Accelerator Science and Particle Therapy

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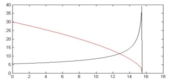
- Introduction: Hadron therapy 
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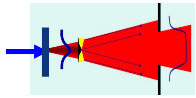
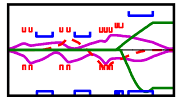
- Dose delivery techniques 
- Beam optics properties 

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Introduction: Hadron therapy

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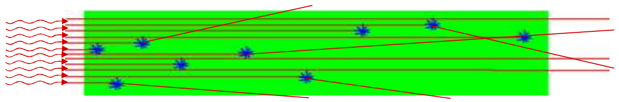
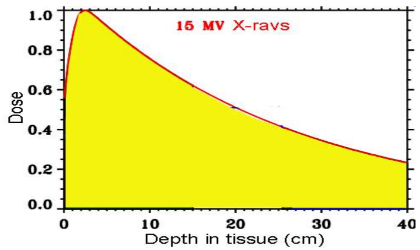
Photon (X-ray) dose



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



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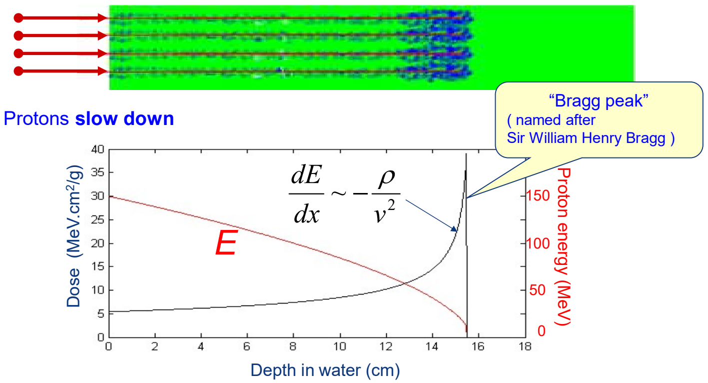
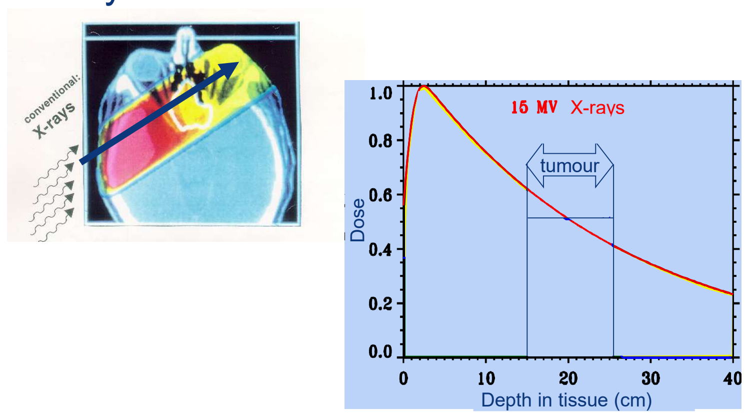
Proton depth-dose curve



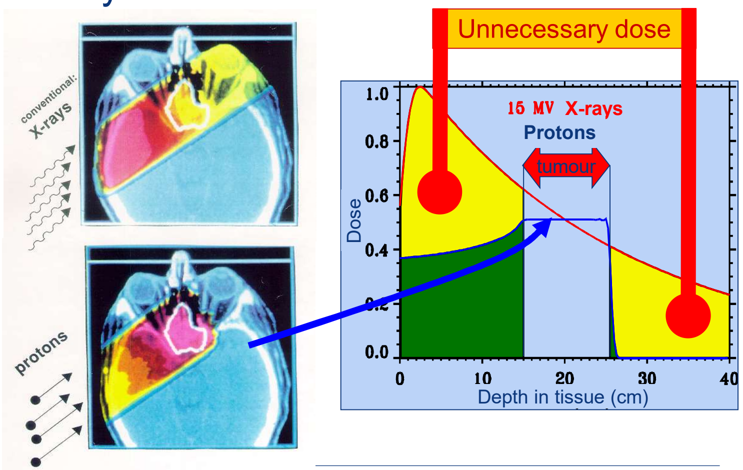
→ Energy → Penetration depth **Range in water** (cm) ≈ $E^{1.77}$ *(in MeV) / 450*

