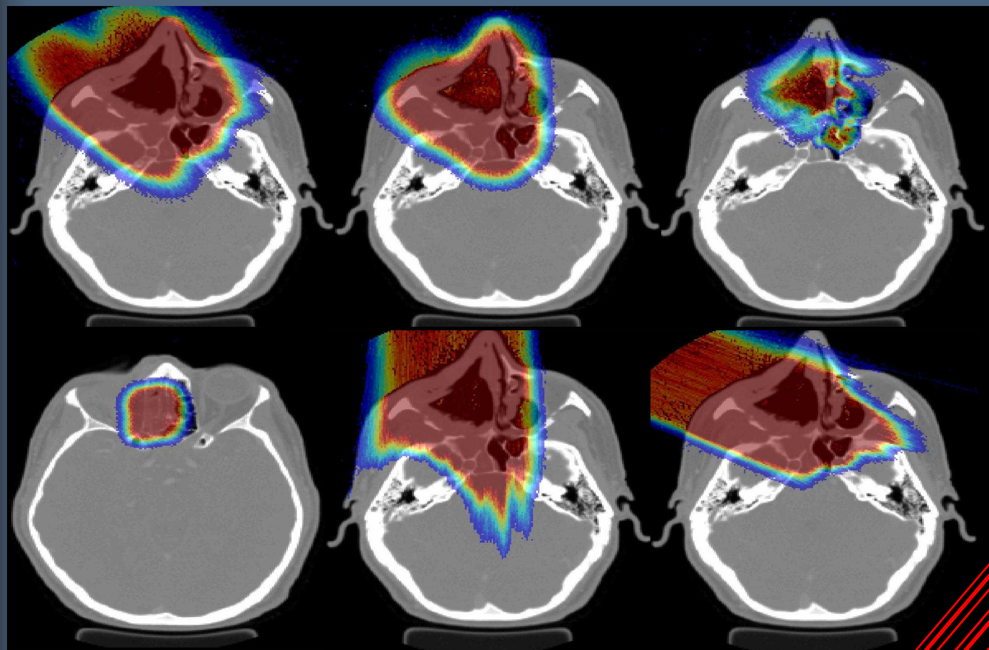
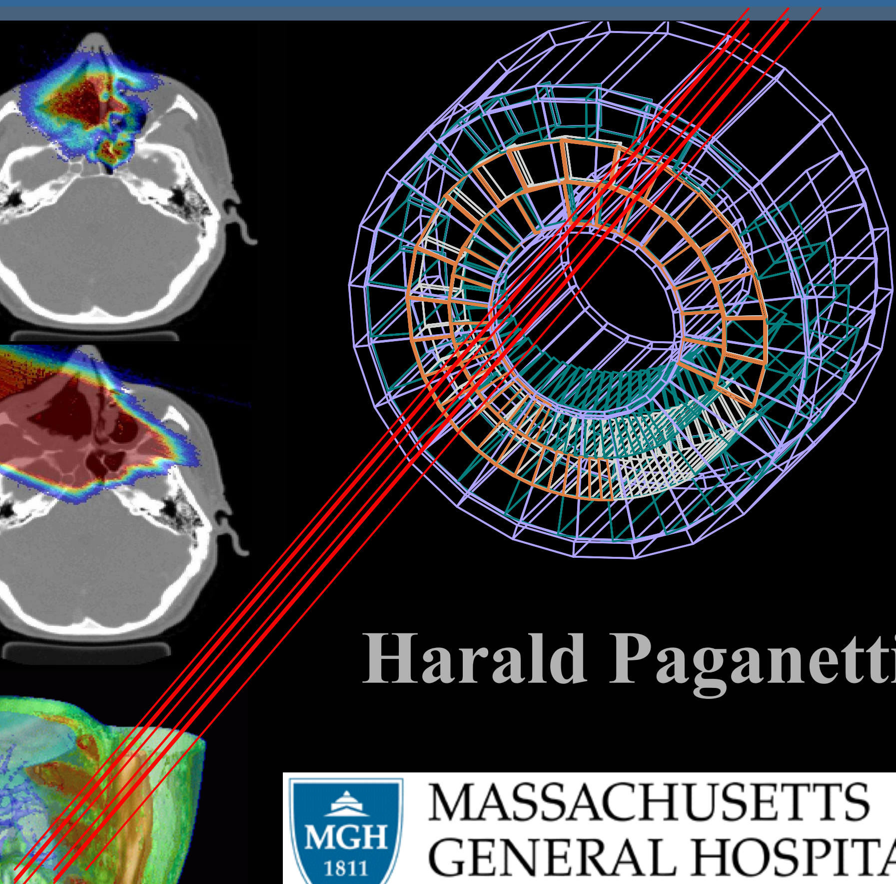
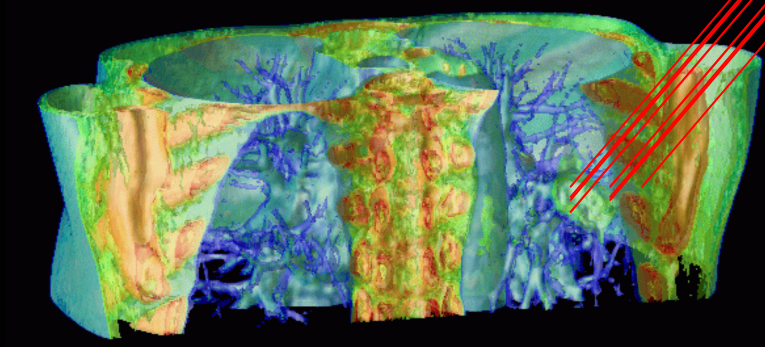
Significance of time-dependent geometries for Monte Carlo simulations in radiation therapy







Harald Paganetti

MASSACHUSETTS GENERAL HOSPITAL

HARVARD MEDICAL SCHOOL

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Modeling time dependent geometrical setups

Key to 4D Monte Carlo:

Geometry changes during the simulation via C++ class architecture based on **GEANT4**

Geometry update command in *DetectorMessenger*

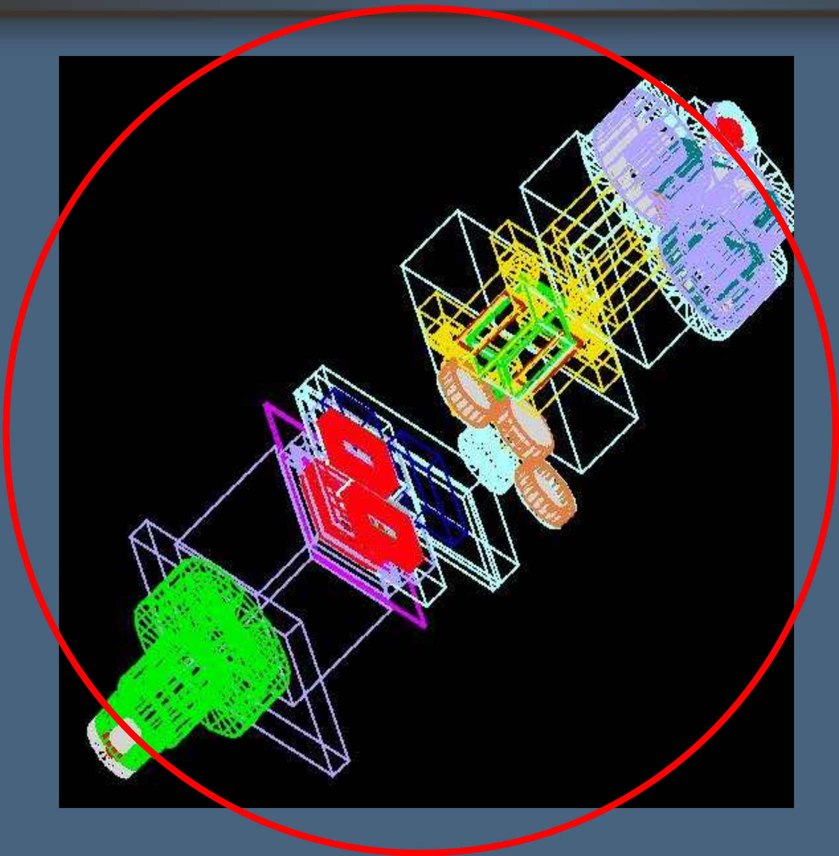
DetectorConstruction:

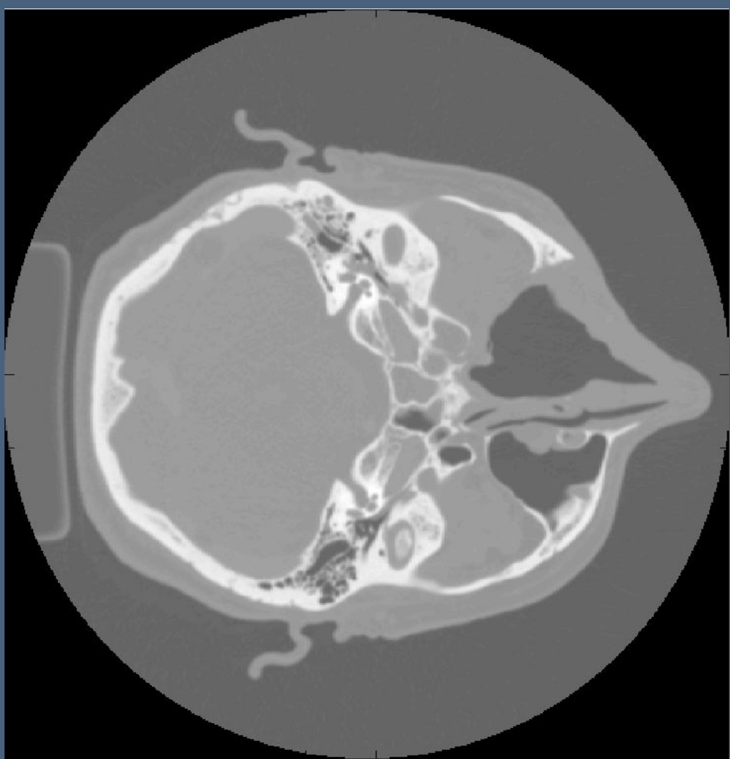
```
rot_RMW = new G4RotationMatrix();
rot_RMW->rotateZ(Wheel_angle*degree);
RMW_Phys -> SetRotation(rot_RMW);
G4RunManager* theRunManager = G4RunManager::GetRunManager();
theRunManager->DefineWorldVolume(WorldPhys);
theRunManager->GeometryHasBeenModified();
theRunManager->ResetNavigator();
```

– geometry updates –

Modification of the GEANT4 source code

Instead of re-doing the optimization for the entire geometry, only re-optimize parts of geometry





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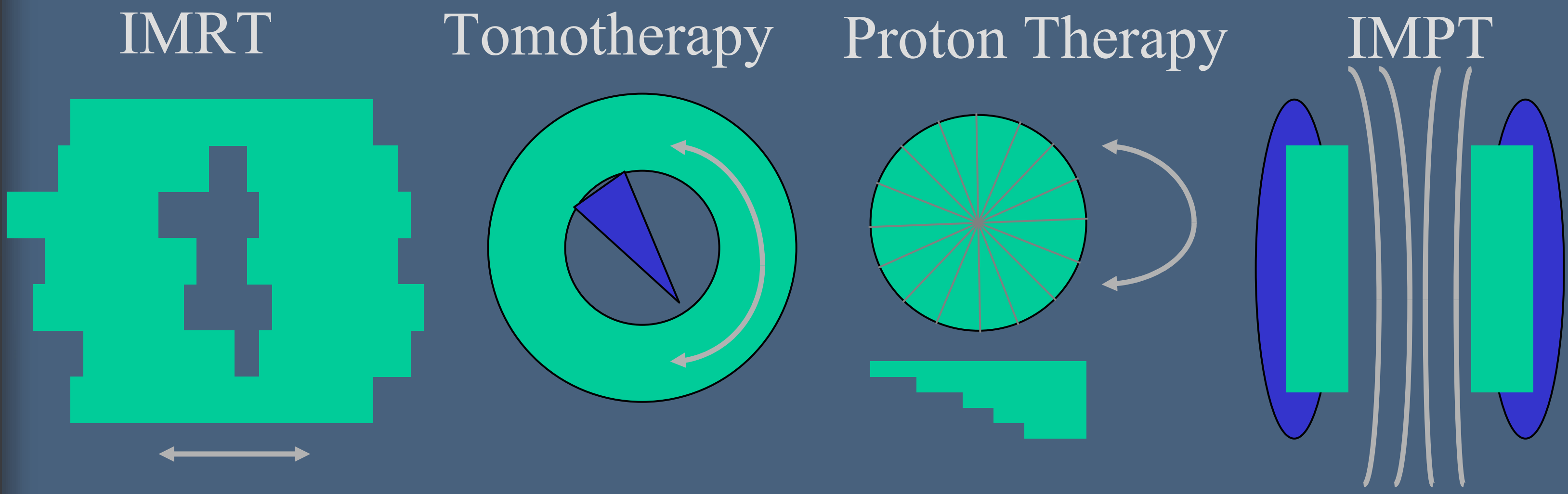
Dynamic Systems in Radiation Therapy
- Beam Delivery -



