Introduction to Hadron Therapy and the MedAustron Project

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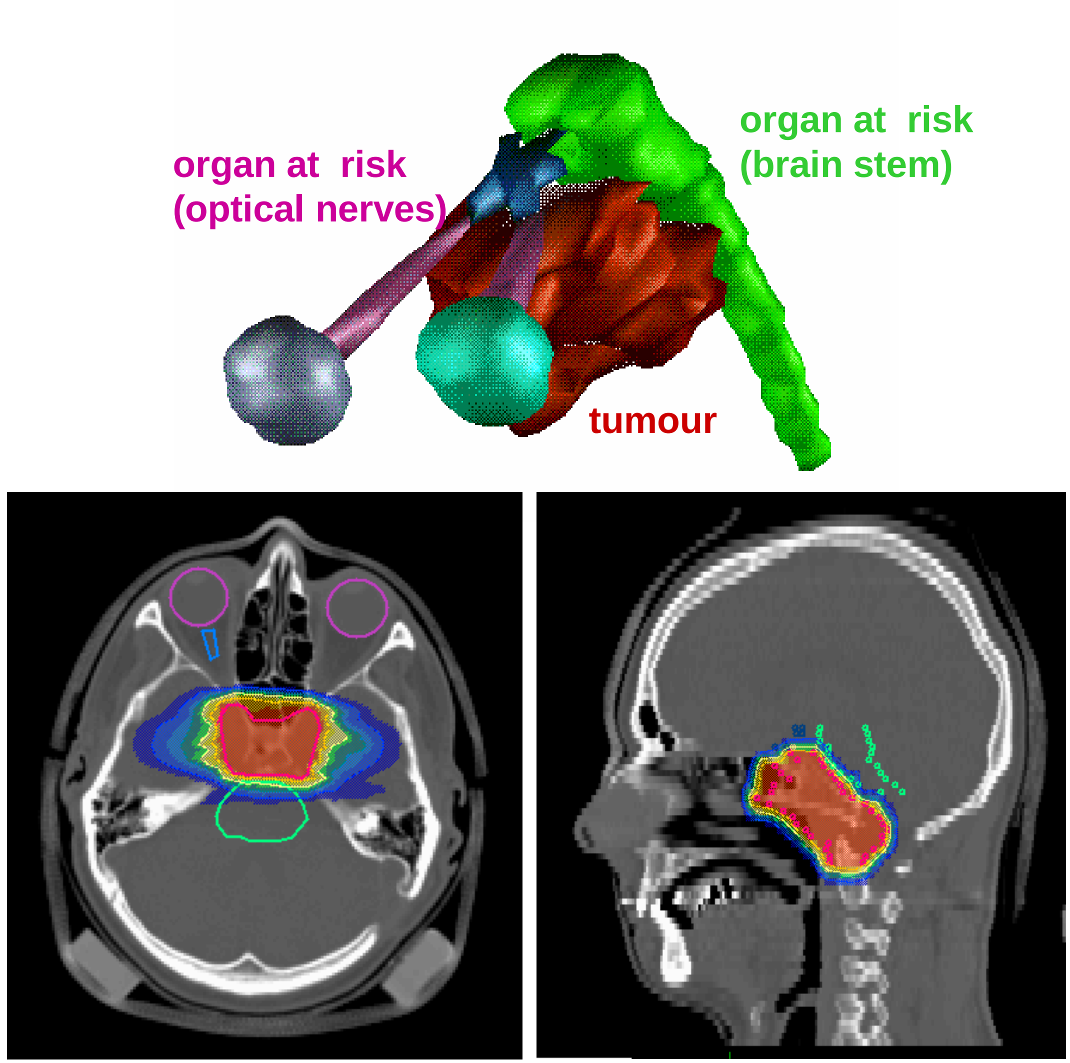
Outline

- General Introduction
  - Aims of radio therapy
  - Accelerators for radio therapy
  - EU-study on tumour therapy
- Introduction to Hadron Therapy
  - Rationale for hadron therapy
  - Bragg peak behaviour
- Irradiation Techniques
  - Passive beam delivery systems
  - Active beam scanning
- The MedAustron Project
  - Main parameters, centre layout, synchrotron
  - Some aspects of slow extraction and extraction line design
  - Matching to rotating gantries
- Conclusions

Introduction to Radiotherapy

- **Goal**
  - Deliver a high radiation dose to the target area to kill all tumour cells.
  - Spare out healthy tissue and organs at risk.
  - Tumour conformal dose distribution.
- **Radiation type**
  - Conventional therapy: electrons, photons
  - Hadron therapy: protons, light ions
  - More exotic: neutrons, pions



Courtesy GSI

Accelerators for Radiotherapy

Accelerator	Application	Kinetic energy	# Machines
Betatron & Microtron	Electron therapy Photon therapy	4 – 45 MeV e^- 4 – 50 MeV e^-	fast decreasing, few experimental
Electron linac	**Electron therapy** **Photon therapy**	**4 – 25 MeV e^-** **4 – 25 MeV e^-**	**~4000 e^- Linacs** **(standard therapy)**
Cyclotron	**Proton therapy** Fast neutron therapy	**70 – 250 MeV *p*** 50 – 75 MeV *p* or *d*	**23 / 7 / ~30** ?
Synchrotron	**Proton therapy** **Light ion therapy (C^{6+})**	**60 – 250 MeV *p*** **120 – 500 MeV/u**	**1** **3 / 1 / 4**

e^- Linac (e^- and photon therapy)

Tumour Treatment - EU Report

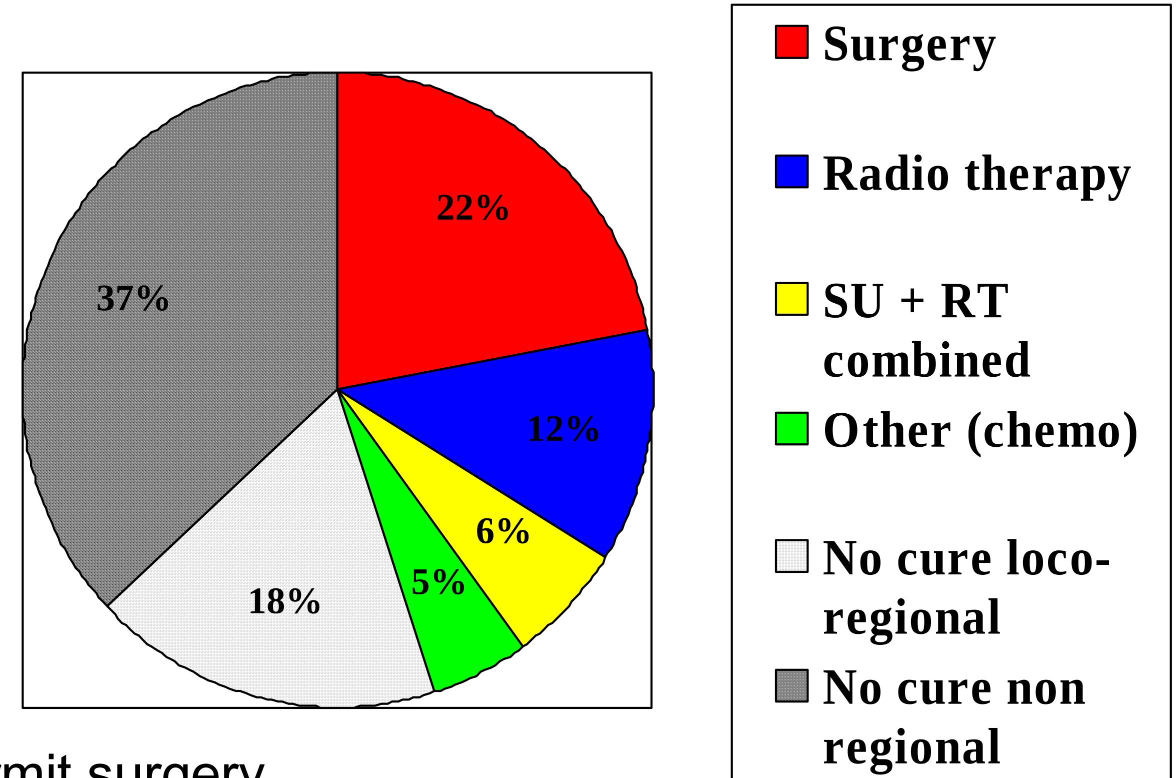
- Every third EU citizen experiences a cancerous disease.

Treated but not cured			55%
Cured			45%
Surgery	22%		40%
Radiotherapy	12%	18%	
SU&RT combined	6%		
Other (chemo therapy)			5%

- – RT involved in 18/45 successful treatments i.e. 40%.
- – SU and RT aim at loco-regional disease (no distant metastasis).
- – 40/45 successful treatments I.e. 90% for loco-regional disease.

Tumour Treatment - EU Report

- Improve control for loco-regional disease to increase cure rate.
- With 100% control, 60-65% cure rate.
- Main problems:
  - Anatomy does not permit surgery.
  - Tumour is radio-resistant or close to critical organs.



- Hadron therapy is a potential answer to these problems
  - Enables more precise and better localised dose distributions.

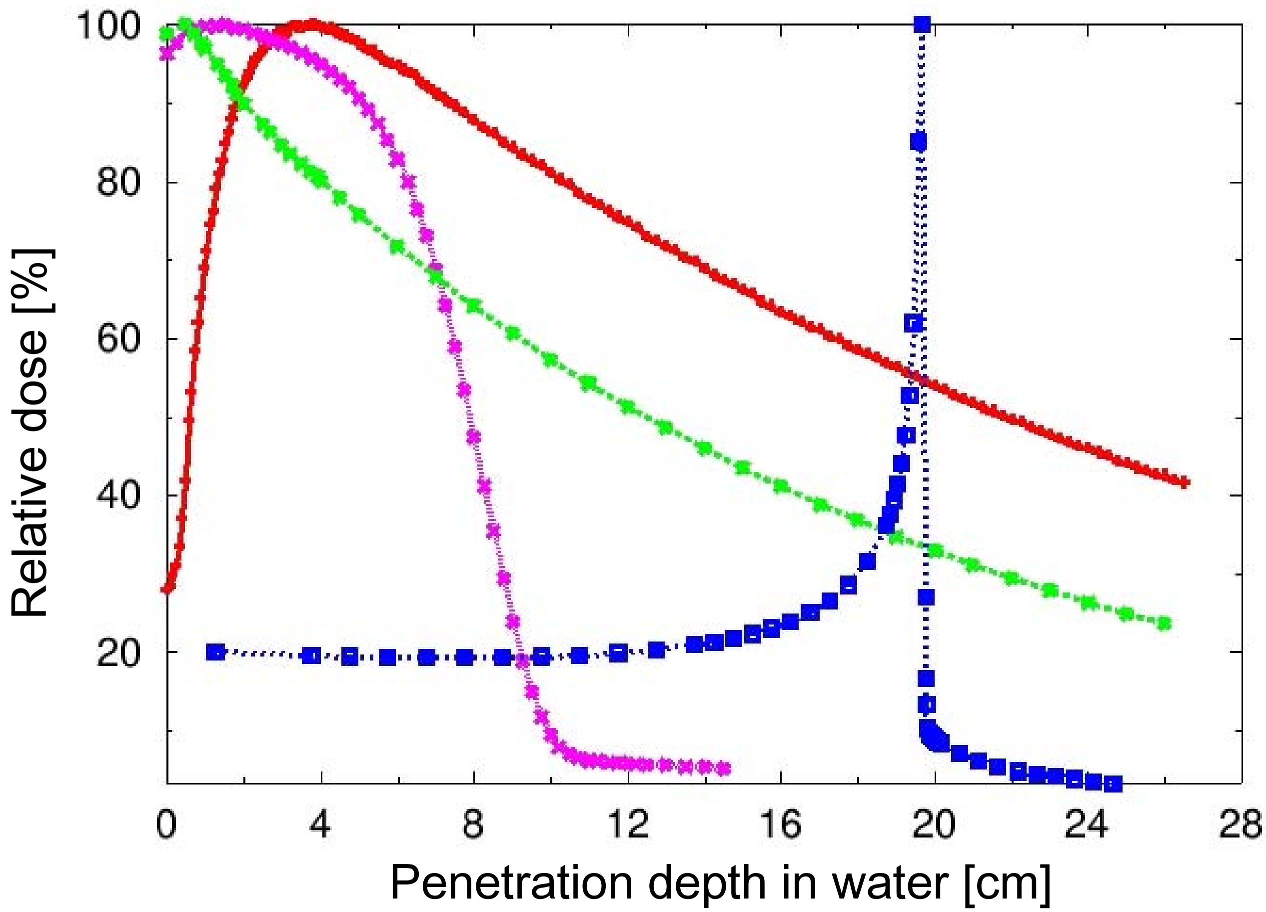
Hadron Therapy - Protons and Light Ions

- Aims at improved conformation of dose to tumour volume.
  - Reduction of radiation dose to healthy tissue.
  - Minimization of dose to organs at risk (nerves, spinal cord, etc).
  - Reduced integrated dose to the patient → reduced side effects.
  - Possibility to deliver a higher dose to tumour compared to conventional radiation therapy (for radio-resistant tumours).

- Based on "Bragg-peak" behaviour of protons and light ions
  - Highest energy deposition occurs at end of particle track.
  - Length of track determined by beam energy.
  - Very fast dose decrease behind the Bragg-peak (quasi zero).

