Gantries and beam delivery (from the synchrotron point of view)

ELENA BENEDETTO, SEEIIST

HEAVY ION THERAPY MASTERCLASS SCHOOL, MAY 2021

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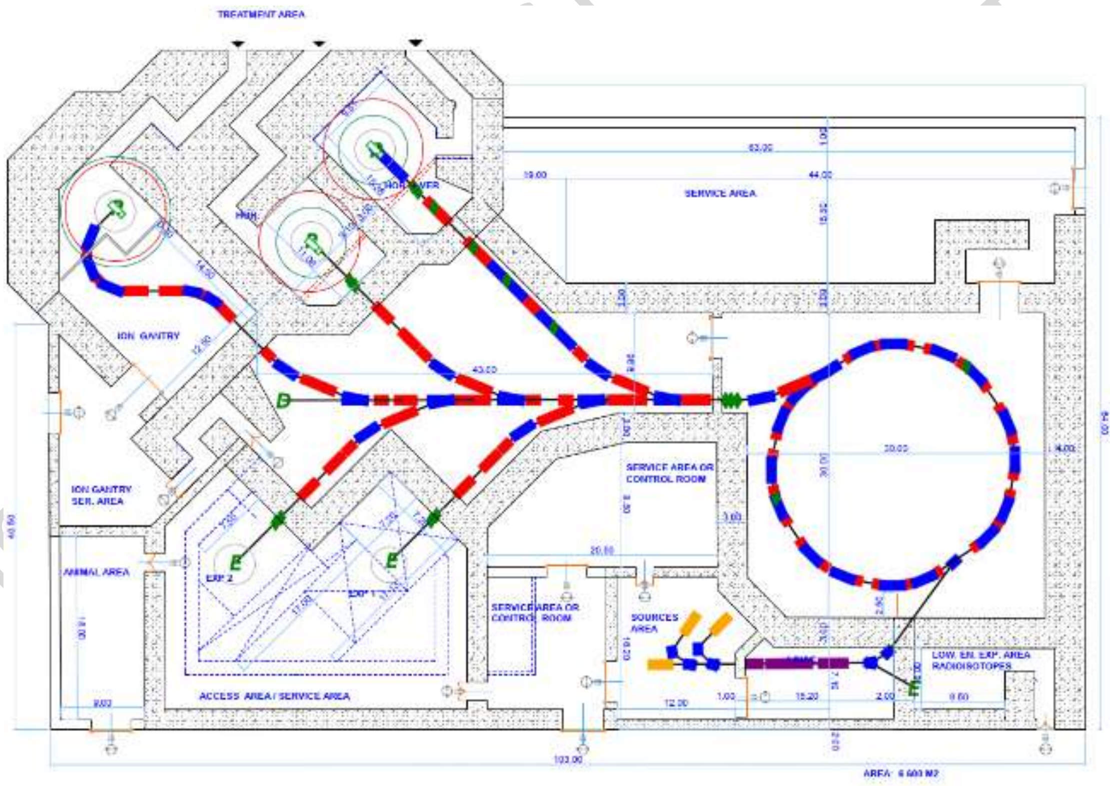
OUTLINE

- High Energy Beam Transfer (HEBT)
- Fixed treatment line
  - Pencil beam scanning
  - Energy change for longitudinal scanning
- Gantry
  - How to deal with the emittance from a synchrotron



HITRI plus
Heavy Ion Therapy Research Integration

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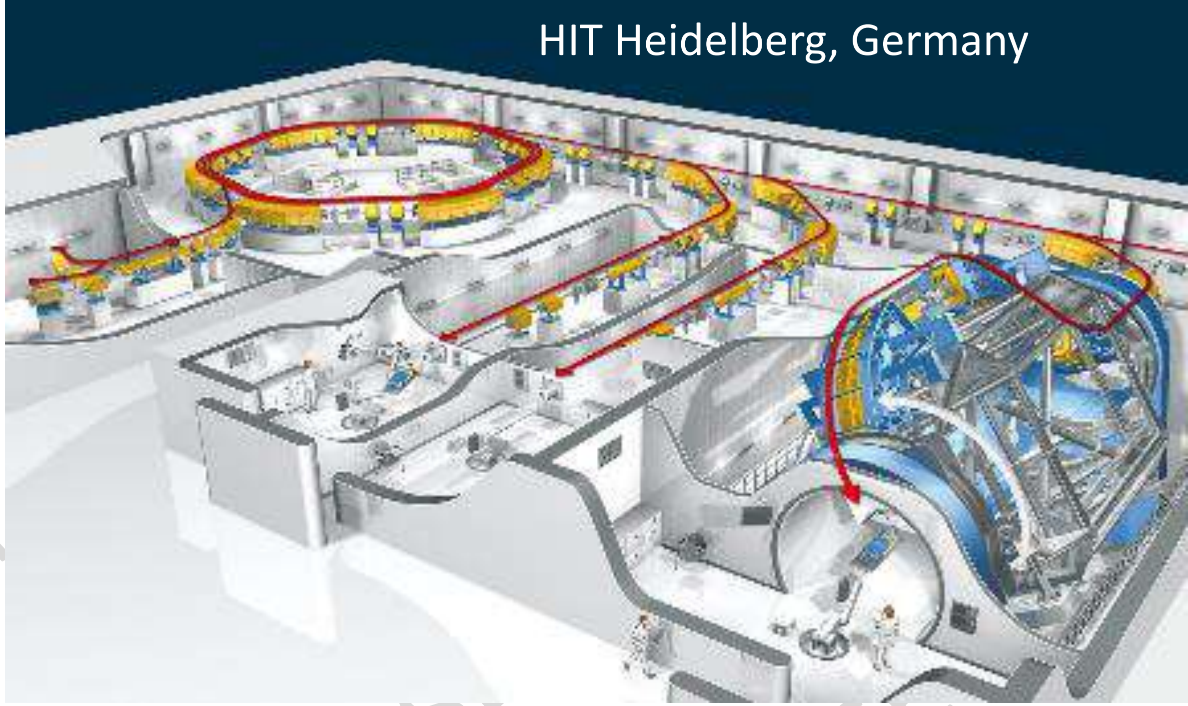

