Influence of target motion on (scanned) particle beam irradiation

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Learning Objectives

- Ability to define the different types of target motion
- Understand the implications the radiological path-length has on the definition of the planning target volume
- Name detriments and advantages of scanned beam delivery and scattered beam delivery for the irradiation of a moving organ
- Explain the principles of gating, rescanning, and beam tracking

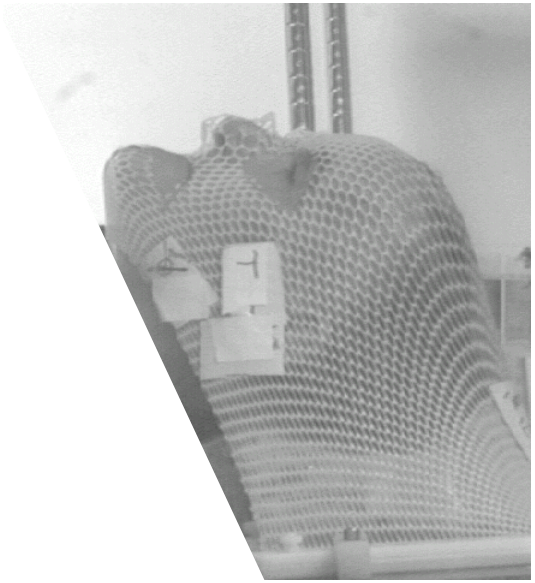
Outline

- Target motion
  - Types, quantification
  - Internal Target Volume concept
  - Implications of particle range
- Mitigation of respiratory motion
  - Broad beam
  - Beam scanning
  - Adaptive radiotherapy
- Summary

Organ motion [Langen & Jones, 2001]

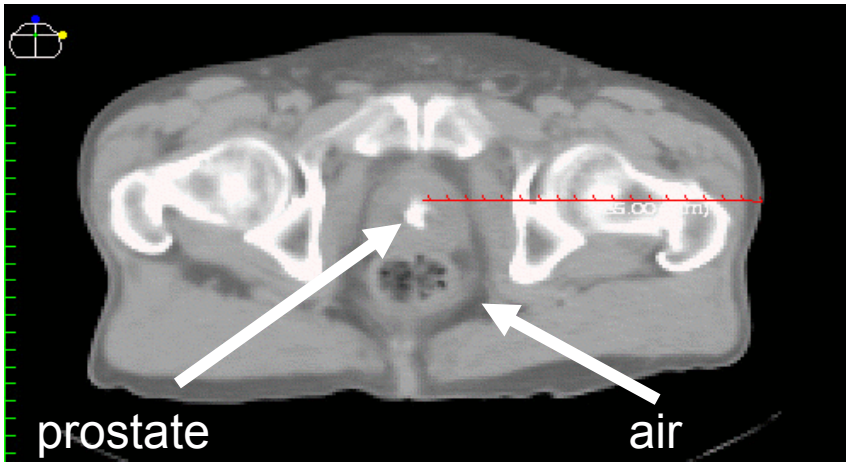
- Position related organ motion
  - Patient positioning prior daily delivery
  - Patient sitting during beam delivery but laying during CT scan
    - Magnitude depends on location
      (<2mm in H&N, most severe in abdomen [Urie 1995])
  - Prone vs. supine positioning
- Inter-fractional organ motion
  - Time scale: several hours … days
  - Cause: digestive system, weight changes, tumor shrinkage
  - Sites: gynecological tract, prostate, bladder, rectum, …
- Intra-fractional organ motion
  - Time scale: seconds … minutes
  - Cause: heart beat, respiration
  - Sites: lung, liver, kidneys, pancreas, …

Target motion



patient positioning

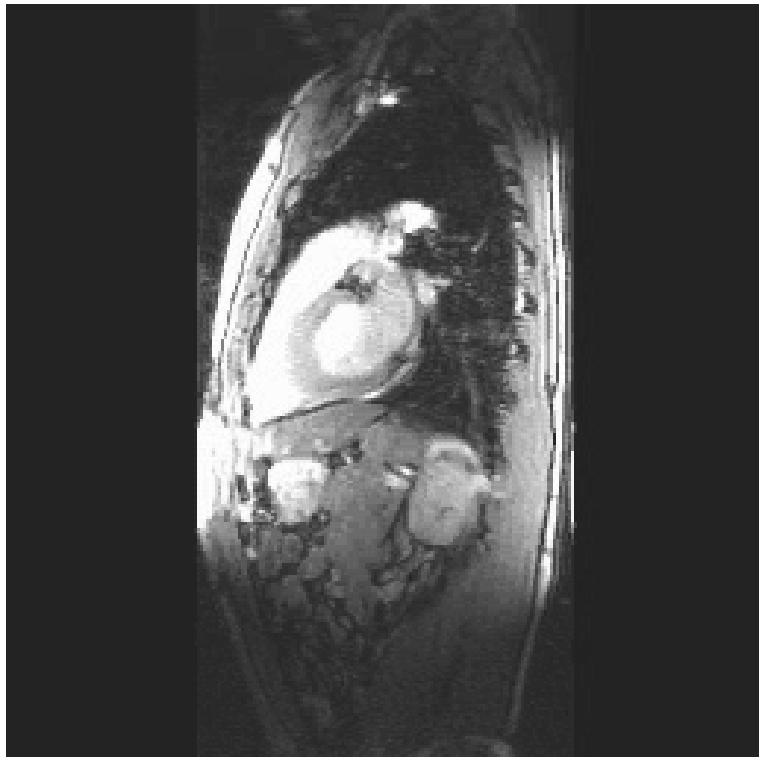
scale: minutes - days



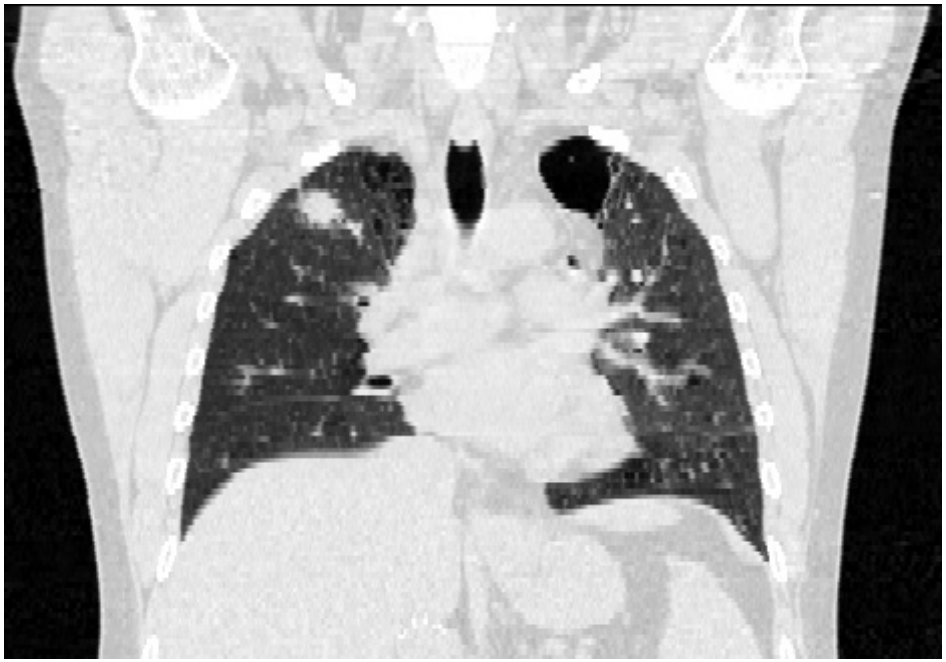
gut filling

scale: minutes

Target motion



heart beat
scale: seconds

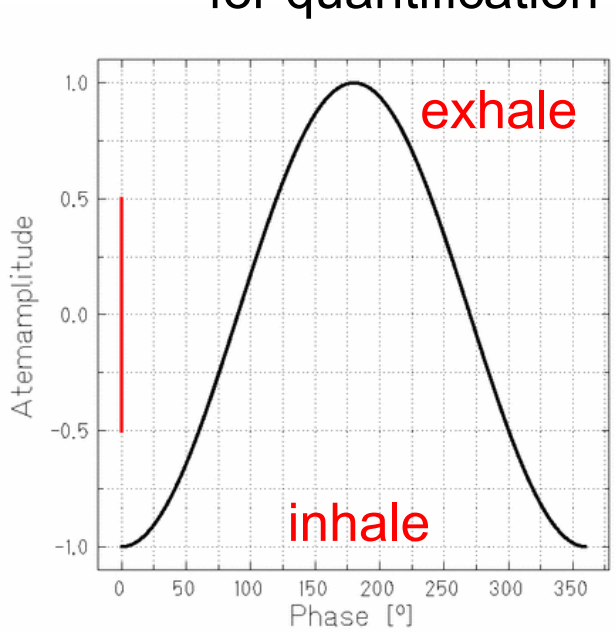


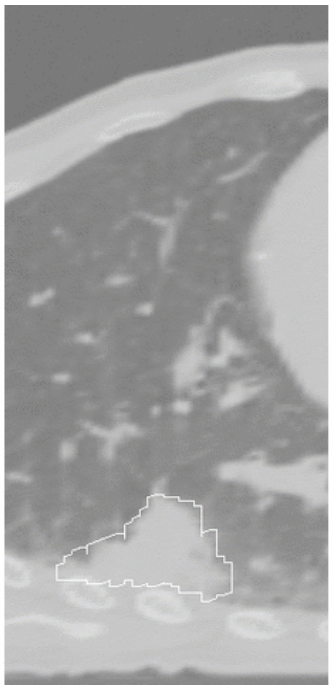
respiration
scale: seconds

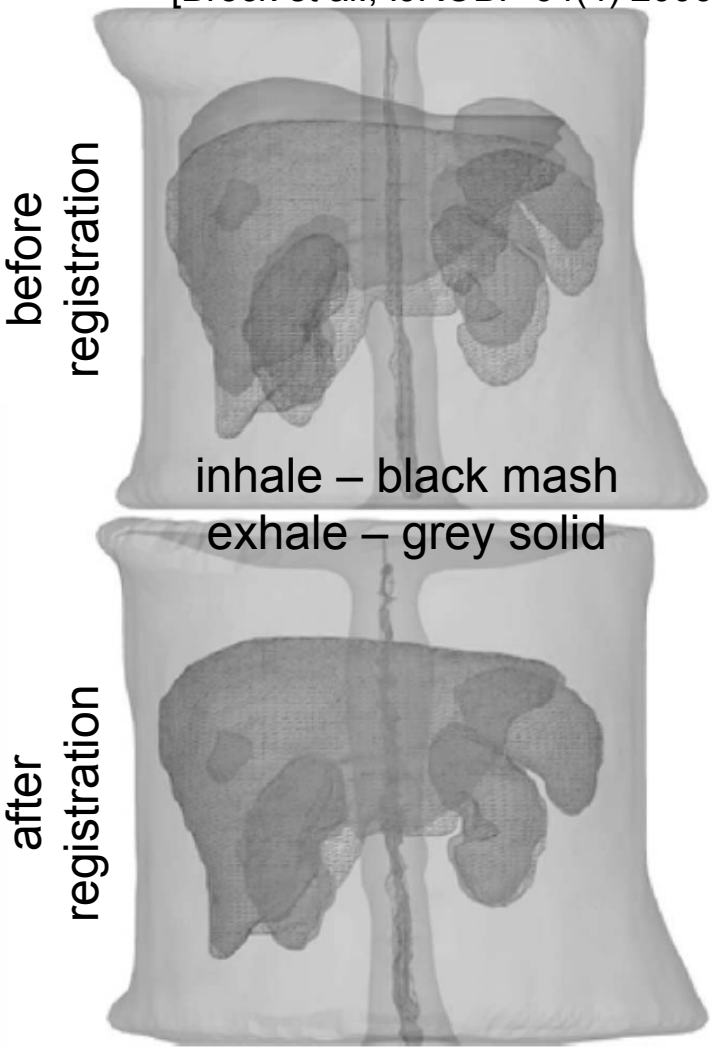
4D quantification of organ motion - lung

[Brock et al., IJROBP 64(4) 2006]

- 3D time-resolved motion detection and quantification
  - 4D CT, 4D MR
  - non-rigid registration techniques for quantification

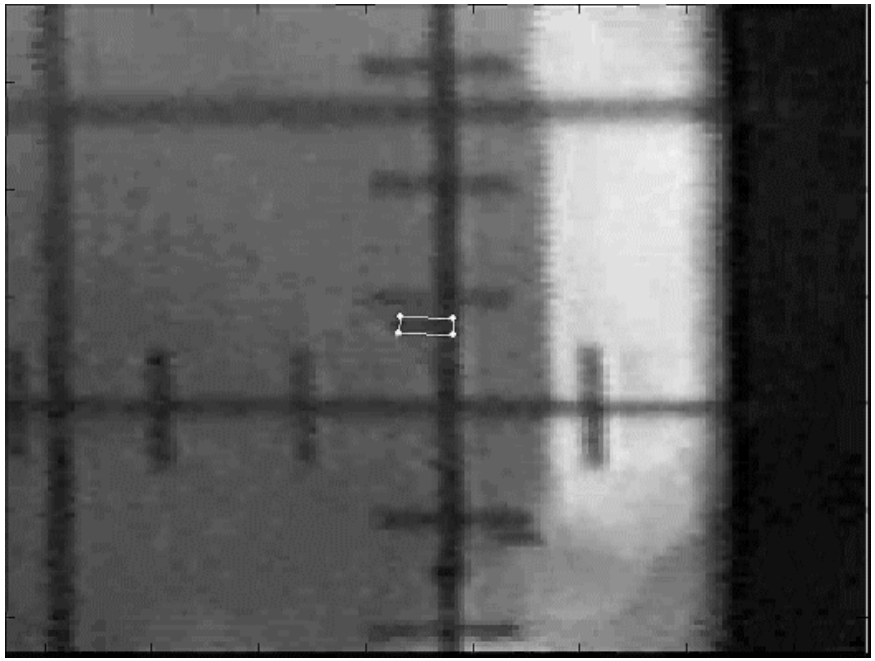




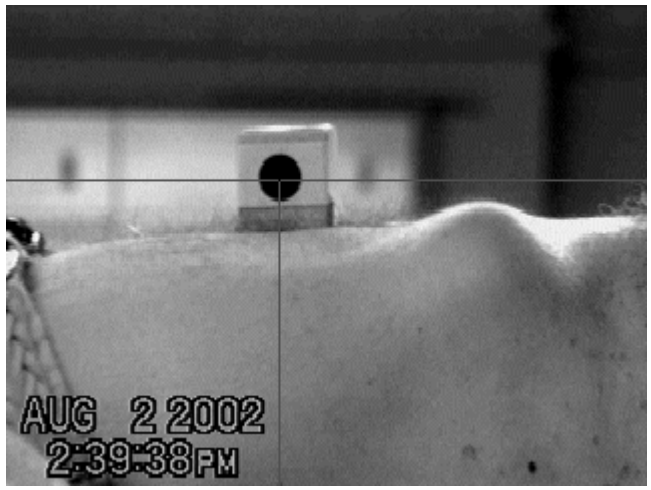


Motion monitoring examples - lung

Internal - fluoroscopy

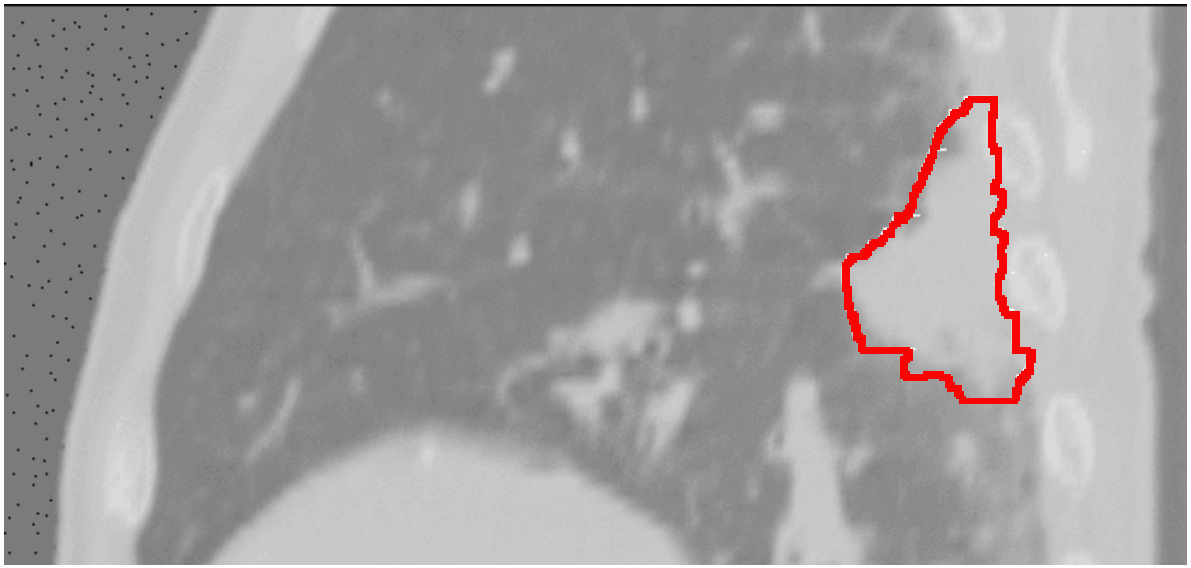


External surrogate - Varian RPM

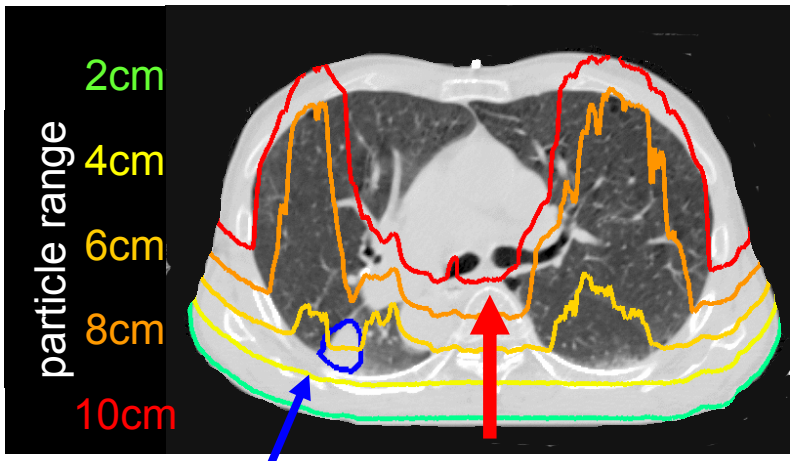


[Jiang, Sharp, Berbeco (MGH)]

Respiratory motion



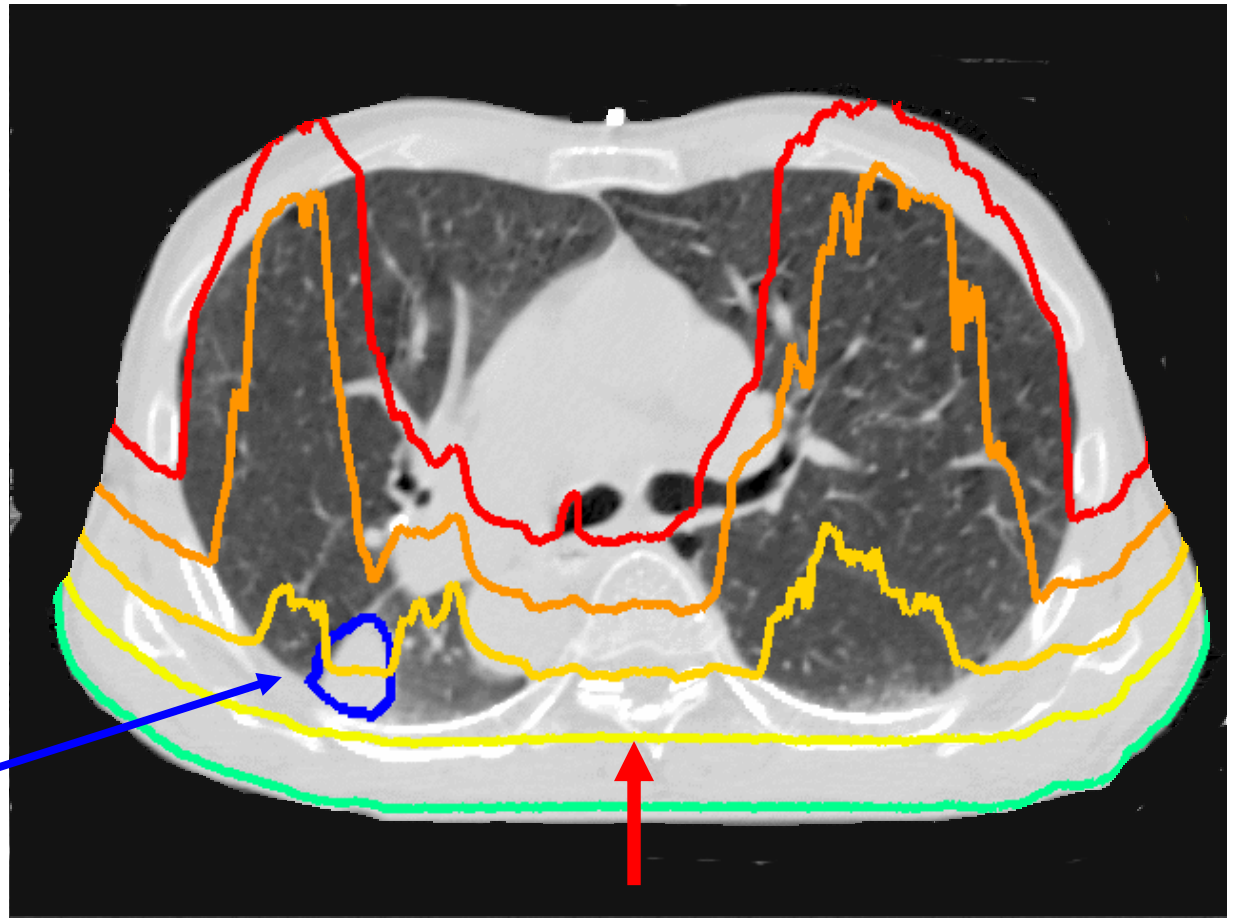
4DCT



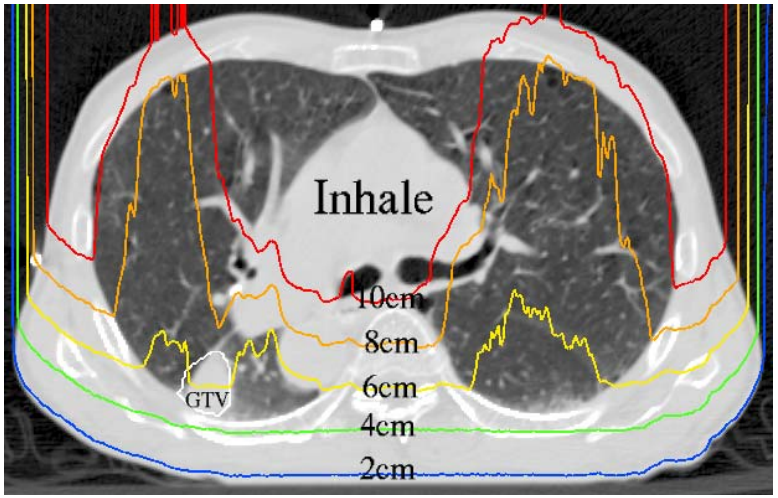
Motion influence on range

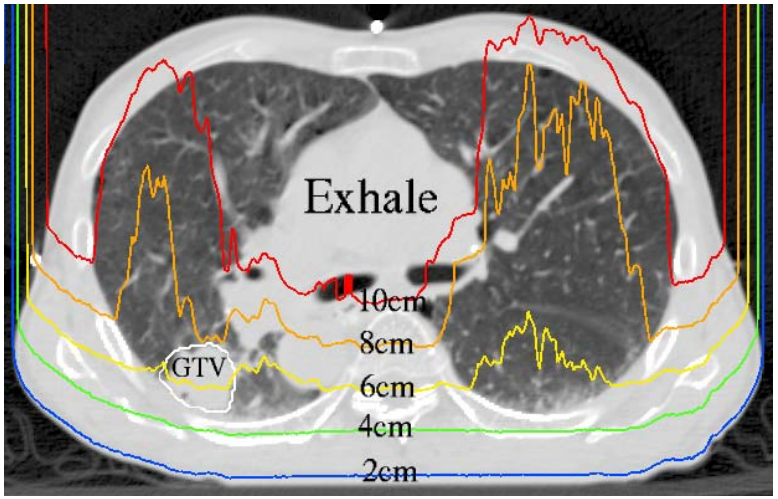
[Bert, Rietzel, MGH]