Types of variations:

IMRT: moving leafs
Tomotherapy: rotating beam
Protons: rotating wheel
IMPT: changing magnetic field

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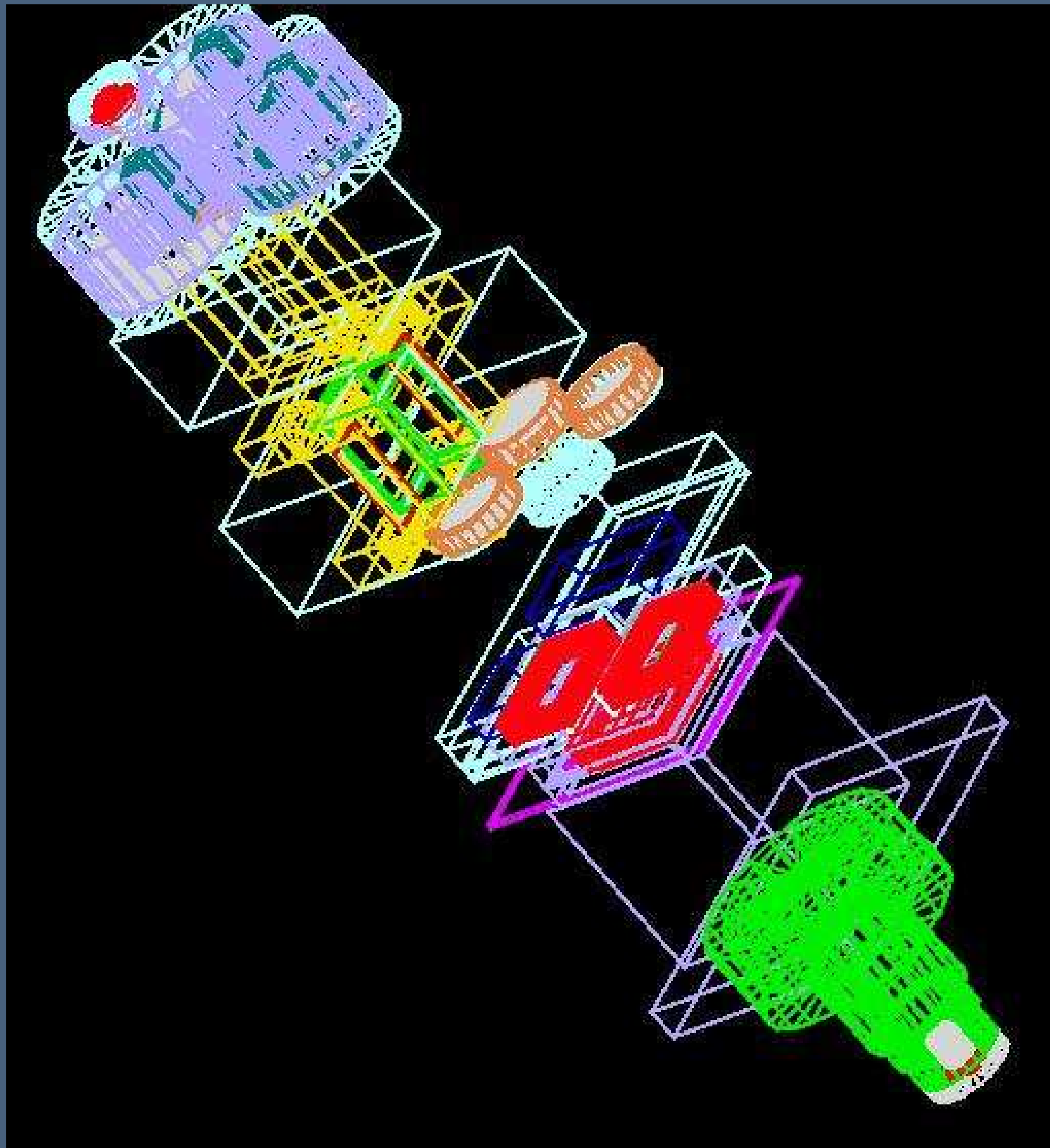
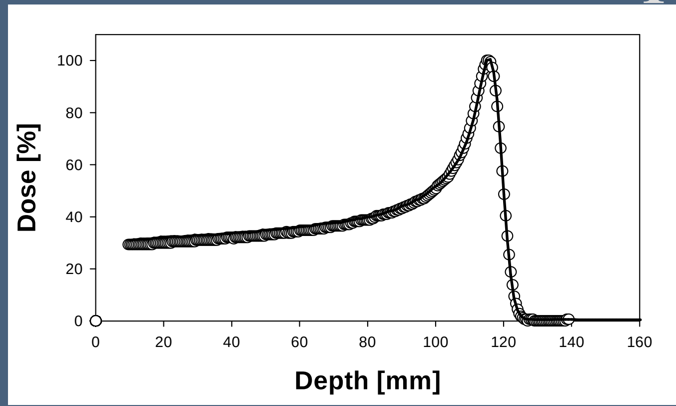
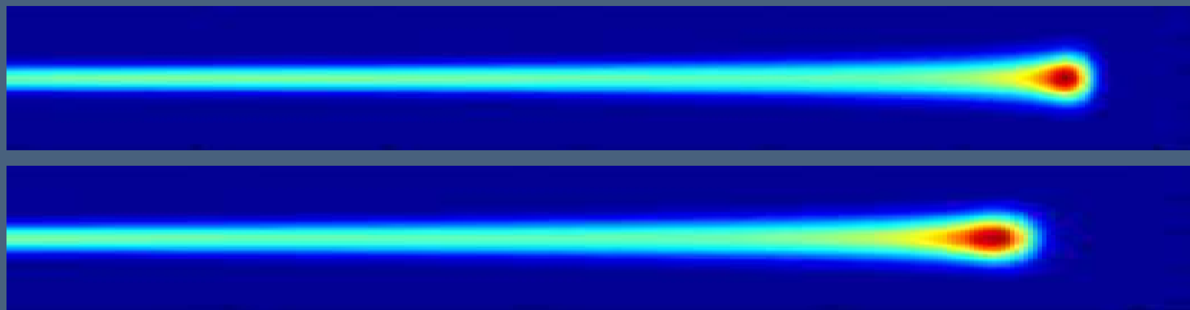
Proton Therapy



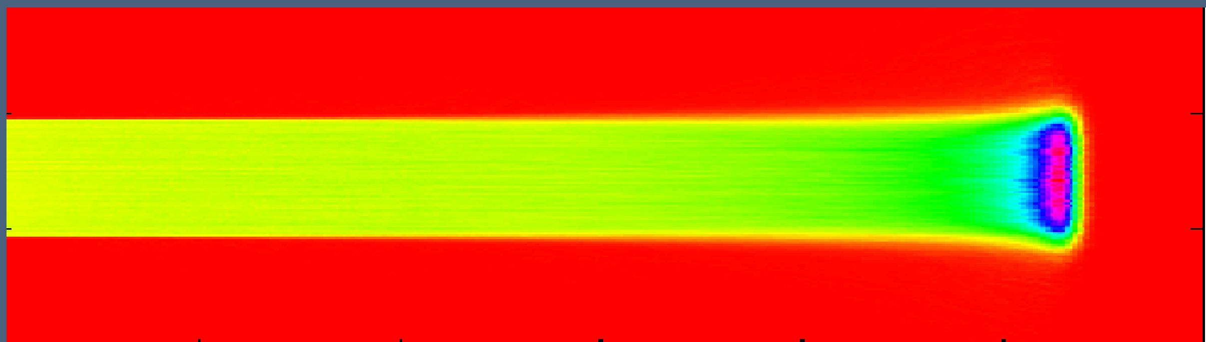
Proton Beam Therapy



Goal 1: Modulation in depth (energy variation)



Goal 2: Lateral modulation (broad beam)



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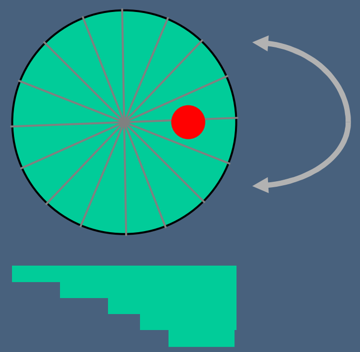
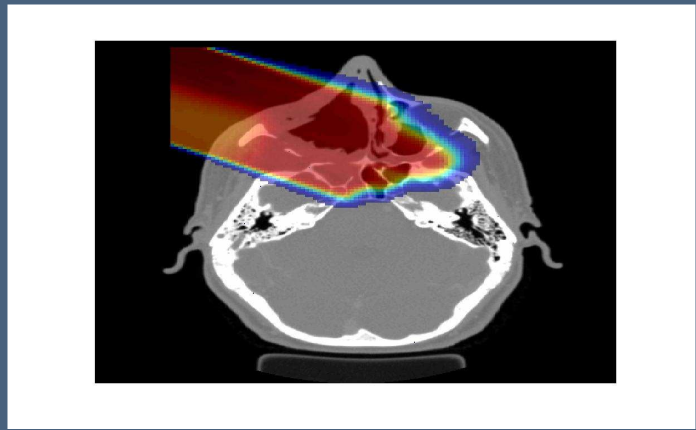
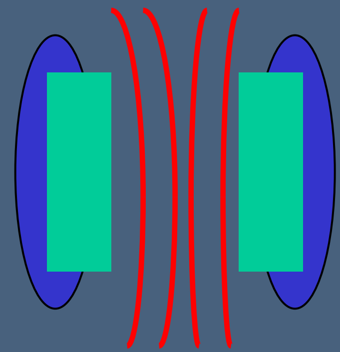
Target Coverage

