PAUL SCHERRER INSTITUT

PSI

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Paul Scherrer Institut

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Proton therapy at PSI: Technical innovations and future developments

Joint Universities Accelerator School – 27.02.2014

Outline

Benefit of particles in tumour treatment

Hadron therapy at PSI

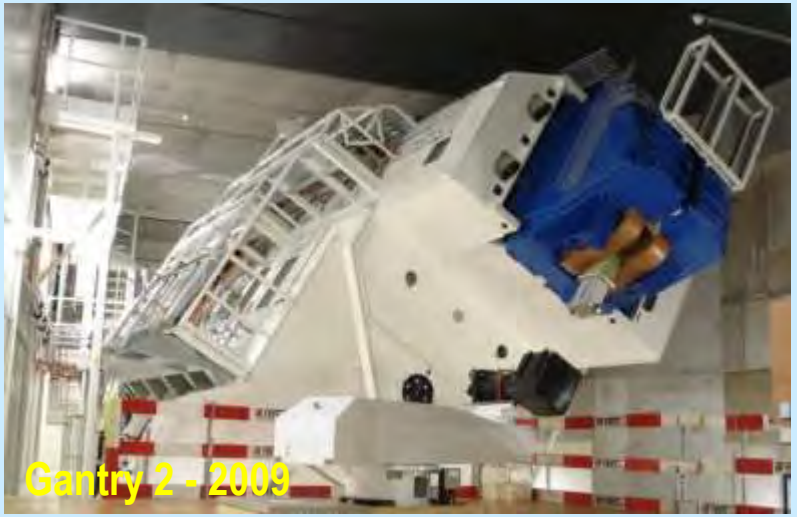
- OPTIS: Passive scattering technique for treating eye melanomas
- Gantry 1: The first spot scanning gantry for protons
- PROScan: Expansion with a dedicated superconducting cyclotron for medical use

Problem of organ motion

- Spot-Scanning and moving targets
- Repainting / Gaiting / Tracking

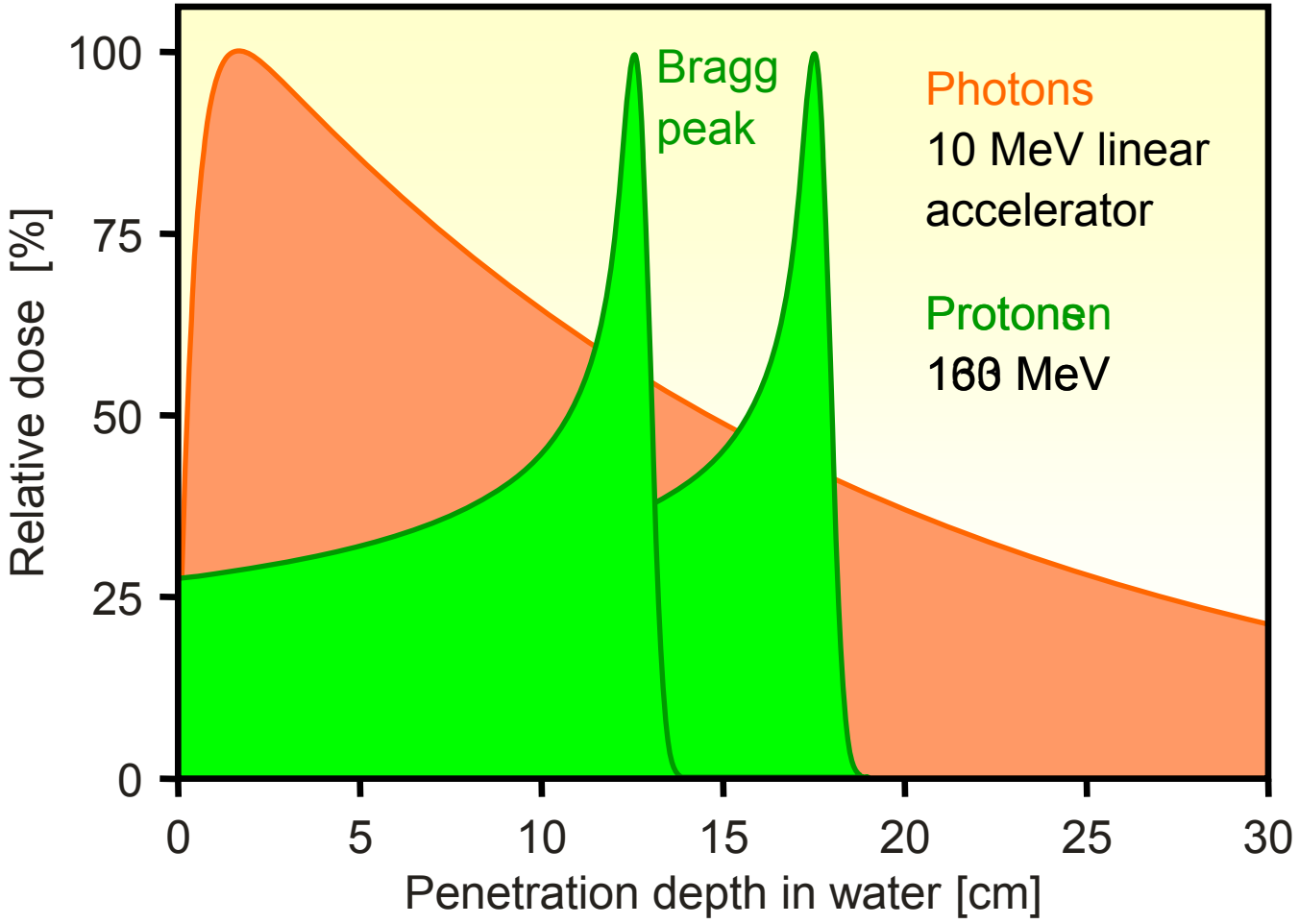
Gantry 2

- Next generation of spot scanning gantry for coping with organ motion

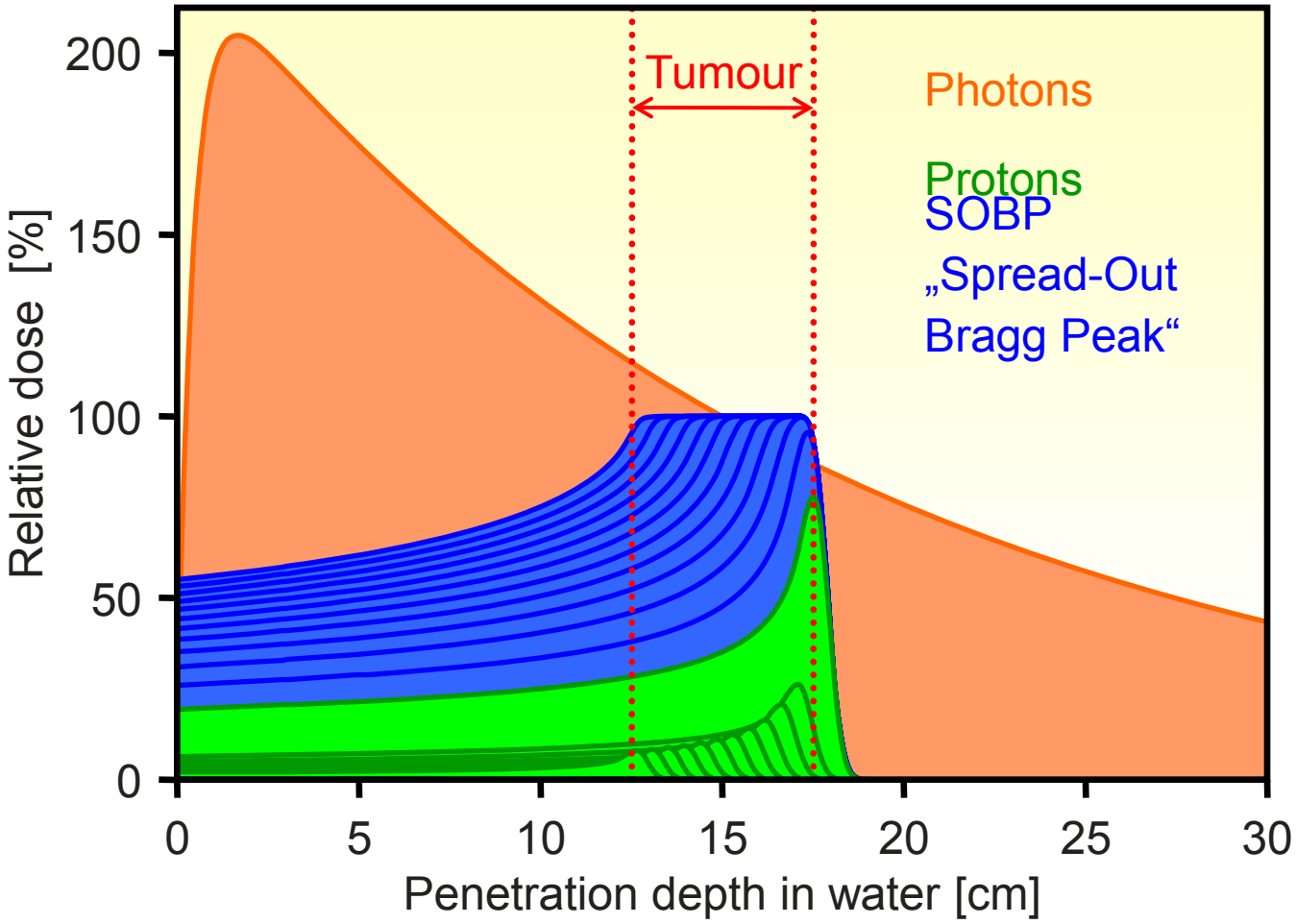


Benefit of particles in tumour treatment

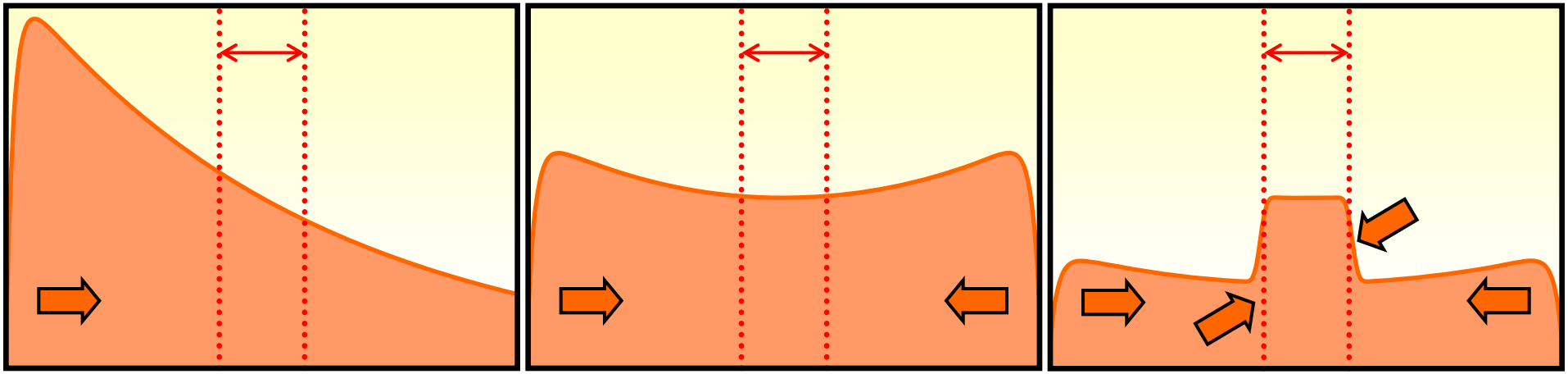
Depth dose profiles of photons and protons