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

X-rays vs. Protons



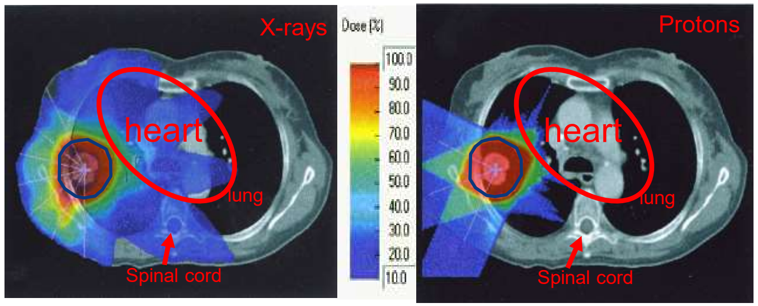
X-rays vs. Protons



X-rays vs. Protons

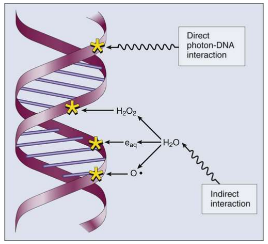
X-ray beams (IMRT)
from 7 directions

Proton beams
from 3 directions

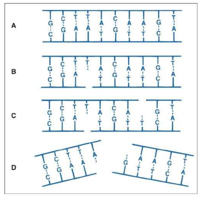


pictures: Medaustron

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

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

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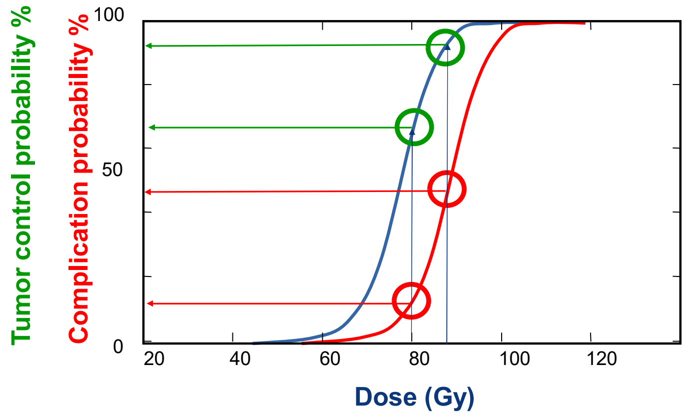
Therapeutic Window



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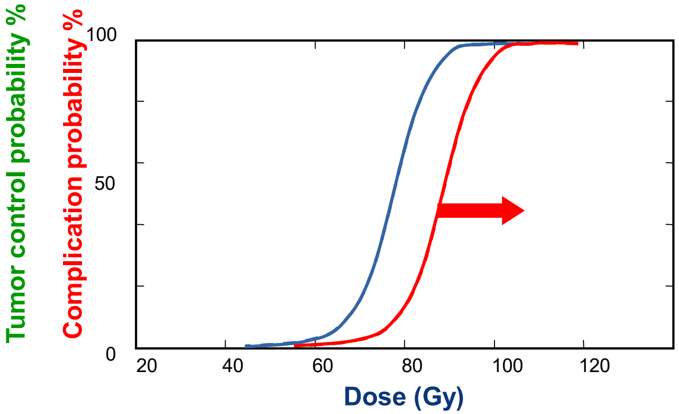
Protons irradiate less normal tissue



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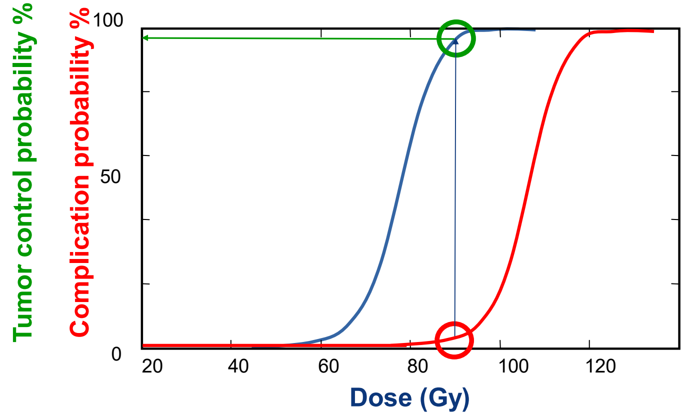
Therapeutic Window



