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Heidelberger Ionenstrahl-Therapiezentrum

Medical Applications Instrumentation & Diagnostics

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(HIT, Head Accelerator Operations)

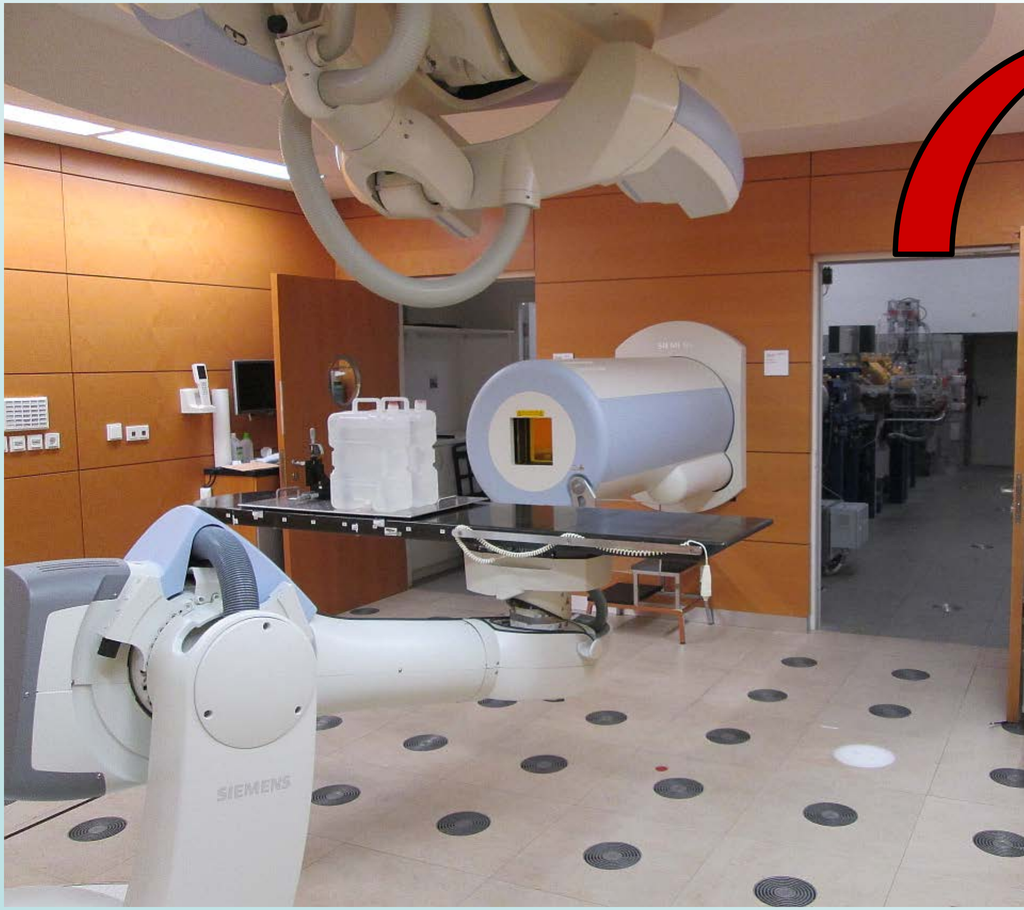
Outline

- The role of beam instrumentation and diagnostics in particle therapy accelerators
- An extended view: Instrumentation – Feedbacks – Detector Technology – Quality Assurance
- Diagnostics and instrumentation techniques used in particle therapy: the interaction of accelerator and irradiation technology – some basics, examples and challenges in near future
- Conclusion and Acknowledgements

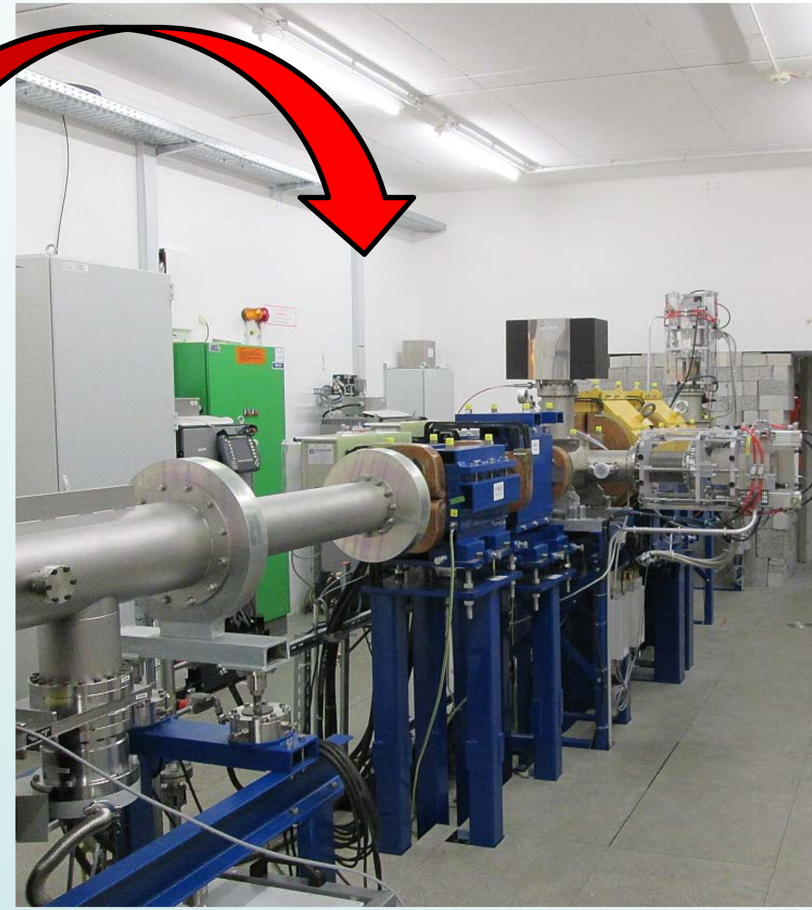
Beam instrumentation and diagnostics in particle therapy accelerators

- Is there any difference between a scientifically used accelerator and a medical accelerator? **No, not at all!**
- Due to the economic effects sometimes only the absolute minimum of beam diagnostics is installed for commissioning and standard operation.
- Most important devices are current transformers for online diagnostics (non-destructive) and beam profile monitors for the daily machine QA (destructive) – theses topics are covered by other talks of this CAS.
- The speciality of medical accelerators is the strong link to the *beam consumer*, in this case the irradiation technology and the high-conformal dose application.

Beam instrumentation and diagnostics in particle therapy accelerators



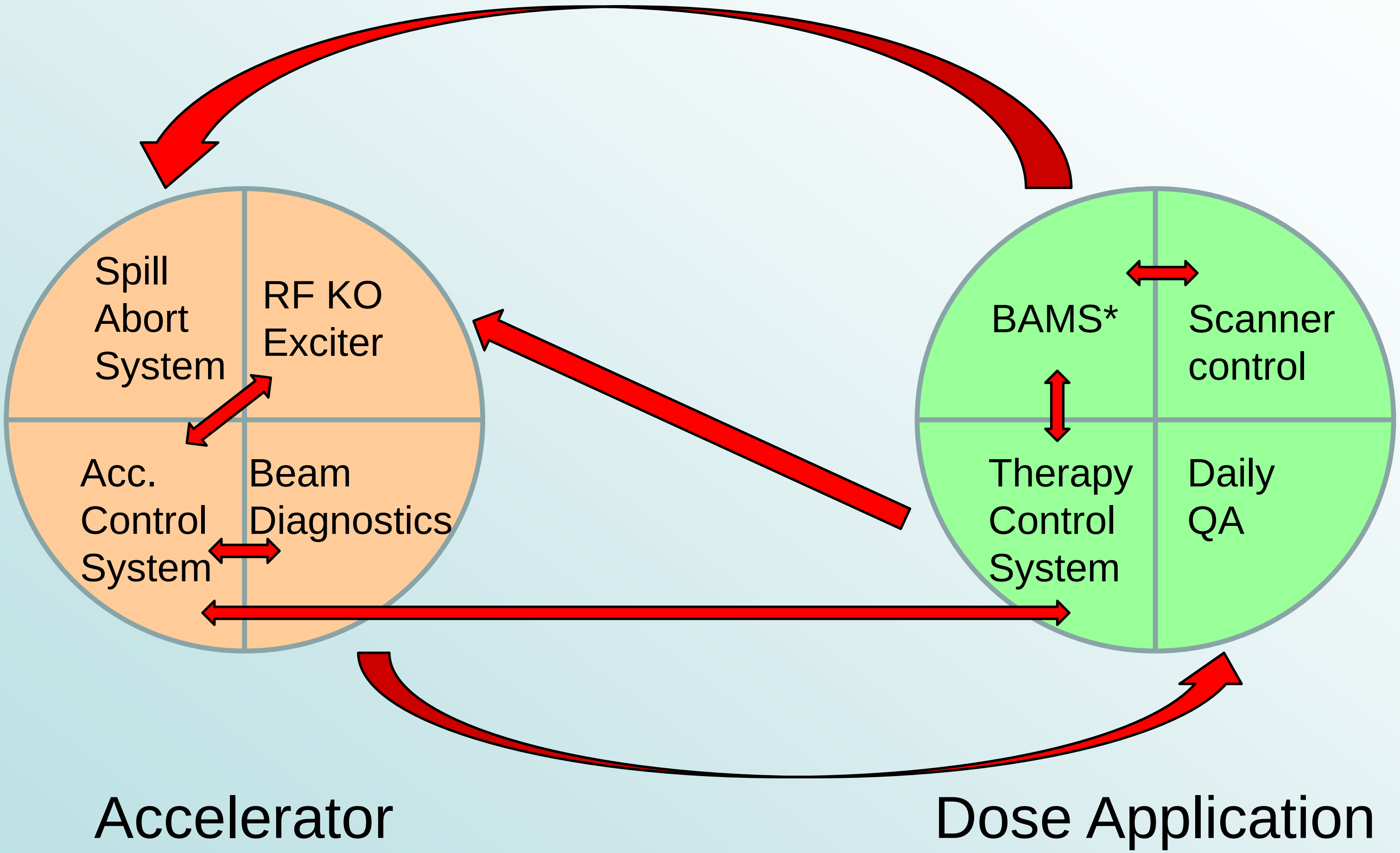
Horizontal patient treatment room at HIT



Beamline with quadrupoles and scanner magnets behind

An extended view

- Instrumentation – Feedbacks – Detector Technology – Quality Assurance



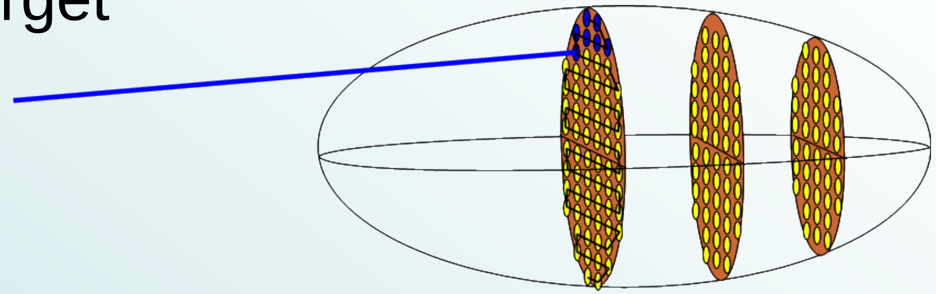
* Beam Application and Monitoring System

Interaction of accelerator and irradiation technology in particle therapy – some basics

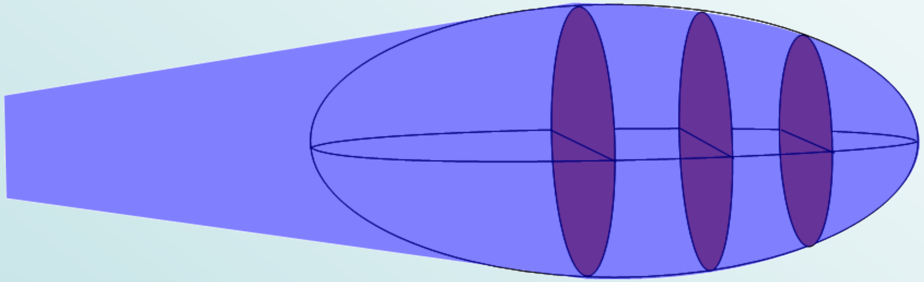
Raster scanning technique

(also named *pencil-beam scanning*)

“Scanning” in the context of particle therapy is the application of the desired dose by means of a pencil beam, which is moved over the target point-by-point to cover the whole target volume.



This is in contrast to broad-beam-techniques that use a expanded particle beam to irradiate the whole area or volume of the target at the same time.



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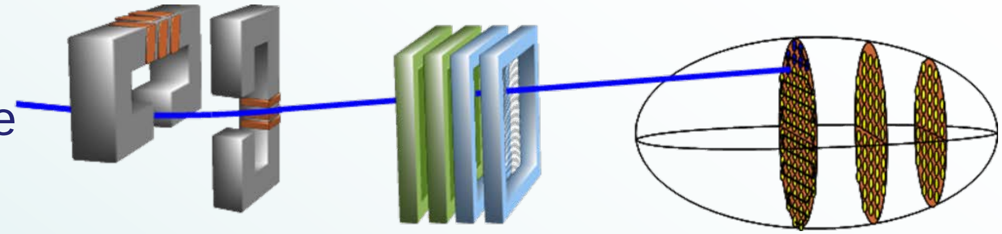
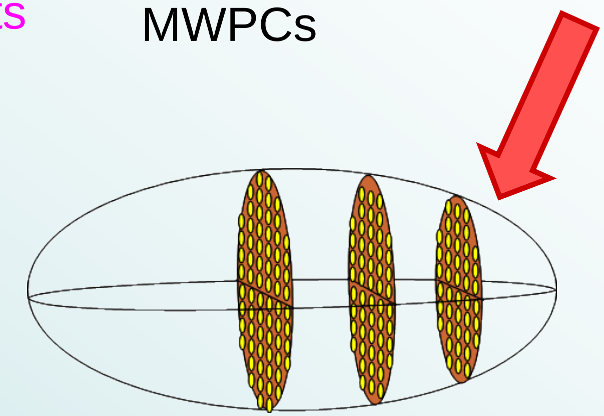
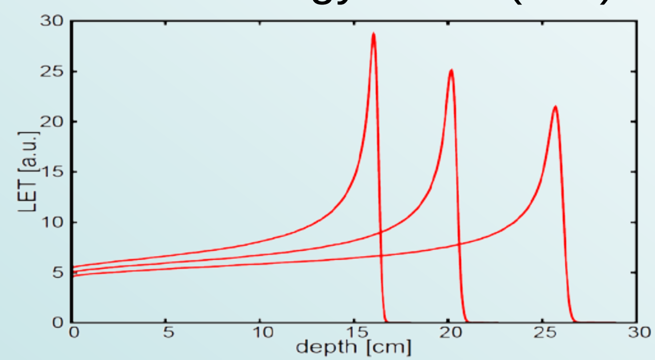
Raster scanning technique

Raster scanning system





iso energy slices (IES)



The part of a treatment plan corresponding to a fixed (water equivalent) depth is called an **iso-energy-slice (IES)**.

Selection of iso energy slices is achieved by varying the beam energy.

