CTU
CZECH TECHNICAL UNIVERSITY IN PRAGUE

Introduction to particle therapy

Petra Trnková

Overview

- Radiotherapy introduction
- Basics of particle therapy
- Particle therapy facility
- (Particle) Radiotherapy workflow

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Radiotherapy

- Radiotherapy is a treatment where radiation is used to kill cancer cells
  - Complete cancer cure (curative radiotherapy)
  - Making other treatments more effective (neo-adjuvant radiotherapy)
    - combination with chemotherapy, application before surgery
  - Reduce the risk of the cancer coming back after surgery (adjuvant radiotherapy)
  - Relieve symptoms if a cure is not possible (palliative radiotherapy)

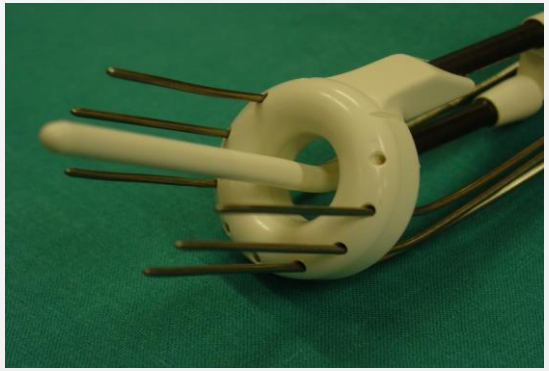
Types of radiotherapy

External beam therapy:

- Photons, protons, ions (**carbons**, helium)

Brachytherapy:

- Intracavitary, interstitial, seeds

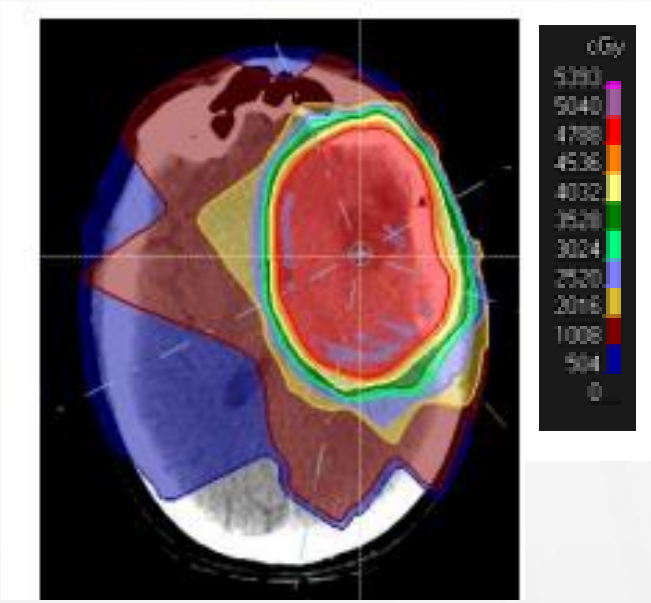


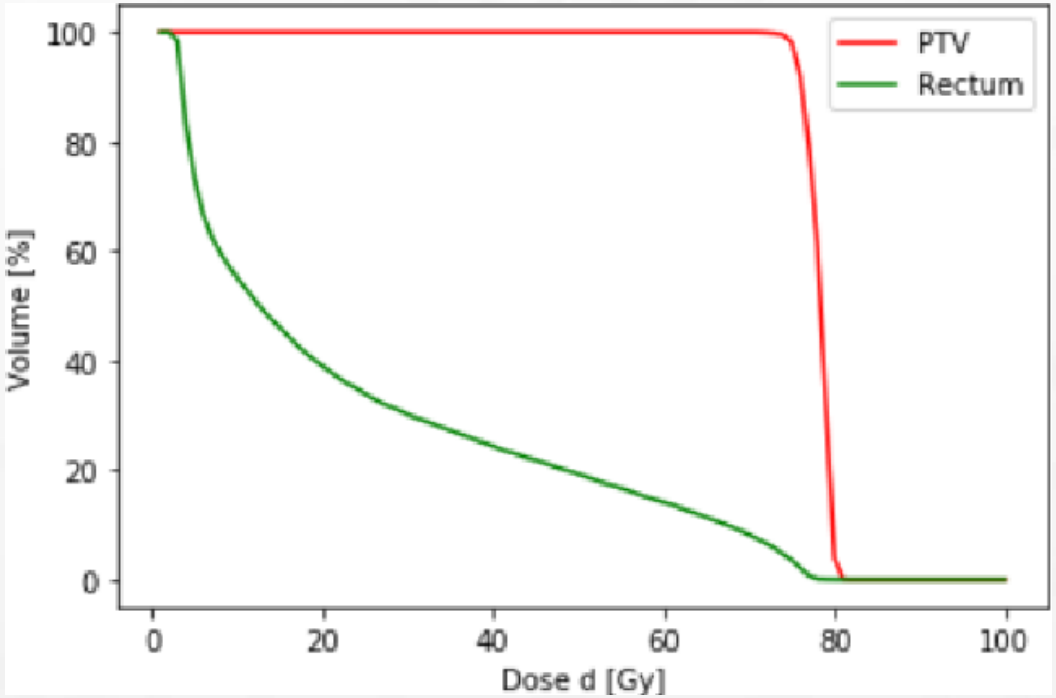
Dose

- Absorbed dose [Gy]: the mean energy $d\varepsilon$ imparted by ionising radiation to matter of mass $dm = \rho\, dV$, with the density, ρ, and the volume element dV

$$D = \frac{\mathrm{d}\bar{\epsilon}}{\mathrm{d}m} = \frac{1}{\rho}\frac{\mathrm{d}\bar{\epsilon}}{\mathrm{d}V}$$

Dose distribution





Radiobiological effectiveness (RBE)

- Ratio of the photon and particle therapy beam dose to reach the same effect biological effect
  - => addressing biological differences among radiation modalities

$$RBE_{iso} = \frac{D_{ref}}{D_{ion}}$$

- Function of dose, tissue and biological end-point, LET
- Protons are currently planned with 1.1 RBE

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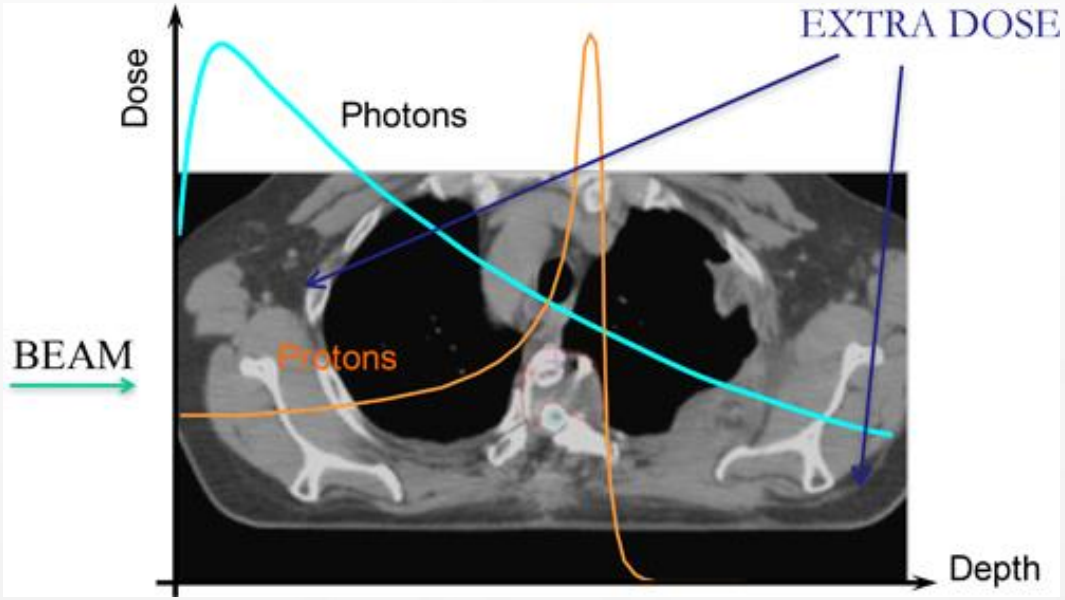
Advantages of particle therapy: physical and biological



Source: Paganetti, Proton Beam Therapy

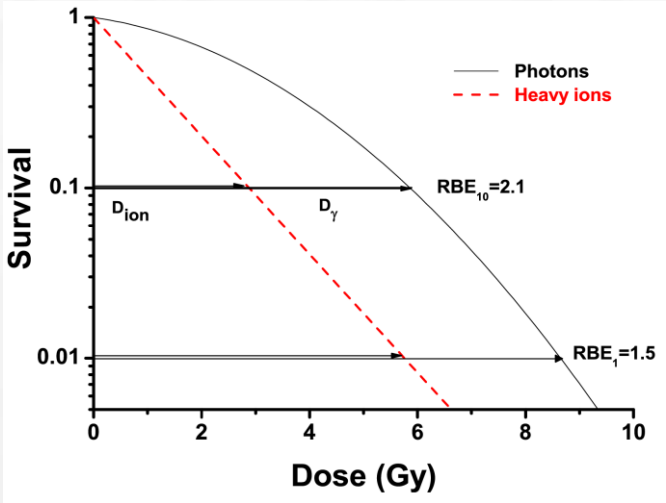
Physical and biological advantages:

- inverted depth-dose profile
- exactly defined penetration path
- treatment of tumours resistant to conventional irradiation (carbon ions!)

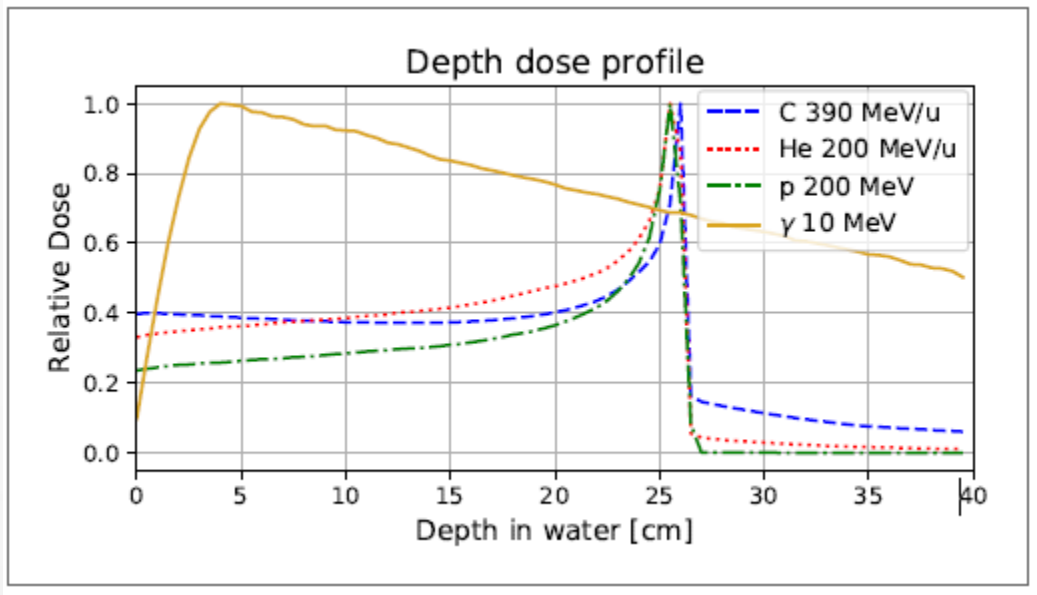
Increased relative biological effectiveness (RBE)

$$RBE_{iso} = \frac{D_{ref}}{D_{ion}}$$

Ratio of energy doses for the same biological effect



Advantages of particle therapy

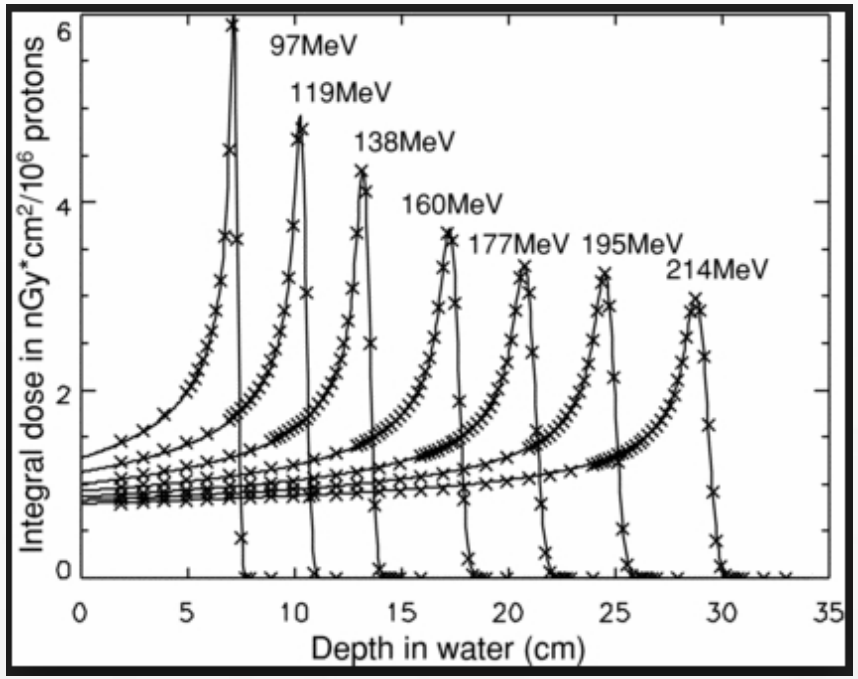


Medical advantages:

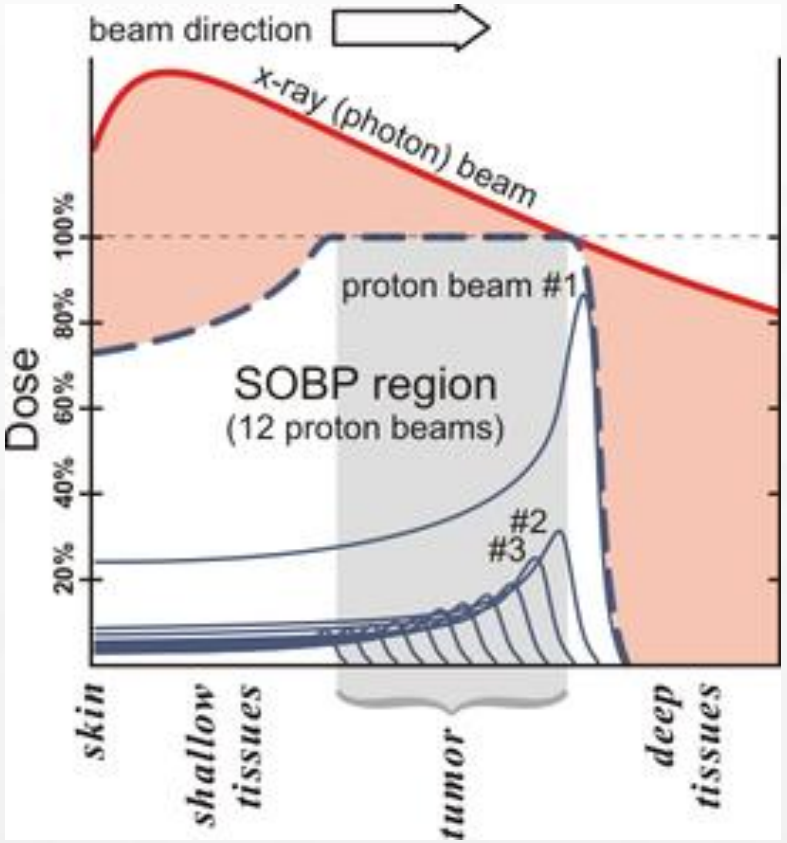
- Treatment of tumours close to radio-sensitive organs
- Reduction of integral dose
  - advantage for children and young adults