Respiratory motion - beam range

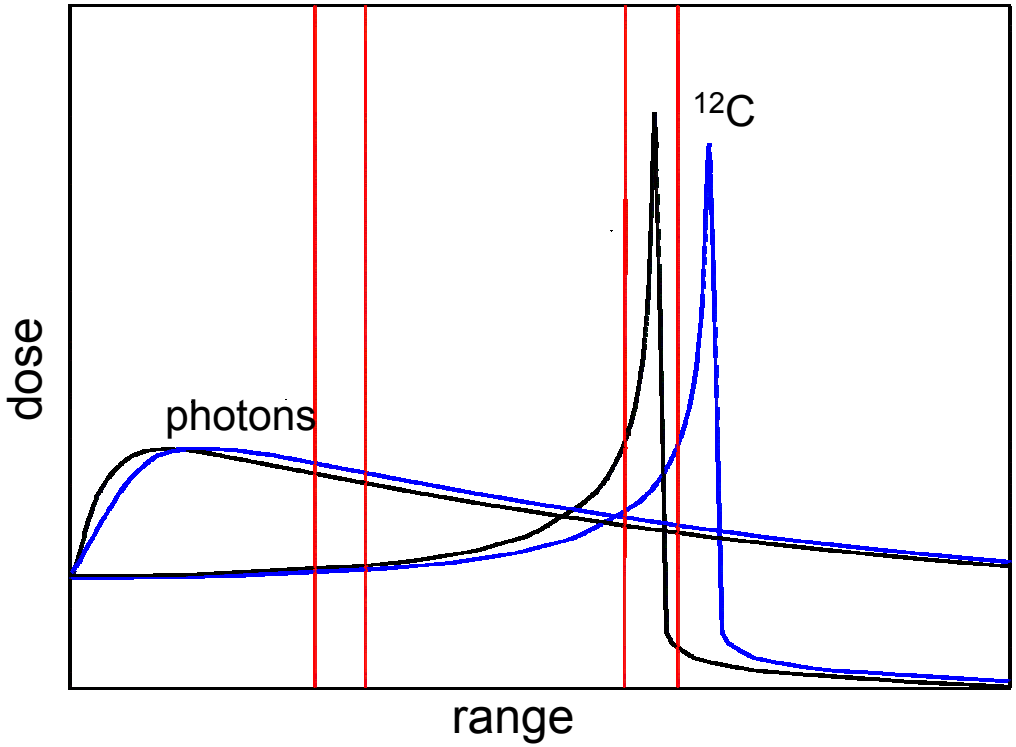


Respiratory motion - beam range





[S.O. Grözinger, GSI]

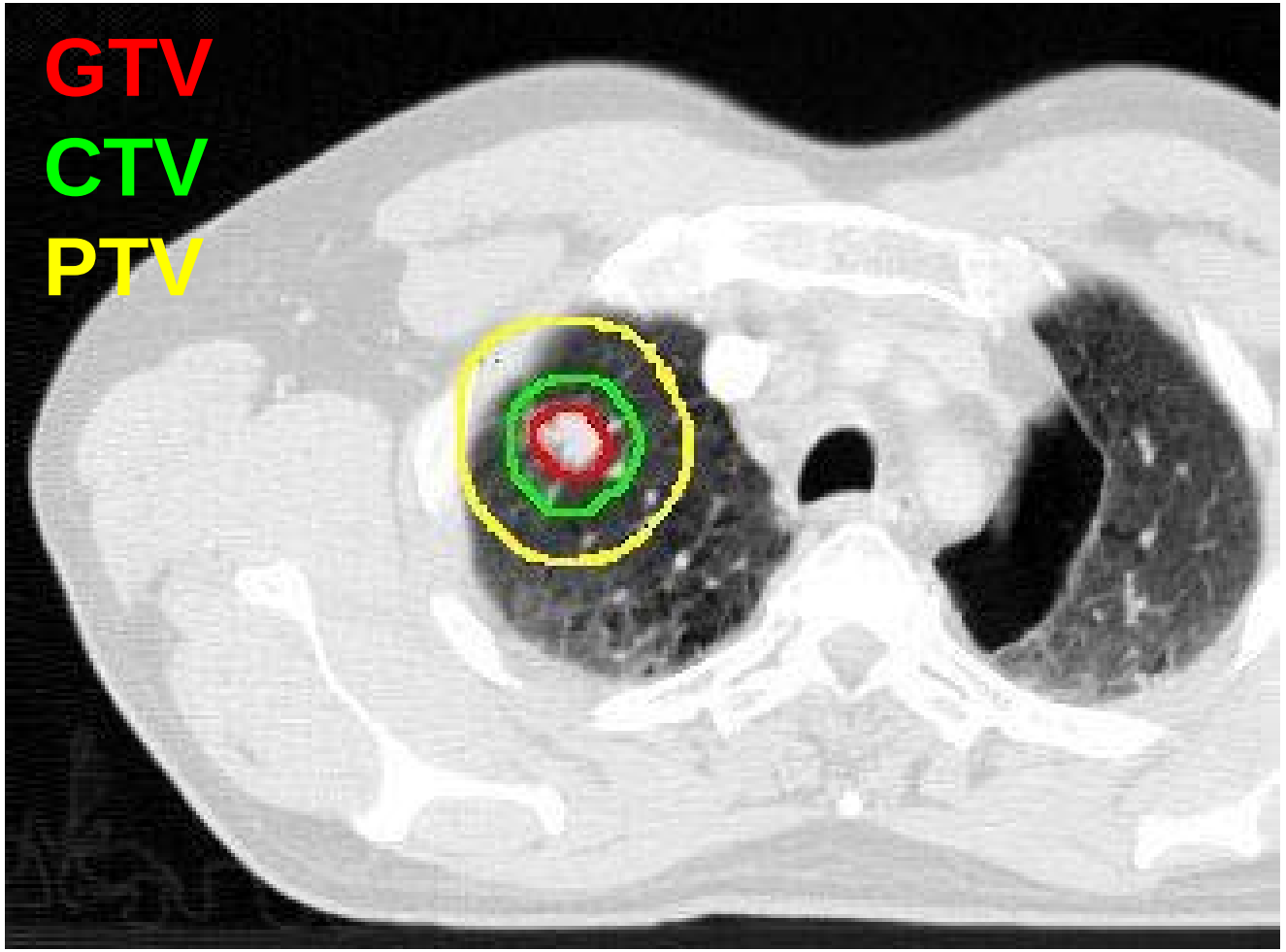


$\Rightarrow$ mitigation of range/longitudinal changes required

How do we handle organ motion

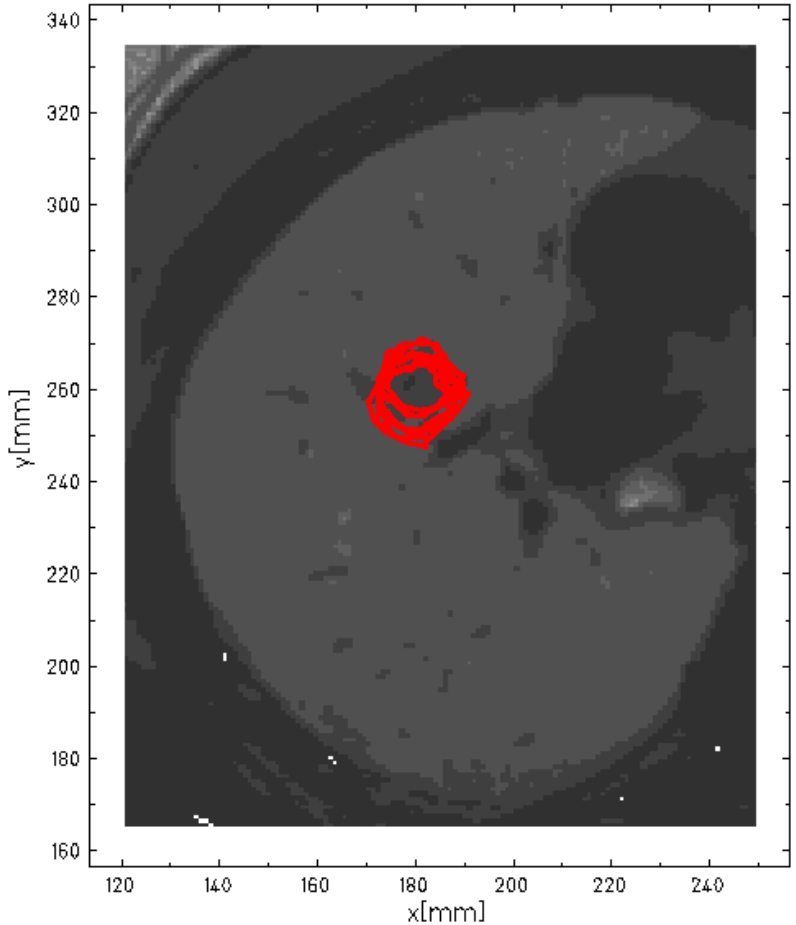
- ICRU reports:
  - Report 50: Electron-Beam Therapy
    - GrossTumorVolume, ClinicalTargetVolume, PlanningTargetVolume
  - Report 62: Photon-Beam Therapy
    - InternalTargetVolume = CTV + InternalMargin
    - IM compensates for respiration, bowel movement, heart beat, …
    - ITV concept is not widely used and not considered compulsory in report 71
  - Report 78: Proton-Beam Therapy
    - Incorporates proton specific aspects such as particle range
- Based on individual and/or population based motion data

Planning target volume concept

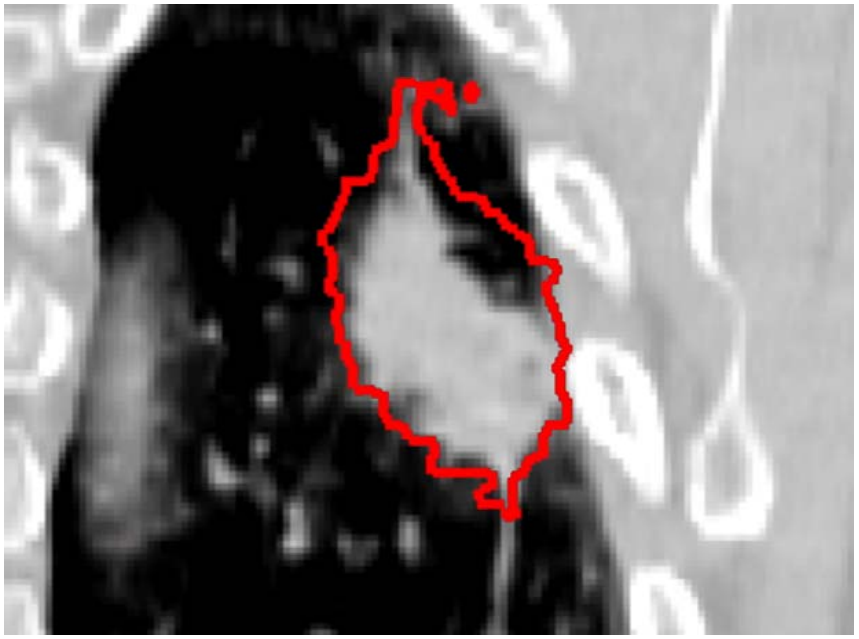


ITV - lung

CTV per motion phase



Internal Target Volume

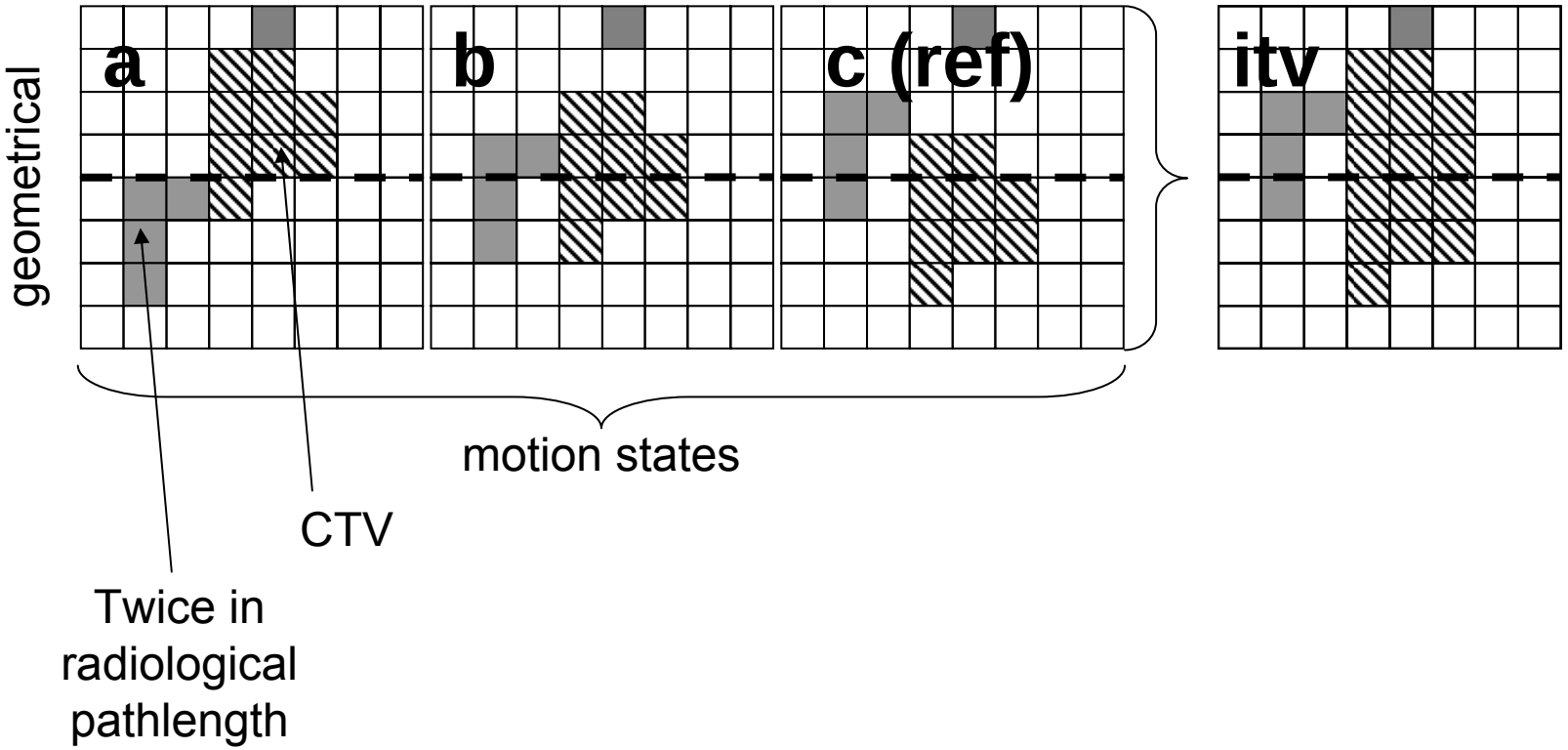


[data courtesy E. Rietzel, MGH]

Margin design for ion beams

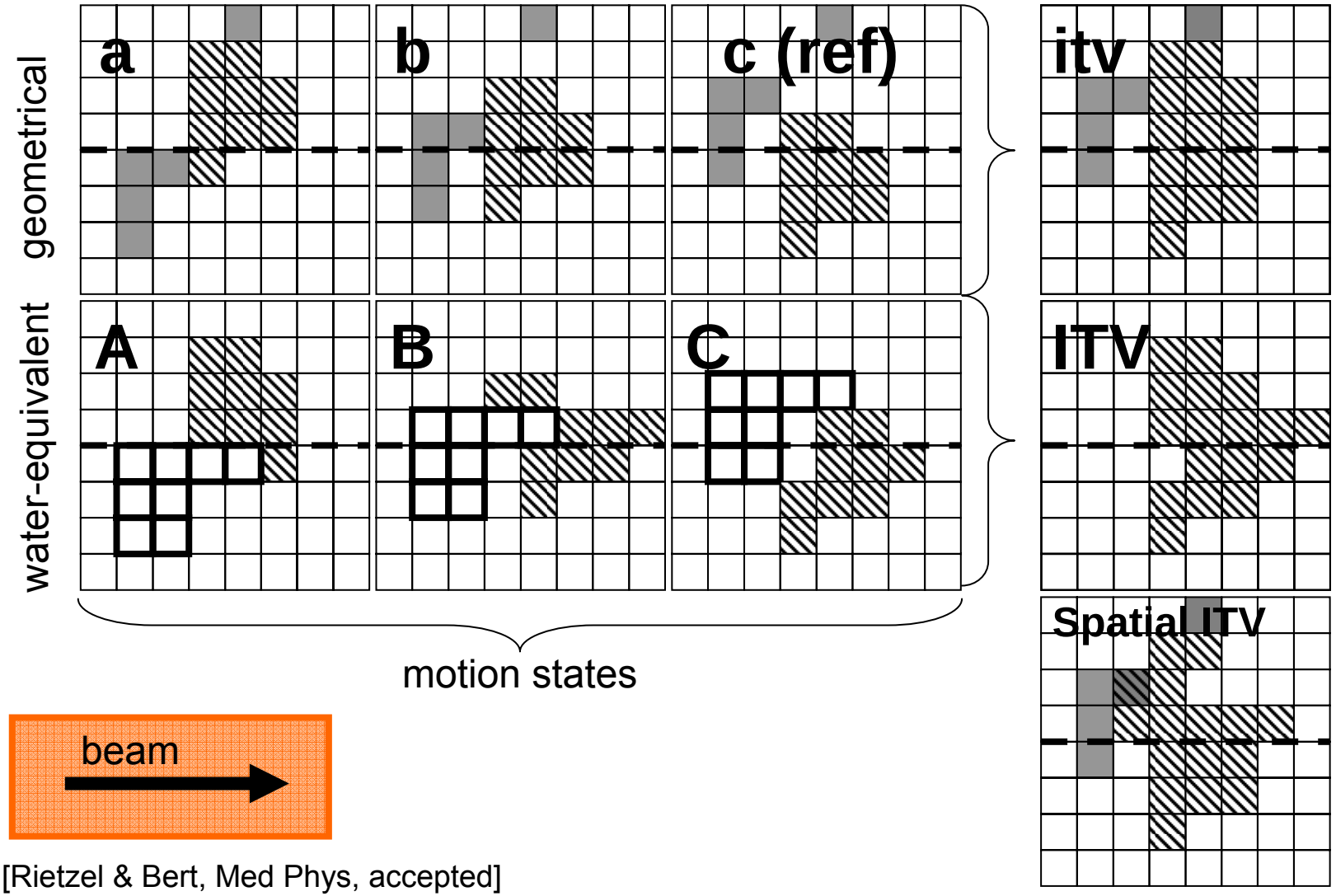
- ITV/PTV need to be port specific
- Not only geometrical extent of target motion has to be considered but also range
  - 4DCT data required to determine patient-specific ITV
  - ITV shaping in water-equivalent space, i.e. margin description in water-equivalence rather than geometrical

Margin design – ion beams



[Rietzel & Bert, Med Phys, accepted]

