PAUL SCHERRER INSTITUT

PSI

David Meer :: Center for Proton Therapy :: Paul Scherrer Institut

Technical challenges and future developments in pencil beam scanning

Topical Workshop: Facility Design Optimization for Treatment, 12.03.18

Content

- From passive scattering to active scanning: Benefit and new options:
  - Advantages pencil beam scanning
  - IMPT
  - Edge enhancement

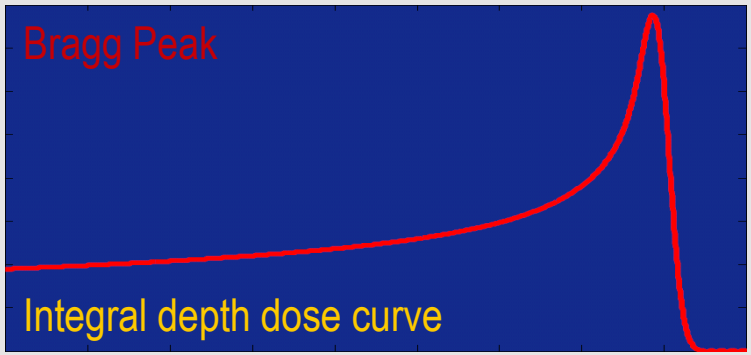
- Implementation scanning system and gantry size
  - 180° gantry design
  - Upstream vs. downstream scanning

- Pencil beam scanning and motion targets
  - Interplay effect
  - Different lateral scanning option
  - Volumetric rescanning
  - Other options for motion mitigation

From the pristine Bragg peak to a conformal dose distribution

- Pristine Bragg Peak of proton beam with given initial position (x) and energy / momentum (p)

  x, p →



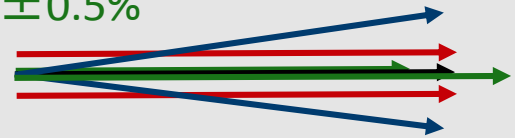
- Typical beam parameters in proton therapy

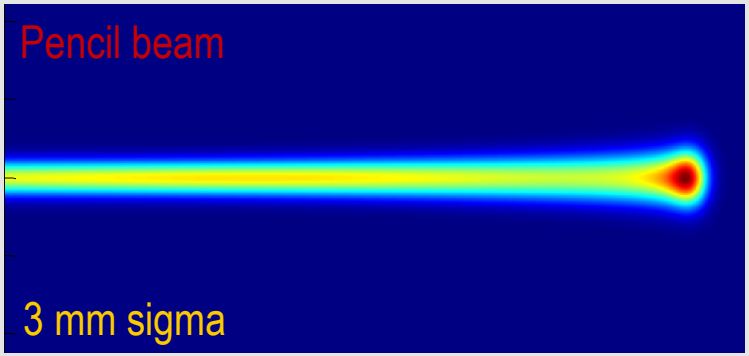
  $\Delta x = \pm 3$ mm

  $\Delta\theta = \pm 10$ mrad

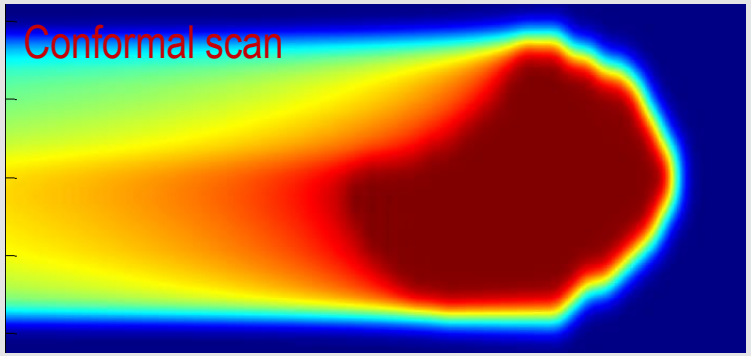
  $\Delta p/p = \pm 0.5\%$

  x, p



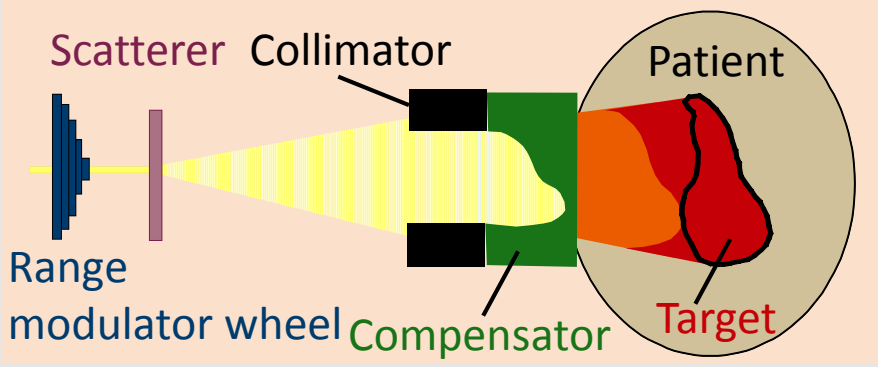


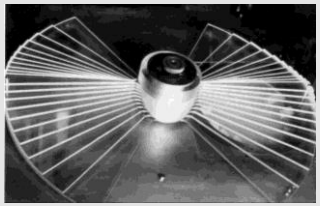
- Conformal dose distribution?
  - Modulation of position (x), momentum (p) and #protons
  - Time structure of beam delivery sequence (organ motion errors!)

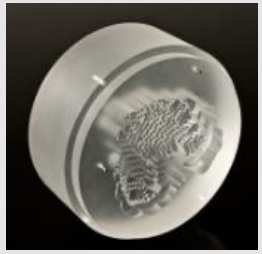


First implementation of particle therapy with passive scattering

- Proton treatments started with passive dose shaping (1960's, Harvard cyclotron)







Rotating wheel

- Creates one fix SOBP (fast, 10 Hz)

Collimator (field specific)

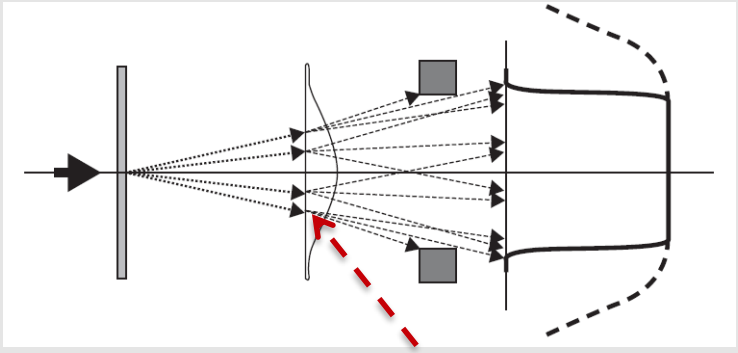
- Lateral conformation to target

Compensator (field specific)

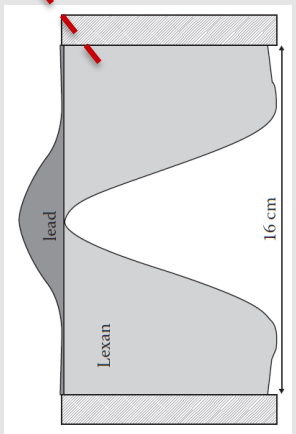
- Conform distal fall-off to target

Double contoured 2nd scatterer

- Increase efficiency by 2nd scatterer that flattens center of field



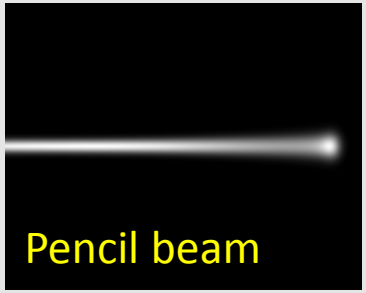
- Extra low-Z material to compensate energy loss at edges
- Today predominant technique for passive scattering

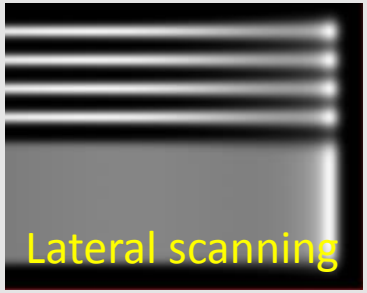


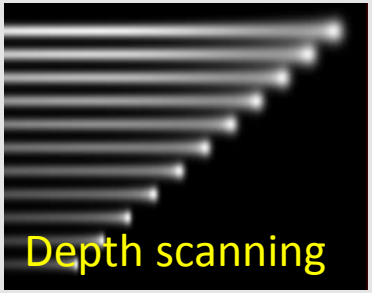
Simple concept but complex practical realisation

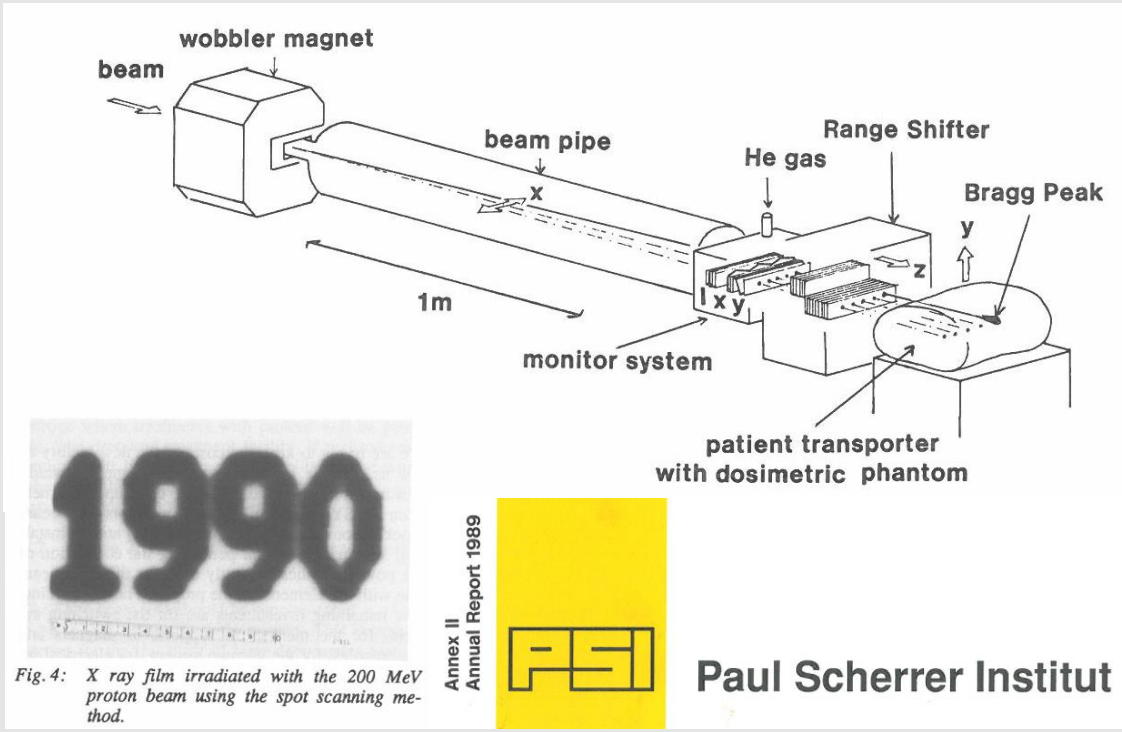
Development of pencil beam scanning

- Charged particles can be directed by electro-magnetic fields
- Experimental set-up to demonstrate technical feasibility of scanning with protons (1990)
- Horizontal beam line:
  - Beam scanning in only one direction
  - Rang shifter for energy modulation
- Similar developments also at GSI



