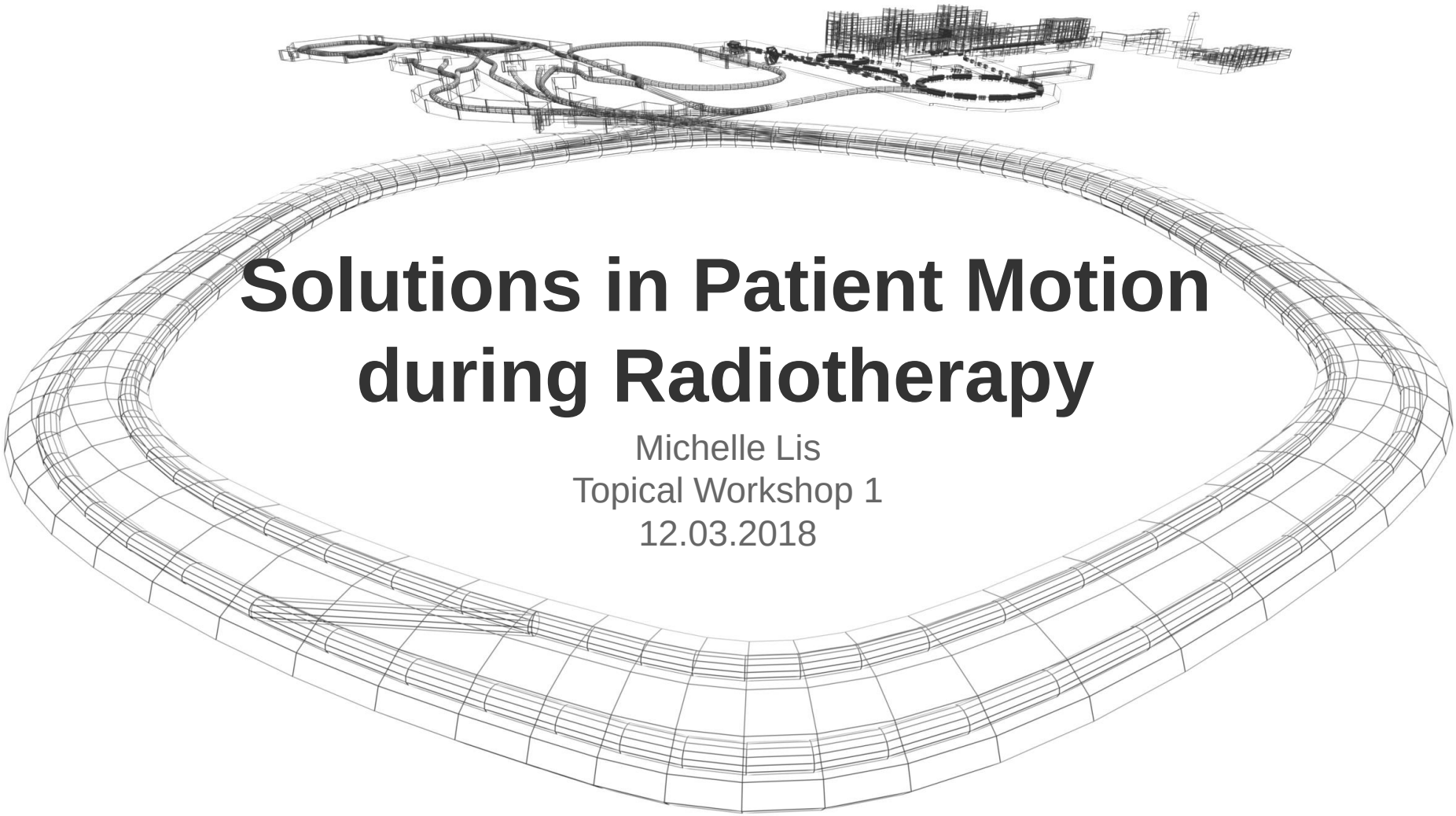
GSI Helmholtzzentrum für Schwerionenforschung GmbH



Solutions in Patient Motion during Radiotherapy

Michelle Lis

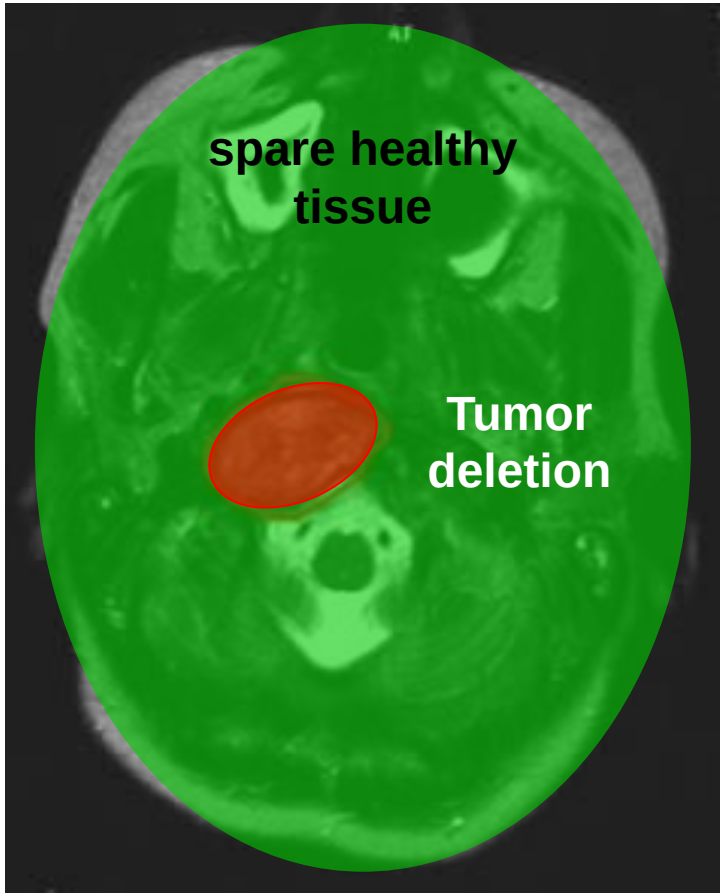
Topical Workshop 1

12.03.2018

Outline

- Rationale for 4D ion therapy
- Issues with tracking
- 4D optimization
- Motion mitigation strategies
- Combining motion mitigation methods

