



# Accelerator Science and Particle Therapy

Alexander Gerbershagen



partrec



university of  
groningen

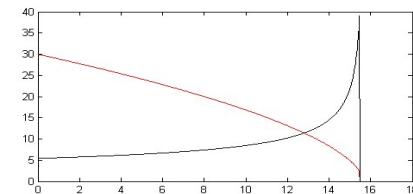


University Medical Center Groningen

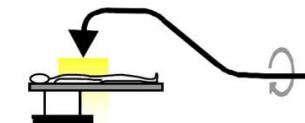
a.ge@cern.ch

# Content

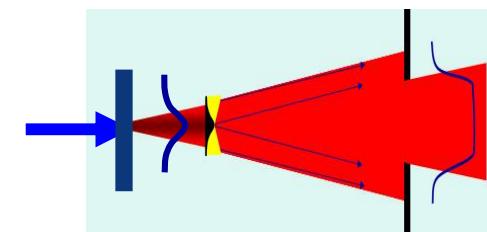
- Introduction: Hadron therapy



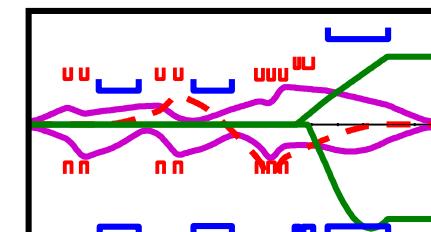
- Possible facility and gantry layouts



- Dose delivery techniques



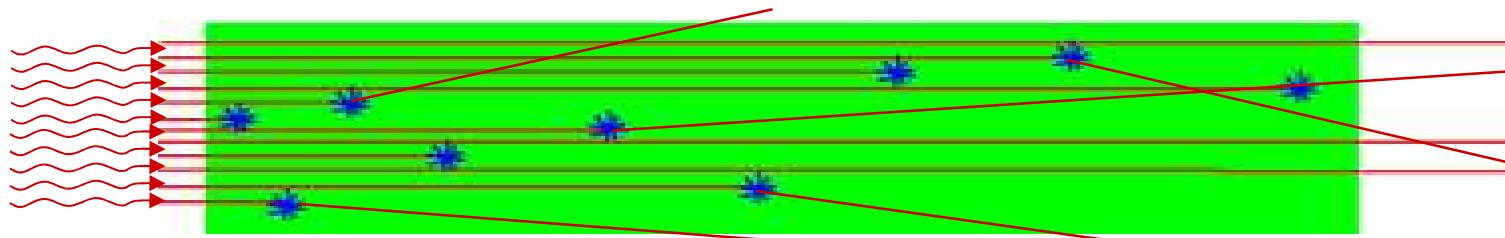
- Beam optics properties



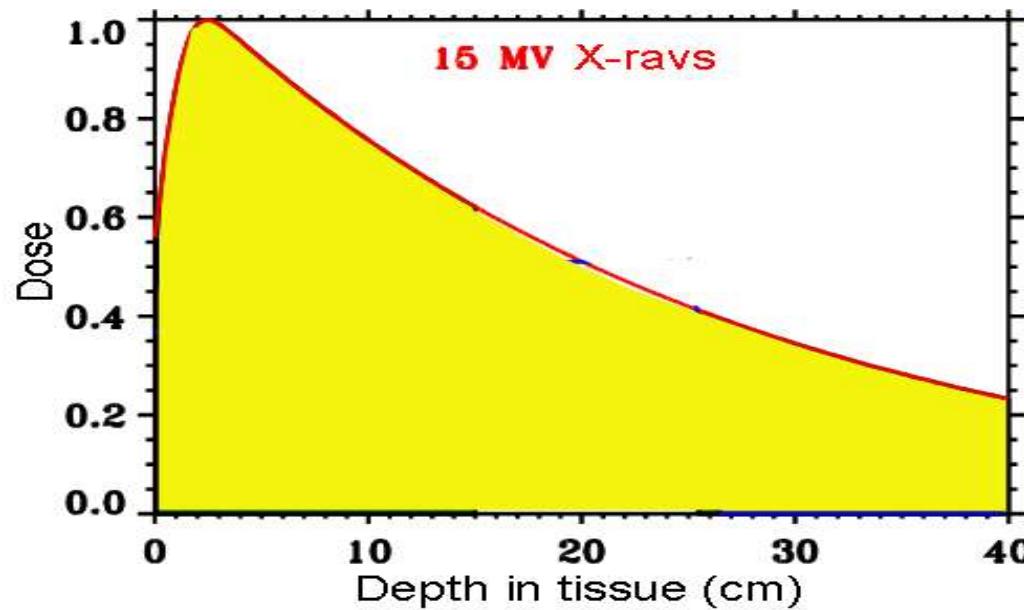
# Introduction: Hadron therapy



# Photon (X-ray) dose



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

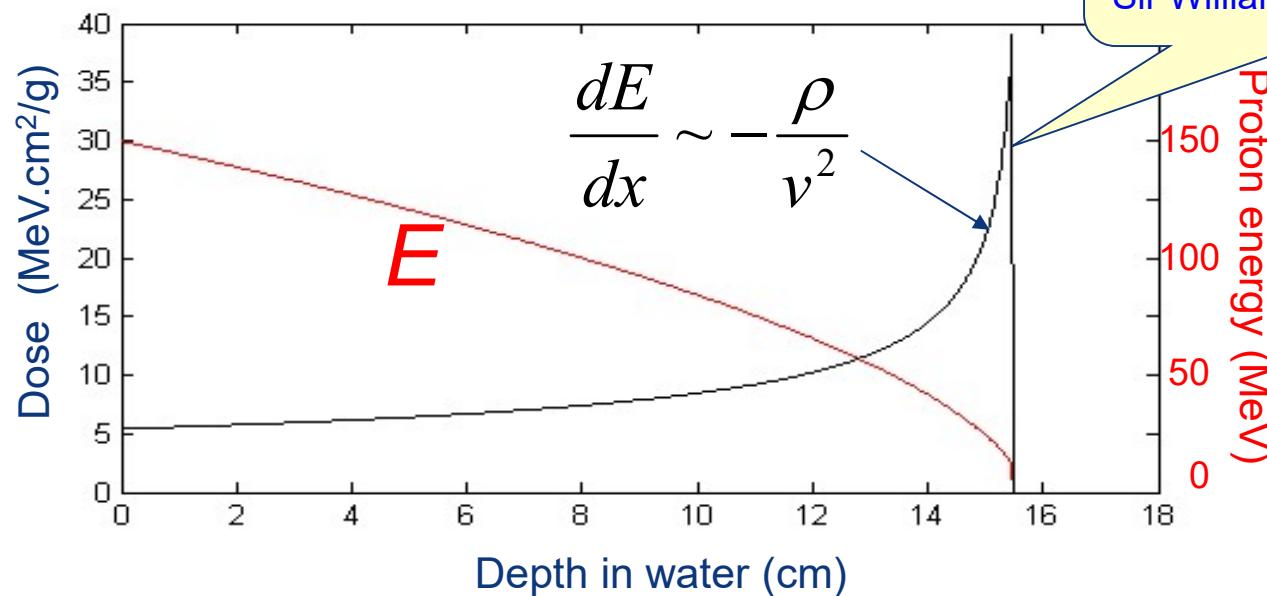


# Proton depth-dose curve



Protons **slow down**

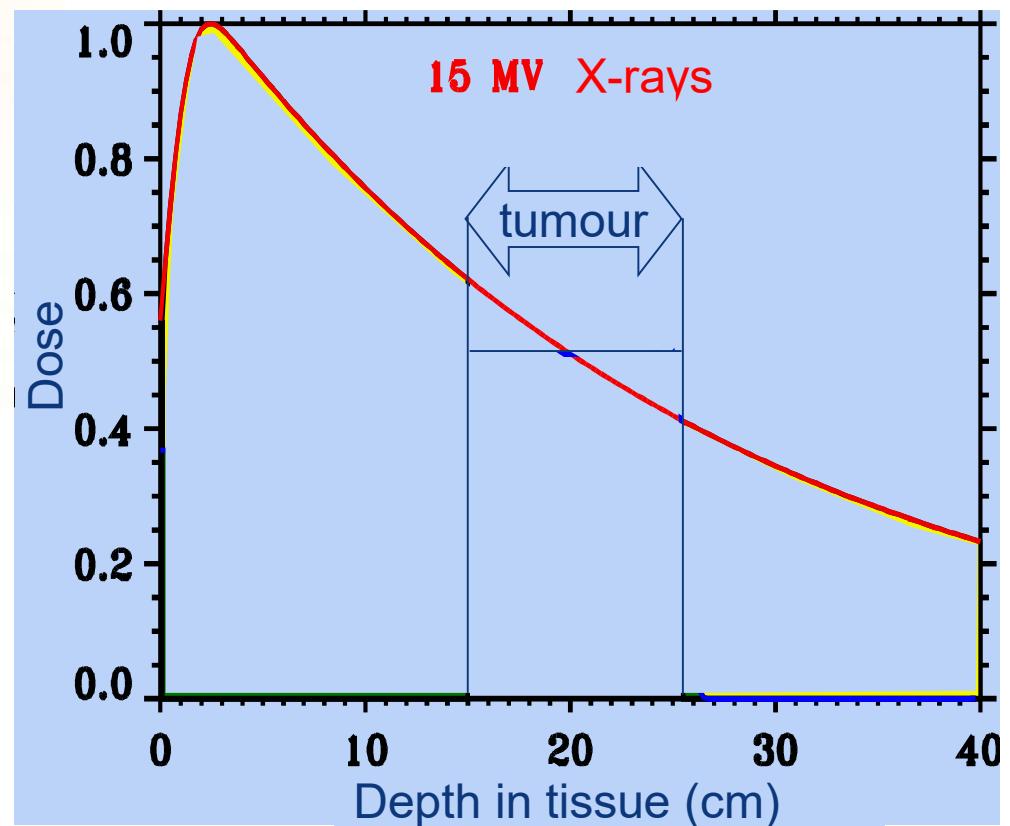
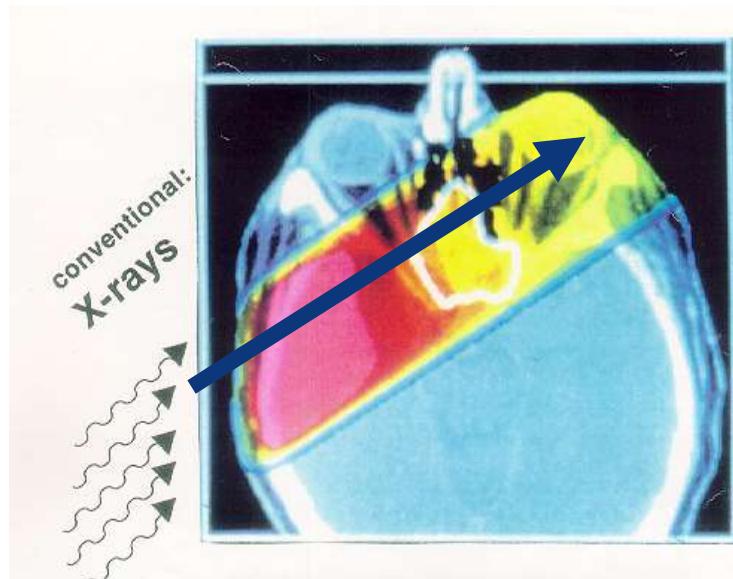
"Bragg peak"  
( named after  
Sir William Henry Bragg )



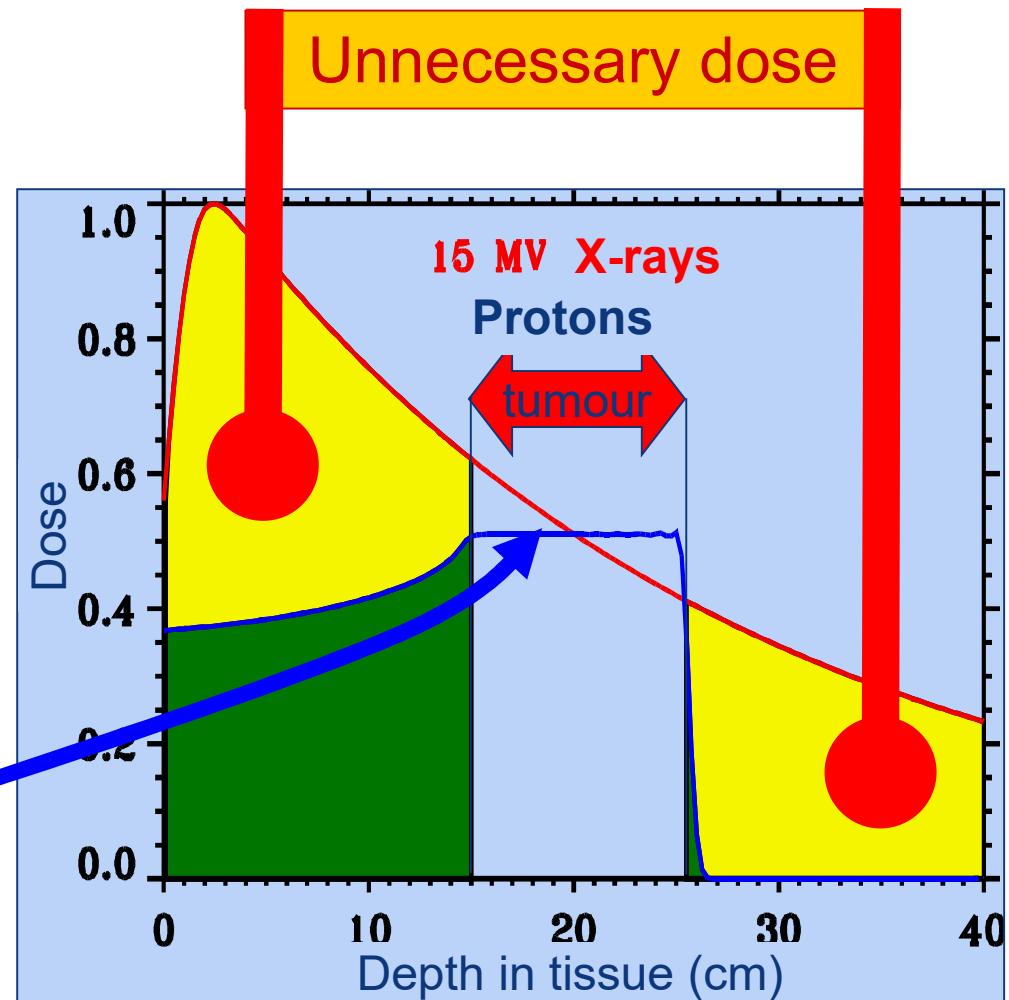
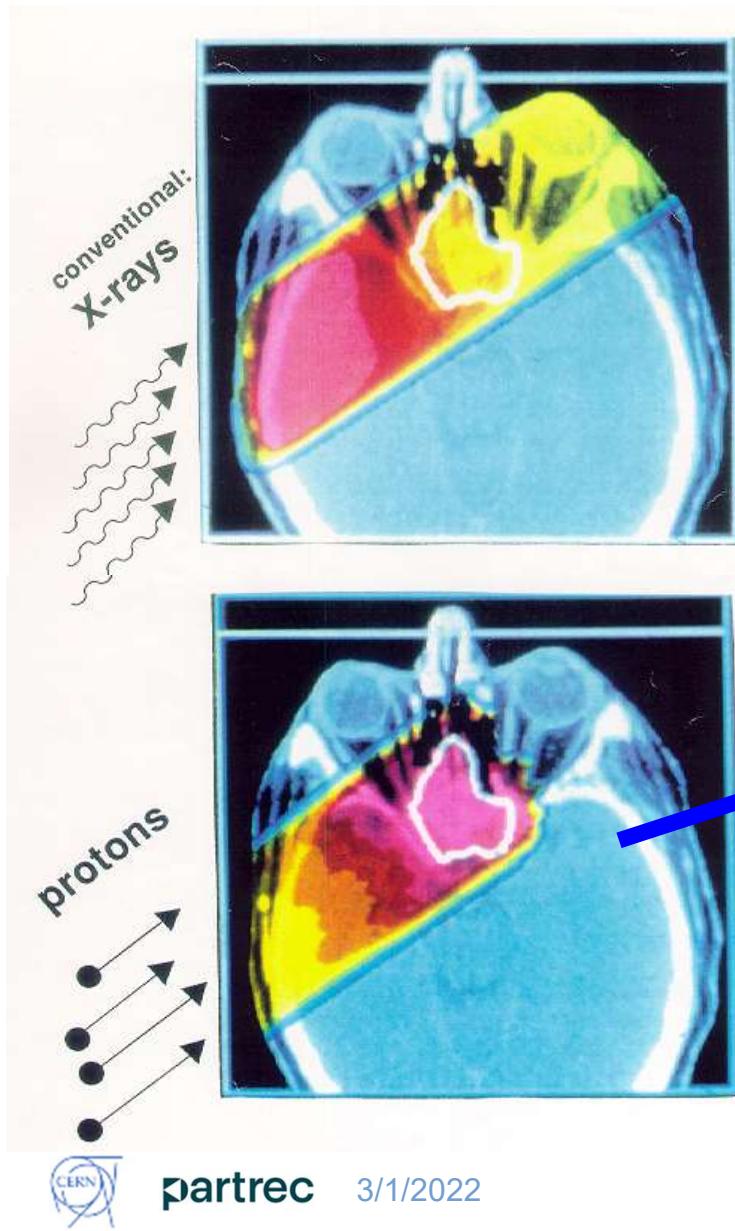
→ Energy → Penetration depth    Range in water (cm)  $\approx E^{1.77}$  (in MeV) / 450