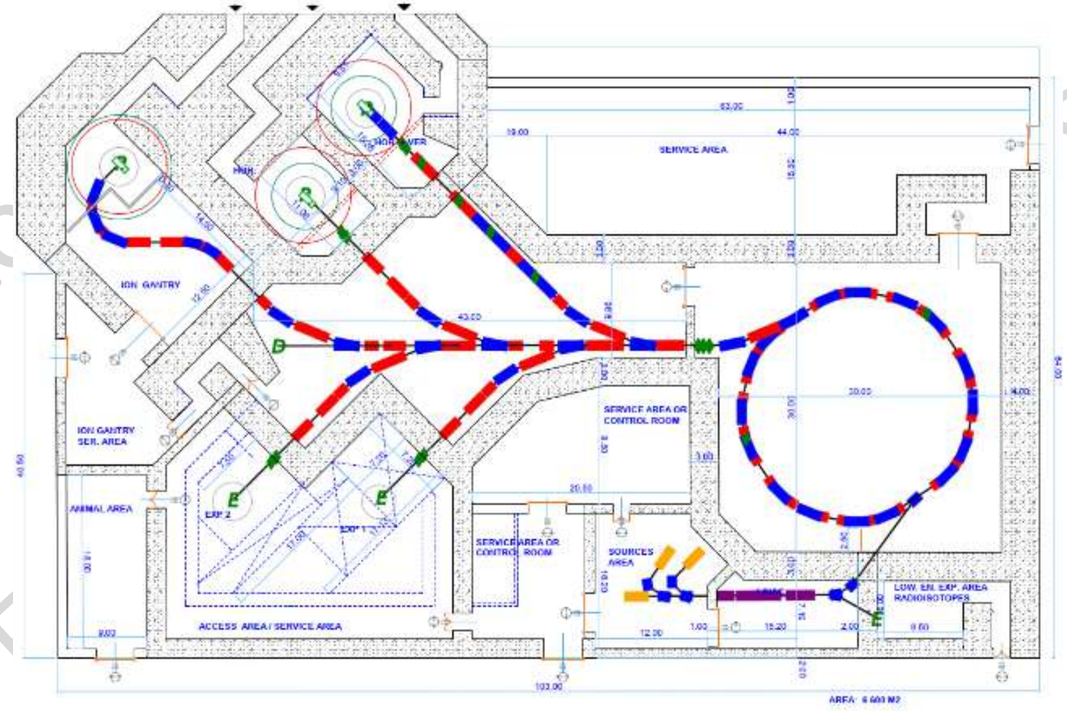

After extraction, the beam is transported to the treatment rooms

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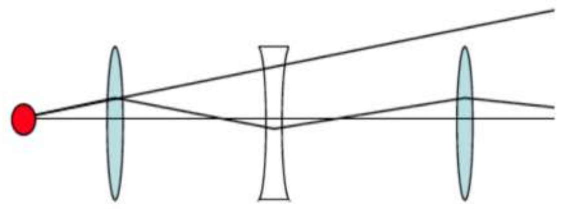
HIGH ENERGY BEAM TRANSFER (HEBT)

The beam is transported with(*):

Dipoles, which bend the beam toward the treatment room (and to the patient)

Quadrupoles which are focusing in one plane & defocusing in the other

- F= focuses in x, defocuses in y; D = focuses in y, defocuses in x;
- An alternation of F.O.D.O provides net focusing



$$\frac{1}{F} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2}$$

(*) see M. Sapinski Accelerator Physics lecture

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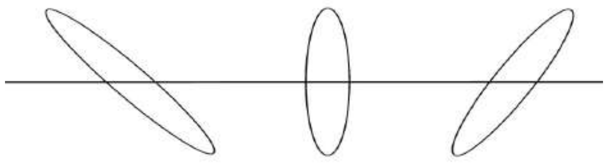
HIGH ENERGY BEAM TRANSFER (HEBT)

Ellipse shape and orientation evolve along the line (emittance stays constant)



$$\sigma = \sqrt{\beta \varepsilon}$$

The HEBT brings the beam to the room with the correct size and "matched" (ellipse orientation) to the treatment line (or gantry) entry point. This is done with quadrupoles.

$$\begin{pmatrix} x \\ x' \end{pmatrix}_{s_1} = M \begin{pmatrix} x \\ x' \end{pmatrix}_{s_0} \qquad M_{total} = M_{QF} \cdot M_D \cdot M_{Bend} \cdot M_D \cdot M_{QD} \cdot \ldots$$

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ACHROMATIC TRANSPORT

Dispersion: is the dependence of the position on the beam energy

- If D=1m (~usual value) if the beam has an error in momentum of 0.5%, the position will be offset by 5 mm (a lot!!!)

At the patient, one needs to have zero dispersion
…again the quadrupoles can do the job!