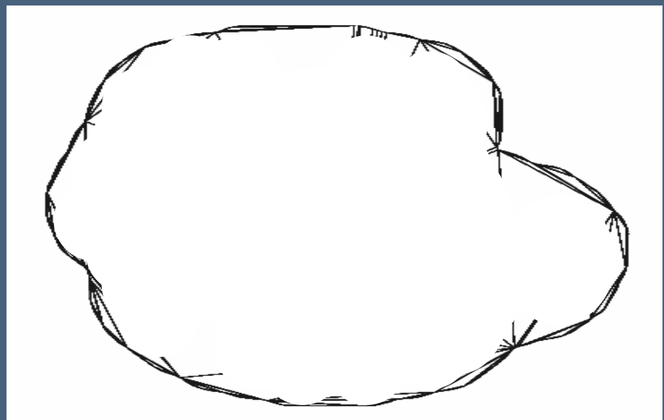
Broad Beam

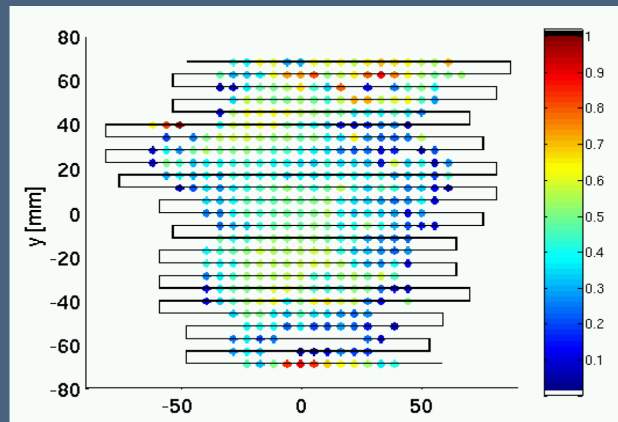


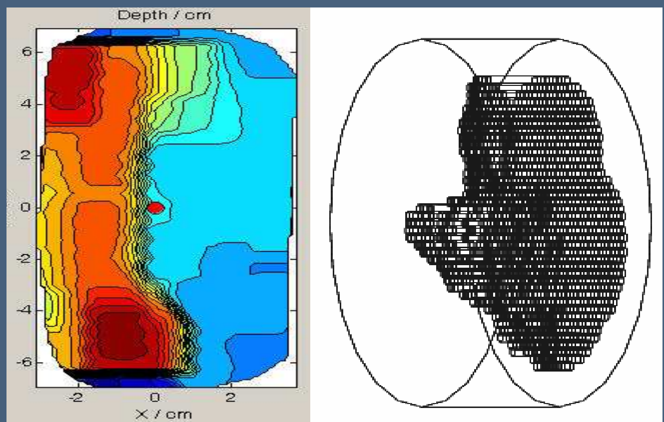


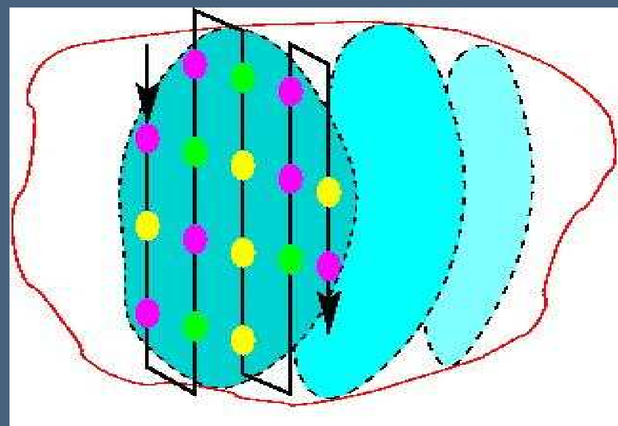
Pencil Beam











4D Monte Carlo: Scanning Magnet

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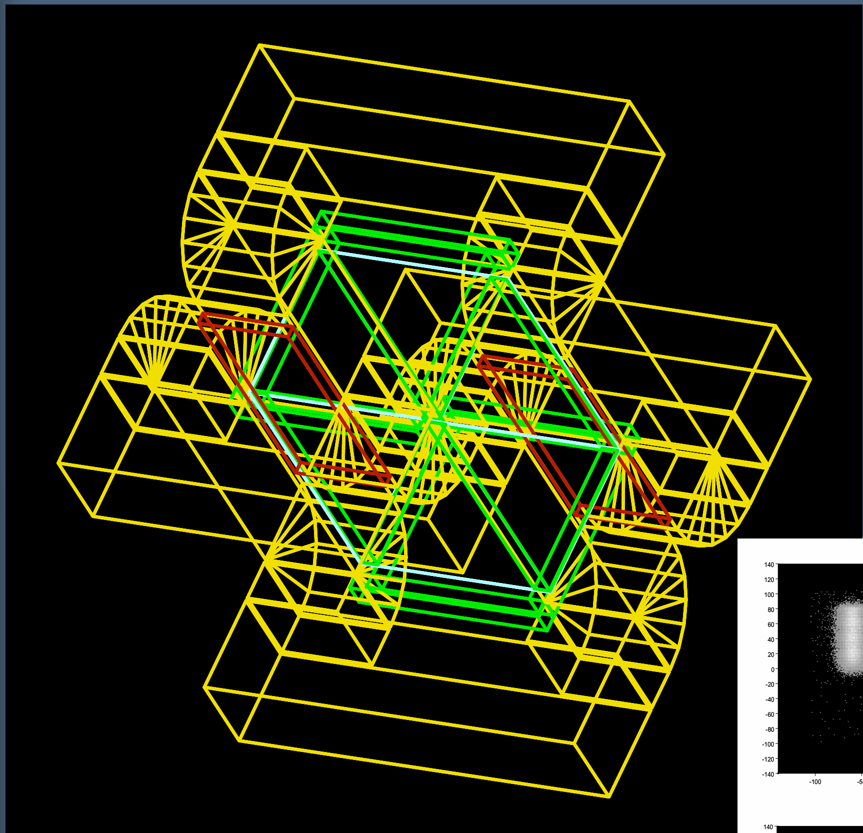

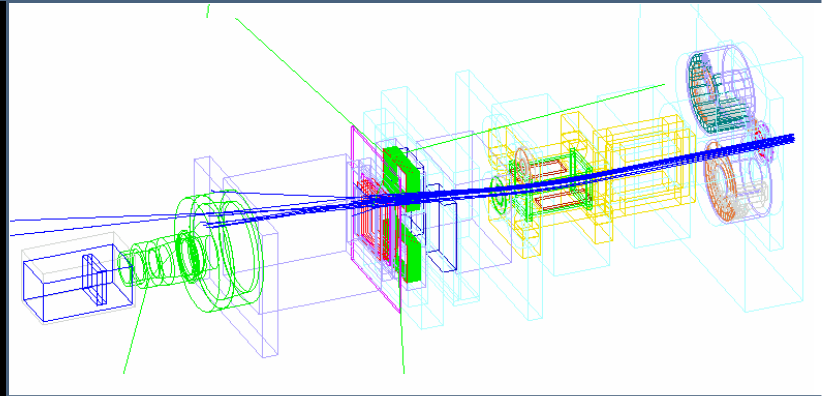

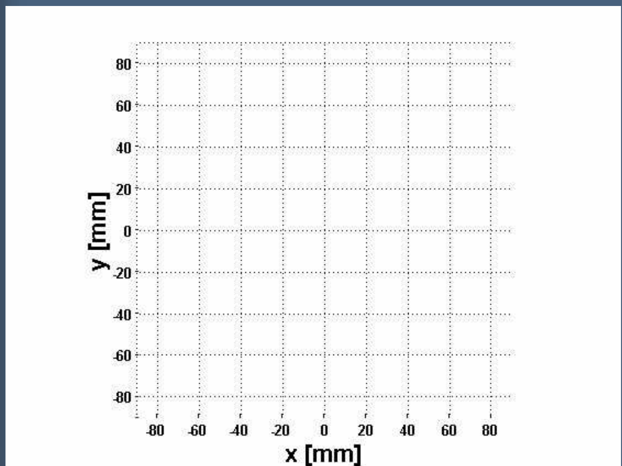

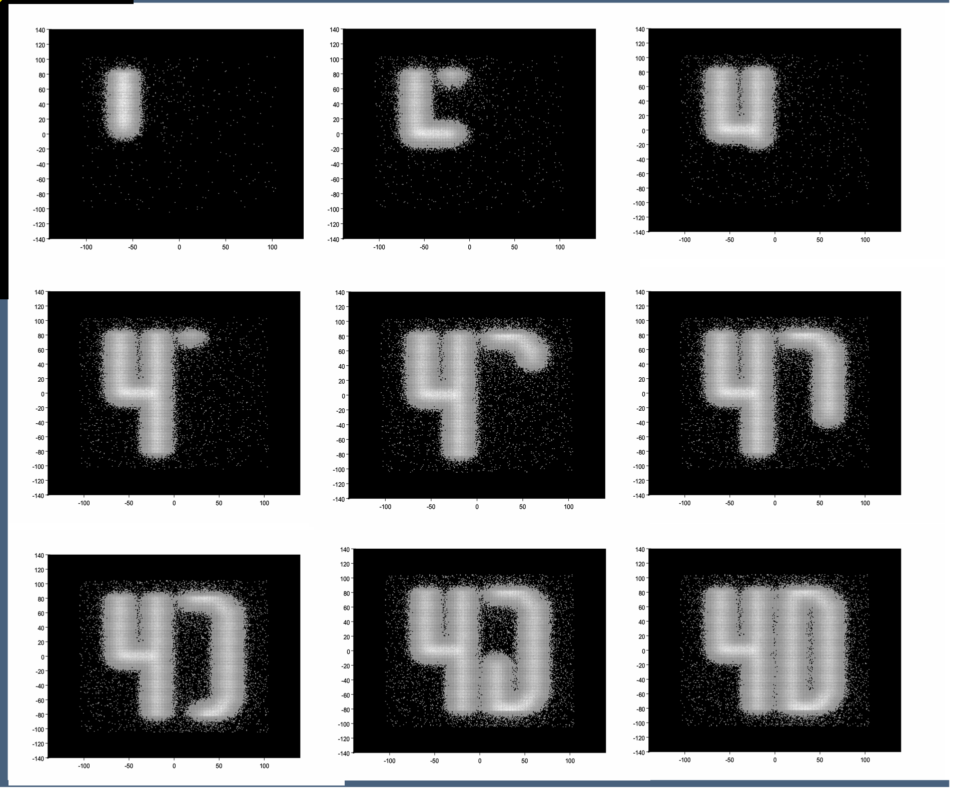

4D Monte Carlo: Range Modulator Wheel

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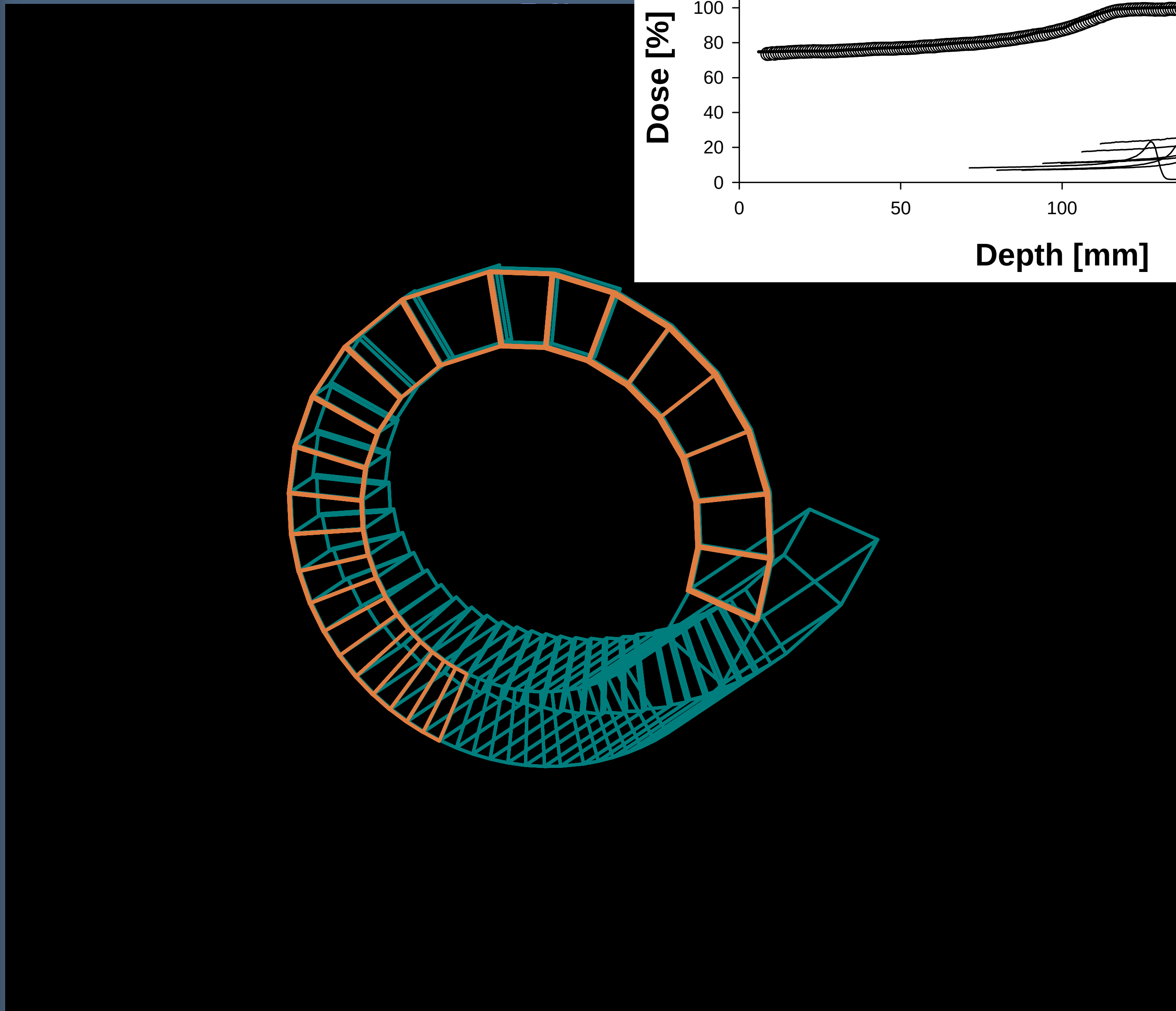
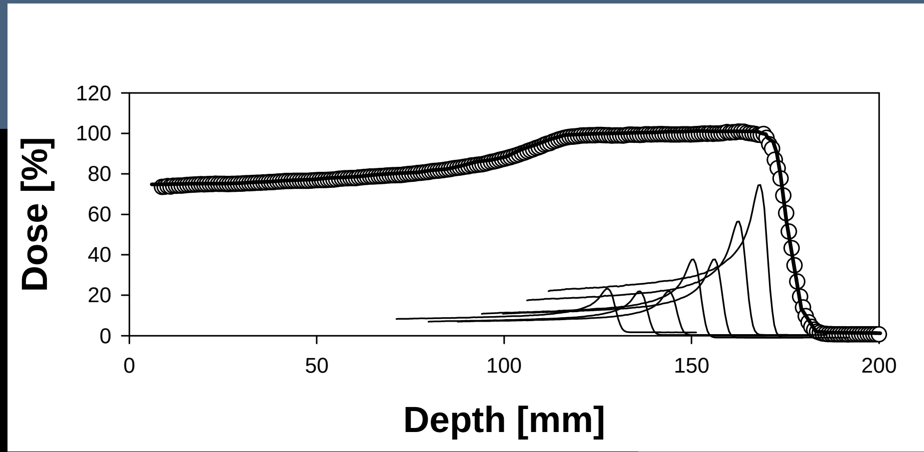
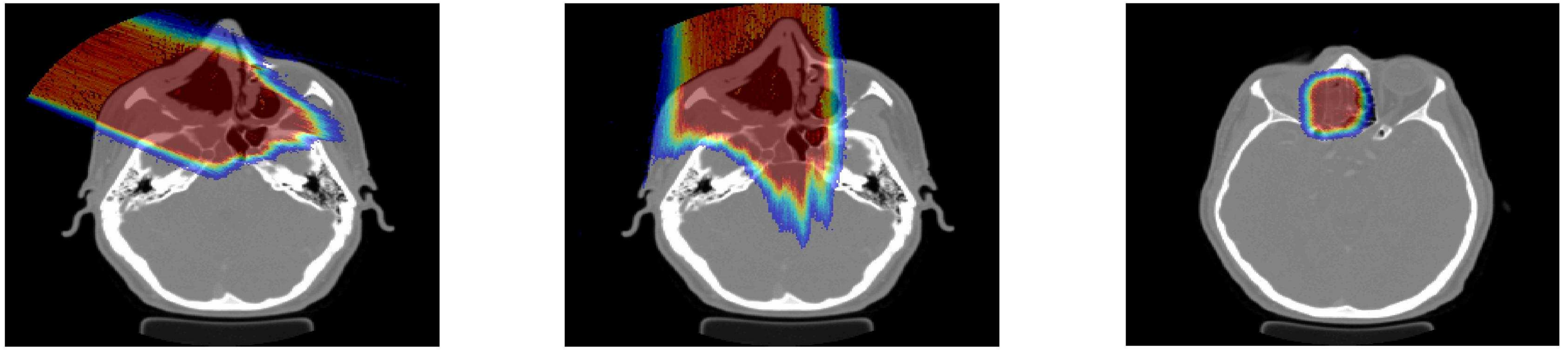
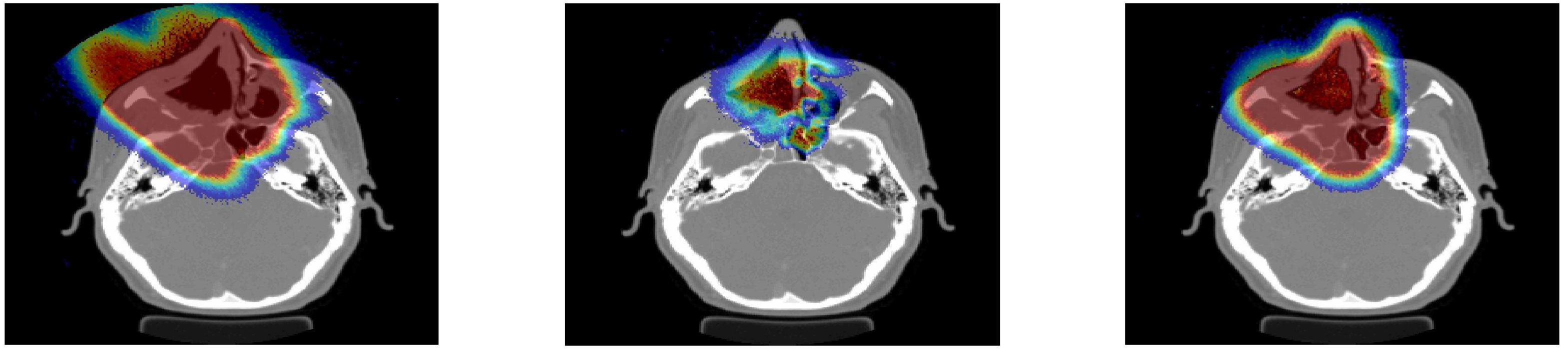