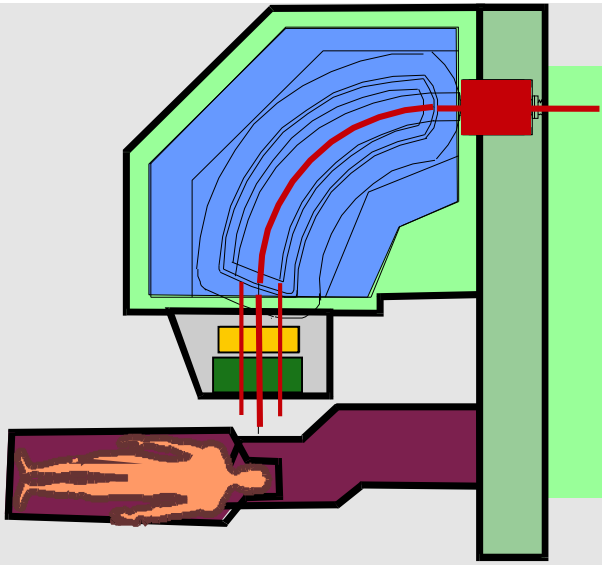


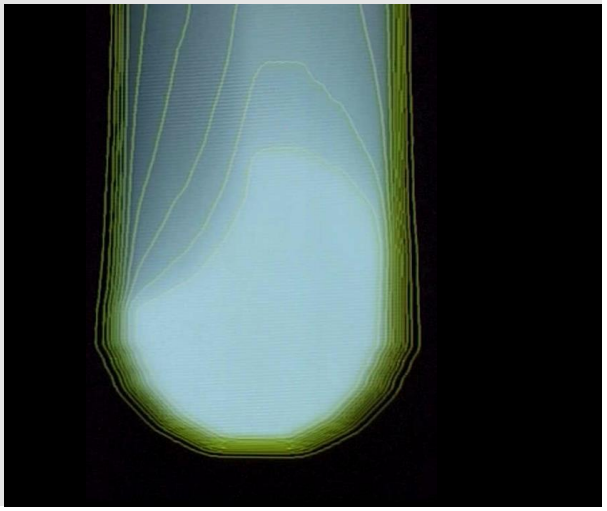




Implementation of pencil beam scanning on Gantry 1

- Implementation of pencil beam scanning on a gantry (PSI Gantry 1, 1996)
- Very compact (r = 2m) design due to eccentric rotation
- Discrete spot scanning



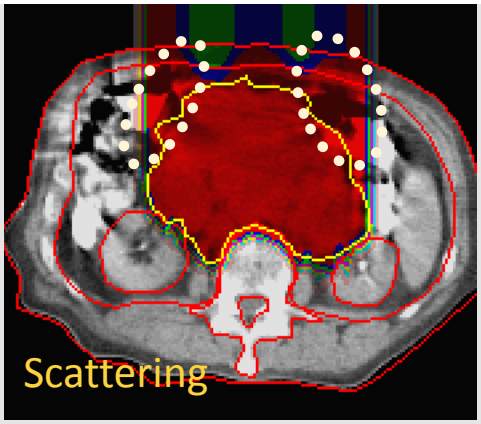


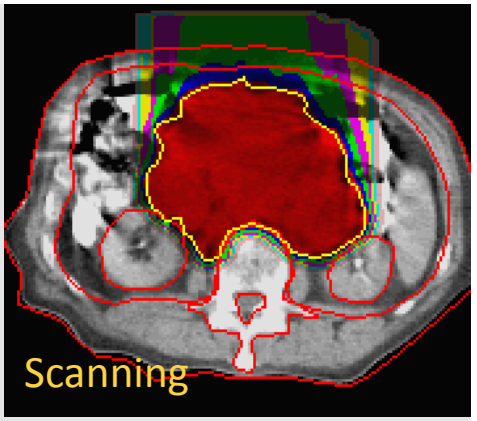
- Elements of scanning:

Dose	Monitor + kicker magnet 100 μs reaction time		
x	Sweeper magnet	6 ms/step	***fast***
y	Range shifter	100 ms	***average***
z	Patient table	1 cm/s	***slow***

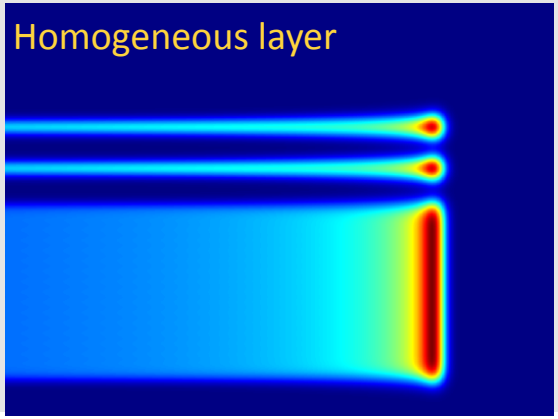
Main benefit of pencil beam scanning

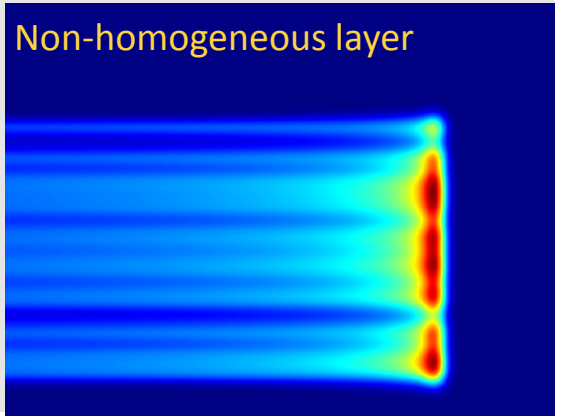
- Scattering with collimator and compensator has a fixed range per field
  - Scanning avoids unnecessary 100% dose to the healthy tissues
  - Especially relevant for large and irregular targets





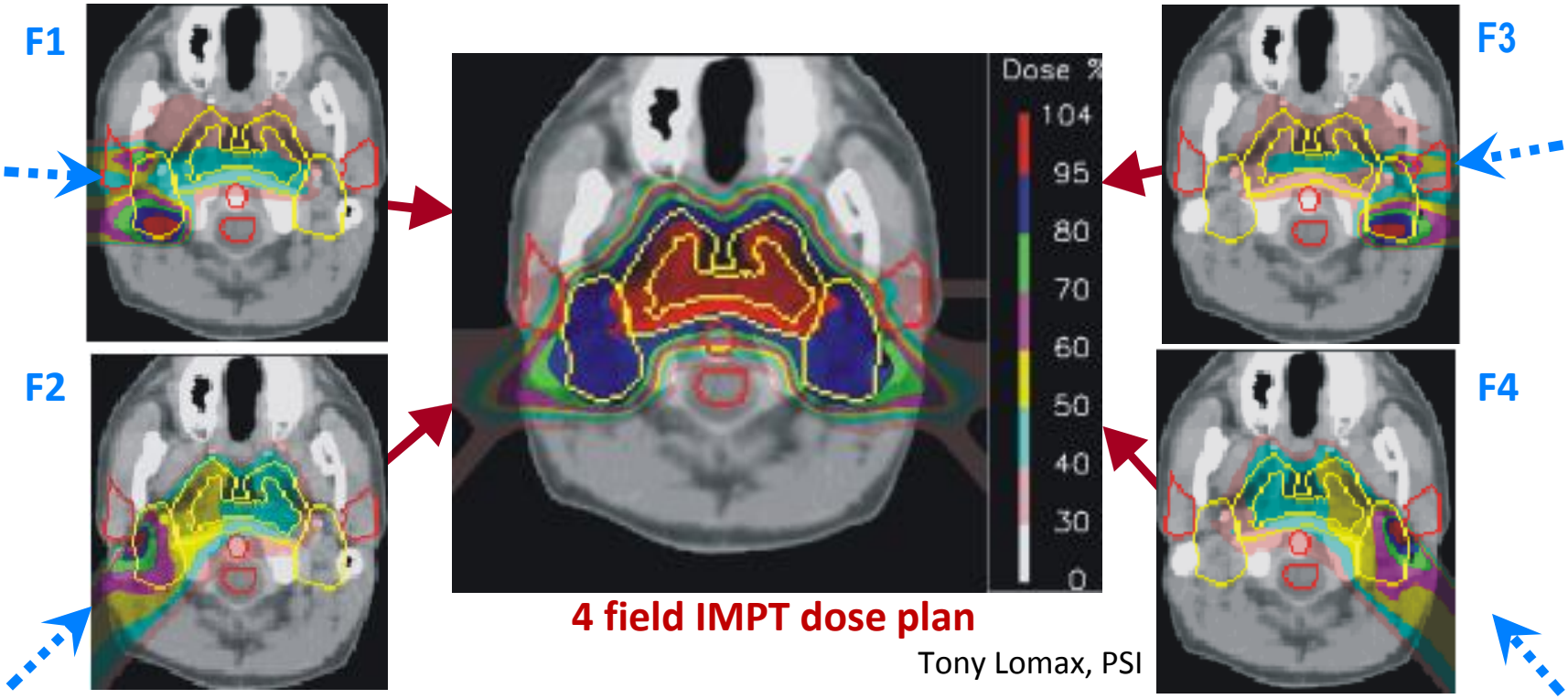
- Scanning can easily deliver non-homogenous energy layers
  - Needed for conformal scanning: Homogeneous energy layers only in trivial case
  - Intensity modulated therapy IMPT: Improved dose conformation
  - Biological targeting: Option of shaping the dose (level) within the target





More flexible dose distributions with IMPT (Intensity Modulated Proton Therapy)

- Each single dose field is not constraint to deliver uniform dose distribution to target
- Uniform dose in target by superposing all field
- Better dose conformation for complex target geometries
- IMPT is only possible with spot scanning technique!