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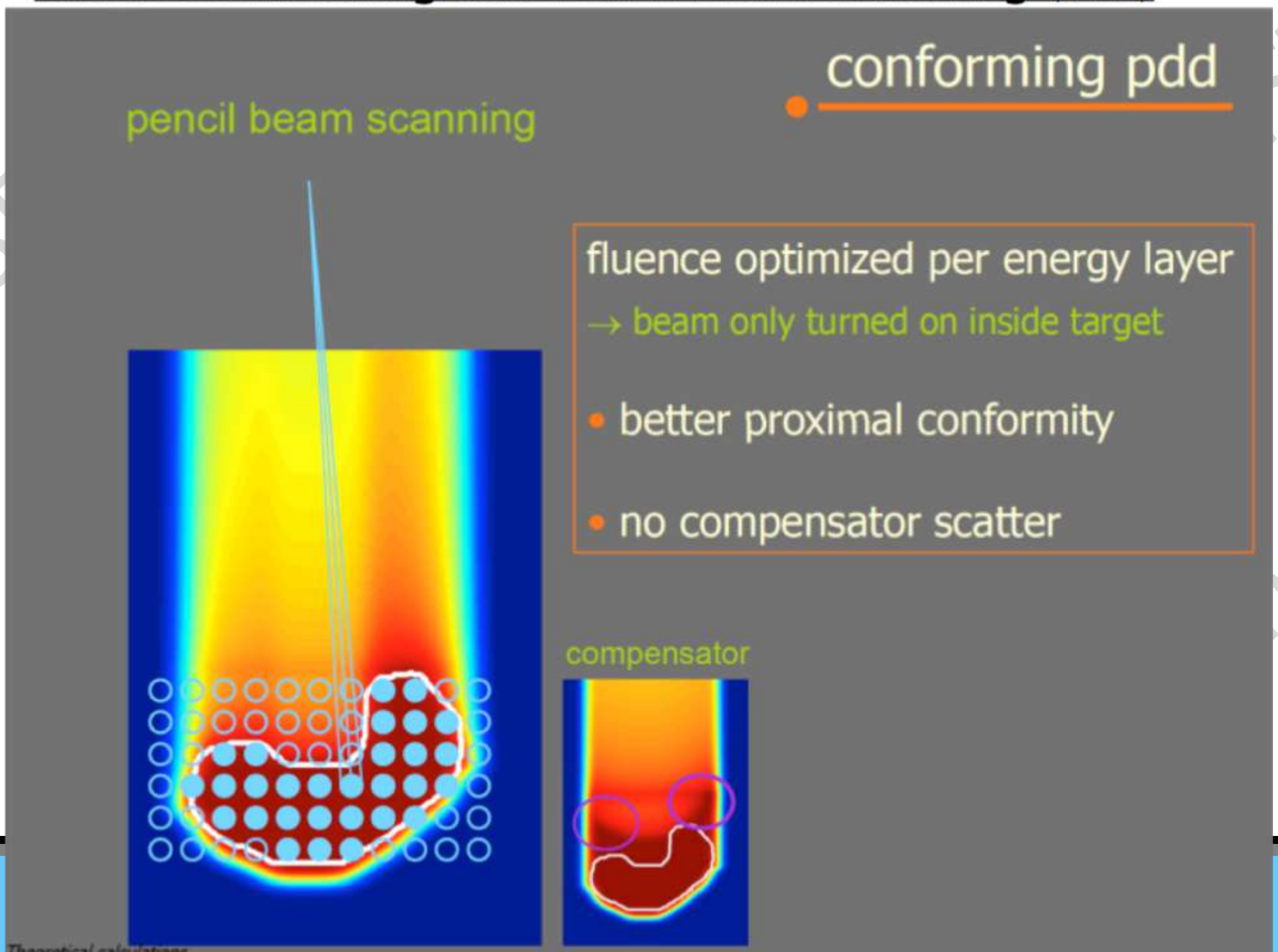
FIXED TREATMENT LINE (OR GANTRY)

This section prepares the beam for being delivered to the patient

Pencil Beam Scanning (Vs. Passive Scattering):

- Dose only in the tumour to spare healthy tissues

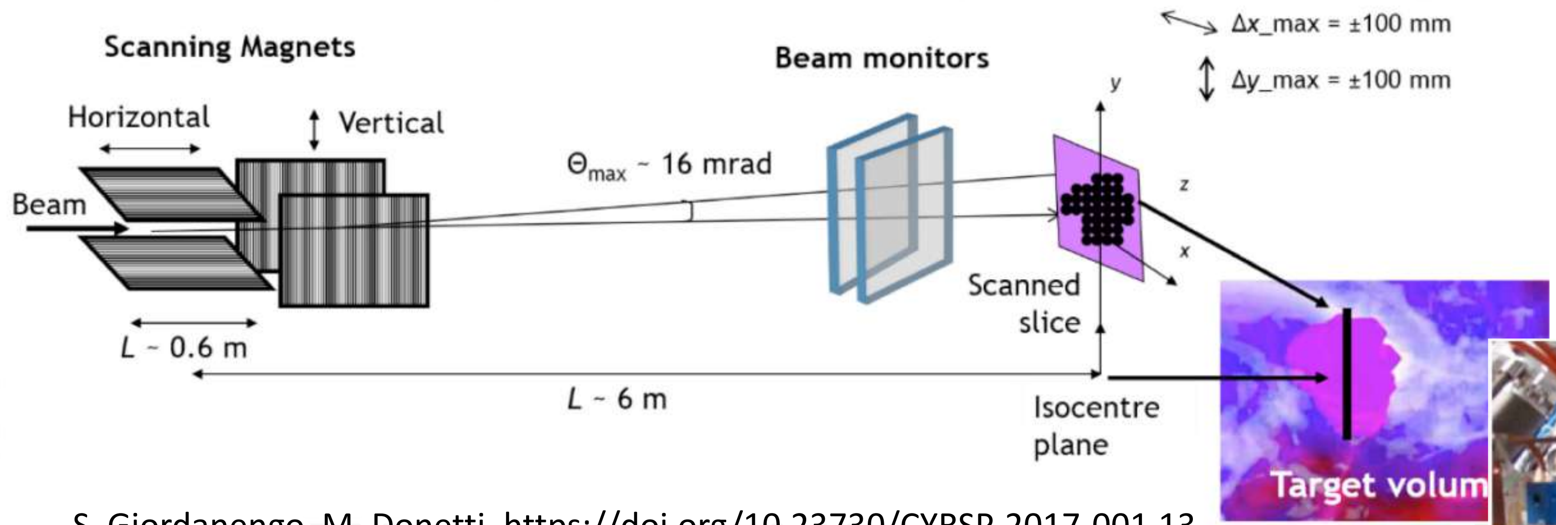
Passive Scattering and Pencil Beam Scanning (PBS)