4D Proton Delivery

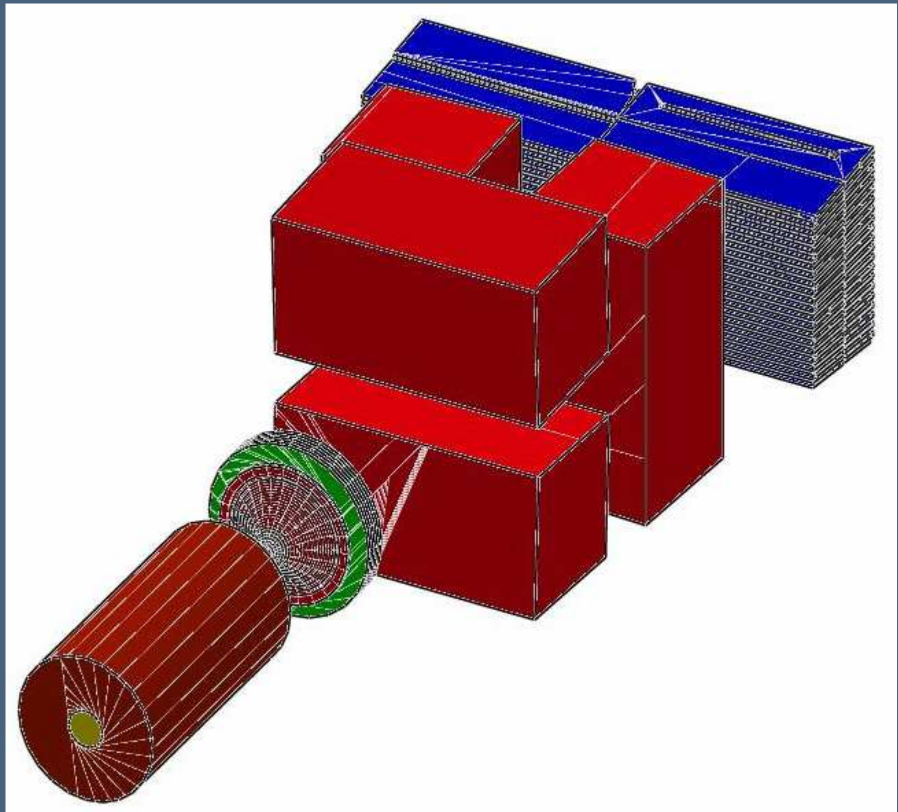


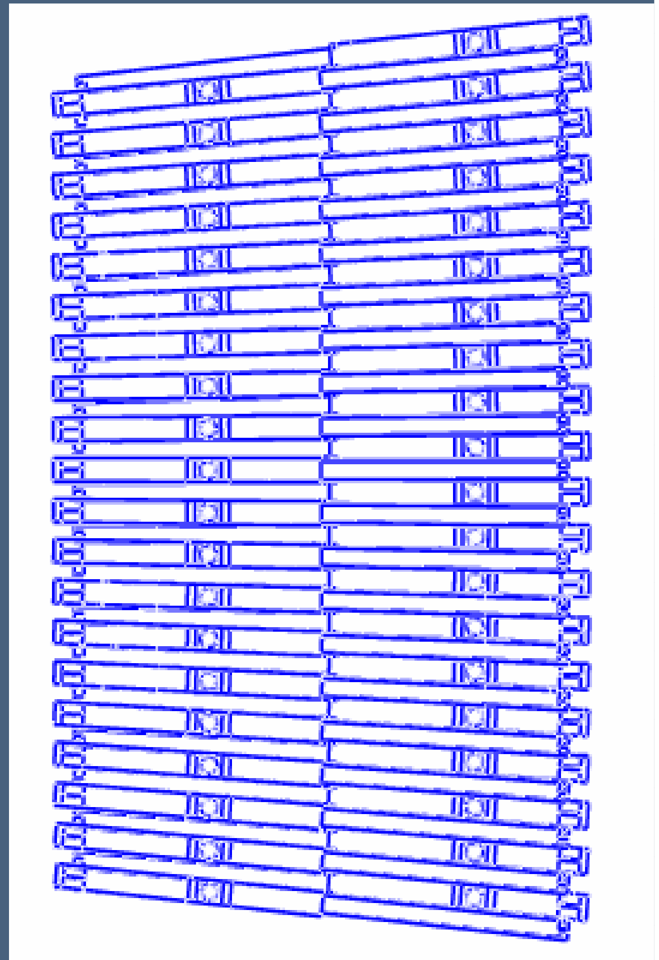
Tumor in the Paranasal Sinus

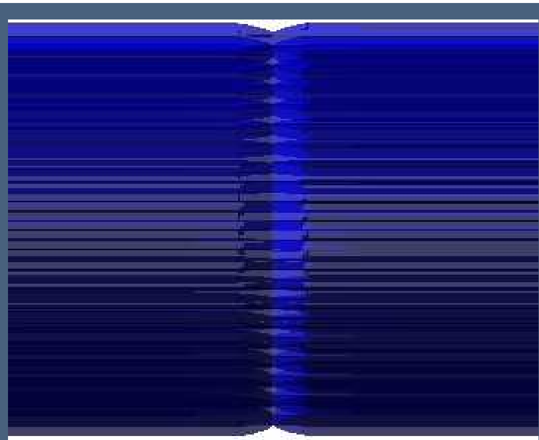


>95% prescription dose (dark red), >80% (red), >70% (orange), >60% (yellow), >50% (green), >30% (blue), ≤30% (dark blue)

4D IMRT







4D IMRT delivery

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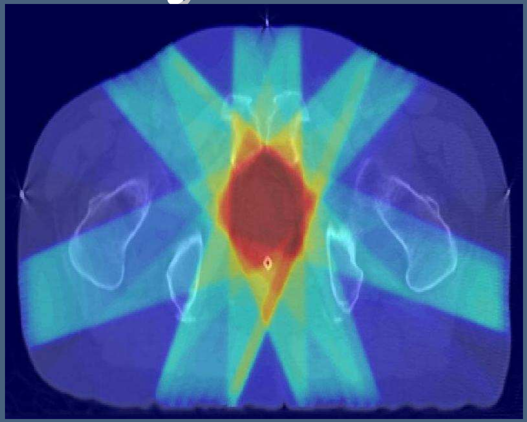
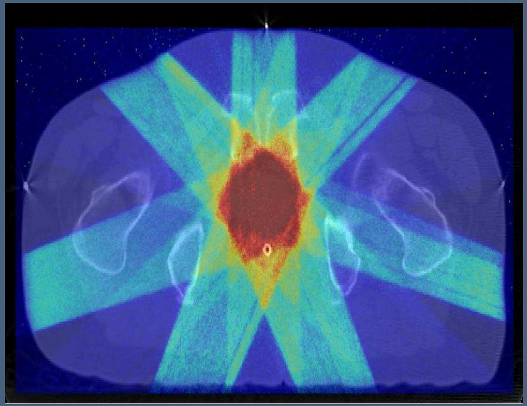
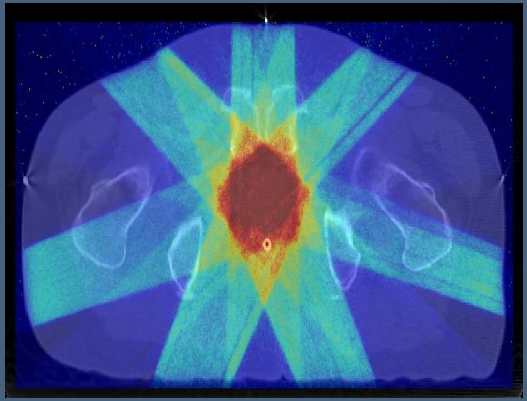
CORVUS plan



Monte Carlo
Step-and-Shoot



Monte Carlo
Sliding-Window



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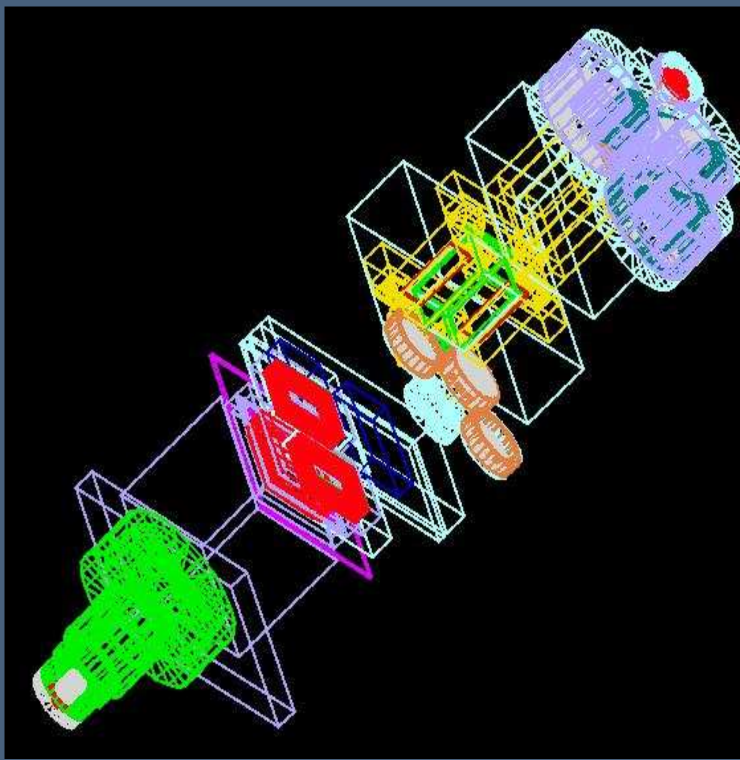