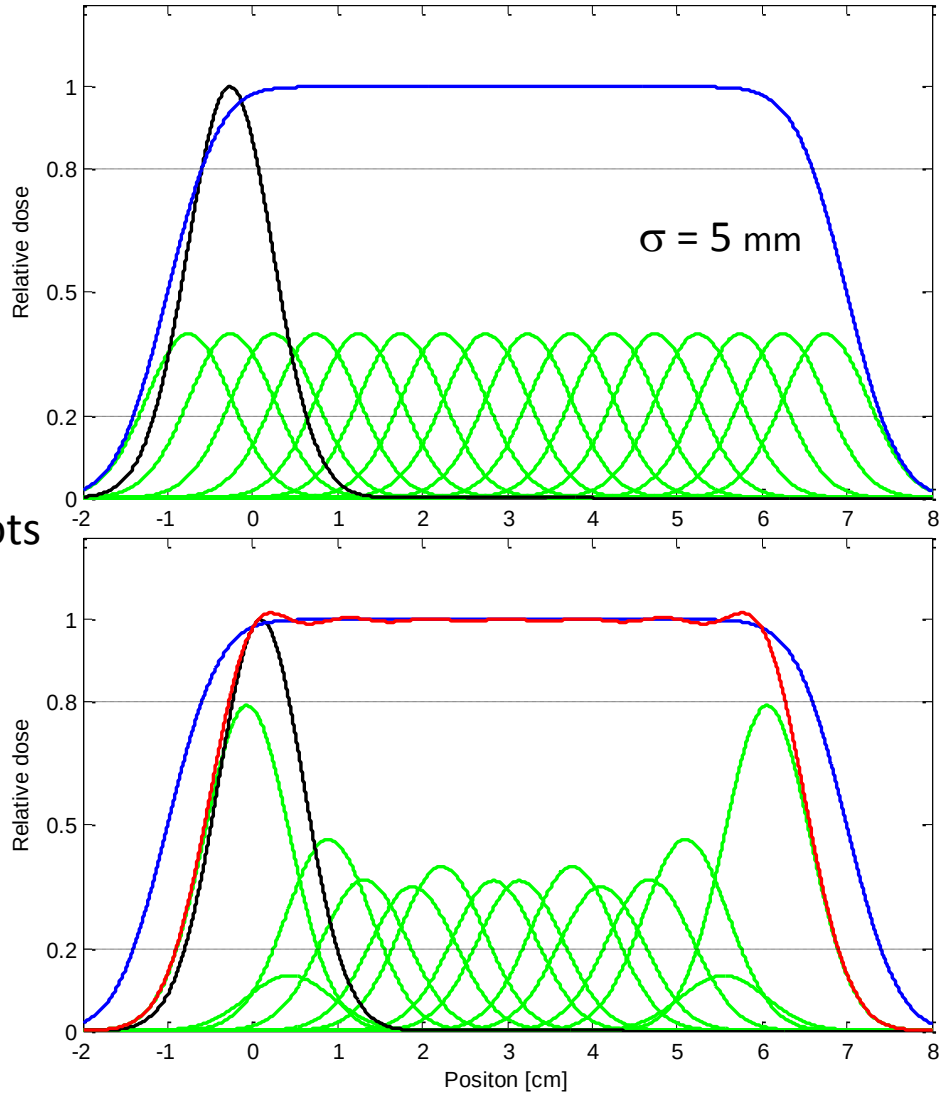
4 field IMPT dose plan

Tony Lomax, PSI

“Edge enhancement capability” of scanning

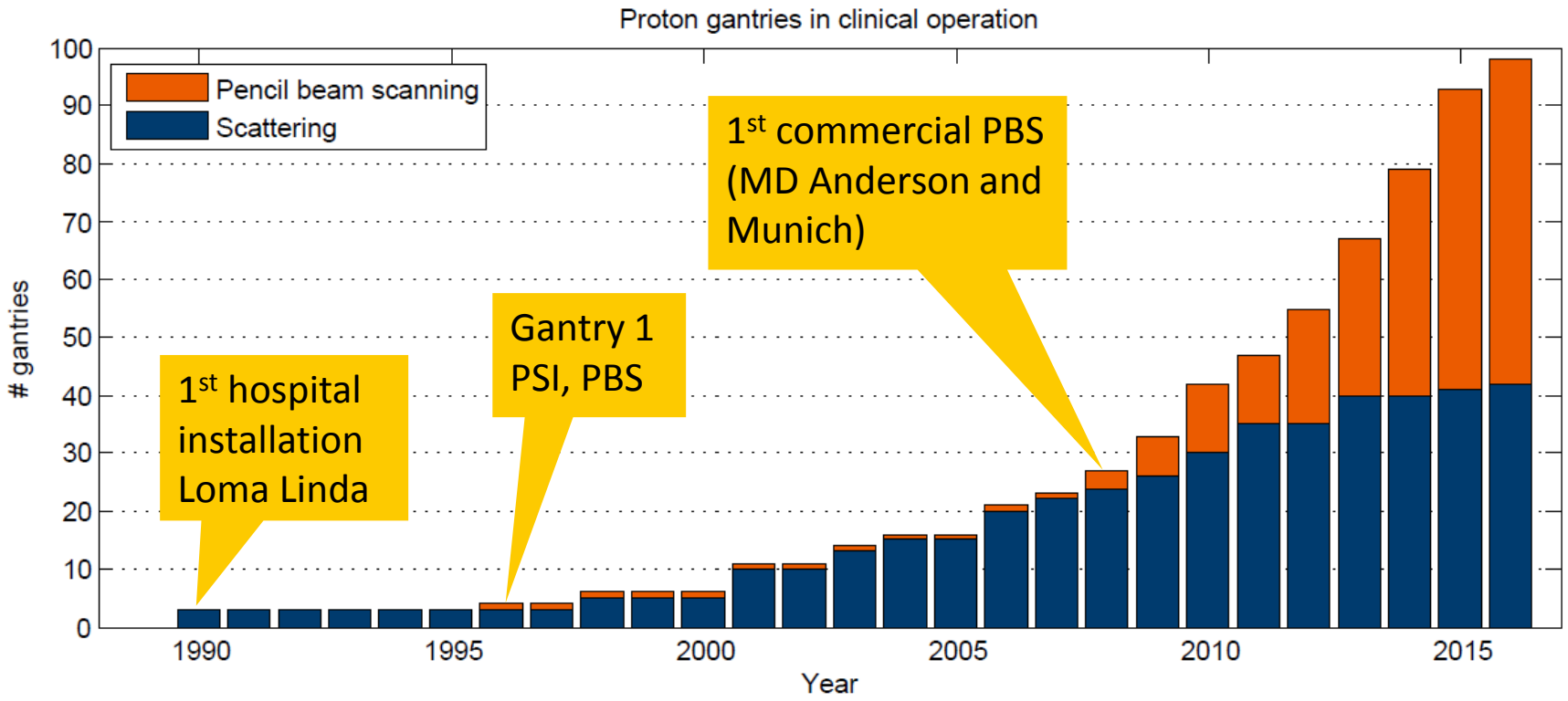
- Uniform fluence of spots
  - Gaussian folded with step function: error-function
- Penumbra (80% - 20%):
  - Error function: 1.7σ
  - Gauss: 1.1σ → 1.5x penumbra
- Scanning: delivery of individual spots
  - Flexible choice of intensity and spot position
  - The dose lateral fall-off can approach the fall-off of the original Gaussian spot

➢Possibility to optimize lateral penumbra with scanning



Increasing importance of PBS

- Number of proton gantries in clinical operation separated by delivery technique

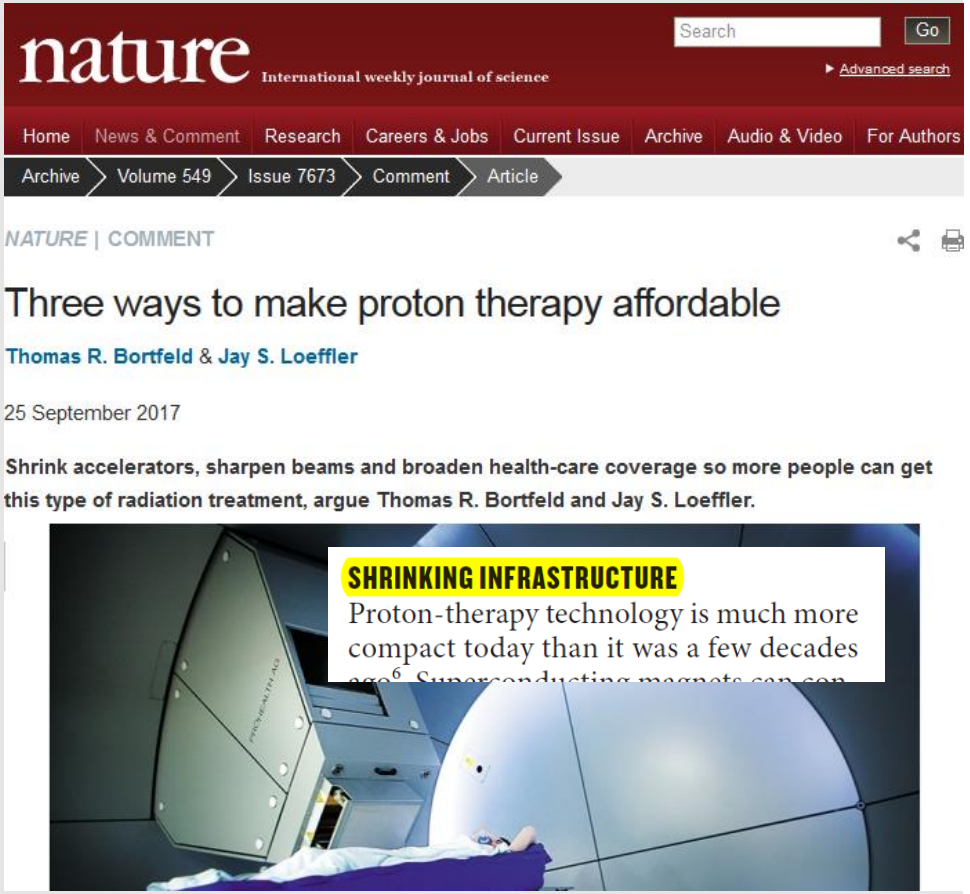


Based on: Meer et al., Mod. Phys. Lett. A 30 (2015)

Promoting proton therapy: Current challenges

T. Bortfeld, J. Loeffler, nature **549**(7673) 2017:

1. Size (and cost) reduction
2. Increase beam precision
3. [Optimize access to proton therapy for all patients]



nature International weekly journal of science

Search Go Advanced search

Home | News & Comment | Research | Careers & Jobs | Current Issue | Archive | Audio & Video | For Authors

Archive > Volume 549 > Issue 7673 > Comment > Article

NATURE | COMMENT

Three ways to make proton therapy affordable

Thomas R. Bortfeld & Jay S. Loeffler

25 September 2017

Shrink accelerators, sharpen beams and broaden health-care coverage so more people can get this type of radiation treatment, argue Thomas R. Bortfeld and Jay S. Loeffler.