Radiation of tumours with energy variation



Multi-field radiation with photons



1-field radiation

Field direction
- from left

2-field radiation

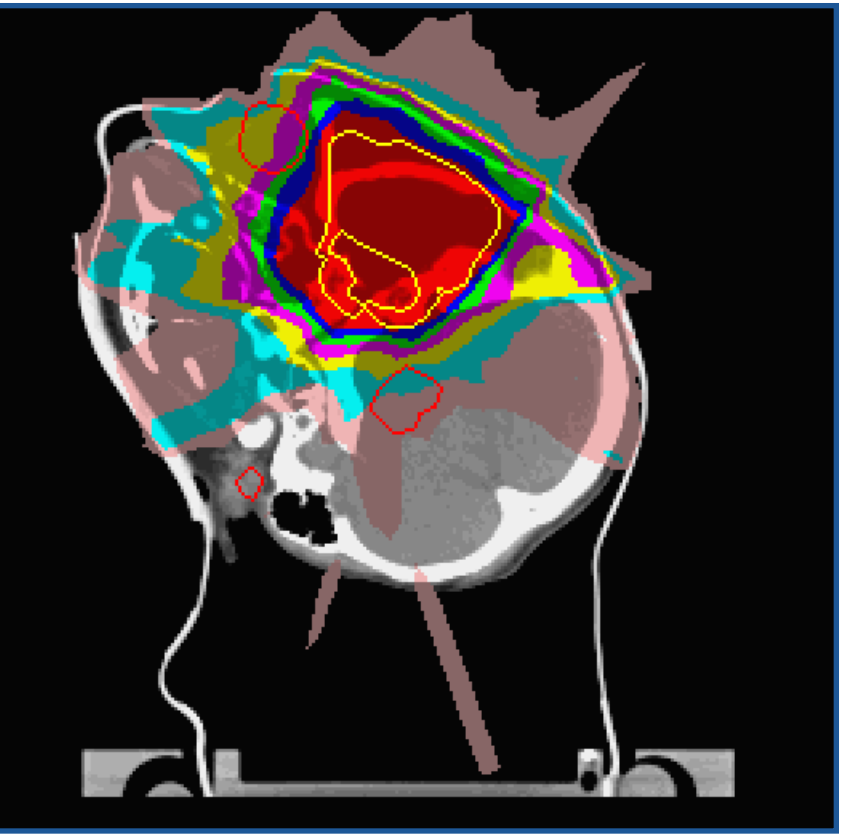
Field direction
- from the left
- from the right

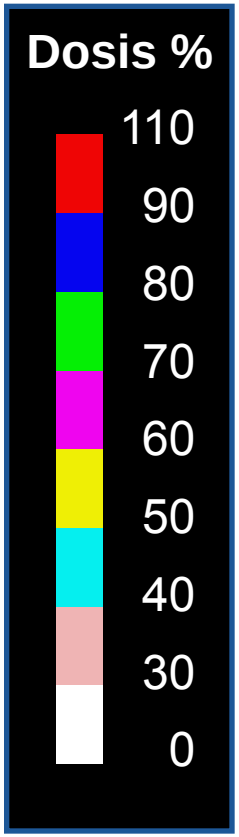
4-field radiation

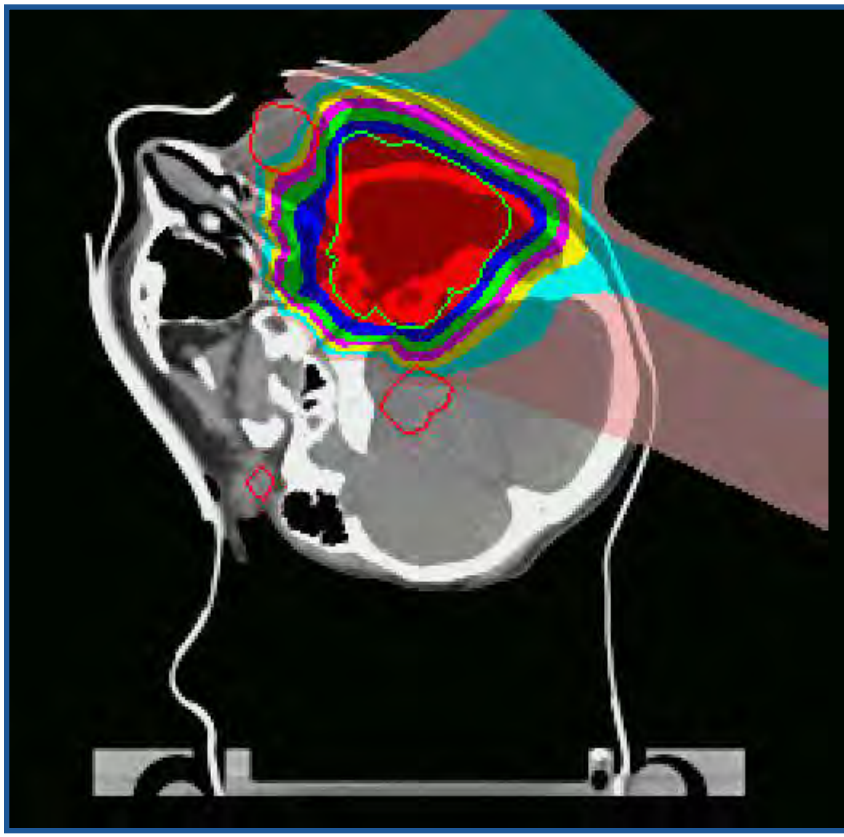
Field direction
- from the left
- from the right
- from the front
- from behind

- Conventional photon therapy >~ 6 fields
- A Gantry (rotating mechanical support) is needed for full flexibility in beam direction
- Trend in photon therapy: increase the number of fields (Arc therapy, Tomo therapy)

Comparison photons ⇔ protons for a cerebral tumour







State-of-the-art **radiation therapy**,
9 fields

Proton therapy PSI,
2 fields

Passive scattering technique for treating eye melanomas

OPTIS: Scattering technique, (1984 -)

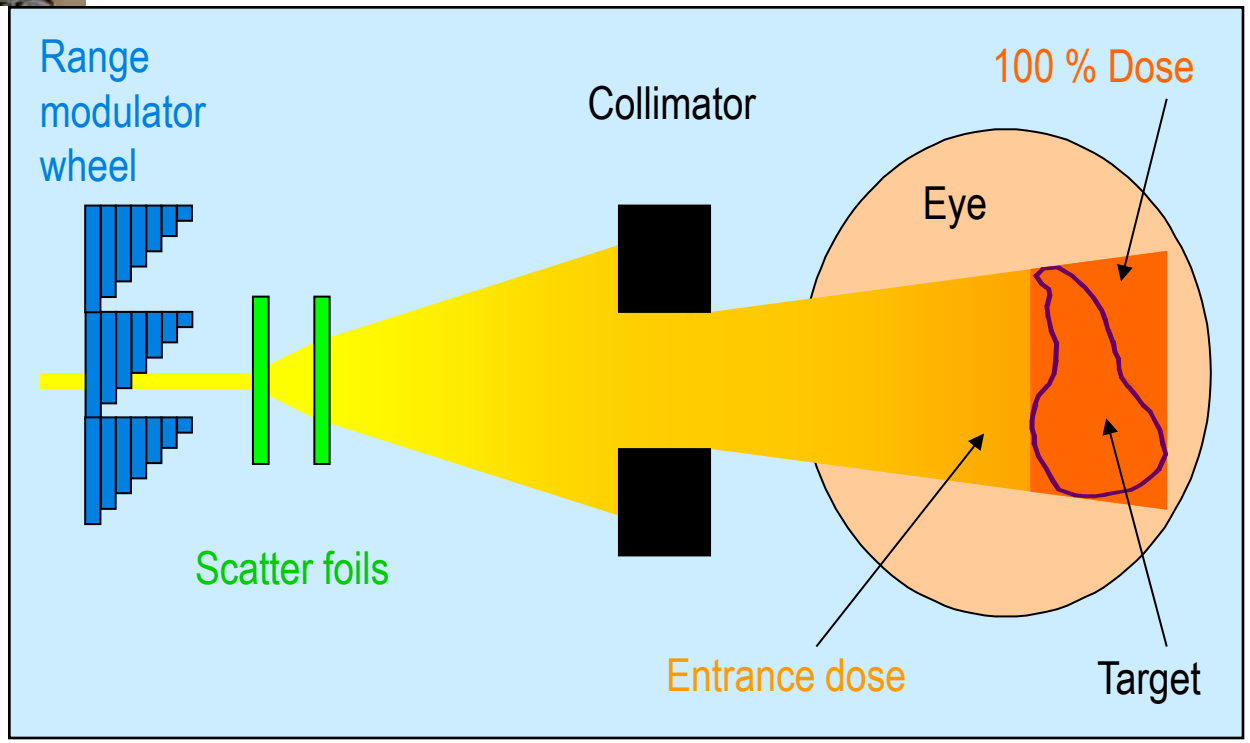
Passive scattering technique:

- The narrow beam is scattered with foils
- A collimator shapes the proton flux to the desired target
- Individual hardware (collimator) is needed for every patient

6000 patients treated since 1984

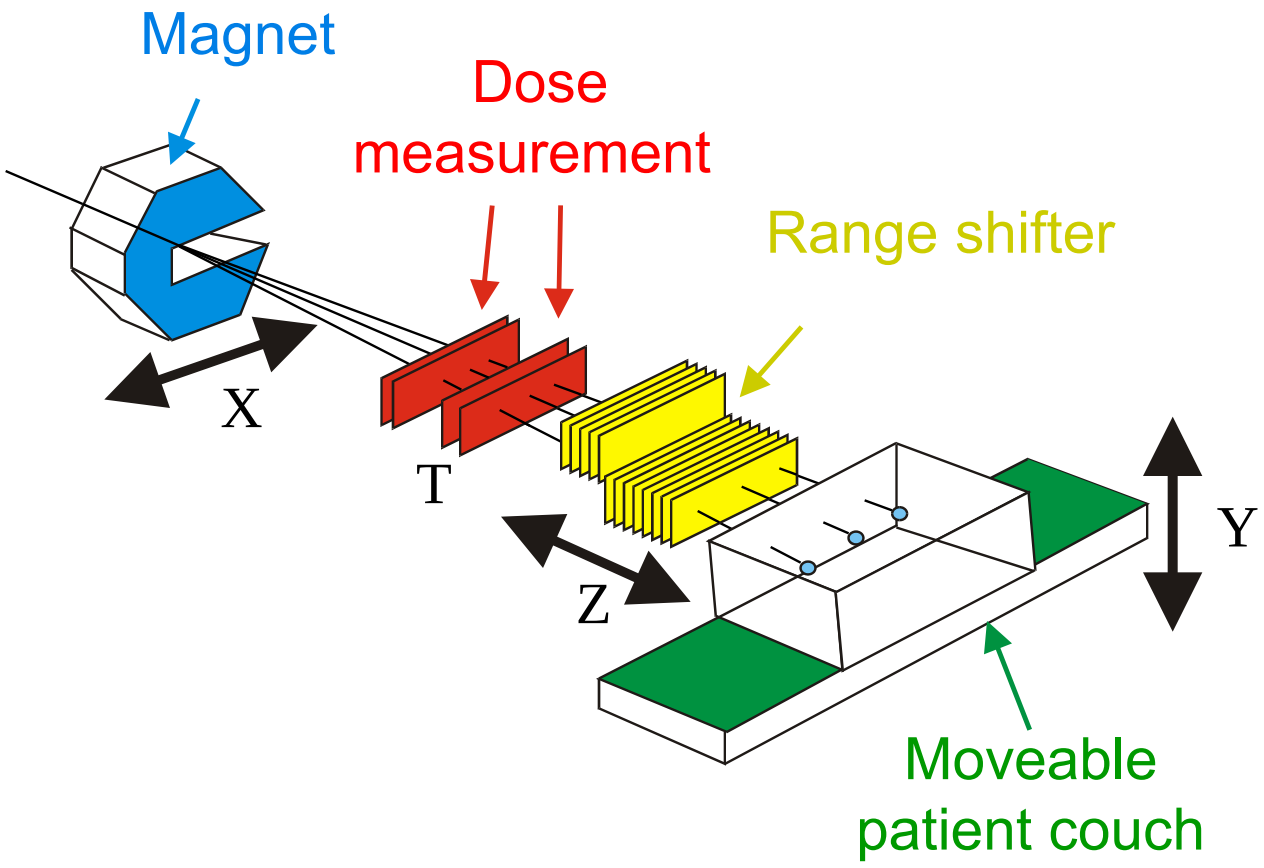
Local control (5 years): 99%

In 2009 the OPTIS program was modernised, upgraded and transferred to a new proton beam line.