* Joao Seco's lecture

PENCIL BEAM 3D SCANNING

Transverse: fast & powerful scanning magnets



S. Giordanengo, M. Donetti, https://doi.org/10.23730/CYRSP-2017-001.13

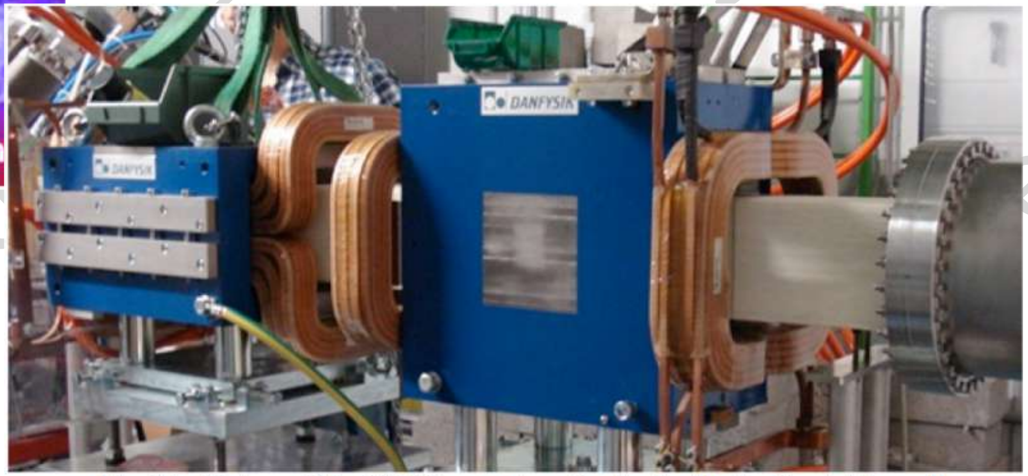


Fig. 11: Picture of the CNAO scanning dipoles for the horizontal beamline

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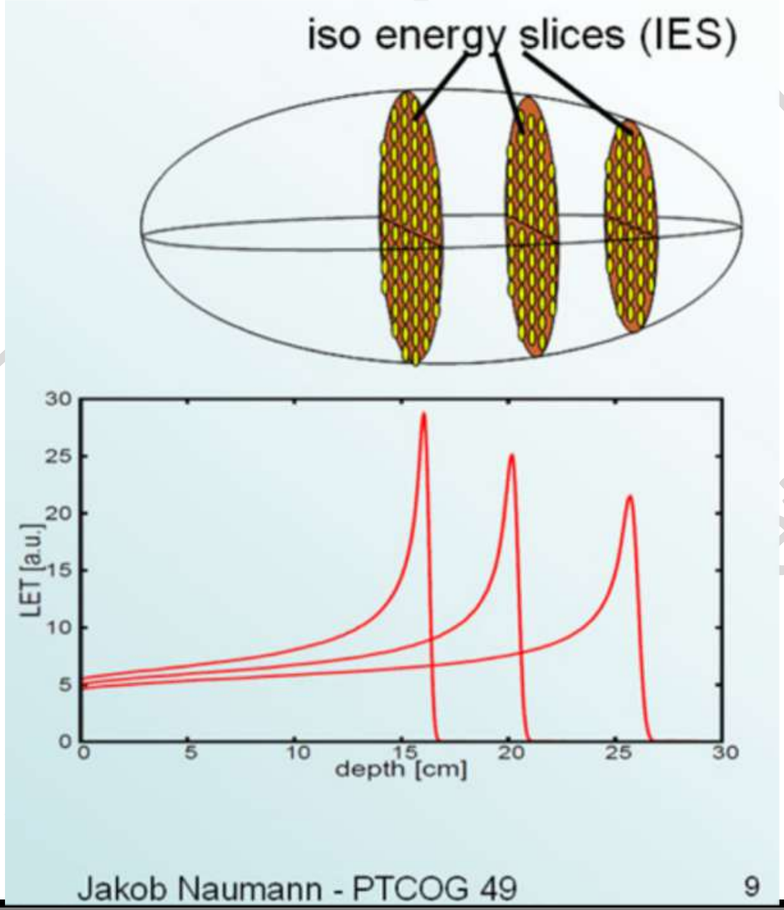
PENCIL BEAM 3D SCANNING

Longitudinal: move Bragg peak by varying beam energy



A range in water of 30 cm corresponds to :

250 MeV for protons

430 MeV/u for Carbon ions

How do we vary the beam energy?

