Accelerator Science and Particle Therapy

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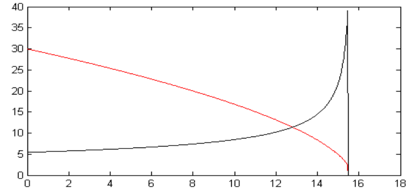
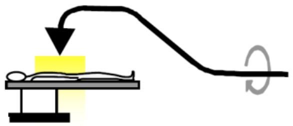
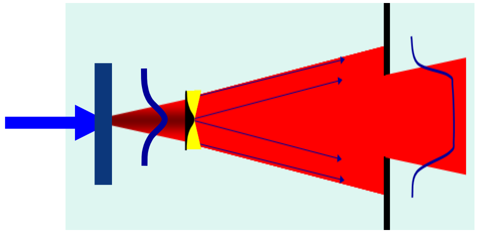


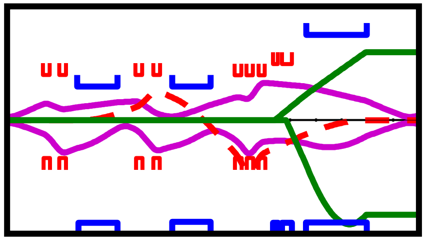
- Possible facility and gantry layouts



- Dose delivery techniques

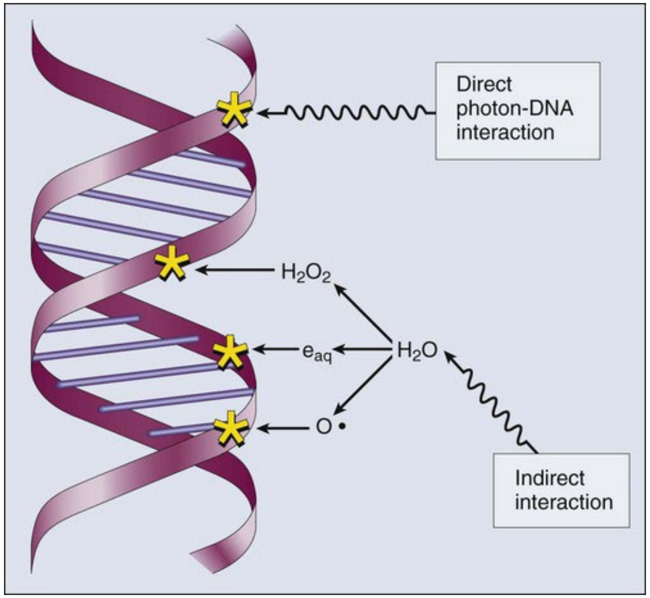


- Beam optics properties



Introduction: Hadron therapy

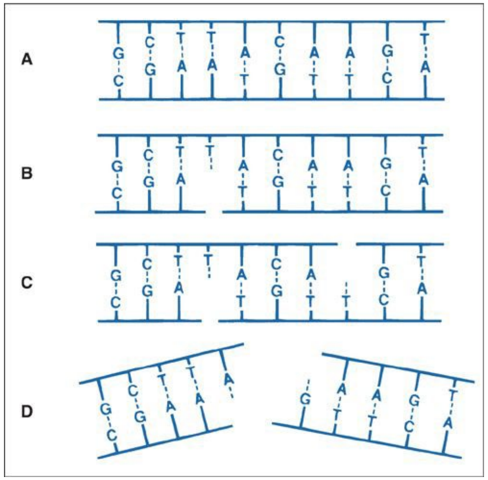
Dose and mechanism of action



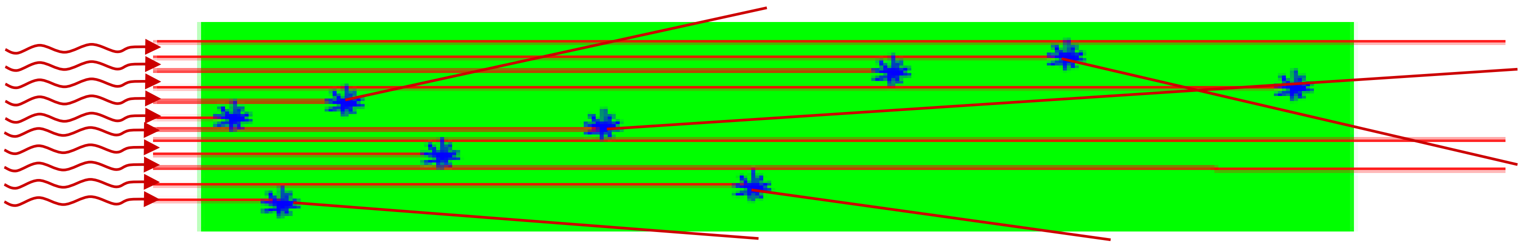
- Direct and indirect interraction
- Single DNA strand breaks are usually reparable
- Double DNA strand breaks are usually irreparable

Dose is measured in gray

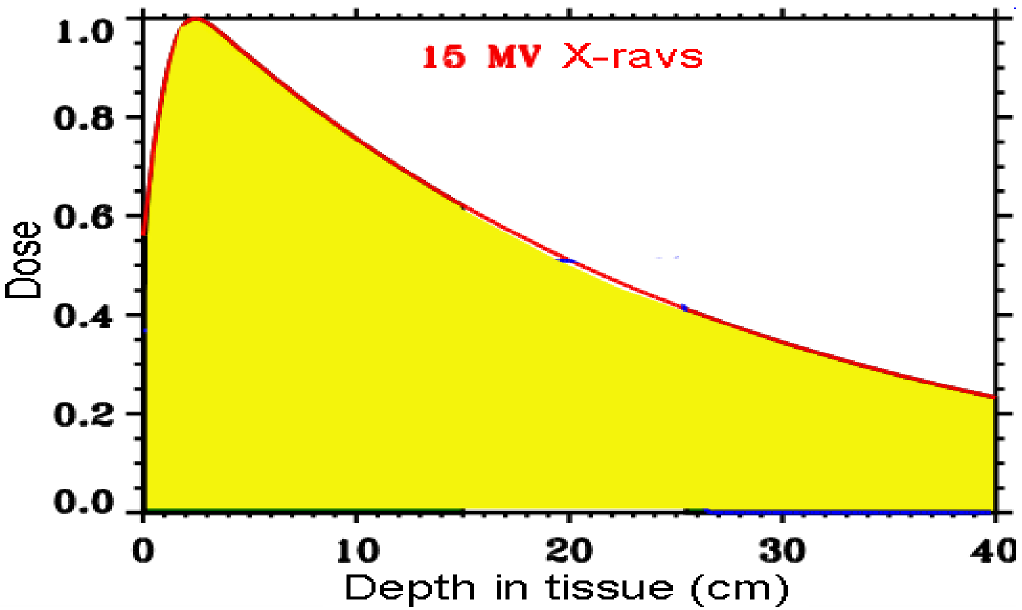
$$1\,\mathrm{Gy} = 1\,\frac{\mathrm{J}}{\mathrm{kg}} = 1\,\frac{\mathrm{m}^2}{\mathrm{s}^2}$$



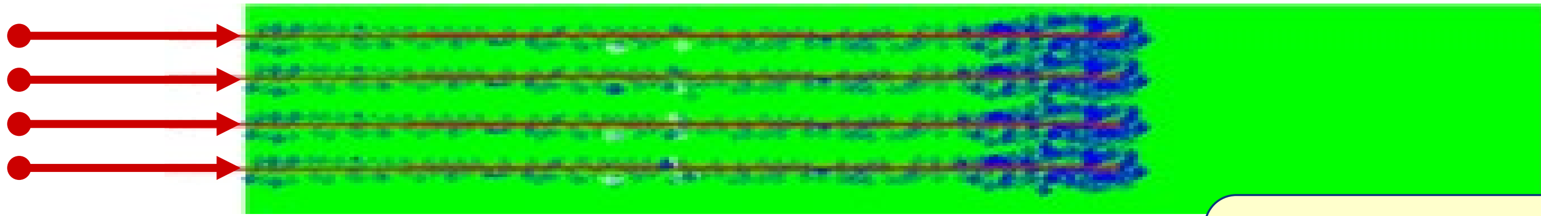
Photon (X-ray) dose



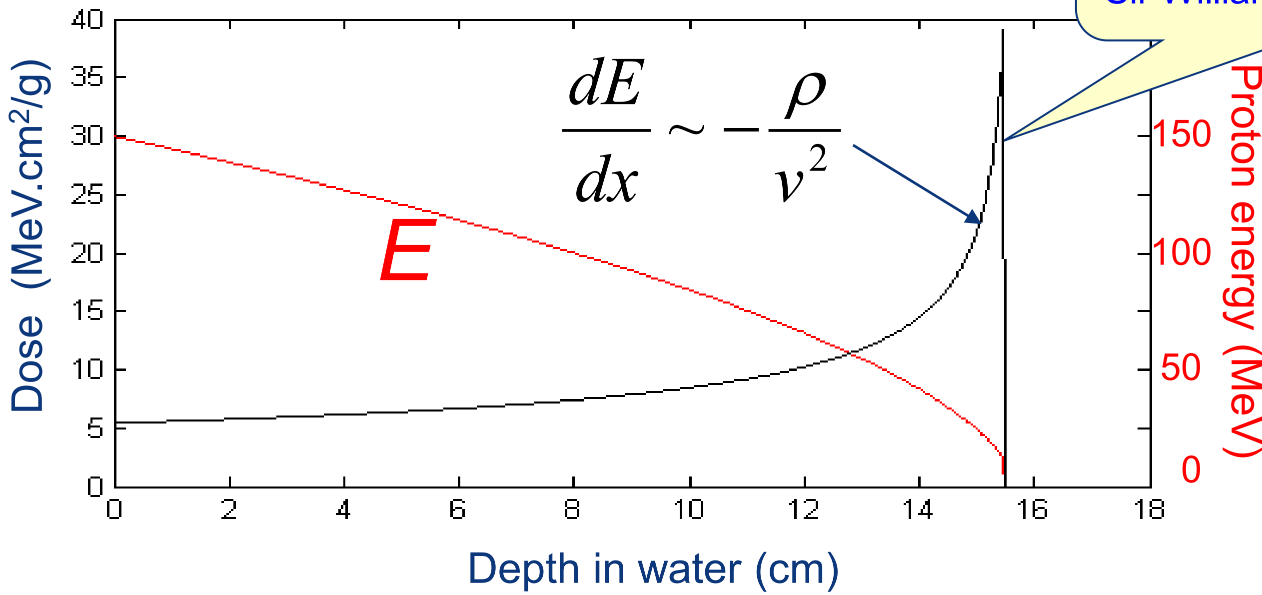
X-rays **scatter** and are **absorbed** → energy deposition in “dots”



Proton depth-dose curve



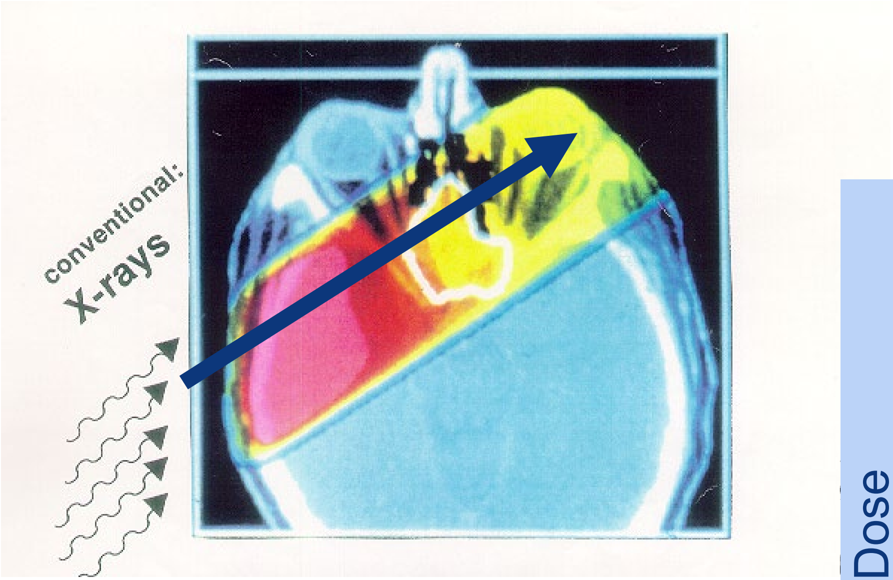
Protons **slow down**

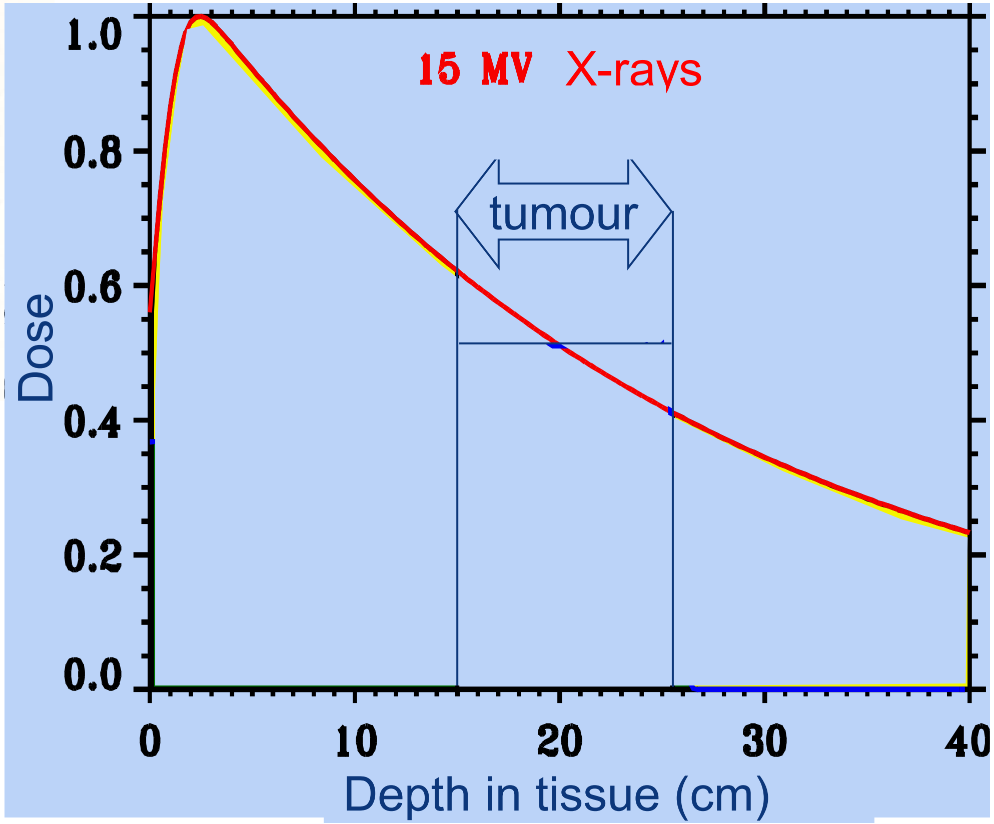


→ Energy → Penetration depth **Range in water** (cm) ≈ $E^{1.77}$ *(in MeV) / 450*