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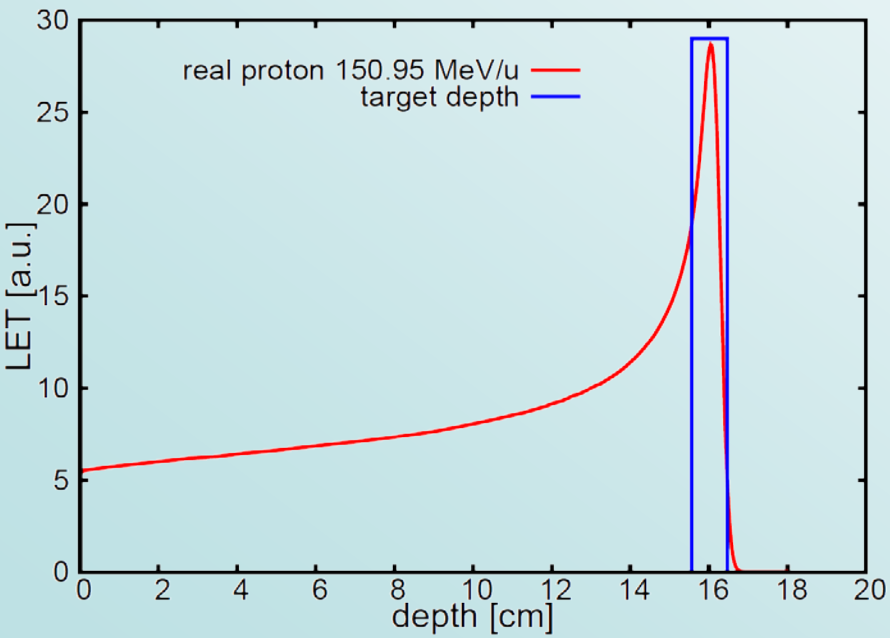
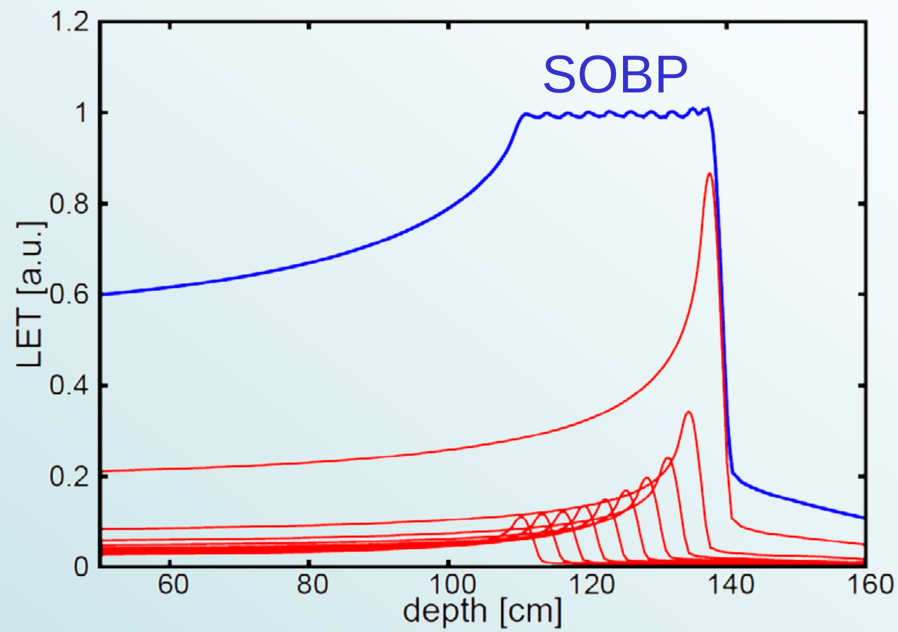
Raster scanning technique

(Longitudinal scan direction)

Due to the shape of the *bragg peak* not only the region where the particle stops is irradiated, but also the region before the peak ("plateau region"). This has to be taken into account during treatment planning. The dose plateau (right), result of overlapping beam with different energies, is called a *spread-out bragg peak* (SOBP).

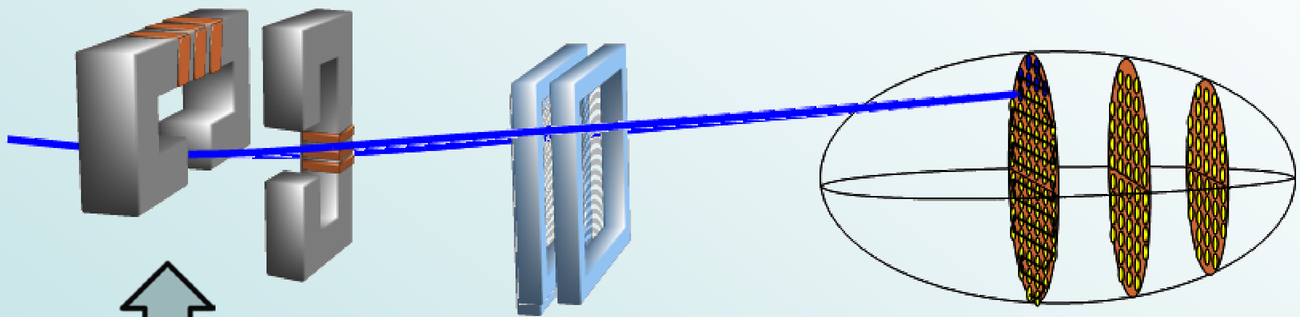


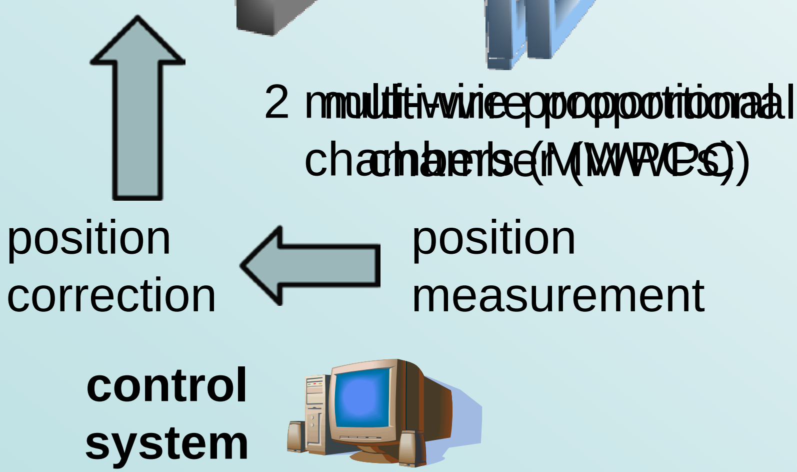


Raster scanning technique

(Transversal scan direction)

In a fully active system scanning in x-y-direction (transversal to the beam) is achieved by deflecting the ion beam in a scanning magnet:



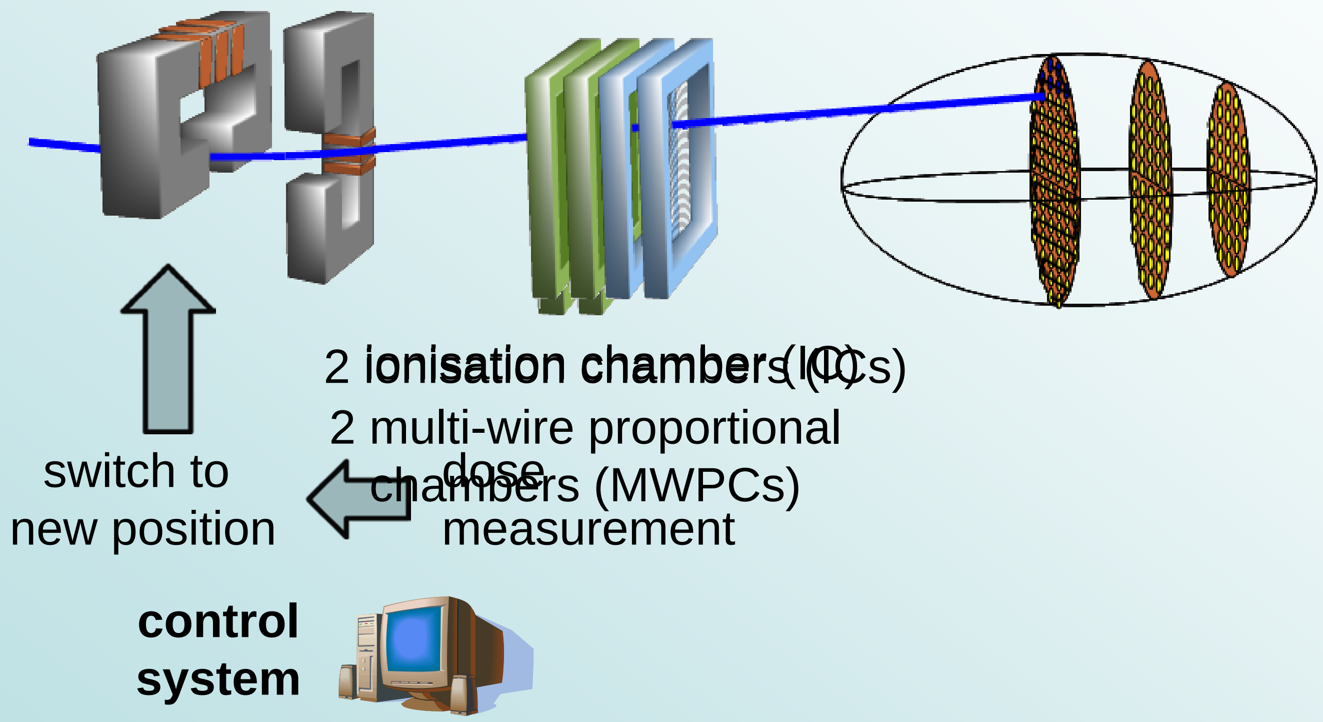


Typically, the beam will be kept at the designated position for each raster point by using a **feedback loop**.

Raster scanning technique

(Transversal scan direction)

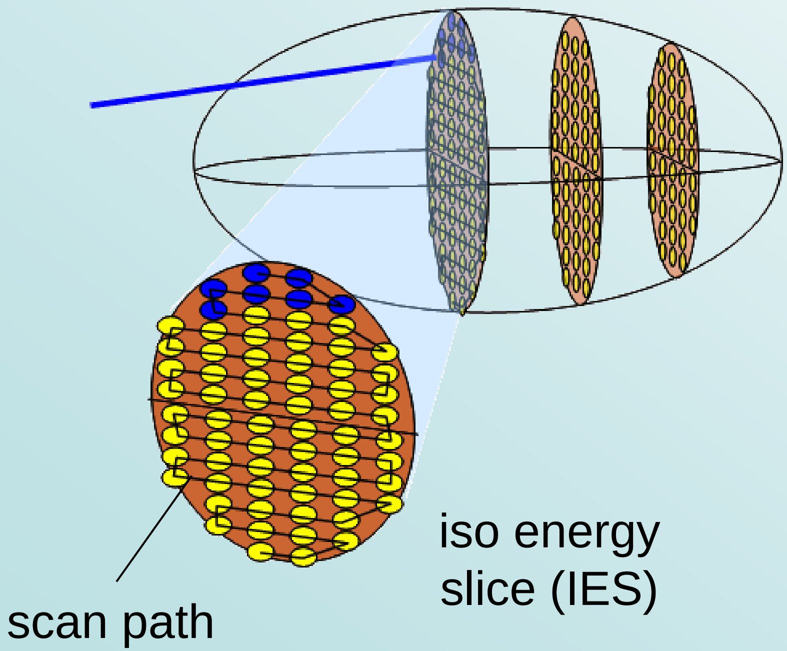
Dose controlled irradiation: the beam stays on a particular raster point until the desired dose for the point has been reached.

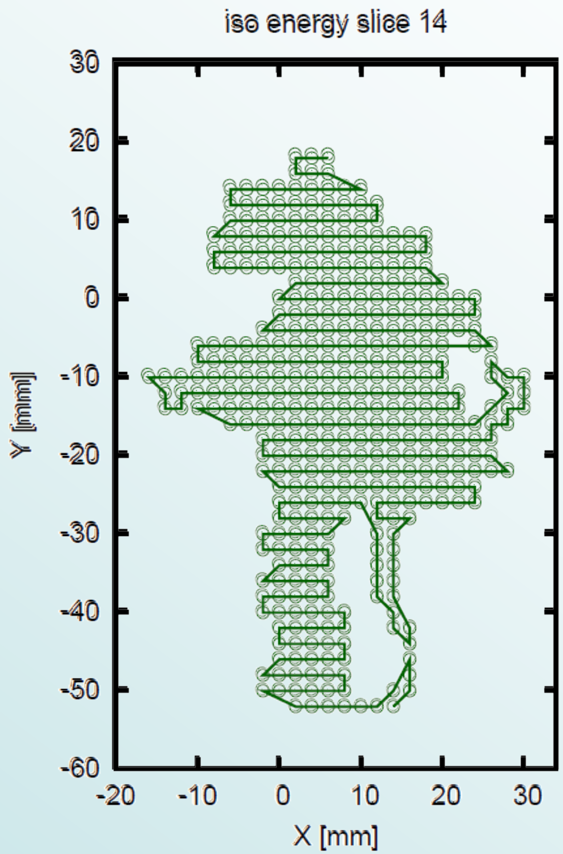


Raster scanning technique

(Transversal scan direction)

In order to cover the whole cross-section of the tumor, a **scan path** (or “work list” of points) must be defined which determines the order in which different scan spots are irradiated:

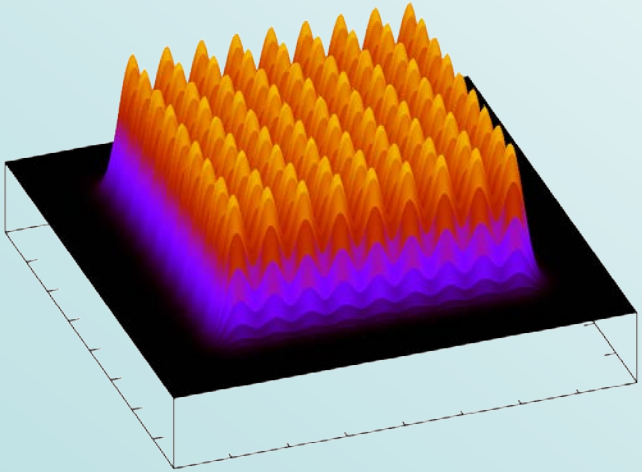




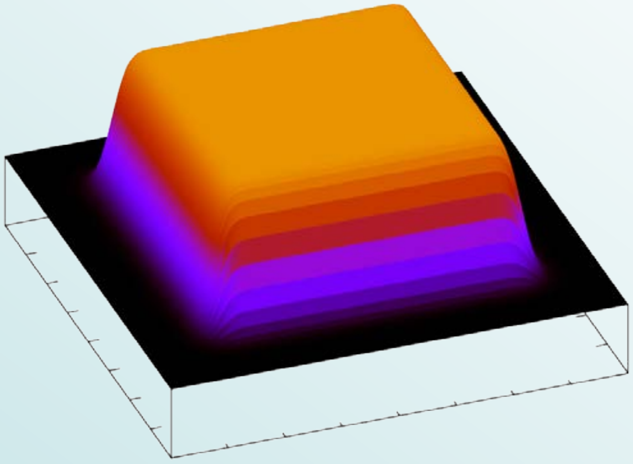
Raster scanning technique

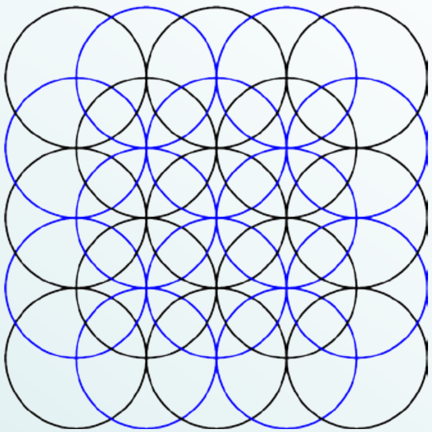
(Transversal scan direction)