SHRINKING INFRASTRUCTURE

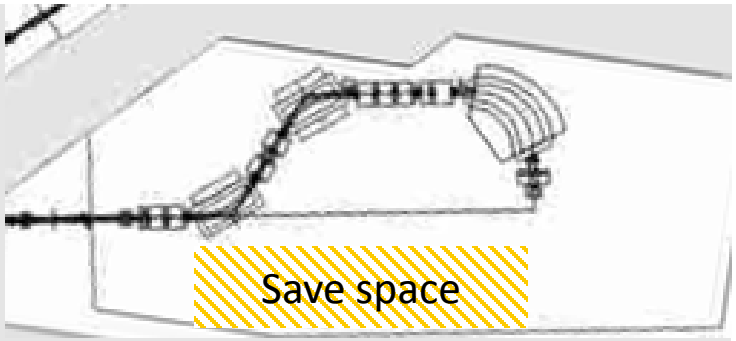
Proton-therapy technology is much more compact today than it was a few decades ago[6]. Superconducting magnets can con-

Demand for compactness taken up by industry

- IBA: ProteusOne
- Sumitomo: Short length gantry
- Mevion: accelerator on gantry
- VMS: ProBeam compact single-room solution
- ProNova: Superconducting gantry
- …

Foot print reduction by 180° gantry design

- Gantry rotation limited to one hemisphere (180° instead 360°) [or a bit more, Gantry 2: -30° to +180°]
- Full flexibility of beam delivery by rotating the table in horizontal plane



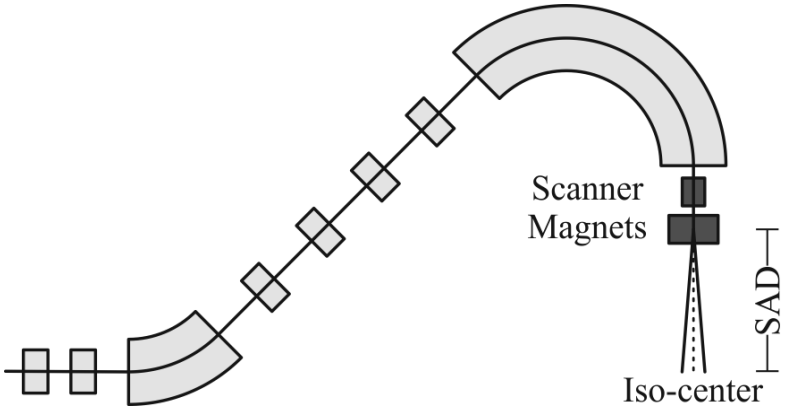
Other Advantages:

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

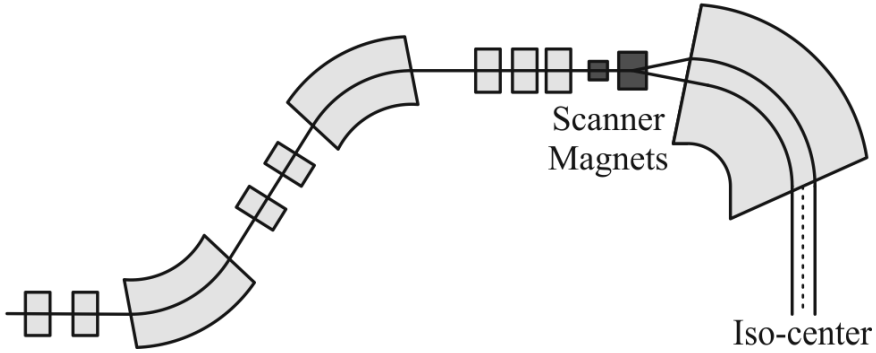
Idea of 180° gantry is now taken-up by industry

Location of scanner magnets: Downstream vs. upstream – scanning

Downstream scanning



Upstream scanning



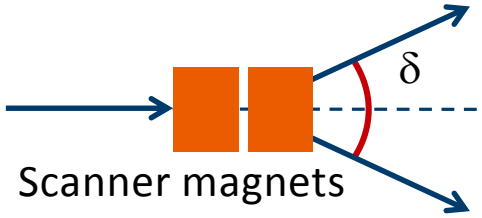
SAD: Source-to-axis distance

- Larger gantry radius
  (Drift space [SAD] + Scanner magnets)
- Building volume $V \propto l \cdot \boldsymbol{r^2}$
- Larger fields possible (40 x 40 cm^2)
- Commercial standard

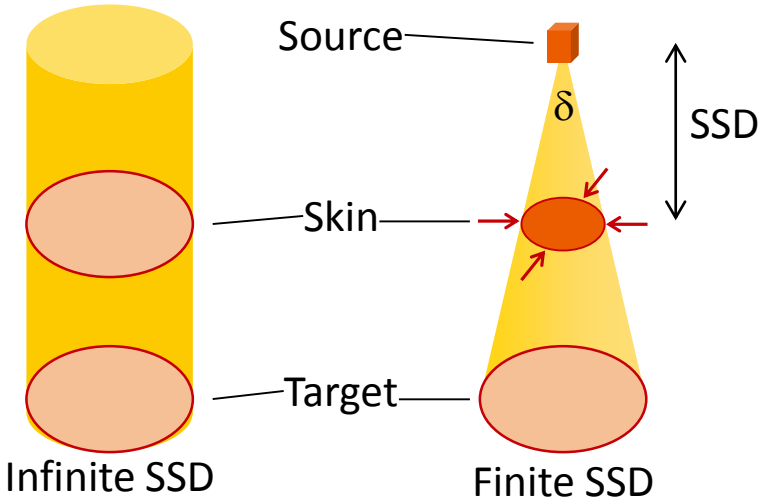
- Parallel beam with infinite SAD
- Large aperture of last bending magnet
  – Heavier (magnet and support)
  – Sophisticated beam optics
- Parallel beam simplifies planning / QA
- PSI Gantry 1/2, HIT carbon gantry

Virtual source and source-skin distance

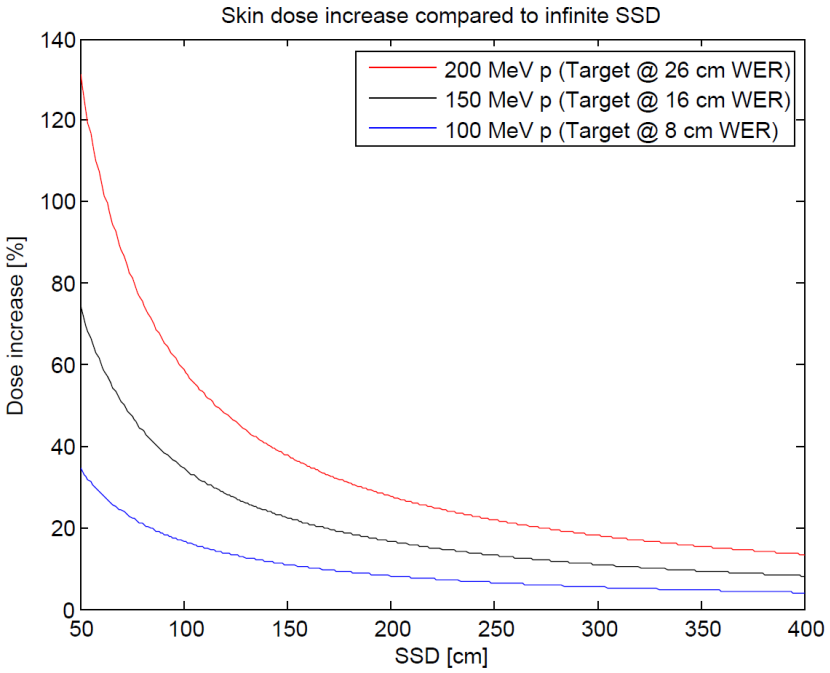
- Scanner magnets deflect beam from trajectory → 'virtual' source



- Beam divergence δ → Finite source-skin distance (SSD)
- Increased skin sensitivity to radiation

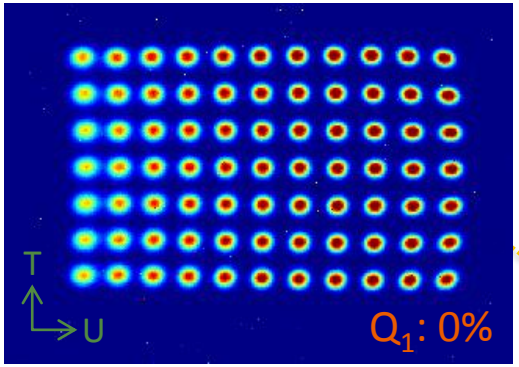


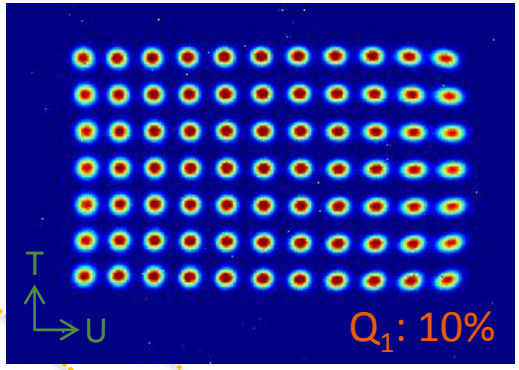
- Finite SSD increases skin dose (simple geometrical model ignoring multiple fields, patient geometry, tumour shape):

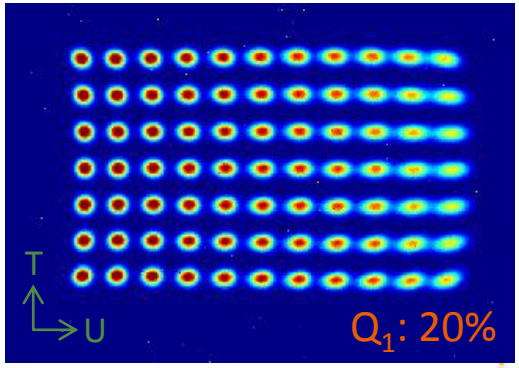


Upstream scanning with dynamic focusing correction (PSI Gantry 2)

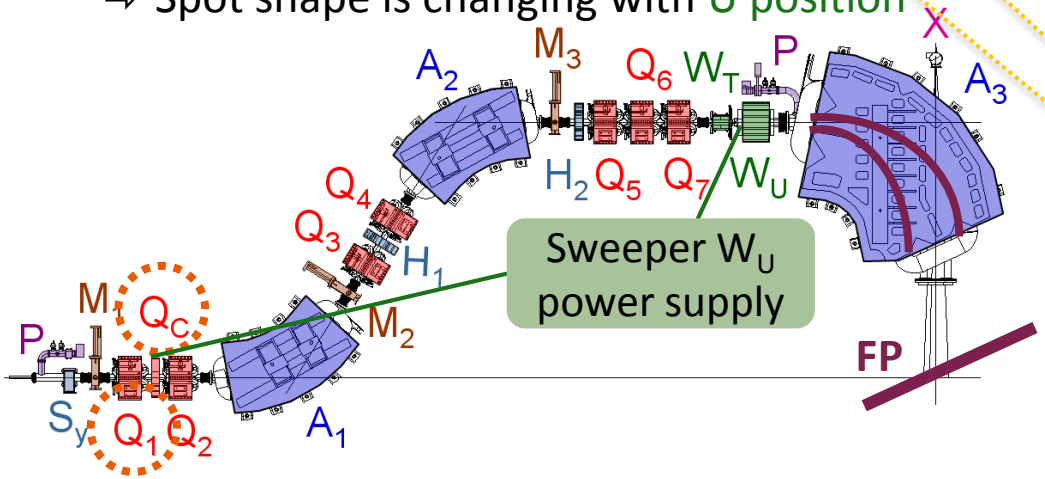
- Static corrections with quadrupole Q_1: varying spot shape while scanning



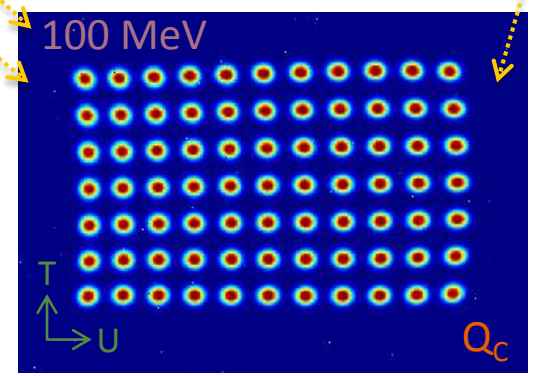




- Focal plane **FP** not orthogonal to transversal direction at iso-center
  ⇨ Spot shape is changing with U position