"Bragg-Peak" Behaviour

Water phantom measurements (~tissue equivalent)



Cobalt 60 (γ, ~1.2 MeV)

Electrons 21 MeV

Photons 25 MeV

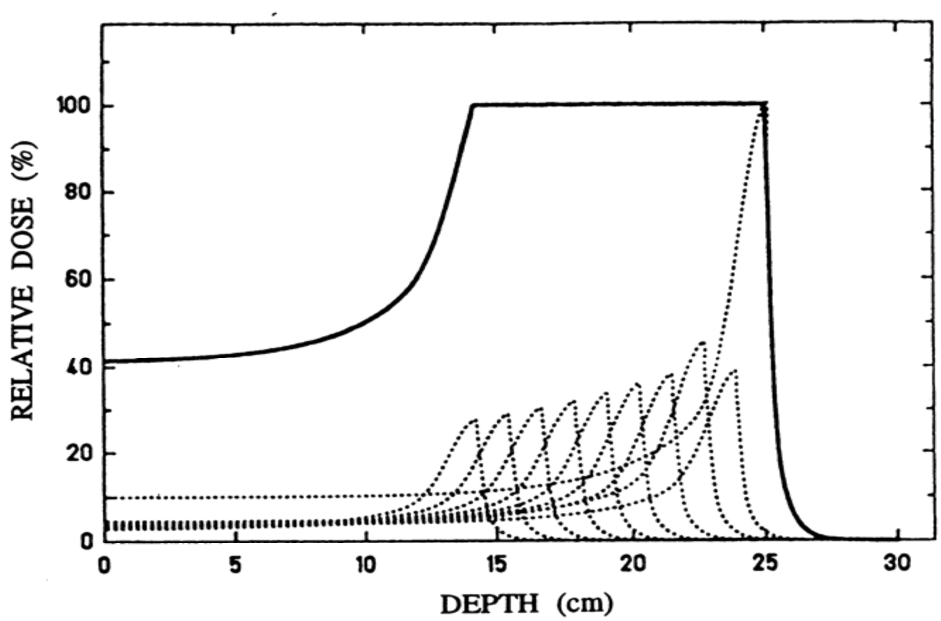
C-ions 330 MeV/u

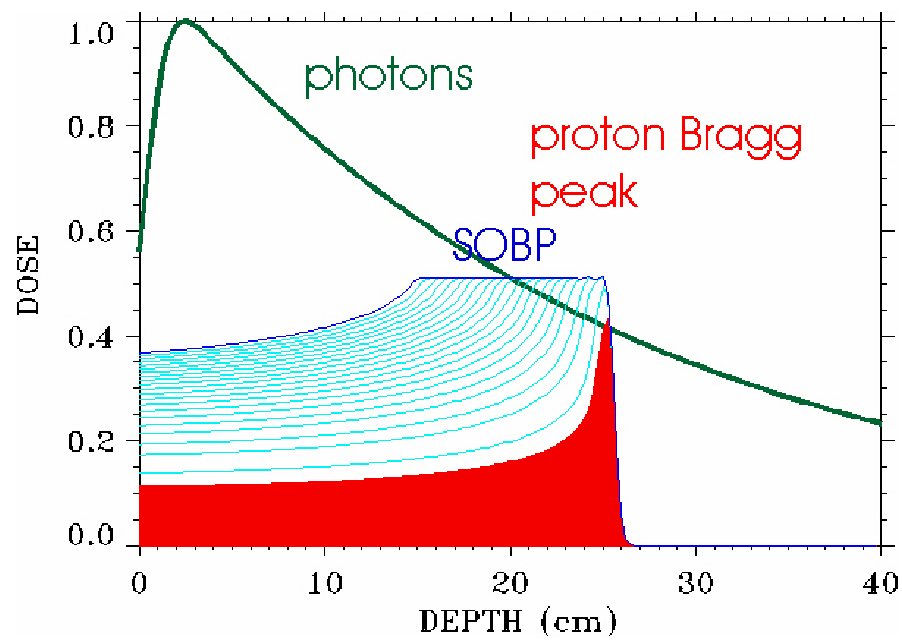
Measurement data:

- Photons and electrons
  - University Clinics Vienna
- C-ions
  - GSI Darmstadt

“Spread out Bragg-Peak” (SOBP)

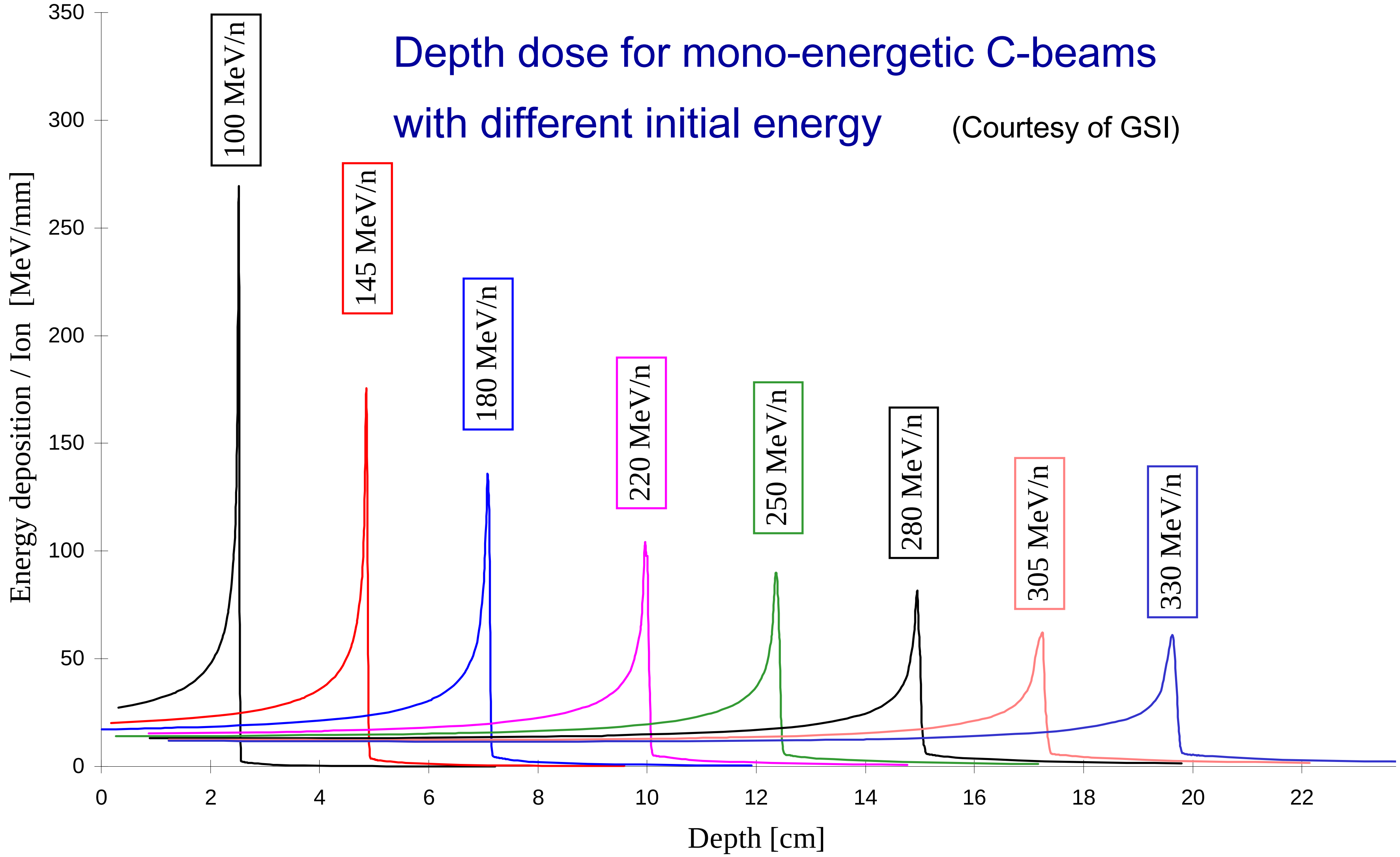
- Bragg peak has to be widened to cover tumour thickness
  - Overlapping of beams with different energies.
  - Active energy variation (synchrotron) or passive (cyclotron).



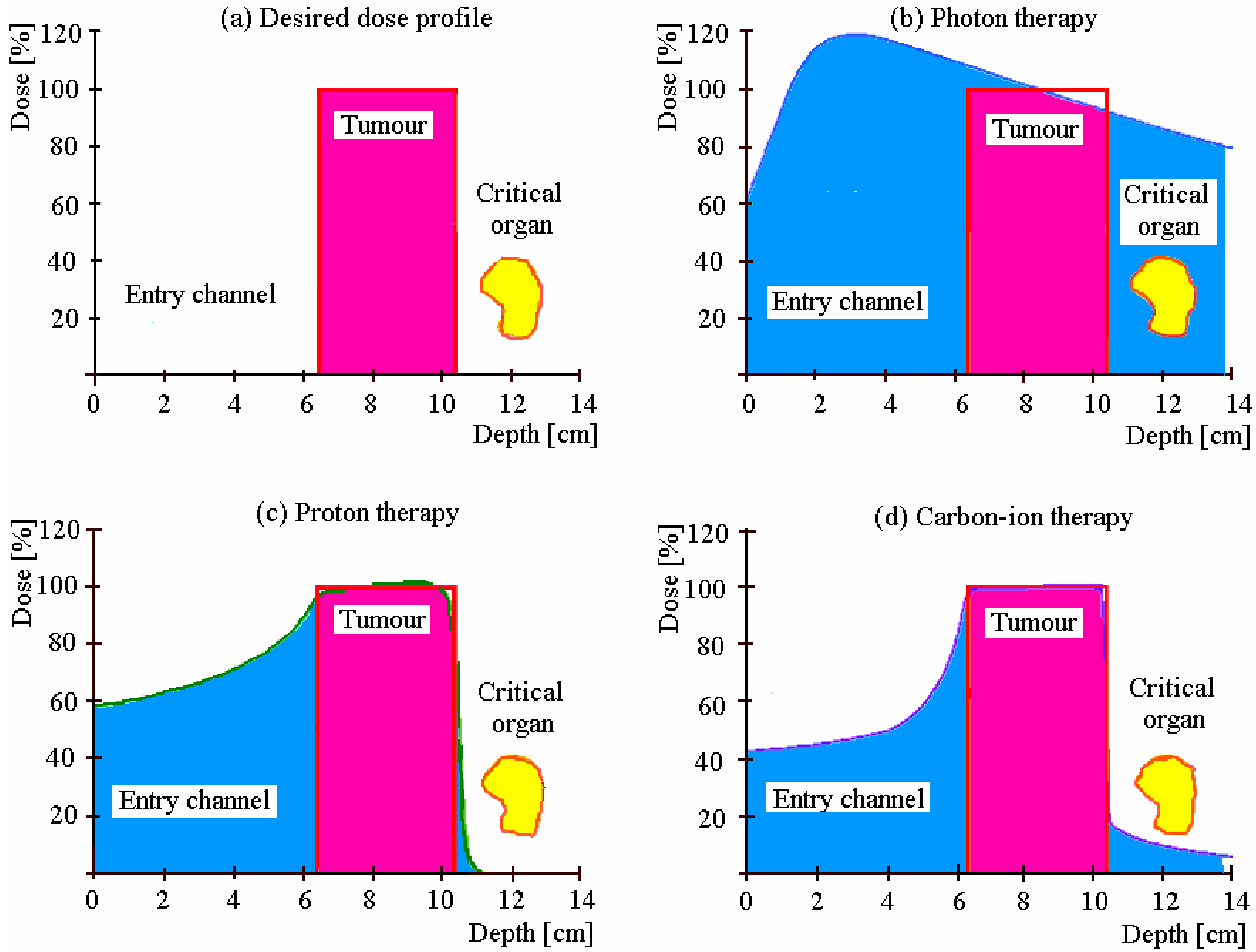


- Beam must also to cover transverse tumour cross section
  - Transverse scanning with small beam or spreading to large field.

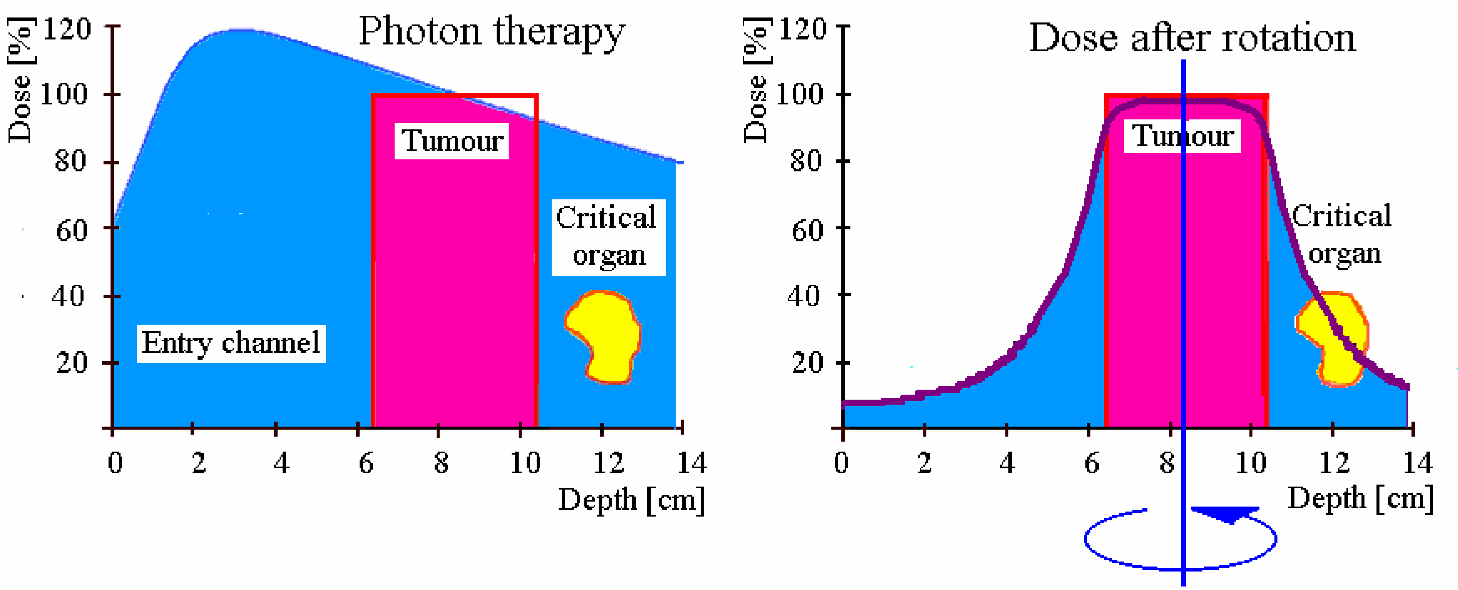
“Bragg-Peak” Energy Dependancy



Dose Profiles with Single Entry Port



Improved Dose Profiles with Rotation



Medical Specifications for Hadron Therapy

- Beam energies:
  - Protons: 60 MeV to 250 MeV (to reach ~30 cm depth)
  - C-ions: 120 MeV/n to 400 MeV/n
- Transverse field size 20 x 20 cm^2 (or larger).
- Spread out Bragg-peak over tumour thickness (→ energy variation).