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FLASH Therapy

- FLASH is a biological phenomenon and not defined via specific physical beam parameters
- Healthy tissue effect (not tumour tissue!)
- What have been the experimental conditions to observe a FLASH effect ?
  - Small volumes of normal tissues (a few cc)
  - Mainly with single dose (> 7-8 Gy)
  - Generally with Overall Treatment Time (OTT) < 200 ms

Conventional FLASH

25 Gy no necrosis

28 Gy | 28 Gy

31 Gy | 31 Gy

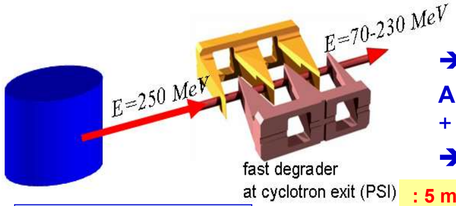
34 Gy | 34 Gy, no necrosis

Source: J. Bourhis, Clinical perspectives for FLASH Therapy

Possible facility and gantry layouts

Cyclotron driven facilities

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



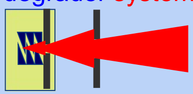
➔ Sets range

And, if fast enough + fast magnets:

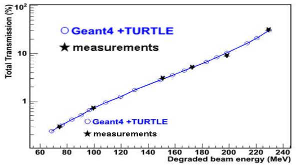
➔ also energy modulation

: 5 mm ΔRange in 50 ms

degrader system



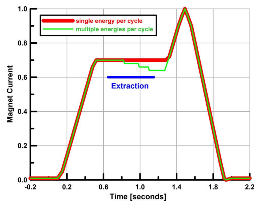
Collimators define transmitted beam size

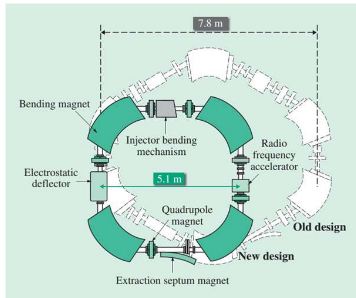


Van Goethem et al., Phys. Med. Biol. 54 (2009)5831

Synchrotrons

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

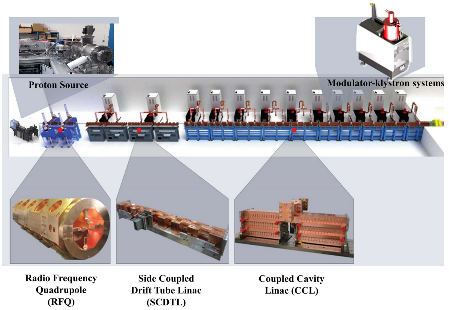




Sources: Hitachi, Loma Linda University Medical Center

Linacs

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



Source: AVO/ADAM SA

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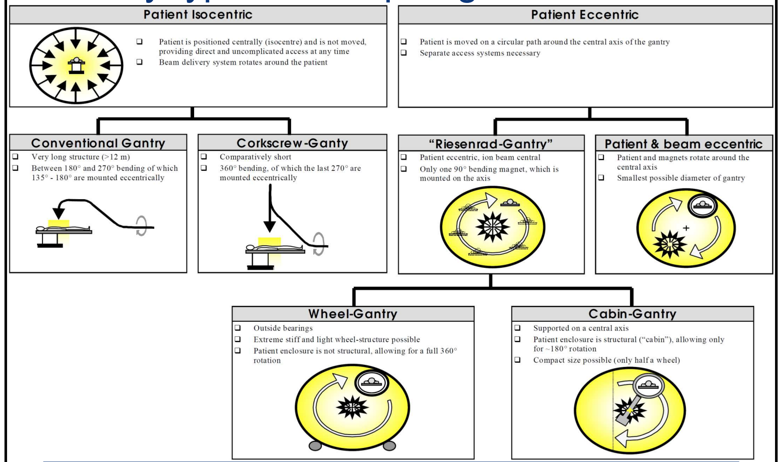
Gantry types and topologies