Aim of radiotherapy

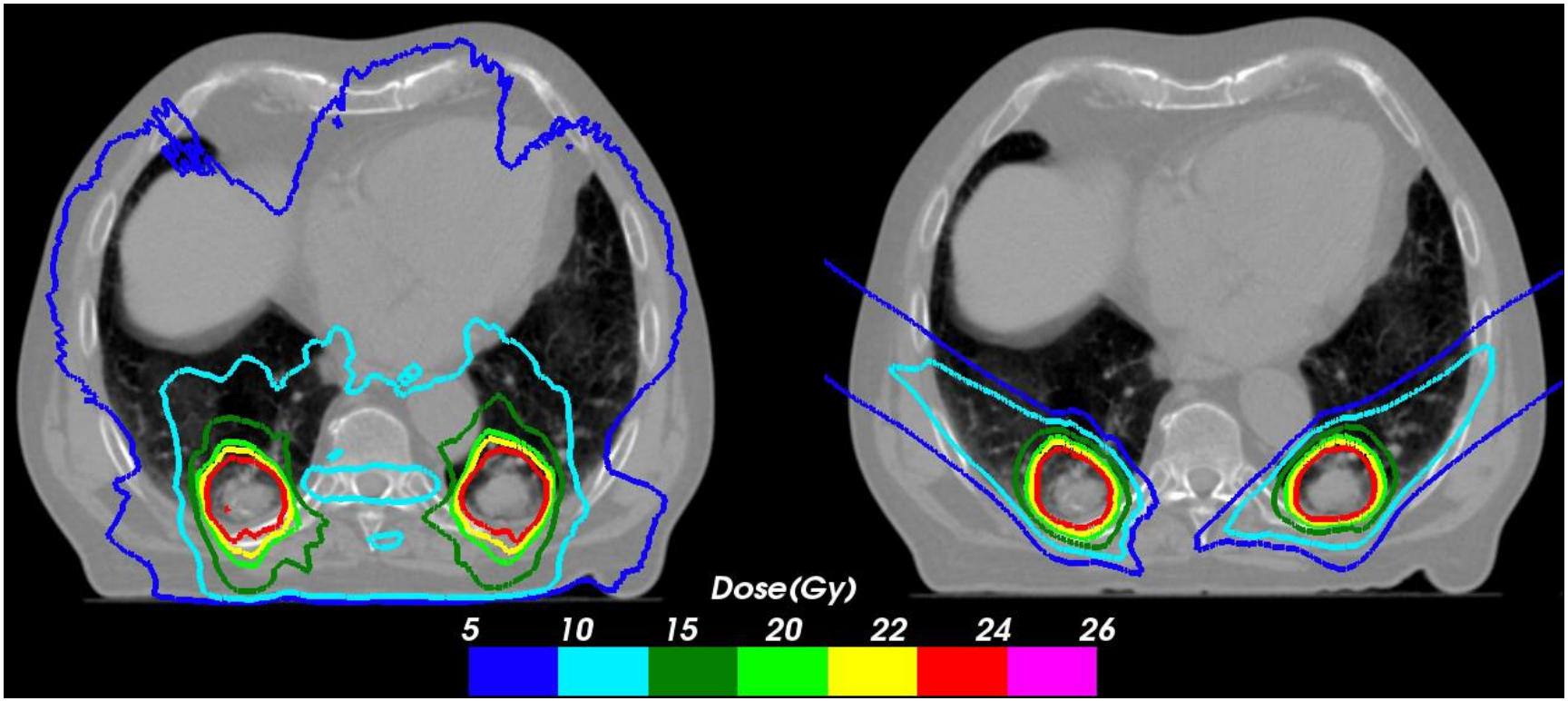


- Treat tumors - spare surrounding healthy tissue
- Conformal treatment

http://xkcd.com/1217

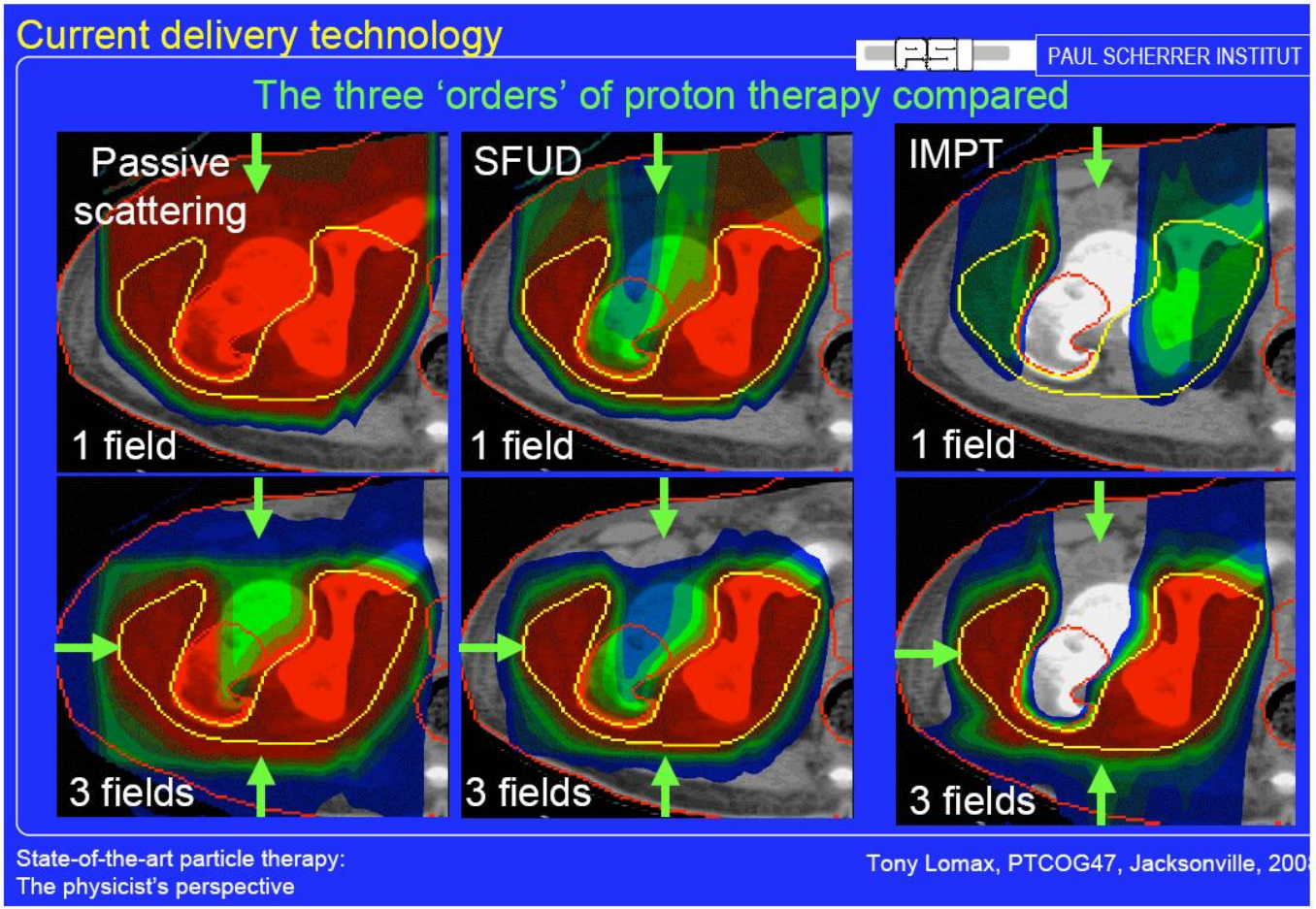
Rationale for 4D-treatment with ions

- Ions more conformal than photons



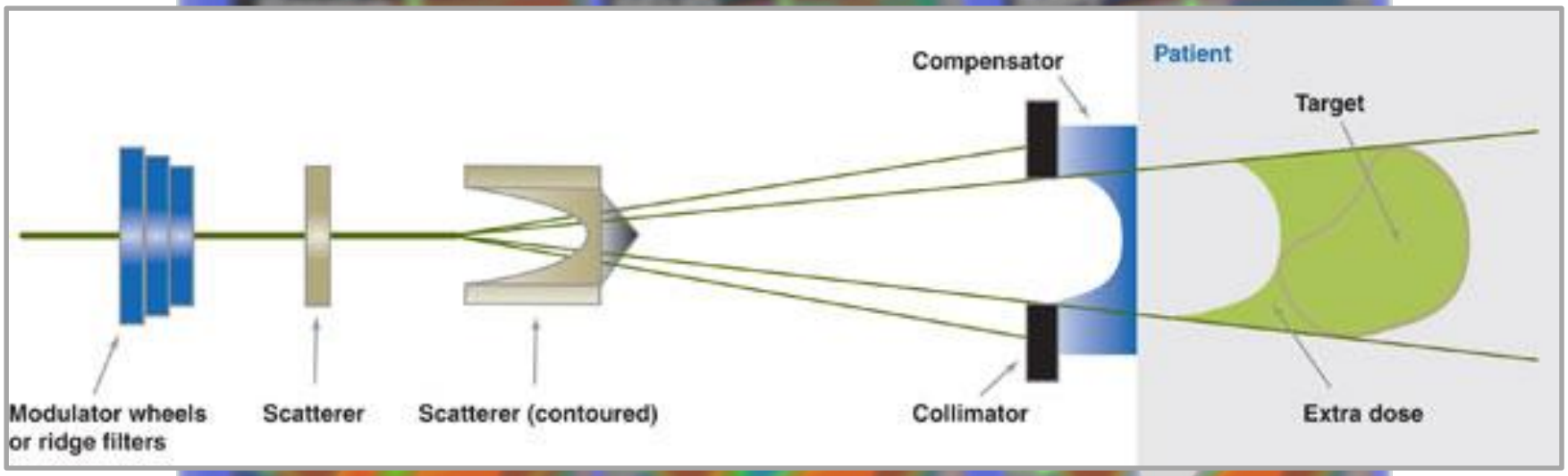
Rationale for 4D-treatment with ions

- Active delivery more conformal than passive



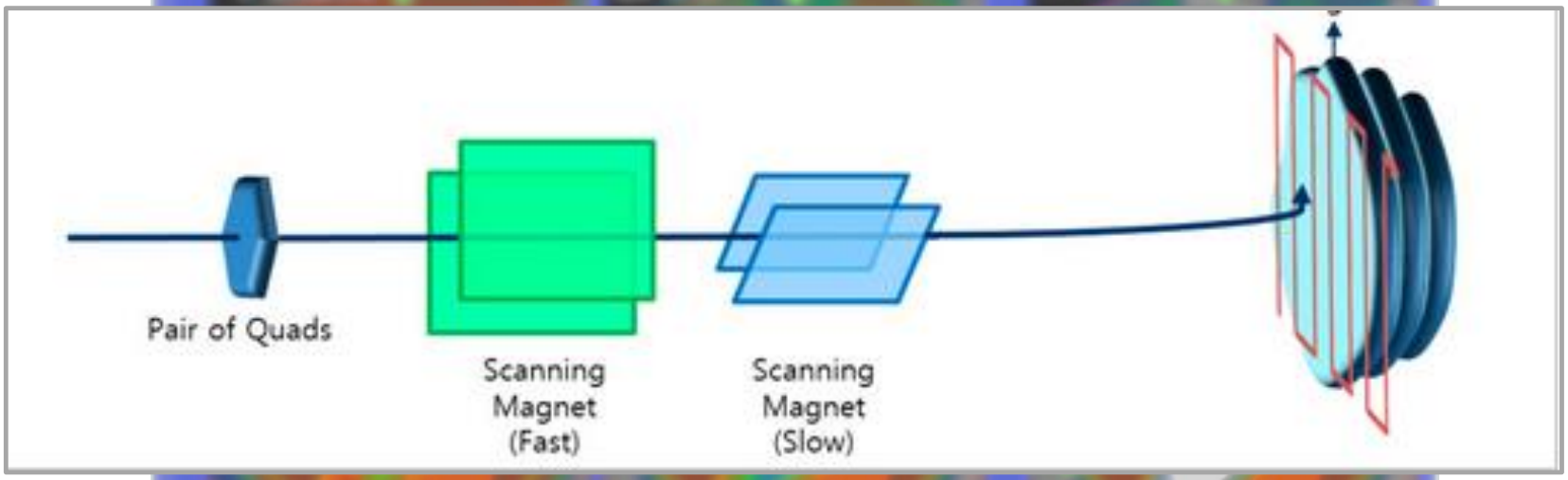
Rationale for 4D-treatment with ions

- Active delivery more conformal than passive

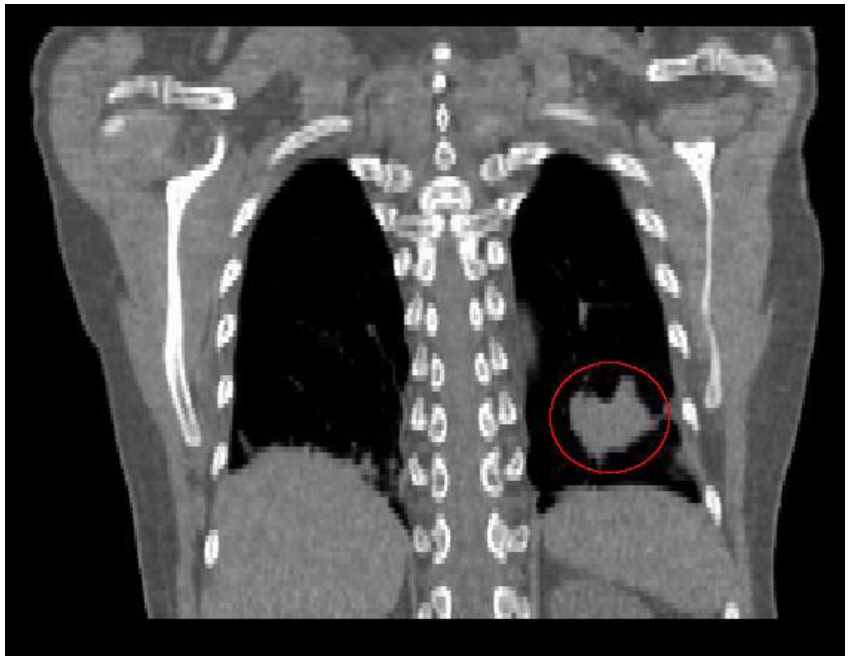


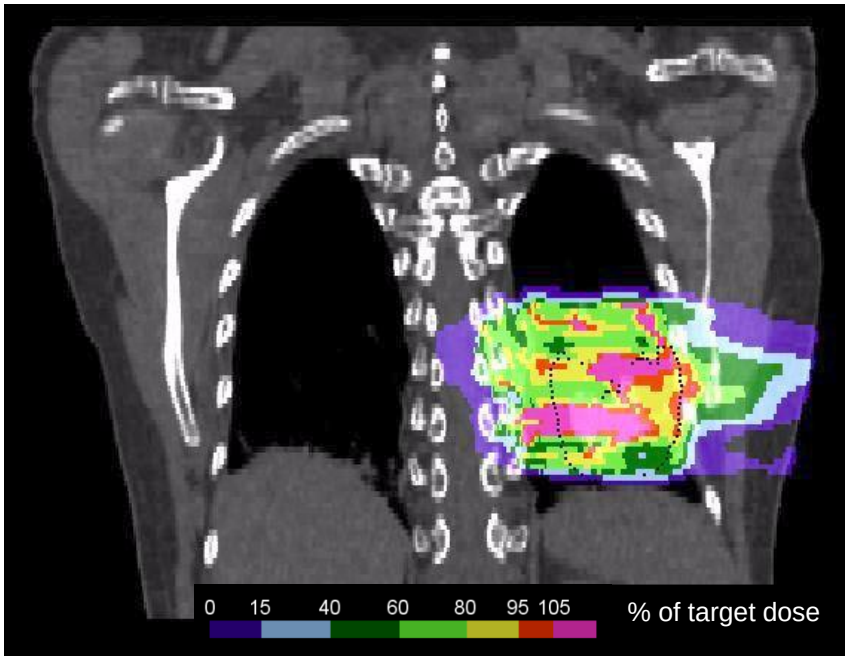
Rationale for 4D-treatment with ions

- Active delivery more conformal than passive



Motion and scanned delivery





Courtesy M. Söhn, LMU

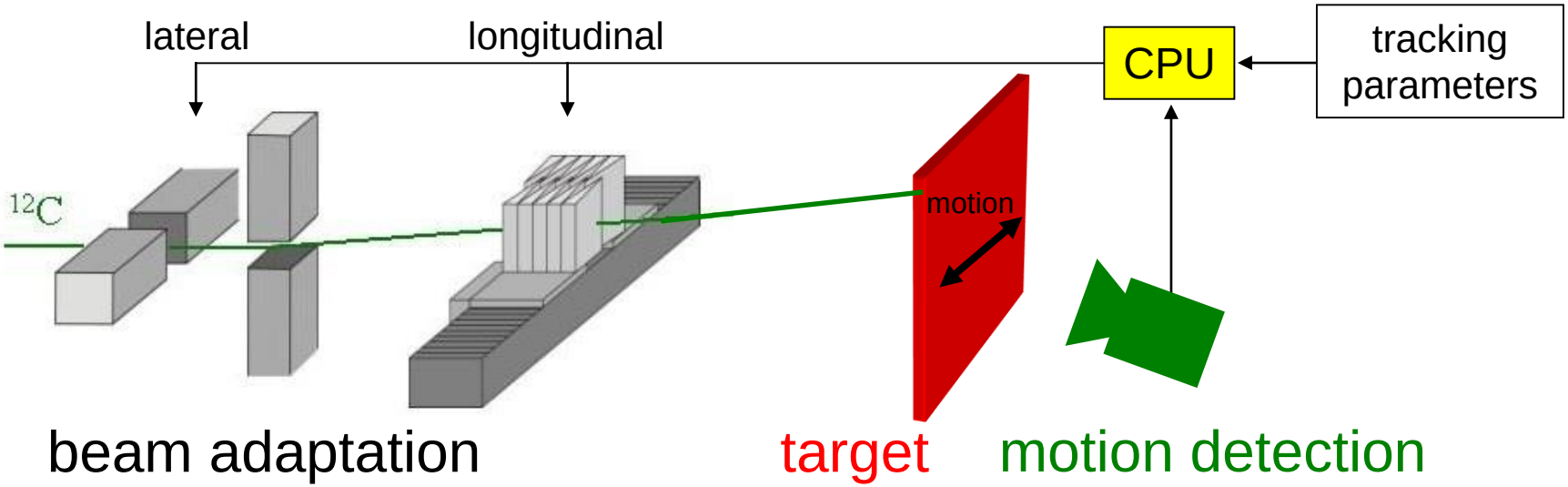
