Proton Treatment Planning Issues

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Issues?

- Proton Treatment Planning is similar to photon treatment planning in many ways:
  - Goal: Physical dose (J/kg) in target with little to none in OAR
  - Entrance dose
  - Tissue Heterogeneities
  - Physical beam attributes
  - Dose delivery uncertainties: dosimetric, mechanical, electronic, IT, patient motion
  - Many More

Issues?

- What are the differences?
- Many well-documented and many subtle issues
  - Range uncertainties
    - CT HU to proton energy deposition (Cross sections and SPR)
    - Heterogeneities
  - LET and RBE: energy, particle
  - Penumbra: air gap, range, particle
  - Scanning beam delivery: spot size, SFUD/MFO, many more
  - Interplay of motion and scanned beams; Robustness

Goals of this session

- To understand how three centers have addressed, eliminated, or reduced the effects of some of these issues in clinical situations.
- To ask: "How can we (physicists) improve proton treatment planning and delivery?"

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Treatment Planning for Proton Radiotherapy

July 2012

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Outline

- Treatment Planning Considerations

  - double scattered protons

  Beam properties

  Treatment devices

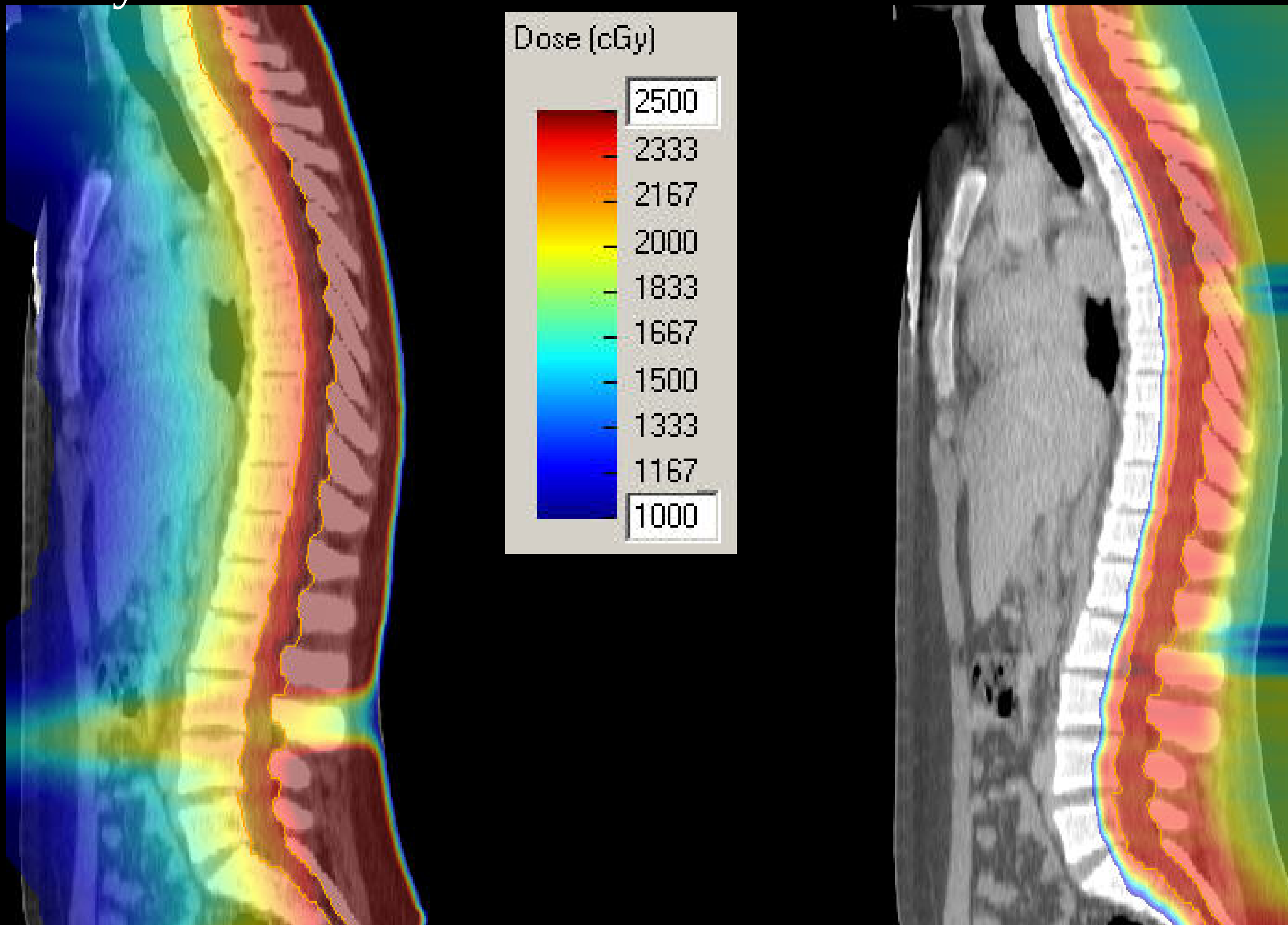
  Accounting for uncertainties

  Techniques

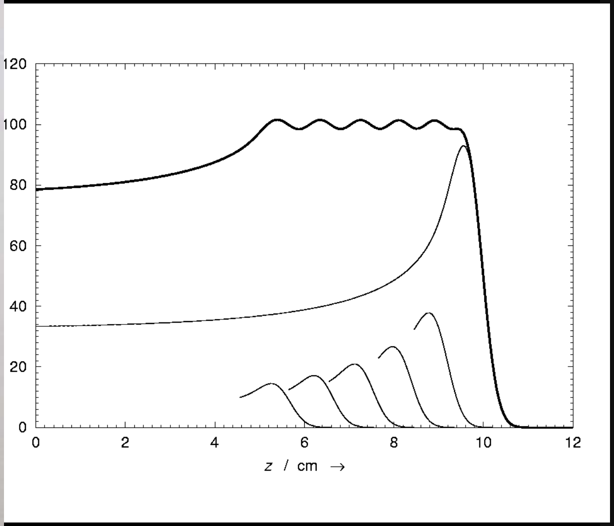
- Pencil Beam Scanning

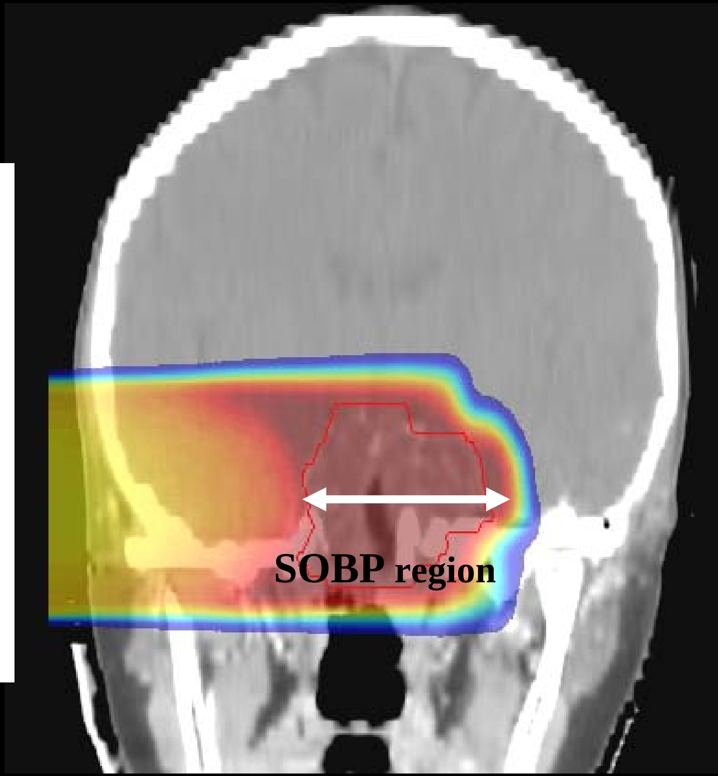
The Proton Advantage – no exit dose

X-ray | Protons



Modulation
Homogeneous Dose

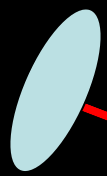




Modulator Wheel or
Uniform Scanning

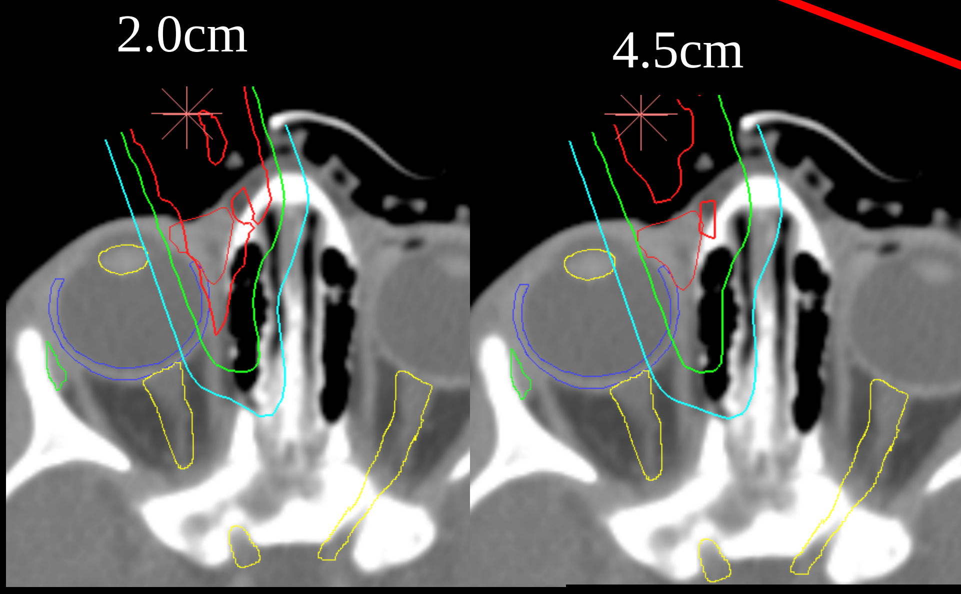
Penumbra and Airgap

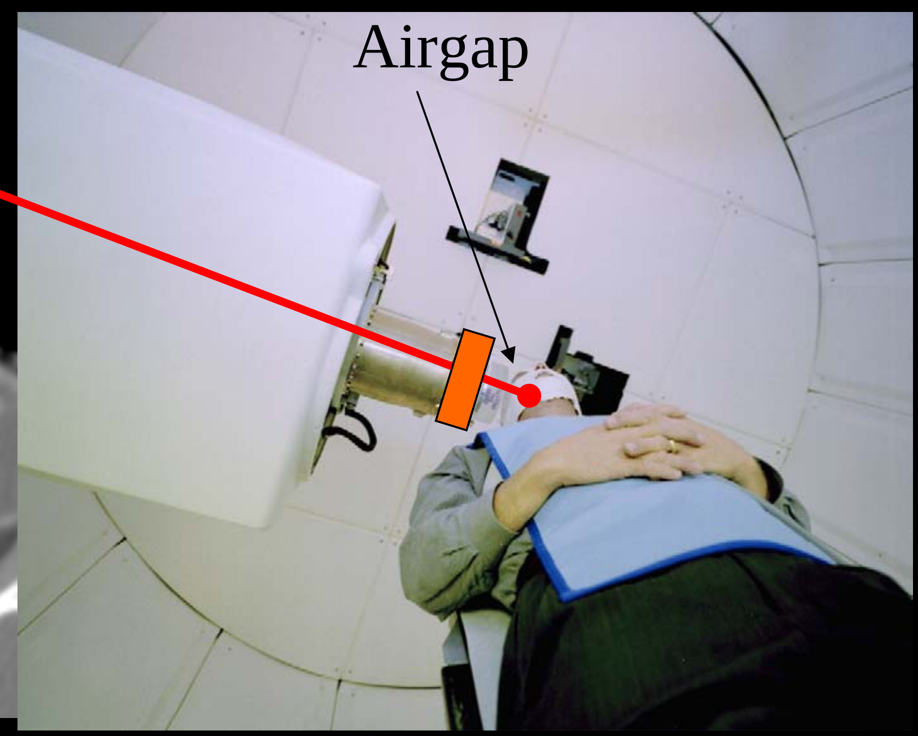
Source Size ~ 5 cm



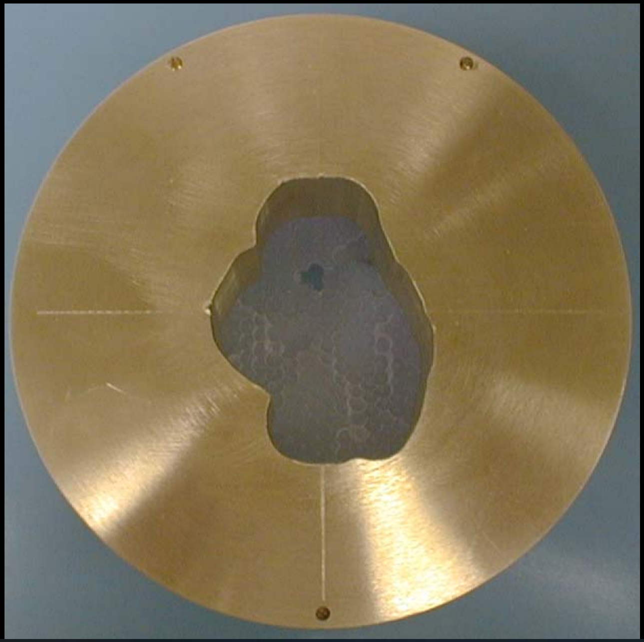
DS: Produces large virtual source size
US: ~0.5-1.5 cm

Patient source size ~ Air Gap / (SAD – Air Gap)

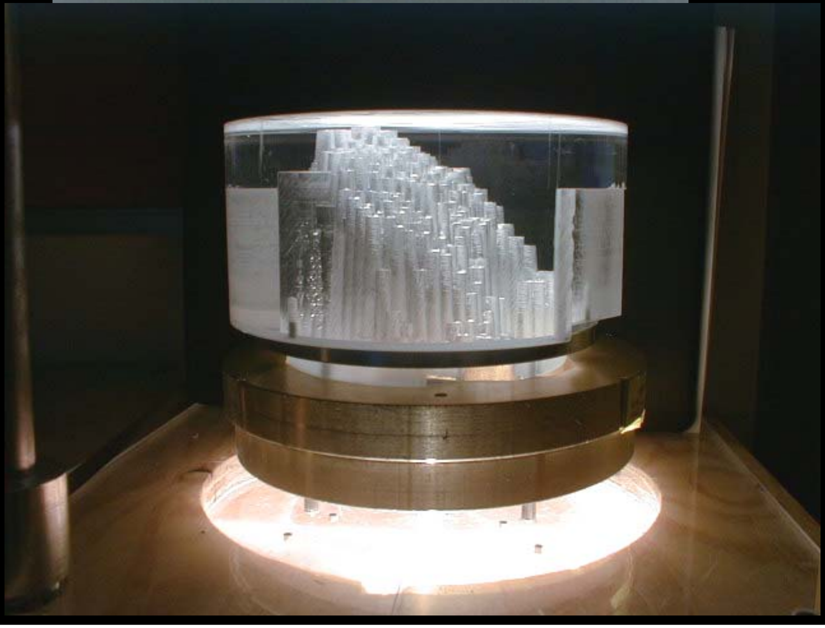




Treatment Devices



- Apertures
  - Penumbra and 2D Shaping
- Range compensator
  - Depth – the 3d dimension unique to protons



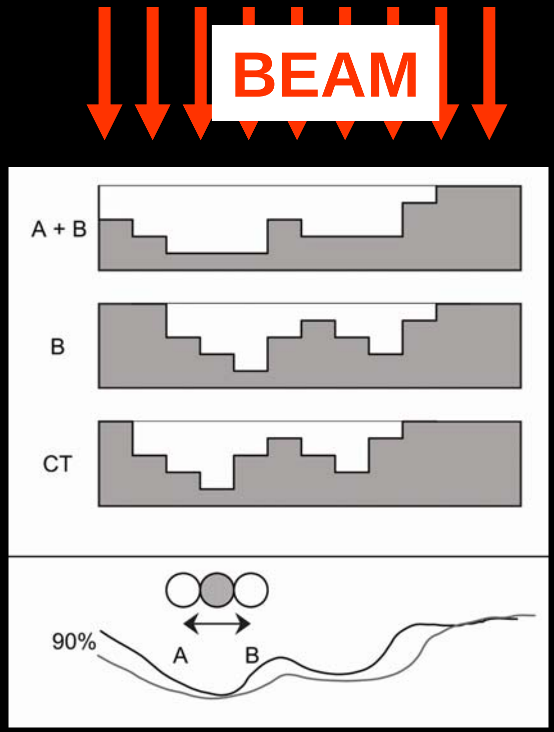
R and M Uncertainty

- Calculations require patient-specific stopping power in lieu of electron density available from patient CT
- We only have a universal conversion curve for HU's to S (rel water)
- We use sampling of HU to "calibrate" curve to the patient
- Considerable (~+/-3.5%) uncertainty
- Account for by increasing range by 3.5% + 1 mm
- Similar increase required for modulation

Setup Error

Compensator smearing

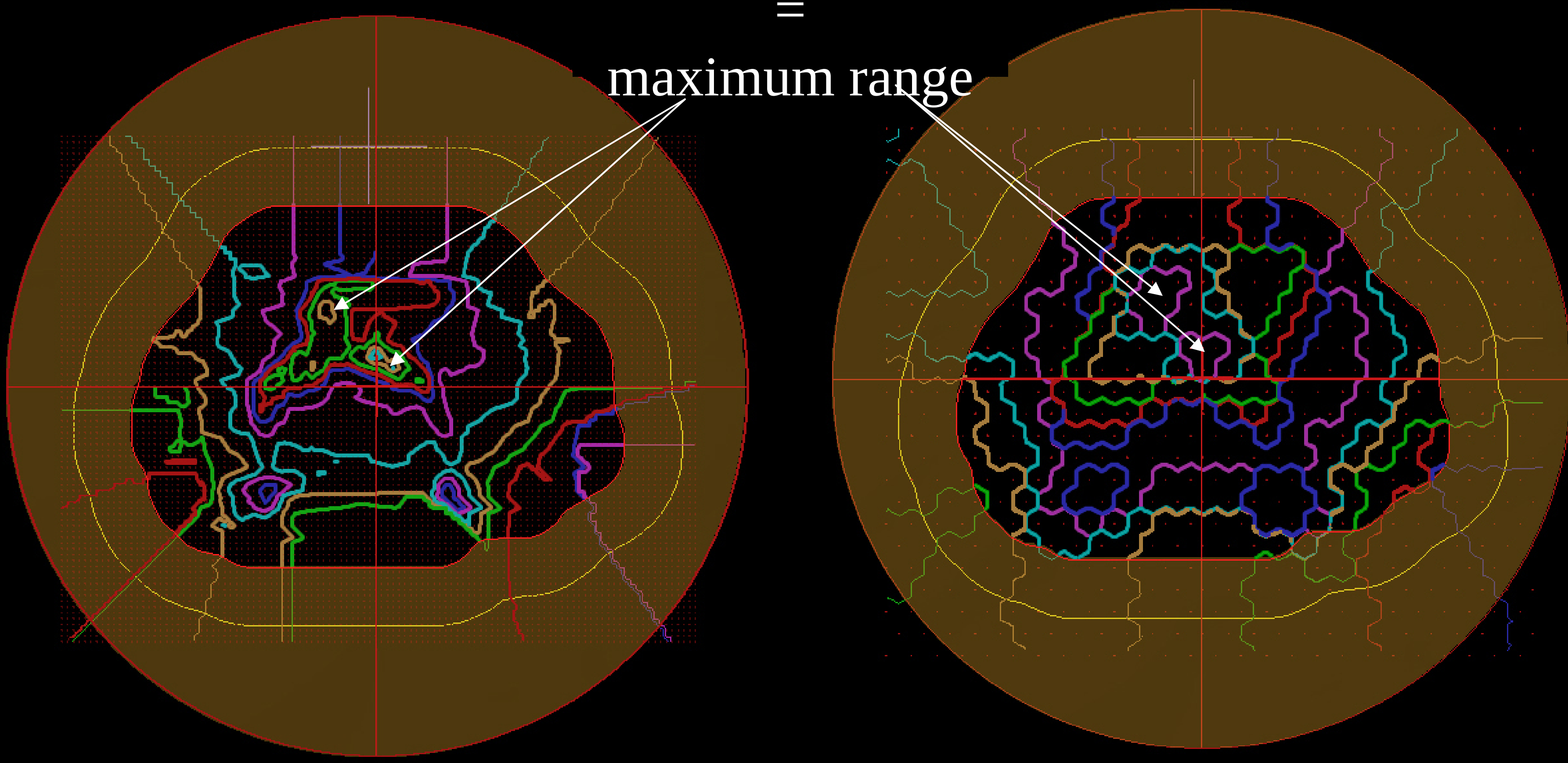
- Smearing considers the effect of non-systematic uncertainties and effectively creates the “worst” case range-compensator to ensure that the target is always covered.
- Smearing results in more dose beyond the distal edge.
- Very effective and necessary methodology



