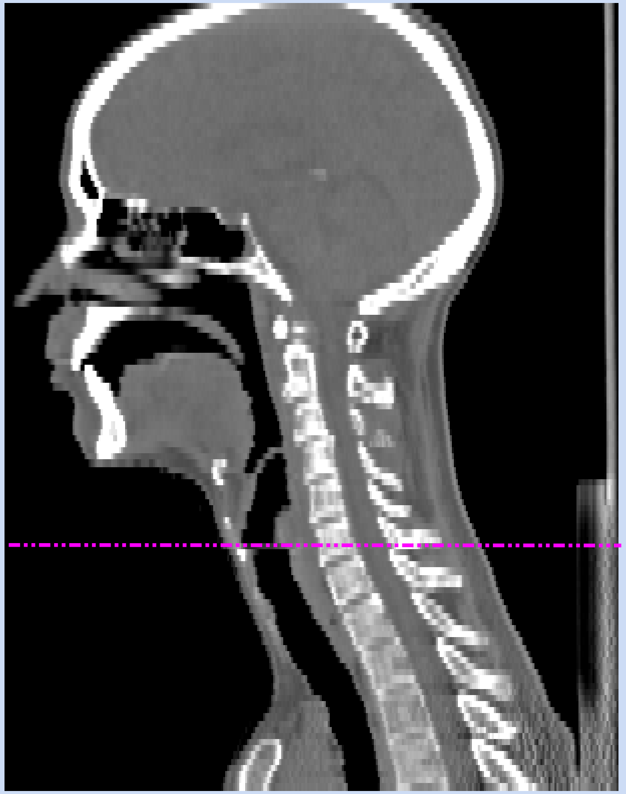
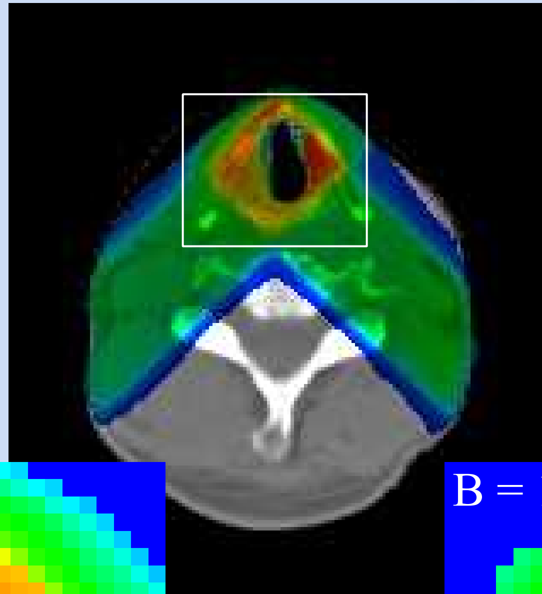
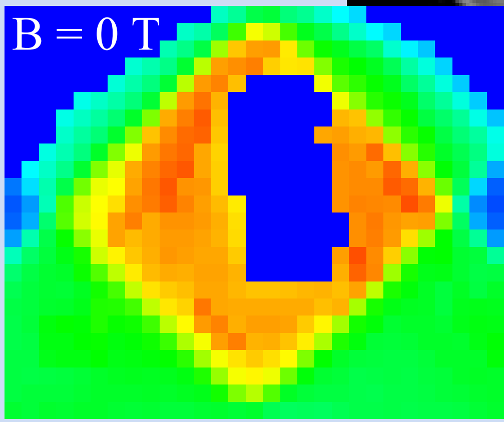
Simulations for the virtual prototyping of a radiotherapy MRI-accelerator system:

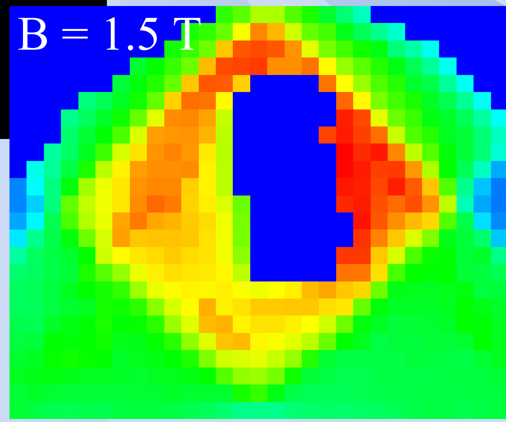
Linear accelerator output, CT-data implementation, dose deposition in the presence of a 1.5 T magnetic field.

A.J.E. Raaijmakers, B. Liu, B.W. Raaymakers, J.J.W. Lagendijk









Outline

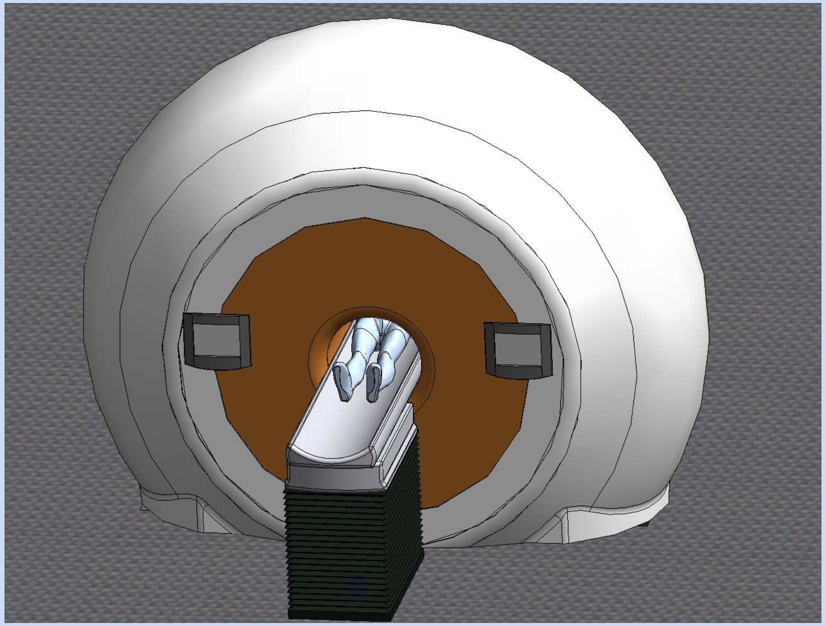
- Introduction MRI-accelerator
- Work done so far
  - Comparison of GEANT4 to TPS PLATO
  - Simulation results of dose deposition in B-field
  - First results for simulation of ionization chamber in B-field
- Problems, pitfalls and solutions working with GEANT4
  - Testing CT-data implementation with inhomogeneity
  - Nearest neighbour navigation
  - Parameterized volume CopyNo mismatch
  - ROG energy misdeposition
- Final remarks and future work

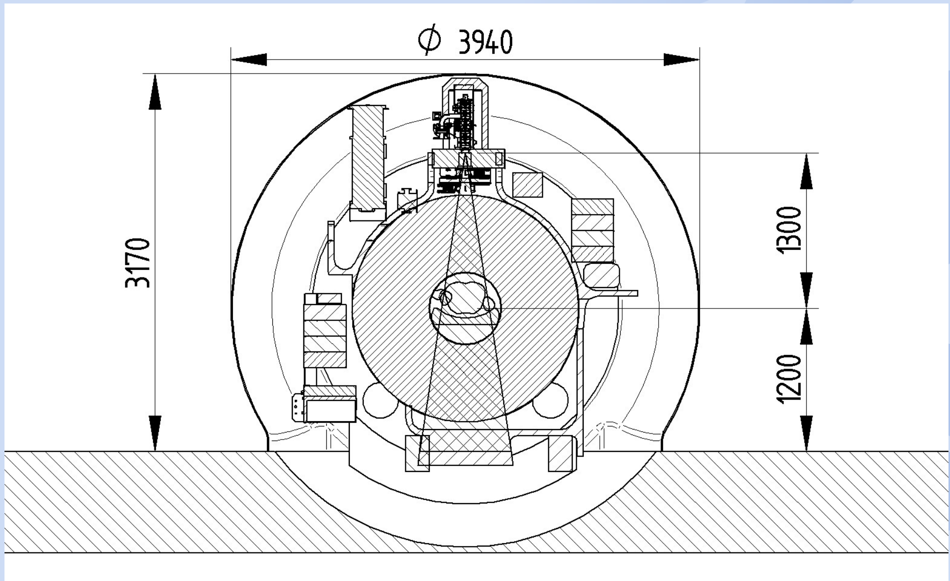
MRI-scanner + 6 MV linear accelerator

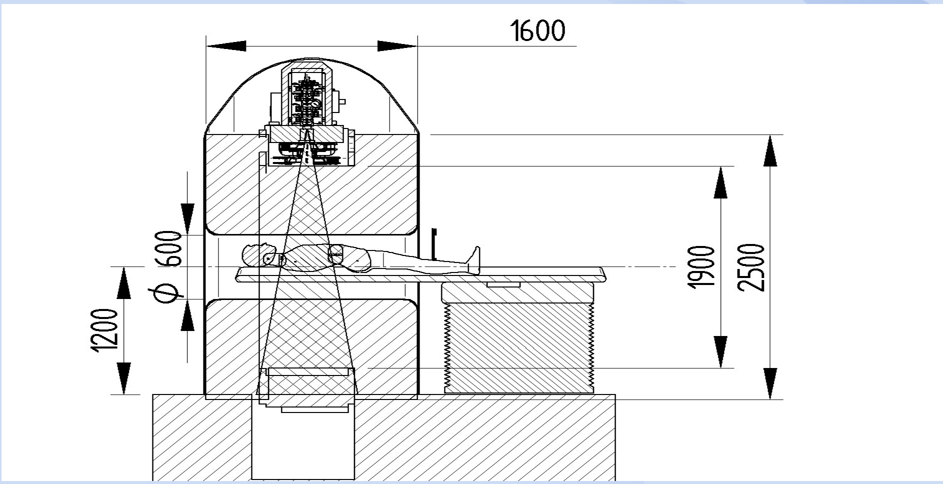
Radiotherapy accelerator

1.5 T MRI system

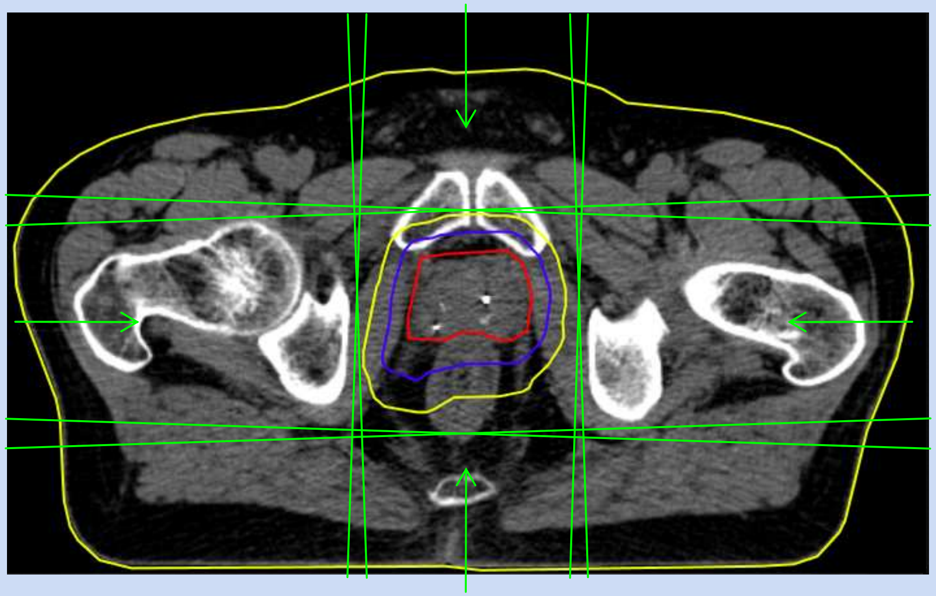
MRI-scanner + 6 MV linear accelerator

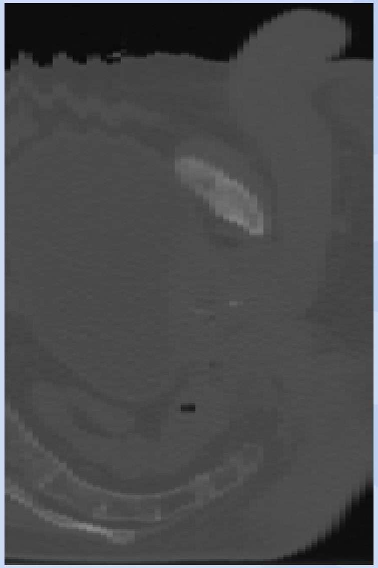


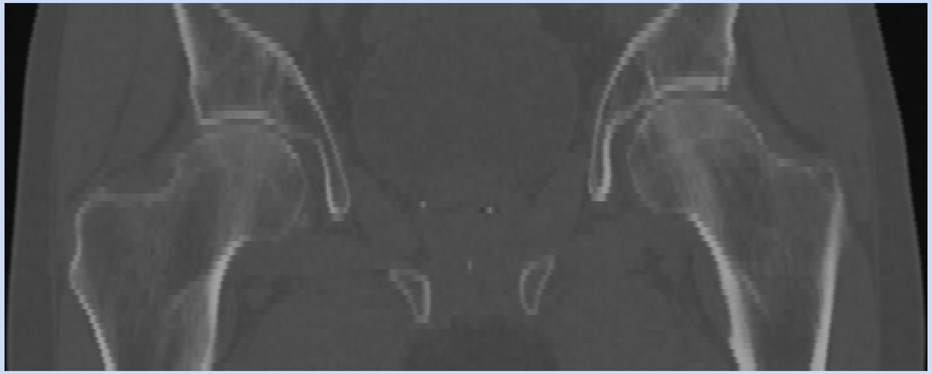




Validation of CT-data implementation
Comparison of simulation results to TPS "Plato"







