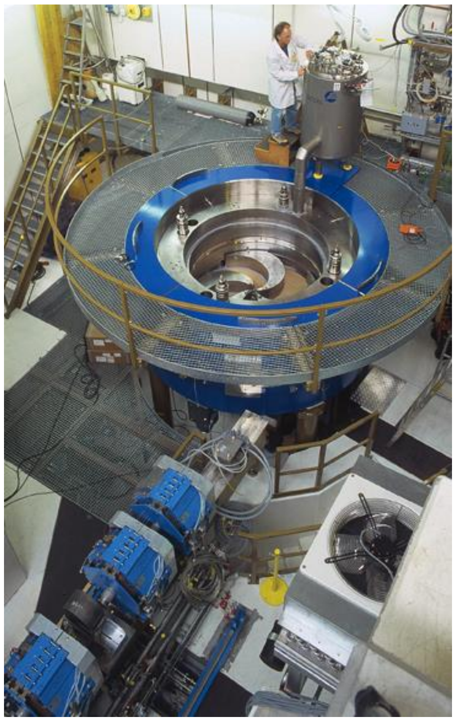
PAUL SCHERRER INSTITUT

PSI

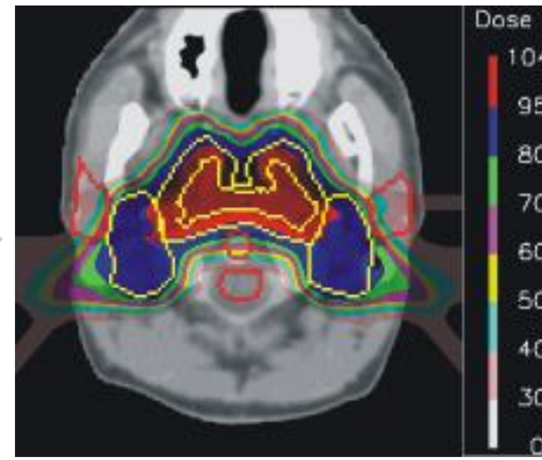
Oxana Actis :: Beam Technology Development :: Centre for Proton therapy :: PSI

Beam Delivery System

OMA School on Medical Accelerator
5-9 June 2017, Fondazione CNAO

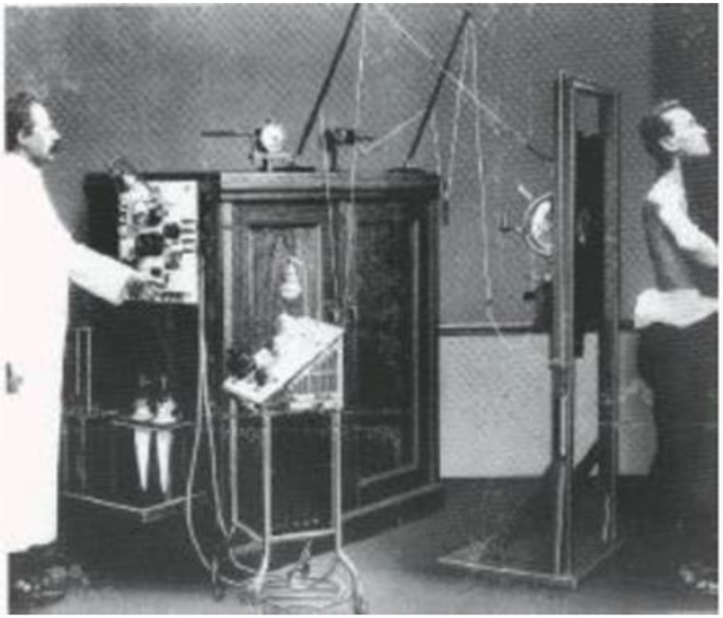


Beam Delivery System



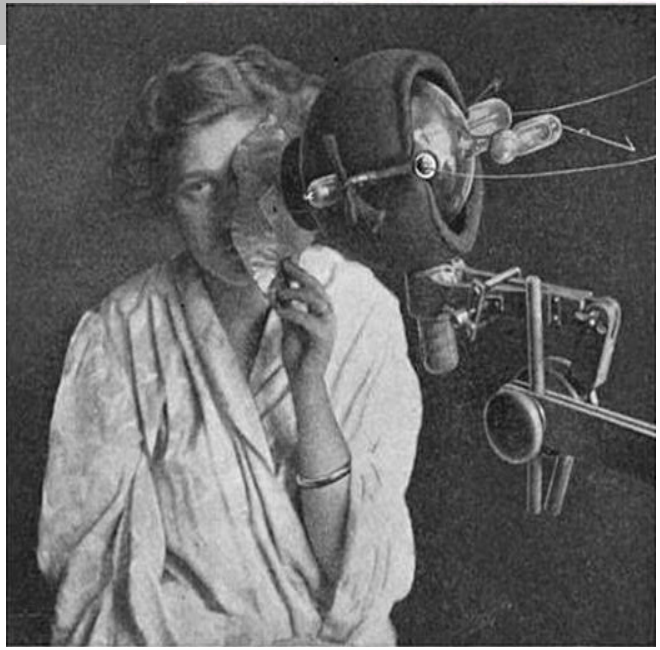
Where it started ...

Very quickly after Roentgen's discovery of X-rays (1895) and Marie Curie's discovery of radioactivity they were both used to treat disease including cancer

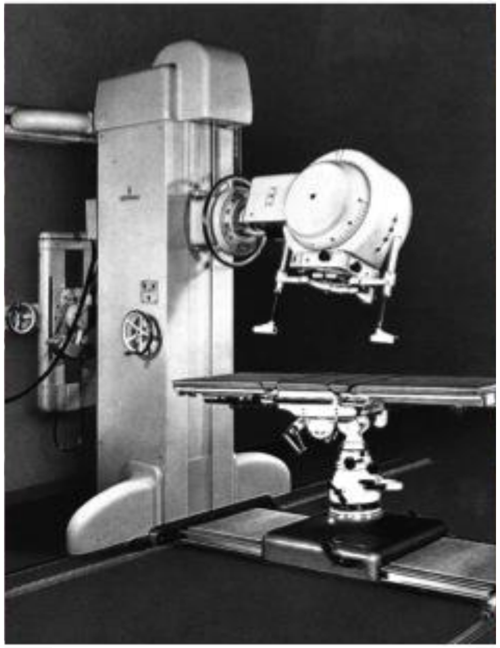


Freund/Schiff 1896 – skin treatments
Emil Grubbe 1897 – cancer treatment
Herbert Jackson 1896 – use of electron focusing

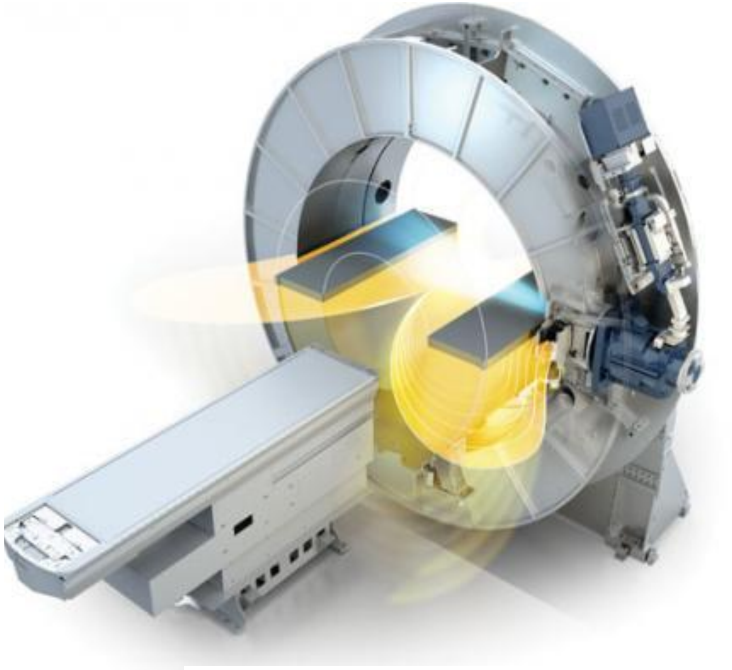
Evolution of x-ray radiotherapy devices



X-ray device



Gammatron Siemens



MR-Linac Elekta

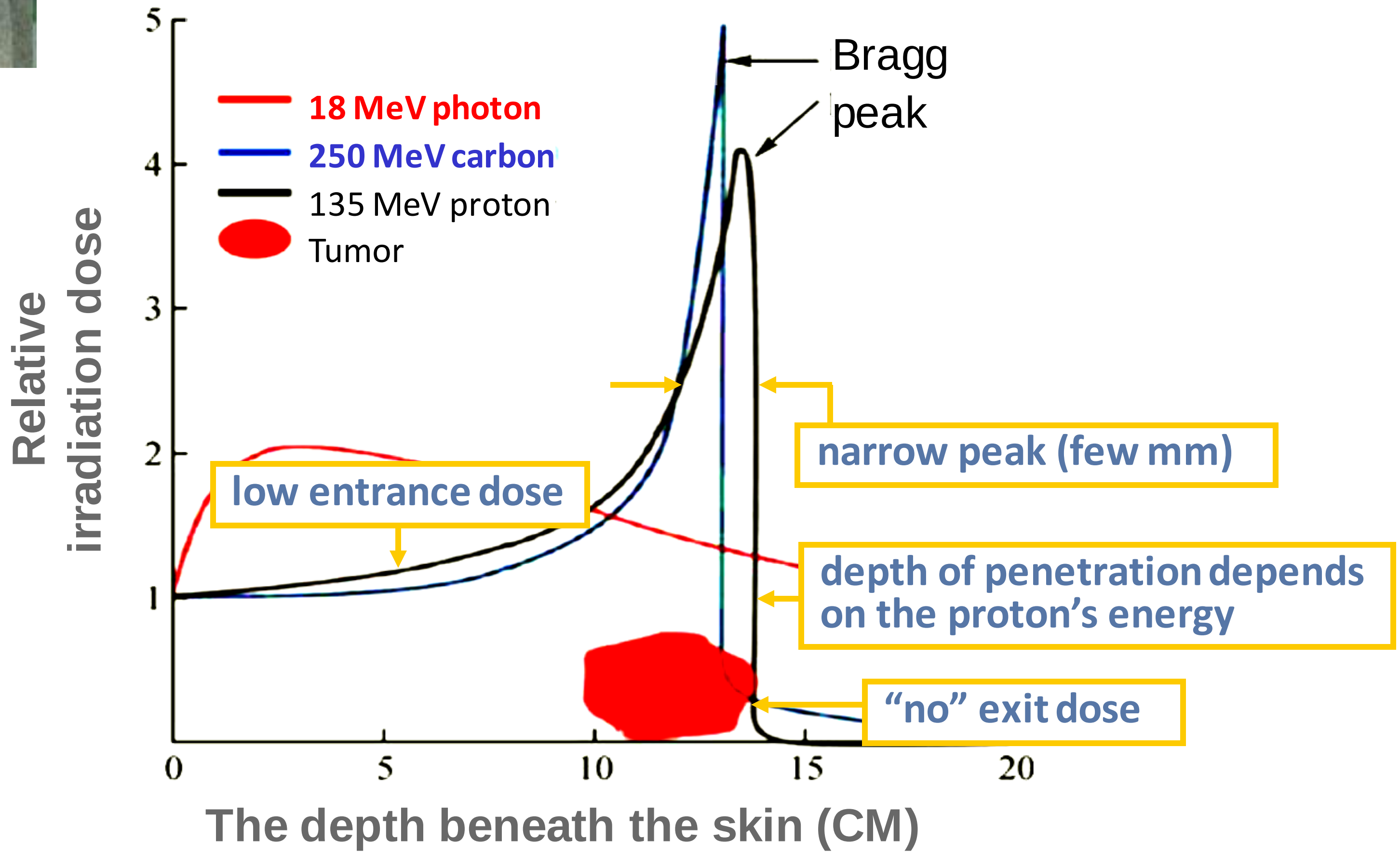
1900 → 1950 → 2016

Particle therapy

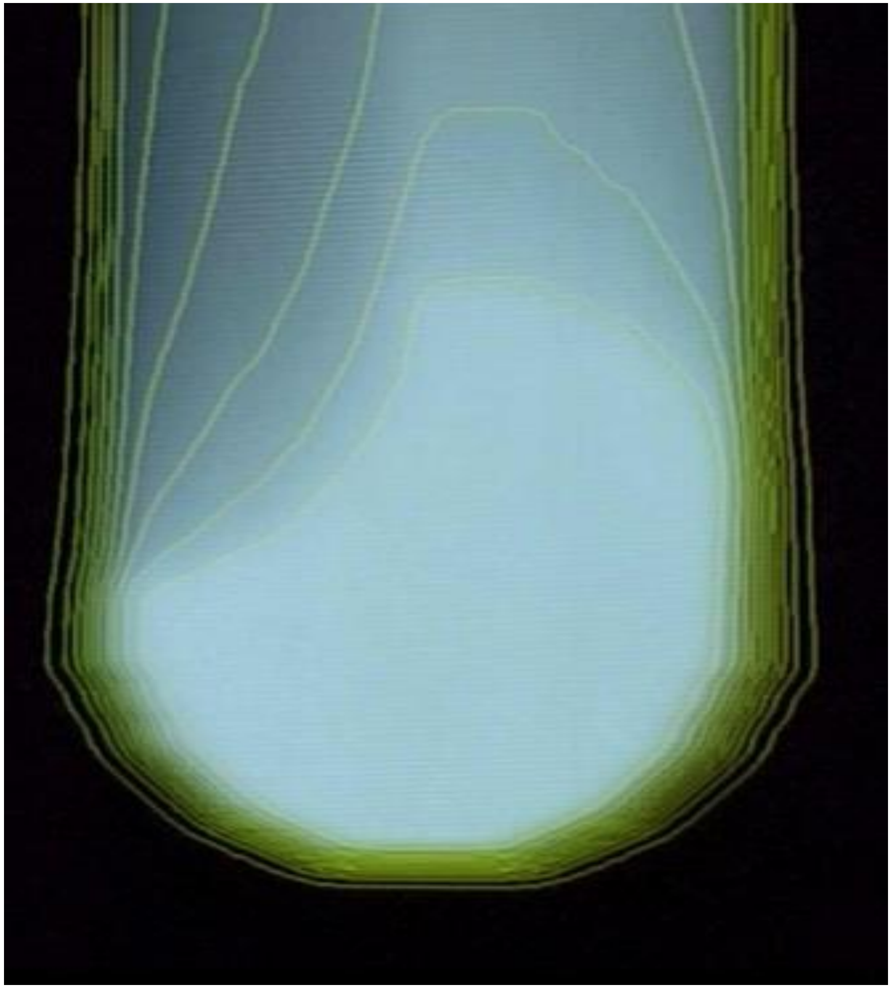
Robert R Wilson:

Radiological Use of Fast Protons

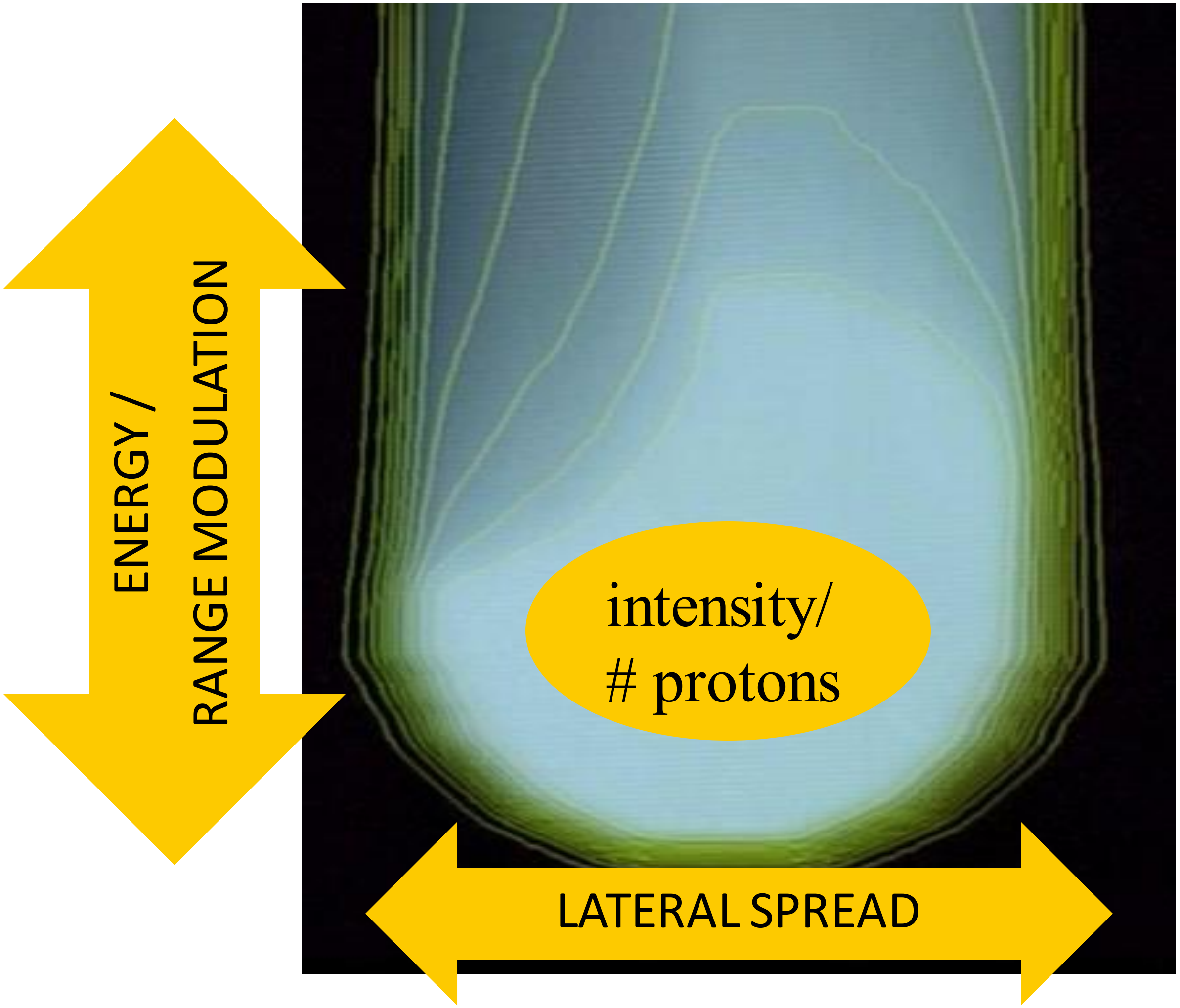
Radiology, **47**:487-491 **(1946)**



Goal- conformal 3D dose distribution

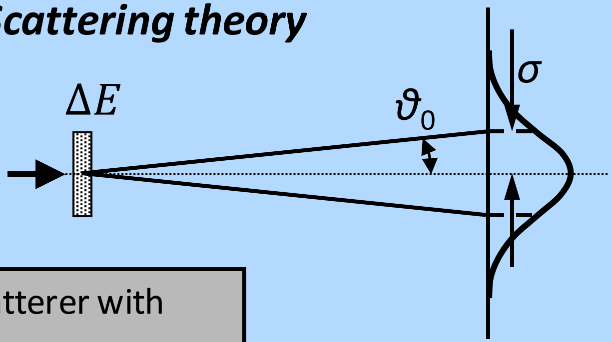


Goal- conformal 3D dose distribution



Lateral spread: scattering system

Scattering theory



$$\theta_0 \propto Z/\sqrt{A}$$

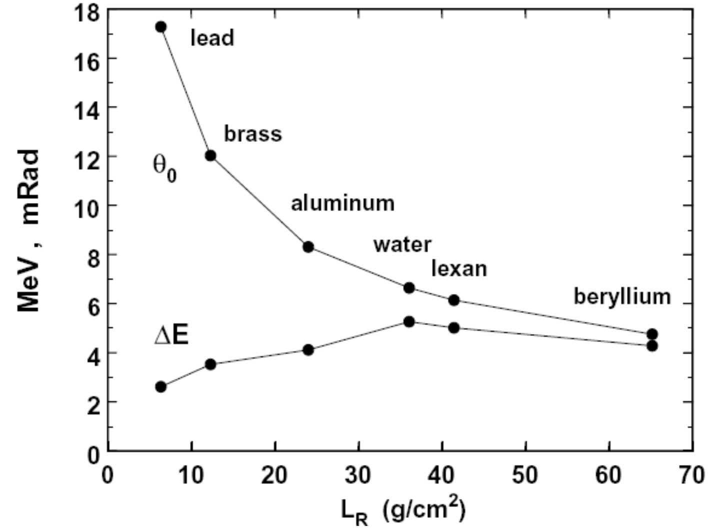
$$\Delta E \propto Z/A$$

Multiple Coulomb Scattering MCS

Scatterer with

A: Mass number

Z: Atomic number



Energy loss and multiple scattering for 160 MeV protons incident on 1 g/cm^2 of various materials

L_R: radiation length

For scattering with minimum energy loss → **Lead**

To reduce energy with minimum scattering → **Beryllium.**

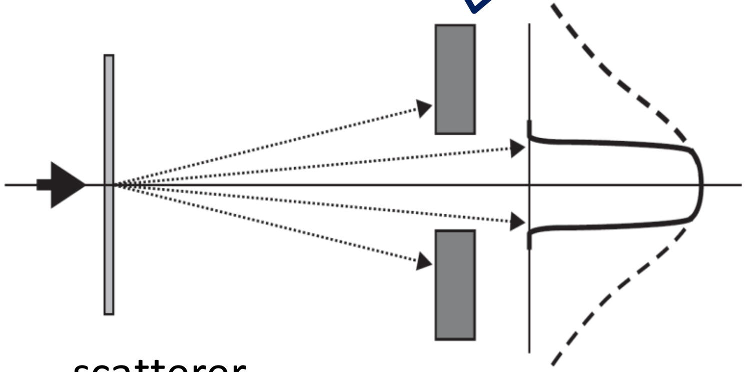
Lateral spread – flat scattering

High Z - material (lead, tantalum)
- Largest amount of scattering
- Lowest energy (range) loss

- Needs **large scattering angle** to have enough flat profile inside useful radius, typ. ±2.5%
- Constant particle fluence (homogeneous dose field)
- Field size and depth dependent solutions

collimator / multi-leaf collimator (MLC) is needed to conform dose to target

Single scattering
- Good penumbra
- Low efficiency → small field



Typically used for shallow small tumors like eye

H. Paganetti, Proton Therapy Physics

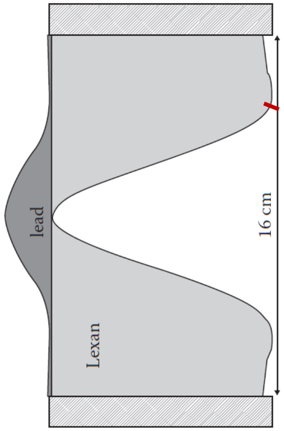
Lateral spread – double contoured scattering

- Increase efficiency by 2nd scatterer that flattens out profile at given distance
- Add low-Z material to compensate energy loss at edges
- Not optimal penumbra

collimator / multi-leaf collimator (MLC) is needed to conform dose to target

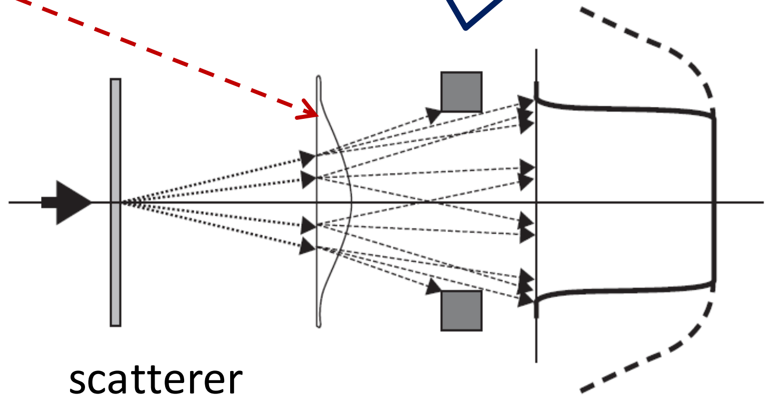
Scattering technique:

Simple concept but complex practical realisation



"Double contoured 2nd scatterer"

p-beam



scatterer

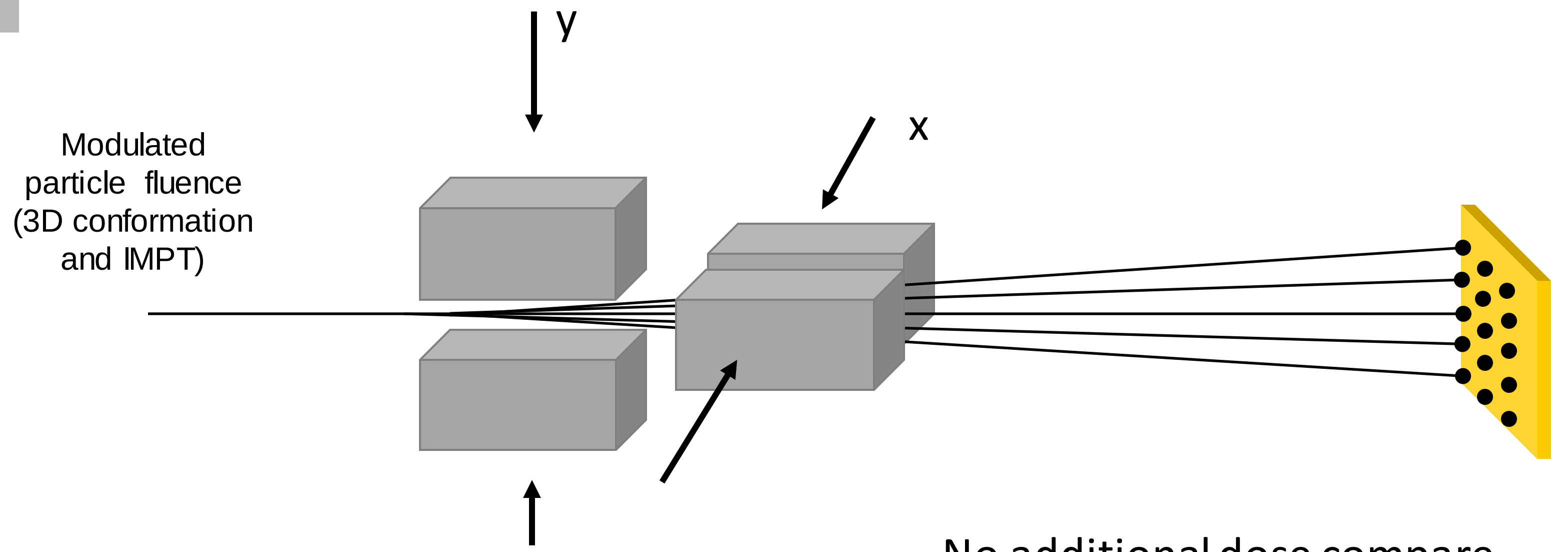
Contoured scatterer systems are the predominant technique for passive scattering

H. Paganetti, Proton Therapy Physics

Lateral spread – active scanning

Main concept:

Protons are charged particles → can be deflected in magnetic fields



Scanning:

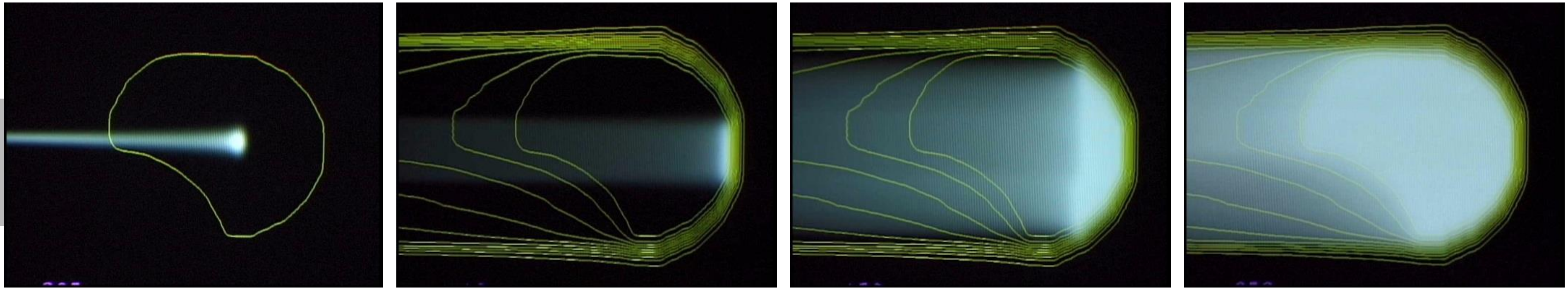
- Magnetic beam motion
- Scanning magnet combined with patient table motion (e.g. Gantry 1, PSI)

No additional dose compare to scattering + collimation

Performance issues:

- Precision of the dose shaping
- Scanning speed

Feasibility of spot scanning 1989



Experimental set-up to demonstrate technical feasibility of spot scanning with protons (1989)

- Horizontal beam line with
- Beam scanning in only one direction (wobbler magnet)
- Range shifter for energy modulation

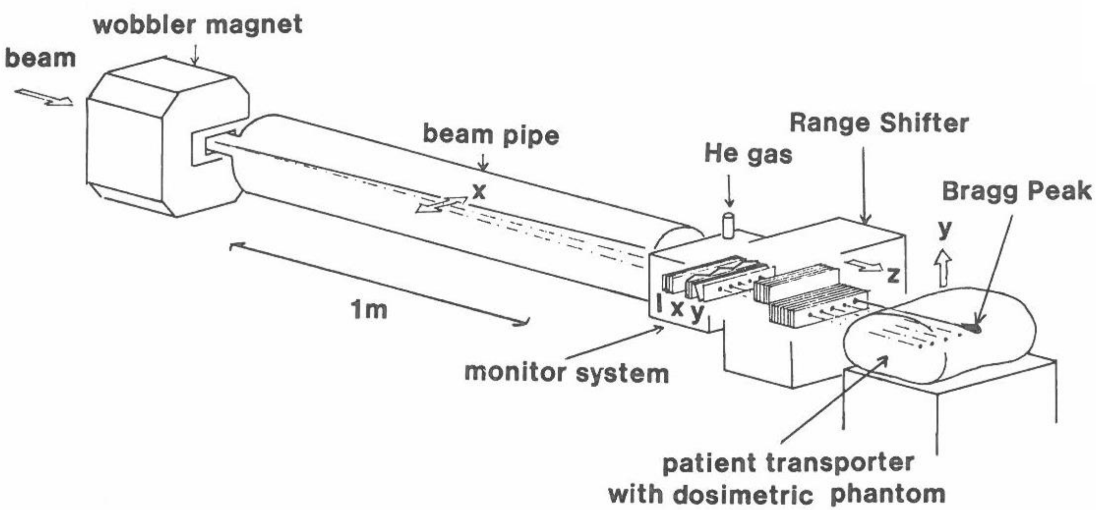


Fig. 4: X ray film irradiated with the 200 MeV proton beam using the spot scanning method.