Decreased risk for secondary tumours

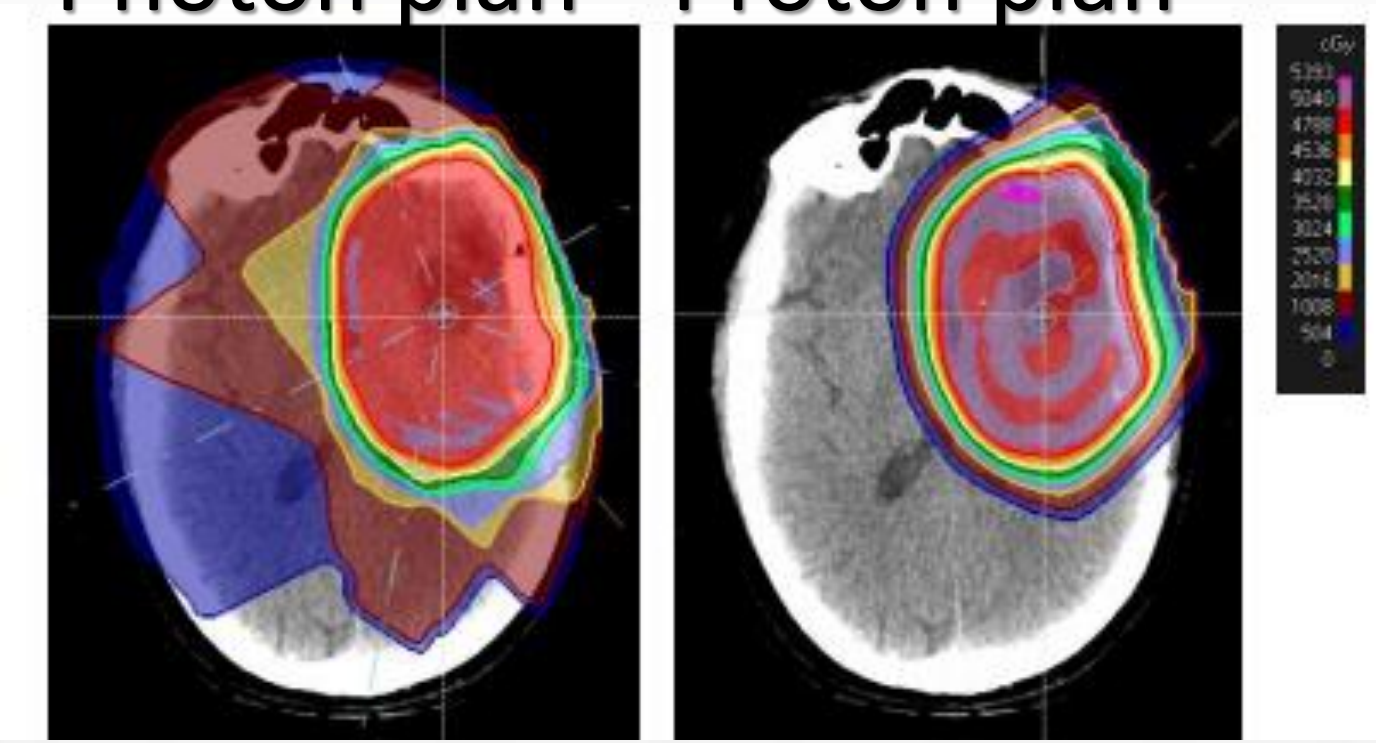
Bragg peak and Spread-out Bragg peak (SOBP)



Pedroni et al, PMB 2015

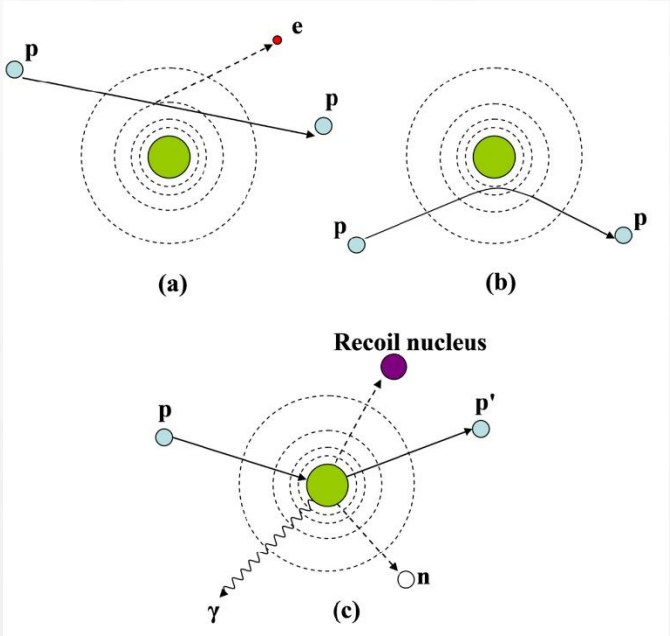


Photon plan Proton plan



Interactions in particle therapy

- Electromagnetic interaction between proton / ion beams with electrons from molecules in human body



Newhauser and Zhang, PMB 2015

Overview

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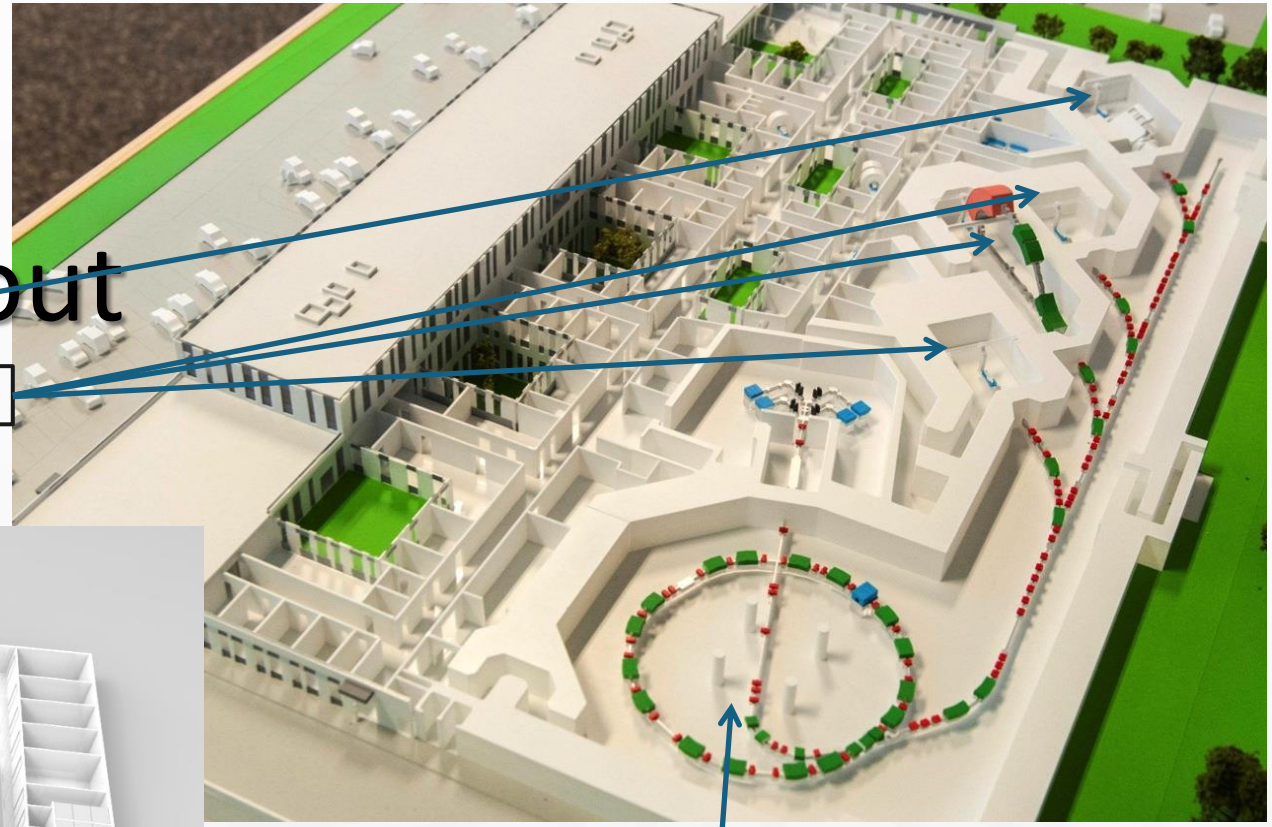
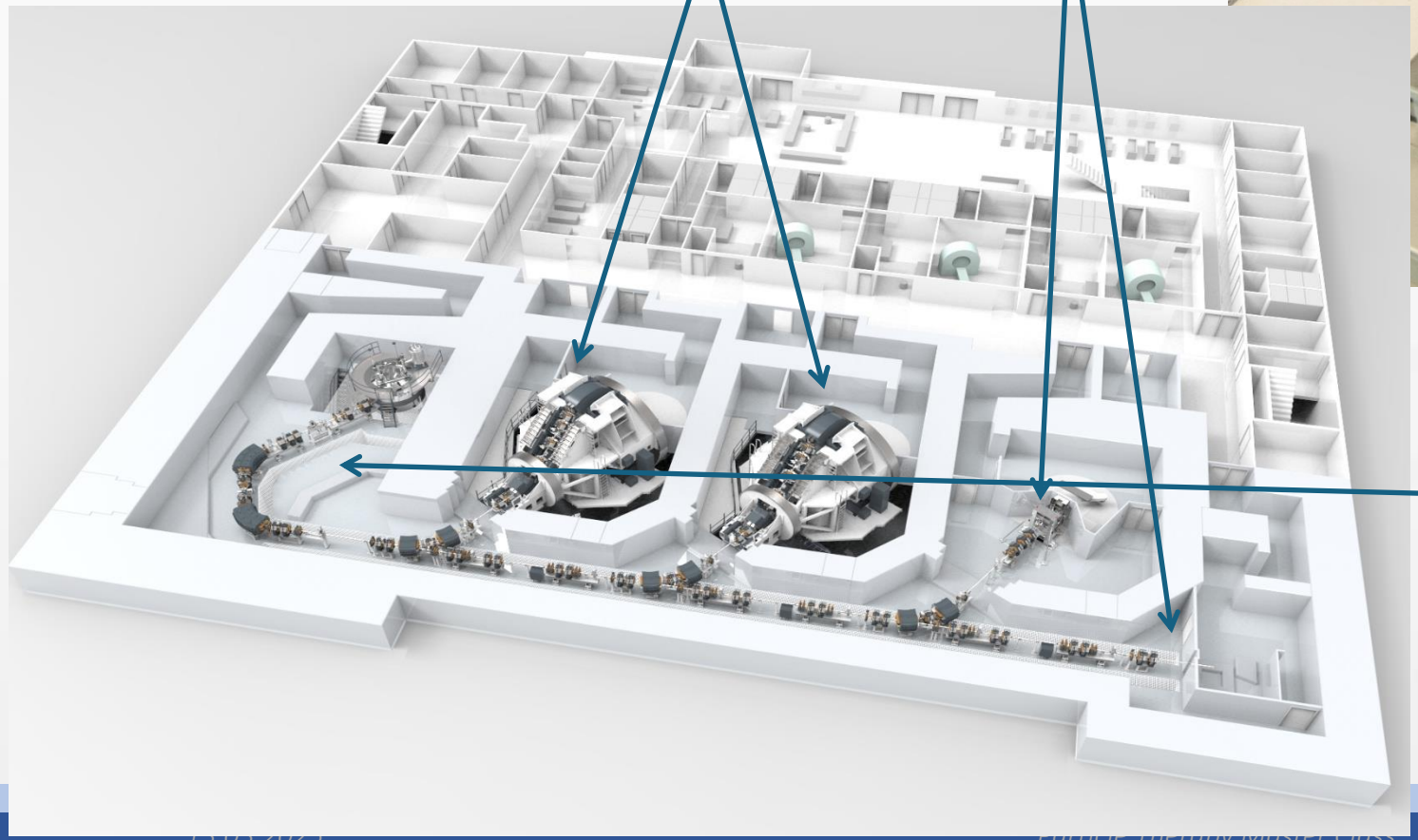
Multi-room facility layout