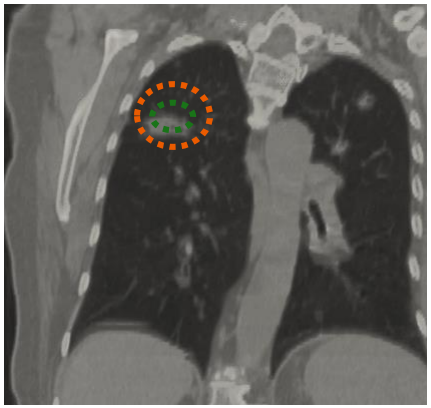


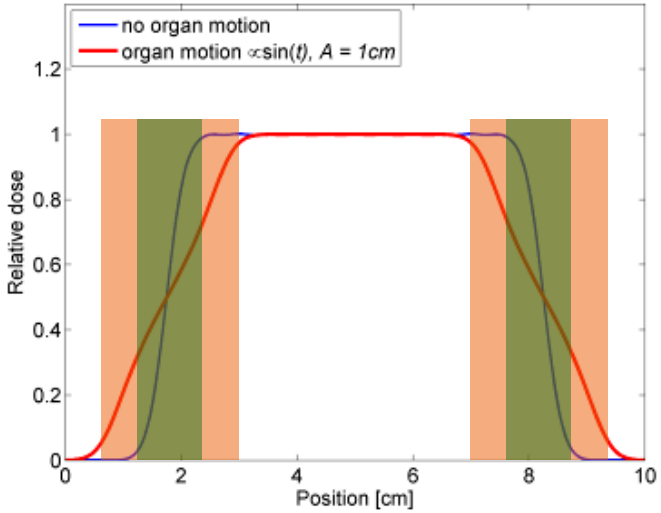
- Dynamic correction with Q_c: Quadrupole corrector in series with U-sweeper power supply
  ⇨ Invariant spot shape



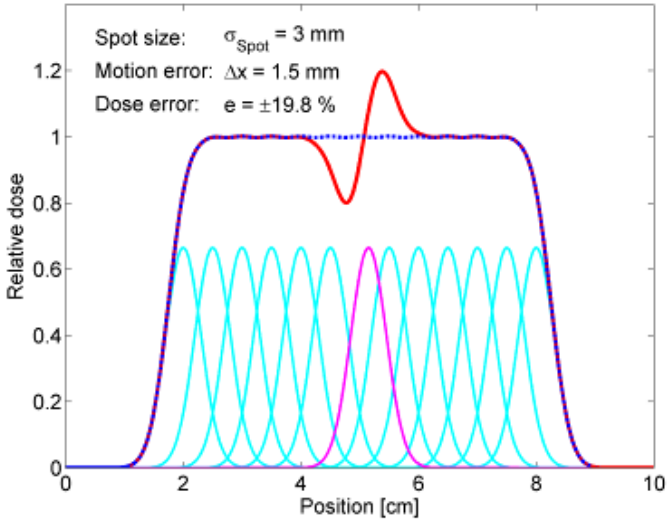
Major challenge for scanning: Treating moving targets

- Blurring of lateral dose fall-off in moving target (same problem for scattering and scanning)
  - Increase safety margins
  - Reduce motion range with gating or tracking





- Destruction of the dose homogeneity
  - Scattering (highly rescanned) → insensitive
  - Single scanning → very sensitive
  - Repeated scanning → acceptable (?)
    - Rescanning alone → medium motion
    - With gating or tracking → large motion

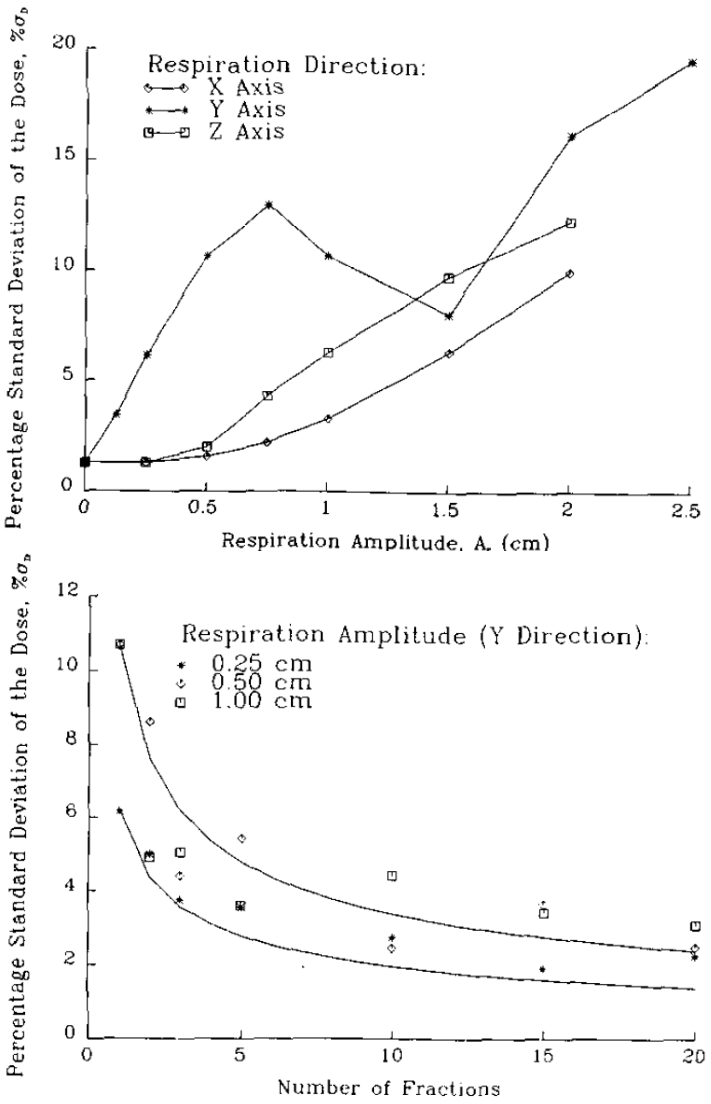


Rescanning – an easy solution to cope with problem of moving targets

- Scanning is very sensitive to organ motion
- Dose homogeneity can be destroyed by interplay effects

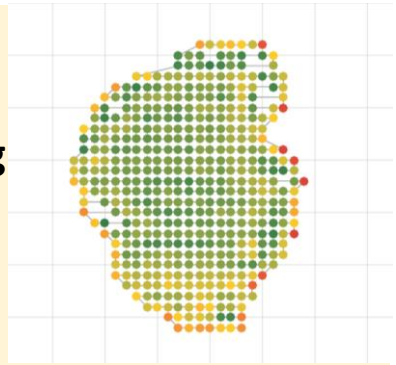
M. Phillips M et al.:
Effects of respiratory motion on dose uniformity with a charged particle scanning method 1992
Phys. Med. Biol. **37** 223:

- "We conclude that spot scanning is applicable when the spot size is not smaller than the motion of respiration […]"
- "In general, one would expect that the more often the volume was scanned, the more likely it would be that the motion due to respiration would average to zero."
  → Rescanning
  → Scanning system with low dead time



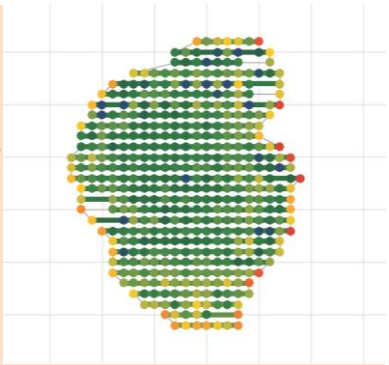
Pencil beam scanning options: Spot – Raster – Continuous Scanning

Spot scanning



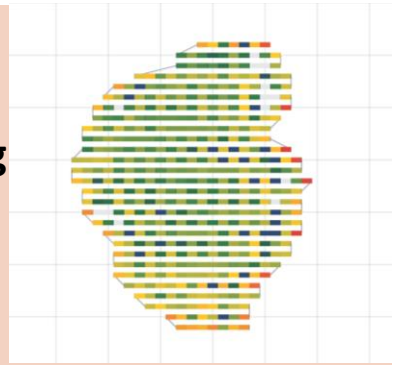
- Switching off the beam after each spot
- Dead time per spot ~3 ms.
- 10’000 spots → 30 s dead time, scales with number of rescans!
- Standard for PSI Gantry 1 since 1996

Raster scanning



- Beam-on from spot to spot position
- Beam off only for larger steps
- Transient dose: Limiting factor
- Dose delivery on fixed grid
- Developed at GSI
- Today commercial default