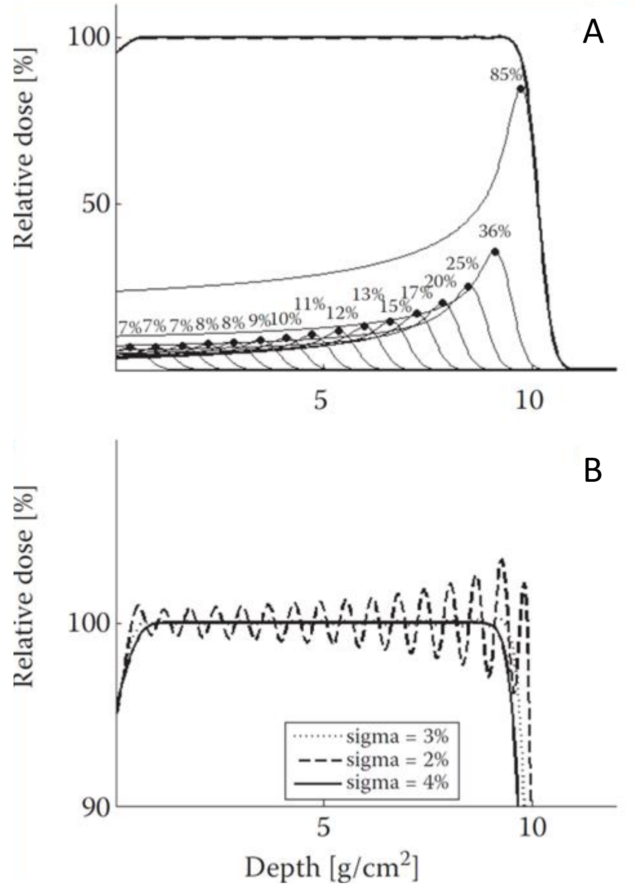
Range modulation and SOBP construction

Mono-energetic Bragg peak covers only part of the target

- Modulate range (energy) of protons
- Spread-out Bragg peak SOBP

- Parameters affecting uniform dose:
- Weight of each Bragg peak (*A*)
- Range spacing between different energies
- Momentum spread in pristine peak (*B*)

- Weights (w_i) of pristine Bragg peaks determined by numerical optimization Algorithm



$$SOBP(d) = \sum_{i=1}^{N} w_i \cdot BP_i(d)$$

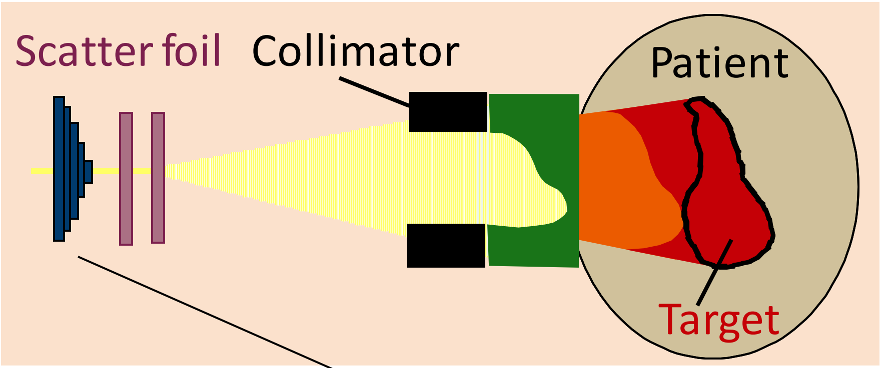
d: Depth

N: Number of different Bragg peaks

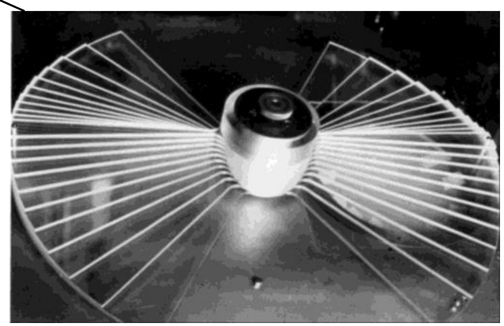
BP_i: Depthdose curve of mono-energetic beam

Usually there are ambiguous solutions for weights (w_i):

Energy modulation: 'traditional'



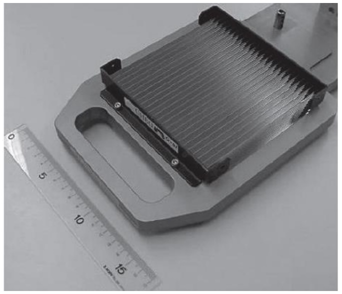
Range modulator wheel

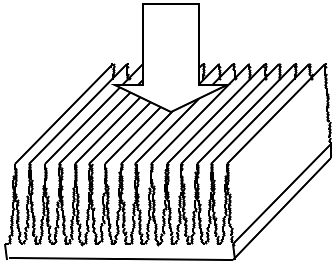


- Fast (~ 100 ms / cycle)
- SOBP mixing (quasi-static)
- Size and rotation speed depend on position
- Must be designed for each SOBP extent
- Not of interest for scanning

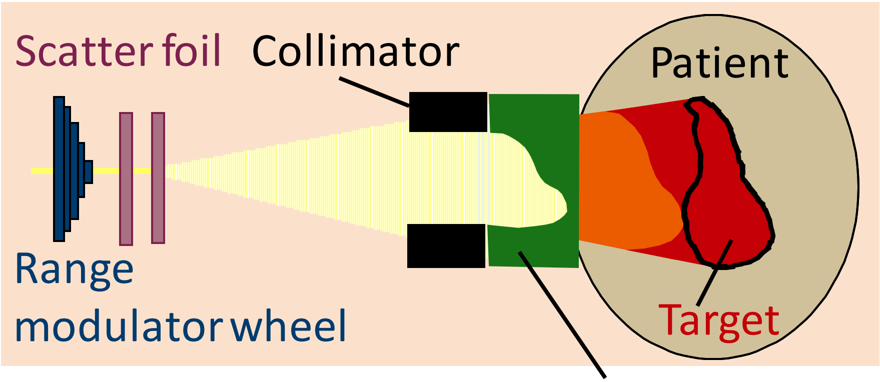
Ridge filter

- Miniature structure blurred by angular confusion
- Generate static SOBP energy mix
  - Must be designed for each: energy - SOBP extent - field size
  - Concern: Angular confusion of the beam → worse penumbra
  - Optional in scanning (carbon ion): broadening Bragg peak

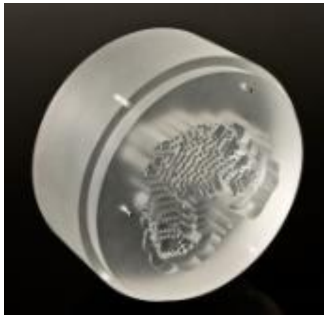




Energy modulation: 'traditional'



Compensator

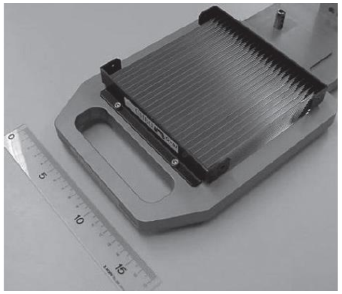


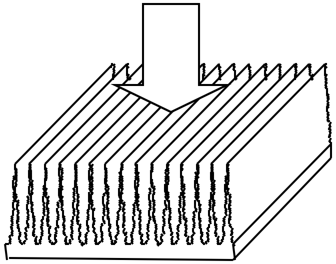
- Conform distal fall-off to target
- Smearing process to compensate for position errors
- Overshoot healthy tissue is necessary to ensure target coverage

Individual production for each field

Ridge filter

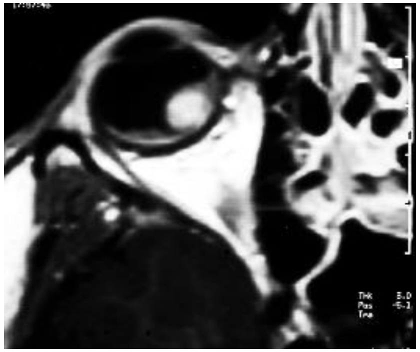
- Miniature structure blurred by angular confusion
- Generate static SOBP energy mix
  - Must be designed for each: energy - SOBP extent - field size
  - Concern: Angular confusion of the beam → worse penumbra
  - Optional in scanning (carbon ion): broadening Bragg peak





Example of of a scattering system: PSI OPTIS2

- Eye melanomas
- More than 6000 patients treated since 1984
- 4 fractions (all in one week)
- Local control 99%
- Survival 90%
- Upgrade from OPTIS to OPTIS2 in 2010



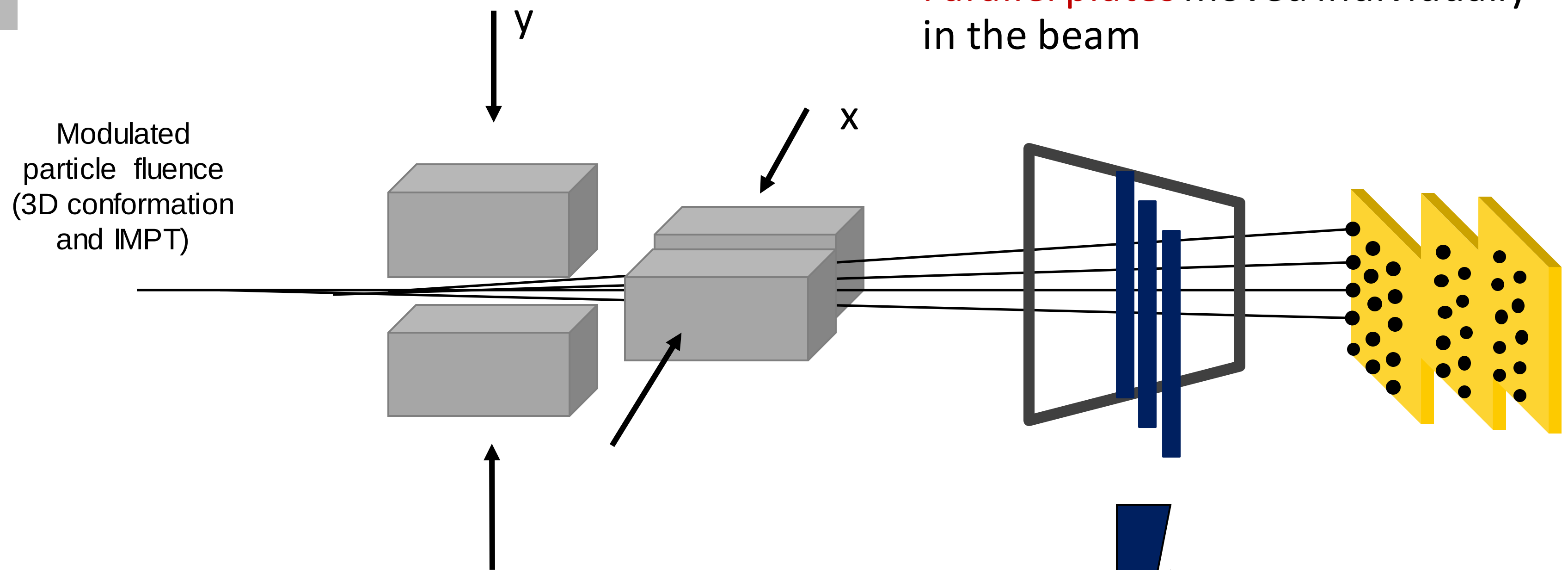
Down stream energy modulation

Down stream:

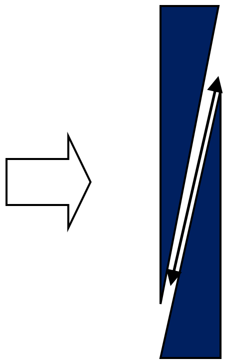
range shifters (e.g. Gantry 1, PSI)

Change of range in binary steps (regular or logarithmic step size)

Parallel plates moved individually in the beam



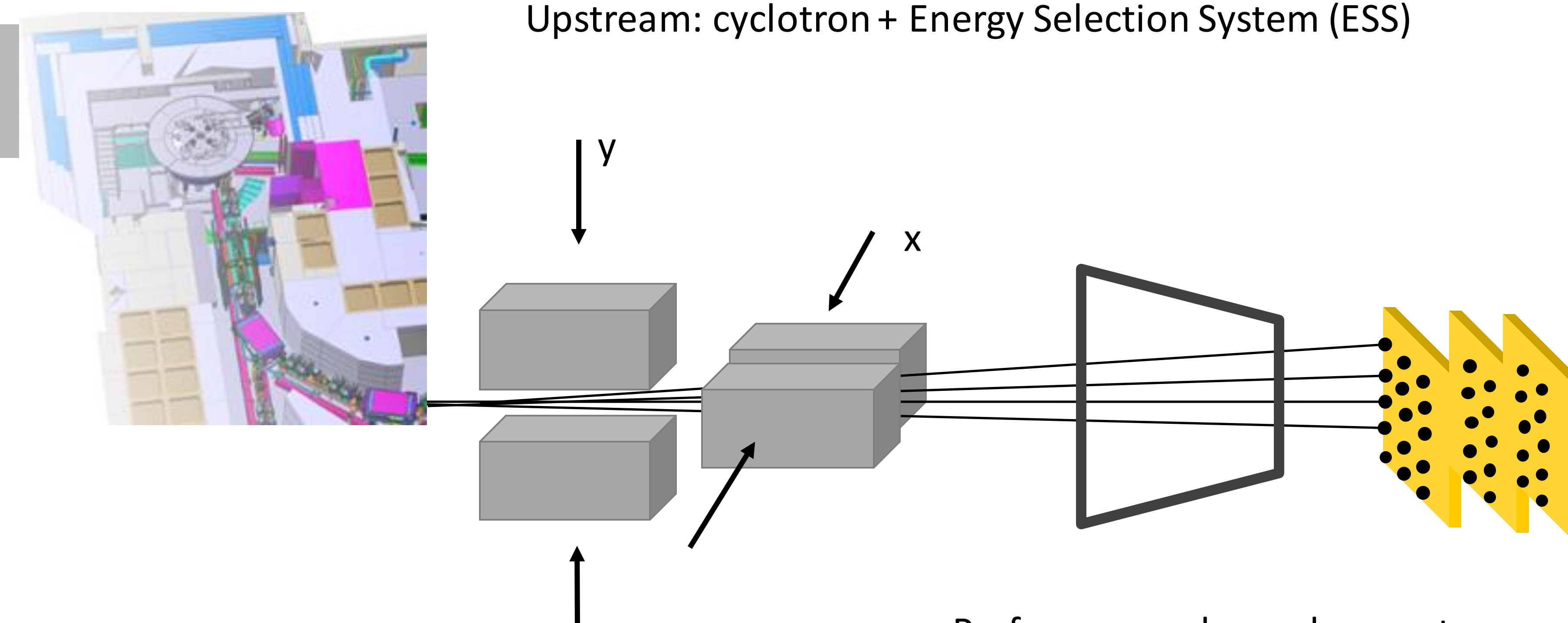
- fastest method
- penumbra degradation
- extra neutron dose, but less than by scattering + collimation



