700t
- 3 sources mounted on top: fully stripped He, C
- extreme magnet design with very deep valleys, many tuning options
- assembly on-site, tuning & commissioning



C400 Carbon ion cyclotron: Proton extraction

- Proton molecule accelerated: H_2+ with A/Q=2
- Stripping foil inserted to extract at 260 MeV
  - mounted on robotic arm,
    has to be removed for other ions
- dissociates molecule: A/Q=1, changes trajectories to green, smaller circles
- proton-specific beam line



Summary cyclotrons

- Compact, superconducting machines for protons
  - first carbon cyclotrons treating patients soon!
- Provides a constant energy, passive degradation necessary
- Provides a continuously available beam
- Energy changes requires (short) time

- Majority of particle therapy centers
- Many different facility layouts

Synchrotrons

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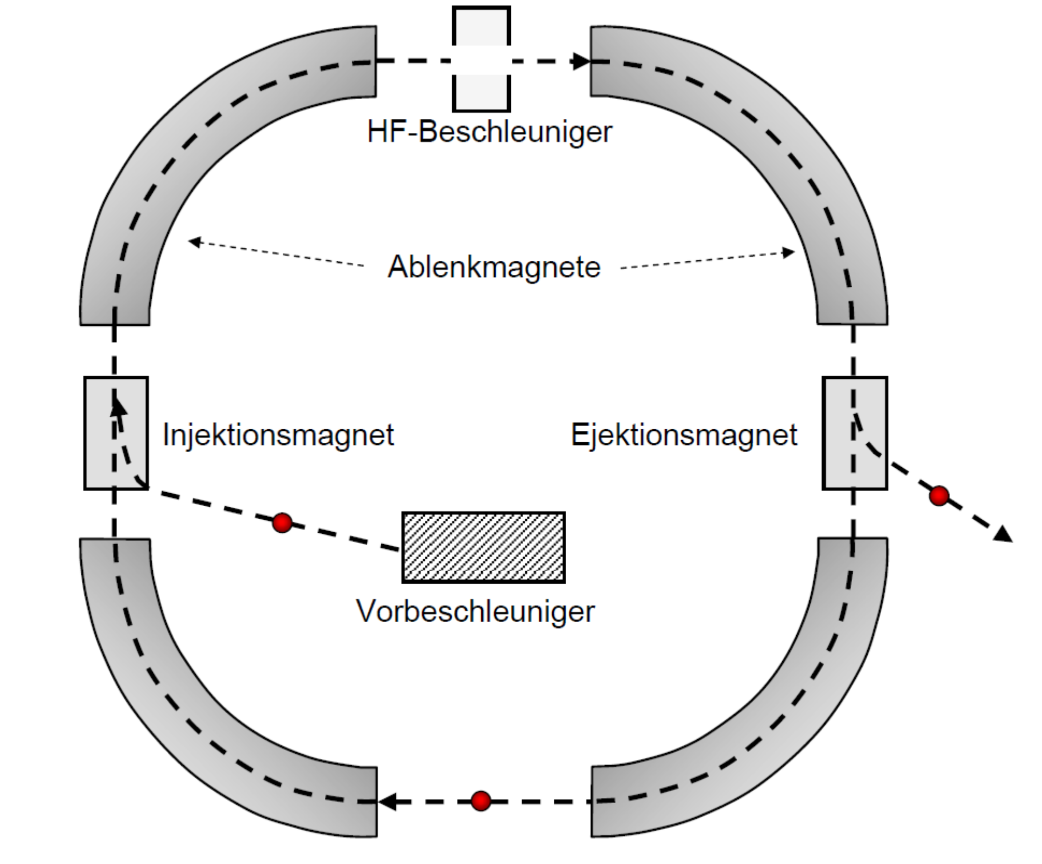
Synchrotrons

- Idea: Bending magnets keep particles on a single, periodic track of a fixed length L containing one or more HF cavities
  - Consists of several (many!) magnets
- Bending radius r in each magnet is constant, but momentum increases after cavity

  $$r = \frac{\gamma m_0 v}{qB} = const$$

  => B has to increase synchronously to $\gamma m_0 v$
- Also cavity HF has to increase with increasing velocity / rotation frequency
  $f = \frac{v}{L} = f_{HF}/h$ h: harmonic mode

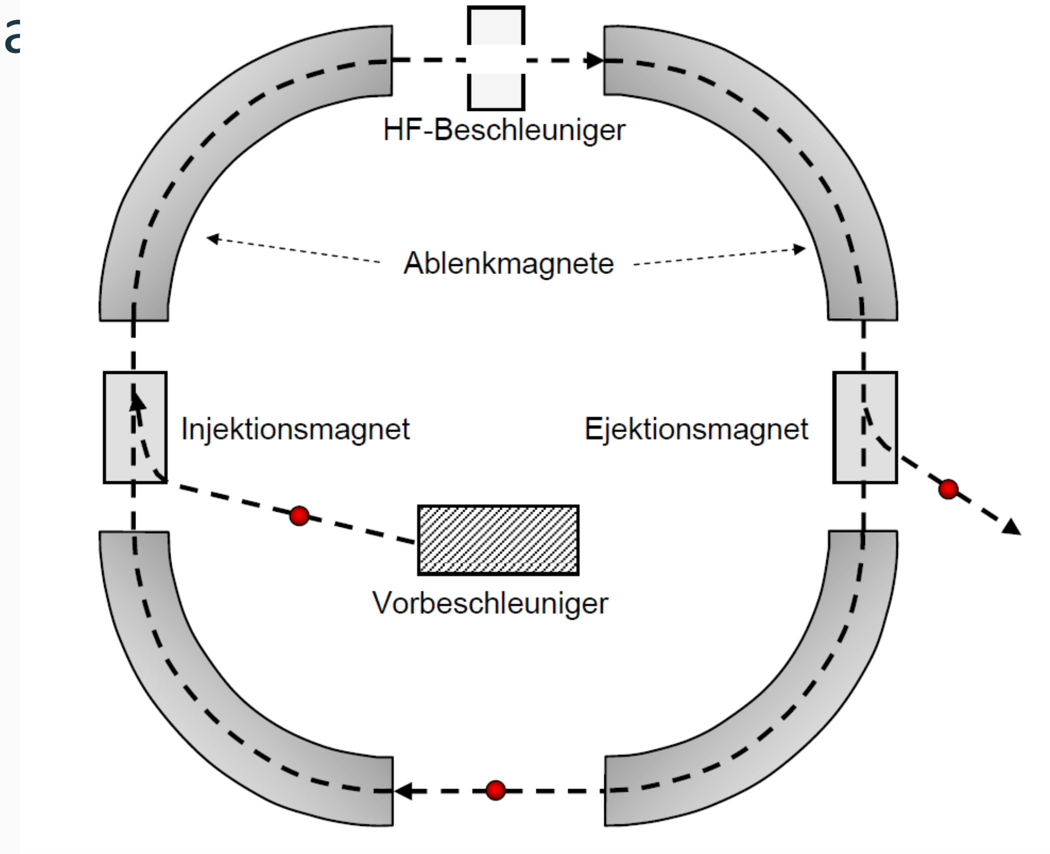
Largest example: LHC @ CERN with E_{max} = 7 TeV