Range compensator: Isothickness lines

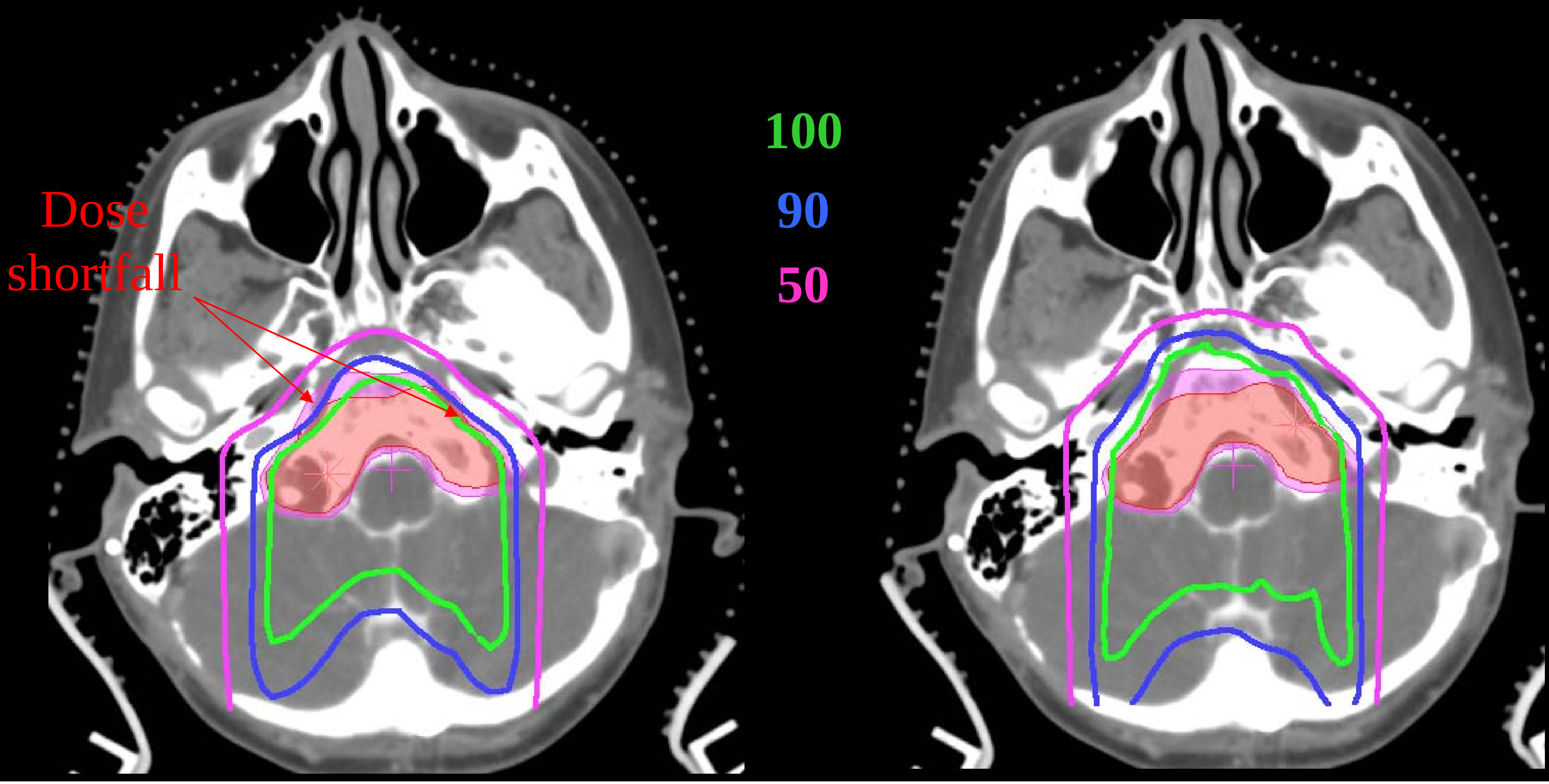
Unsmeared

Smeared



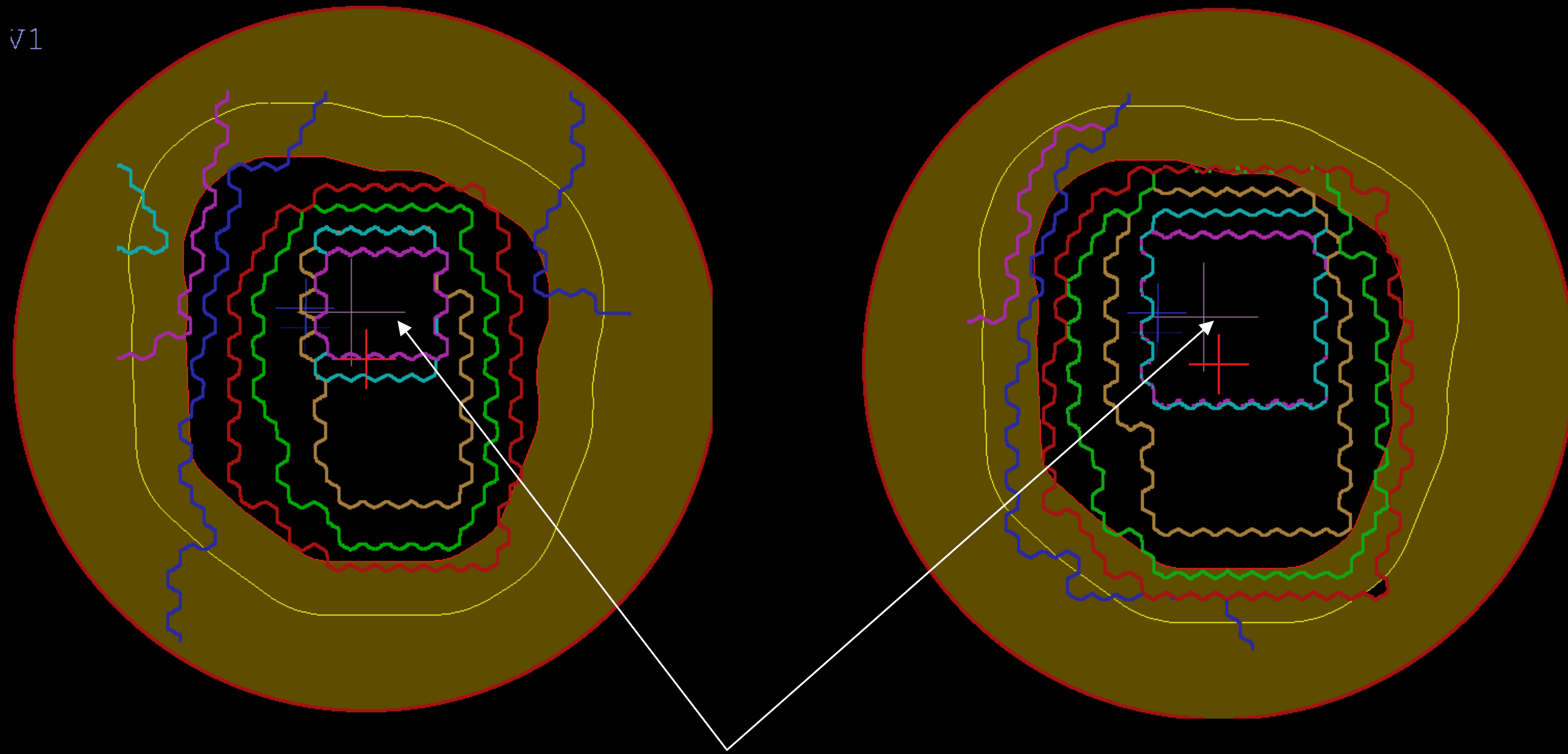
Range compensator and Dose

Unsmeared RC | Smeared RC



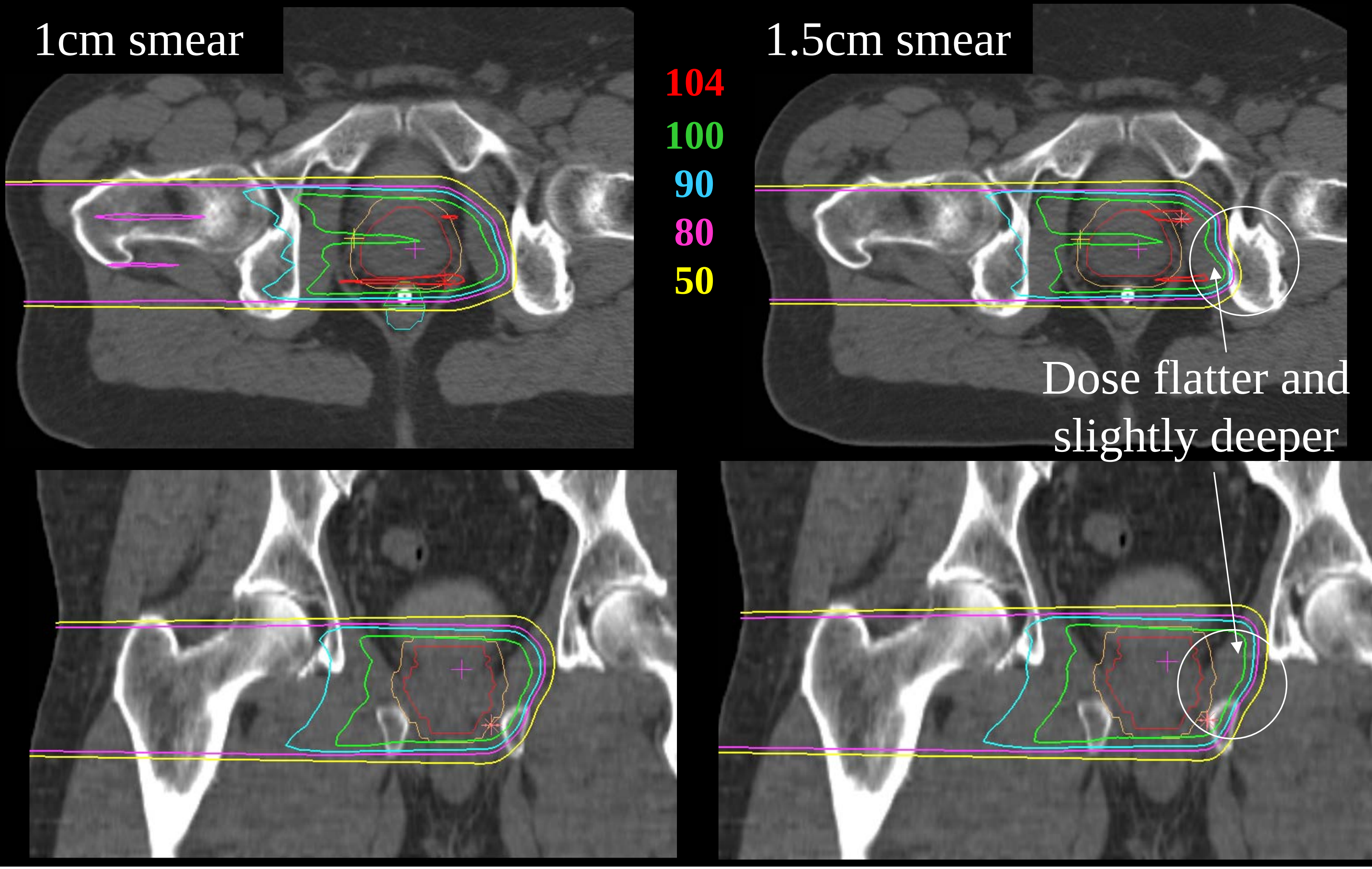
Organ motion and smearing

1.0 cm smear | 1.5 cm smear

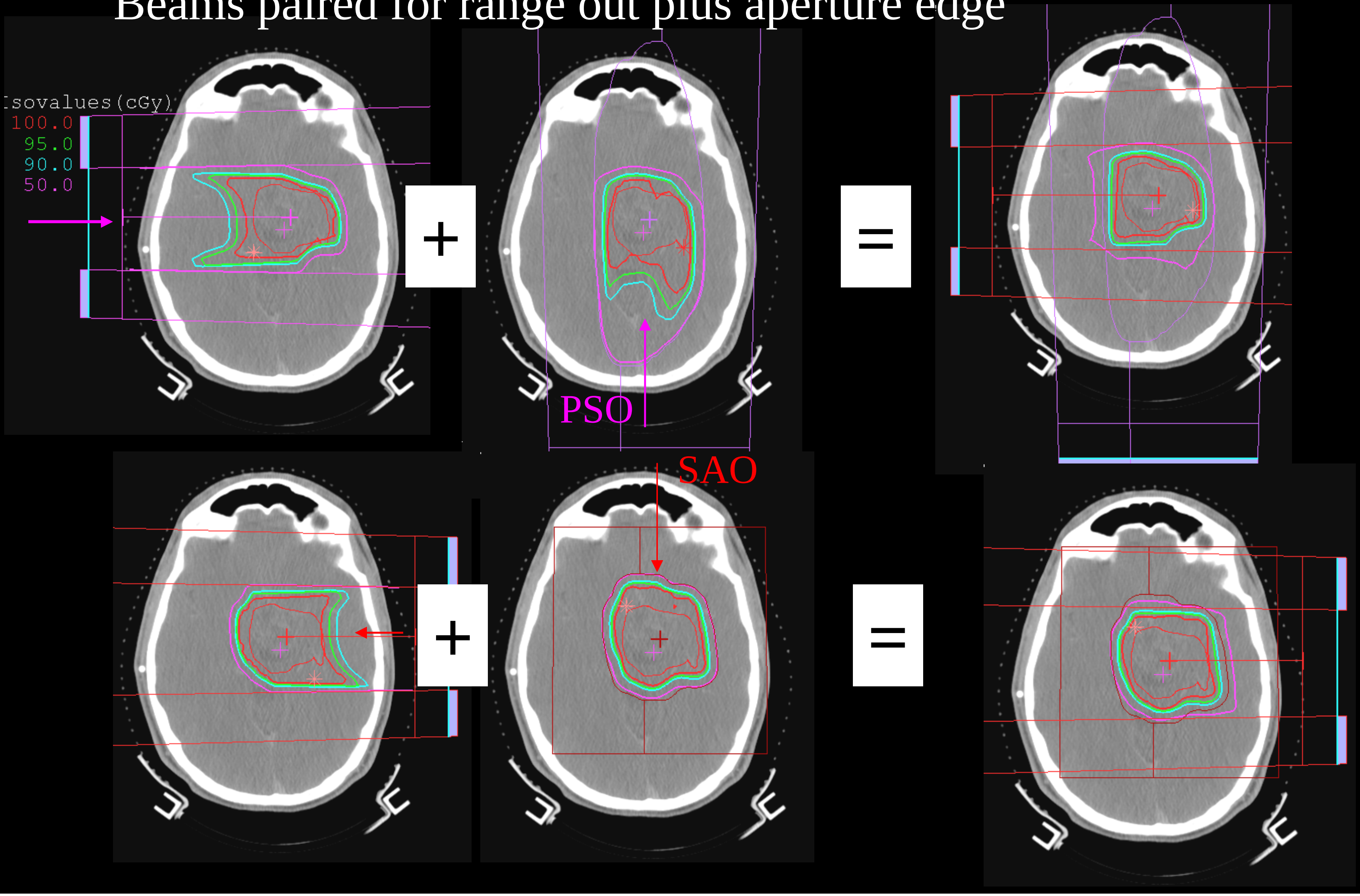


Compensator ‘flattened’

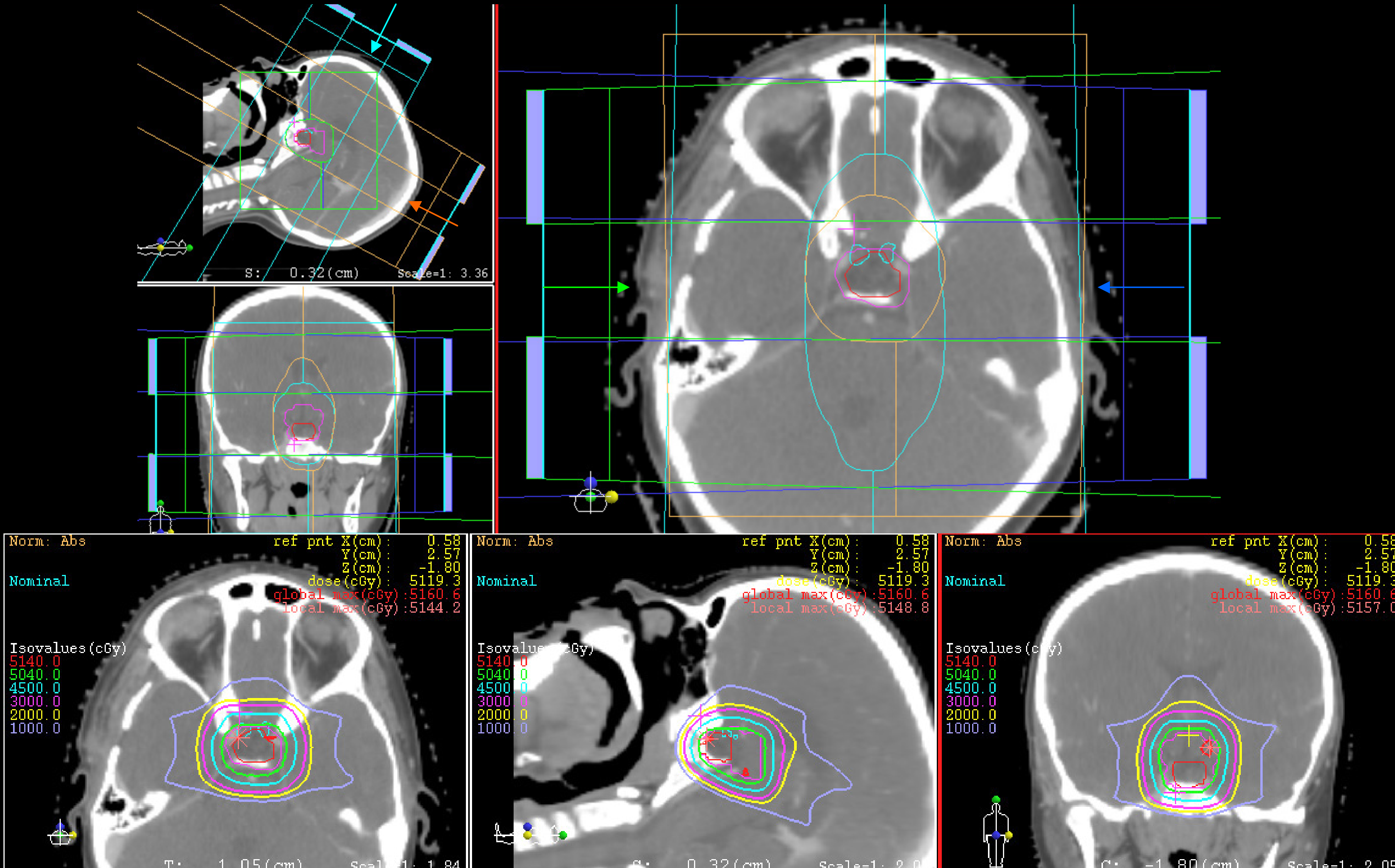
Smearing and dose



Range uncertainty and field arrangement
Beams paired for range out plus aperture edge



Craniopharyngioma – 4 fields/2 per day

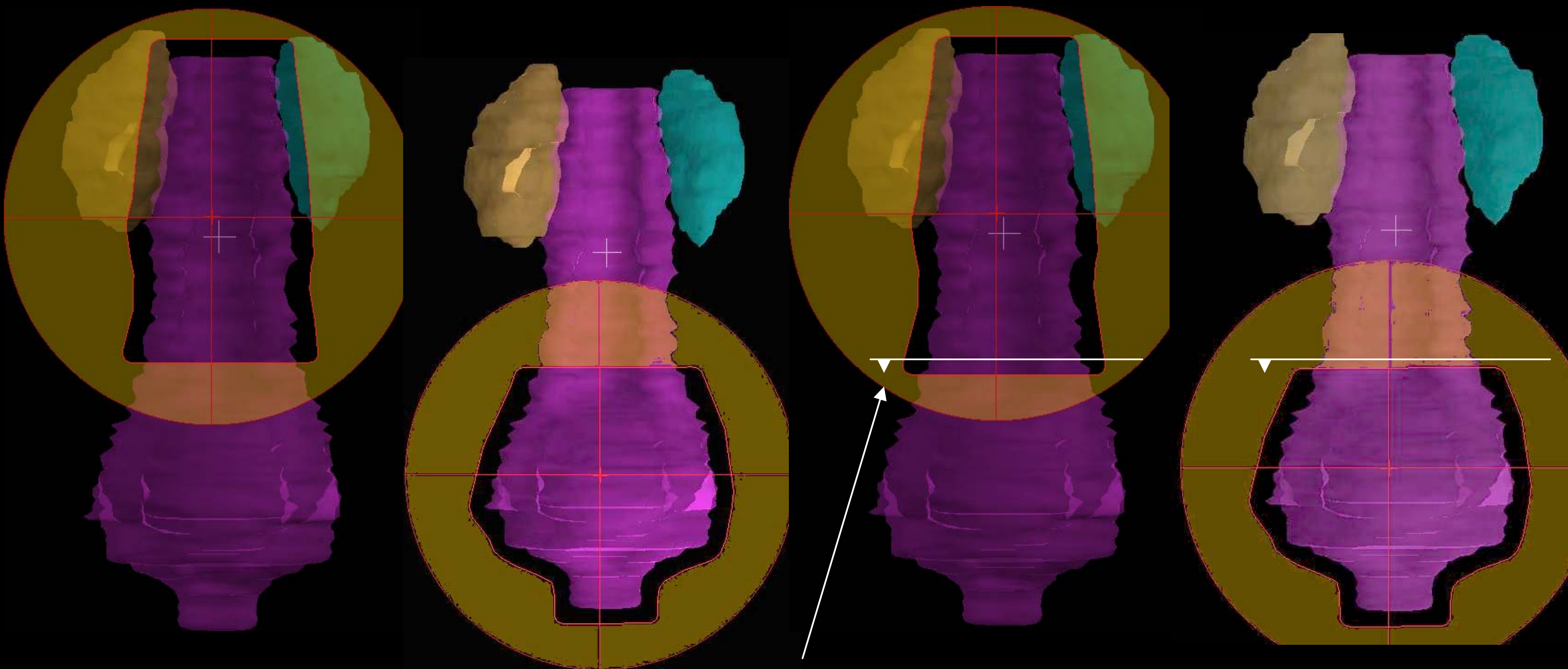


Matching Techniques

- Large tumors
- CSI
- Head and Neck
- Changing target geometries
- Feathering matchlines minimizes dose uncertainties at matchlines

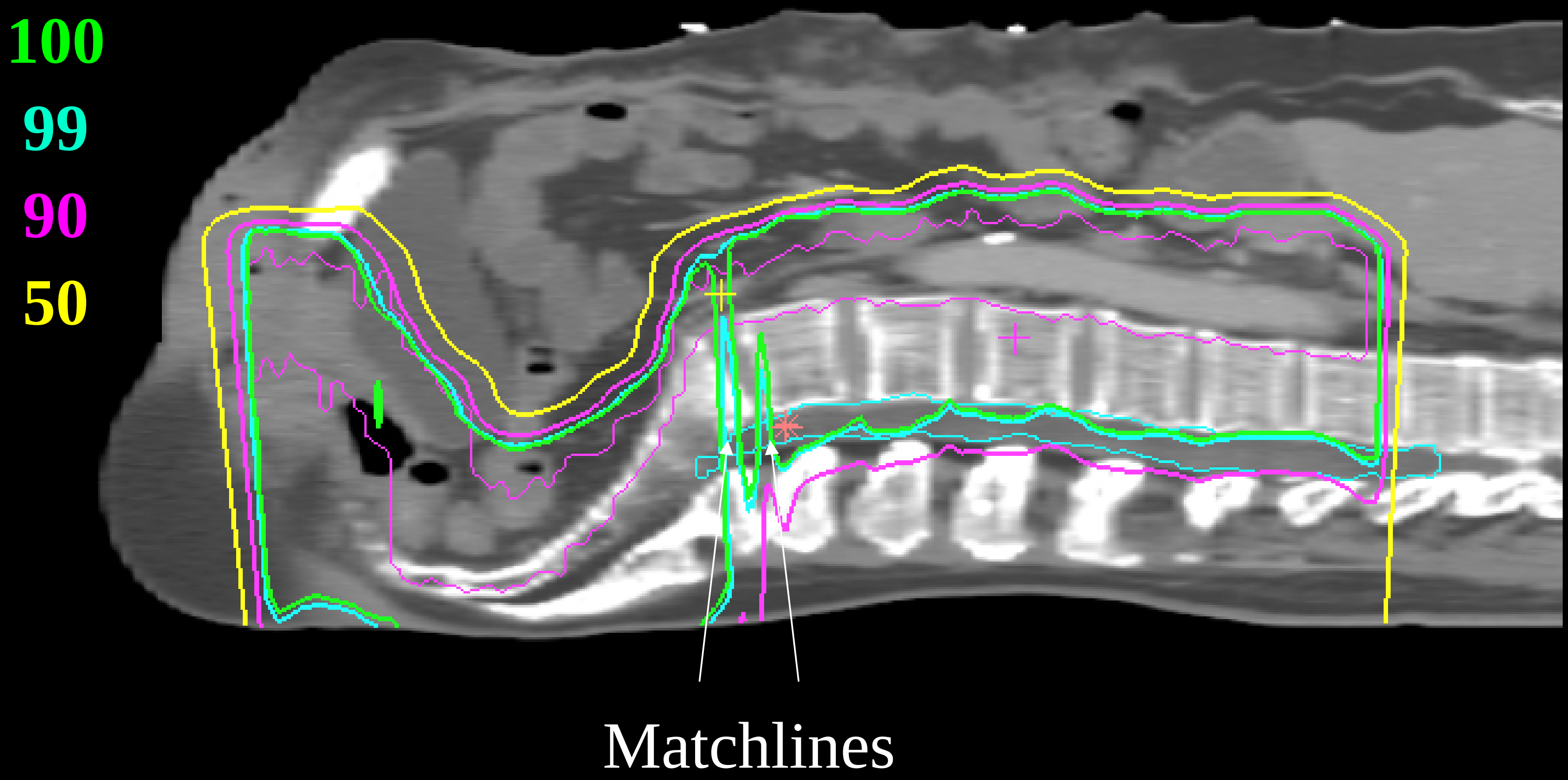
Field Matching
Para Aortic Lymph Nodes

Level 1 Level 2



1cm ‘feathered’ matchline – alternating daily

Field Matching
Para Aortic Lymph Nodes

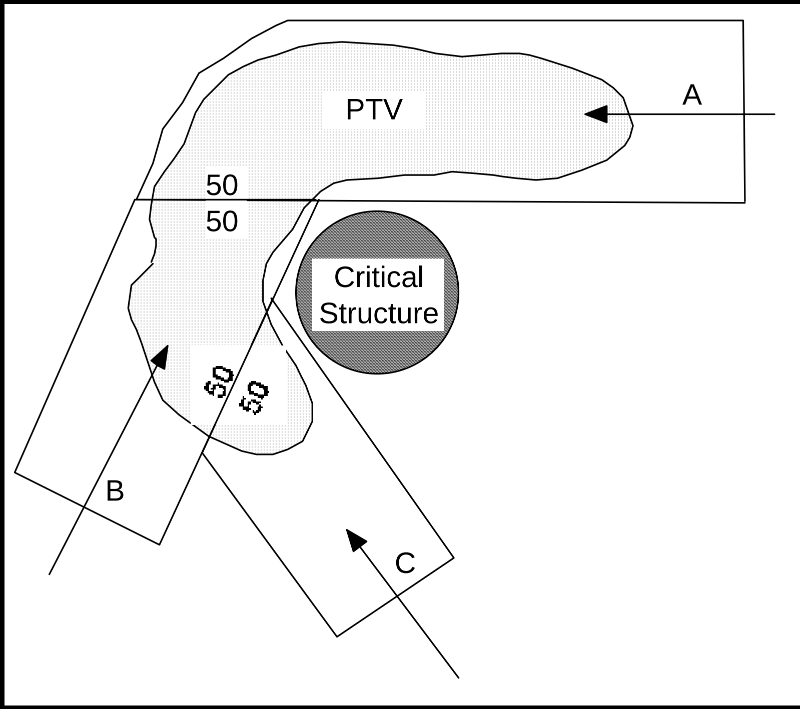


Patching Technique

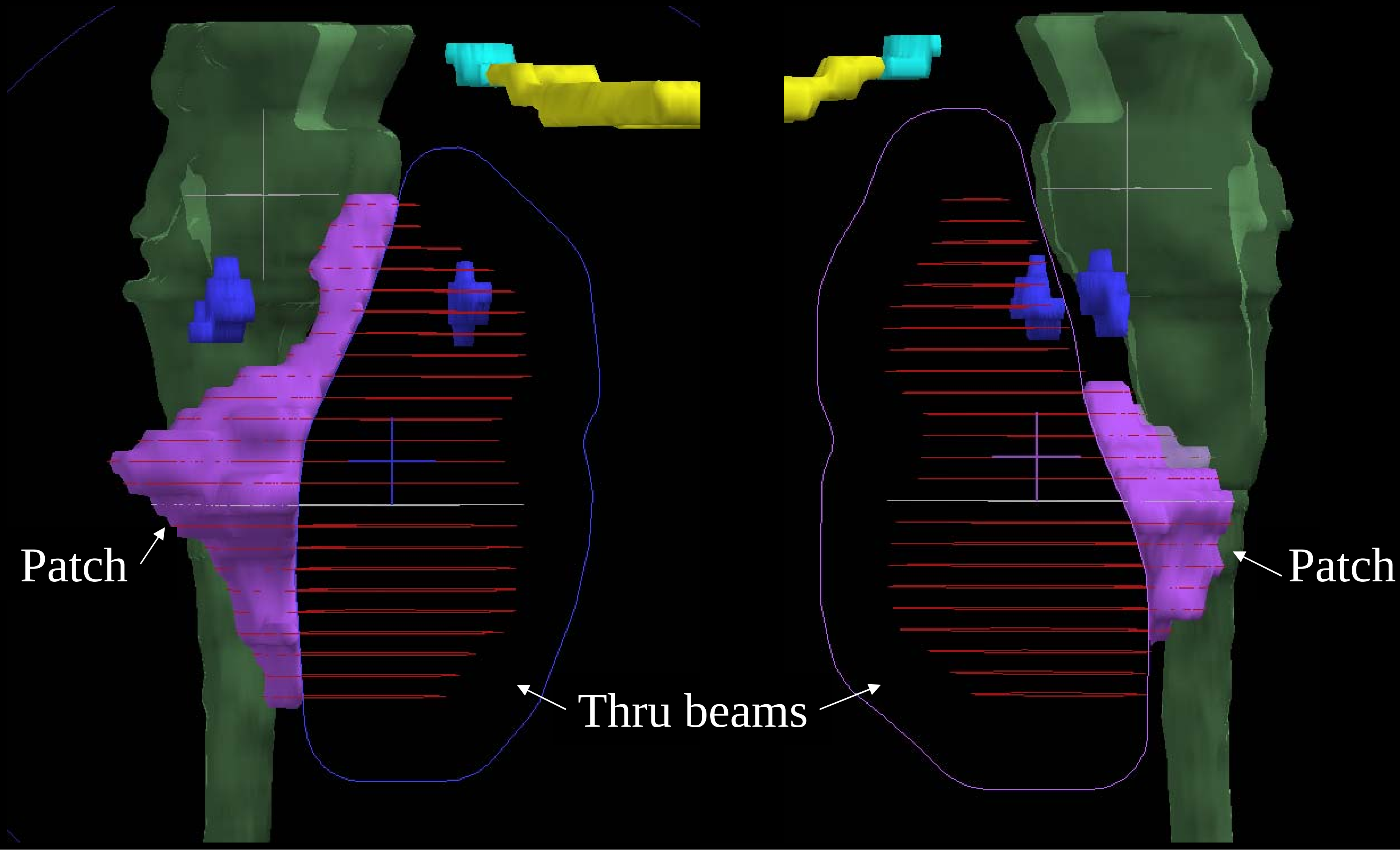
- Unique to proton therapy
- Target volume(s) segmented
- Automated ‘patch volume’ generated
- Manual or automated range compensator design

Field Patching

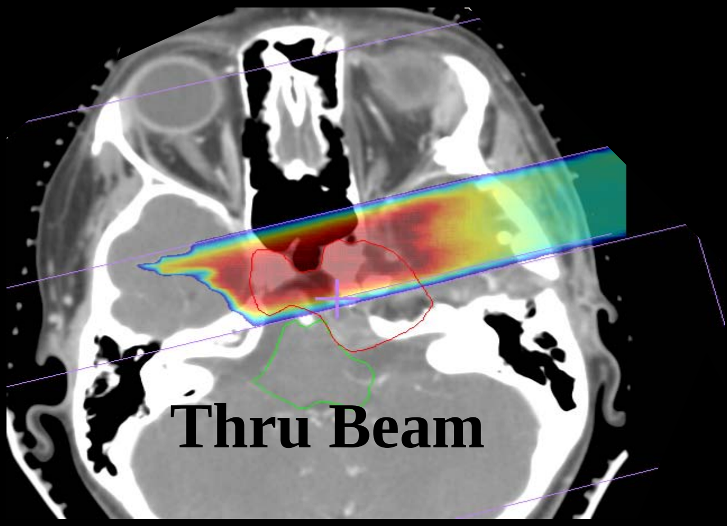
- Patching is a hierarchical sequence of proton fields.
  - "THROUGH" Field A: Achieved distal conformation to TV with the Range Compensator.
  - PATCH Field B: Achieve matching of distal edge of B with the Range Compensator at the lateral (50%) field edge of A
  - Match at 50% isodose, lateral + distal, levels