The spacing of the raster points has an influence on the dose homogeneity:



raster spacing = 3 sigma



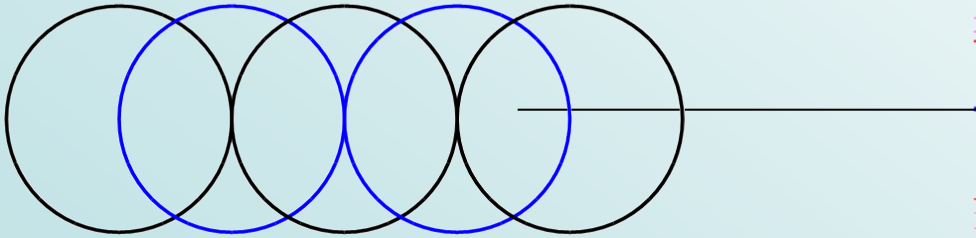


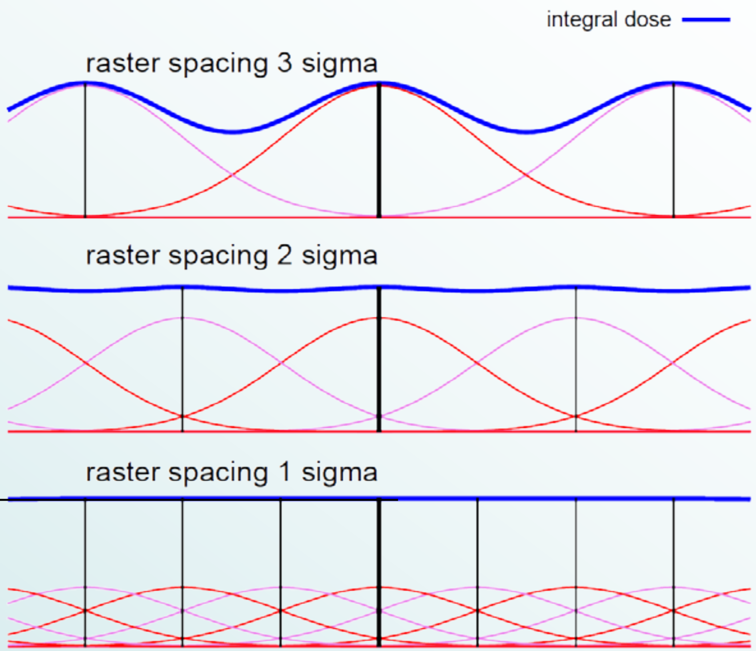
raster spacing = 1 sigma

Raster scanning technique

(Transversal scan direction)

For a gaussian beam shape a dose profile will become perfectly flat if the spot separation is smaller than **one sigma**:

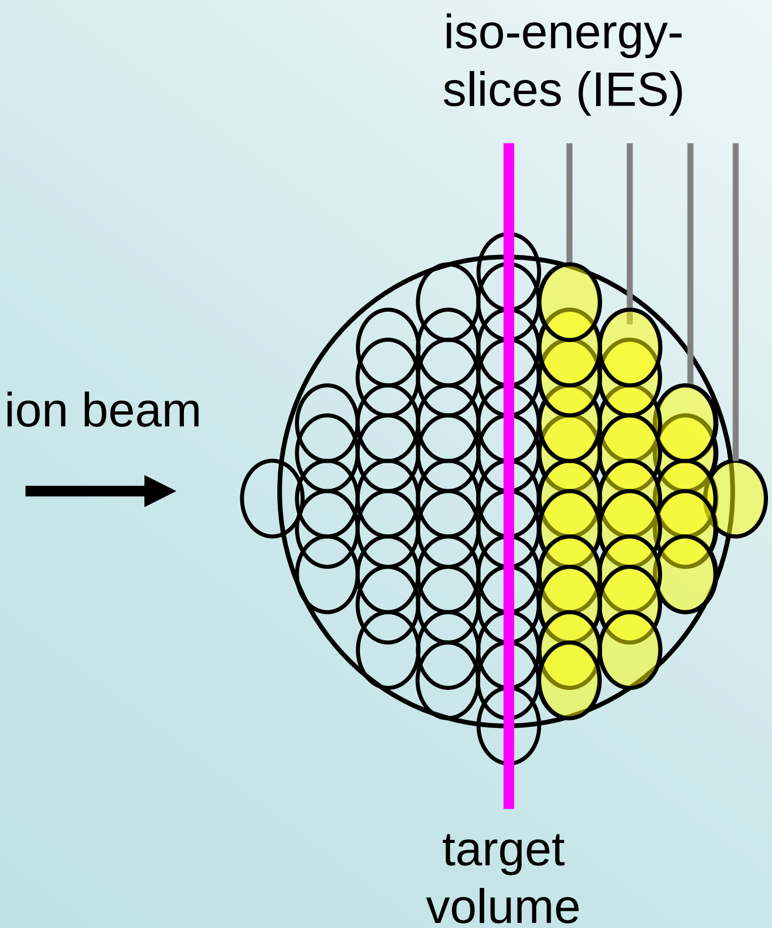


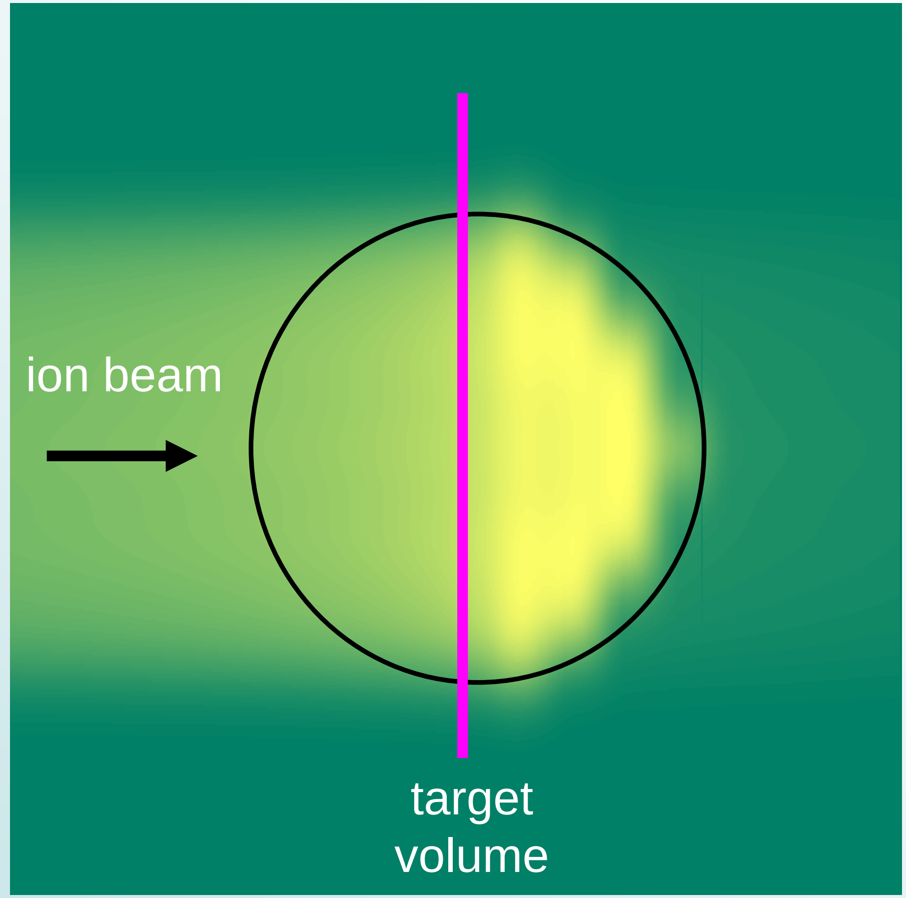


Dose profiles become clinically acceptable at a spacing of ~2σ;
For treatment planning at HIT a spacing of 0.8σ or less is used as a rule of thumb to allow for some error in spot size.

Raster scanning technique

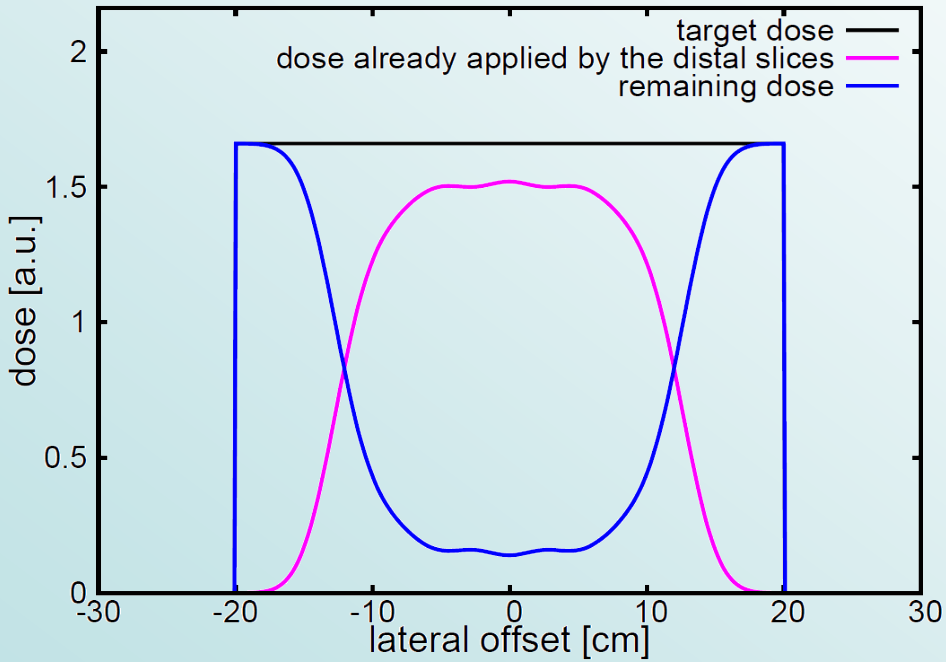
(Spot doses)

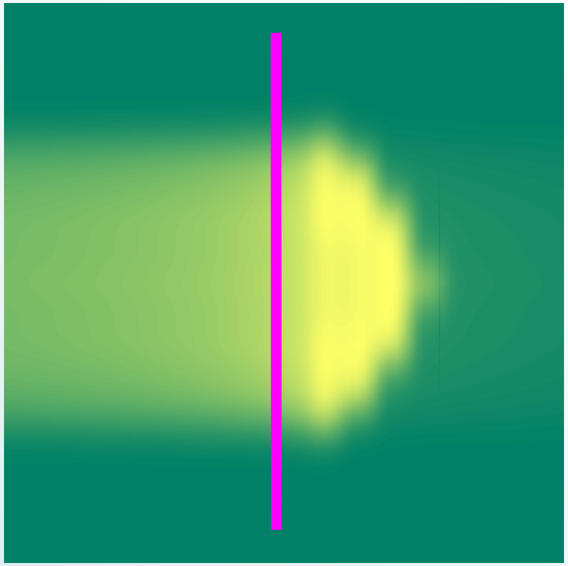




Raster scanning technique

(Spot doses)

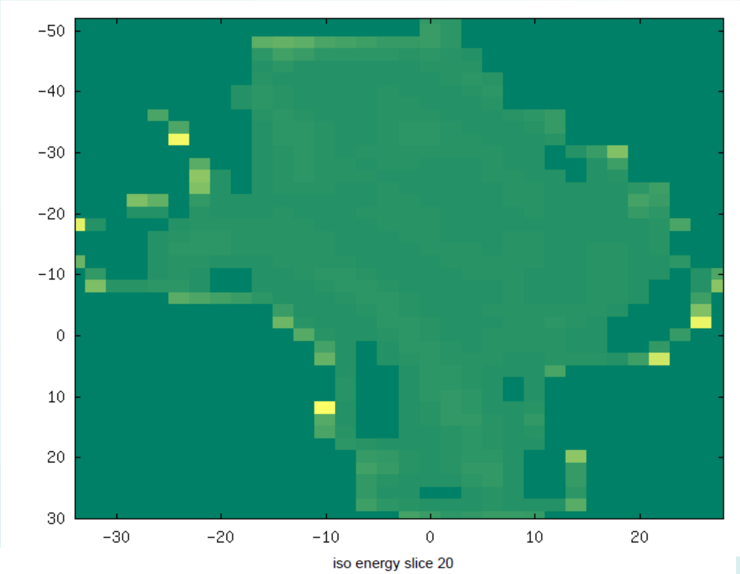


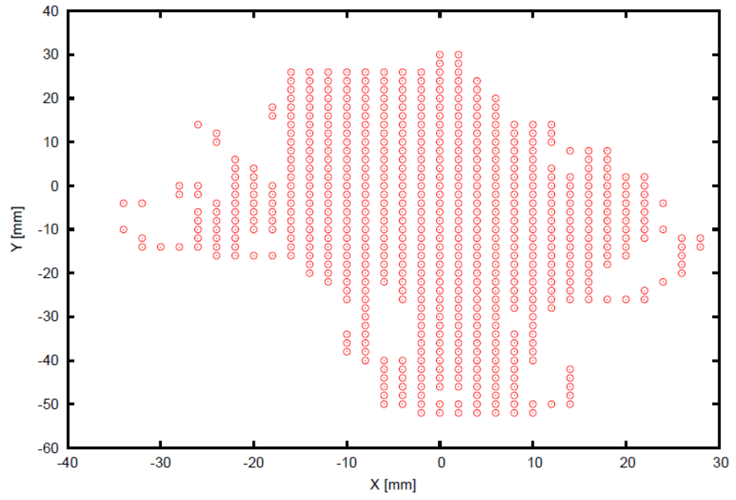


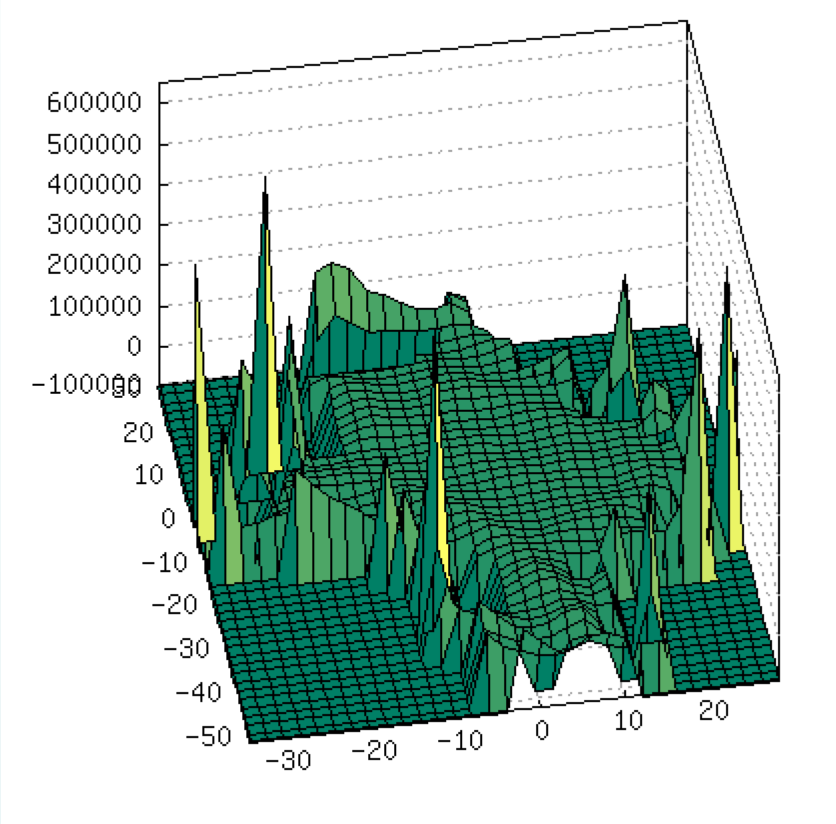
In the central region most of the dose was already applied by the distal IESs; at the lateral edges nearly the full dose is still missing.