- Cyclotron:
  - Protons only.
  - Beam radius ~cm.
  - Fixed extraction energy.
  - $\Delta p/p \sim 10^{-3}$ (sharp B-Peak)

- Synchrotron:
  - Protons and C-ions.
  - Beam radius ~cm.
  - Energy variable, cycle to cycle.
  - $\Delta p/p \sim 10^{-3}$ (sharp Bragg peak)

- Beams from accelerators do not fulfill medical specifications.

Beam Delivery Techniques

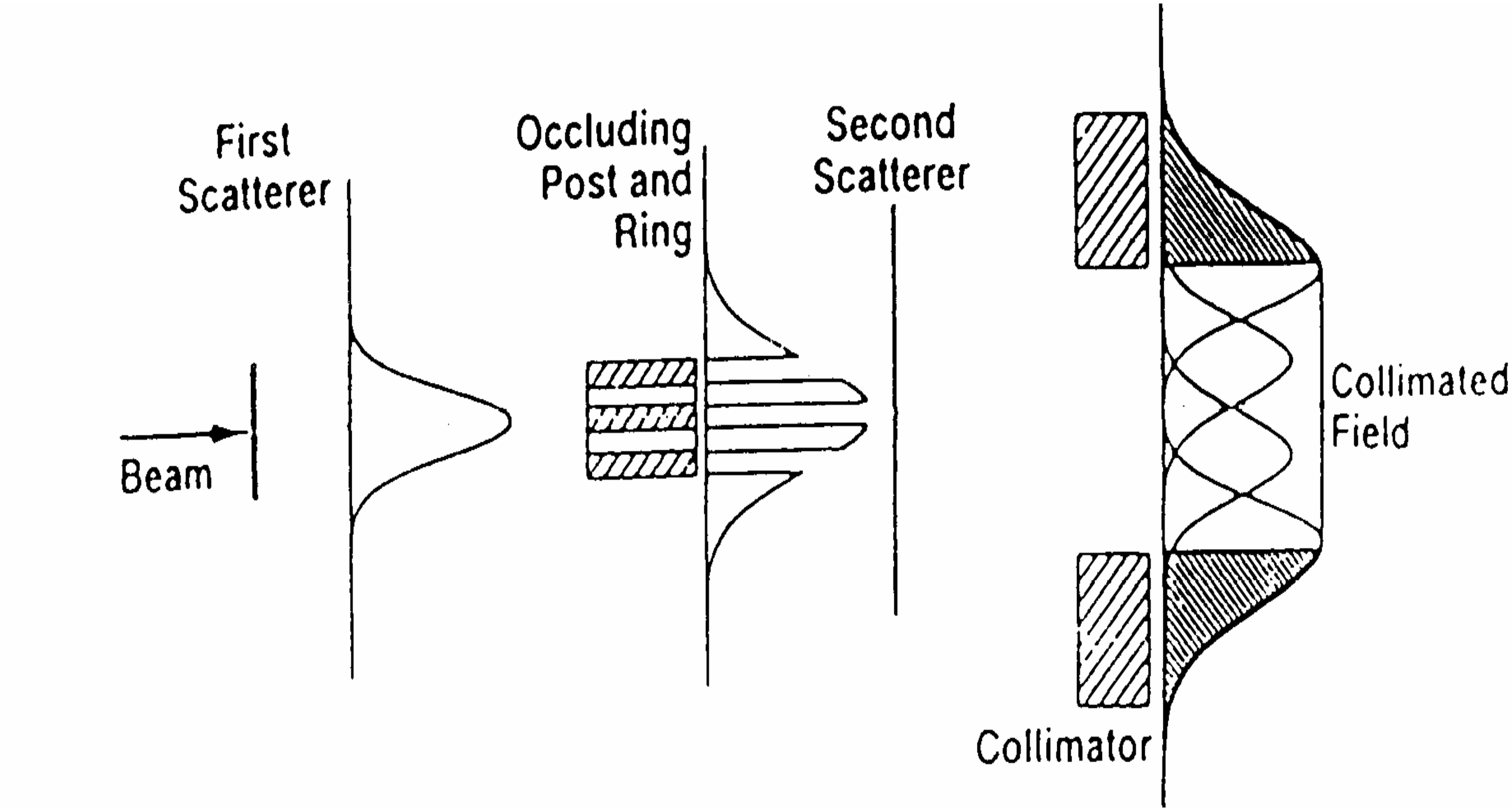
- Reduce beam energy according to maximum depth of tumour.
- Modulate beam energy to have SOPB covering tumour thickness.
- Adjust beam size to cover maximum tumour cross-section.

- Passive systems (material in beam path):
  - Scatterers to generate transverse field size.
  - Absorbers to adjust energy and generate SOBP.
  - For cyclotrons and synchrotrons.

- **Active systems:**
  - Transverse scanning of small beam over tumour cross section.
  - Energy adjustment with the accelerator.
  - Method of choice with a synchrotron.

Passive Beam Spreading

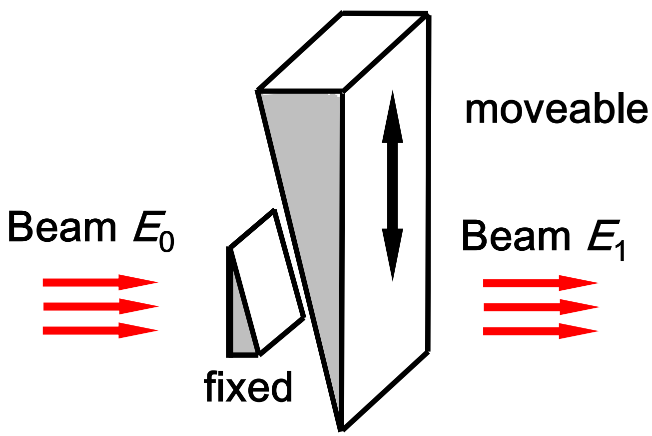
- Increase transverse beam size by scattering to ≥ 20 x 20 cm^2.
- Required field homogeneity is ± 2.5%.
- Technique implies large beam losses (acceptable with cyclotron).



Passive Beam Energy Adjustment

- Adjust the beam energy (Bragg-peak) to the maximum tumour depth.
- Low-Z materials preferred for less scattering (plexiglass).
- Less suitable with ions because of fragmentation.

"Double wedge system"



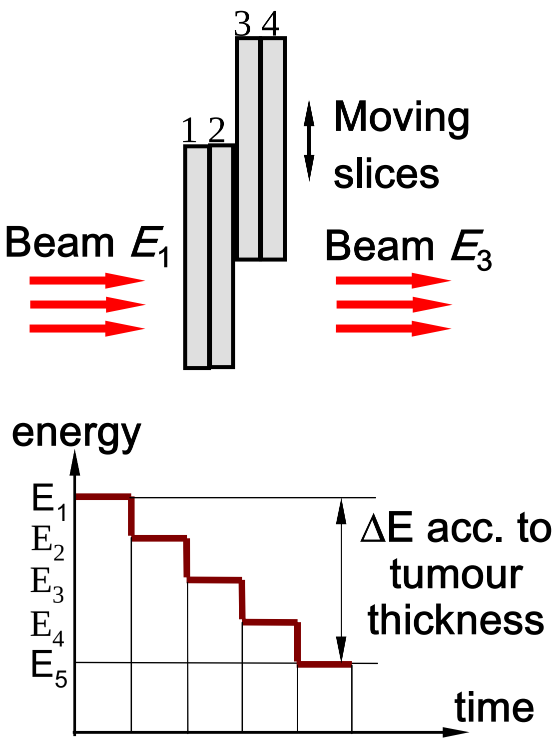
- Thickness according to max. depth.
- Stays constant during treatment.
- Adjustment from patient to patient.
- Followed by spectrometer line to select the desired energy.

Passive Energy Modulation

- Create “Spread Out Bragg Peak” according to tumour thickness.
- Time structure is very important in case of tumour movement.