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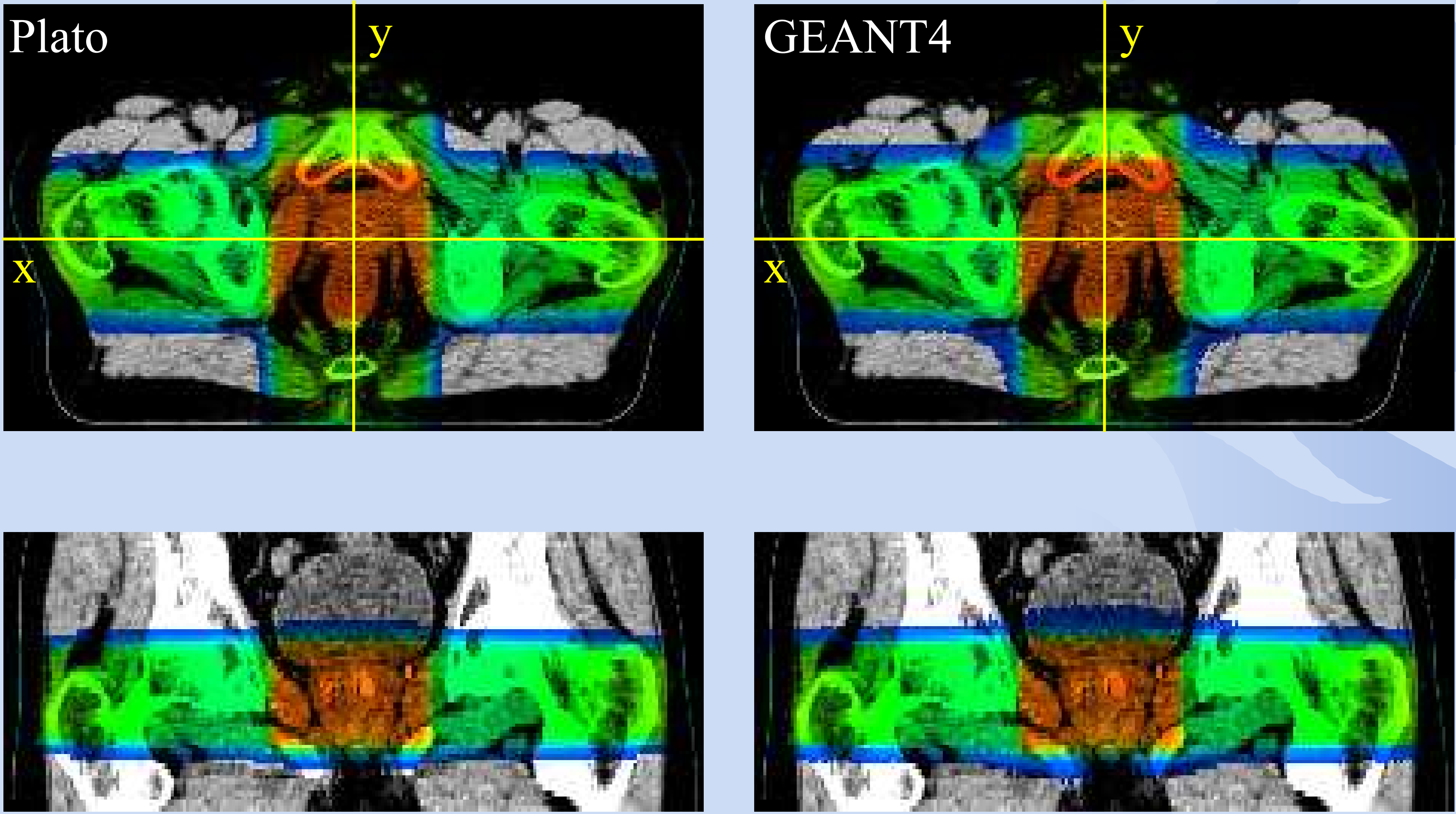

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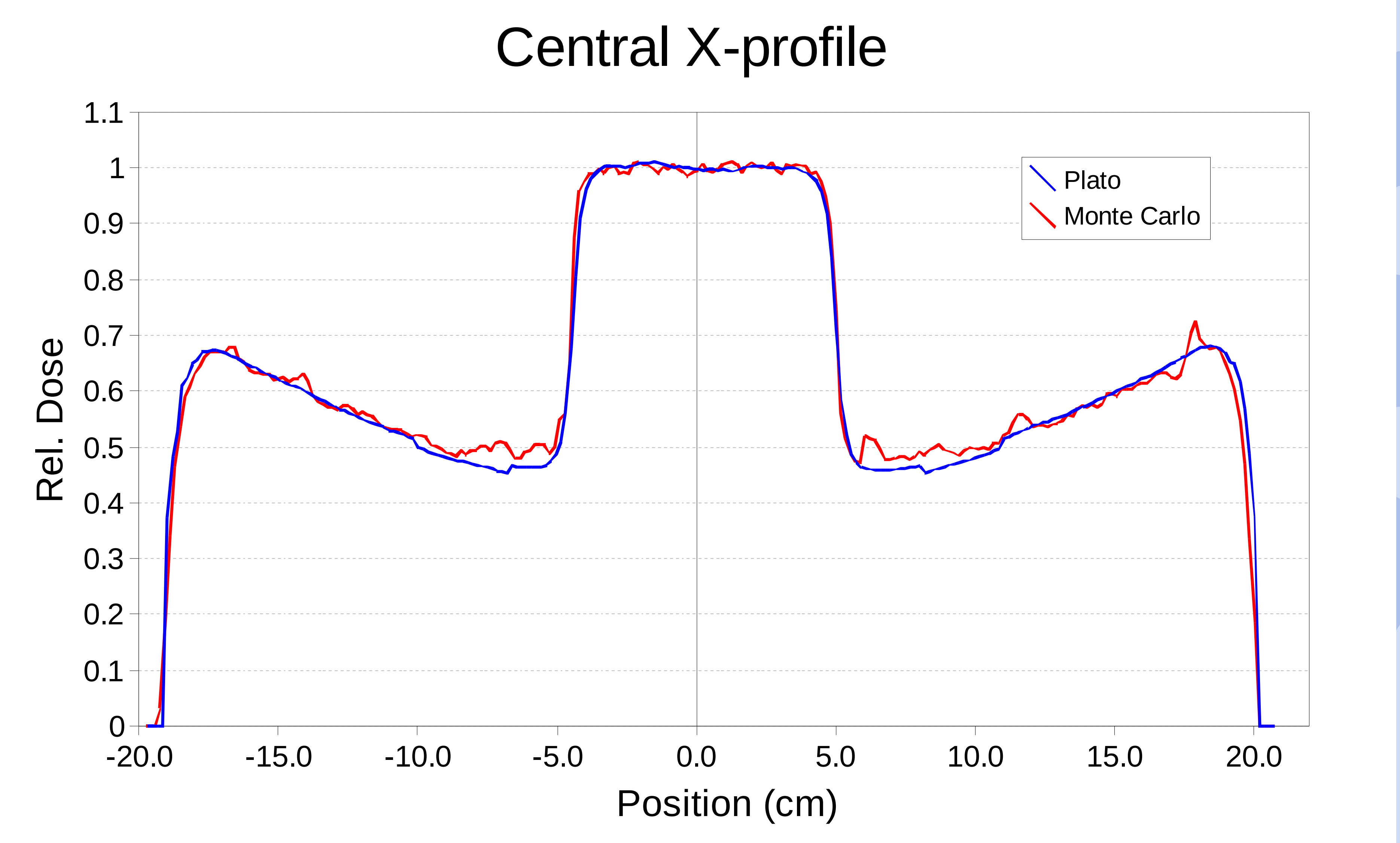

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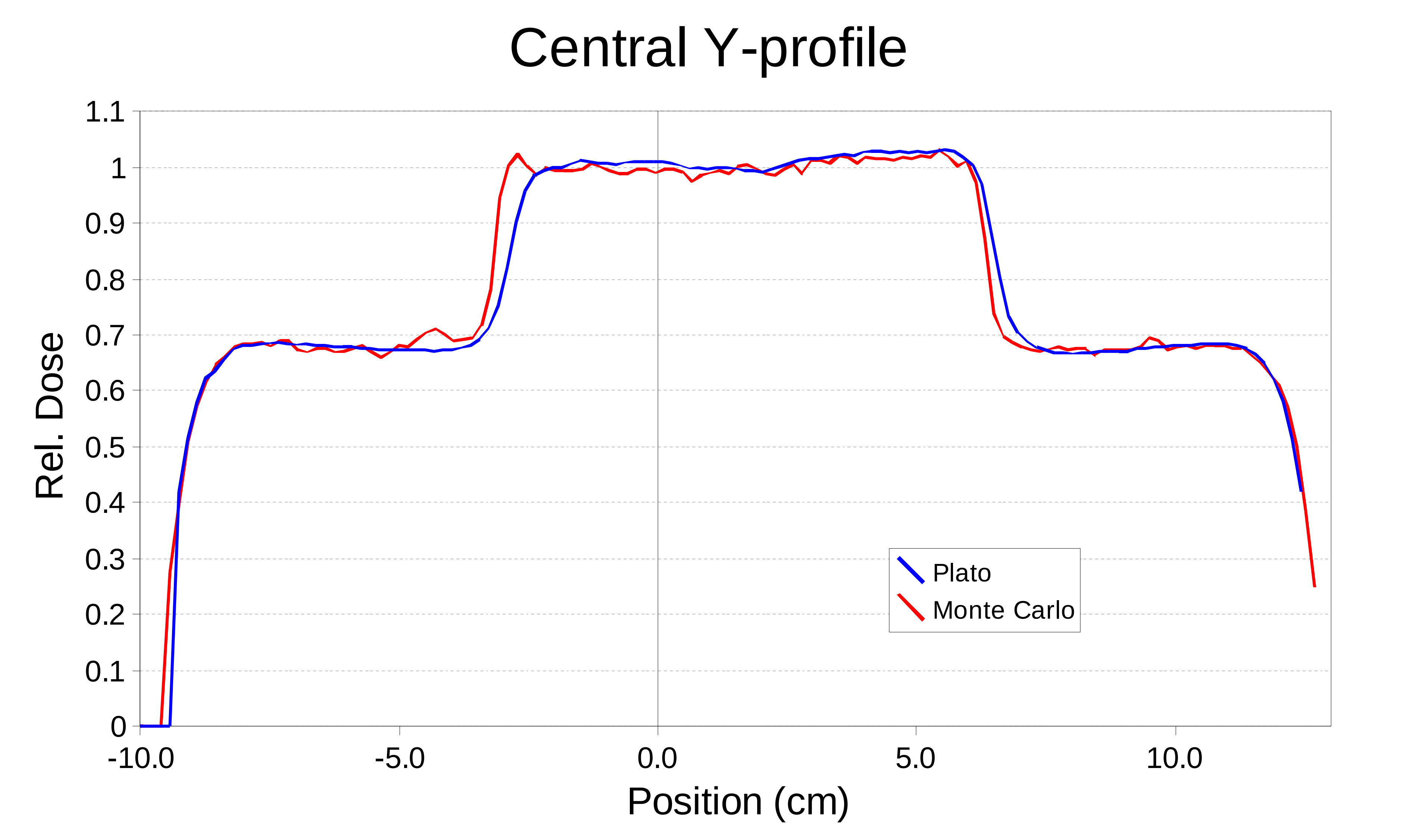
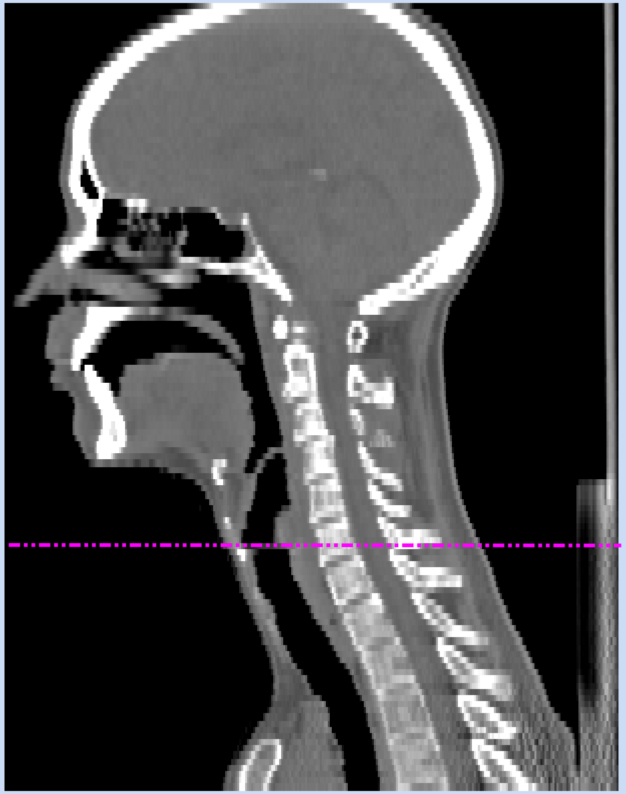
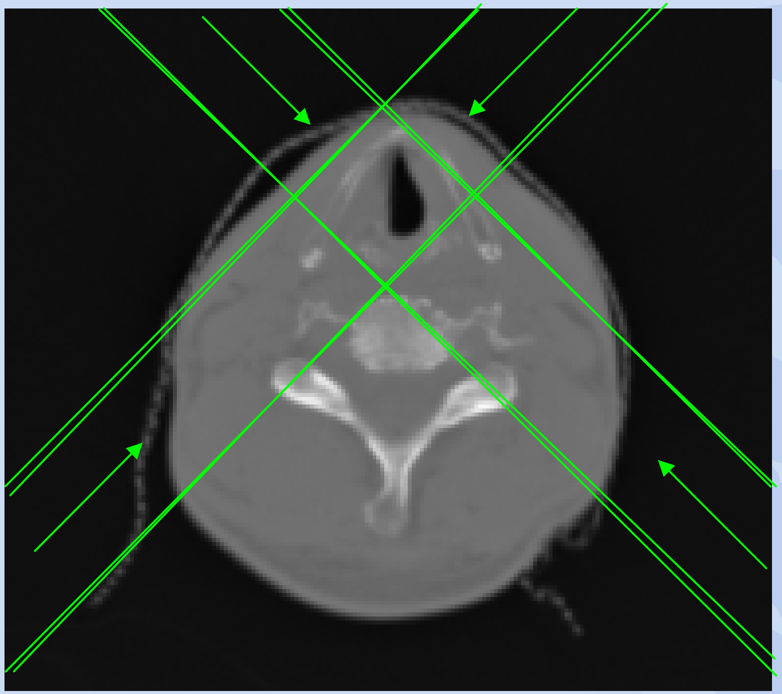