- **Motion**: Target miss
- **Range changes**: variable position of Bragg peaks
- **Interplay**: Interference between target and scanning motion

Treatment Methods

- Tracking
- Robust 4D-optimized radiotherapy
  - rescanning, sectoring, fast gating
- Image guided gating with fast scanning

Beam Tracking

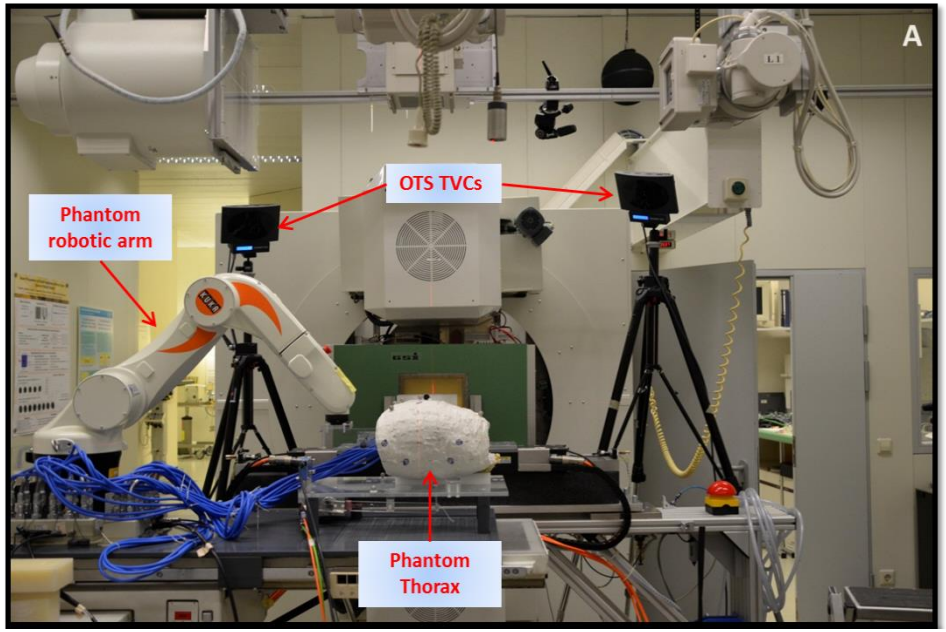
- Tremendous advantage over photons:
  Easy, fast beam deflection



Benefits of tracking

- No increase in treatment time
- Real-time
- Straightforward to use

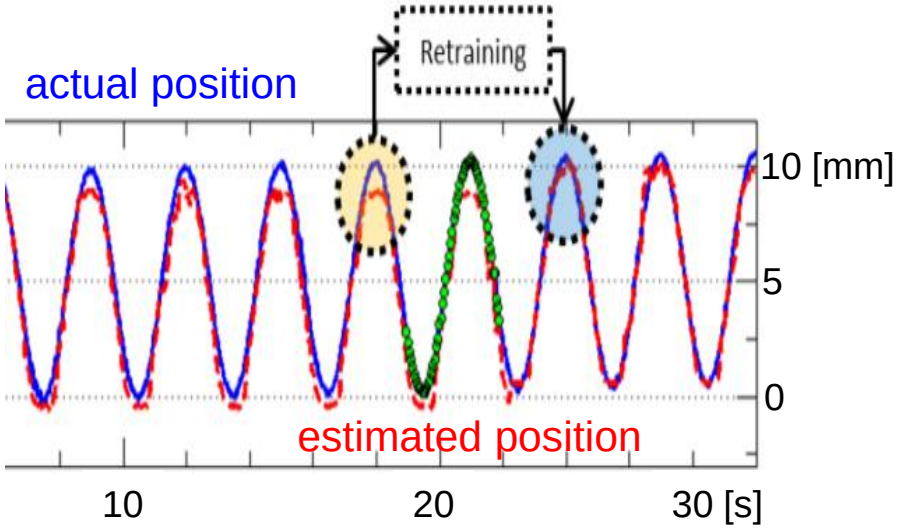
Beam tracking in cave M with 3D optical position monitoring and motion prediction



~1ms/1mm scan speed

Technical demands of tracking

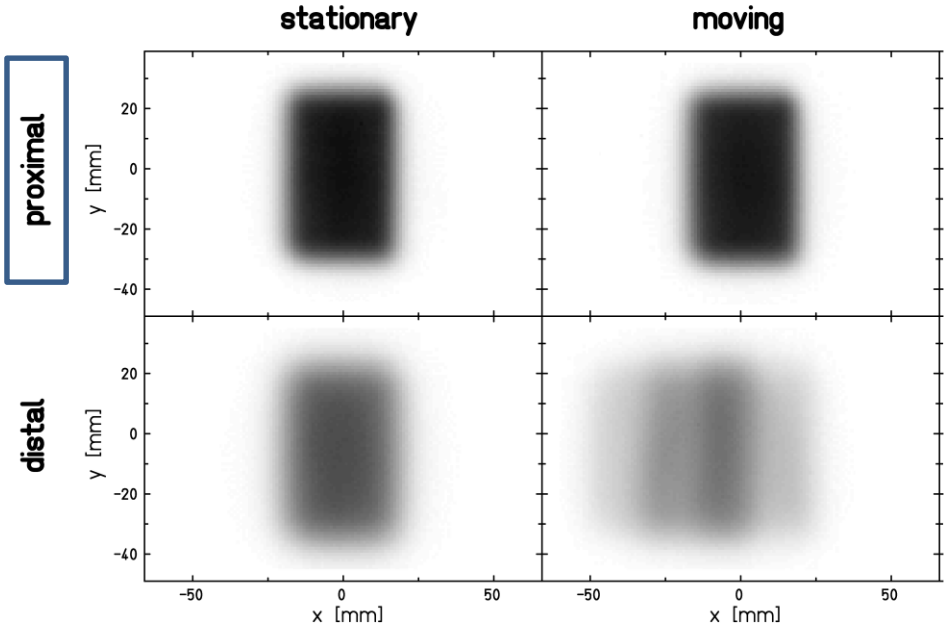
- Adjustments to depth and density
- Real-time tumor position (accounting for delays)