Stepwise modulation

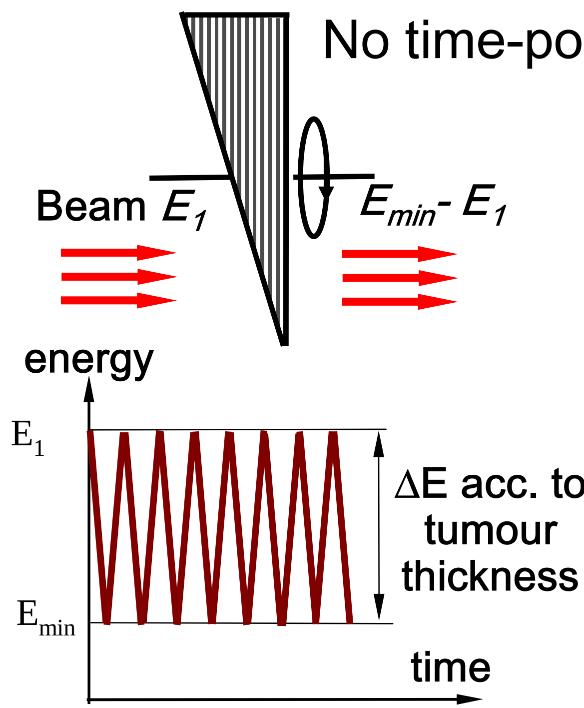
Plexiglass layers



Fast modulation

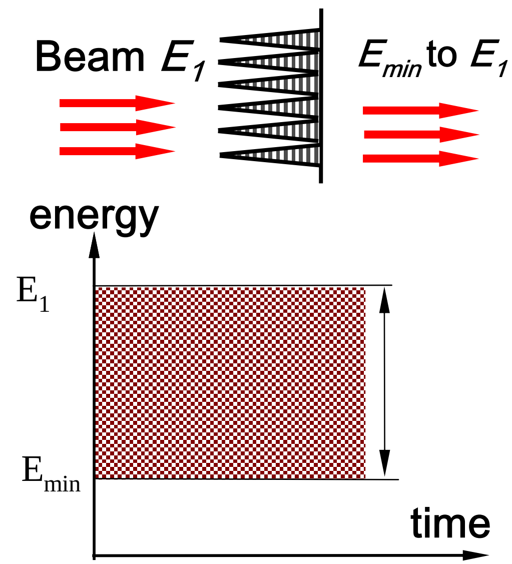
Rotating propeller

No time-position correlation

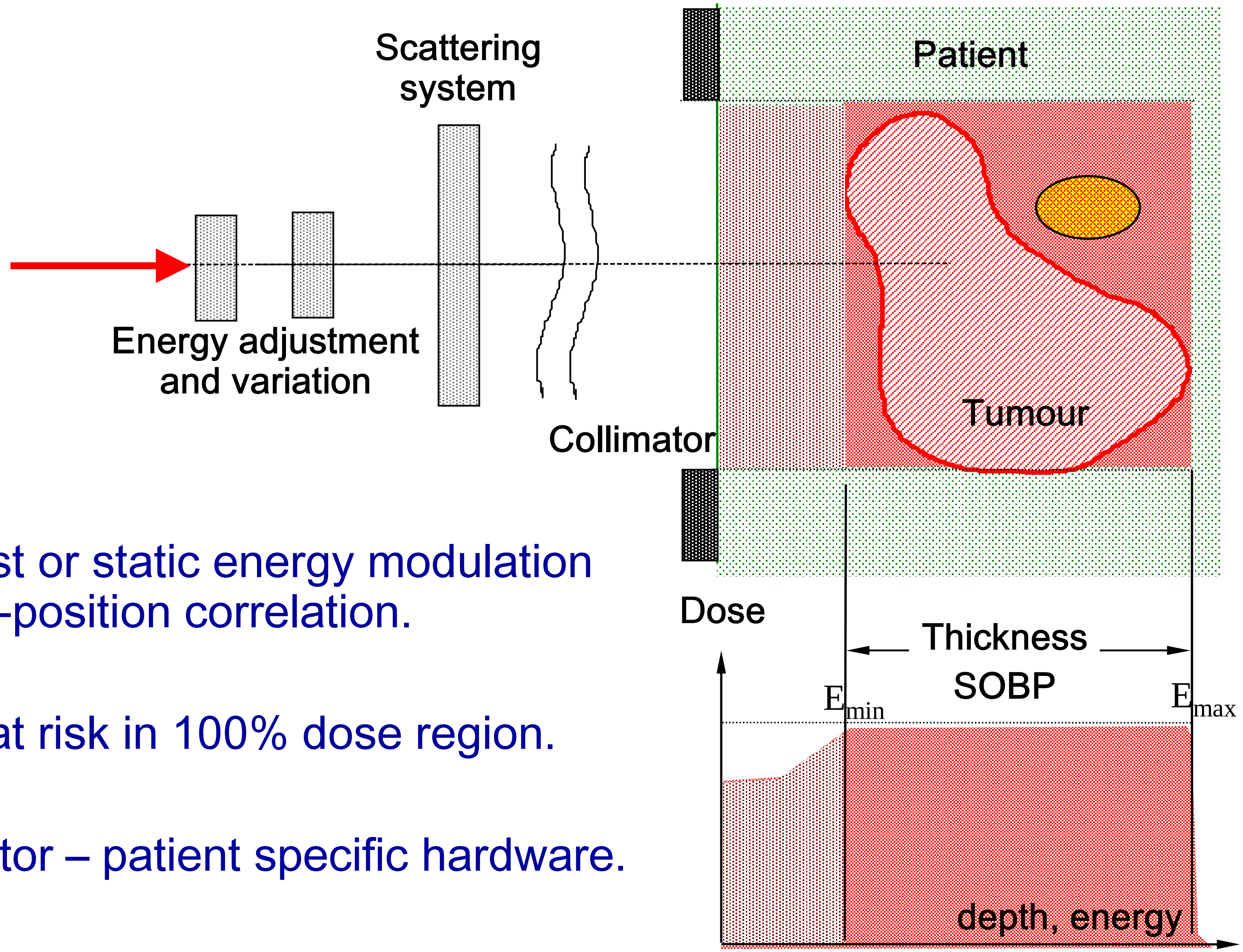


Static modulation

„Ridge“ filter



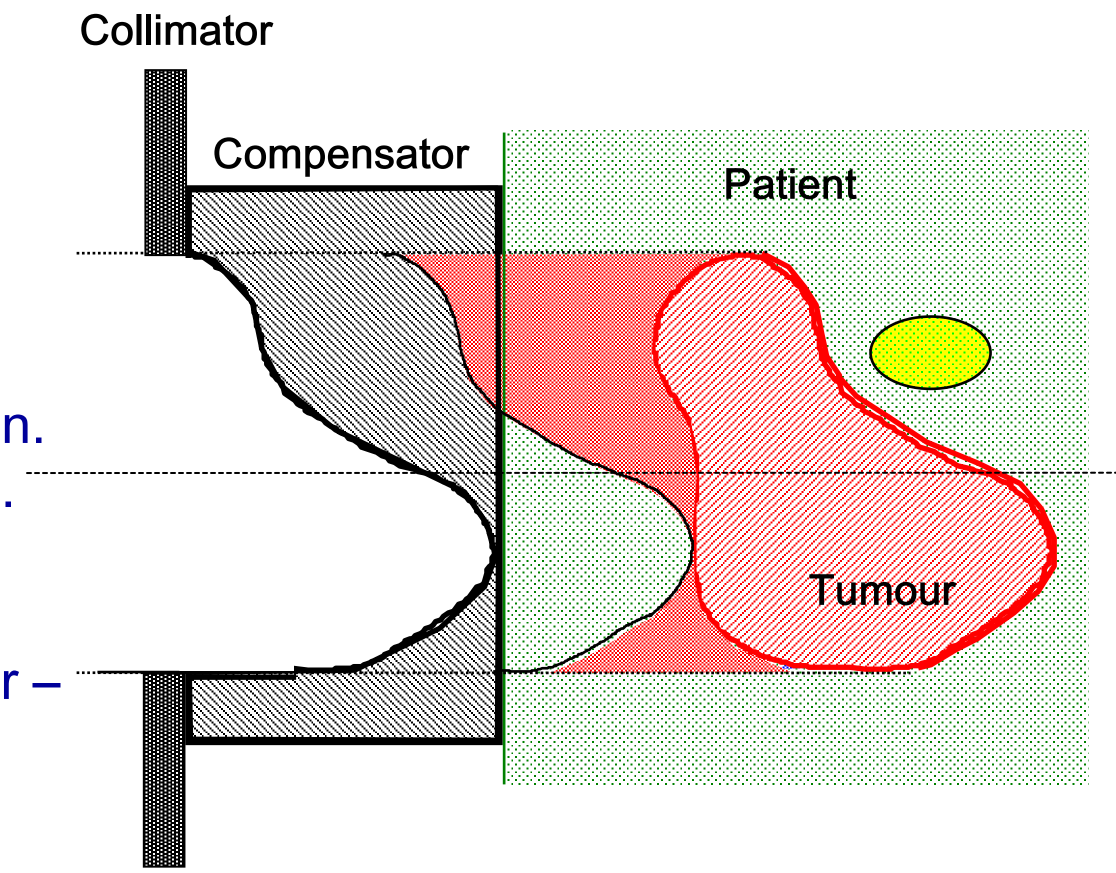
Passive Beam Delivery



- With fast or static energy modulation no time-position correlation.
- Organ at risk in 100% dose region.
- Collimator – patient specific hardware.

Passive Beam Delivery - Compensator

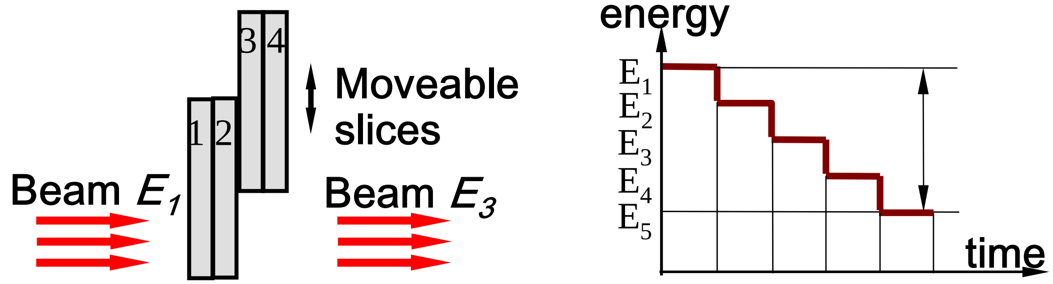
- Tissue equivalent compensator to adjust dose to distal tumour side.
- Creates energy loss (Bragg peak shift) as fct. of transverse position.



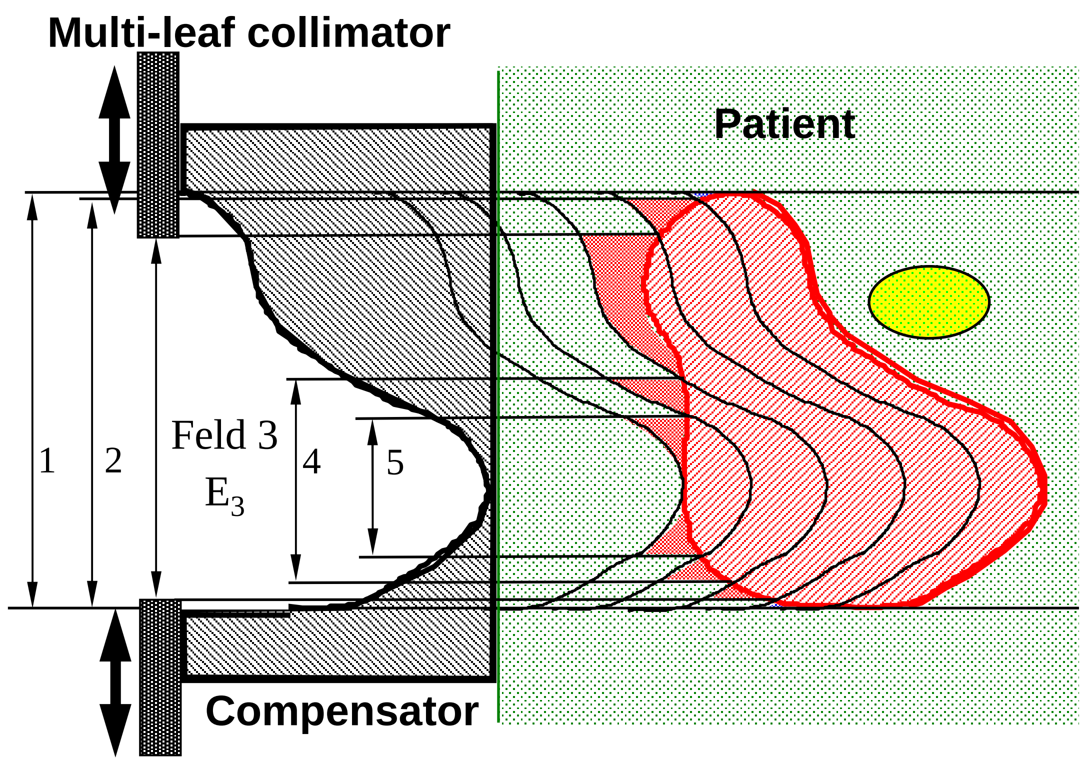
- Best dose distribution with fast/static energy modulation.
- No time-position correlation.
- No dose to organ at risk.
- High skin dose.
- Collimator and compensator – patient specific hardware.

Passive B. D. – Multi-Leaf Collimator

- Multi-leaf collimator: size can be changed during treatment.

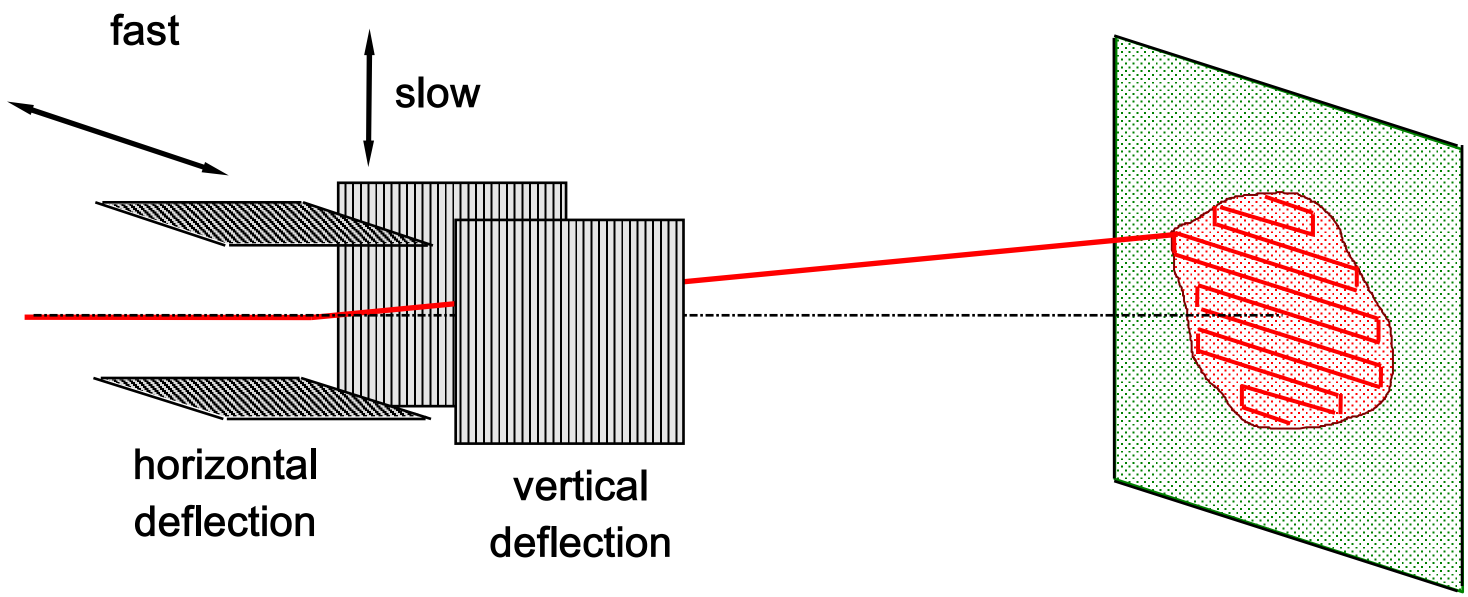


- Best dose distribution with passive systems.
- No dose to organ at risk.
- Low skin dose.
- Only compensator is patient specific.
- Time - position correlation



Active Scanning

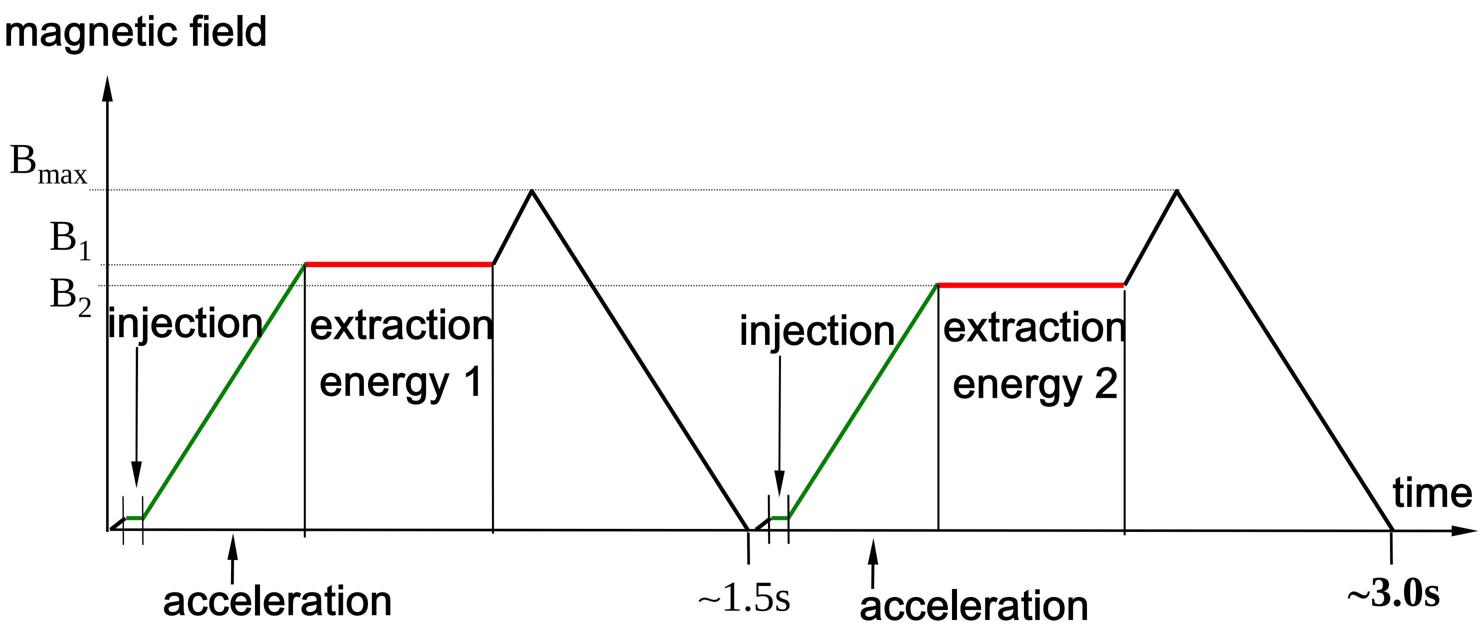
- Transverse scanning with a small “pencil” beam.
- Fast magnetic deflection (≤ 10m/s).
- Transverse beam size adjustable from 4 to 10 mm.