Margin design – ion beams



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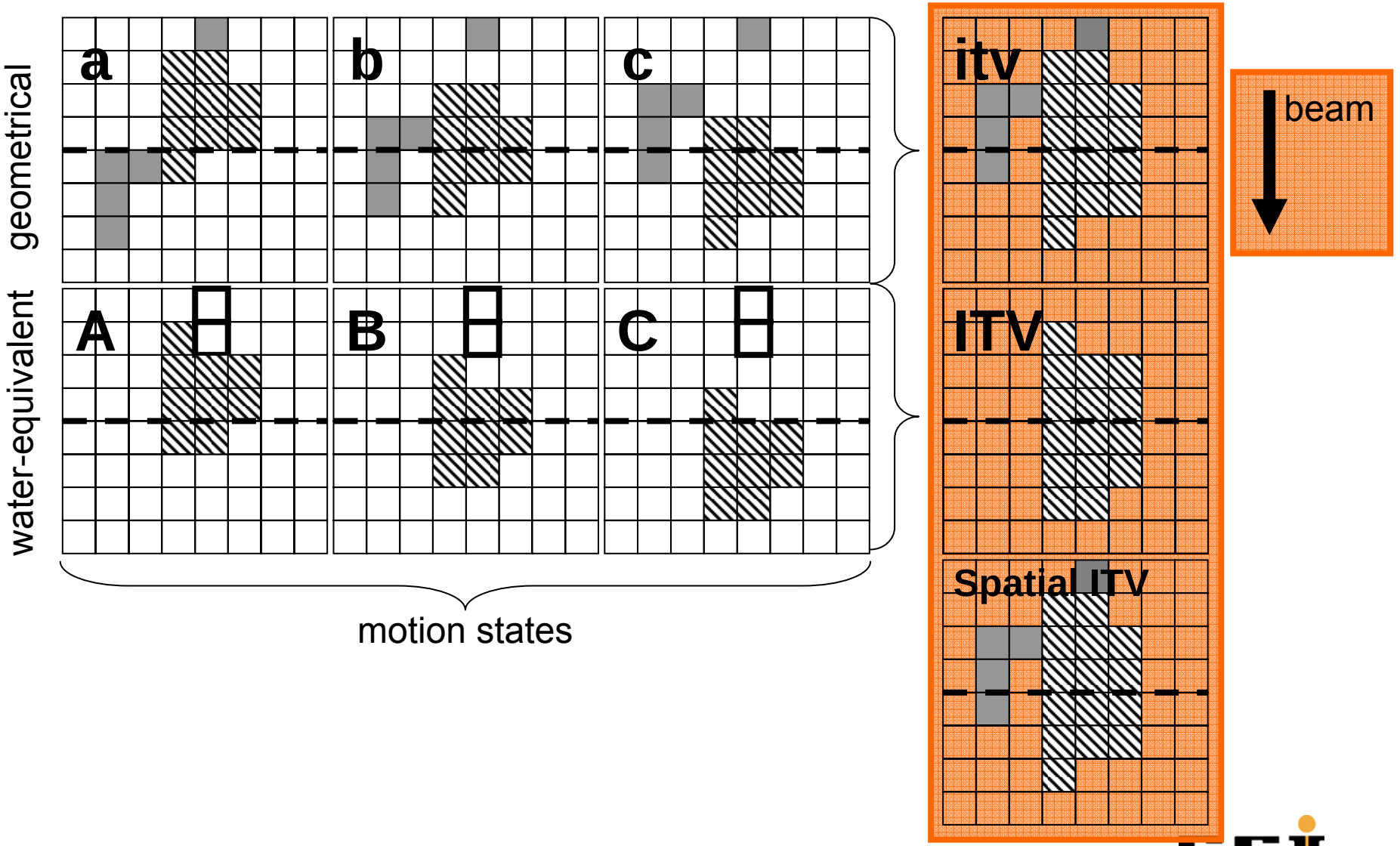
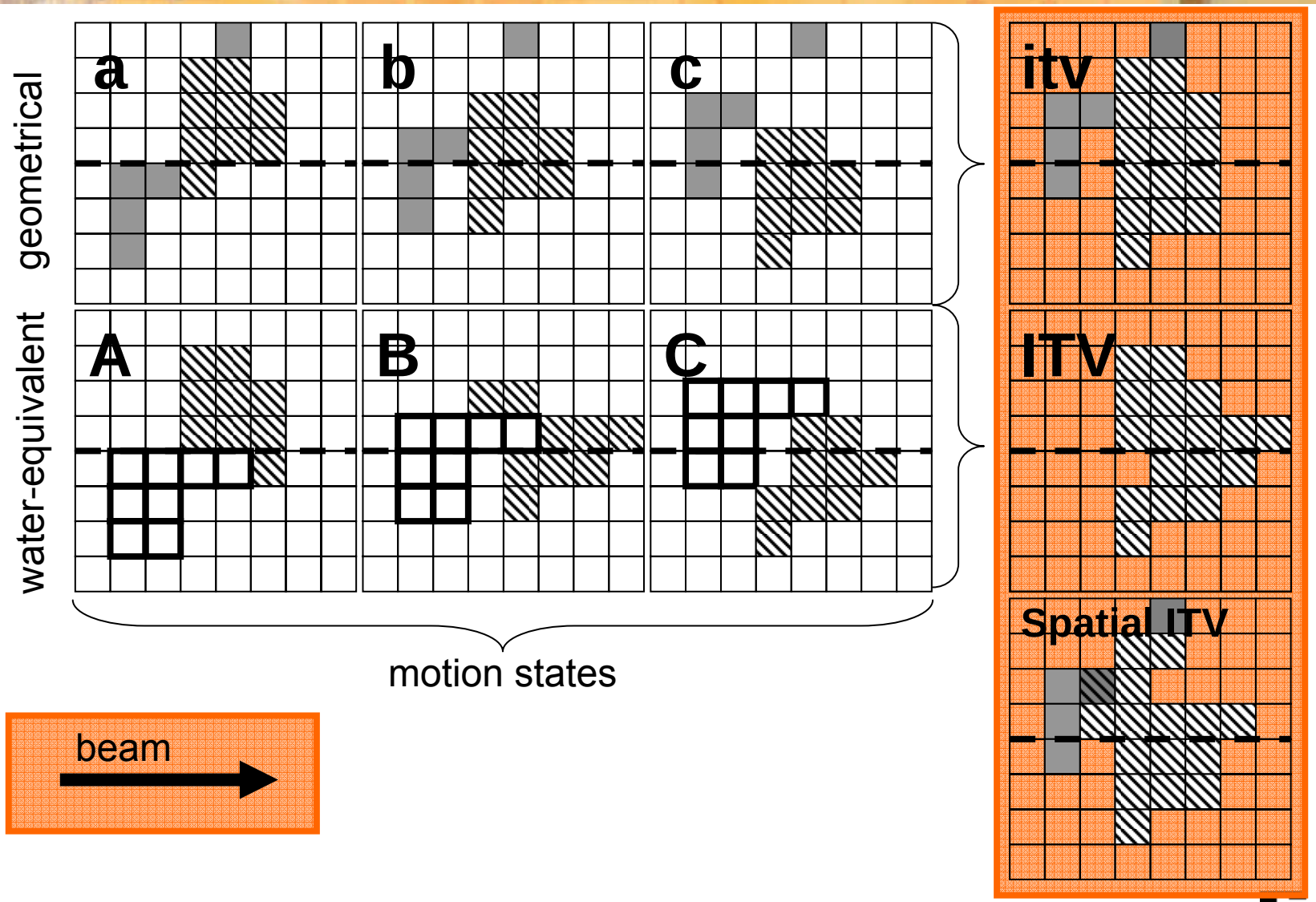
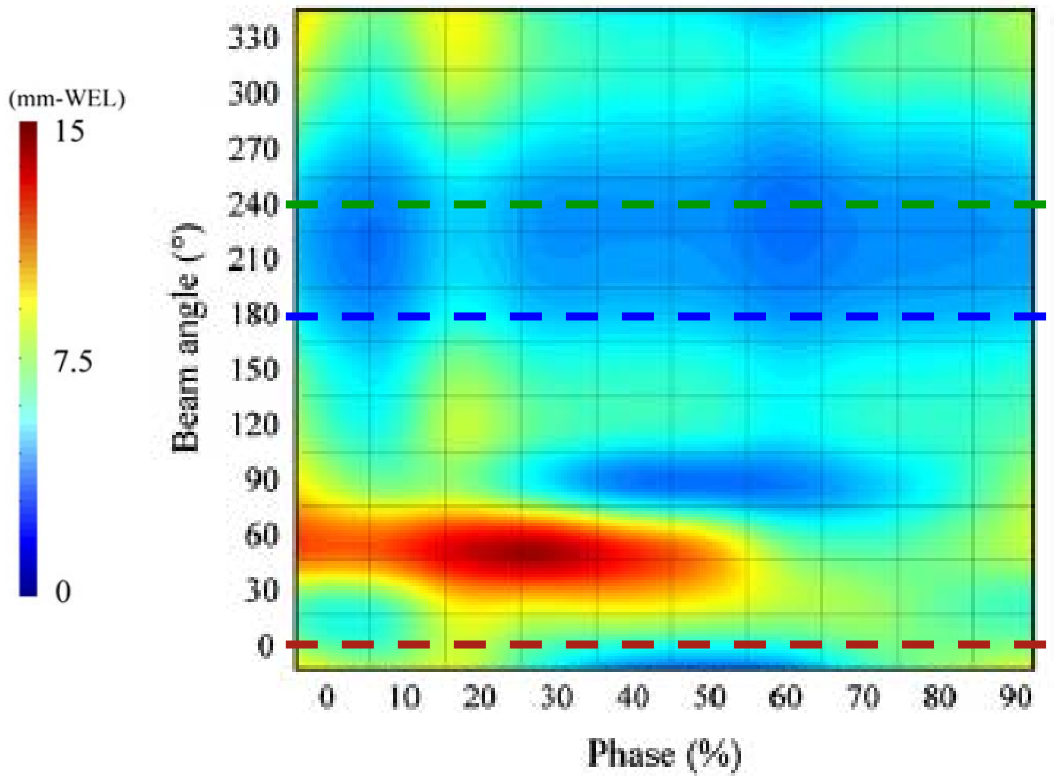
Margin design – ion beams

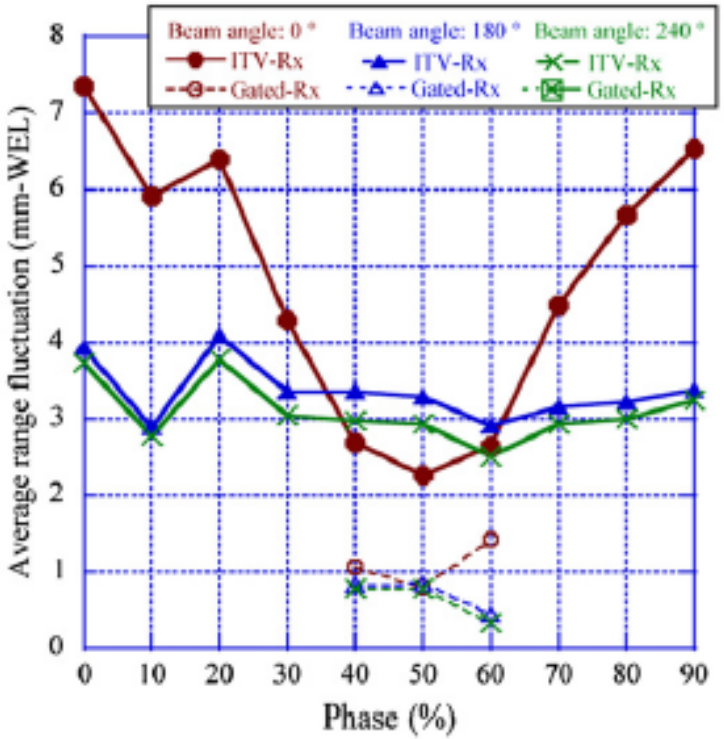


Margin design – ion beams



Lung cancer patient – average range fluctuation

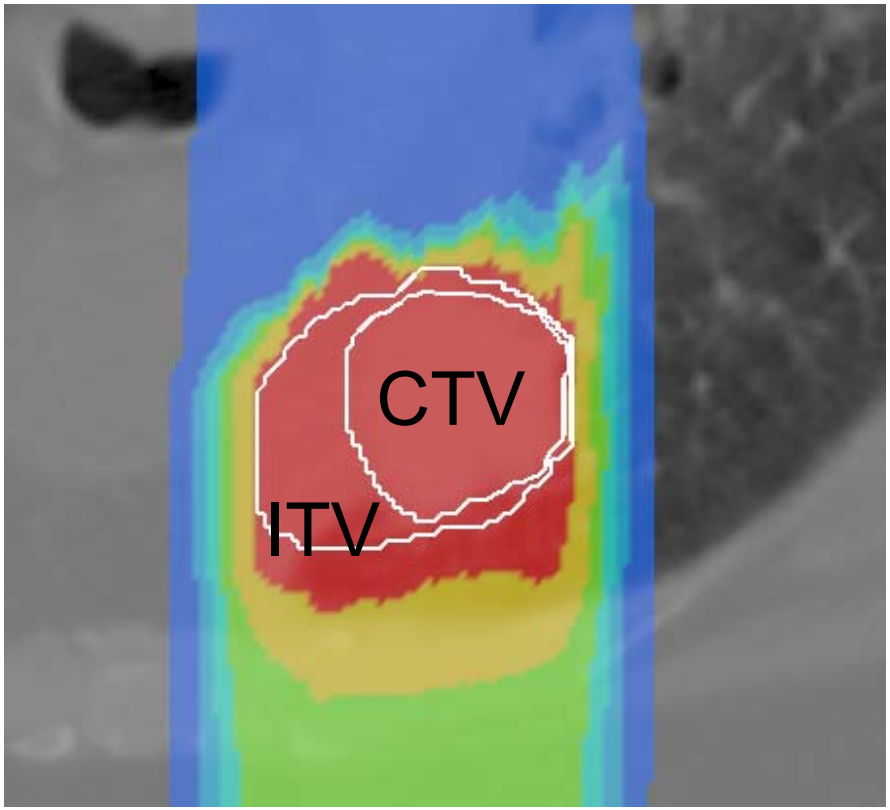




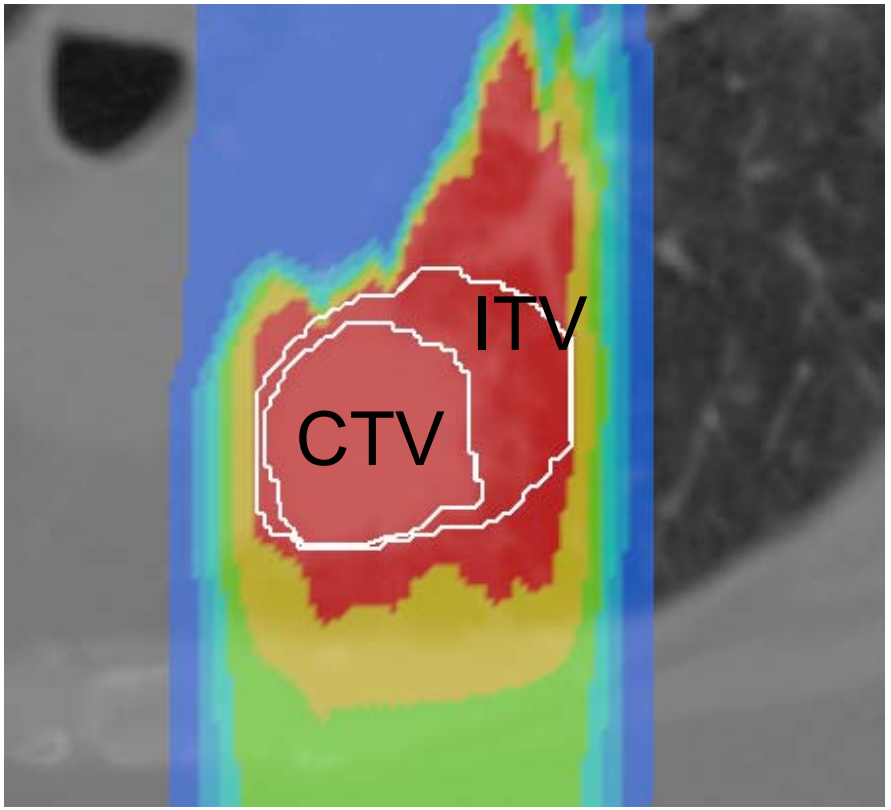
[according to Moori et al., IJROBP 70(1) 2008]

ITV design including range - lung

exhale



inhale



Outline

- Target motion
  - Types, quantification
  - Internal Target Volume concept
  - Implications of particle range
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  - Broad beam
  - Beam scanning
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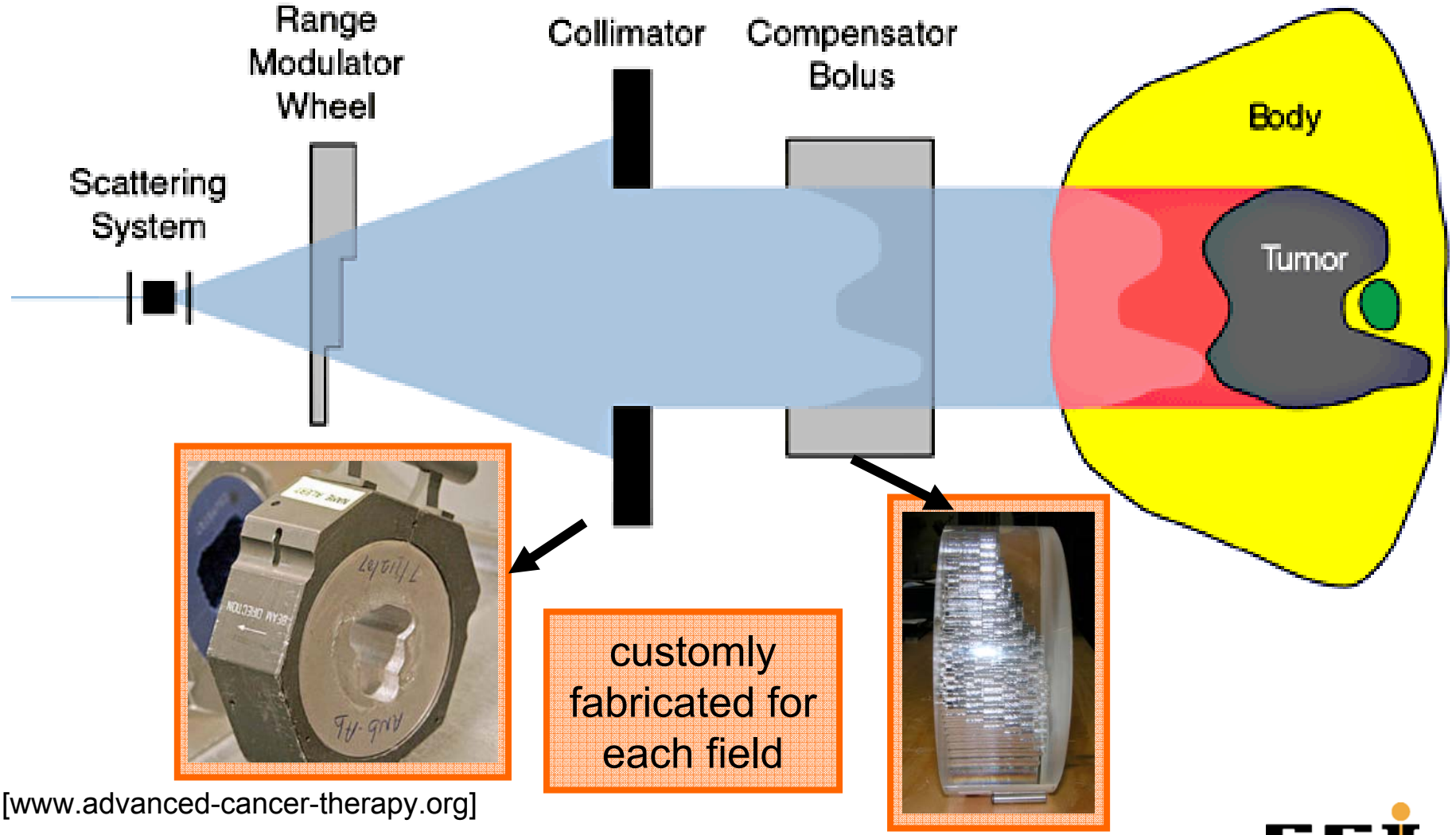
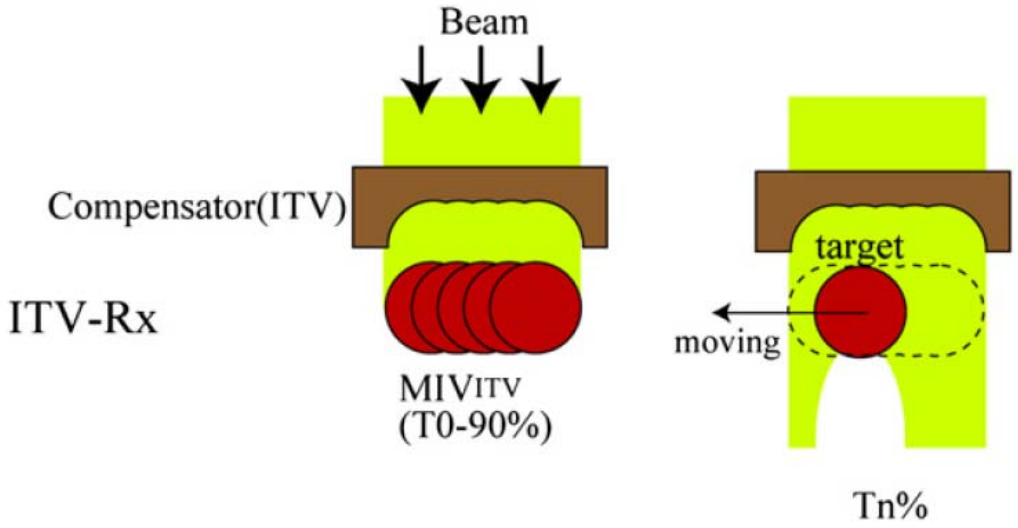
Broad beam delivery

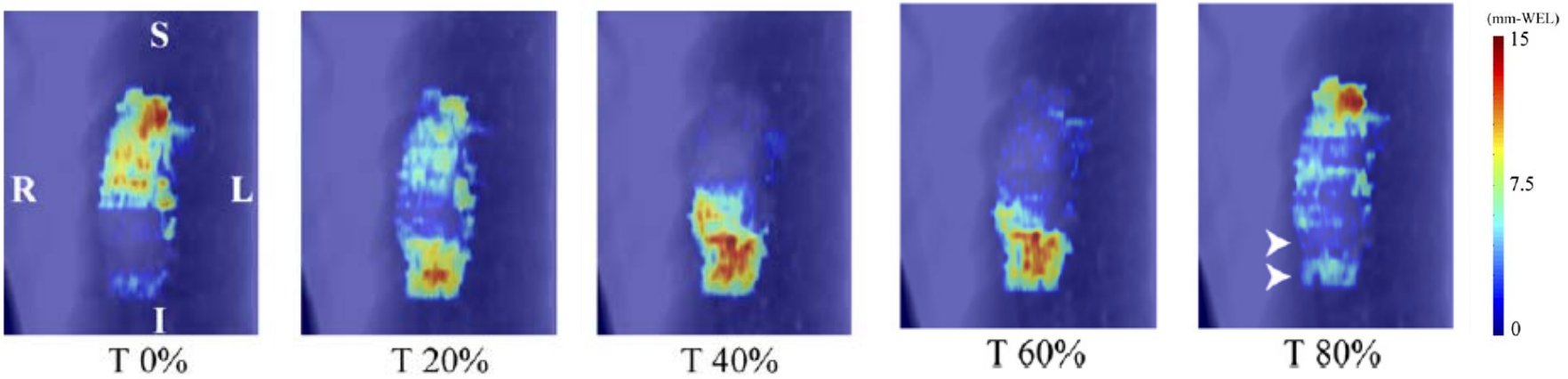


[www.advanced-cancer-therapy.org]