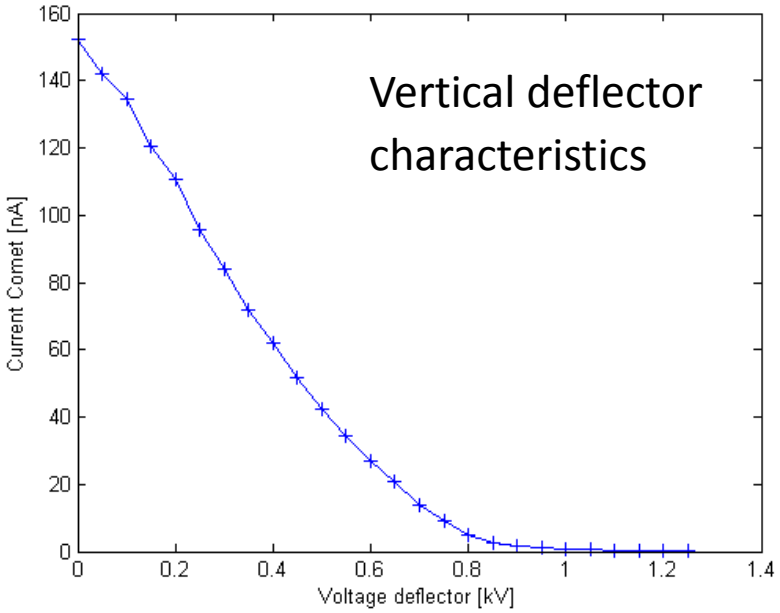
Line scanning

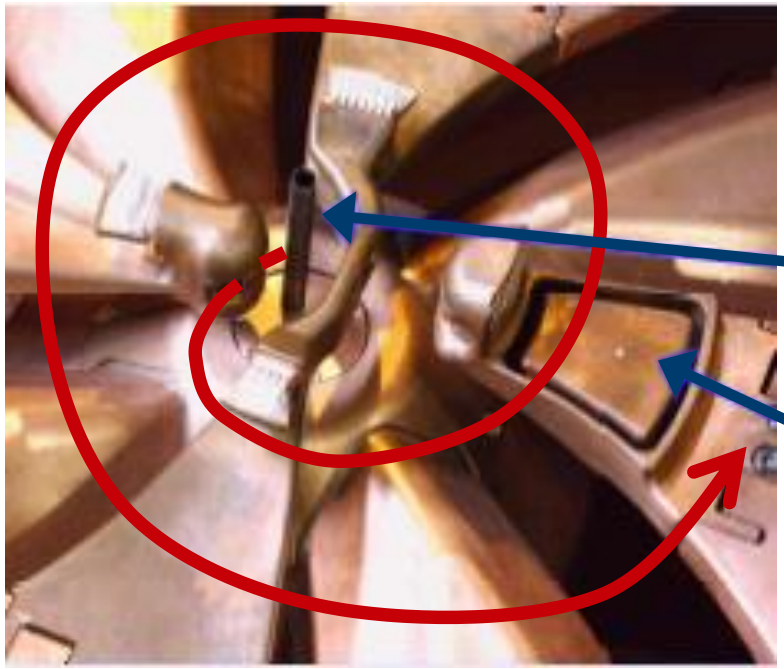


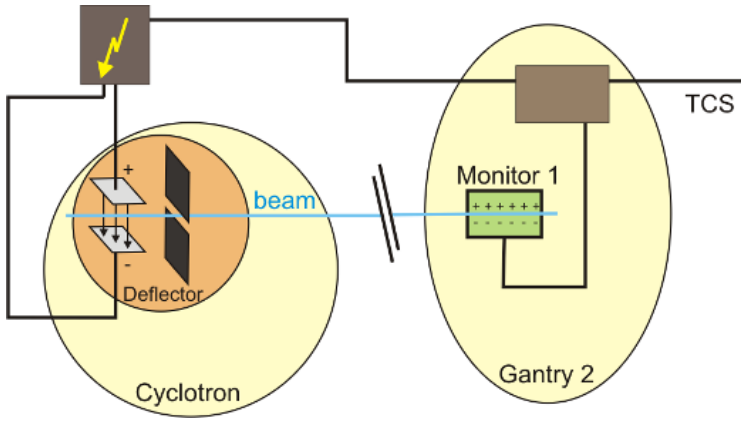
- Continuous modulation of dose profile along lines
- Faster and more flexible form of dose delivery
- Minimize dead time
- For maximal rescanning
- Development at Gantry 2
- Commercially available by Sumitomo (only speed modulation)

Fast and precise intensity modulation: Vertical deflector inside cyclotron

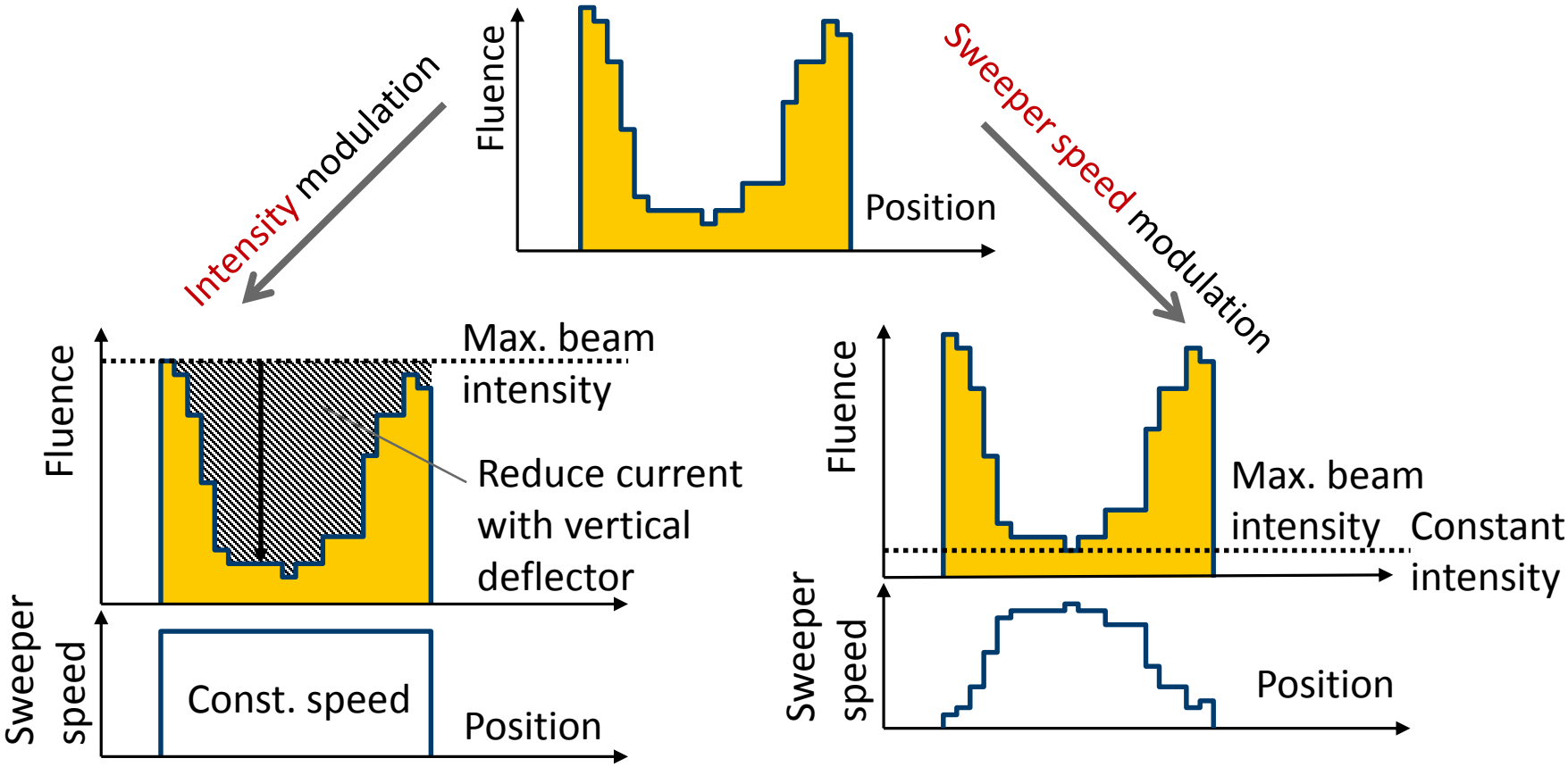
- Fast electrostatic beam deflection inside accelerator at ion source (~50µs)
- Suppress proton current with no activation of the machine
- Feed-back loop to control the dose rate based on primary dose monitor







Line scanning: Intensity vs. speed modulation



- Suppress beam with vertical deflector
- Wasting protons, hence less efficient
- Large number (~100) of rescans needed if working with highest sweeper speed

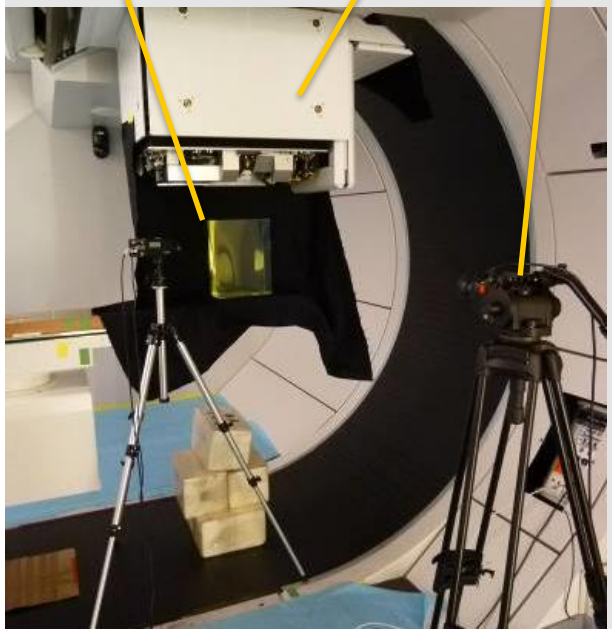
- Adapt sweeper speed to requested profile
- Work with maximal proton current
- Problem: Painting low dose profiles

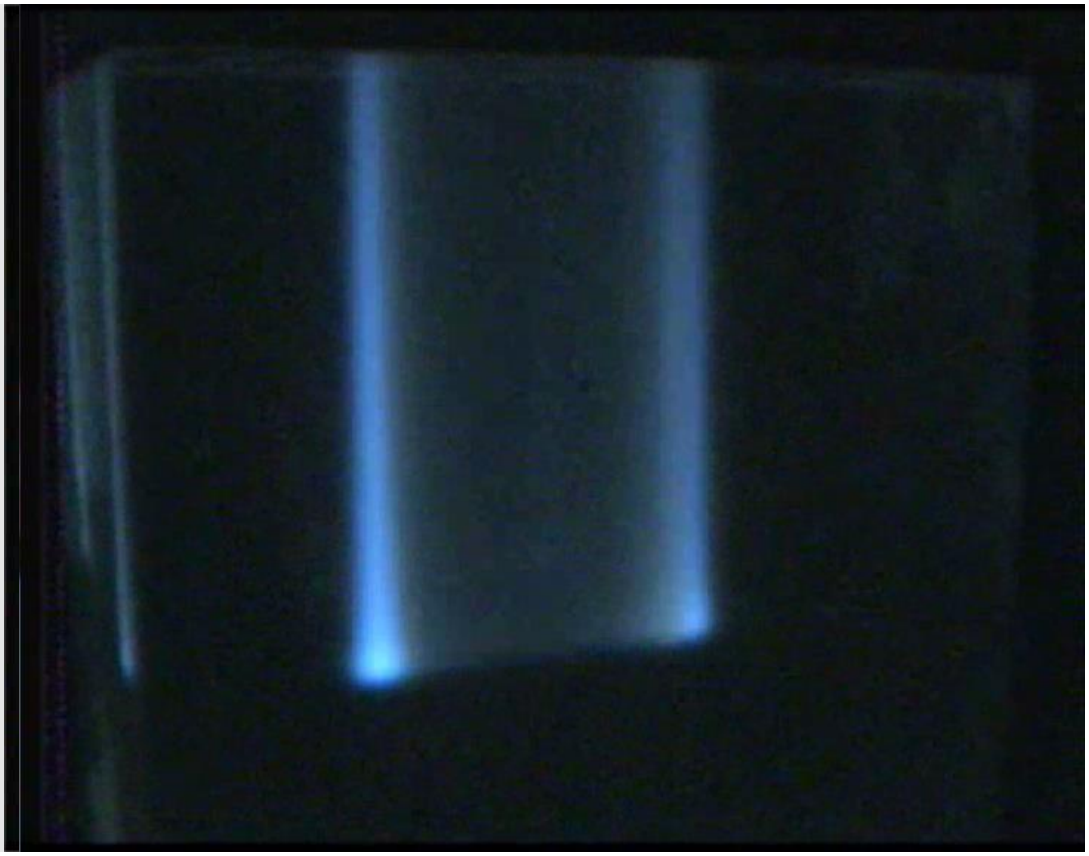
⇨ Find optimal combination of both modes