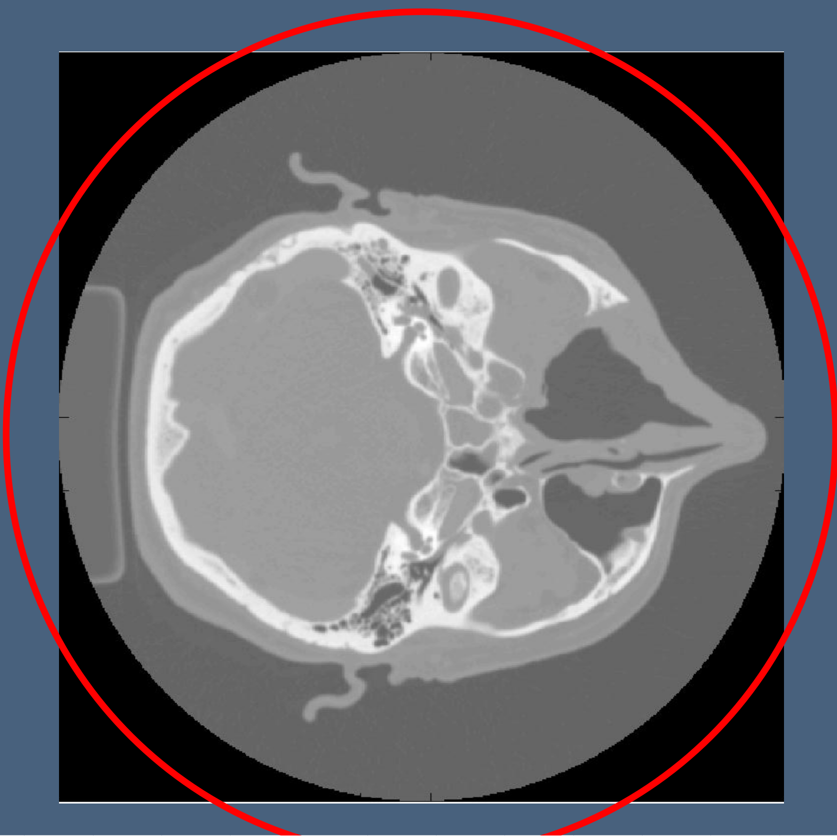

Dynamic Systems in Radiation Therapy
- Breathing Patient -

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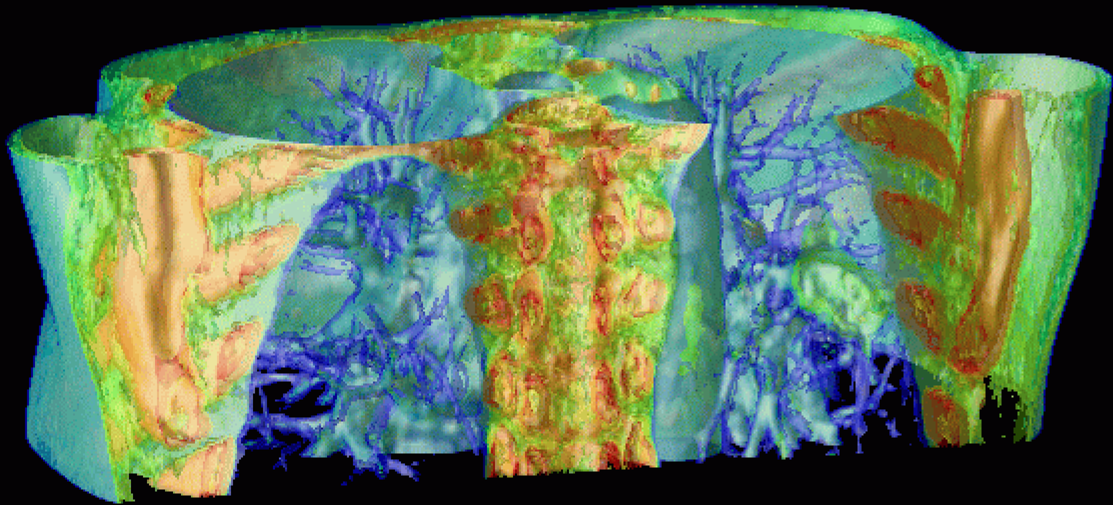

- posterior view
- posterior cut

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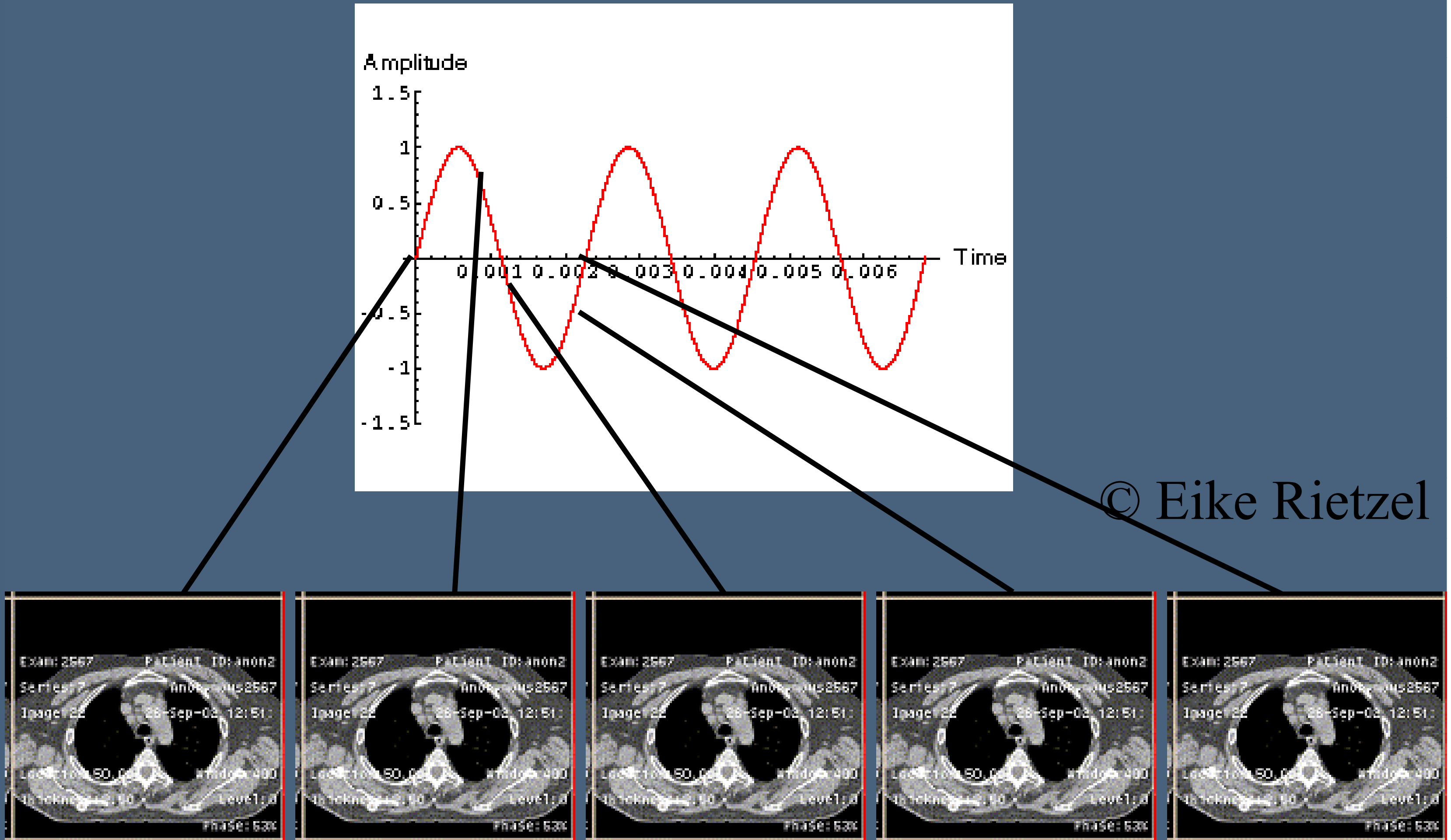
Time-resolved anatomy using 4D CT



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Four-dimensional Monte Carlo simulation based on 4D CT

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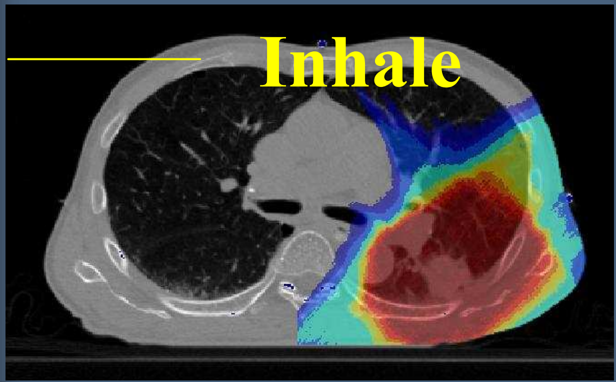

