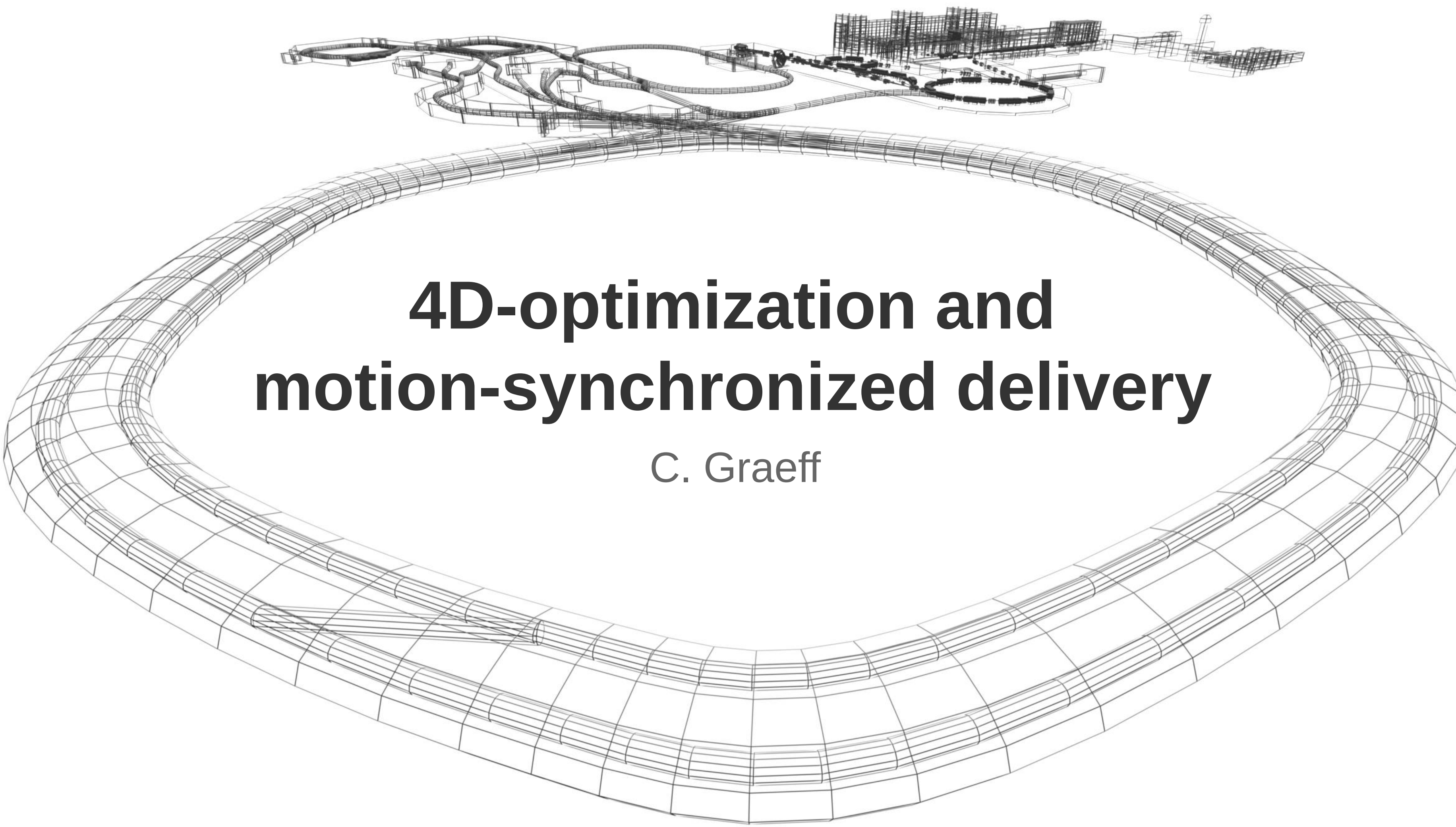
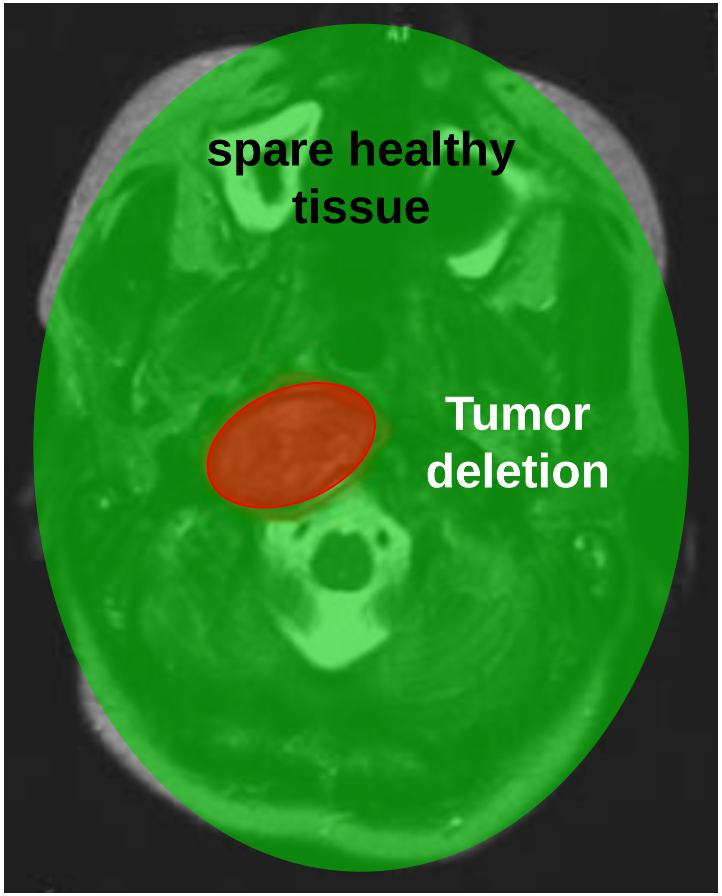
GSI Helmholtzzentrum für Schwerionenforschung GmbH