Dose deposition around larynx using 4-field box technique





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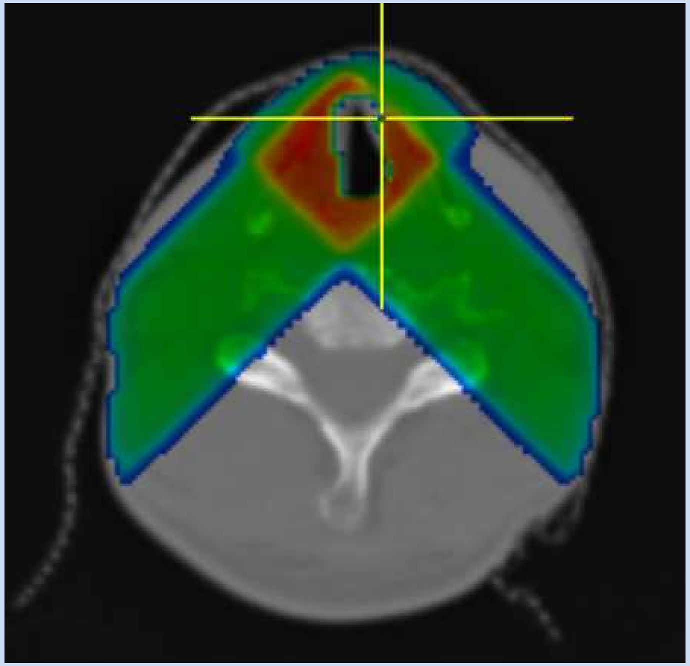
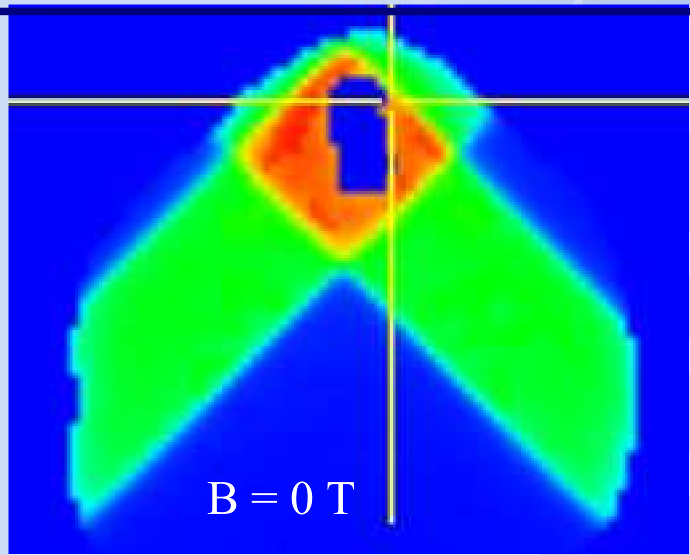
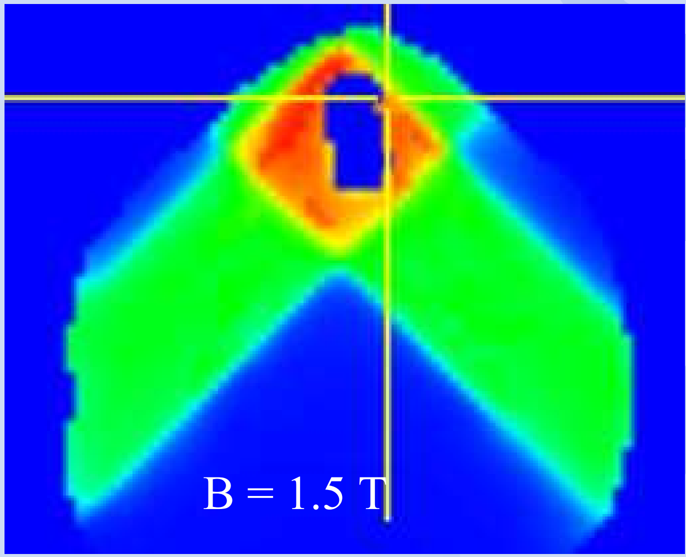
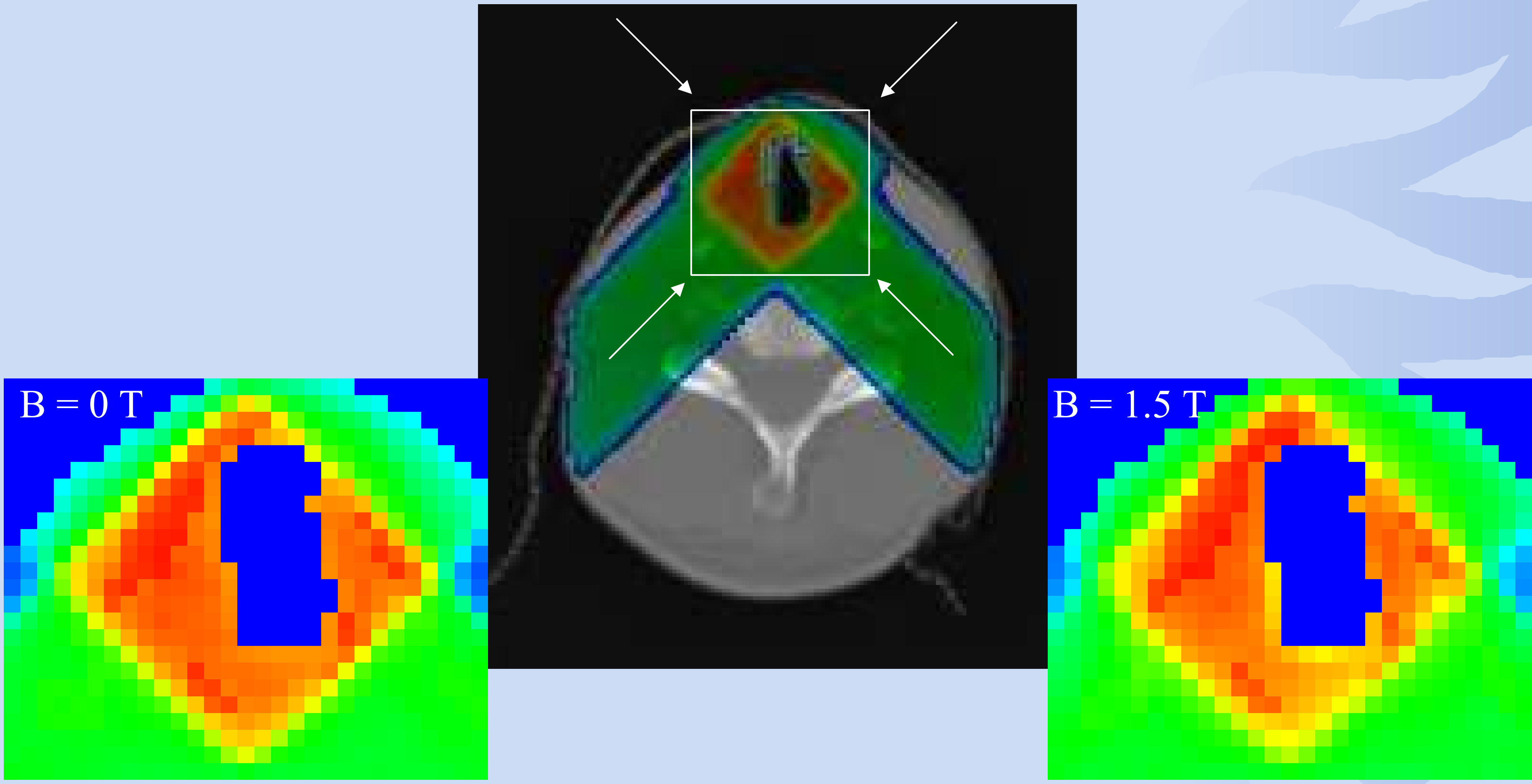






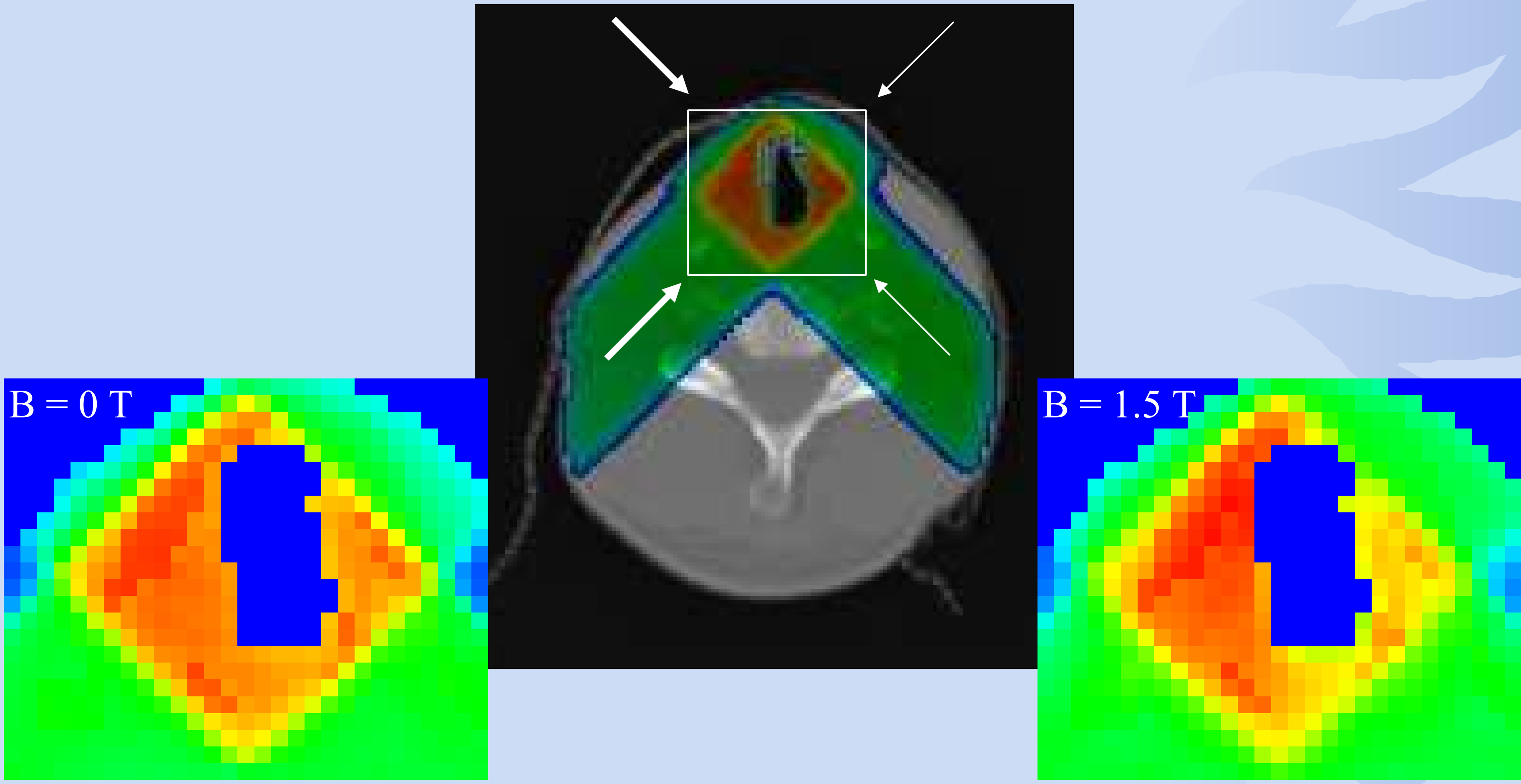
Raaijmakers et al, "Integrating a radiotherapy accelerator…" Physics in Medicine and Biology, 2005

Dose deposition around larynx using 4-field box technique



Manipulating the dose around the larynx

Applying different weight factors



Manipulating the dose around the larynx

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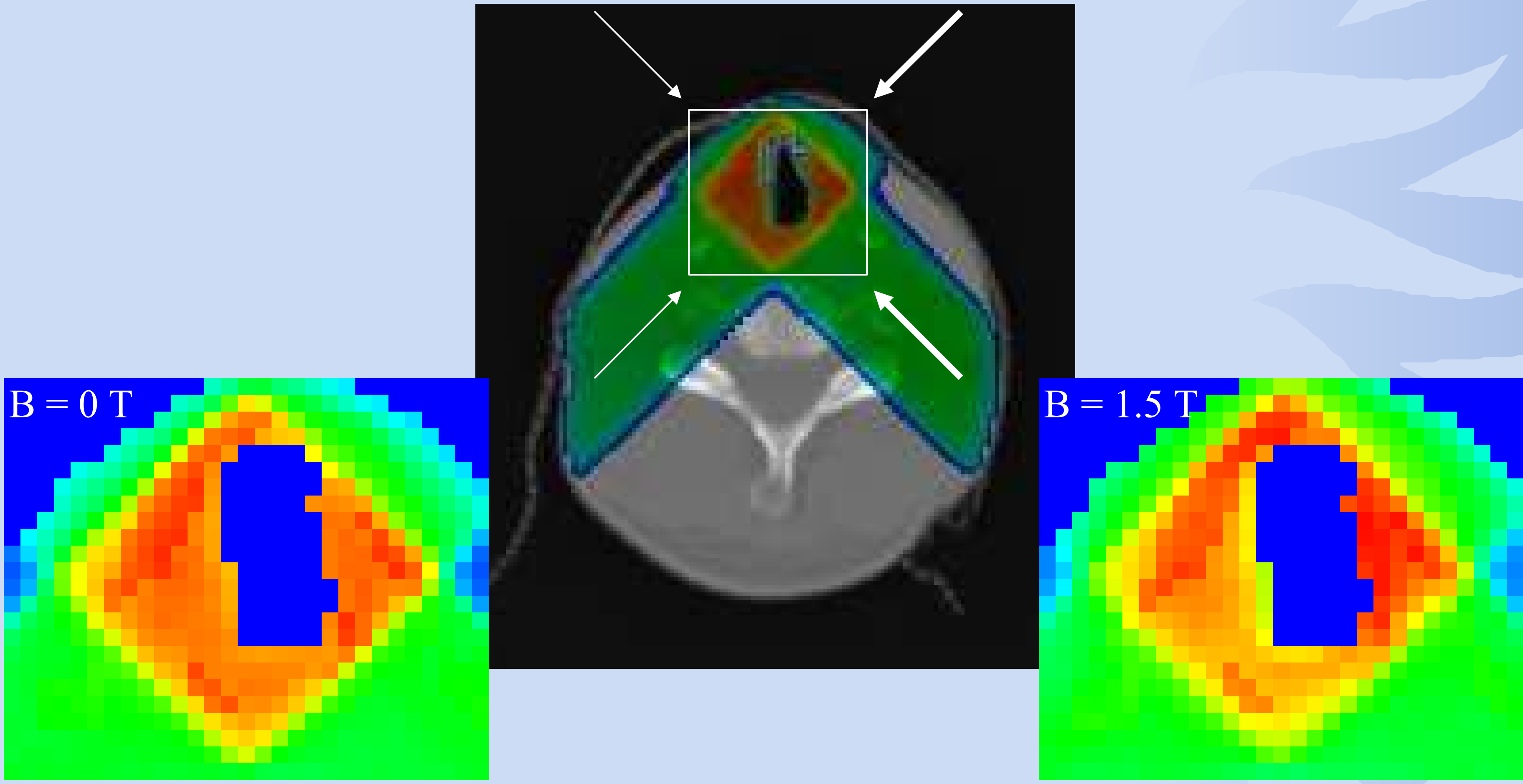