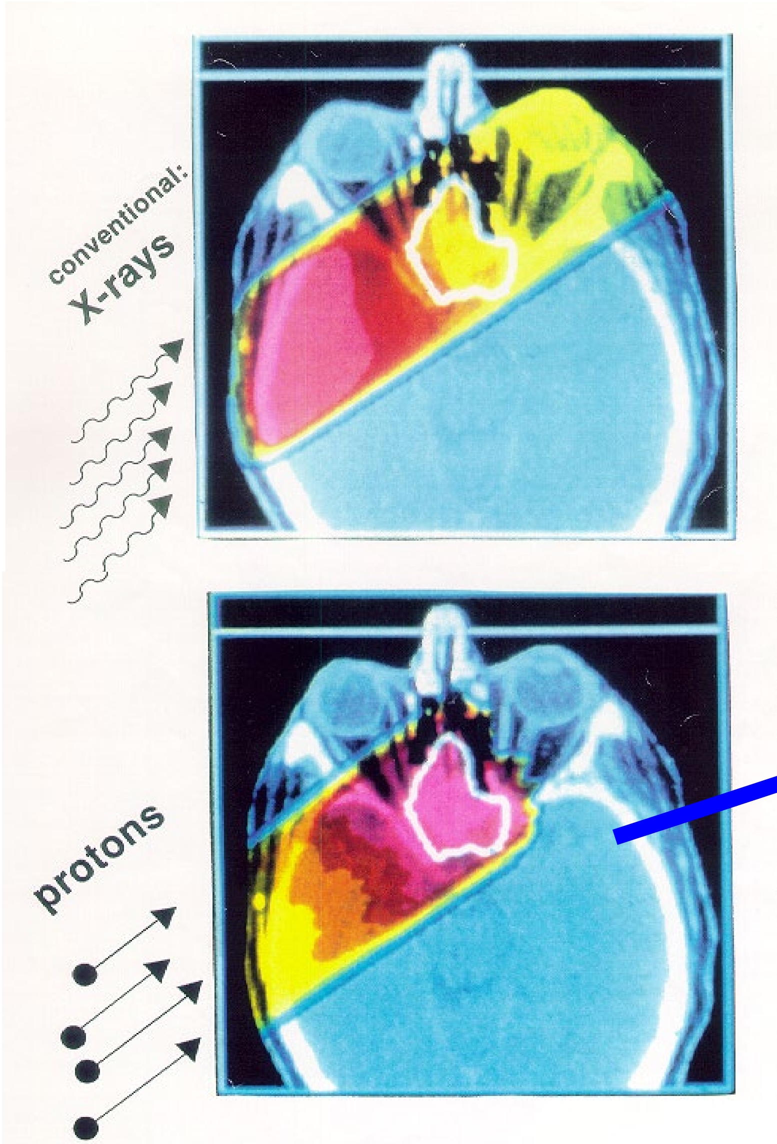
Range scales with 1/density: $1/\rho$

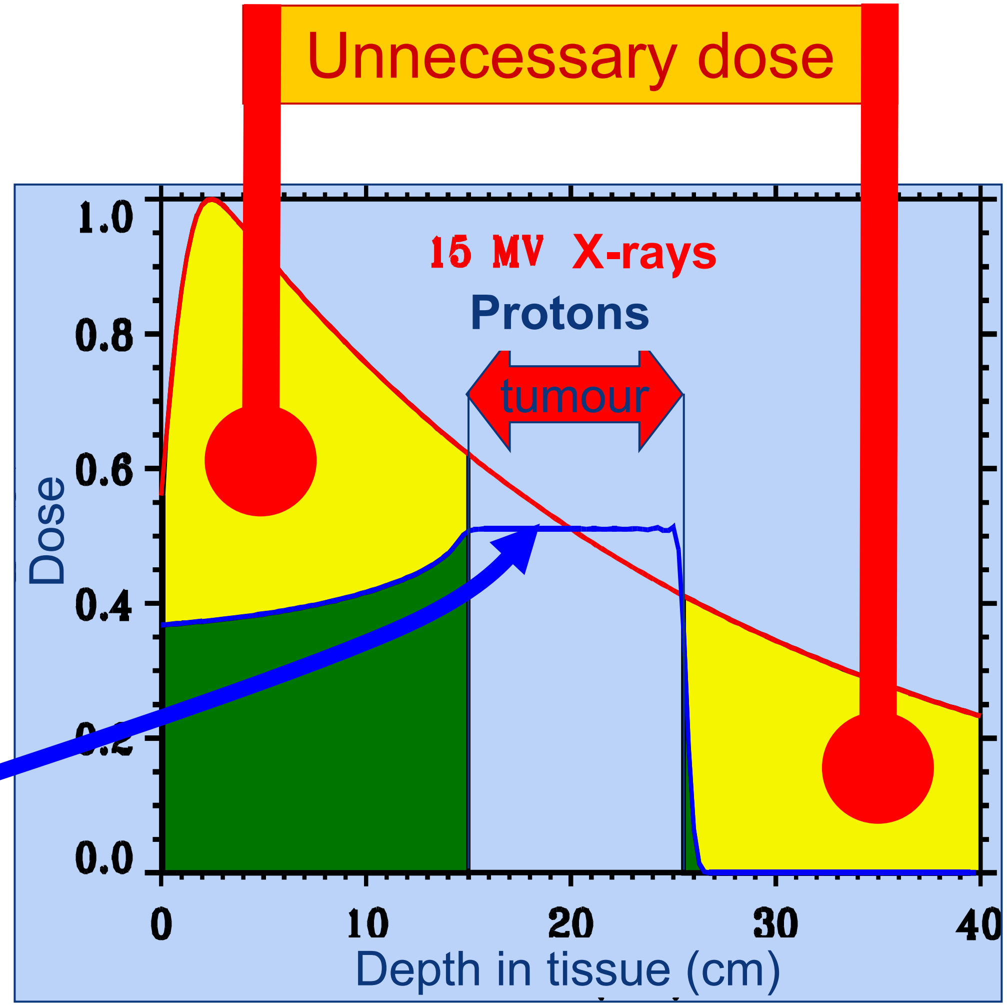
X-rays vs. Protons





X-rays vs. Protons

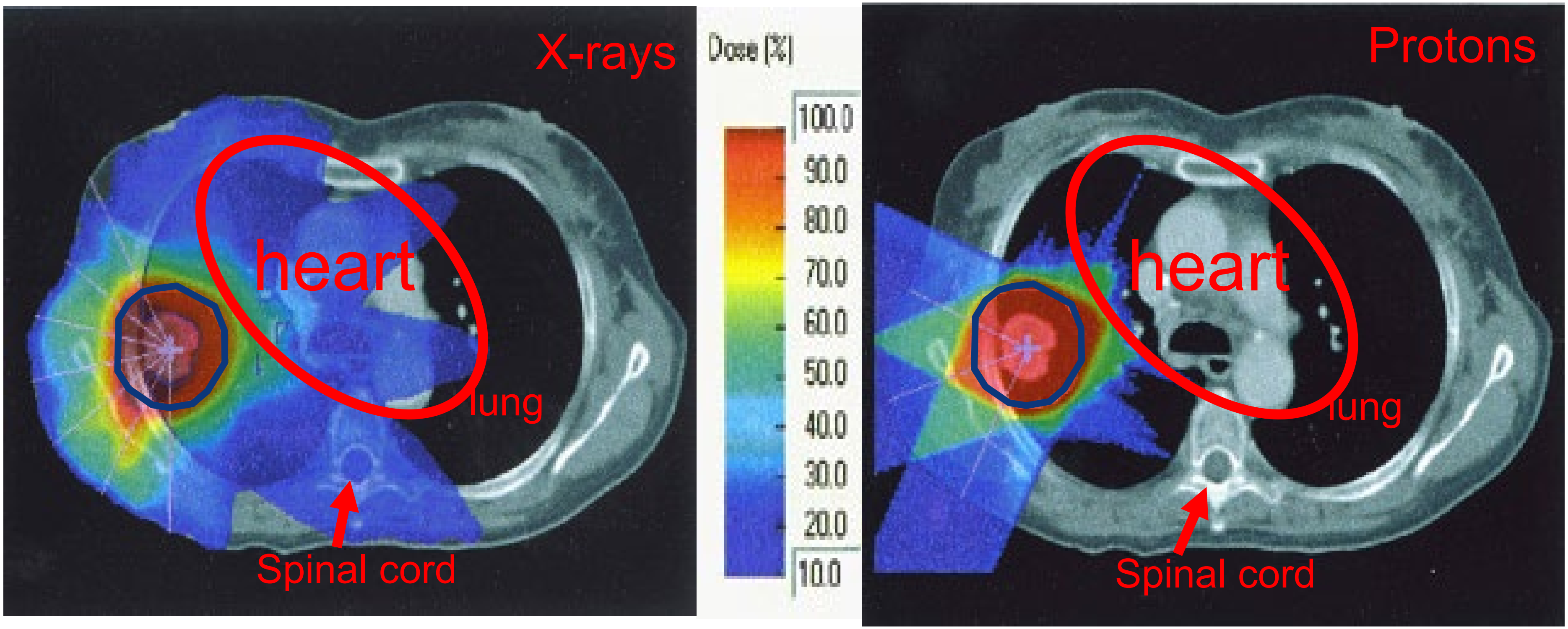




X-rays vs. Protons

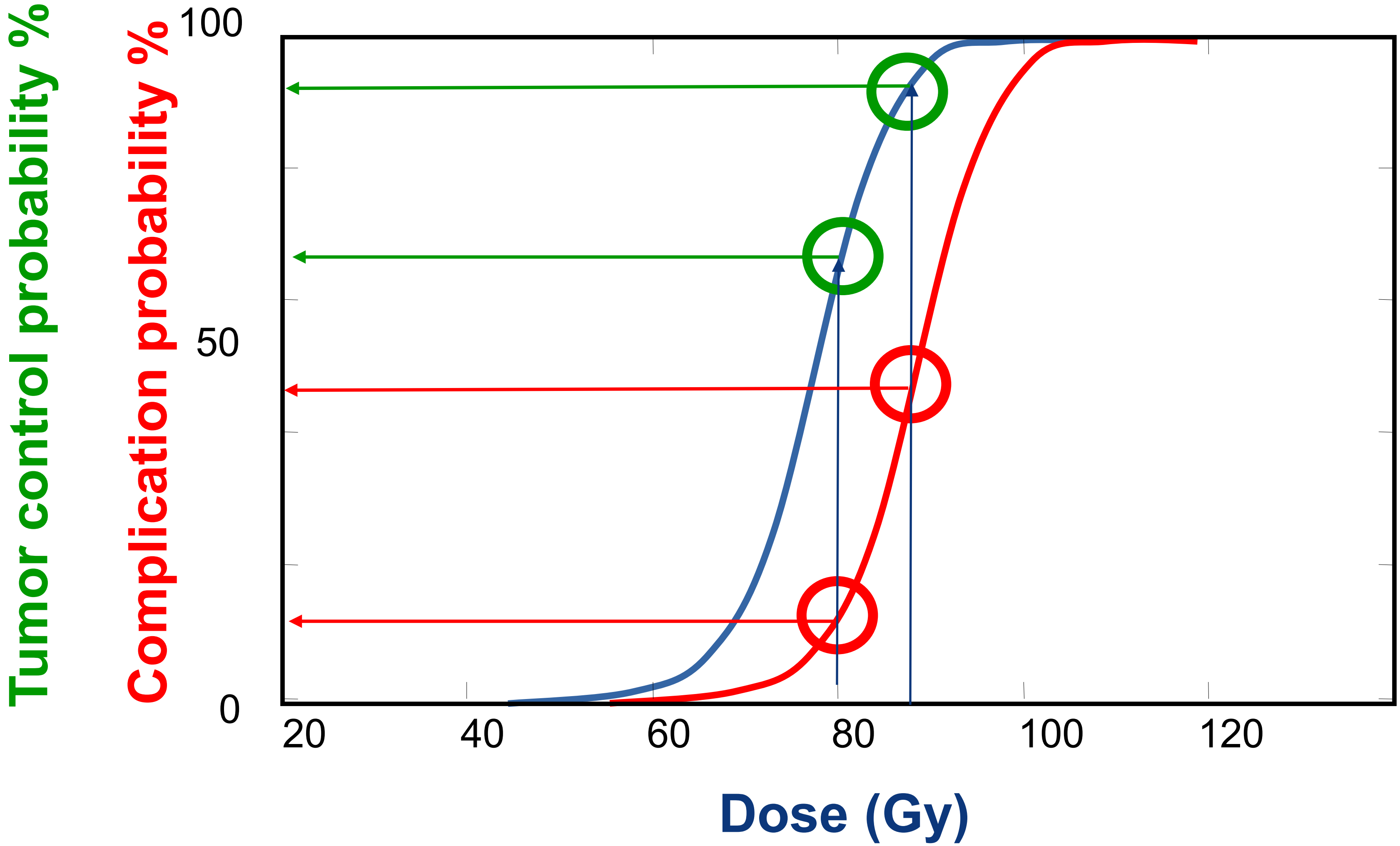
X-ray beams (IMRT)
from 7 directions

Proton beams
from 3 directions

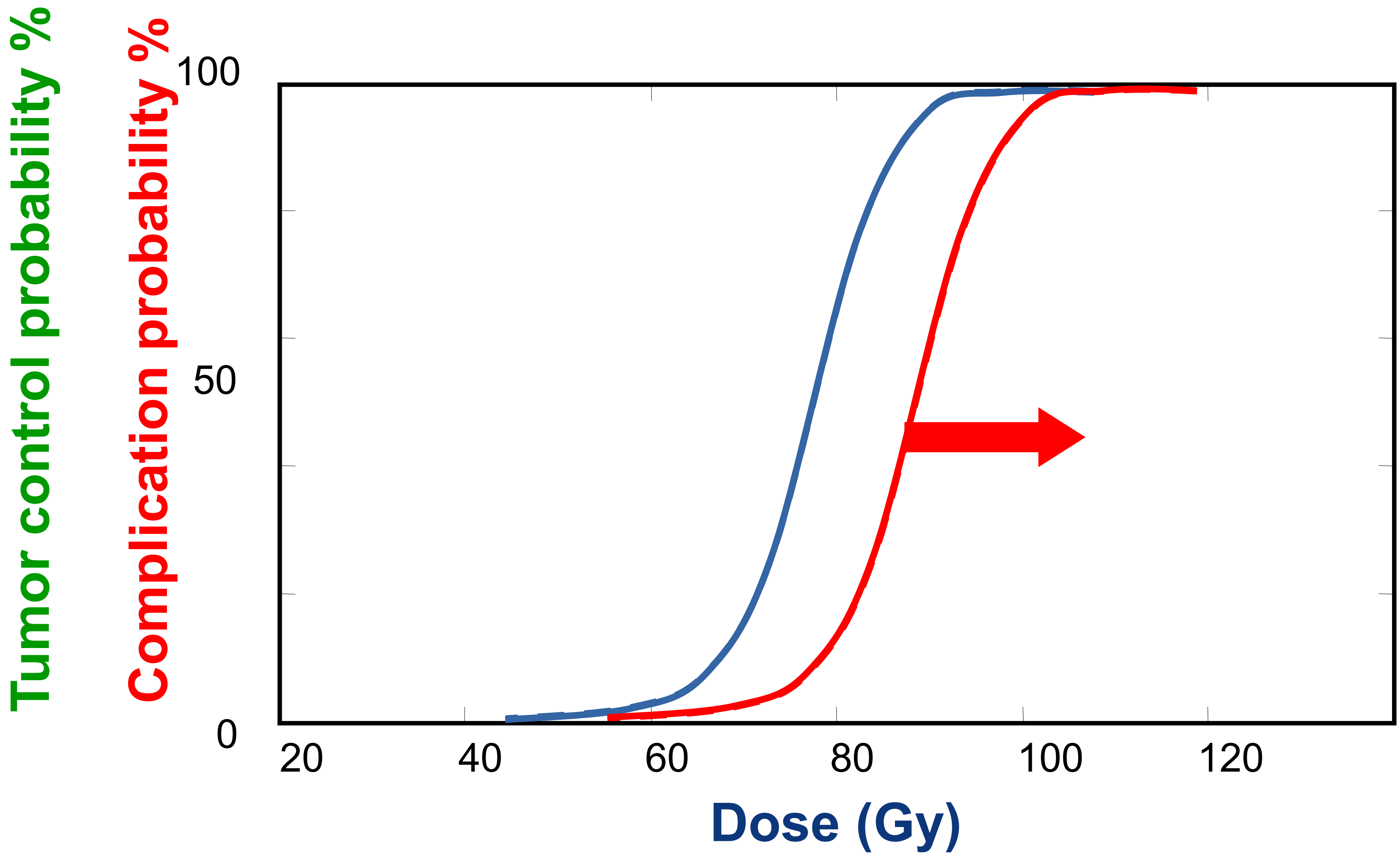


pictures: Medaustron

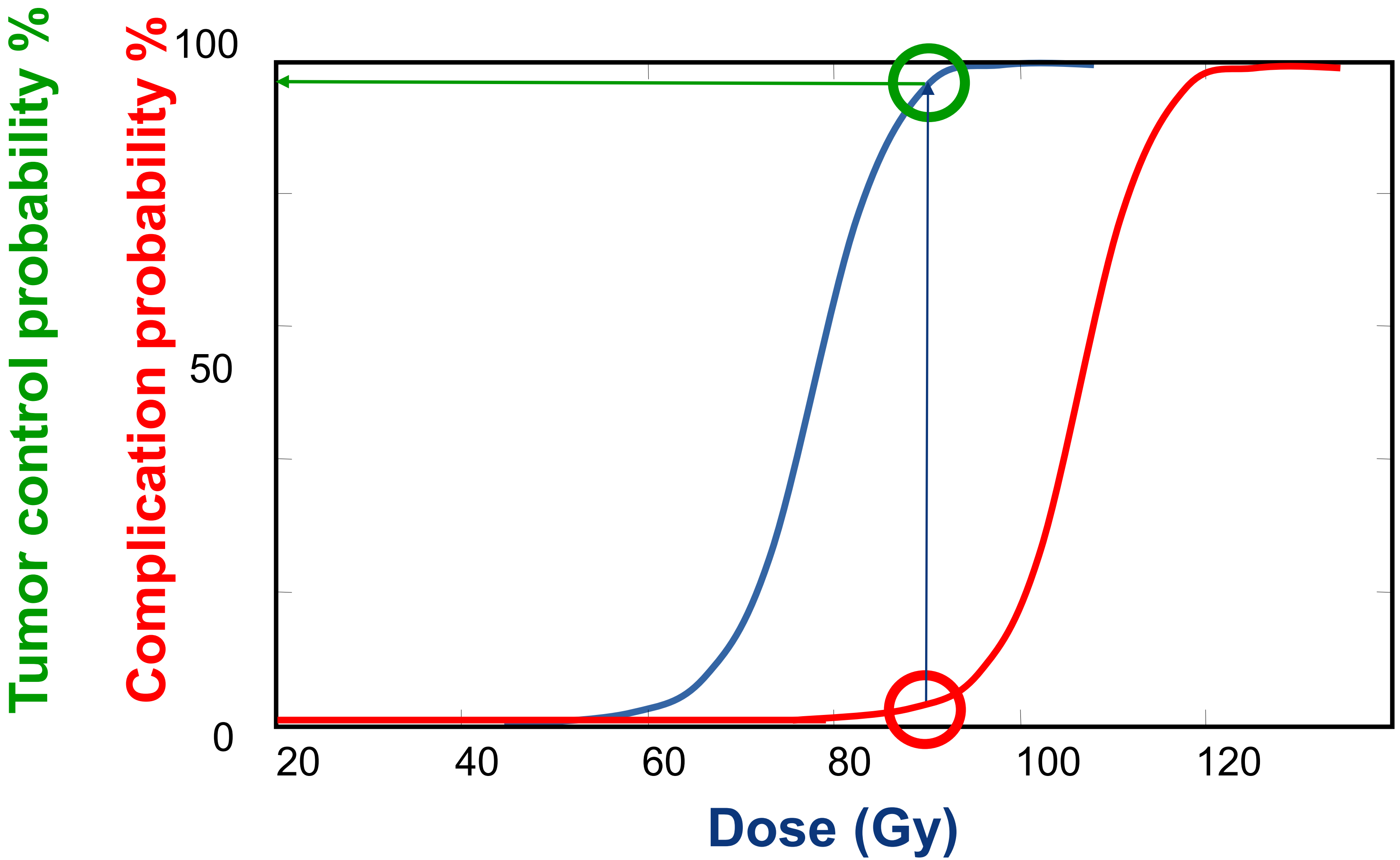
Therapeutic Window



Protons irradiate less normal tissue



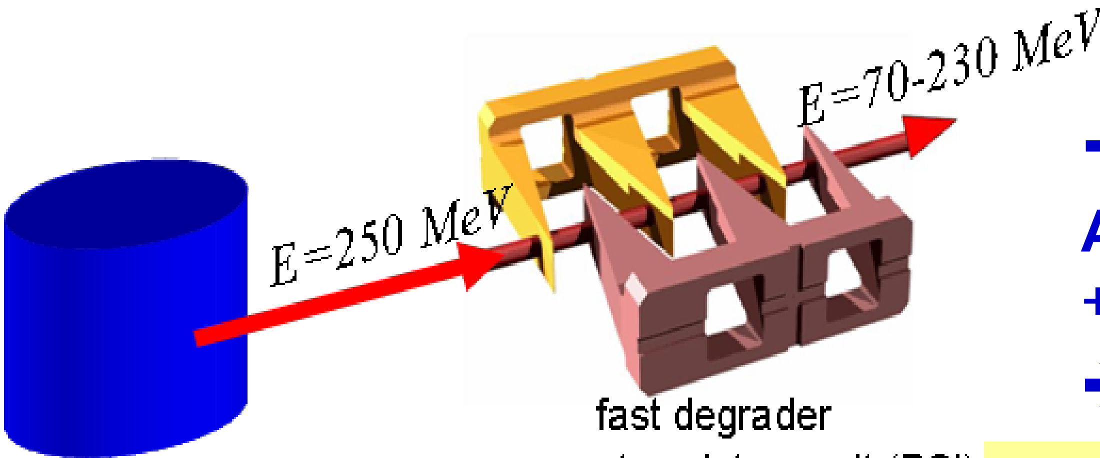
Therapeutic Window



Possible facility and gantry layouts

Cyclotron driven facilities

Cyclotron has fixed energy => slow down (degrade) to desired energy



fast degrader