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

# X-rays vs. Protons

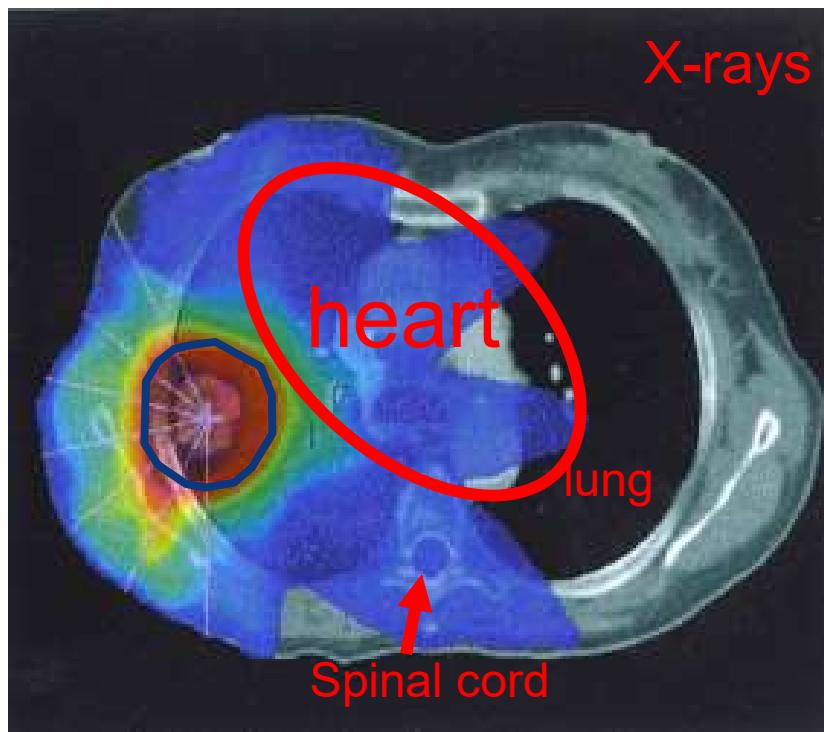


# X-rays vs. Protons

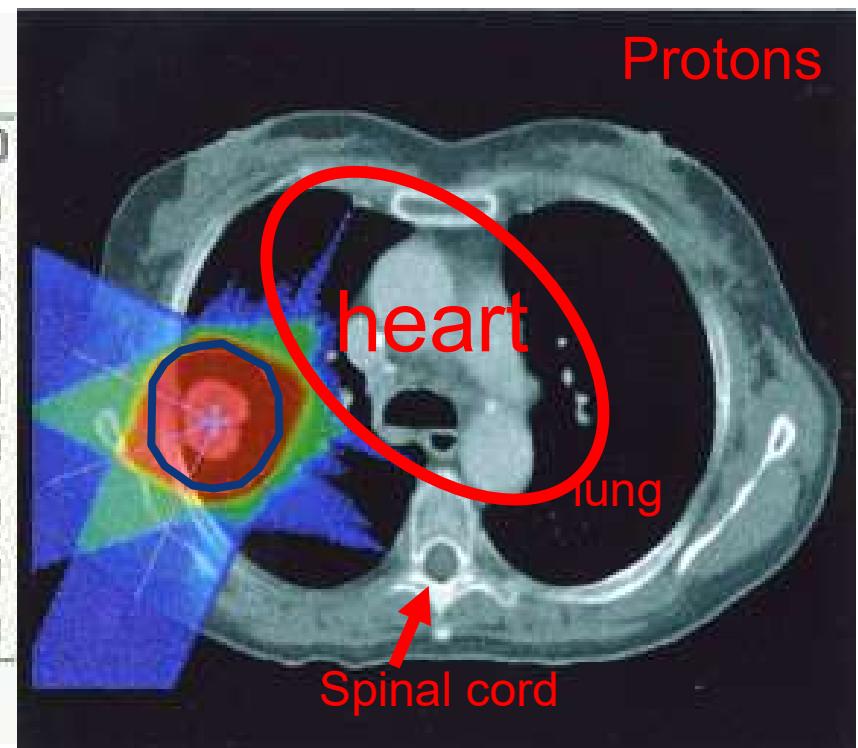


# X-rays vs. Protons

X-ray beams (IMRT )  
from 7 directions



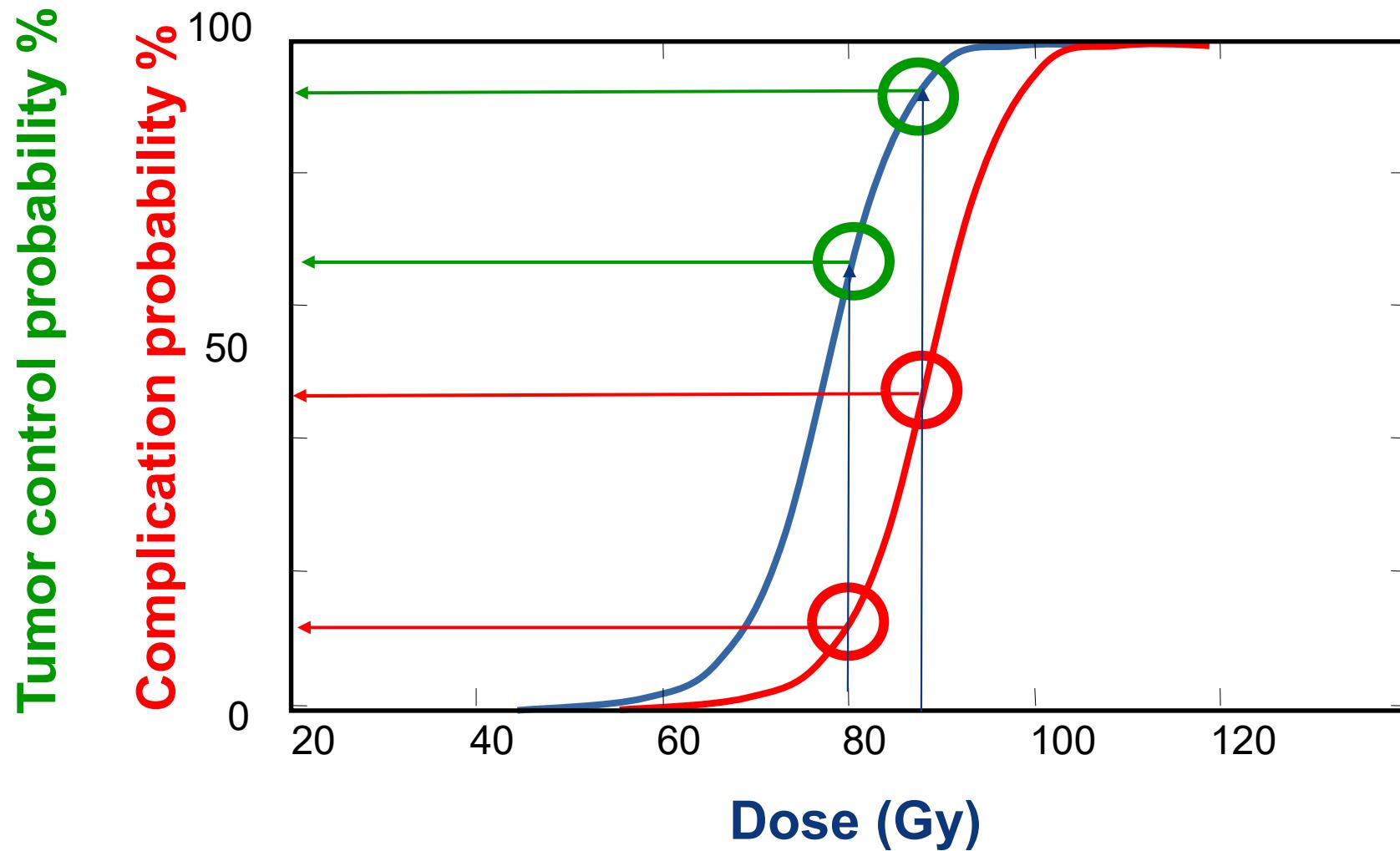
Proton beams  
from 3 directions



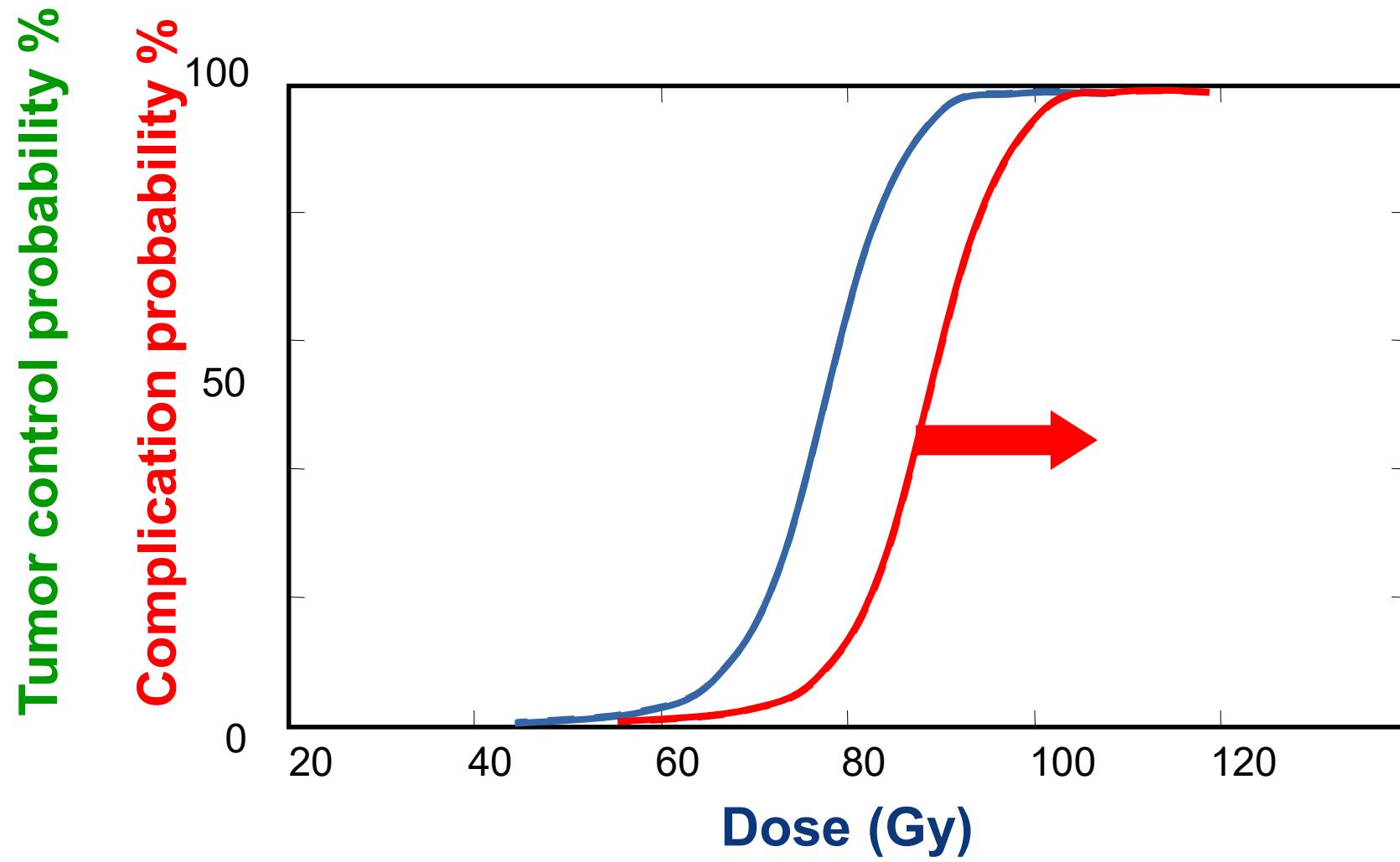
pictures: Medaustron



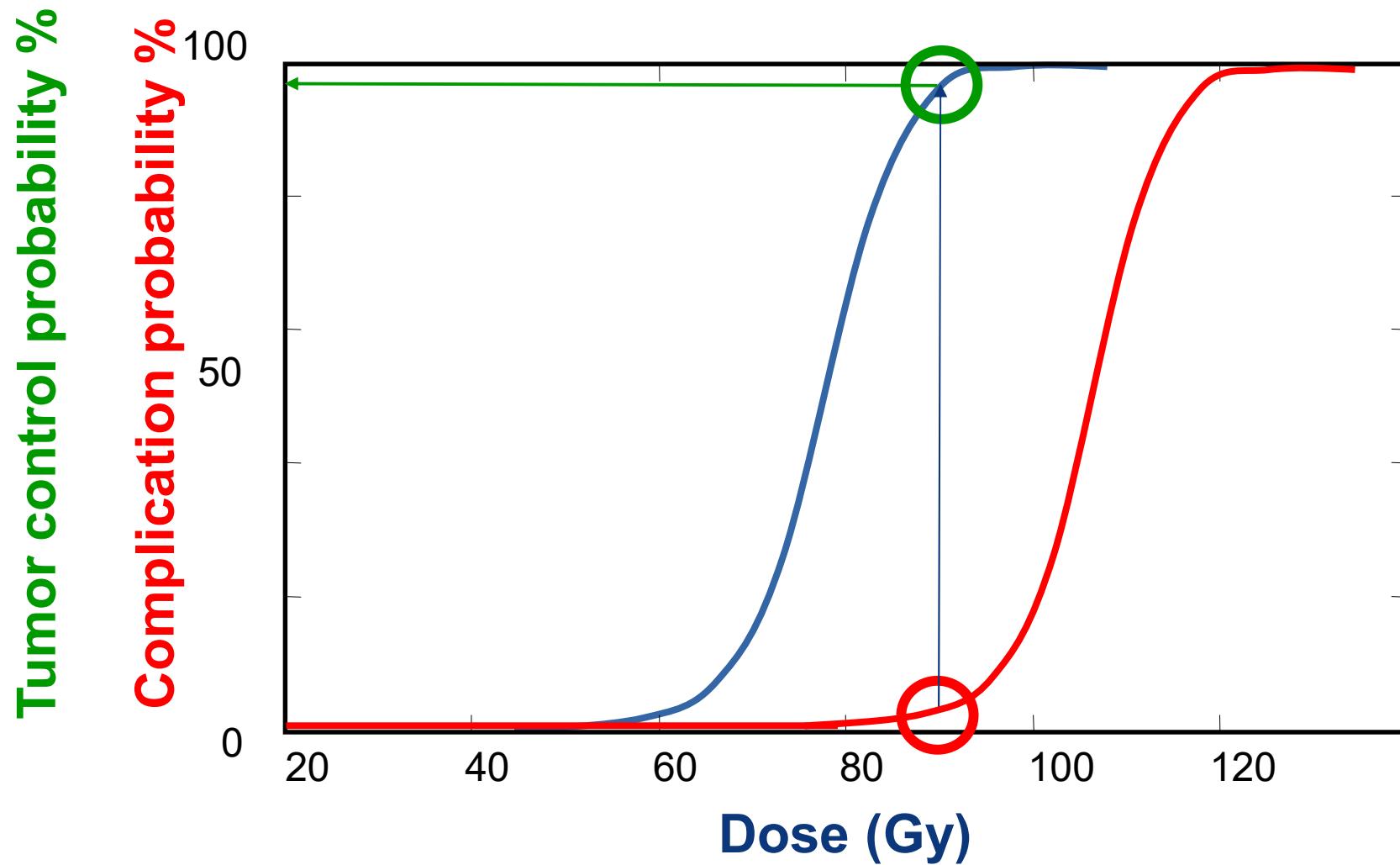
# Cure versus Complications



# Protons irradiate less normal tissue



# Cure versus Complications

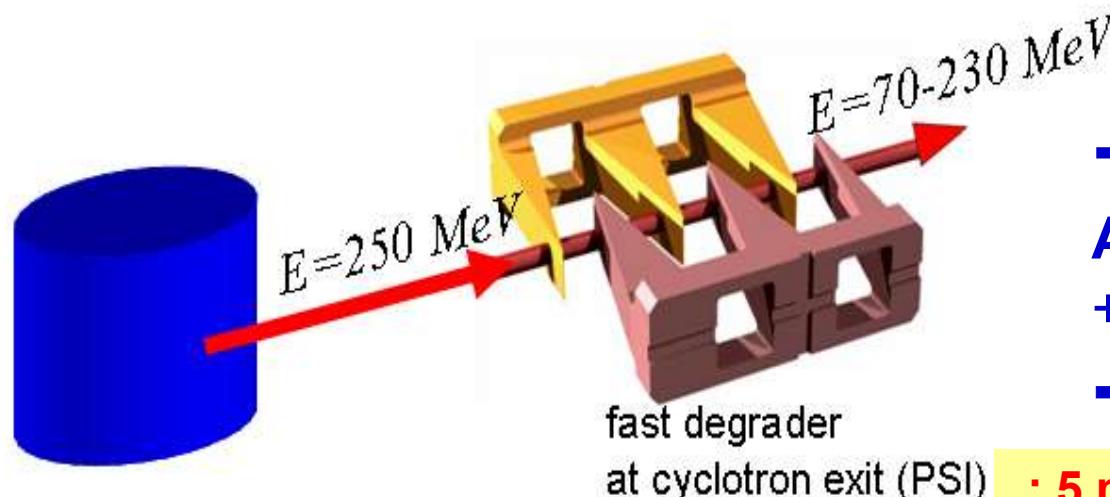


# Possible facility and gantry layouts



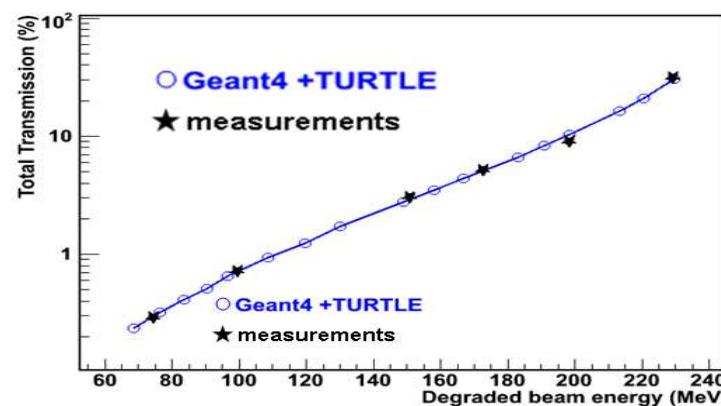
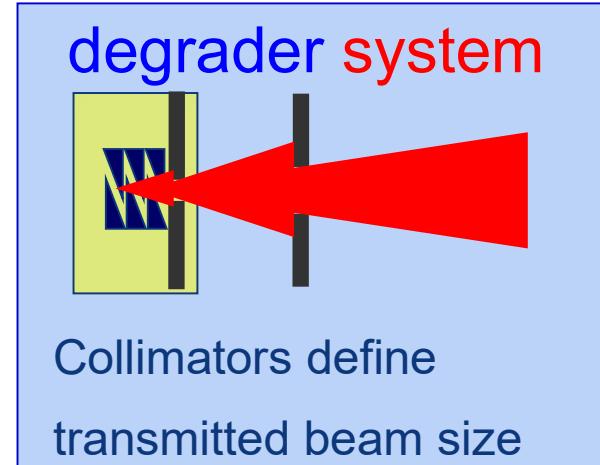
# Cyclotron driven facilities

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



- Sets range
- And, if fast enough + fast magnets:
  - also energy modulation

: 5 mm ΔRange in 50 ms

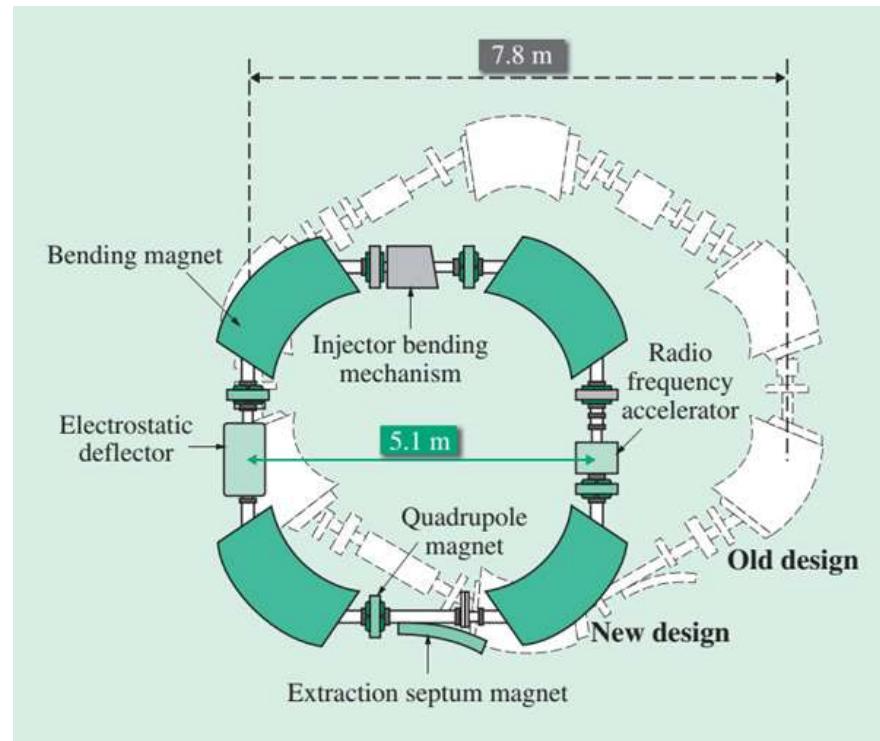
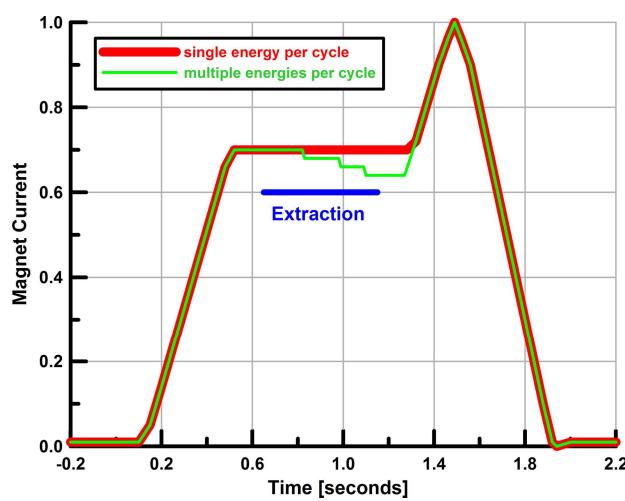


Van Goethem et al.,  
Phys. Med. Biol. 54  
(2009)5831



# Synchrotrons

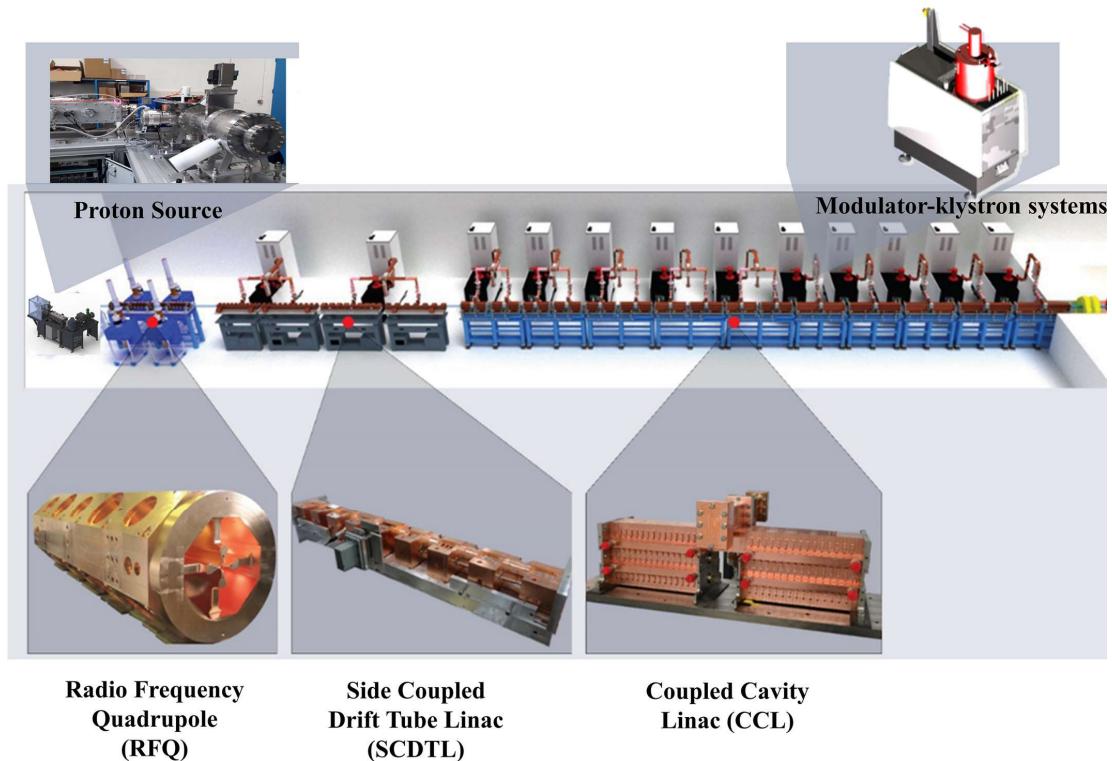
- Asymmetric emittance
  - Cause: Extraction in one plane
- Single turn vs multi-turn extraction



Sources: Hitachi, Loma Linda University Medical Center

# Linacs

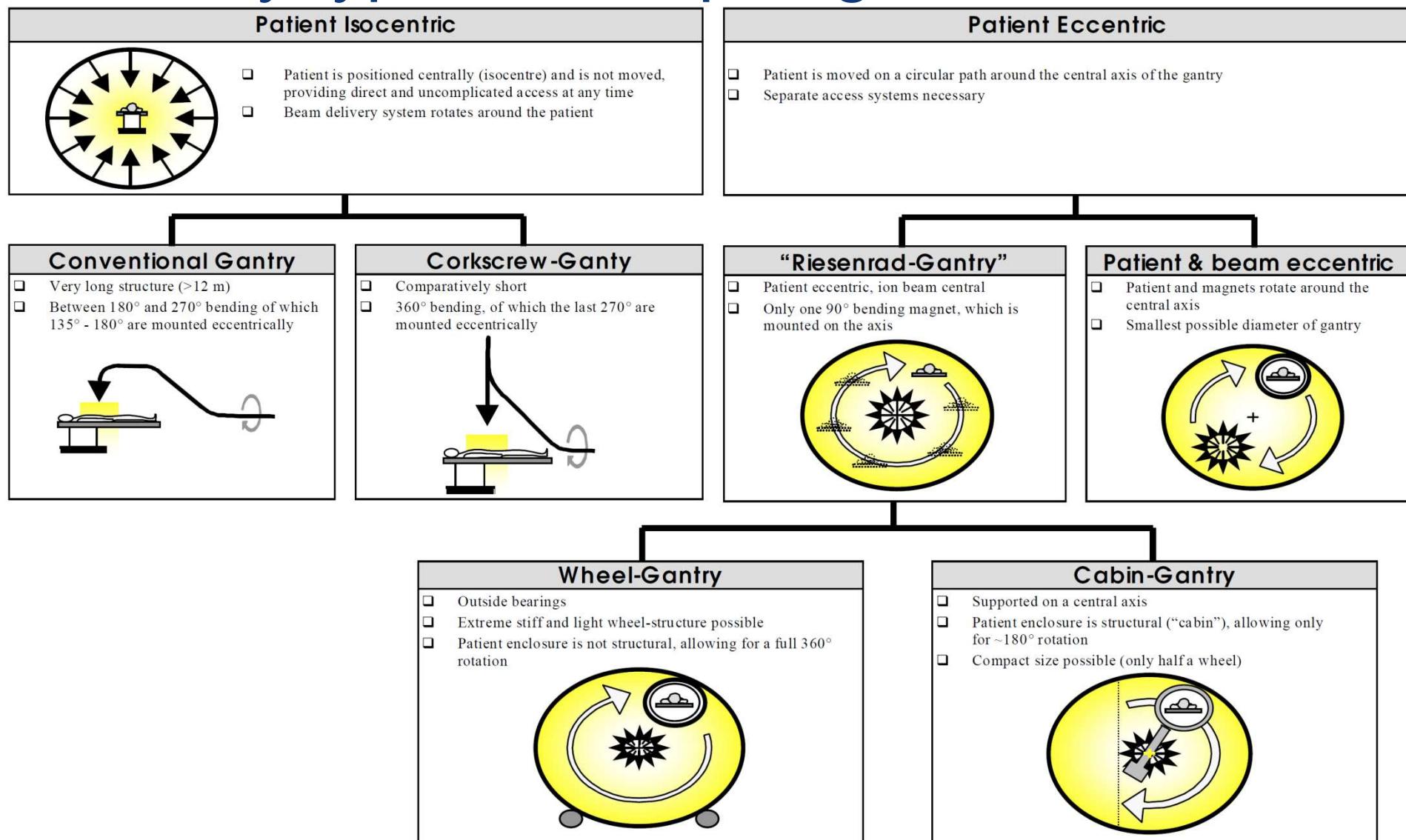
- Fast energy switching (milliseconds)
- Very low beam emittance ( $\sim 1 \text{ mm mrad}$ )
- Lower average current than cyclotrons



Source: AVO/ADAM SA



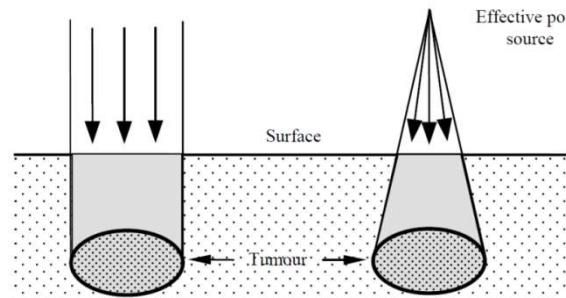
# Gantry types and topologies



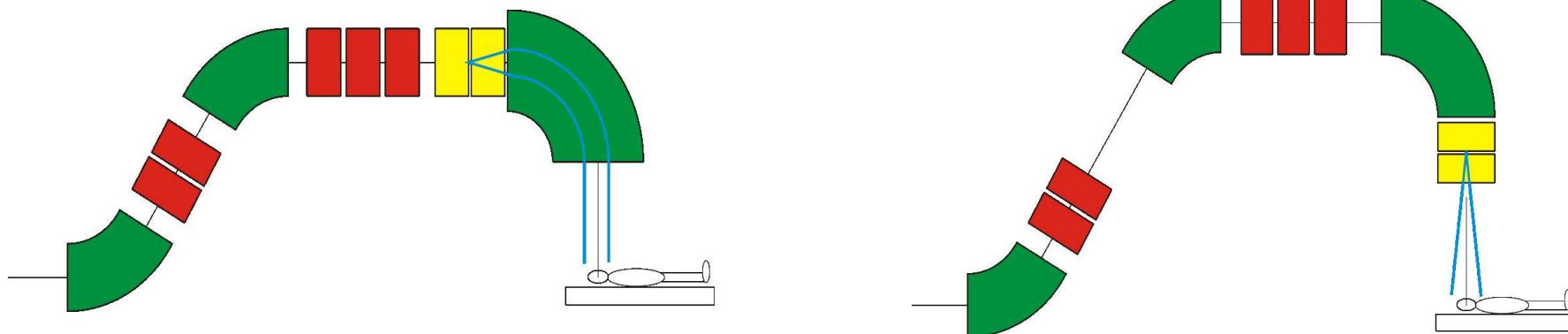
# Upstream versus downstream scanning

- 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)