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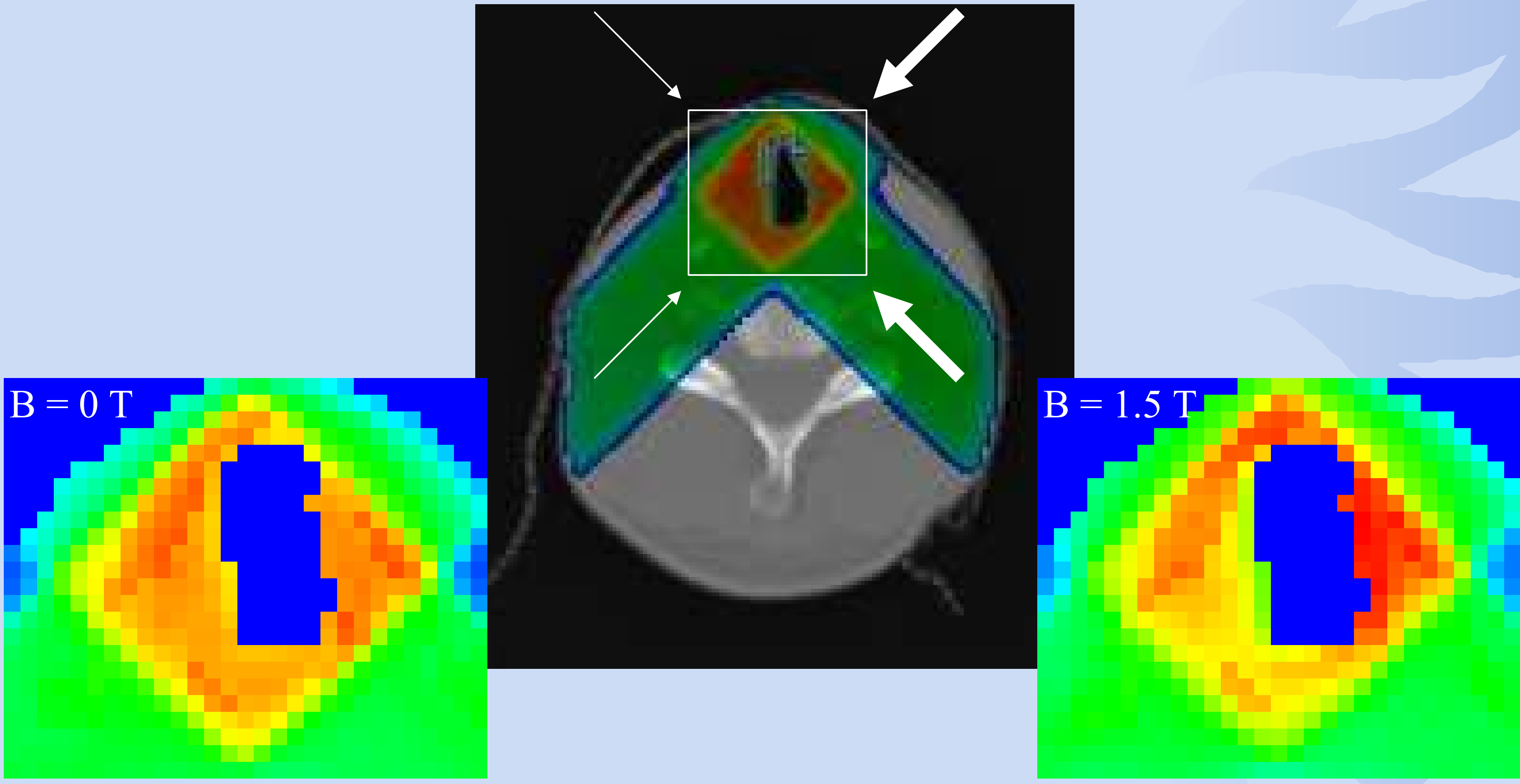
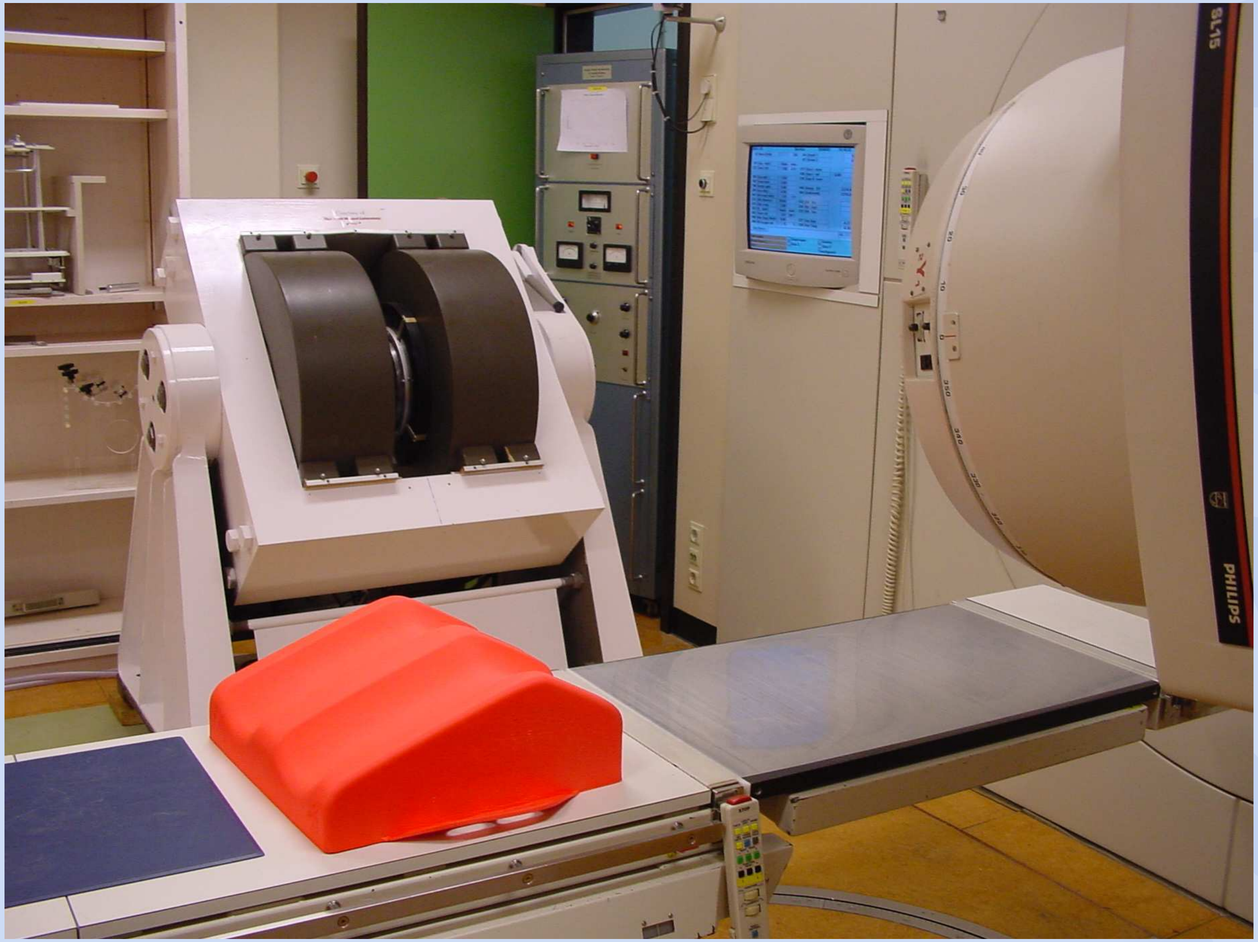


Simulation of ionization chamber in B-field

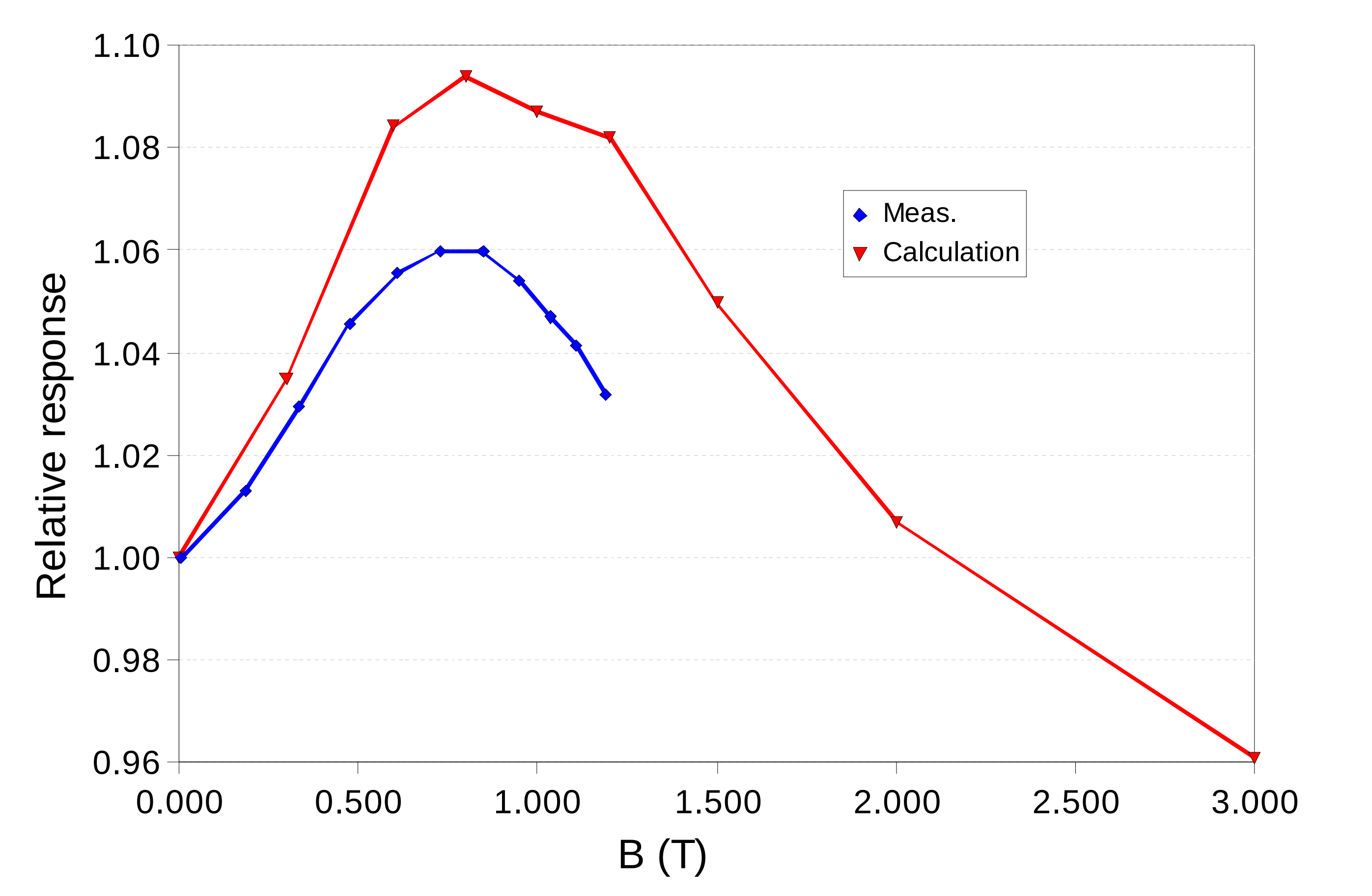
On-site 1.25 T Bruker magnet



Simulation of ionization chamber in B-field
Best obtained result so far after parameter study:

Energy deposition with B field

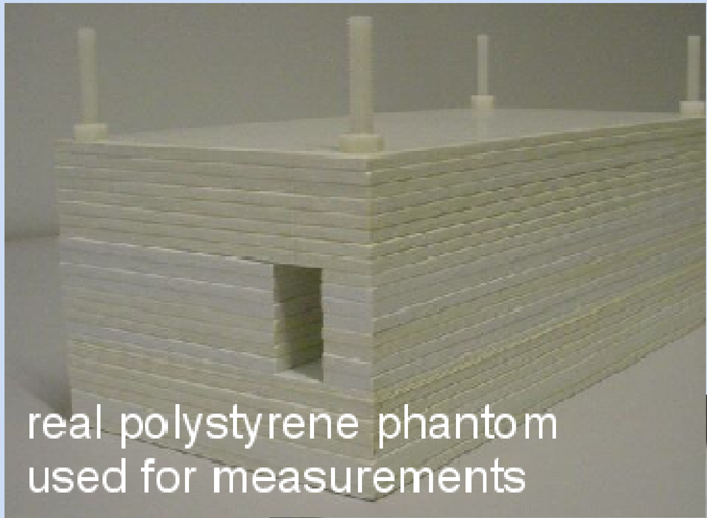
Calculation: 0.6cc air cavity with graphite wall (water phantom)
Measurement: 0.6cc Thimble chamber with builded up cap

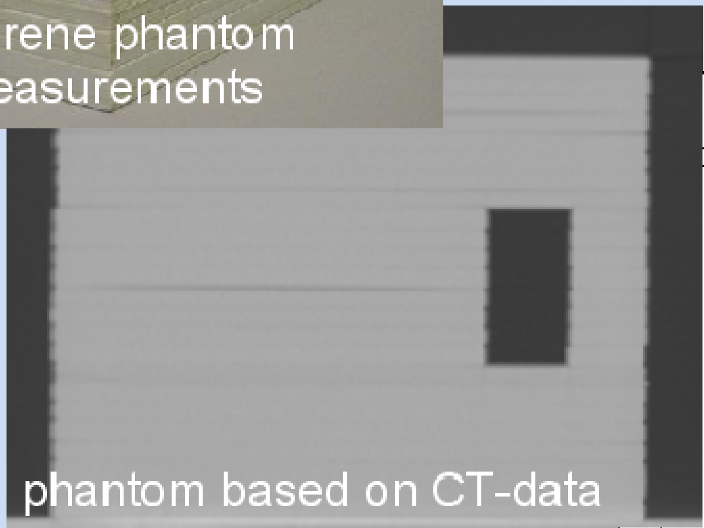


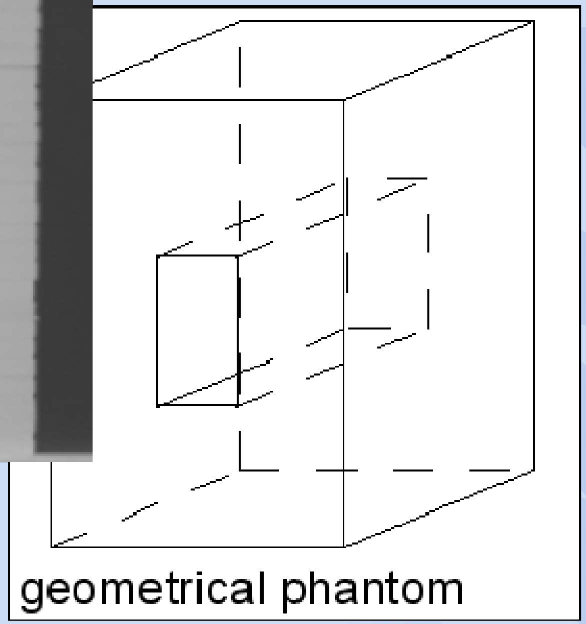
Parameters:
MS=1 m
RC=0.005 mm
fr=0.01
SF=0.1/100 nm
B field, RK4 model