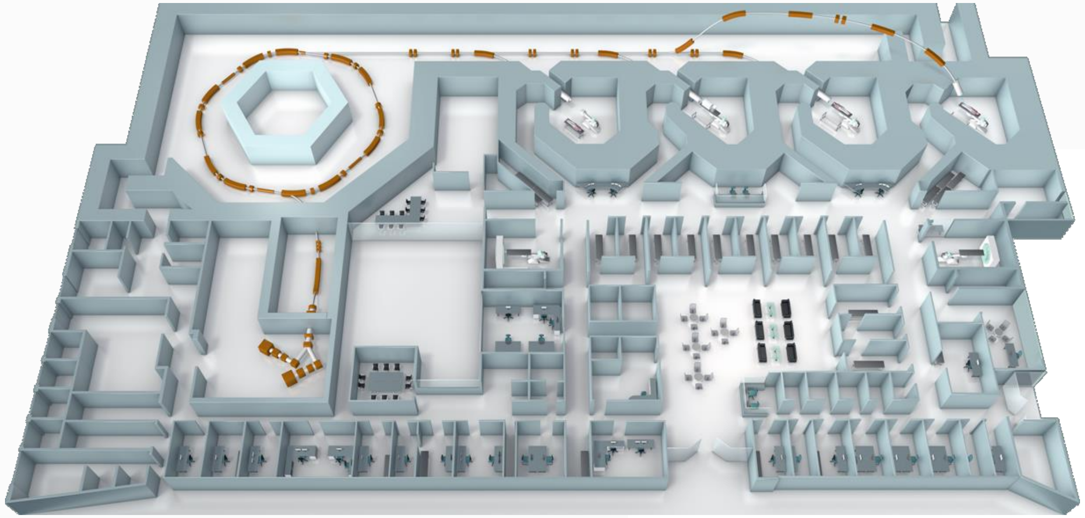
Synchrotrons need an injector

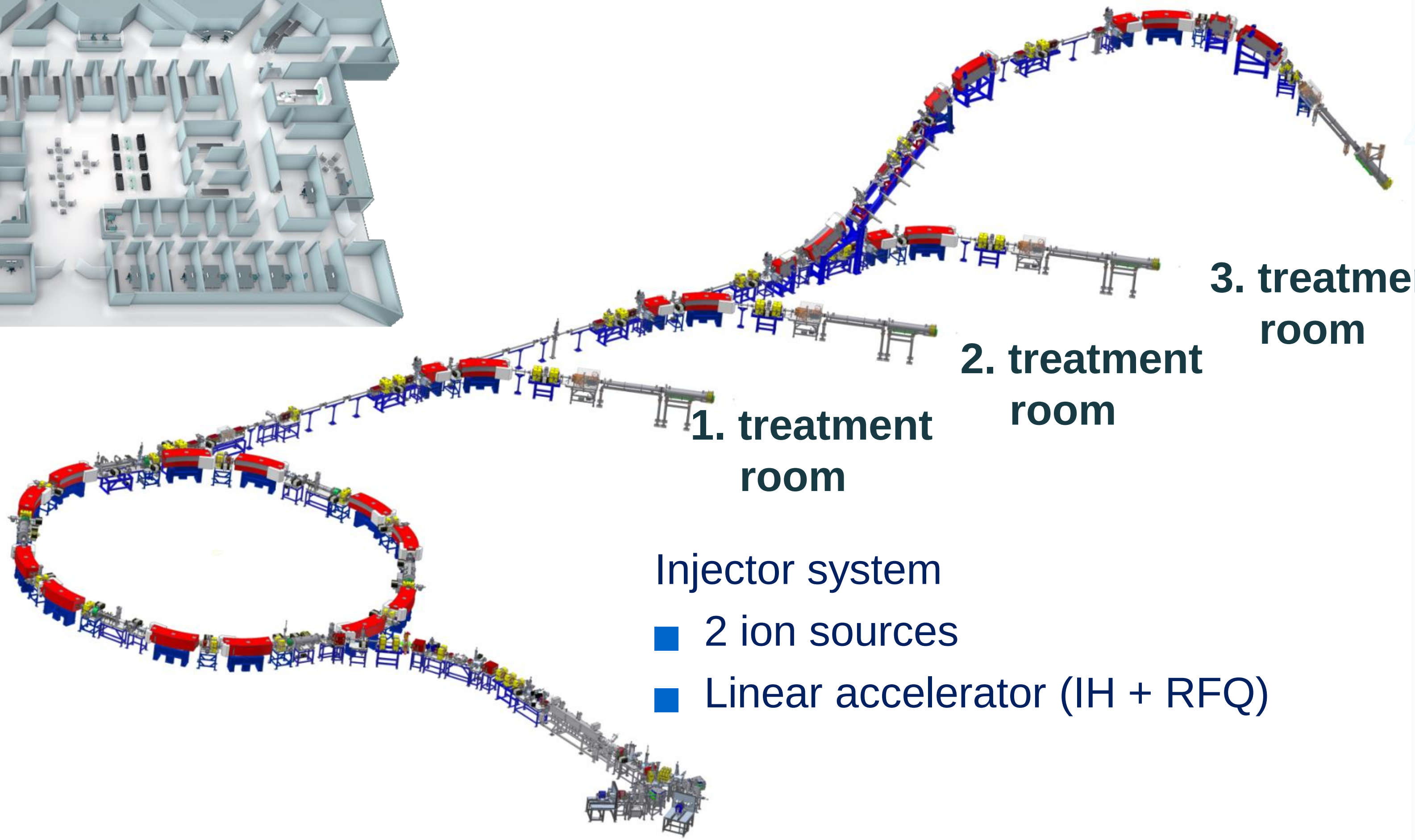
- In contrast to cyclotron, ions are not directly injected into the cavity
- Minimum velocity is needed to guide the bea
  to the cavity & keep it on the circular track

- Injection chain consists of
  - an ion source
  - a low-energy accelerator, typically a Linac
- Trade-off between injector & synchrotron
  - high injection energy reduces demands on synchrotron, but injector becomes larger
  - Also accelerator chains of multiple synchrotrons possible