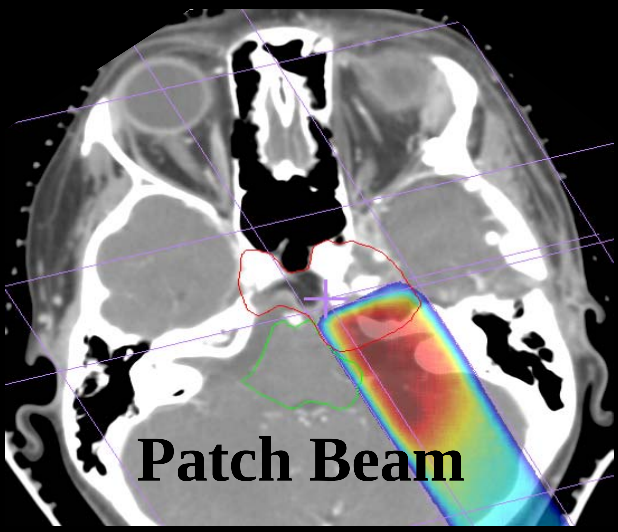


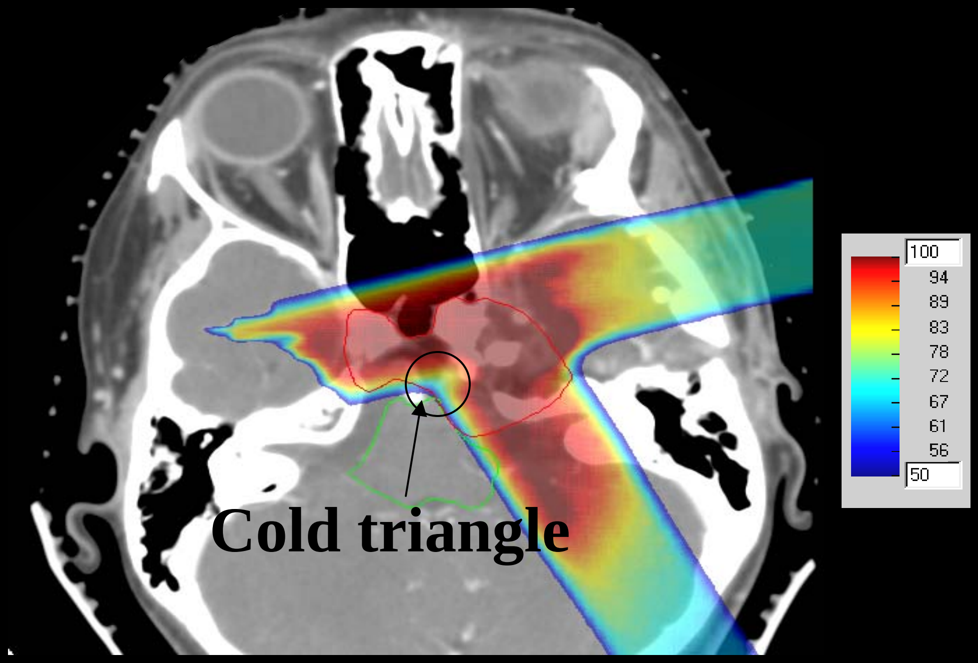
Automatically generated patch volumes



Patch Technique





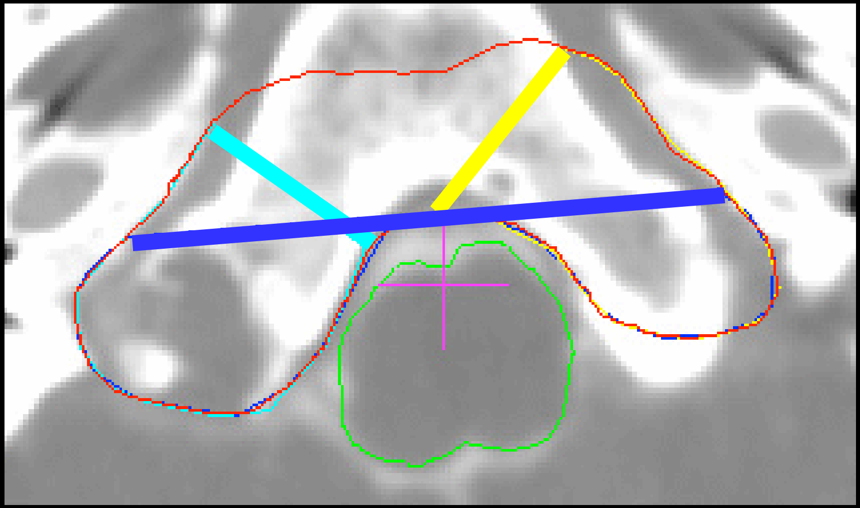


Accounting for uncertainty

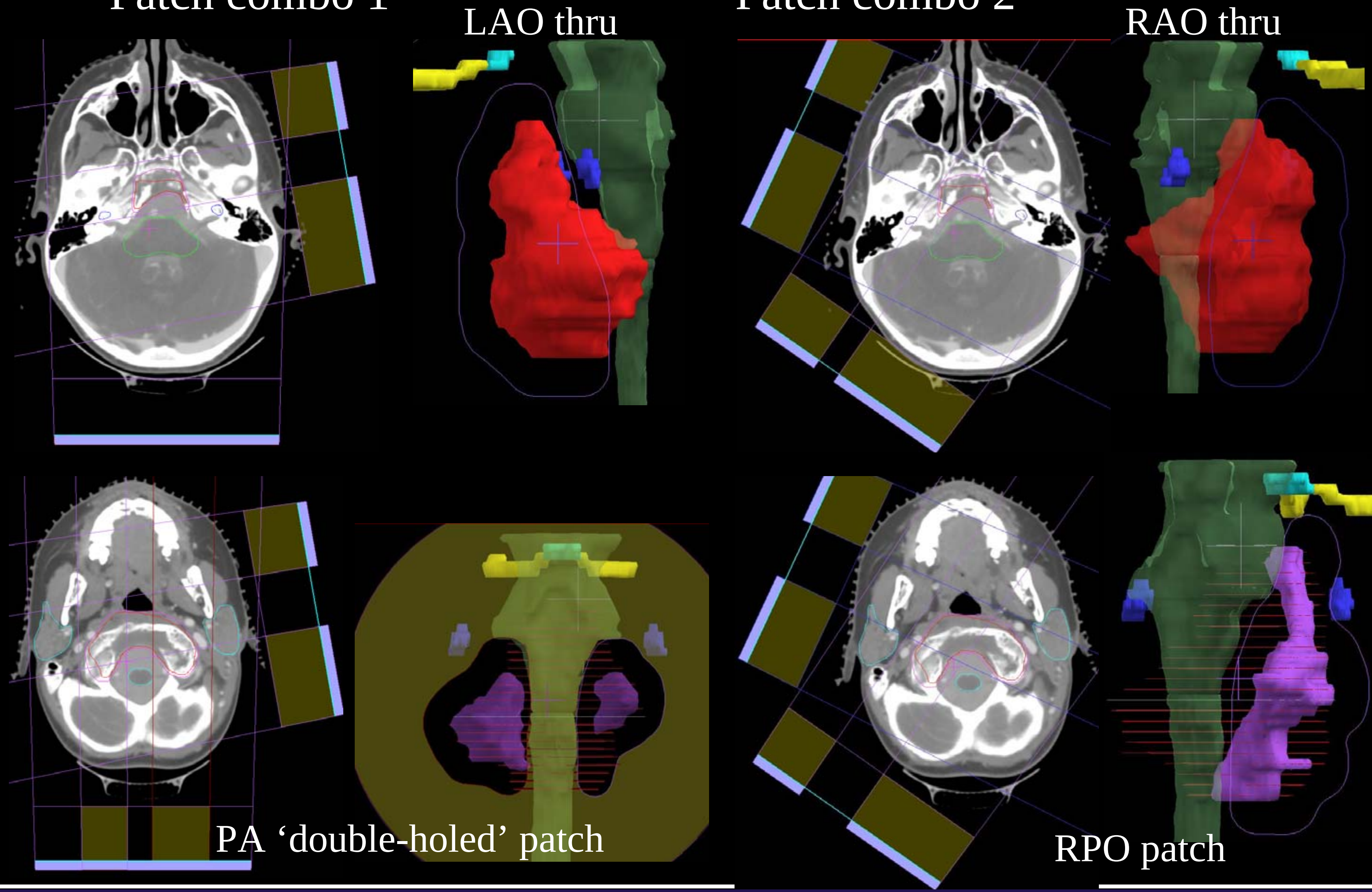
- Multiple (2 or 3) patch combinations usually required

  - move around hot and cold regions

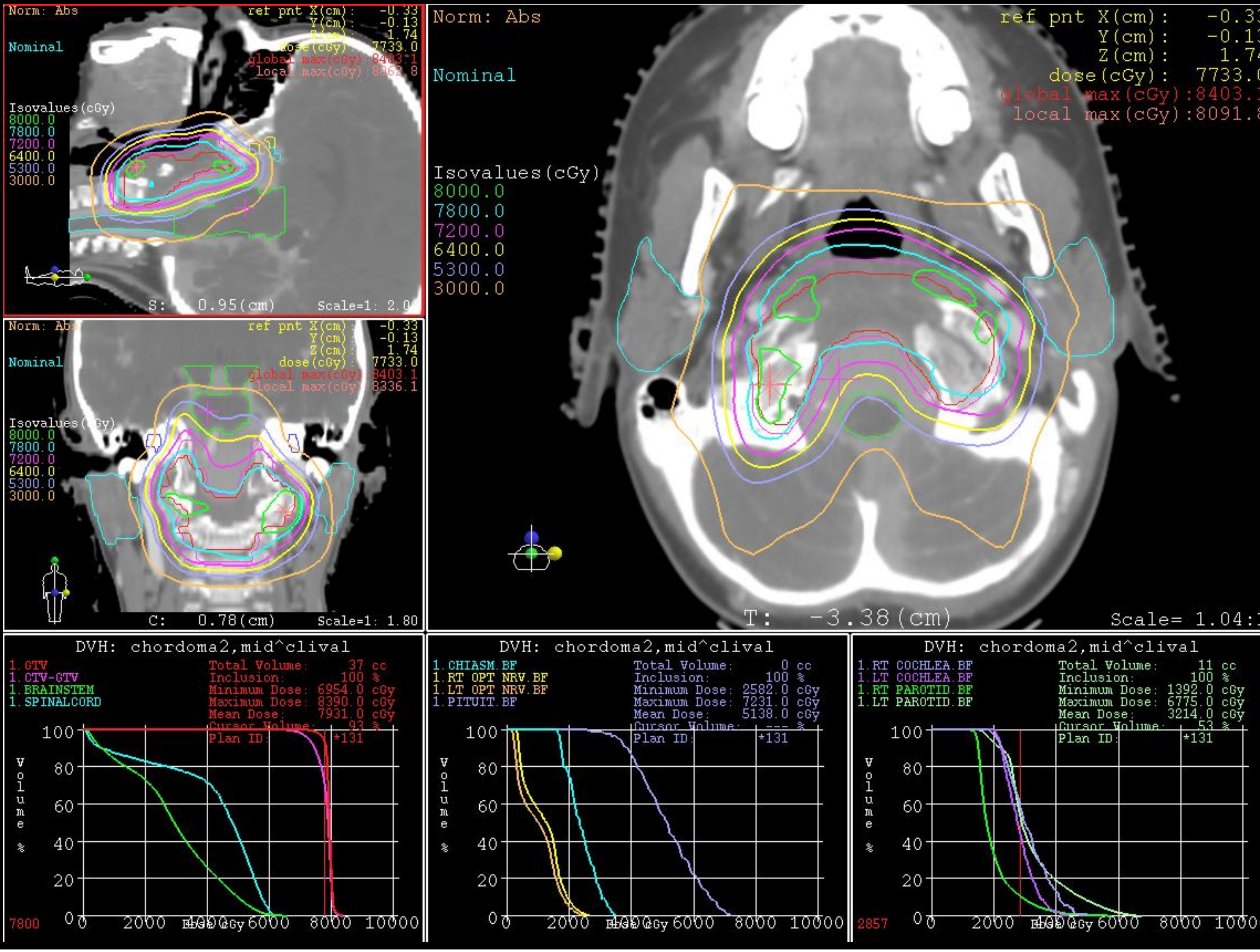
  (hot at patchline, but cold triangle at aperture intersections)



Patch combo 1   Patch combo 2

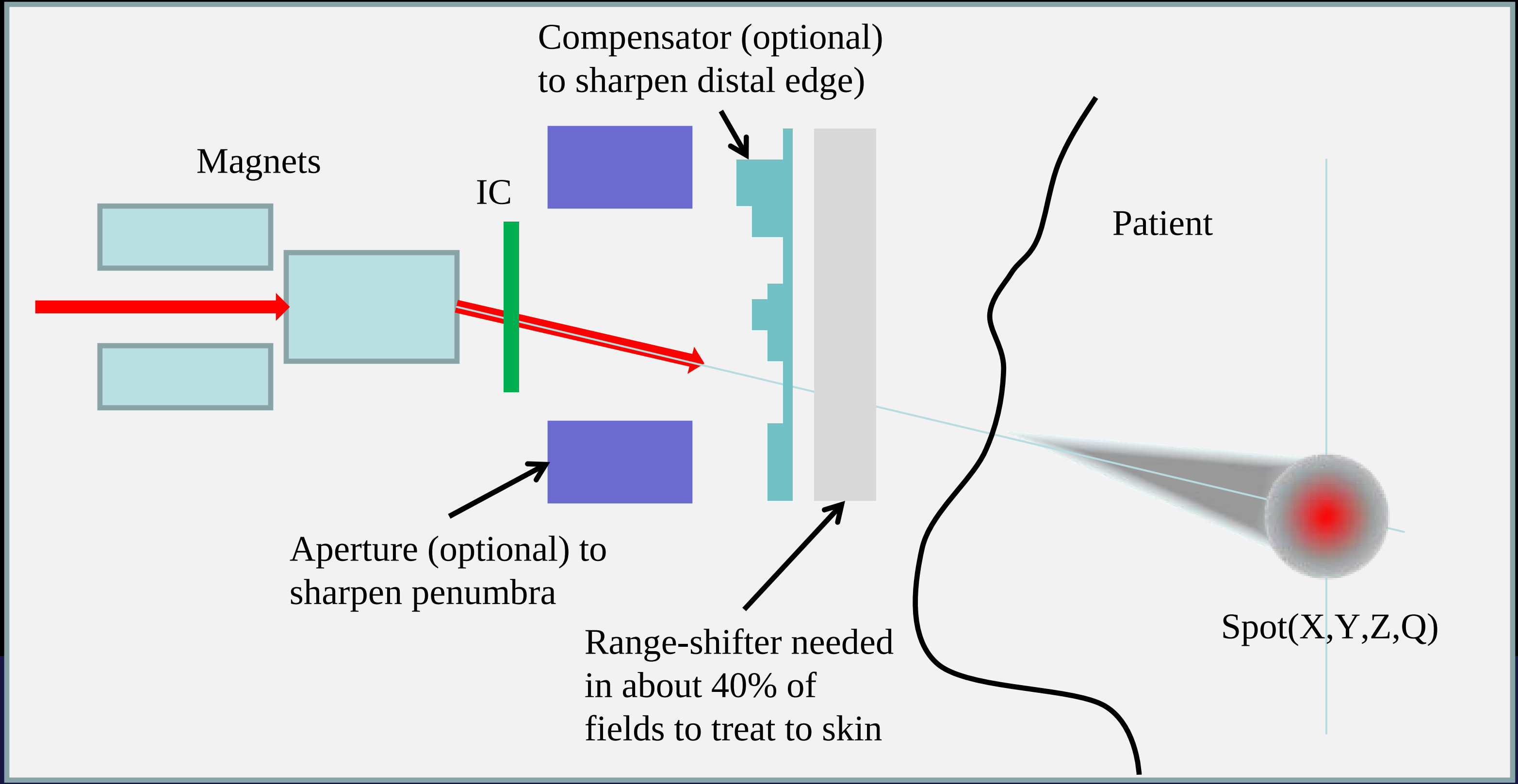


Composite to 78Gy(RBE)



Pencil-Beam Scanning

- Control all parameters of narrow proton “pencil” beams
  - Position [X,Y] with magnets, depth [Z] with beam energy E
  - Dose in patient with total charge [Q] in the pencil-beam
  - Dose resolution proportional to pencil-beam width σ (3 - 12 mm)
- Allows local dose modulation not possible in DS fields



Pencil-Beam Scanning: Robustness

Mitigate the greater sensitivity to uncertainties

- Geometric:
  - "Appropriate" expansion of TV's (Lomax: STV)
- Optimization:
  - variable lateral and distal margins and SFUD non-uniformity index

layer spacing:	1 distal W80
spot spacing:	1 sigma
lateral margin:	15 mm
distal margin:	10 mm
max SFUD non-uniformity:	10 %

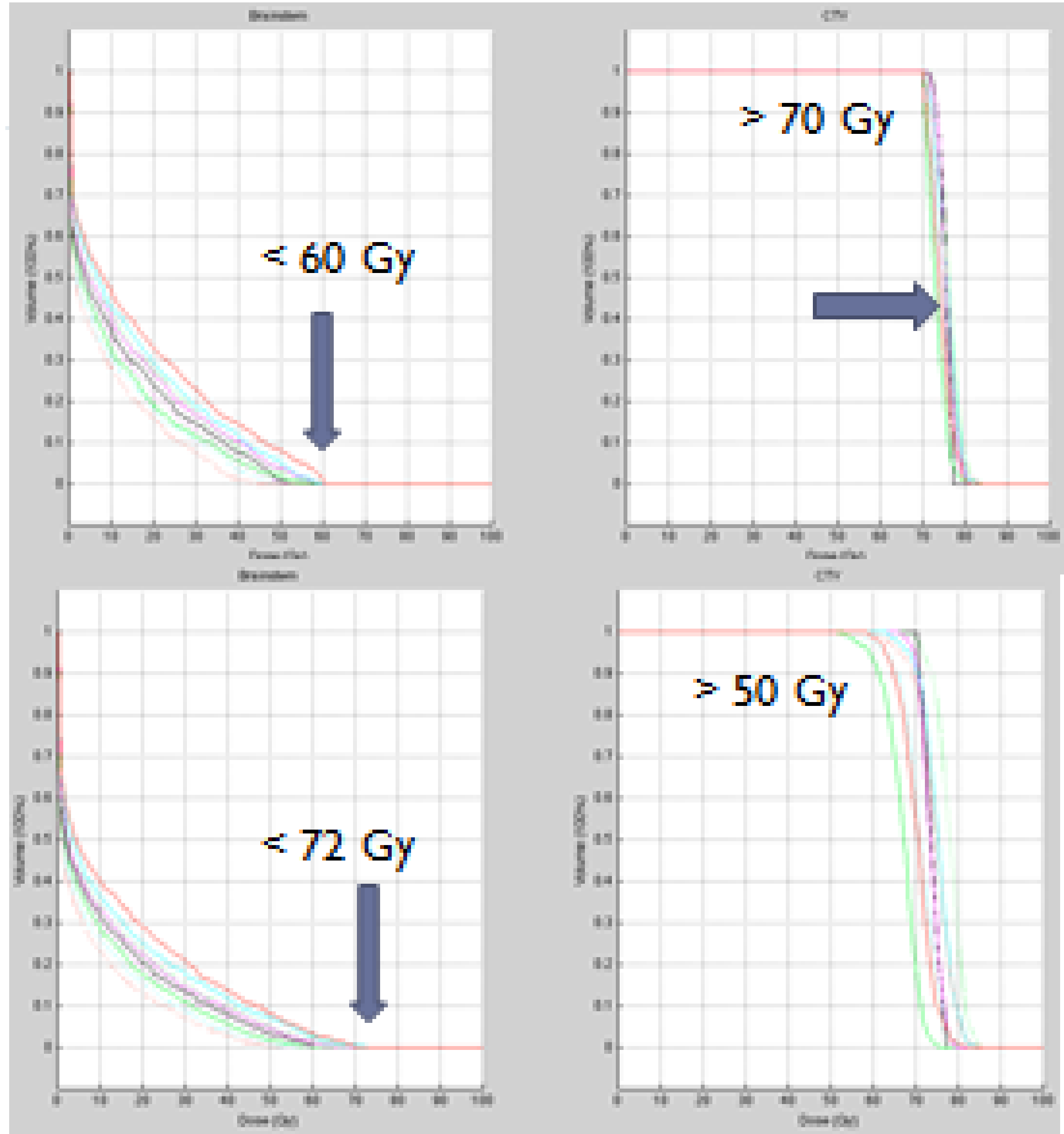
  - Robustness: Incorporate uncertainties directly into the Astroid MCO optimizer to yield plans that are invariant, as quantified by constraints, to stated uncertainties

Robust MCO

Achieve constraints invariant to (assumed) variations.

Robust

Non-robust



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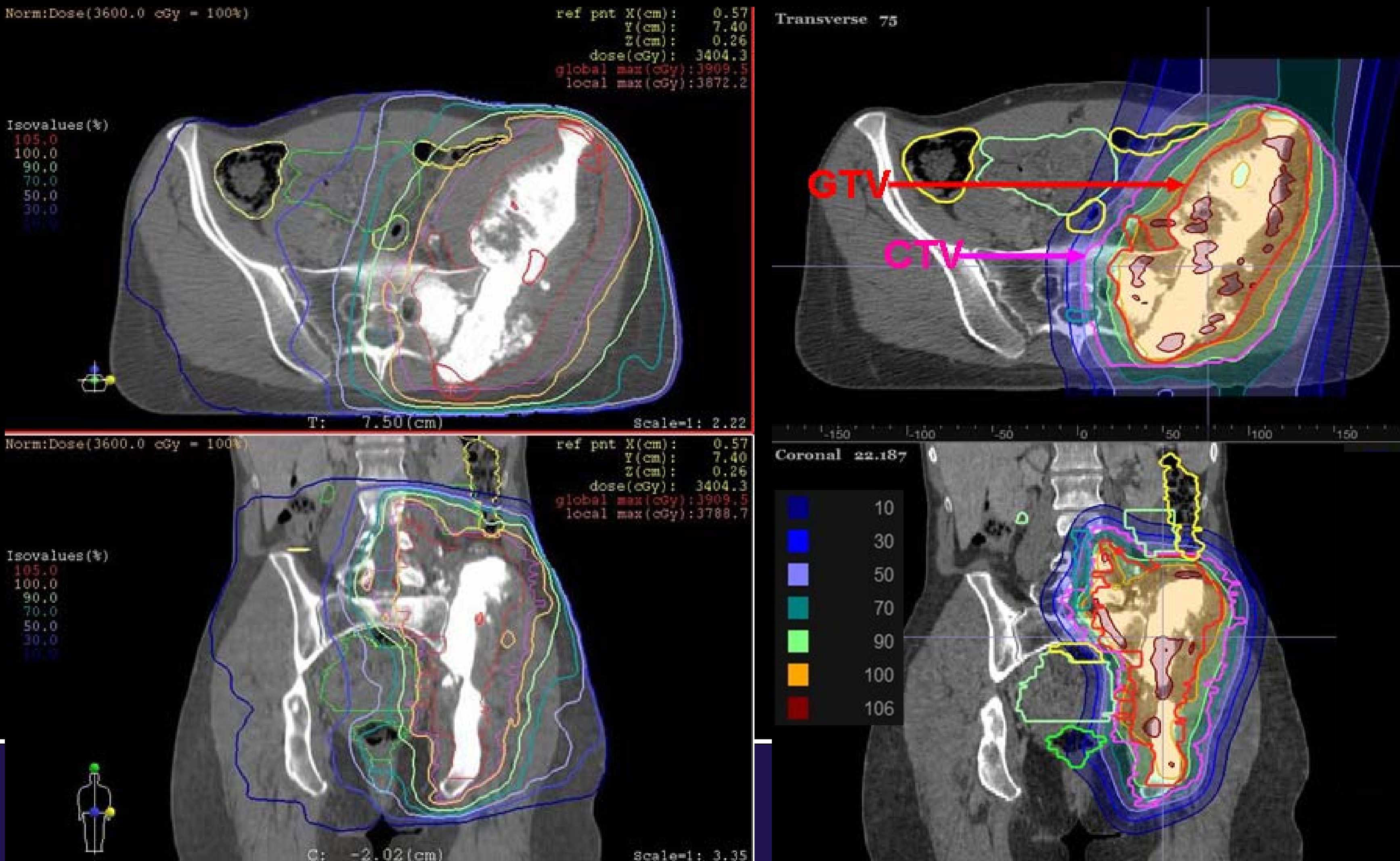
Osteosarcoma – 2 treatment fields (LA + PA)

Prescription:

- IMRT 36 Gy to CTV / 10 fractions
- p PBS 36 Gy(RBE) to GTV and 14.4Gy(RBE) to CTV / 20 fractions

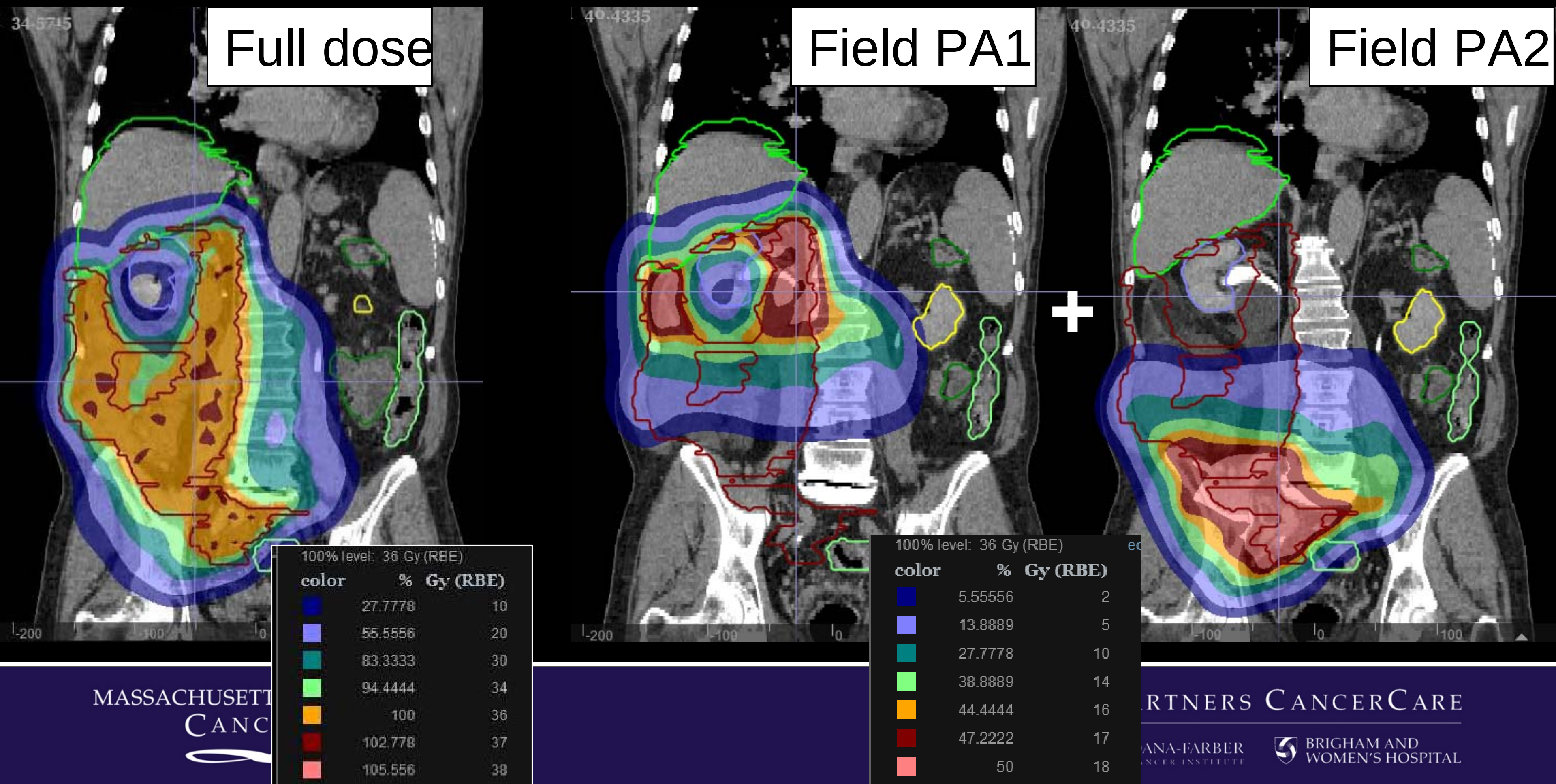


Retroperitoneal Sarcoma with Overlapping Fields

Prescription:

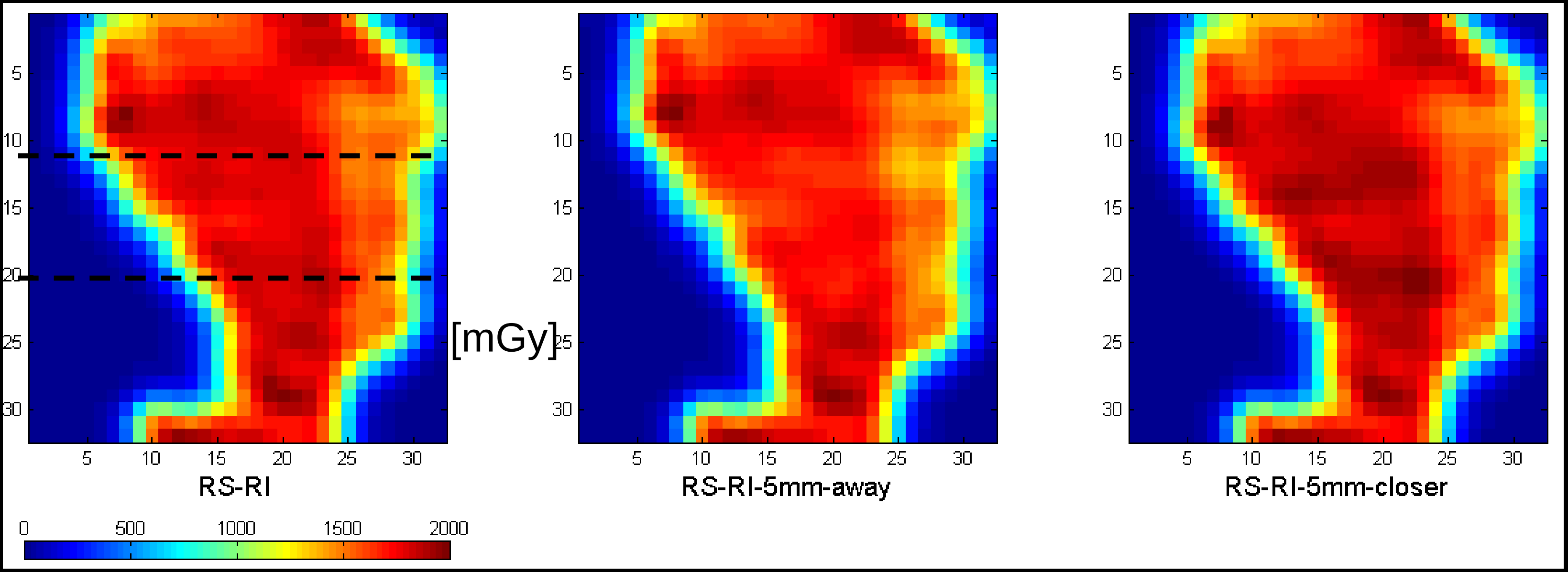
- IMRT 20 Gy to CTV /16 fractions
- p PBS 36 Gy(RBE) to retroperitoneal margin /18 fractions