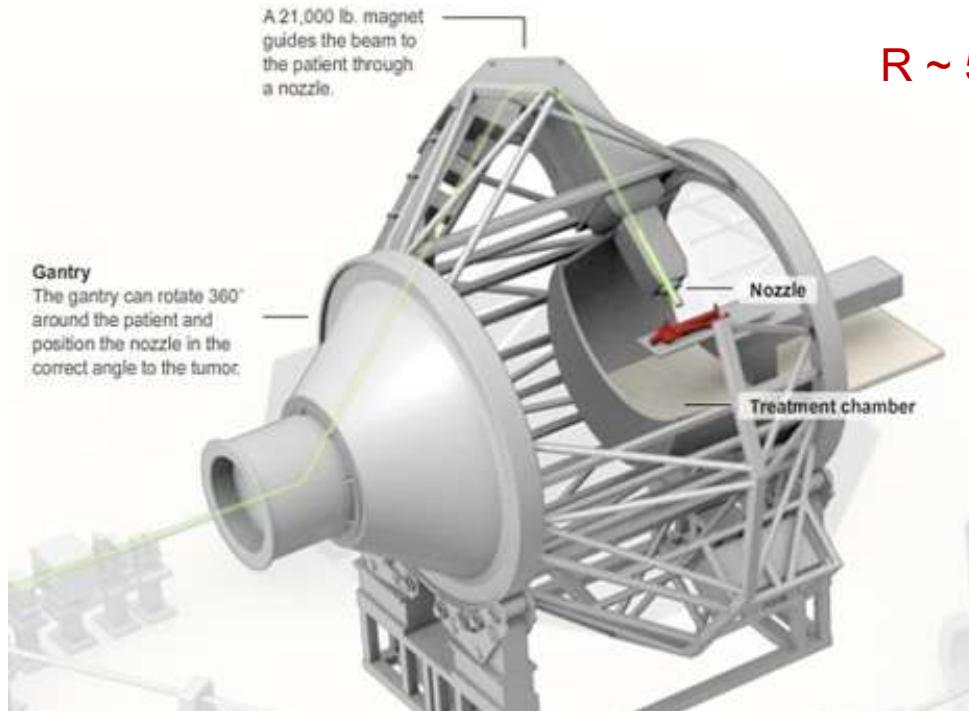
- Downstream scanning
- Divergent beam
- Finite source-to-axis distance (SAD)
- Larger skin dose
- Large fields possible with large SAD (increase diameter)
- Larger diameter → larger room (costs)



Also possible: Combination of  
1 sweeper upstream  
1 sweeper downstream



# Conical gantry - Commercial standard layout



$R \sim 5\text{m}$

*Beam scanning  
downstream of the last  
bend*

IBA  
Sumitomo  
Hitachi  
Mitsubishi  
Varian

- 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



Munich



partrec

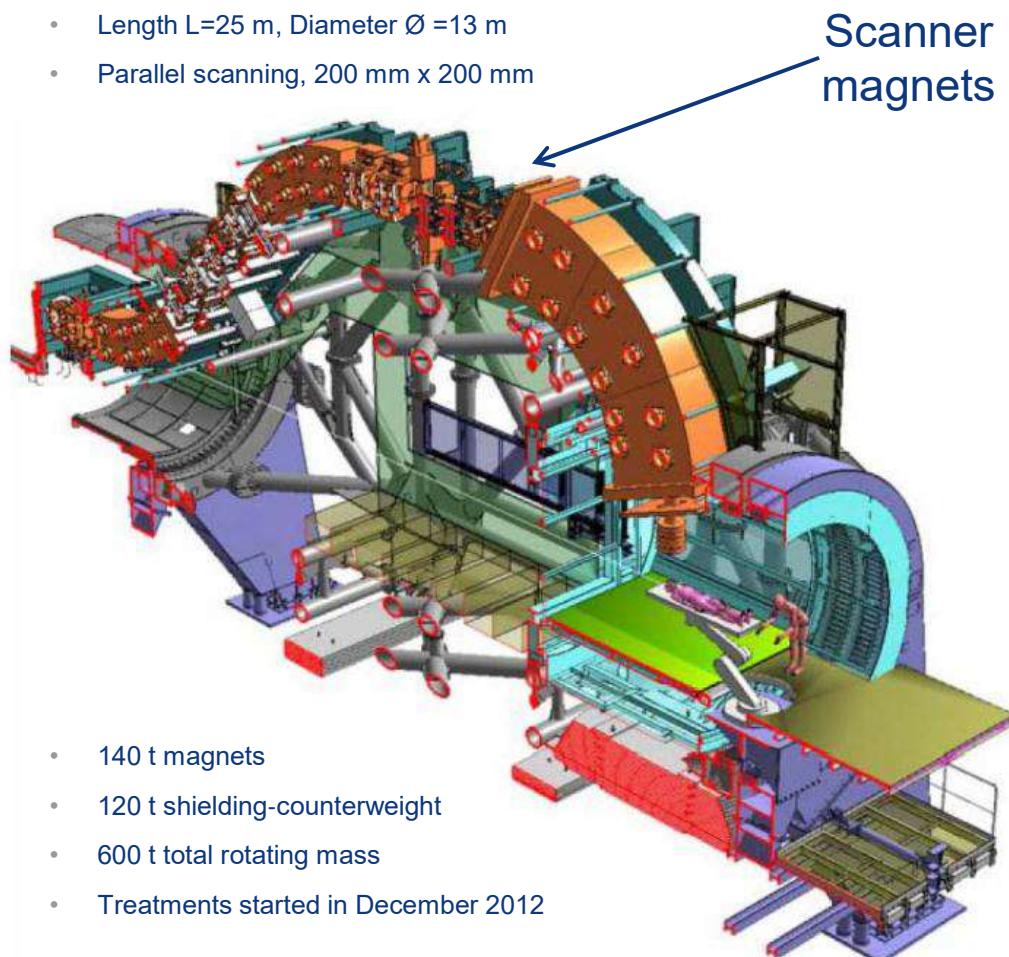
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18

# 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

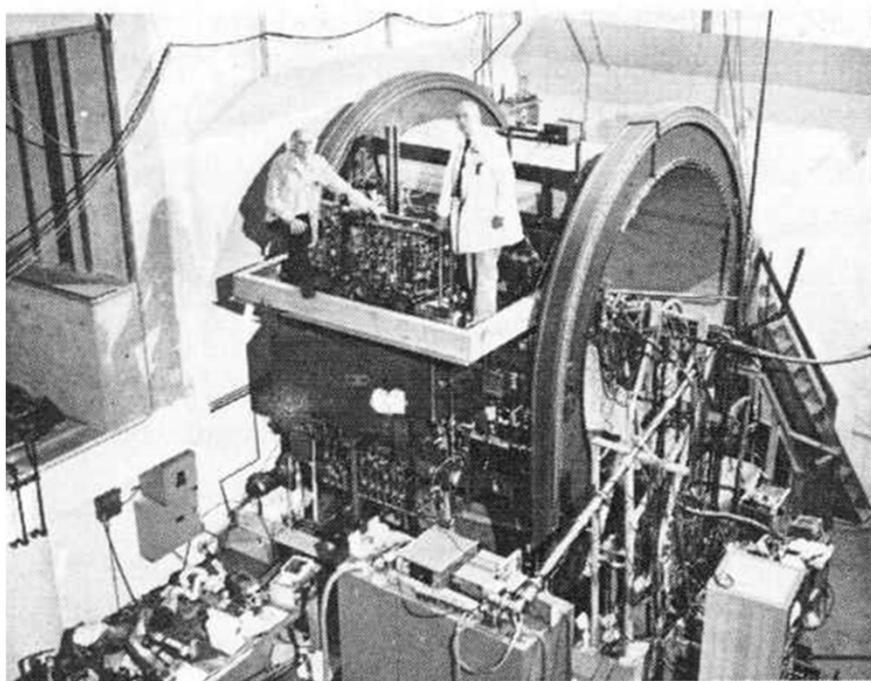


Fig. 2 Photo of the superconducting medical cyclotron on its gantry. Dr. William Powers and



For proton therapy  
70-230 MeV  
Treating patients since 2013



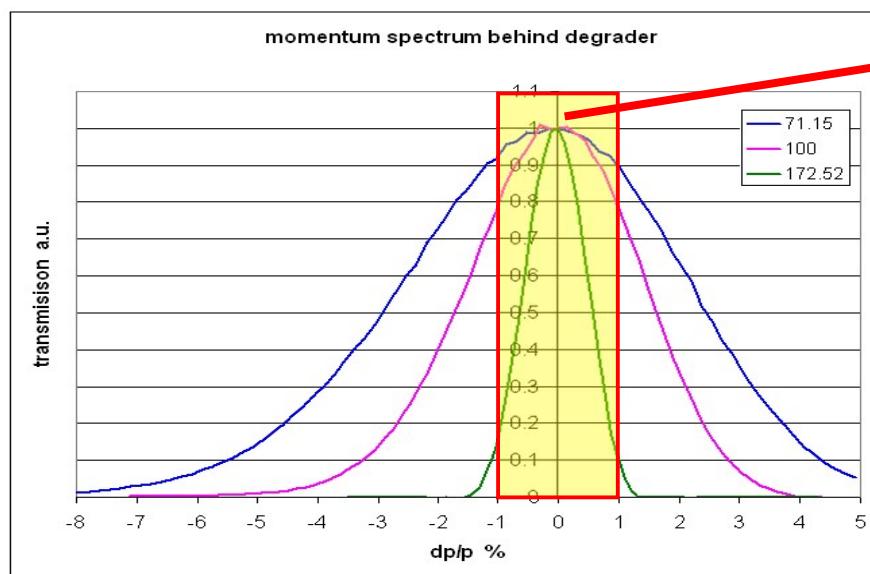
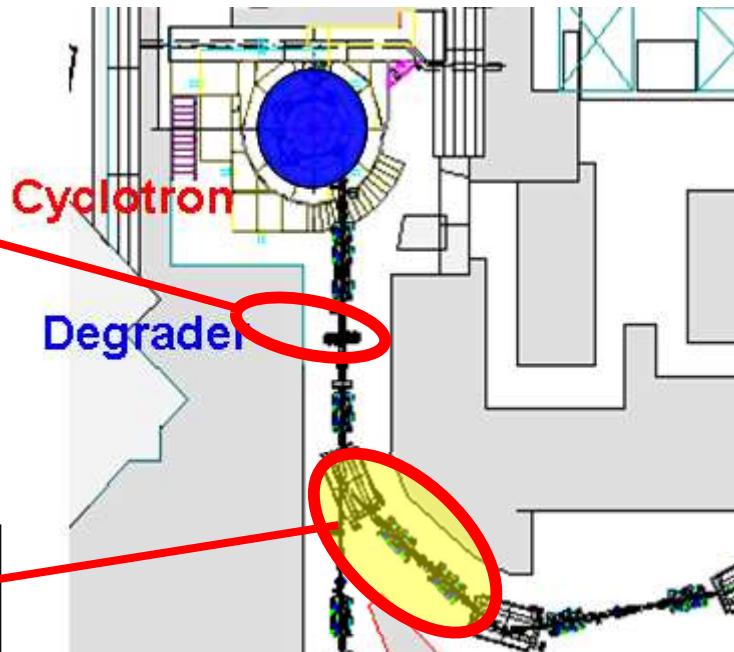
# Dose delivery techniques



# Energy selection system



multi-wedge degrader  
235-67 MeV

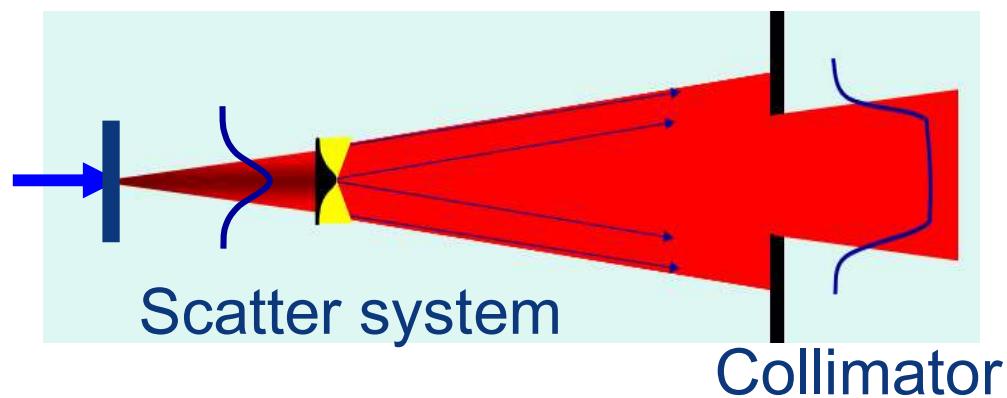


Beam analysis:  
energy selection  
 $dp/p < \pm 1\%$

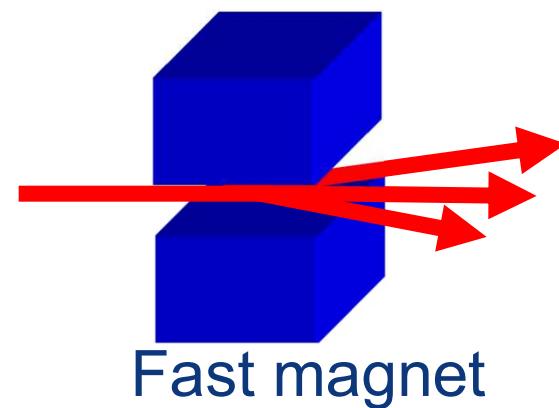
# Dose delivery techniques: Width

transversal spread:

scattering

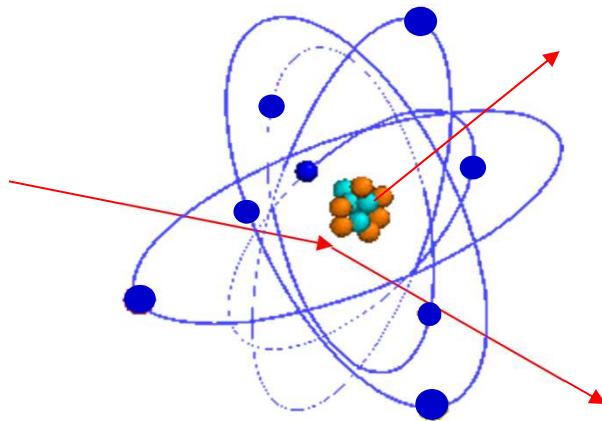


scanning



# Scattering

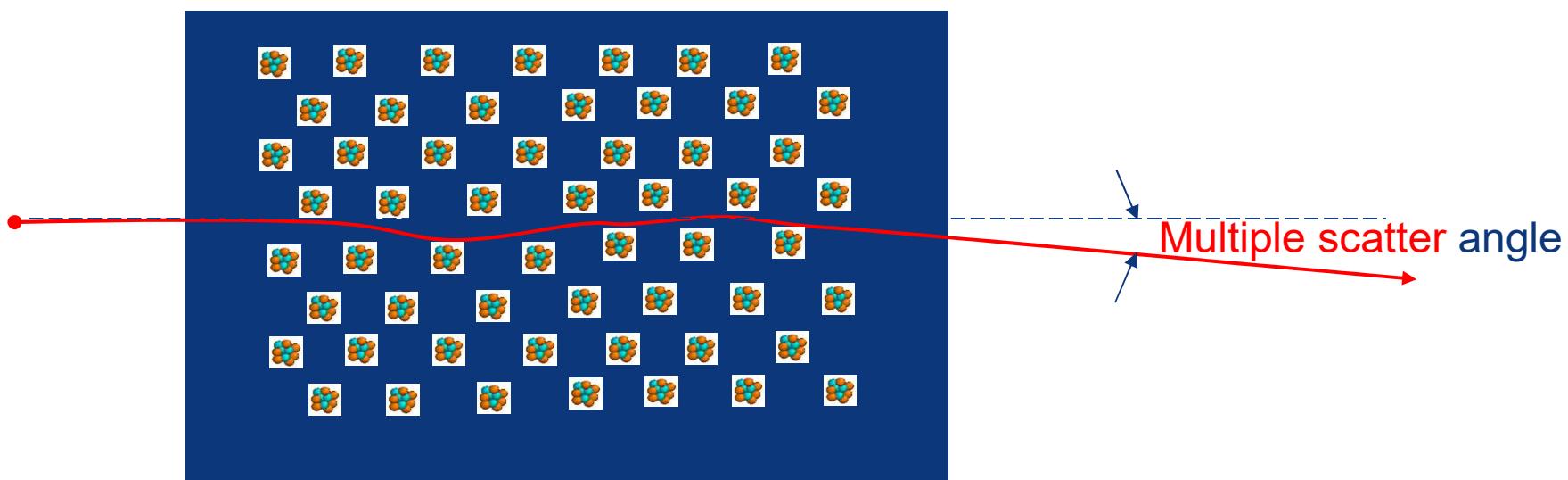
## Nuclear Coulomb scattering



Nucleus is several times heavier as a proton

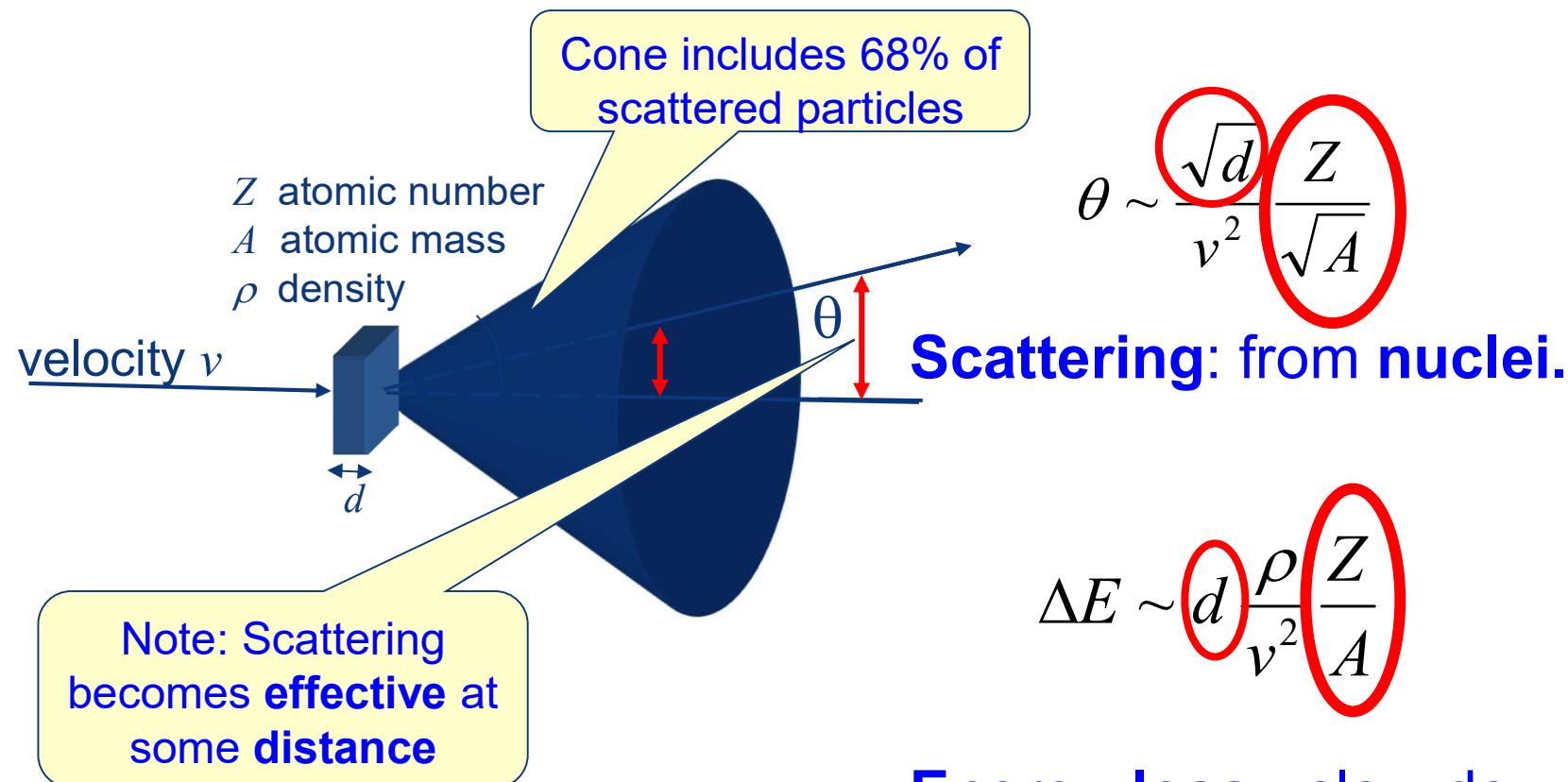
→ Almost no energy loss („elastic“)

→ Much larger deflection than from electrons



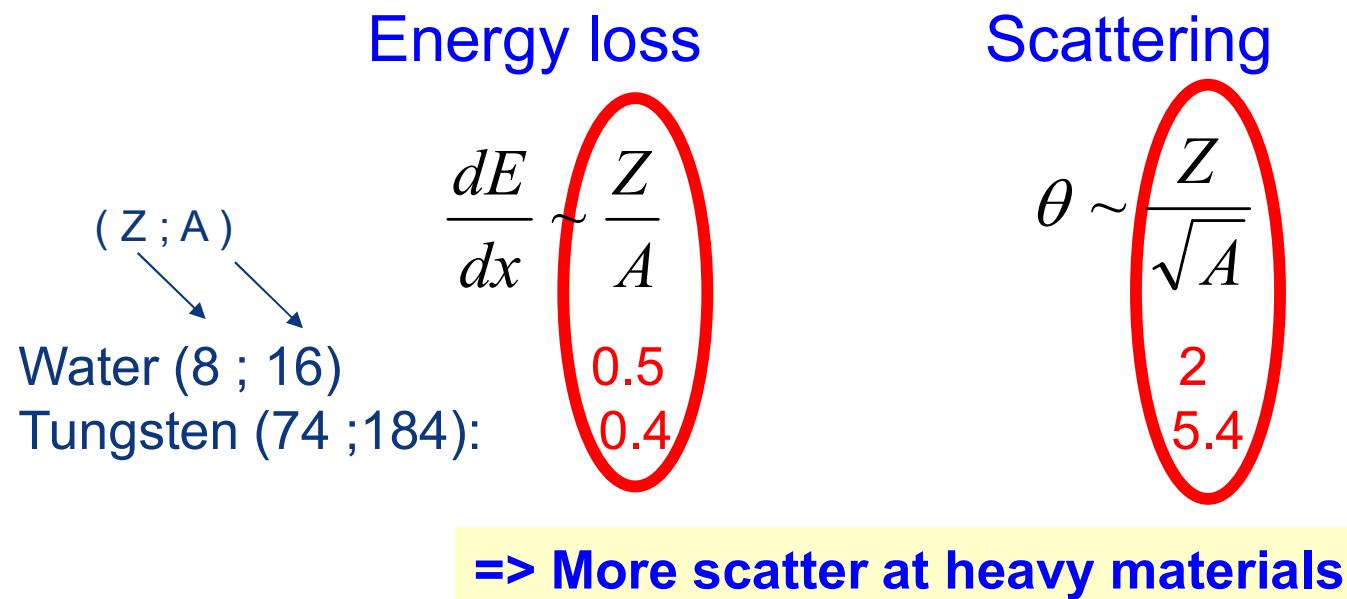
# Scattering

## Multiple Scattering



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

# Scattering



250 MeV p:

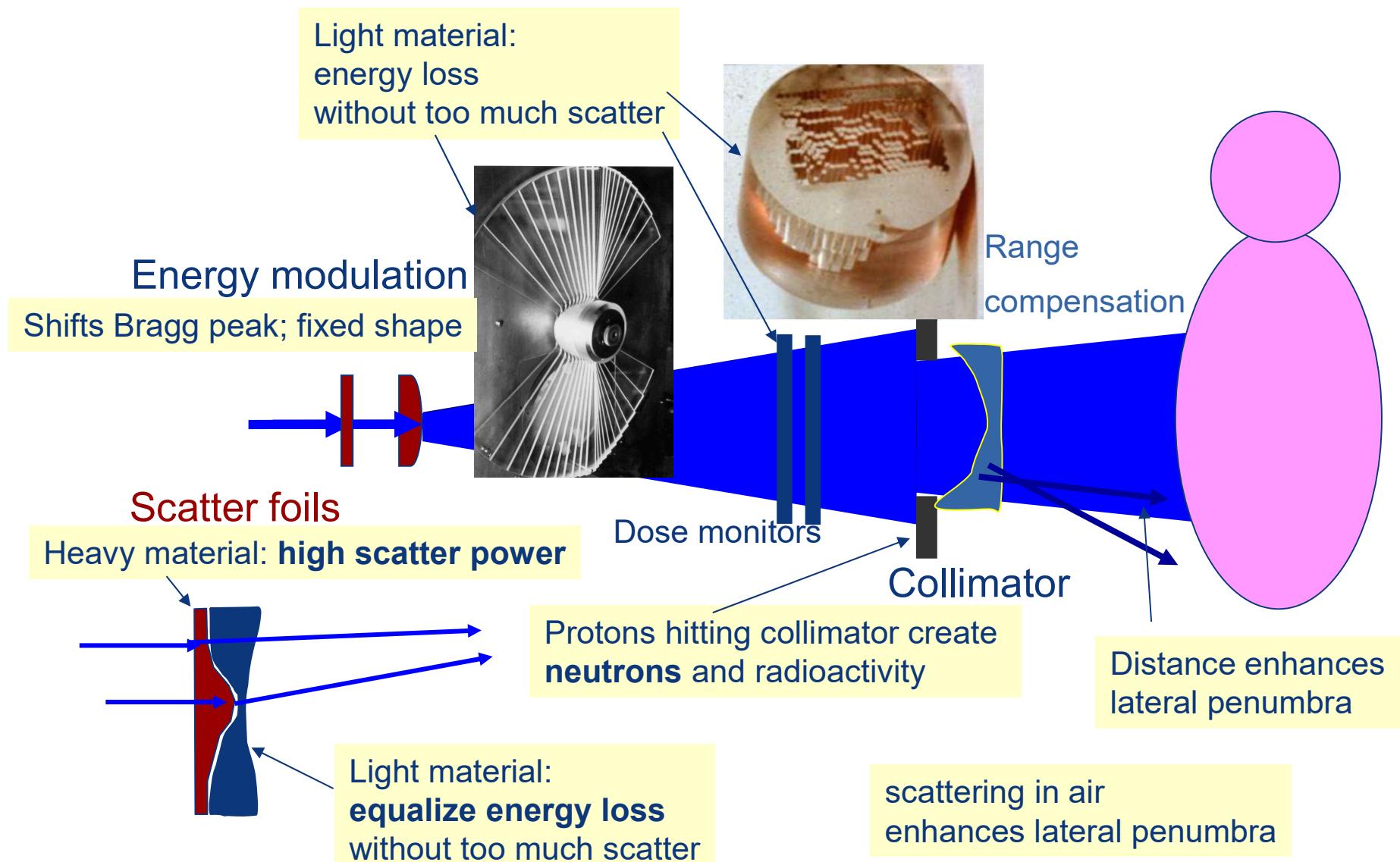
Energy loss:	$\Delta E =$	<u>1 cm H<sub>2</sub>O</u>	1 mm W
		4 MeV	4 MeV

Scattering angle:

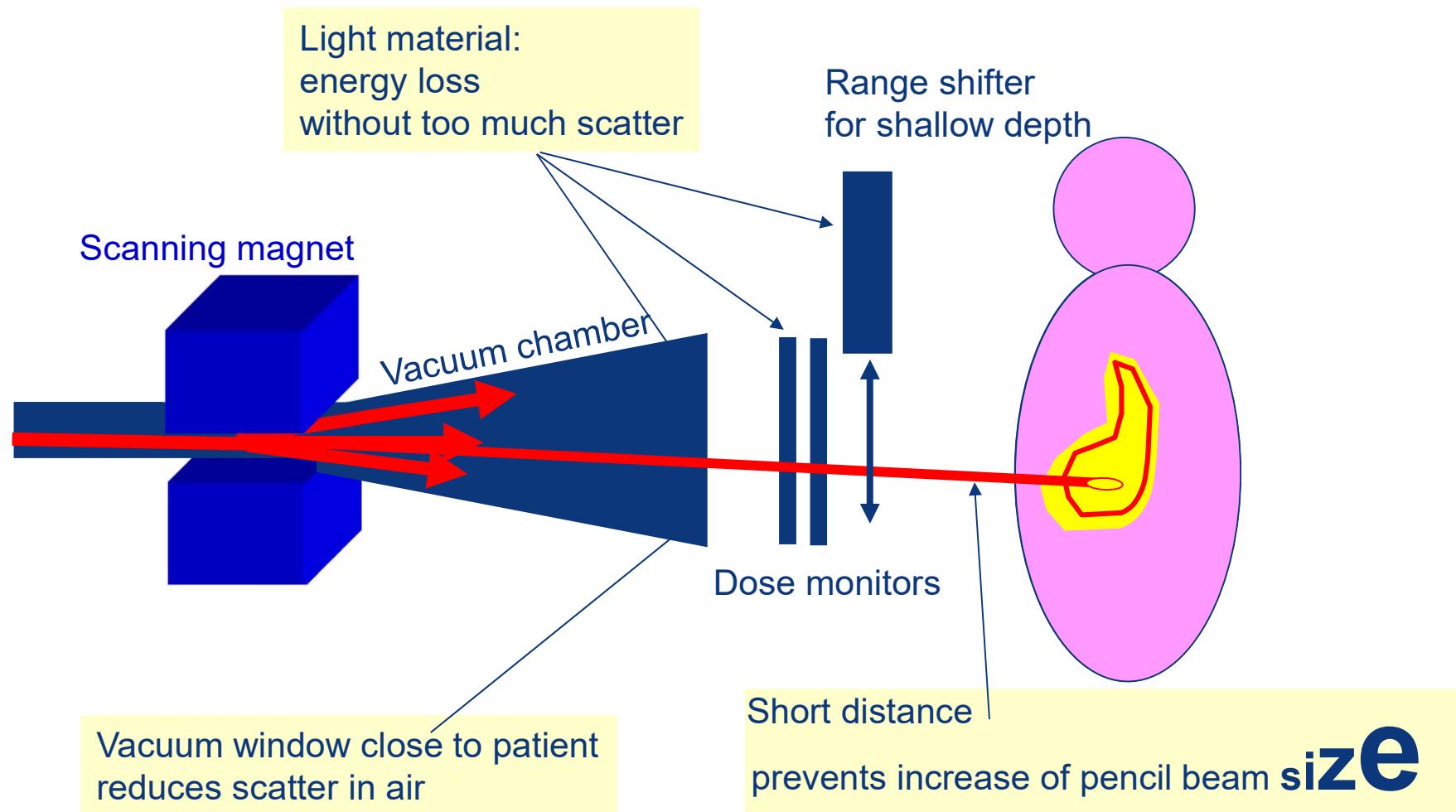
$\theta =$  5 mrad      16 mrad



# Nozzle for a scattered beam



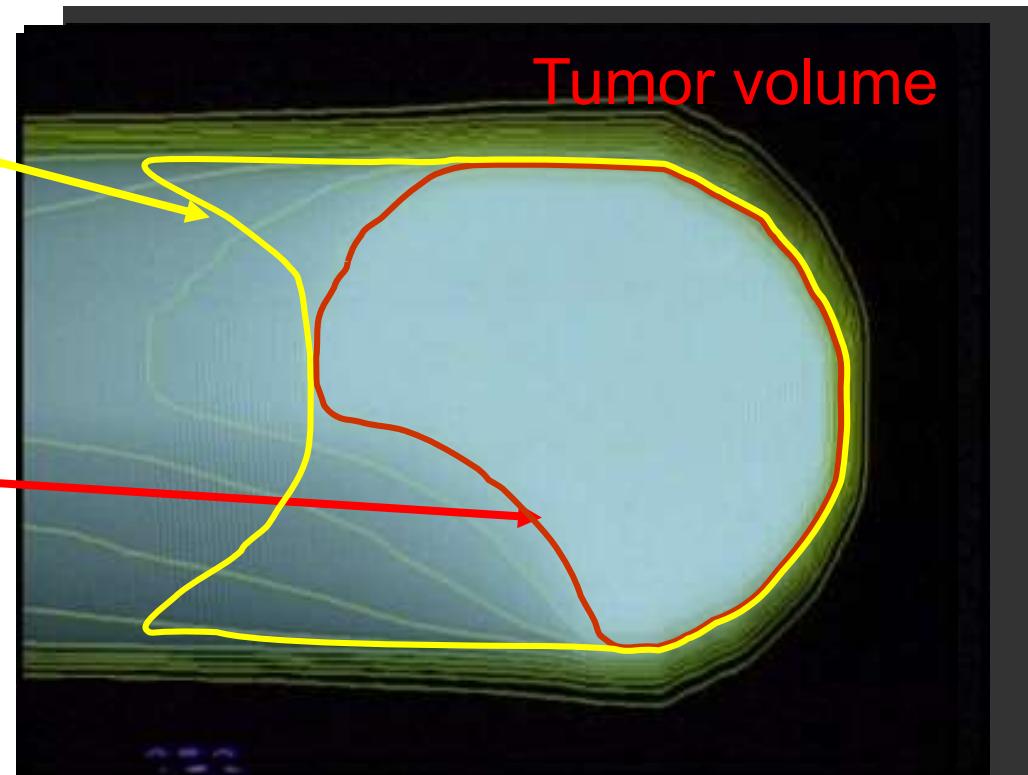
# Nozzle for a scanning beam



# Scanning: best dose distribution

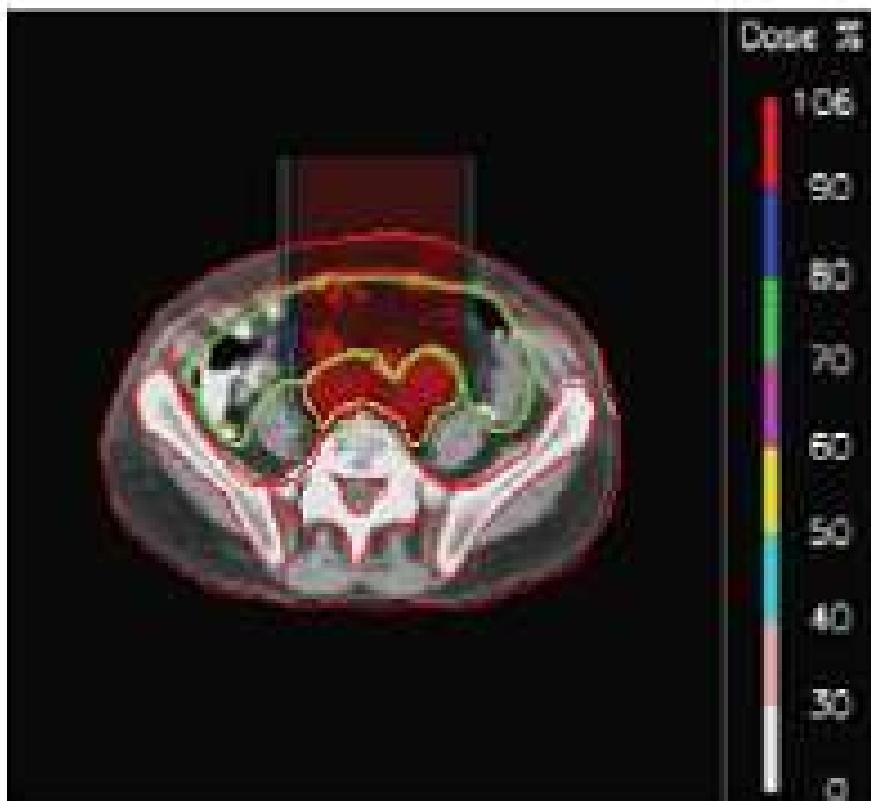
Dose distribution of  
scattered beam:

**Pencil-beam scanning:**  
behind & in front of tumor  
optimal

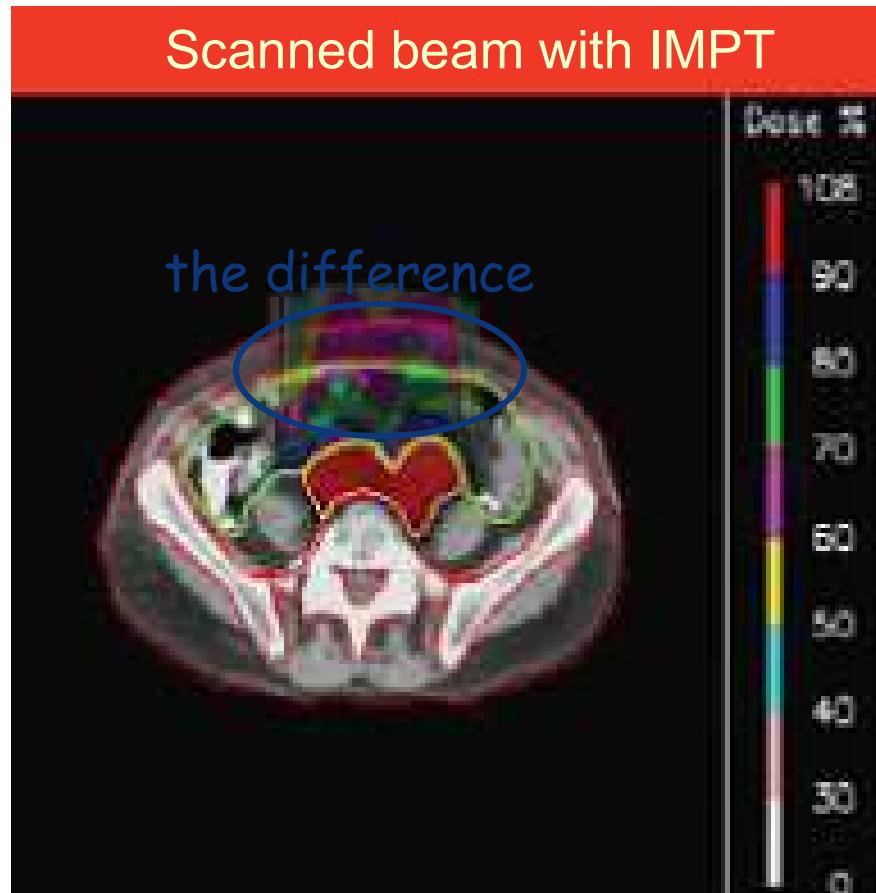


# Scatter – IMPT

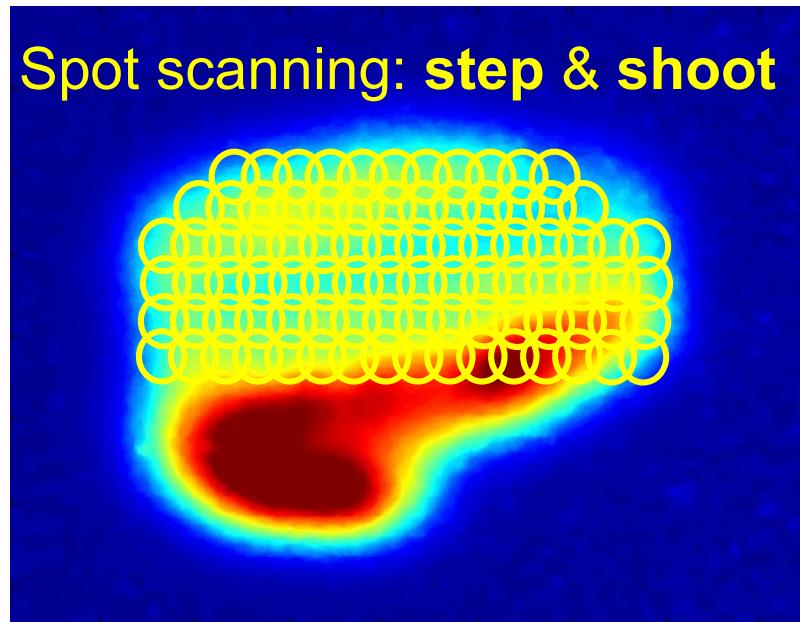
Scattered beam



Scanned beam with IMPT



# Spot scanning



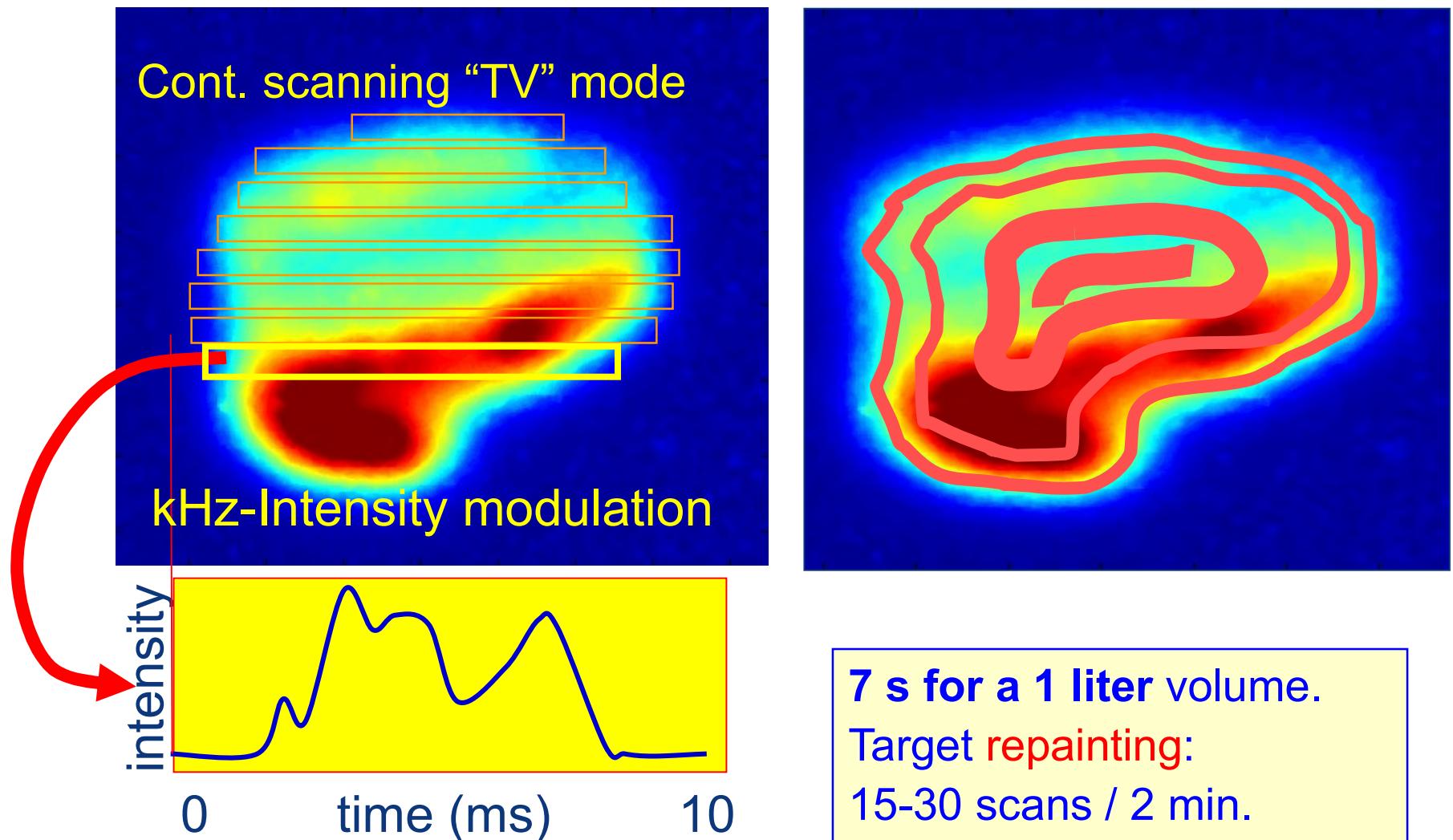
Beam size 7 mm FWHM  
5 mm steps

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

**~1 Gy / liter / minute**

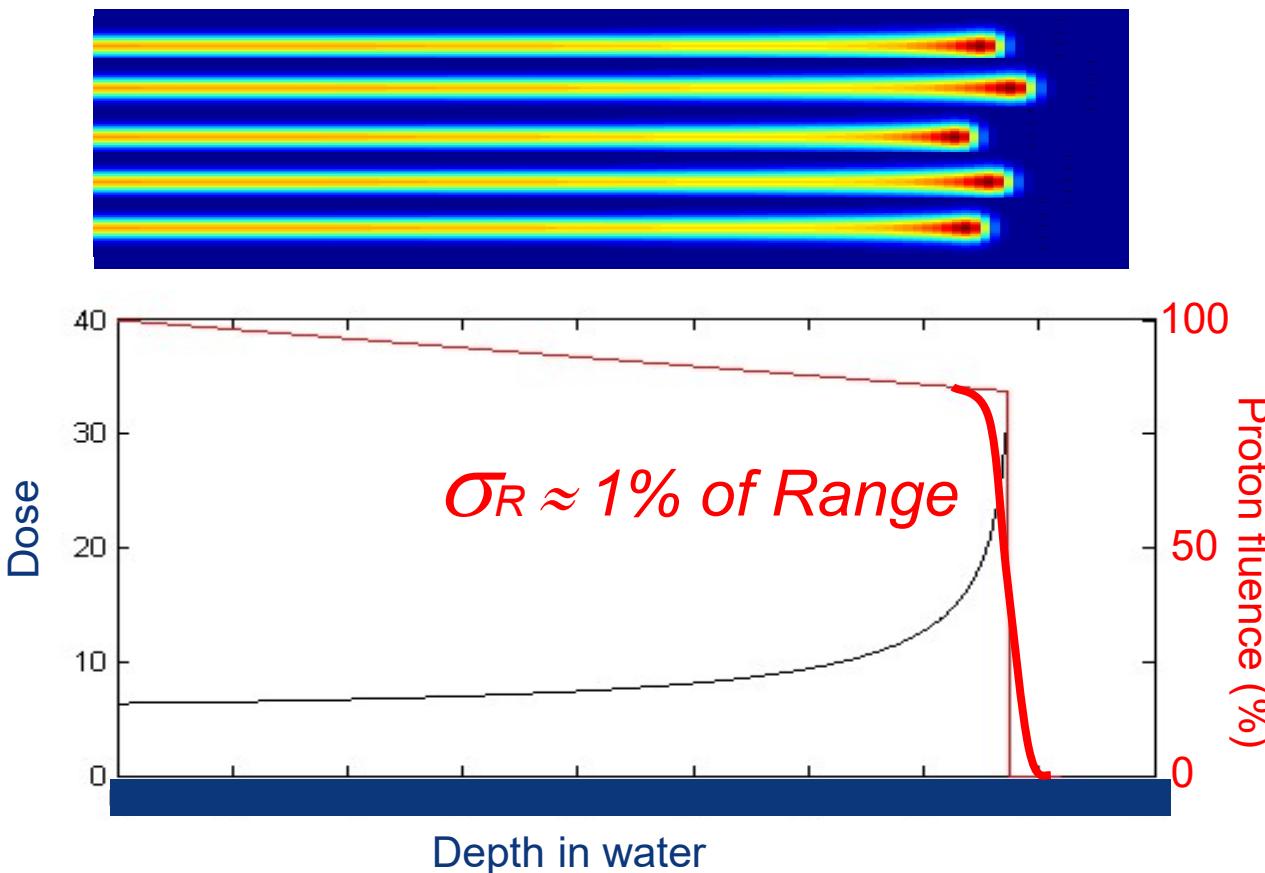


# Fast pencil beam scanning in 3D



# Proton depth-dose curve

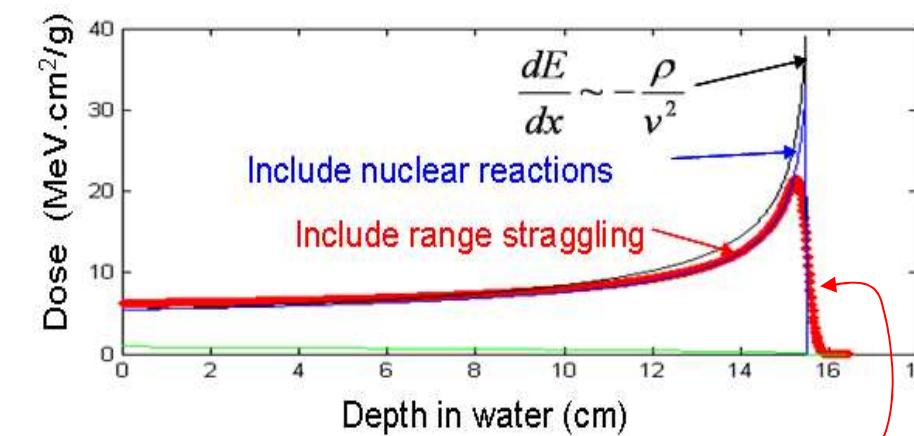
- Energy straggling
- Slight variations in track length due to **Multiple Scattering**  
→ Range straggling