Continuous range variation (e.g. moving wedges)

Energy modulation: upstream

Upstream: cyclotron + Energy Selection System (ESS)



- degrader system is required
- beam at ISO as selected at ESS
- Can be used in a combination with upstream energy changes (e.g. Gantry 1)

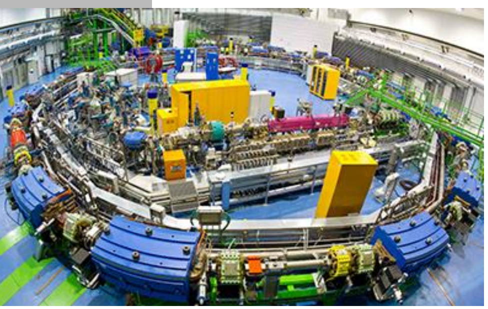
Performance depend on system magnets/power supply design

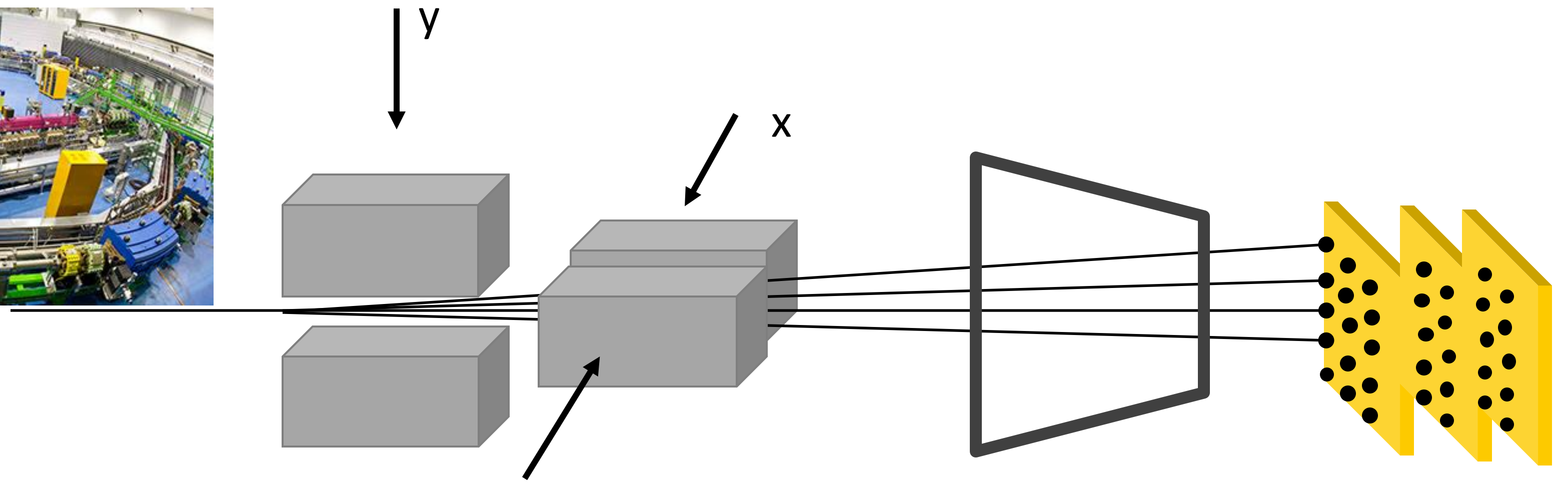
Can such a system be fast enouth ?

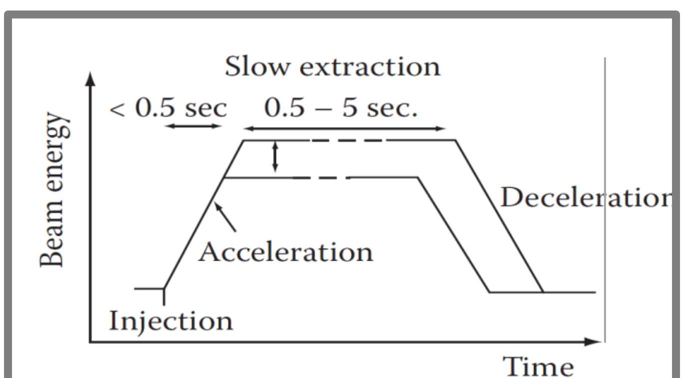
Typical energy switching time ~1 s
The fastest system – 100 ms

Energy modulation

Upstream: synchrotron





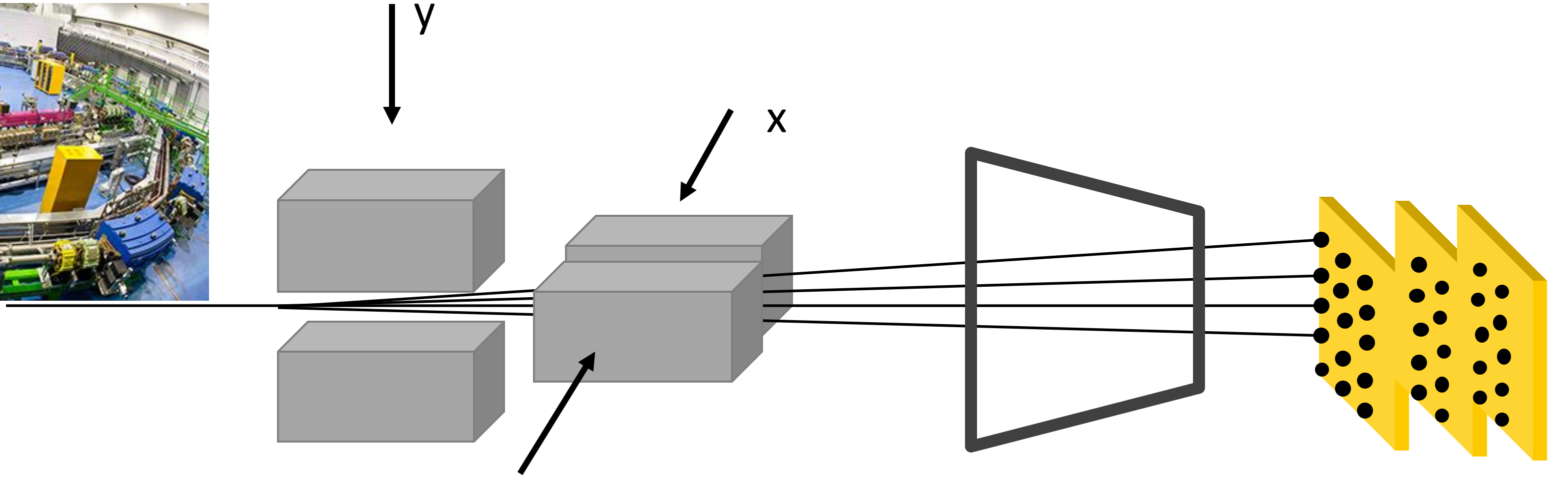


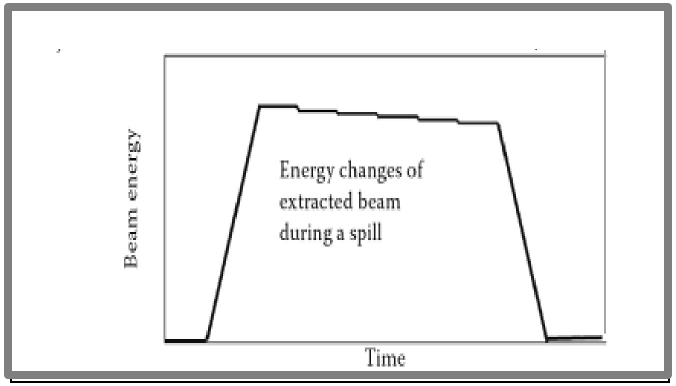
Paganetti, H. (2011), *Proton Therapy Physics*

- Beam at ISO as selected at ESS
- Limited accelerator performance
- Limited number particles/spill

Energy modulation

Upstream: synchrotron





Paganetti, H. (2011), *Proton Therapy Physics*

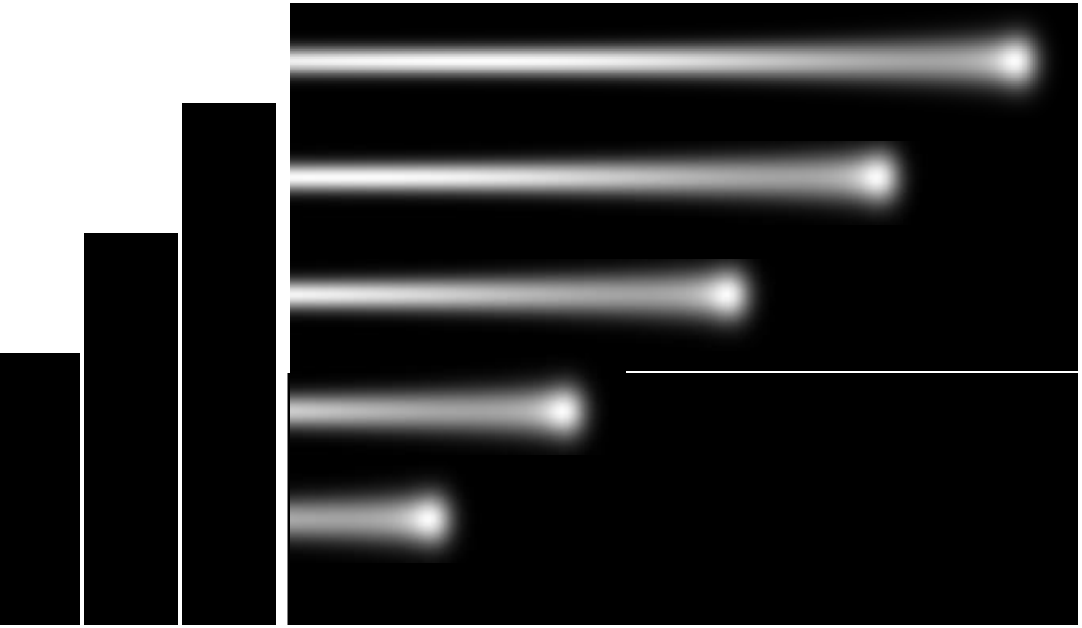
- Beam at ISO as selected at ESS
- Limited accelerator performance
- Limited number particles/spill

- Multiple energy extraction / spill

Energy modulation: Impact on depth dose distribution

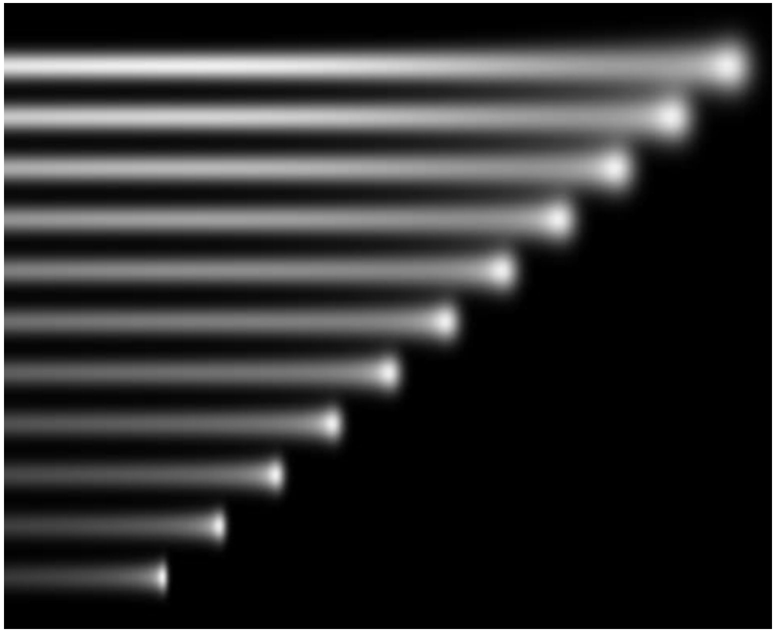
Range shifter

- Variable amount of material in the beam with zero air gap
- Pencil beam size invariant with range

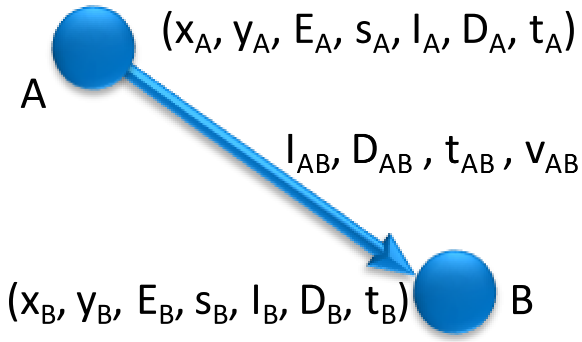


Variable energy of the beam

- Degrader and beam line select different phase space
- Spot size not invariant for different energies



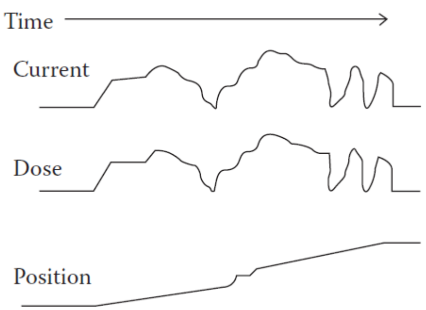
Driving the scan sequence



- Delivery of one dose elements after the other
- Needs trigger, when dose element is finished
- Next dose element is delivered

Two trigger mechanism:

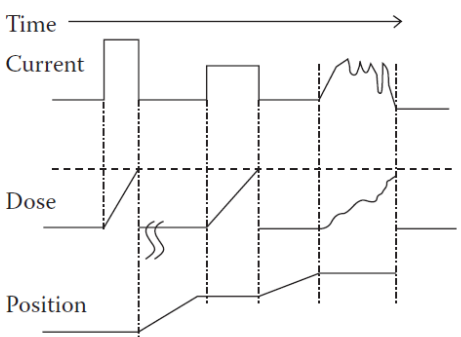
- **Time driven scanning**, element terminated by t_A.
  Beam motion is determined by the time the beam spends at location.
  Relies on accurate intensity control



Time driven

Continuous scanning

- **Dose driven scanning**, element terminated by D_A.
  Beam motion is controlled by whether the desired dose has been reached at each location.
  Relies on **accurate dose measurements**