Layout Marburg ion beam therapy center





Synchrotron

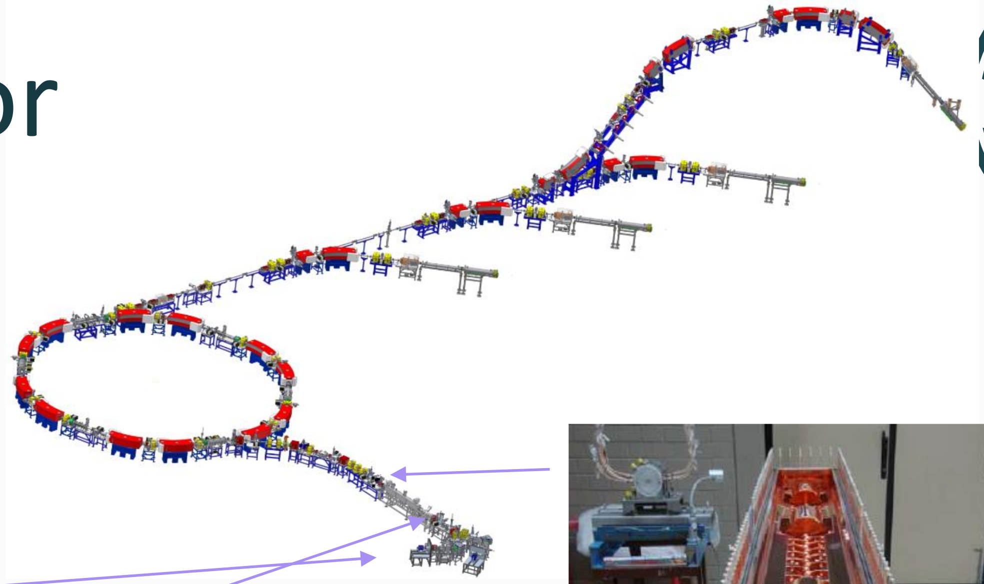
- 430 MeV/u ^{12}C

Injector system

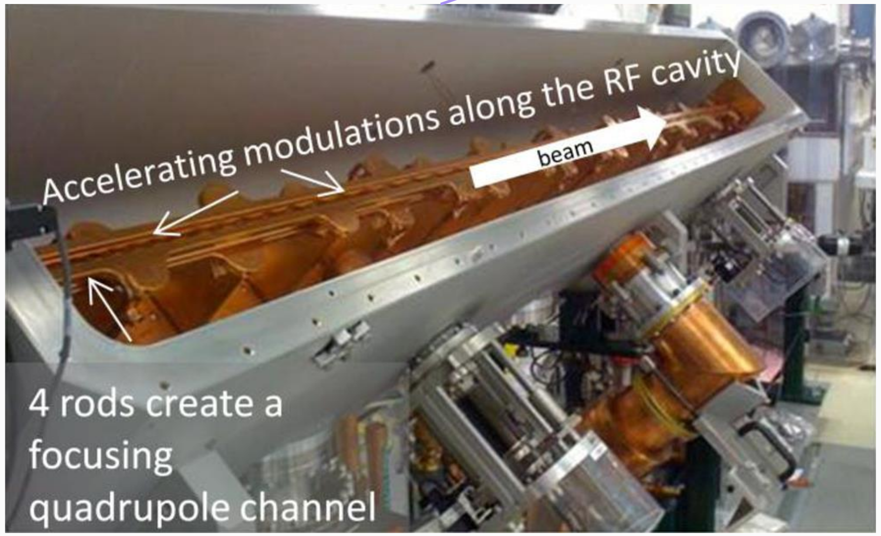
- 2 ion sources
- Linear accelerator (IH + RFQ)

Ion source and injector

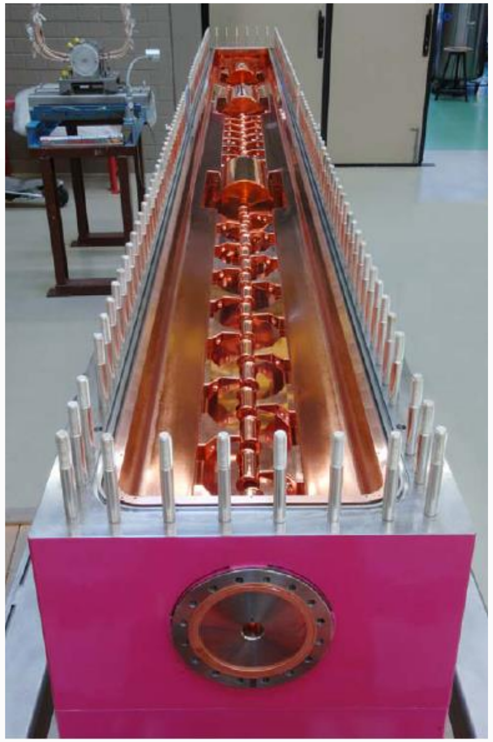
- 2 ECR ion sources for p/C
- Linac RFQ + IH
- injection at 7 MeV/u