ITV via compensator design

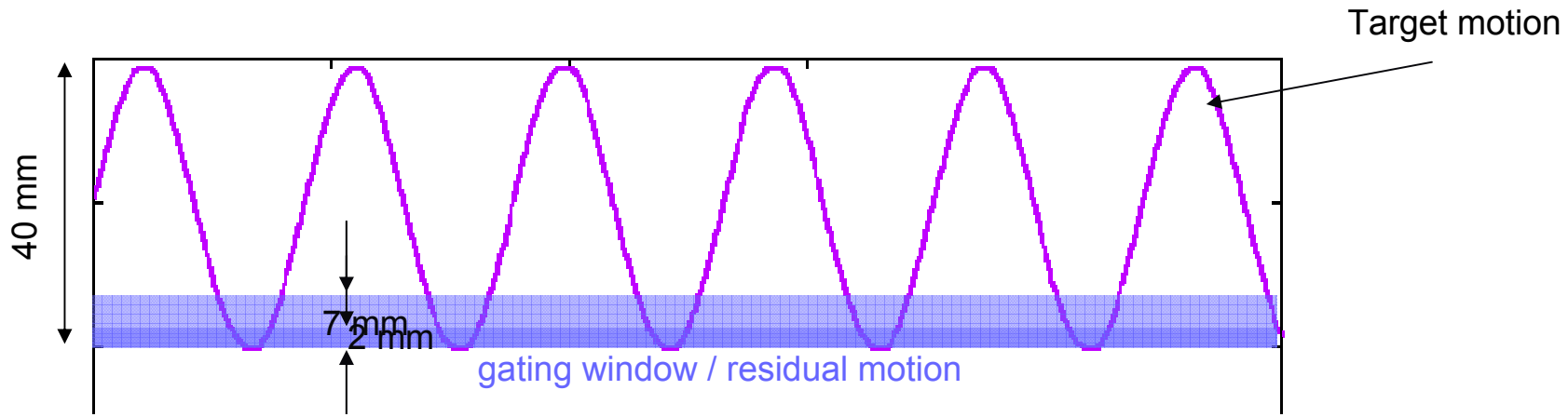


Range fluctuation in beam‘s eye view

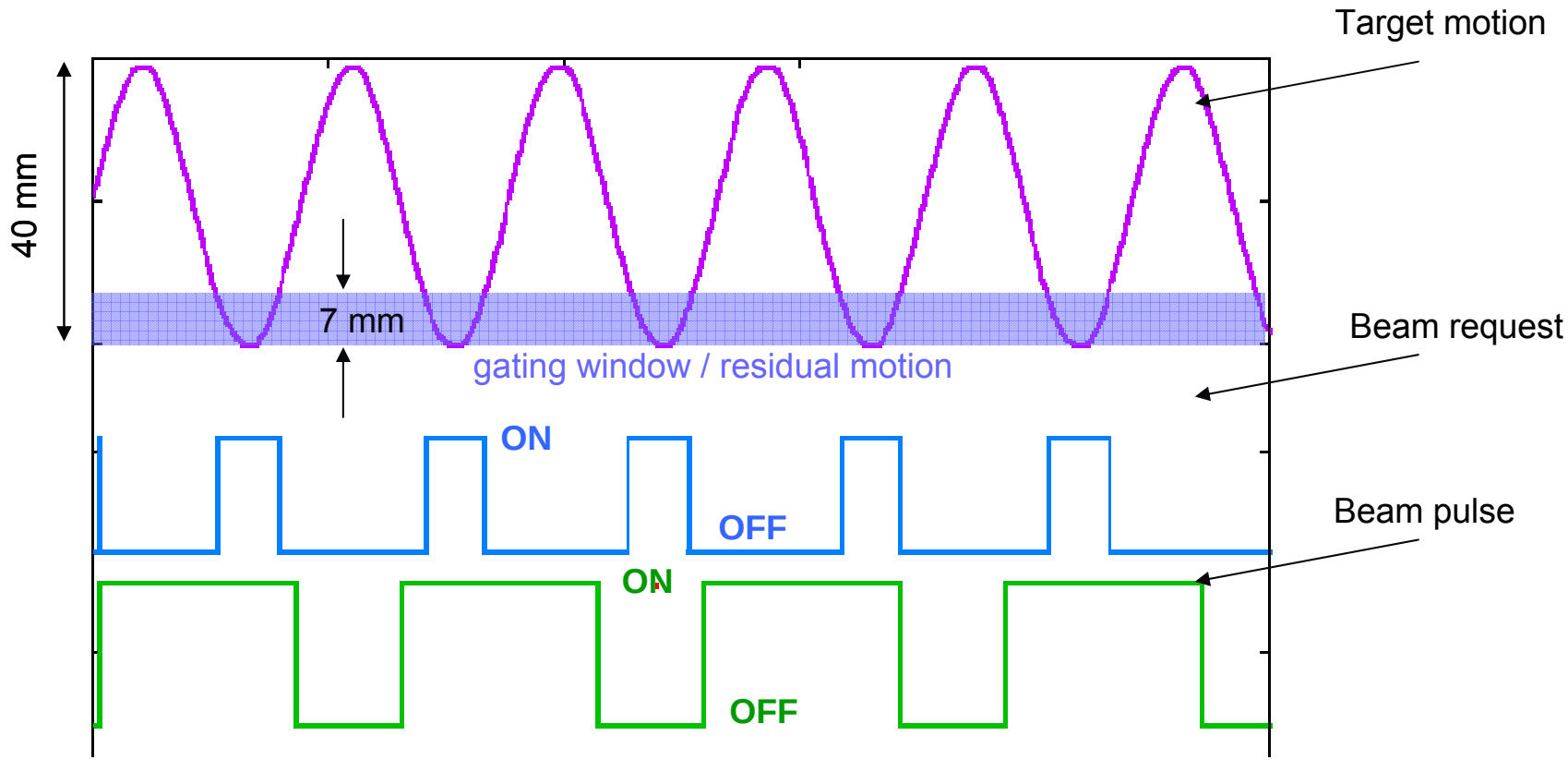


[Moori et al., IJROBP, 70(1) 2008]

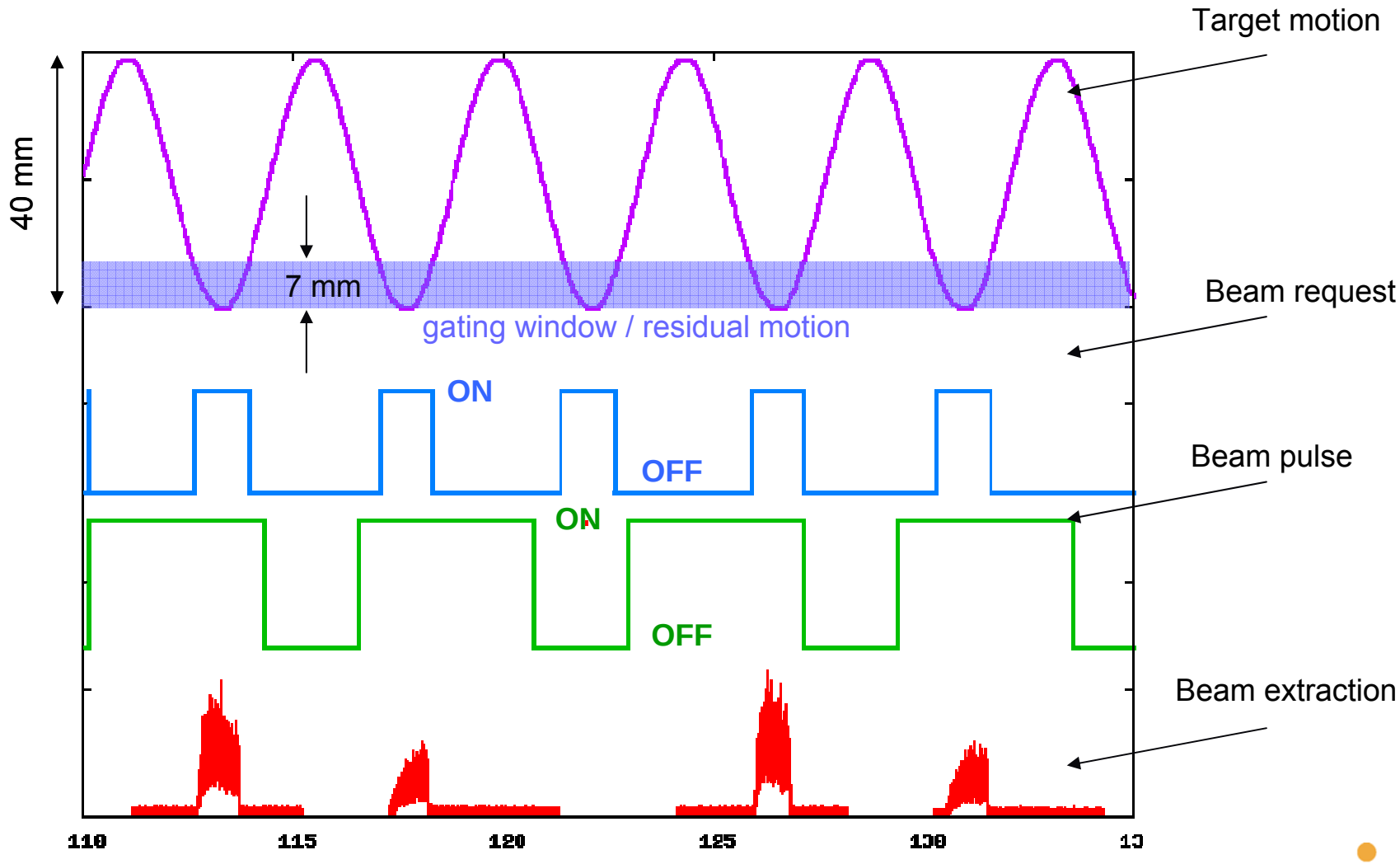
Motion mitigation - Gating



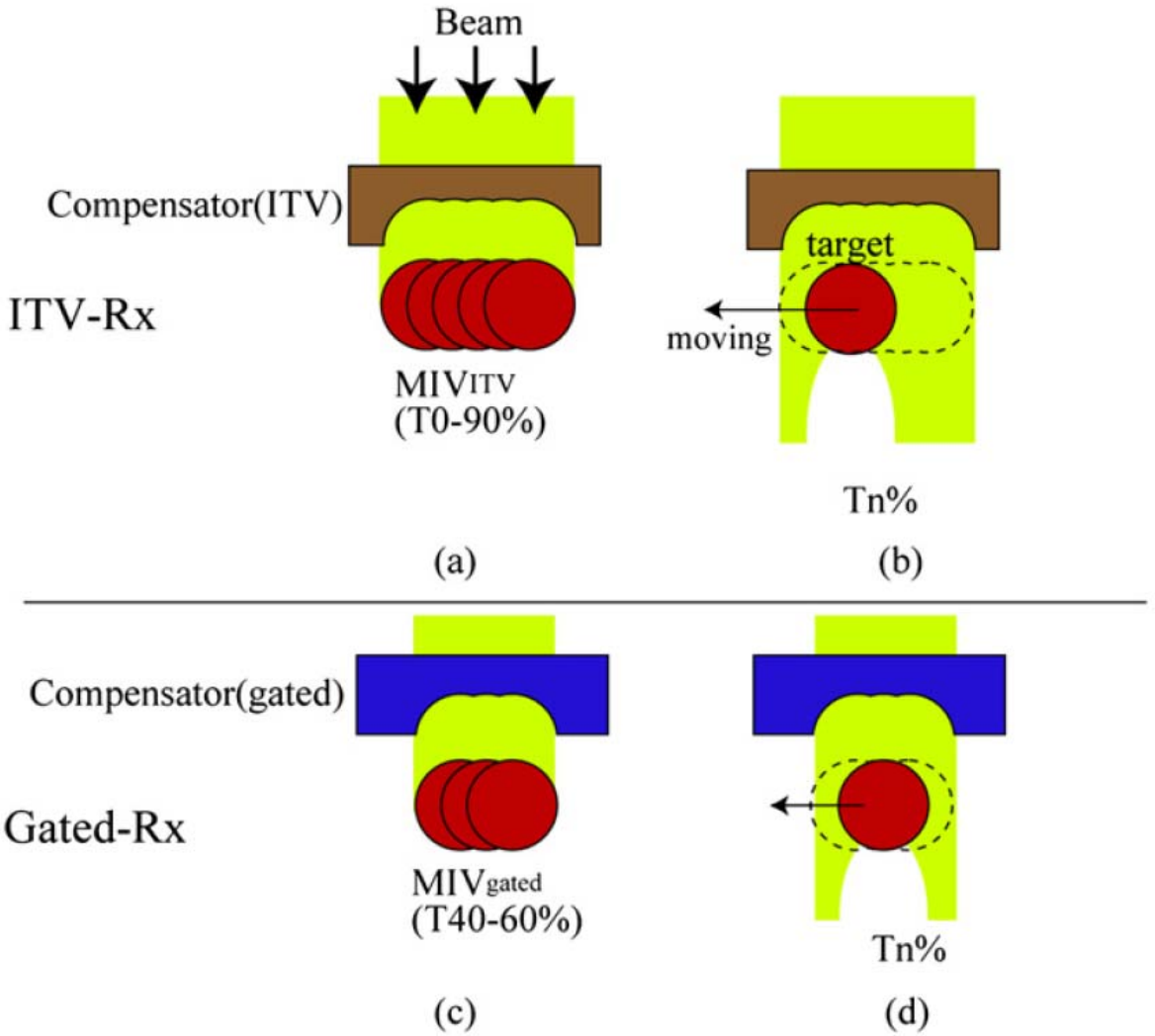
Motion mitigation - Gating



Motion mitigation - Gating

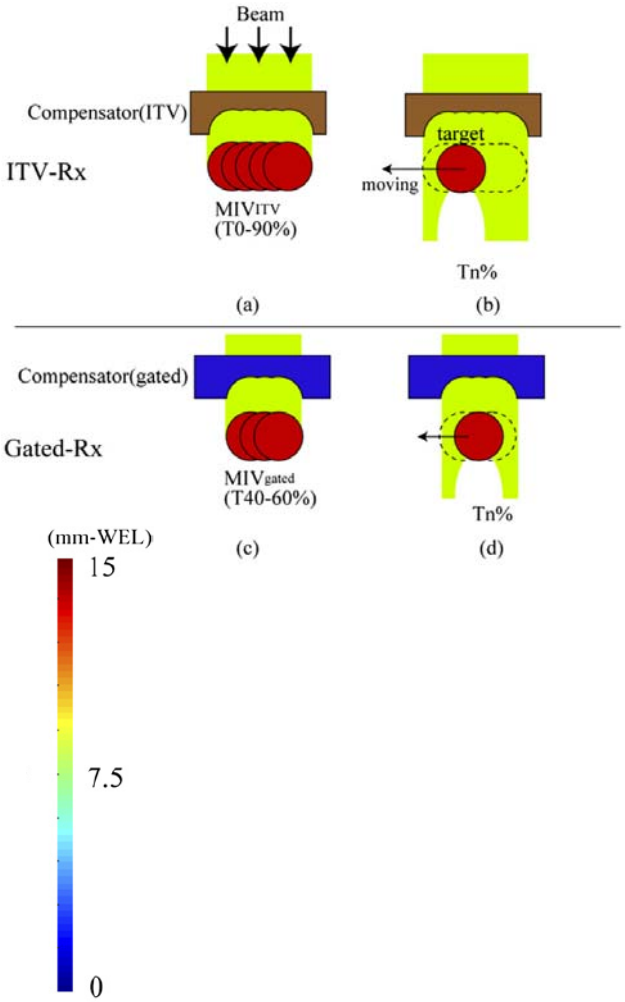


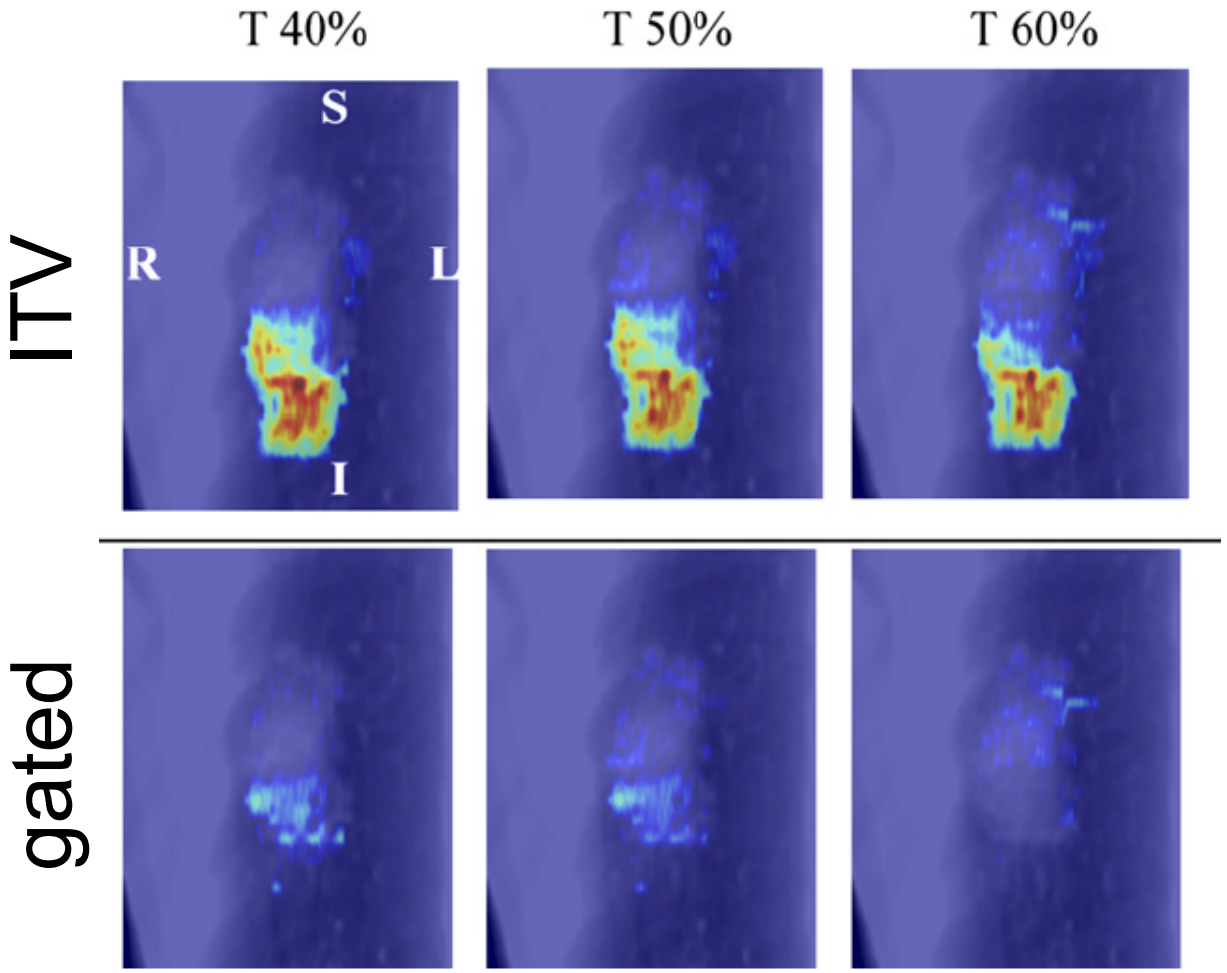
ITV via compensator design



[Moori et al., IJROBP, 70(1) 2008]

ITV / range change - gating



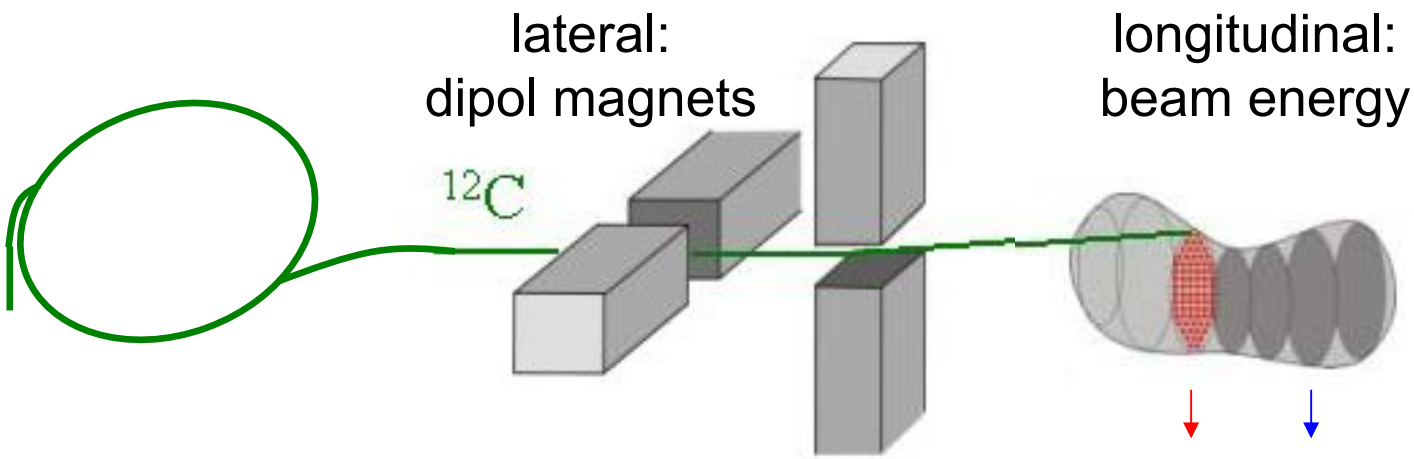


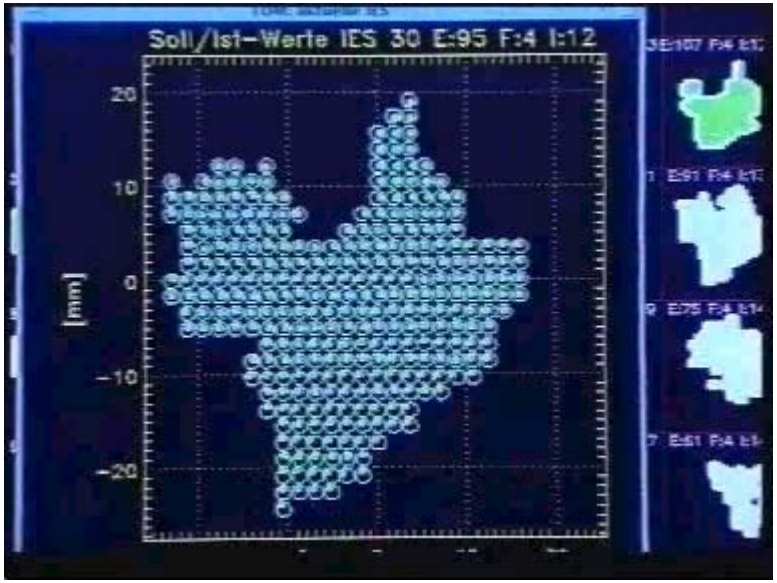
[Moori et al., IJROBP, 70(1) 2008]