Boxue Liu

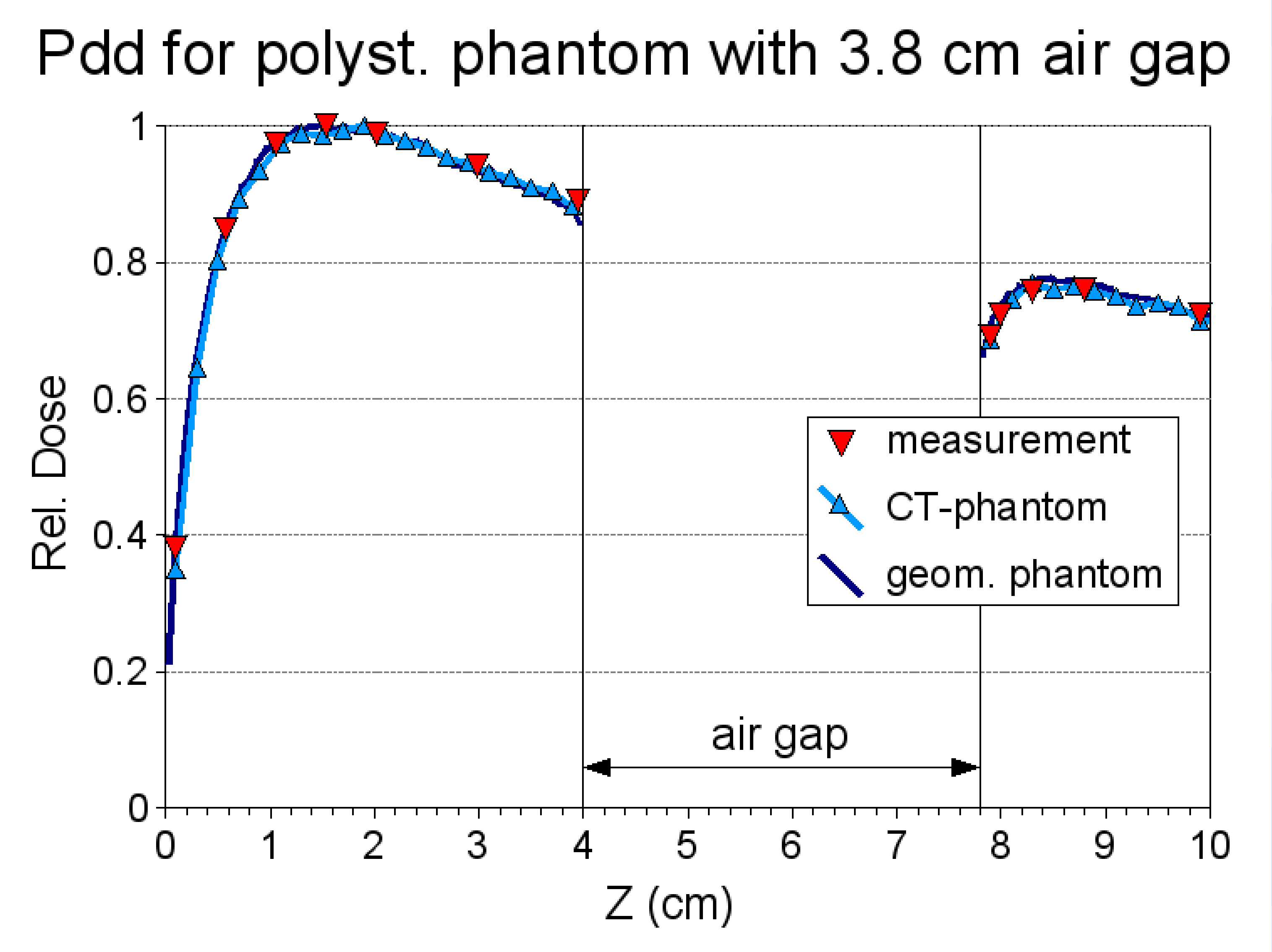
Testing the CT-data implementation
with inhomogeneity







Testing the CT-data implementation



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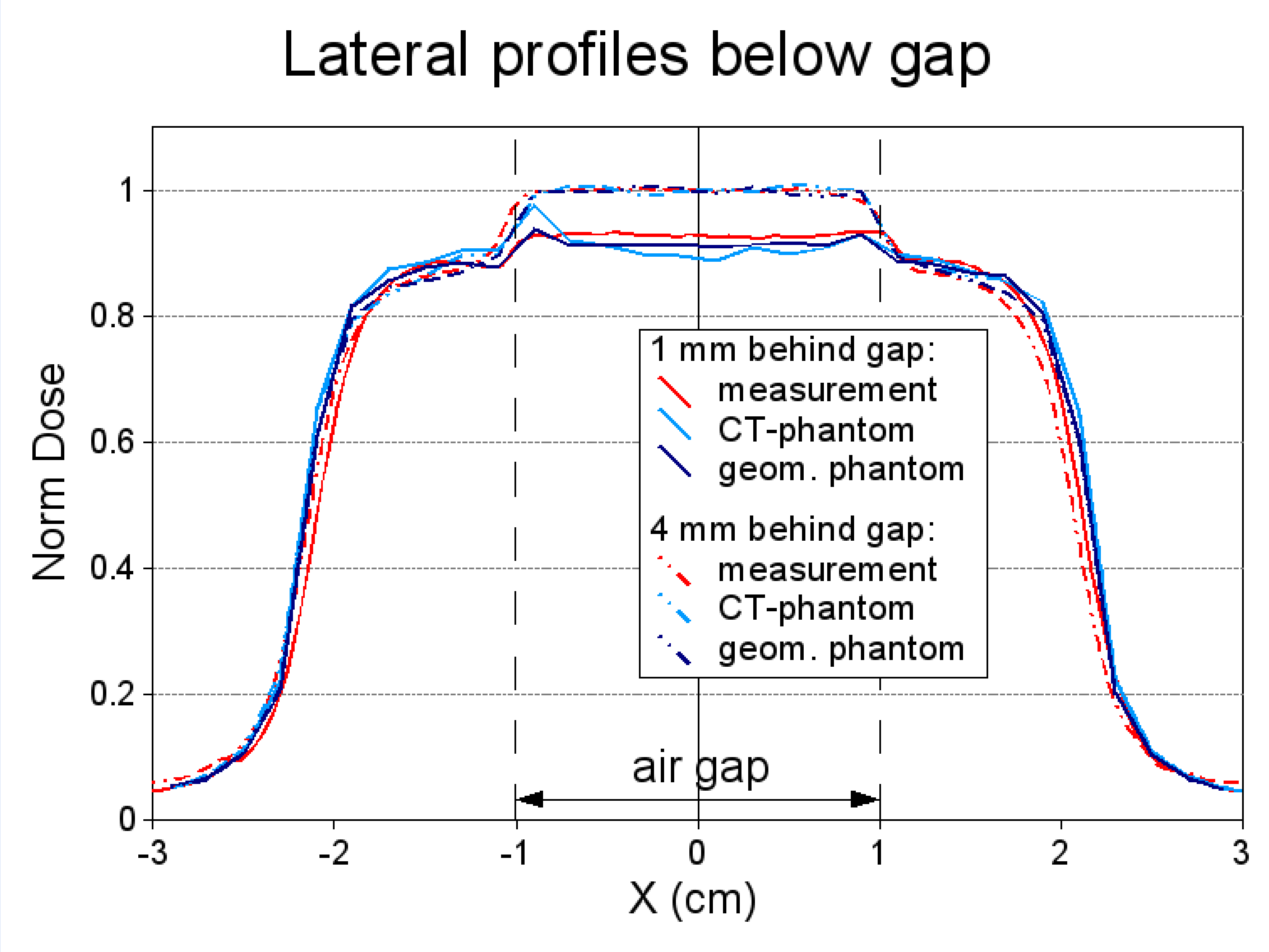

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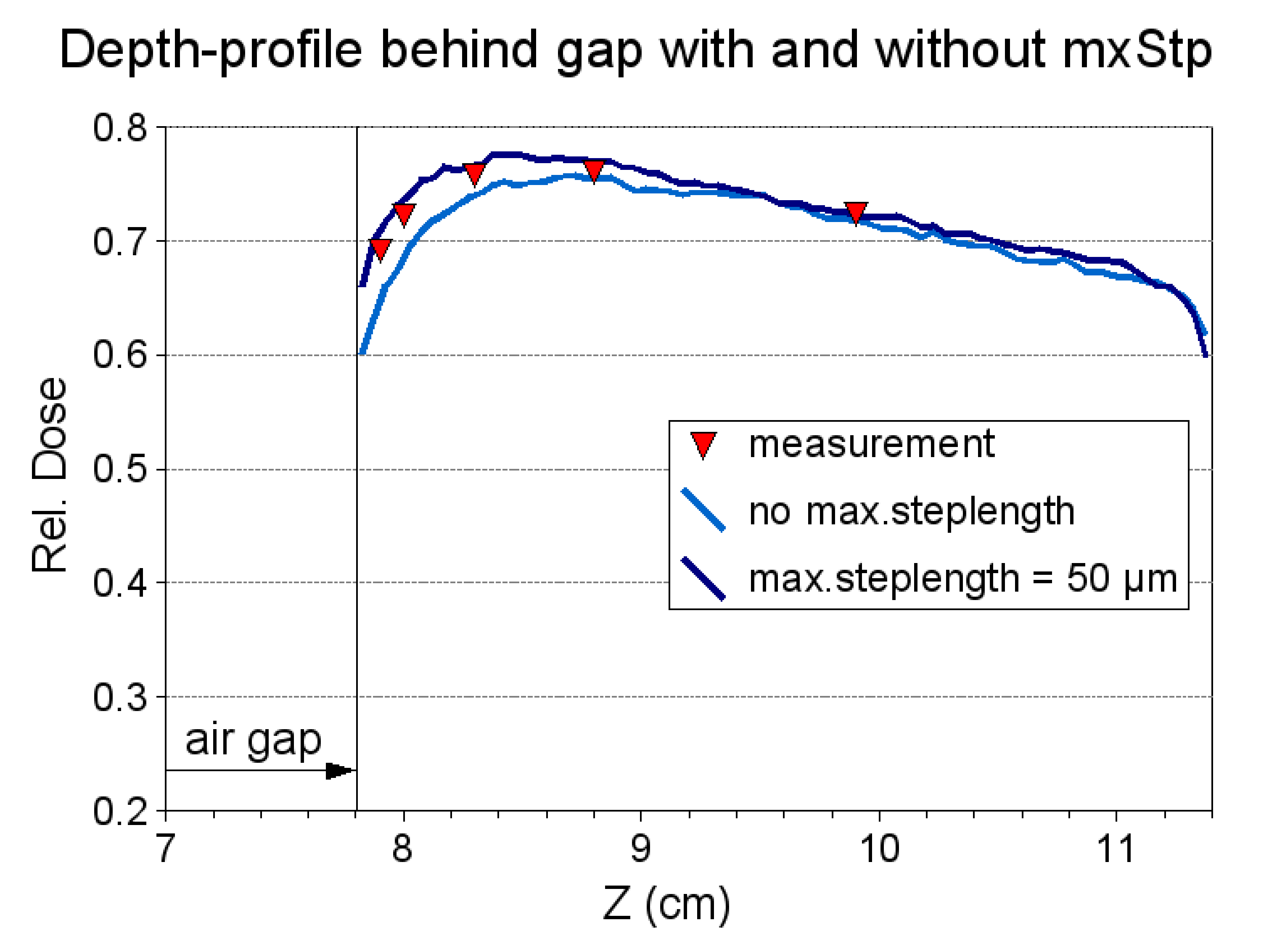


Testing the CT-data implementation

- **This tests shows on a very basic level the validity of the CT-data implementation.**
- **It also exposes the need for stepsize restrictions when dealing with high density-low density boundaries.**

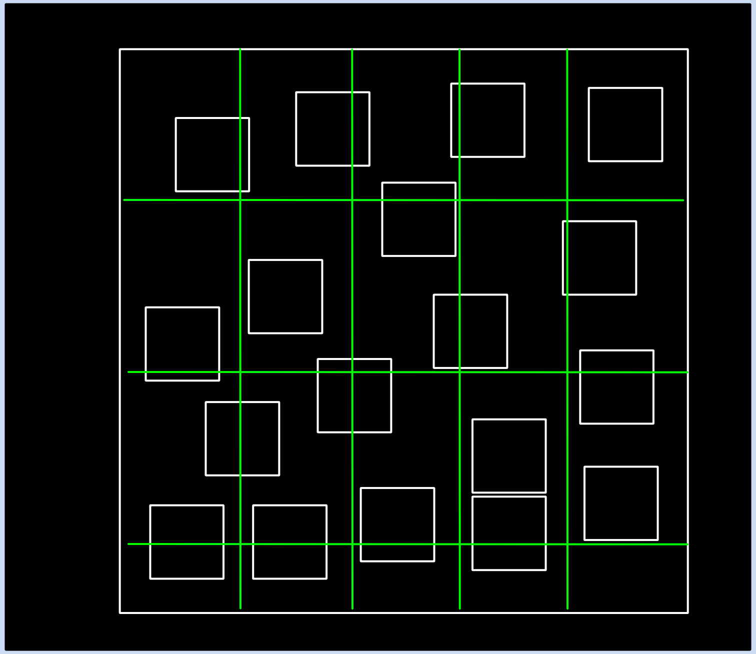
E. Poon, J. Seuntjens and F. Verhaegen, “Consistency test of the electron transport algorithm in the GEANT4 Monte Carlo code”, Phys, Med. Biol. 50 (2005)