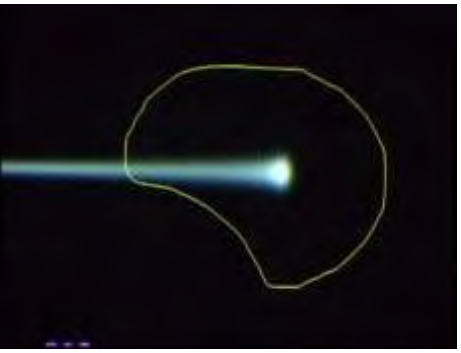
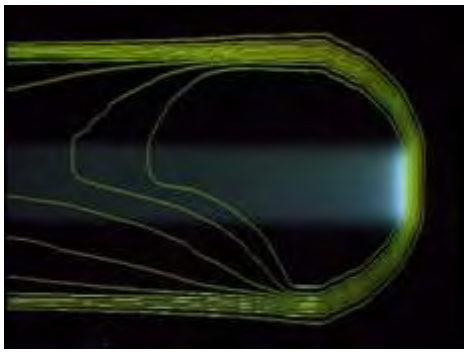
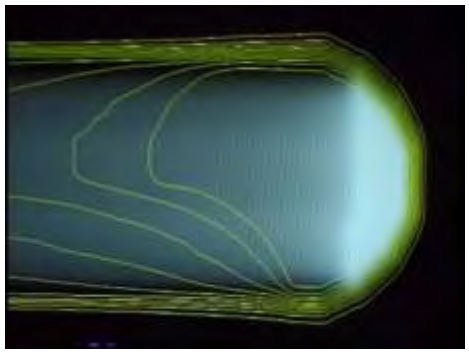
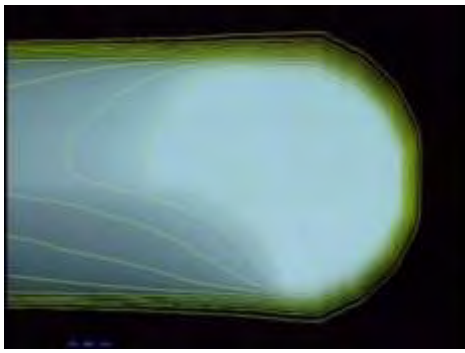


Gantry 1: The first spot scanning gantry for protons

Important PSI innovation: Spot-scanning technique, 1990



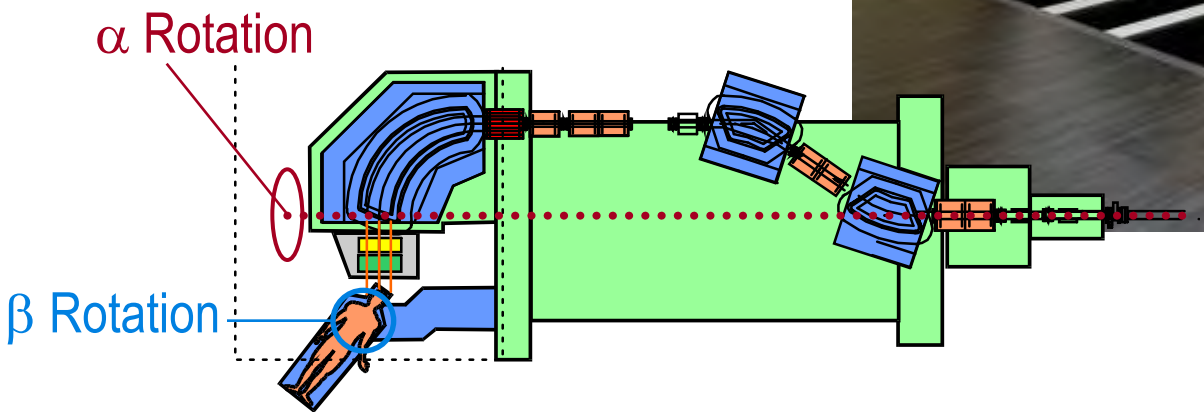
- Protons are guided as a thin beam into the target
- The tumour is irradiated sequentially spot by spot
- Better conformation of dose to shape of the tumour
- Less exposure of the surrounding healthy tissue to radiation

Gantry 1: A compact system for spot-scanning, 1996

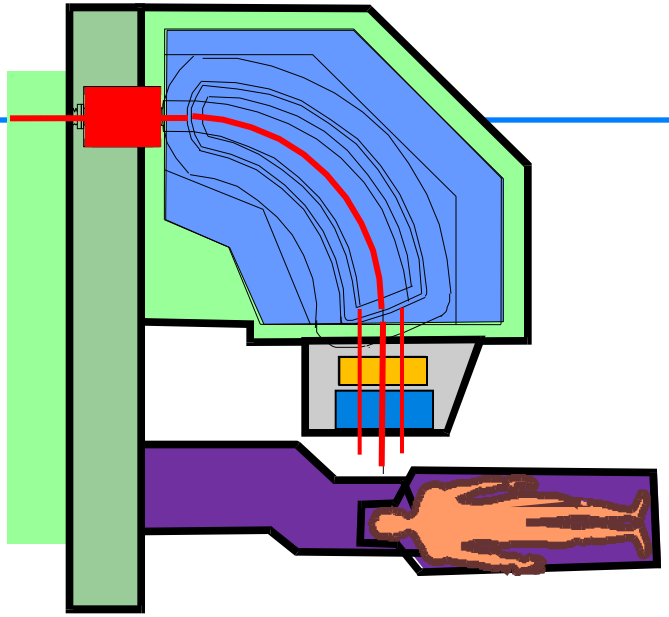
- Flexibility to apply the beam from almost any direction
- During 12 years the only proton spot-scanning machine
- Worldwide the most compact system, radius 2 meters

Problem 1: irradiations form below



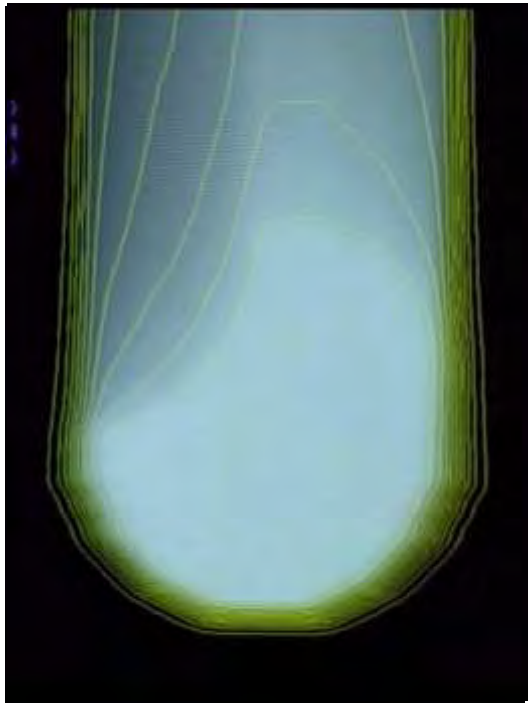
Design: Eros Pedroni

Dynamic pencil beam scanning



- Gaussian pencil beam: 3 mm σ in air
- Cartesian scanning with infinite SSD, “step and shoot” on a 5 mm grid
- Beam is switched-off with a kicker magnet after every spot
- Elements of scanning:

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



Problem 2: Slow mechanical scanning axis

The clinical use of Gantry 1

Since 1996 ~ 1000 pa

Treatment: 7 weeks (>
Maximal 19 patients p

Mainly tumors in the

- Skull / Spinal cord /

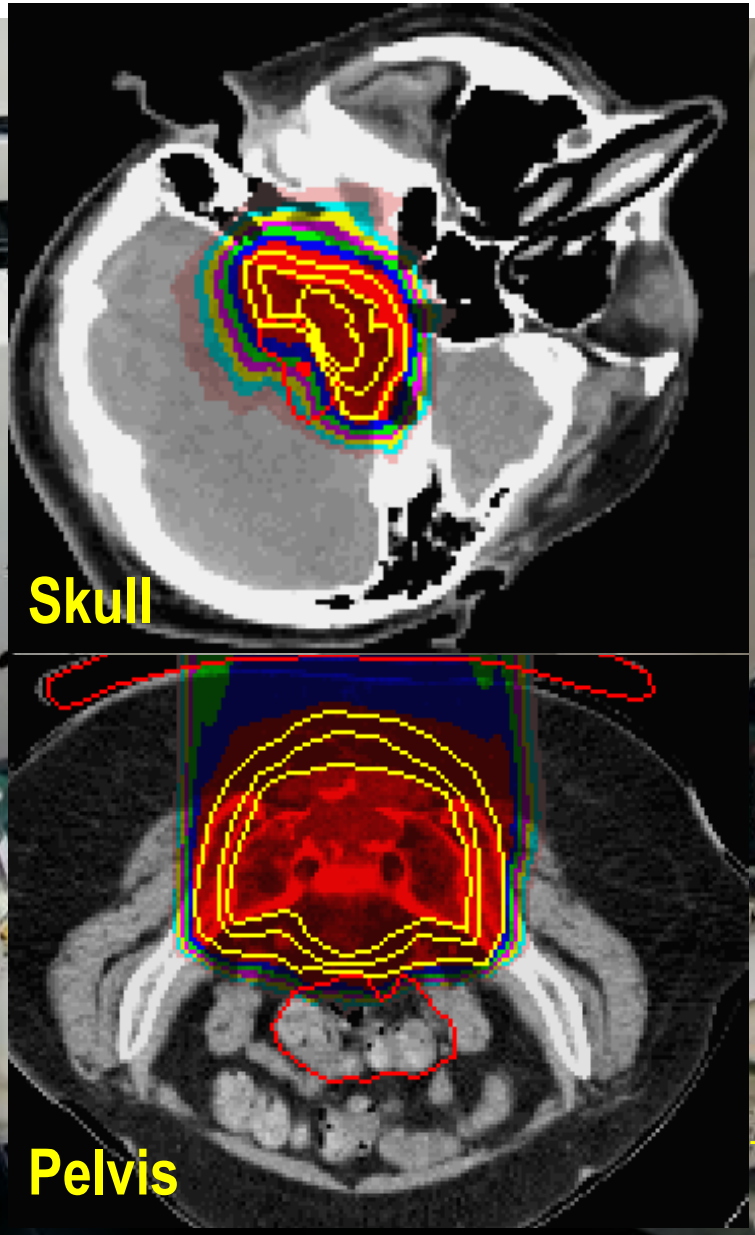
Problem 3: Moving tar

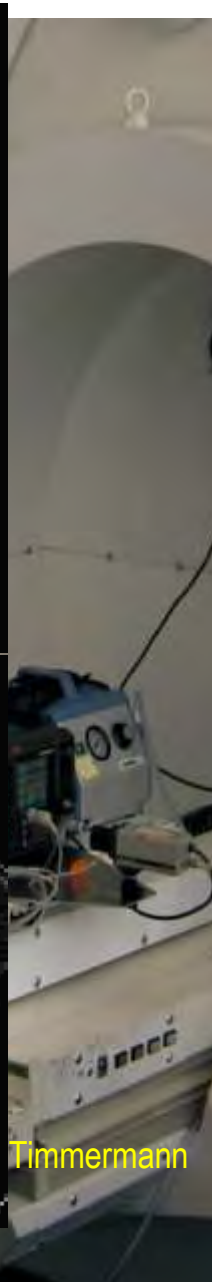
Since 2002: reimburse
Swiss health insuranc