4D-optimization and motion-synchronized delivery

C. Graeff

Aim of radiotherapy

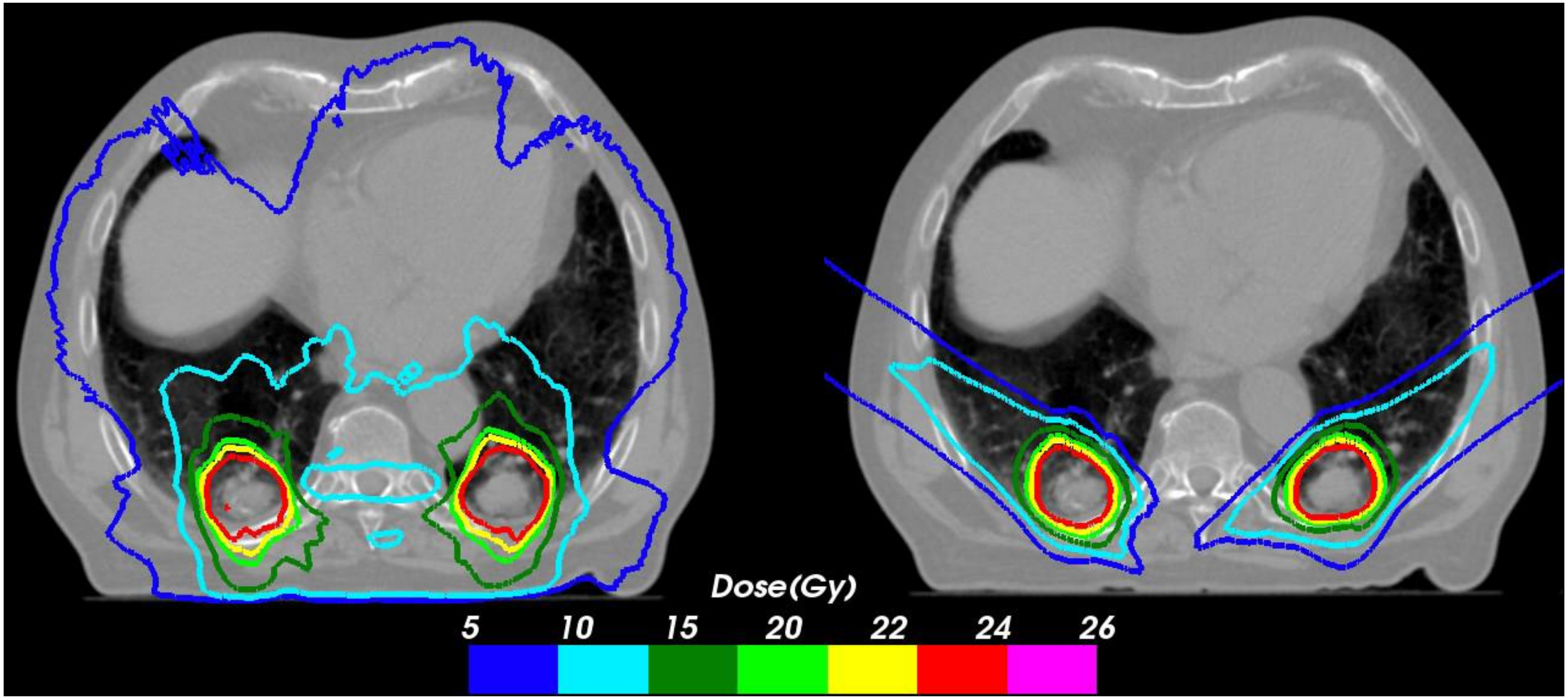


- Treat tumors - spare surrounding healthy tissue
- Conformal treatment

http://xkcd.com/1217

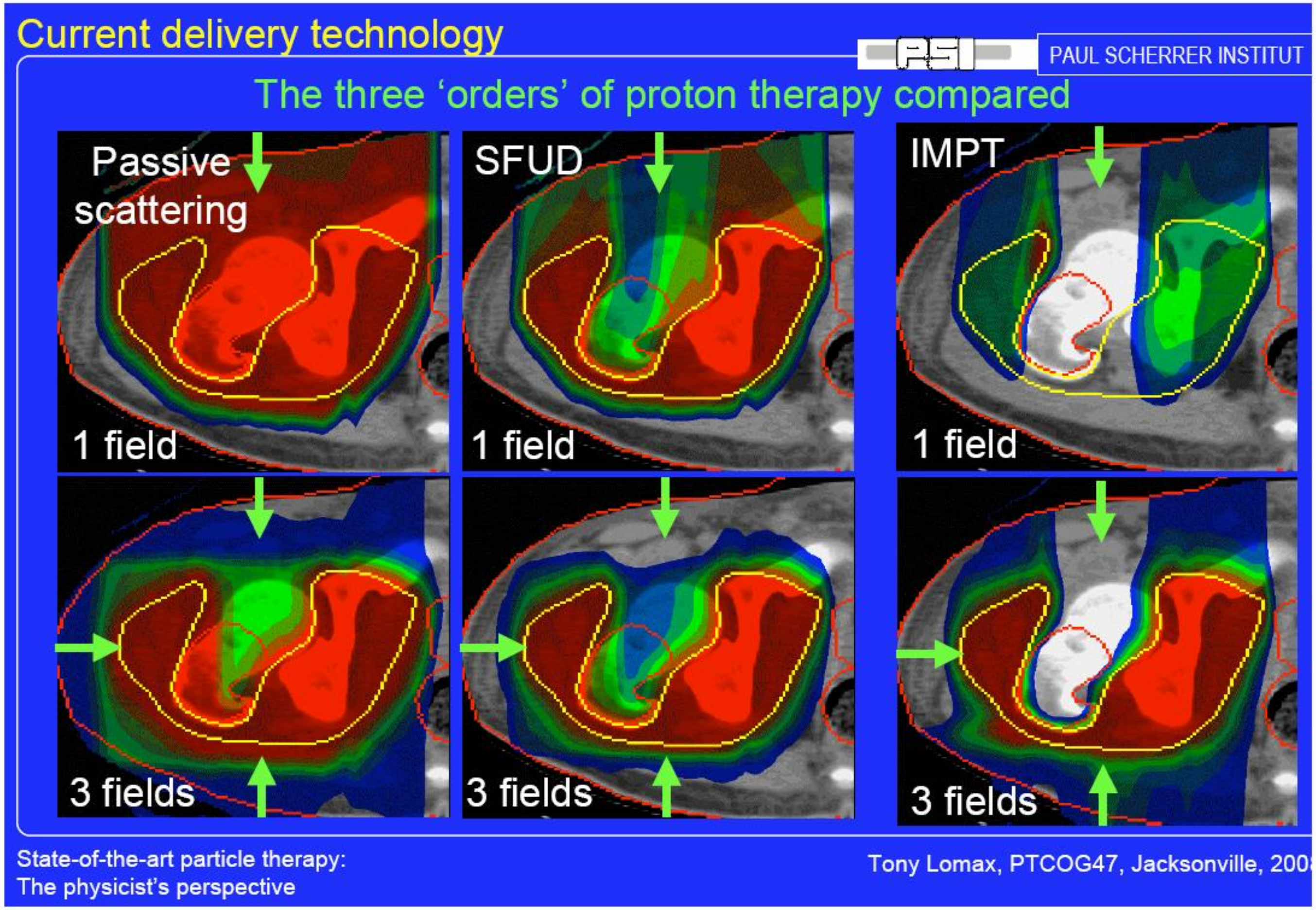
Rationale for 4D-treatment with ions

- Ions more conformal than photons

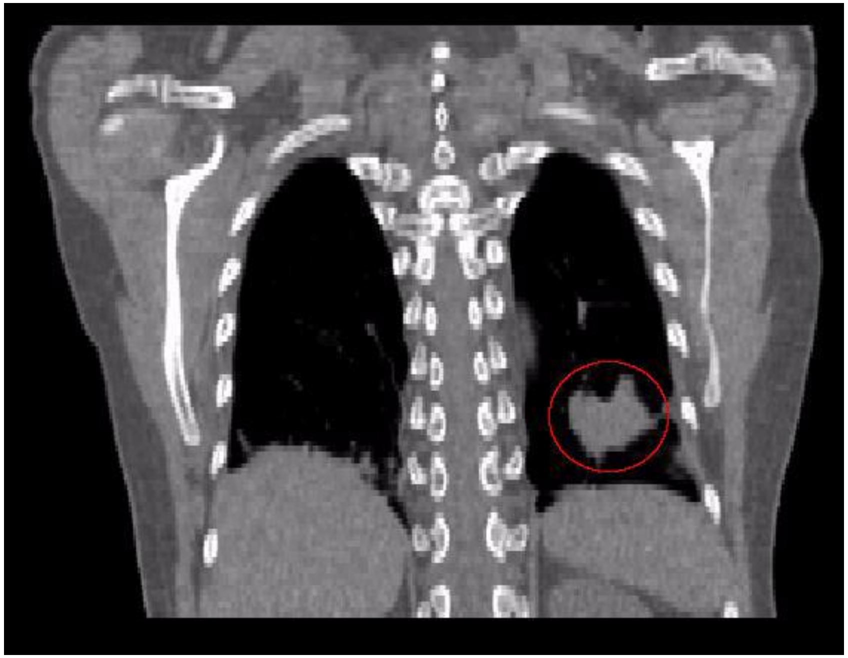


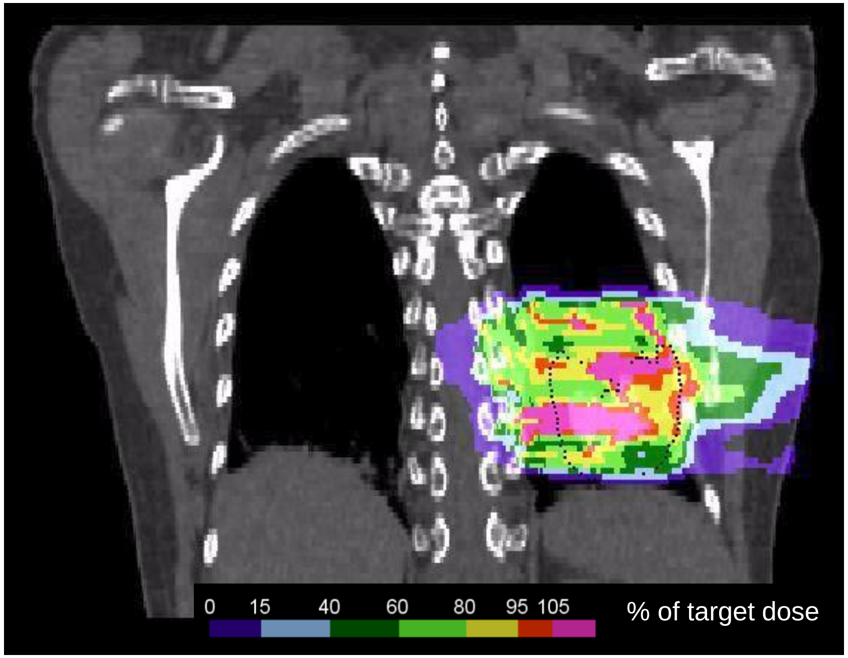
Rationale for 4D-treatment with ions