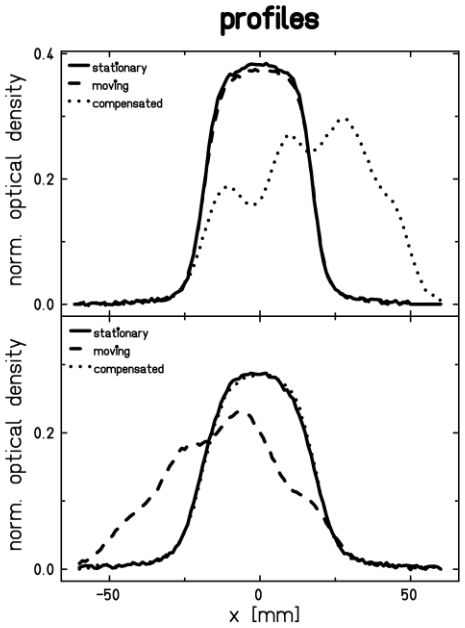


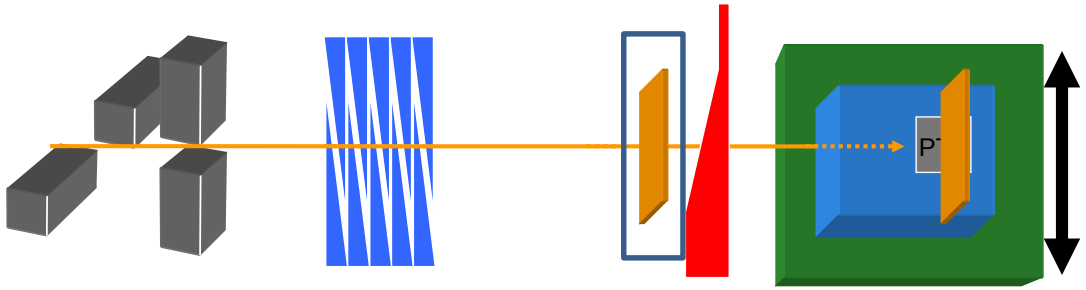
dose error reduced from 24% to 3%

Tracking issues I: inverse interplay

residual motion from higher weight beams

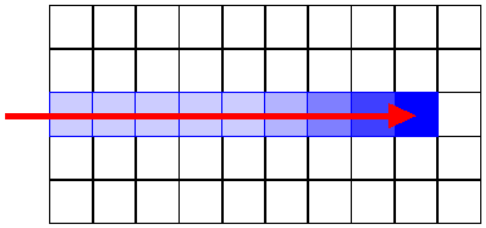




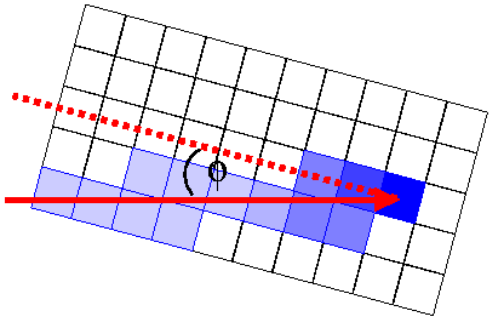


Tracking issues II: complex motion

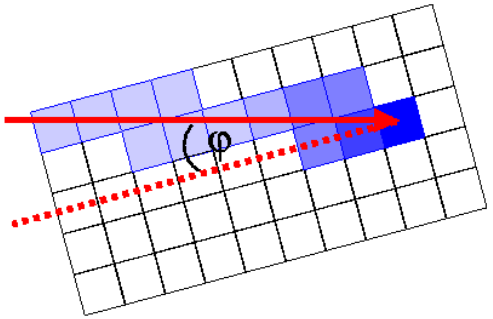
- Beam tracking compensates translation only
- Preplanned entry channel doses may be wrong!



Motion State Reference



Motion State k

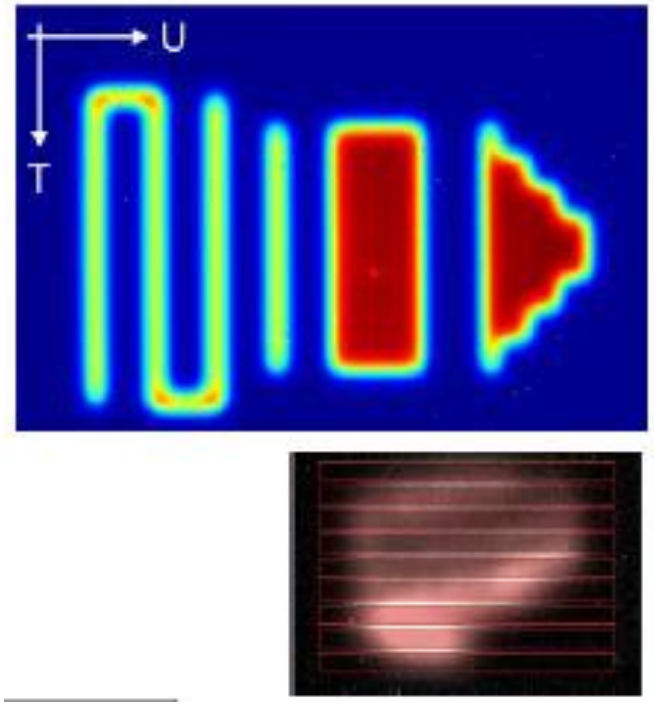


Motion State i

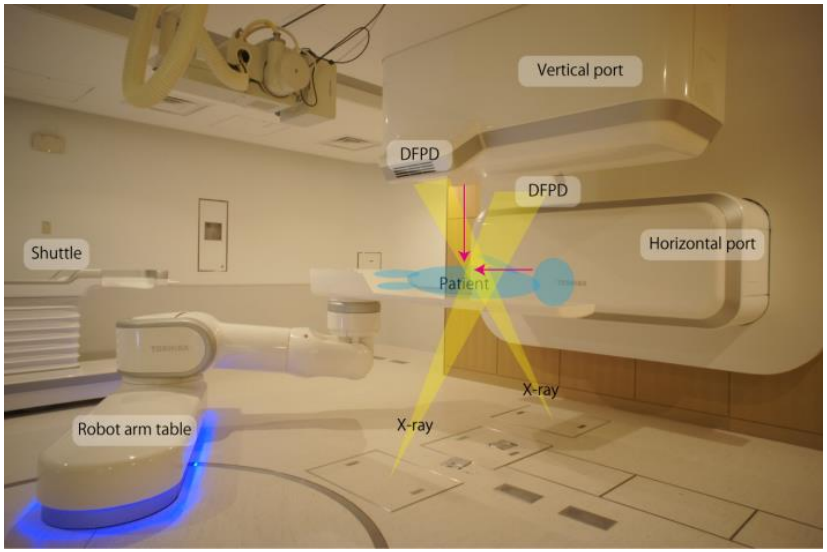
Ion therapy at PSI

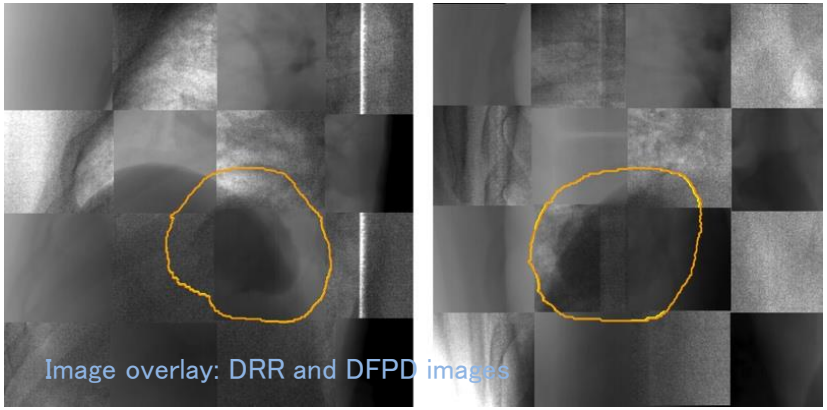
- Fast scanning proton beams
- Onboard imaging