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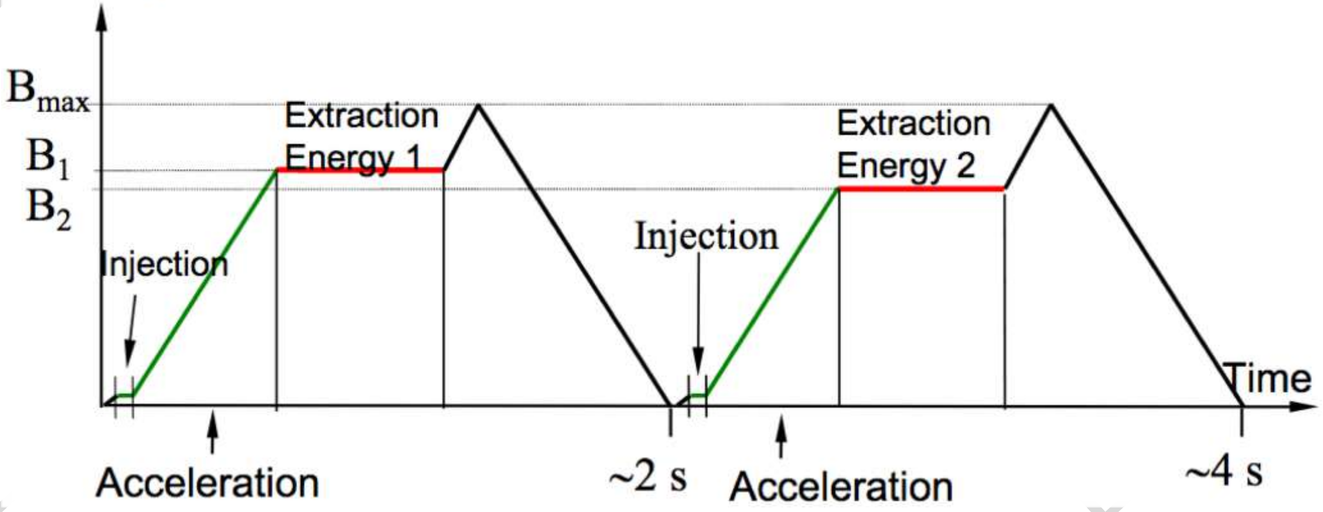
HOW TO VARY BEAM ENERGY?

Cyclotron: Energy is fixed, with degraders

Linac: Pulse to pulse energy variation by "switching-off" RF cavities

Synchrotron: Accelerate the beam to the required energy and extract

Dipole magnetic field ~ Beam Momentum



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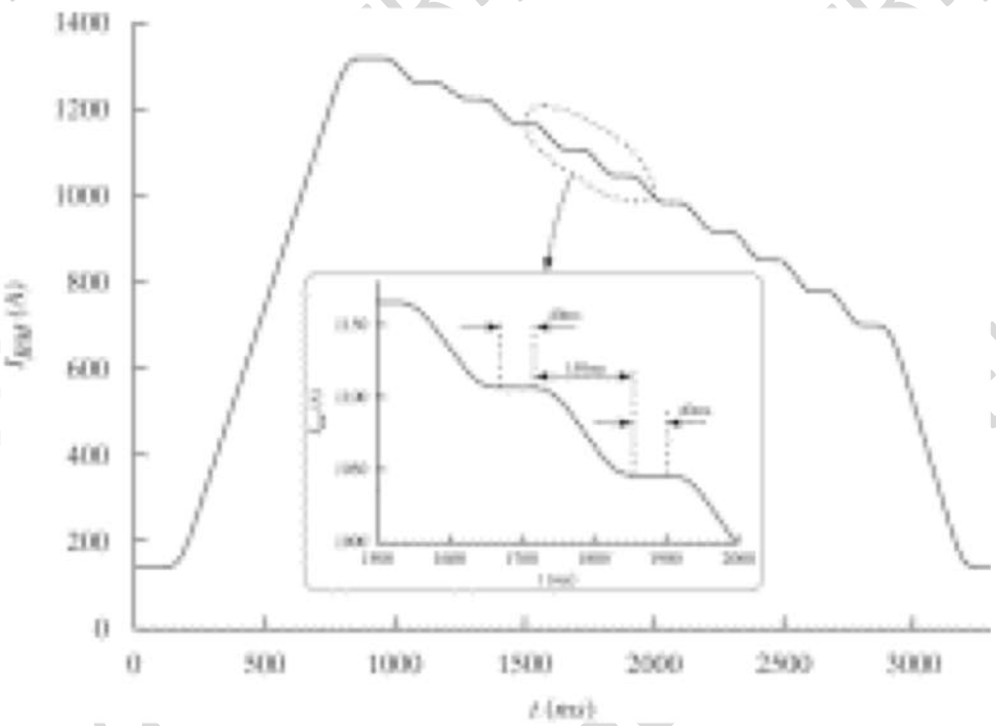
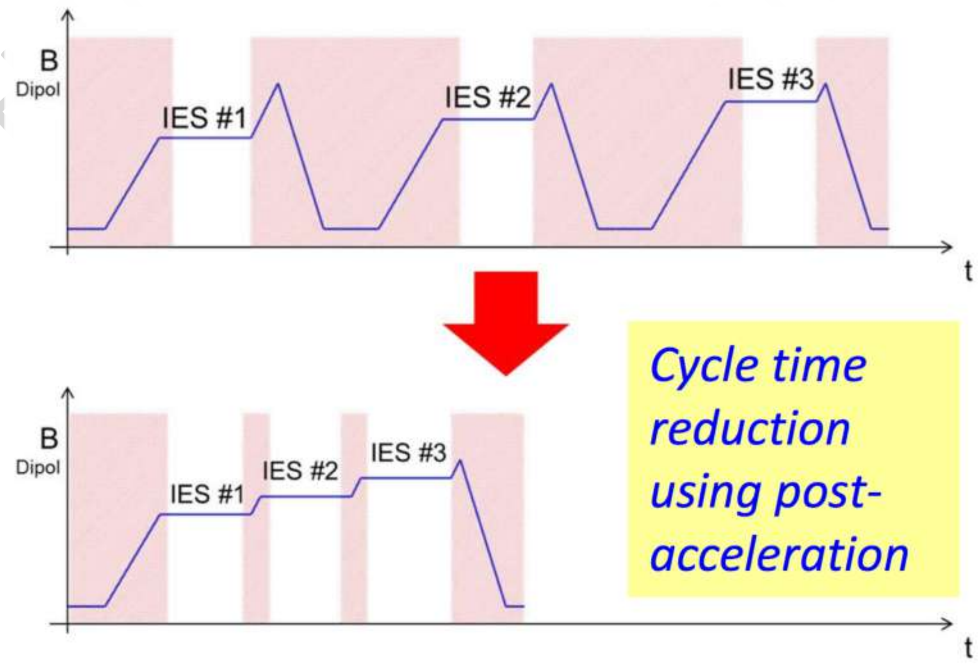
MULTI ENERGY EXTRACTION – TO REDUCE TREATMENT TIME