PBS plan with tapered dose distribution at matchline (N. Depauw)



Retroperitoneal Sarcoma with Overlapping fields

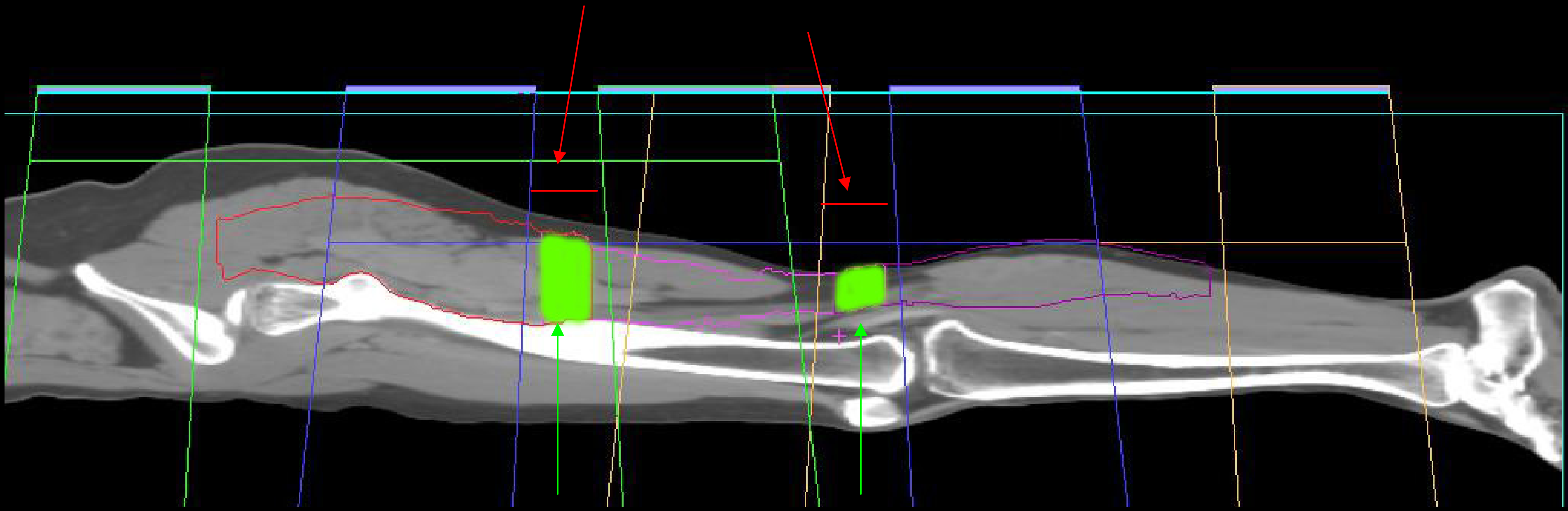
Overlap region



- Change in dose within overlap region for ±5 mm relative shift between fields is < 0.2 Gy

PBS fields – no apertures or range compensators

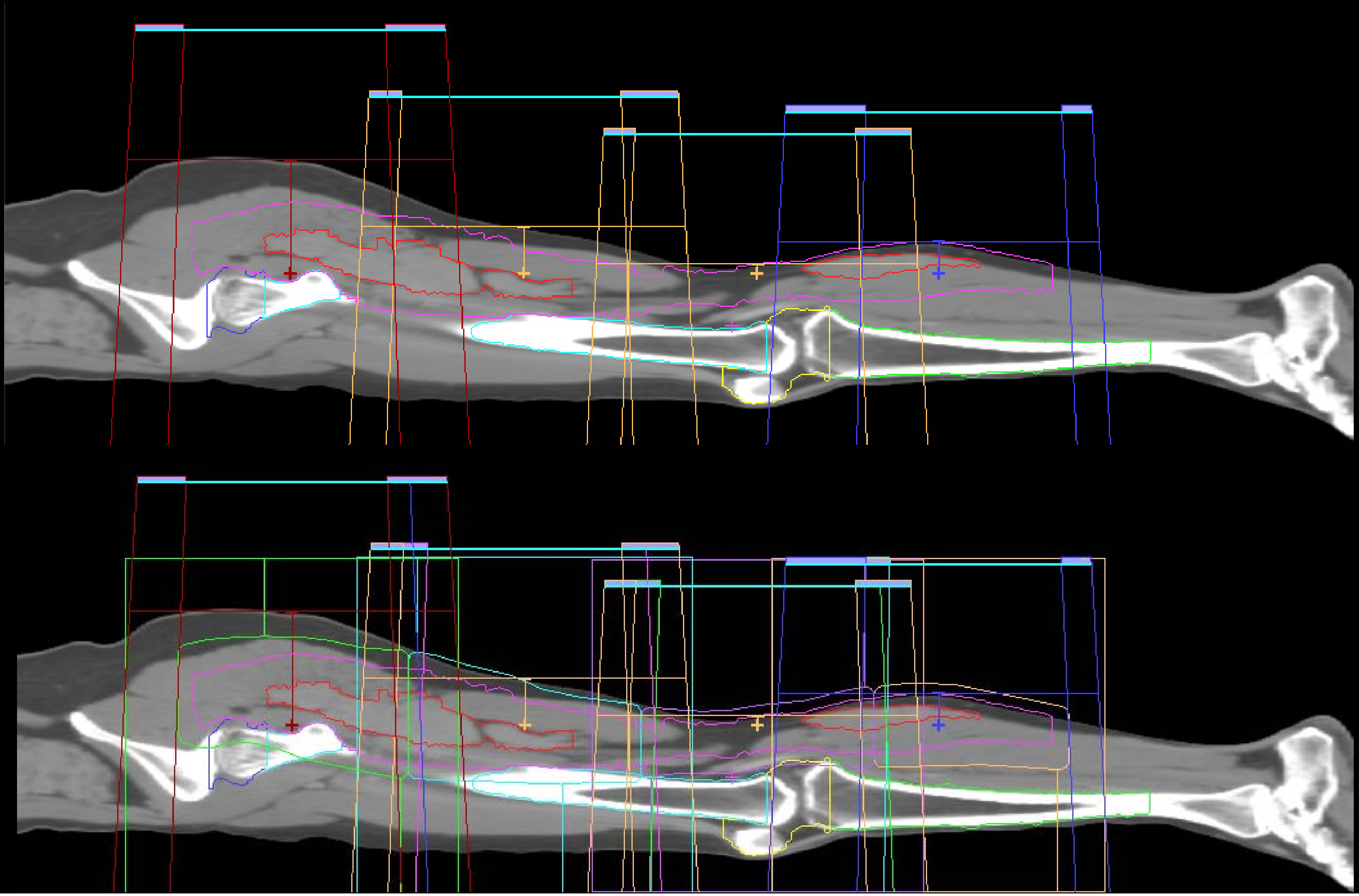
3 flds overlapping by 5.5cm



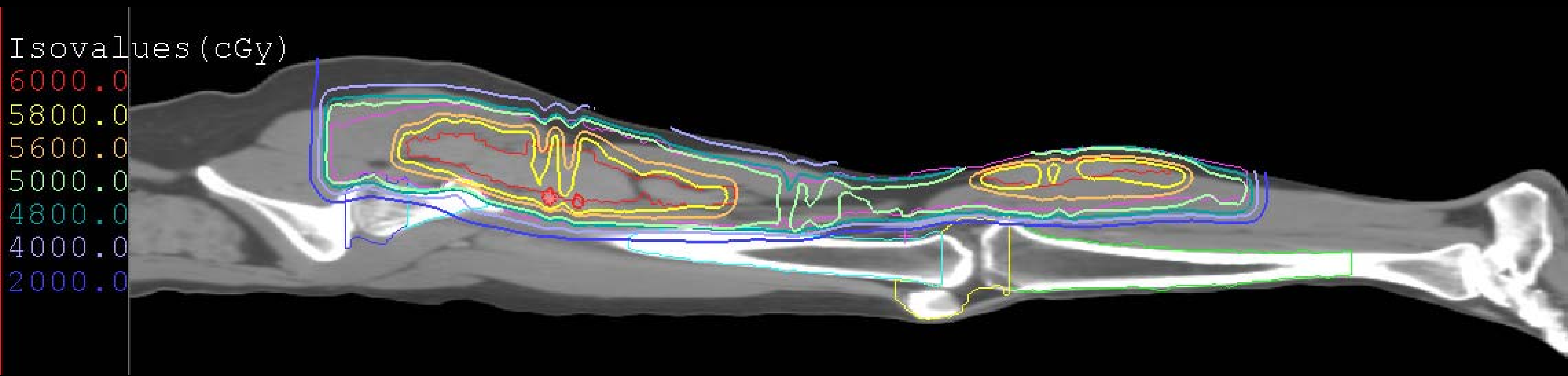
3.5cm overlap volume

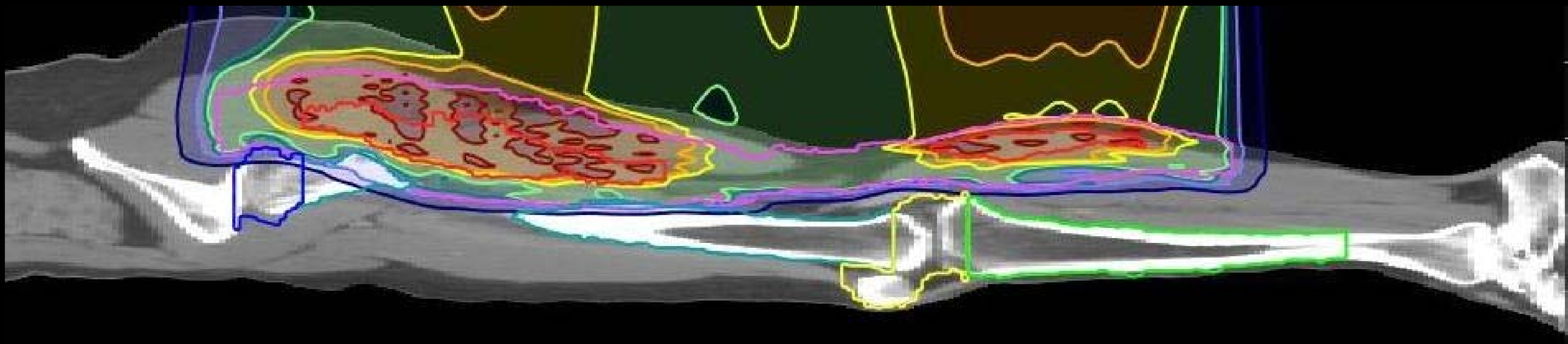
Optimzer controls dose in overlap region

Double scattered protons:
3 level moving matchline technique



Comparison: DS and PBS protons





Thank you

Spot Scanning Proton Therapy – Treatment Planning

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AAPM Therapy Education Course
Proton Treatment Planning Issues
MO-E-BRCD-1, July 30, 2012

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Acronyms

- SFO - Single field optimization:
  - Each field is optimized to deliver the prescribed dose to target volume(s):
  - SFUD - Single field uniform dose
  - SFIB - Single field integrated boost*

- MFO - Multi-field optimization or Intensity modulated proton therapy (IMPT):
  - All spots from all fields are optimized simultaneously
  - More flexible with more degrees of freedom – more conformal dose distribution
  - Complex dose distribution for each field

*Zhu *et al*. PTCOG50 - 2011

SFO vs. MFO

SFO

- "Open Field" for simpler volumes
- Uniform or non-uniform dose distributions
- Less sensitive to uncertainties
- Use SFO plan if IMPT plan is not significantly better

MFO

- "Patch Field" for complex volumes
- More versatile to get a good plan
- More sensitive to uncertainties
- Robustness of MFO is important

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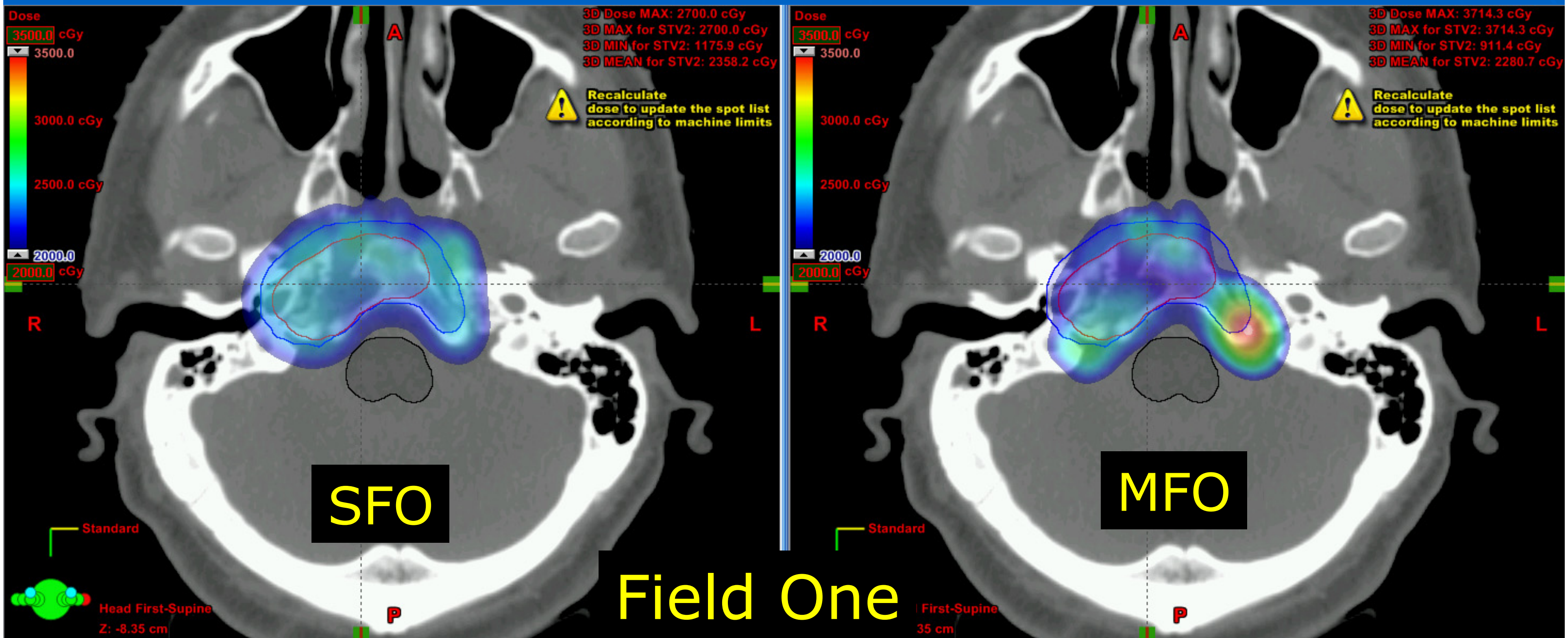
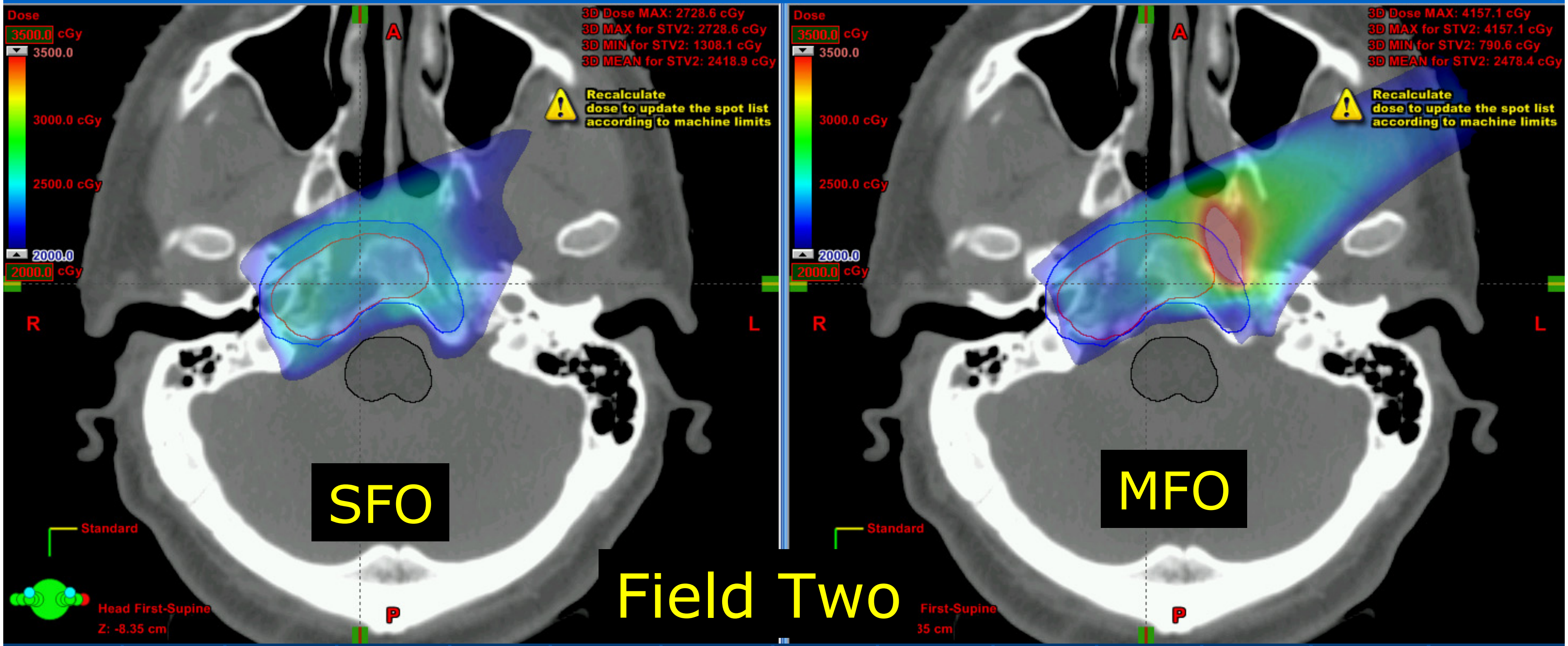
SFO vs. MFO (IMPT)



- 42 yr old male
- BOS/Chordoma
- Post resection

SFO vs. MFO (IMPT)



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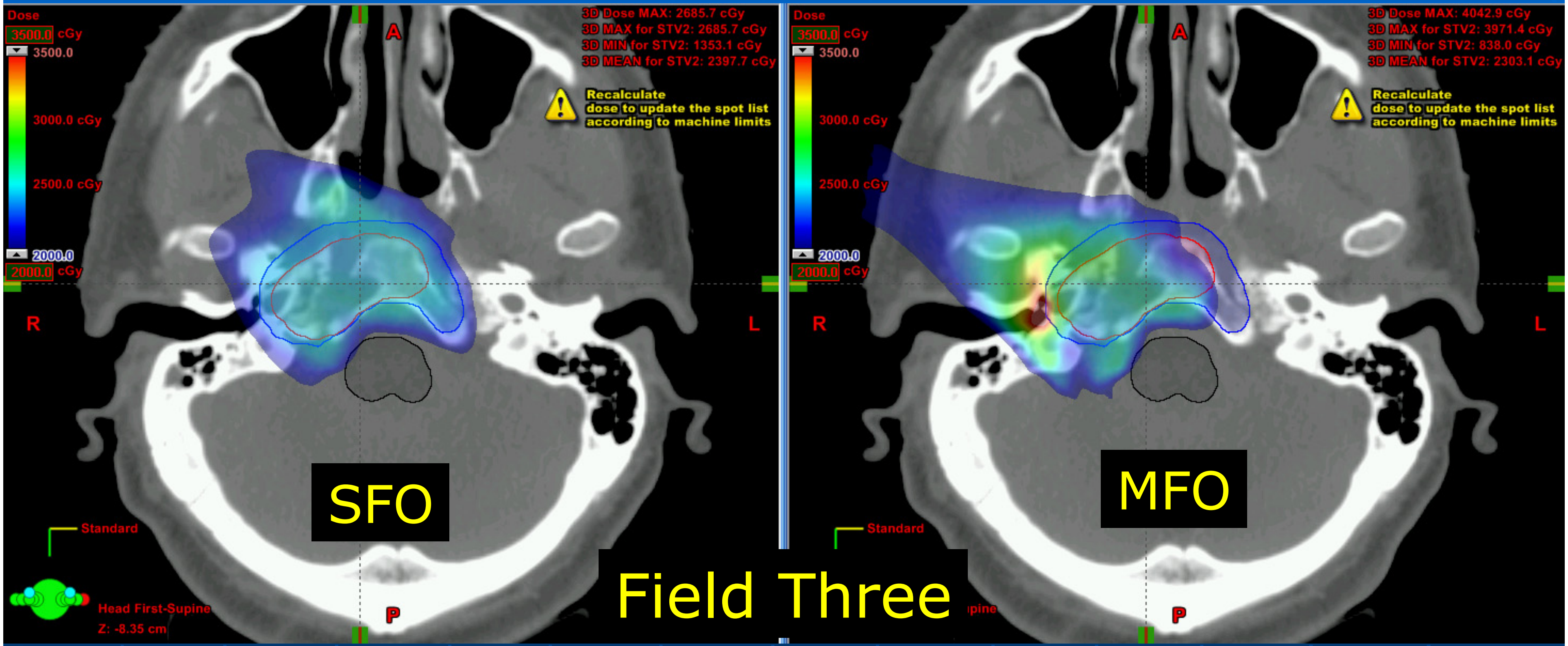
SFO vs. MFO (IMPT)



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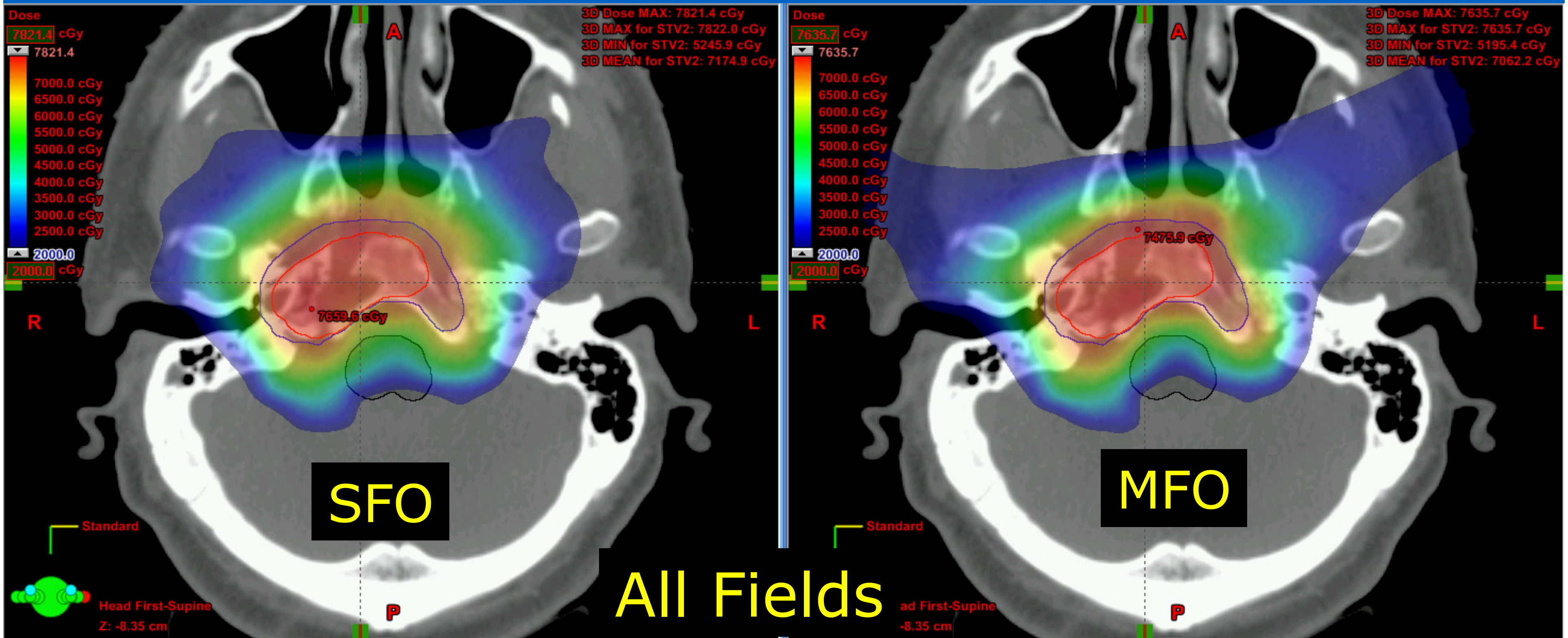
- BOS/Chordoma
- Post resection

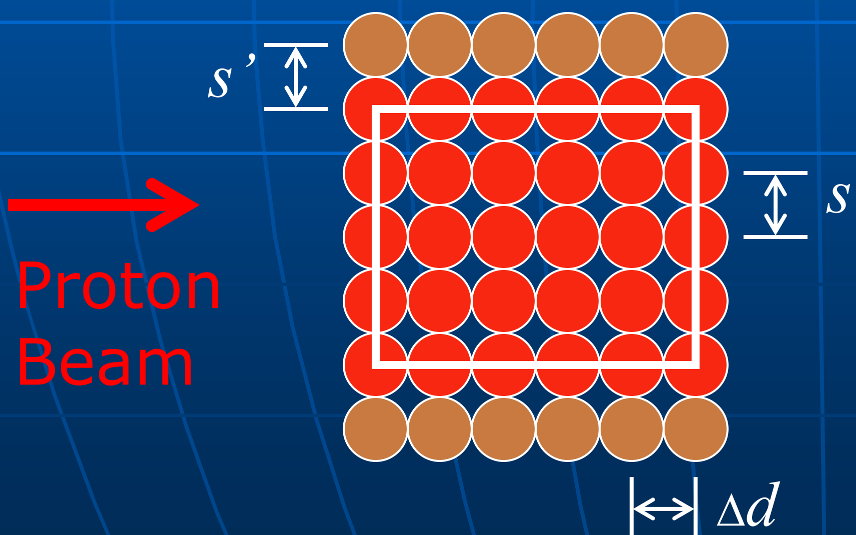
BOS – SFO vs. MFO (IMPT)



- 42 yr old male
- BOS/Chordoma
- Post resection

Spot Spacing & Lateral Margins

- Current TPS limits to:
  - Rectlinear spot positions
  - Lateral spot spacing, s is constant for each beam
  - Spot spacing in depth direction, depending on available proton beam energies (Δd = 0.1 ~ 0.6 cm for MDACC)



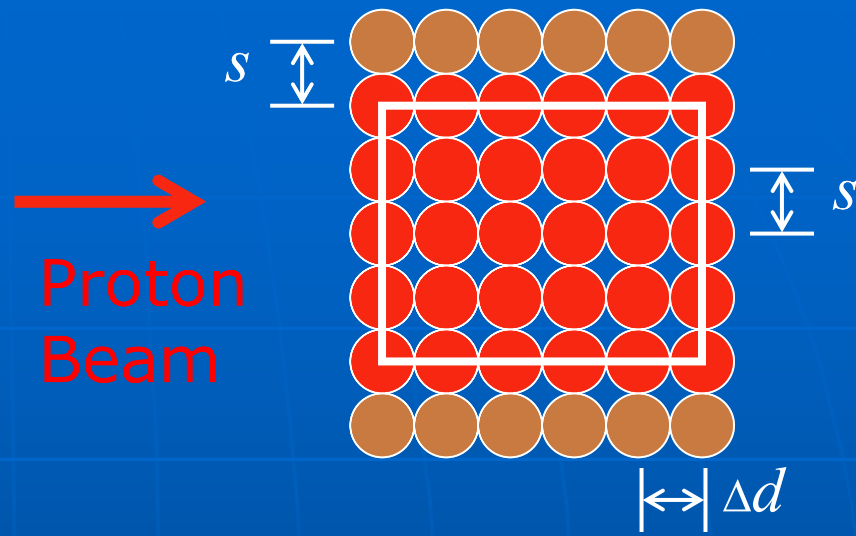
- Lateral spot margins:
  - Allow one spot outside the planning target volume, $s' = s$.
  - For better penumbra, s' can be slightly $< s$.
  - s' is equivalent to block margin