at cyclotron exit (PSI)

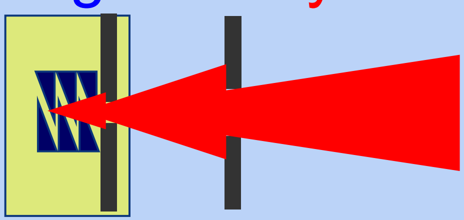
➔ Sets range

And, if fast enough
+ fast magnets:

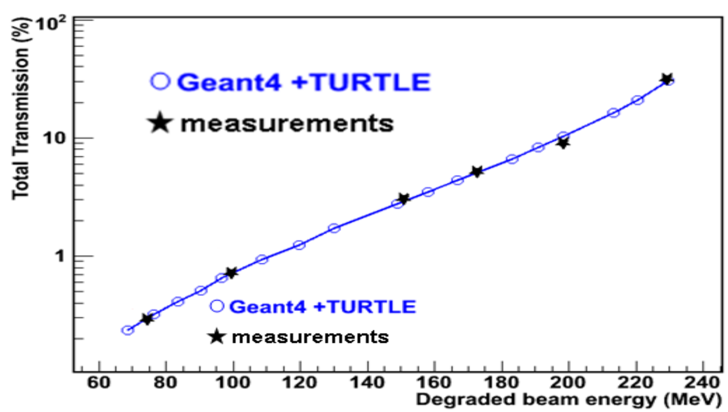
➔ also energy modulation

: 5 mm ΔRange in 50 ms

degrader system



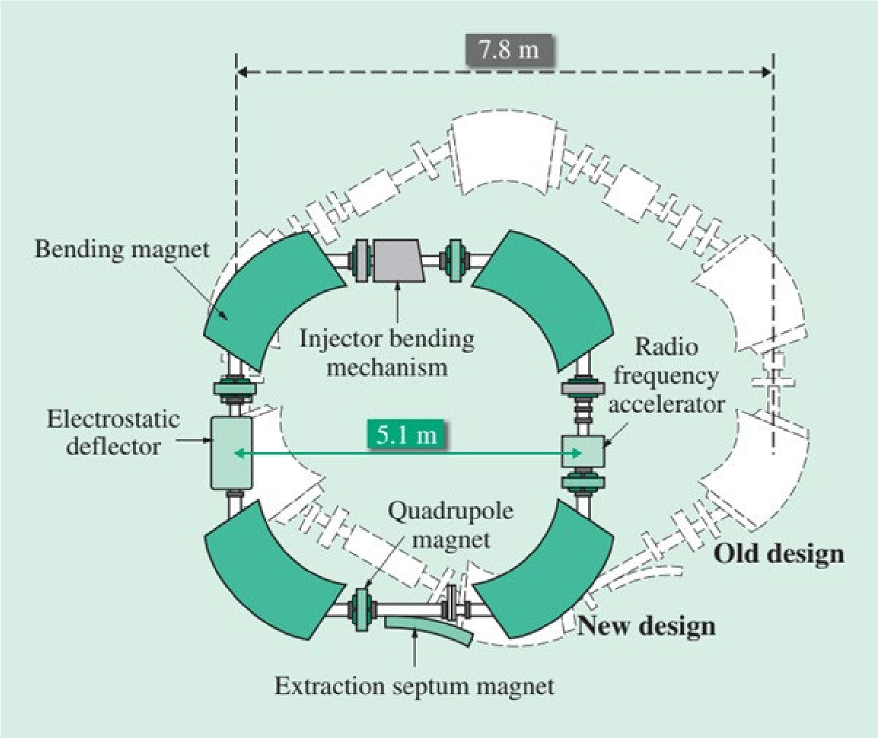
Collimators define
transmitted beam size

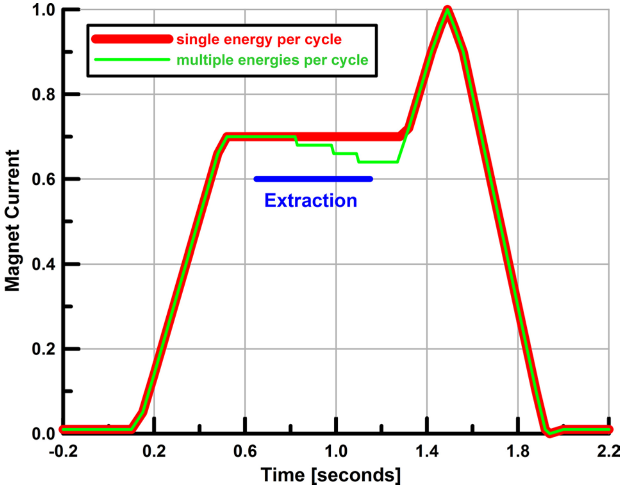


Van Goethem et al., Phys. Med. Biol. 54 (2009)5831

Synchrotrons

- Asymmetric emittance
  - Cause: Extraction in one plane
- Single turn vs multi-turn extraction

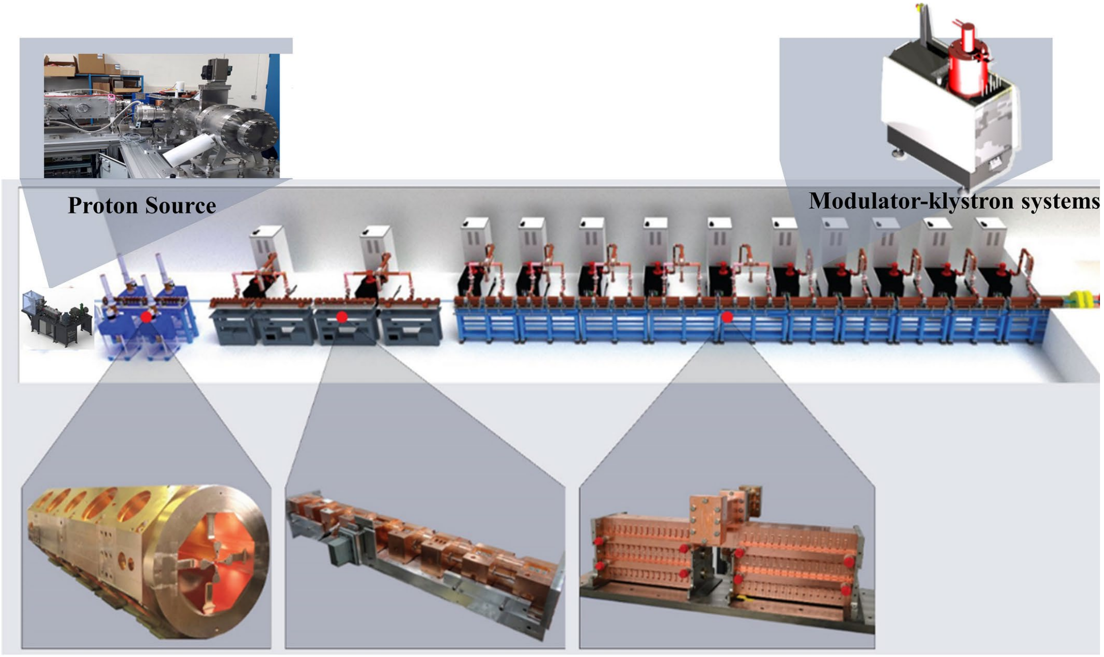




Sources: Hitachi, Loma Linda University Medical Center

Linacs

- Fast energy switching (milliseconds)
- Very low beam emittance (~1 mm mrad)
- Lower average current than cyclotrons