- Active delivery more conformal than passive



Motion and scanned delivery



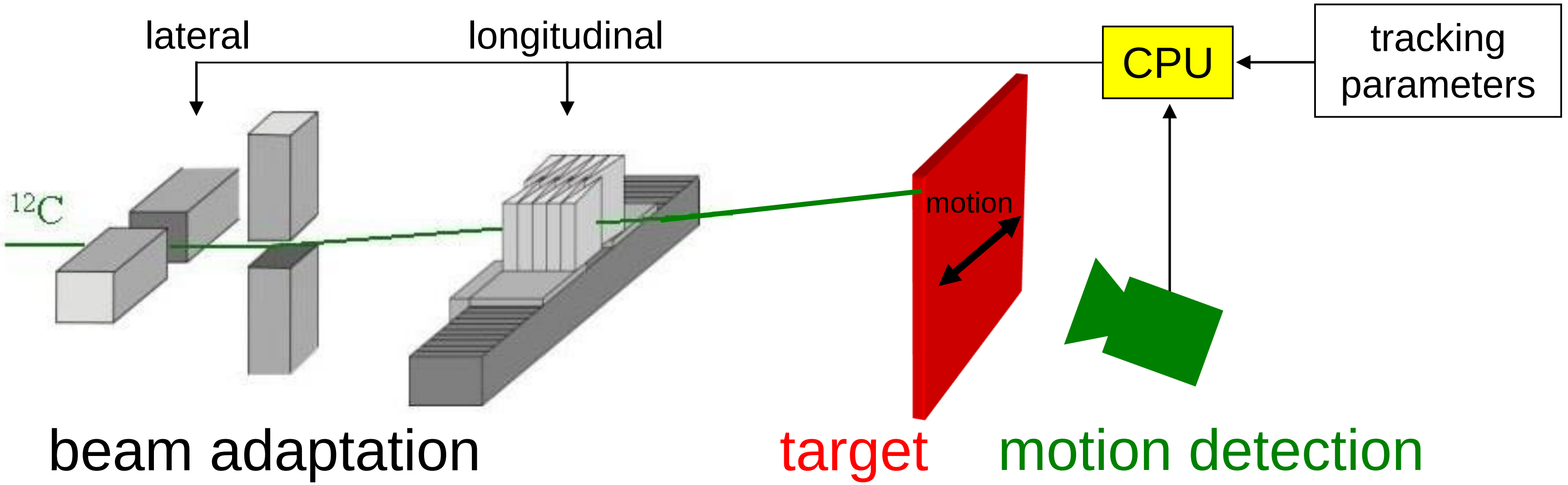


Courtesy M. Söhn, LMU

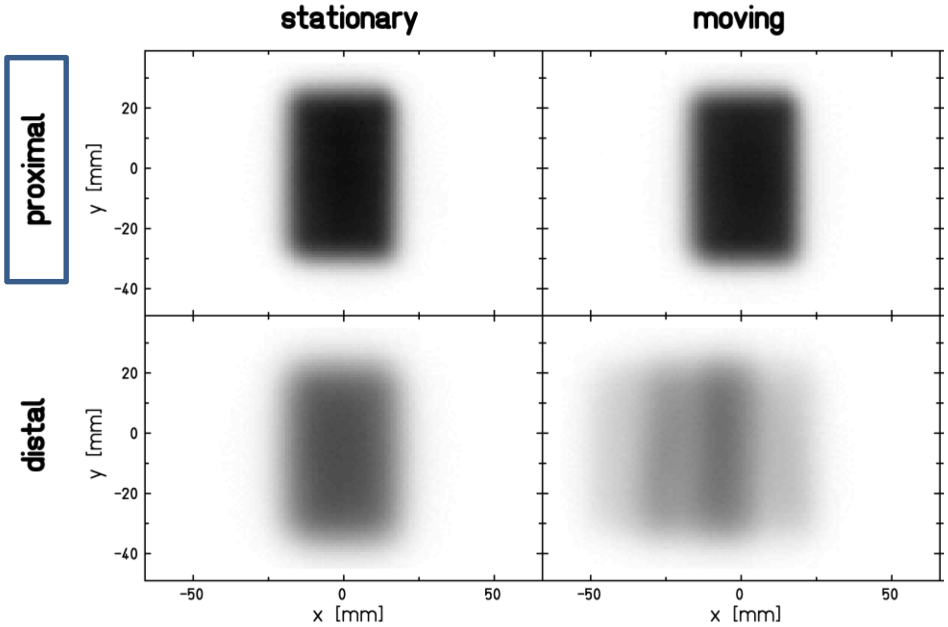
- **Motion**: Target miss
- **Range changes**: variable position of Bragg peaks
- **Interplay**: Interference between target and scanning motion

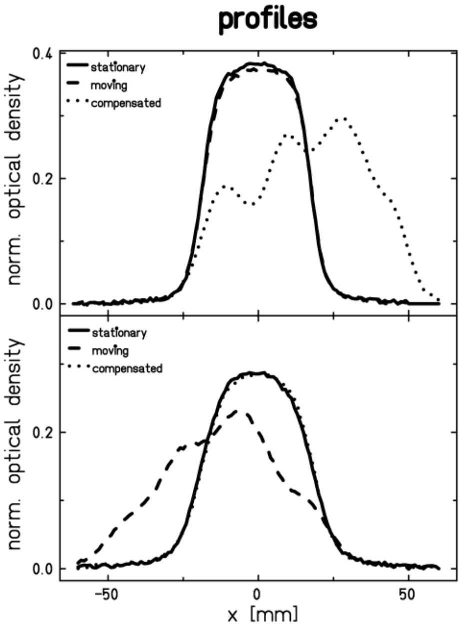
Beam Tracking

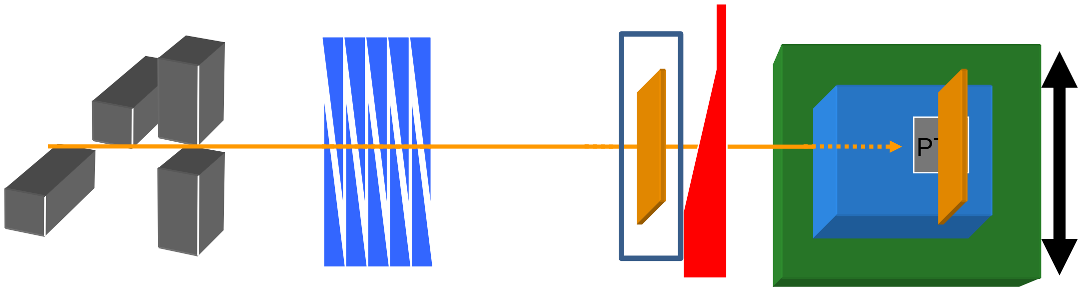
- Tremendous advantage over photons:
  Easy, fast beam deflection