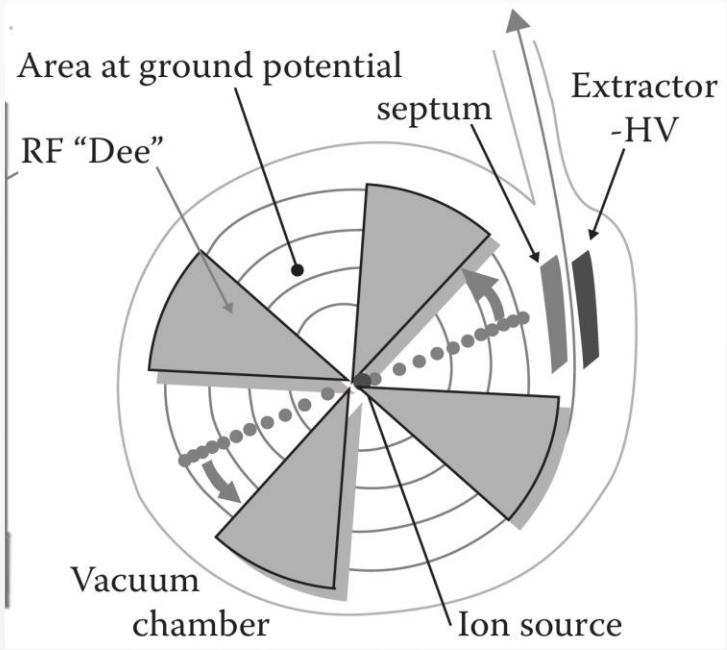


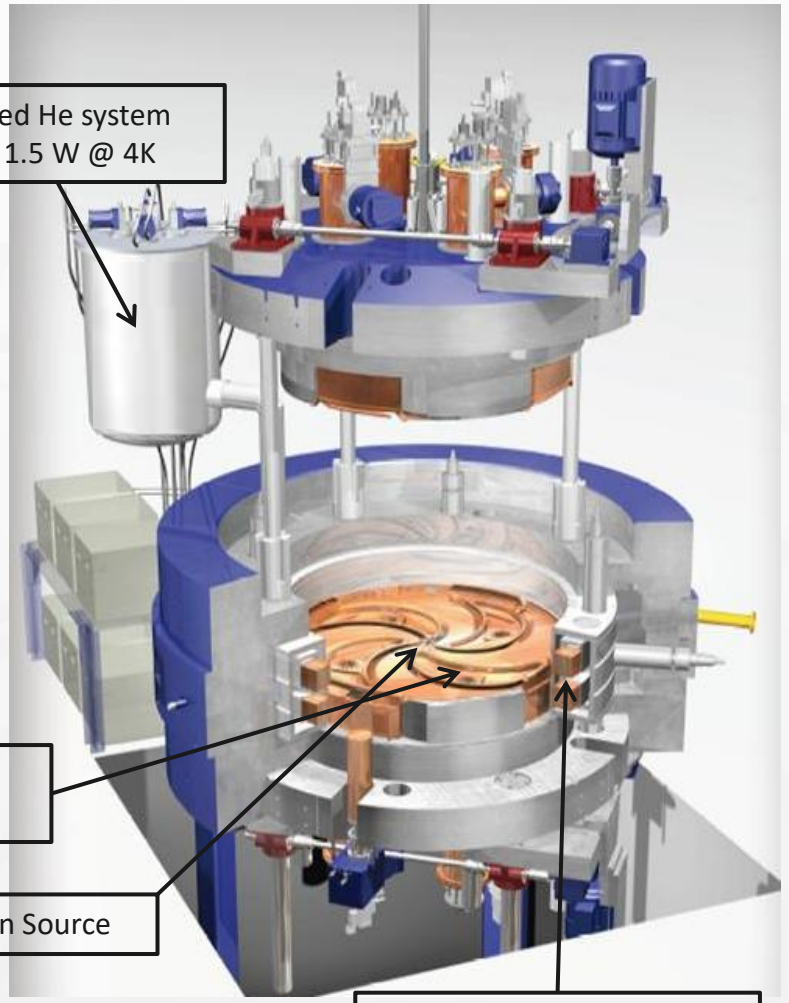
Rotational gantry

Fixed beam lines

Accelerator

Accelerators: Cyclotron

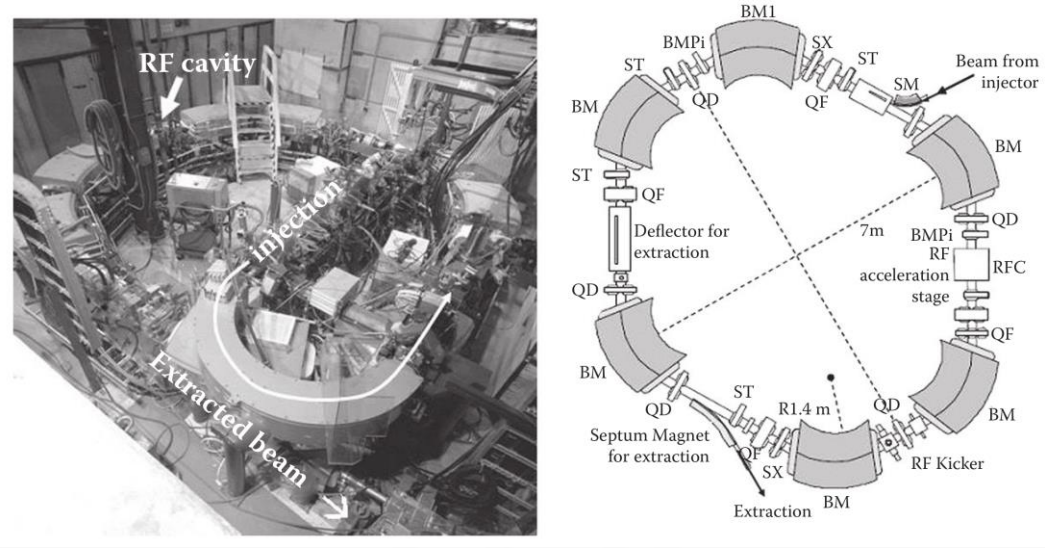


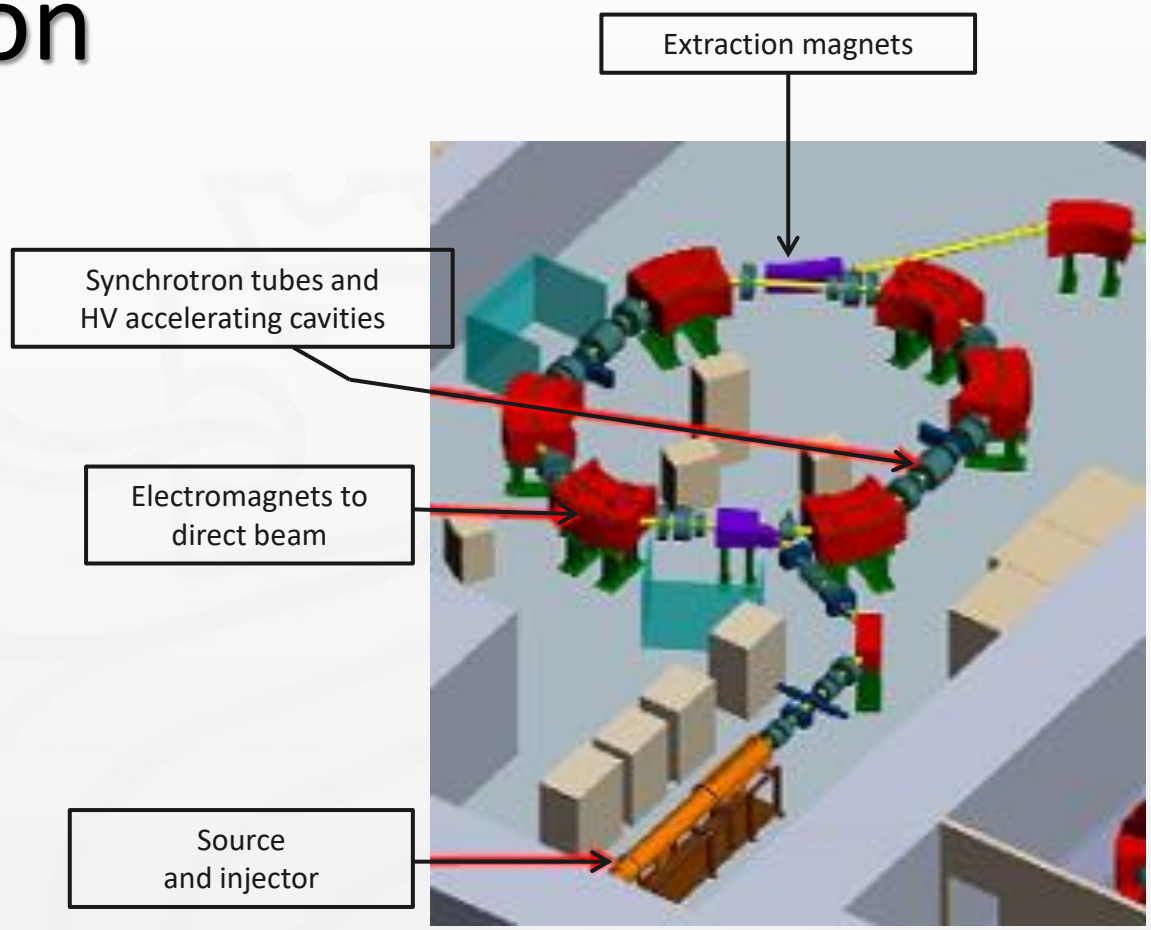


Technical parameters:

- ∅ 3.5 - 5 m
- Clinical energies: ~70 MeV – 250 MeV
- Weight: 900 t
- Power: 300kW

Accelerators: Synchrotron





Technical parameters:

- ∅ 8 - 10 m
- Acceleration to desired energy
- Spill time:
  - Fill ring with ~10^{11} particles
  - Slow extraction: 1-10 sec
  - Deceleration and dump of unused particles

Accelerators: Cyclotron vs Synchrotron

Cyclotron

- ∅ 3.5 m - 5 m

+ high, accurate and adjustable intensity

+ continuous beam

+ fast energy change with degrader

- degrader needed
- activation
- one particle type (protons)

Synchrotron

- ∅ 8 m - 10 m

+ high energy

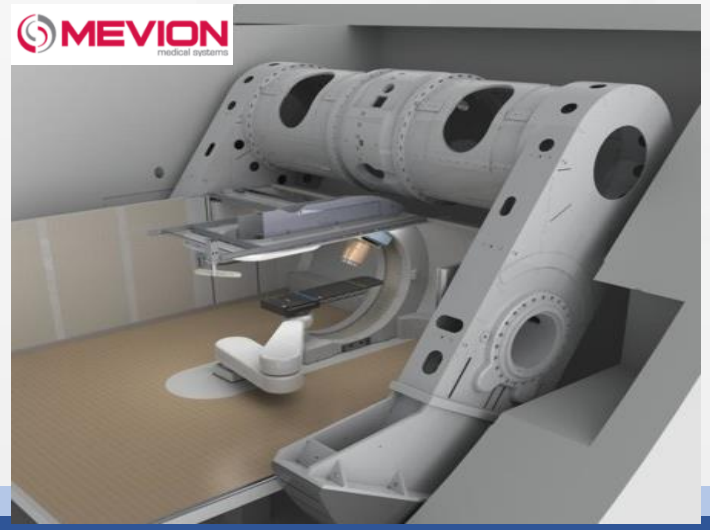
+ any particle

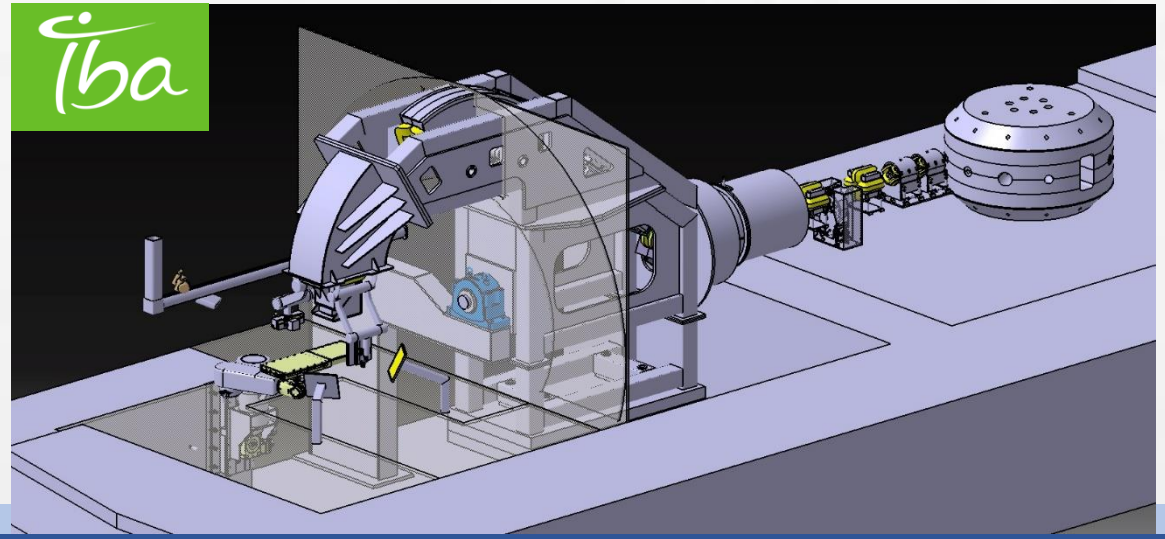
+ low radioactivity

- limited average intensity (ring filling)
- spill structure (low dose rate)
- noisy beam intensity
- fast continuous scanning is difficult

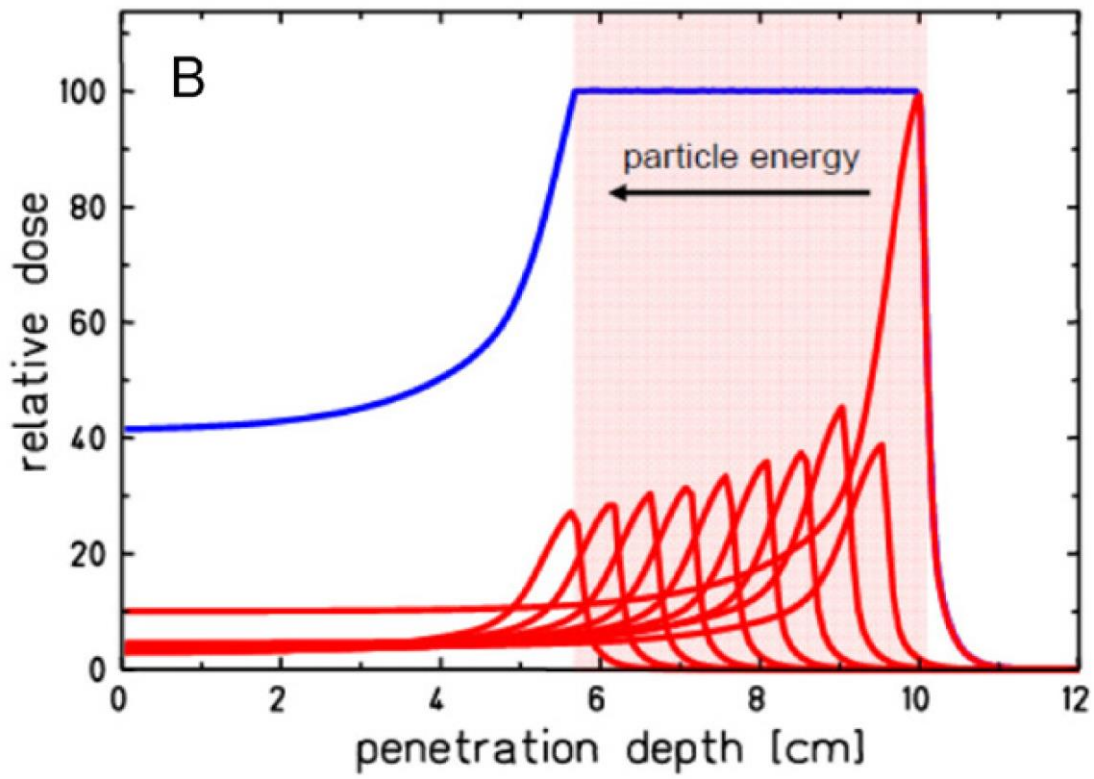
Accelerators: Synchro-cyclotron

- One small (cheap) accelerator for treatment room
- Increased magnetic field results in smaller radius
- RF frequency is synchronous to the increasing proton mass
- More compact solutions that can be positioned directly in the gantry