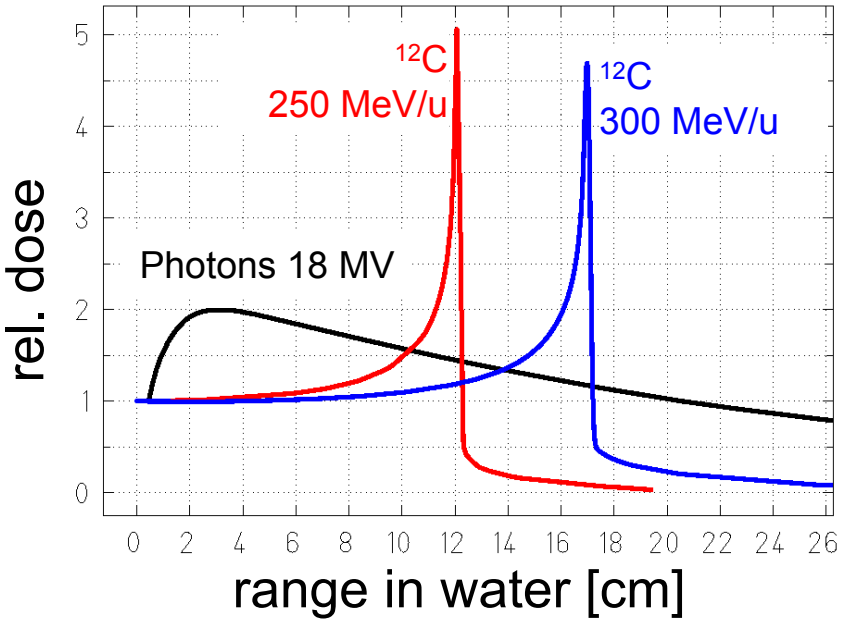
Broad beam delivery - moving target

- Little influence of target motion
- ICRU ITV/PTV concept applicable if ion beam‘s range is considered
- Can be combined with gating to decrease target motion amplitude
  - Smaller margins
  - Longer treatment time
- Used as therapy option for several years
- Excellent clinical results – see clinical talks of educational sessions

Beam scanning

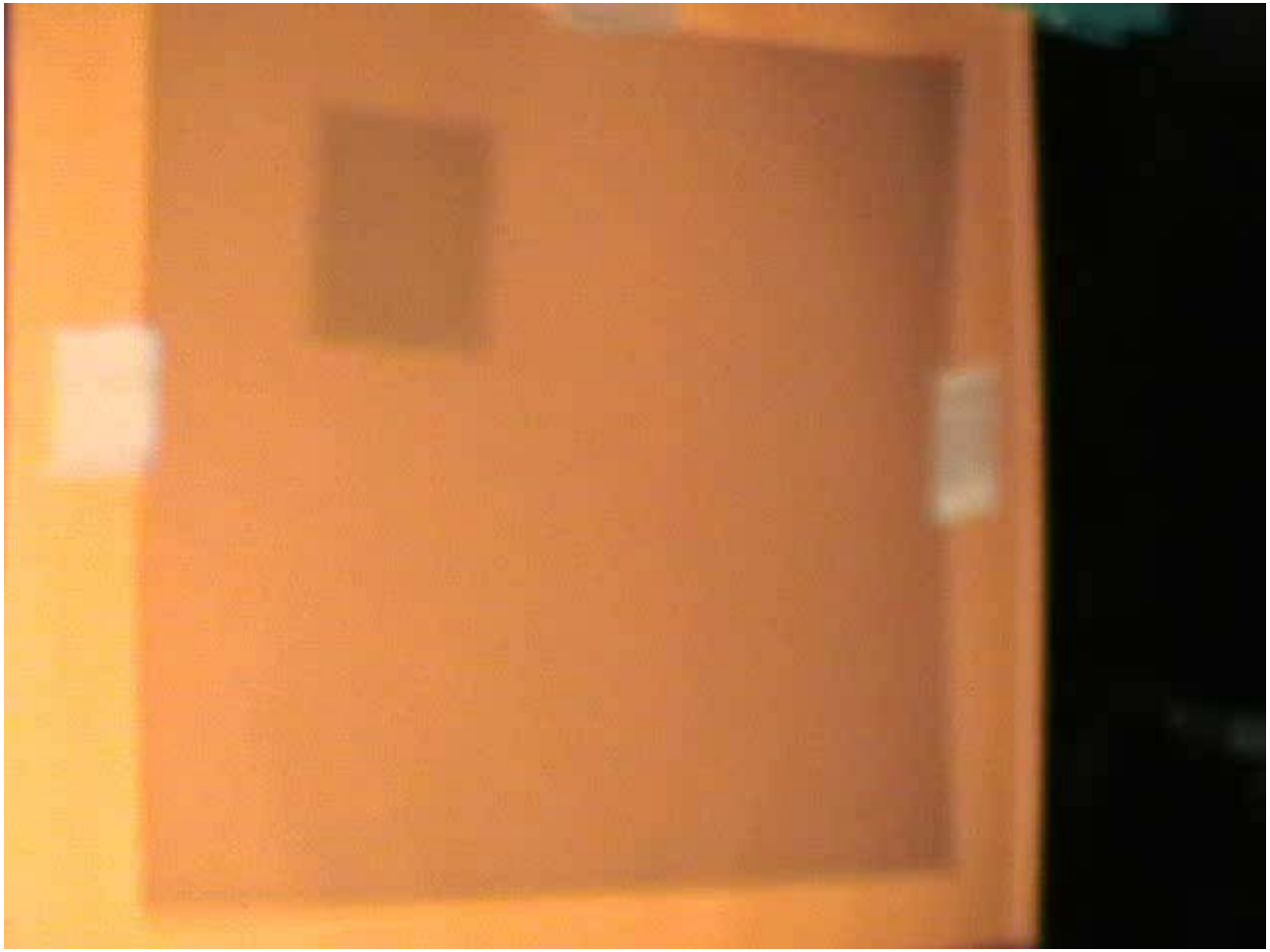






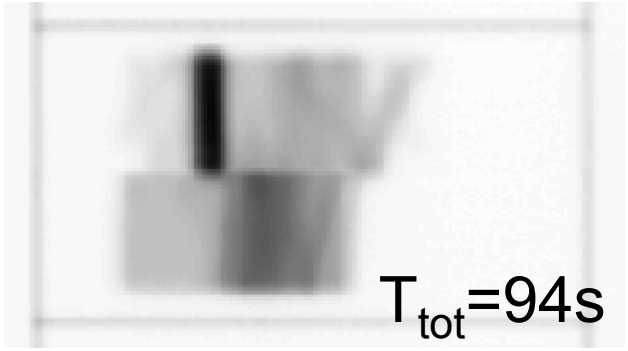
Rasterscanning – GaFChromic film

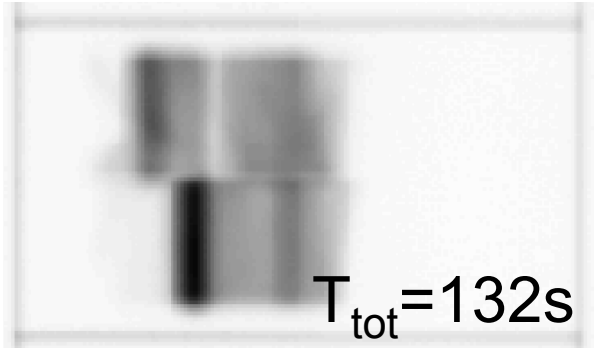
Rasterscanning – target motion - Interplay

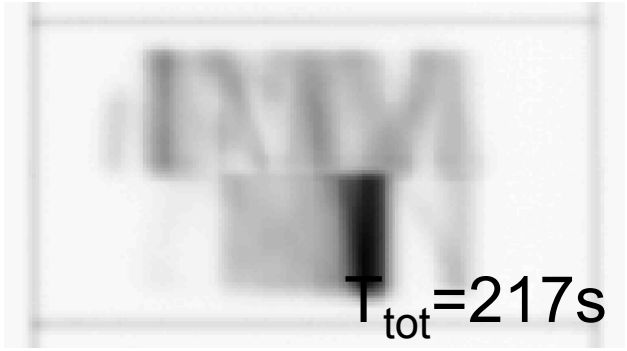


Interplay - parameters

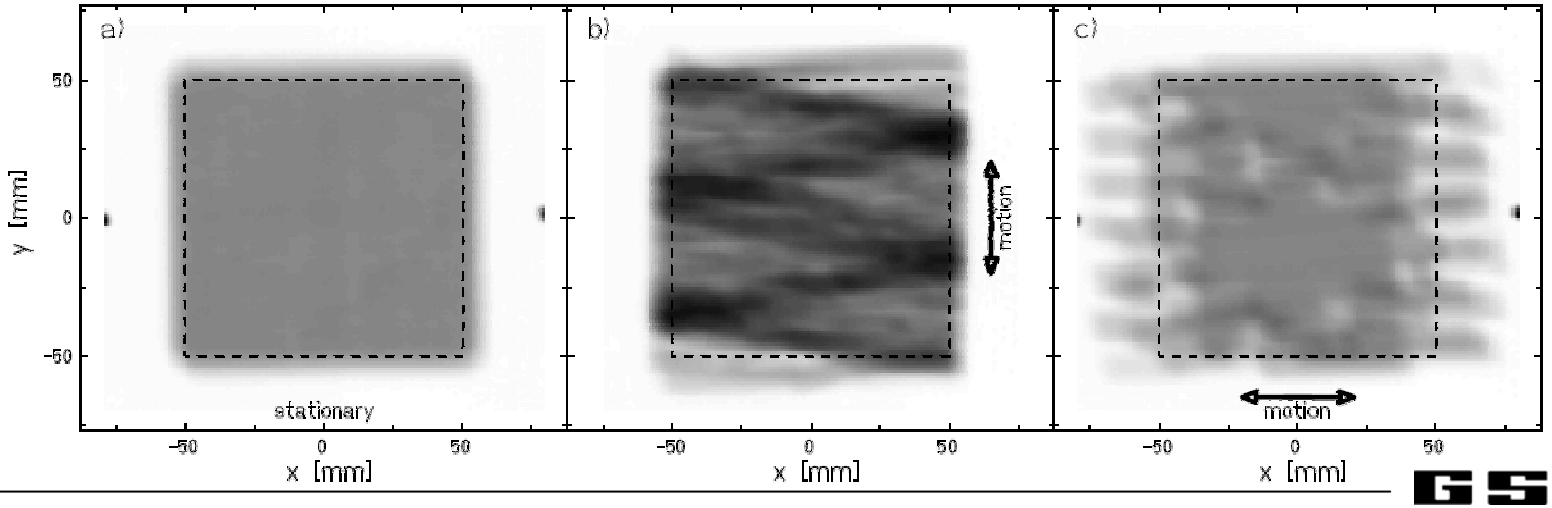
Influence of scan speed





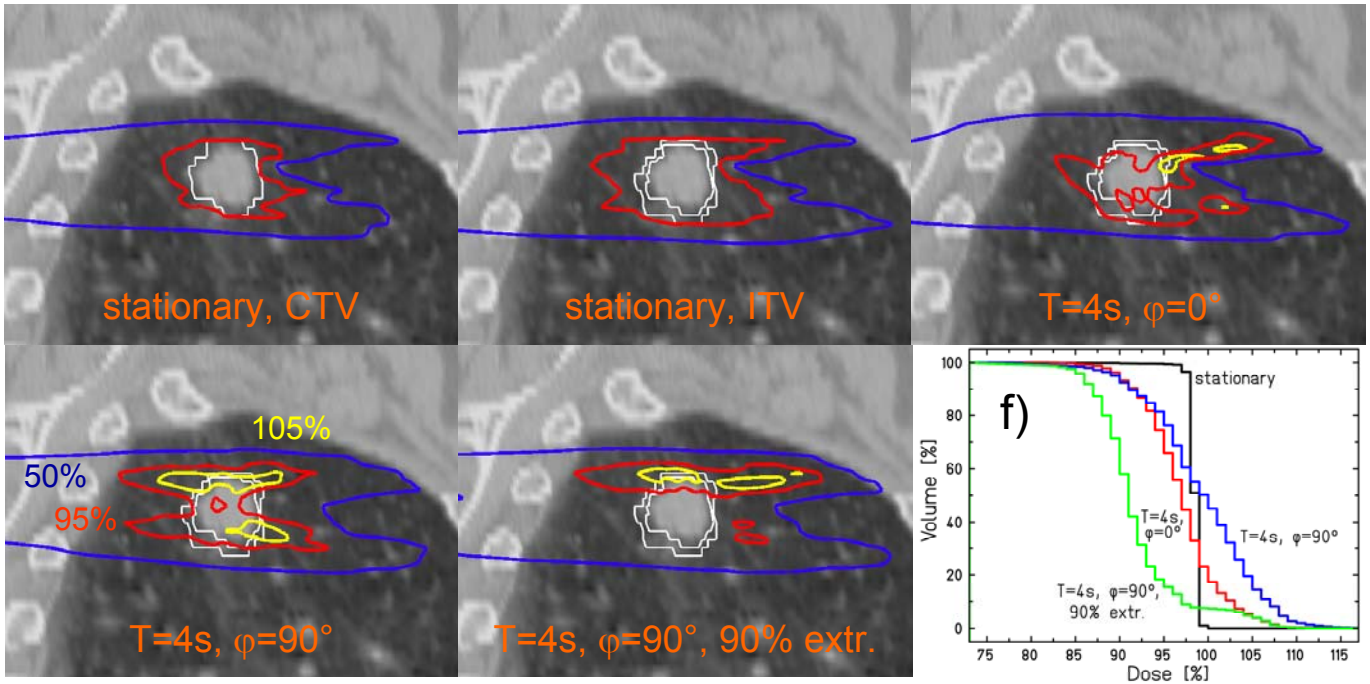


Influence of motion direction



Interplay - simulation data

4D treatment planning study:

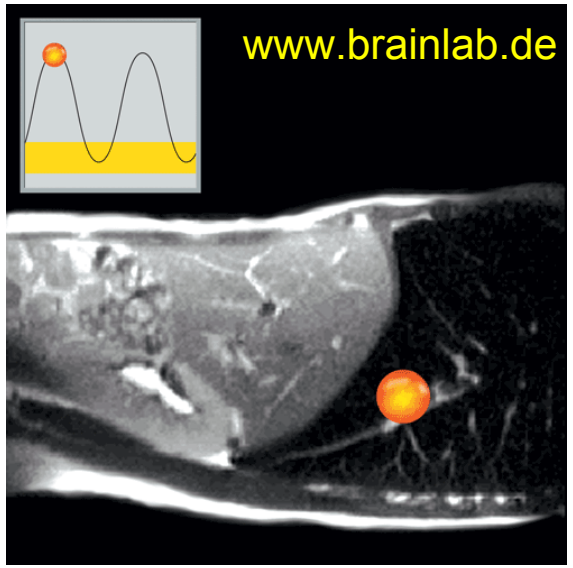


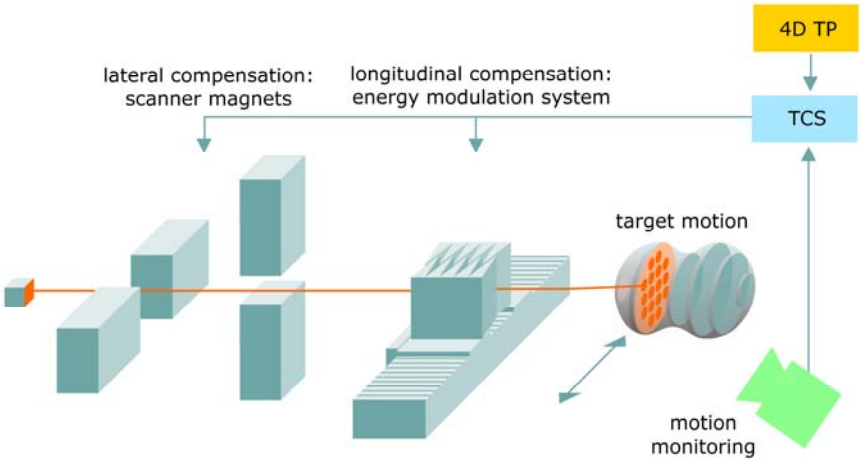
→ IM / ITV / PTV not sufficient

[Bert et al, Phys Med Biol, 2008]

4D treatment delivery

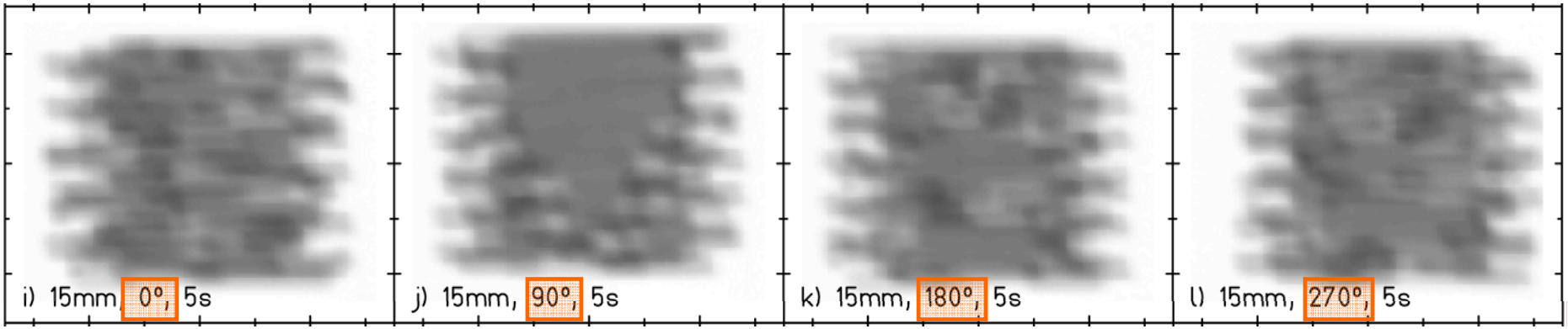
- Rescanning
  - N irradiations with 1/N dose
  - large margins
- Gating
  - only part of motion period
  - residual interplay requires mitigation
- Tracking
  - compensation of target motion
  - lateral: scanner
  - longitudinal: wedge, active



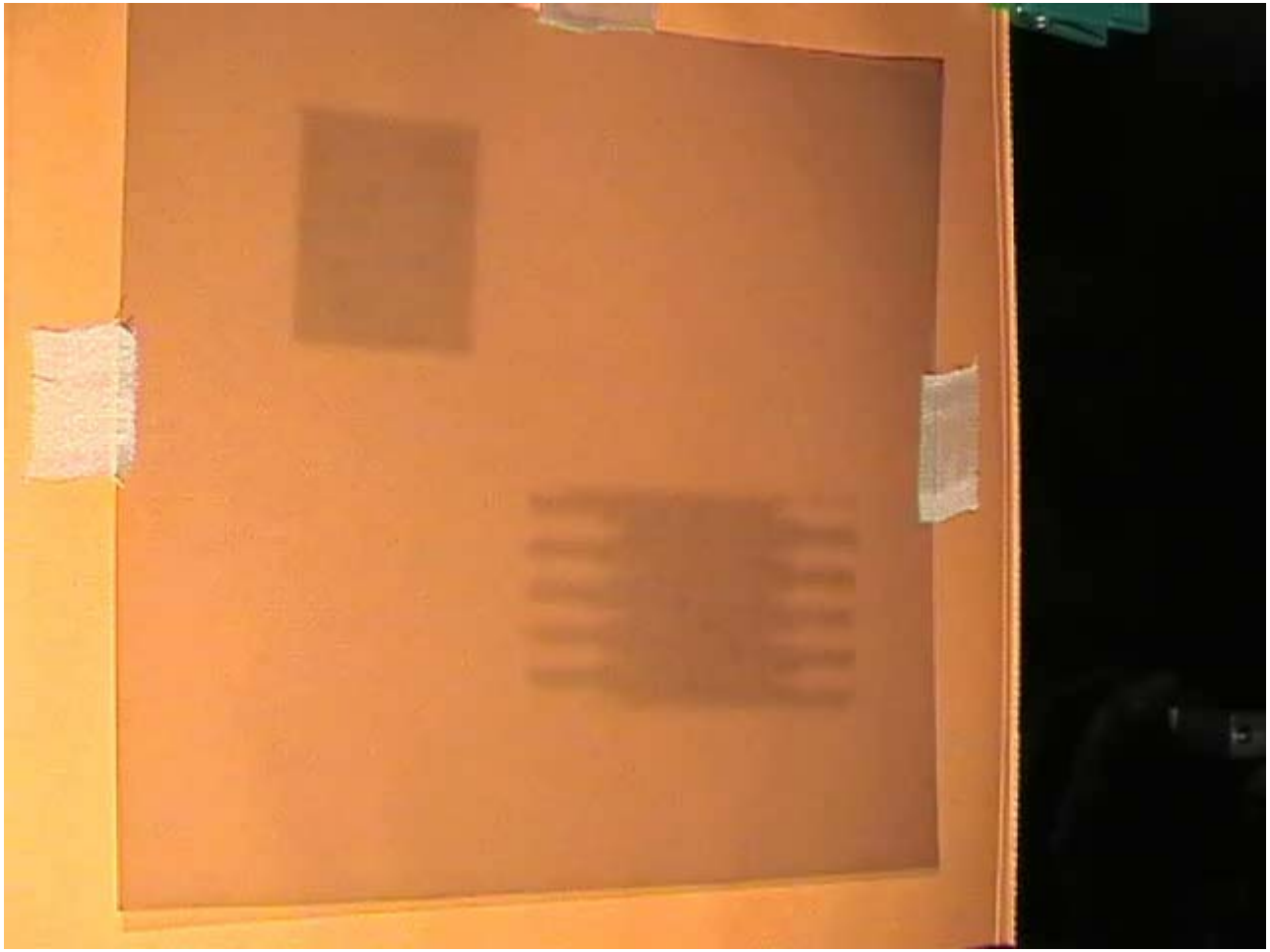


Principles of rescanning

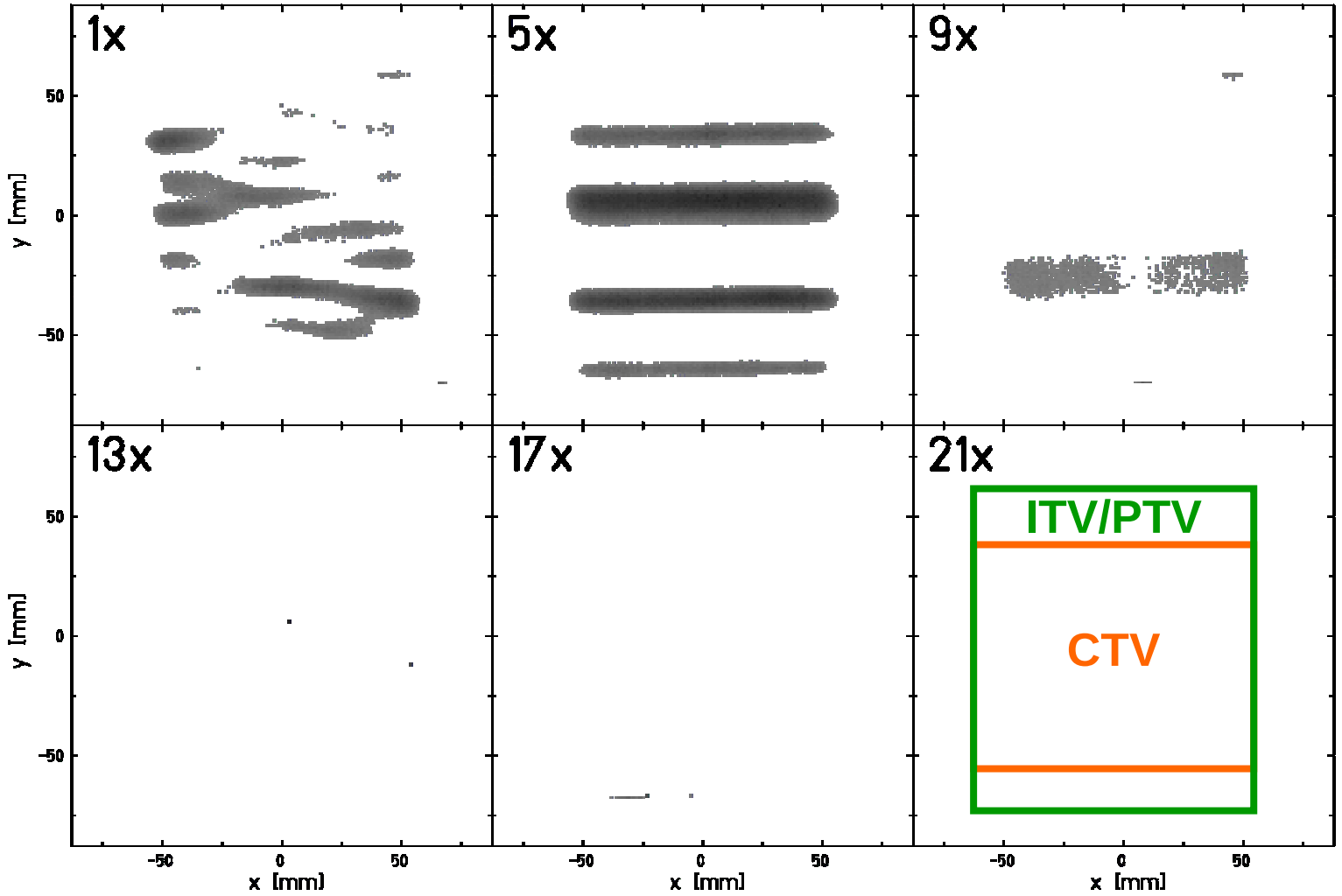
- Interplay / misdosage pattern very sensitive to motion / irradiation parameter changes
- Multiple irradiations per fraction
  - Averaging of interplay patterns
  - Homogeneous target coverage if no. rescans high enough