Noda et al., HIMAC, Japan (in operation)



Peters et al., HIT, Germany (studies)

Consequence: Need to inject >10x higher intensity

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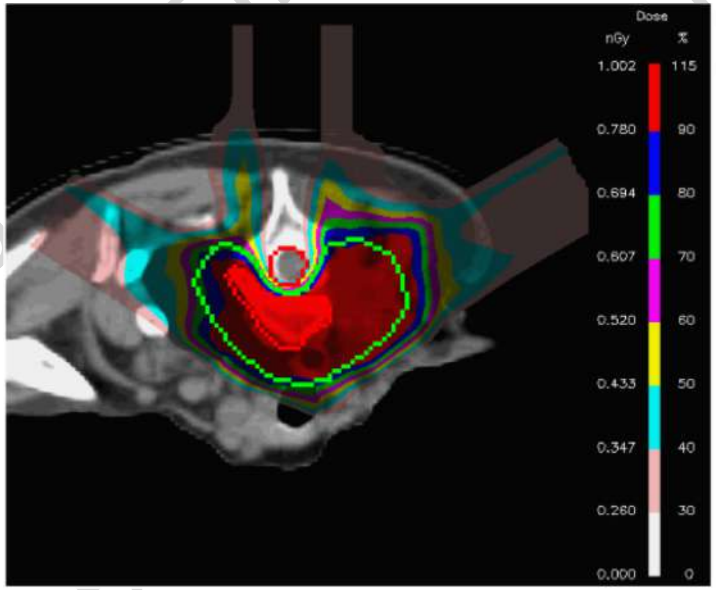
GANTRIES

To deliver the beam from multiple angles and spare Organs At Risk



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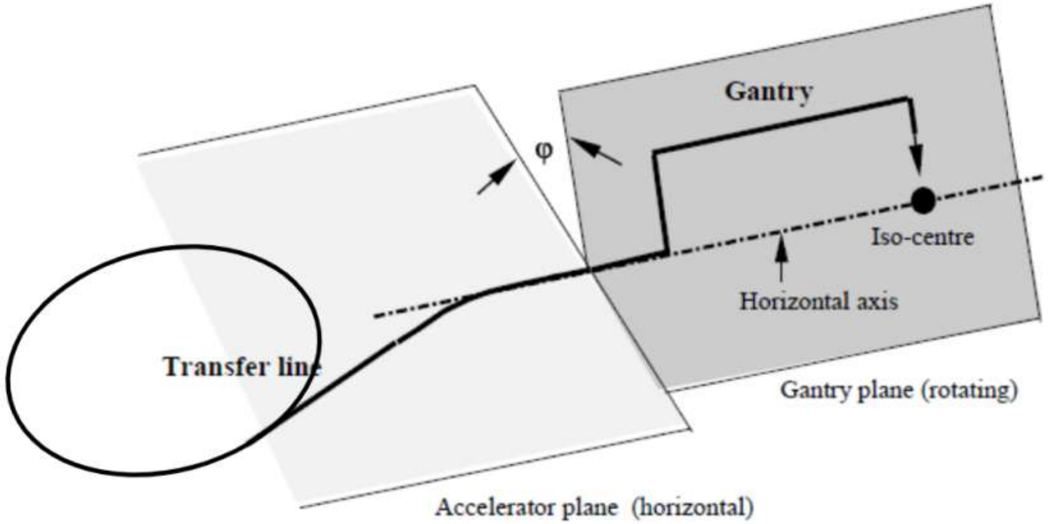
GANTRIES

The gantry is a beamline (vacuum chamber, dipoles, quads, instrumentation)…

…which is rotating around the patient to direct the beam to the **isocenter** from any direction, to optimize the dose delivery

(EVERYTHING said for the fixed lines is valid: correct size, matched, zero dispersion)



* most of the material is derived from M. Pullia's several lectures, e.g. at the CERN Accelerator Schools in 2015

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GANTRY FOR X-RAYS (e-), PROTONS and CARBON IONS

electrons, protons & carbon ions have different **rigidity**

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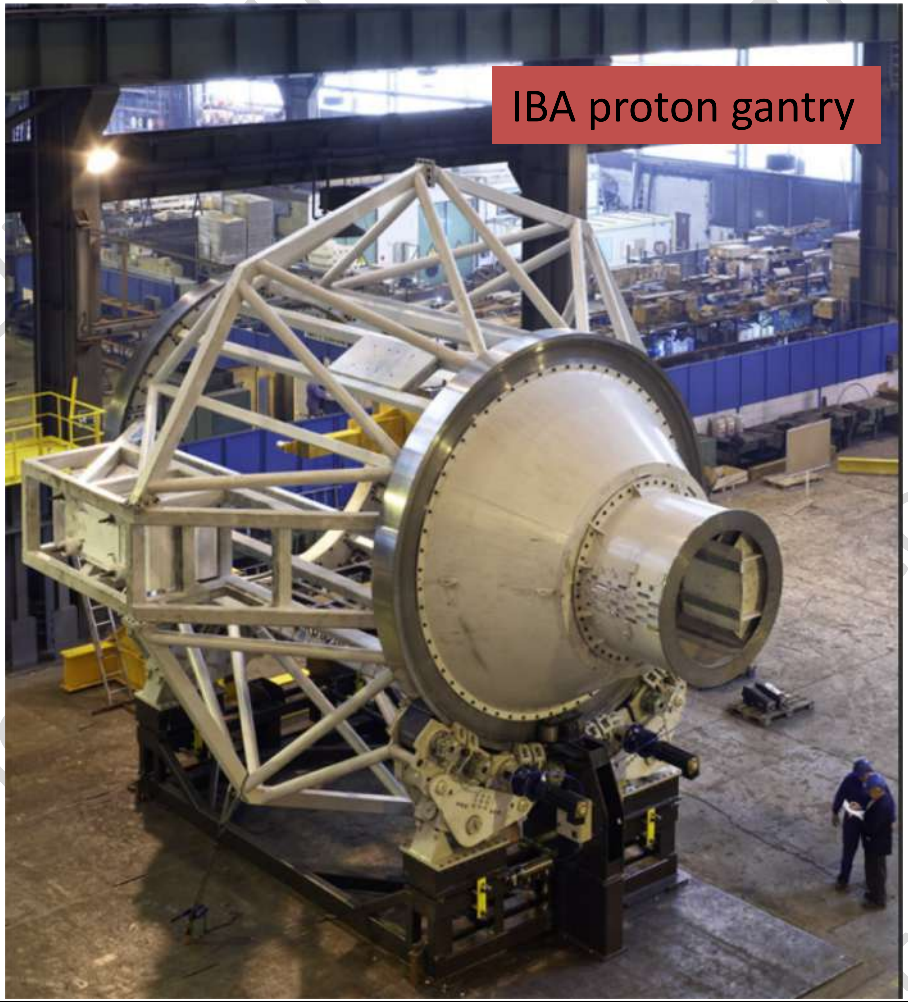