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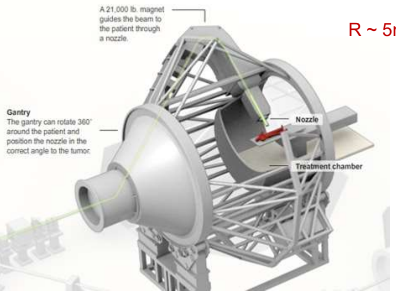
Conical gantry - Commercial standard layout



R ~ 5m

IBA
Sumitomo
Hitachi
Mitsubishi
Varian

Beam scanning downstream of the last bend

Munich

First commercial scanning-gantry of Varian in Munich

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

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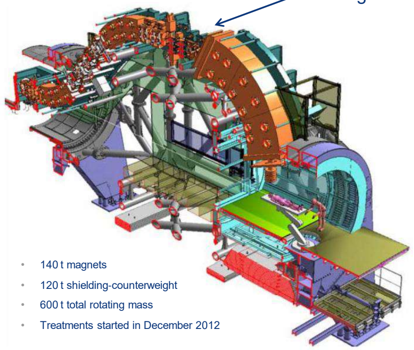
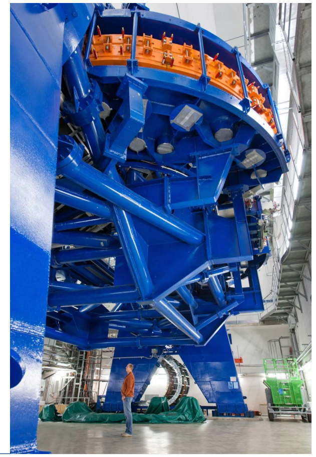
First gantry for heavy ion therapy at HIT

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

Scanner magnets



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



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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

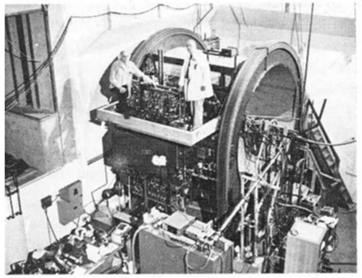
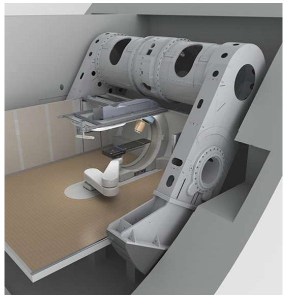


Fig. 2 Photo of the superconducting medical cyclotron on its gantry. Dr. William Powers and

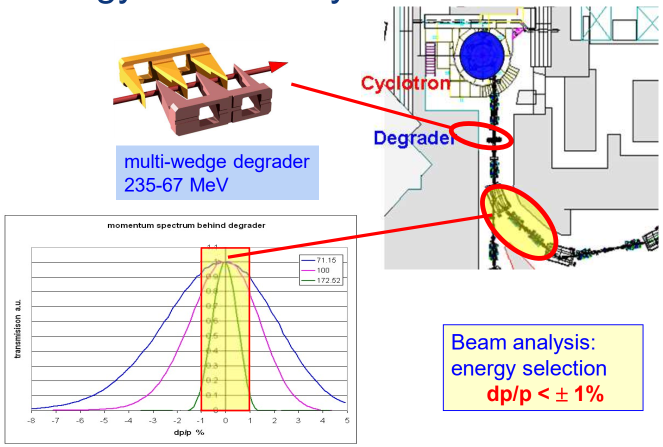
MEVION

For proton therapy
70-230 MeV
Treating patients since 2013



Dose delivery techniques

Energy selection system

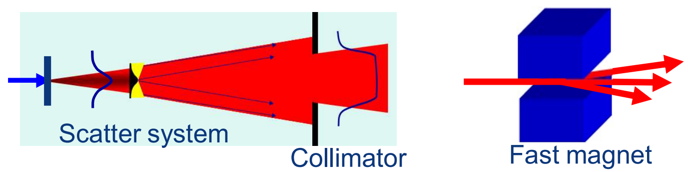


Dose delivery techniques: Width

transversal spread:

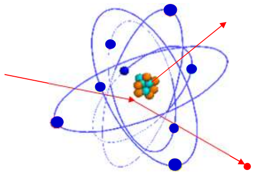
scattering

scanning



Scattering

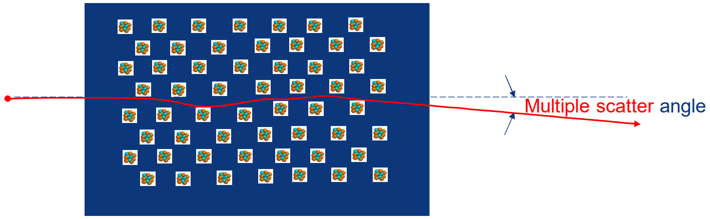
Nuclear Coulomb scattering



Nucleus is several times heavier as a proton

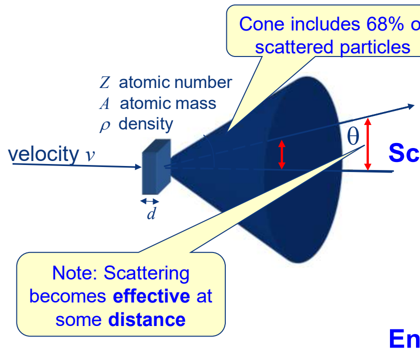
→ Almost no energy loss („elastic“)

→ Much larger deflection than from electrons



Scattering

Multiple Scattering



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

Scattering: from **nuclei.**

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

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

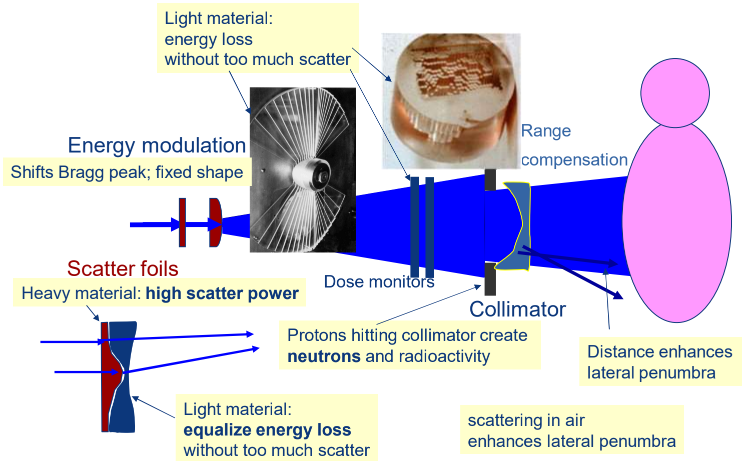
Scattering

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

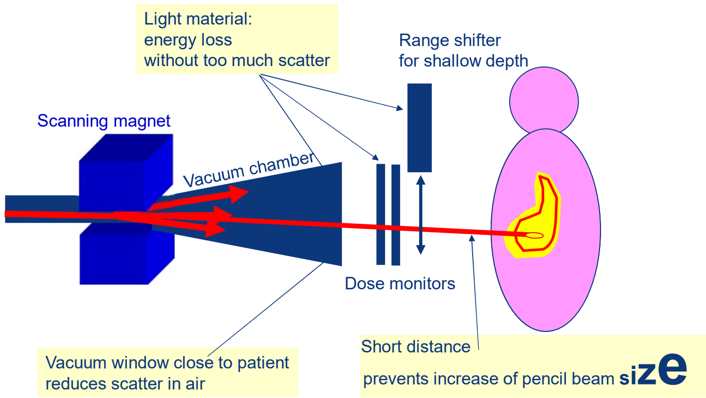
=> More scatter at heavy materials

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



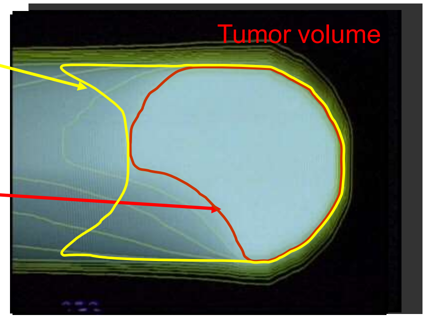
Nozzle for a scanning beam



Scanning: best dose distribution

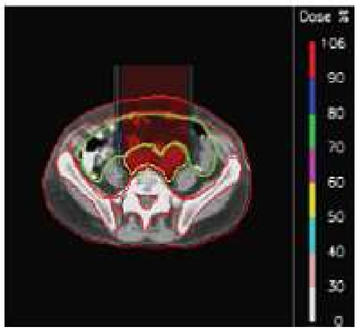
Dose distribution of scattered beam:

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

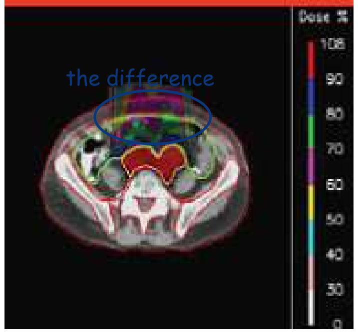


Scatter – IMPT

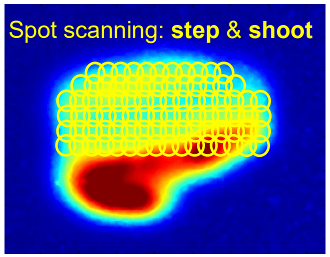
Scattered beam



Scanned beam with IMPT



Spot scanning

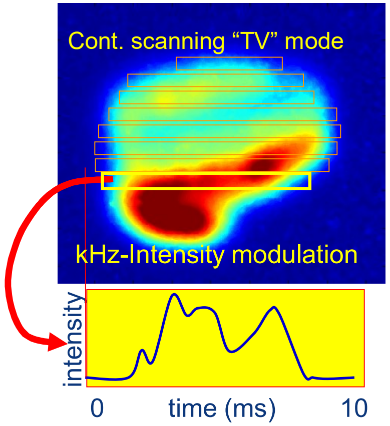


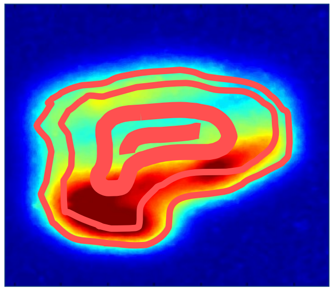
Beam size 7 mm FWHM
5 mm steps

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

~1 Gy / liter / minute

Fast pencil beam scanning in 3D



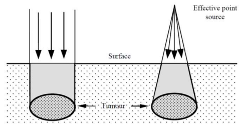


7 s for a 1 liter volume.
Target repainting:
15-30 scans / 2 min.

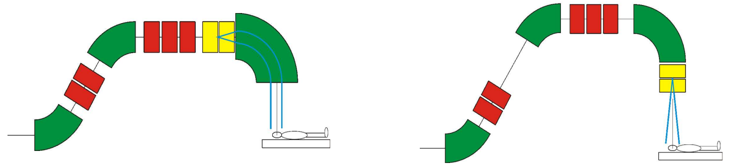
Upstream versus downstream scanning

- 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)

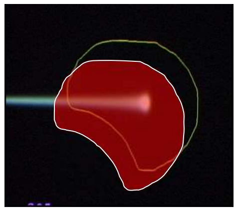


Also possible: Combination of
1 sweeper upstream
1 sweeper downstream



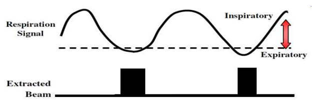
Organ / tumor motion

Organ motion

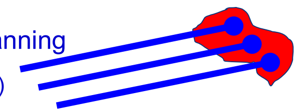


Possible solutions:

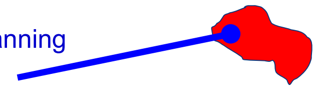
- Gating



- Adaptive scanning
  (tumor tracking)