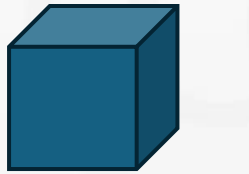
Bragg-peak vs spread-out Bragg peak: refresher

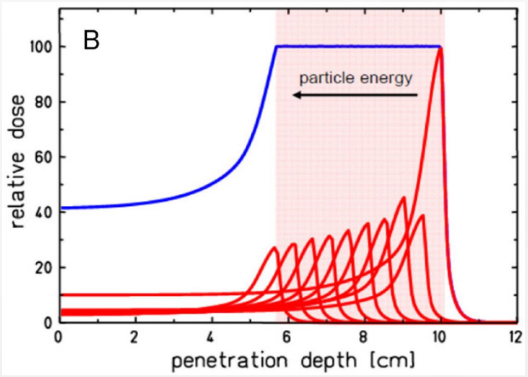


- Single Bragg peak (pristine peak):
  - Strongly localised dose deposition in small region
  - Low dose in entrance channel
  - Advantageous peak-to-plateau ratio

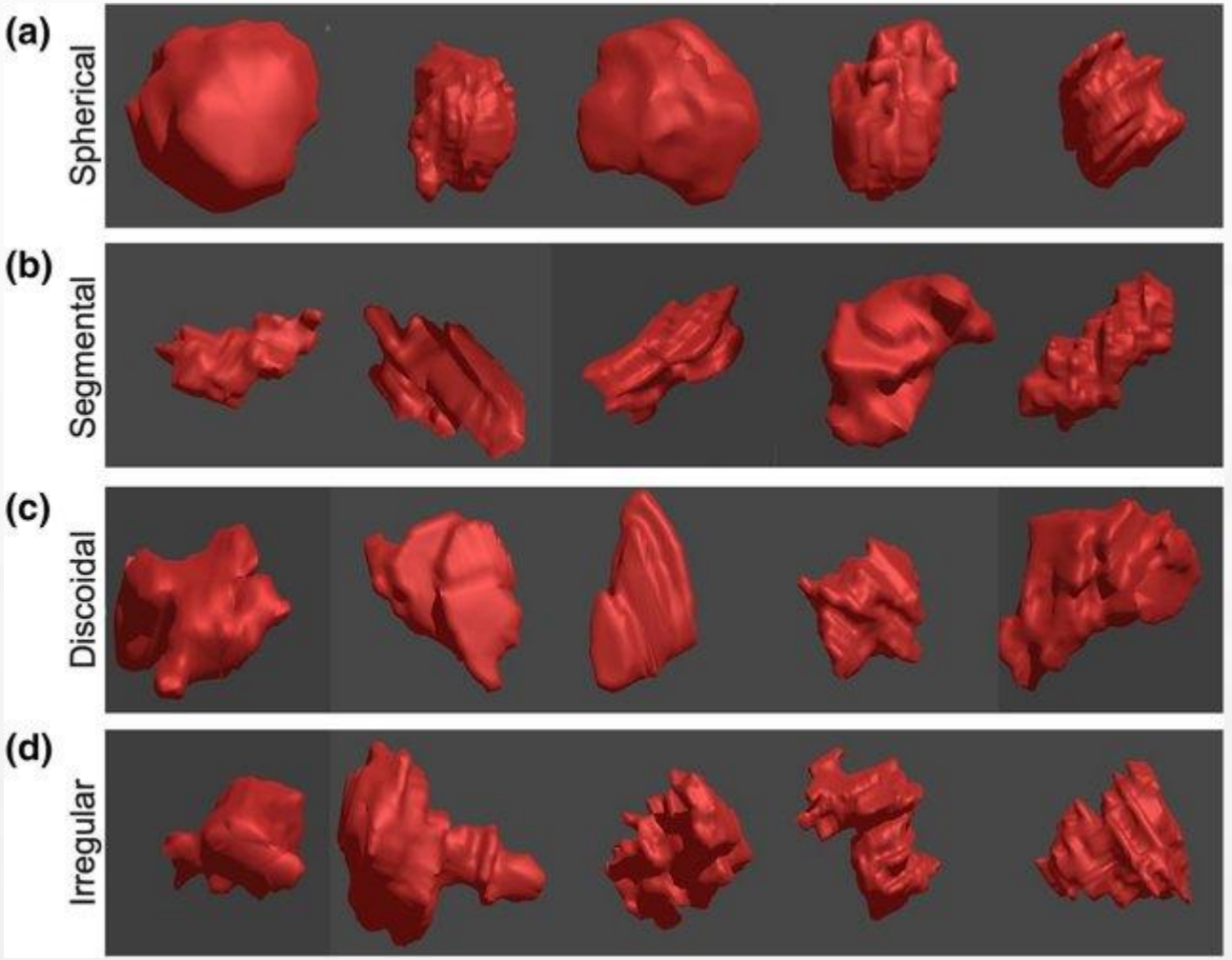
- Spread-out Bragg peak:
  - To irradiate the whole extend of tumours
  - Overlapping of many Bragg-peaks with different energy and intensity
  - Peak-to-plateau relation decreases slightly
  - Dose in peak still higher than entrance dose

Clinical application





Tumour shapes

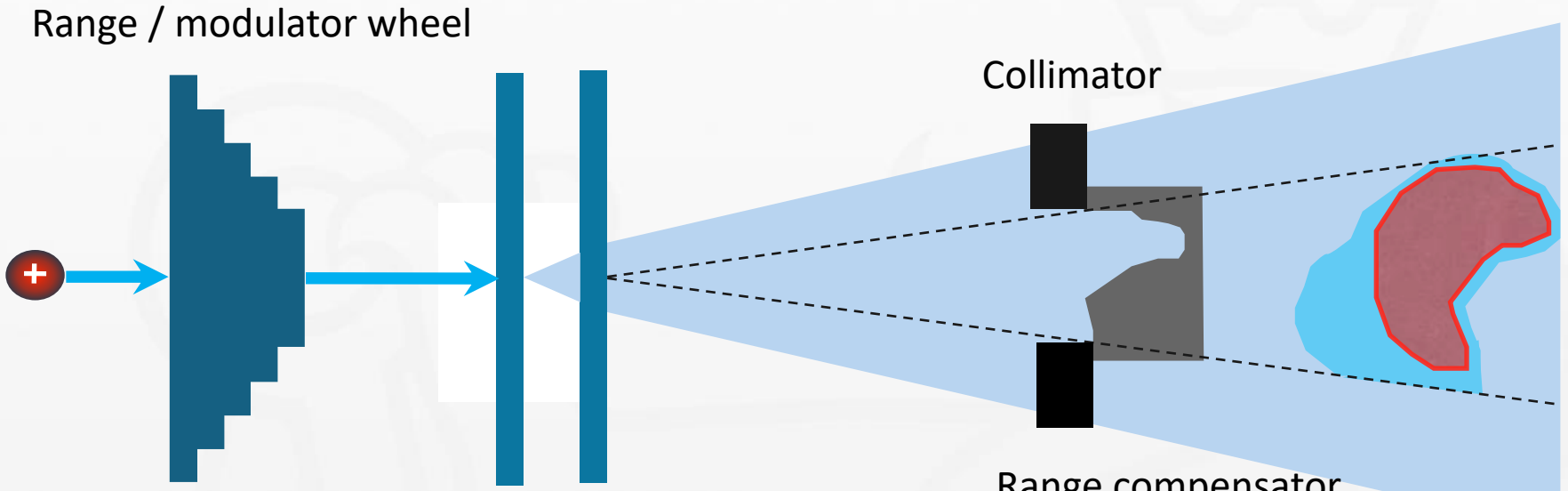


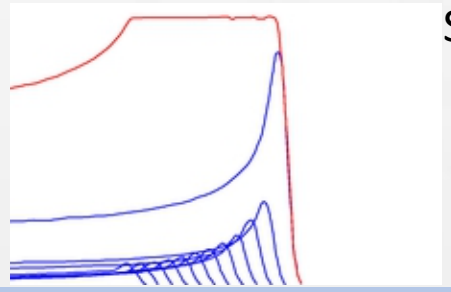
Byrd et al, Breast Cancer Res Treat 2021

Beam delivery systems

- Passive scattering:
  - Passive elements are used to fit 3D target
  - Single scattering vs Double scattering
- Pencil beam scanning:
  - The target volume is split into voxels and is scanned by narrow pencil beams
  - Energy modulation in the nozzle
  - Energy selection system at the accelerator

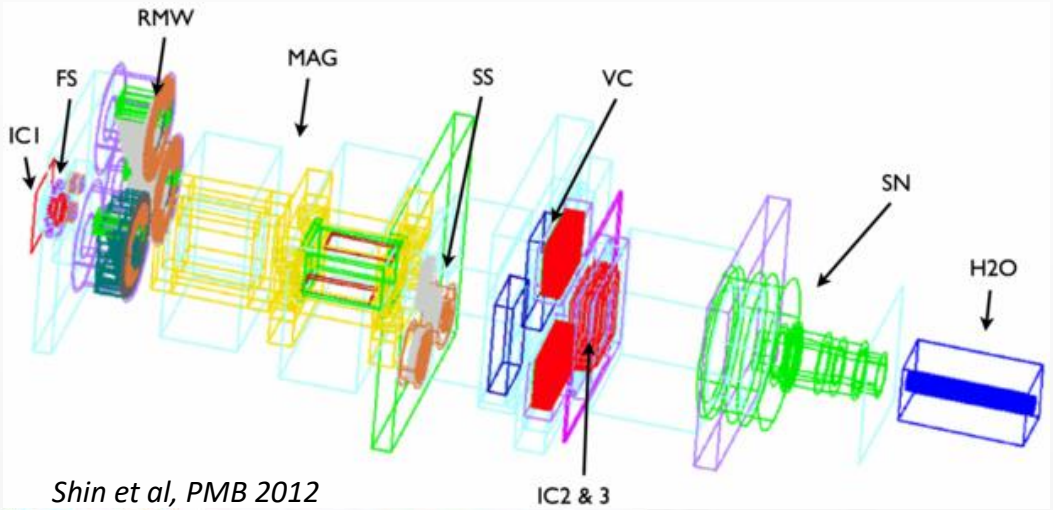
Passive scattering





Scatter foils

Nozzle for passive scattering

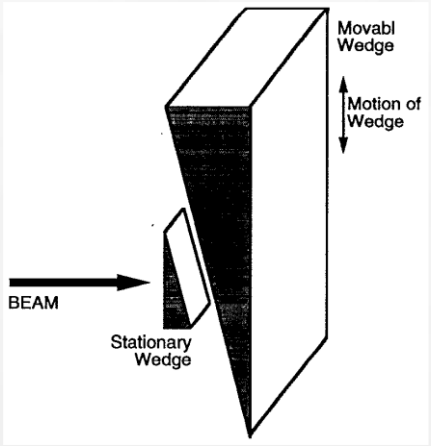


Shin et al, PMB 2012

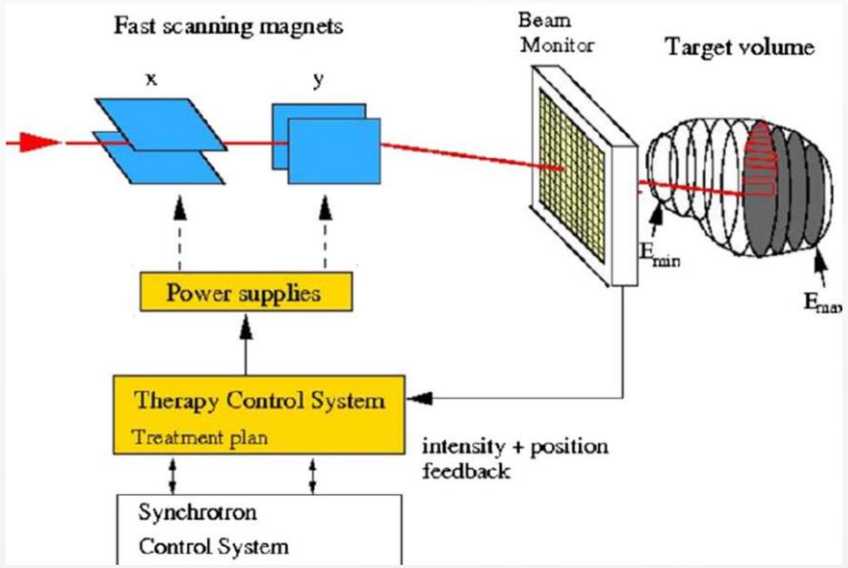
- Passive elements:
  - Range modulator wheel
  - Range shifter
  - Range compensator
  - Aperture / collimator

Library of components

Patient specific

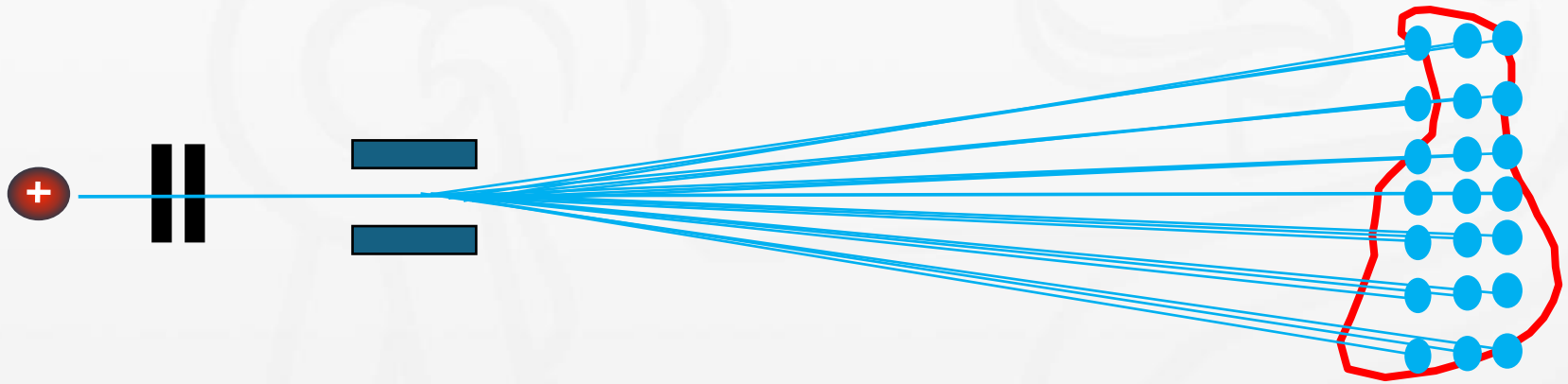


Active scanning

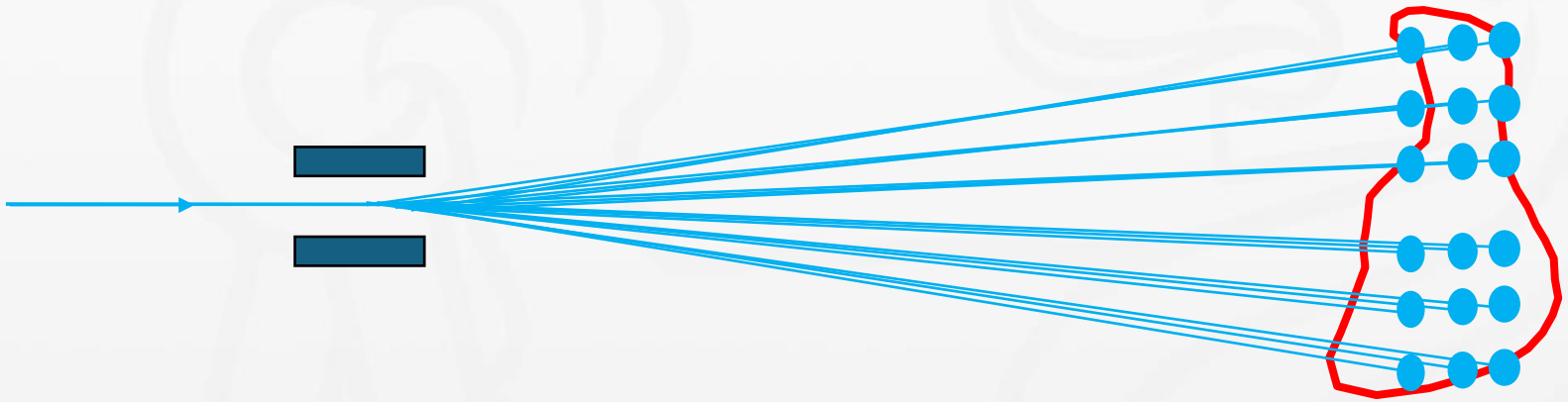


- two dipole magnets deflect the beam approx. +/-20cm in horizontal and vertical direction in the isocentre
- apart from range modulation (range shifter) no absorber material
- using discrete movement of a small beam spot, a larger area can be scanned -> once dose is achieved in that spot, the next spot is started
- variation of beam energy for SOBP