Tracking issues I: inverse interplay

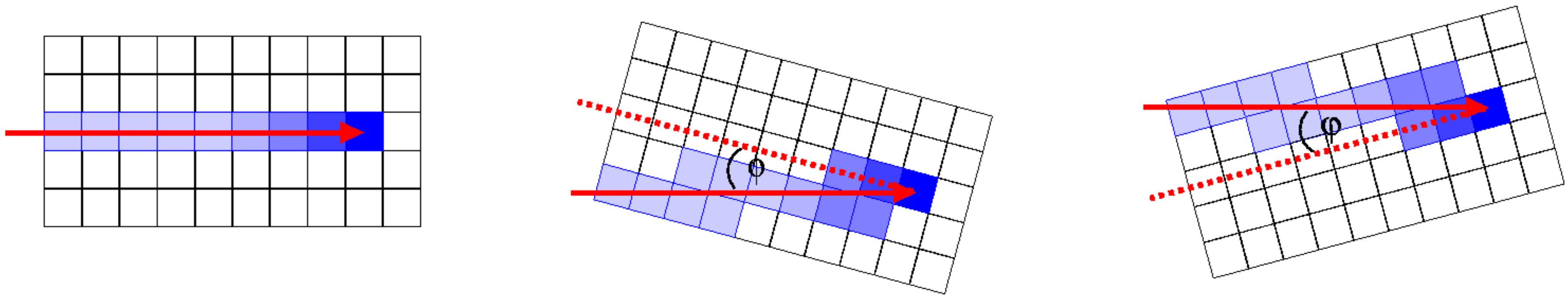






Tracking issues II: complex motion

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



Motion State Reference | Motion State k | Motion State i

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

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

Voxels

beam spots

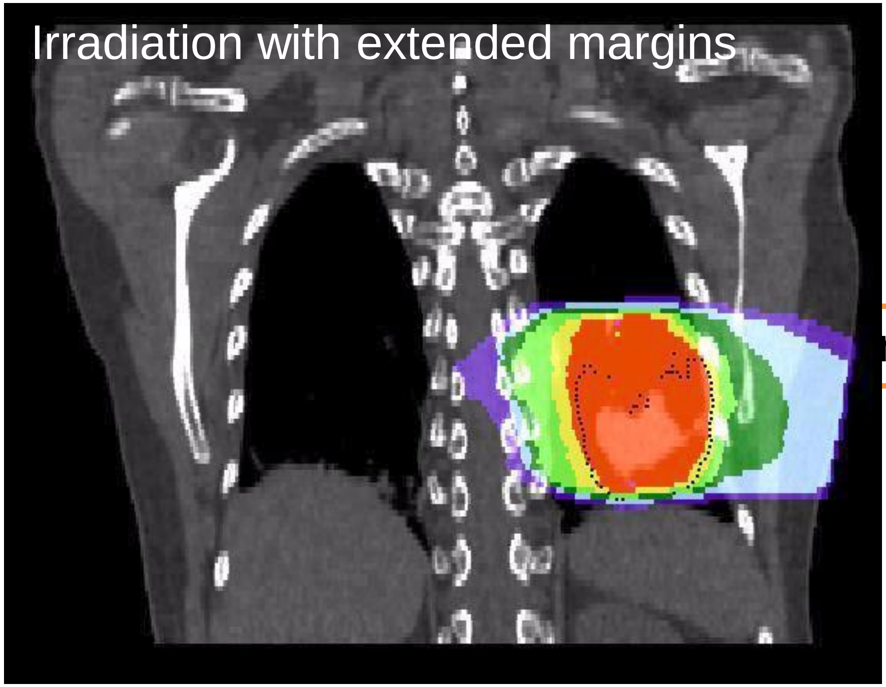
motion phases

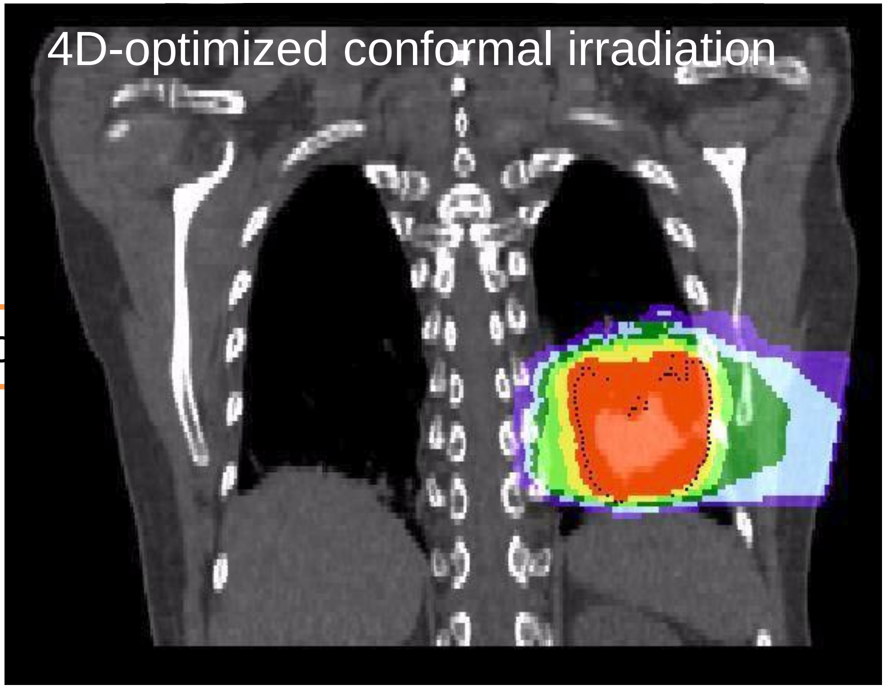
- Different strategies possible to control gradients, reduce problem size, ...

- (OAR terms omitted)