ion source



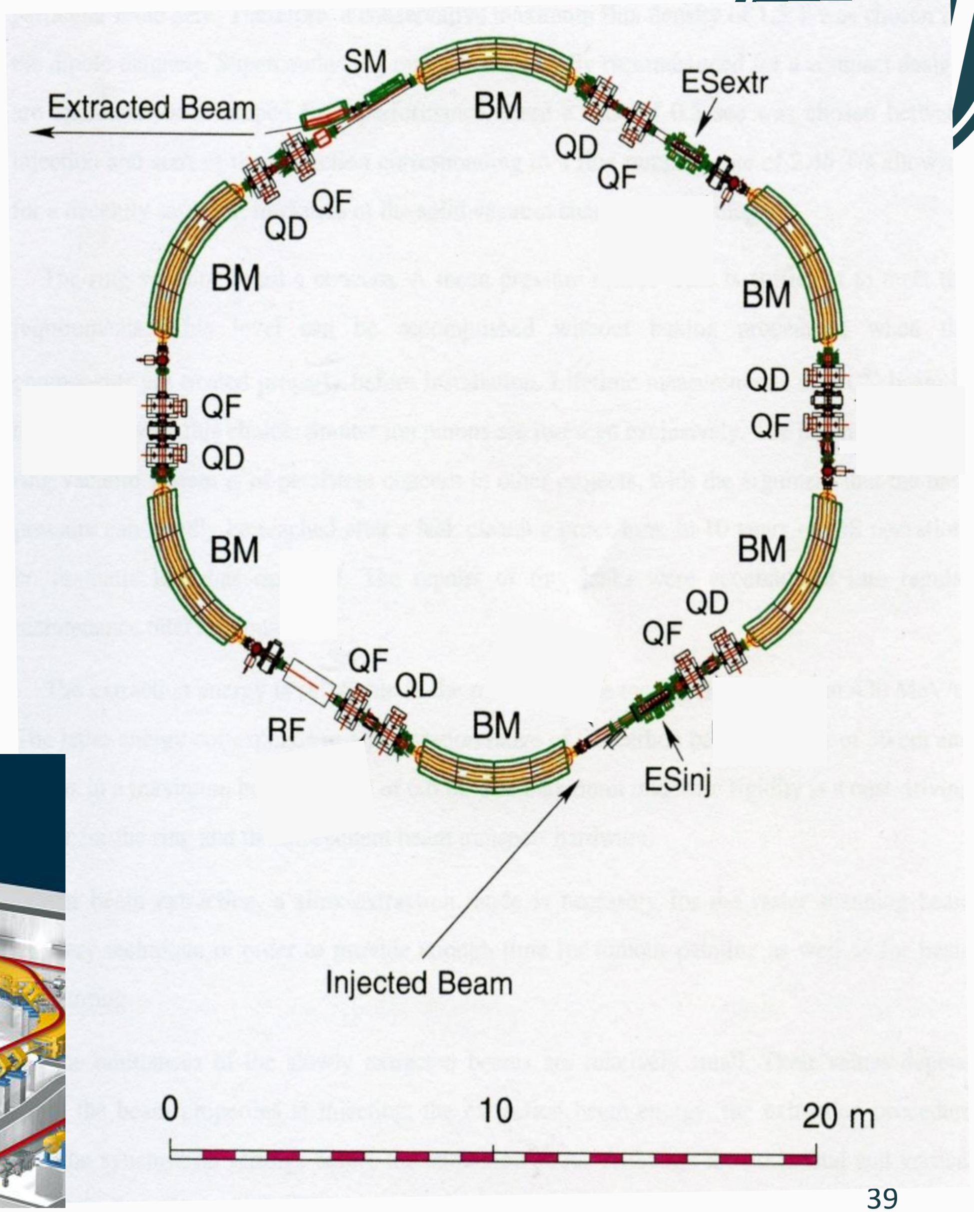
radiofrequency quadrupole

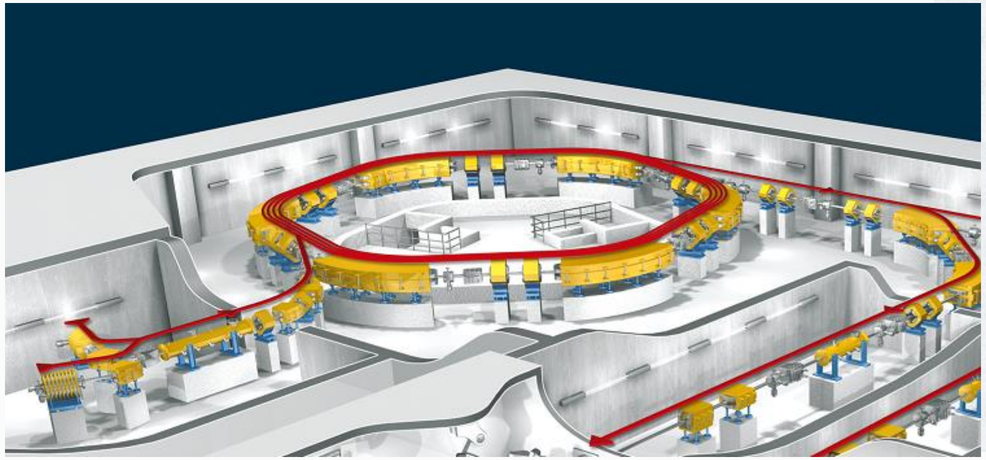


Linac, IH tank

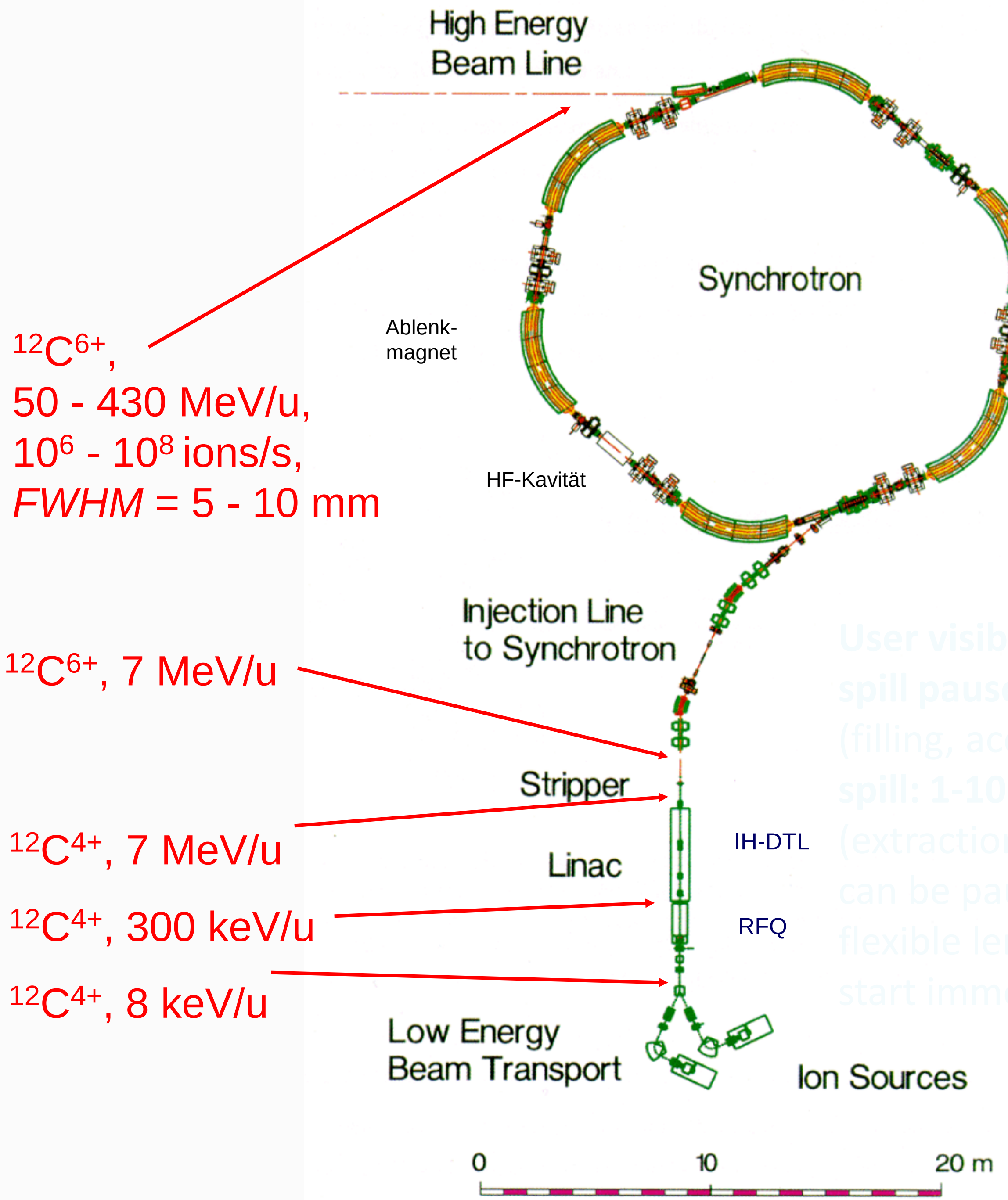
Example: HIT synchrotron

- Injection at 7 MeV/u
- 6 elements
  - dipole bending magnet (BM)
  - 2 quadrupoles for strong focusing (QF, QD)
- Injection & Extraction septum
  - fast electrostatic kickers
- Septum magnet for extraction
- RF cavity