Pencil beam scanning with range shifters

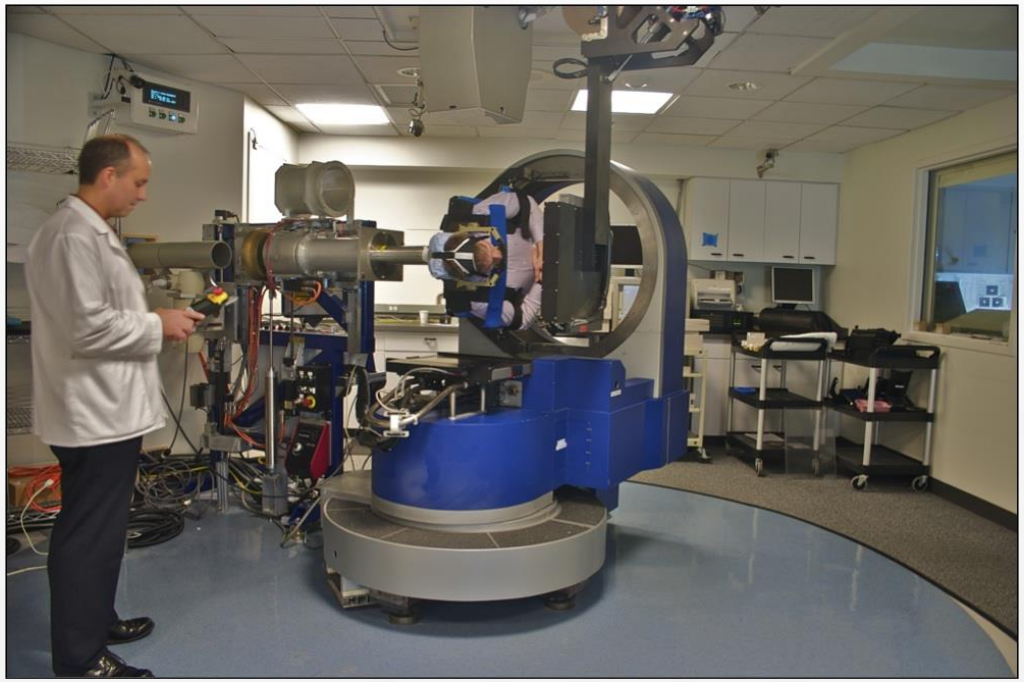


Pencil beam scanning with ESS



Gantry system

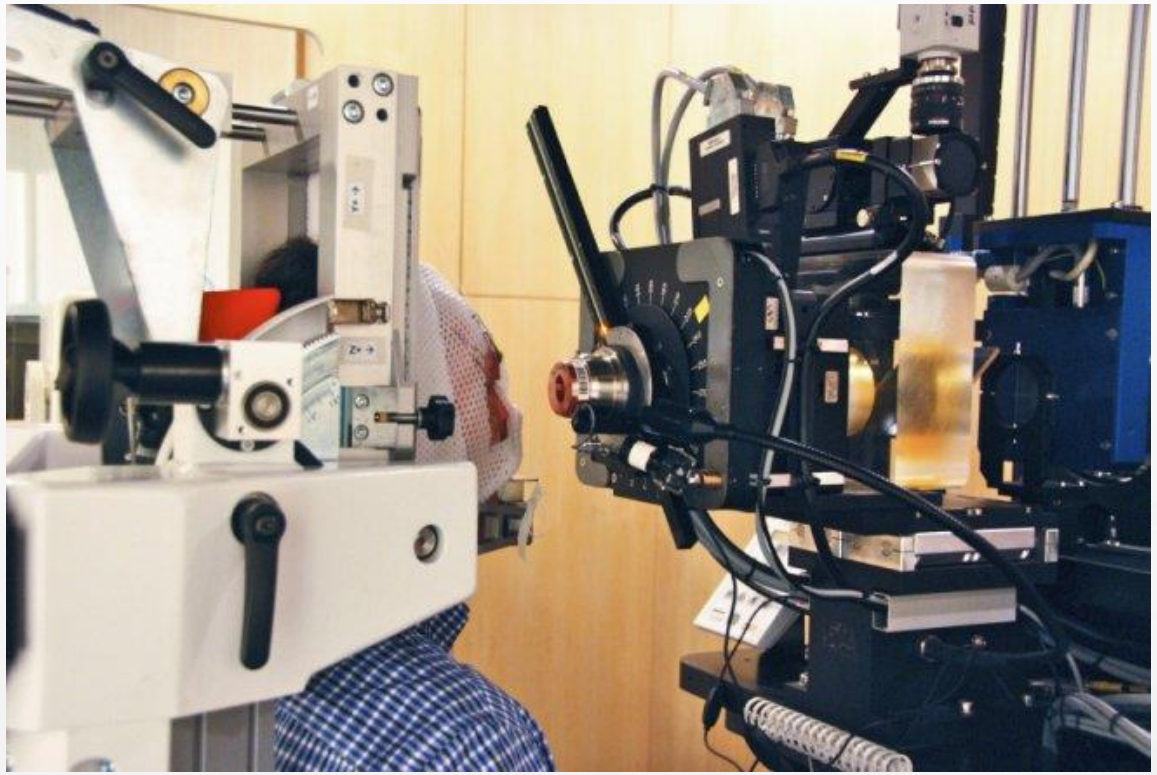
Fixed beamline



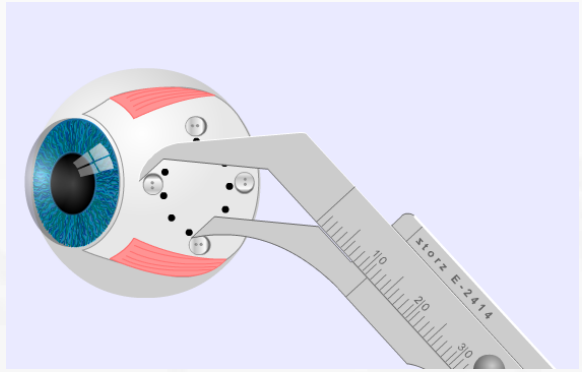
Francis H Burr Proton Therapy, MGH Boston

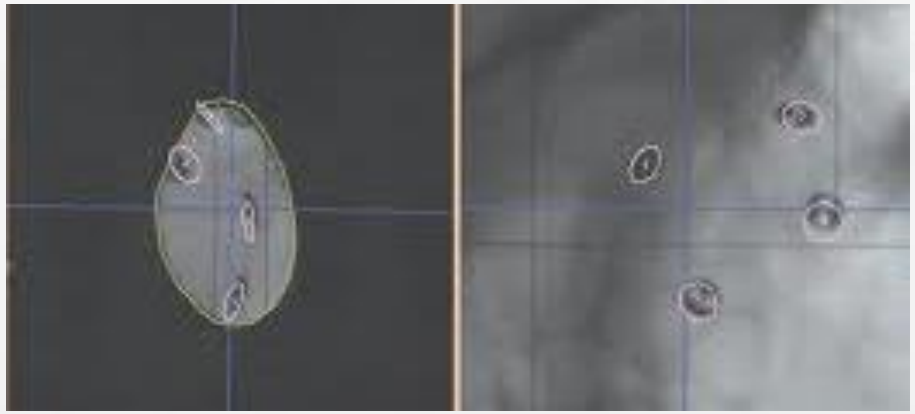
MedAustron, Wiener Neustadt

Fixed beam line for eye treatment

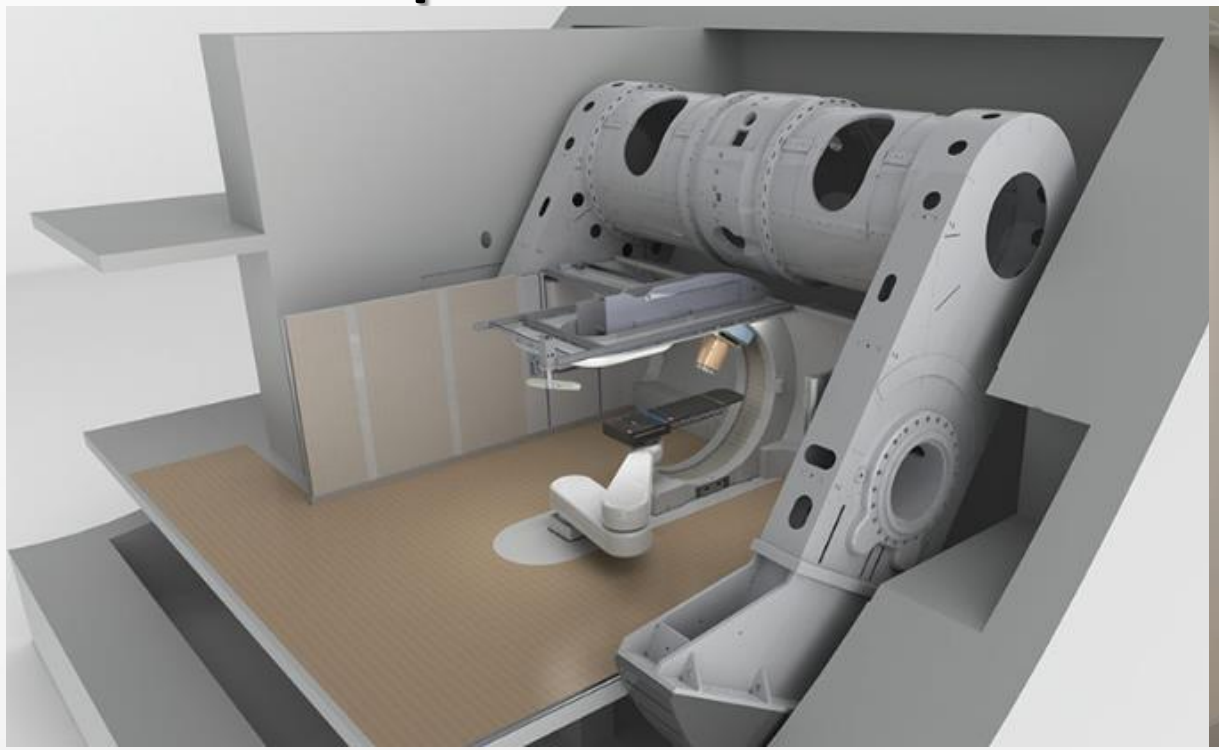


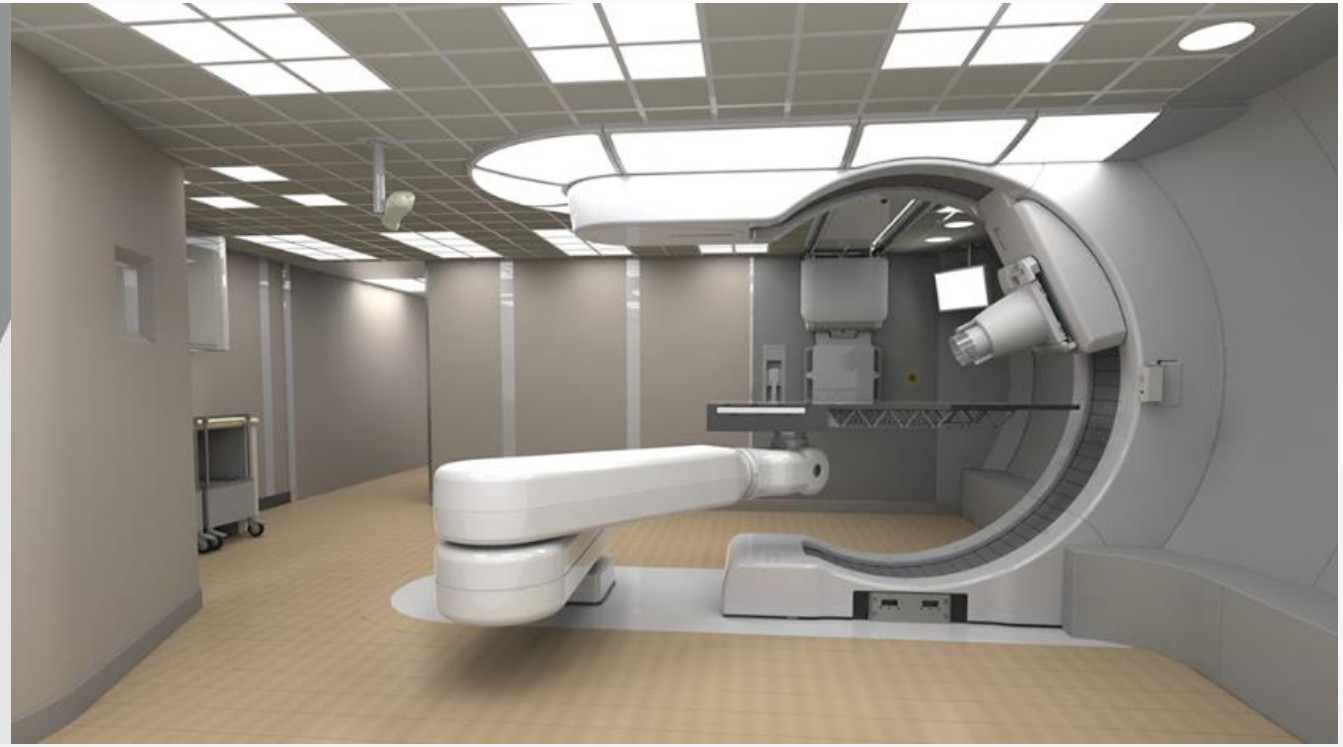
Proton Therapy center at Paul Scherrer Institute





Compact solutions





Radiation therapy process

Diagnosis and treatment decision

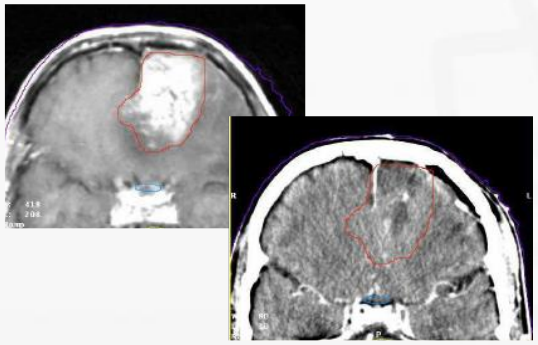
Treatment preparation

Treatment

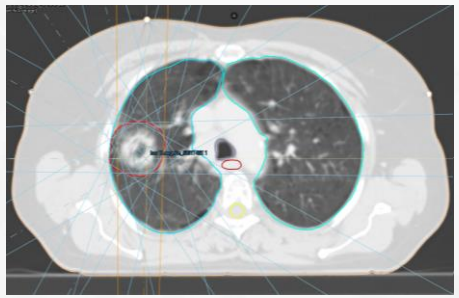
Post-treatment care

Positioning and immobilization

Images acquisition (CT, MRI, PET-CT, ...)