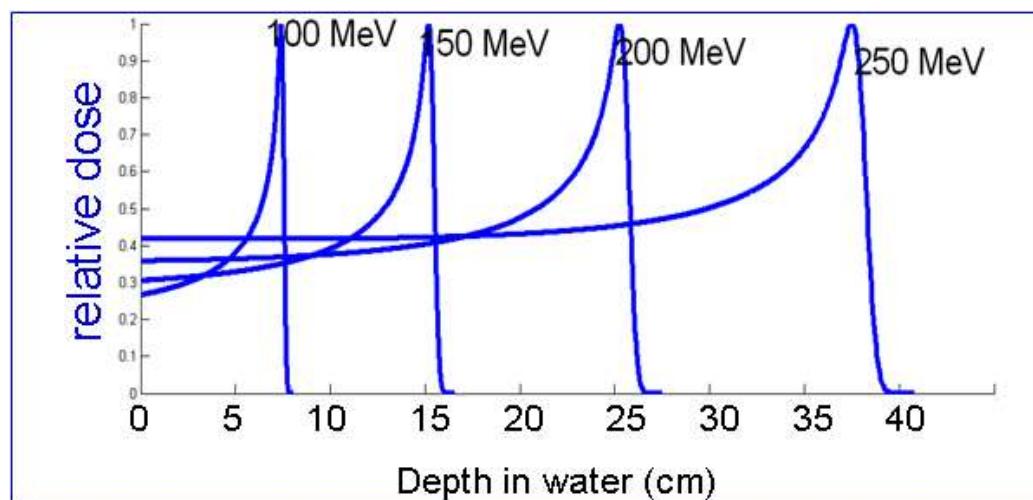
# Proton depth-dose curve

## Range straggling:

- broadens Bragg peak
- broadening increases as:



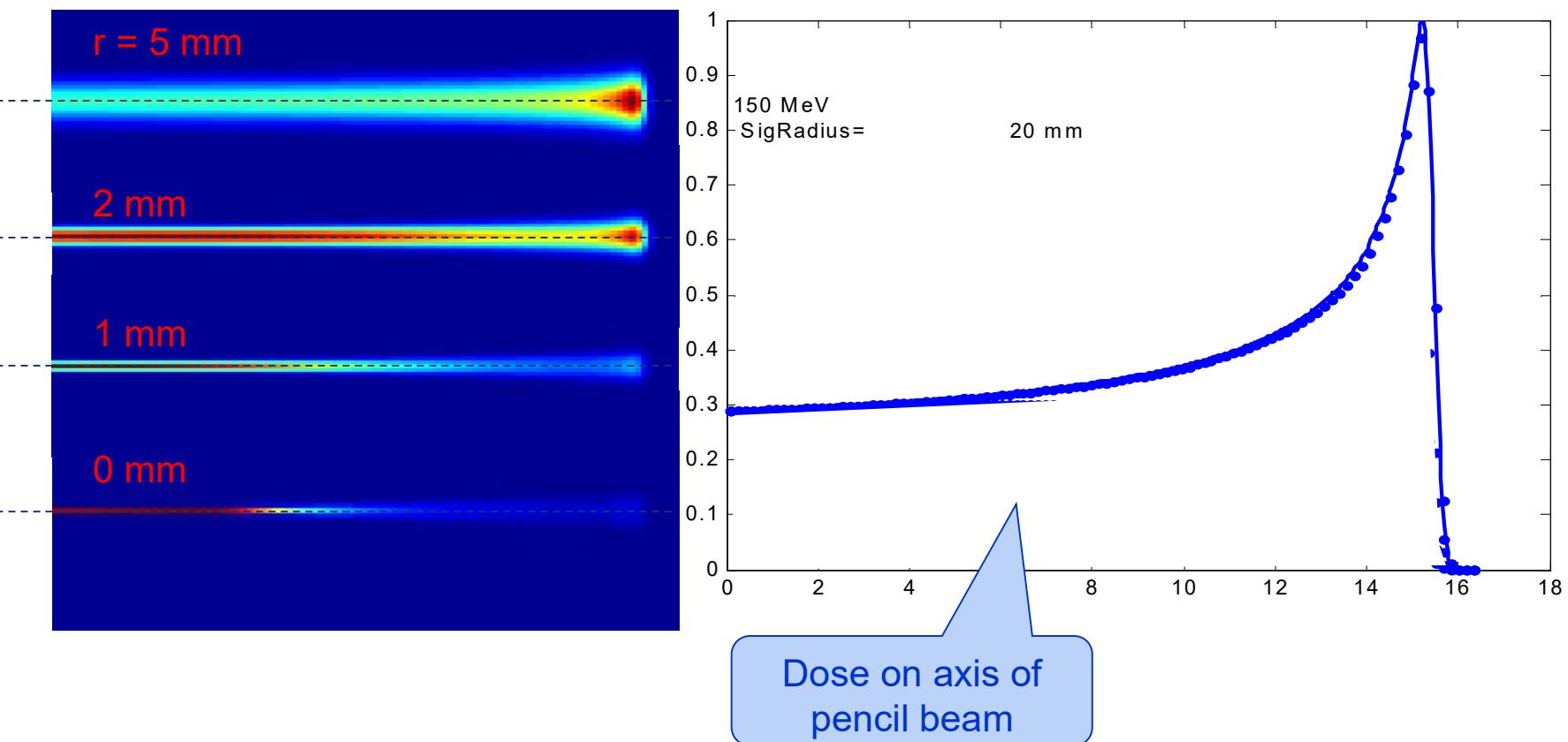
$$20-80\% \approx 2.5\% \text{ of } R$$



# Effect of scattering in a pencil beam

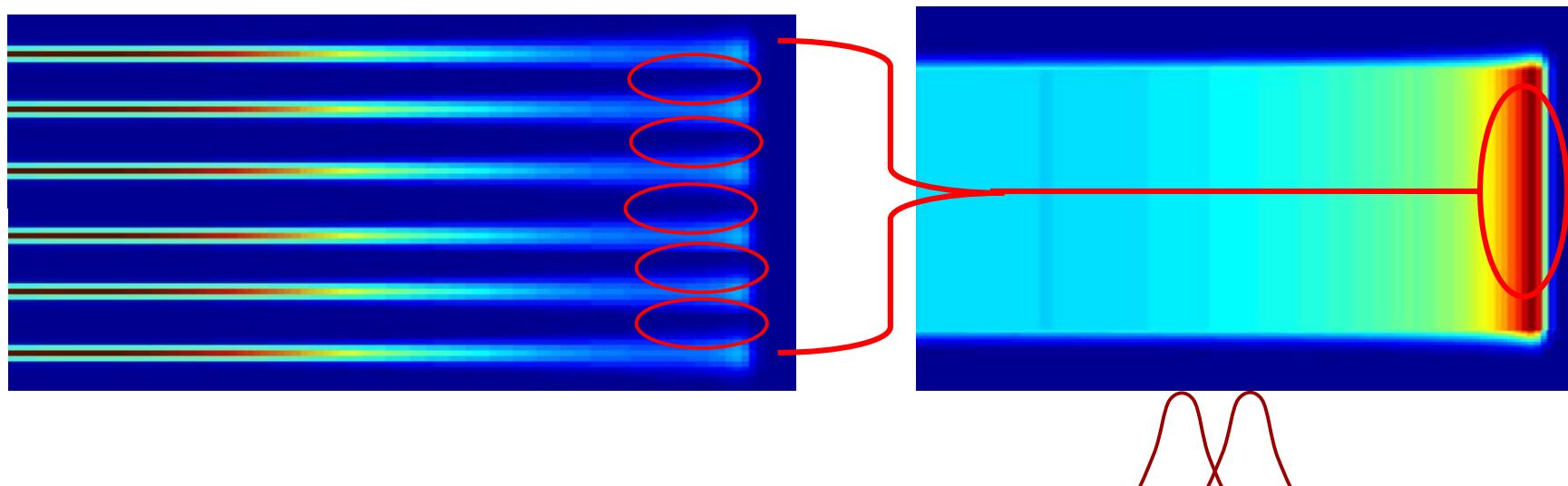
Small lesion needs small beam.....BUT...

⇒ Bragg peak depression in pencil beam



# Effect of scattering in a pencil beam

Broad beam = addition of many adjacent pencil beams



When pencil beams are located close enough:  
transversal dose tails of adjacent pencil beams add => Bragg peak „re-appears“

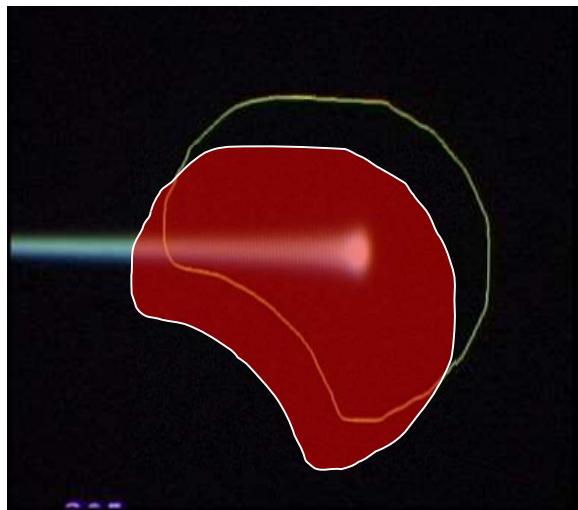
Typical beam size requirement at the iso-center:  $2\sigma_x = 2\sigma_y = 4\text{-}6 \text{ mm}$



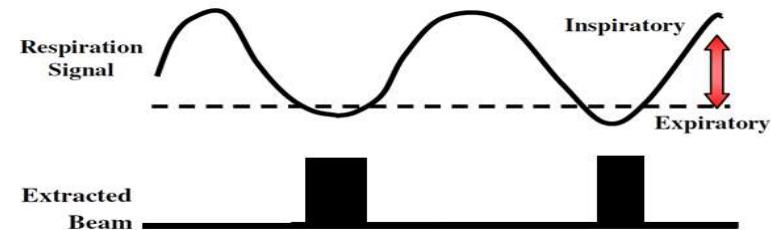
# Organ / tumor motion

## Possible solutions:

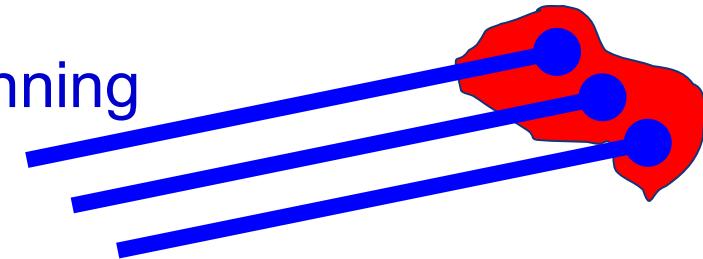
### Organ motion



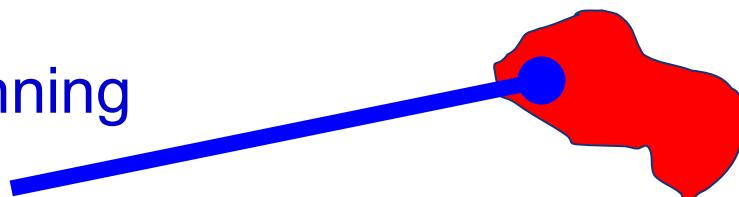
- Gating



- Adaptive scanning  
(tumor tracking)



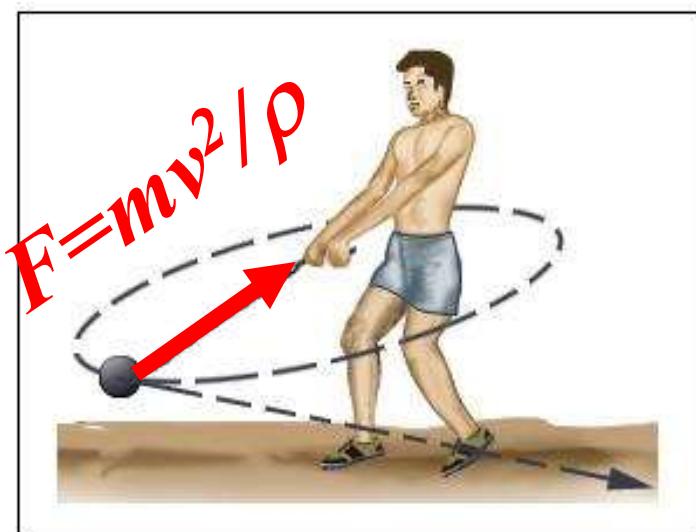
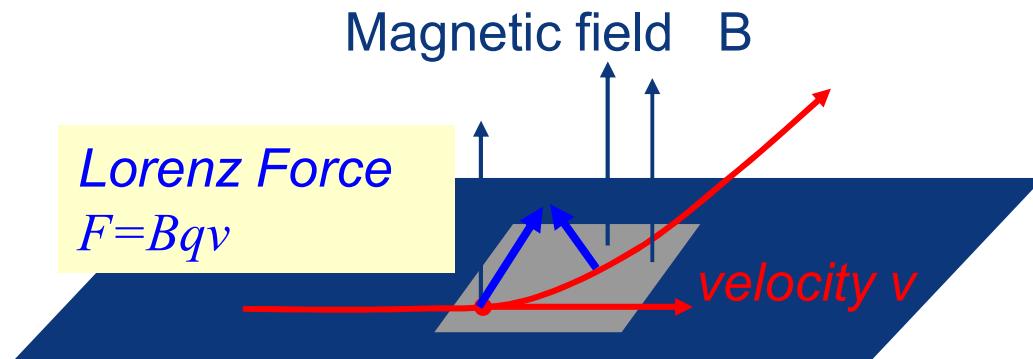
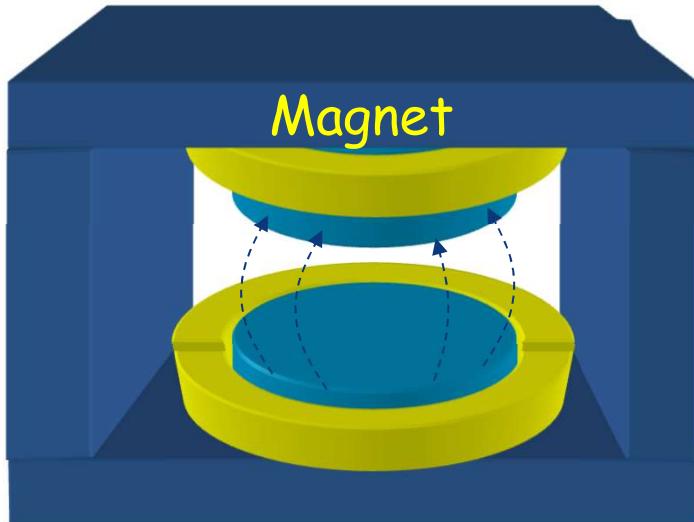
- Fast rescanning