Raster scanning technique

(Spot doses)







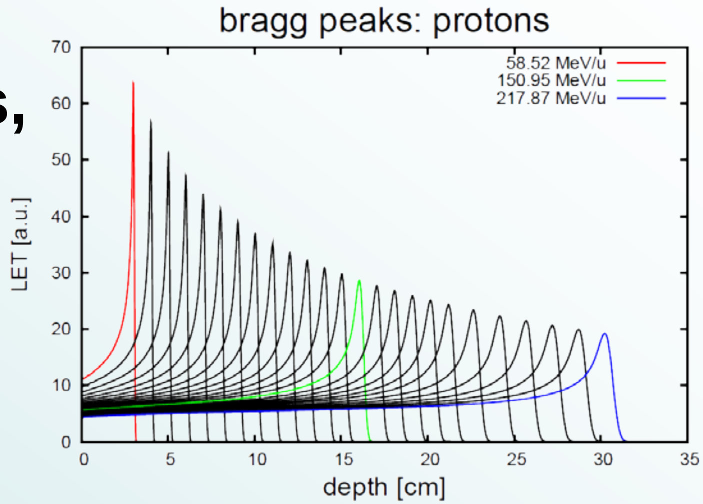
The variation in particle number in one single IES can be quite large (factor of ~100)!

Interaction of Accelerator and Irradiation Technology in Particle Therapy – Examples and Challenges in Near Future

Raster scanning technique
(Example: HIT)

For scanning the accelerator should

- allow to request **different energies, beam spot sizes ("focus levels") and intensities**
- deliver a different combination of all of these beam parameters **within a few seconds**



- deliver all of these combinations with a **high beam quality** sufficient for medical use
- provide a **spill pause functionality** (in case of disjoined raster point "isles" in one IES)

Raster scanning technique

(Example: HIT /Parameters)

Beam parameters of the Heidelberg Ion Beam Therapy (HIT)

Parameter	
ions	protons and carbon, (oxygen) – **2 ion sources** In addition: helium (3. ion source; permission for patient treatment by end of 2019 awaited)
intensity	2 x 10^6/s to 8 x 10^7/s for carbon 8 x 10^7/s to 4 x 10^8/s for protons **10 steps**; maximum extraction time 5 s
energy	88-430 MeV/u for carbon 50-221 MeV/u for protons **255 steps**, 1-1.5 mm spacing, 2-30 cm range in water
focus	3.5-13 mm FWHM for carbon 11-33 mm FWHM for protons **4 steps**

→ a total of 4 x 10 x 255 x 4 = **40.800 settings** (max.) per treatment room!

…and much more for the gantry!

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Raster scanning technique

(Example: HIT / Parameters)

The therapy control system has to monitor the system on a timescale that matches the typical irradiation time of a raster point (~1-100 ms); this implies:

- Dose controlled irradiation system: dose measurement on a time scale that is short compared to the irradiation time of one point (here: 10 µs – faster than drift time of ions in the ionization chamber);
- Position measurement with MWPCs on a time scale that is “short” compared to typical position variations (HIT: 250 µs)
- Beam position feedback system (linear) – see next two slides
- Online monitoring of beam focus size and limit checks; focus feedback loop planned with next generation control system – beam optics have to be considered!

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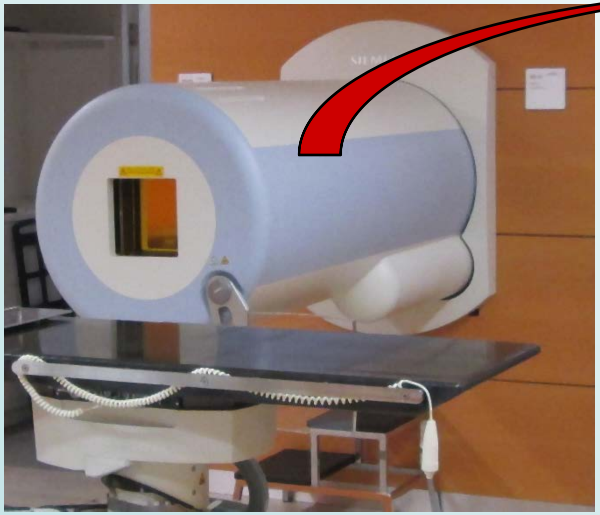
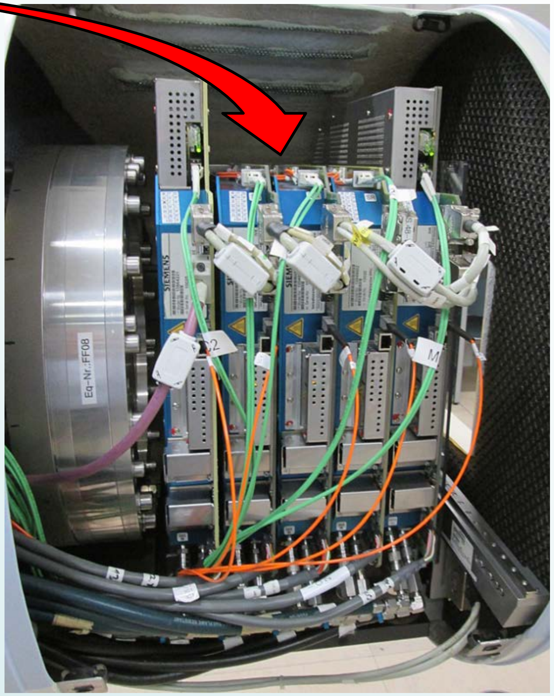
Raster scanning technique

(Example: HIT / BAMS)

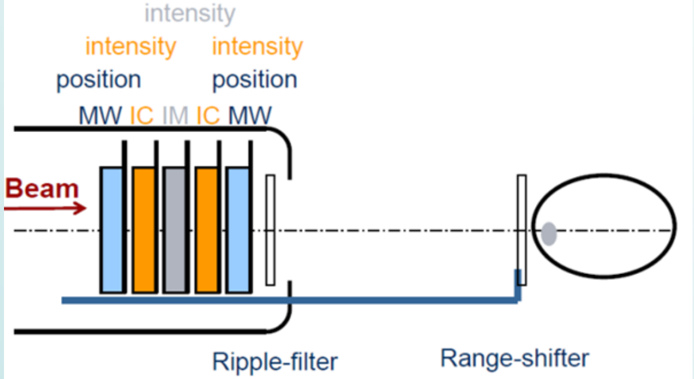


Beam
Application
and
Monitoring
System



- 2 (redundant) MWPCs for profile monitoring and position feedback

- 3 (diverse redundant) ionization chambers for dose measurement



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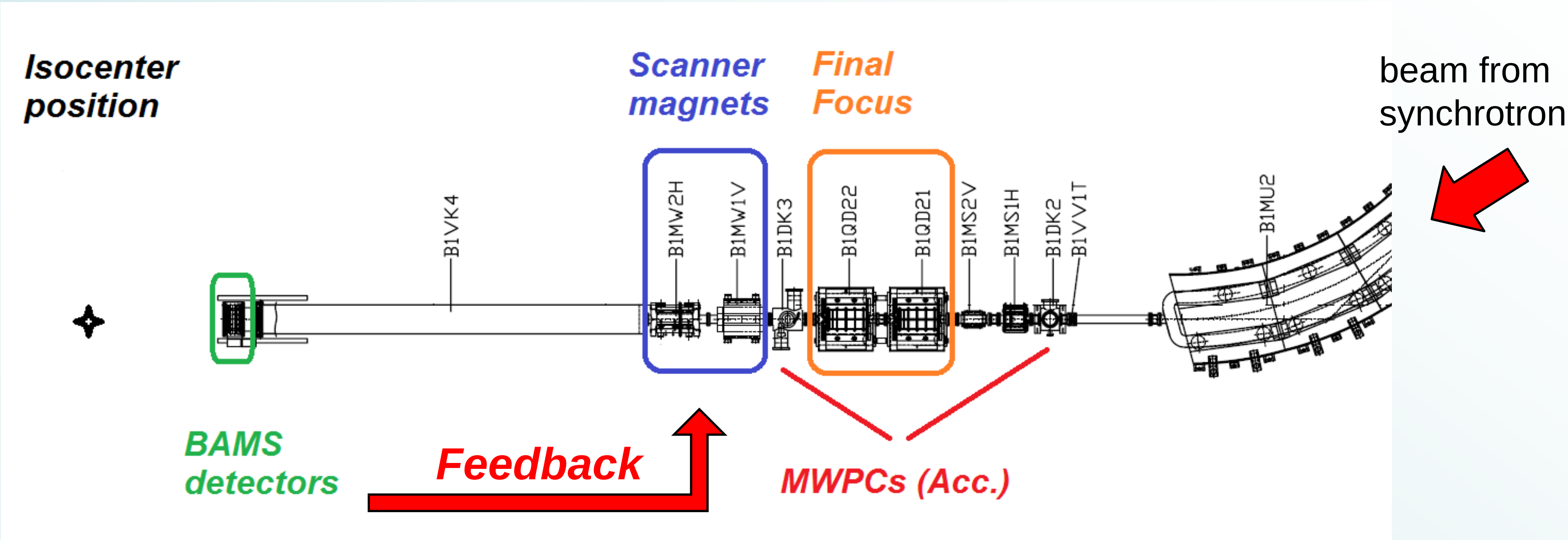
Raster scanning technique

(Example: HIT / beam position feedback)



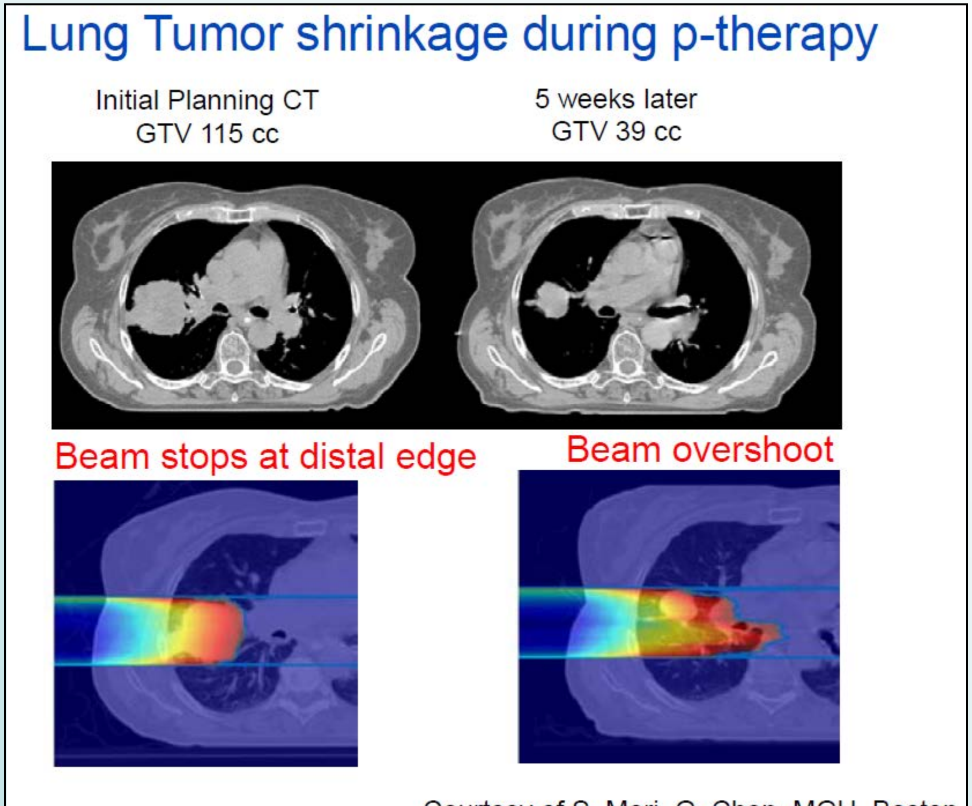
The „source point" for the raster scanning system (example: horizontal treatment room at HIT) are the scanner magnets, where the beam gets small angles (h,v) to hit the "right" voxel position in the isocenter plane (and a corresponding position in the BAMS detectors). In case of deviations (h,v) the scanning angles are corrected, the beam optics simply follows the intercept theorem.

Combining PT and MRI

Combining PT and MRI

Motivation:

- "Seeing what you treat" → Online diagnostics would be favorable
- CT is almost standard today, but MRI causes no further radiation dose (especially important in pediatric treatments!)
- Tumor shrinkage during therapy – avoidance of errors in adapted dose allocation



Courtesy of S. Mori, G. Chen, MGH, Boston

- MRI-Linac Systems (with photon beams) are currently being introduced in radiotherapy, see slide after next

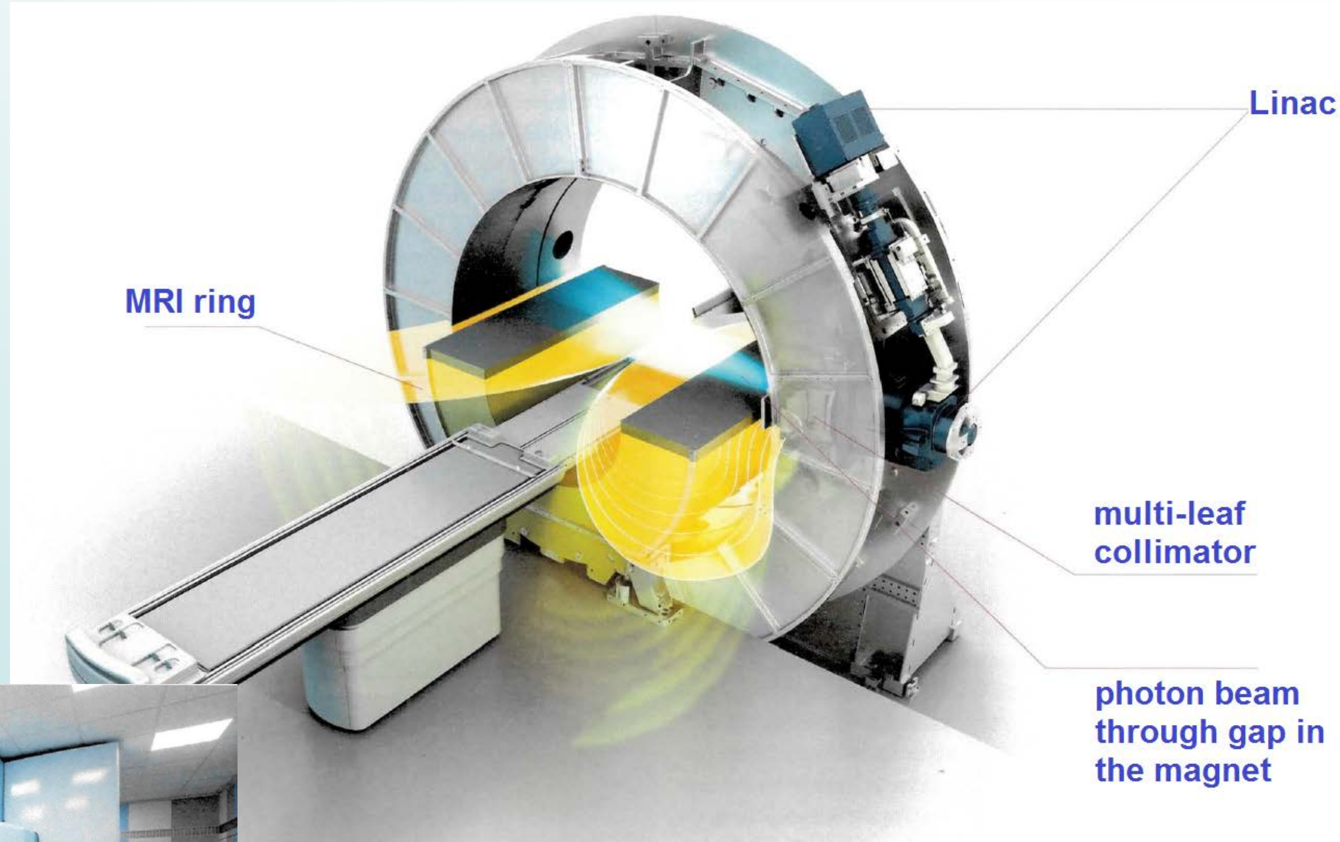
Combining PT and MRI

<u>Furthermore:</u>
Doctors normally use large margins around the tumor volume because of possible range uncertainties, movement of the tumor along the irradiation, etc. → Better diagnostics is necessary to shrink these margins!

A 6.5 mm thick margin (peel) consists of the same volume as a 5 cm diameter target (orange).