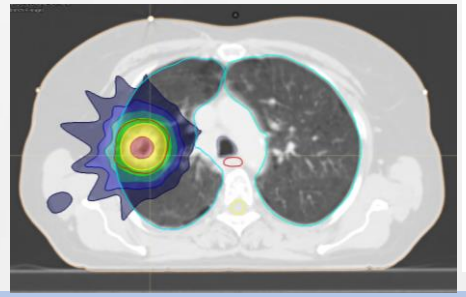


Target / Normal tissue delineation

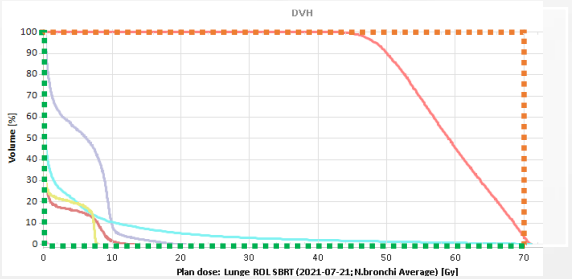


Beam / source definition

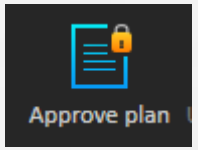
Dose Calculation / Plan Optimization



Plan evaluation



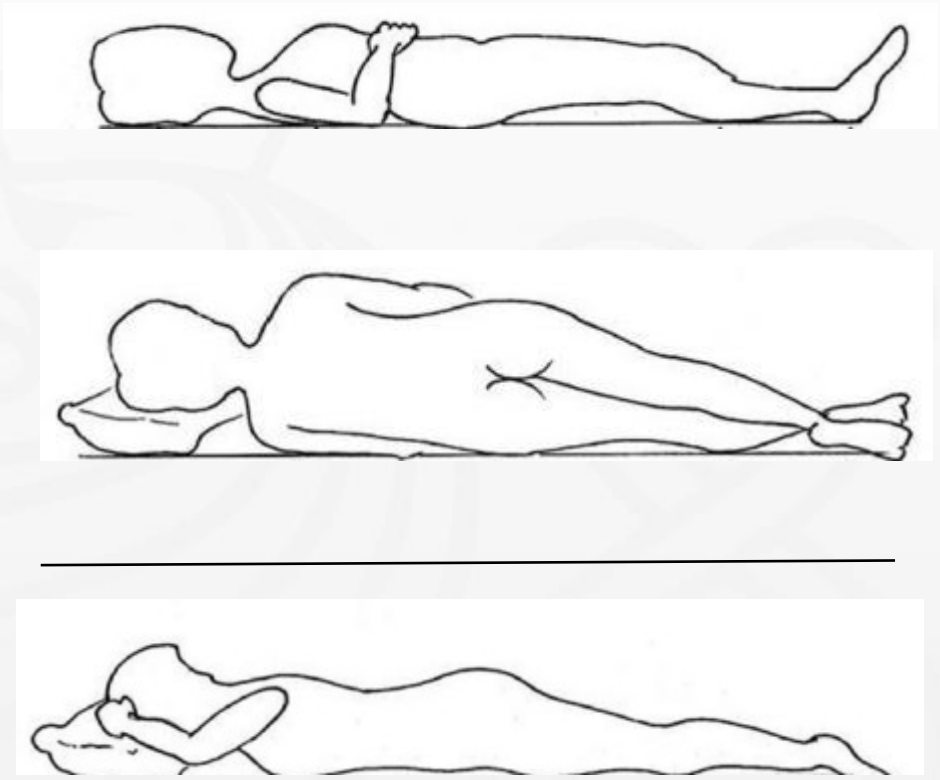
Plan Approval



Plan verification

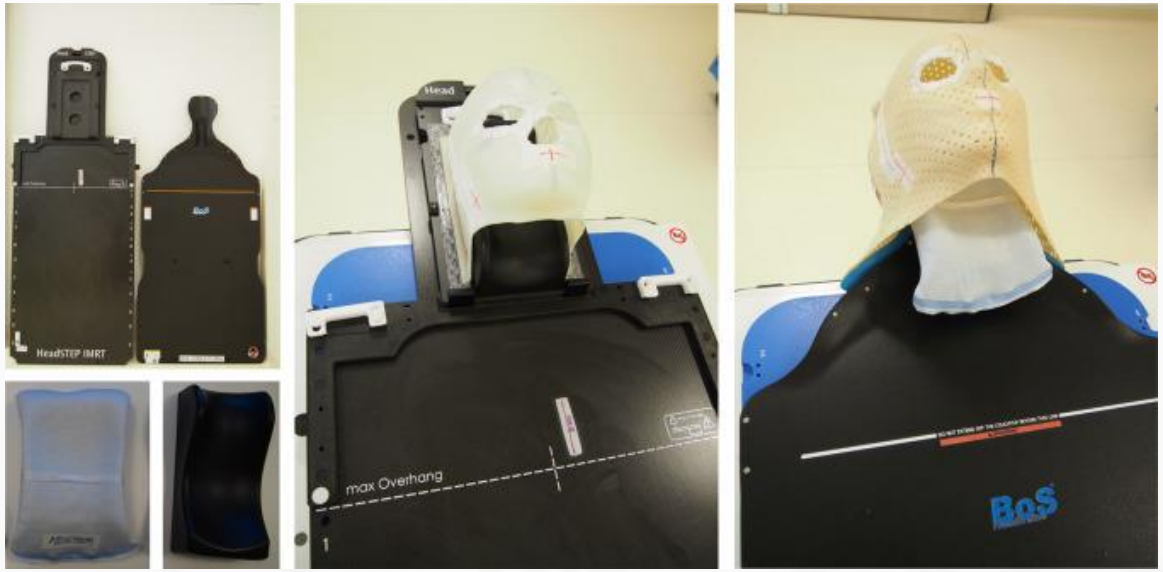
Immobilization

- To provide a stable position during the treatment
- Must be reproducible during the course of treatment
- Must be suitable for proton therapy
- Positioning: supine, prone, decubitus lateral
- Paediatric patients: Anaesthesia
- Table-top extension



Immobilization devices

- Thermoplastic masks
- Vacuum cushions, moldcare
- Arms support
- Belts
- Bite blocks



Zechner A, ZMB2022

HollandPTC

Klarity

MacroMedics

Imaging

- Planning CT:
  - Performed in the treatment position
  - No contrast material allowed
  - Correction for artefacts: IMAR
- Additional imaging:
  - MRI, CT with contrast, PET/CT
  - In treatment position if available
  - Diagnostic imaging

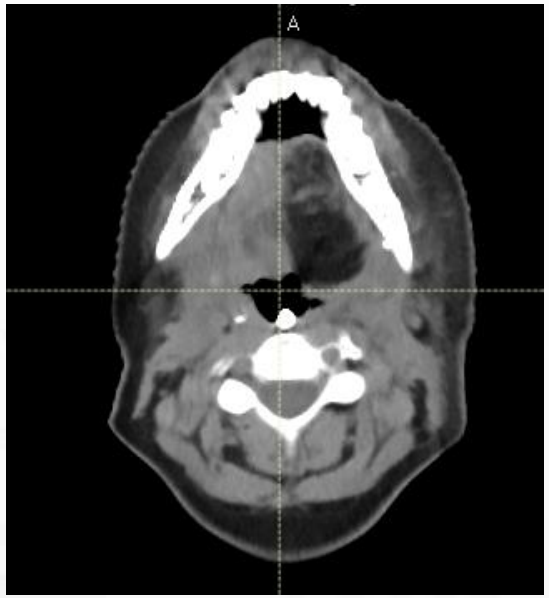
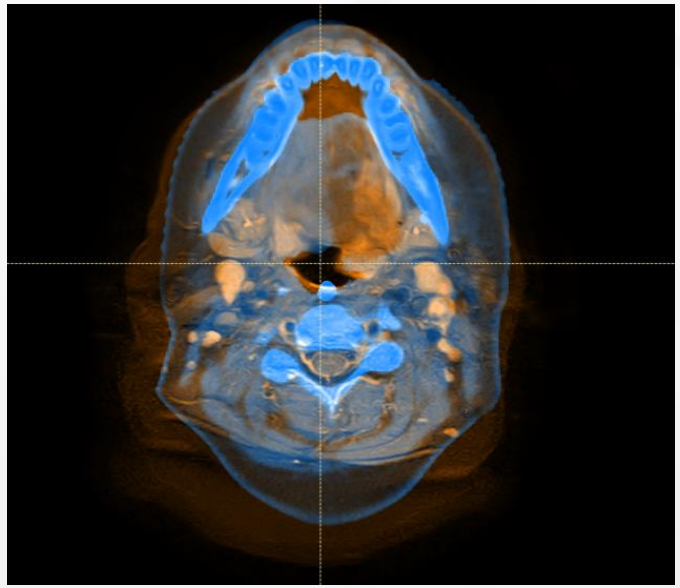
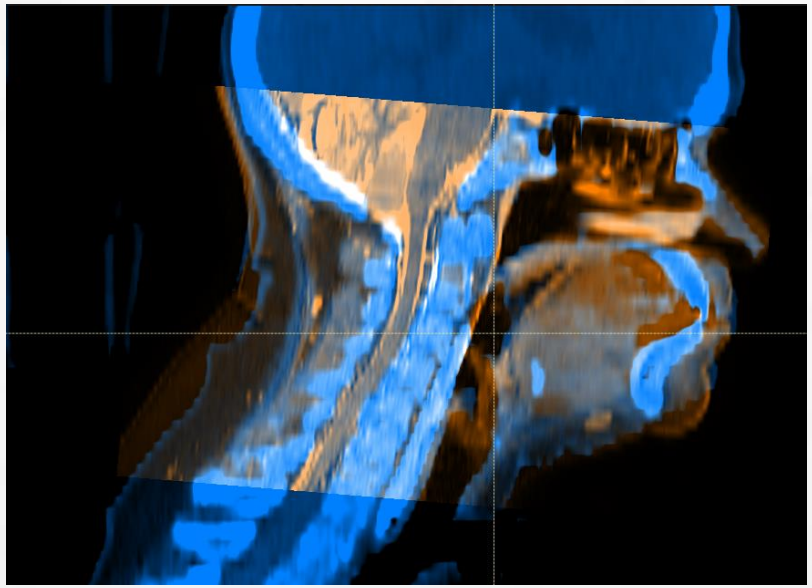
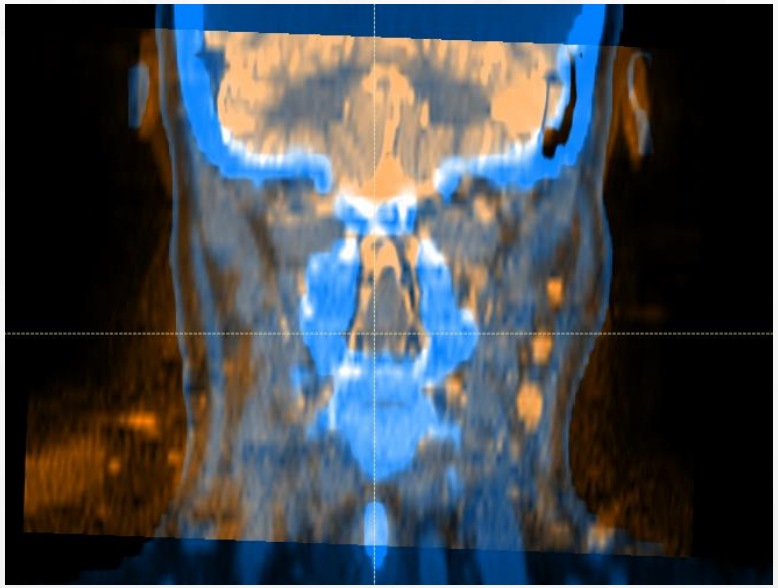


Image registration

- Geometrical translation and rotation, potentially deformation
- Often difficult -> selection of the focus area







Treatment planning: sneak peak

- Delineation of organs at risk
- Definition of GTV, CTV, ITV, PTV
- Beam selection
- Plan optimization
- Plan evaluation
- Final dose calculation
- Plan approval