Source: AVO/ADAM SA

Gantry types and topologies

Patient Isocentric

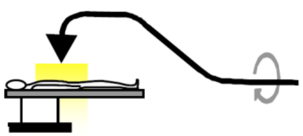
- Patient is positioned centrally (isocentre) and is not moved, providing direct and uncomplicated access at any time
- Beam delivery system rotates around the patient

Patient Eccentric

- Patient is moved on a circular path around the central axis of the gantry
- Separate access systems necessary

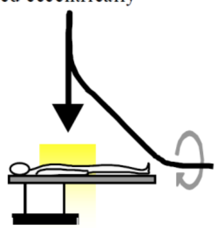
Conventional Gantry

- Very long structure (>12 m)
- Between 180° and 270° bending of which 135° - 180° are mounted eccentrically



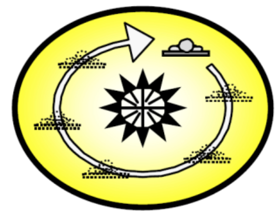
Corkscrew-Ganty

- Comparatively short
- 360° bending, of which the last 270° are mounted eccentrically



"Riesenrad-Gantry"

- Patient eccentric, ion beam central
- Only one 90° bending magnet, which is mounted on the axis

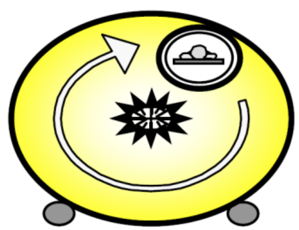


Patient & beam eccentric

- Patient and magnets rotate around the central axis
- Smallest possible diameter of gantry

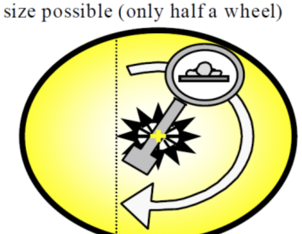
Wheel-Gantry

- Outside bearings
- Extreme stiff and light wheel-structure possible
- Patient enclosure is not structural, allowing for a full 360° rotation

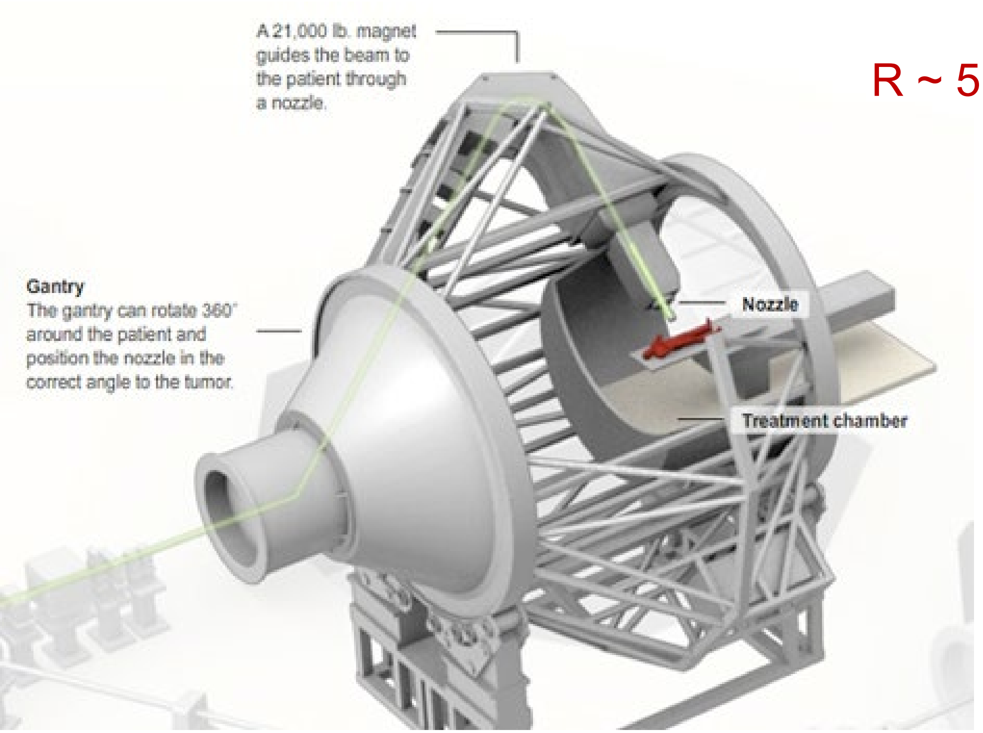


Cabin-Gantry

- Supported on a central axis
- Patient enclosure is structural ("cabin"), allowing only for ~180° rotation
- Compact size possible (only half a wheel)



Conical gantry - Commercial standard layout



R ~ 5m

Beam scanning downstream of the last bend

IBA
Sumitomo
Hitachi
Mitsubishi
Varian

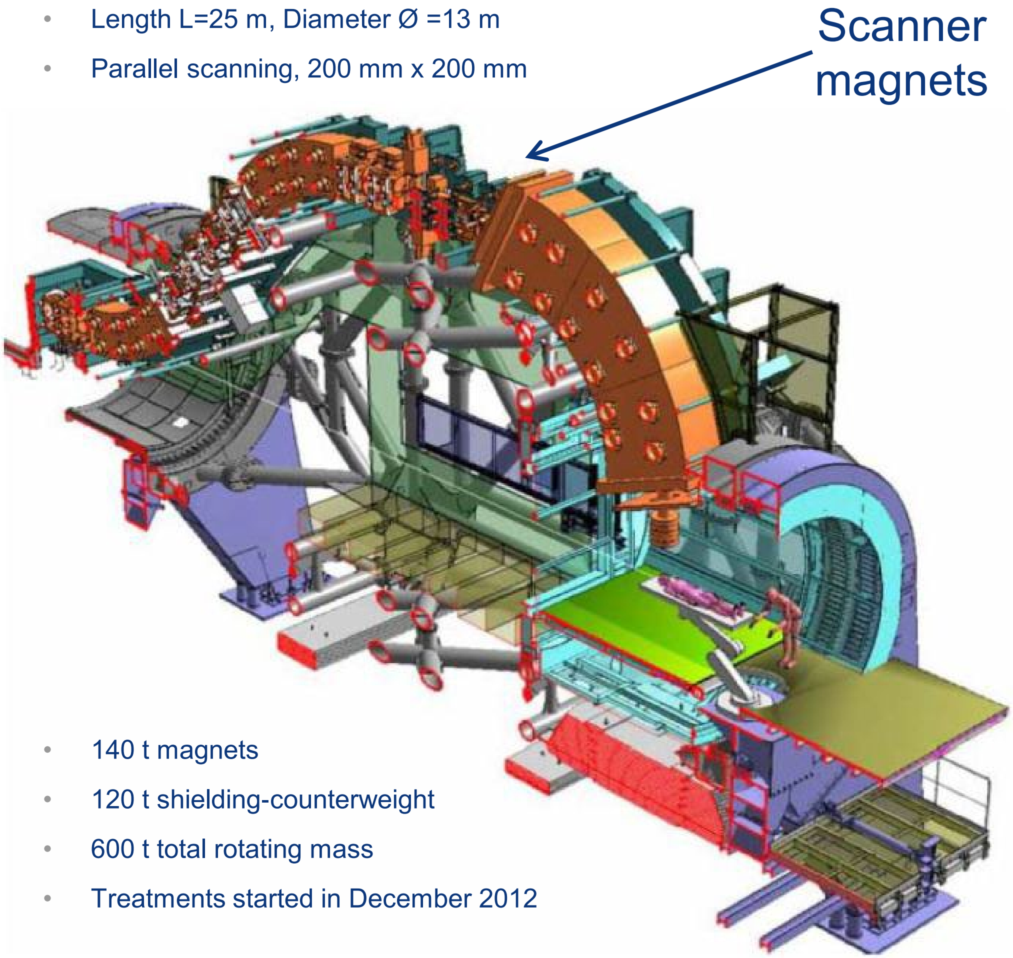
Munich

- 135°bending magnet
  - Shorter length - but larger radius
  - Cylindrical treatment cell
- Initially only for passive scattering
- Lately also for scanning

First commercial scanning-gantry of Varian in Munich

First gantry for heavy ion therapy at HIT

- Heidelberger Ionenstrahl-Therapiezentrum HIT
  - 360° gantry
  - Length L=25 m, Diameter Ø =13 m
  - Parallel scanning, 200 mm x 200 mm



  - 140 t magnets
  - 120 t shielding-counterweight
  - 600 t total rotating mass
  - Treatments started in December 2012

Small cyclotron on a gantry

H. Blosser, NSCL (~1990):
cyclotron for neutron therapy;
30 MeV protons, mounted on a gantry
Used in Harper Hospital, Detroit

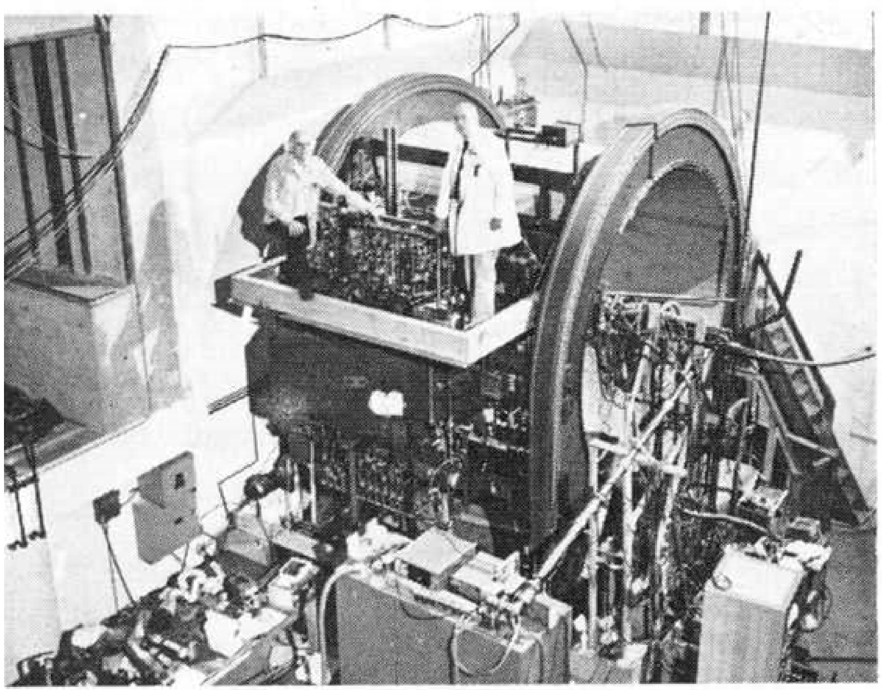
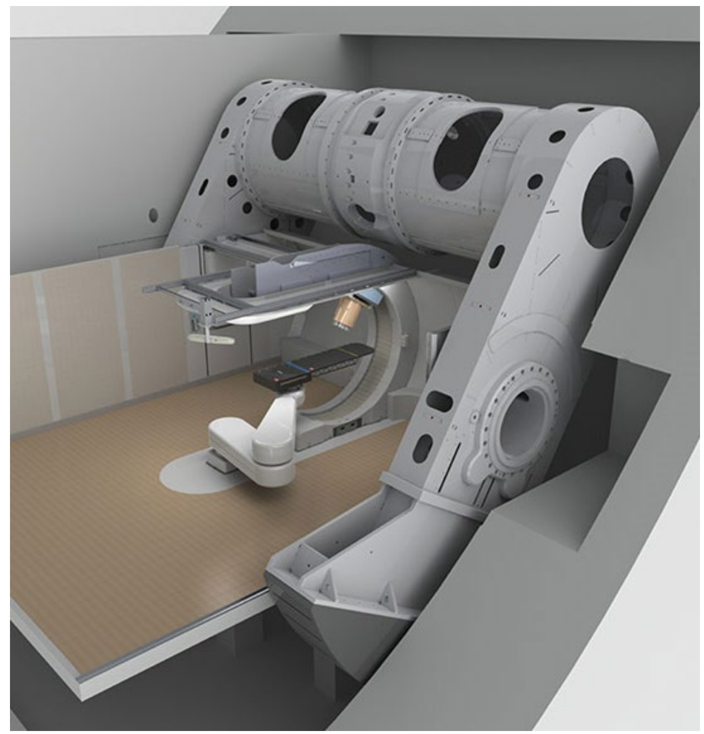


Fig. 2 Photo of the superconducting medical cyclotron on its gantry. Dr. William Powers and