- trend towards young
- more strict patient s

Pediatric tumors:

- Under anesthesia if
- Proton dose sparing
  the growing organis

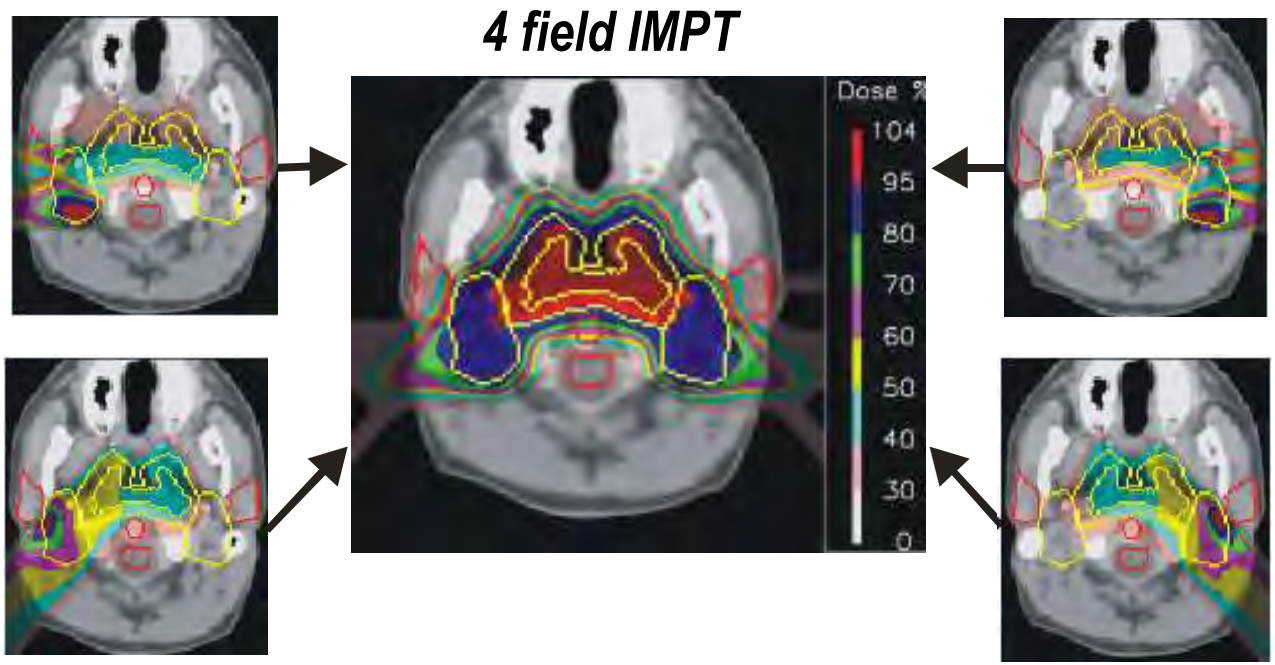




IMRT with Protons: IMPT

Intensity modulated Proton Therapy (IMPT)

- Modulation of the proton flux and range for each field direction
- IMPT is only possible with pencil beam scanning
- Today, more than 1/3 of all Gantry 1 patients are treated with IMPT



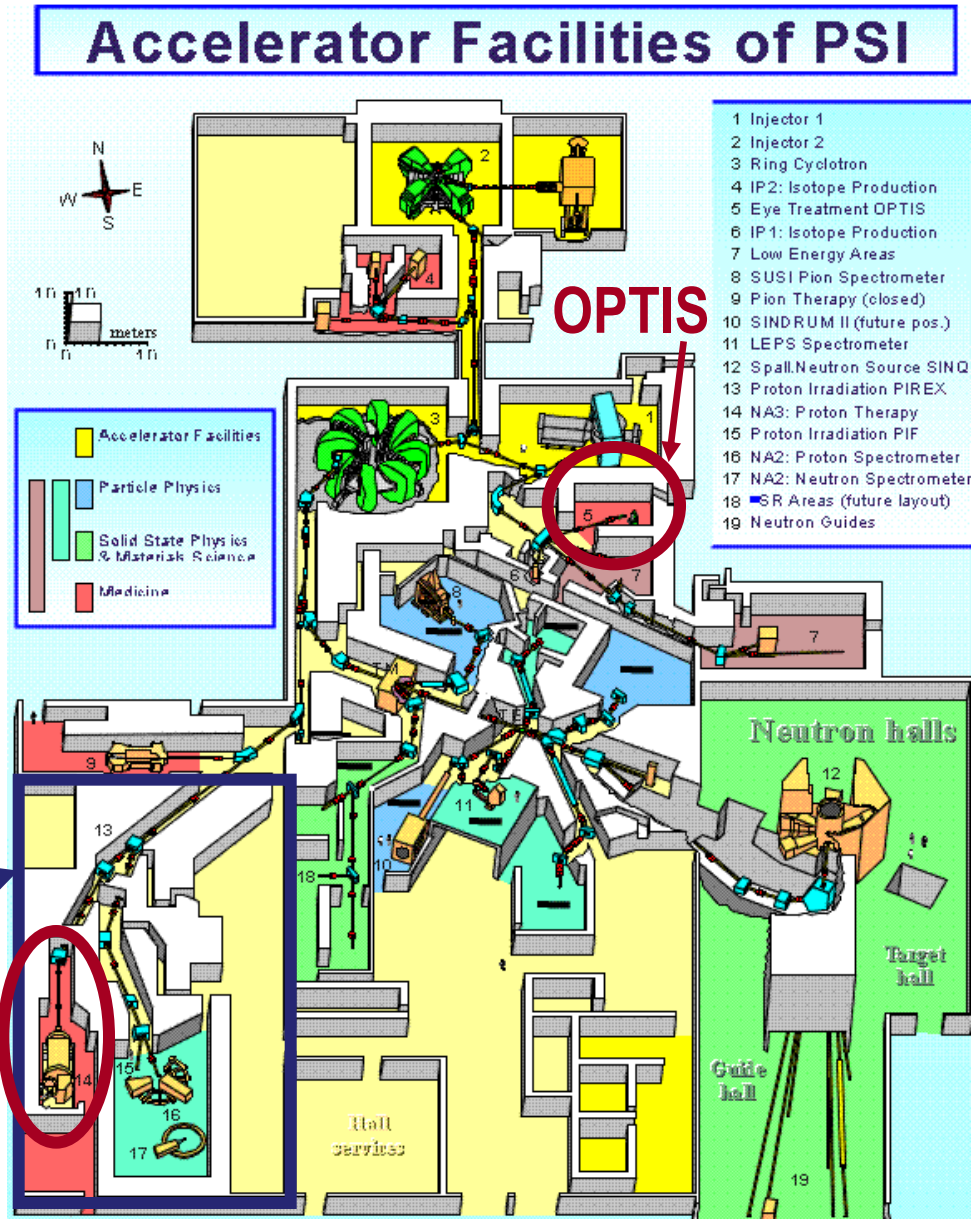
Courtesy of A. Lomax

Situation until 2005

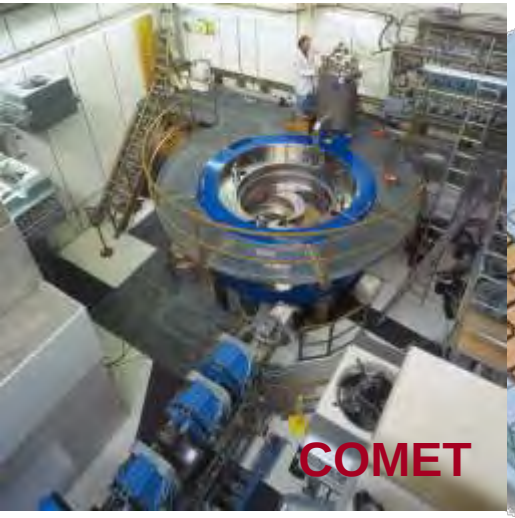
Clinical success with proton therapy but

- parasitic beam extraction of the 590 MeV cyclotron
- long shut-down period per year
- only 4 day per week

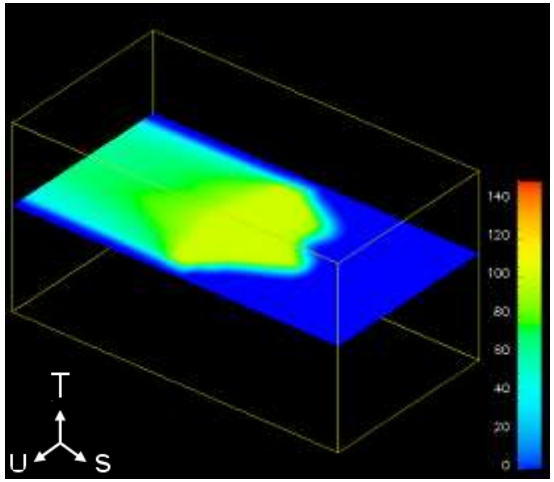
→ Launch of the project PROSCAN with own medical accelerator and additional Gantry 2



PROScan facility at PSI

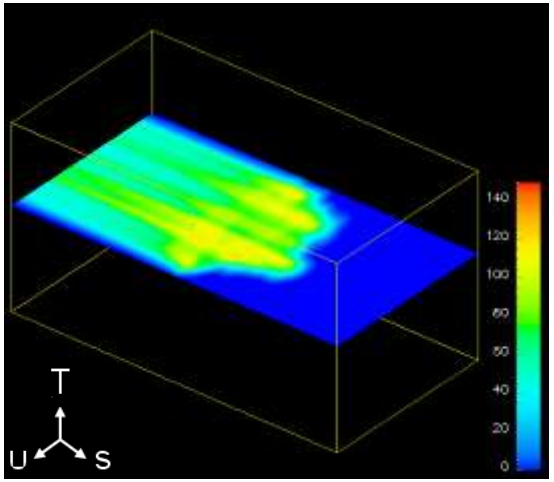


Problem of organ motion



Static target

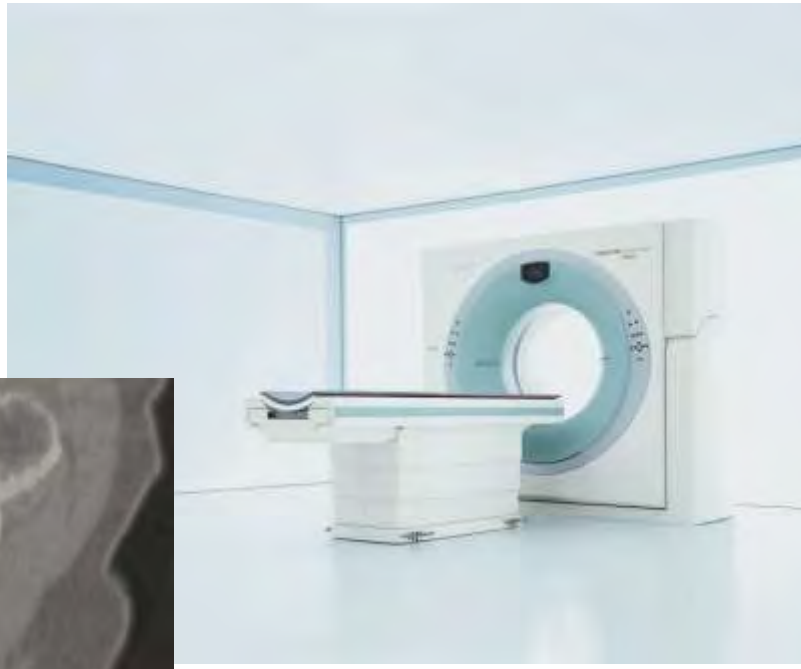
Target in motion (sinusoidal motion in U-direction, 1cm amplitude)