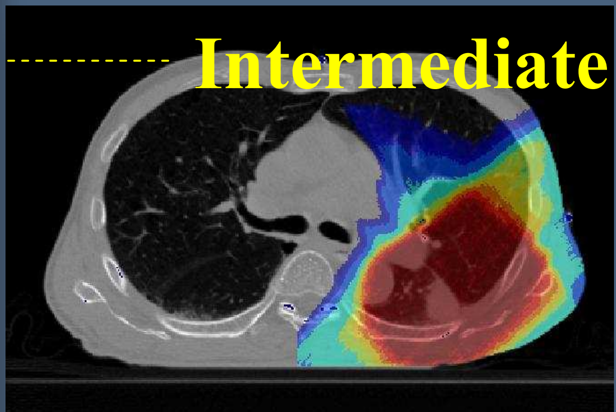

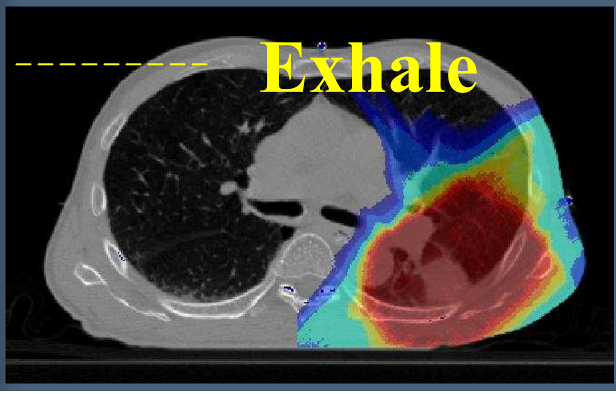

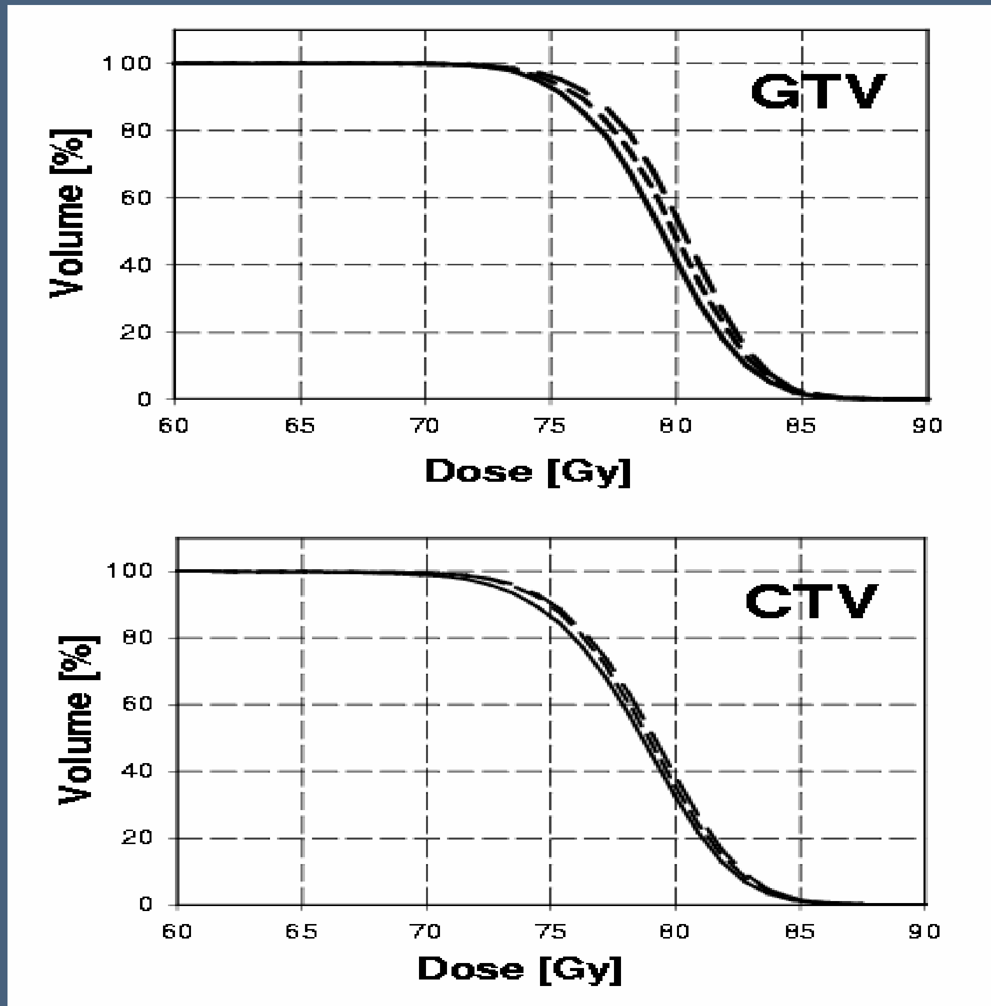

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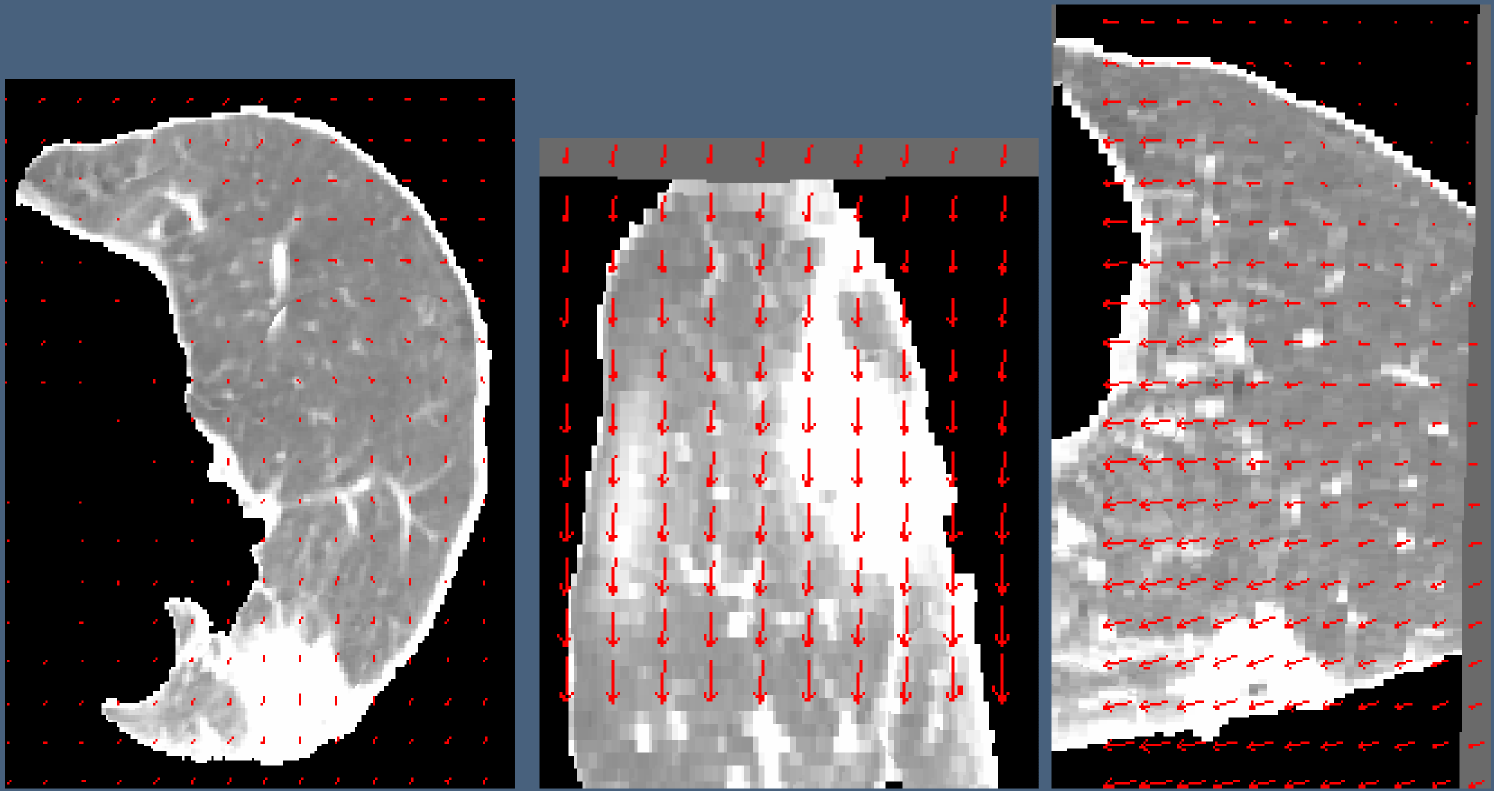
Four-dimensional Monte Carlo simulation

- Based on 4D CT information -

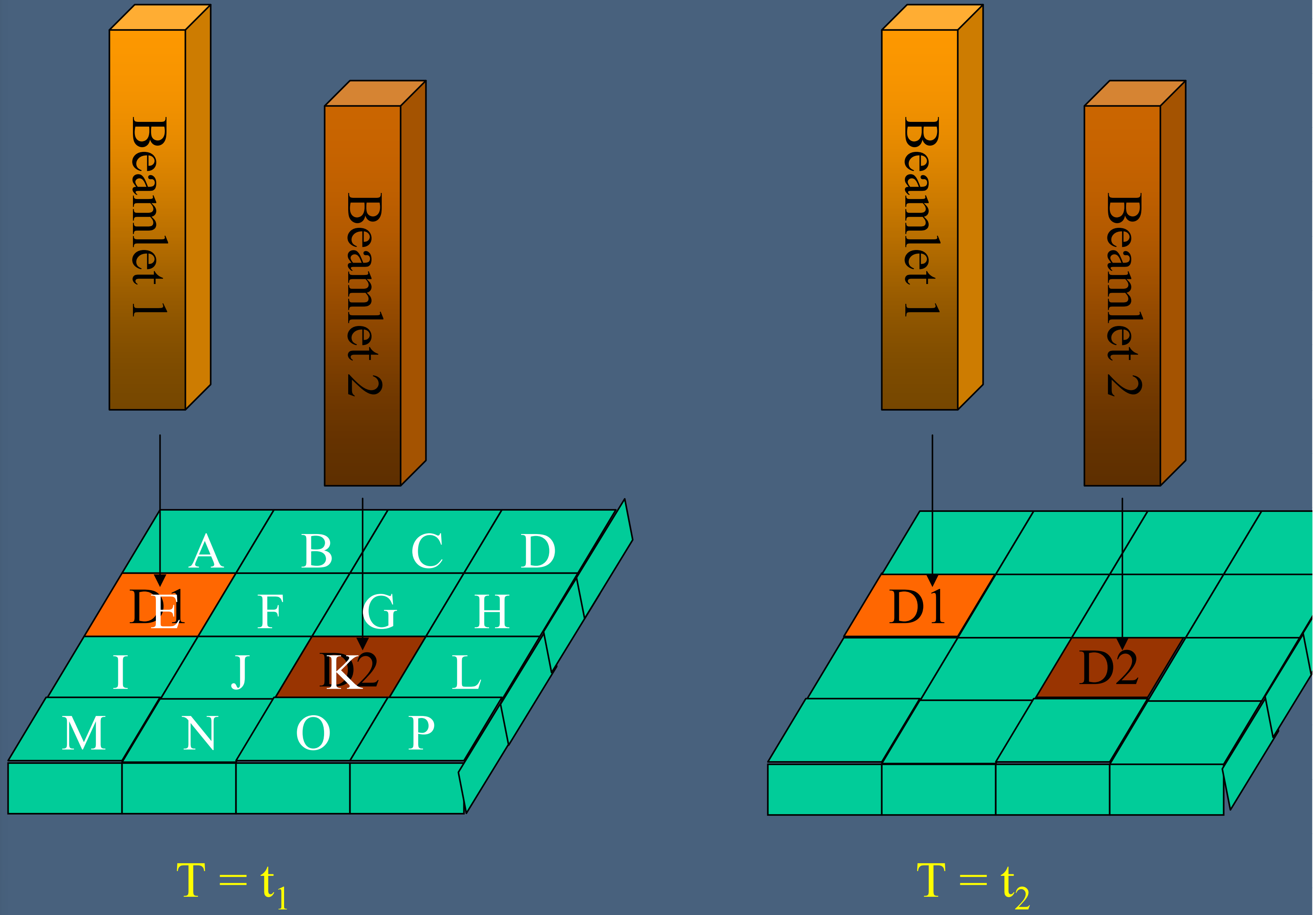


Volume Displacement Information

Software: CISG Kings College London

[T.Hartkens, BVM 2002, Springer-Verlag, March 2002]

4D Dose Deposition



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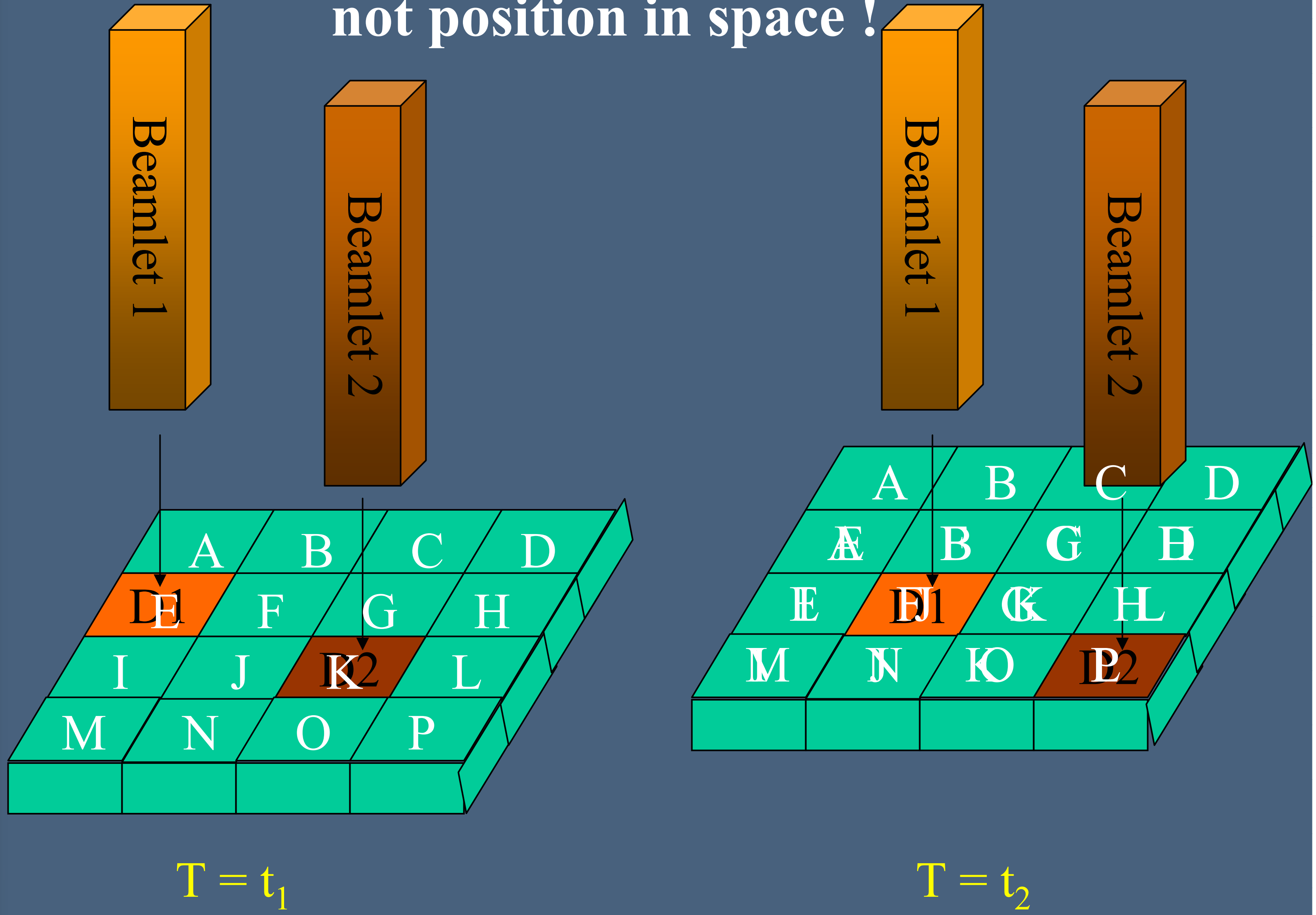
4D Dose Deposition

Dose deposition defined via voxel identifiers, not position in space !