- No beam losses.
- No patient specific hardware.
- Requires sufficient time (~1s per slice) for online dosimetry.
  - Slow resonant extraction if a synchrotron is used.

Active Energy Variation

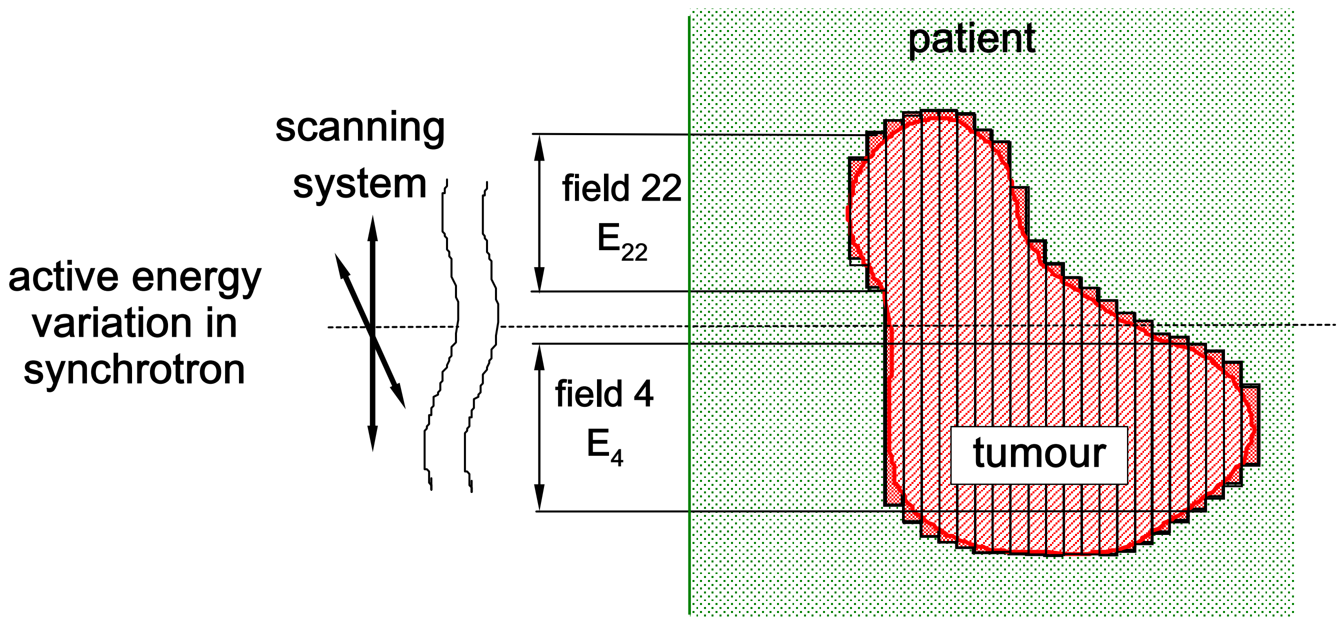
- Requires synchrotron as accelerator.
- Change extraction energy from cycle to cycle to create actively a SOPB according to tumour thickness.



- No beam losses.
- No patient specific hardware.

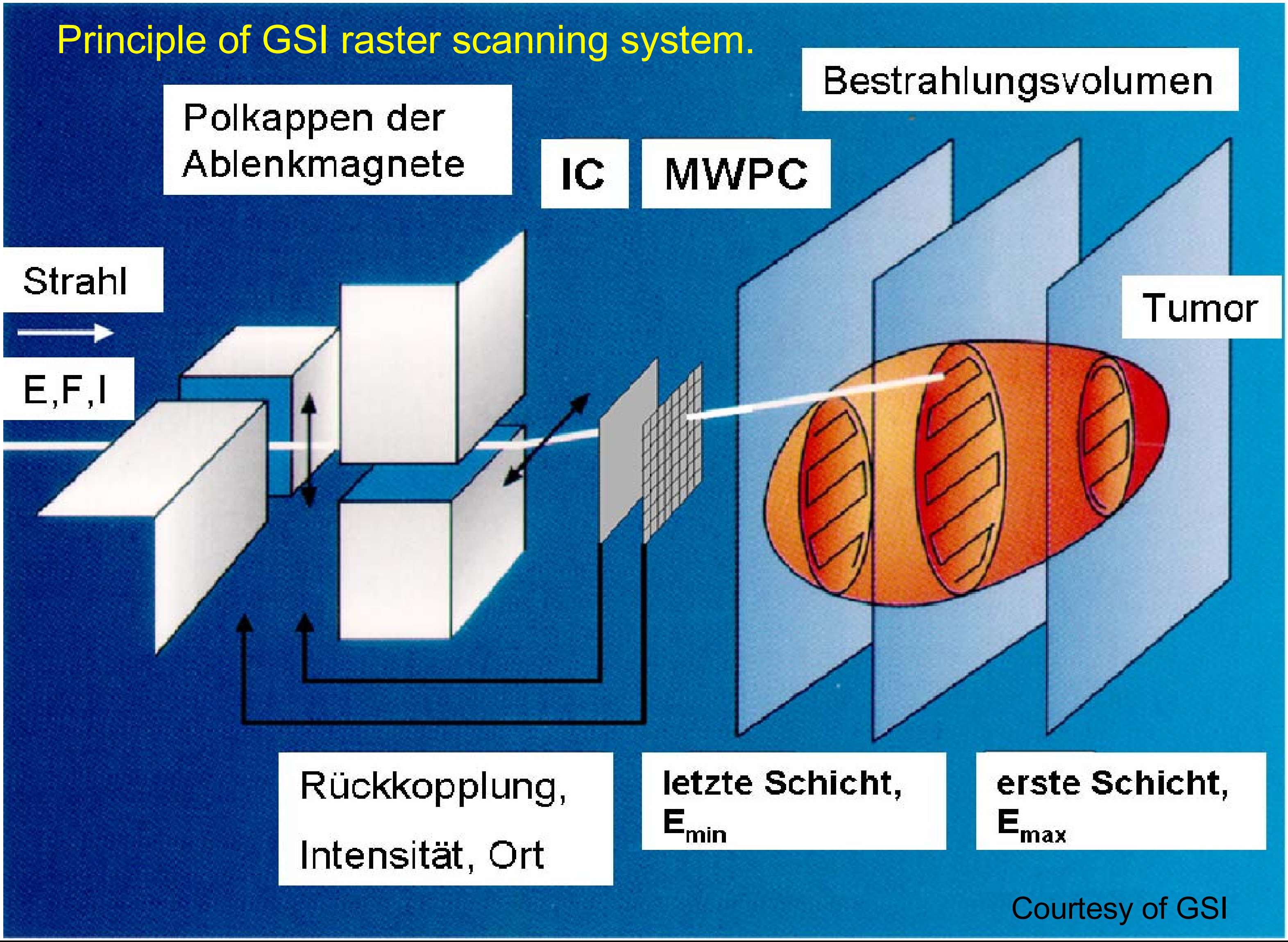
Active Beam Delivery

- Cut tumour into many slices with different depth.
- Transverse scanning, slice by slice, with corresponding energy.
- Intensity and beam size adjustable from slice to slice.



- Best achievable dose distribution.
- Strong time-position correlation, problematic for tumour movements.

Active Beam Delivery



Courtesy of GSI

MedAustron

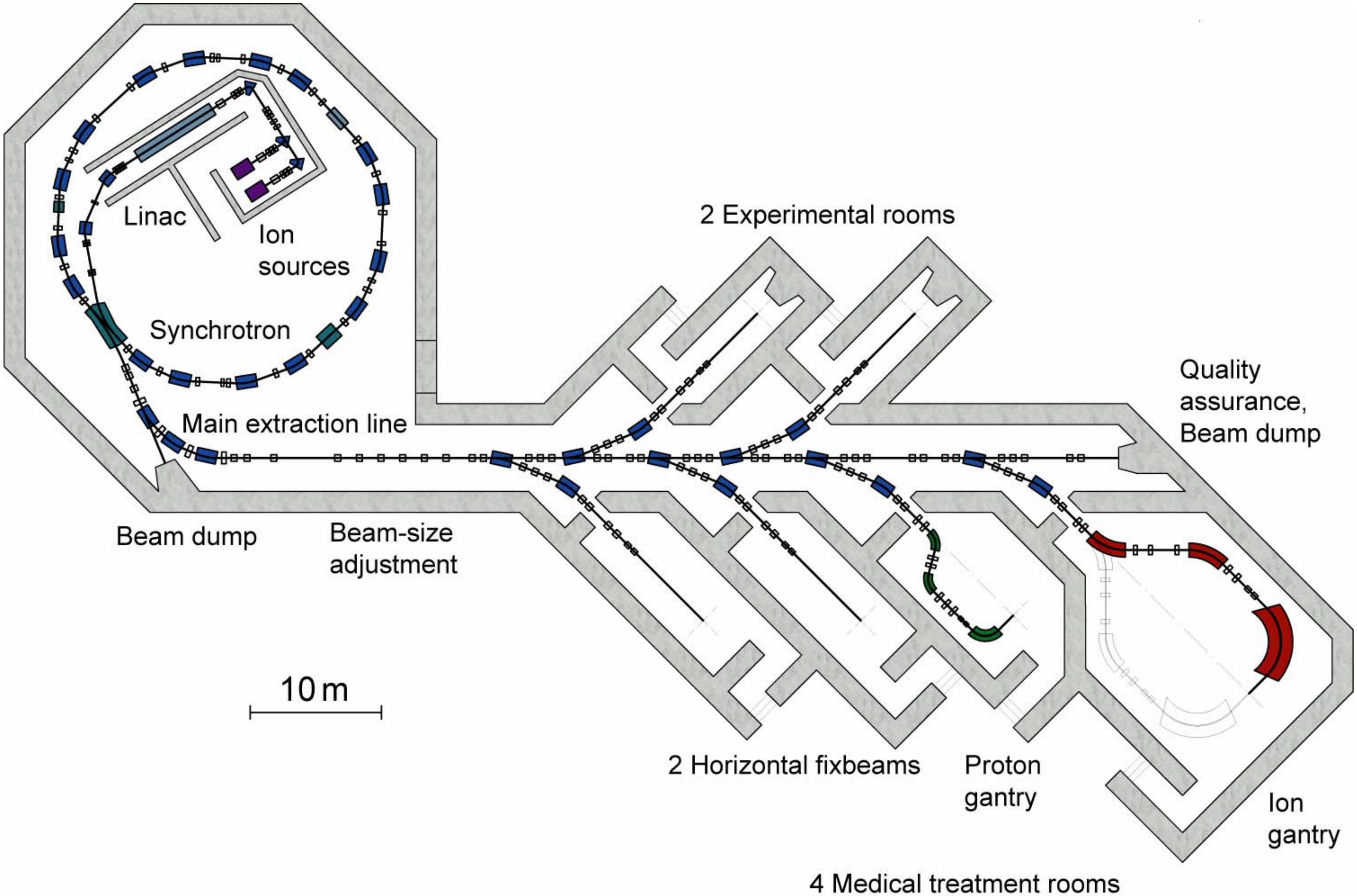
- Project to build a hadron therapy centre in Austria.
  - 1991 - 1994: AUSTRON Neutron Spallation Source Feasibility Study,– including the „AUSTRON Radio-Biological Facility", P.Bryant, M.Regler, M.Schuster.
  - 1997 - 1998: Feasibility Study „Med-AUSTRON", R.Pötter, M.Regler, T.Auberger.
  - 1995 - 2000: Proton-Ion Medical Machine Study (PIMMS) at CERN, P.Bryant et al.
  - 2001 - 2004: Design-Study MedAustron, FOTEC Company, Wiener Neustadt, T. Auberger, E. Griesmayer