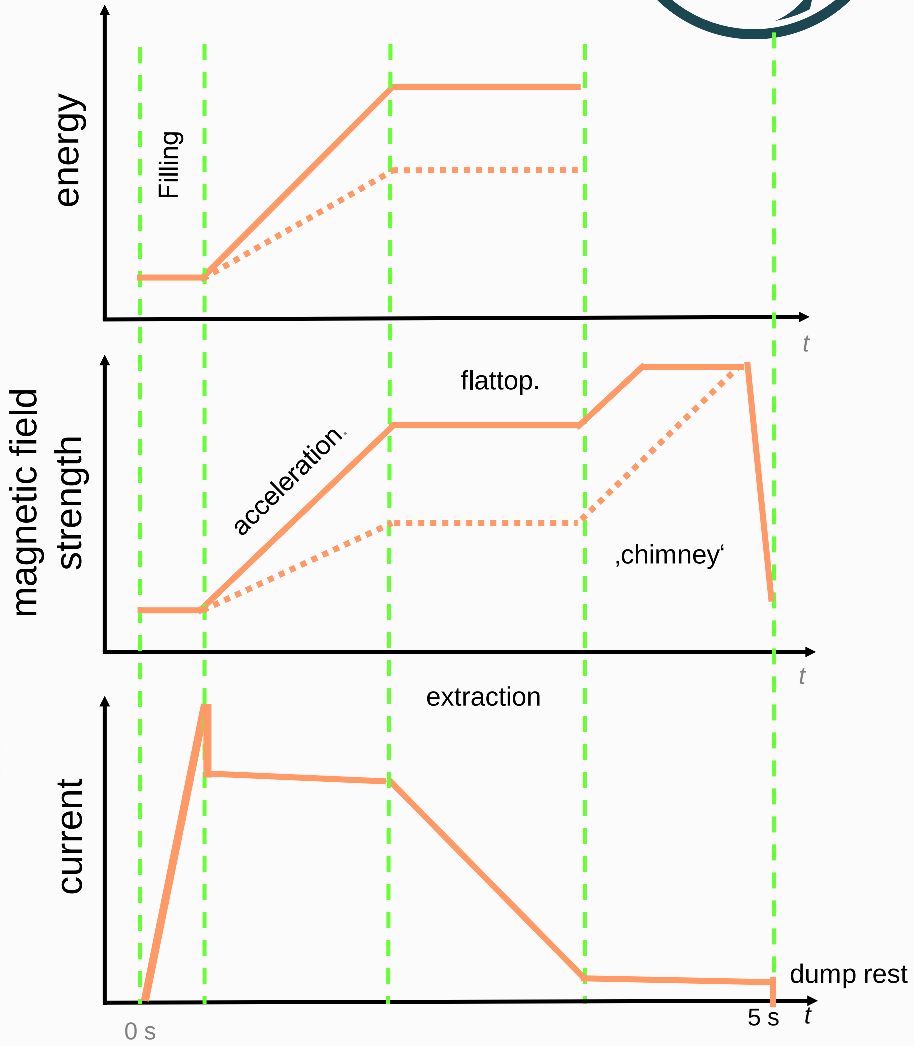




HIT synchrotron cycle

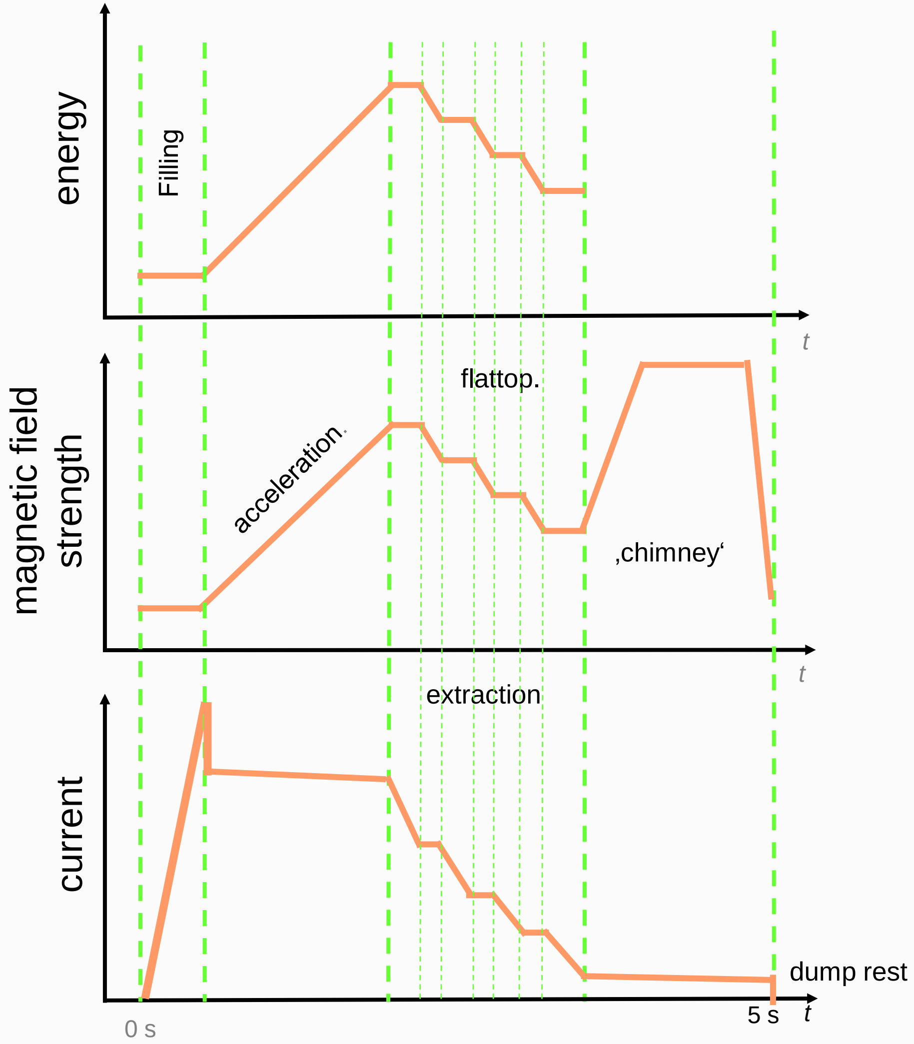


User visible cycle:
spill pause: 4-5s
(filling, acceleration, chimney)
spill: 1-10s
(extraction)
can be paused for beam gating
flexible length, chimney will start immediately on request



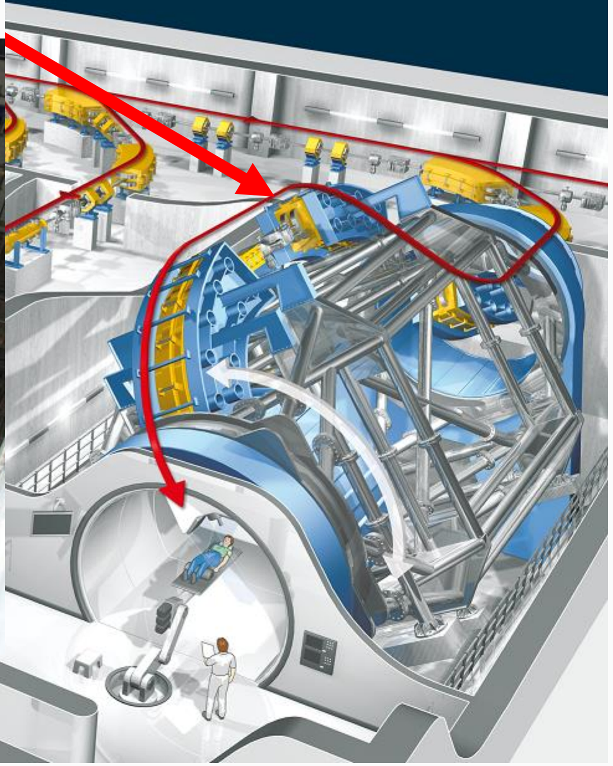
Energy selection synchrotron

- Direct extraction of any desired energy within specs
- Traditionally energy change only possible from spill-to-spill (2-5s)
- NIRS: Energy change on flattop – reduced to ~100 ms
  - Limiting factor: adjustment of large dipoles in high-energy beam transport (as in fast cyclotron systems)
  - Regular treatments can be completed with a single spill of max 2 10^{10} carbon ions