Dose driven

Discrete spot scanning

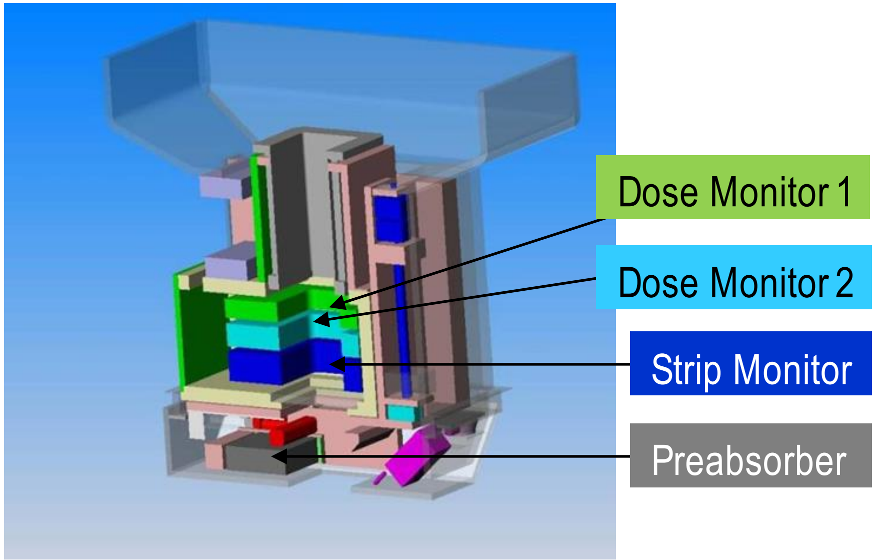
Scanning beam verification system

Dose Monitors:

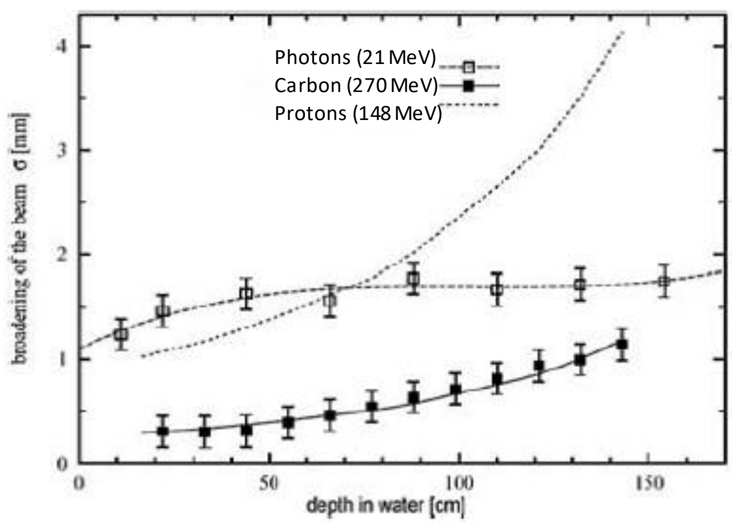
Ionization Chambers (0.5,1 cm, air gap)

Position Monitor

- Choice is based on Gantry 1 experience
- No aging effect (~ 20y experience Gantry 1)
- Stability and flexibility in operation
- (Sub-)optimal material budget (technical limitations)

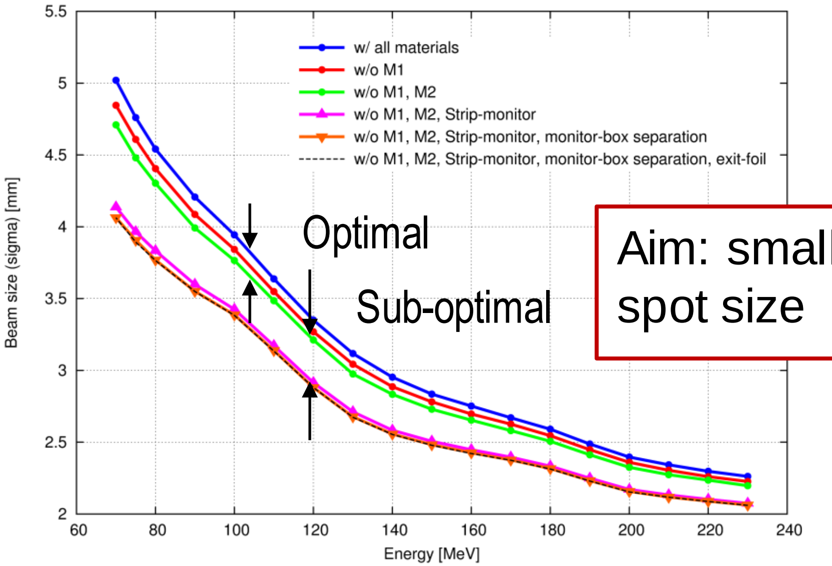


Beam broadening due to multiple scattering



Radiat Prot Dosimetry. 2009 Nov;137(1-2):156-66

Spot Size at patient location

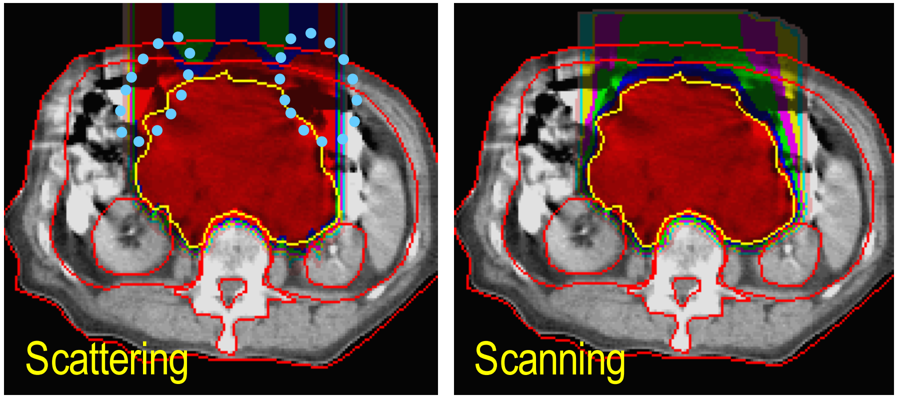


Aim: small spot size

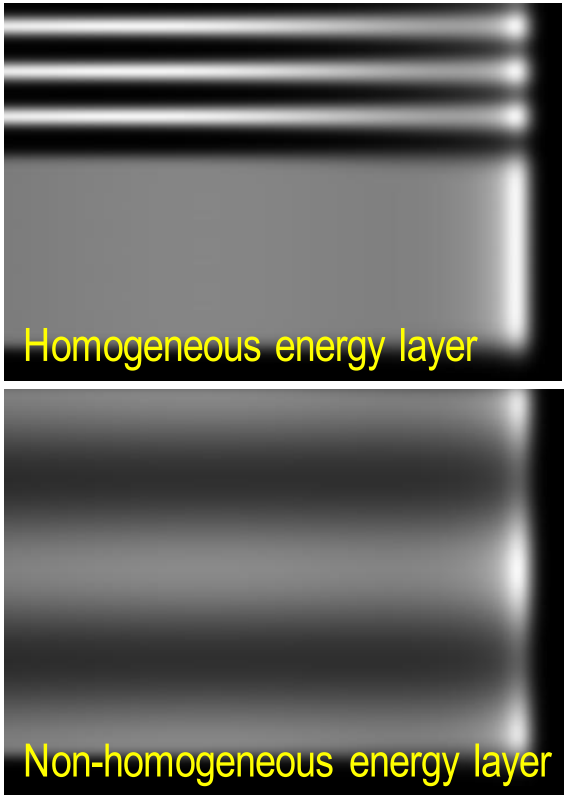
Benefit of beam scanning

Scattering with collimator / compensator has a fixed range (SOBP) per field

- Scanning avoids unnecessary 100% dose on the healthy tissues
- Especially relevant for large and irregular
  shaped tumors



- Scanning can easily deliver non-homogenous energy layers
- This is must or can be used for:
  - Conformal scanning
    (Homogeneous energy layers only in trivial case)
  - Biological targeting
    Option of shaping the dose (level) within the target
  - Intensity modulated proton therapy IMPT
    Competition with IMRT in conventional therapy

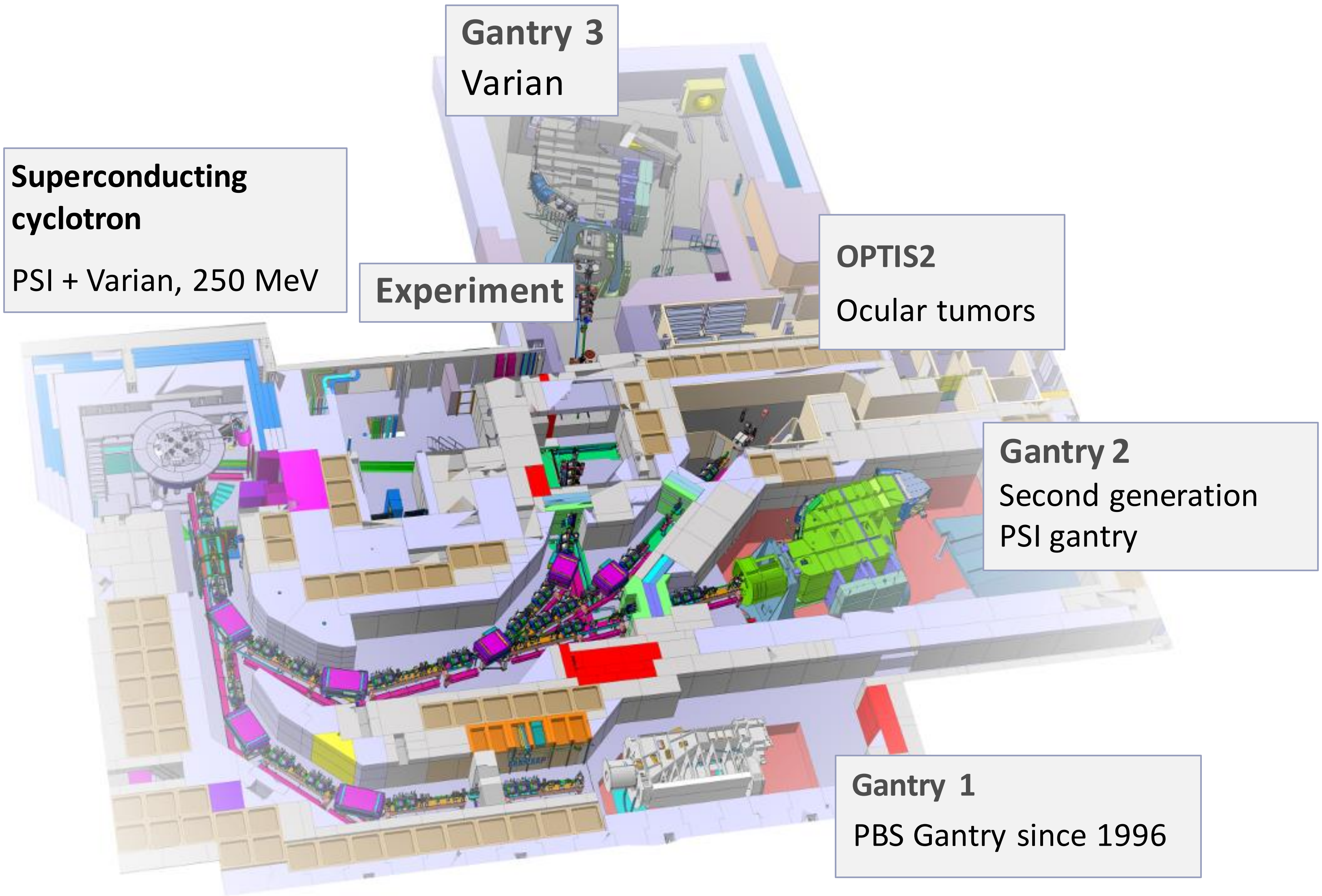


3D active scanning allows …

TO REDUCE ALL ASPECTS RELATED TO COLIMATORS AND COMPENSATORS

- Storage of radioactive material
- Calculation, optimization (air gap,…)
- Workshop or outsourcing
- Daily setup
- Neutrons
- Cost

PROSCAN at PSI



PROSCAN timeline

1984 | 1996 | 2006 | 2010 | 2013 | 2016


Gantry 1

- First worldwide PBS gantry
- 3 energies after degrader + RS system
- Scanning:
  - 1st direction scanning magnet
  - 2nd direction table
- Exocentric compact design to fit into existing facility

OPTIS 1:
Eye Treatment

- Fixed beam line
- Mono-energetic beam + RM wheel
- Collimator (produced at PSI)

PROSCAN timeline

1984 — 1996 — 2006 — 2010 — 2013 — 2016


Gantry 1

OPTIS 1:
Eye Treatment


OPTIS 2

PROSCAN timeline

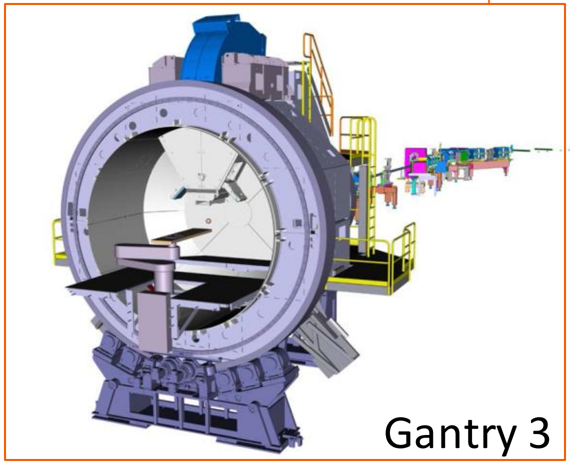
1984 | 1996 | 2006 | 2010 | 2013 | 2016


Gantry 1


Gantry 2

OPTIS 1:
Eye Treatment

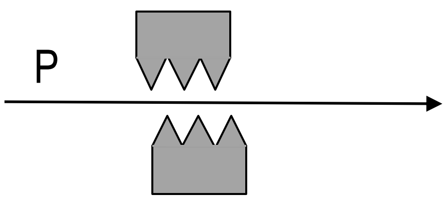

OPTIS 2

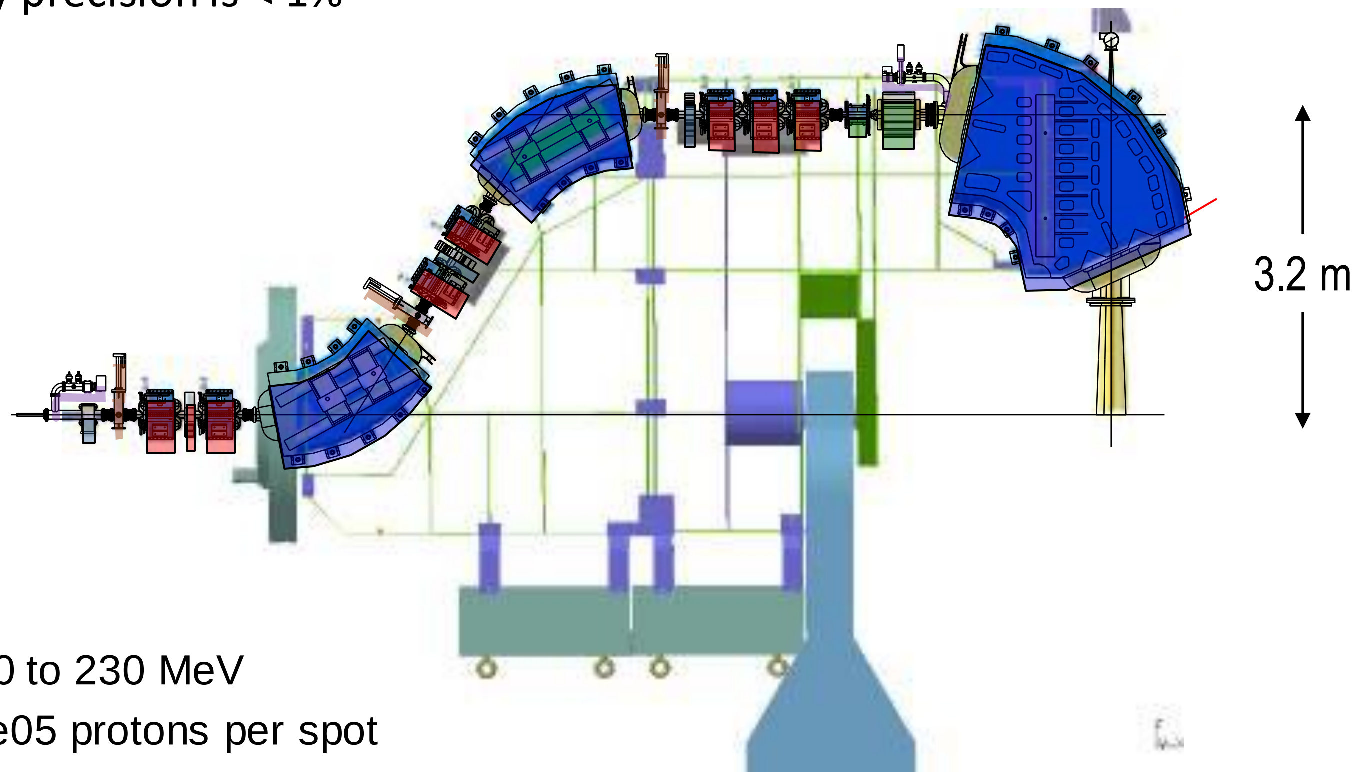

Gantry 3

Gantry 2: designed for fast 3D scanning

Fast Energy Change

- Degrader based energy change within **< 100 ms**
- Optimized magnet power supply & controller
- Delivered energy precision is < 1%