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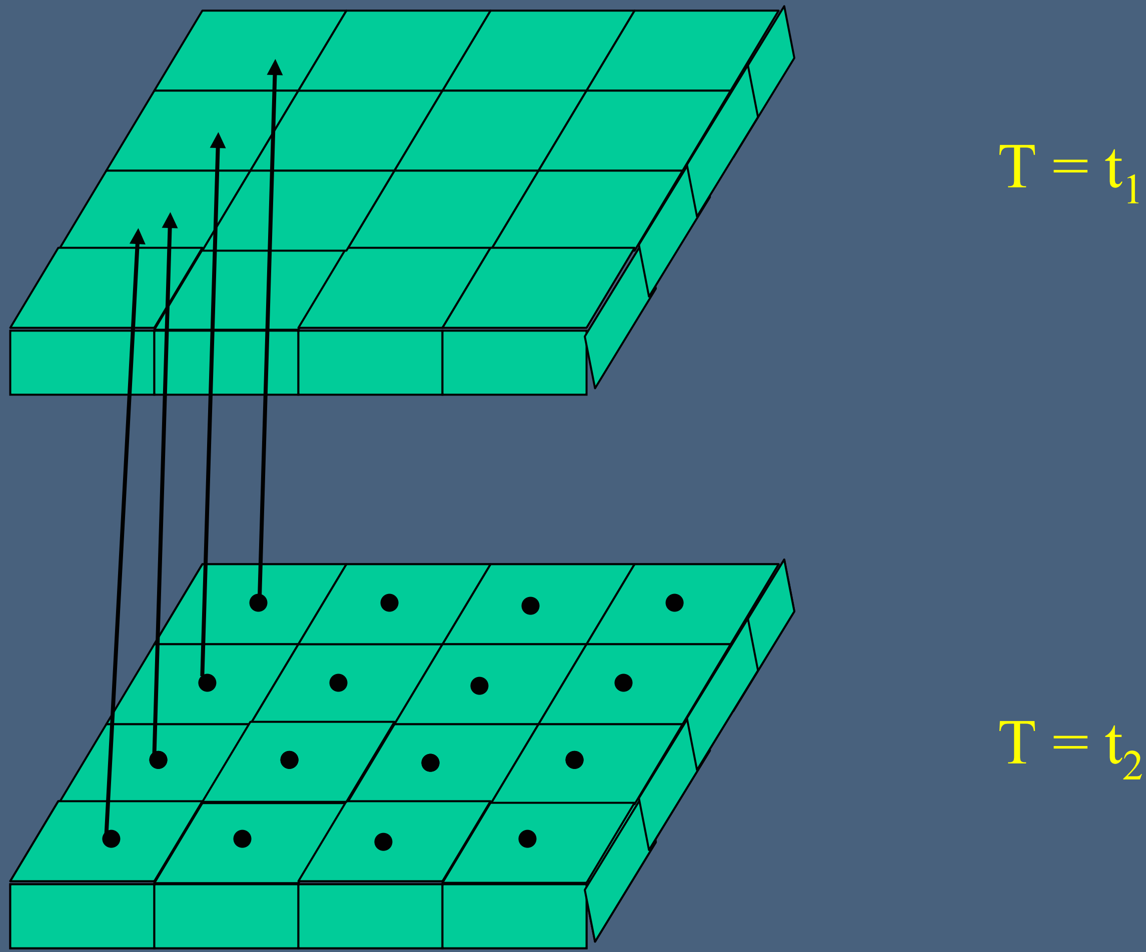
Dose calculation during non-rigid motion



Four-dimensional Monte Carlo simulation based on 4D CT

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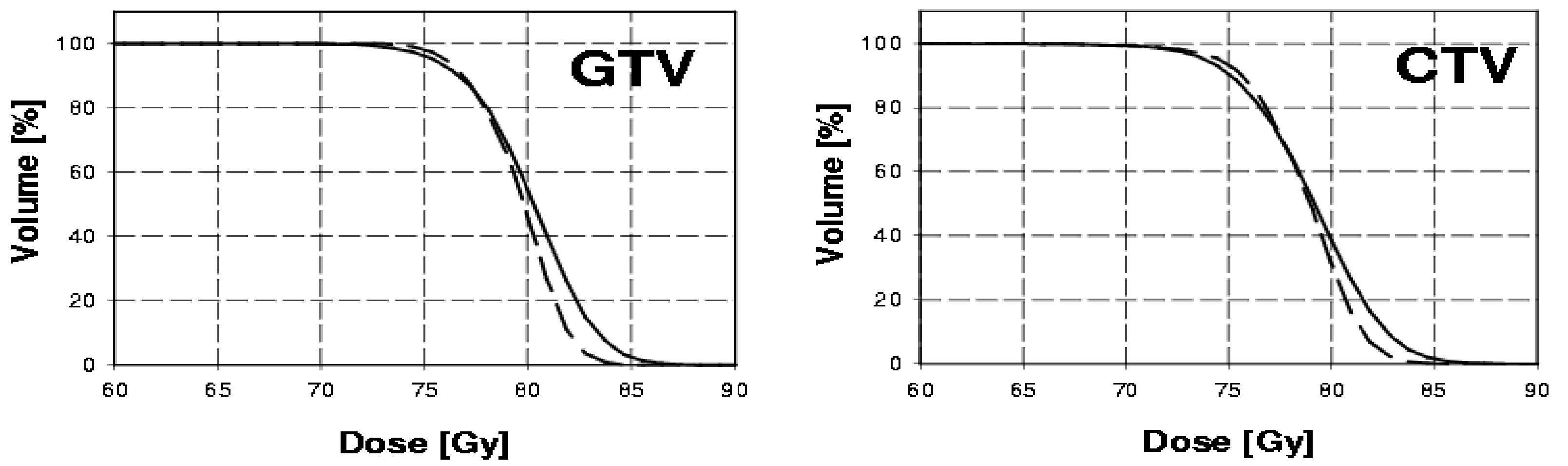

Solid lines: Patient in inhale

Dashed lines: Considering the entire breathing phase

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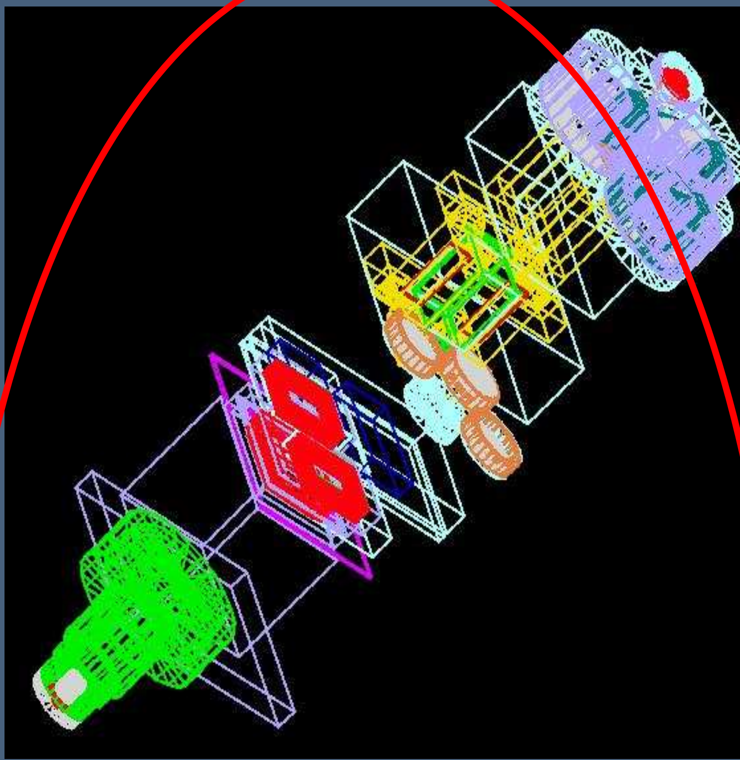

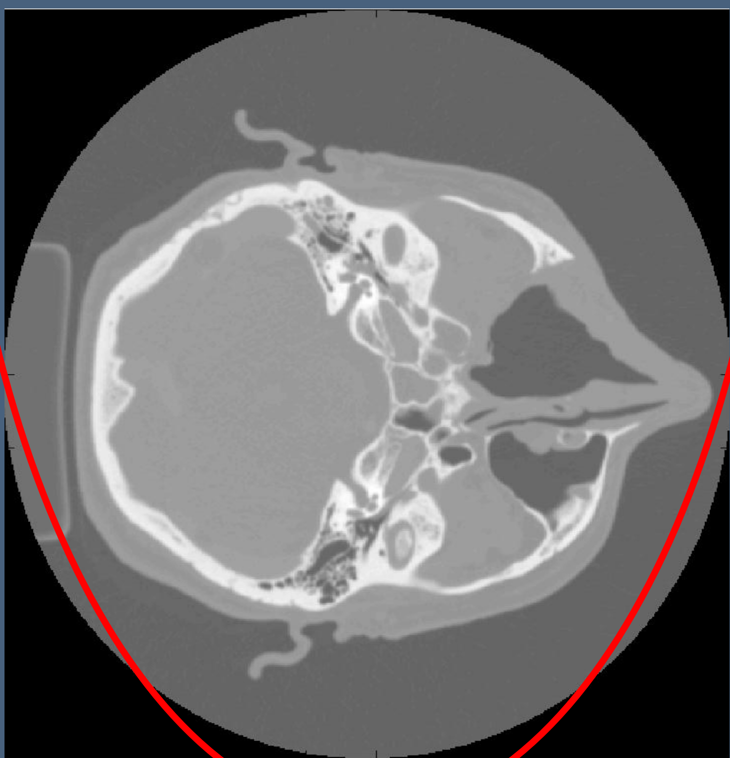

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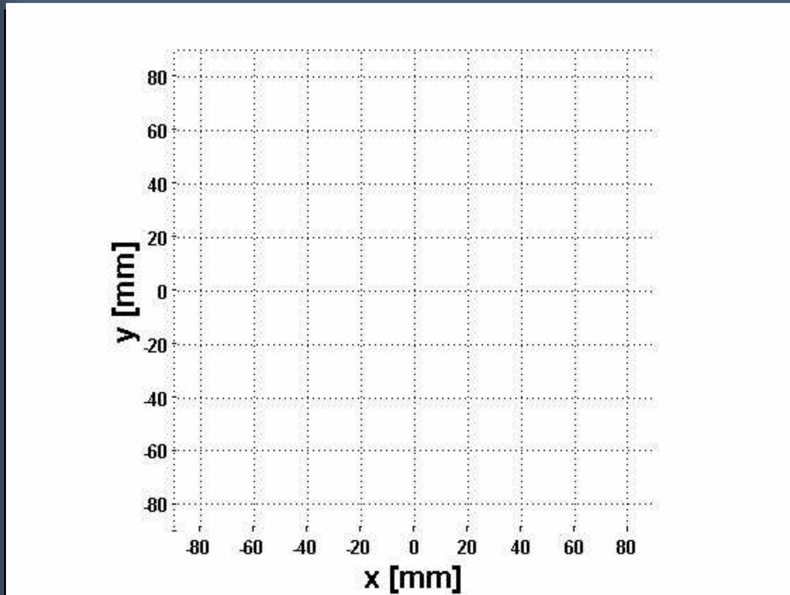
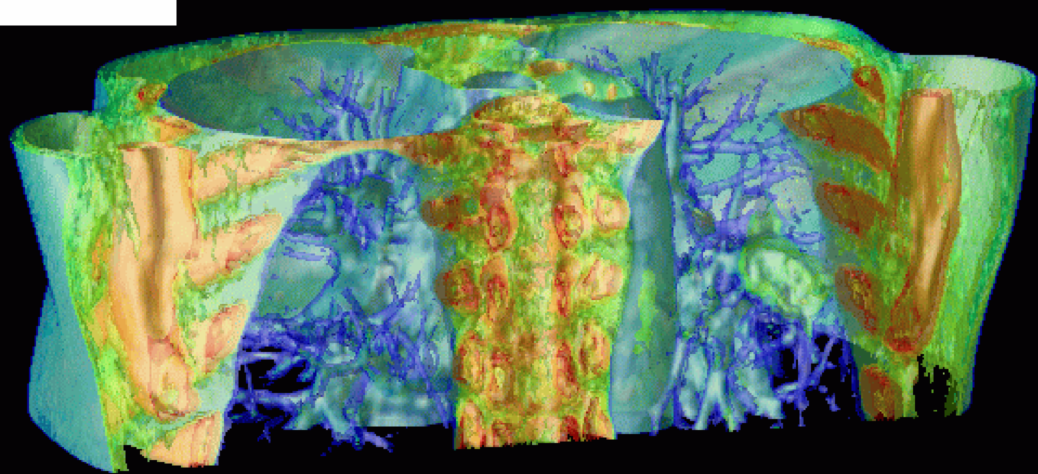
Moving patient in IMPT (double dynamic)