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GANTRY FOR X-RAYS (e-), PROTONS and CARBON IONS

Rigidity: "how difficult" is to bend the beam

$$qvB = \frac{mv^2}{\rho} \Rightarrow B\rho = \frac{p}{q}$$

electrons @ 20 MeV: Bρ=0.068 T m

protons @ 250 MeV: Bρ=2.43 T m

C-ions @ 430 MeV/u: Bρ=6.6 T m

B = Magnetic field < 1.5T (normal conducting magnets)
ρ = Radius of curvature is 1.6m (protons) vs. 4.4m for C-ions

Let's use superconducting magnets!!!
B>3T, ρ < 2.2m for C-ions

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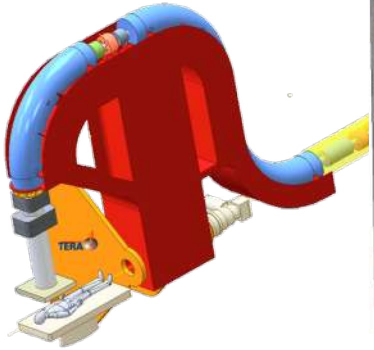
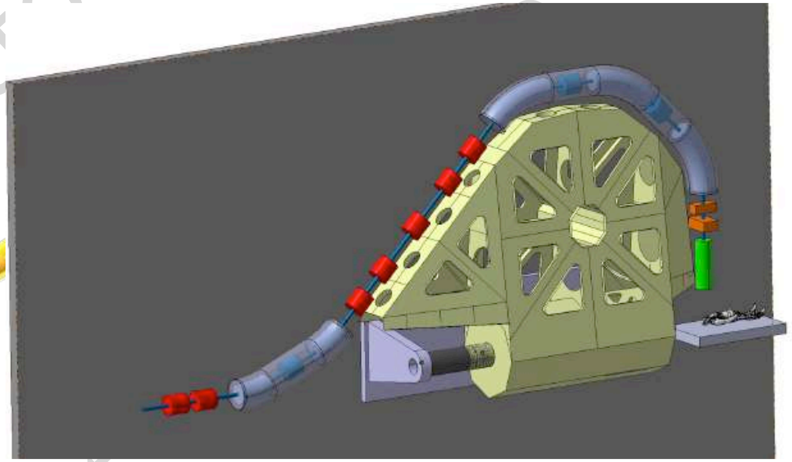
CARBON ION GANTRIES

HIMAC (Japan) gantry has superconducting magnets of 3T and weigths “only” 300 tons, compared with 600 tons of HIT





C-ion gantries studied in HITRIplus, will be ~similar size but a much lighter structure of only ~35 tons (TERA Foundation proposal)

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CHOICES WHEN DESIGNING A GANTRY

- Angle of rotation
- Position of the fast scanning magnets
- How to deal with non-symmetric beam from synchrotron - because the question was raised few times! ;)

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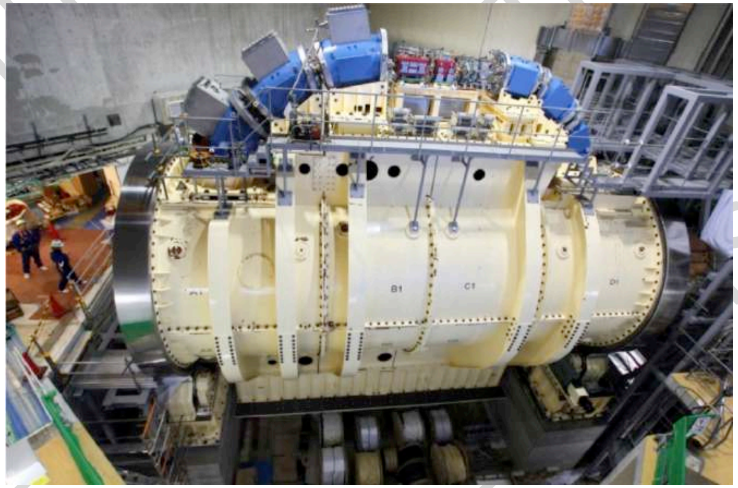
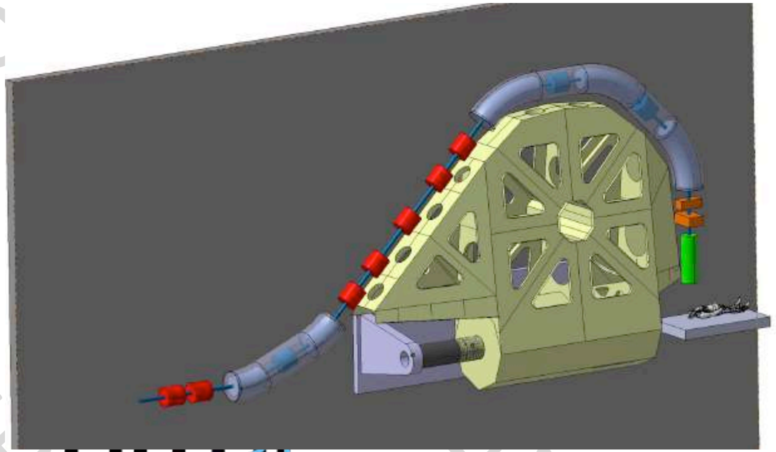
ANGLE OF ROTATION