Demonstration of fast conformal line scanning

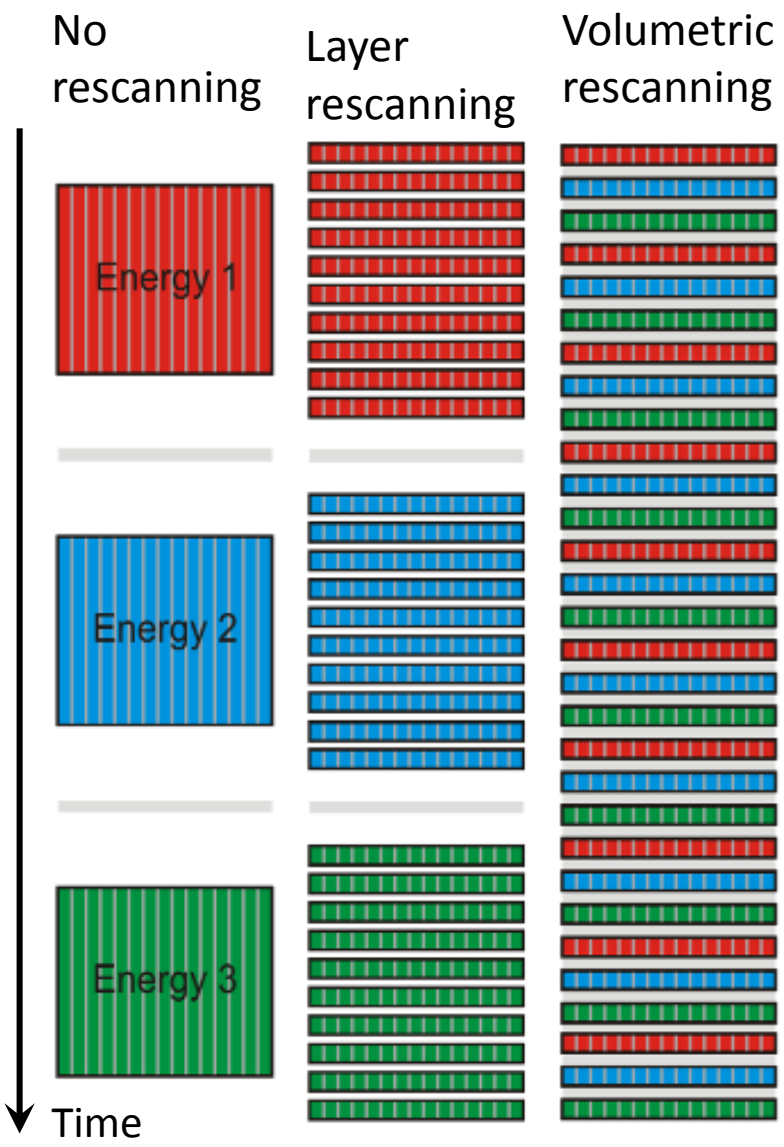
- Delivery of 3 dose distributions with line scanning: Box / Diamond / Sphere
- Dose: 0.2Gy / Delivery time ~10s
- Combination of sweeper speed and beam intensity modulation

Experimental setup:





Different options of rescanning



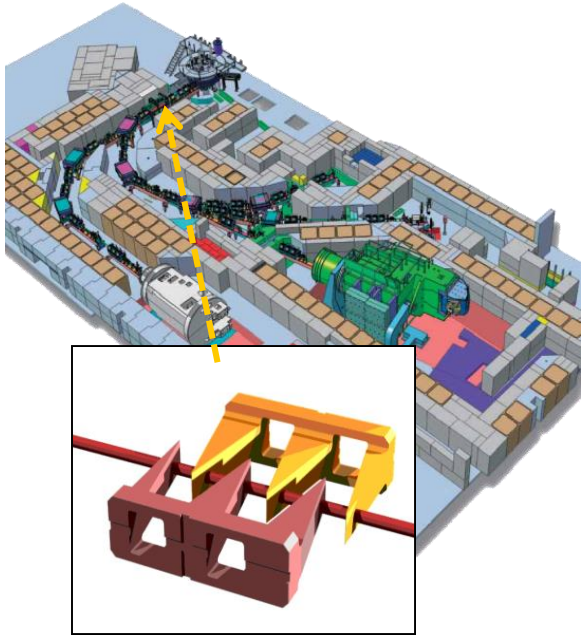
- Layer rescanning:
  Repeat scan sequence within in a energy layer

- Volumetric rescanning:
  Repeat scan multiples times over full target volume

For volumetric rescanning, beam energy must be change more often

➢Volumetric rescanning requires fast energy changes, otherwise ineffective!

Fast changes of the beam energy



PROScan (Gantry 2) was optimized for fast energy changes:

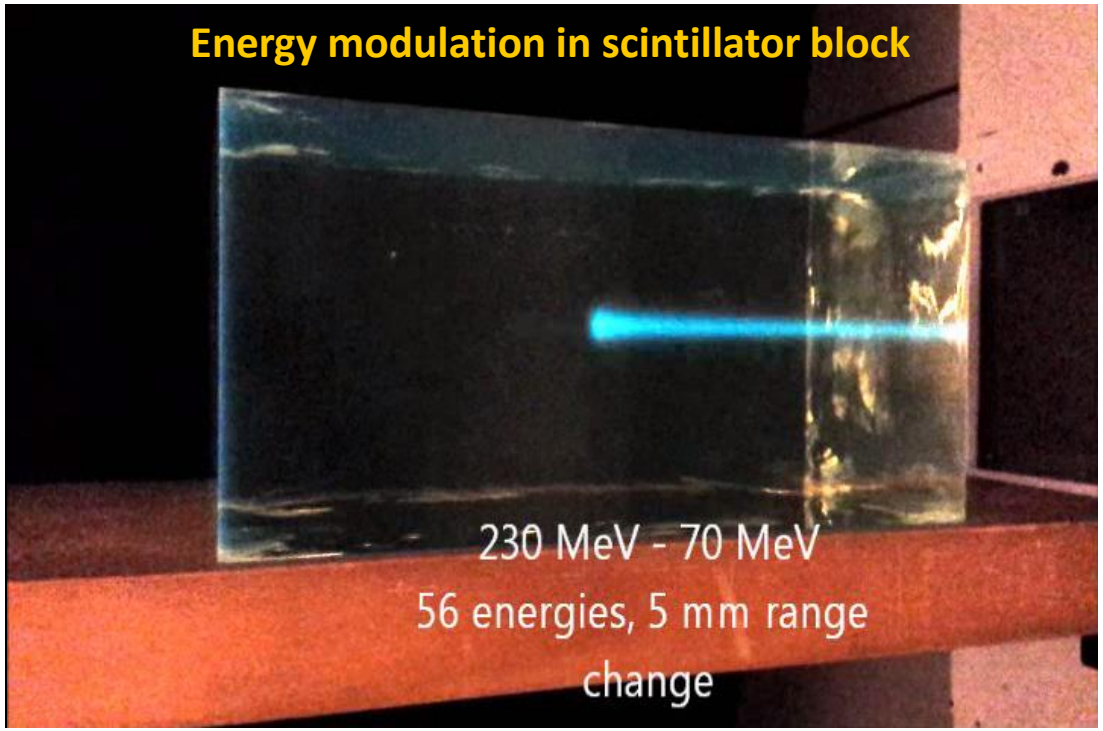
- Fast mechanical degrader
- Laminated magnets / dedicated power supplies
- On-line corrections of ‘drift’ effects

Realized:

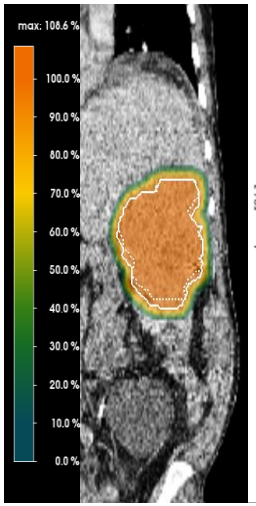
- <100ms dead time for 5mm change in range

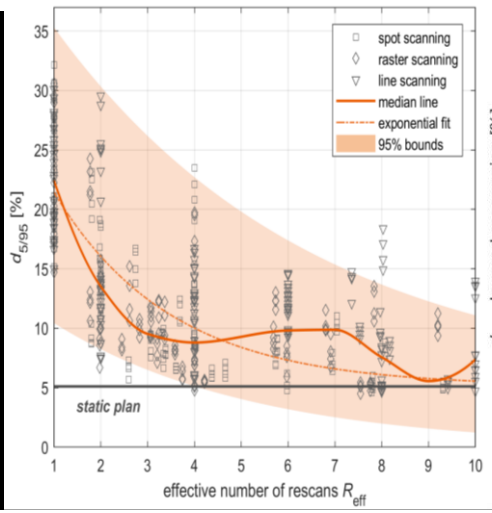
Benefit:

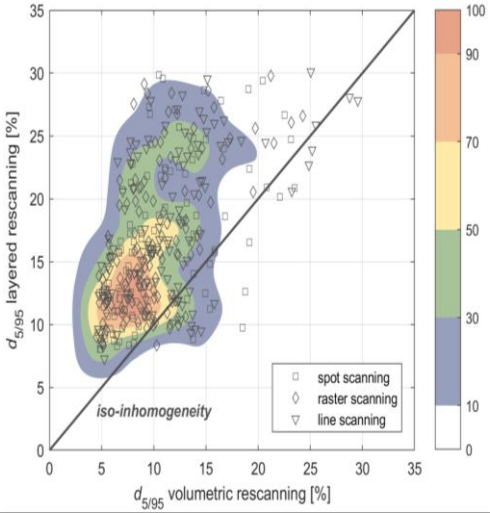
- Faster treatments
- Efficient volumetric rescanning

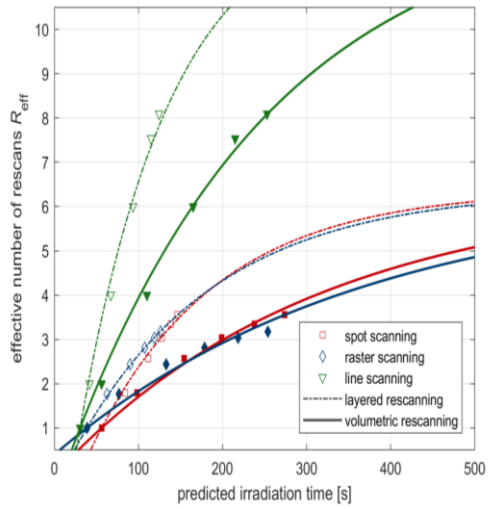


Effectiveness of volumetric rescanning with line scanning: Simulations and exp. verification







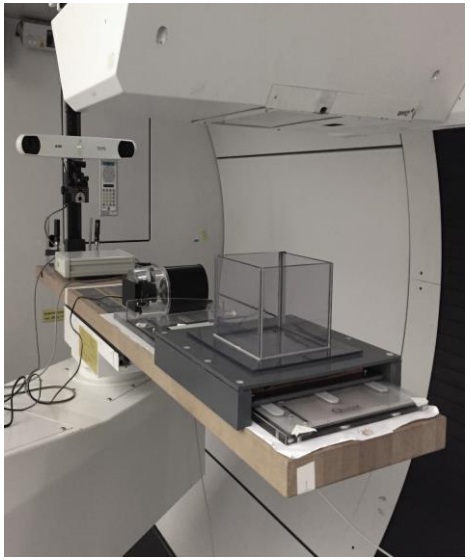


~800 4D dose calculations of a liver case (460 ccm) for *spot / raster / line scanning* and *layered / volumetric* rescanning:

- Inhomogeneity ($d_{5/95}$) inside target decreases with increasing number of effective rescans (R_{eff})
- Volumetric rescanning is more effective than layered rescanning for the same number of rescans
- Line scanning is the fastest delivery technique