The MedAustron Hadron Therapy Centre

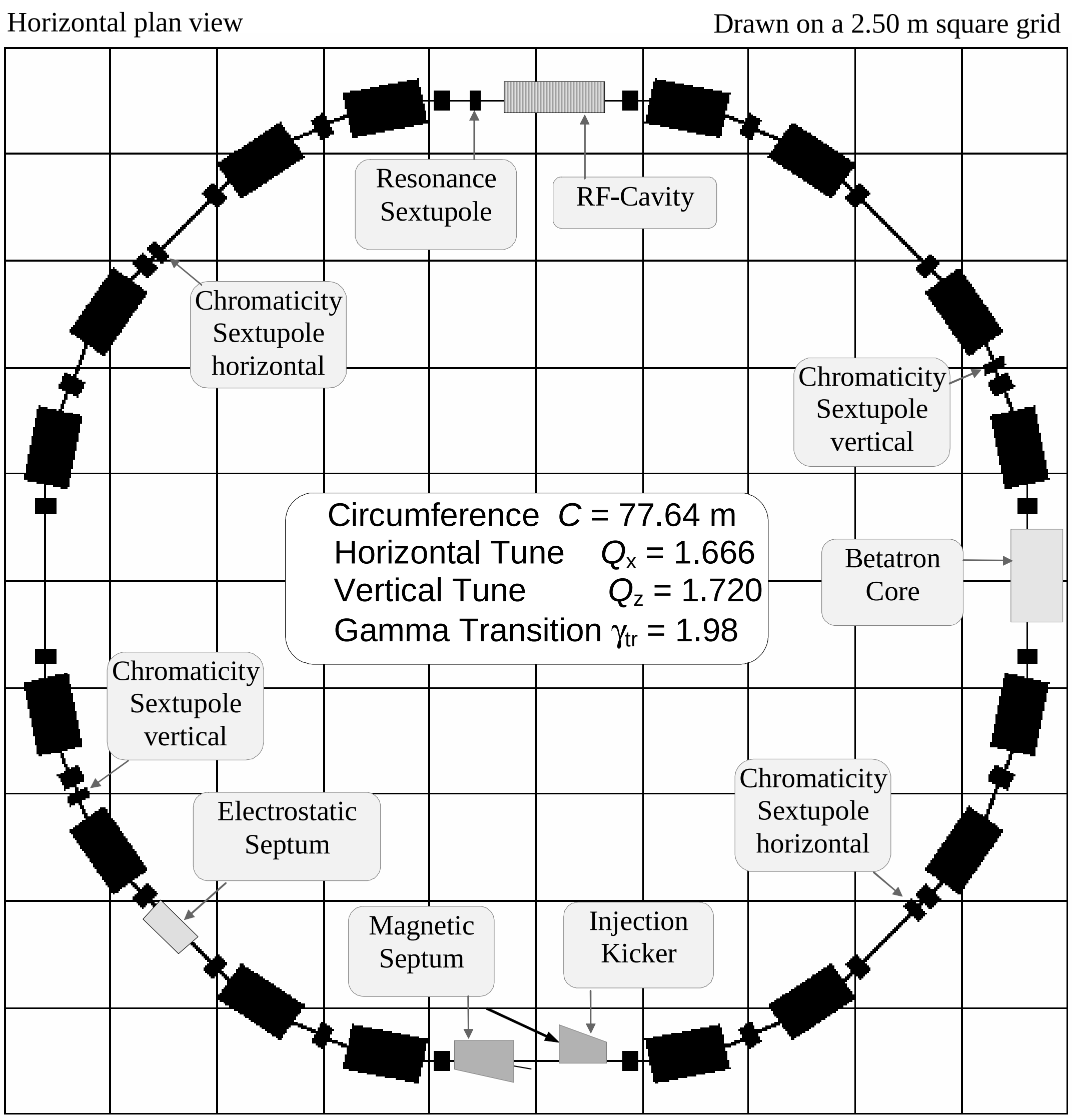
- Synchrotron based for therapy with C-ions and protons.
  - 4 medical treatment rooms all with active scanning.
  - Treatment capacity is around 1200 patients/year.
  - 2 horizontal beam lines with active scanning for clinical and radio biological research.

Beam energy:	protons	60 to 250 MeV
	C-ions	120 to 400 MeV
Beam intensity:	protons	$\leq 1 \times 10^{10}$
	C-ions	$\leq 4 \times 10^{8}$
Beam size for active scanning		4×4 to 10×10 mm^2

MedAustron Centre Layout



MedAustron Synchrotron

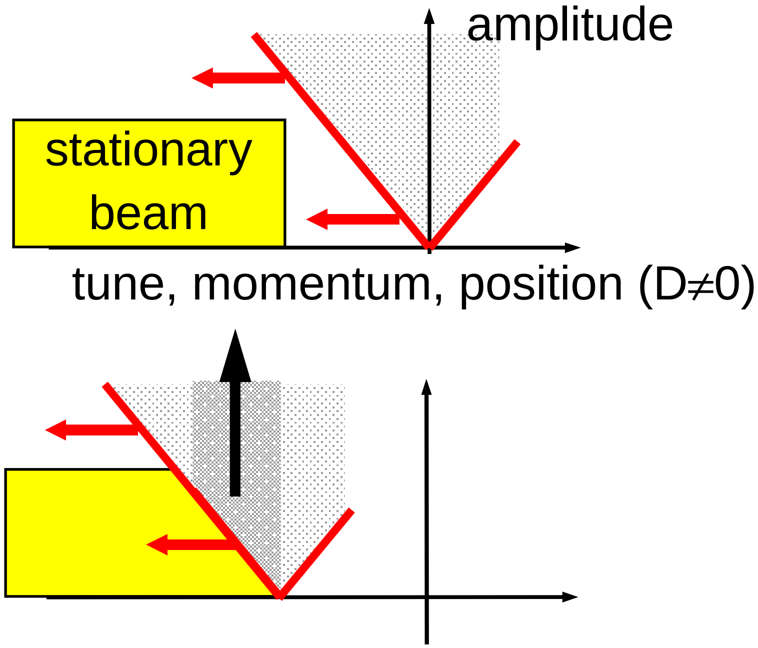


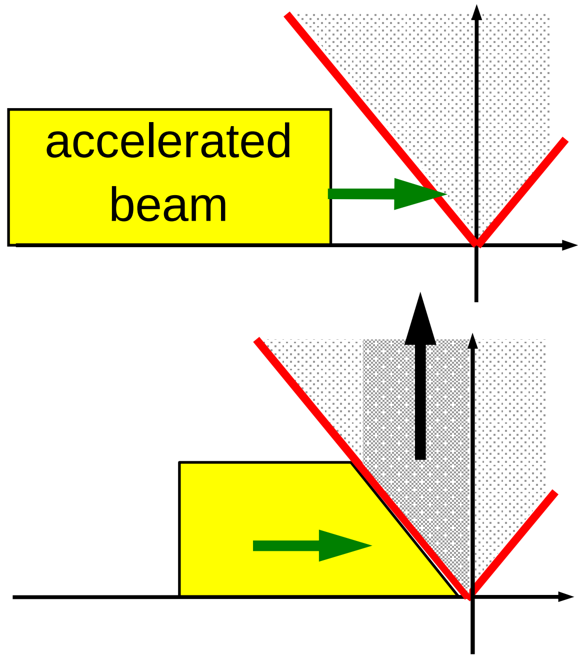
- **Based on PIMMS, optimized by TERA (I)**
  - Protons: 250 (1200) MeV
  - C-ions: 400 MeV/u
  - Multi-turn injection (≤10)
  - Slow extraction horiz. (5/3)
  - Spill time ~1s to 10 s
  - Extraction with a Betatron core: inductive acceleration
  - "Orthogonal" control of resonance and chromaticity

Choice of Extraction Method

Standard method:
resonance moves through beam

PIMMS synchrotron:
beam moves into **stationary resonance**



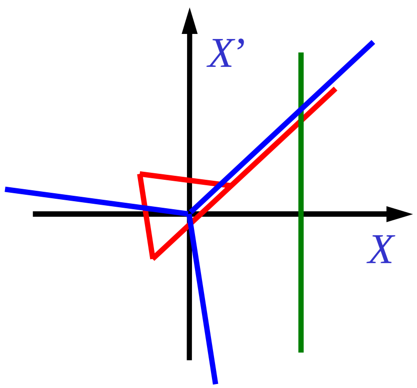


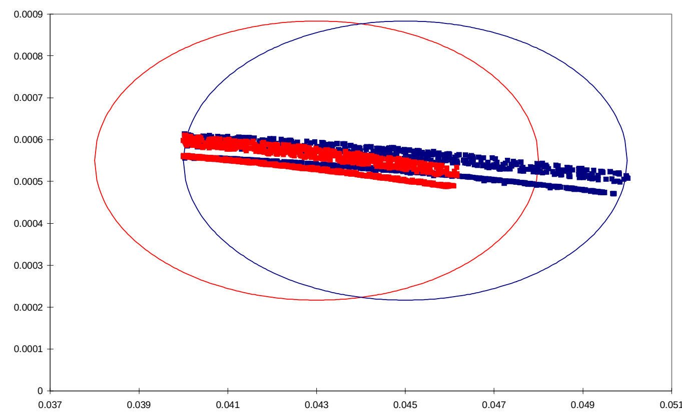
- Energy of extracted beam changes
- Extraction position changes
- On-line corrections needed

- Energy of extracted beam constant
- Extraction position constant
- No on-line corrections

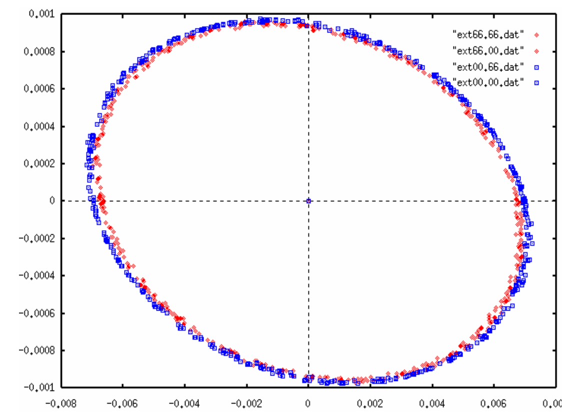
The Slow Extracted Beam

- Slow extracted beam shows strong asymmetry:
  - "Bar of charge" in the horizontal plane (plane of extraction).
  - Standard emittance ellipse in vertical plane.





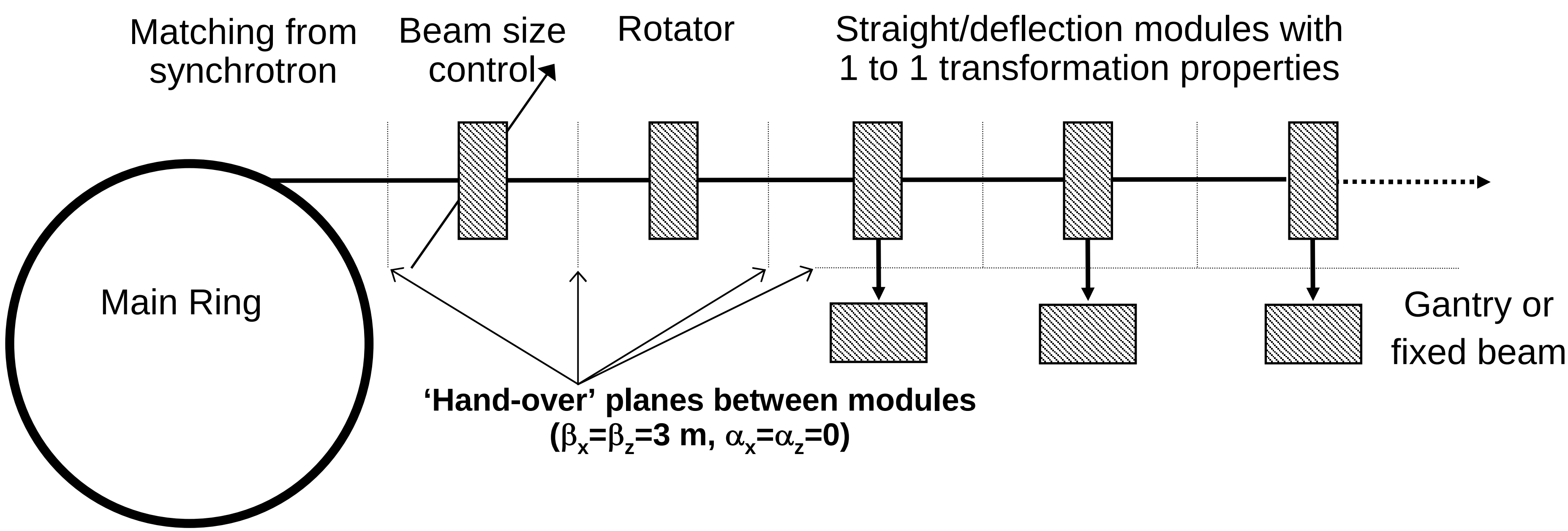
horizontal phase space at ES



vertical phase space at ES

- Description of horizontal phase space with "unfilled ellipse".
  - Shift between blue (on-momentum) and red (off) defines Dispersion for transfer line matching.