Combining PT and MRI

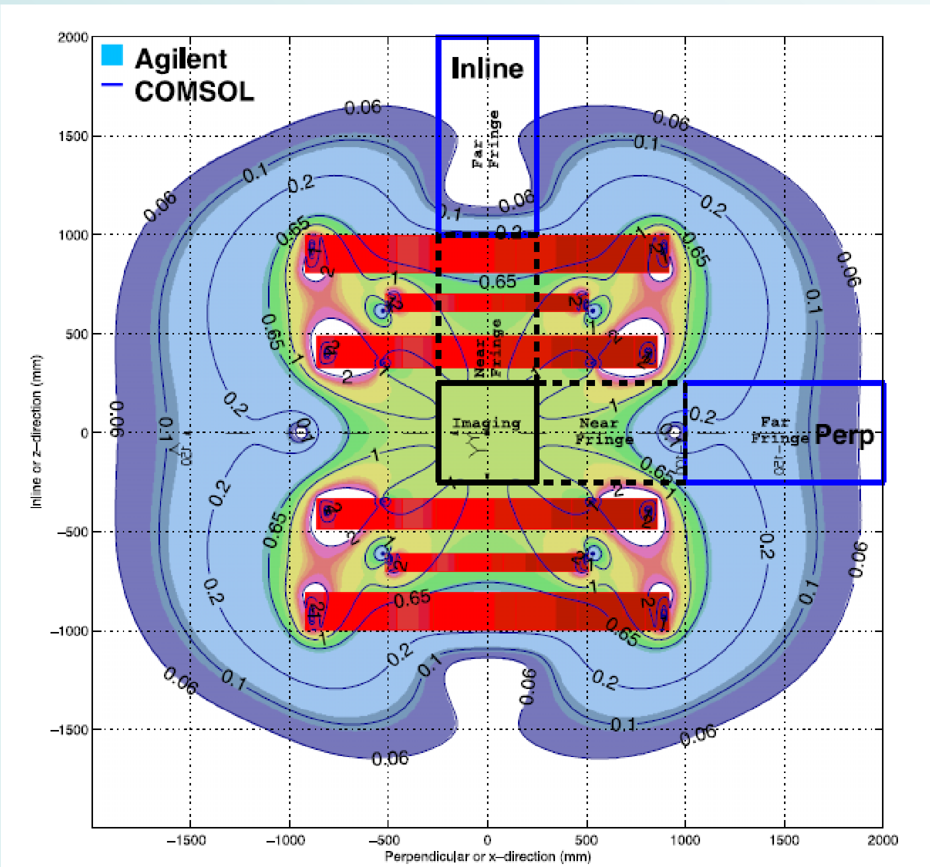
Cross section of a combined MRI and <u>photon</u> linac

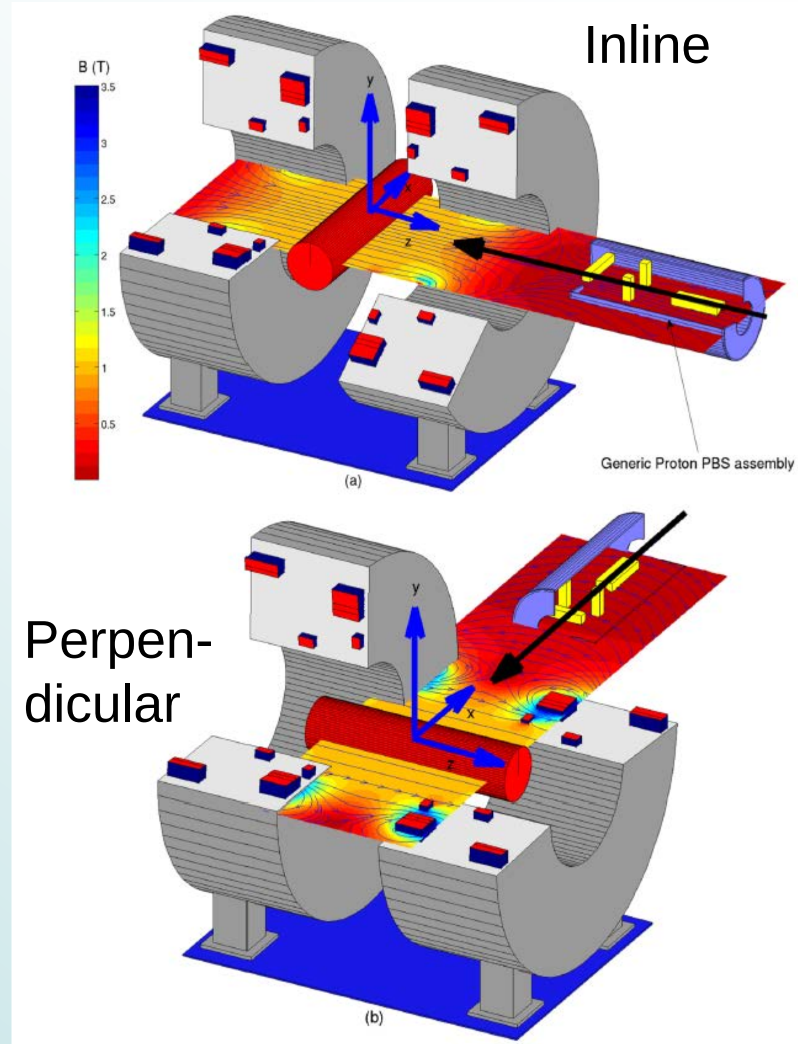


Installation of the MRIdian® Linac (with 0.35 T magnetic field) at the University Hospital Heidelberg / Section RadioOncology

Combining PT and MRI

MRI devices have complex magnetic fields, which would interact with proton/ ion beams – compensation, feedback?





Possible arrangements of MRI device vs. beam direction

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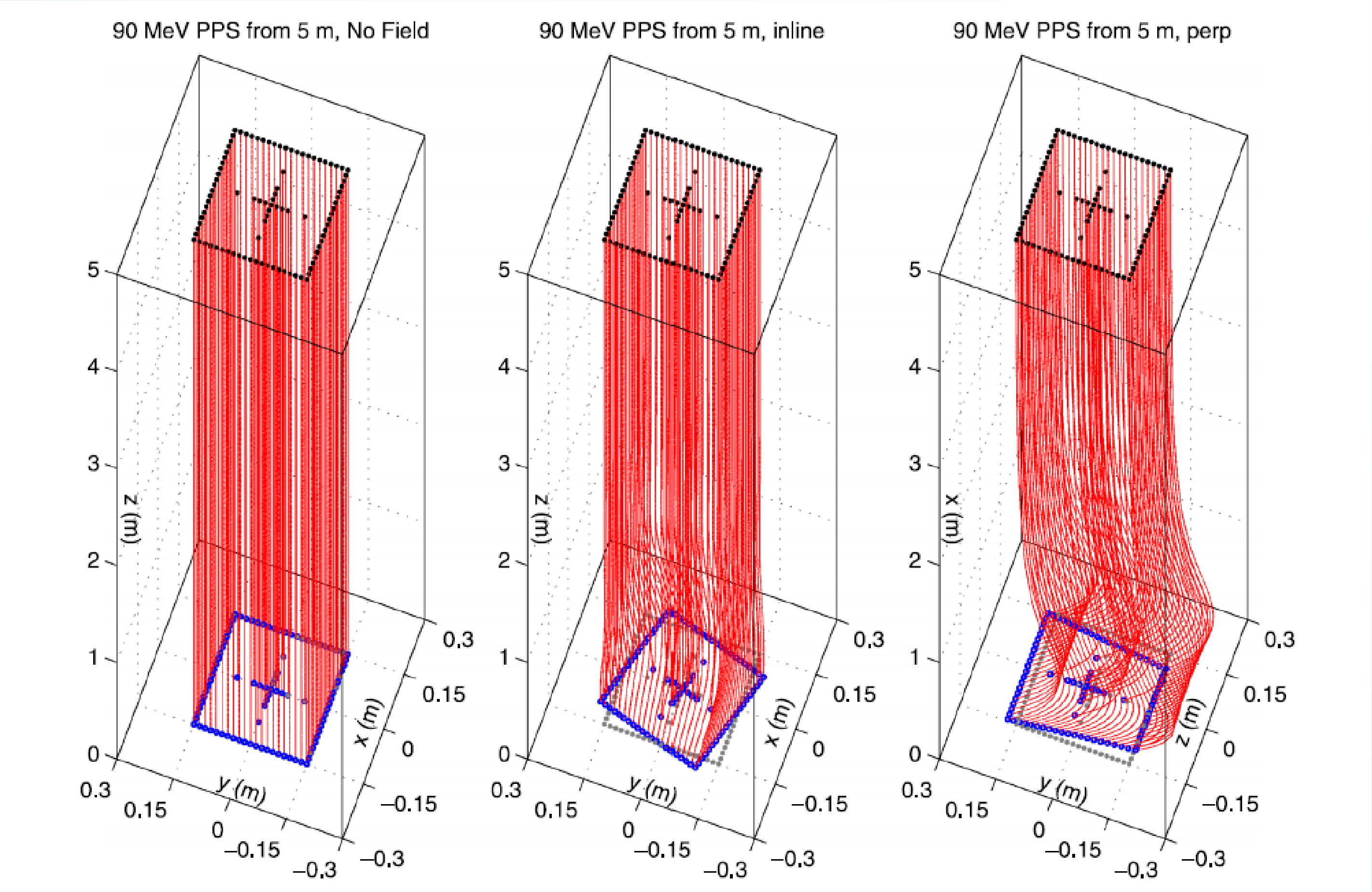
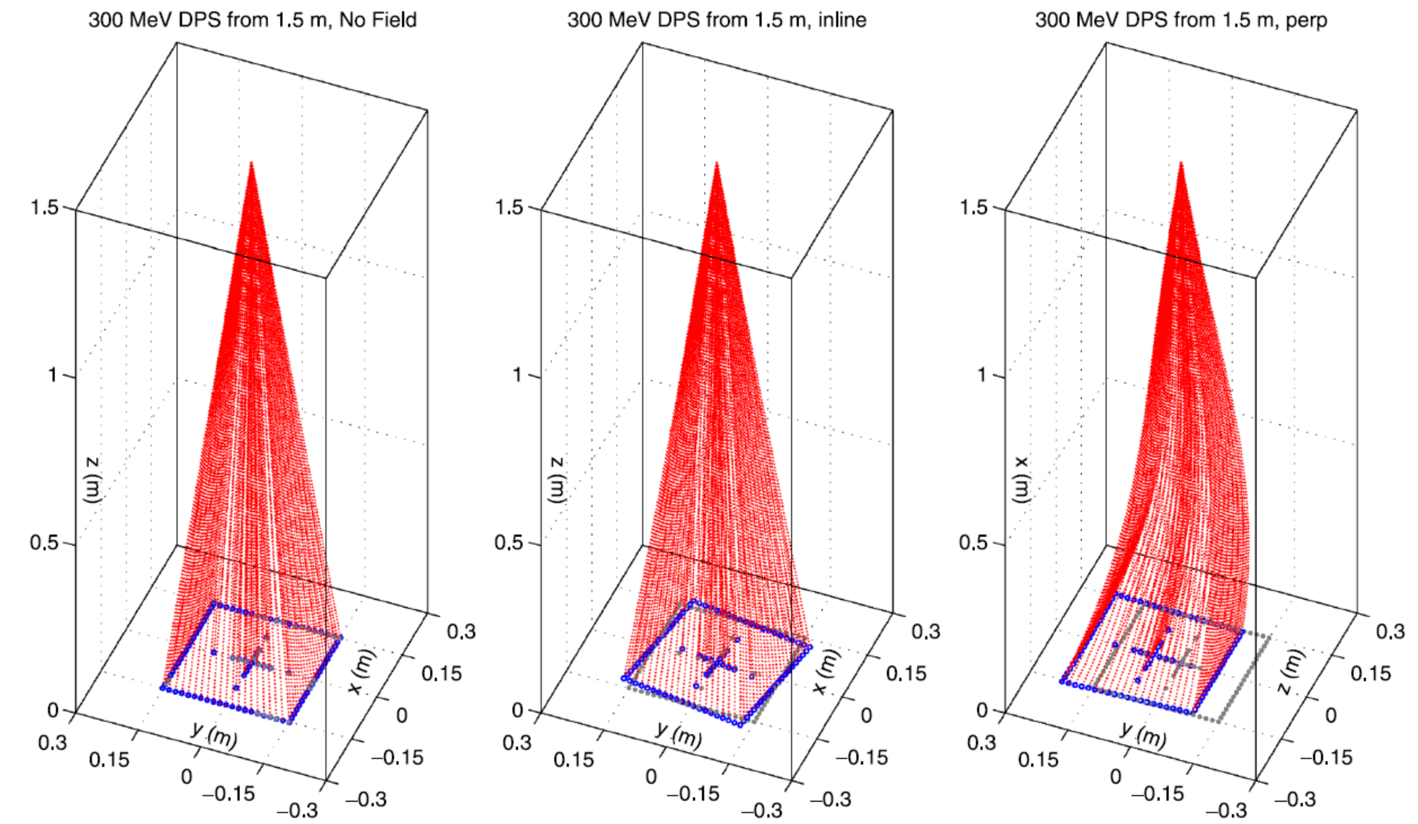
Combining PT and MRI

In case of a parallel particle source (PPS) the MRI device causes (complex) distortions and deflections of the beam!



Combining PT and MRI

In case of a Diverging point source (DPS), e.g. a raster scanning system, similar (complex) distortions and deflections of the beam occur!



Furthermore:

- Effects on secondary particles have to be taken into account!
- Influence of pulsed magnetic fields (MRI) have to be carefully examined!