Experimentally validated on Gantry 2 with moving phantom

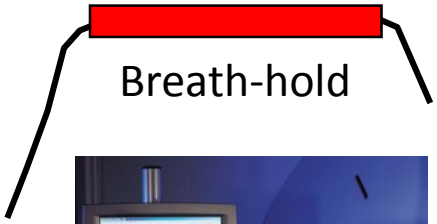
→ Klimpki et al. (2018), Phys. Med. Biol. manuscript submitted

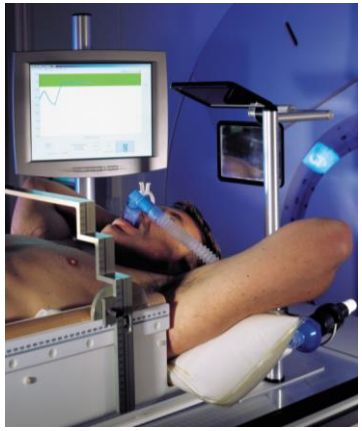


Motion mitigation: Breath-hold and Gating

Breath-hold

- Patient actively hold his breath
- Irradiation only during breath-hold window



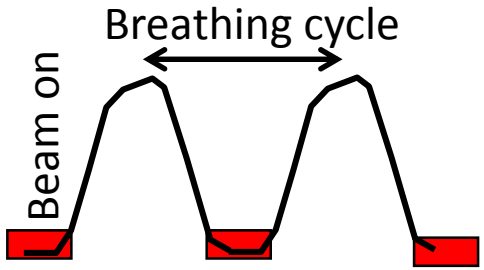


Benefit:

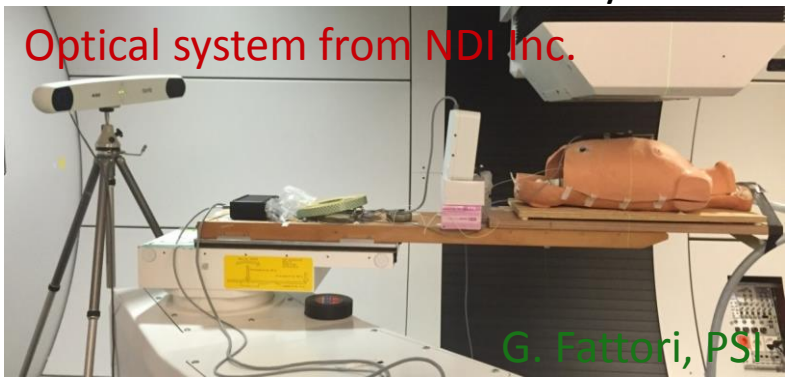
- Dose application in quasi-static condition
- 4D problem is reduced to 3D (planning / verification)
- Efficient irradiations

Attractive for line scanning:
Treating a small volume < 10s

Beam gating



- Breathing cycle is monitored (externally)
- Irradiation only during defined window (e.g. exhale phase)
- Longer treatments
- Interaction with dose delivery



→ Both techniques are established in conventional therapy ←

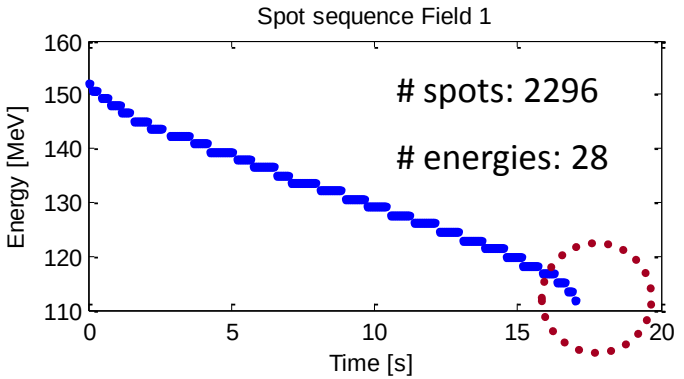
Additional benefit of fast scanning: Faster patient treatments

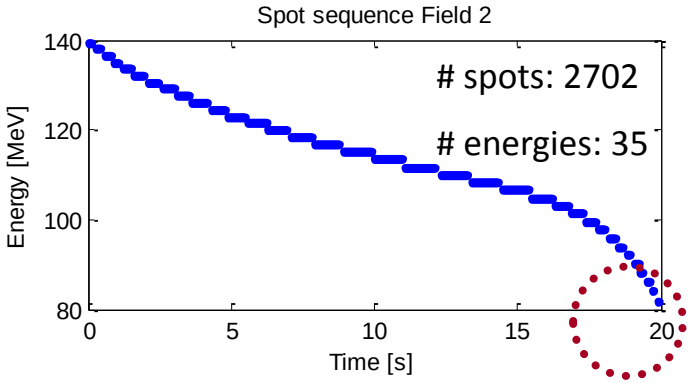
Faster patient treatments:

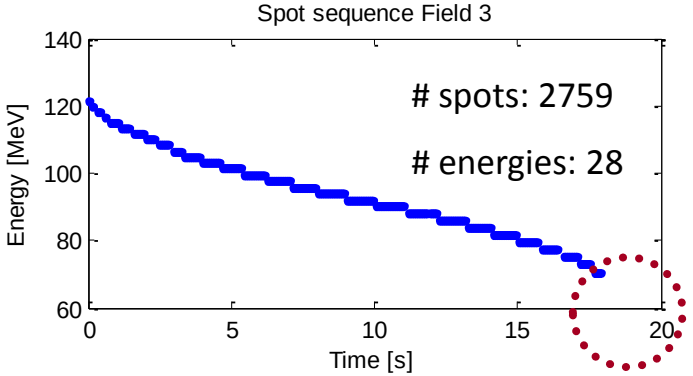
- Reduced intra-fractional motion
- More comfort for the patient
- Higher patient capacity
- Optimized workflow

Example: First patient Gantry 2 (Nov. 2013)

- Skull base meningioma, 3 fields, 1.8 Gy
- Discrete spot scanning, energy change 100ms
- Delivery time per field < 20s

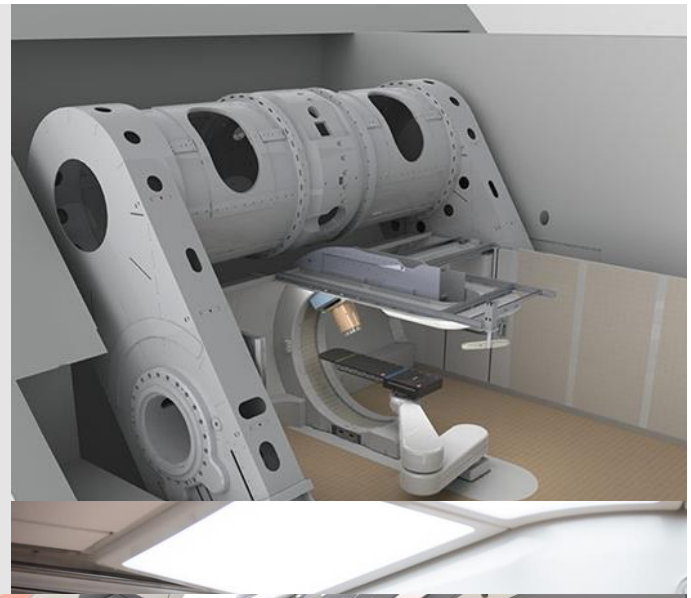


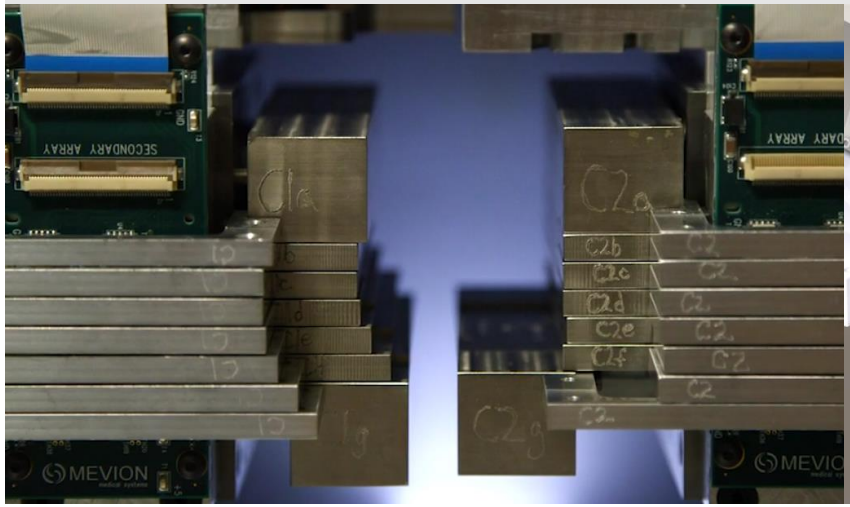


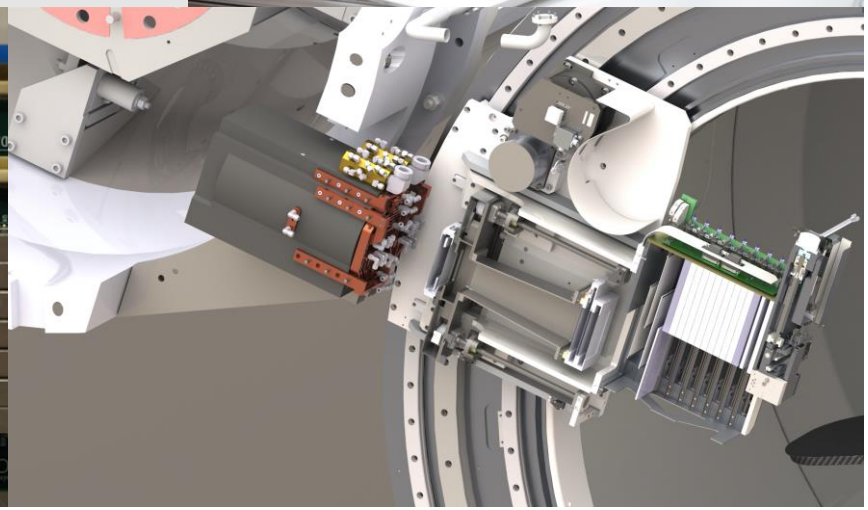


Mevion hyperscan – the ultimate solution?

- Gantry-mounted proton accelerator
- SC synchro-cyclotron, originally for scattering
- Proton pulse rate 500 Hz (Pulse <20 us)
- Development of a scanning nozzle (Hyperscan):
  - Single focus, dual direction scanner magnet
  - Energy modulation with range shifter (fast, no beam line)
  - Fast automated collimation (better penumbra)
- FDA 510(k) clearance







Summary and conclusion

- Pencil beam scanning has become the standard delivery technique and enables:
  - Intensity modulated proton therapy (IMPT)
  - 'Sharper' dose distributions due to 'edge' enhancement
- Need for more compact system
  - Different gantry design options affect facility size (upstream scanning / 180° rotation)
- Treating moving targets is one of the main challenges for PBS
  - Possible solutions: Rescanning, gating or irradiation during one breath-hold
  - Require fast scanning systems with fast energy switching and dose delivery (lines)