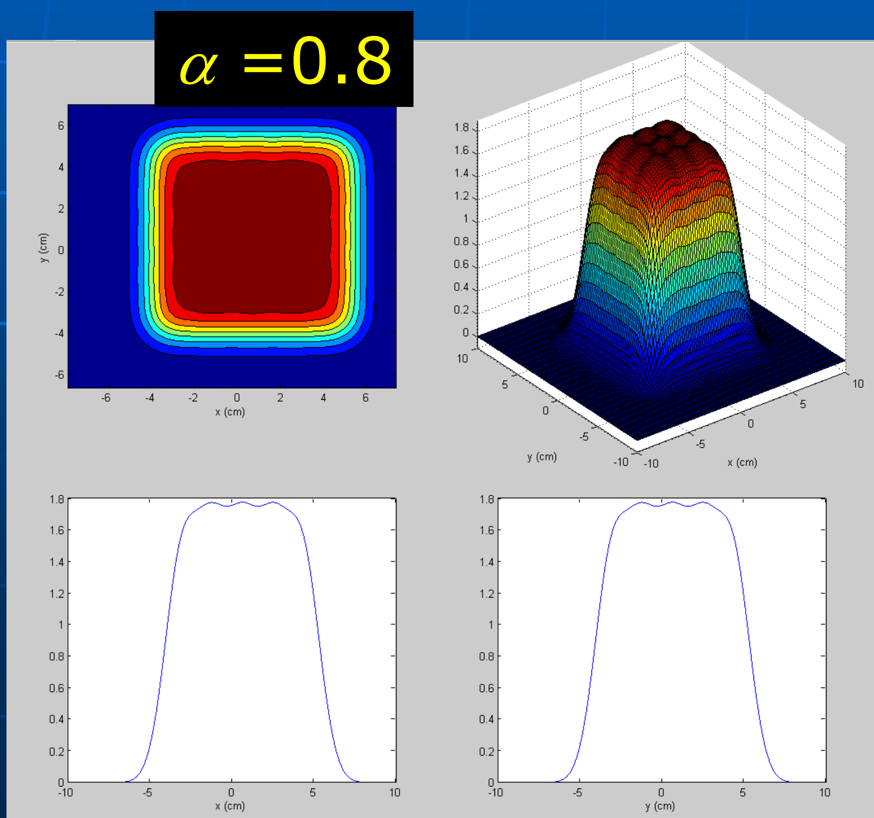
Spot spacing

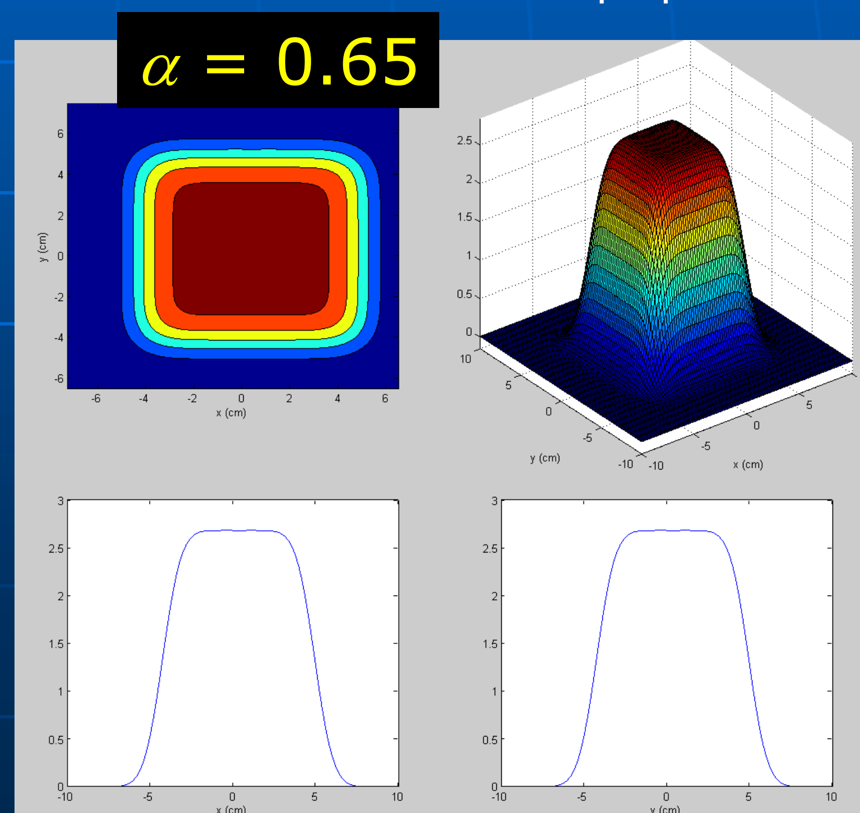
- Spot spacing

$$s = \alpha \times FWHM_{air}$$

- What α should be?







Delivery Constraints

- Spot spacing, $s = \alpha \times FWHM$, **α <= 0.65**
- Smaller α is better for penumbra
- How small α can be?
- Hitachi PROBEAT – minimum MU 0.005 per spot
- Current clinical TPS optimizer does not incorporate this constraint in the optimization process – similar to early days of IMRT
- Truncation errors could significantly degrade a optimized plan when converted to a deliverable plan
- If α is too small, "MU starvation" effect – too many spots to share finite numbers of MU

Zhu *et al*. Med. Phys. 2010

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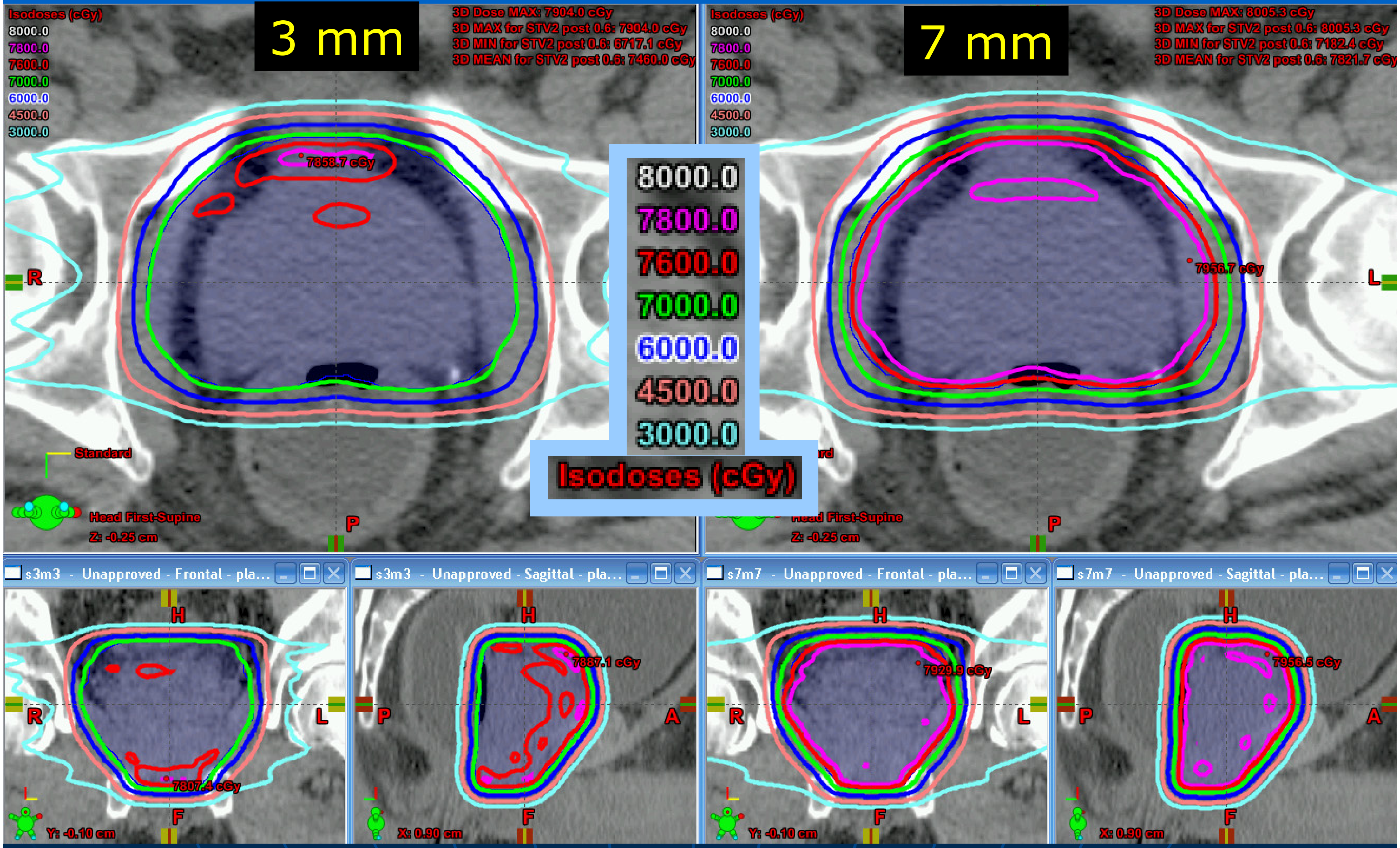
Impact of Spot spacing



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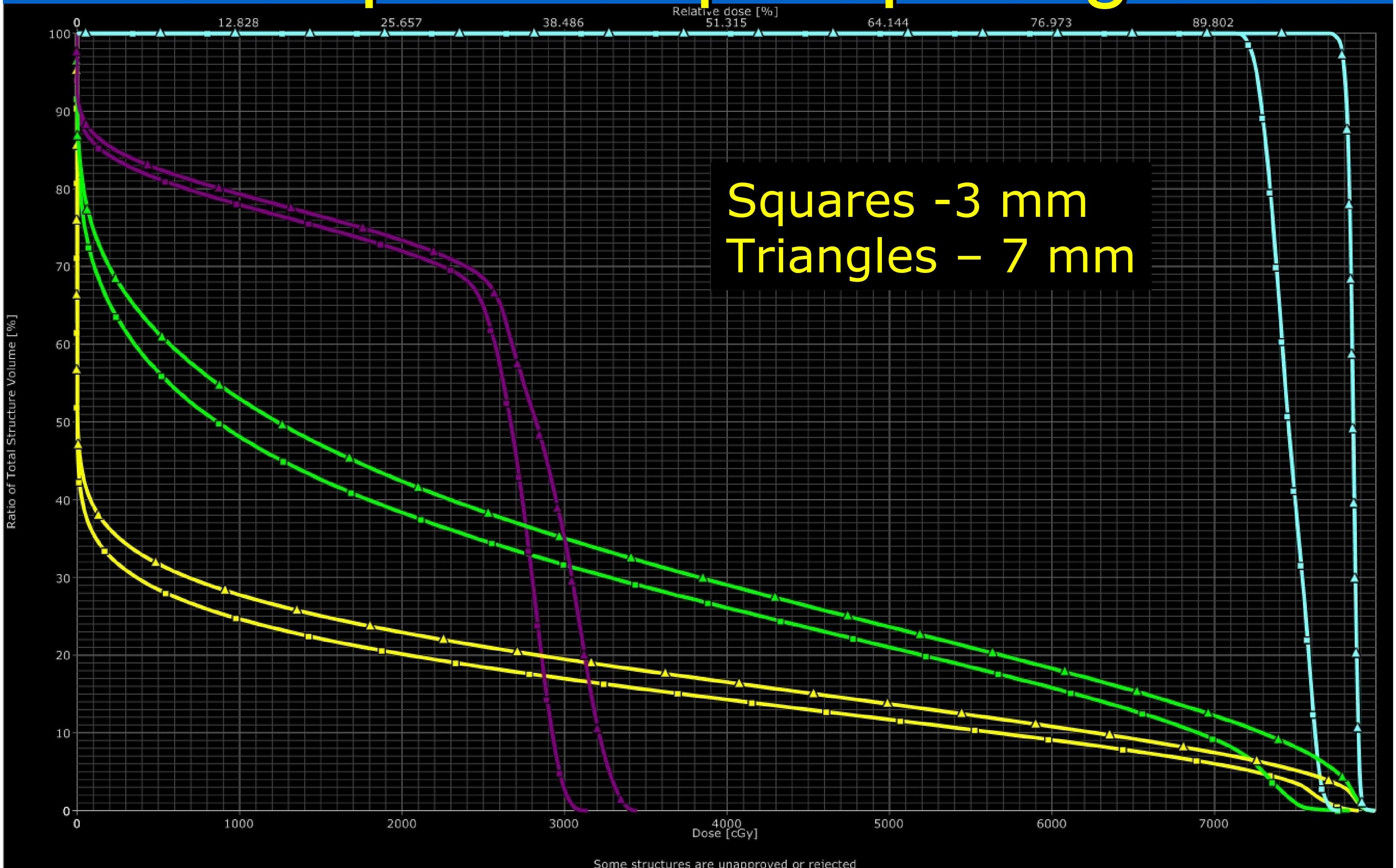

Margins & Target Volumes

- There is no smearing (except spot size)
- Current TPS does not support proximal & distal margins for scanning beam
- For single or parallel opposed beam in major axis directions, an approximated bsPTV* may be used for SFO.
- For others, a conventional "PTV" is used
- bsPTV does not applicable to MFO*.
- Plan robustness should be evaluated.

*Park *et al*. IJRBP 2011

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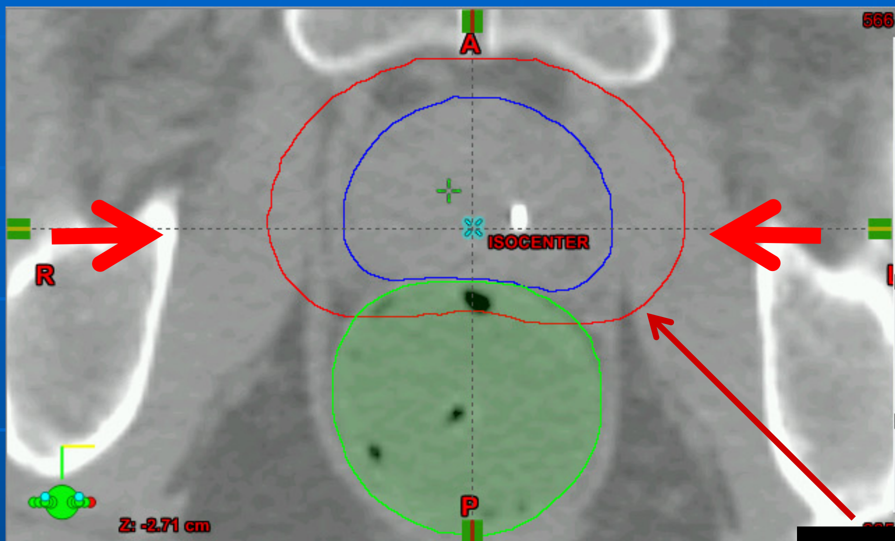
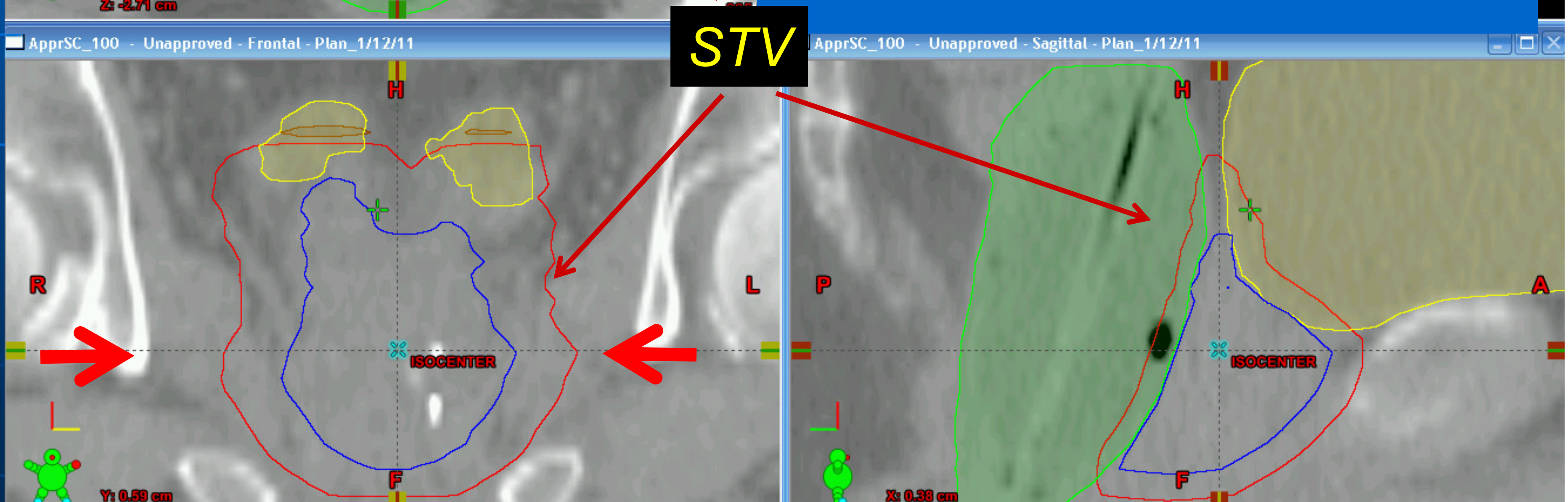
Approximated bsPTV – Example

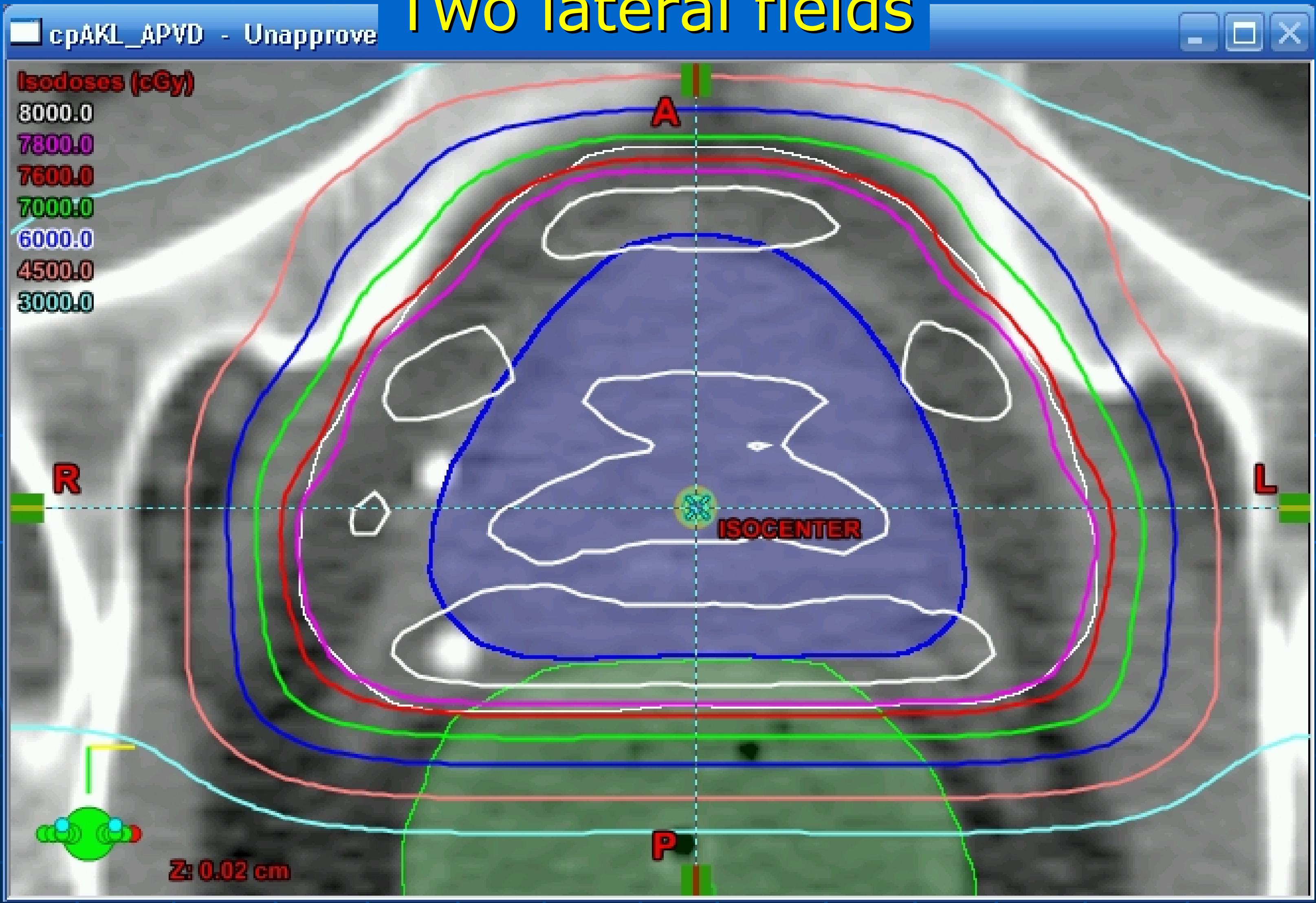


- STV = CTV + Margins
- Margins:
  - Lateral: Distal margin ~ 1.1 cm
  - Posterior: ~ 0.5 cm
  - Else where: ~ 0.6 cm

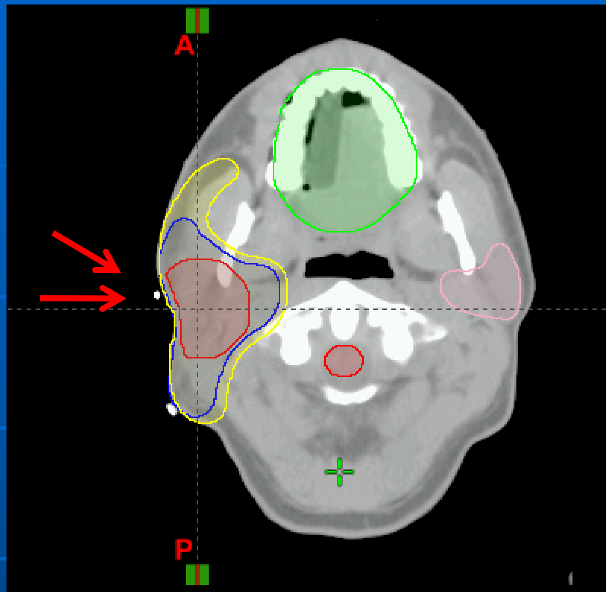


SFUD

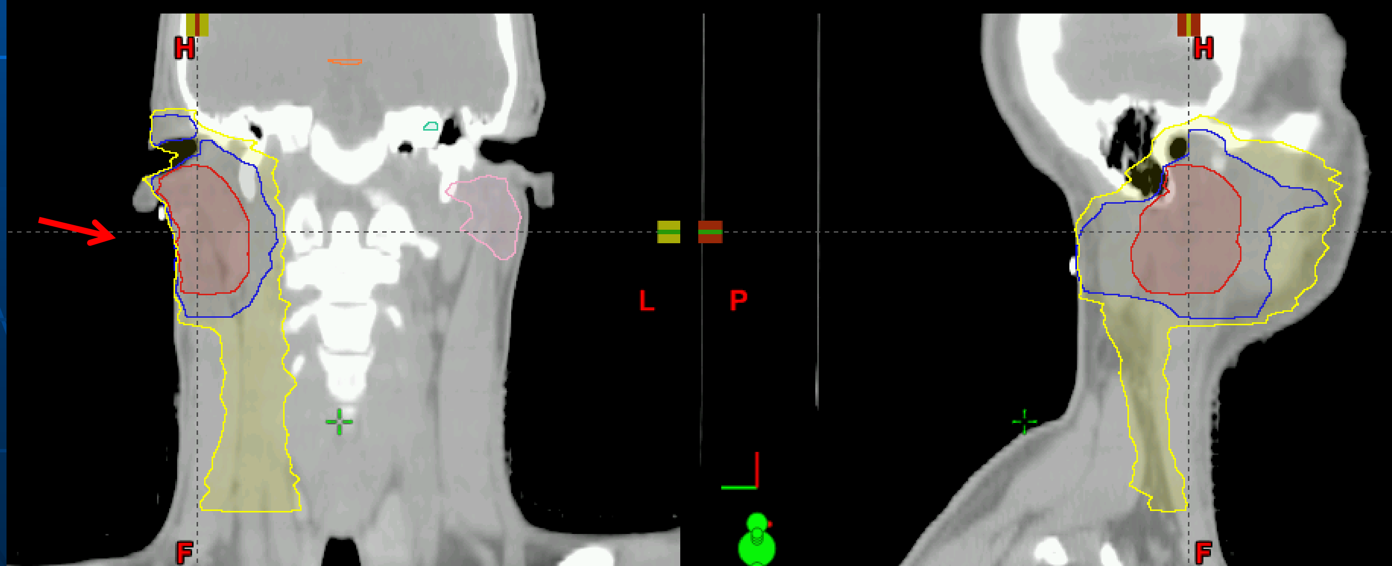
Two lateral fields



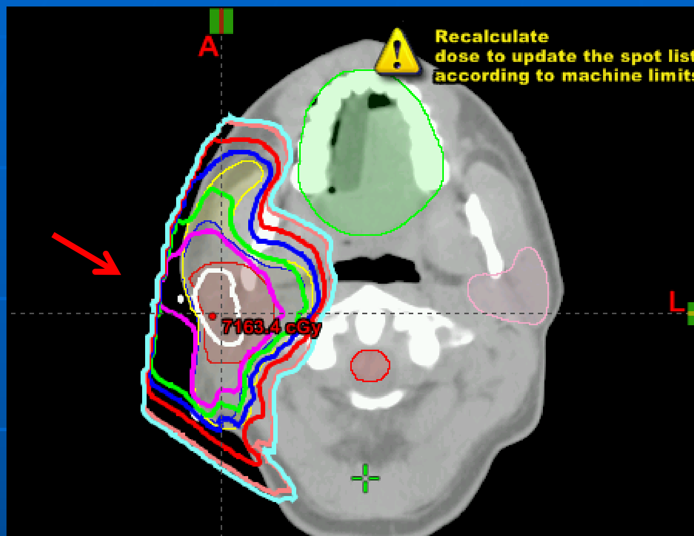
Head & Neck - SFIB



- 26-year-old male
- Right parotid
- Acinic cell carcinoma
- CTV1 64 Gy(RBE)
- CTV2 60 Gy(RBE)
- CTV3 54 Gy(RBE)