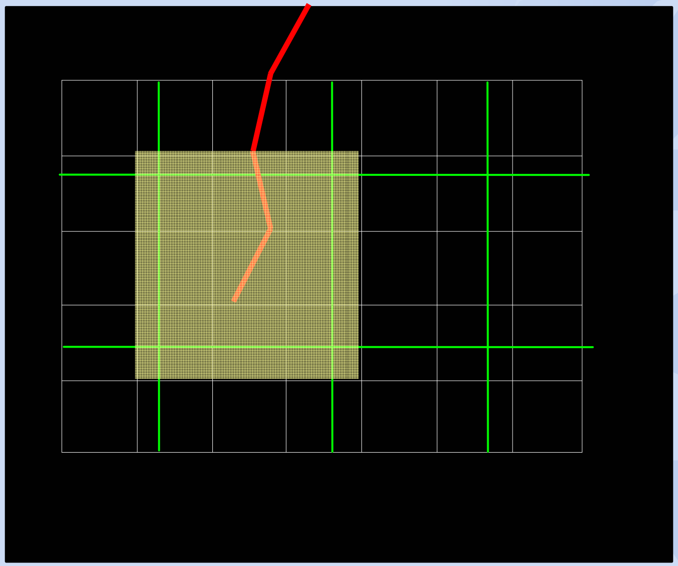
Nearest neighbour navigation

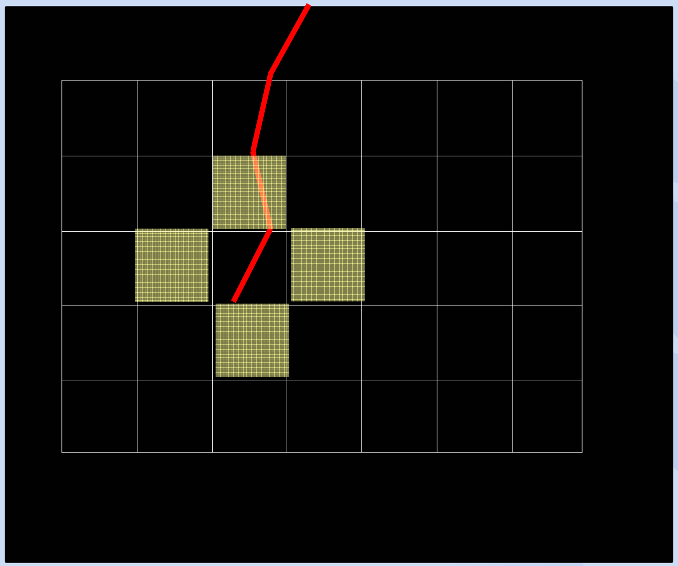
- **Navigation in a voxelised phantom (CT-data set), conventionally, is done using a superimposed SmartVoxel grid.**
- **The SmartVoxel grid navigation is meant for a general situation, regardless of voxel size, shape or positioning.**
- **Moreover, the SmartVoxel grid requires a lot of memory.**
- **A typical geometry with CT-data implementation consists of fixed-size, adjacent cubes.**
- **This creates the possibility for nearest-neighbour navigation.**

H. Jiang and H. Paganetti, "Adaptation of GEANT4 to Monte Carlo dose calculations based on CT-data" Med. Phys. 31, 2004

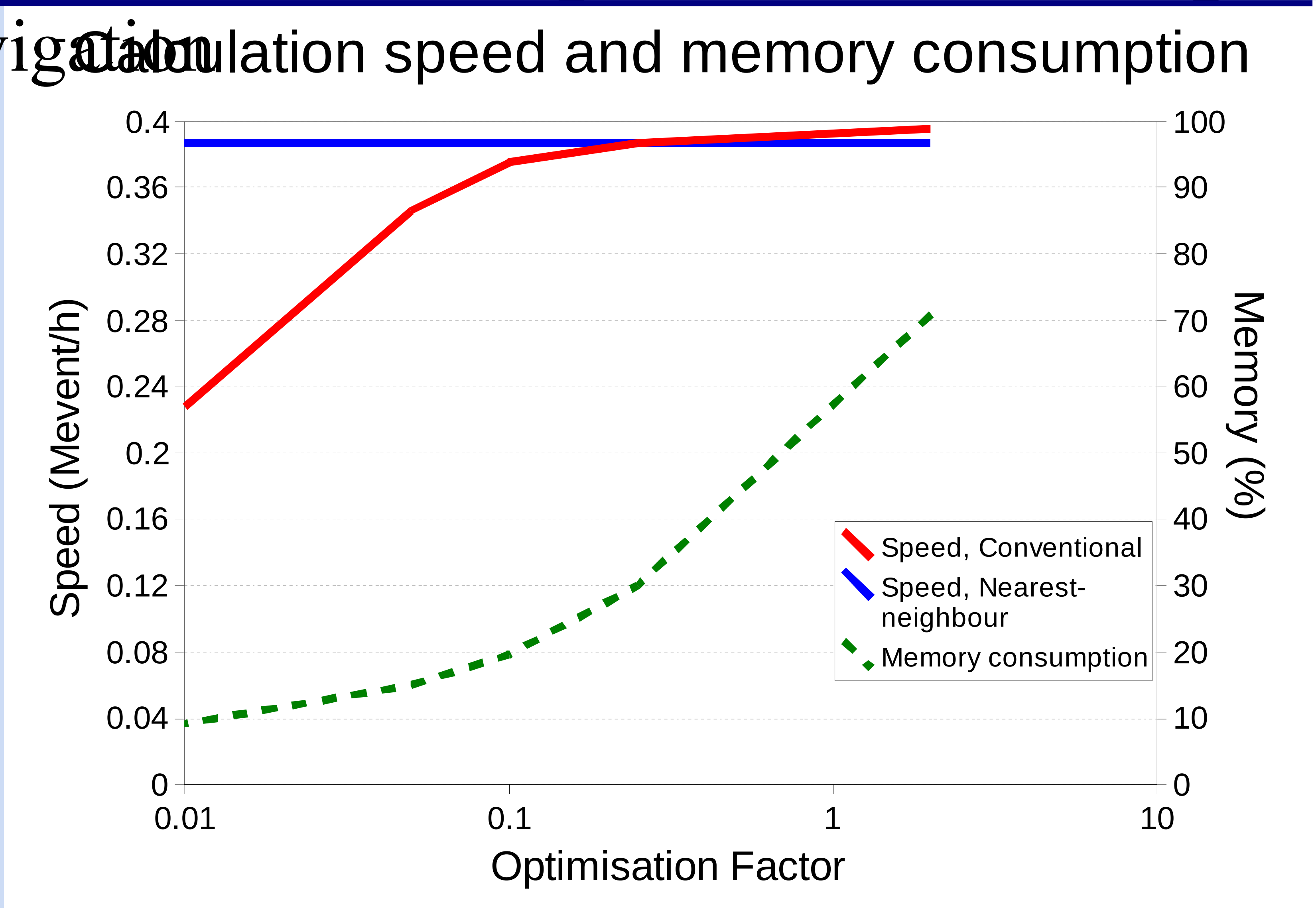
Nearest neighbour vs. conventional navigation





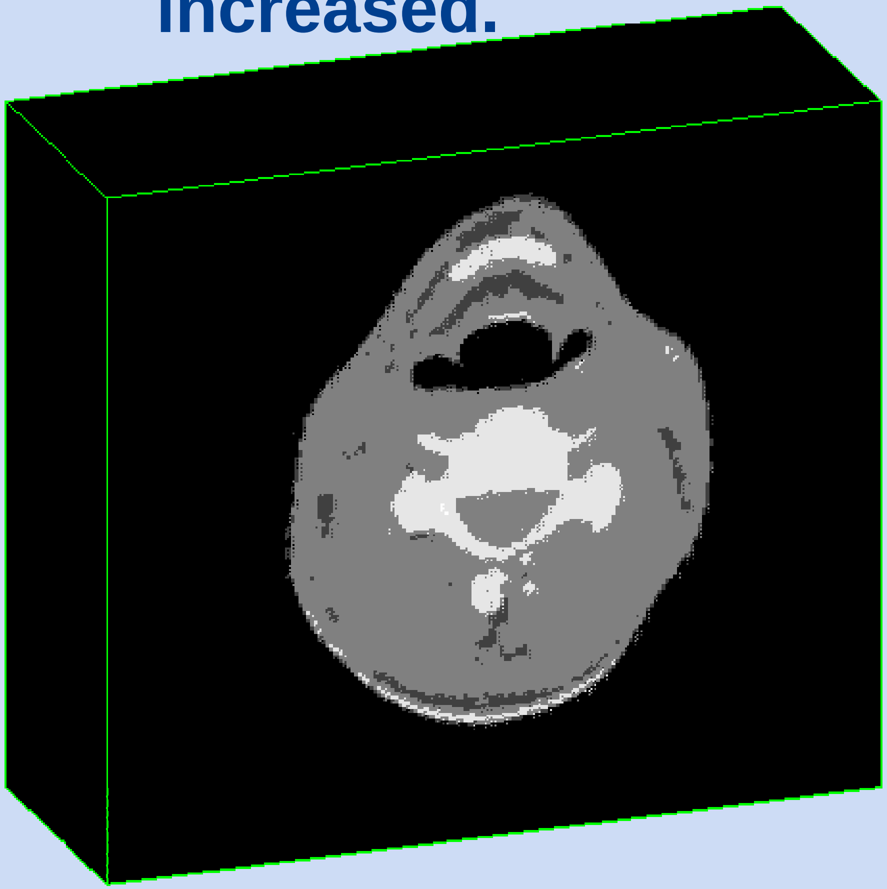


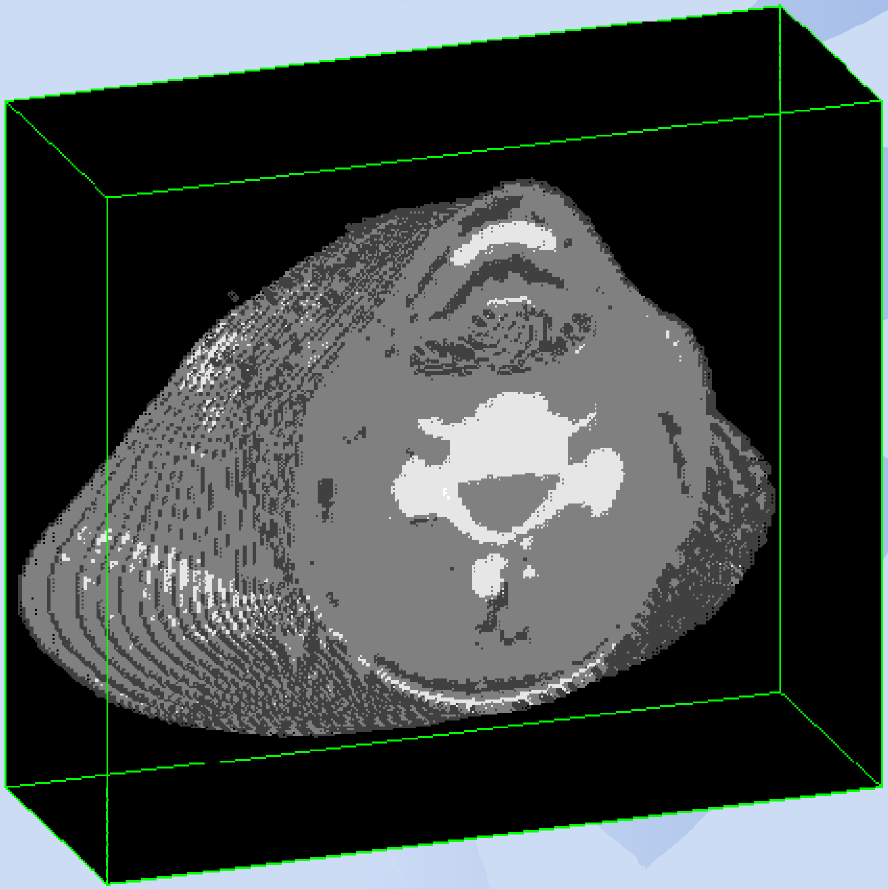
Calculation speed and memory consumption
For conventional navigation vs. nearest-neighbour navigation



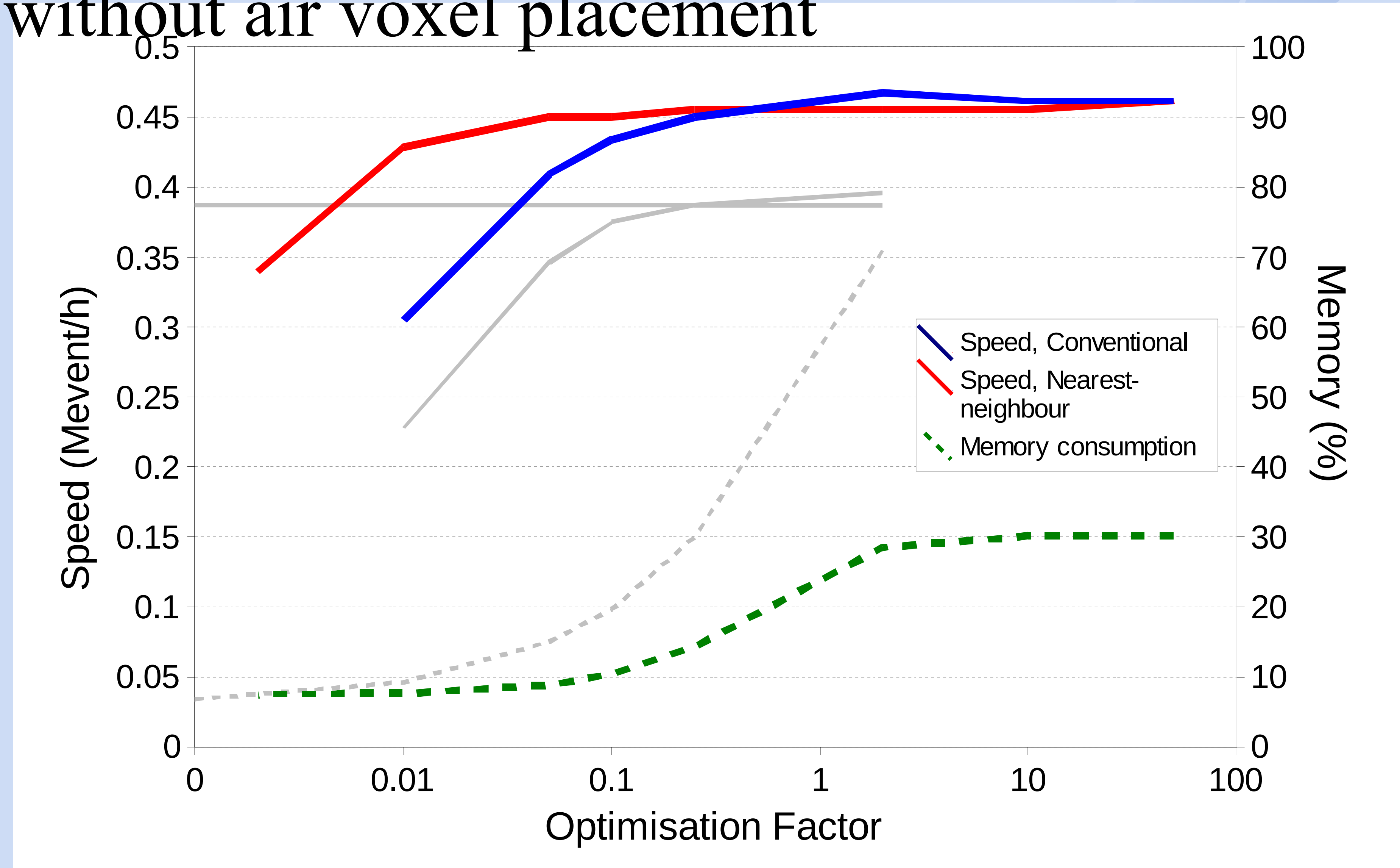
Not placing the air voxels

- **By not placing the air voxels, and instead defining the mother volume material as air, speed is increased.**