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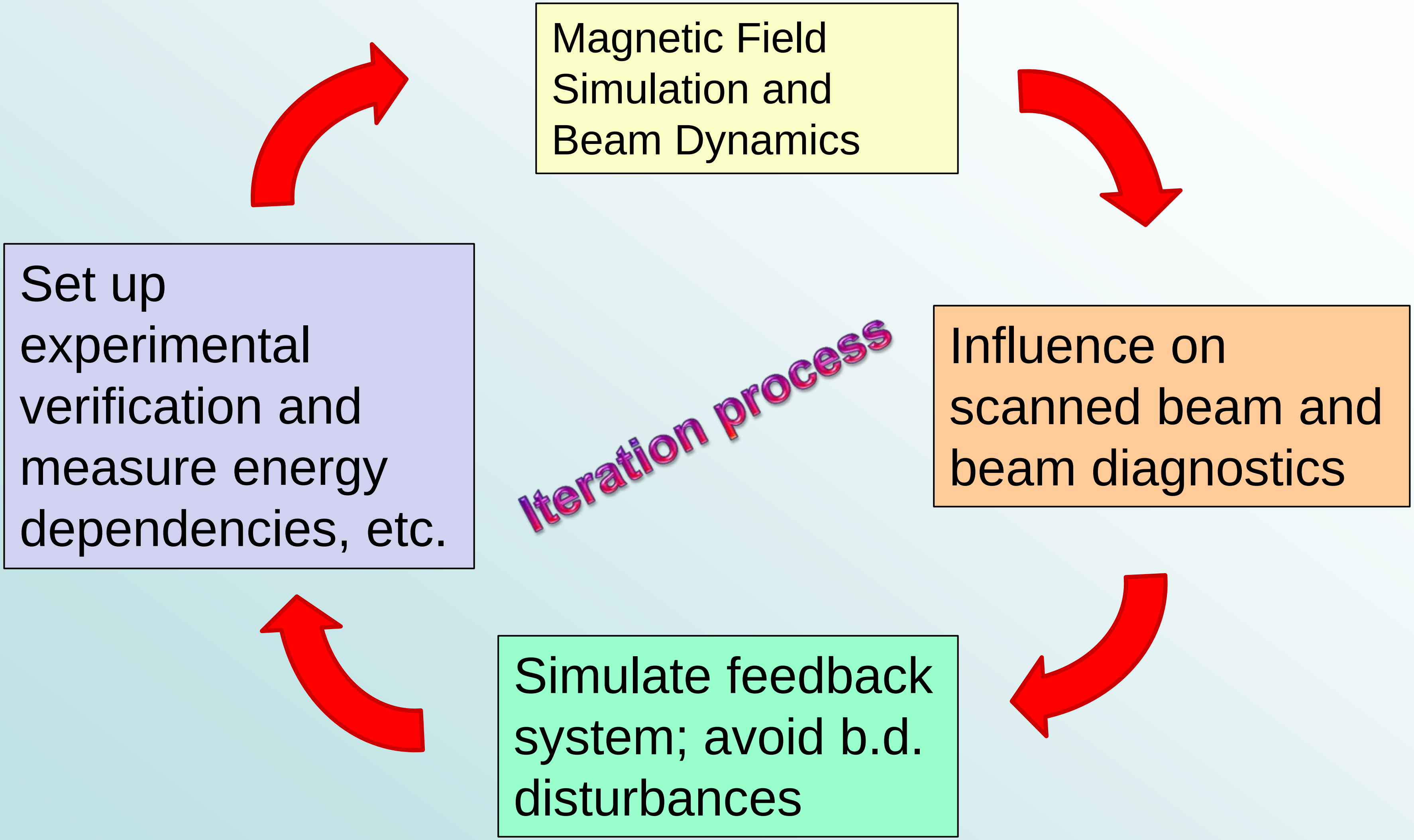
Combining PT and MRI



Solutions still under study…

Dynamic Intensity Control – a Variable Feedback System for Fast Dose Application

Dynamic Intensity Control

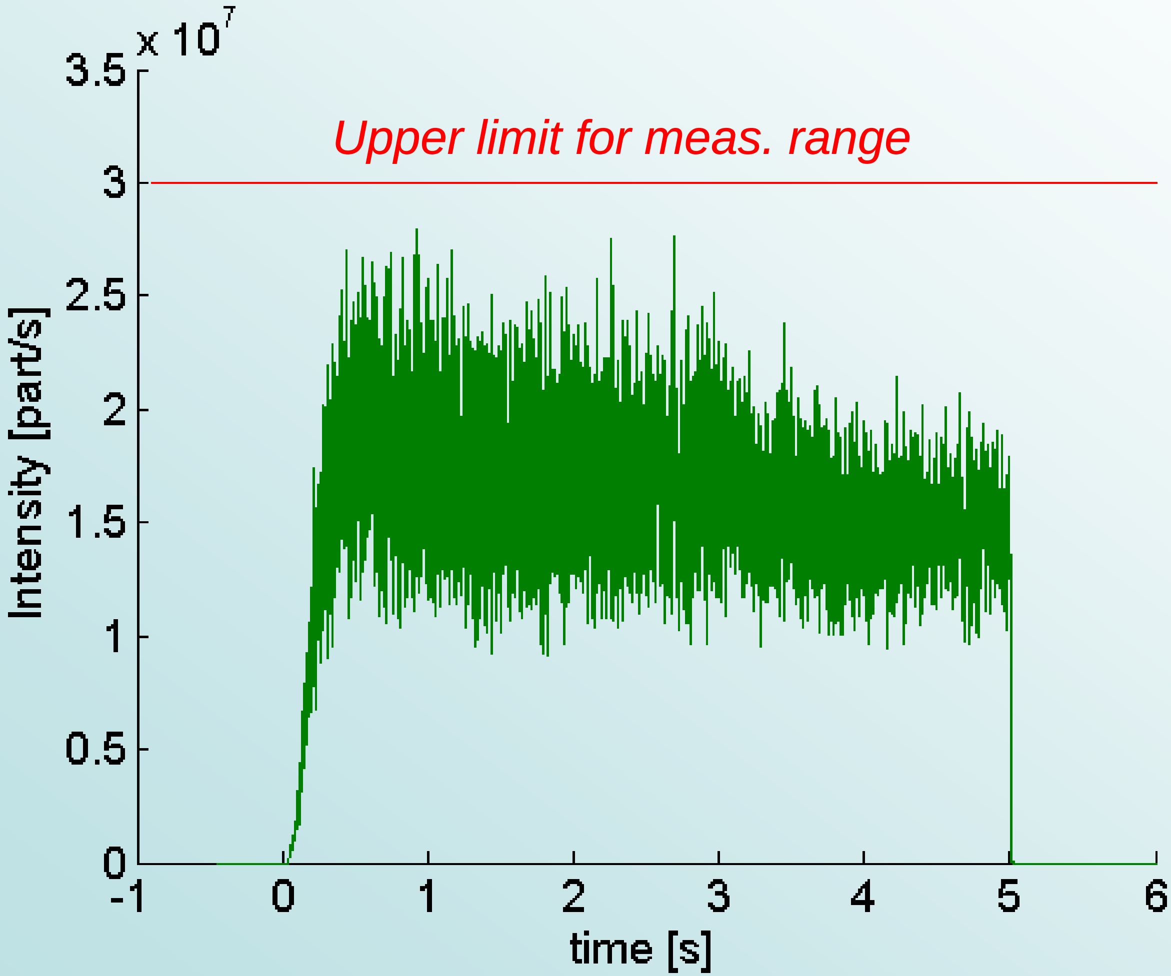
Motivation:

Therapy works fine – why do we need higher performance in dose application?

Reasons for the reduction of individual treatment time are:

- Higher patient comfort (locally immobilized!)
- Higher dose conformity
- More patients
- Economic facility operation

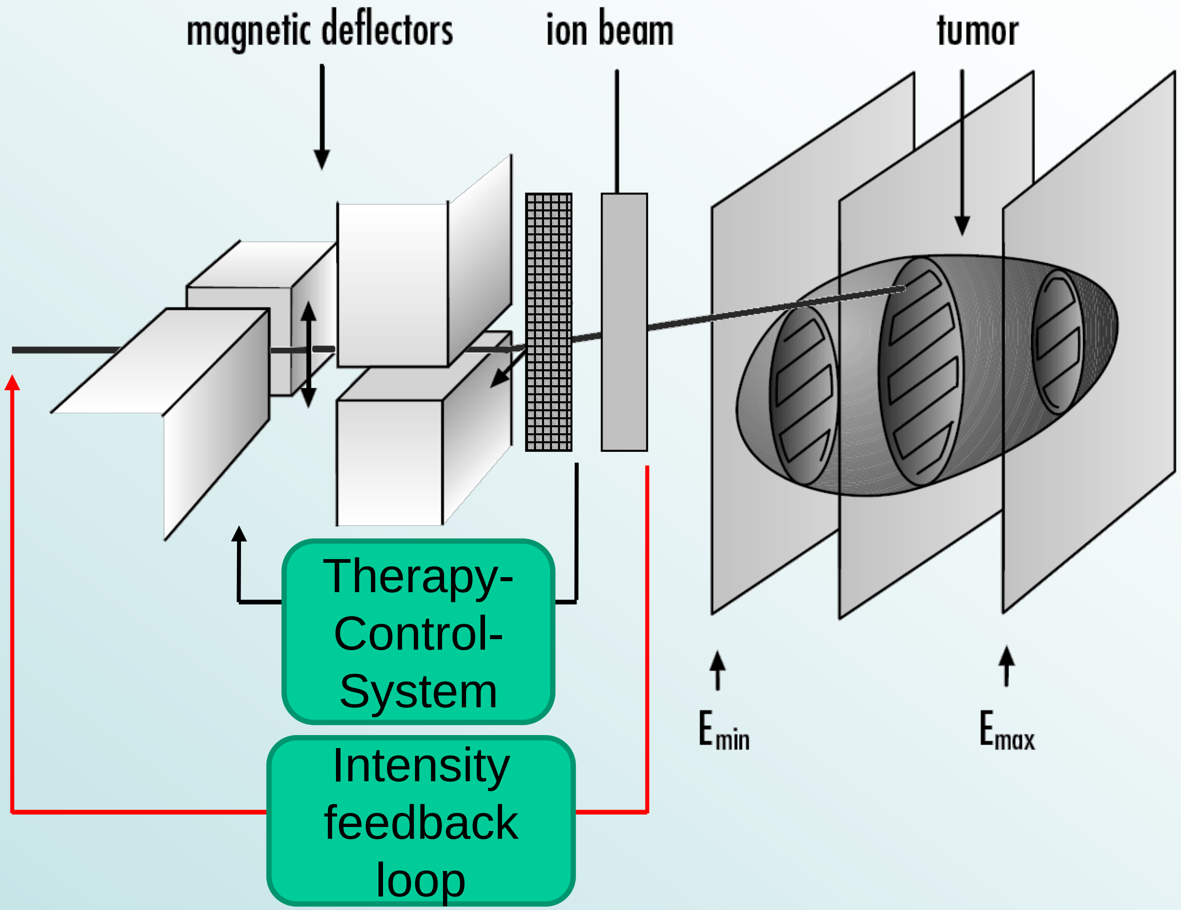
Dynamic Intensity Control



- Typical spill structure achieved with RF knock-out method
- Ideally intensity as high as possible close to the limit
- Reality: Scanning velocity is lower than desired
- Spill-quality is essential for the treatment time!

Dynamic Intensity Control

- Use intensity signal
- Add feedback loop
- Position and intensity is measured, the scanning velocity and the intensity is adapted
- Challenge: Coupling the *medical product* with the *industrial product* accelerator



Dynamic Intensity Control

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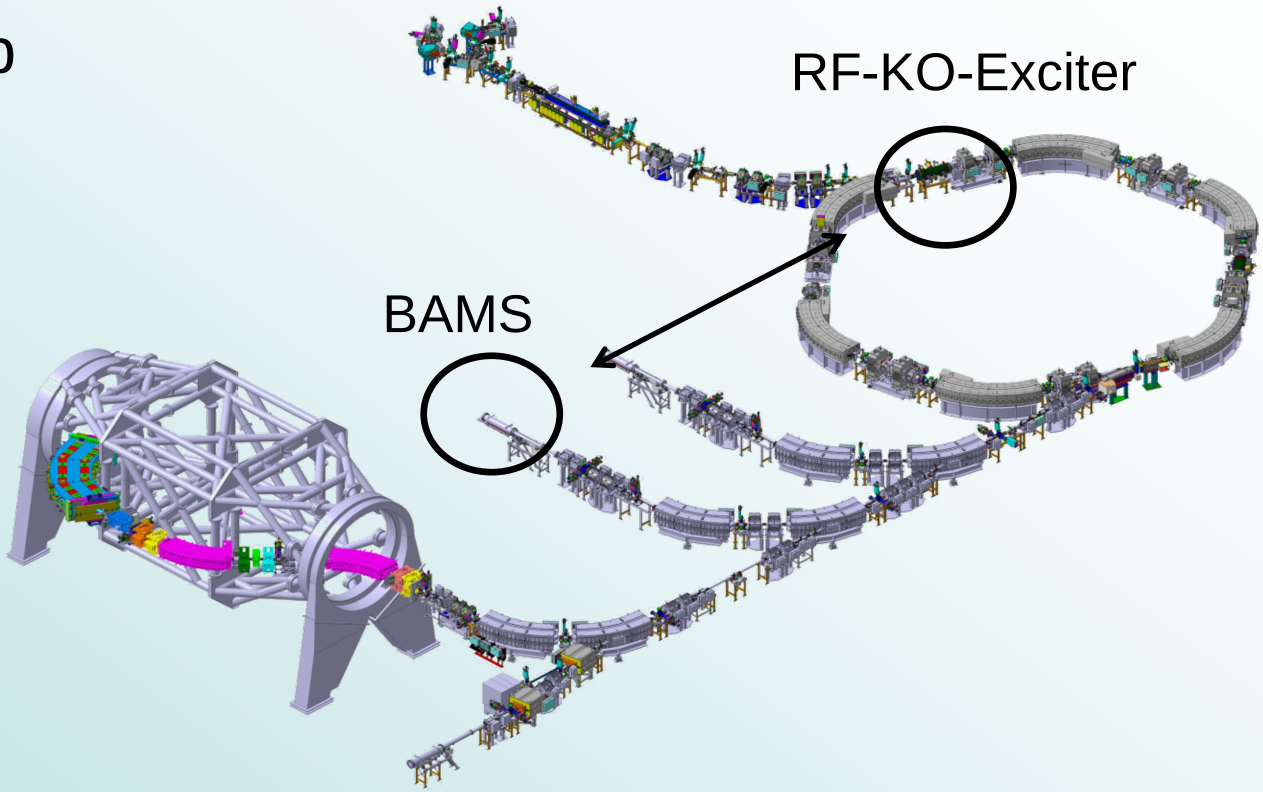
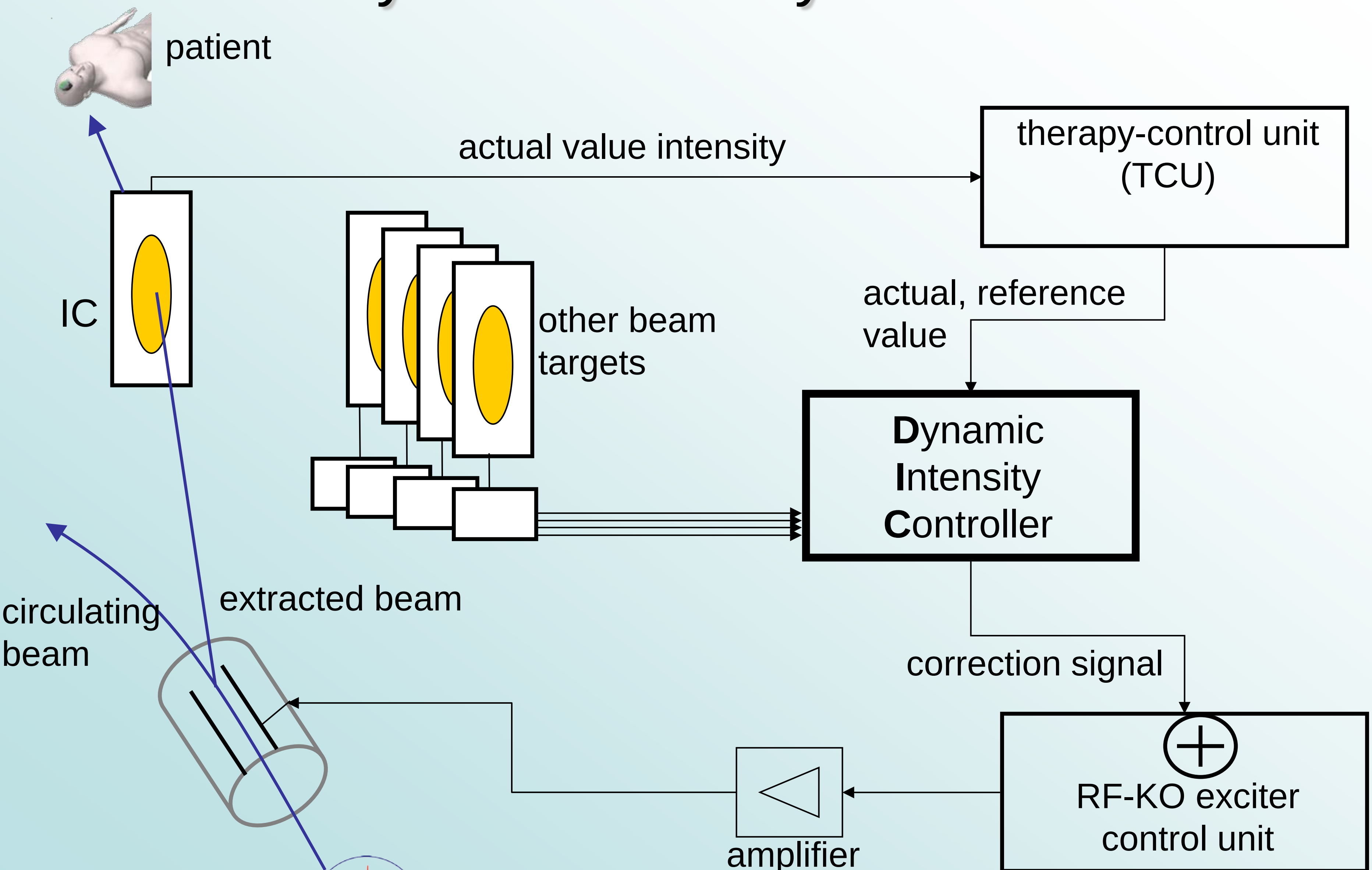


4 treatment rooms plus beamdump with IC detectors

Dynamic Intensity Control



Dynamic Intensity Control

Feedback realization:

- PID controller
  - "P" for a fast response
  - "I" for no remaining control deviation
  - "D" optional and currently deactivated
- PID-parameters as a function of (ion, energy, intensity)
  - ≈ 10000 combinations
  - 1% was defined in commissioning, all other values were calculated by spline interpolation
- Additional features:
  - Mitigate intensity overshoot
  - "Early abort" – controller realizes when synchrotron is empty
  - ...