Head & Neck – SFIB – Field 1



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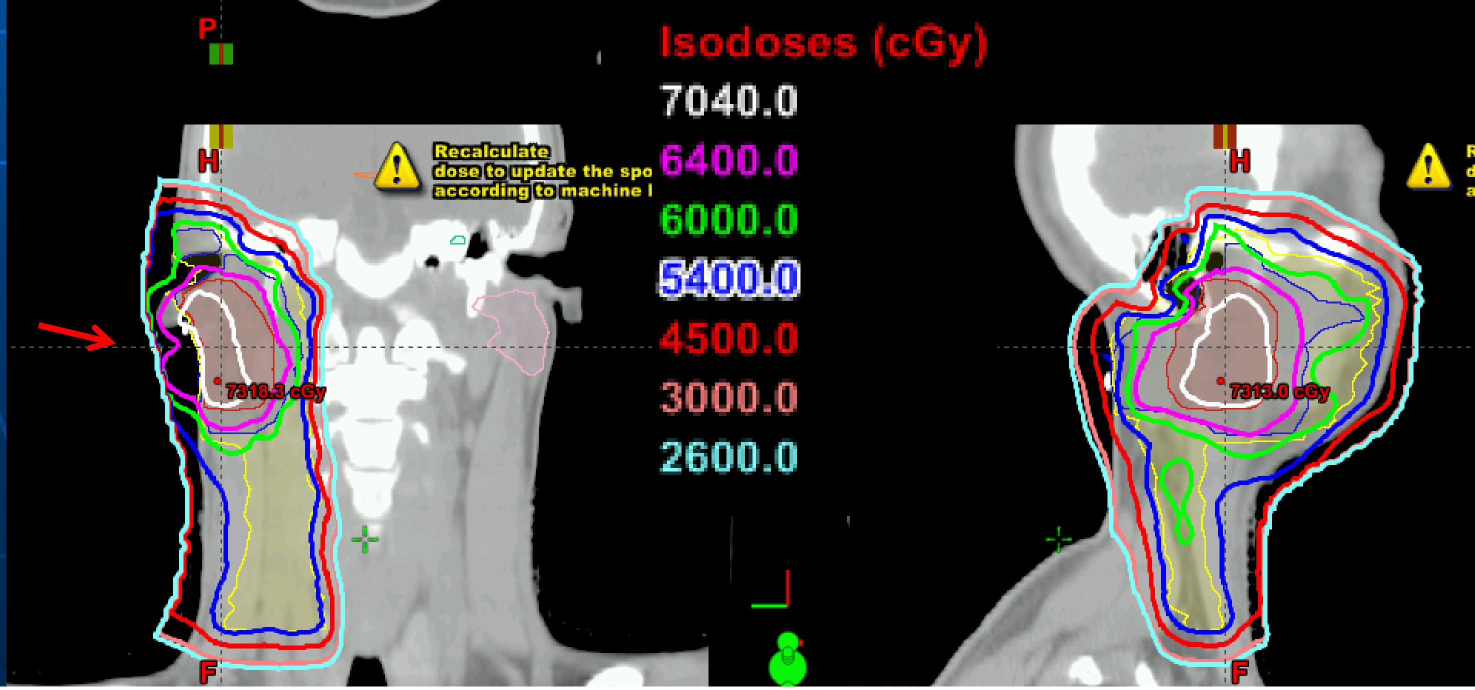
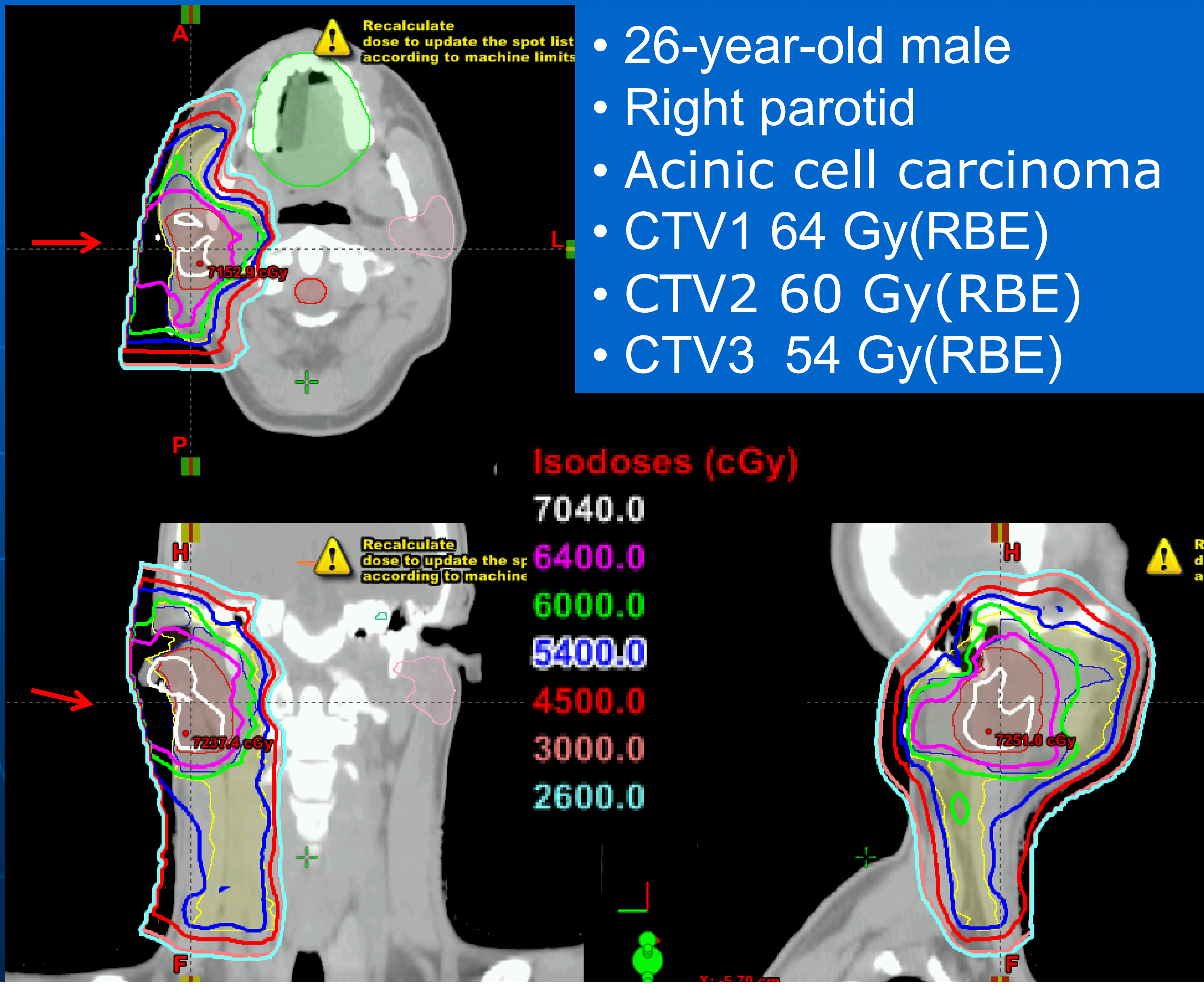
- CTV3 54 Gy(RBE)

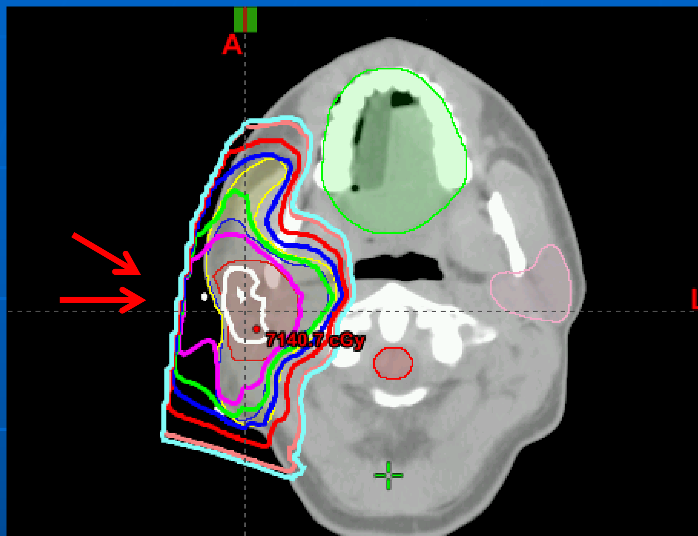


Head & Neck – SFIB – Field 2

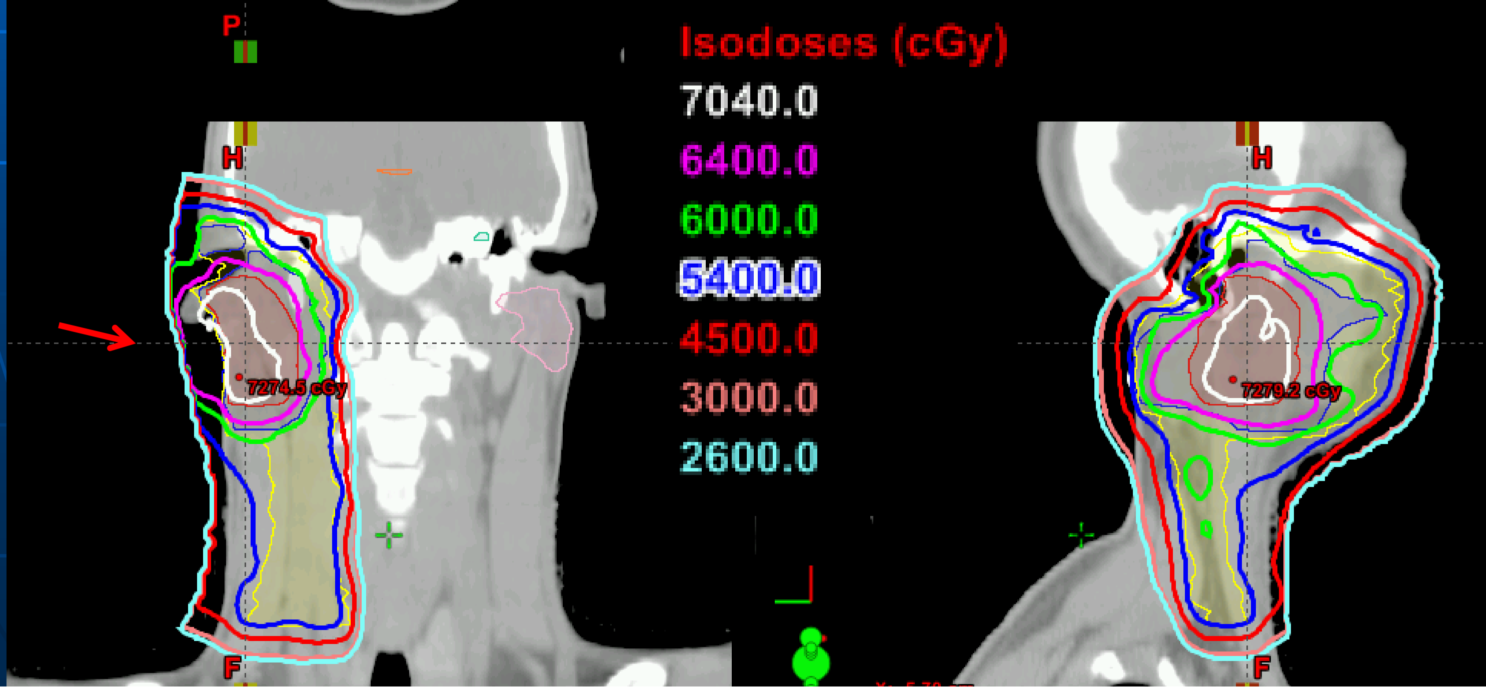
- 26-year-old male
- Right parotid
- Acinic cell carcinoma
- CTV1 64 Gy(RBE)
- CTV2 60 Gy(RBE)
- CTV3 54 Gy(RBE)



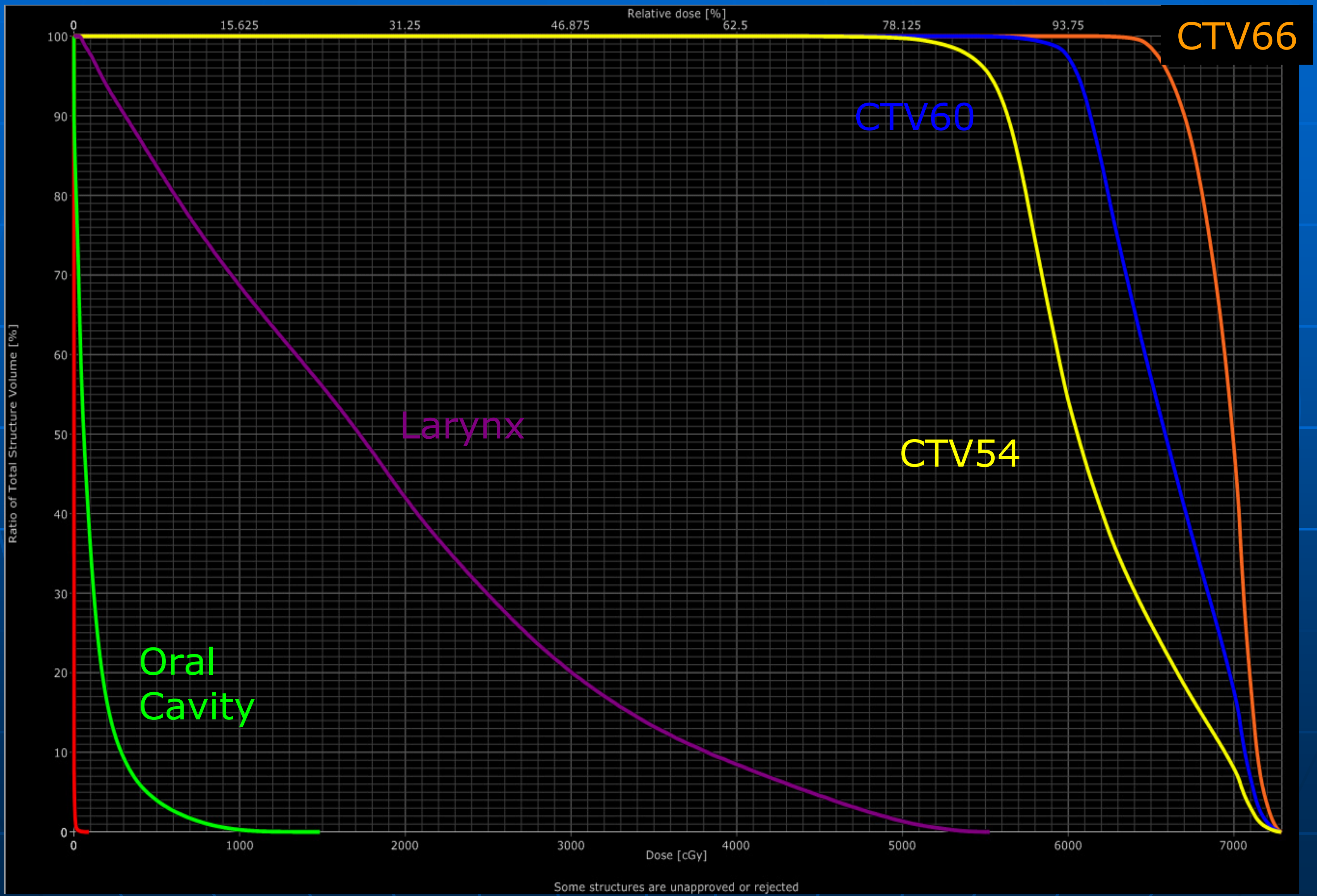
Head & Neck - SFIB



- 26-year-old male
- Right parotid
- Acinic cell carcinoma
- CTV1 64 Gy(RBE)
- CTV2 60 Gy(RBE)
- CTV3 54 Gy(RBE)

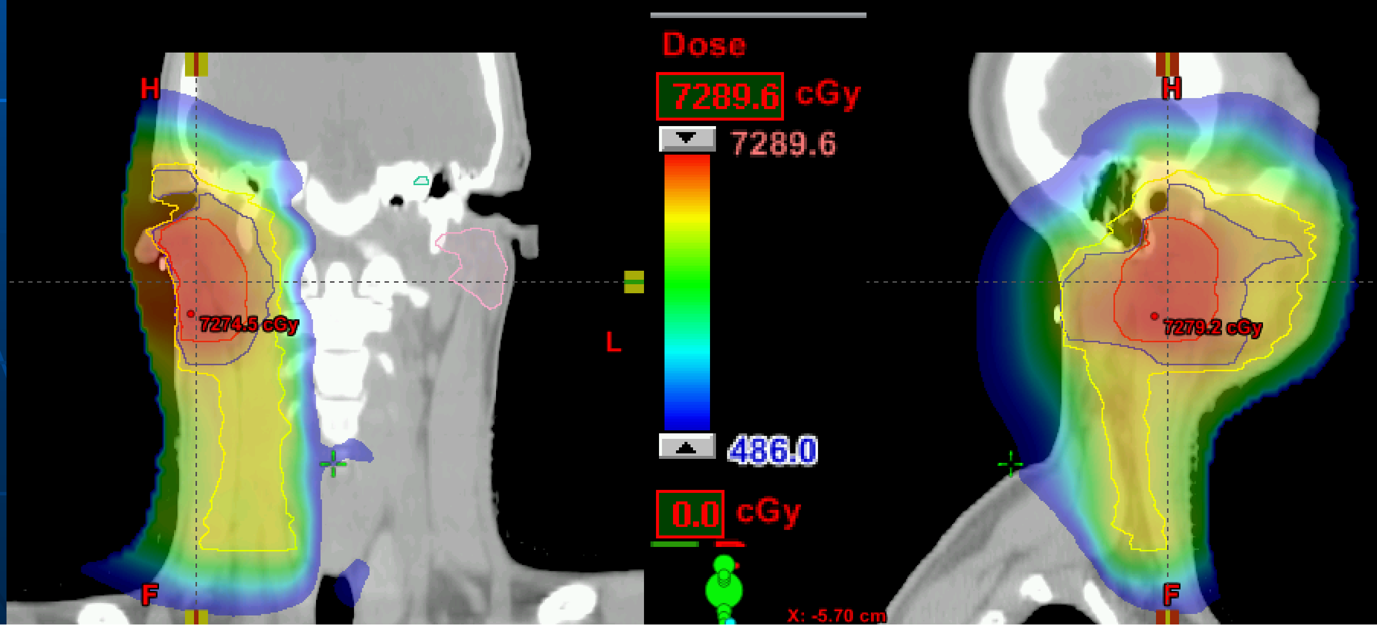


Head & Neck – SFIB DVH

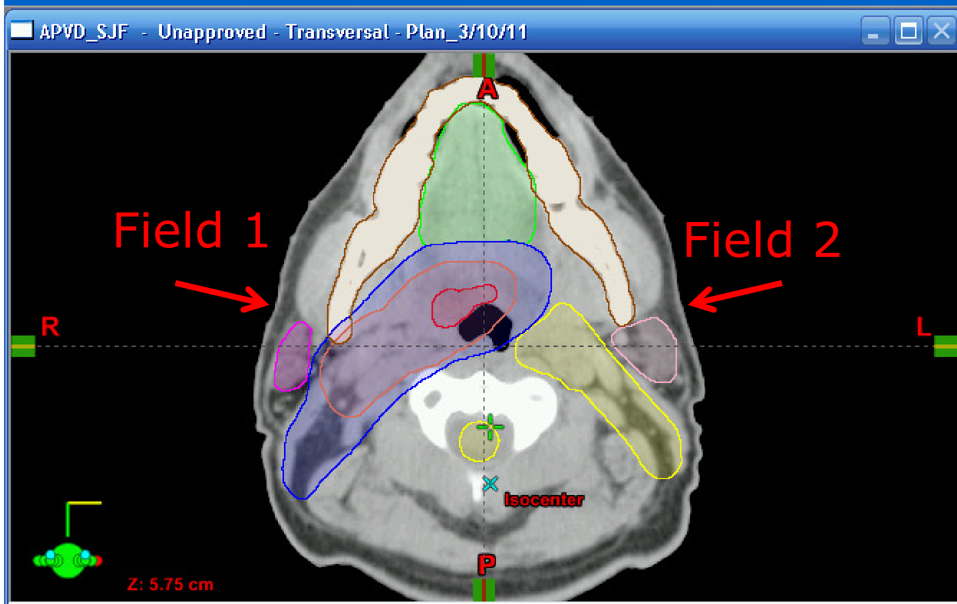


Head & Neck - SFIB

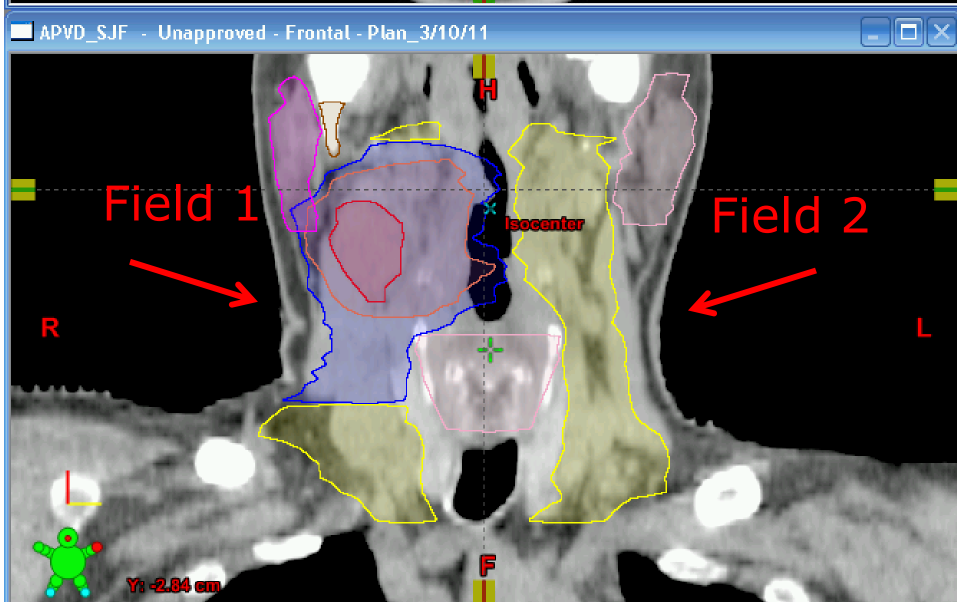
- Problem
  - Larger penumbra
- Solutions
  - Smaller spot size
  - Aperture

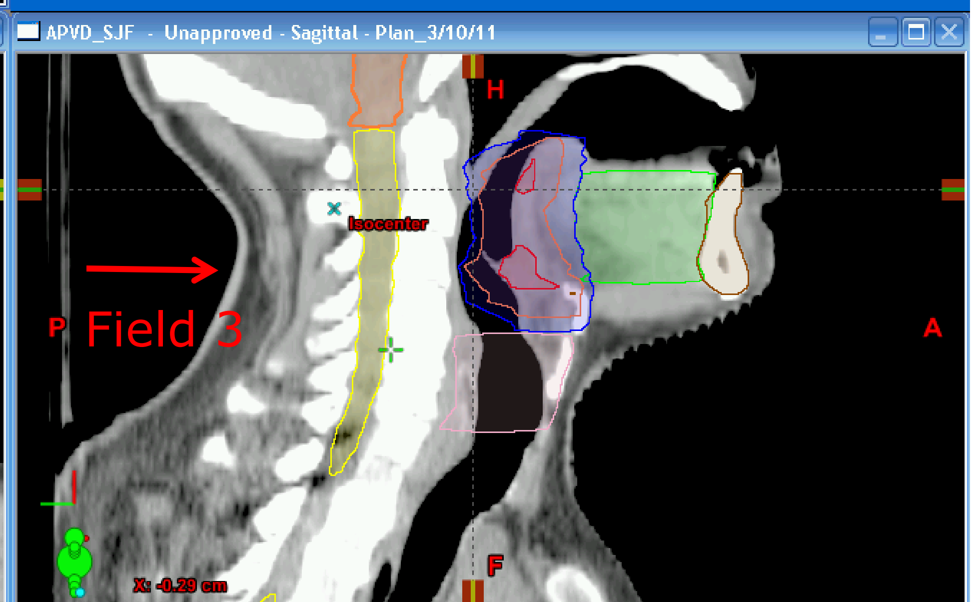


Head & Neck – MFO

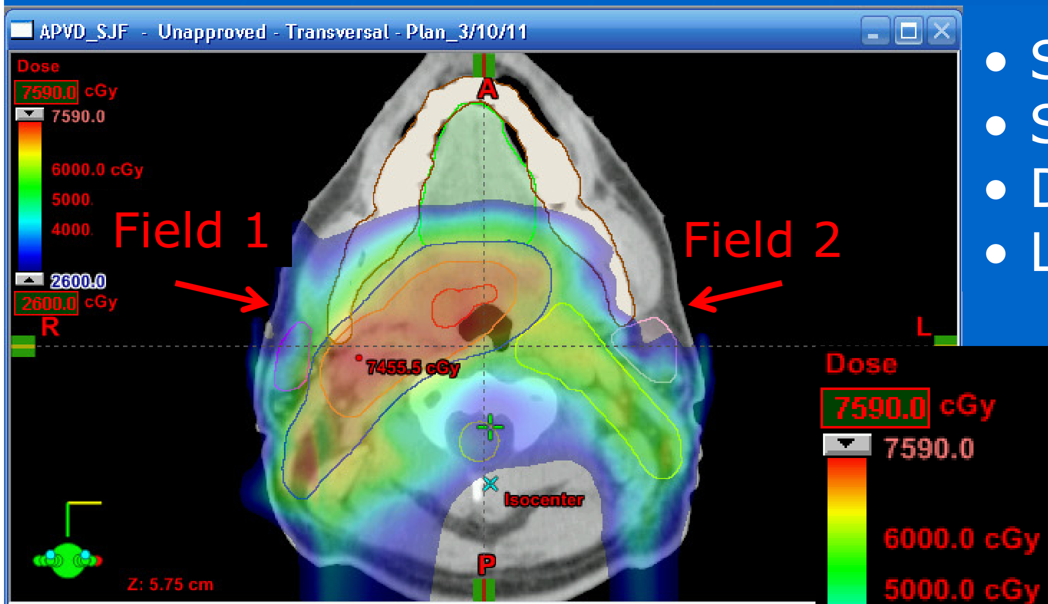


- 67 yo male
- Squamous cell carcinoma
- Right base of tongue
- CTV66, CTV60 & CTV54
- 3 fields: G280°/C15°, G80°/C345° & G180° /C0°

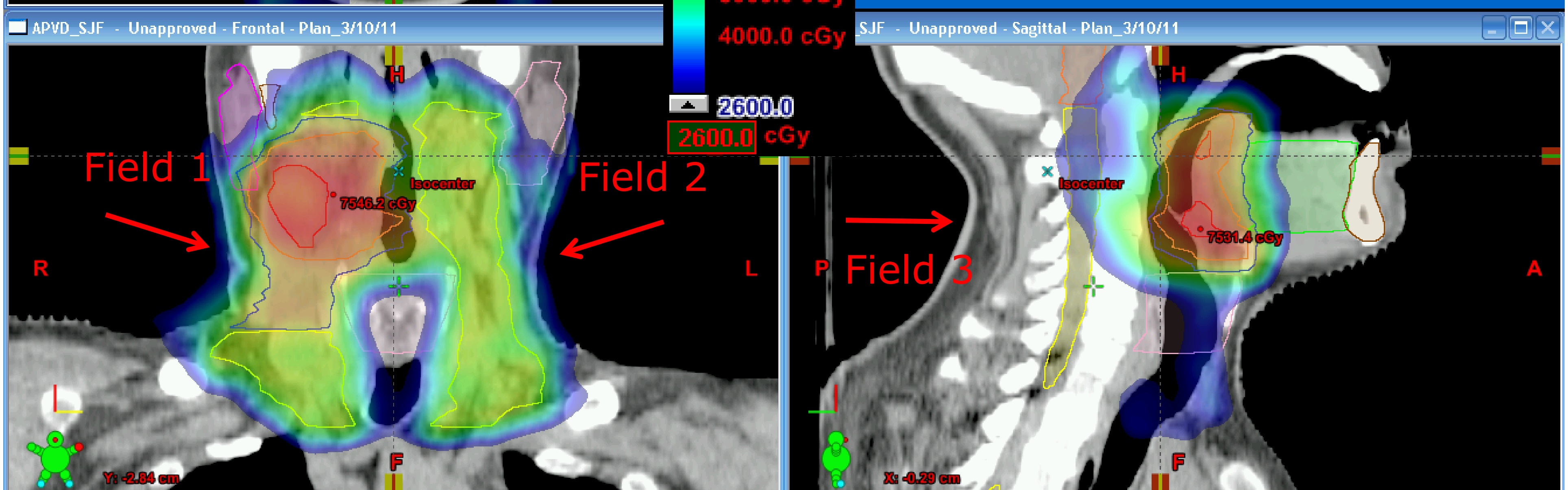




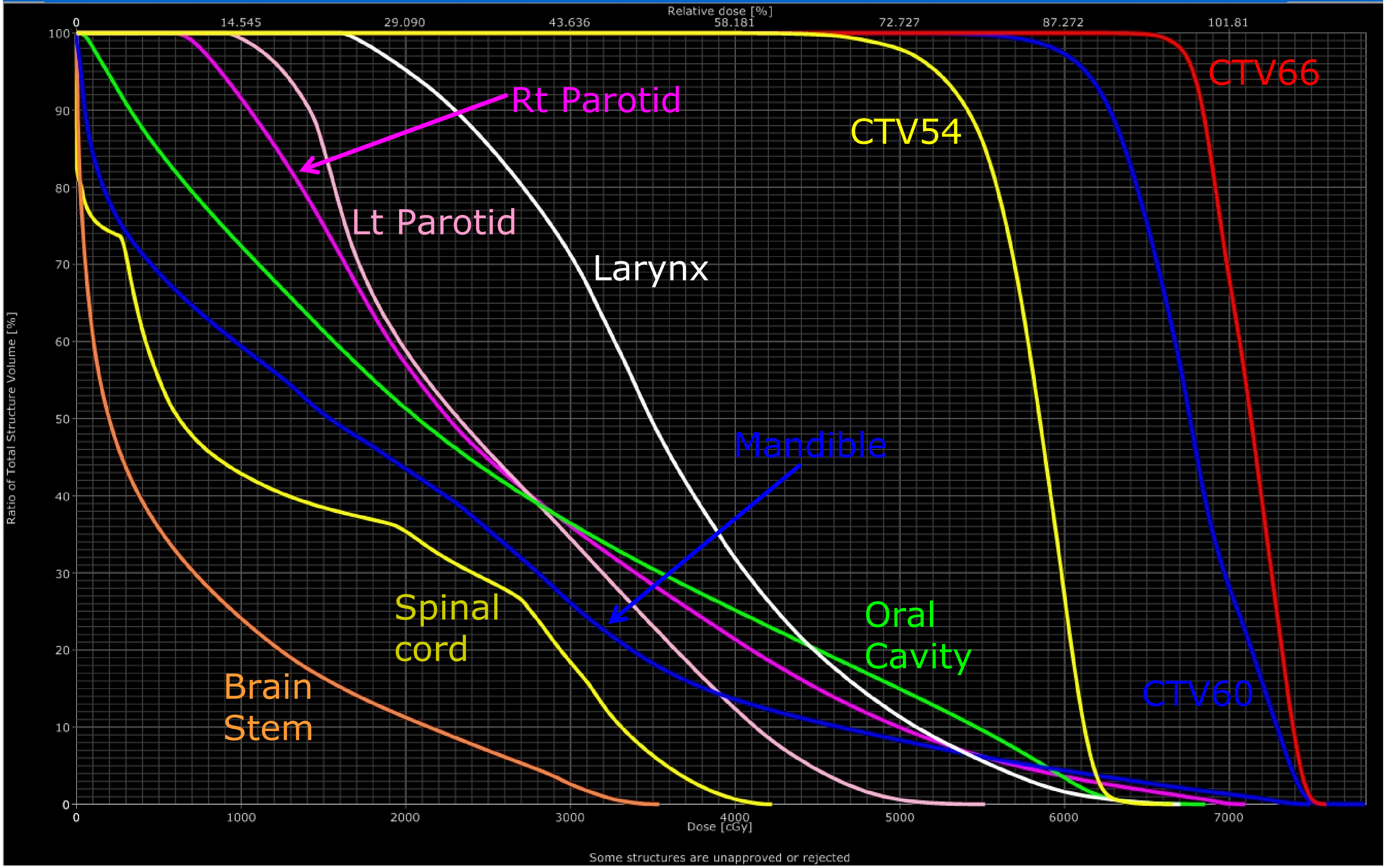
Head & Neck – MFO



- Simultaneous spot optimization
- Spot spacing = 1 cm
- Distal & prox. margins = 0 cm
- Lateral margin = 0.8 cm