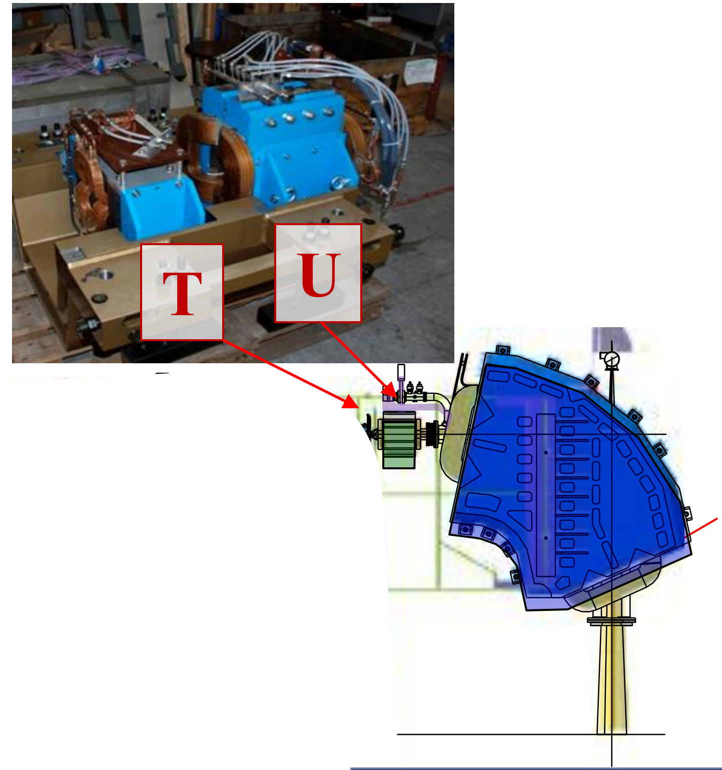


- Energies from 70 to 230 MeV
- Dose down to 5e05 protons per spot

Gantry 2: designed for fast 3D scanning

Fast Lateral Scanning

- T sweeper magnet 2 cm/ms
- U sweeper magnet 0.5 cm/ms



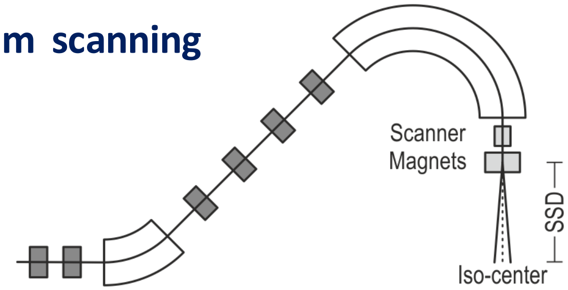
Challenge – scan through the last bend

- Large aperture to accommodate deflected beam
  - Scan area 20 x 12 cm
  - Field patching for larger fields
- Special lamination to suppress eddy currents effect for fast energy changes but no entirely
- Residual drifts have to be corrected online

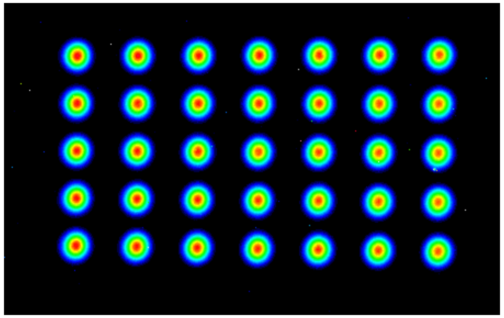
Required spot precision at ISO < 0.5 mm + no deformation!

Gantry design for PBS

Downstream scanning



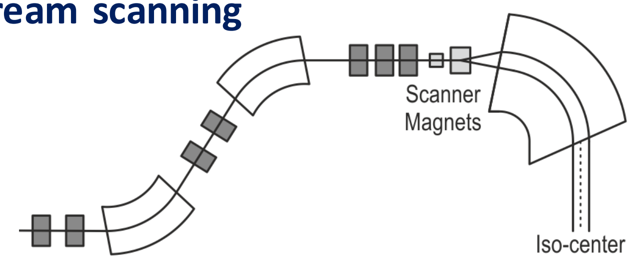
- Sweeper magnets are last active beam elements
- In first order linear correlation between
  - Spot position at isocenter
  - Sweeper current
- Spot shape unaffected for different scan position
- Divergent scanned beam; calibration relies on exact longitudinal alignment at isocenter
- Situation similar to horizontal beam line



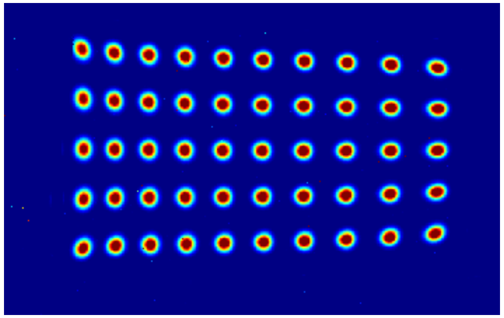
Example:
Horizontal beam line,
PSI test area,
170 MeV

Spot position with linear current steps

Upstream scanning



- Sweeper magnets placed in-front of last dipole
- Large gap of last dipole
- Field inhomogeneity can affect spot shape
- Beam focus depends on lateral position
- Beam with little / no divergence (= parallel beam)
- Higher order corrections for position-to-current conversion needed

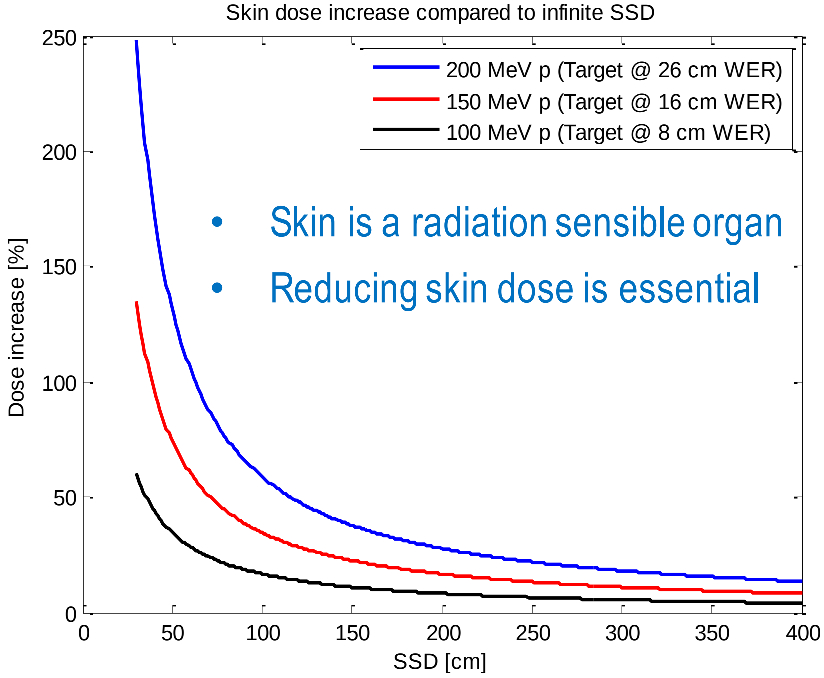


Example:
Gantry 2, 100 MeV

Spot position with linear current steps

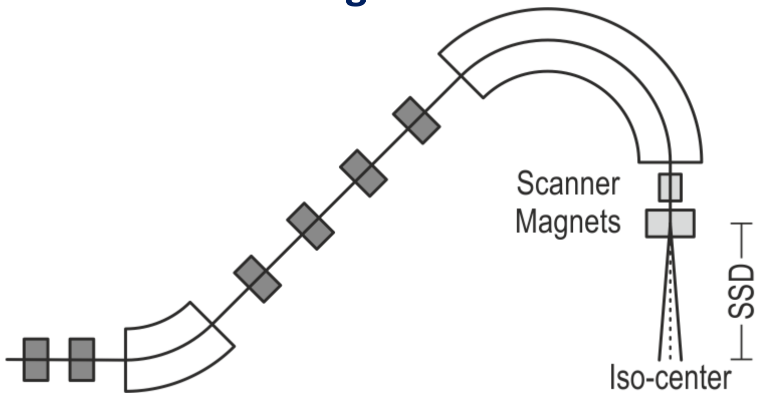
Advantages of parallel beam scanning

- No source to target ~1/d² dosimetry effects
- Simplified QA
- Easy field patching for large fields
- Almost infinite SSD possible



- Skin is a radiation sensible organ
- Reducing skin dose is essential

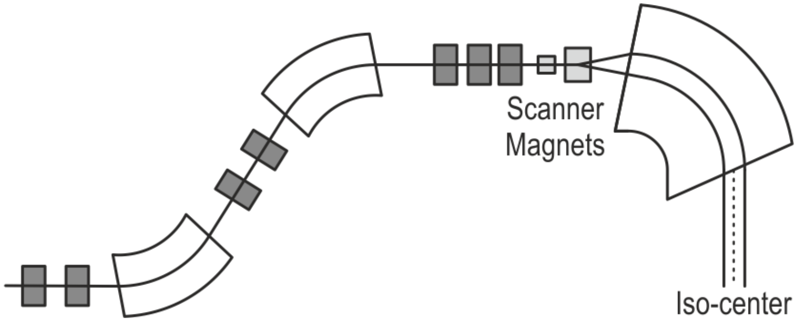
Downstream scanning



- Typical SSD (source skin distance) ~ 2m

Upstream scanning

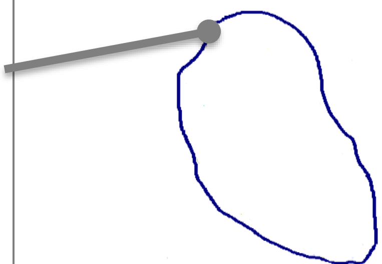
- PSI Gantry 2:
  SSD > 17 m

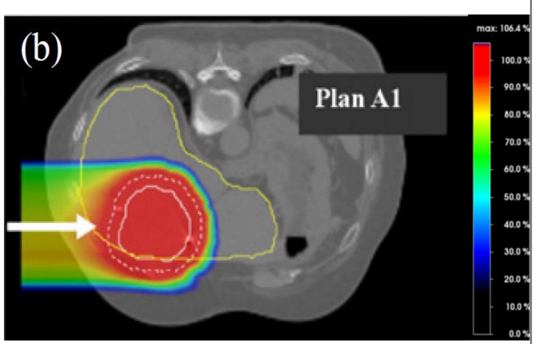


PBS for static and moving targets

Static tumor

PBS has been proven to be one of the most effective methods for static tumor treatment





K. Bernatowicz 2013, PMB

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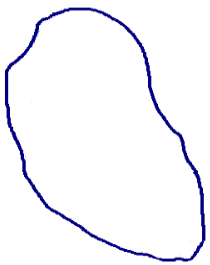
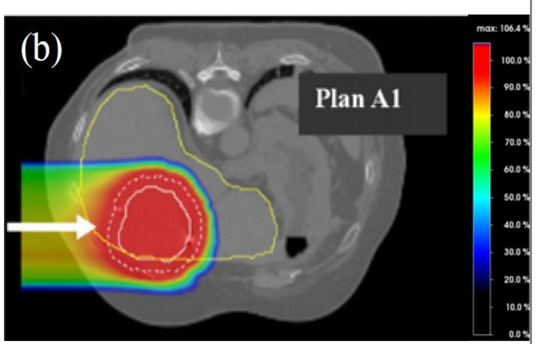
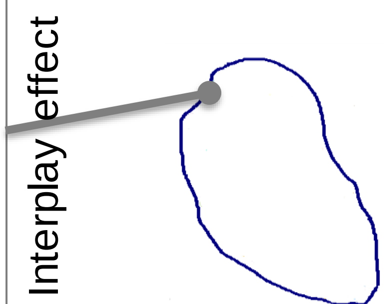


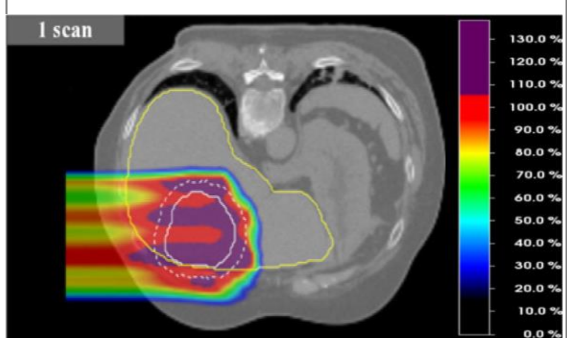


K. Bernatowicz 2013, PMB

Moving target: single scan

- Irradiated volume blurring
- inhomogeneity within the target
- Cold and hot spots





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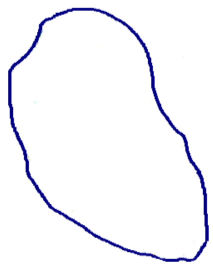
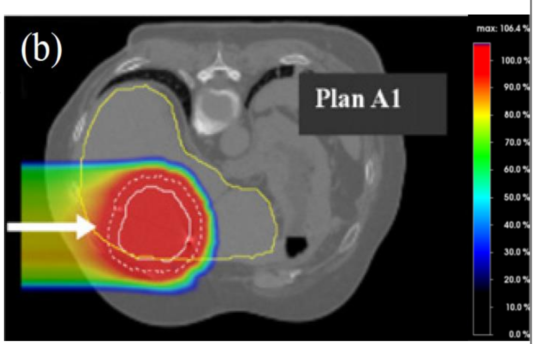