# Beam optics properties



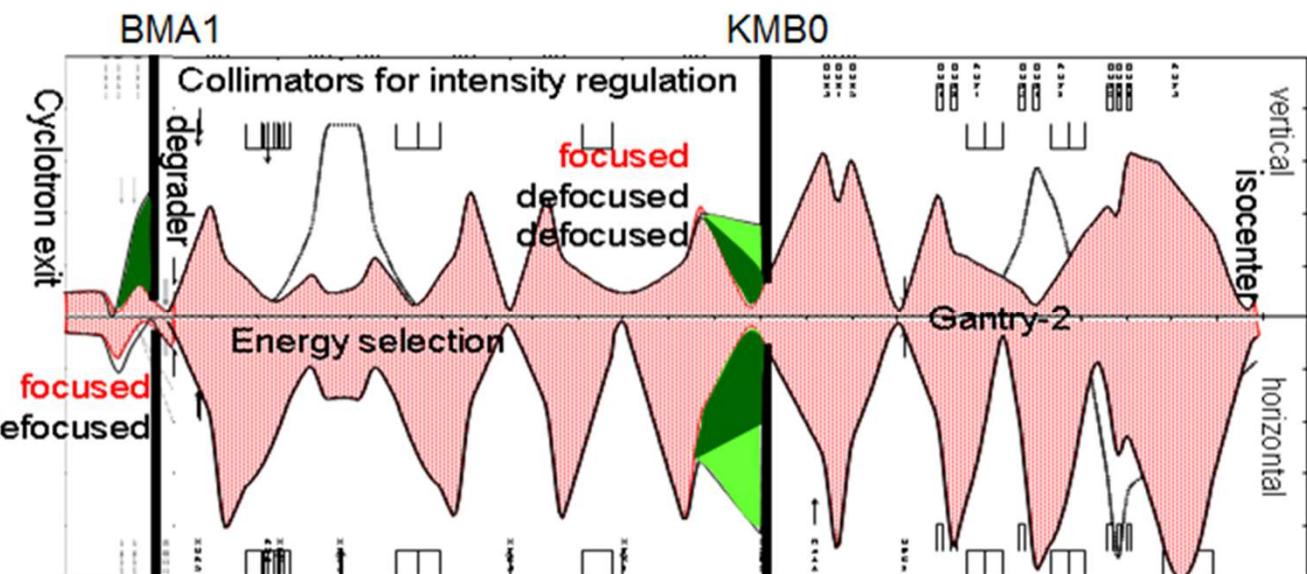
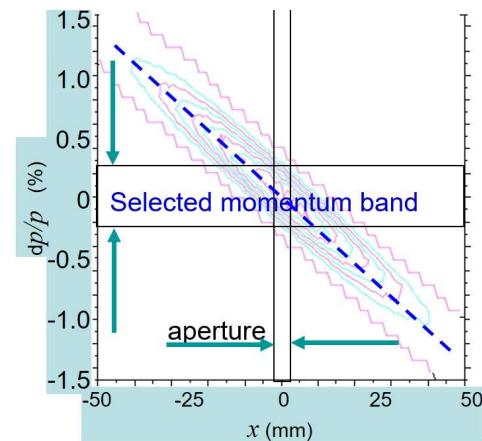
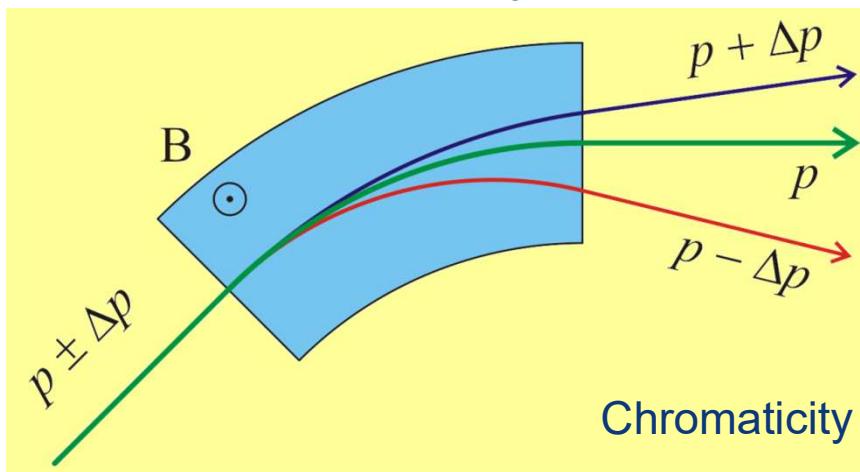
# Magnetic fields



Lorenz force = “centripetal force”  $mv^2/\rho$   
⇒ track = circular orbit with radius  $\rho$

energy  $E$  and charge  $q$   
determine magnetic rigidity  $B\rho$ :  
**magnet strength  $B$  to bend with radius  $\rho$**   
 $B\rho$  [in Tm] =  $p/e = 3.3356 p$  [in GeV]  
250 MeV p:  $B\rho = 2.4$  Tm  
450 MeV/nucl C<sup>6+</sup>:  $B\rho = 6.8$  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

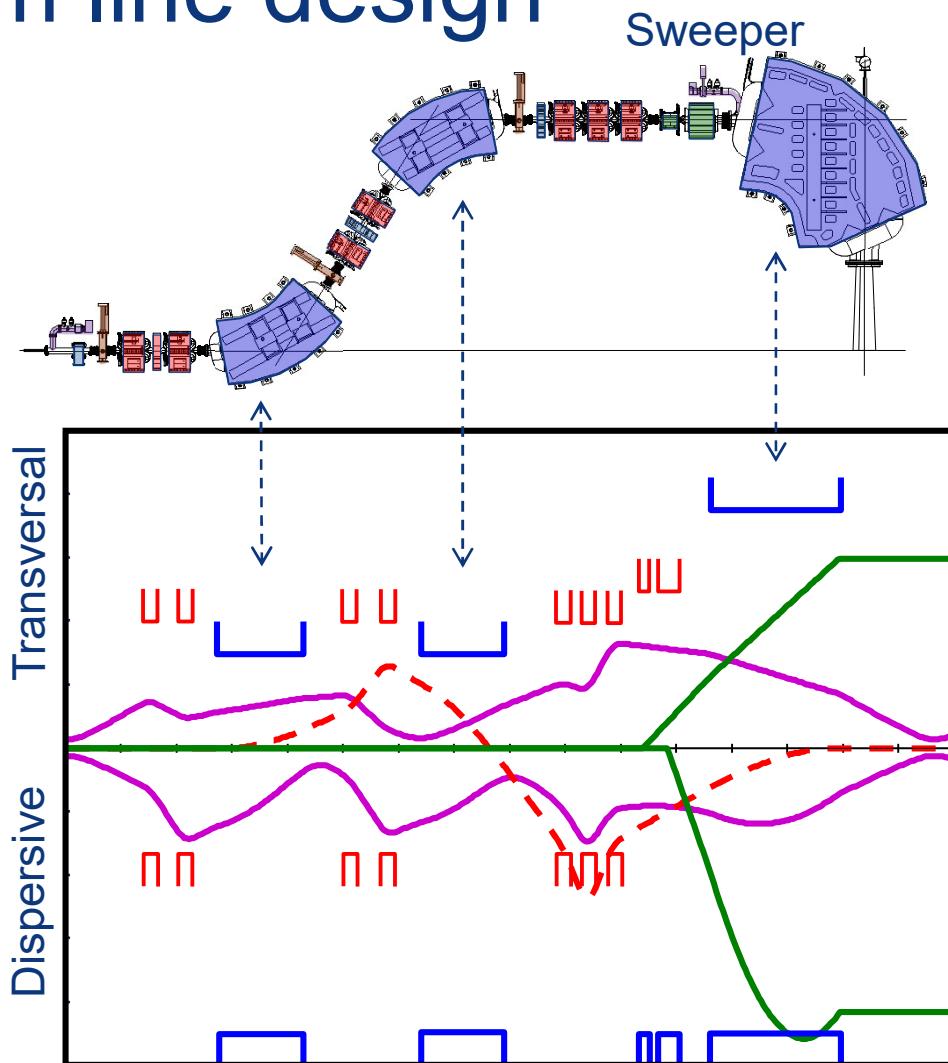
## Beam optics

- 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 through Gantry 2

Green: Action of the sweepers

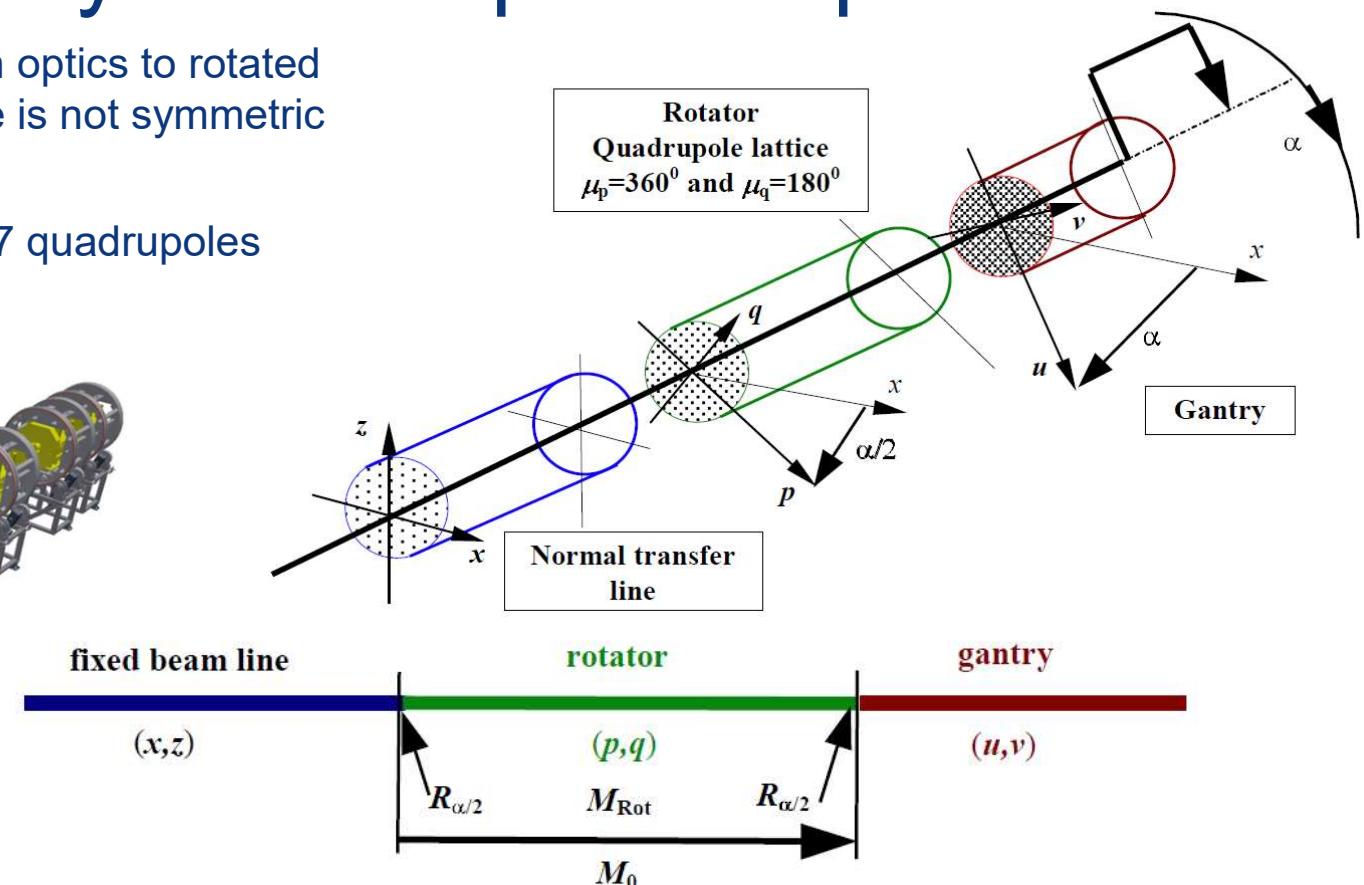
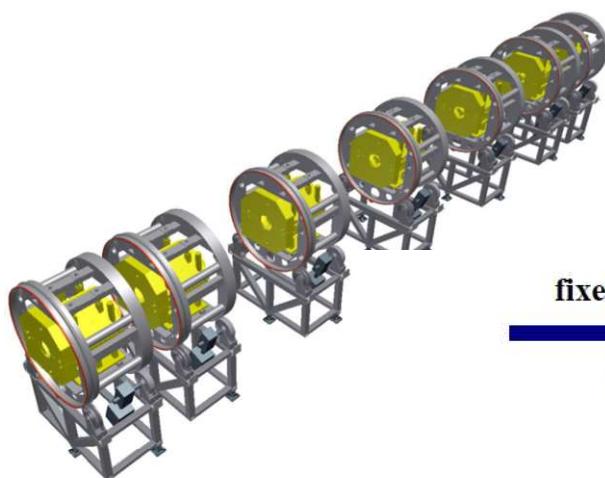
Red: Dispersion trajectory for a 1% momentum band



# Matching asymmetric phase-space

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

Example of  $\alpha/2$  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



partrec

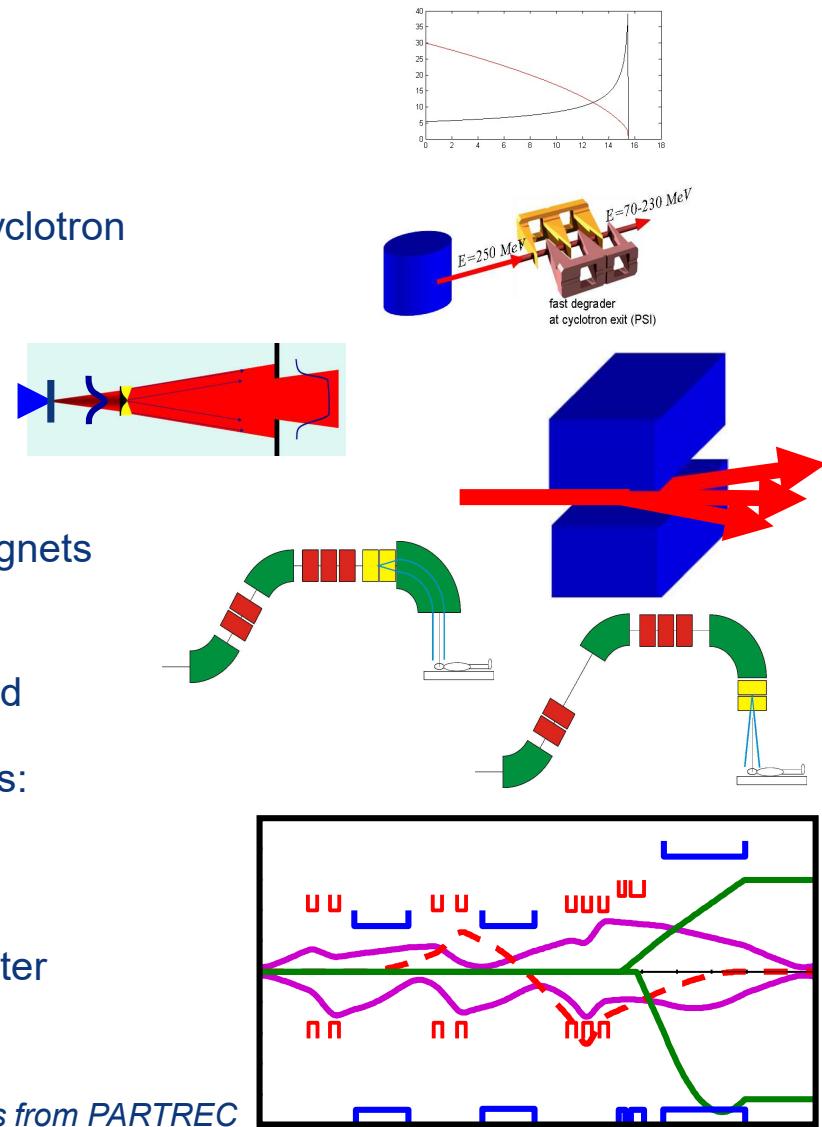
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42

# 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 pencil beam with sweeper magnets
    - Upstream or
    - Downstream of the final bend
- Necessary properties of the gantry beam optics:
  - Rotational symmetrical phase space at coupling point and iso-center
  - Imaging between coupling point and iso-center
  - Achromaticity



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Questions?