Head & Neck – MFO DVH

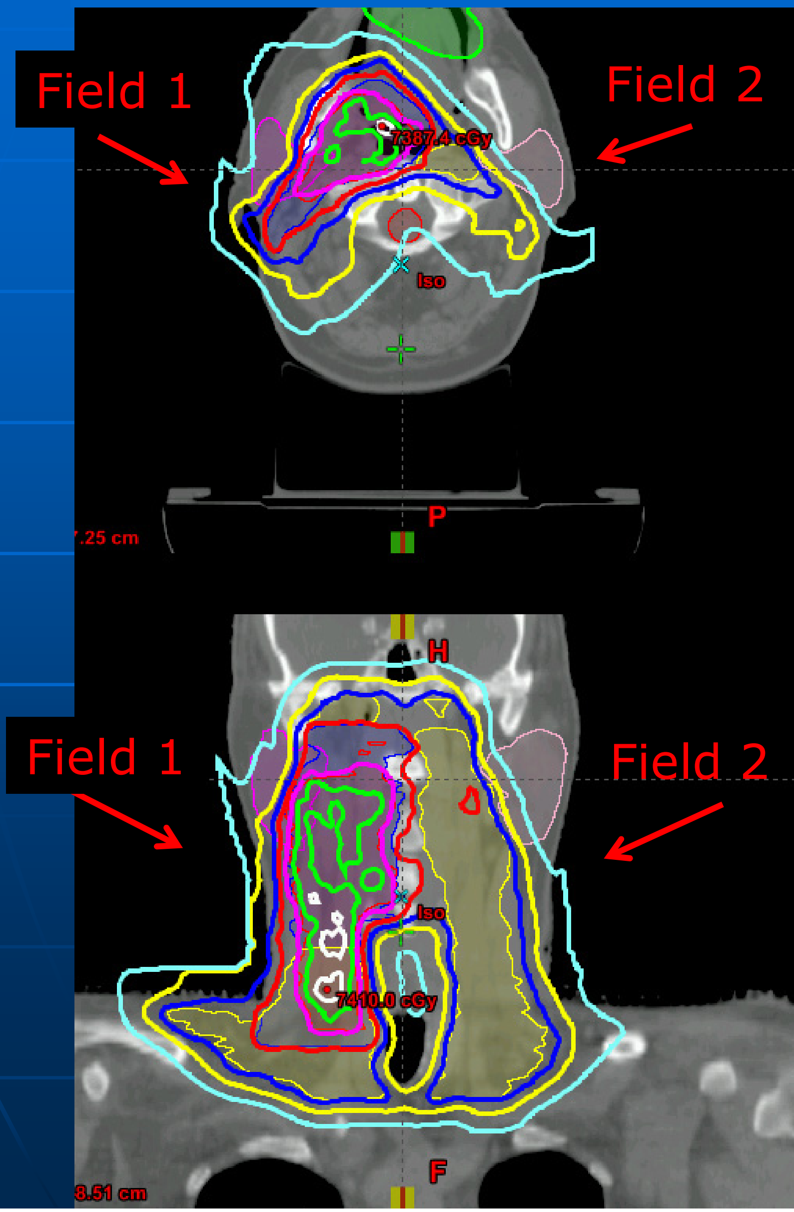


Robust evaluation

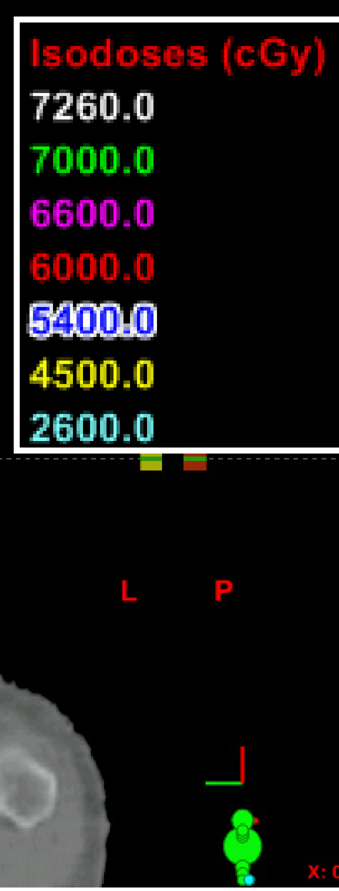
- Is the plan robust with respect to the range & setup uncertainties?

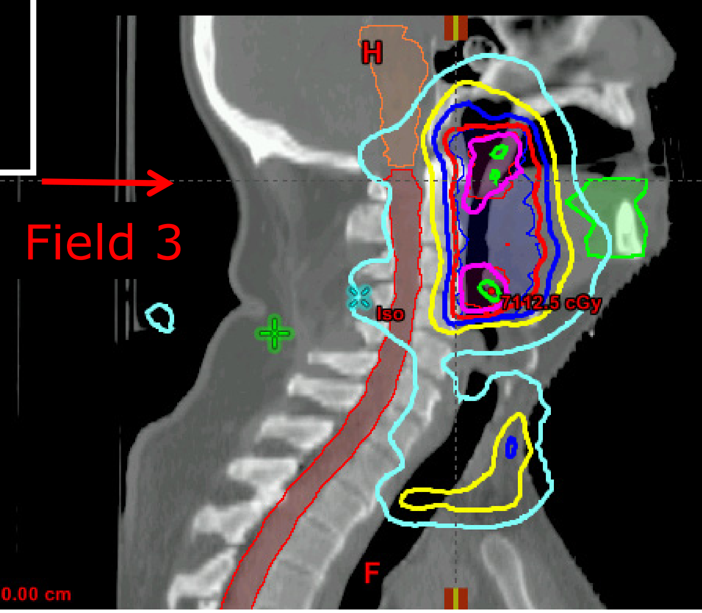
- Robust Evaluation
  - Assuming isocenter moved ±3 mm
  - Range uncertainties: ± 3.5% of the range
  - Total 9 plans including the nominal plan
  - DVH band for each volume
  - Maximum dose or minimum dose to each volume to see the worst case scenarios

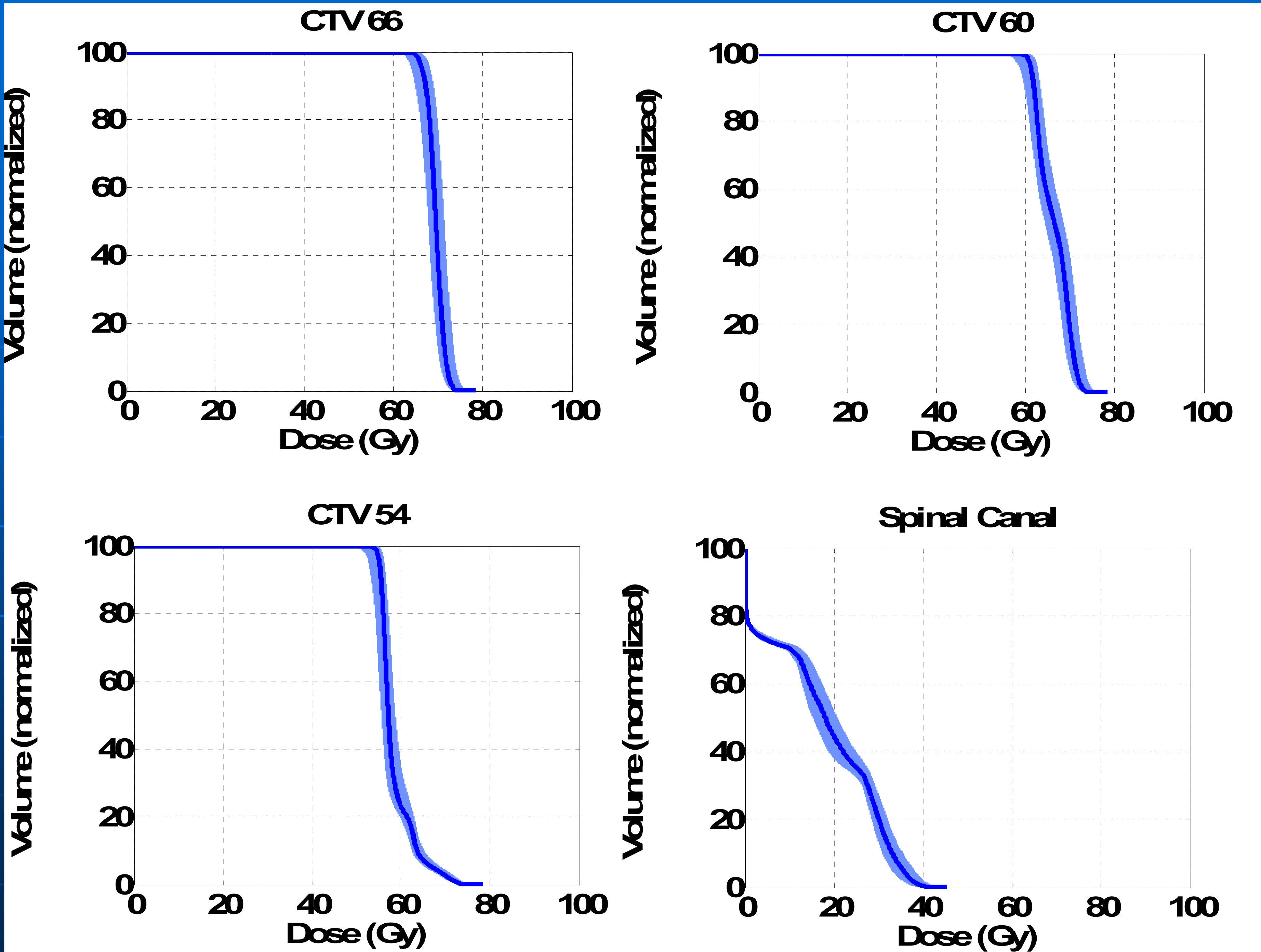
Robustness Evaluation – H&N MFO IMPT with EA



- 57 yo male
- Squamous cell carcinoma
- Right tonsil
- CTV66, CTV60 & CTV54
- 3 fields: G310°/C30°
  G70°/C340°
  G180° /C90°







CTV 66
CTV 60
CTV 54
Spinal Canal
Volume (normalized)
Dose (Gy)
0
20
40
60
80
100

Summary

- Spot scanning proton therapy is challenging, exciting, and rewarding:
  - SFO (SFUD & SFIB) & MFO (IMPT)
- Further development/improvement:
  - Robust optimization for SFO & MFO
  - Better optimizer in general
  - Implementation of bsPTV for SFO by TPS
  - Aperture (TPS modeling) for scanning
  - Moving target with scanning beam
  - Patient QA program
  - Dose algorithm

Acknowledgements

- Falk Poenisch, PhD
- Narayan Sahoo, PhD
- Richard Wu, MS
- Jim Lii, MS
- Xiaodong Zhang, PhD
- Jennifer Johnson, MS
- Heng Li, PhD
- Richard Amos, MS
- Wei Liu, PhD
- Radhe Mohan, PhD
- Michael Gillin, PhD
- Others

- M. Brad Taylor, BS
- Charles Holmes, BS
- Matt Kerr, BS
- Others

- Seungtaek Choi, MD
- Steven Frank, MD
- David Grosshans, MD
- Andrew Lee, MD
- Anita Mahajan, MD
- Others

- Mayank Amin, CMD
- Matt Palmer, CMD
- Beverly Riley, CMD
- Others

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Proton Treatment Planning

Stefan Both
University of Pennsylvania

Proton Treatment Planning

OUTLINE

- Proton Technologies and Treatment Technique at UPenn
- MLC Based Delivery and Treatment Planning
- Pencil Beam Scanning
- Summary

Proton Technologies and Techniques at UPenn

Technologies:

SS DS US PBS

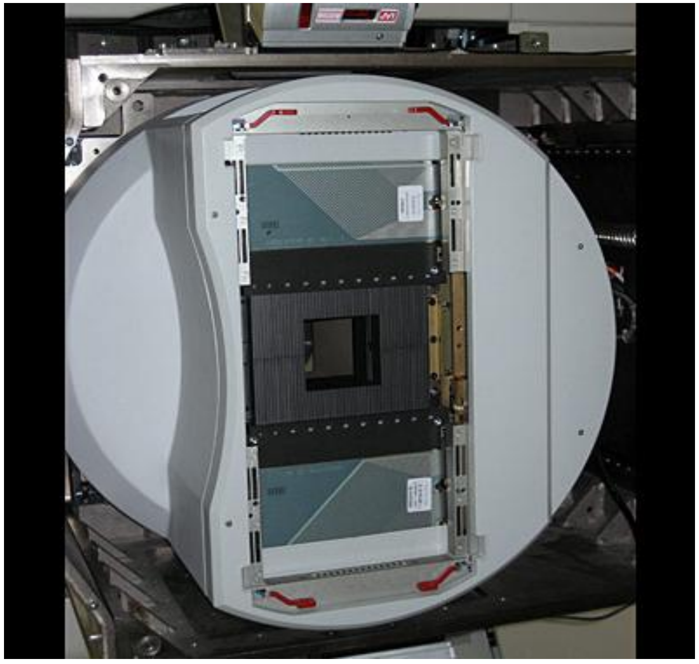
Techniques:

SOBP SFUD IMPT

3DCRT/IMRT IMRT

Proton Treatment Planning

In PS, the integration of MLC allows for safer and more efficient automated processes.



MLC redesigned based on the Varian MLC allows for:

- Automated field shaping
- Automated field matching patching (SOBP)
- Automated delivery

MLC Based Delivery and Treatment Planning

- Field Size: 22cm x 17cm
- Neutron production

"The neutron and combined proton plus gamma ray absorbed doses are nearly equivalent downstream from either a close tungsten alloy MLC or a solid brass block."

Diffenderfer et al. Med. Phys 11/2011; 38(11):6248-56

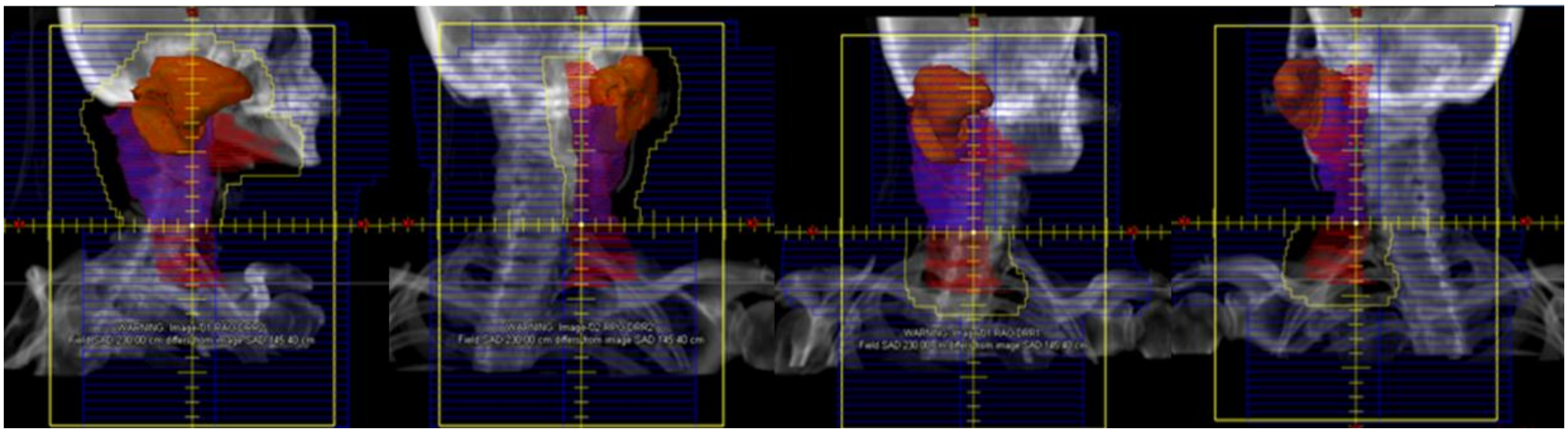
- Penumbra characteristics:

$PDS_{MLC} > PDS_{AP}$ (~2mm)

$PUS_{MLC} = PDS_{AP}$

MLC Based Delivery and Treatment Planning

- MLC allows for automated field matching/patching based on volume segmentation techniques.

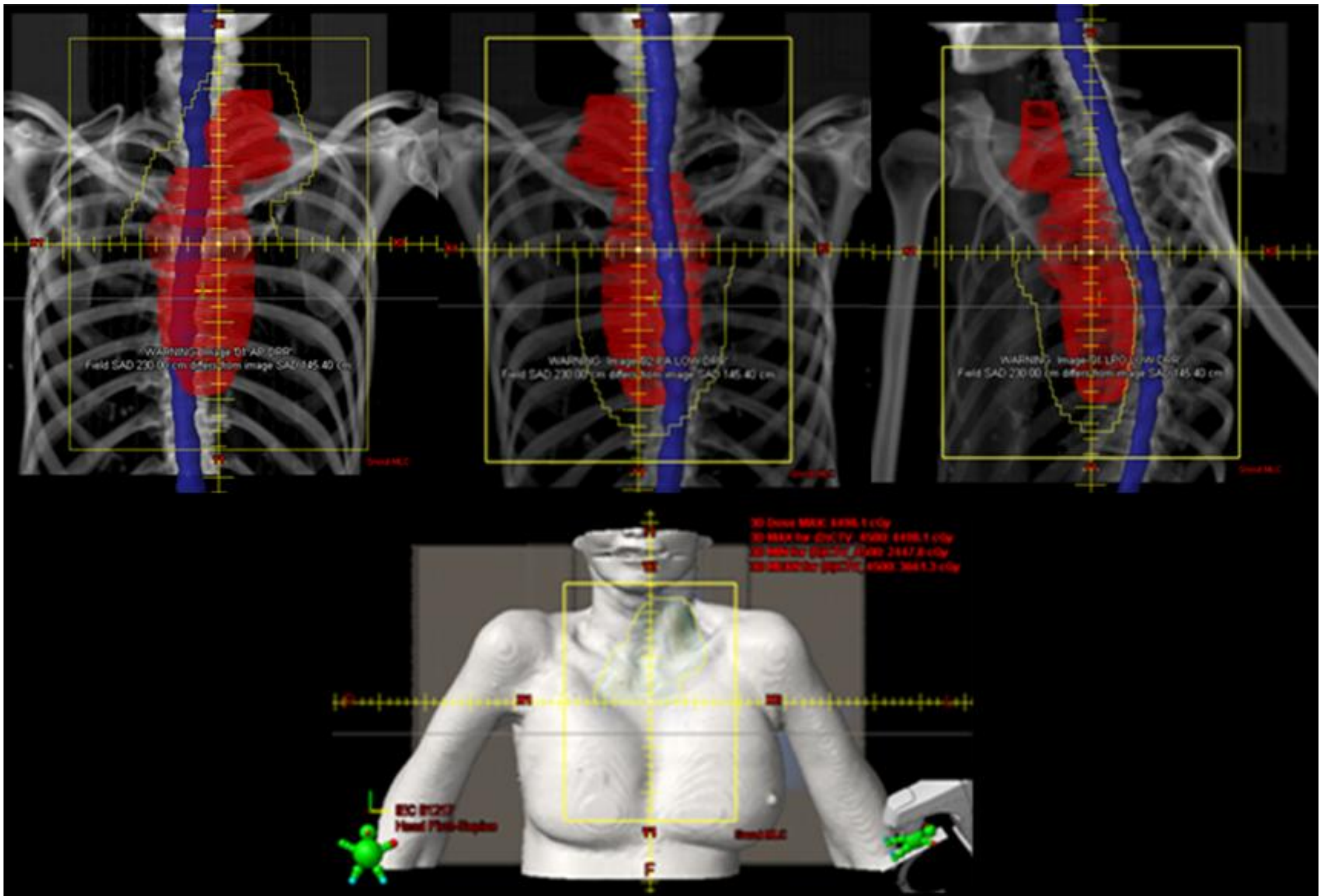


- Facilitate the use of Half Beam Techniques.

  For example: Esophagus, Sarcoma.

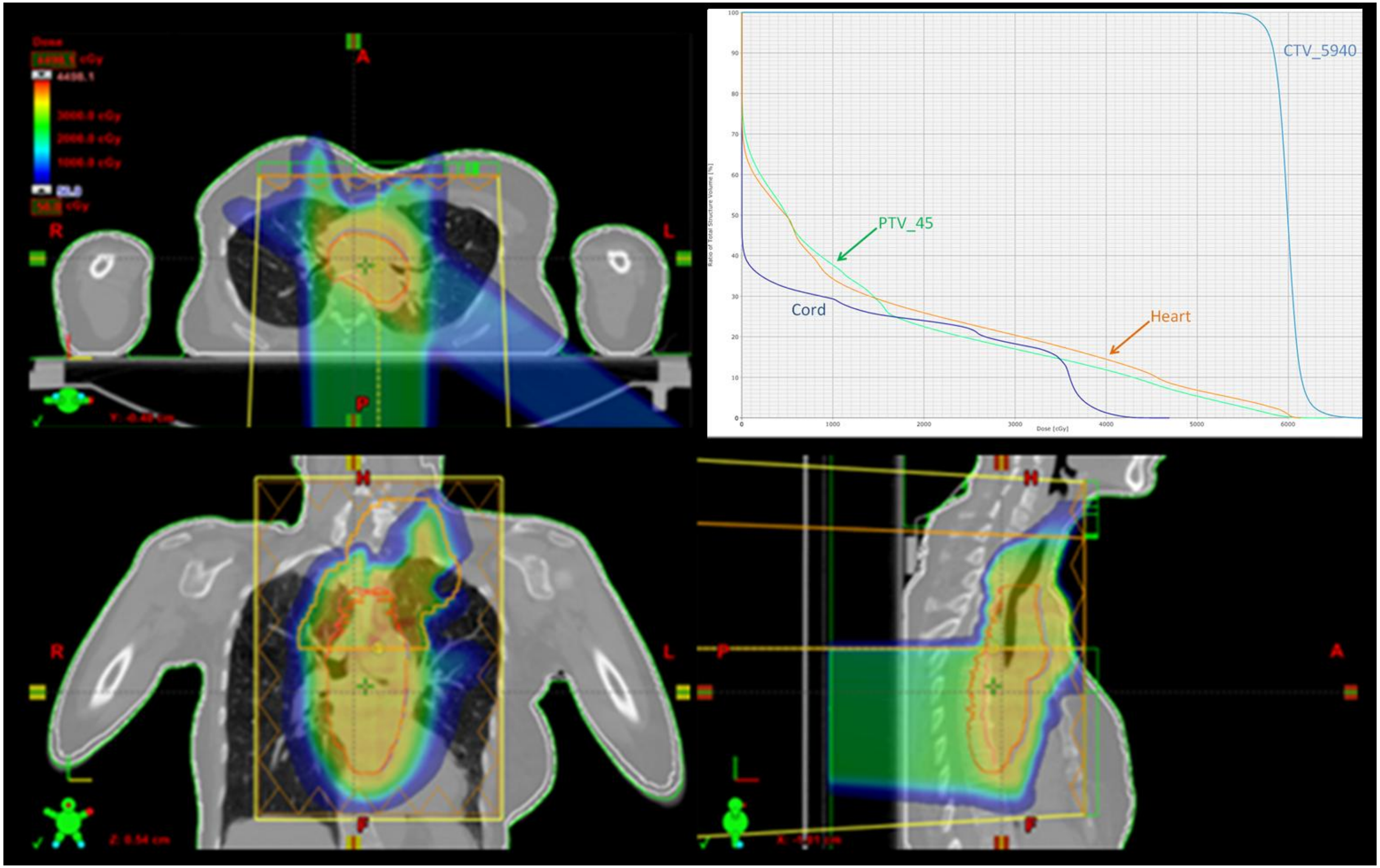
MLC Based Delivery and Treatment Planning

Esophagus



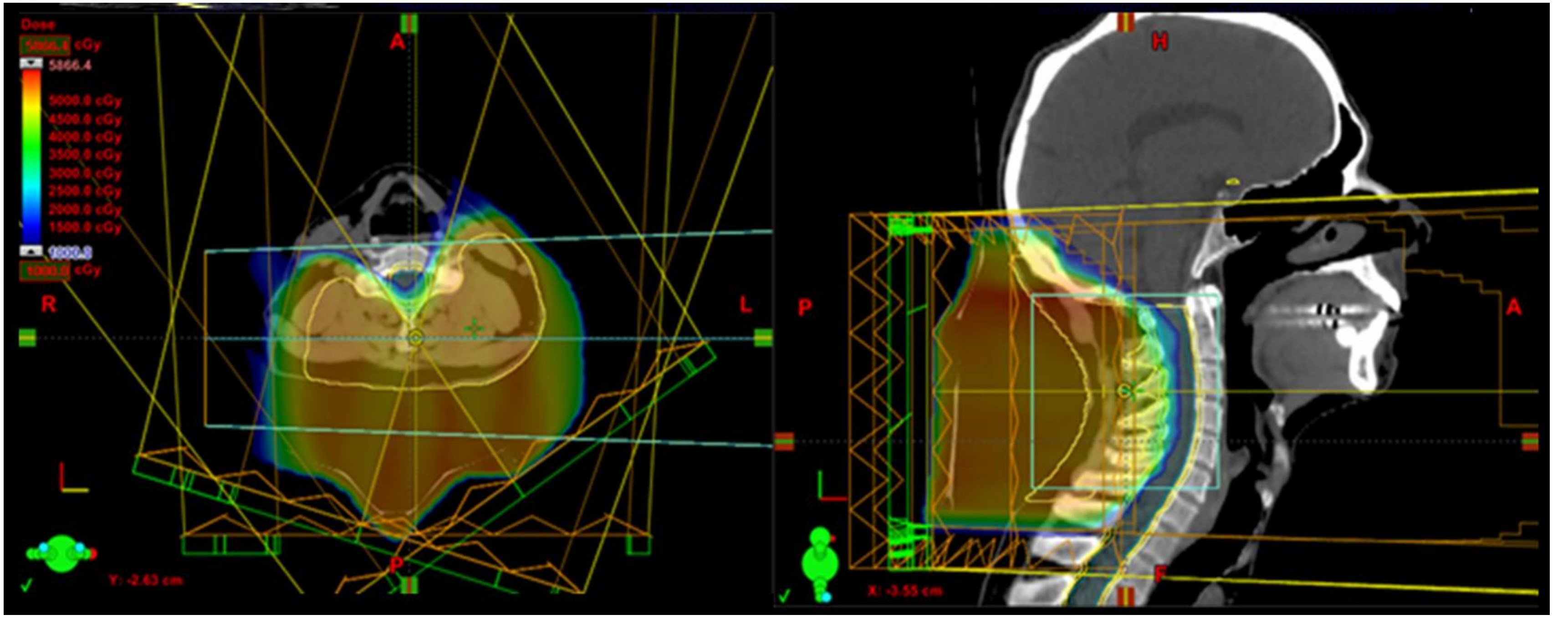
MLC Based Delivery and Treatment Planning