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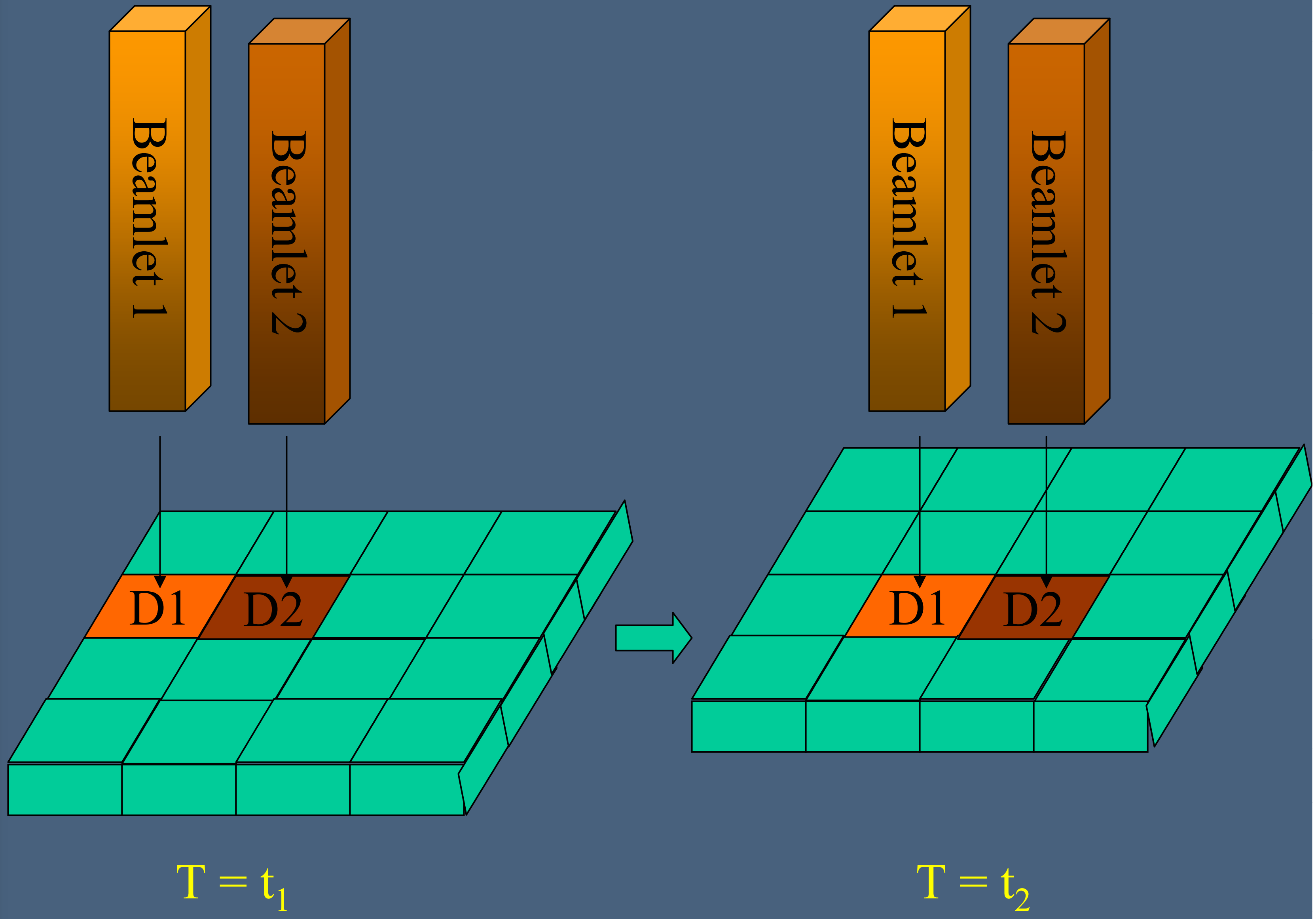
Single-dynamic (patient movement ; static beam delivery)



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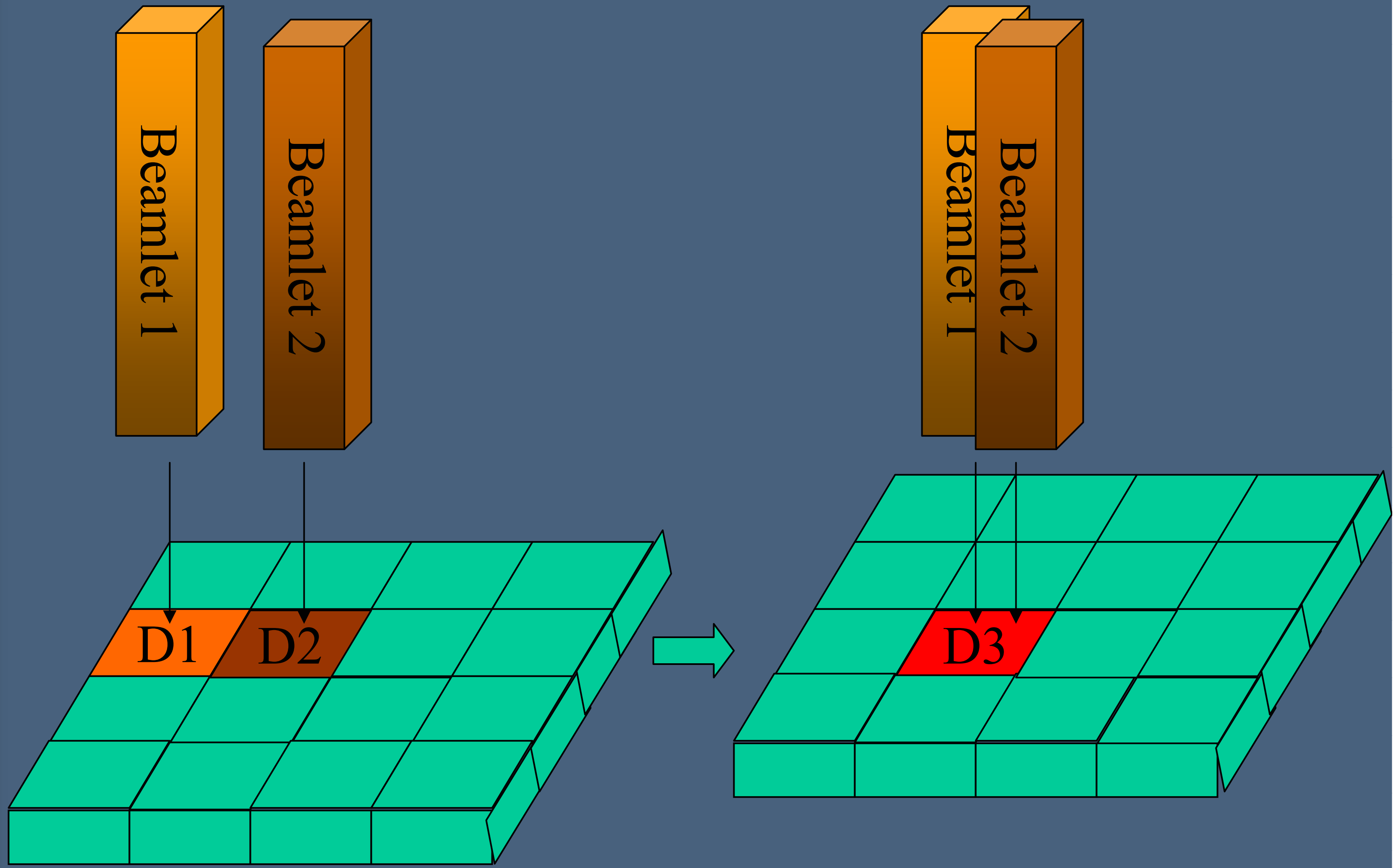
Double-dynamic (patient movement; dynamic beam delivery)



$T = t_1$ $T = t_2$

Effect can be reduced by 'repaiting'

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4D Monte Carlo of IMPT

- Beamlets and patient are moved continuously (rigid)
- Assumptions:
  - Irradiation time per slice is 0.4 seconds (on average)
  - Changing the cyclotron beam energy with a degrader takes a few seconds
  - Breathing cycle is 4 seconds
- Choose a specific scanning pattern
- Choose a specific number of protons per second
- Update the beam delivery setup and the patient setup every 0.1 virtual seconds

4D Monte Carlo of IMPT

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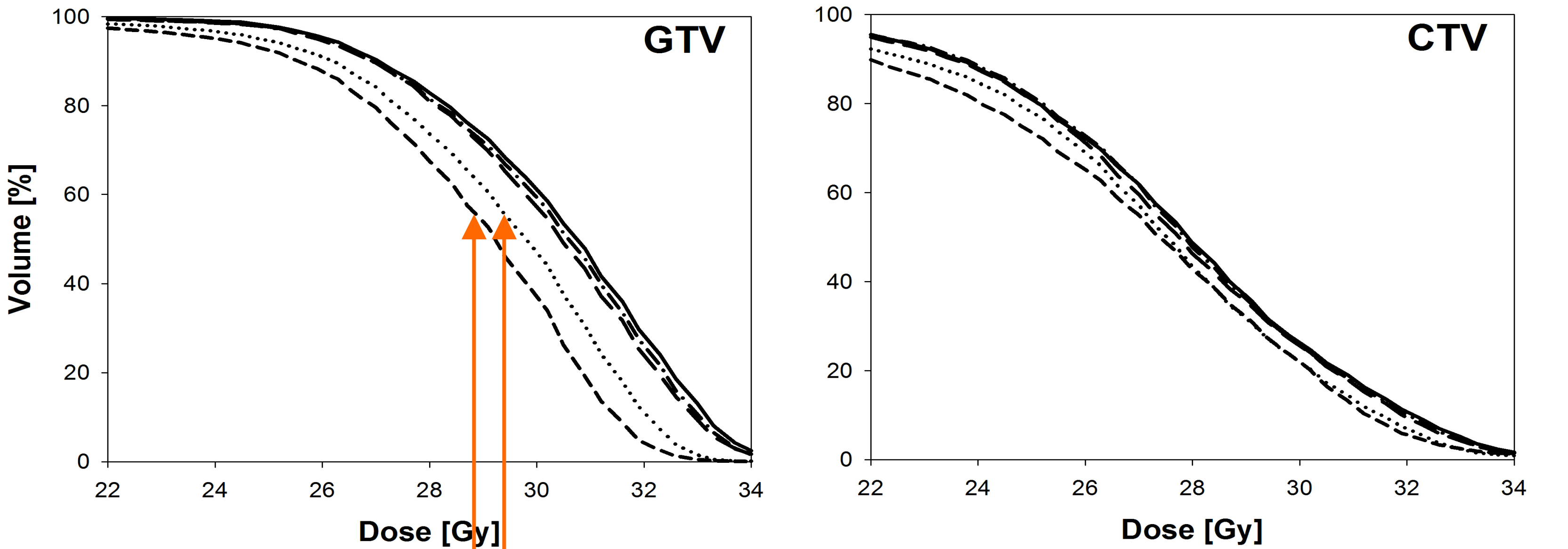

DVH for left anterior field

- Static
- Patient moves ±0.5 cm
- Patient moves ±1.5 cm
- Patient moves ±0.5 cm; repainting
- Patient moves ±1.5 cm; repainting

Conclusion

Four-dimensional Monte Carlo (based on GEANT4) is a technique capable of simulating geometry variations (beam delivery or patient) during dose calculation.

The technique allows the investigation of interplay effects for any given dose rate.

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ACKNOWLEDGMENTS

Hongyu Jiang (GEANT4)

Eike Rietzel (4D CT)

NIH/NCI grant # P01 CA 21239

NIH/NCI grant # R01 CA 111590

PUBLICATIONS

Paganetti "Four-dimensional Monte Carlo …"
Phys Med Biol 2004: 49, N75-N81

Paganetti et al "Monte Carlo simulations with time-dependent …"
Int J Radiat Oncol Biol Phys 2004: 60, 942-950

Paganetti,Jiang,Trofimov "4D Monte Carlo simulation of proton beam …"
Phys Med Biol 2005: 50, 983-990