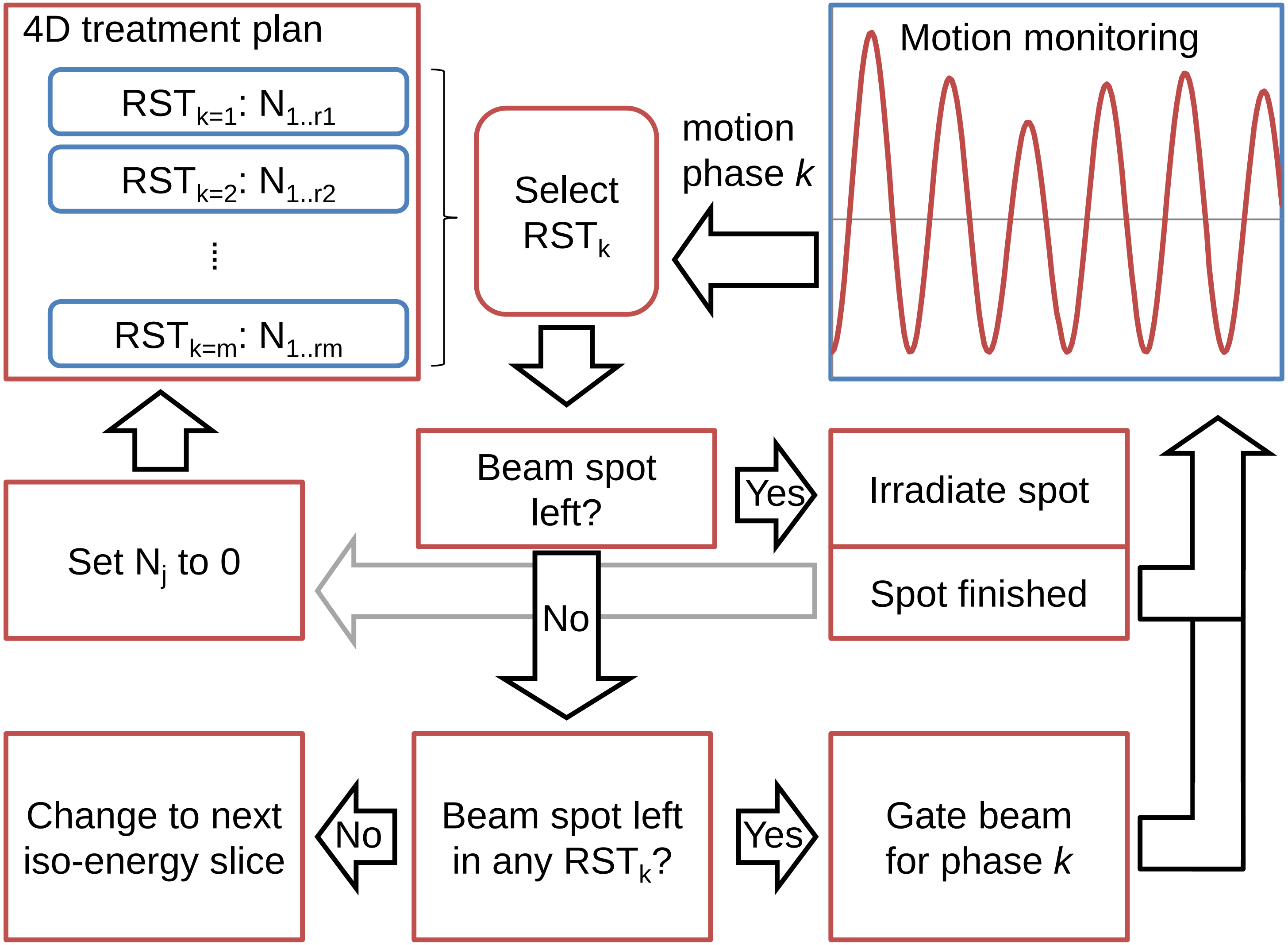
Motion-synchronized delivery

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





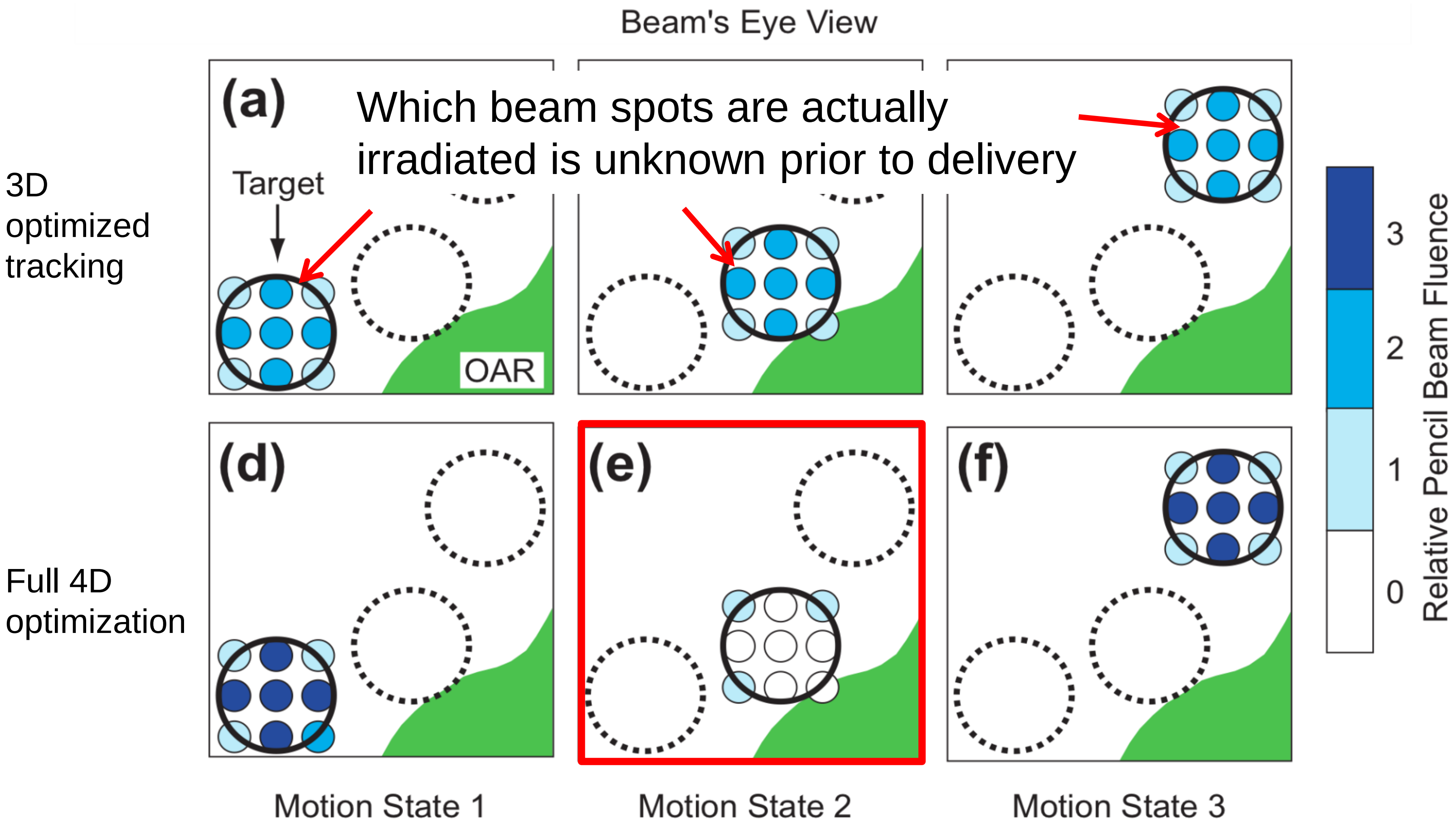
Delivery: The 4D therapy control system



Graeff at al. Green Journal 2013

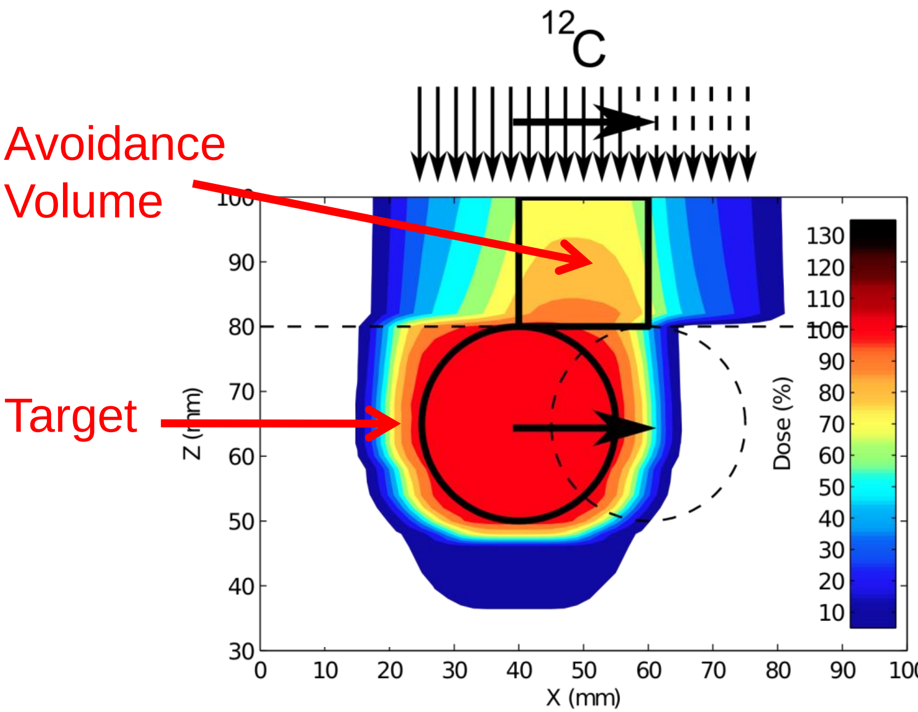
Potential exploitation of differential motion

- Reduce fluence when target is closest to organ at risk (OAR)

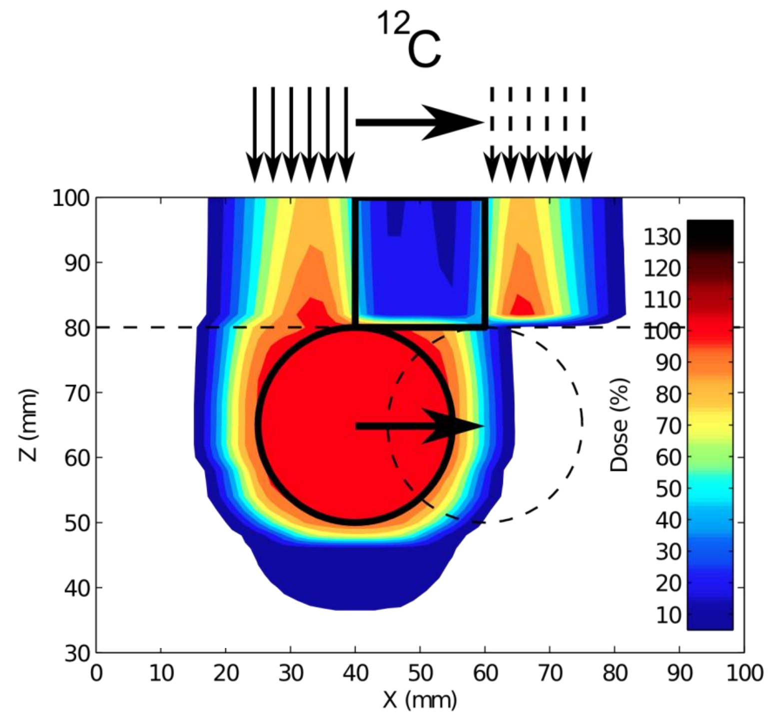


JG Eley et al, PMB, 2014

Simulation - Moving Target in Water Phantom



3D Opt. Tracking



Full 4D Optimization

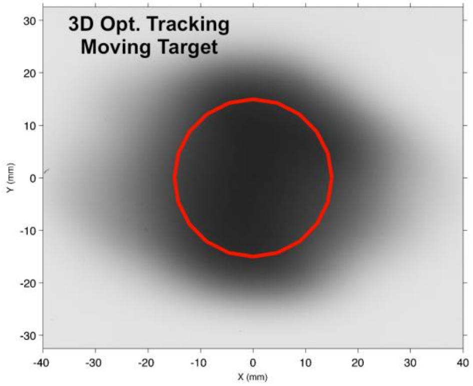
JG Eley et al, PMB, 2014

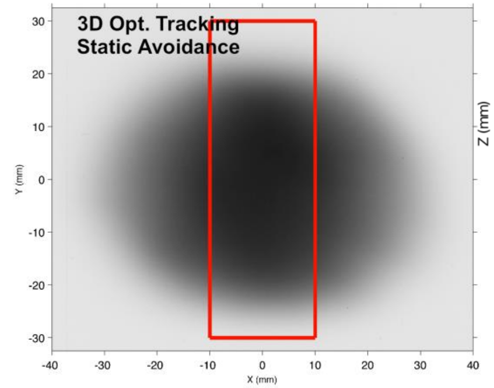
Experimental reproduction

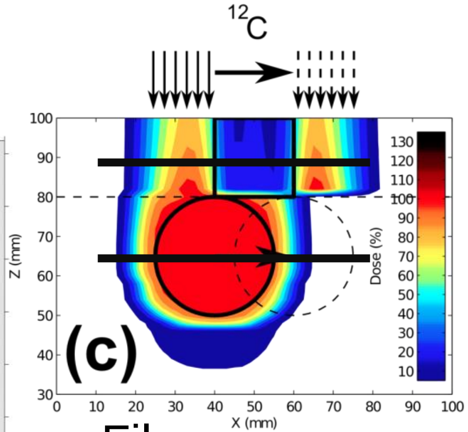
Film Measurements

Moving Target | Avoidance Volume

3D Optimized Tracking

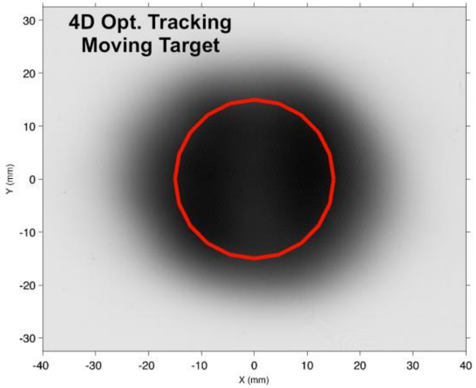


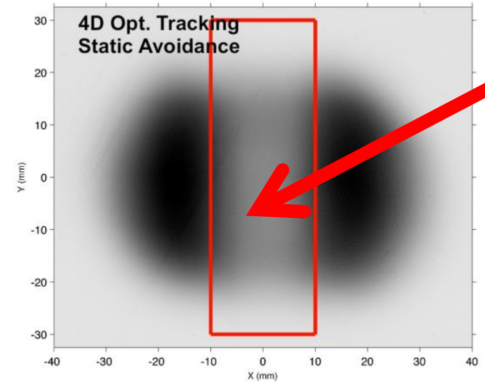




Films

Full 4D Optimization



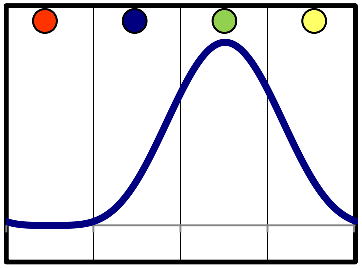


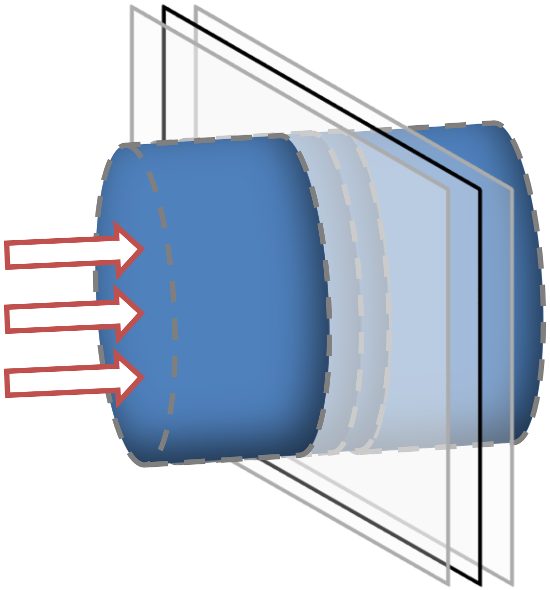
Sparing of avoidance volume using 4D optimization