360 degrees



220 degrees,
fixed to the wall

More space, BUT requires rotation of the bed

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FAST SCANNING MAGNETS IN A GANTRY

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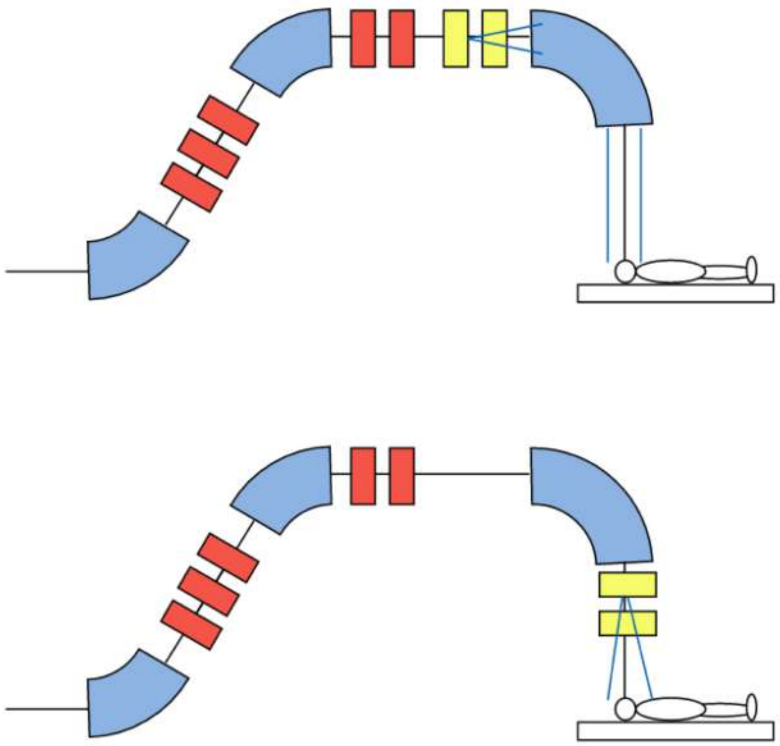

- **Large aperture dipole: weight and power consumption**

SC magnets gantry tend to have downstream scanning magnets, to reduce magnet aperture

- **Large gantry radius and large room size**

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NON SYMMETRIC BEAM FROM SYNCHROTRON

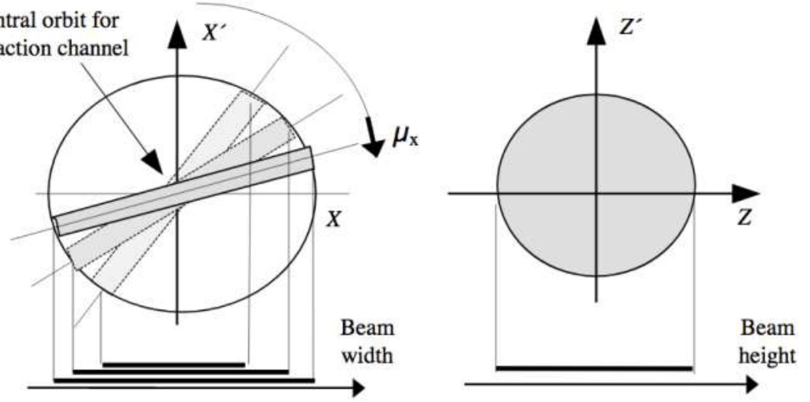
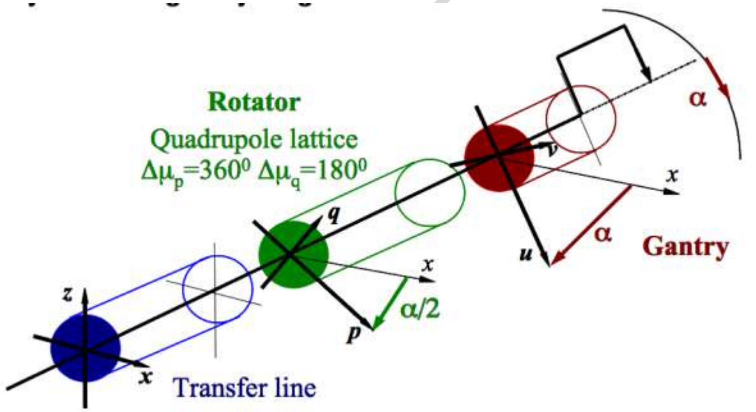


Figure 9.7 Rotation of the 'bar of charge' with phase advance

1. Insert a scatterer (Japanese) to blow-up the beam in horizontal plane
2. Round beam method
   - as long as the two beams are “round”: $(\varepsilon_x \beta_x) = (\varepsilon_y \beta_y$
     one can find a partial matching



3. Rotator
   - a set of Quads that rotate by ½ the gantry angle

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TO CONCLUDE…

Beam lines to the patient:

- Fast scanning magnets to perform 3D scanning of the tumour
- Vary the energy of the beam to move the Bragg peak

The Gantry is a rotating beam line (whose structure can weigth up to 600 tons) to provide beam from different directions

Quadrupoles along the line and on the gantry focus the beam and provide the correct size and shape of the beam.

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