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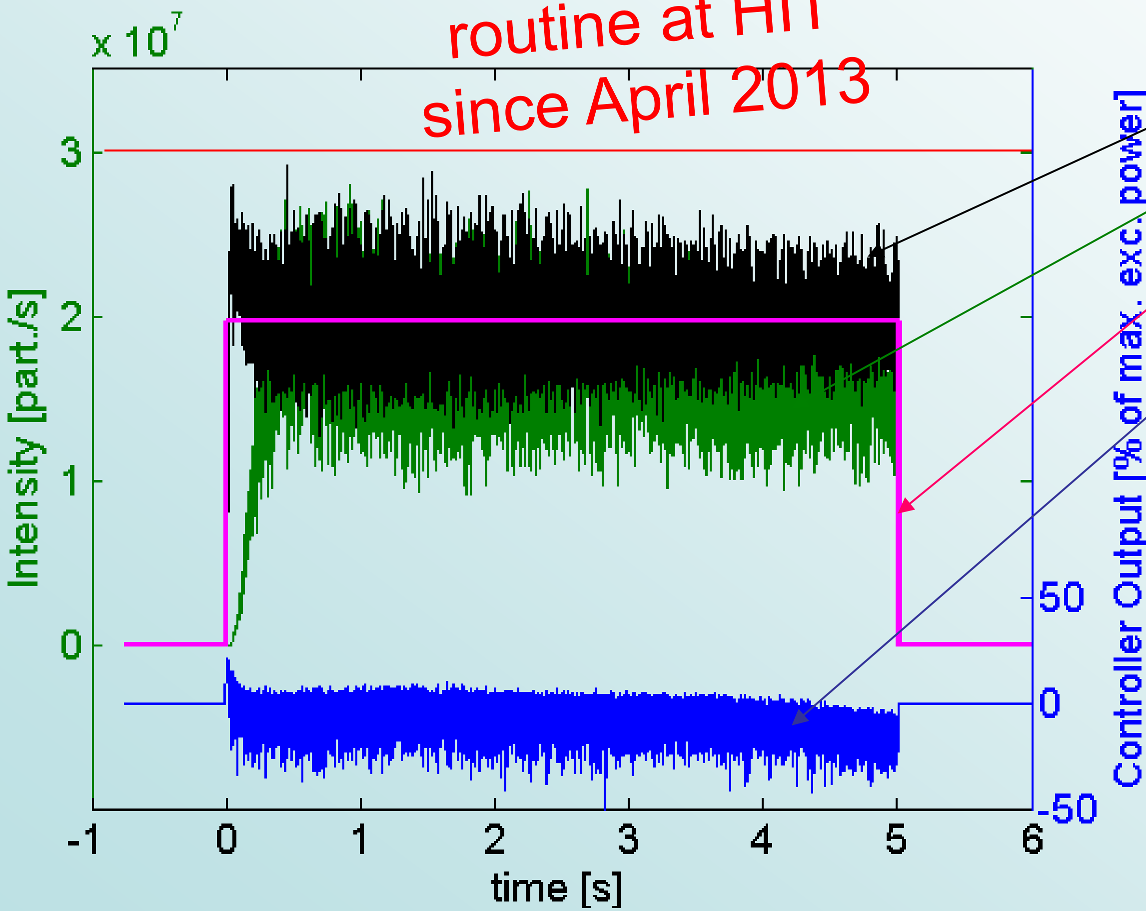
Dynamic Intensity Control

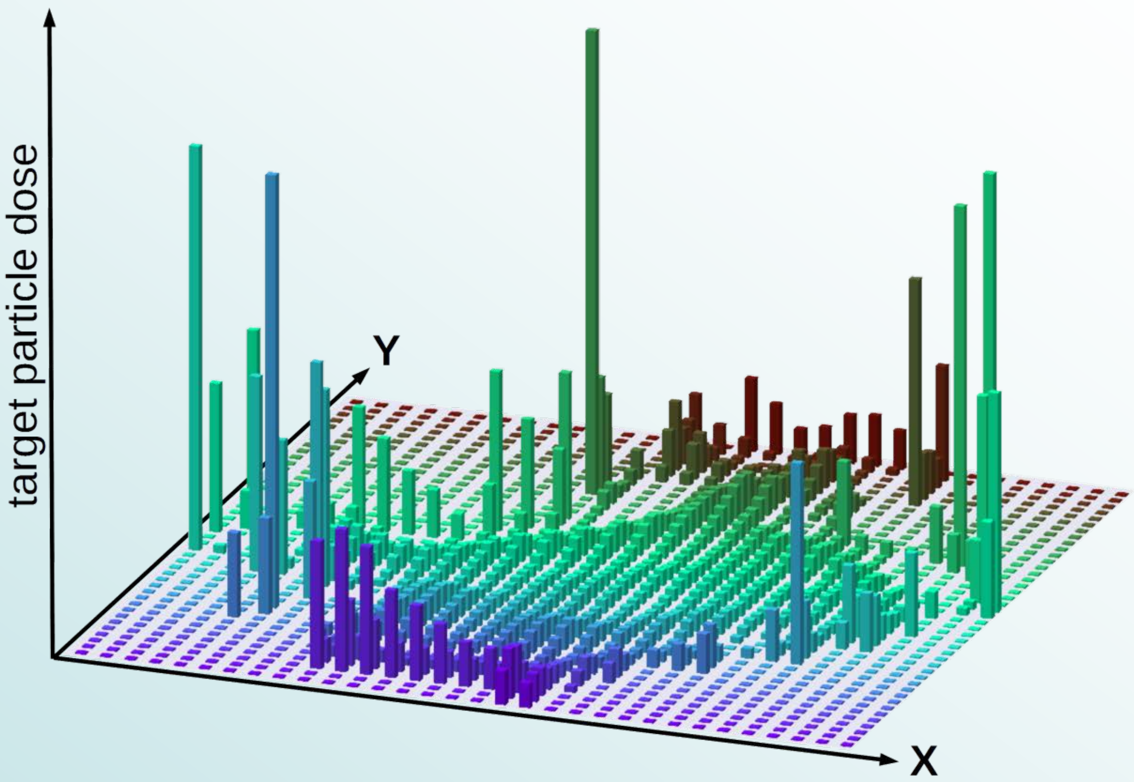


Results (StepI):

- Spill shape
  - With feedback
  - Without feedback
  - Reference value
  - Controller output
- Higher average intensity (15 %!)
- Faster irradiation
- Less machine tuning

Dynamic Intensity Control

- Example of dose distribution of one slice
- Lowest particle fluence determines intensity for whole slice
- Fixed intensity: irradiation time per raster point can vary by a factor of > 100!



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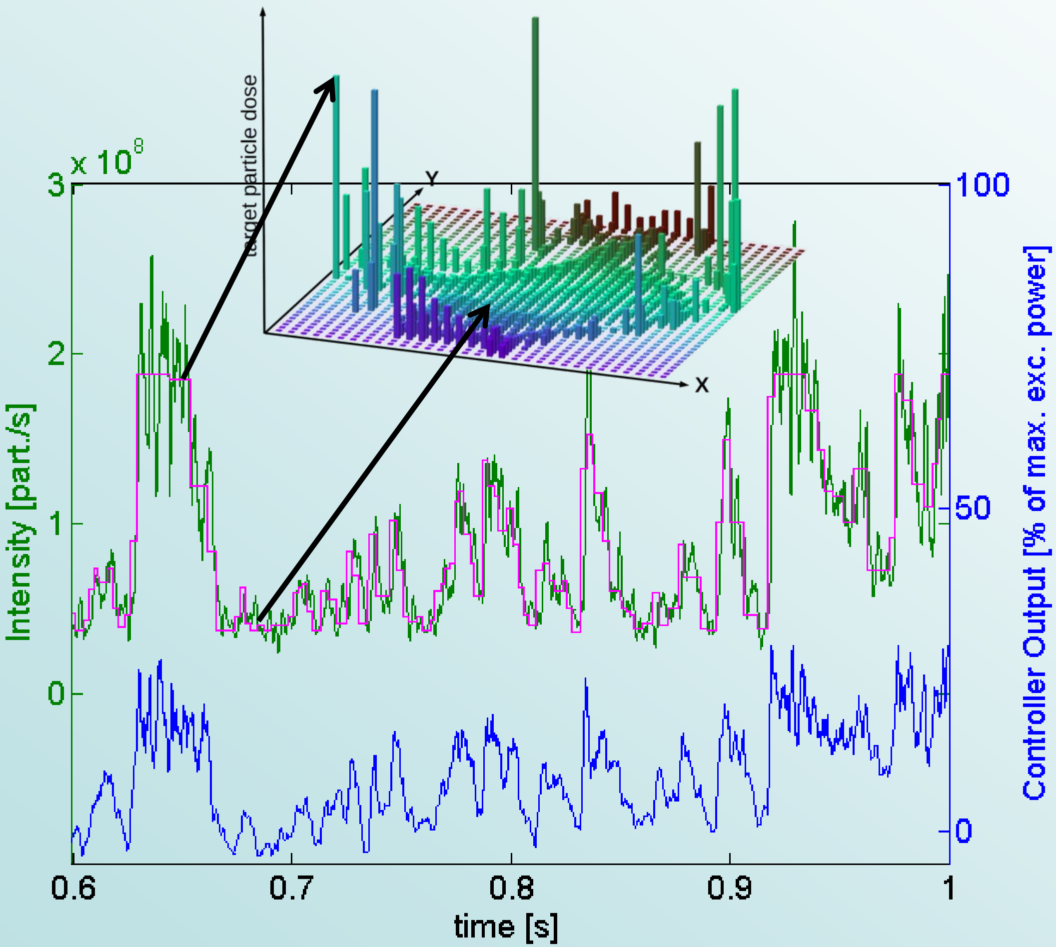
Dynamic Intensity Control



2nd Step of DIC development:

Intensity-modulated spill

- Rasterpoint individual reference value
- Feedback loop adapts the actual intensity
- Beam-on time can again be reduced by ≈45%!

- In clinical operation at HIT since April 2014!

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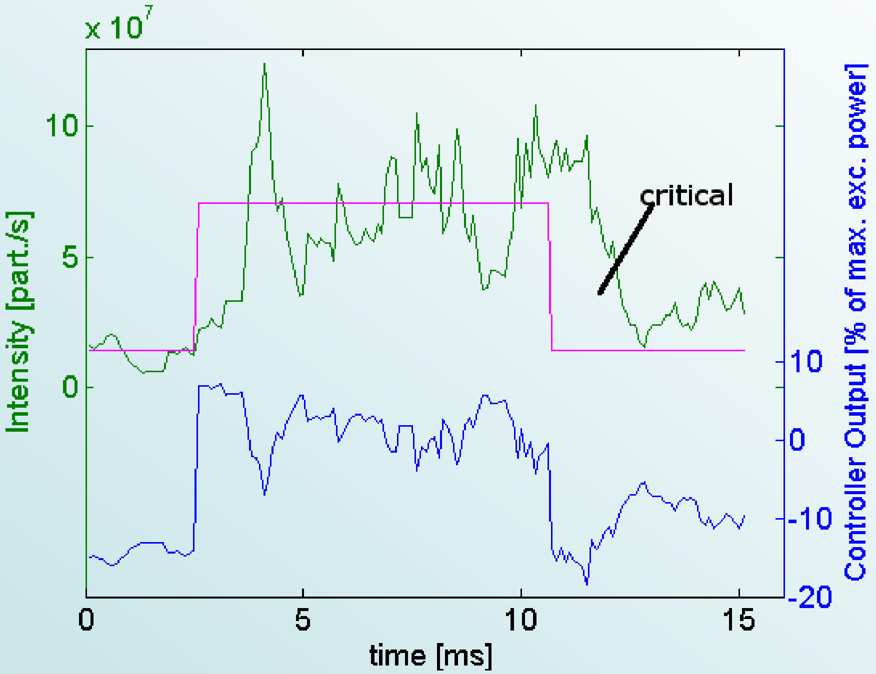
Dynamic Intensity Control

Challenges and limitations:

- Limits of the feedback loop due to dead times
  - Signal detection and digitization, ionization chamber ~ 150µs
  - Particle excitation ~ 0 - 600µs
  - Latencies in digital transmission ~ 100µs

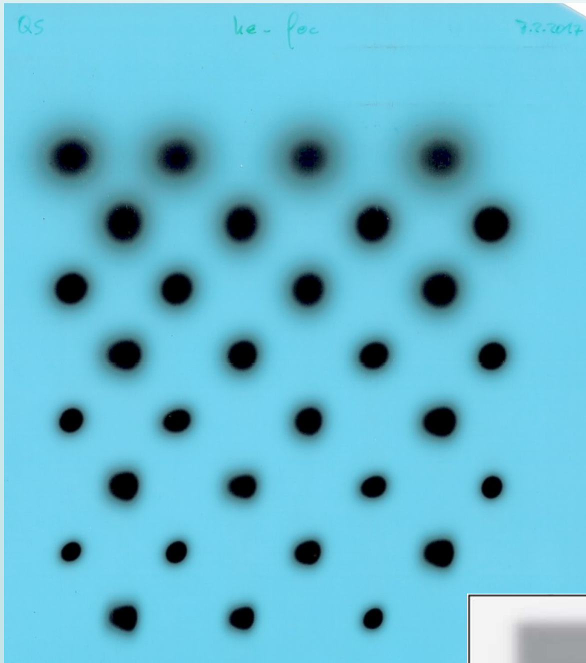
- Irradiating too fast leads to interlocks and must be avoided!

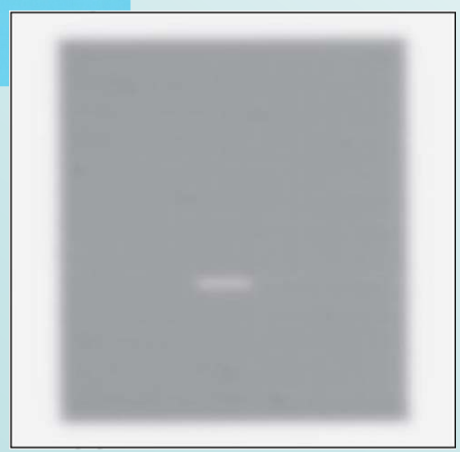
- Reference value pattern must be defined in an intelligent way!