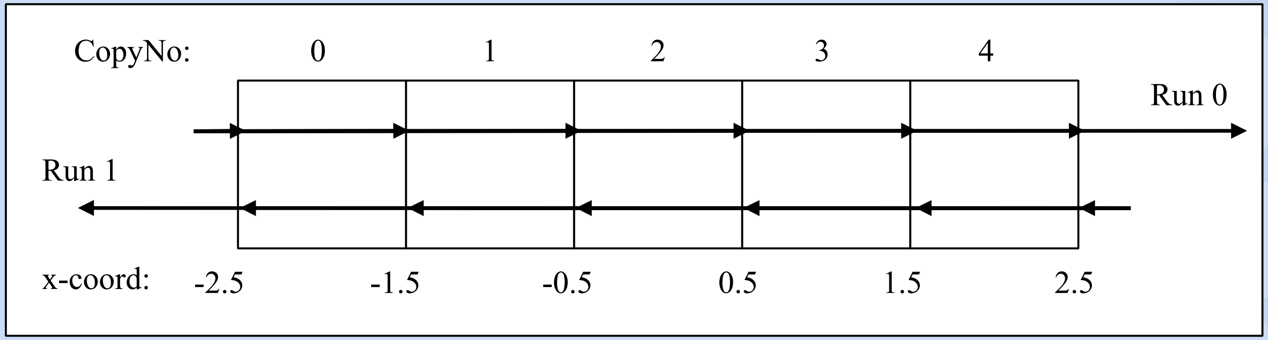




Calculation speed and memory consumption
without air voxel placement



copyNo mismatch for parameterized volumes



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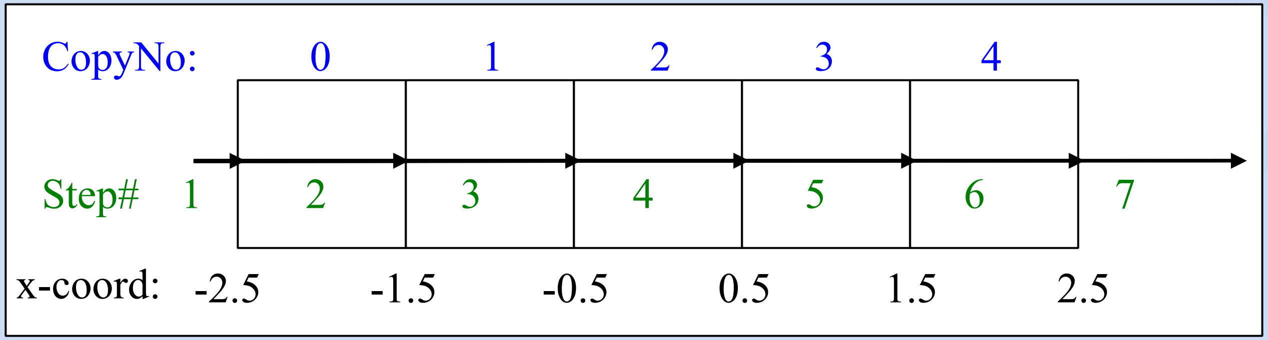
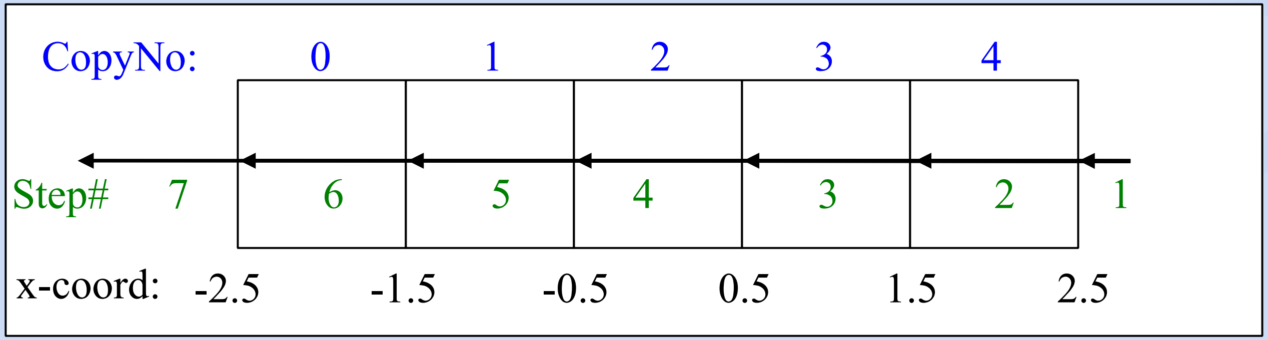



```
### Run 0 start.
----------
/vis/scene/notifyHandlers
Start Run processing.
1.1: gamma (-2.7,0,0)->(-2.5,0,0) in 'Param. mother vol.' copyNo: 0 Mat: Air
1.2: gamma (-2.5,0,0)->(-1.5,0,0) in 'cn1' copyNo: 1 Mat: Water
1.3: gamma (-1.5,0,0)->(-0.5,0,0) in 'cn2' copyNo: 2 Mat: Air
1.4: gamma (-0.5,0,0)->(0.5,0,0) in 'cn3' copyNo: 3 Mat: Water
1.5: gamma (0.5,0,0)->(1.5,0,0) in 'cn4' copyNo: 4 Mat: Air
1.6: gamma (1.5,0,0)->(2.5,0,0) in 'cn4' copyNo: 4 Mat: Water
1.7: gamma (2.5,0,0)->(10,0,0) in 'Param. mother vol.' copyNo: 0 Mat: Air
1.8: gamma (10,0,0)->(50,0,0) in 'World' copyNo: 0 Mat: Air
Run terminated.
Run Summary
  Number of events processed : 1
  User=0s Real=0s Sys=0s
/vis/viewer/update
```

copyNo mismatch for parameterized volumes

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Start Run processing.
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1.4: gamma (0.5,0,0)->(-0.5,0,0) in 'cn1' copyNo: 1 Mat: Water
1.5: gamma (-0.5,0,0)->(-1.5,0,0) in 'cn0' copyNo: 0 Mat: Air
1.6: gamma (-1.5,0,0)->(-2.5,0,0) in 'cn0' copyNo: 0 Mat: Water
1.7: gamma (-2.5,0,0)->(-10,0,0) in 'Param. mother vol.' copyNo: 0 Mat: Air
1.8: gamma (-10,0,0)->(-50,0,0) in 'World' copyNo: 0 Mat: Air
Run terminated.
Run Summary
  Number of events processed : 1
  User=0s Real=0s Sys=0s
```

copyNo mismatch for parameterized volumes

```
void OwnSteppingAction::UserSteppingAction(const G4Step* aStep)
{
  G4int trackID = aStep->GetTrack()->GetTrackID();
  G4int stepID  = aStep->GetTrack()->GetCurrentStepNumber();

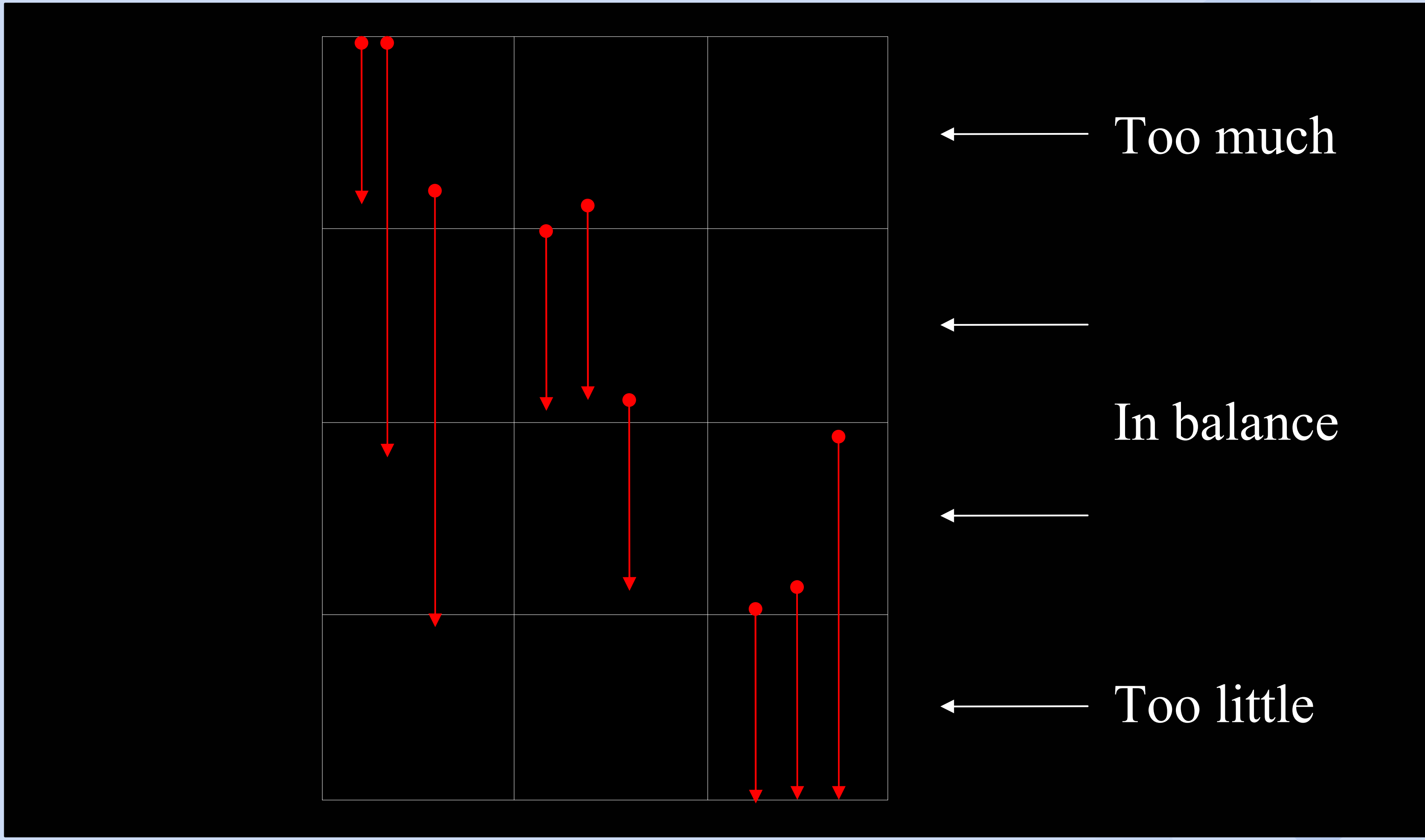
  G4String particleName = aStep->GetTrack()->GetDefinition()->GetParticleName();

  G4ThreeVector startPoint = aStep->GetPreStepPoint()->GetPosition();
  G4ThreeVector endPoint   = aStep->GetPostStepPoint()->GetPosition();

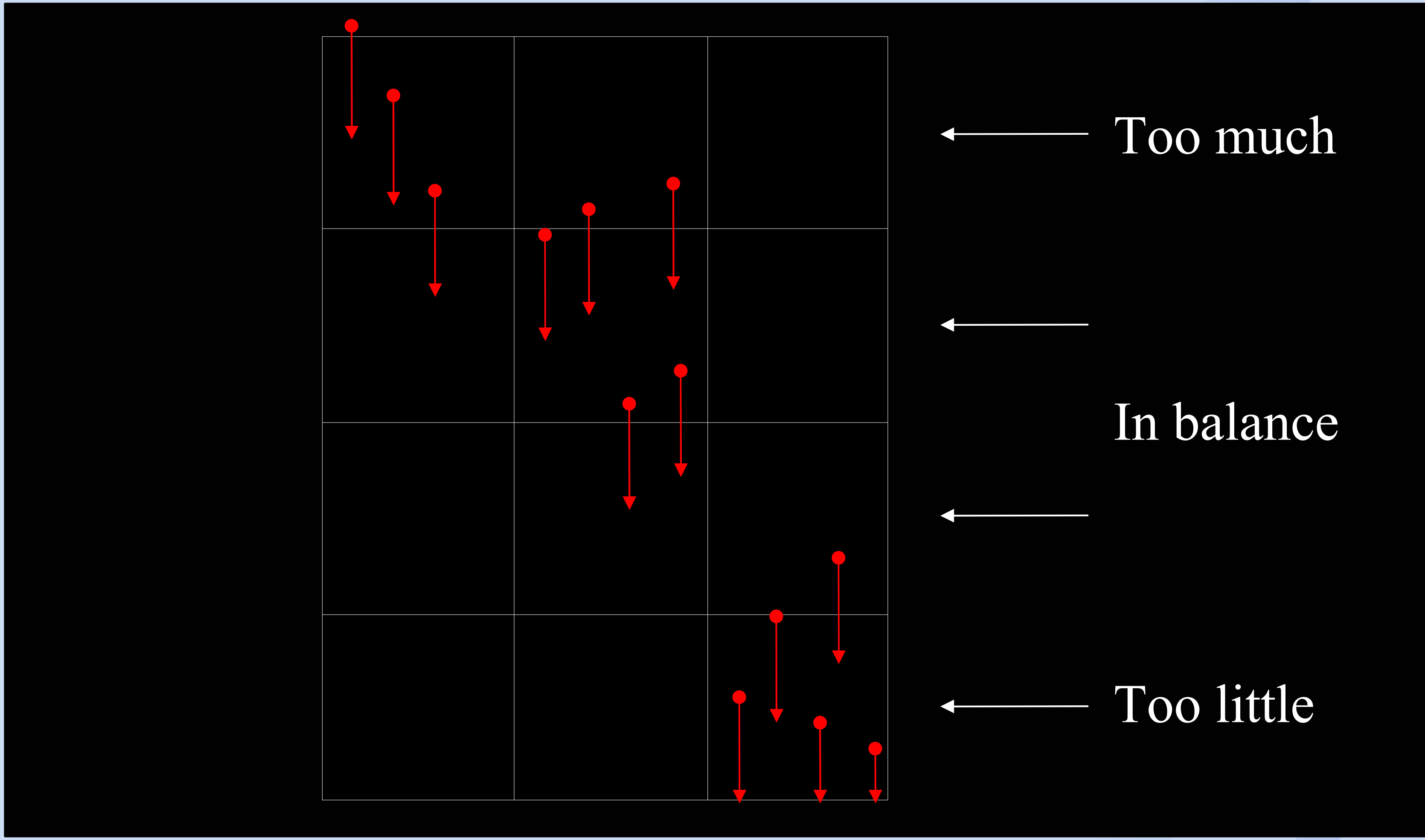
  G4String volName = aStep->GetPreStepPoint()->GetPhysicalVolume()->GetName();
  G4int copyNo =     aStep->GetPreStepPoint()->GetPhysicalVolume()->GetCopyNo();
  //G4String volName = aStep->GetTrack()->GetVolume()->GetName();
  //G4int copyNo =   aStep->GetTrack()->GetVolume()->GetCopyNo();
  G4String matName = aStep->GetTrack()->GetMaterial()->GetName();