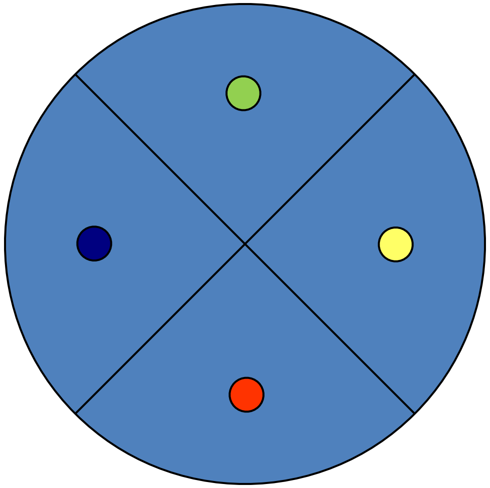
JG Eley, PhD thesis, 2013

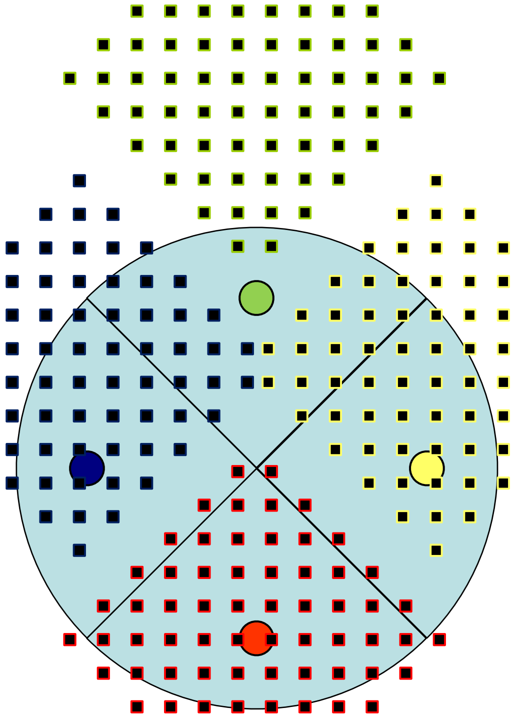
4D-sectors: Definition of subsections

- 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



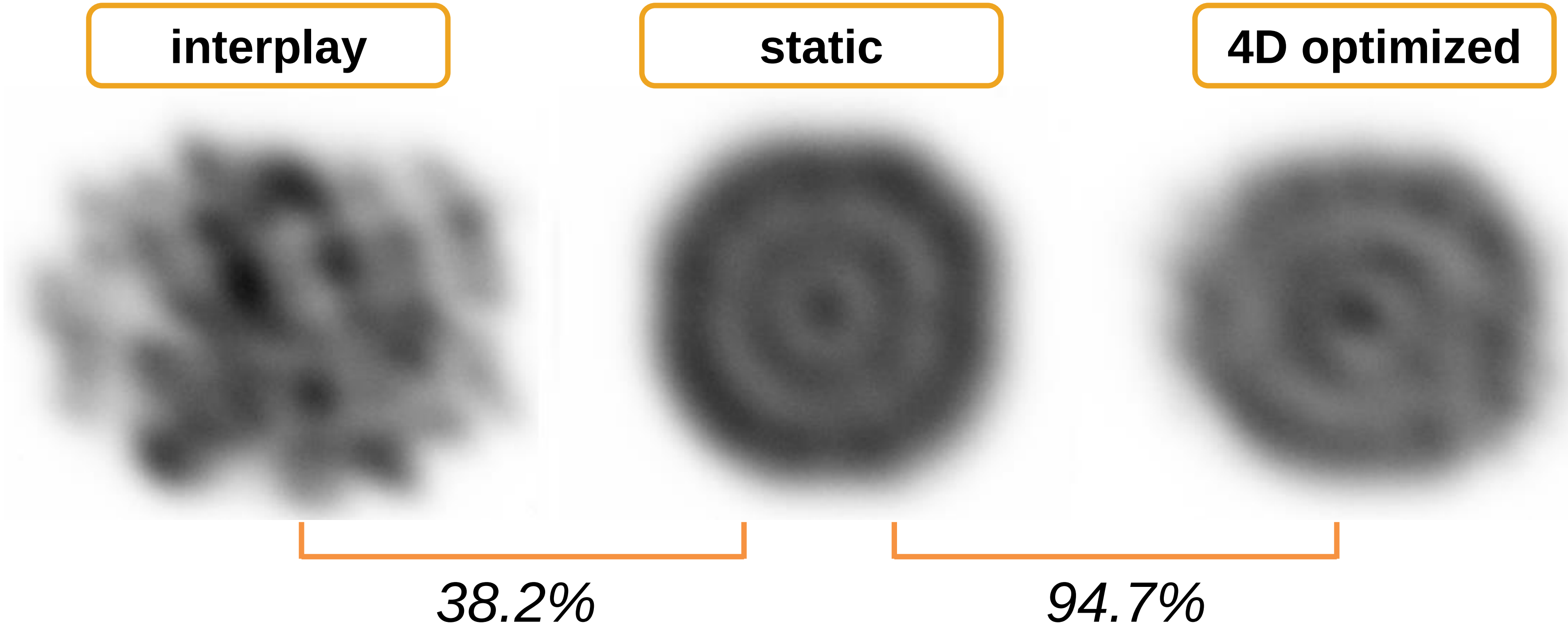






Graeff at al. Green Journal 2013

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

Requirements for synchronized delivery

- Dose delivery system has to
  - 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