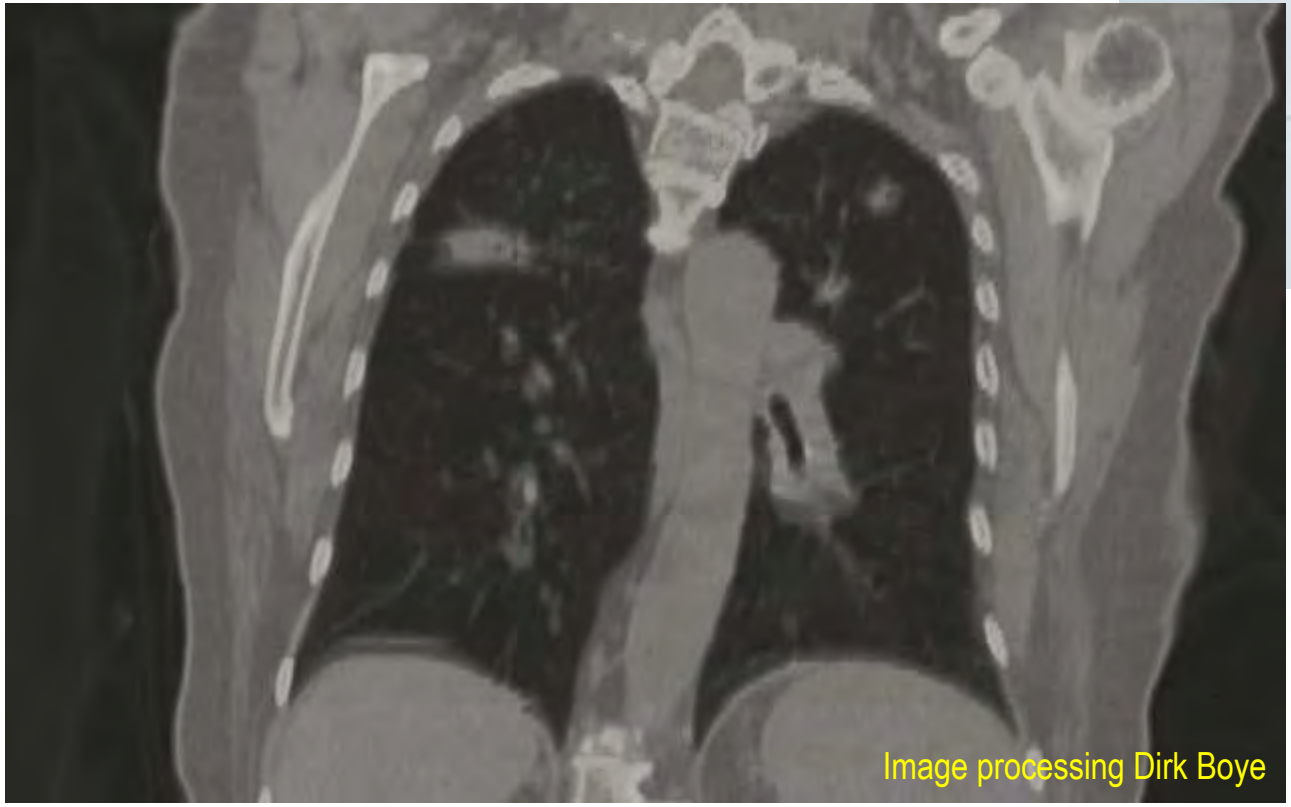


Time resolved CT images of moving organs

Imaging is essential in the presence of organ motion
(for example Computer Tomography (CT))

Latest devices allow to record time resolved pictures
(4d images)



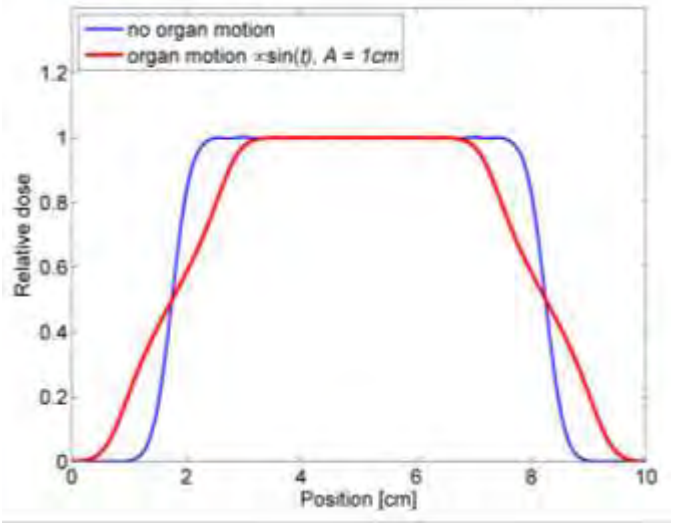


CT image of the thorax

Organ motion and repainting

Effect of organ motion:

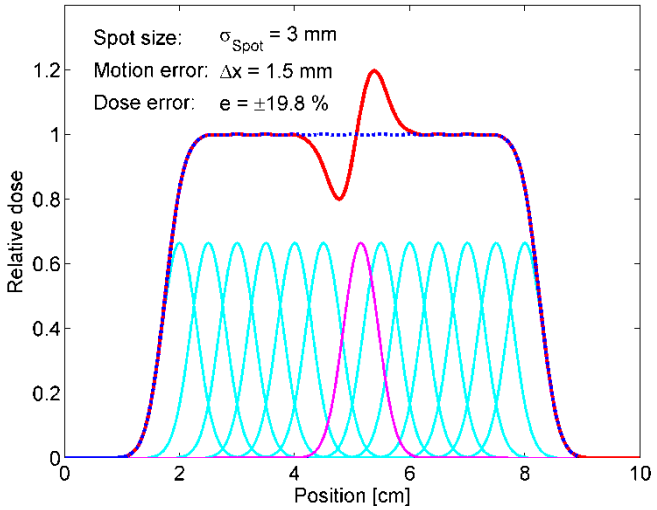
- Lateral dose conformation (scattering / scanning)
- Disturbance of the dose homogeneity (scanning)
  → Spot scanning very sensitive to organ motion

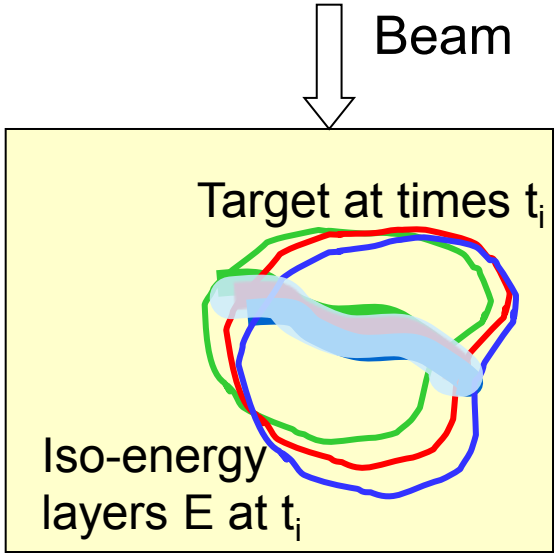


Approach to solve the problem: **Repainting**

Applying the total prescribed dose in *n* steps improves homogeneity:

- The error is statistically decreased by $\sqrt{n}$
- The dose for one energy slice can be applied much faster than the respiration cycle, the interference effects are minimized

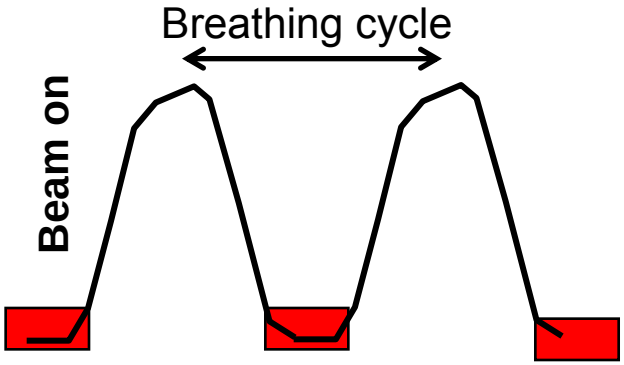


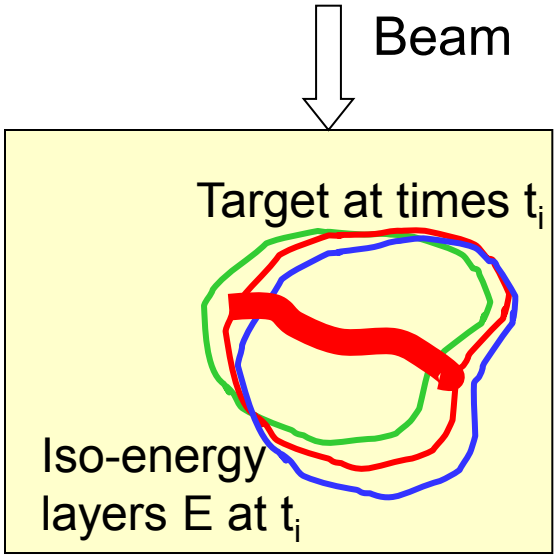


Other motion mitigation techniques

Gating

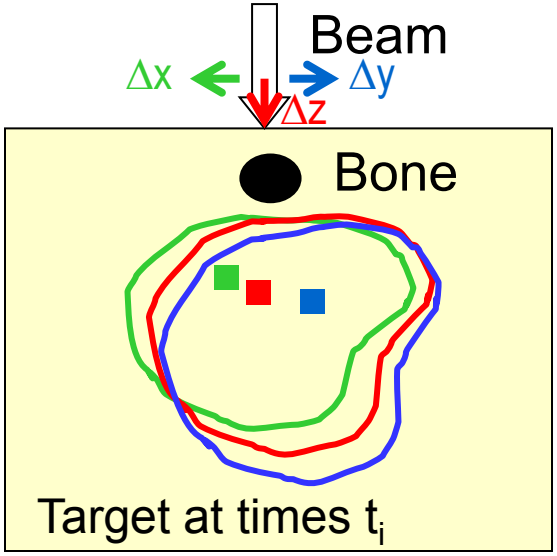
- Synchronization to a phase of breathing cycle
- As add-on to repainting possible for larger motion amplitudes





Tracking

- The beam follows the motion of the tumour:
  - Lateral corrections (Δx, Δy)
  - But also energy corrections (Δz) due to tissue inhomogeneities
- Many (unsolved) issues:
  - How to detect motion? (Correlation between internal tumour movement and external surrogate)
  - Tumour deformation? -> Treatment planning
  - Density changes proximal to tumour (Rib bones before lung tumour)

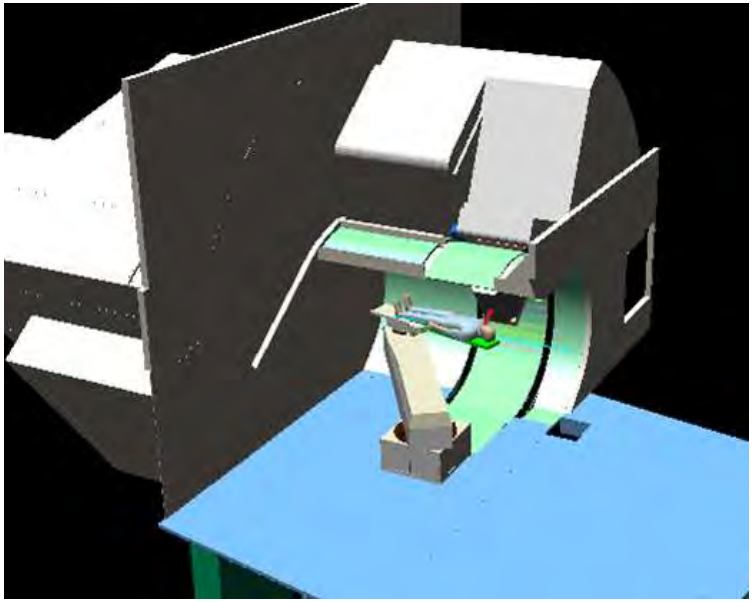


Next generation of spot scanning gantry for coping with organ motion: Gantry 2

Gantry 2: The next generation of scanning gantry at PSI

Mechanical design:

- Iso-centric layout
- Gantry rotation limited from -30° to + 180°
- Beam delivery flexibility by rotating the table in the horizontal plane



Advantages:

Fixed floor for better access to the patient table

Fixed walls for mounting supervision equipment

Large access in front of the gantry for mounting commercial equipment (CT)

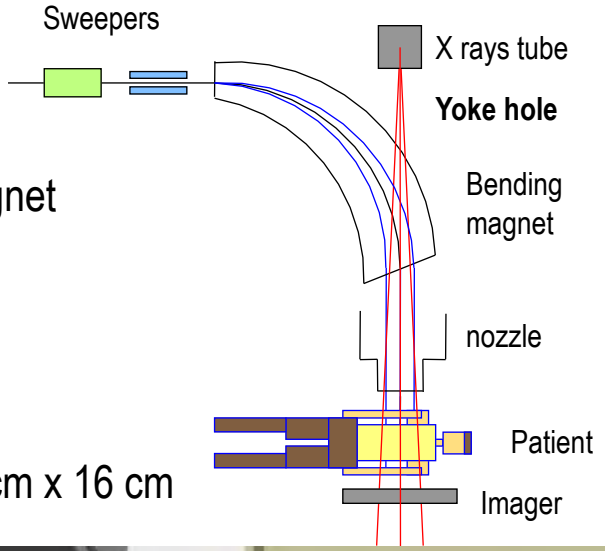
Imaging options with Gantry 2

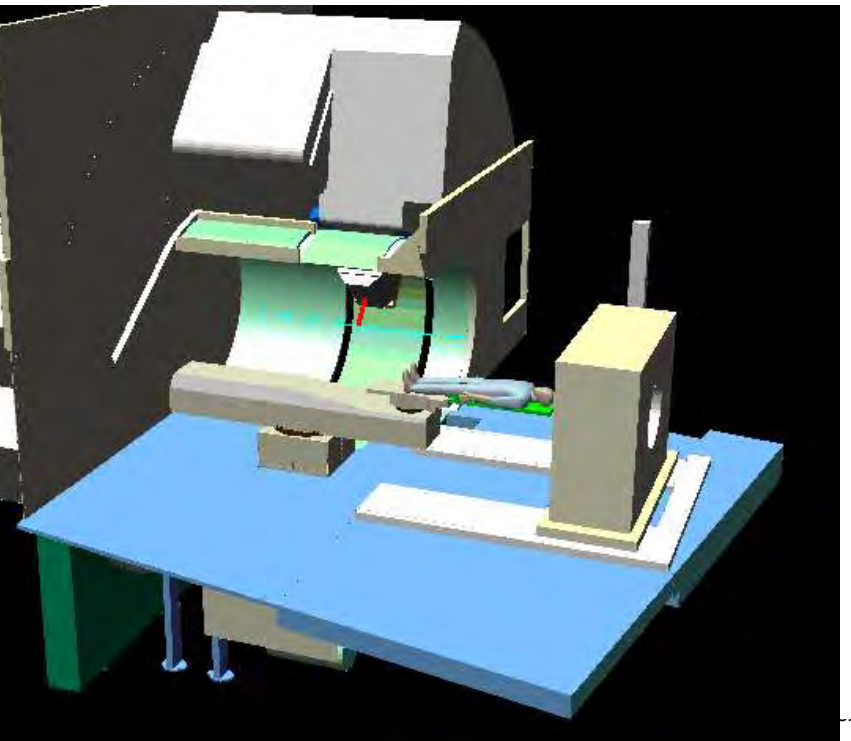
CT on rail (Sliding CT):

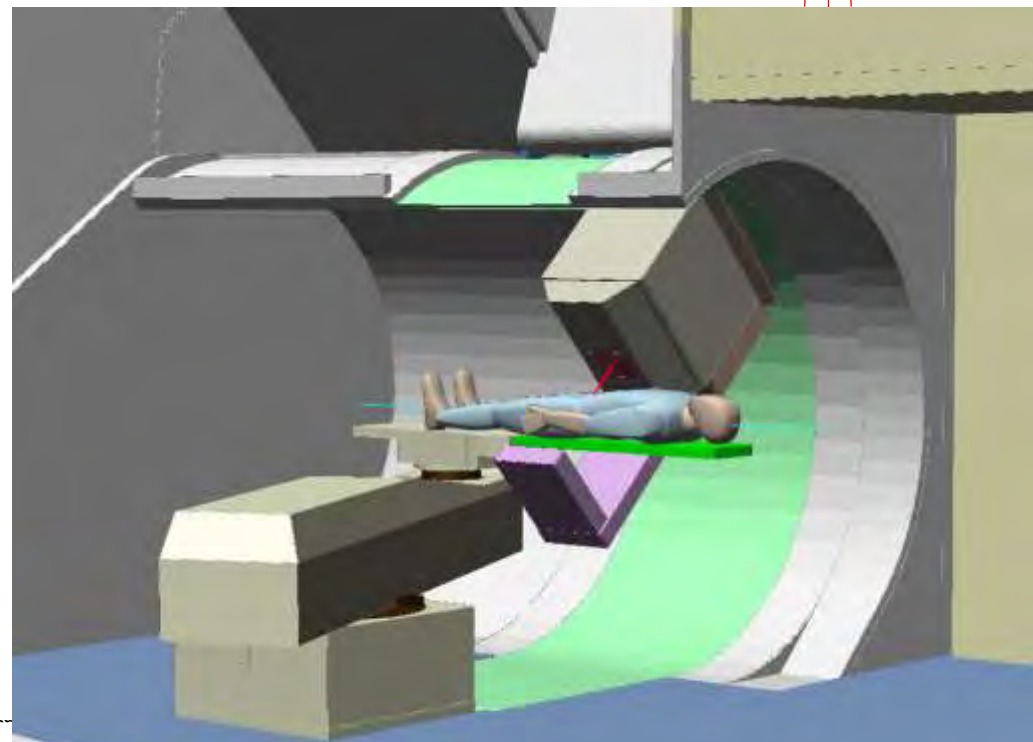
- Within reach of the patient table
- In-room patient positioning
- Use of time-resolved images (4d) before and after treatment
  - For treating moving targets
- Setup for gating

Beam's Eye View (BEV):

- X-ray through a hole in the yoke of the 90° magnet
- An equivalent of portal imaging with photons
- QA control of gating
- Large field-of-view, 26 cm x 16 cm



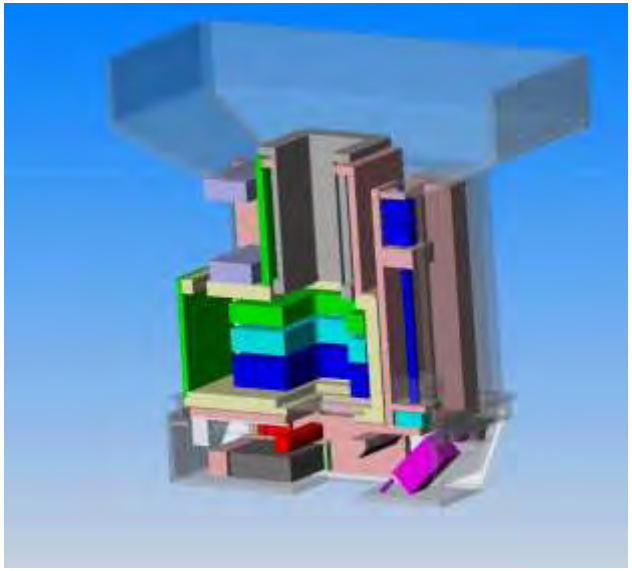




Main hardware innovations

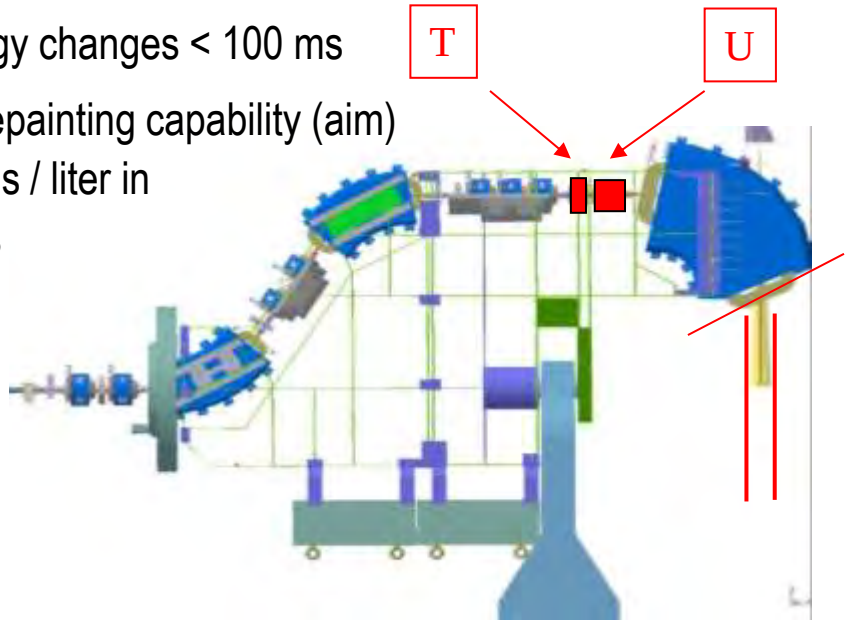
Fast parallel lateral scanning:

- Scan area of 12 by 20 cm
- Plus motion of patient table
- Parallel beam at iso-center
- Scanning-invariant beam focus



Fast energy change for efficient volumetric repainting:

- Laminated beamline magnets
- Typical energy changes < 100 ms
- Volumetric repainting capability (aim)
  10 repaintings / liter in
  1 - 2 minutes