Rescanning

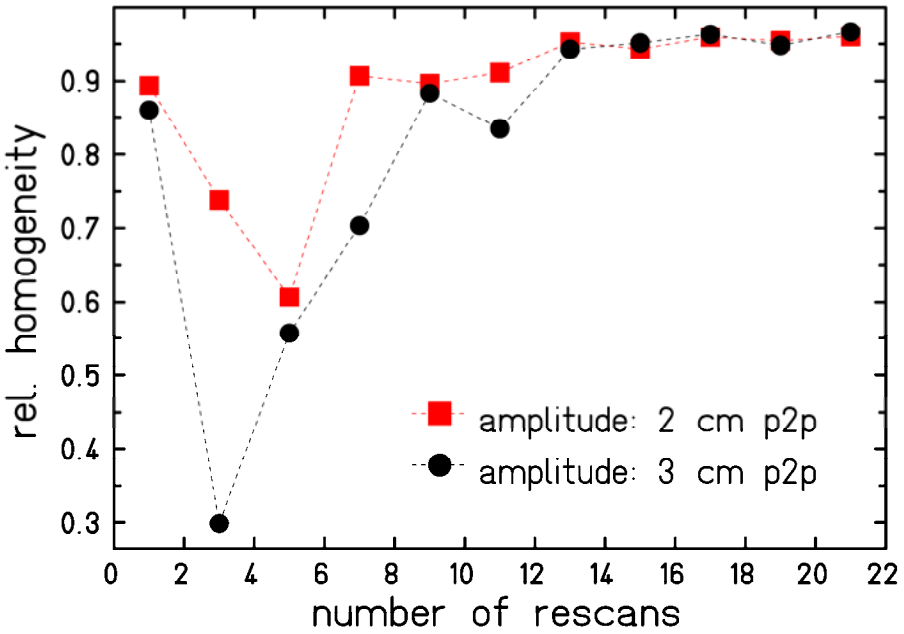


Rescanning – experimental data

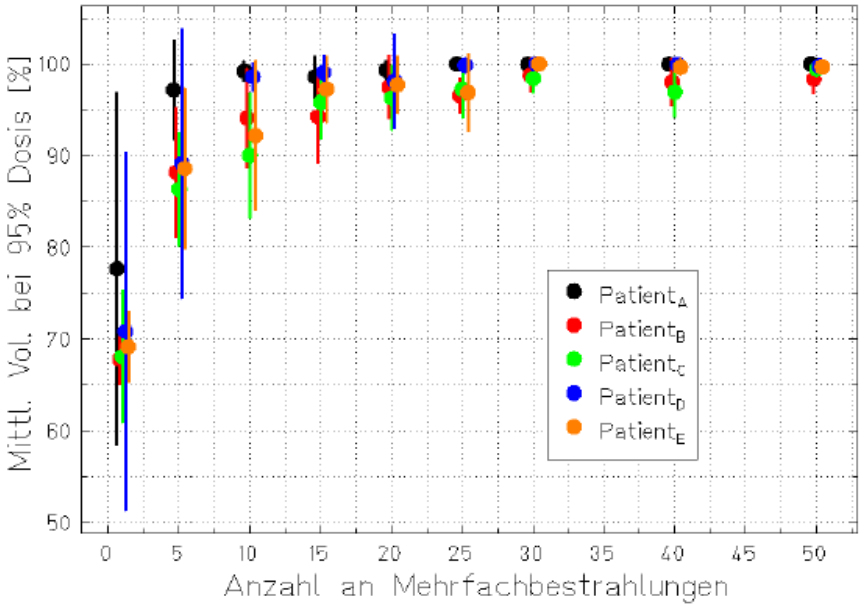


Rescanning - # rescans

Experiment
(preliminary)



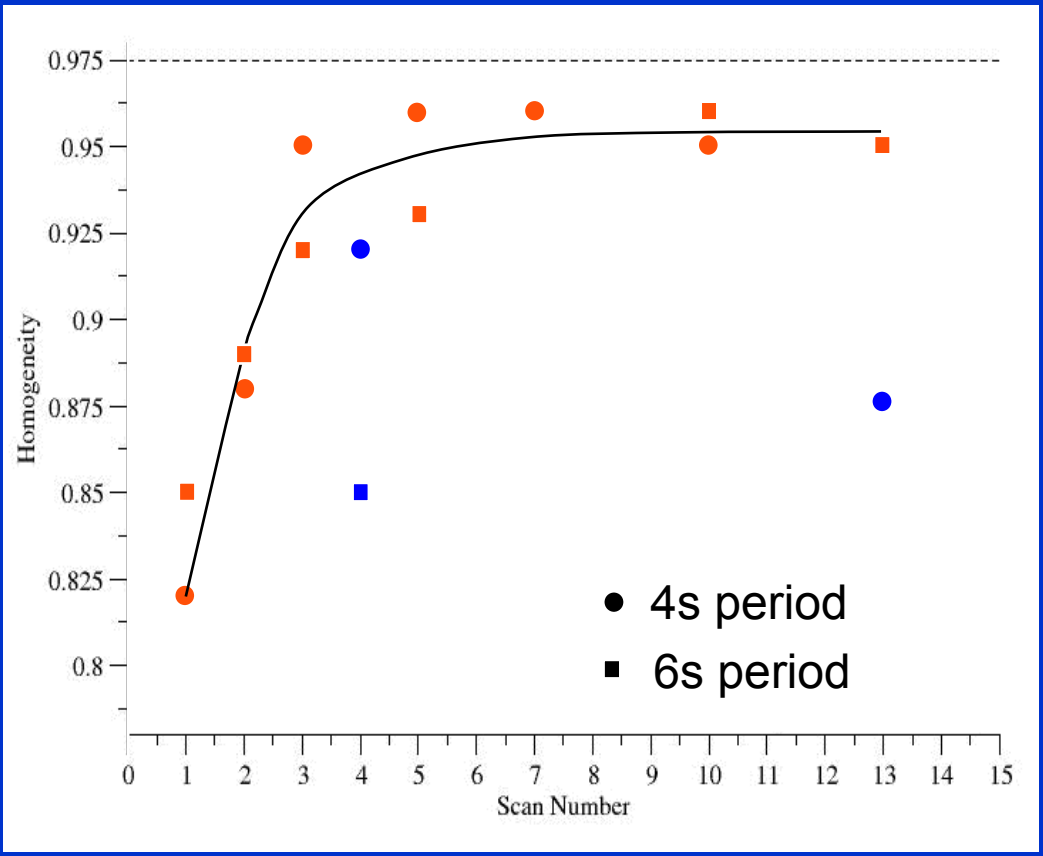
Simulation



Proton therapy at PSI – Organ motion management

Dose homogeneity and re-scanning factor

Analysis of Cos^4 motion with 1cm peak-to-peak amplitude



- Cylindrical target volume
- Re-scanned different times to same total dose
- Scan times calculated for realistic beam intensities and dead times between spots
- Analysis carried out for different periods of motion

Not always improving homogeneity with number of re-scans!

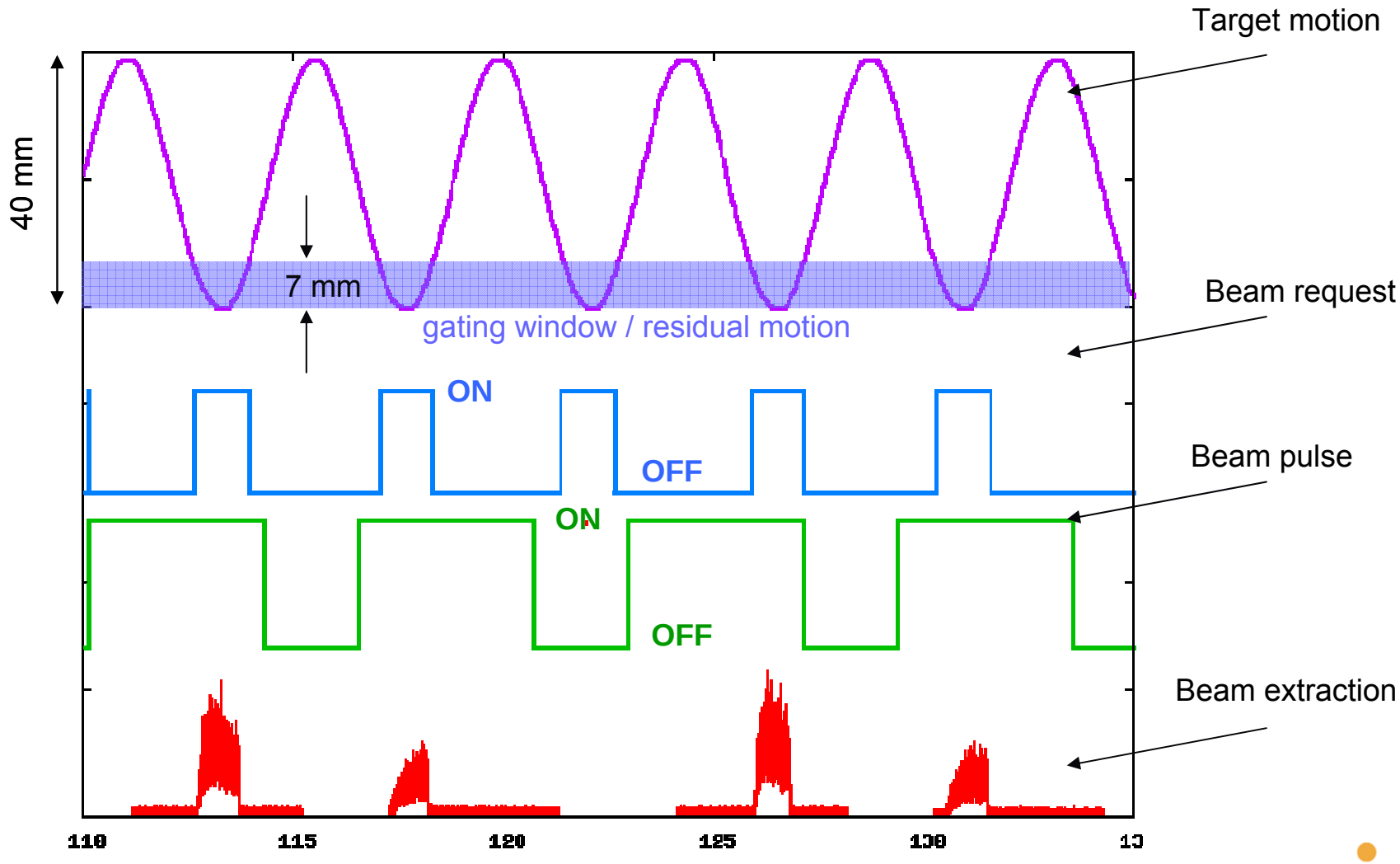
Marco Schwarz, Sylvan Zenklusen ATREP and PSI

Rescanning - Summary

- Multiple irradiations per fraction
- Minimal solution does not require motion monitoring
- Technical effort low

- IM/ITV/PTV covers full motion extent
  $\Rightarrow$ large normal tissue dose
- Works on statistical average; outliers, especially for regular motion parameters, possible

Gating


Target motion
40 mm
7 mm
gating window / residual motion
Beam request
ON
OFF
Beam pulse
ON
OFF
Beam extraction
110
115
120
125
130

Gating with a scanned beam

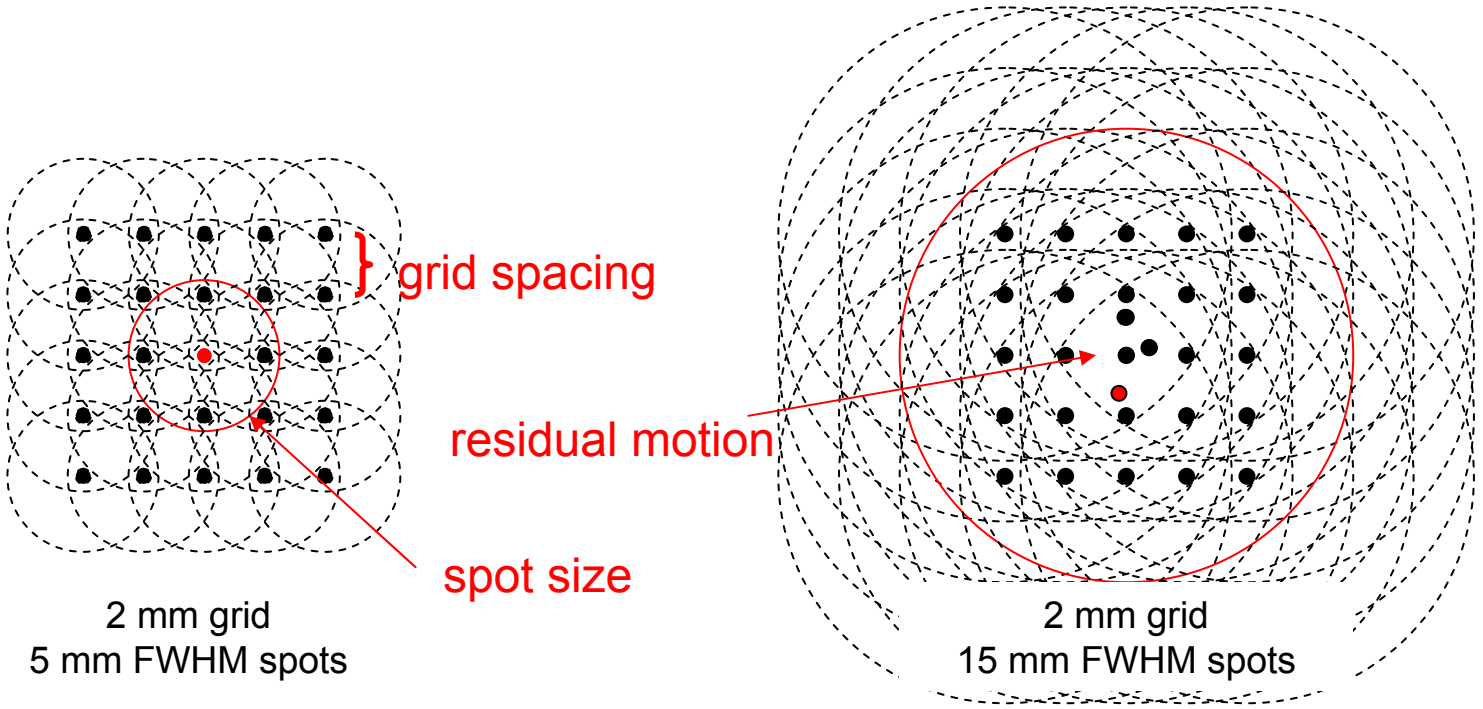
- Residual motion within gating window leads to residual interplay

- Mitigation of residual interplay:
  - Combination with rescanning
    details: Furukawa et al. *Med.Phys.* **34**(3), 2007
  - Increased overlap of adjacent beams
    details: Bert et al., *IJROBP* **73**(4), 2009

Beam overlap

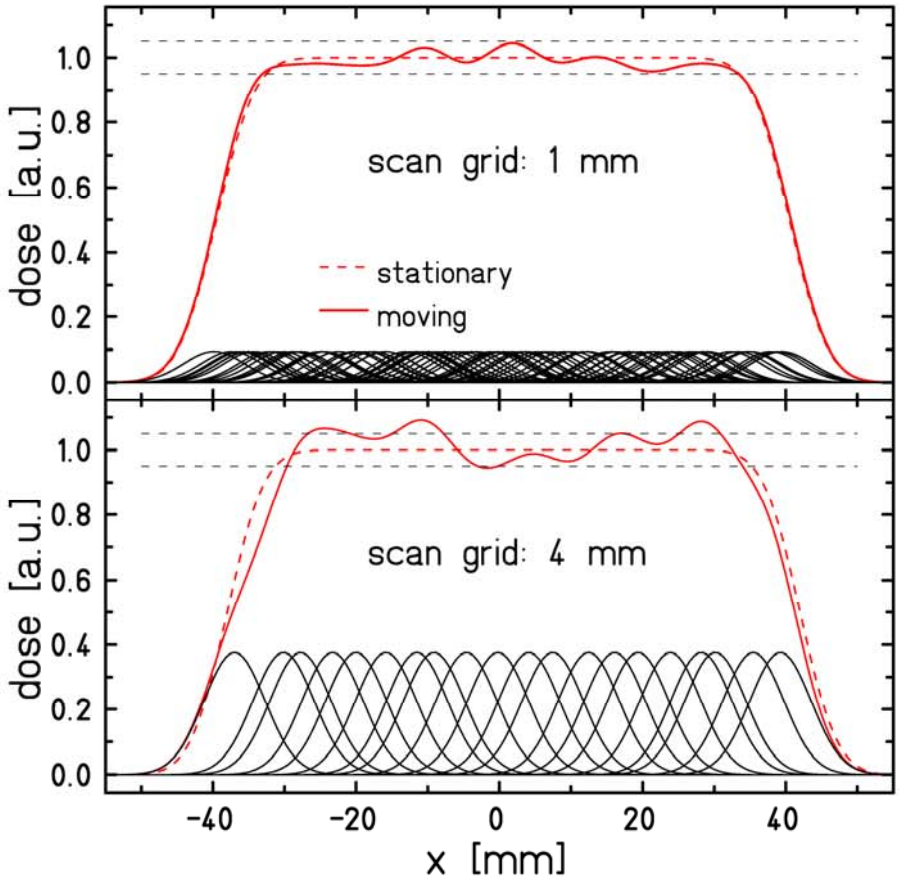
Gating: residual motion in gating window