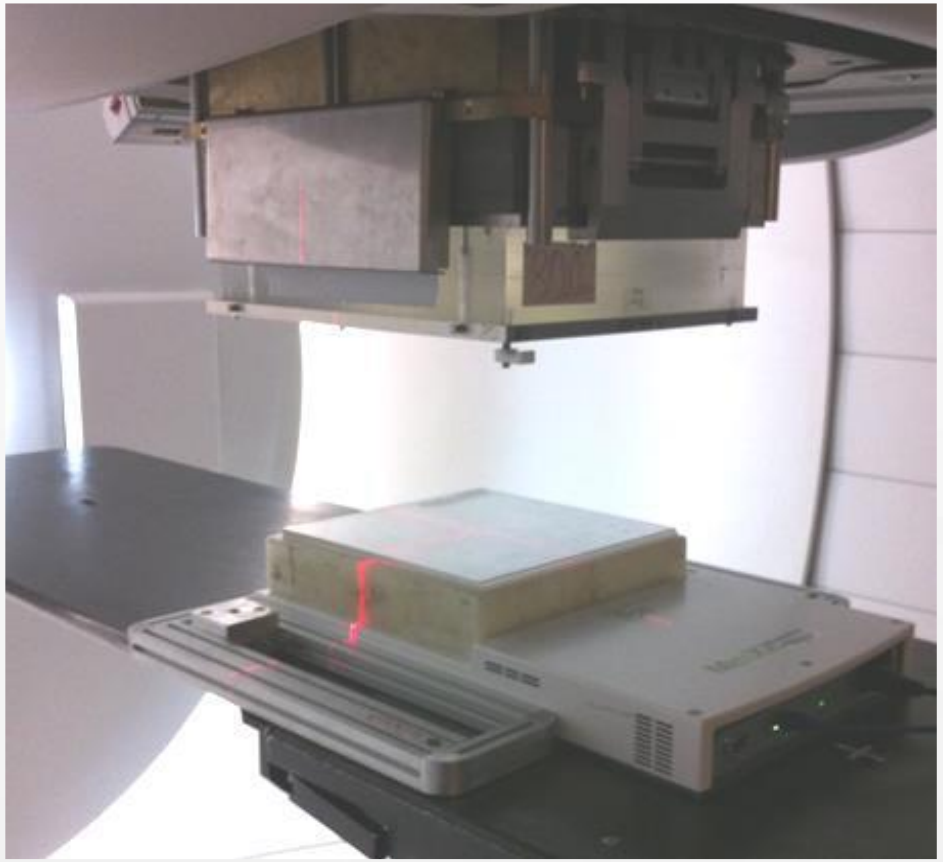
Treatment planning: sneak peak

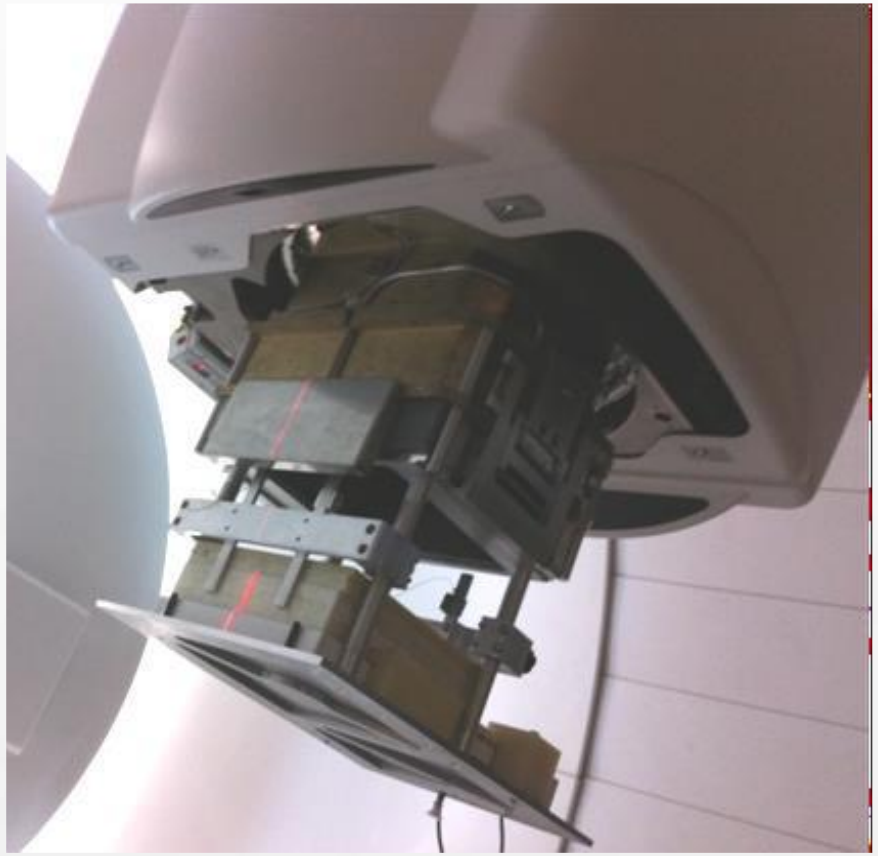
- **Delineation of organs at risk**
- **Definition of GTV, CTV, ITV, PTV**
- **Beam selection**
- **Plan optimization**
- **Plan evaluation**
- Final dose calculation
- Plan approval

Treatment plan verification

- Plan quality and data transfer control (visual):
  - Checking factors influencing a plan quality
  - Check of the plan parameters: beam selection, spot position and weight
  - Prescription fulfilment
  - Data transfer between treatment planning system and oncology information system
- Dosimetric verification:
  - Independent dose calculation
  - Dosimetric measurements
  - Log-file analysis

Dosimetric measurements

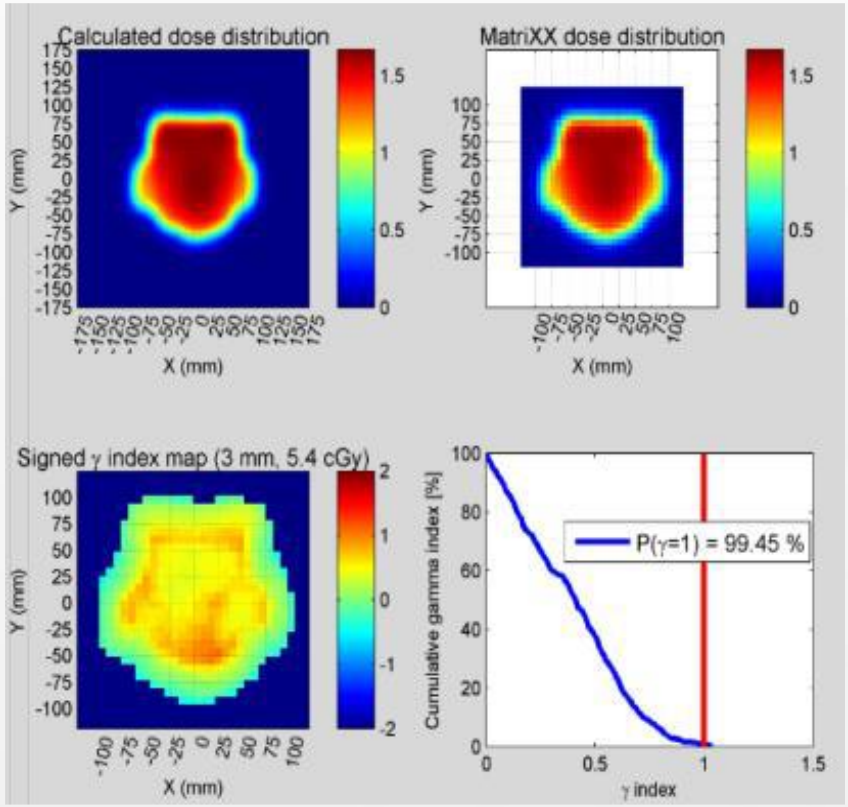


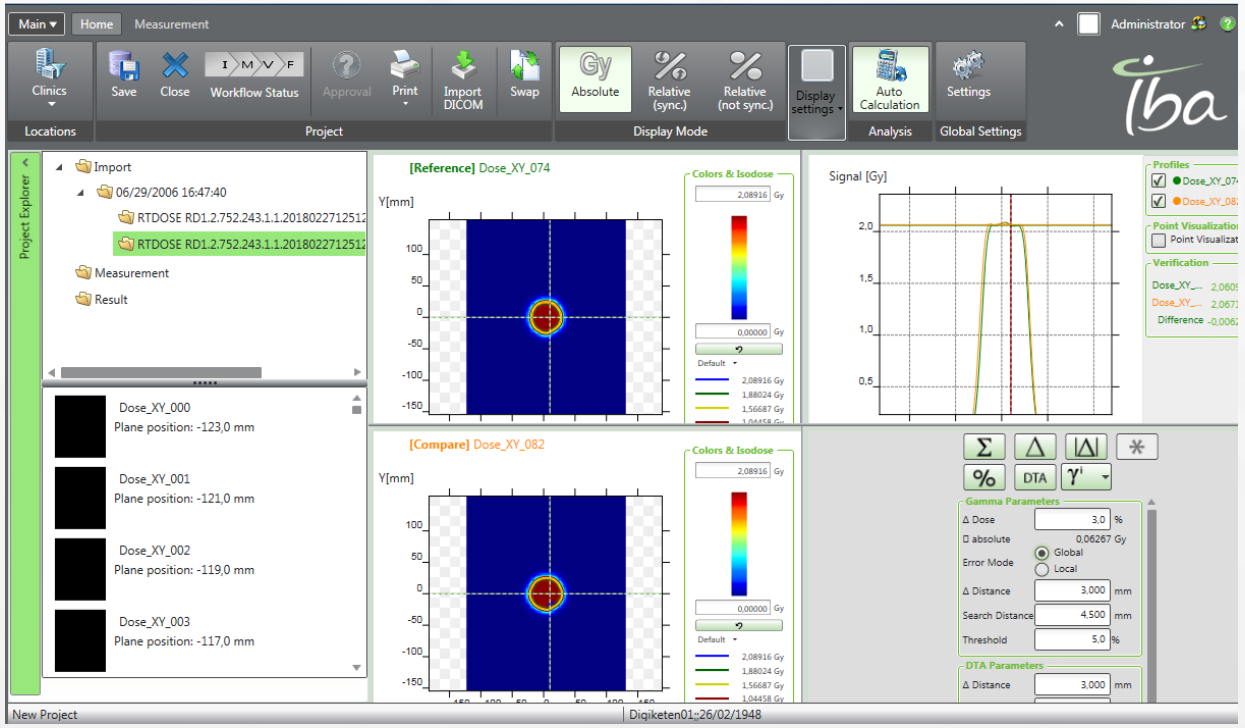


Courtesy of E. Batin

PSQA evaluation

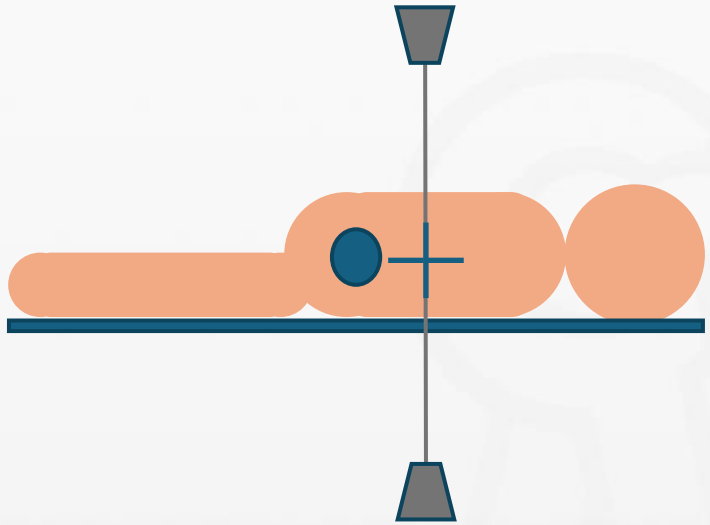
- Dose difference
- Profile comparison
- Gamma analysis



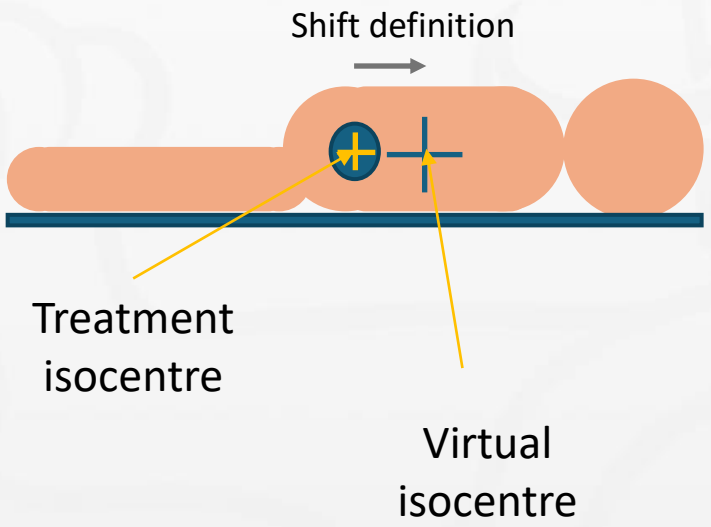


Patient positioning

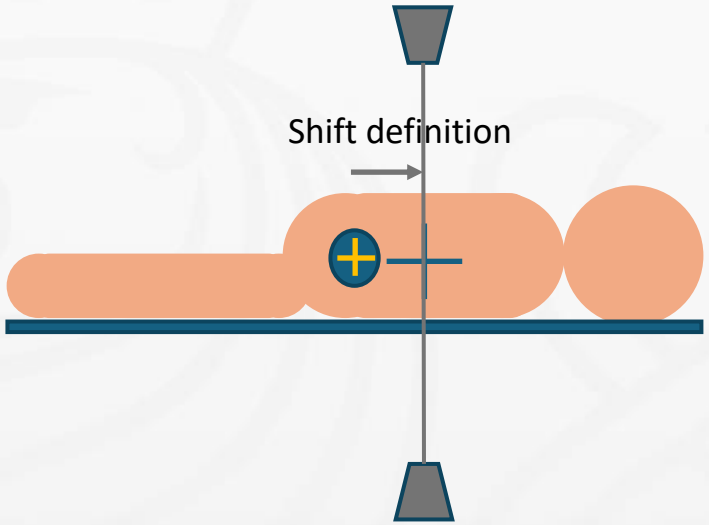
Planning CT acquisition



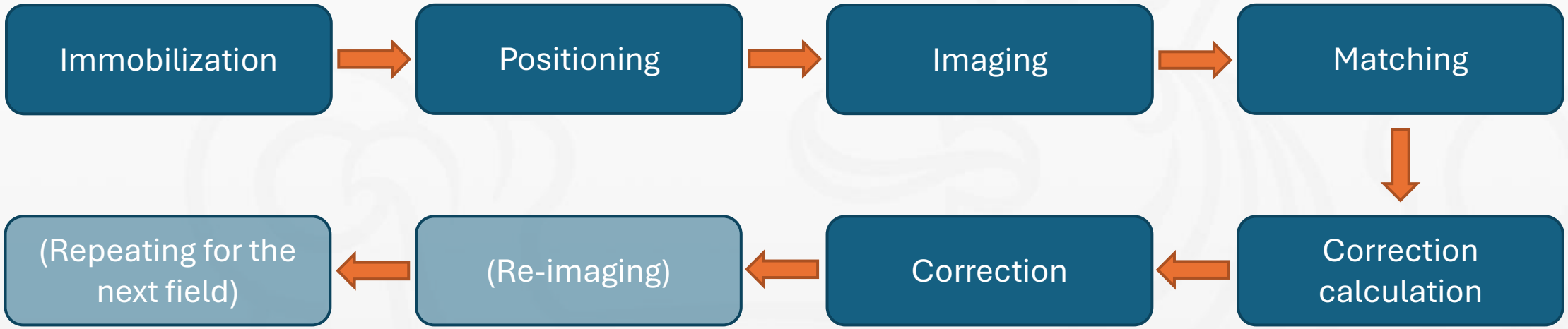
Treatment planning



Positioning for treatment



Patient positioning workflow



Patient couch

Conventional table radiotherapy

Robotic couch

In-room imaging

- Gantry-mounted: kV, CBCT
- Table mounted: imaging ring (kV, CBCT)
- Stand-alone: CT on-rails, surface imaging