K. Bernatowicz 2013, PMB



Moving target: single scan

- Irradiated volume blurring
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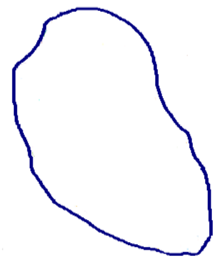
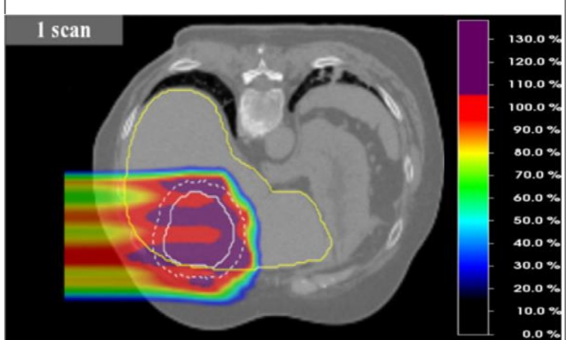
- Cold and hot spots

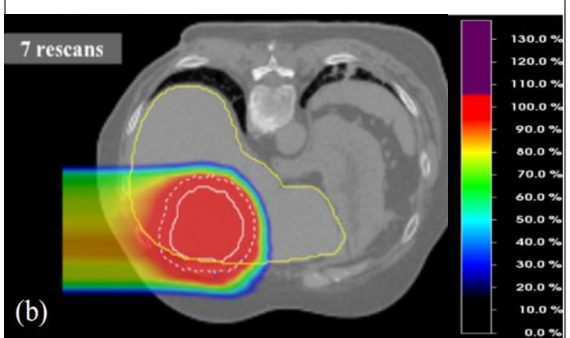
Interplay effect





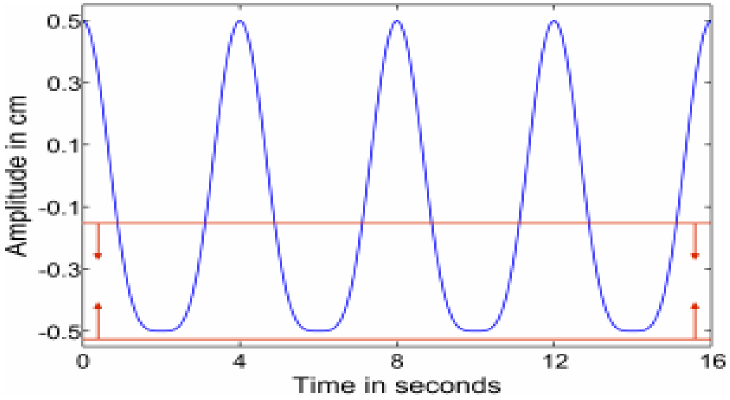
Moving target: options

Rescanning – most studied solution for motion mitigation

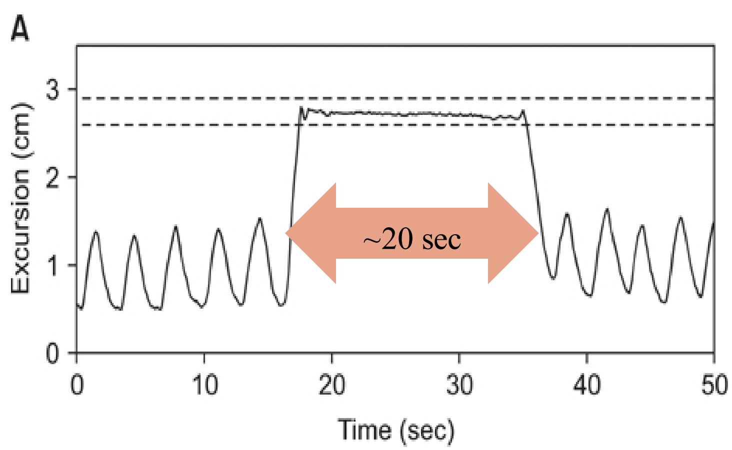


PBS for static and moving targets

A. Schaetti, PSI



Radiat Oncol J. 2014 Jun;32(2):84-94



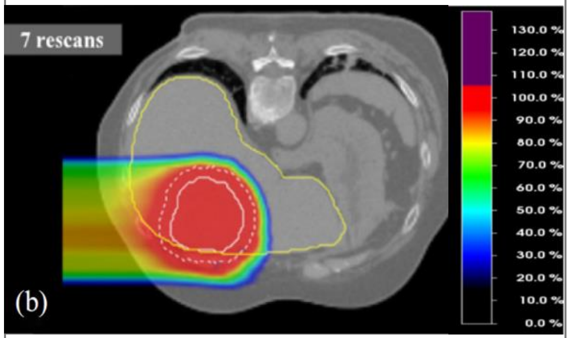
For all options/combinations scanning must be fast in all 3 dimensions

Moving target: options

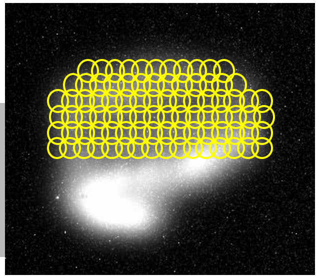
Rescanning – most studied solution for motion mitigation

Depending on system & motion parameters - combination with:

- **Gating**: scan target during part of the breathing cycle
- **Breath hold**: irradiate while patient is holding the breath



Another way to optimize scanning performance



Discrete spot scanning

20412 spots, 28 energies

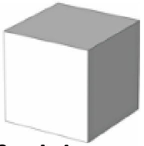
Beam-on time: 17s

Dead time: 80s

Total time: 97s

→ 5 re-scans: ~7min

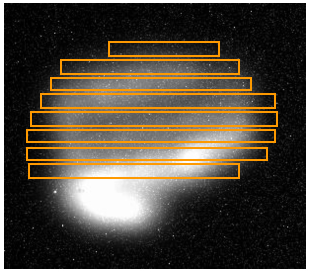
Cubical target, V = 1L



Spot grid 4 mm

Dose: 0.6 Gy (typical 3 field fraction dose)

Standard dose rate (<6 Gy/s)



Continuous line scanning

27 lines/energy, 28 energies

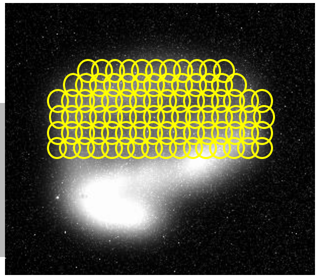
Beam-on time: 17s

Dead time: 3s

Total time: 20s

→ 5 re-scans: ~30s

Another way to optimize scanning performance



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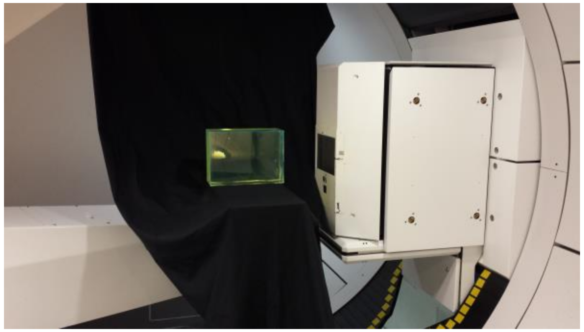

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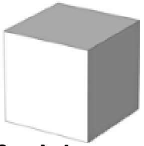

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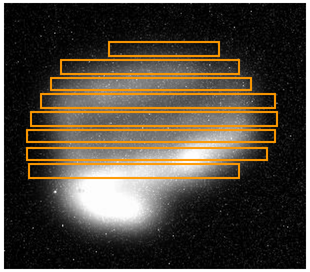

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Beam-on time: 17s
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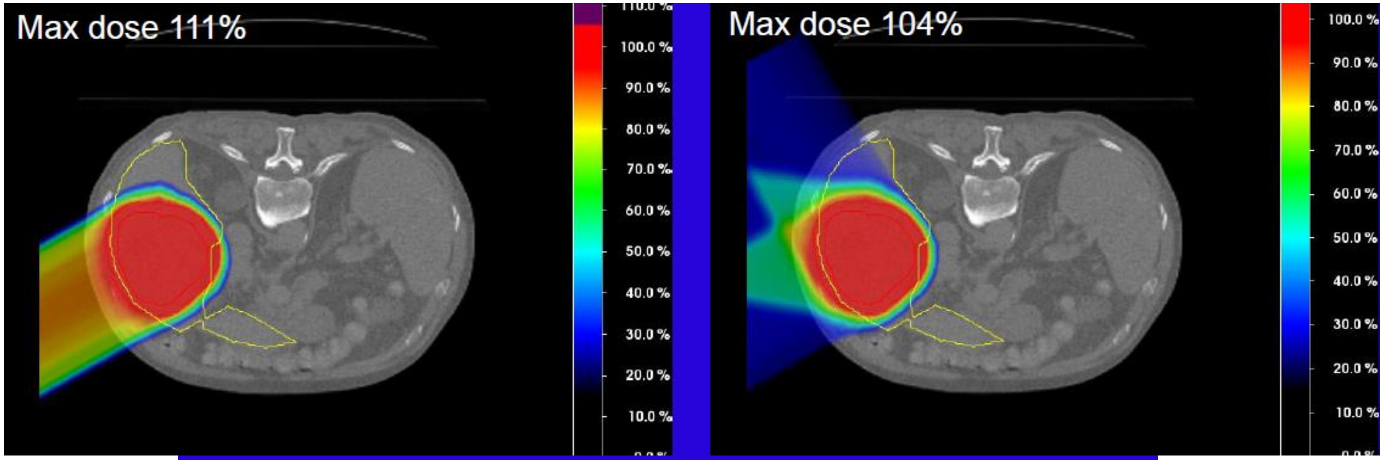
Flexible beam delivery– Gantry

Why do we need gantries for proton therapy?

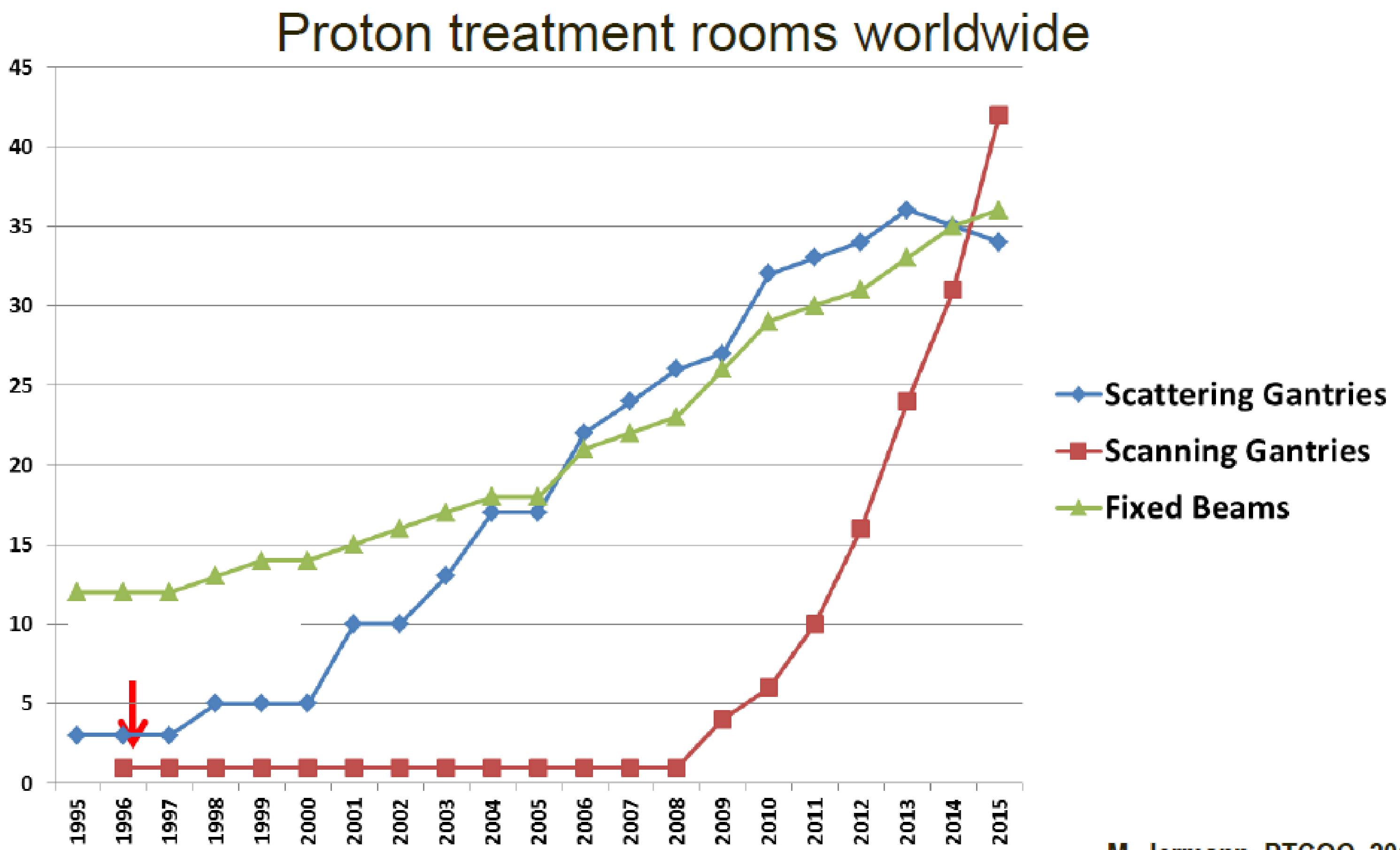
- To be flexible
- To deliver multiple, angularly spaced fields

- For dose homogeneity and conformity
- For plan robustness
- For improved delivery accuracy