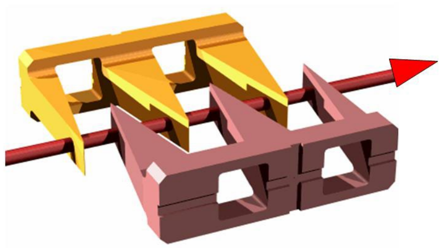
MEVION medical systems

For proton therapy
70-230 MeV
Treating patients since 2013

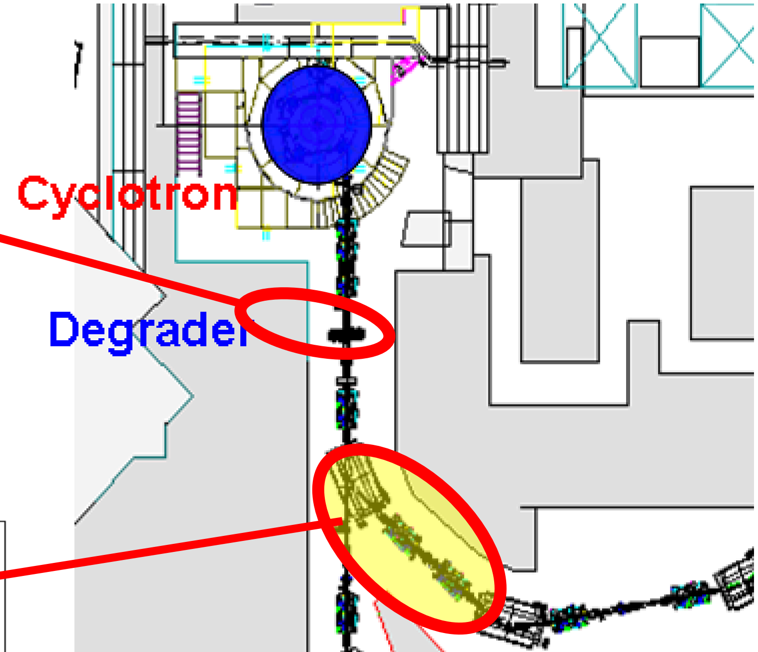


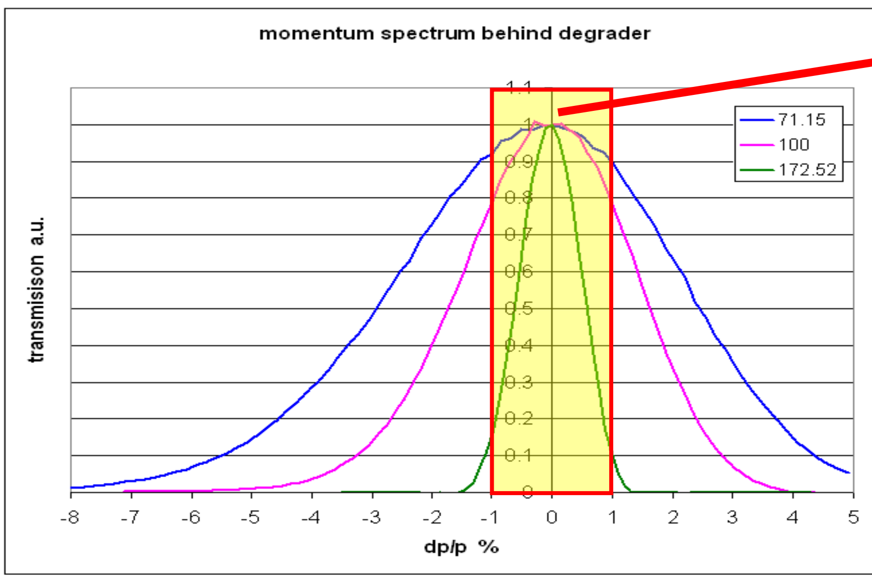
Dose delivery techniques

Energy selection system



multi-wedge degrader
235-67 MeV



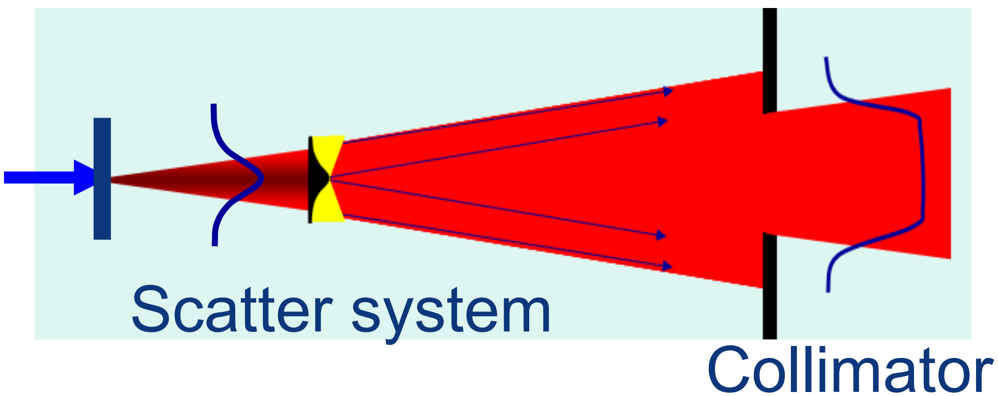


Beam analysis:
energy selection
dp/p < ± 1%

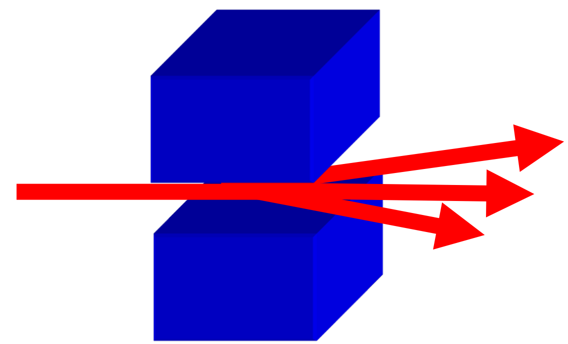
Dose delivery techniques: Width

transversal spread:

scattering



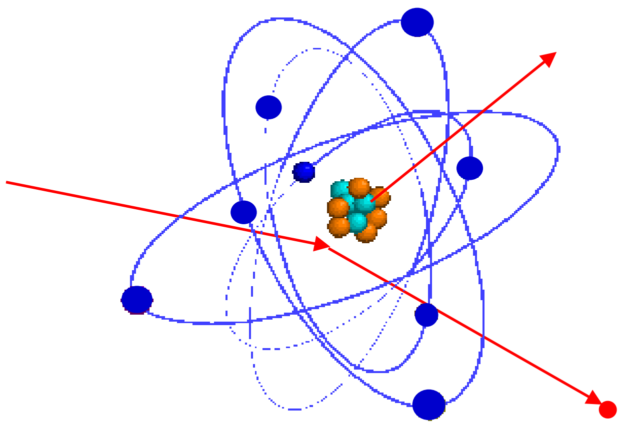
scanning



Fast magnet

Scattering

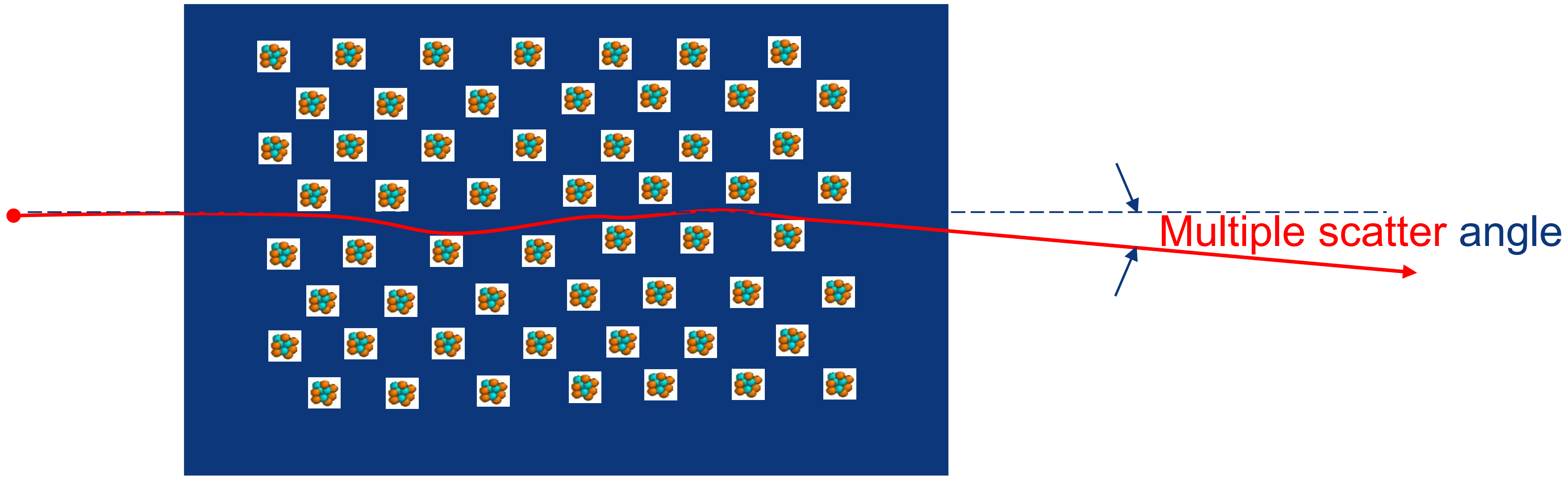
Nuclear Coulomb scattering



Nucleus is several times heavier as a proton

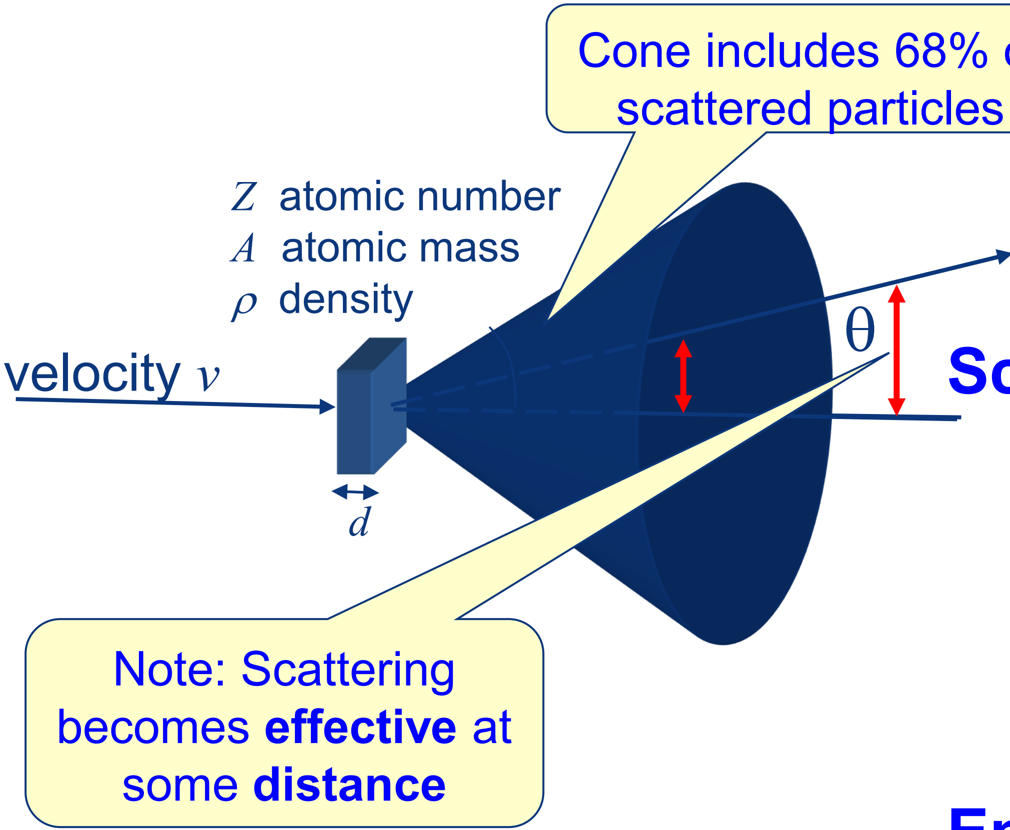
→ Almost no energy loss („elastic“)

→ Much larger deflection than from electrons



Scattering

Multiple Scattering



$$\theta \sim \frac{\sqrt{d}}{v^2} \frac{Z}{\sqrt{A}}$$

Scattering: from **nuclei.**

$$\Delta E \sim d \frac{\rho}{v^2} \frac{Z}{A}$$

Energy loss: slow down by **electrons.**

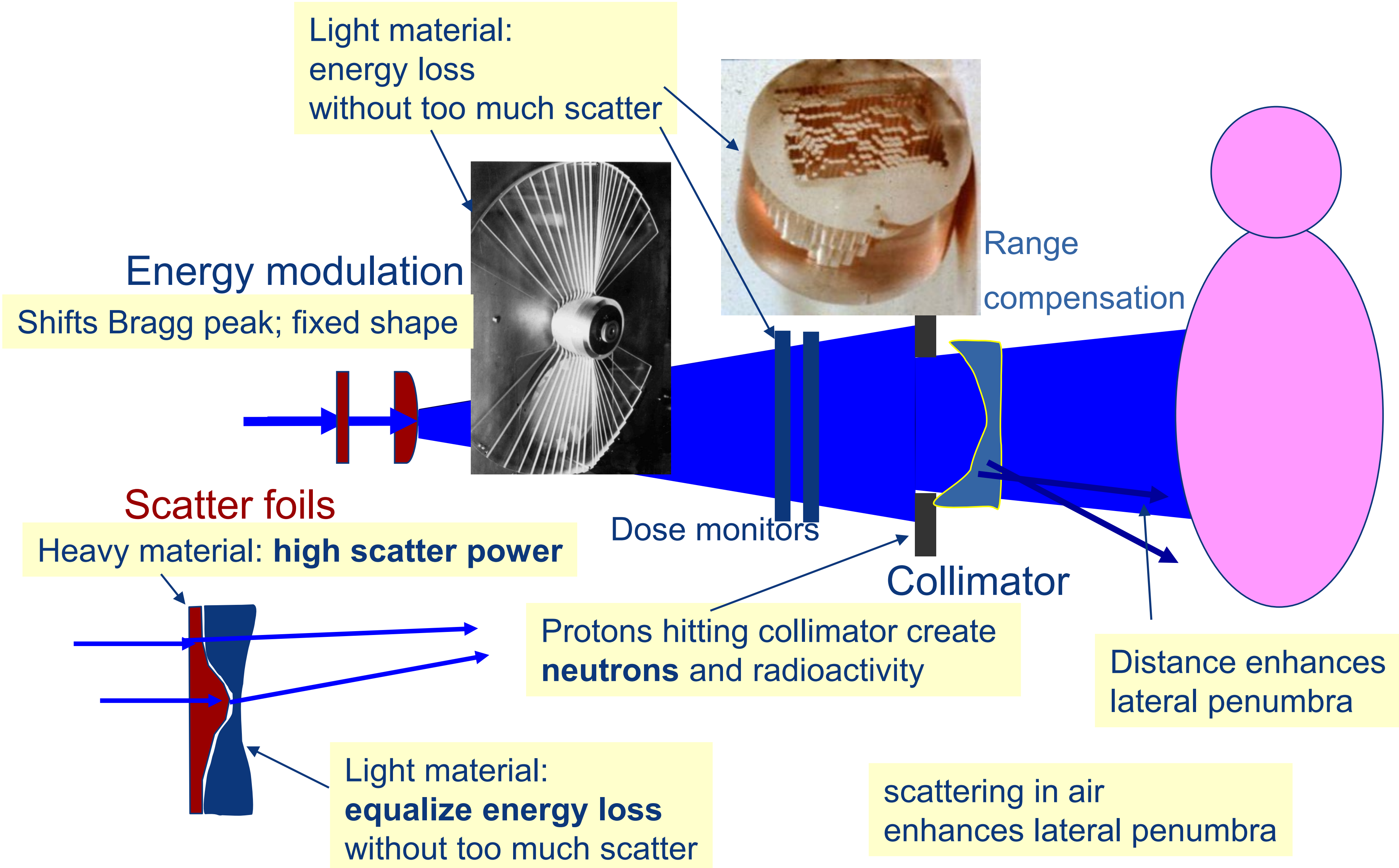
Scattering

	Energy loss	Scattering
(Z ; A)	$\frac{dE}{dx} \sim \frac{Z}{A}$	$\theta \sim \frac{Z}{\sqrt{A}}$
Water (8 ; 16)	0.5	2
Tungsten (74 ;184):	0.4	5.4