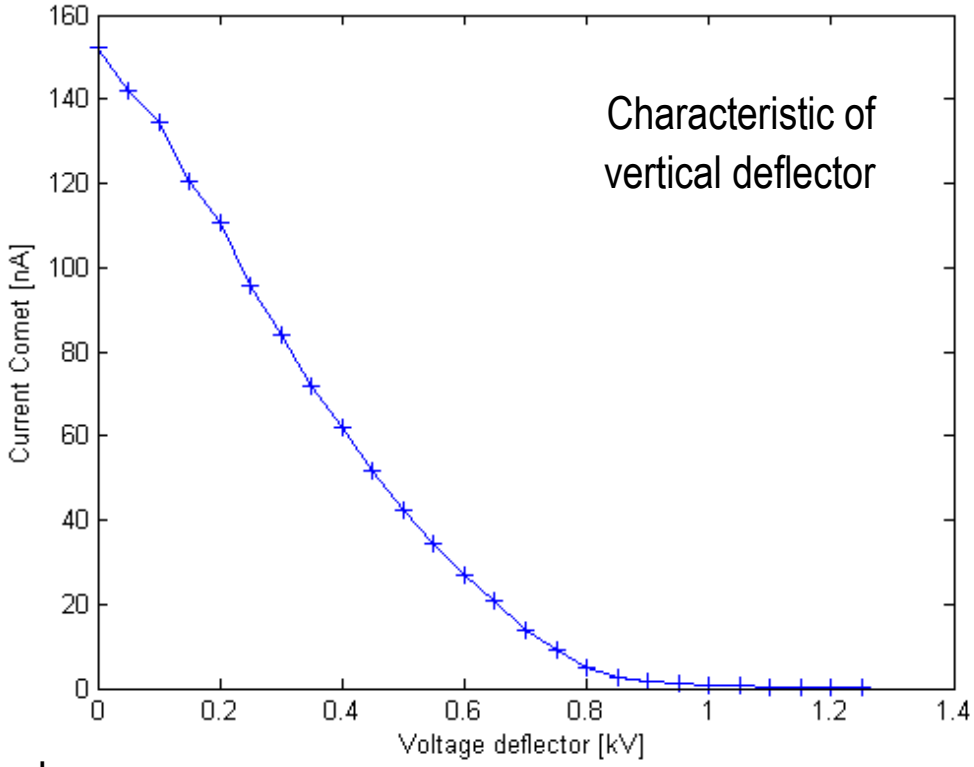


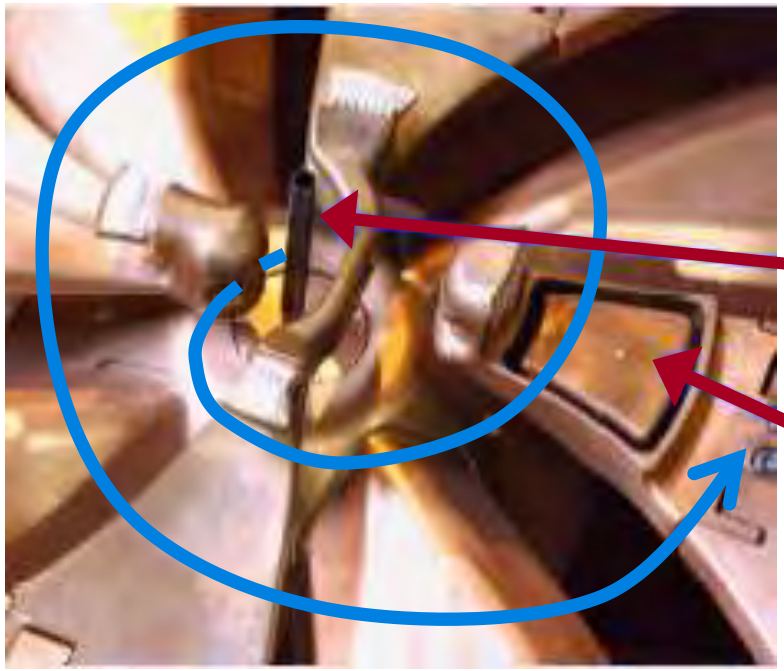
Compact optimized nozzle:

- Vacuum “up to the patient”
- Telescopic motion of the nozzle
  – Sharp pencil beam ~3mm sigma
- Two monitors and a strip monitor
- Removable pre-absorber
- Option to add collimator and compensators

Intensity modulation

- Fast electrostatic beam deflection inside accelerator (< 50 μs)
- Switch beam on/off
- Intensity modulation
- Little activation of the cyclotron

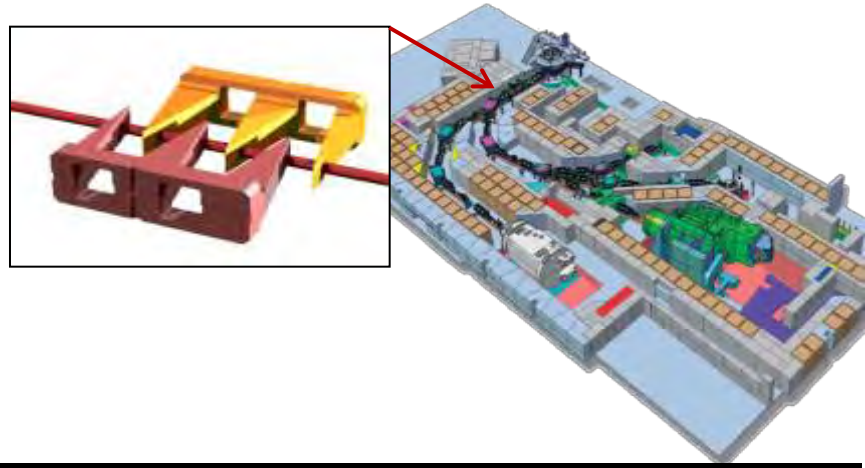




Fast changes of the beam energy

The Gantry 2 is optimized for fast energy changes using upstream energy modulation:

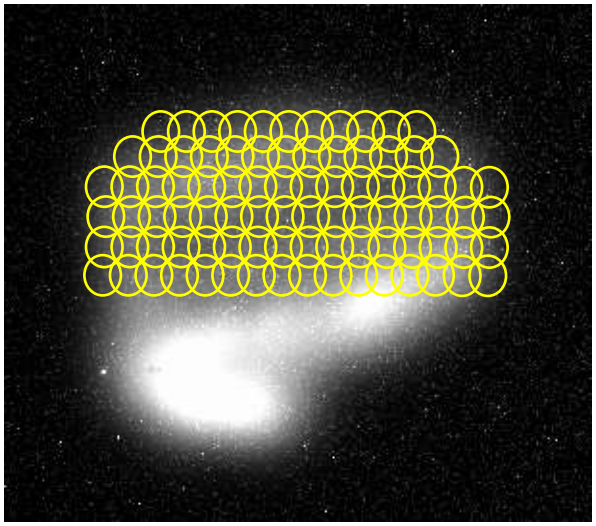
- Cyclotron (fixed energy)
- Fast degrader right after cyclotron
- Continuous choice of beam energy
- The beam line follows energy variations in the degrader
- Laminated magnets (avoid eddy currents)
- Dedicated power supplies

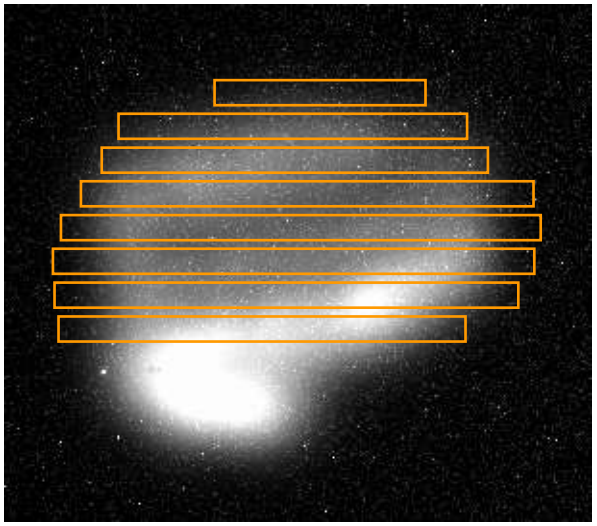


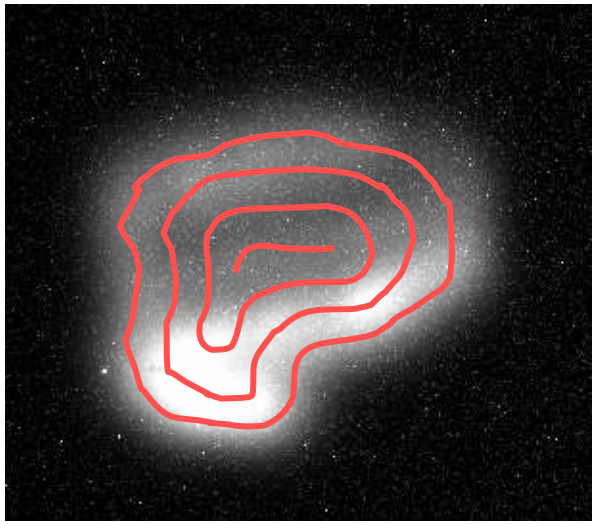
Shown

- **~100 ms** dead time for range steps of 5 mm

Advanced scanning modes







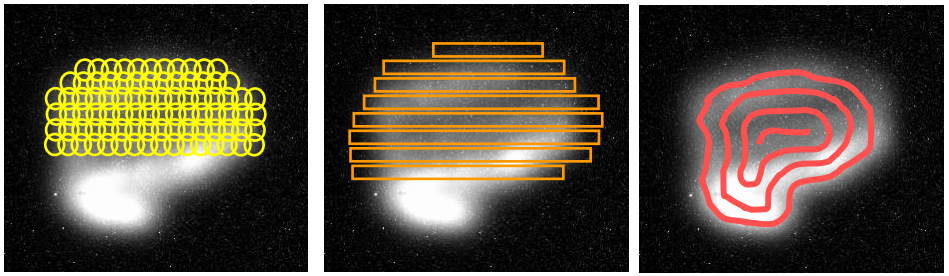
- Discrete spot scanning (Gantry 1)
  - Switching off the beam after each spot
  - Dead time per spot ~3 ms.
    Typically field: 10'000 spots -> 30 s dead time, scales with number of repaintings!
  - Spot scanning will be the default (starting) mode for Gantry 2

- Continuous line scanning
  - Paint lines with beam intensity modulation
  - For maximum repainting number and simulated scattering
  - Example for a 1 liter box:
    Line 10 ms, Layer 200 ms, Volume 6 s
- Contours scanning (?)
  - For optimizing repainting and lateral fall-off (difference Gaussian to error-function)

A flexible control system for different scanning options

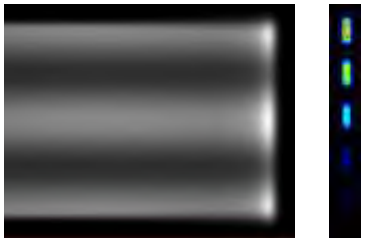
Drive sweeper magnets

Different modes: *Spot scanning* / *Lines scanning* / *Contours scanning* in the same steering file



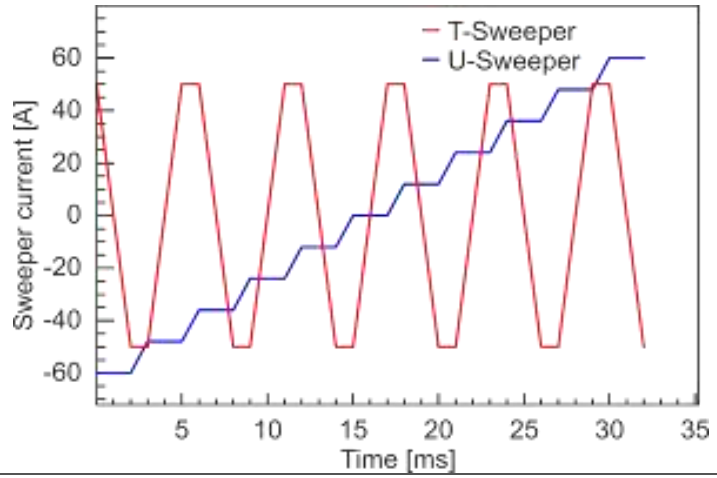
Vertical deflector plate for intensity modulation

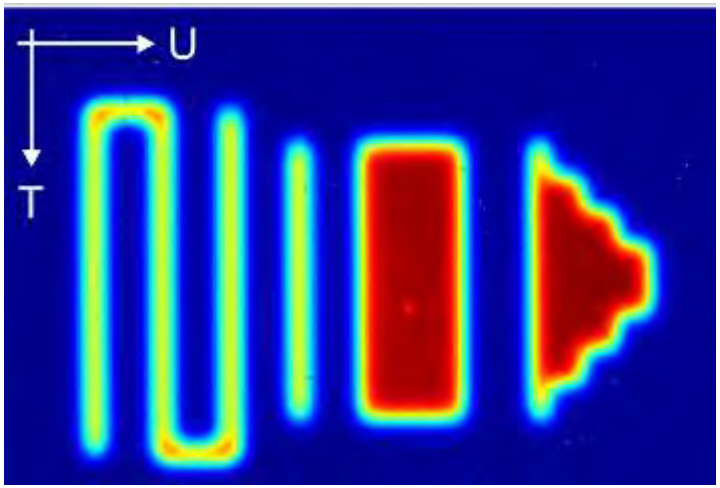
- Fast intensity control on time scale of 100 μs
- Control dose with feed-back loop



Requires flexible control system

- Synchronous control of fast actuators (sweepers, deflector plate) with 100 kHz
- Tabulated dose delivery based on state-of-the-art electronics (FPGA)
- Example: Painting shaped energy iso-layer