  G4cout.precision(10);
  G4cout<<trackID<<"."<<stepID<<": "
        <<particleName<<" "
        <<startPoint<<"->"
        <<endPoint<<" in '"
        <<volName<<"' copyNo: "
        <<copyNo
        <<G4endl;
}
```

ROG energy deposition biasing



ROG energy deposition biasing (maximum stepsize)



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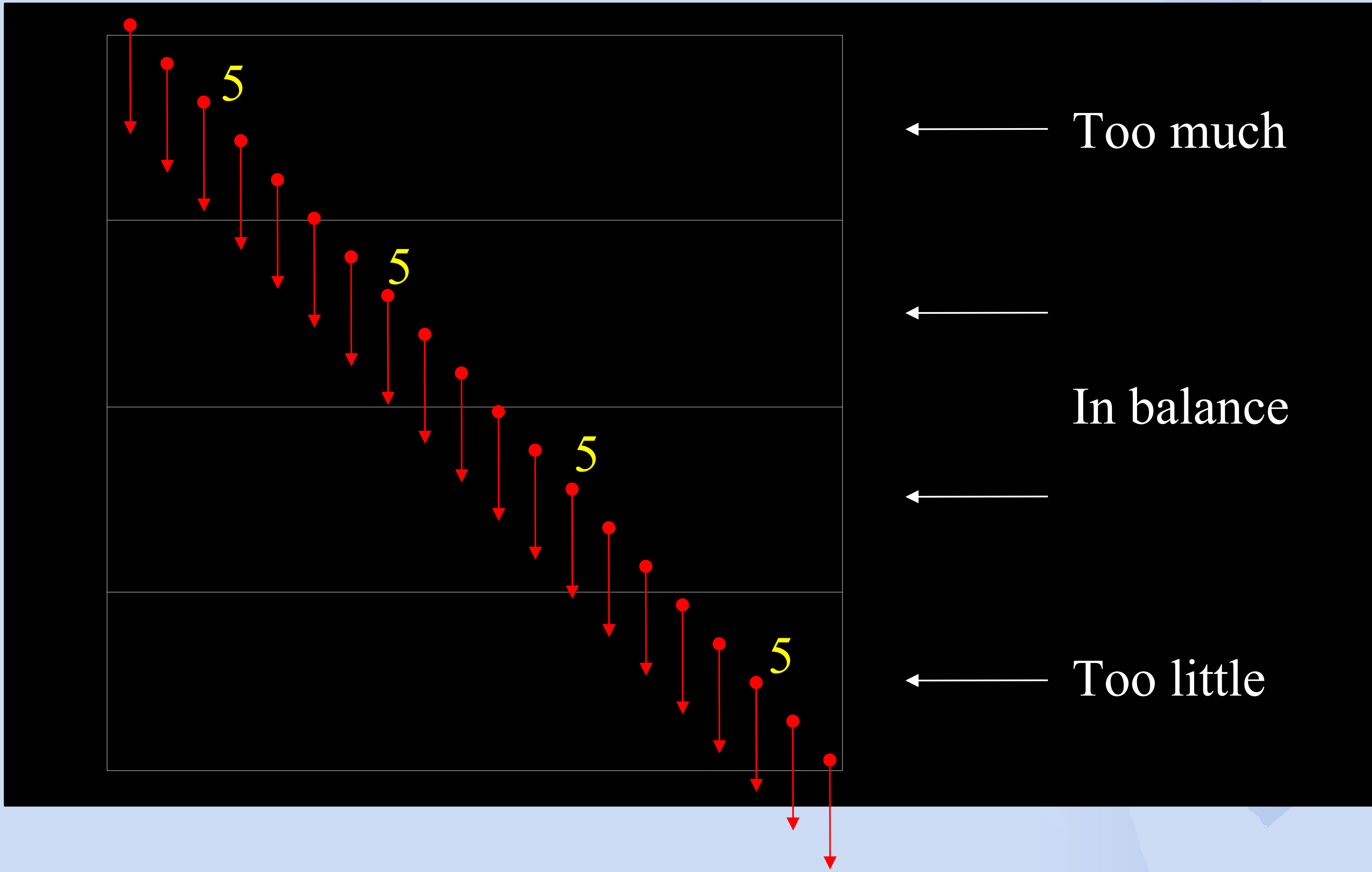

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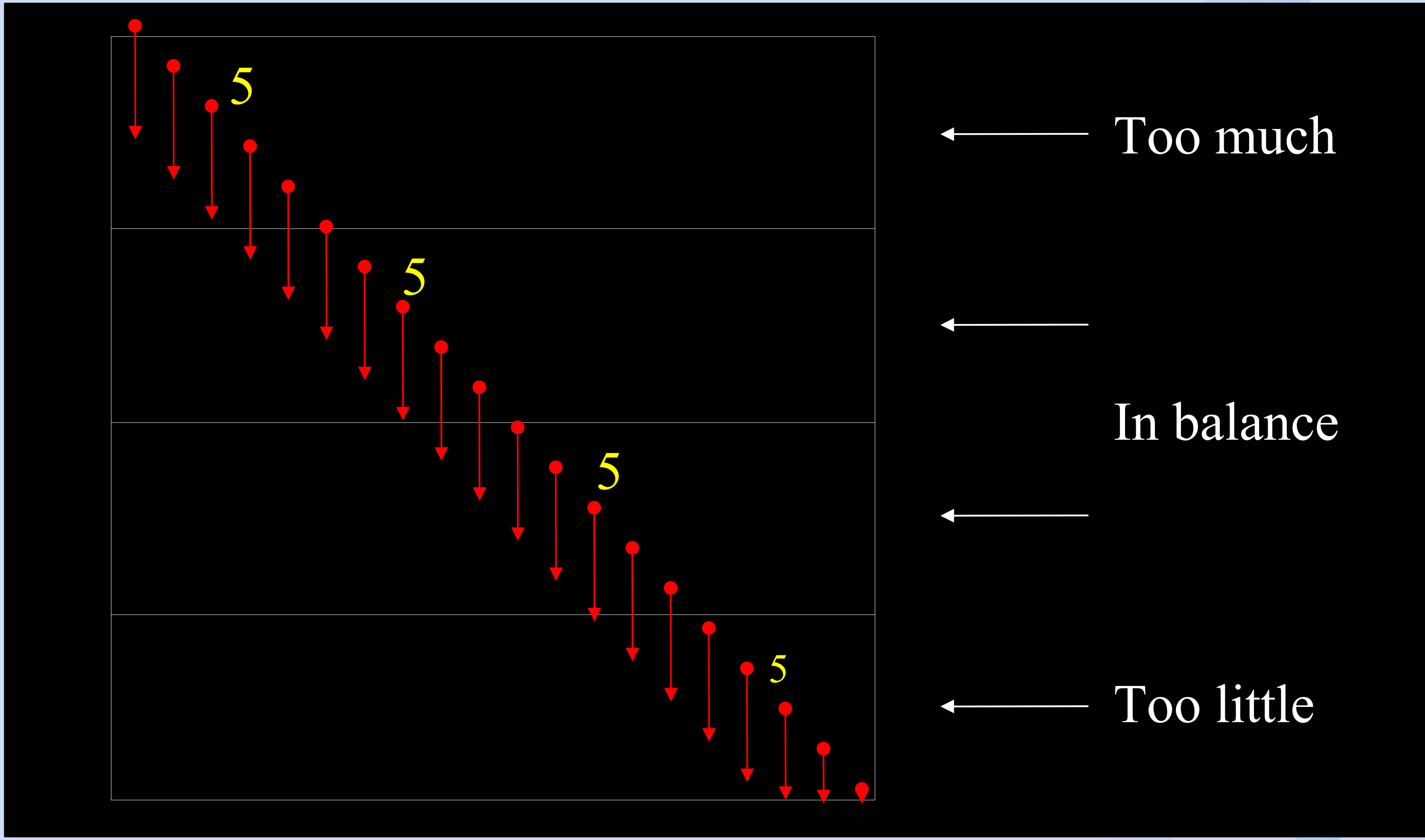
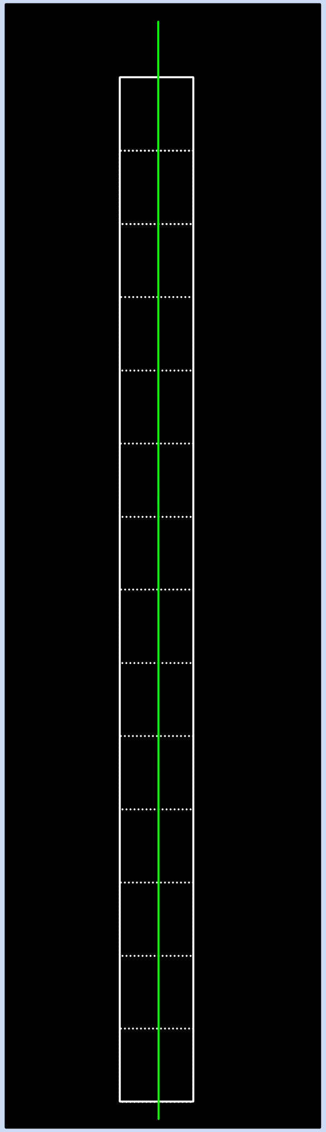
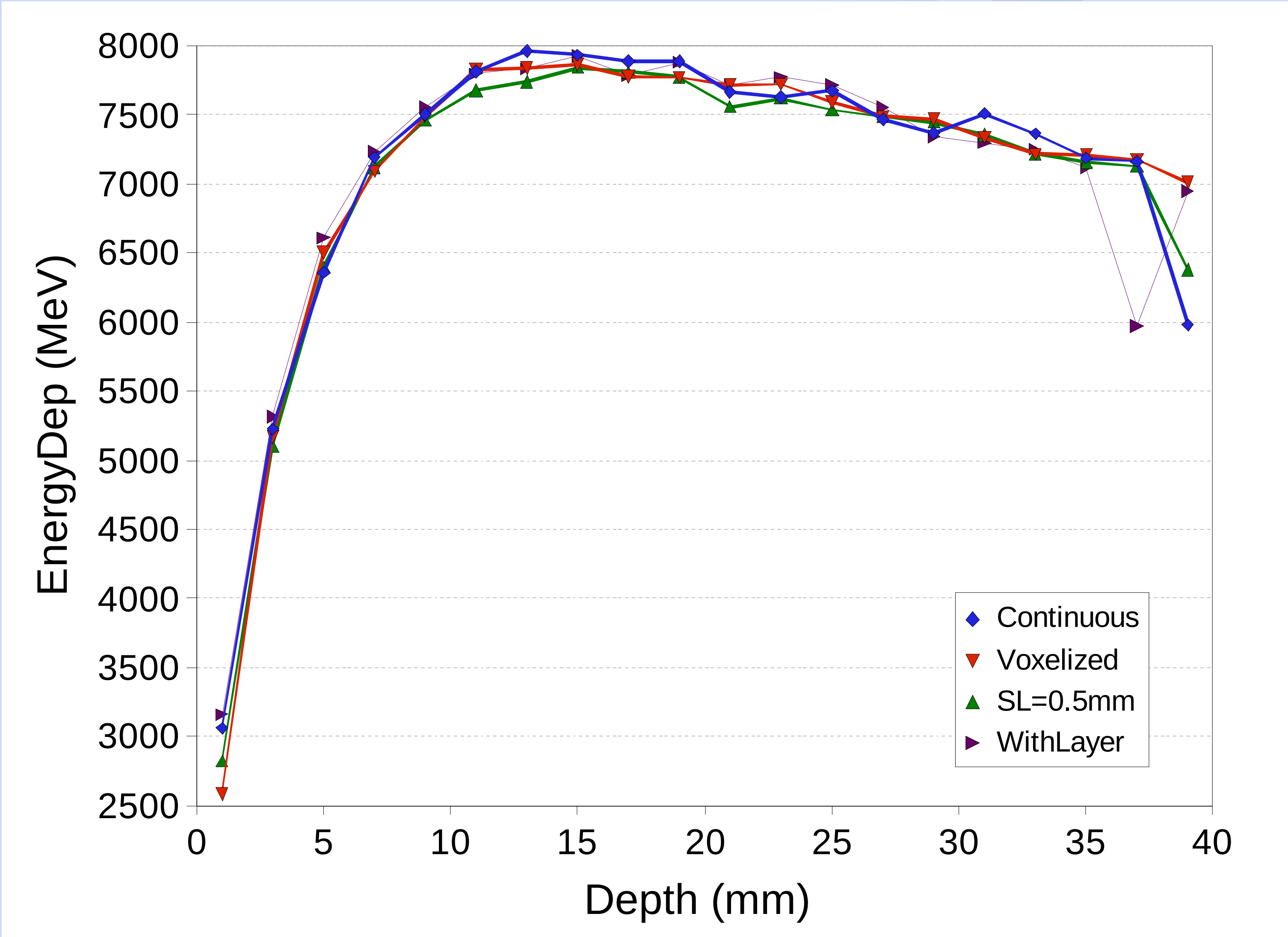


In-depth dose profile for ROG-based energy deposition in comparison to parameterized volume.





ROG energy deposition biasing

- When the dose distribution of a vertically irradiated phantom is determined using a ROG, the simulated dose levels of the upper and lower voxel plane may be biased.
- The effects are reduced, but not diminished, by
  - scoring the energy deposition of a step in the voxel at the middle point of the step
  - limiting the maximum stepsize to a fraction of the voxel size
- Best results are obtained by using an algorithm that divides the energy deposition of each step over the voxels that are traversed.

Final remarks and future work

- Simulation of a radiotherapy accelerator has been achieved
- CT-data implementation is working fine and is showing agreement with TPS PLATO
- Already, physicians come up with clinical cases of inhomogeneous target volumes in patients, where they want to know the dose distribution more accurately
- Need to validate our simulated dose distributions in a magnetic field
- Ionization chamber response in a magnetic field is still a problem

GEANT4 is a very practical tool for our purposes, though there is room for some improvement
(navigation, boundary crossing)

THANK YOU FOR YOUR ATTENTION

A.J.E. Raaijmakers, B.W. Raaymakers, J.J.W. Lagendijk