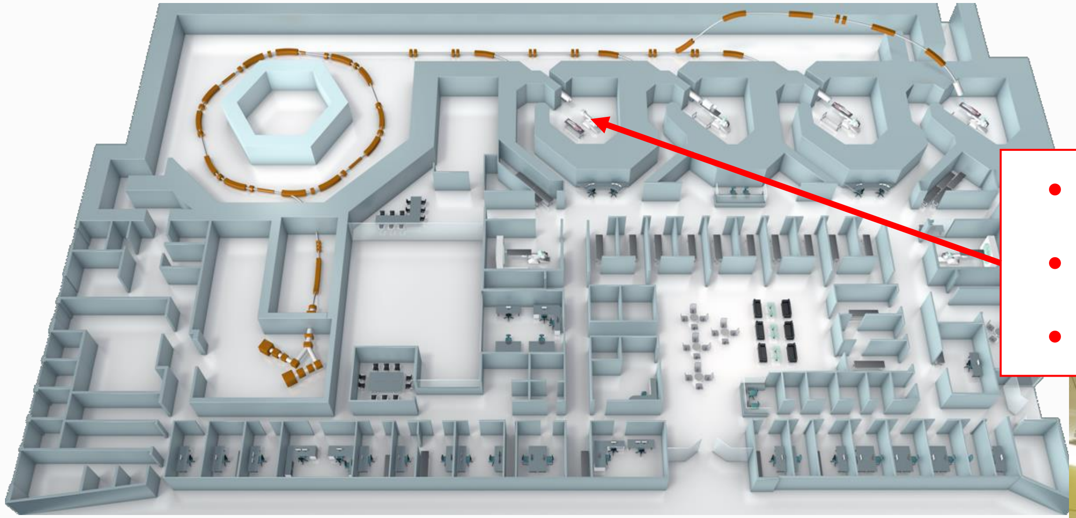


First carbon gantry in the world

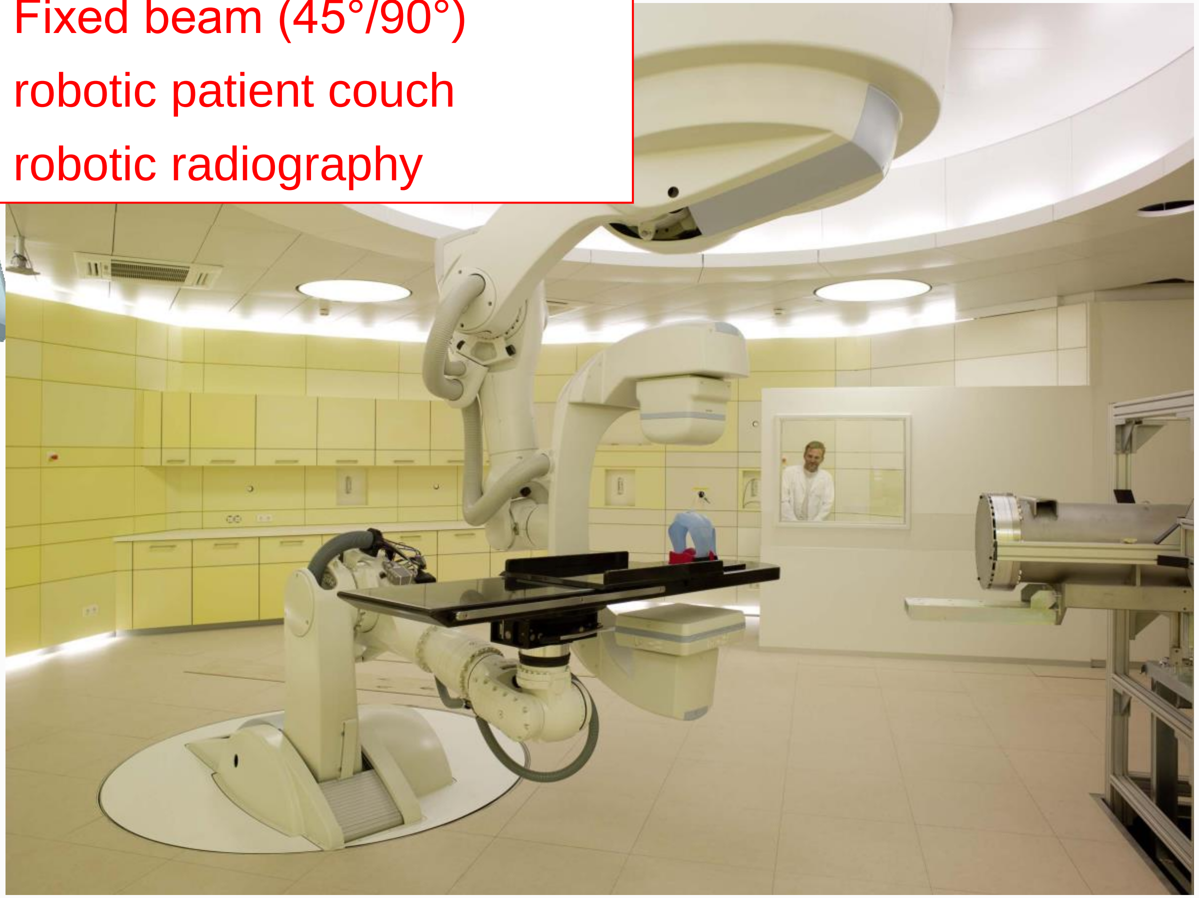
- mass 670t
- upstream scanning before
  last bending magnet
- 360° rotation
- ~ 1 mm precision
  in isocenter



Marburg treatment room

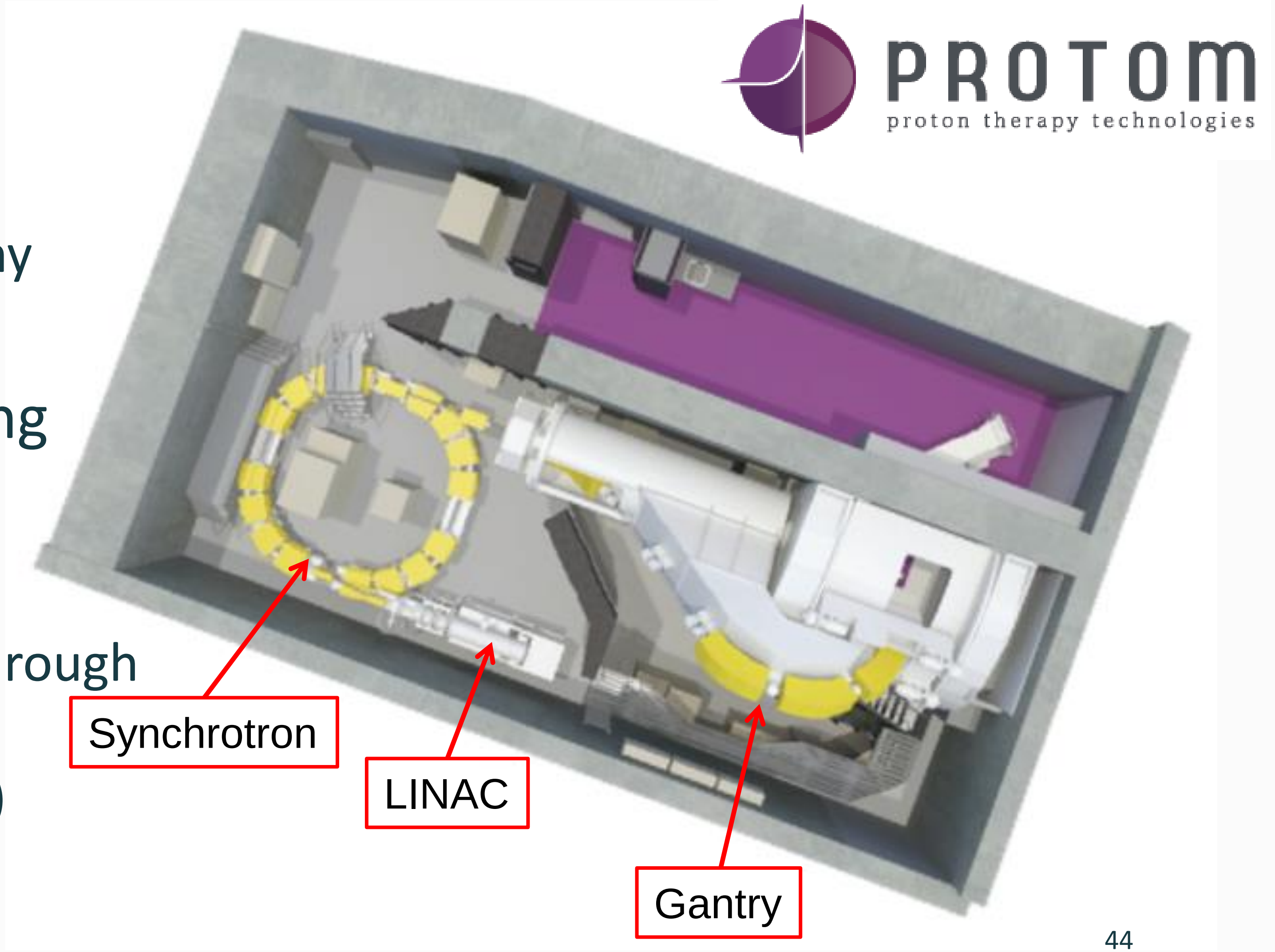


- Fixed beam (45°/90°)
- robotic patient couch
- robotic radiography



One-room synchrotron facility example: Protom

- Proton synchrotron
  - Emax= 330 MeV
  - capable of proton radiography
  - d = 6 m
- Was retrofitted into 2 existing Linac bunkers
- Advantages over cyclotrons:
  - more modular, installation through elevator shafts
  - 'cleaner' beam (no degrader)