Robustness:4D-controlled rescanning

- Optimize target coverage **in each motion phase**

4D Optimized Rescanning

Full 4D optimization

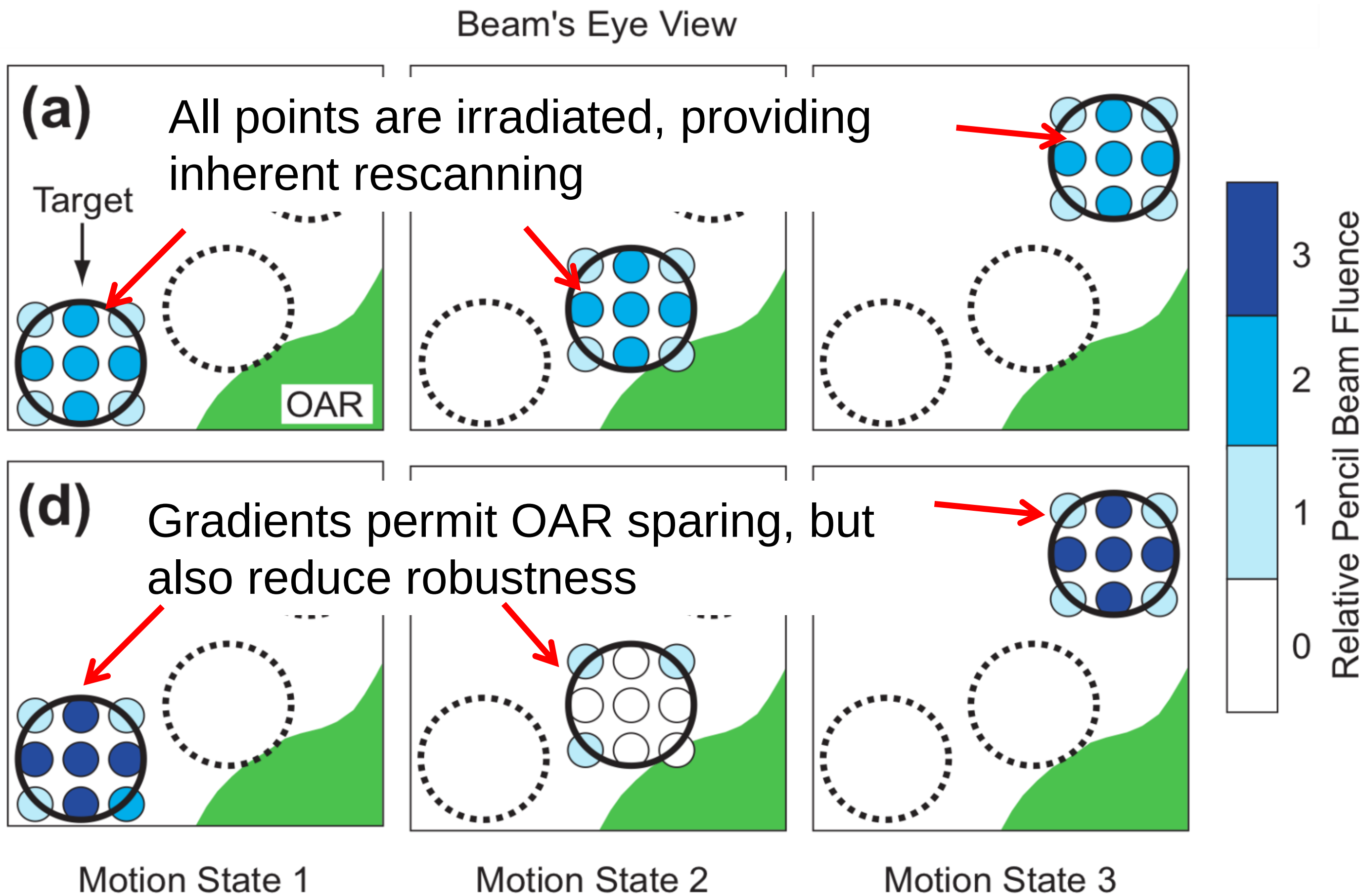


image courtesy of John Eley

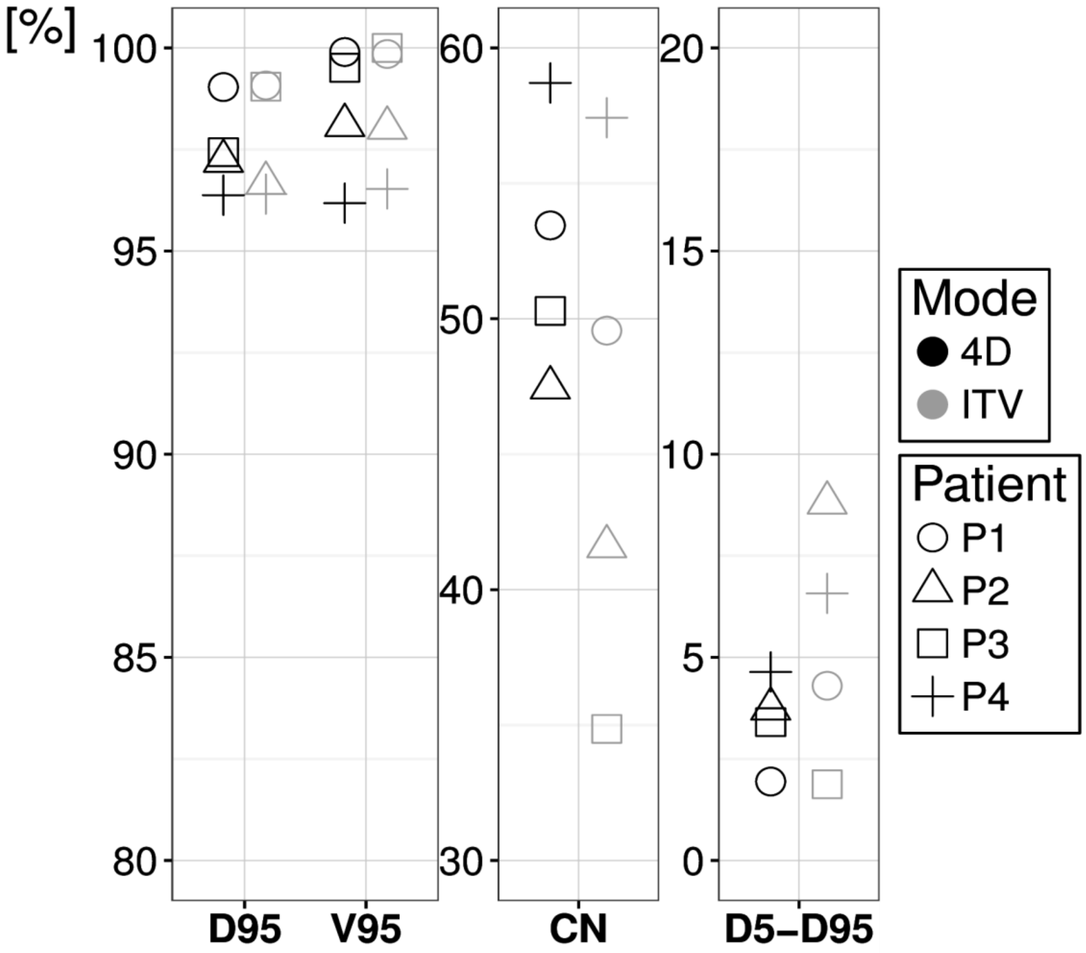
A patient simulation study

- 6 weekly 4D-CTs for each patient
- Planning on first CT, simulation on all subsequent CTs
- Margins needed to achieve V95 > 95% in cumulative dose

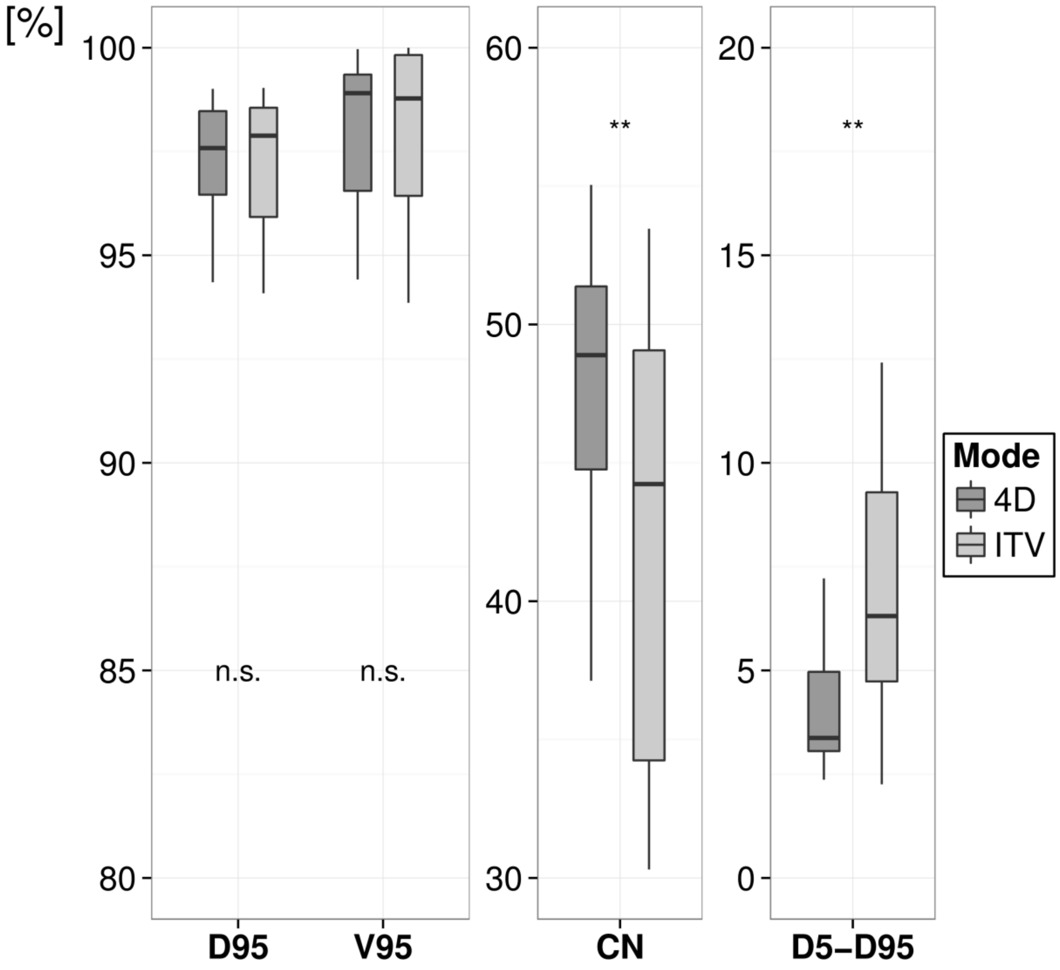
	Fraction 4DCTs (weeks 2 - 6)		
Patient	CTV Amplitude (min - max) [mm]	abs ΔRange: week n - week 1 (median, range) [mm H2O]	Necessary Margins V95>95% [mm + mm,%]
P1	2.8 - 3.9	2.2 (1.3 – 5.9)	3 + 2
P2	6.6 - 15.9	4.3 (1.3 – 6.3)	7 + 2
P3	2.1 - 5.4	1.6 (0.8 – 3.0)	3
P4	20.6 - 27.5	6.9 (4.4 – 11.2)	7 + 2