Gantry-mounted in-room imaging

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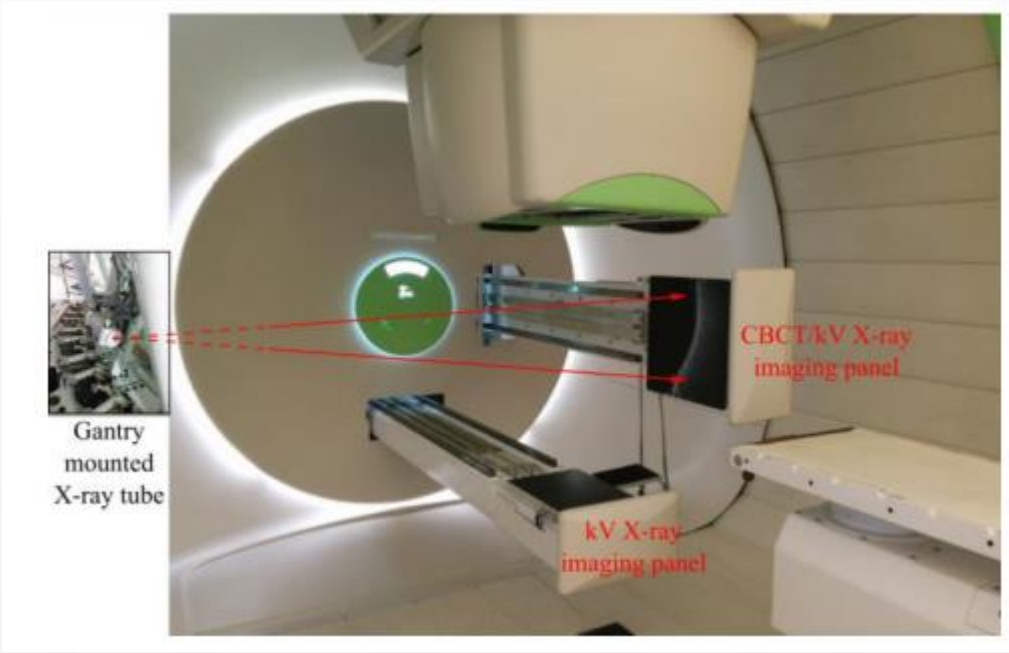

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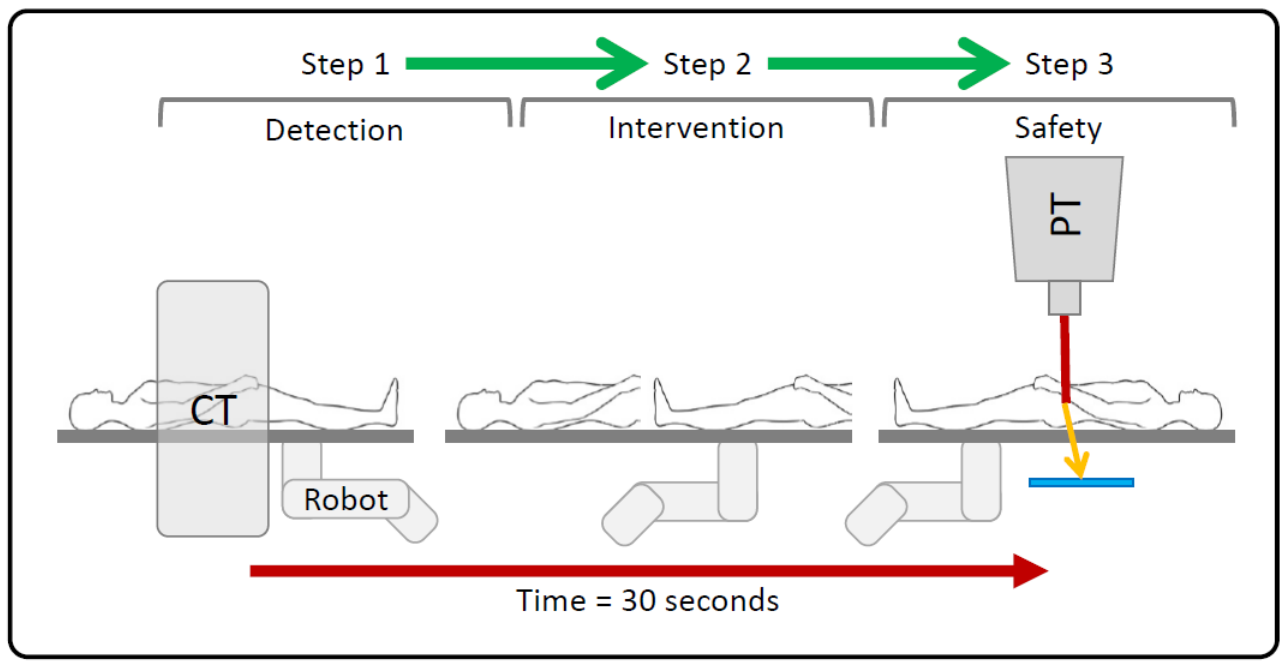
Table-mounted in-room imaging

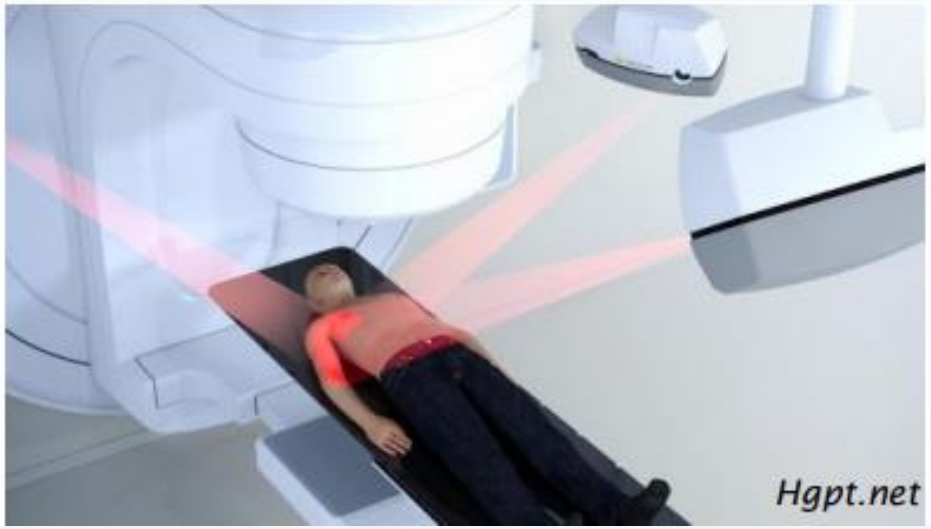
CT on-rails

Albertini Br J Radiol 2020



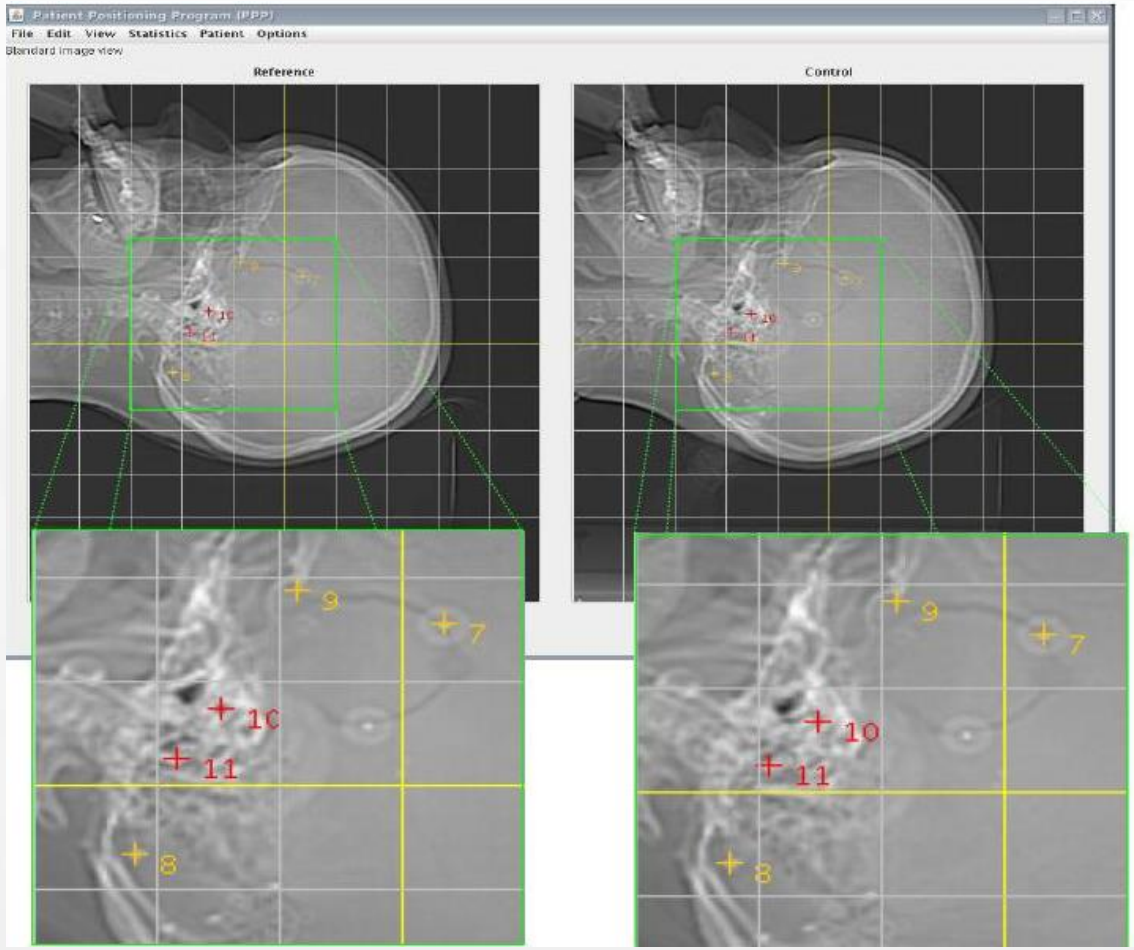
Thyrza Z. Jagt, PhD Thesis, 2020

Surface scanner

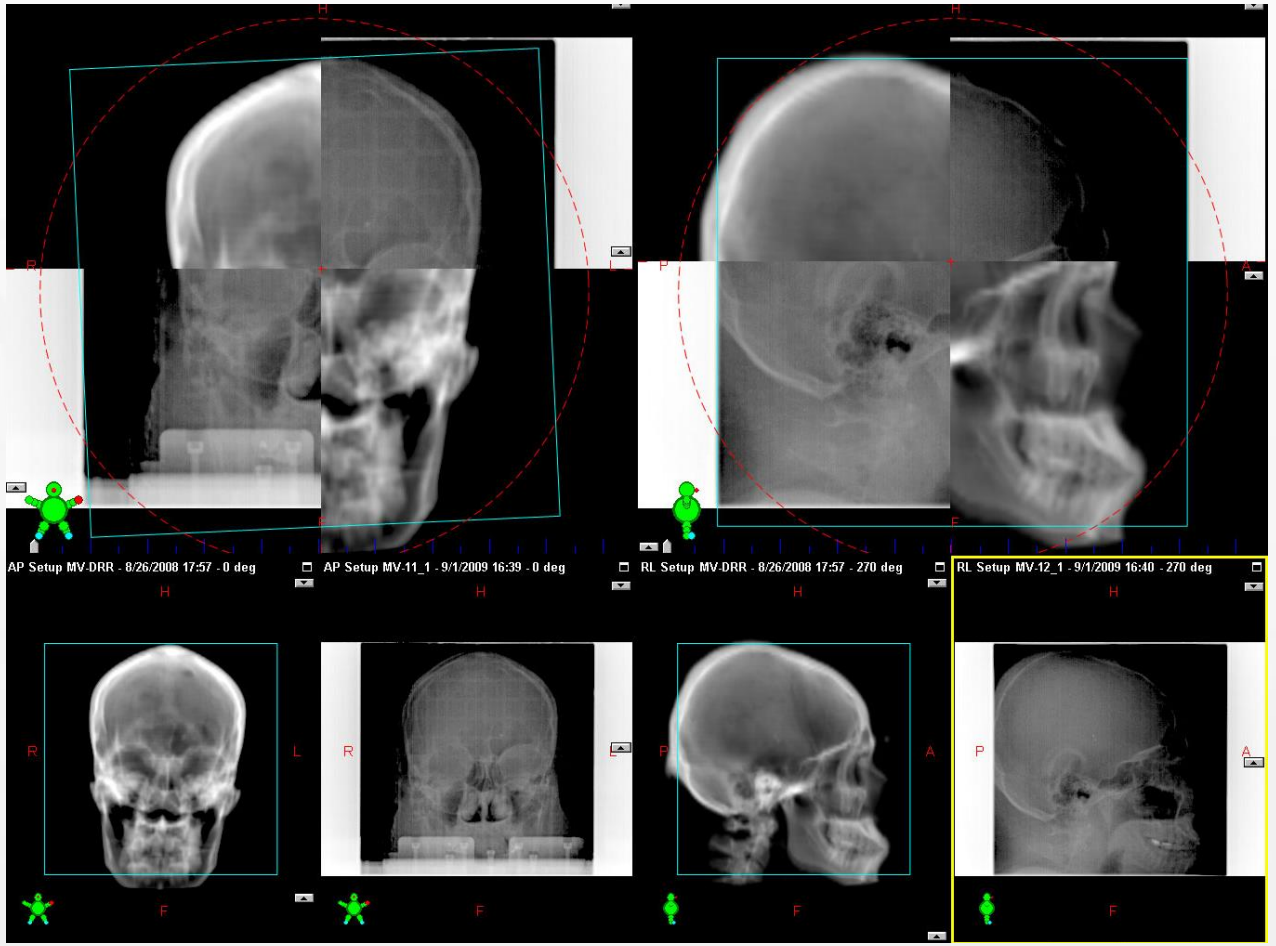


Sorgato et al. TIPSRO 2022

2D – 2D matching



3D - 3D matching



Take home message

- Particle therapy has several physical, biological and medical advantages
- Smaller integral dose and dose to critical structures leads to reduces side effects
- Clinical machines have very complex technology