Using Scintillating Screens for Beam Quality Assurance

Beam Diagnostics for QA





Not long ago irradiated films were produced and evaluated for the daily QA by the medical physicist to check:

- Focus width
- 2D „Roundness" of the beam
- Homogeneity of dose application

And in the case of a gantry this for a lot of angles of incidence…

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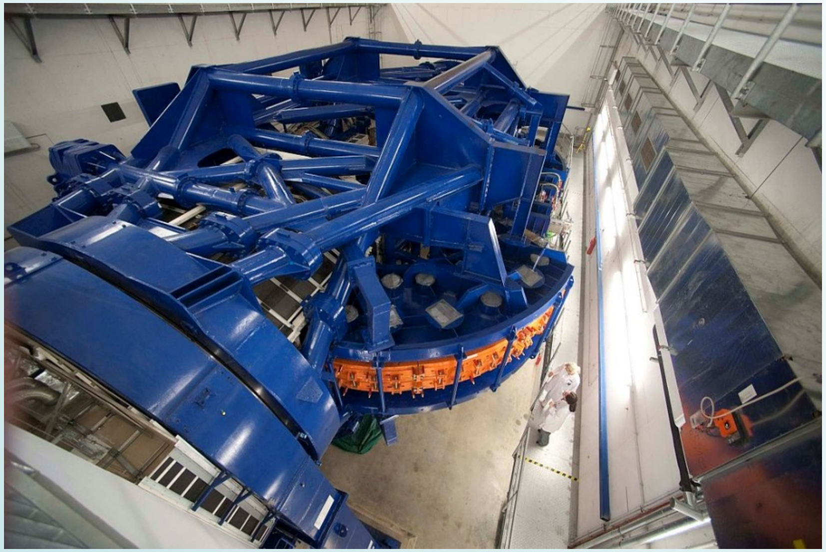
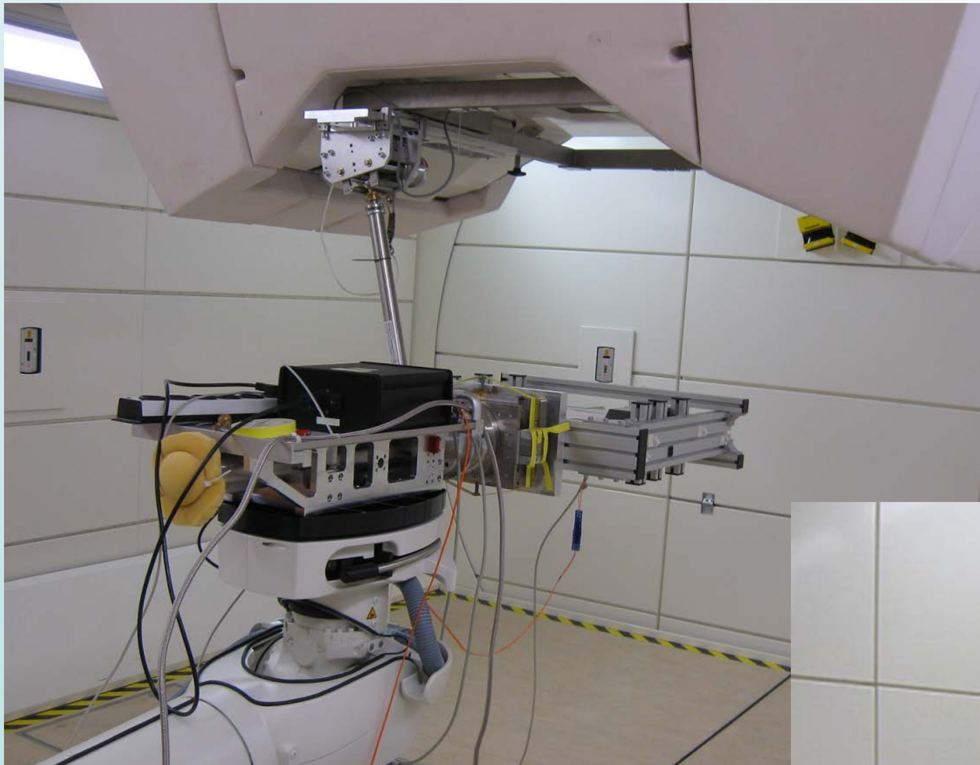


The HIT gantry:

- Structure with beamline (upper left)
- Treatment room (lower left)
- …and rotating (below)

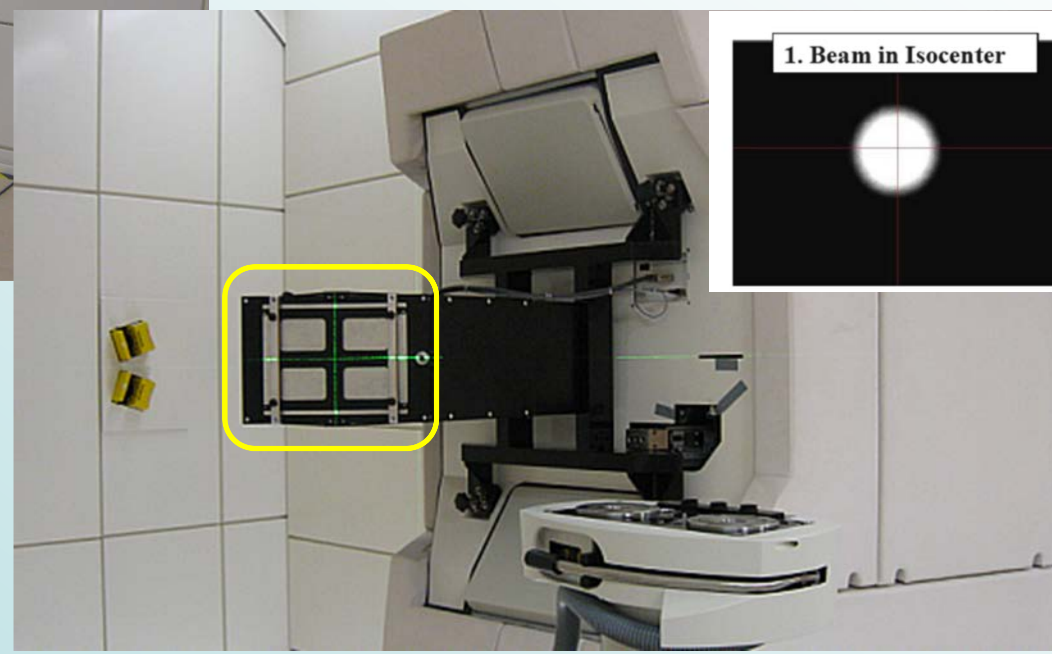
Beam Diagnostics for QA



Left: Adapter to robot with rotating mount for

- Films
- MWPCs
- Other QA measurement equipment

→ **Patient coordinate system**



Right: Beam Diagnostics for commissioning – large scintillating screen fixed to gantry nozzle → **Gantry coordinate system**

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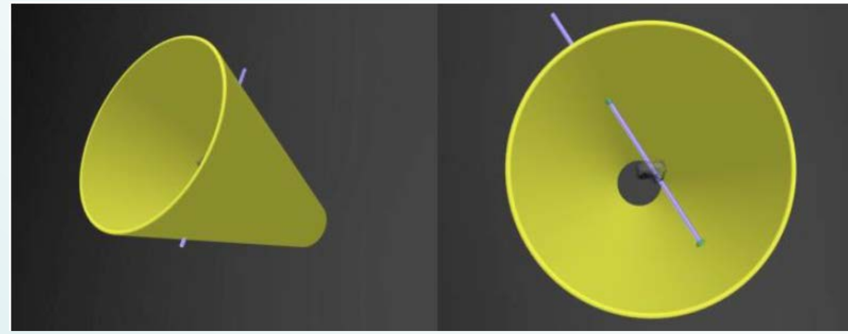
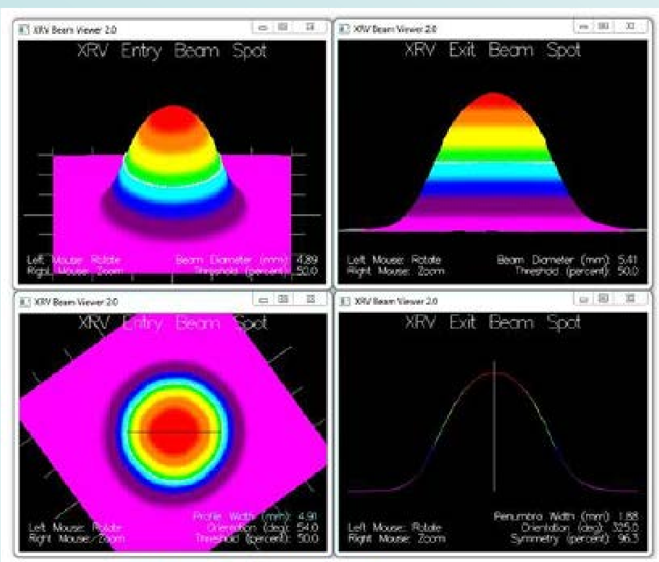
Scintillating Screens for QA

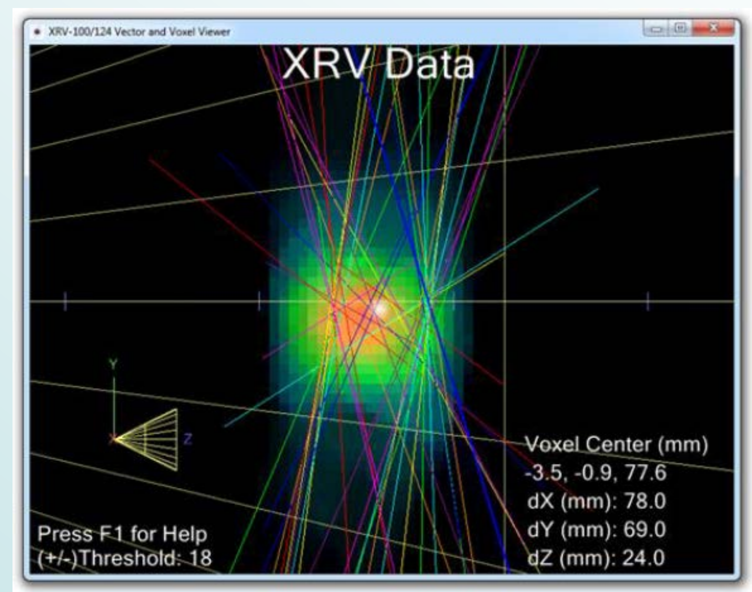
System by *www.logosvisionsystem.com* for photon and proton beams



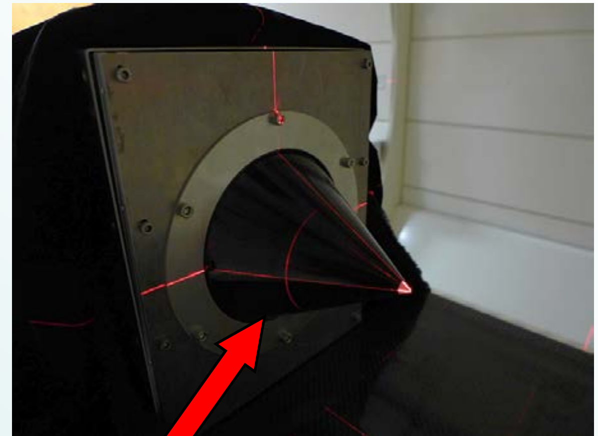


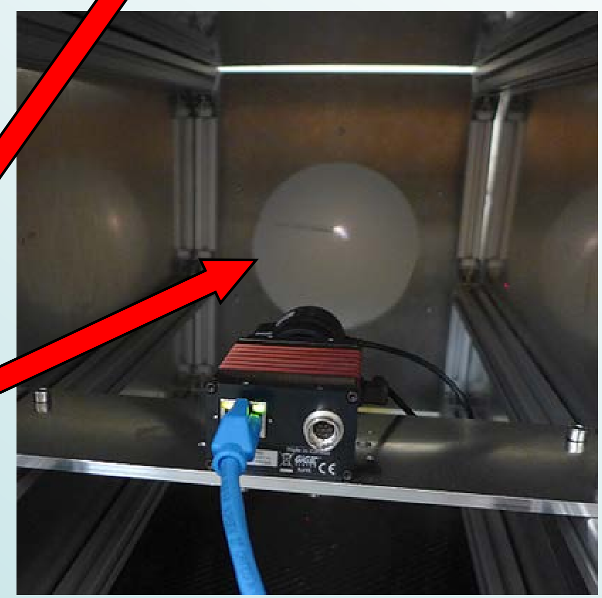
3D Beam Profile Measurements

Geometrical reconstruction leads to beam profile data including focal point and focus width



Scintillating Screens for QA



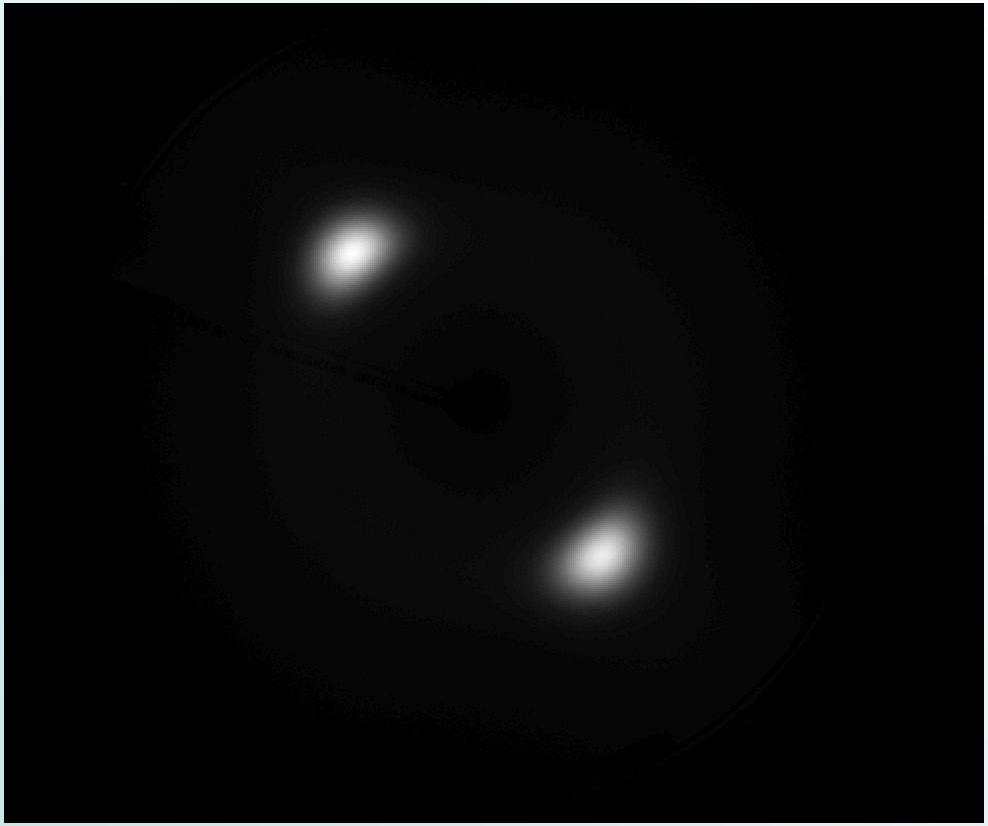


Prototype at HIT (with higher dynamics needed for ion beams); cone-shaped shell made of carbon fiber; Scintillating materials: Lanex or P43 foils from Proxivision (www.proxivision.de)

Scintillating Screens for QA

Series of images taken shot by shot at different gantry angles:

Proton beam with 106.8 MeV and a focus width of 15 mm



Optimization of HW and SW for (triggered) image acquisition and data evaluation now under development.

Conclusion and Acknowledgements

- There is no difference between a scientifically used accelerator and a medical accelerator concerning beam diagnostics equipment, only economic effects may play a role.
- The speciality of medical accelerators is the strong link to the *beam consumer*, in this case the irradiation technology and the high-conformal dose application.
- The coomon topics “Instrumentation – Feedbacks – Detector Technology – Quality Assurance” lead to close collaboration of accelerator and medical physics people in such a facility, resulting in new and innovative tools for dose application, beam tuning and daily QA.

Conclusion and Acknowledgements

Many thanks to all colleagues from HIT – especially to Jakob Naumann, Christian Schömers, Oliver Jäckel, Julian Horn and Jochen Schreiner – for their advice and providing me interesting slides, example measurement results, photos and literature links!

(Intensity modulated raster scan, ^{12}C at 430 MeV/u)

Thank you for your attention!