in-room imaging



Ion therapy in NIRS, Chiba, Japan

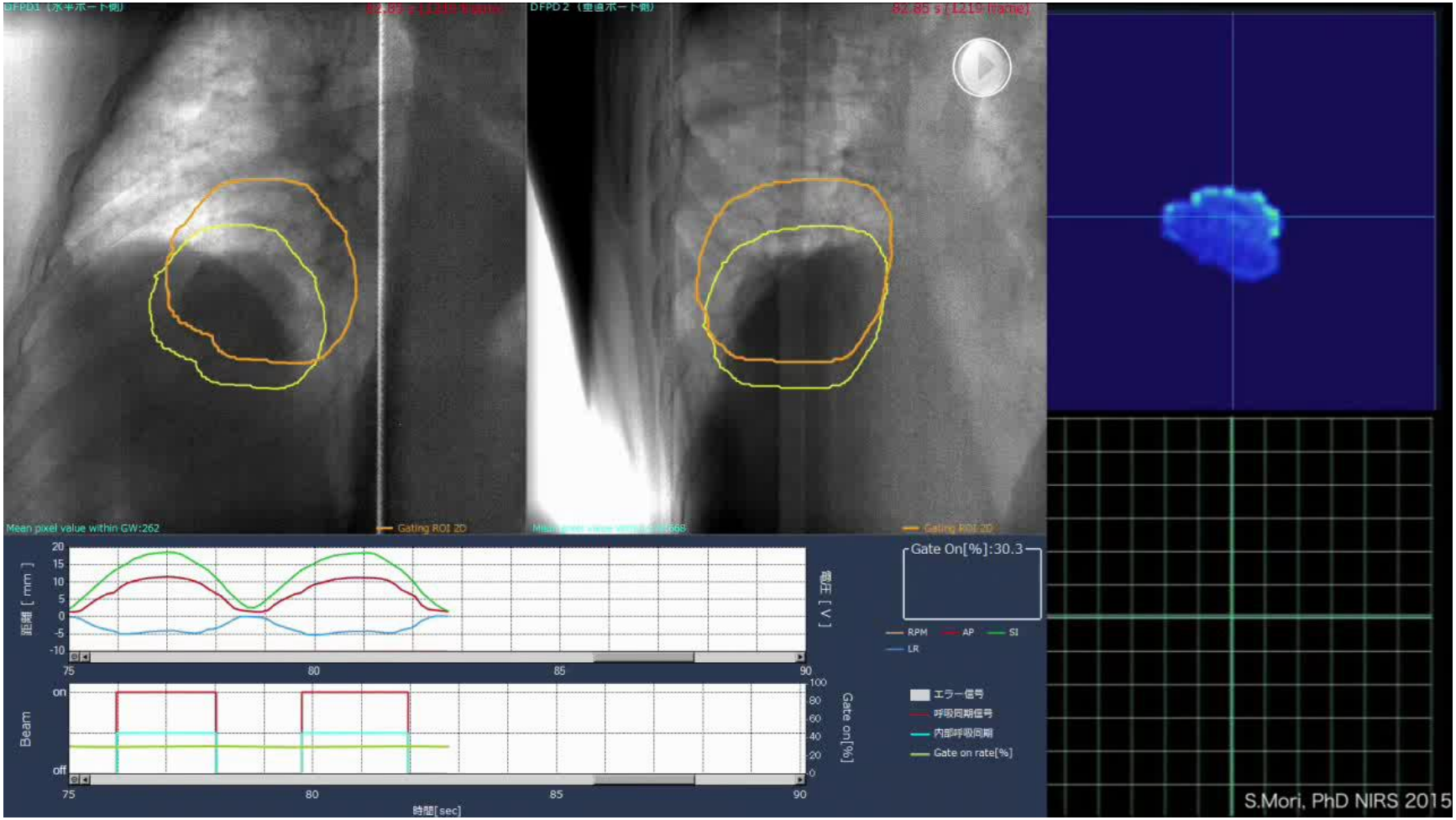




- Amplitude-based gating to counter irregular respiration
- Real time fiducial-free tumor tracking using fluoroscopy
  - liver 20-80mA/4ms, lung 20-40mA/4ms
  - variable rate during treatment: 1-30fps
  - X-ray acquisition to beam on gate < 50ms
  - Accuracy < 0.4±0.1mm

National Institute of Radiological Sciences
Research Center of Charged Particle Therapy

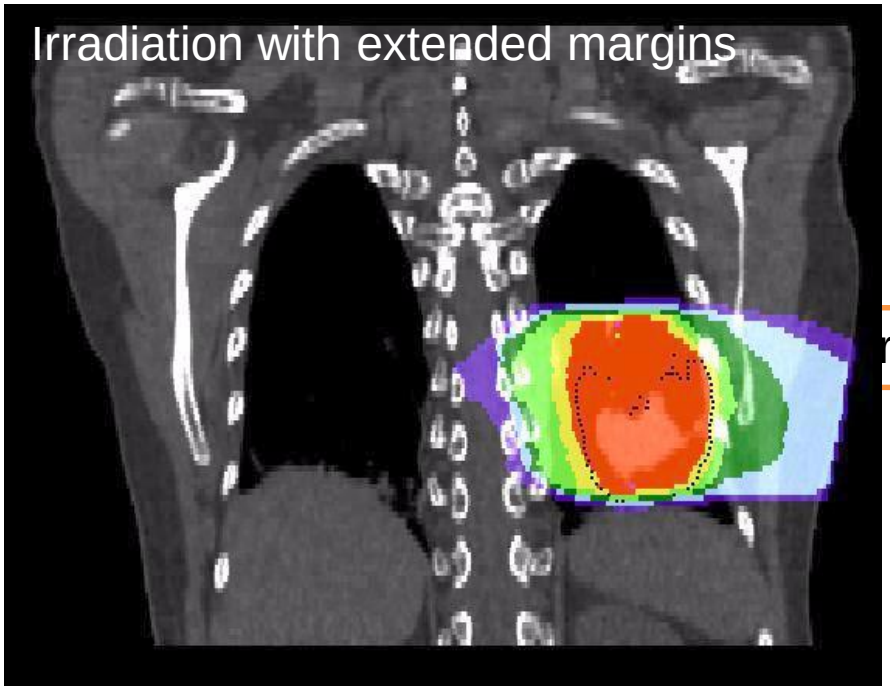
Amplituden-basiertes Gating

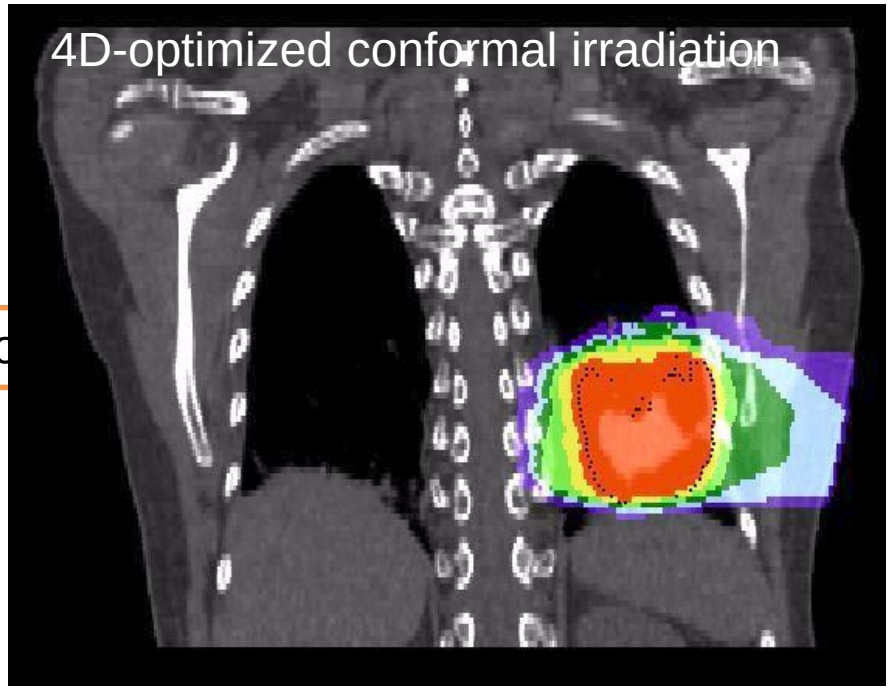


National Institute of Radiological Sciences
Research Center of Charged Particle Therapy

Motion-synchronized delivery

- Conformal 4D-optimization results in a plan library
- Delivery of all plans has to be synchronized to motion





Conformal 4D-optimization

- 3D Optimization cost function

$$E(\vec{N}) = \sum_{i=1}^{v} \left[D_{pre}^{i} - D_{act}^{i}(\vec{N})\right]^2 = \sum_{i=1}^{v} \left[D_{pre}^{i} - RBE(\vec{N}_k) \sum_{j=1}^{r} c_{ij} N_j\right]^2$$

- Full 4D Optimization cost function

$$E(\vec{N}) = \sum_{k=1}^{m} \sum_{i=1}^{v} \left[D_{pre}^{i} - D_{act}^{ik}(\vec{N}_k)\right]^2 = \sum_{k=1}^{m} \sum_{i=1}^{v} \left[D_{pre}^{i} - RBE(\vec{N}_k) \sum_{j=1}^{r} c_{ijk} N_{jk}\right]^2$$

- Different strategies possible to control gradients, reduce problem size, ...

- (OAR terms omitted)

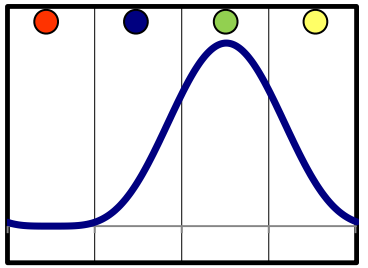
Voxels

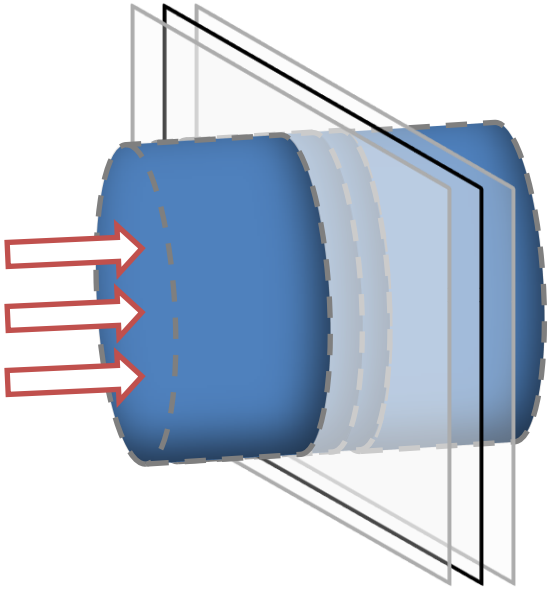
beam spots

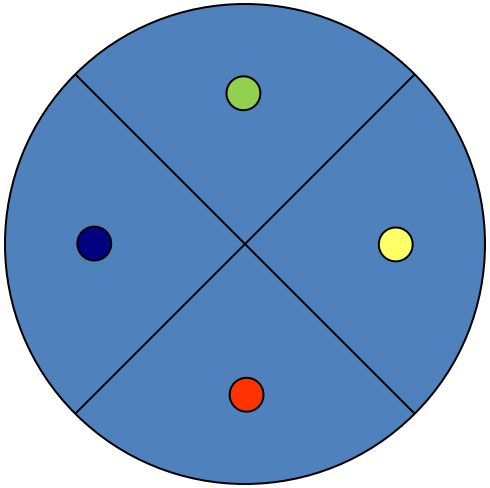
motion phases

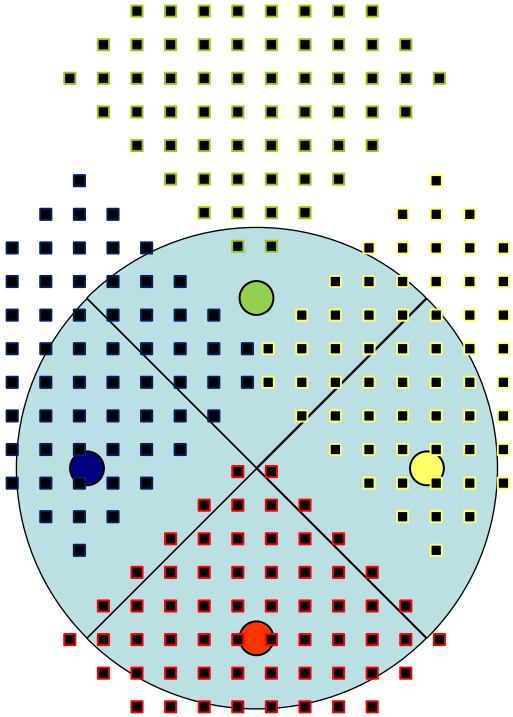
4D optimized dose delivery strategies:
Sectoring Rescanning Multigating