ProTom International Holding Corporation, Flower Mound, TX, 2018

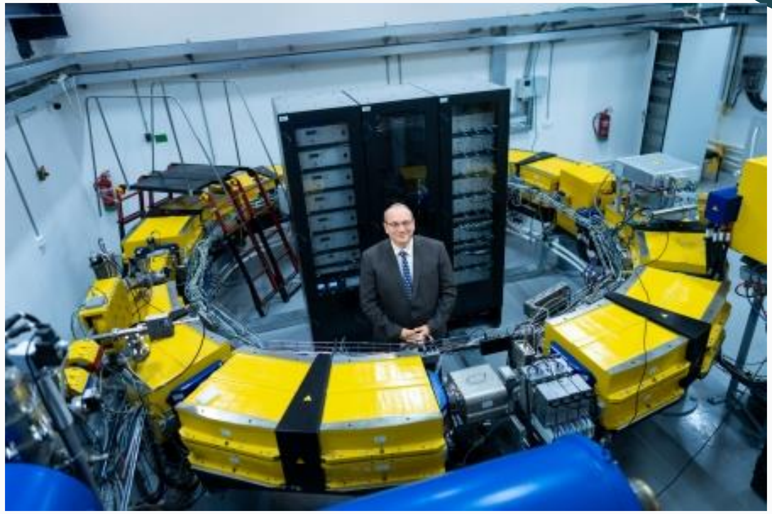
Summary synchrotrons

- Larger than cyclotrons, but individual magnets much smaller
  - ramping magnets makes superconductivity challenging!
- Desired energy can be directly extracted
- Distinct rhythm of acceleration and extraction
  - multi-energy extraction for much higher duty-cycle

- All currently treating carbon ion facilities
- Some proton facilities

Dedicated upright facilities

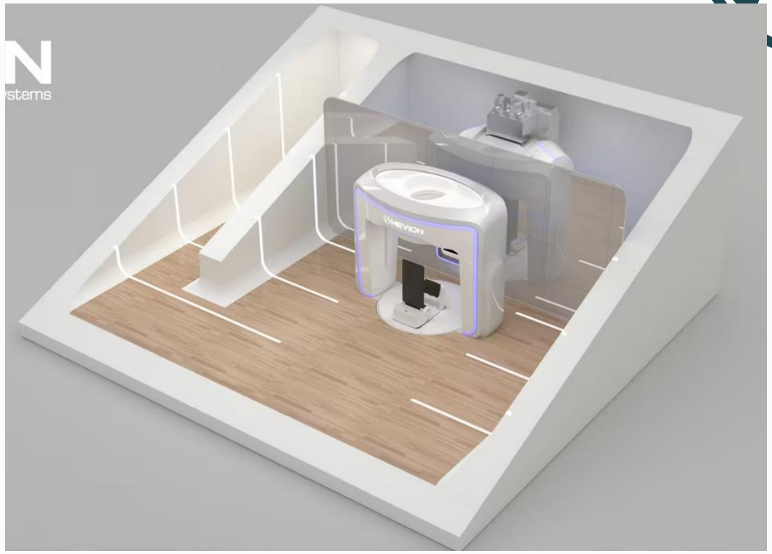
- p-Cure facility at Hadassah Hospital
- operational since 2023
- features synchrotron with fixed beamline
  - synchrotron contains only dipoles („weak focusing“): compact and simple
- Dedicated in-room upright CT + chair
- Already treated multiple cancer types in patients in clinical pilot studies



source: https://hadassahinternational.org

Dedicated upright facilities

- Mevion FIT system
  - FDA cleared in September 2025
  - In installation at several sites
- Features very compact cylcotron combined with LEO chair & CT
  - cyclotron is „self-shielded“, should fit in an existing photon linac bunker
  - isocentric CT



source: https://mevion.com

Summary upright facilities

- Two very different designs are on the market
- Cyclotron with direct beam + LEO positioner + iso-centric CT
- Synchrotron + robot-mounted chair + in-room CT

➢ Multiple installations are ongoing

➢ This is very good for the field!

Some numbers to follow…

Properties of protons and carbon

- protons: an elementary particle, mass $m_0 = 1{,}673\ 10^{-27} kg$ and charge $q = 1.602\ 10^{-19} C$
  - this is ~1800 times heavier than an electron, with same (negative) q
- carbon is an element with 6 neutrons, protons, and electrons
  - for acceleration, has to be ionized by removing up to 6 electrons
  - fully ionized carbon with 6 removed electrons: 12C6+
- a 12C6+ ion has a mass $m_0 = 1{,}993\ 10^{-26} kg$ and charge $q = 9.613\ 10^{-19} C$
- These numbers stink – so we normalize to unit atomic mass u and unit elementary charge e

Nicer units

- unit elementary charge $\mathrm{e} = 1.602\ 10^{-19} C$
- unit atomic mass $\mathrm{u} = 1.661\ 10^{-27} kg$ – conveniently defined as 1/12th of the mass of a carbon atom

- and a unit for energy: electron volts [eV] (remember $\boldsymbol{E} = \boldsymbol{qU}$)
  - energy of an object with charge $\mathbf{e}$ at an electric potential of $\boldsymbol{U} = \mathbf{1}\boldsymbol{V}$

$$[\mathrm{eV}] = 1.602\ 10^{-19} J$$

  - using $\boldsymbol{E} = \boldsymbol{mc^2}$, mass can be stated as $\boldsymbol{m} = \boldsymbol{E}/\boldsymbol{c^2}$ in units of $[\mathrm{eV}]/c^2$

Properties of protons and carbon

- protons: an elementary particle, mass $m_0 = 938.3\ MeV/c^2$ and charge $\mathrm{Q} = 1[\mathrm{e}]$
  - this is ~1800 times heavier than an electron, with same (negative) q
  - the mass of a proton is $m_0 = 1.007u$ – individual protons are heavier due to the mass defect!
- carbon is an element with 6 neutrons, protons, and electrons
  - for acceleration, has to be ionized by removing up to 6 electrons
  - fully ionized carbon with 6 removed electrons: 12C6+
- a 12C6+ ion has a mass $m_0 = 12u = 12\ x\ 931.5\ MeV/c^2$ and charge $\mathrm{Q} = 6\ [\mathrm{e}]$

Magnetic rigidity of clinical beams

$$B\rho = \frac{m}{q}v = \frac{A[u]}{Q[e]}v$$

Particle	mass at rest m_0 [MeV/c²]	Mass [u] : Charge [e]	Clinical energies [MeV]	Max Magnetic rigidity [Tm]
Electrons	0.511	0.00055	6 .. 25	0.085
Protons	938.3	1.007	50 .. 230	2.27
Carbon 12C6+	12 x 931.5	2	12 x (80 .. 430)	6.62