- Same margins necessary for ITV coverage

Cumulative dose results

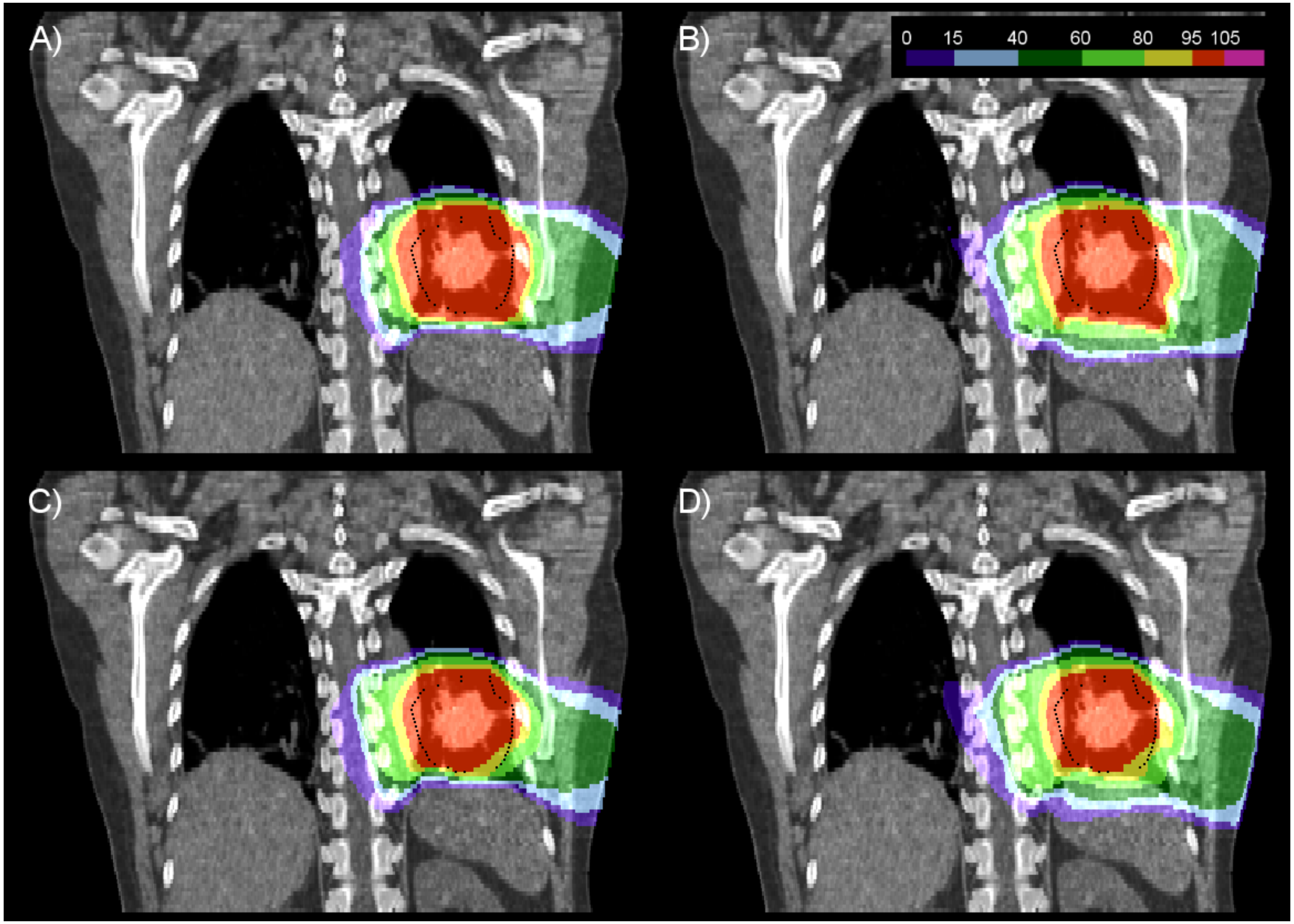


Individual fractions



- paired t-test, **: p< 0.001

Comparison of ITV and 4D-opt



planned 4D-dose

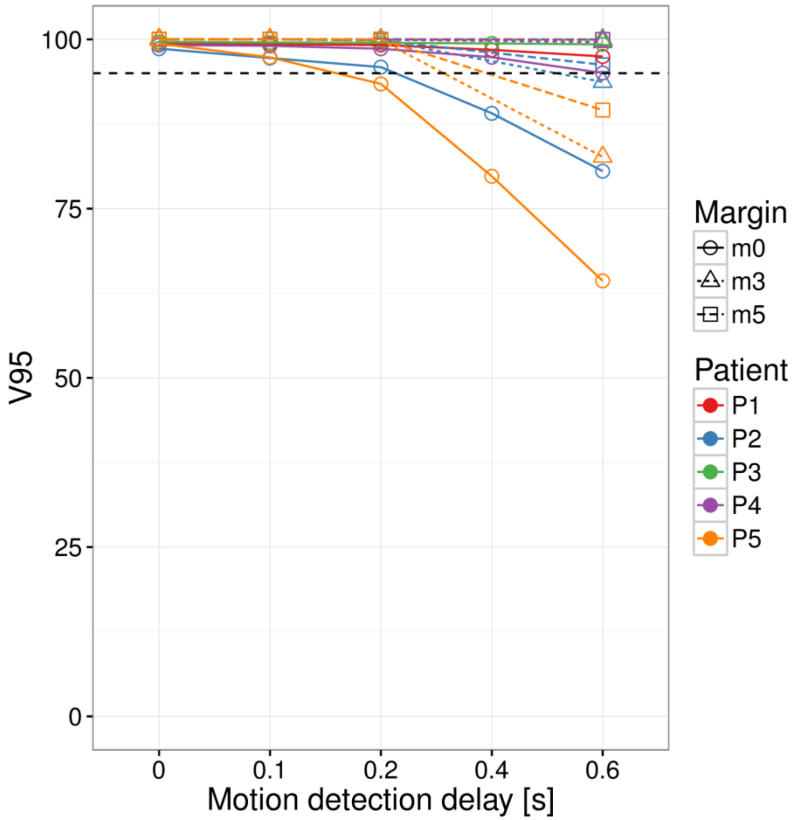
cumulative 4D-dose

4D-opt

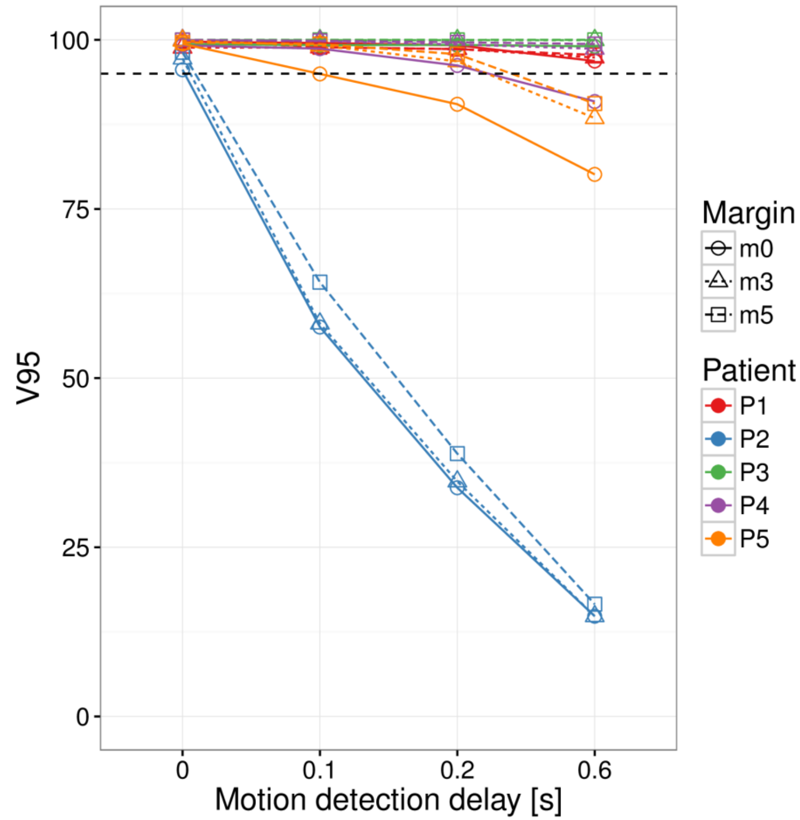
ITV

Robustness: Desynchronization

- Artificial delay induced between motion detection and irradiation



4D-rescanning



4D-sectors

➢ Gradients between phases are highly relevant!

Outlook

- Renovation of GSI Cave M dose delivery system until 2019 – based on the CNAO DDS

1. Increased scan speed:
   detectors, algorithms,
   (intensity control, multi-energy extraction)
2. Motion integration:
   motion detection, 4D-dose reconstruction
3. Synchronized dose delivery:
   within ITN „Optimization of Medical Accelerators“
   - Fully functional, clinically valid system – patient trials??

fondazione CNAO
Centro Nazionale di Adroterapia Oncologica per il trattamento dei tumori