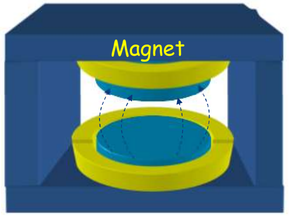


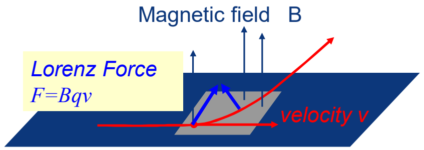
- Fast rescanning

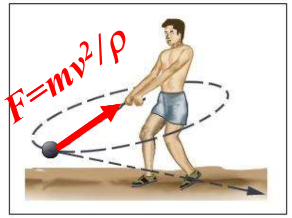


Beam optics properties

Magnetic fields



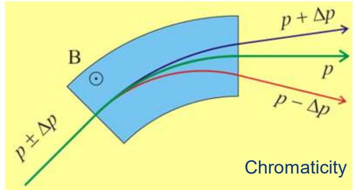


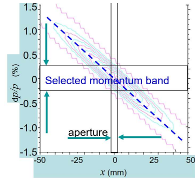


Lorenz force = "centripetal force" mv^2/ρ
⇒ track = circular orbit with radius ρ

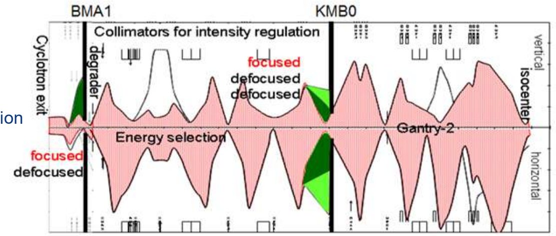
energy E and charge q
determine magnetic rigidity $B\rho$:
magnet strength B to bend with radius ρ
Bρ [in Tm] = p/e = 3.3356 p [in GeV]
250 MeV p: $B\rho$ = 2.4 Tm
450 MeV/nucl C^{6+}: $B\rho$ = 6.8 Tm

Chromaticity and dispersion suppression

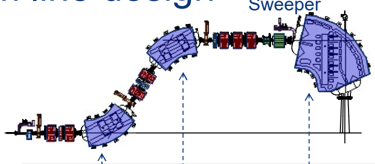




- Horizontal axis: z-position
- Vertical axis
  - above zero: $2\sigma_y$
  - below zero: $2\sigma_x$

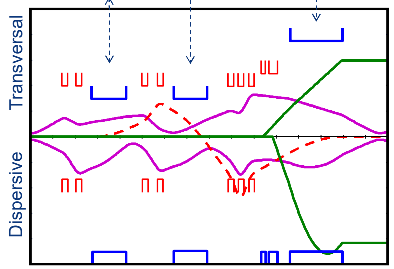


Optimal gantry beam line design



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)

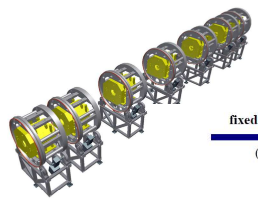


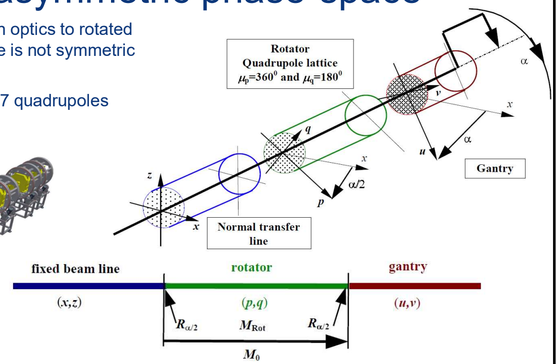
Purple: Beam envelopes trough Gantry 2
Green: Action of the sweepers
Red: Dispersion trajectory for a 1% momentum band

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

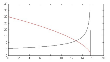




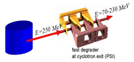
$$M_0 = \begin{pmatrix} \cos\frac{\alpha}{2} & 0 & \sin\frac{\alpha}{2} & 0 \\ 0 & \cos\frac{\alpha}{2} & 0 & \sin\frac{\alpha}{2} \\ -\sin\frac{\alpha}{2} & 0 & \cos\frac{\alpha}{2} & 0 \\ 0 & -\sin\frac{\alpha}{2} & 0 & \cos\frac{\alpha}{2} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 &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

M. Benedikt, CERN

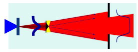
Summary

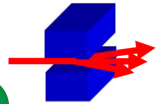


- Proton therapy makes use of the Bragg peak

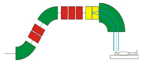


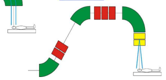
- In most facilities the beam is accelerated in a cyclotron and the energy is reduced by a degrader
- The target can be



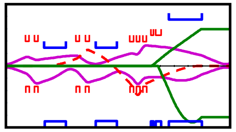


  - irradiated by a scattered beam or
  - scanned by a pensil beam with sweeper magnets
    - Upstream or
    - Downstream of the final bend





- 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



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