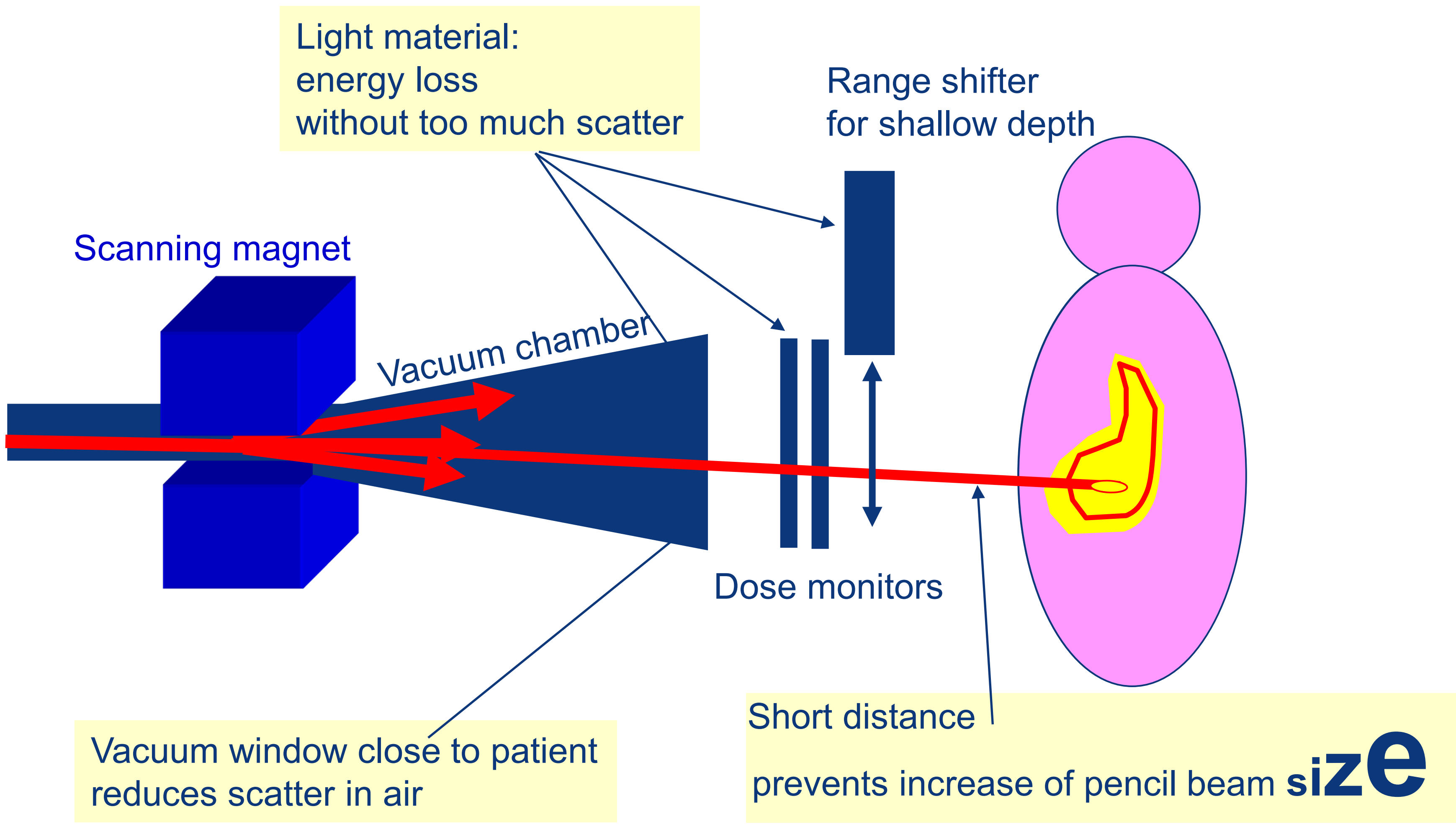
=> More scatter at heavy materials

250 MeV p:		1 cm H_2O	1 mm W
Energy loss:	$\Delta E =$	**4 MeV**	**4 MeV**
Scattering angle:	$\theta =$	**5 mrad**	**16 mrad**

Nozzle for a scattered beam



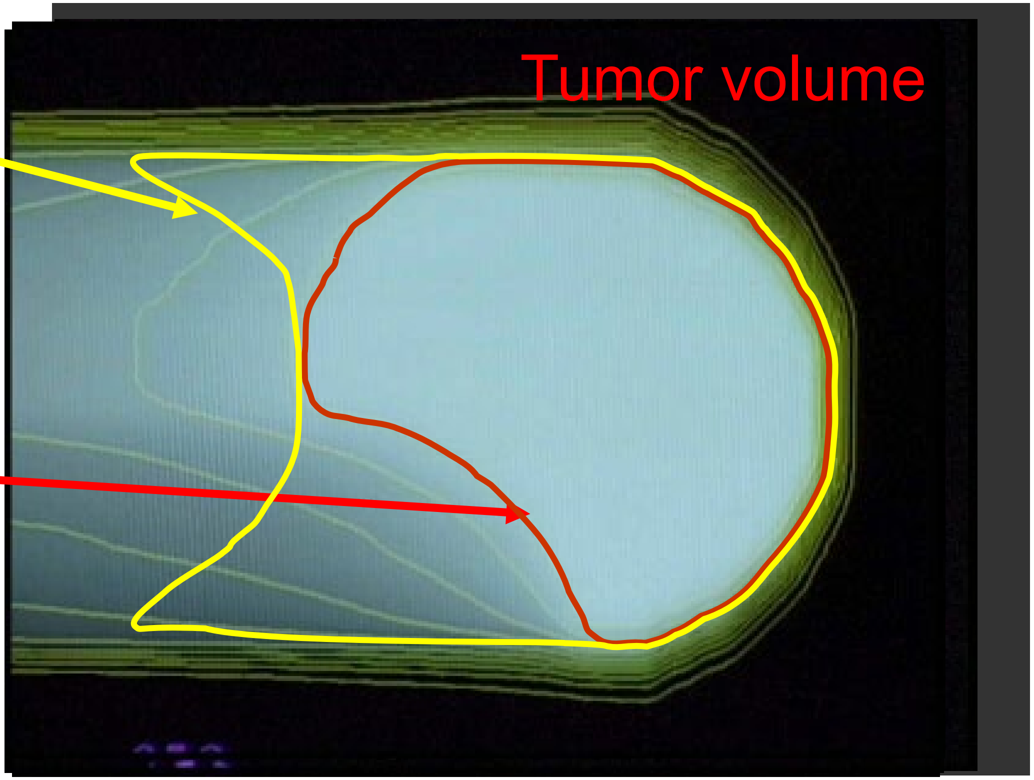
Nozzle for a scanning beam



Scanning: best dose distribution

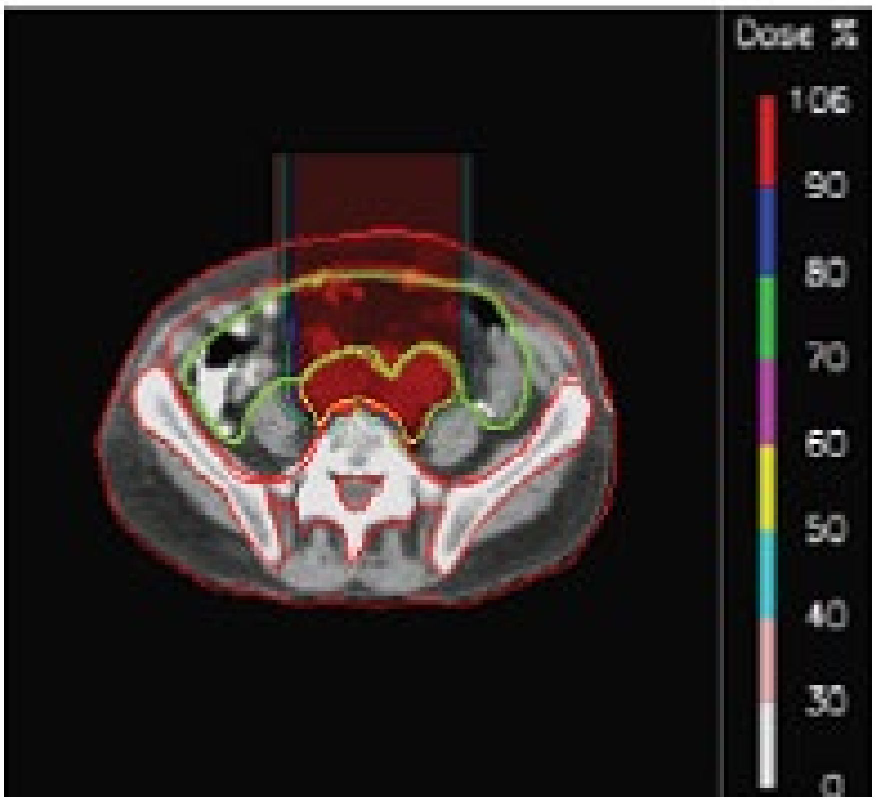
Dose distribution of scattered beam:

Pencil-beam scanning: behind <u>& in front of</u> tumor optimal

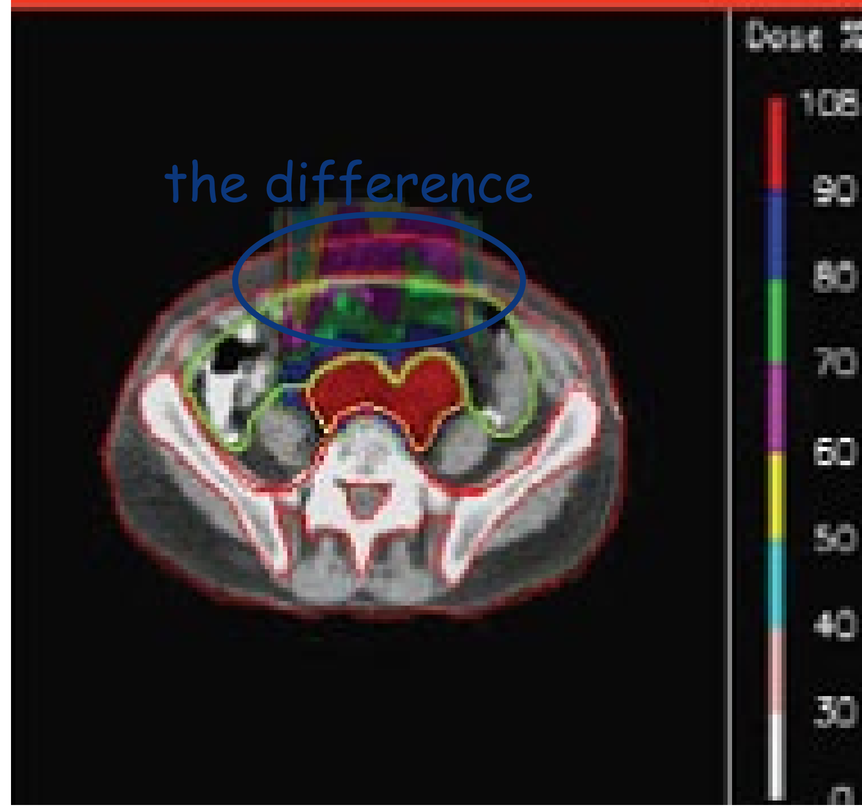


Scatter – IMPT

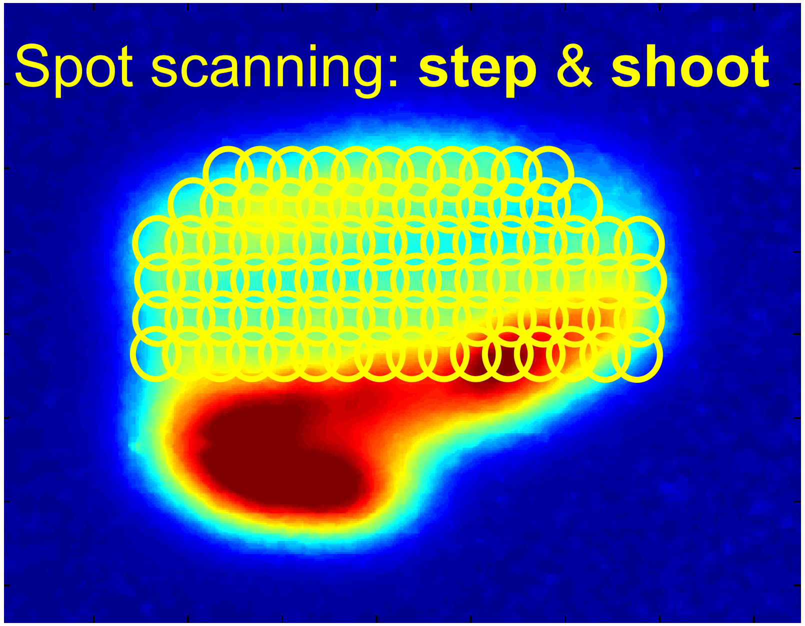
Scattered beam



Scanned beam with IMPT



Spot scanning

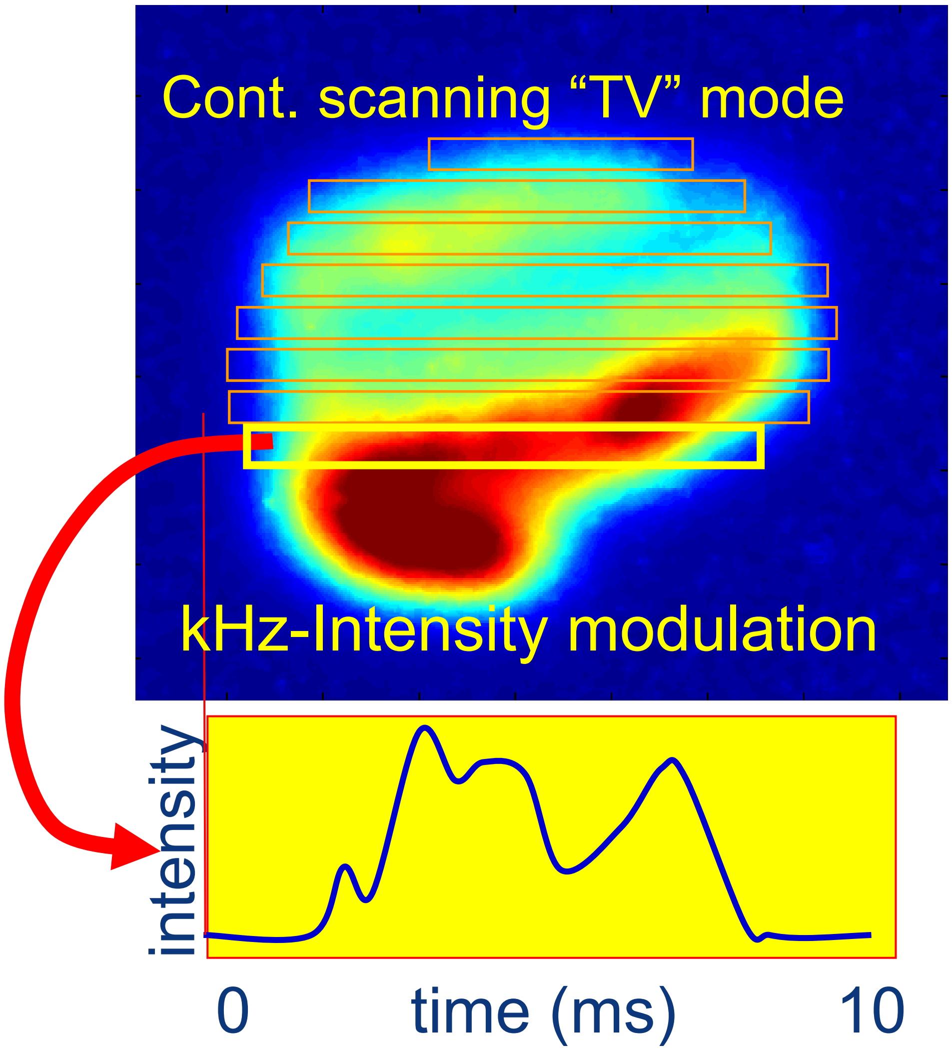


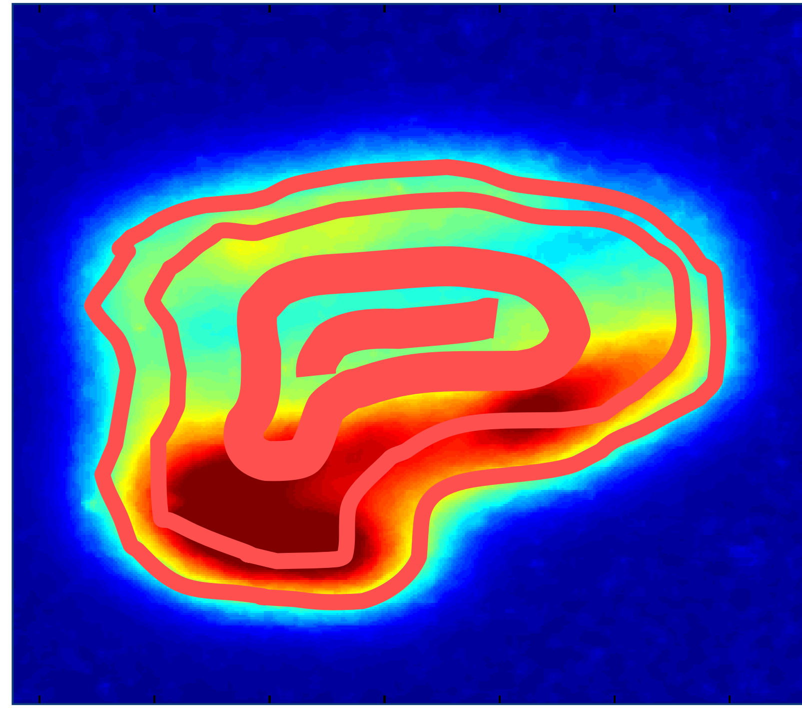
Beam size 7 mm FWHM
5 mm steps

10‘000 spots/liter (21 x 21 x 21)
Dose painted only once

~1 Gy / liter / minute

Fast pencil beam scanning in 3D



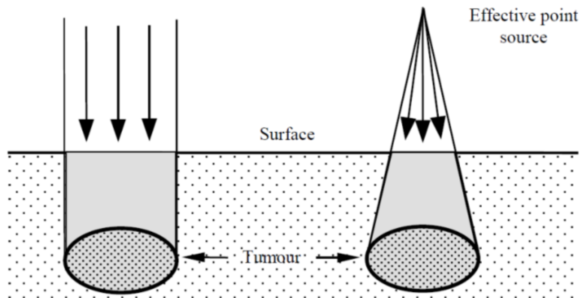


7 s for a 1 liter volume.
Target repainting:
15-30 scans / 2 min.

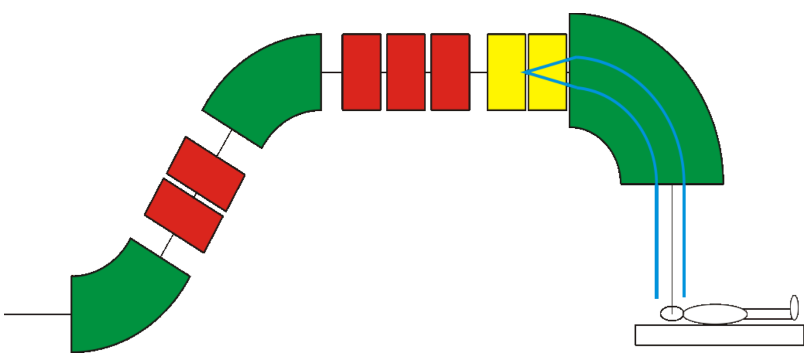
Upstream versus downstream scanning

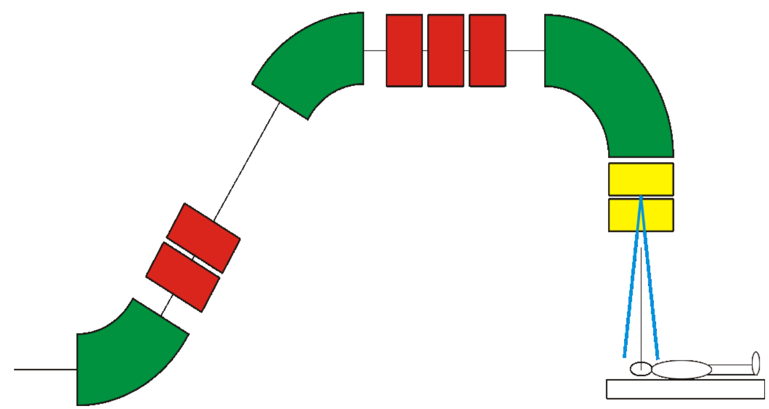
- Upstream scanning
- Parallel beam
- Infinite source-to-axis distance (SAD)
- Reduced skin dose
- Large aperture last bend
  - Heavier
  - Higher costs (magnet, mechanical support)
- Easy to implement movable nozzle to reduce air gap (monitors, passive elements)

- Downstream scanning
- Divergent beam
- Finite source-to-axis distance (SAD)
- Larger skin dose
- Large fields possible with large SAD (increase diameter)
- Larger diameter → larger room (costs)



Also possible: Combination of
1 sweeper upstream
1 sweeper downstream

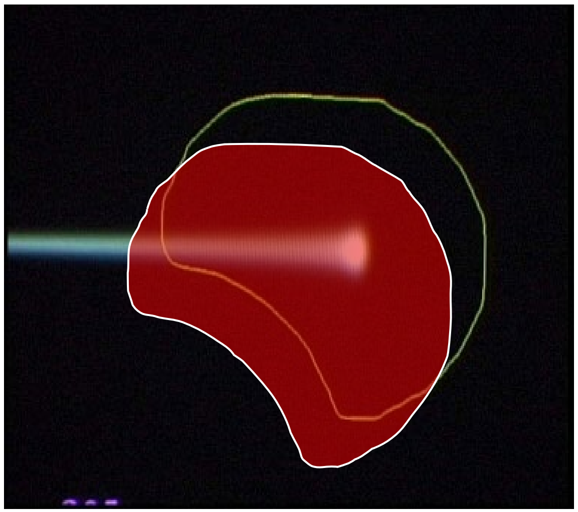




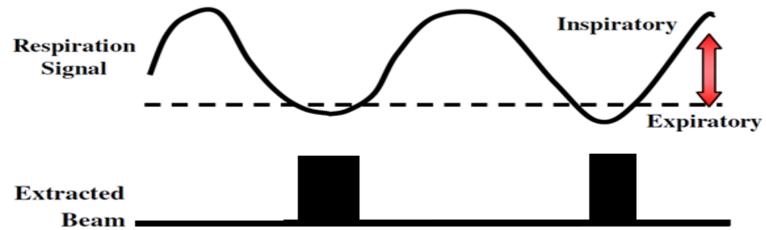
Organ / tumor motion

Possible solutions:

Organ motion

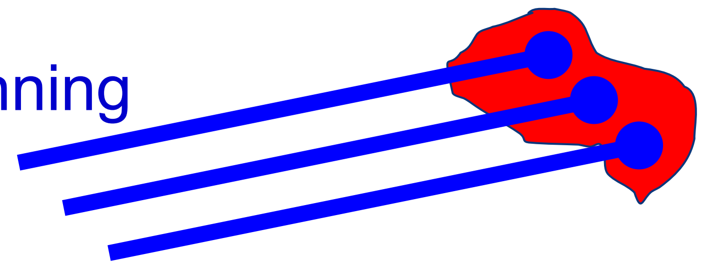


- Gating

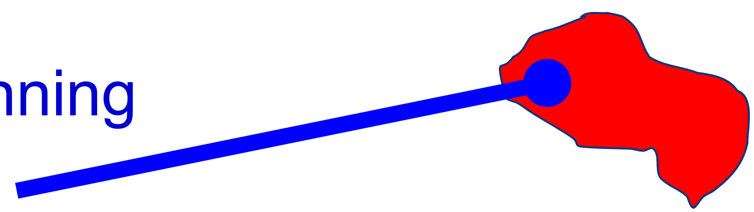


- Adaptive scanning

  (tumor tracking)

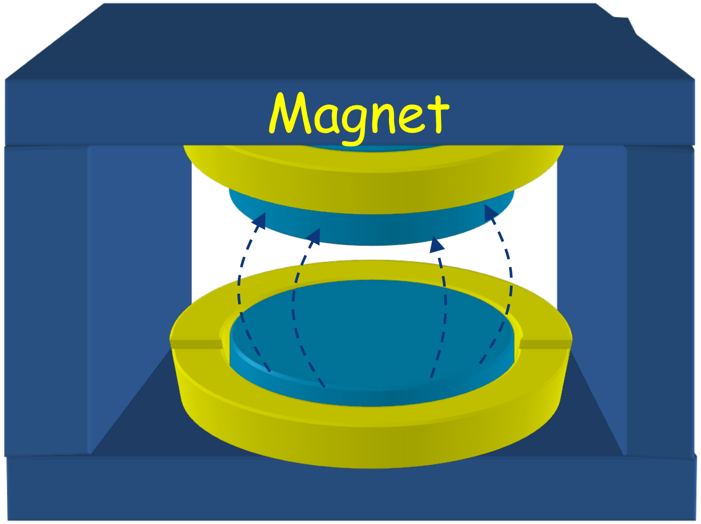


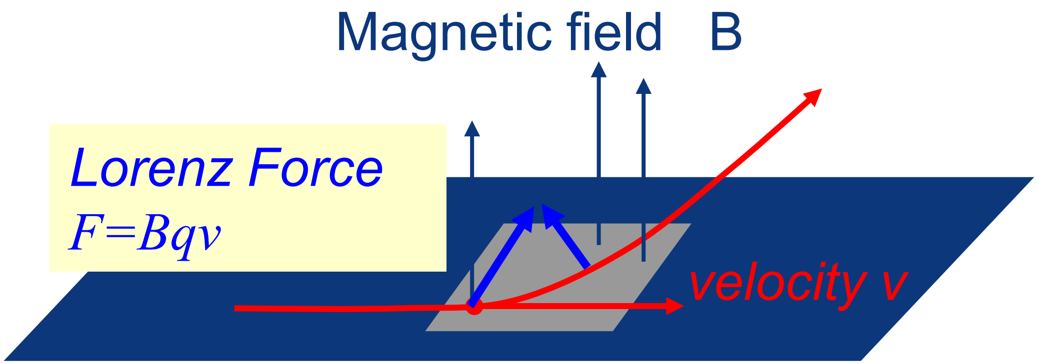
- Fast rescanning

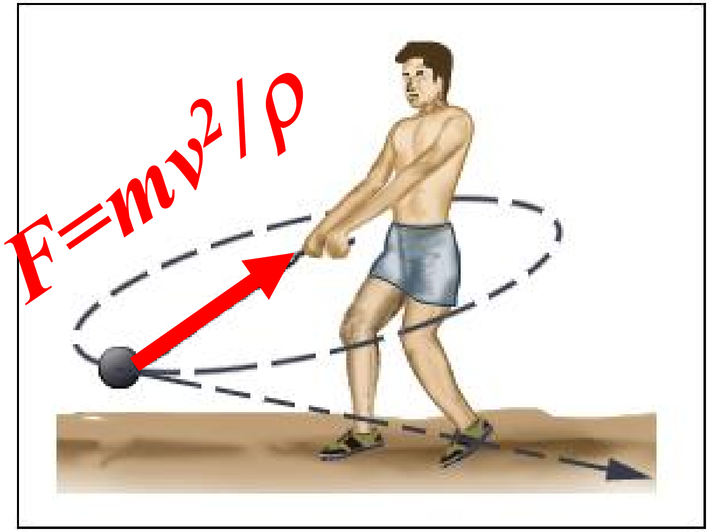


Beam optics properties

Magnetic fields







Lorenz force = "centripetal force" mv^2/ρ

$\Rightarrow$ track = circular orbit with radius ρ

energy E and charge q

determine magnetic rigidity $B\rho$:

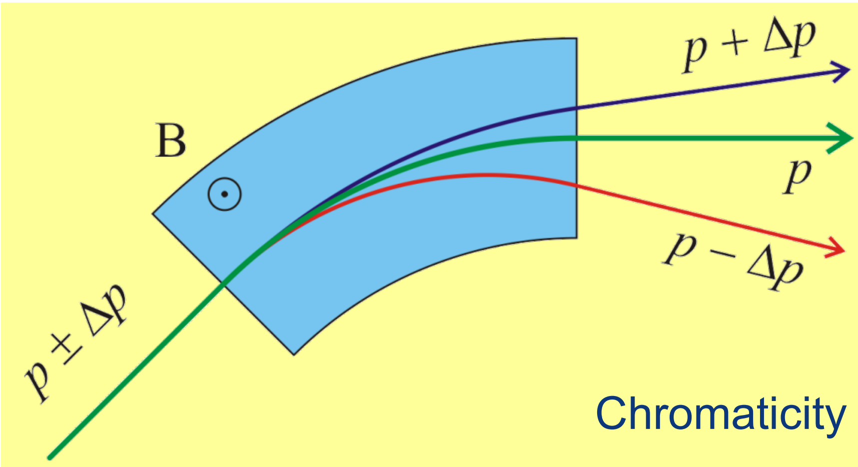
magnet strength B to bend with radius ρ

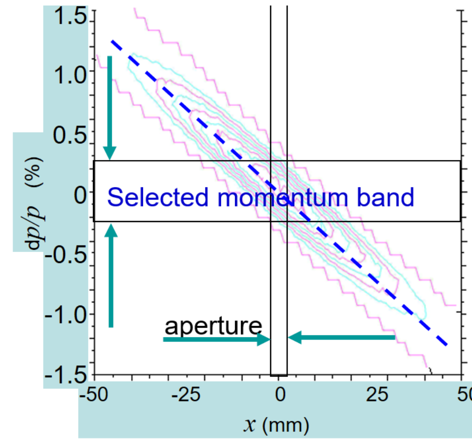
$B\rho$ [in Tm] = p/e = 3.3356 p [in GeV]