Mitigation: increase pencil beam overlap



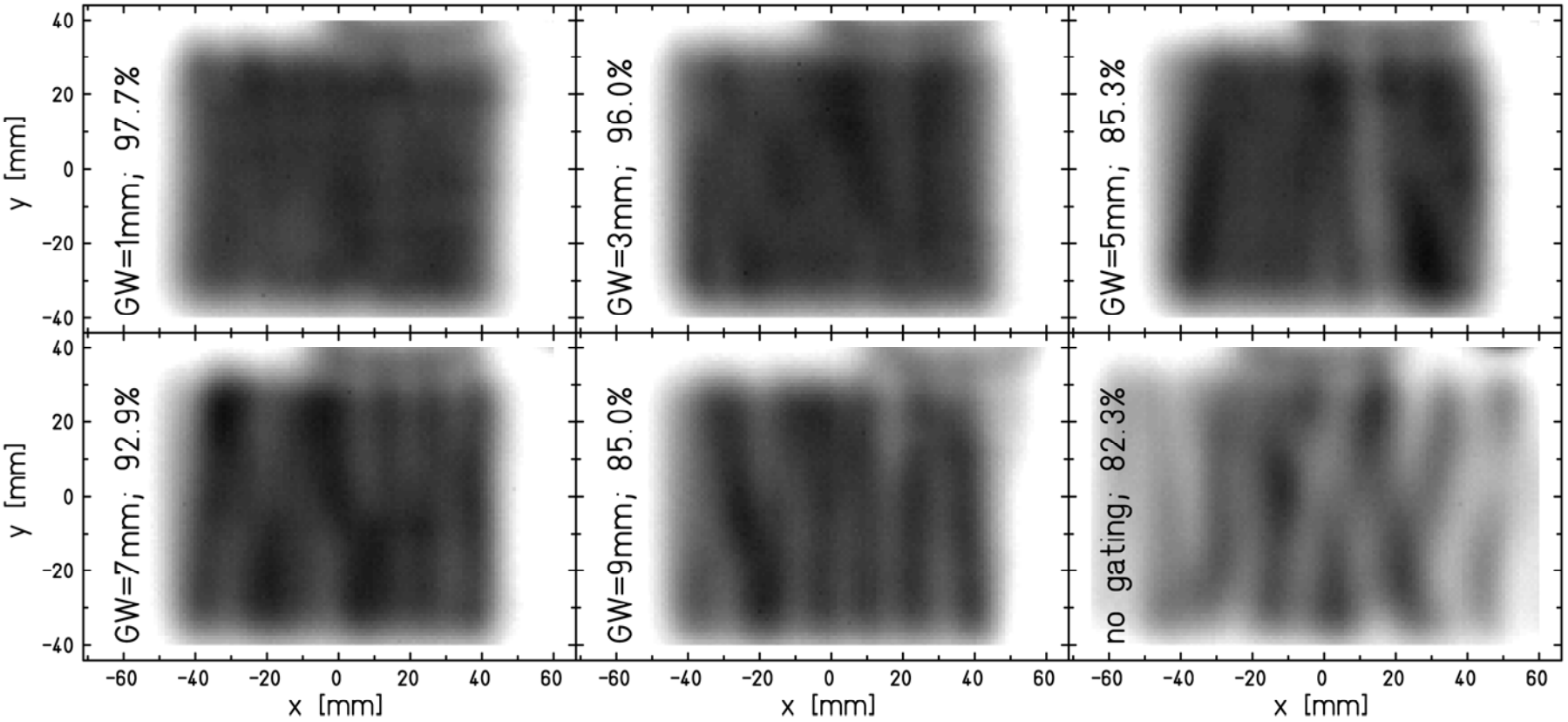
Increased range and lateral overlap

lateral



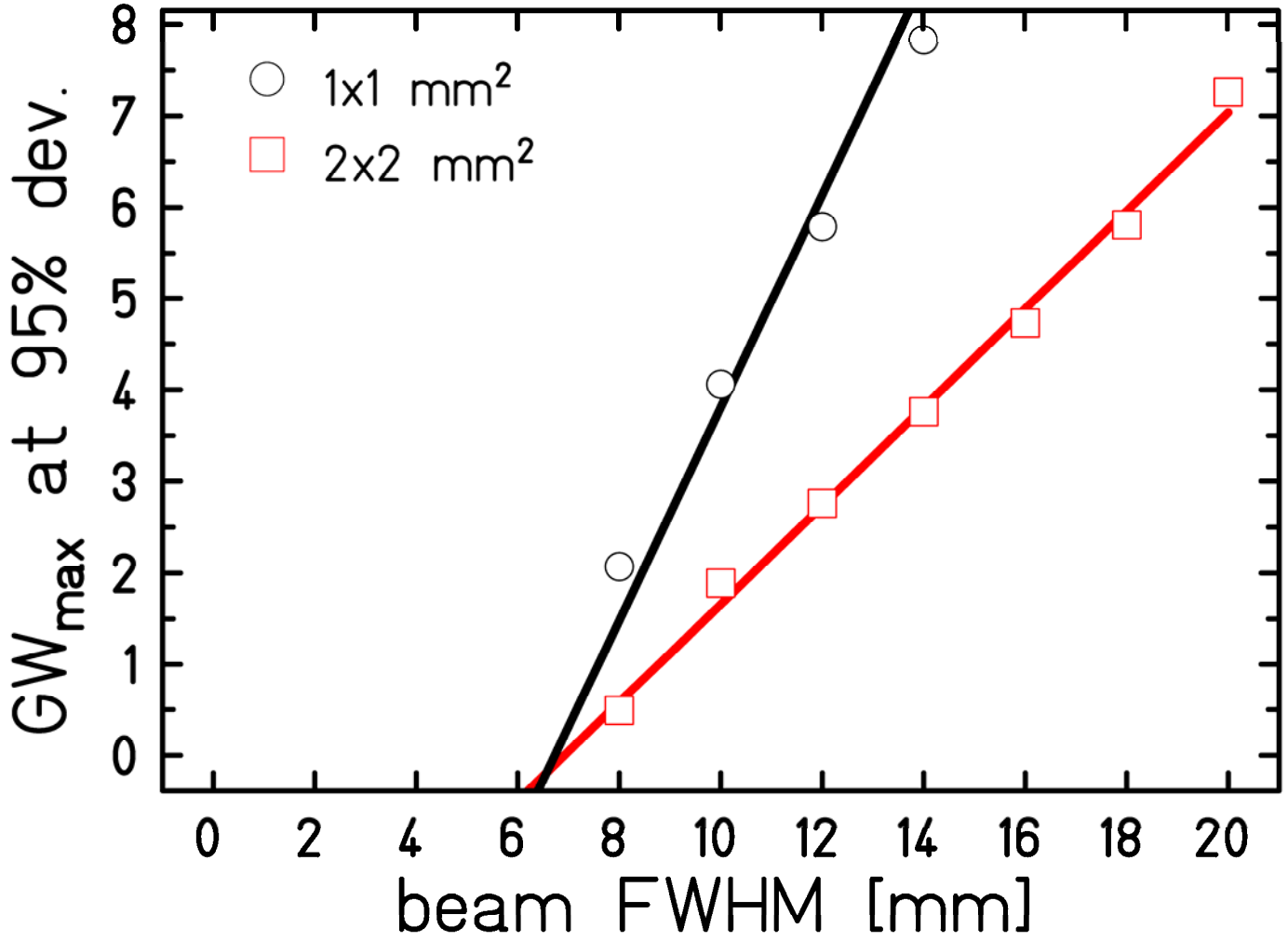
[Bert et al., IJROBP 73(4) 2009]

Experimental data



[Bert et al., IJROBP 73(4) 2009]

Simulation data

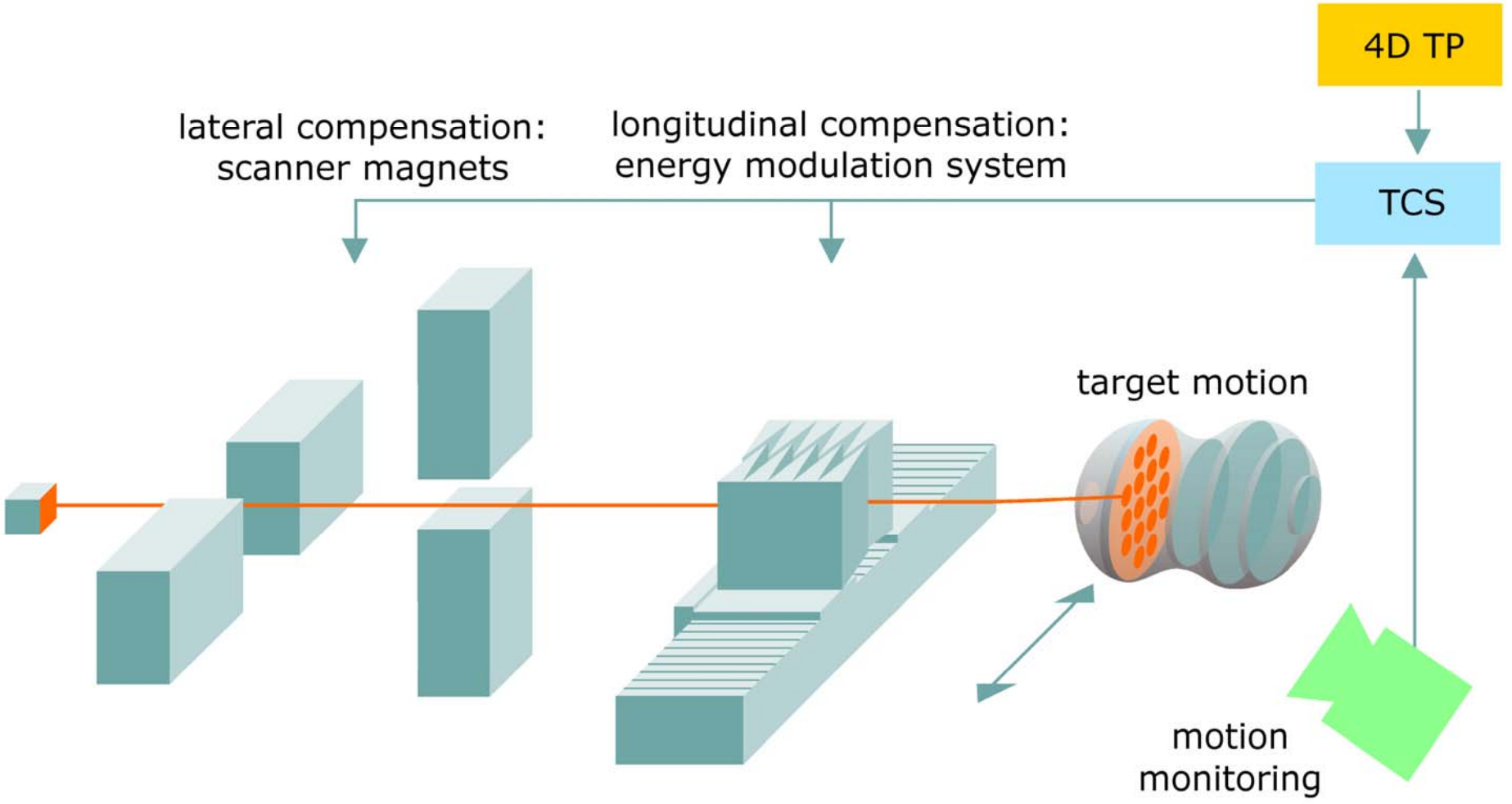


[Bert et al., IJROBP 73(4) 2009]

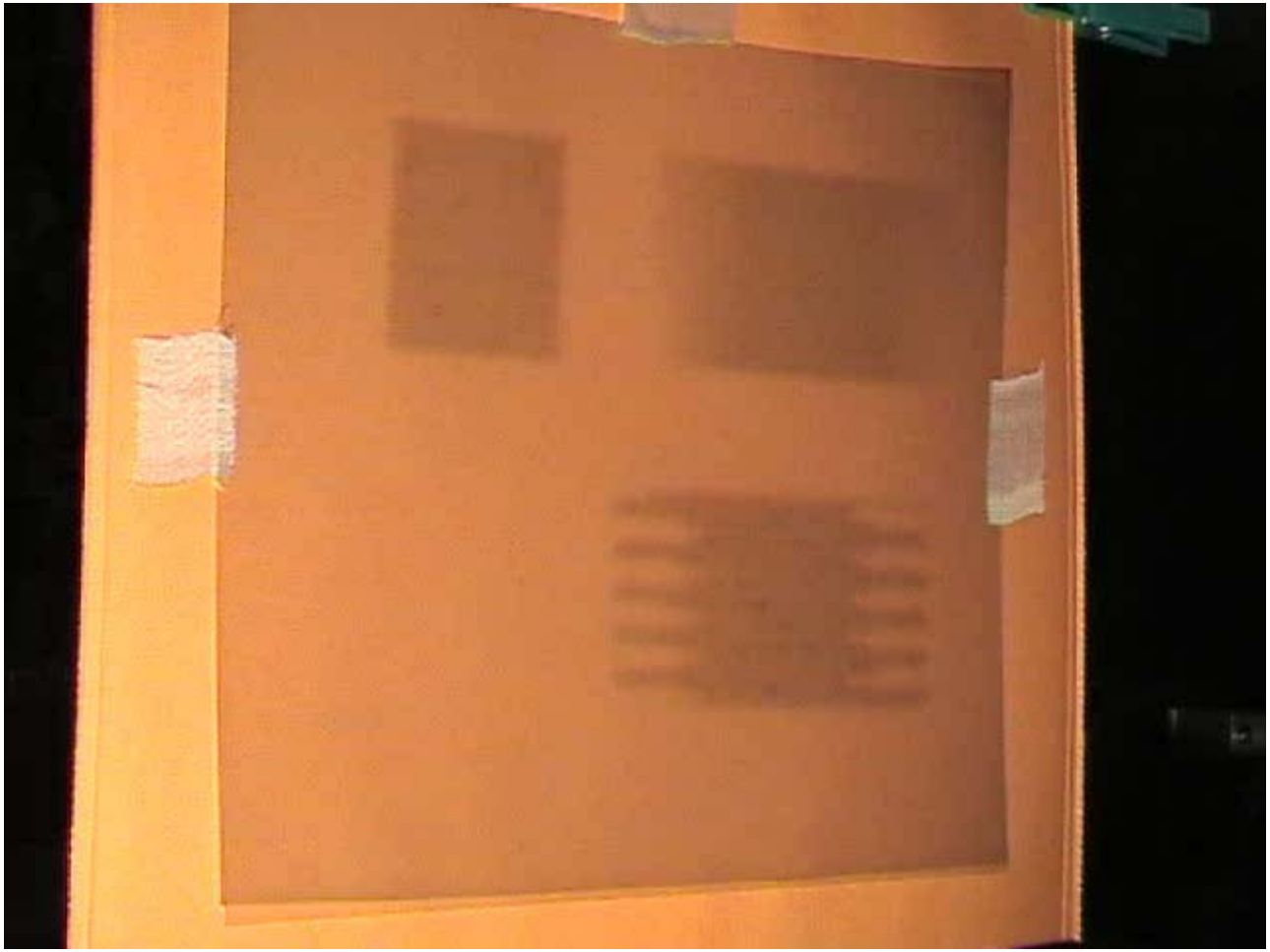
Gating for beam scanning - summary

- Pause beam based on motion surrogate
- Beam scanning $\Rightarrow$ residual interplay in gating window
- Mitigation of interplay:
  - (Phase-controlled) rescanning
  - increased pencil beam overlap
- Implementation: Fair technical effort
- IM/ITV/PTV smaller than for rescanning due to reduced motion amplitude within gating window