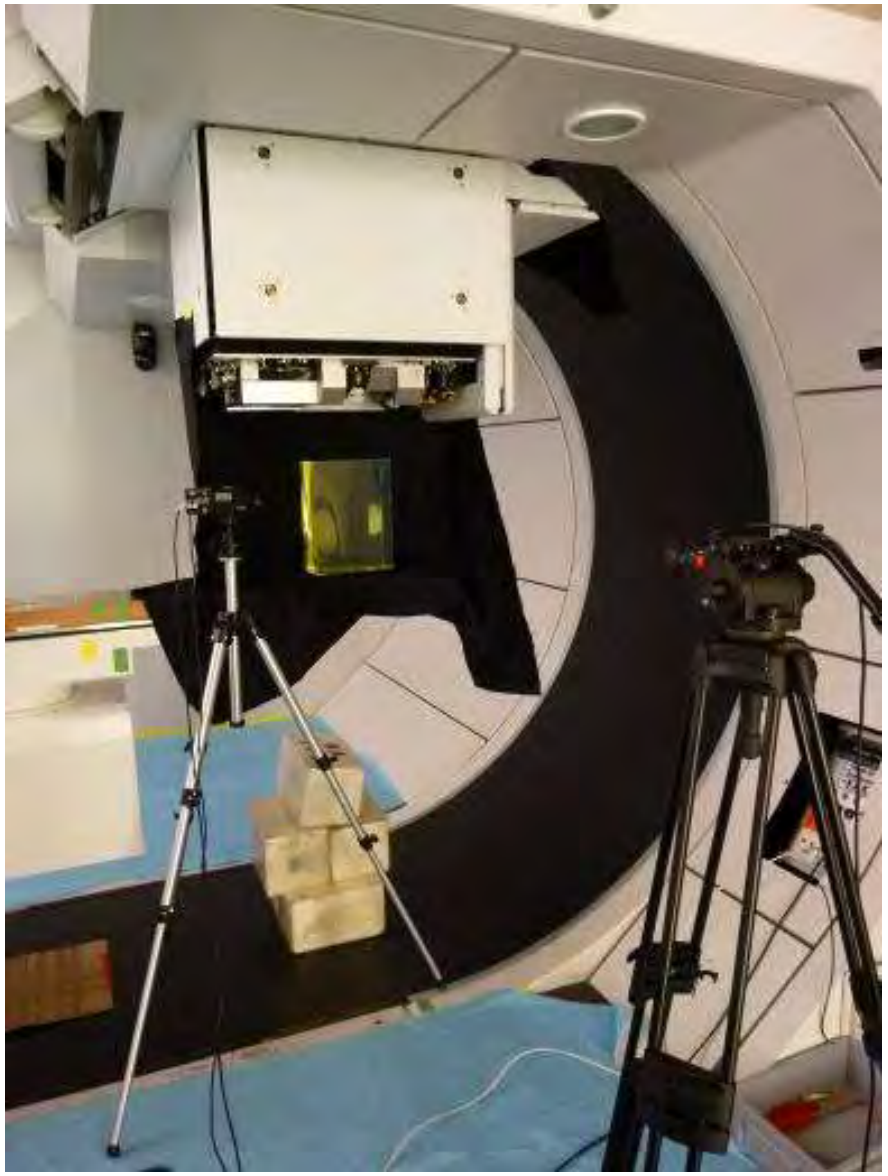




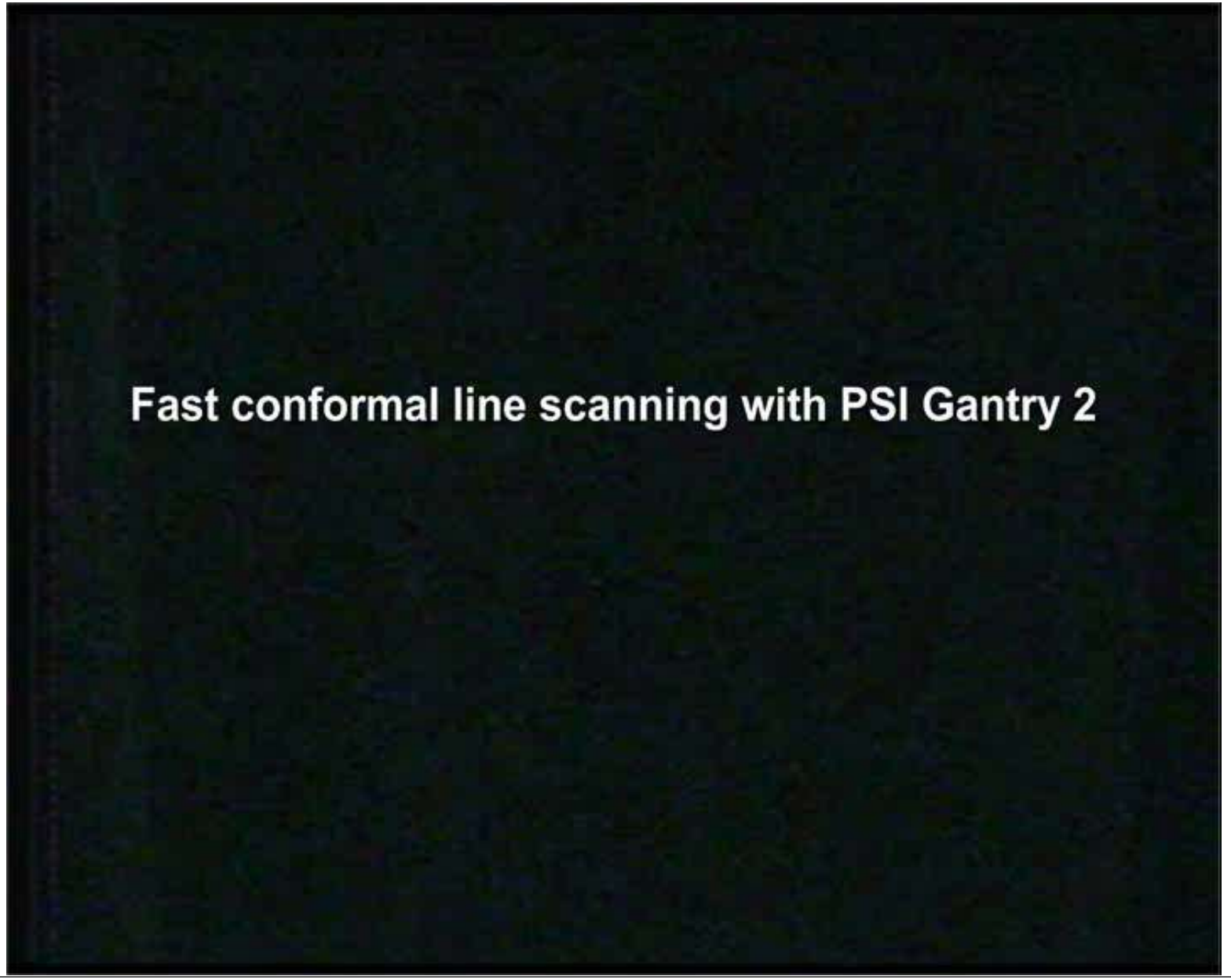
Demonstration: Fast conformal line scanning

- Show feasibility of fast conformal line scanning
- Three target shapes:
  - Box / Diamond / Sphere

- Sequence applied in a scintillator block and record with camera
- Combination of speed modulation and intensity modulation to paint inhomogeneous iso-energy layers
- In order to bring enough dose to the target
  - Work mainly with reduced sweeper speed (speed modulation)
  - Intensity modulation only in proximal layers



Video showing fast conformal line scanning



Respiration motion (> 5mm): Our preferred solution breath hold

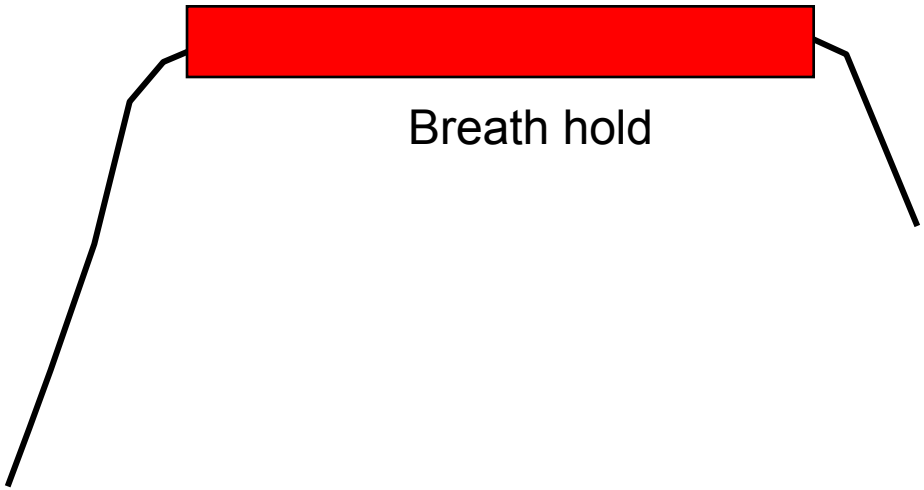
Our preferred solution: Whole painting within a breath hold cycle

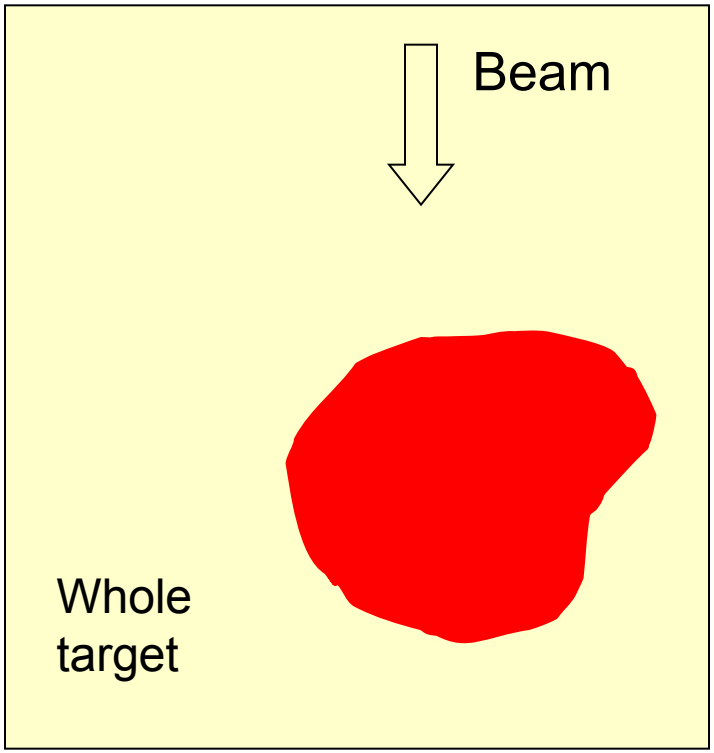
Small volume (<1/4 liter)

- Full volume treated within 4s with intensity modulated line scanning (Not the full dose!)
- Needs fast energy changes
- High dose rate could be of advantage for reducing treatment time
  - Especially in the context of a hypo-fractionation

A breath hold length of 5s would then be sufficient

- Repainted, high efficiency, static planning, easier QA





Conclusion

- Proton (particle) therapy offers less damage to healthy tissue compared to conventional therapy (photon)

- PSI has more than 30 years of experience in hadron therapy
  - The success of OPTIS with 99% local tumour control will be continued with OPTIS2
  - Spot scanning and IMPT are realized with Gantry 1 and are important innovations of PSI

- Gantry 2 will be the next generation of proton scanning gantry:
  - Started patient treatment in November 2013
  - Treating moving tumours will be the challenge for the next years
  - A fast scanning is mandatory for an efficient repainting
  - 80 ms for energy change → Potential for volumetric repainting
  - Gantry 2 is a universal system to explore new scanning techniques with maximum benefit for patients