- Divide target in slices perpendicular to beam
- Divide slices in sectors for each motion state
- Transform sectors to motion states
- Create RST for each motion state





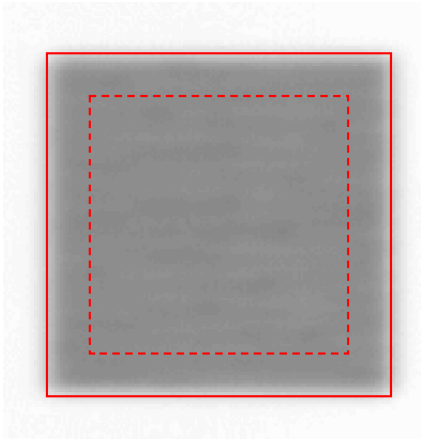




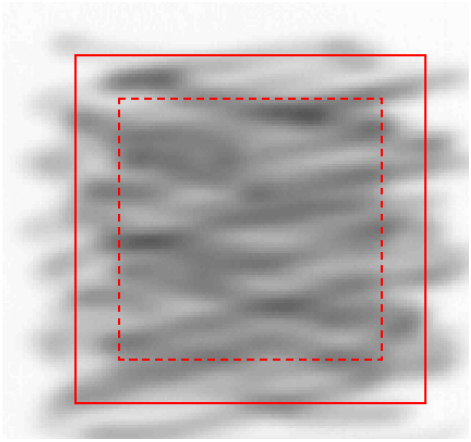
Graeff at al. Green Journal 2013

4D optimized dose delivery strategies:

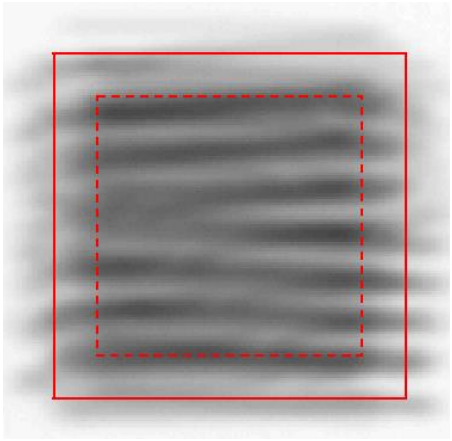
Sectoring **Rescanning** Multigating



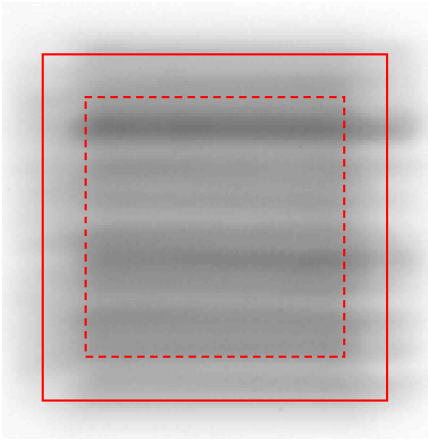
Static



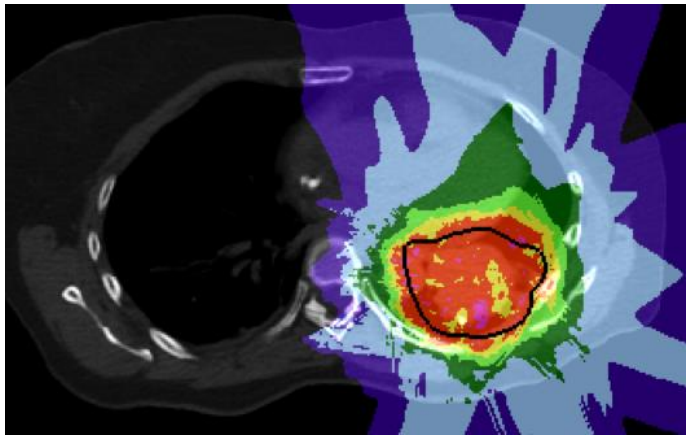
1 scan



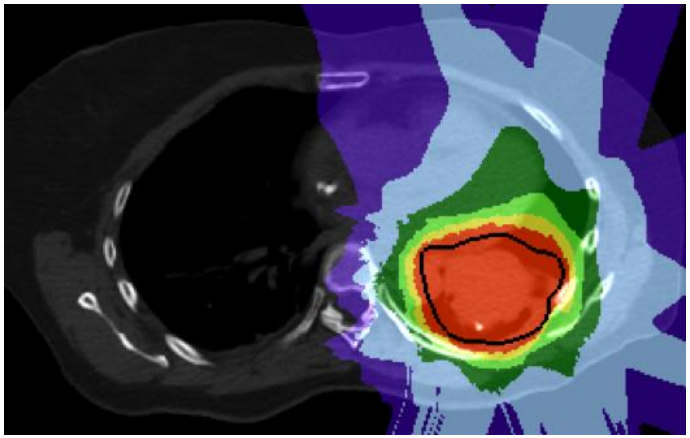
2 scans



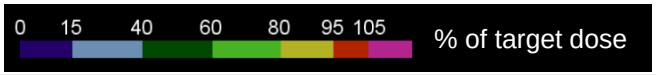
10 scans



Interplay



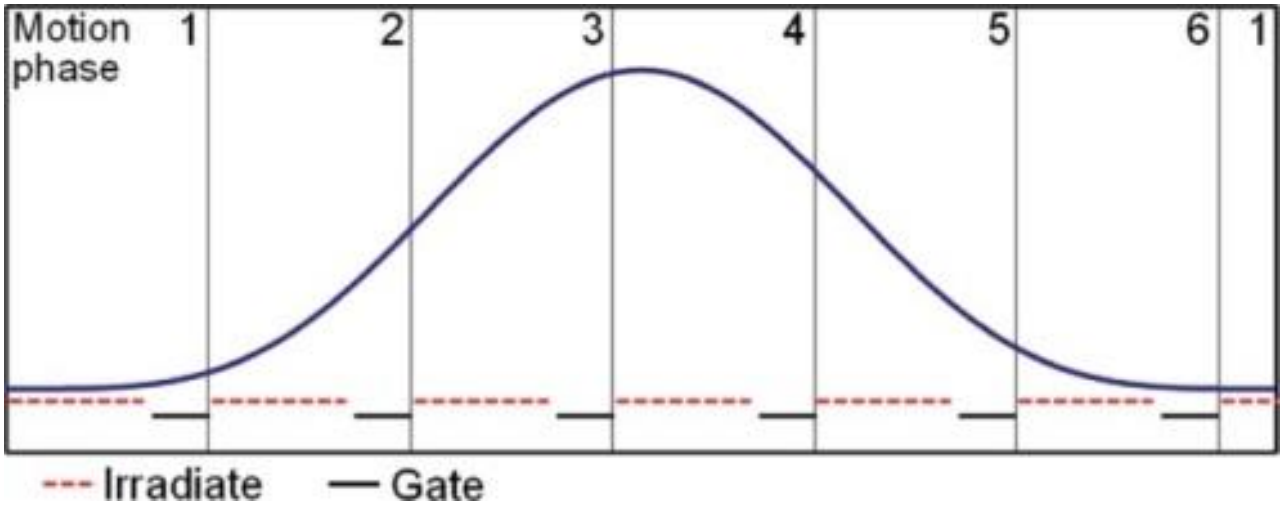
9 x Phase-controlled rescanning



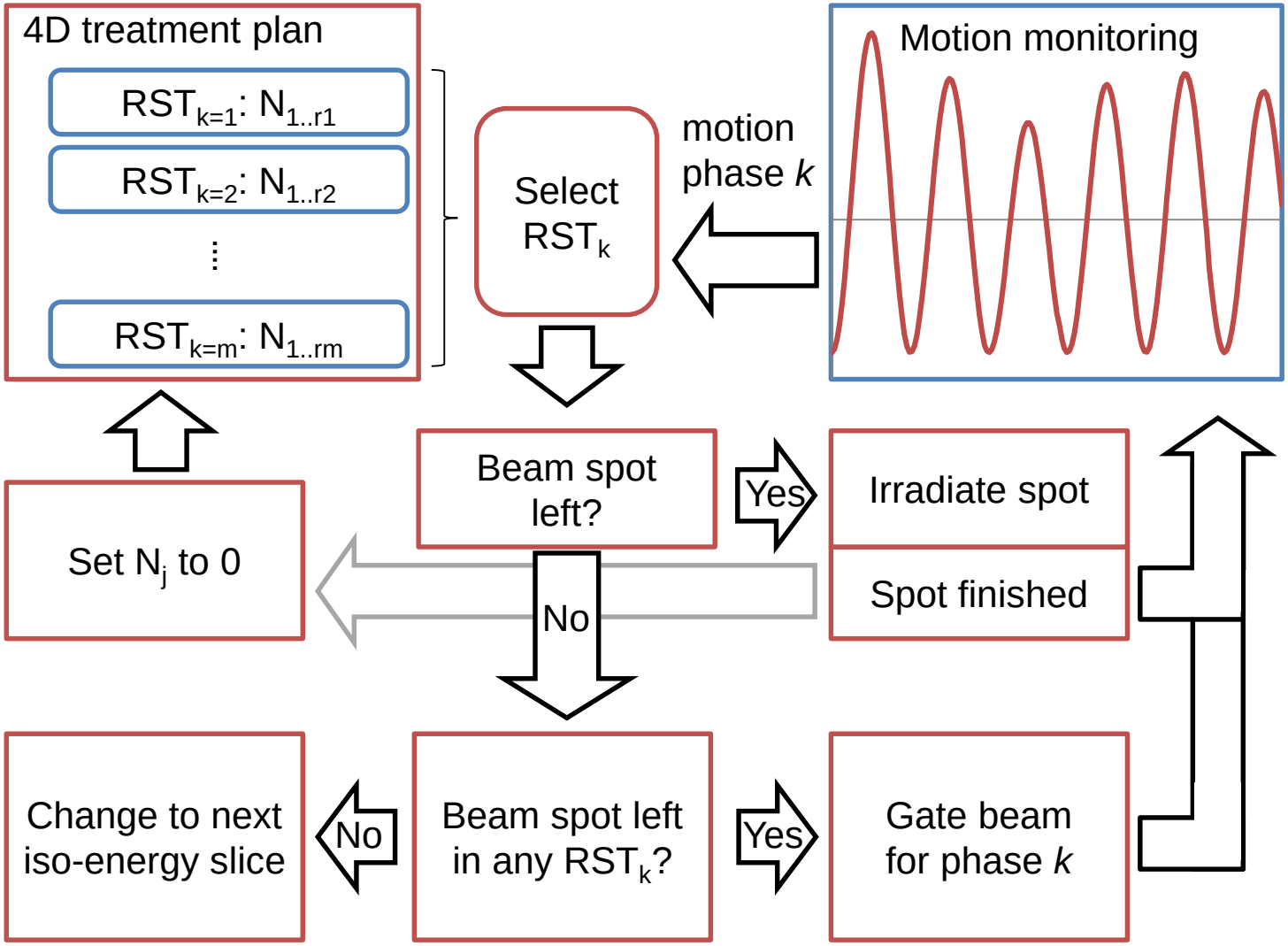
4D optimized dose delivery strategies:

Sectoring Rescanning **Multigating**

- Used in conjunction with tracking for online motion monitoring
- Alleviates limitations of tracking be re-optimizing particle number of 4DCT
  - complex motion, range changes
- Uses 4D optimization to minimize dose to OAR
- Delivers spots to each motion phase



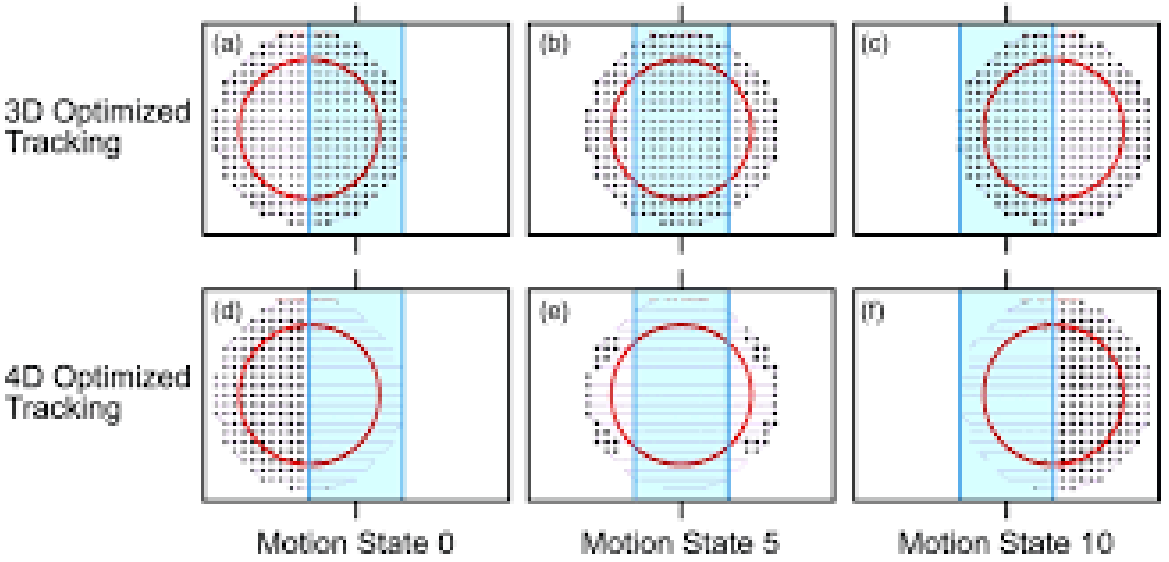
Delivery: The 4D dose delivery system



Graeff at al. Green Journal 2013

Combination of methods

- Possibilities:
  - Combing 4D optimization with tracking adjustments
  - more sophisticated tracking methods with imbedded 4D optimization
  - Fast scanning



Requirements for synchronized delivery

- Dose delivery system updates:
  - store a set of treatment plans instead of a single one
  - *detect motion phases*
  - dynamically switch sequence of beam spots to be irradiated
  - gate beam if motion phase is finished
    - gating on flat-top is necessary,
      i.e. fast recovery of irradiation
  - intensity control and flexible flattop duration is extremely helpful for fast & efficient delivery
- Extras:
  - using multiple ion species
  - Multi-energy extraction, dynamic intensity control
- Provide an open test bench for pre-clinical innovations *which are not possible under (legal) clinical constraint*

Thank you for your attention!

...questions?