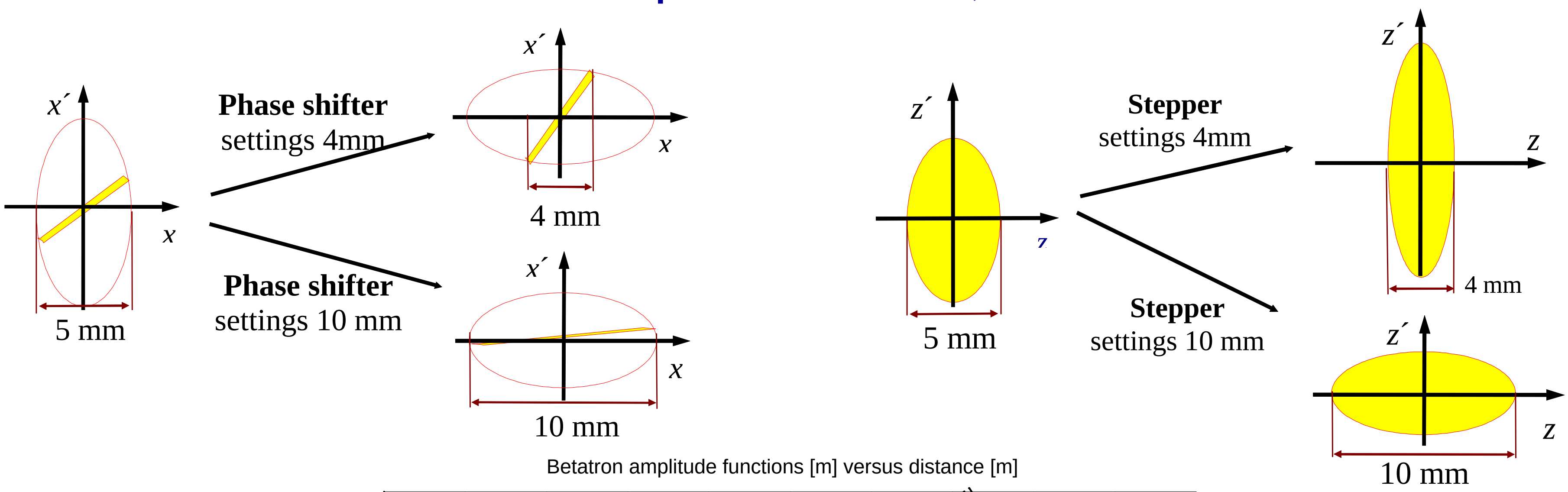
Modular Extraction Line Design

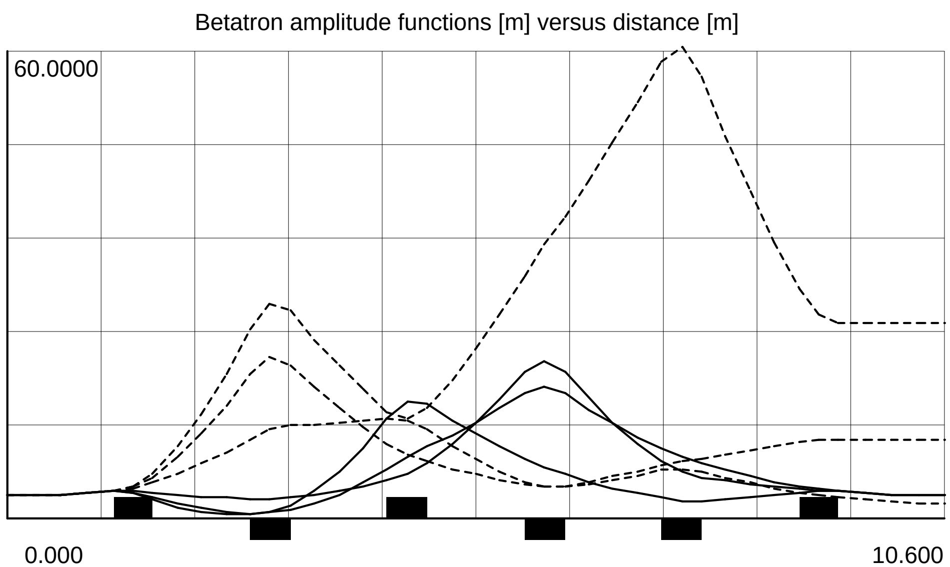


- **Modular concept**
  - Single beam size control
  - Single rotator for gantries
  - 1:1 transfer to all rooms
- **Advantages**
  - Identical magnet types
  - Identical power supply types
  - Similar optics settings
  - Simplified operation & control

Beam Size Control in Extraction Lines

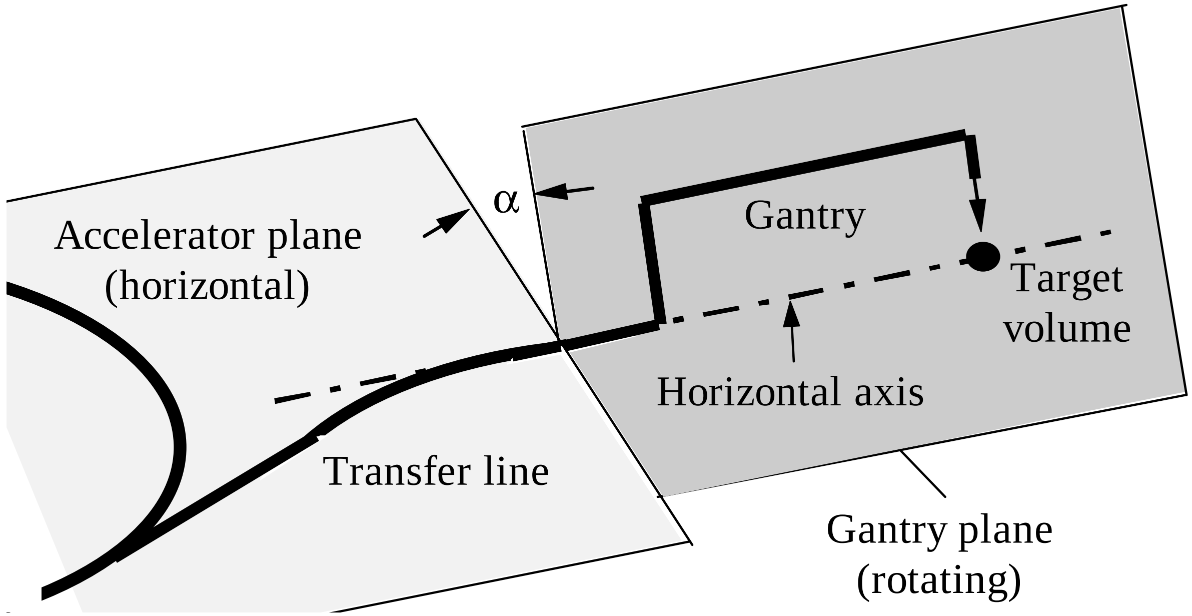
- Horizontal beam size via phase advance, vertical via beta-function





Matching to Gantries

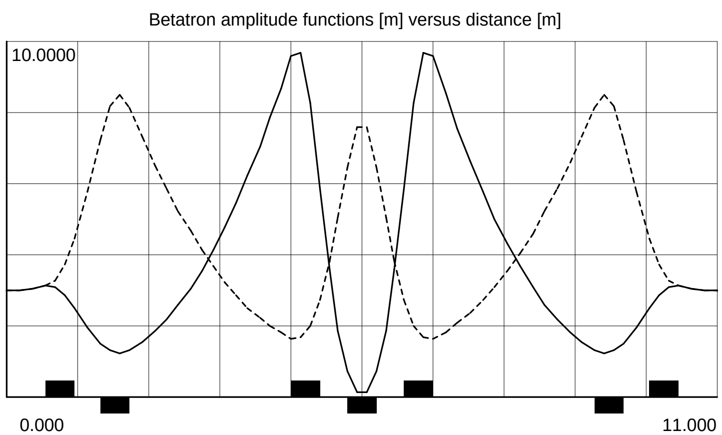
- Problem: matching of the fixed TL to the rotating gantry.

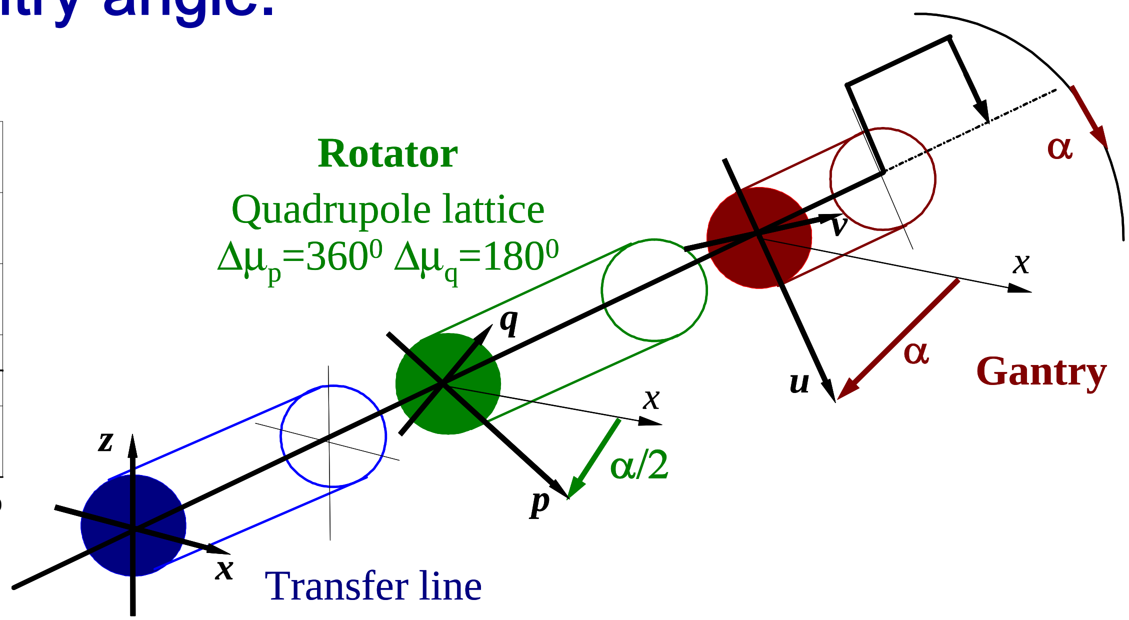


- Requires symmetric beam and identical optical functions at rotation point
- For medical application any dependency of e.g. beam size, distribution, on gantry angle must be avoided.
- No conventional solution for slow extracted beam → “Rotator”.

Rotator

- Beam line (quads) with 1:1 and 1:-1 optics in front of gantry rotated by ½ the gantry angle.

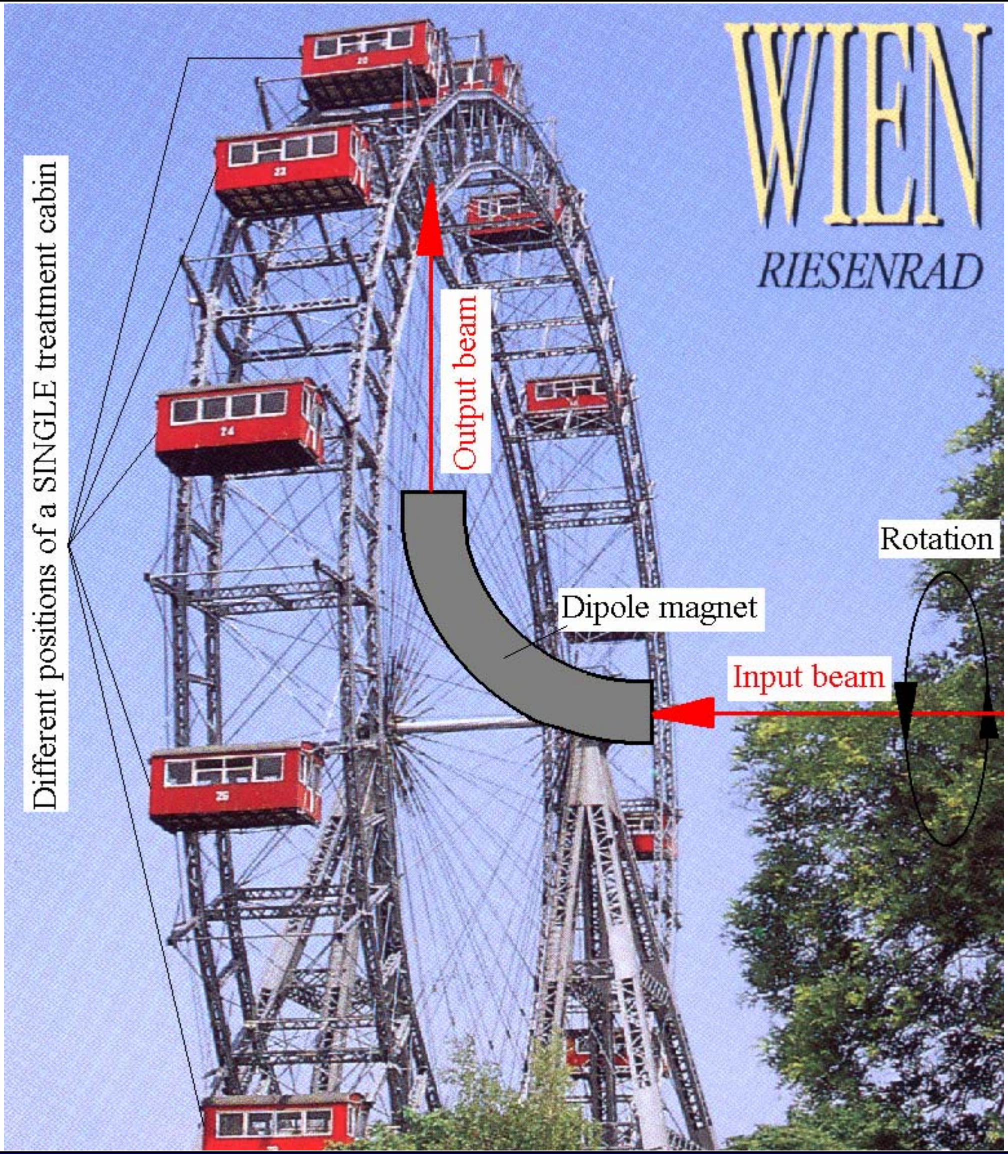




$$M_0 = \begin{pmatrix} \cos\frac{\alpha}{2} & 0 & \sin\frac{\alpha}{2} & 0 \\ 0 & \cos\frac{\alpha}{2} & 0 & \sin\frac{\alpha}{2} \\ -\sin\frac{\alpha}{2} & 0 & \cos\frac{\alpha}{2} & 0 \\ 0 & -\sin\frac{\alpha}{2} & 0 & \cos\frac{\alpha}{2} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \begin{pmatrix} \cos\frac{\alpha}{2} & 0 & \sin\frac{\alpha}{2} & 0 \\ 0 & \cos\frac{\alpha}{2} & 0 & \sin\frac{\alpha}{2} \\ -\sin\frac{\alpha}{2} & 0 & \cos\frac{\alpha}{2} & 0 \\ 0 & -\sin\frac{\alpha}{2} & 0 & \cos\frac{\alpha}{2} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