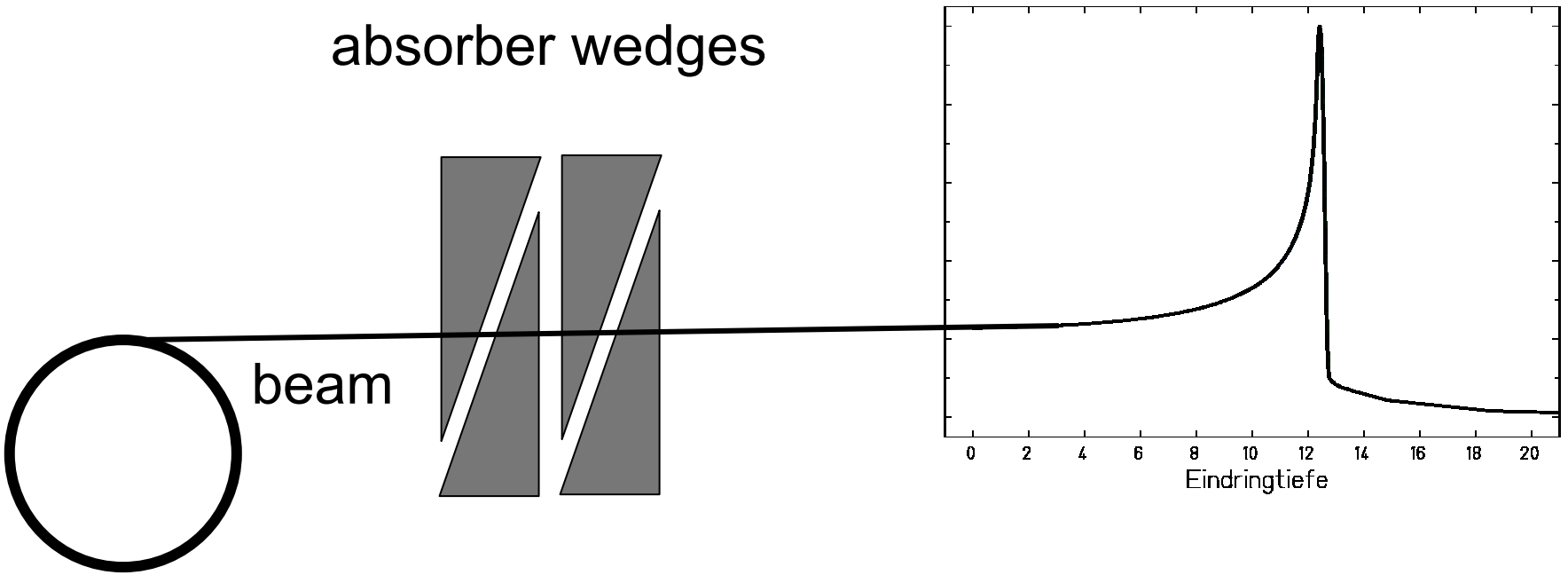
Beam Tracking



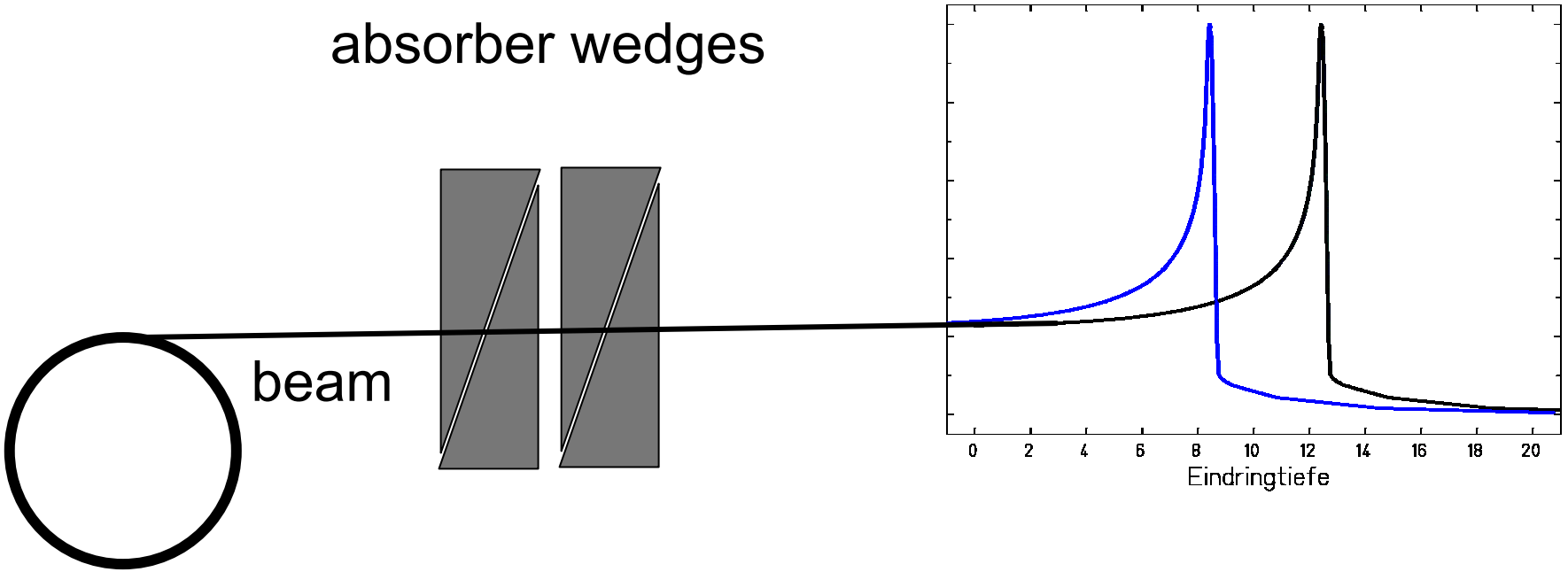
Beam Tracking



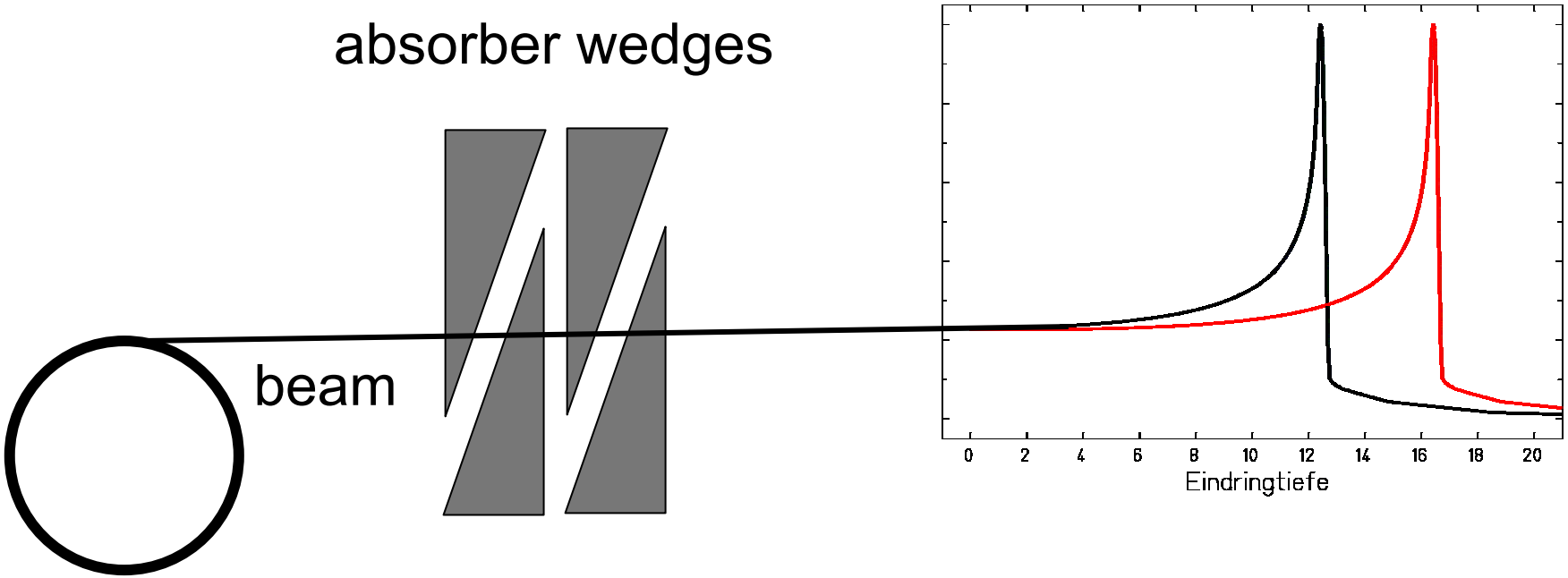
Range modulation



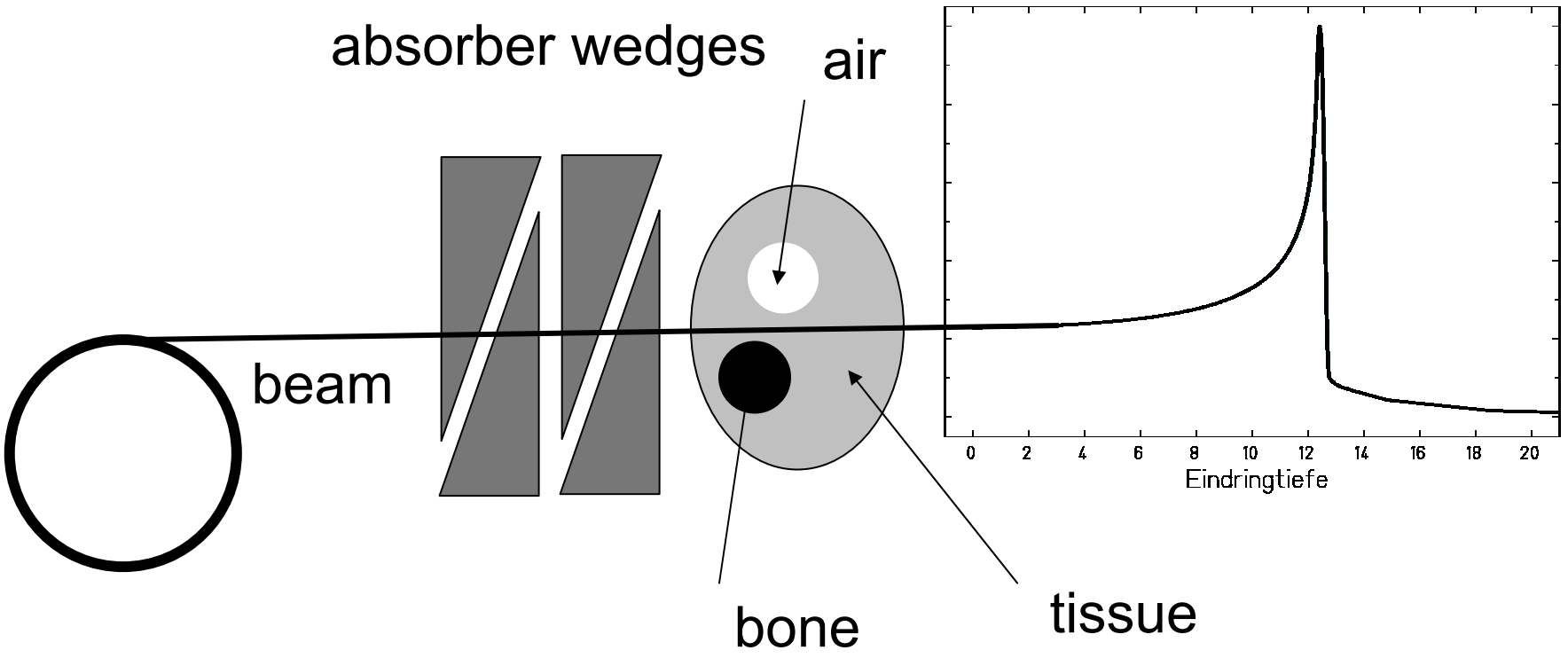
Range modulation



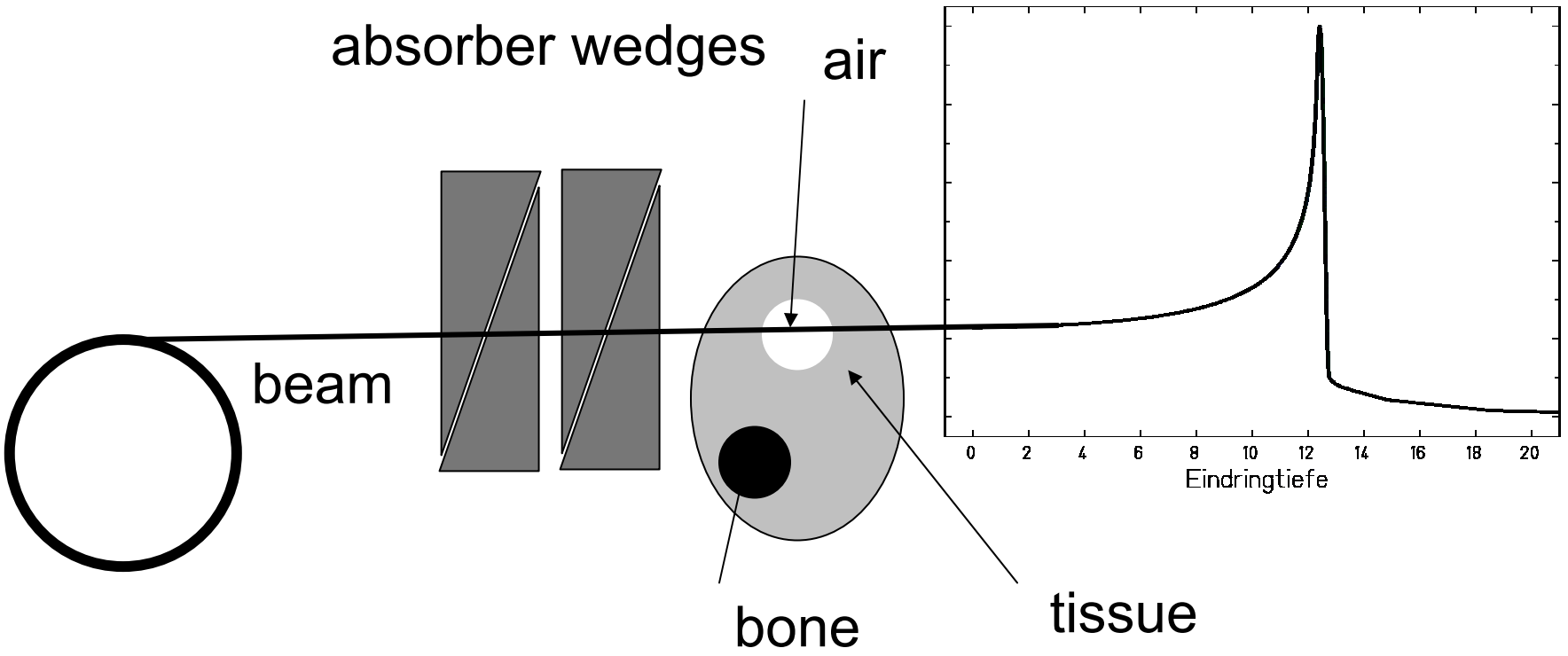
Range modulation



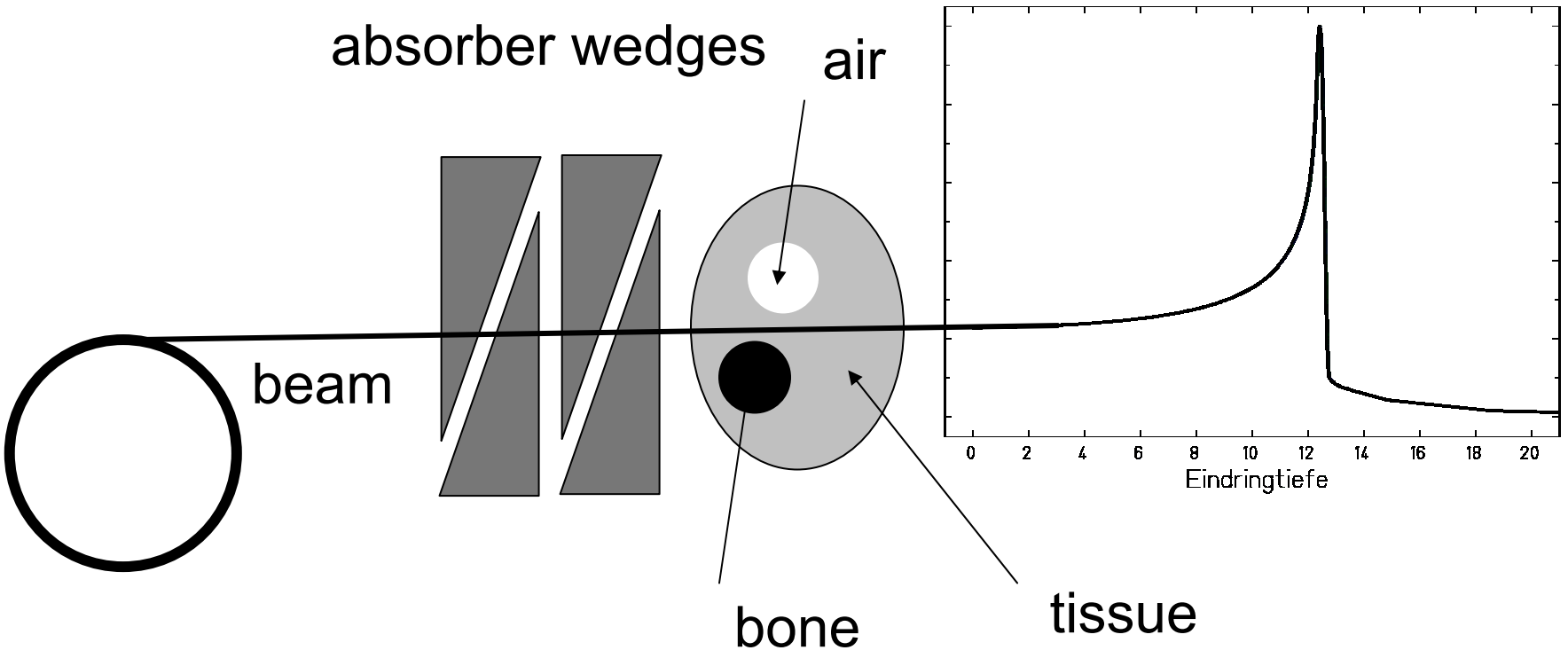
Range modulation



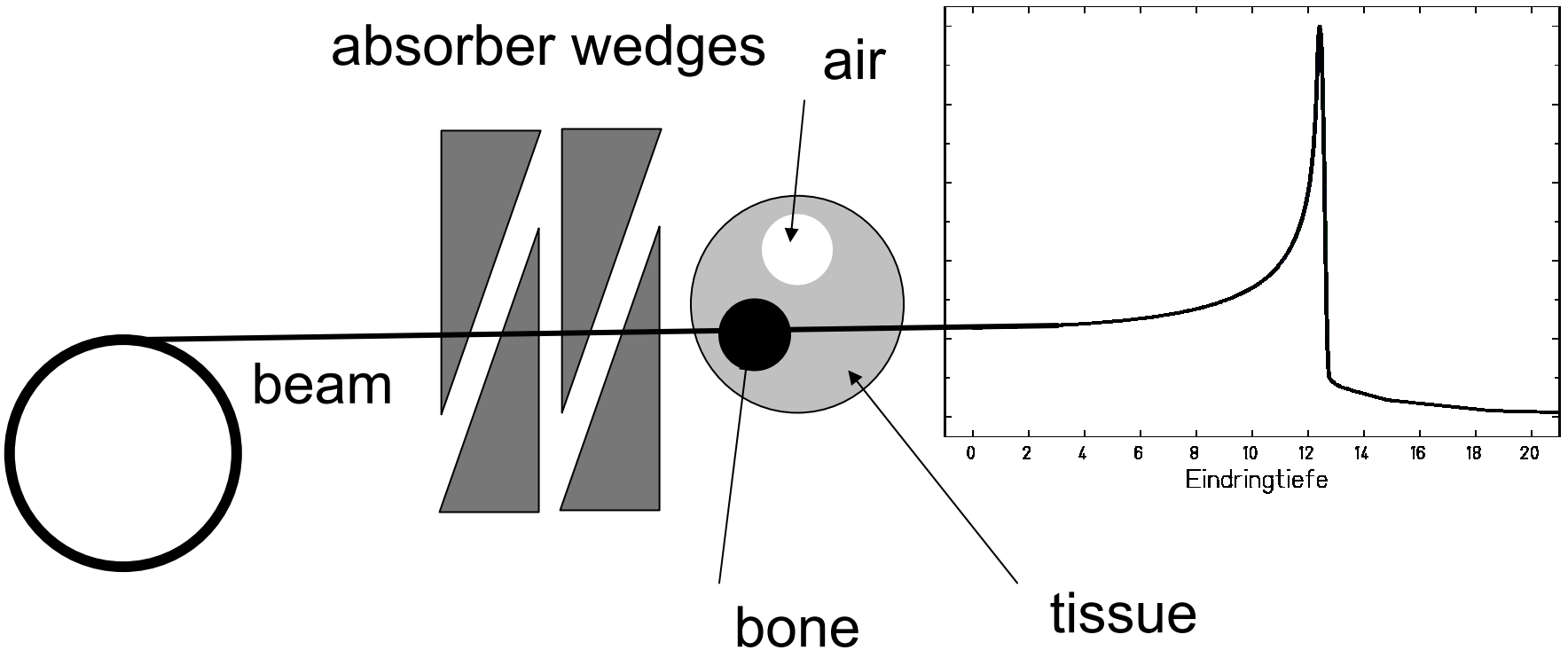
Range modulation

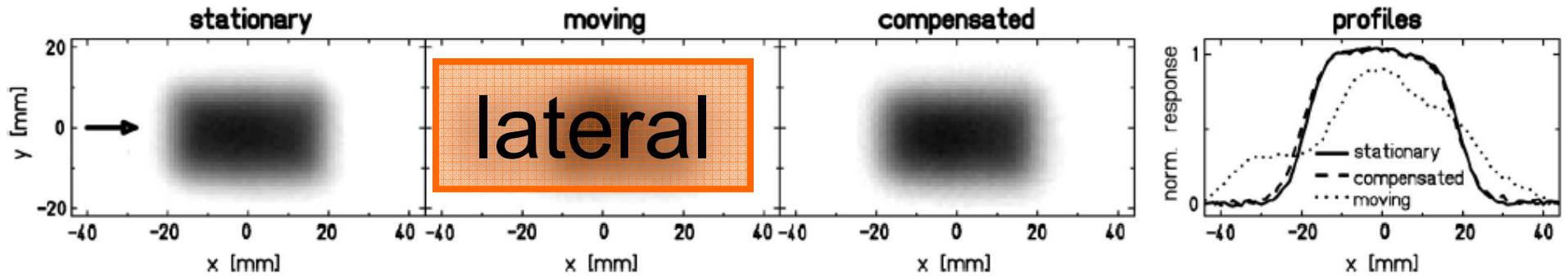


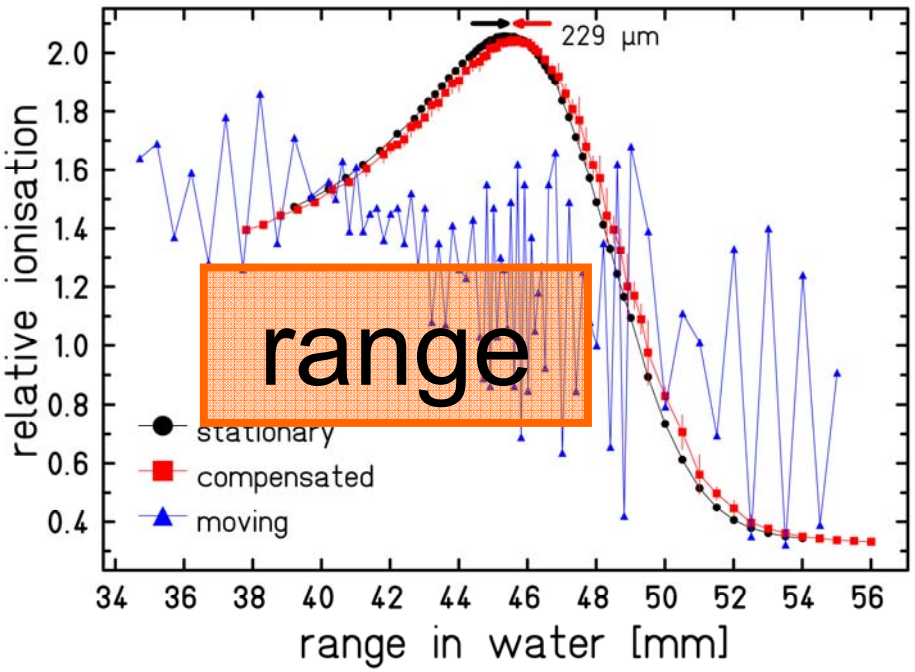
Range modulation

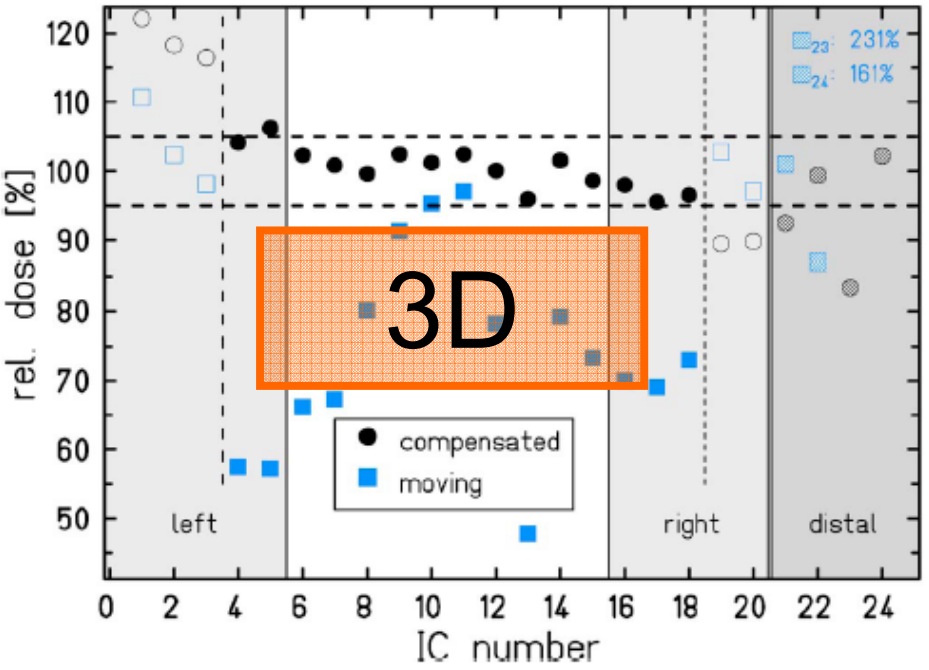


Range modulation





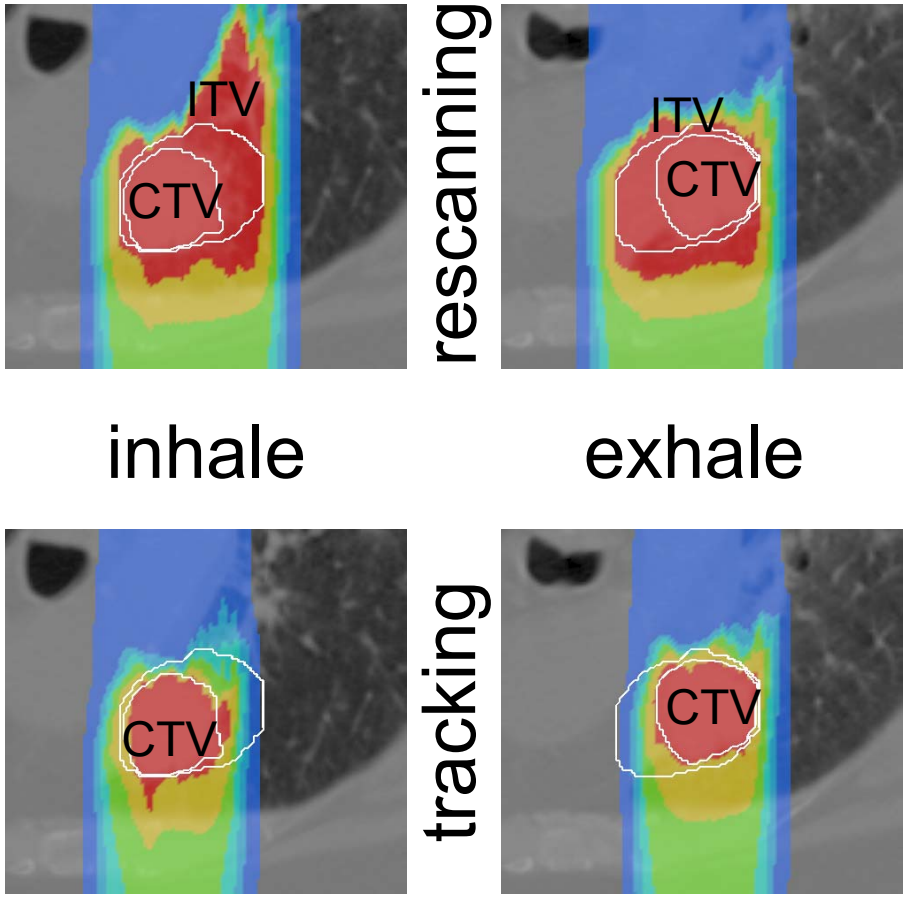




[Bert et al., Med. Phys. 34(12) 2007]

Beam Tracking - summary

- Adaptation of pencil beam position (lateral and longitudinal/range)
- Requires dedicated 4D treatment planning
- Precise motion monitoring
- Implementation: large technical and medical physics effort
- ITV=CTV



Possible future of mitigation techniques

- All techniques are planned to be used
  - Individually or in combination
  - clear emphasis on gating

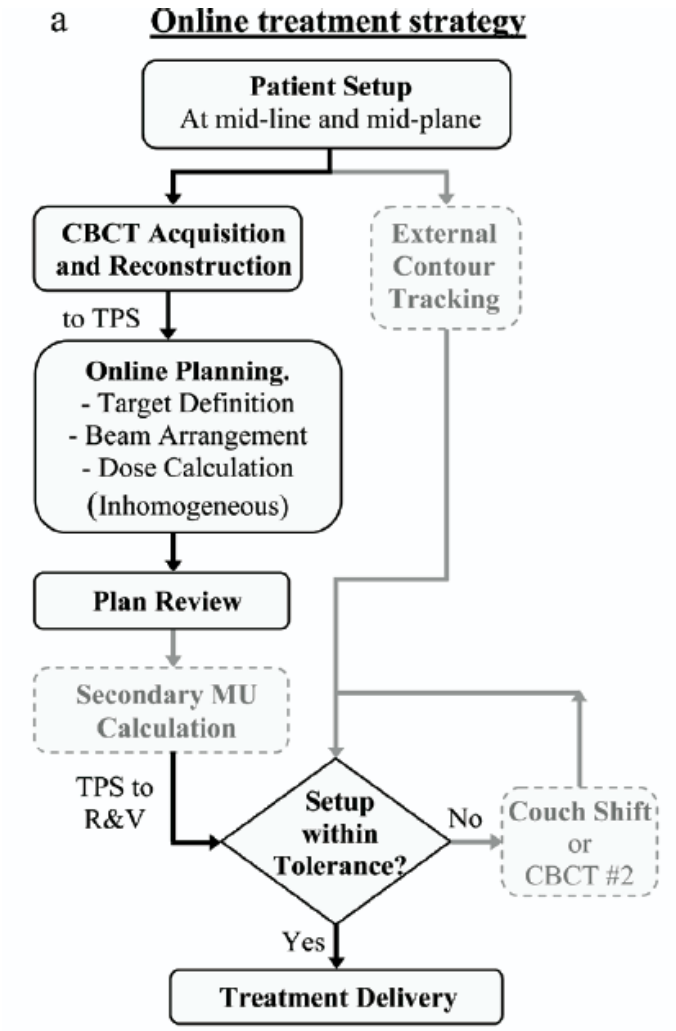
- Class solutions seem likely
  - Irregular motion or small amplitude: rescanning
  - Large amplitude: gating or beam tracking
    beam tracking: pro: smaller margins
    faster treatment
    con: regular motion only

- More clinical research required

Adaptive treatment planning

- „Adaptive radiation therapy is a closed-loop radiation treatment process where the treatment plan can be modified using a systematic feedback of measurements.“
  [Yan et al., Phys. Med. Biol. 42(1), 1997]
- Several styles of adaptive radiotherapy
- Common goals
  - Dose escalation / reduction of normal tissue burden
  - Patient-specific field margins
  - Reduction of systematic and random setup uncertainties
- Use of image guided radiation therapy methods to determine patient geometry

Online Treatment Planning



[Letourneau et al., IJROBP 67(4) 2007]

- Most advances adaptive radiotherapy concept:
- Online Treatment Planning
  - Reduction of systematic and random setup errors
- Requirements
  - TP-suitable on-board 3D imaging
  - Fast segmentation and plan optimization
  - Quick treatment delivery
- Not suitable for classical broad beam shaping due to compensator and collimator fabrication

Summary

- Target motion affects geometry and range
- Dedicated margin concepts required
- Broad beam delivery
  - Insensitive to target motion
  - Margin concepts can be applied
  - Several years of clinical experience
  - Advances concepts (tracking, adaptive Rx, …) most likely not feasible due to patient-specific hardware
- Scanned beam delivery
  - Affected by interplay
  - Rescanning, gating, and beam tracking technically implemented for motion mitigation
  - Clinical implementation can be expected in the next years
  - Adaptive / online protocols feasible (fully active beam delivery)

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