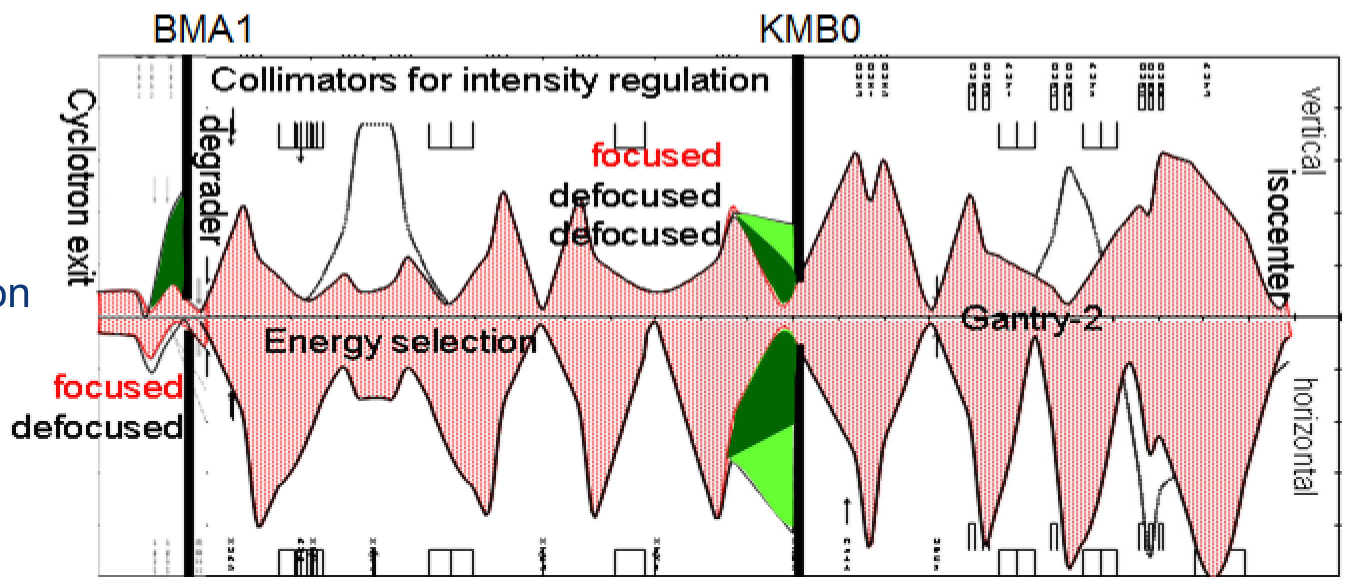
250 MeV p: $B\rho$ = 2.4 Tm

450 MeV/nucl C^{6+}: $B\rho$ = 6.8 Tm

Chromaticity and dispersion suppression







- Horizontal axis: z-position
- Vertical axis
  - above zero: $2\sigma_y$
  - below zero: $2\sigma_x$

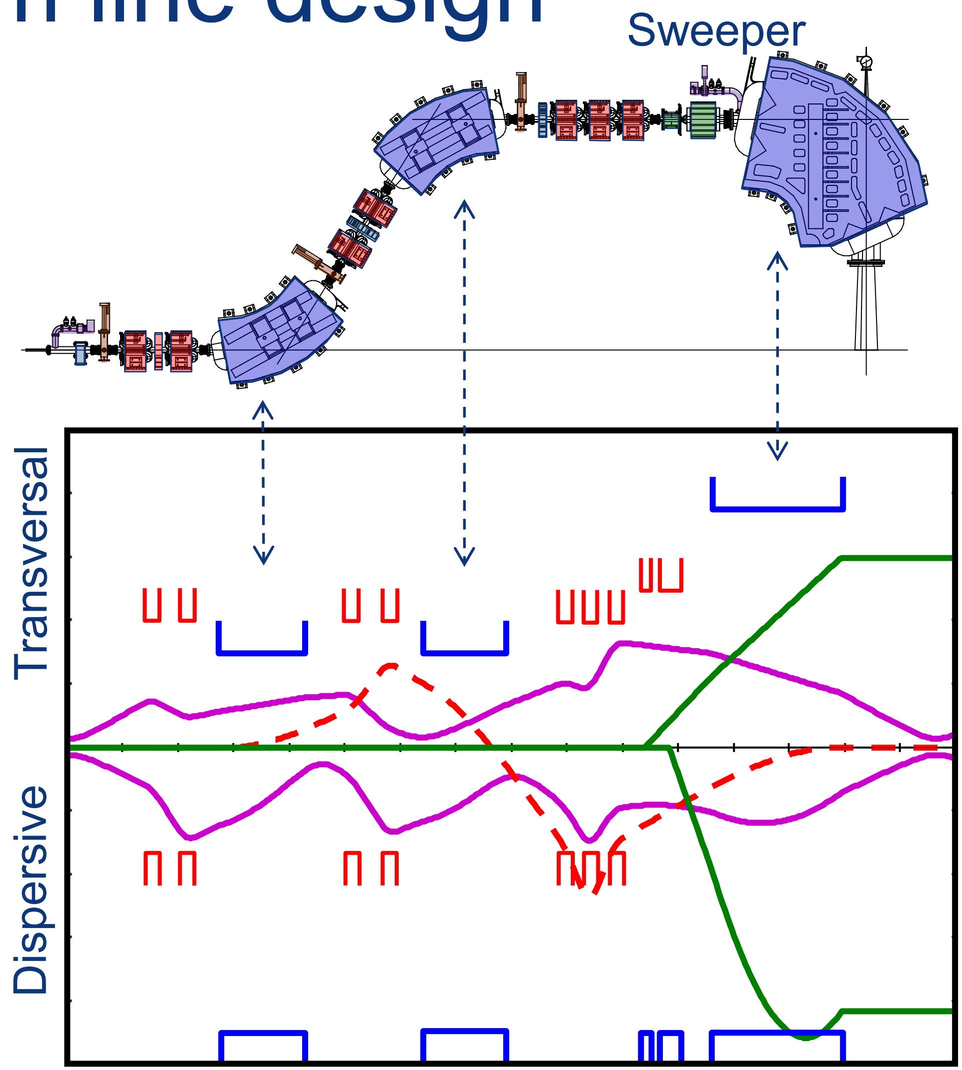
Optimal gantry beam line design

Coupling point

- Rotational symmetrical phase space
- Fixed collimator

Beam optics

- Imaging from coupling point to iso-center ($R_{12} = R_{34} = 0$)
- Achromatic beam optics ($R_{16} = R_{36} = 0$)
- Point-to-parallel setting from scanning magnets to iso-center ($R_{22} = R_{44} = 0$)

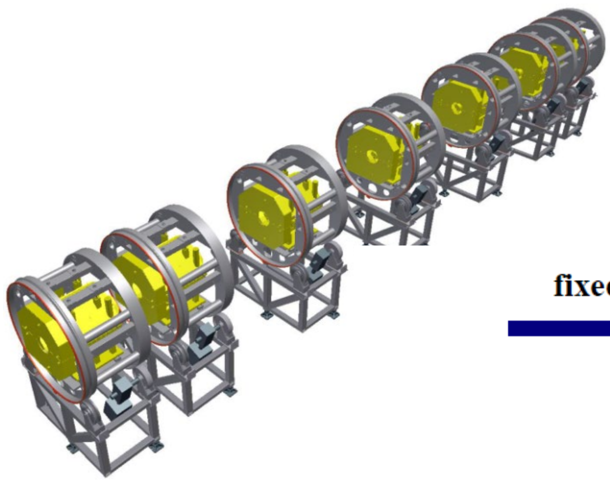


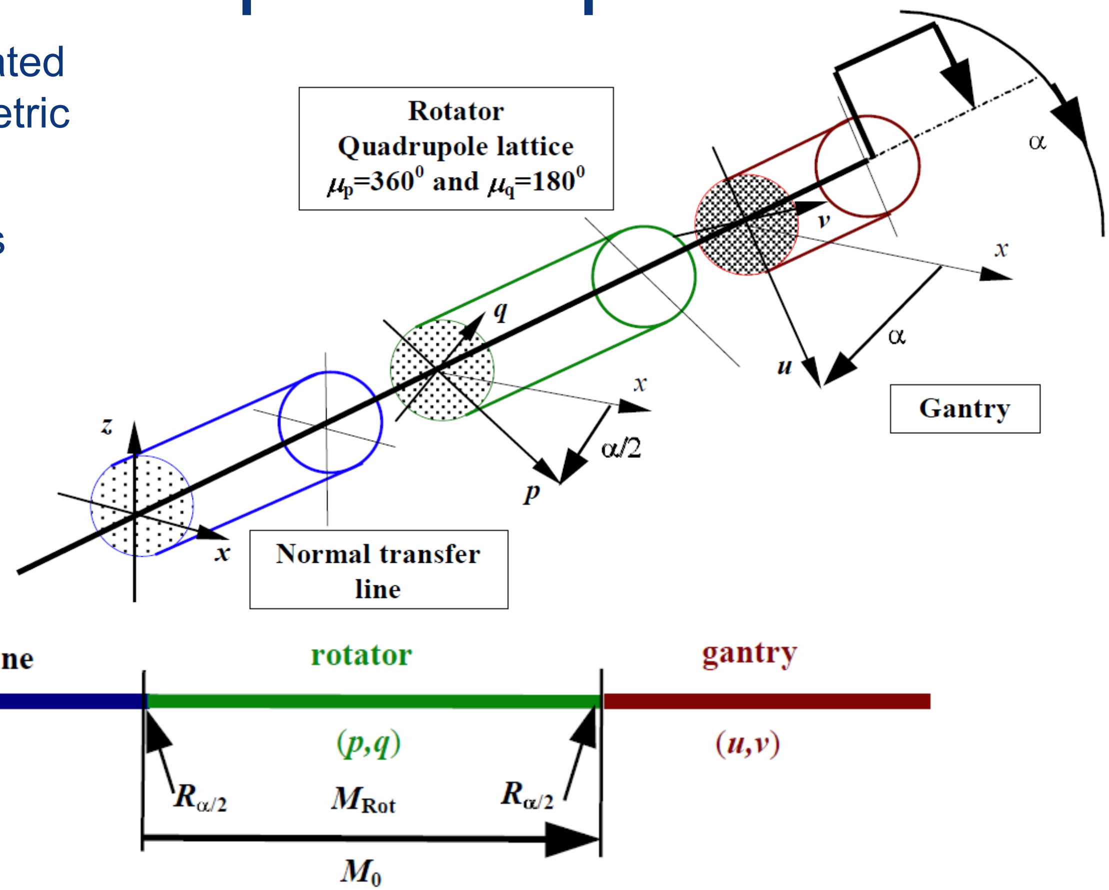
Purple: Beam envelopes trough Gantry 2
Green: Action of the sweepers
Red: Dispersion trajectory for a 1% momentum band

Matching asymmetric phase-space

A rotator is needed to match optics to rotated Gantry if beam phase space is not symmetric (Synchrotron)

Example of a/2 rotator with 7 quadrupoles



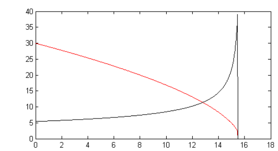


$$M_0 = \begin{pmatrix} \cos\frac{\alpha}{2} & 0 & \sin\frac{\alpha}{2} & 0 \\ 0 & \cos\frac{\alpha}{2} & 0 & \sin\frac{\alpha}{2} \\ -\sin\frac{\alpha}{2} & 0 & \cos\frac{\alpha}{2} & 0 \\ 0 & -\sin\frac{\alpha}{2} & 0 & \cos\frac{\alpha}{2} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 &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

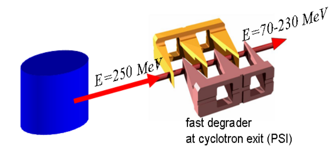
M. Benedikt, CERN

Summary

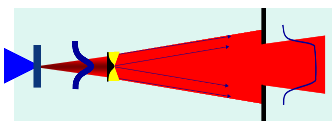
- Proton therapy makes use of the Bragg peak

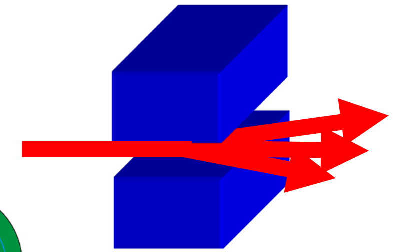


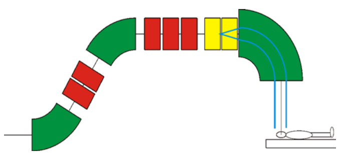
- In most facilities the beam is accelerated in a cyclotron and the energy is reduced by a degrader

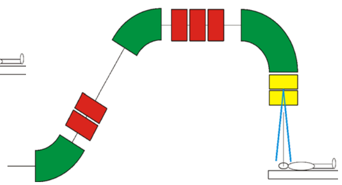


- The target can be
  - irradiated by a scattered beam or
  - scanned by a pensil beam with sweeper magnets
    - Upstream or
    - Downstream of the final bend

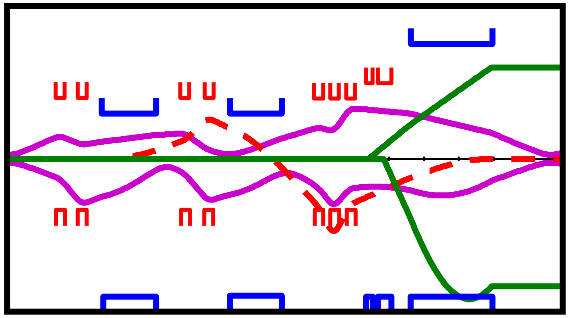








- Neccessary properties of the gantry beam optics:
  - Rotational symmetrical phase space at coupling point and iso-center
  - Imaging between coupling point and iso-center
  - Achromaticity



Many thanks for the slides to D. Meer from PSI and M. Schippers from PARTREC