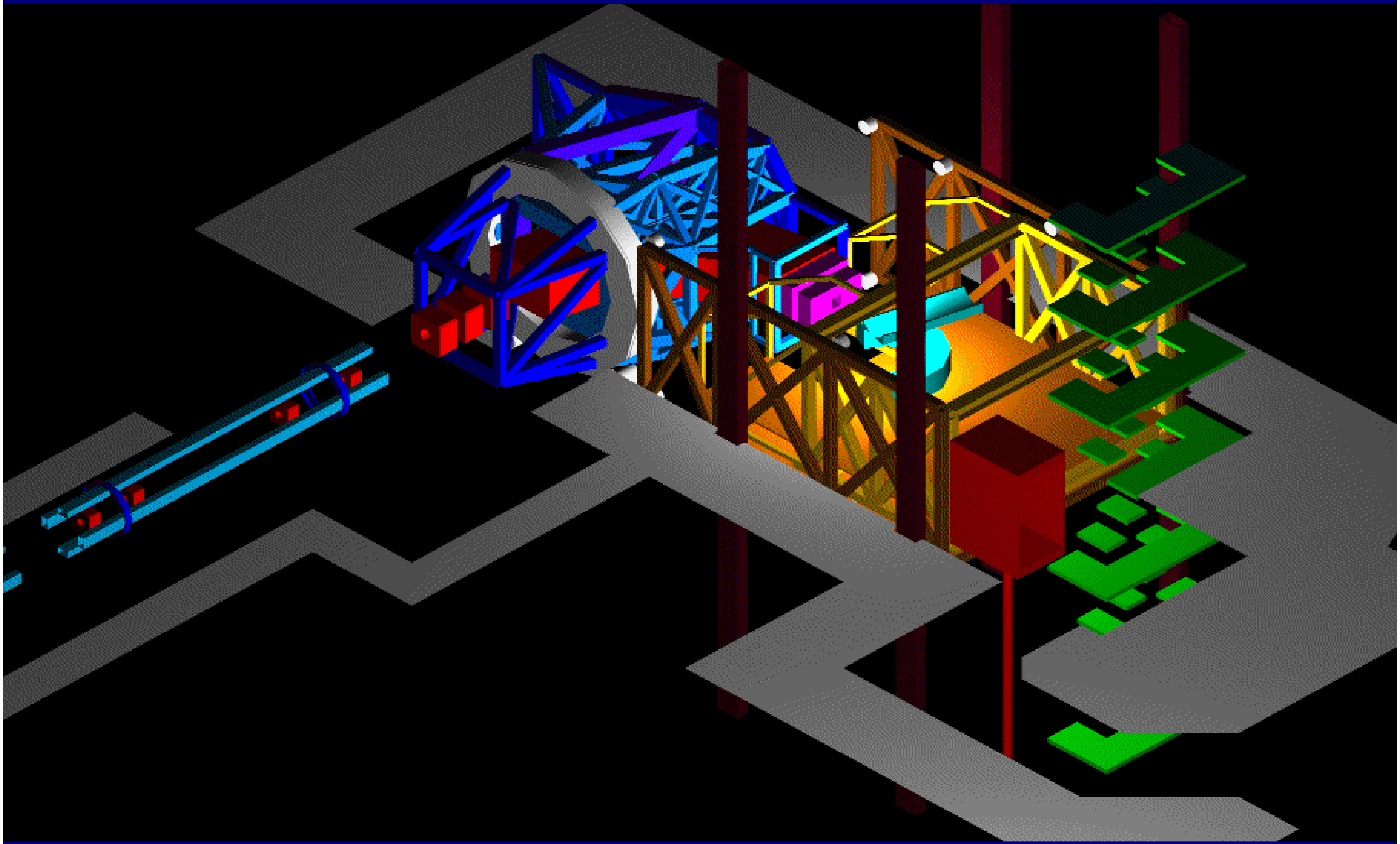
Maps the beam 1:1 to the gantry independent of the angle.

The Riesenrad Gantry



- Patient in “false” room
- Keep the heavy magnet close to the axis
- Only 90° of bending
- Studied within PIMMS

The Riesenrad Gantry

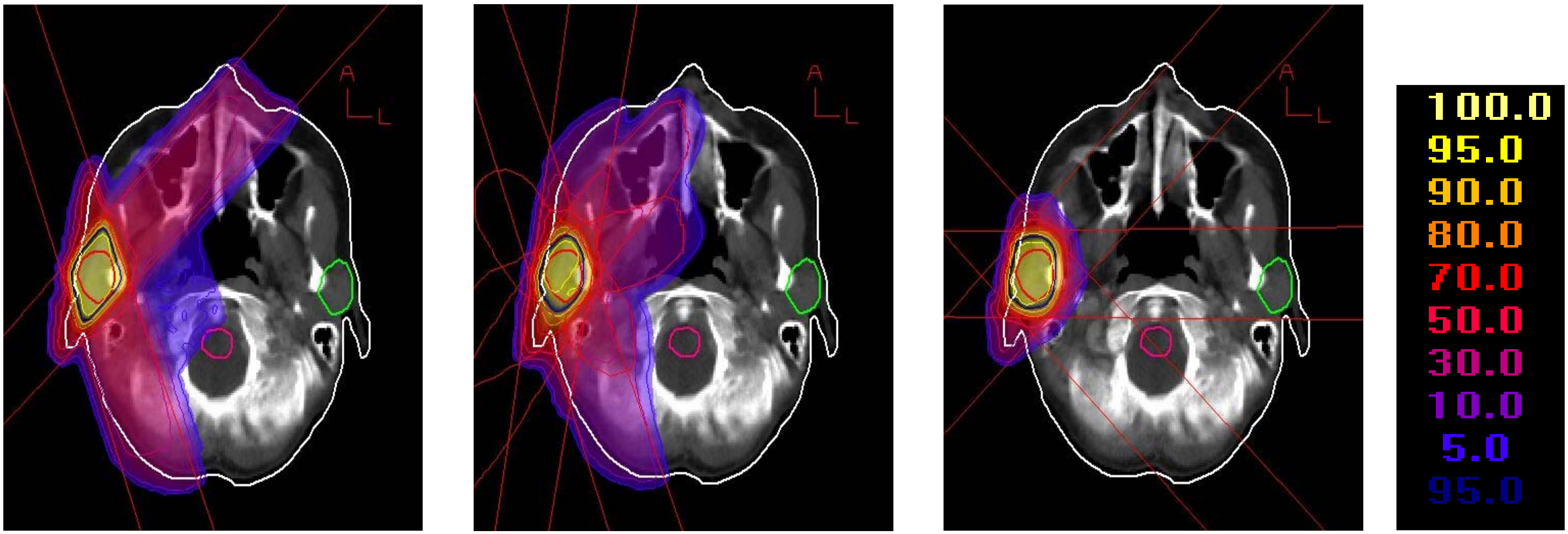


Comparative Treatment Plannings

Glandula parotid cancer

(Ohrspeicheldrüsenkarzinom)

Photons 2 fields | Photons 5 fields | Protons 3 fields

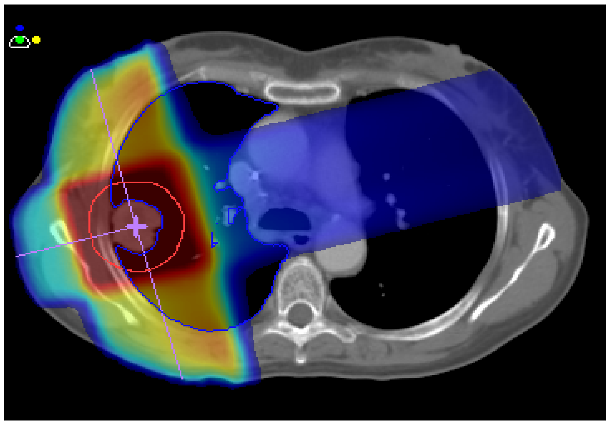


Universitätsklinik für Strahlentherapie und Strahlenbiologie, AKH, Wien

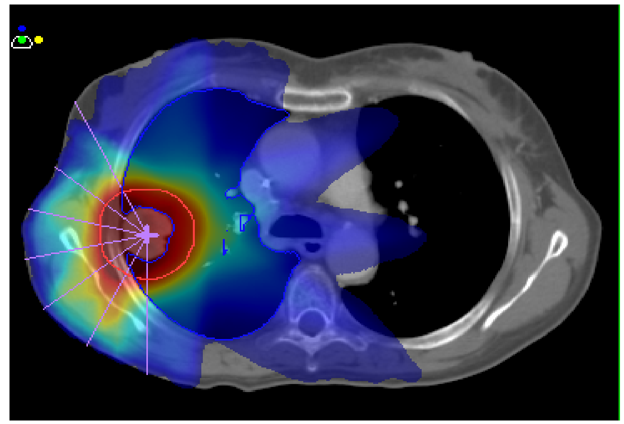
Comparative Treatment Plannings

Bronchial cancer

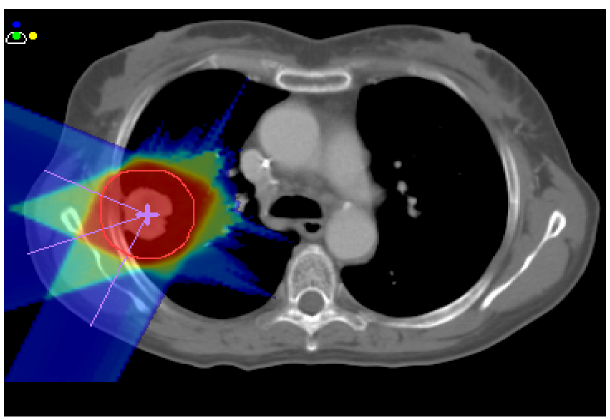
Photons 3 fields

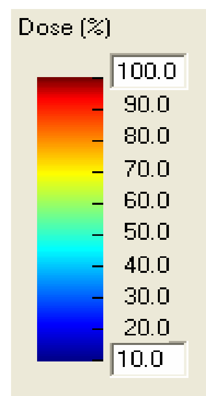


Photons 7 fields



Protons 3 fields





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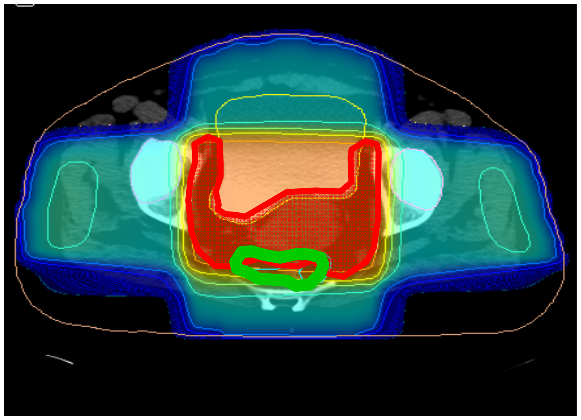
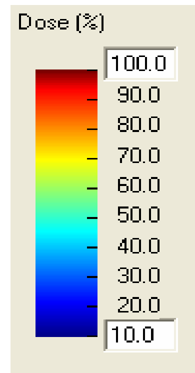
Comparative Treatment Plannings

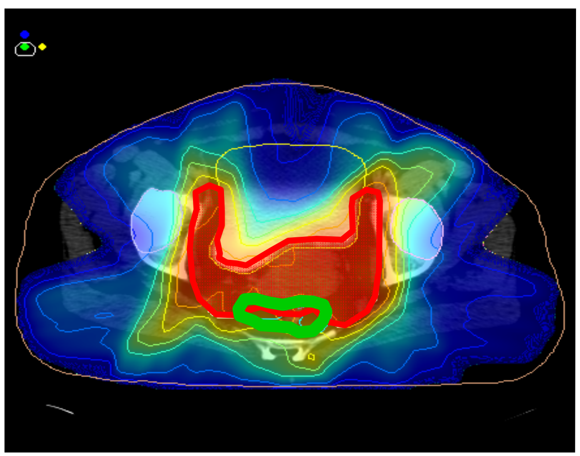
Cervical carcinoma

Conformal RT 4 fields

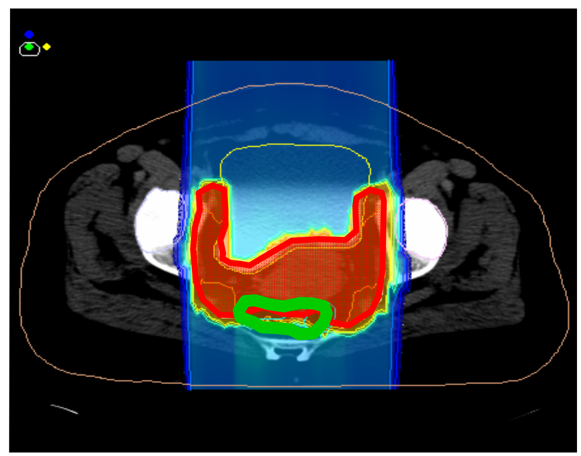




IMRT 7 fields



Protons 2 fields



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Conclusions

- **Hadron therapy is an important ingredient in the treatment of tumours.**
- **Cannot (and should not) replace conventional therapy - but clearly the method of choice for certain tumours.**
- **Very interesting technical challenges in the field e.g. slow extraction, transfer line optics, rotator.**
- **Presently there are worldwide several centres already under construction or in the starting phase.**
- **MedAustron could be the hadron therapy centre for the Central European region.**