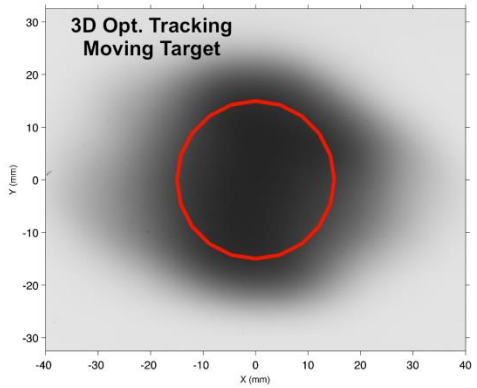
Experimental reproduction

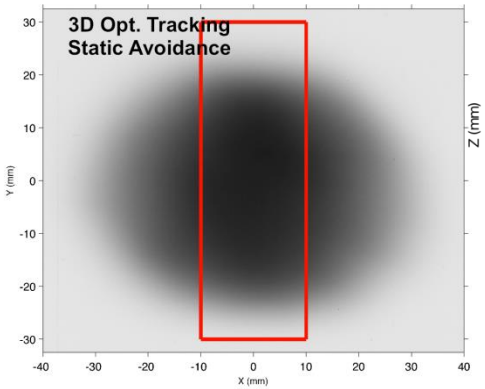
Film Measurements

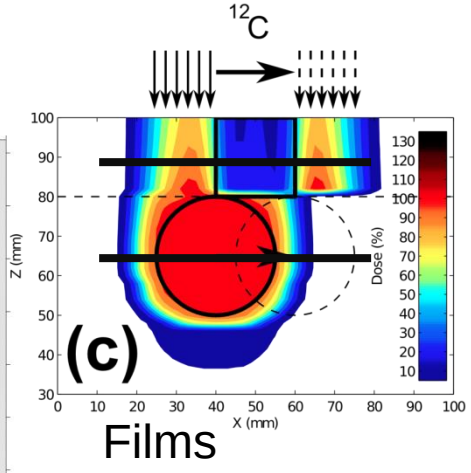
Moving Target

Avoidance Volume

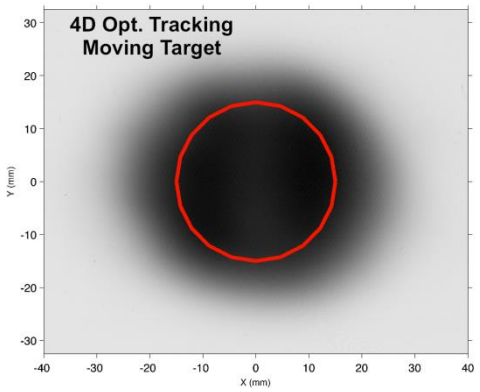
3D Optimized Tracking

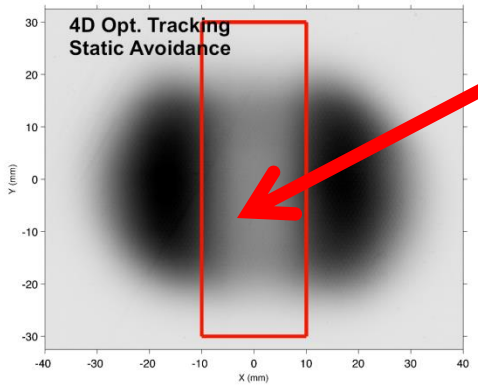






Full 4D Optimization

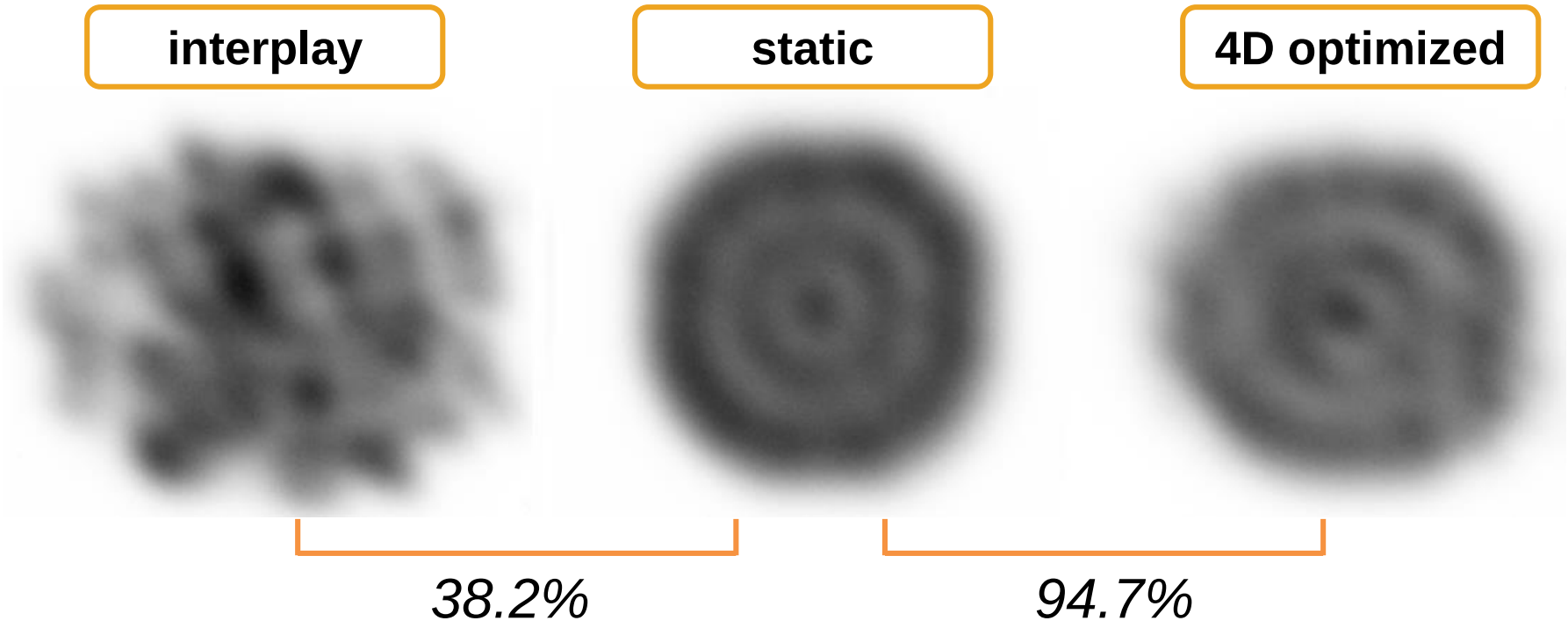




Sparing of avoidance volume using 4D optimization

JG Eley, PhD thesis, 2013

Feasibility of 4D-TCS: Film experiment



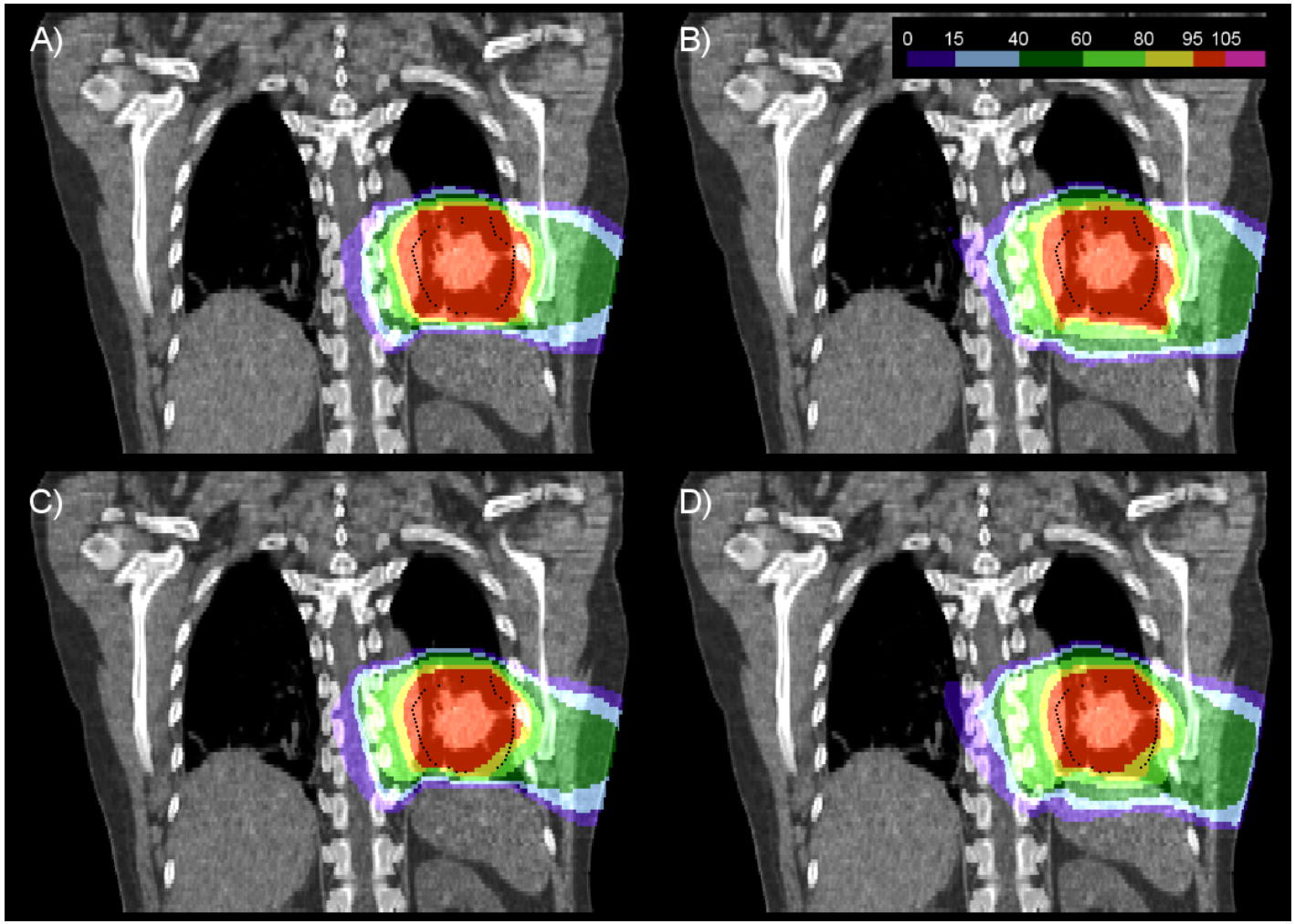
- Target: 30 mm circle, 20 mm left-right-amplitude
- Comparison: Gamma coefficient (3 mm, 3%)
- Residual motion within the states

Graeff at al. Green Journal 2013

Comparison of ITV and 4D-opt

planned 4D-dose

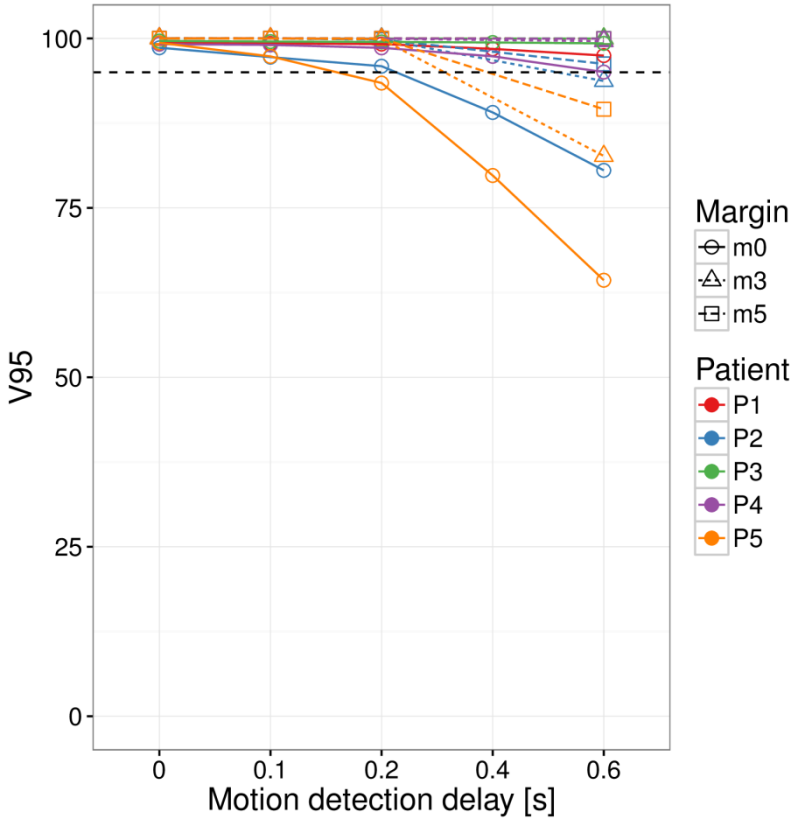
cumulative 4D-dose



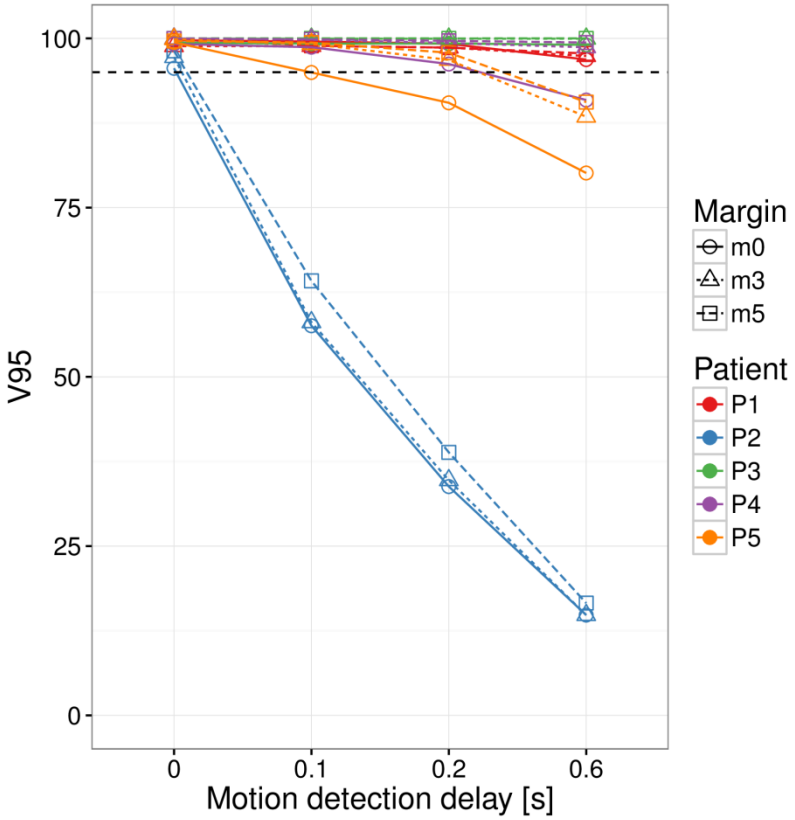
4D-opt ITV

Robustness: Desynchronization

- Artificial delay induced between motion detection and irradiation



4D-rescanning



4D-sectors

- Gradients between phases are highly relevant!