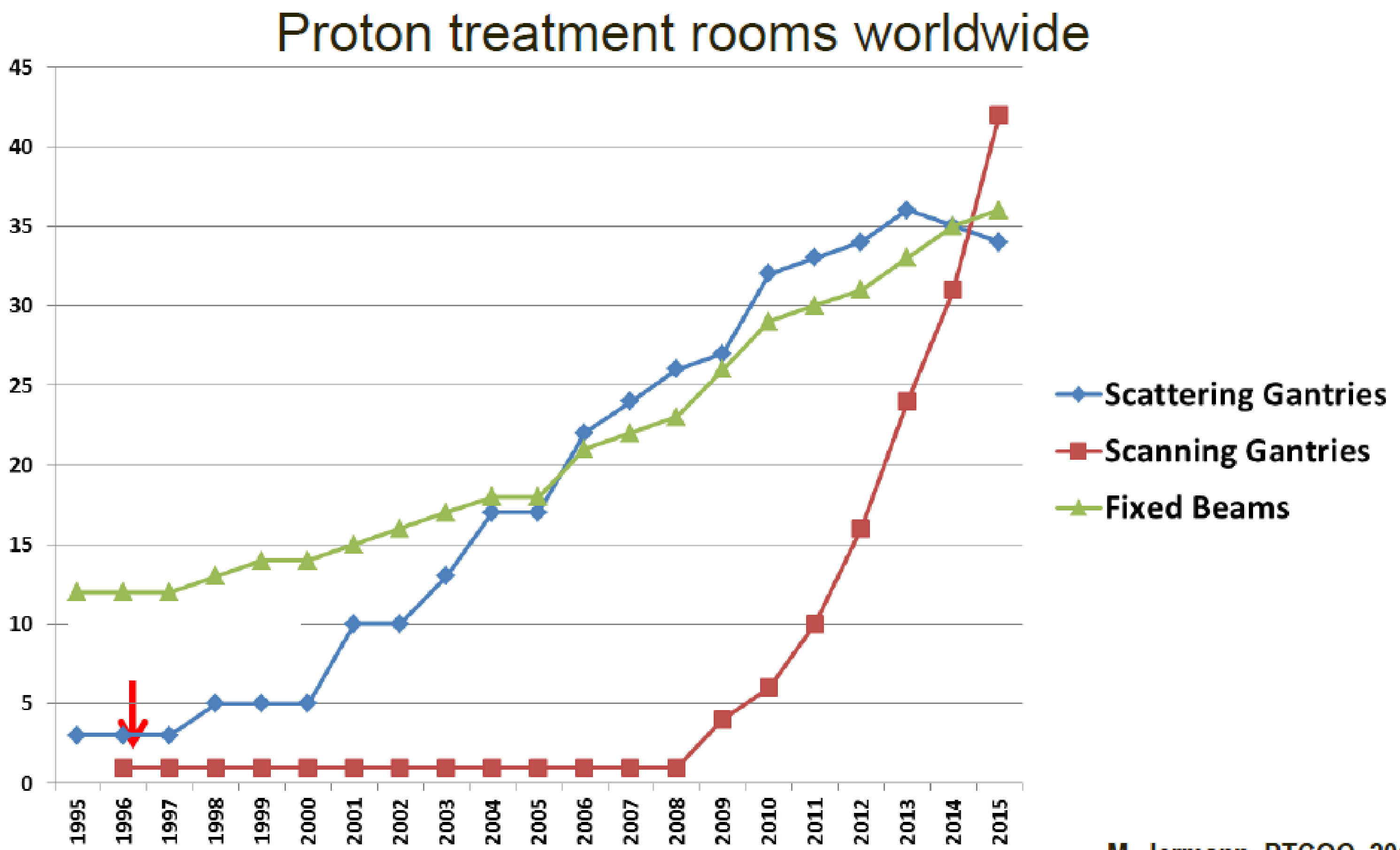
Knopf et al, Phys. Med. Biol. 56 (2011) 7257-7271

World-wide trend



M. Jermann, PTCOG, 2014

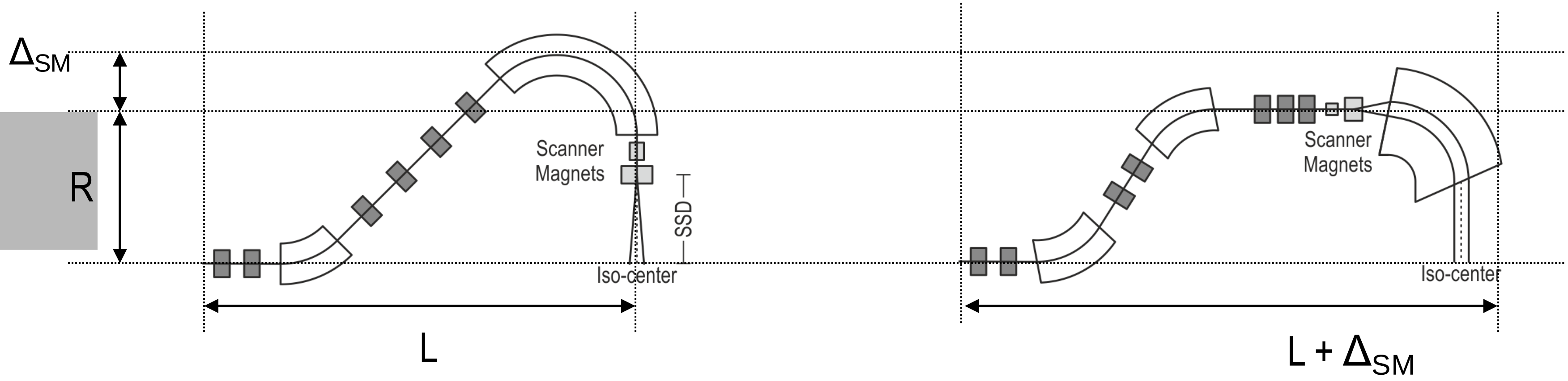
World-wide trend



M. Jermann, PTCOG, 2014

PBS gantries are preferred, but what about costs?

Gantry size and room volume



Downstream

Assuming square room cross-section

Upstream

$$V_{down} = 4*(R + \Delta_{SM})^2 * L$$

$$V_{up} = (L + \Delta_{SM}) * 4R^2$$

Using Gantry 2 as an example

$L \approx 3R \quad R \approx 3.5m \quad \Delta_{SM} \approx 1m$

$$V_{down} = 4m*(4.5m)^2*10.5m = 850\ m^3$$

$$V_{up} = 11.5m*4m*(3.5m)^2 = 570\ m^3$$

$$V_{down} - V_{up} > 250\ m^3$$

Benefits from limitation

Gantry 2, PSI

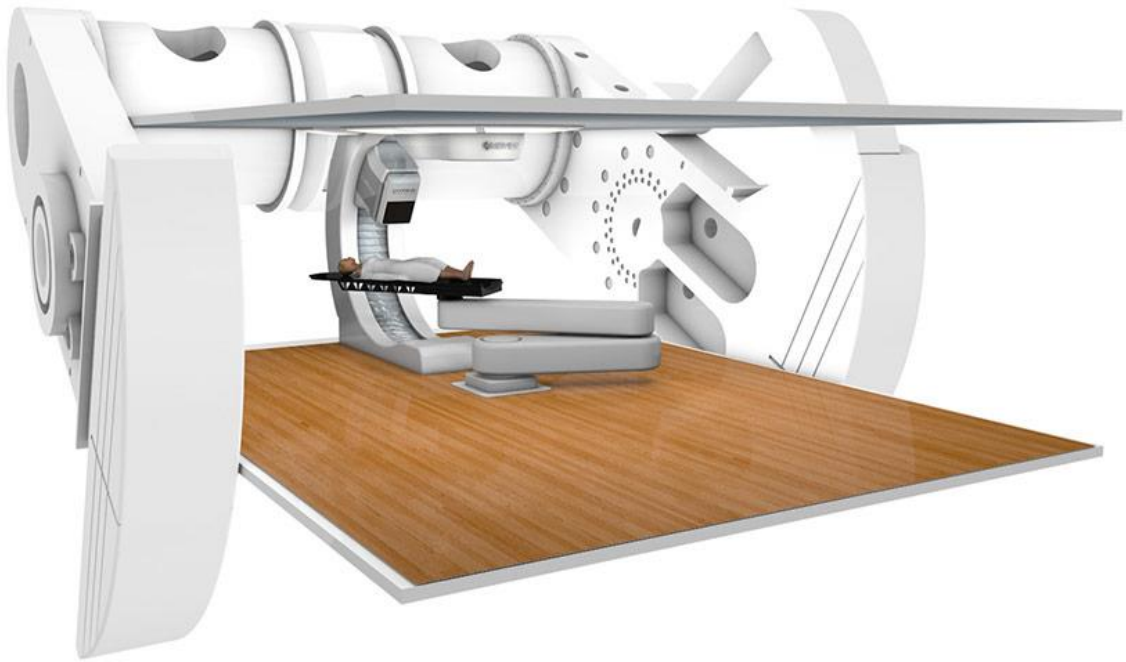
- Gantry rotation limited from -30° to + 180° (instead of 360°)
- Flexibility of beam delivery by rotating the table in the horizontal plane
- Important: Stable structure & beam line support

Advantages:

- Open treatment room
- Fixed walls for mounting imaging equipment
- Permanent fixed floor for a better access to the patient table

Idea of 180° gantry is taken-up by industry

Mevion Hyperscan system



- Compact synchro-cyclotron (17t) rotating around the patient
- No beam transport -> no additional beam loss
- Down stream range modulation
- Adaptive aperture
- Neutron dose is comparable to passive scattering

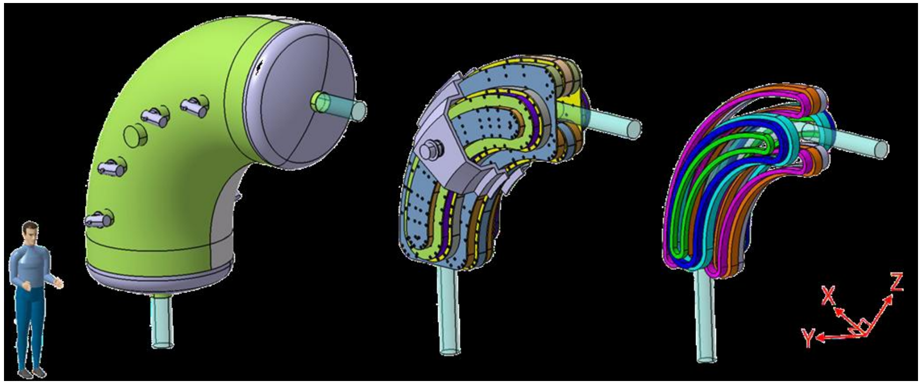
Possibility for improvement?

Advantages

- Higher magnetic fields
  - Smaller bending radius
- Weight reduction (less iron)
- Possible increase of Δp/p acceptance

Problems

- Field homogeneity is difficult -> complex optics
- Cryogenic engineering
- Slow changes of the beam energy



- More studies are required for scanning speed optimization
- Size/weight reduction is prominent carbon ion system

Carbon therapy systems

$B * \rho \sim 3$ larger for carbon beam

Conventional carbon gantry, HIT

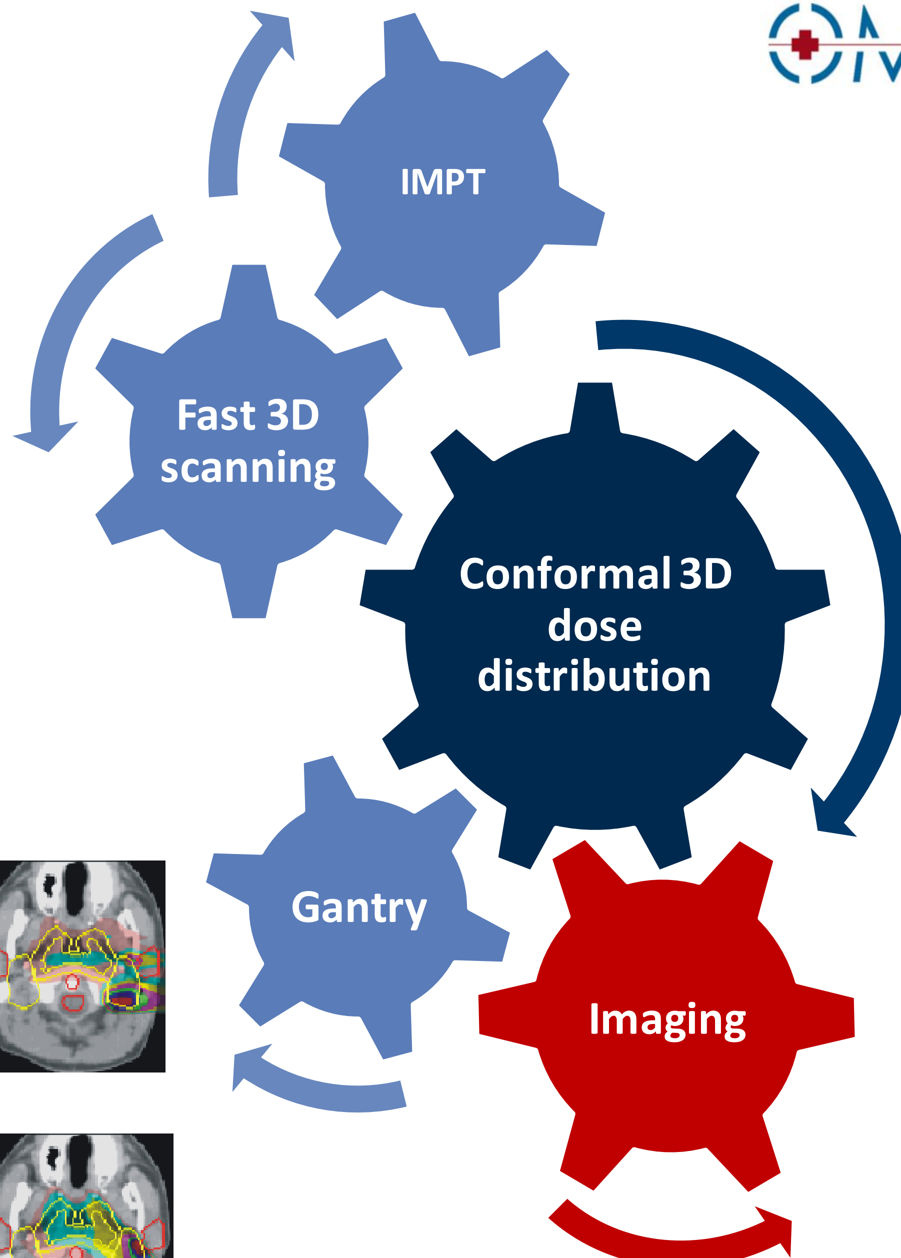
- Only operating carbon gantry (2009)
- 360° gantry
- Size: 25 x 6.5 m
- 600 t total rotating mass
- Magnets: 145 t

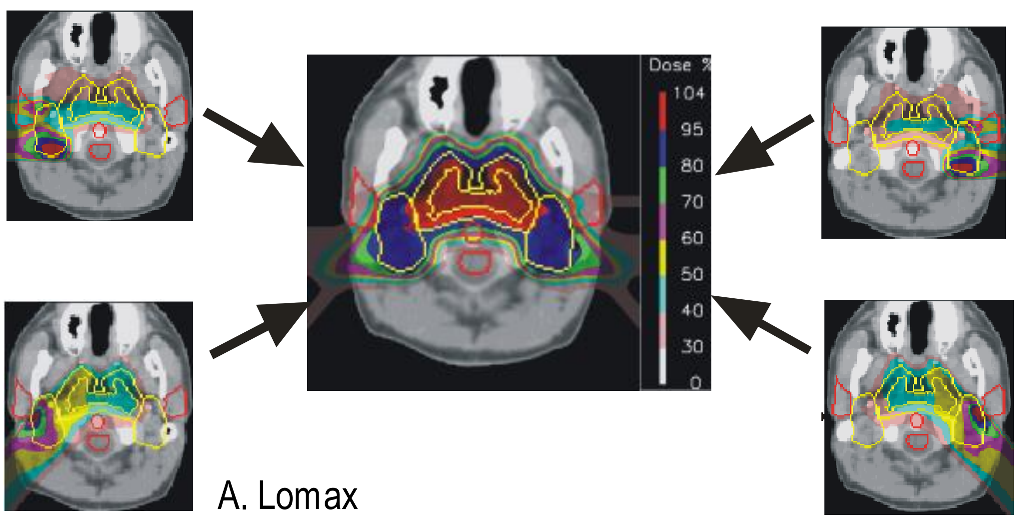
Superconducting gantry at NIRS, Japan

- Beam orbit radius: 5.45 m
- Length: 13 m
- 10 superconducting magnets
  - Combined function (dipole + quad)
- He-free cooling (cryocoolers)
- ~300 t total weight

PAUL SCHERRER INSTITUT

Take home message





A. Lomax

Two talks later during this school