Esophagus



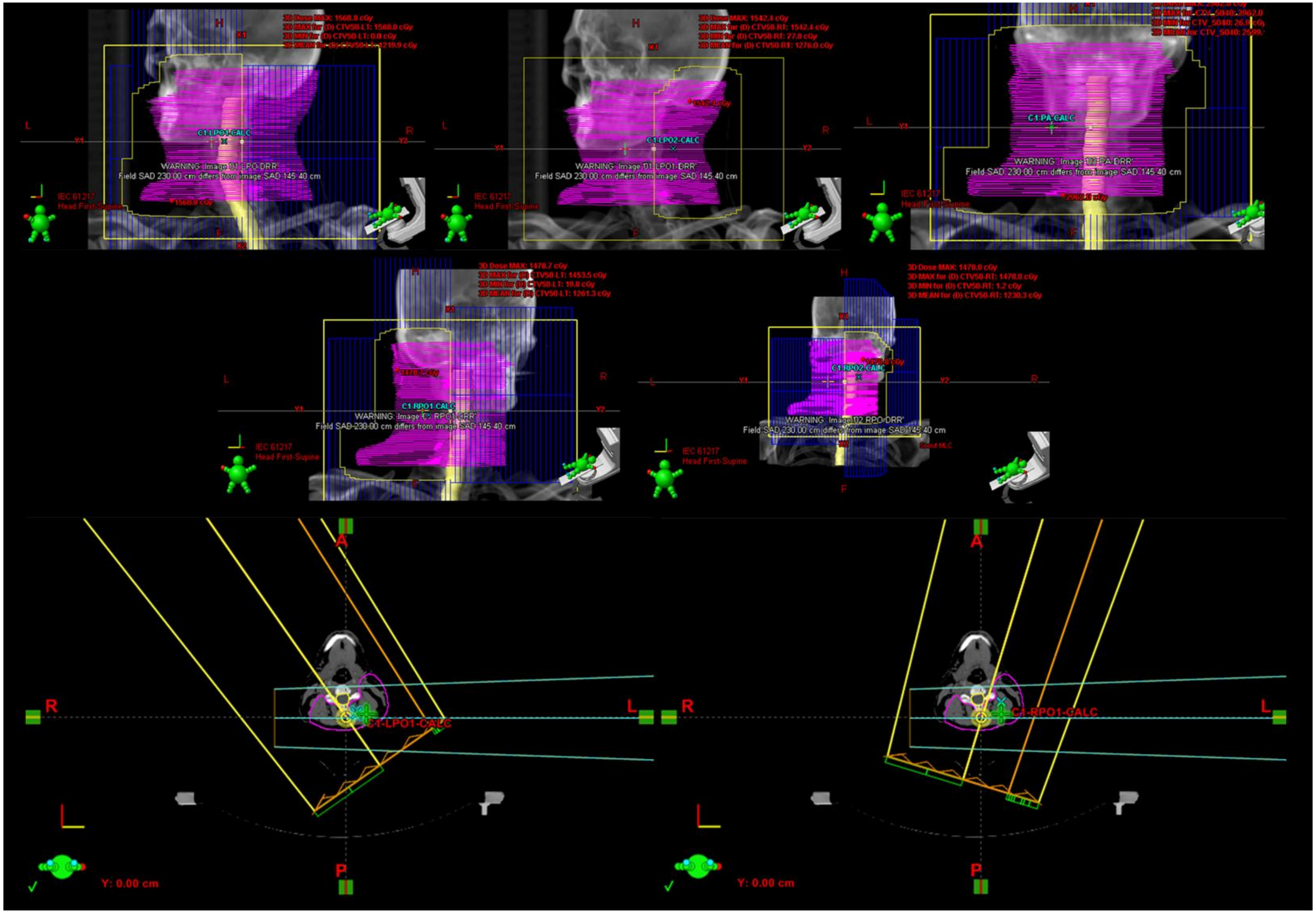
MLC Based Delivery and Treatment Planning

Sarcoma



MLC Based Delivery and Treatment Planning

Sarcoma

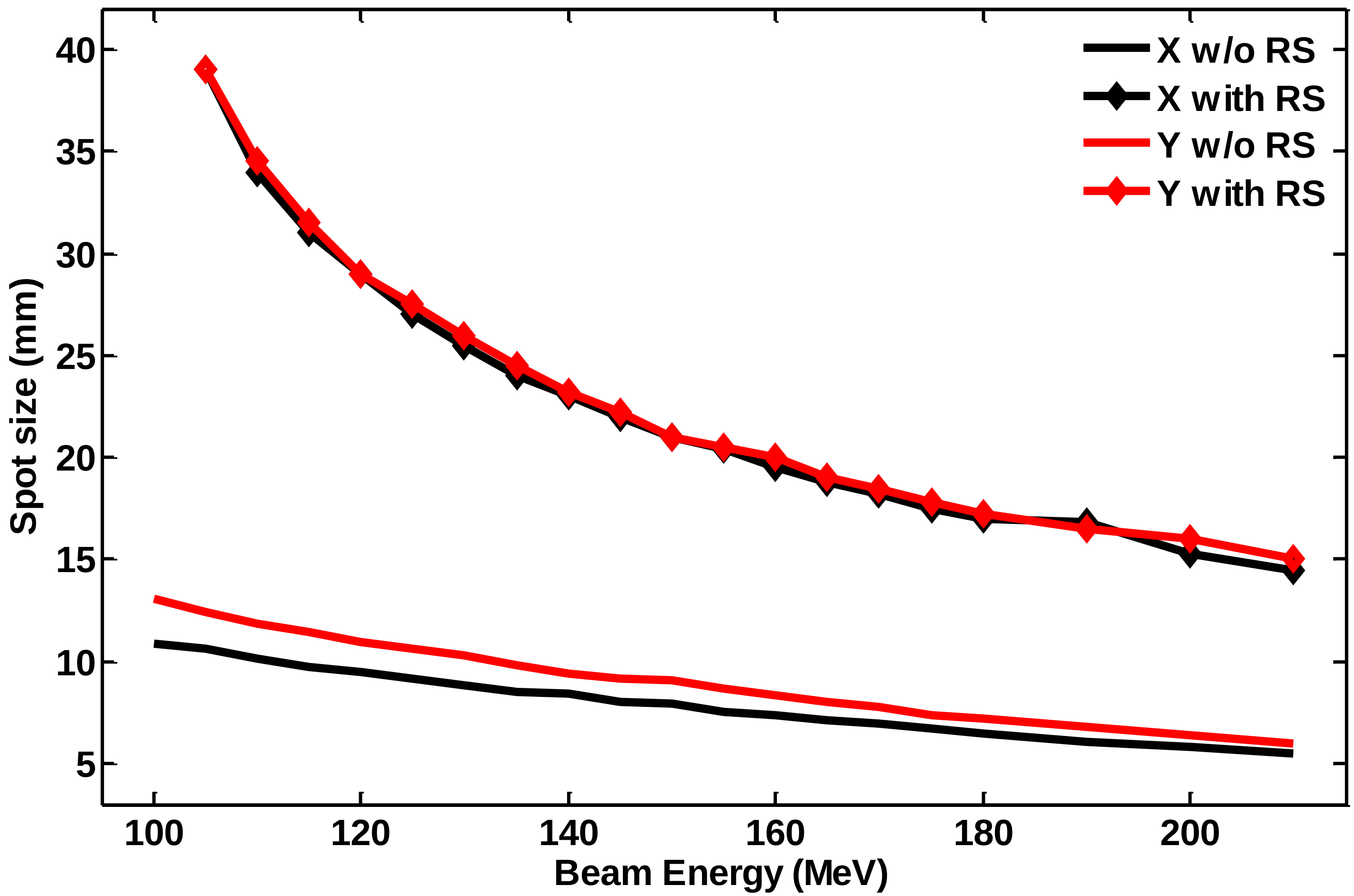


PBS Technology at UPenn

- The Fix Beam Line Range (100 MEV to 235 MEV).
- The Fix Beam Line Geometry allows for imaging at ISO & treatment AT &OFF ISO.
- Targets <7 cm WEPL from the surface require the use or an absorber (range shifter).

- Range shifter positioned surface of the snout.

Spot Size



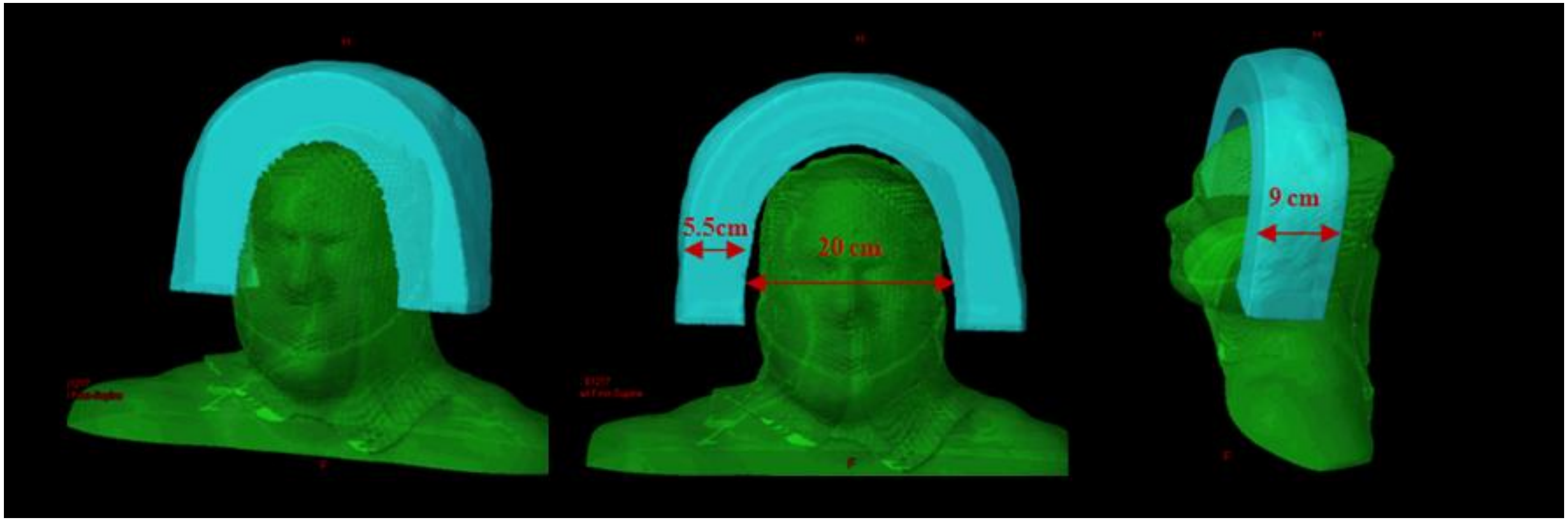
X w/o RS
X with RS
Y w/o RS
Y with RS
Spot size (mm)
40
35
30
25
20
15
10
5
100
120
140
160
180
200
Beam Energy (MeV)

Spot Size Integrity

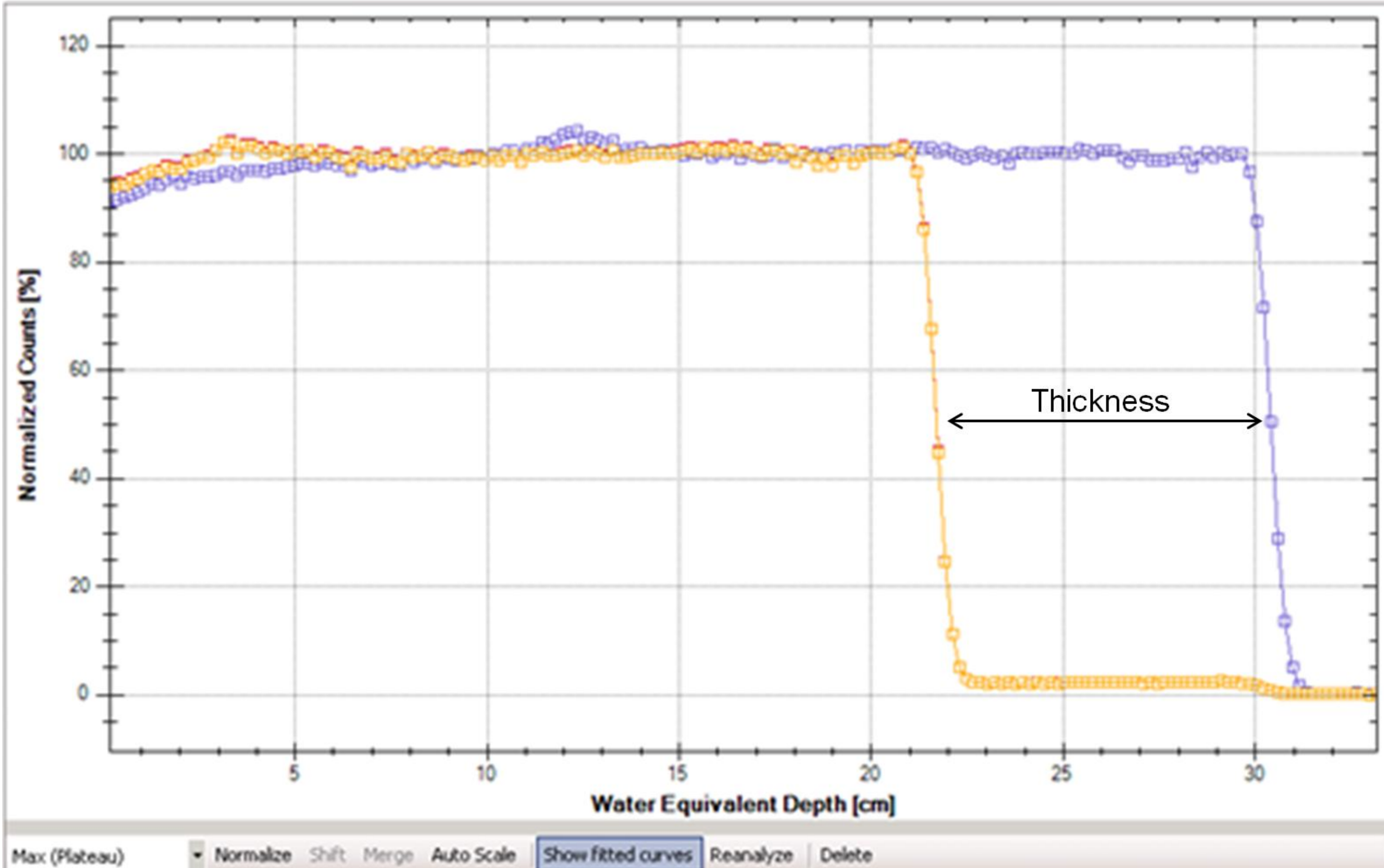
- A Universal/Patient Specific Bolus was designed in order to be able to image and treat at the ISO while:

  - minimizing the air gap and the amount of material in the beam

  - maintain the size of the pencil beam



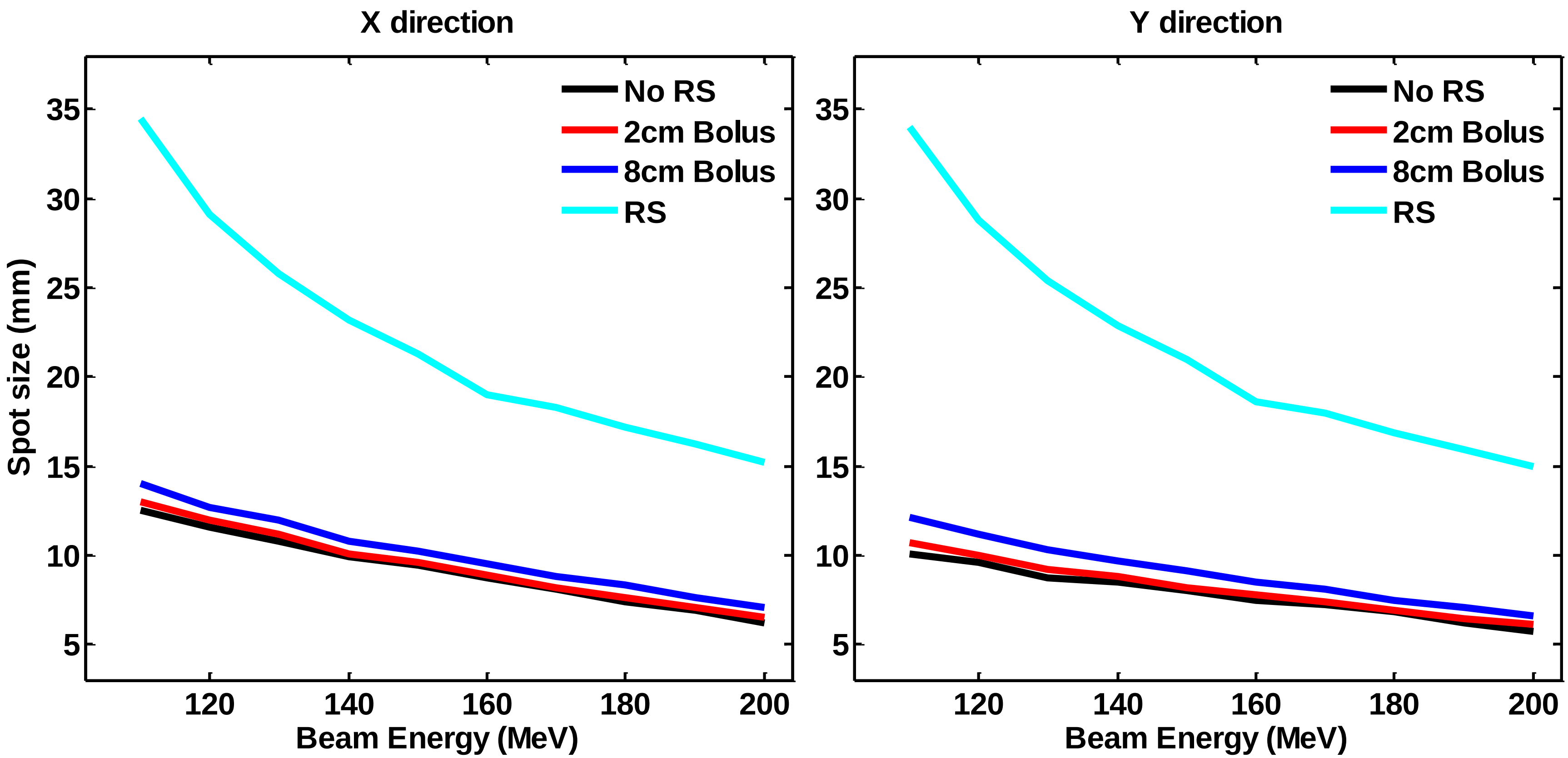
Bolus Thickness



	Visible		Id	Time	Date	Type	Field Size	SSD	Snout Dim.	Snout Dist.	Shift	Beam deli...	Sampling ...	Analy...
	☑		1.1	5:15:52 PM	6/29/2012	SOBP	10 x 10 cm	230.00...	n/a	n/a	0.00 cm	SingleScat...	1000 ms	A
	☑		2.1	5:24:09 PM	6/29/2012	SOBP	10 x 10 cm	230.00...	n/a	n/a	0.00 cm	SingleScat...	1000 ms	A
	☑		4.1	5:15:52 PM	6/29/2012	SOBP	10 x 10 cm	230.00...	n/a	n/a	0.00 cm	SingleScat...	1000 ms	A

In TX Room Implementation

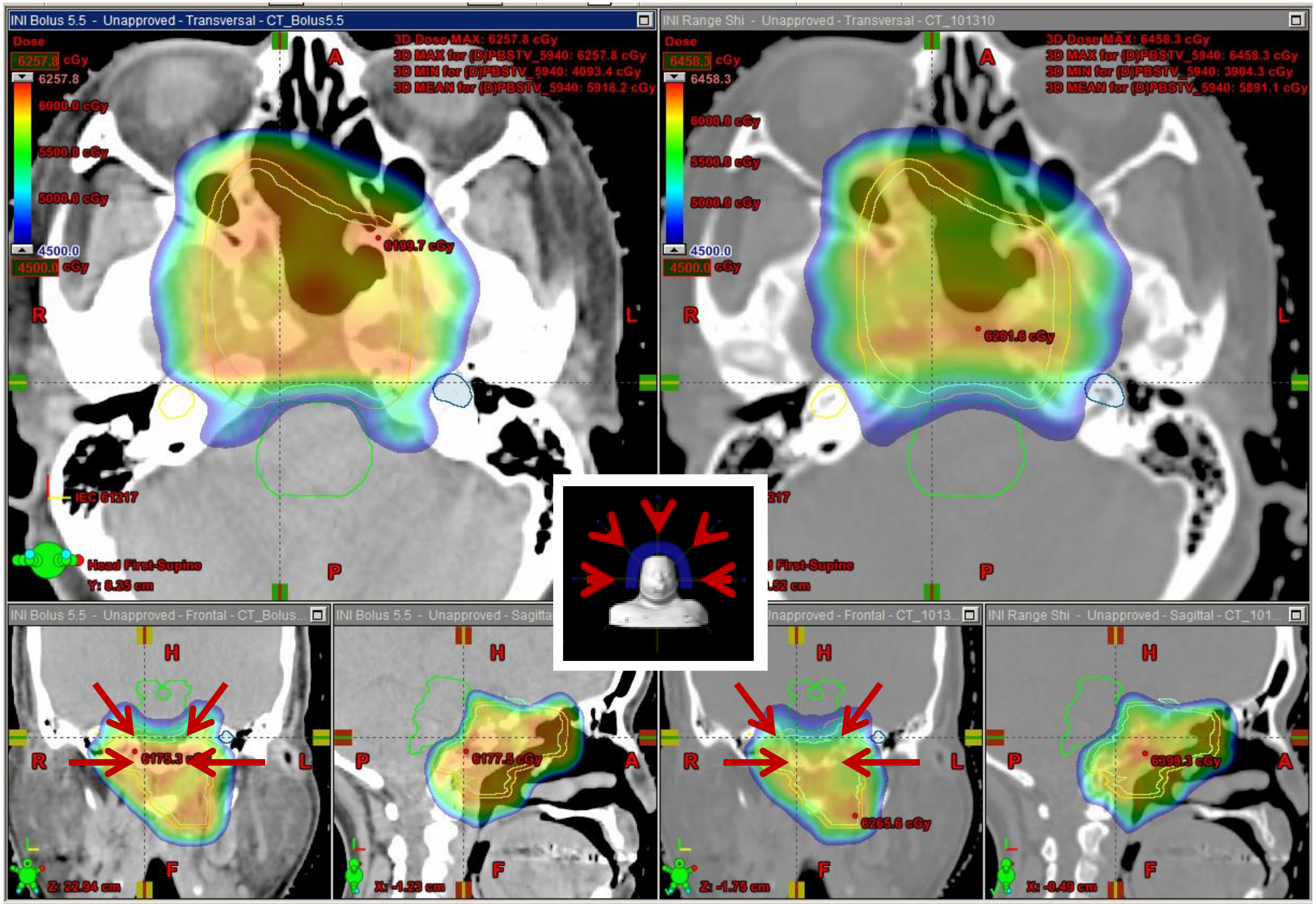
Spot Size (Bolus vs. Range Shifter)



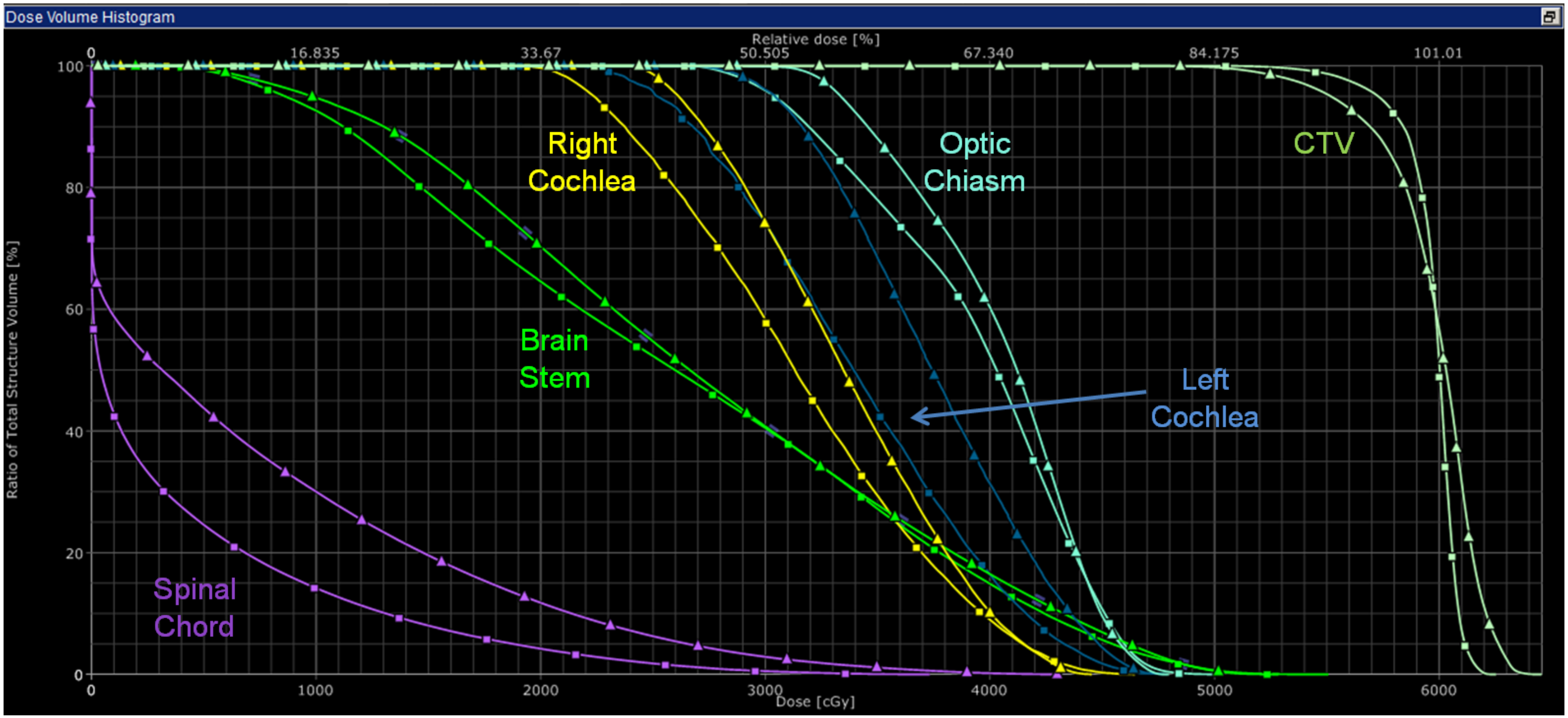
The “Perfect” Clinical Example
Base of Skull RT

- Limited by proximity to the brainstem
- Limited by proximity to optical structures
- Limited by dose to the brain

Bolus vs. Range Shifter

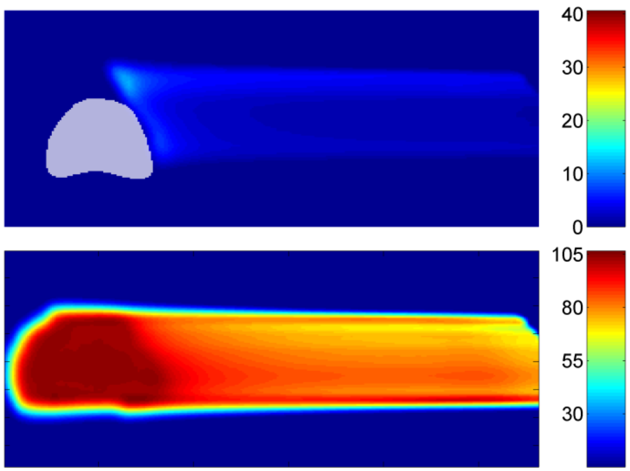


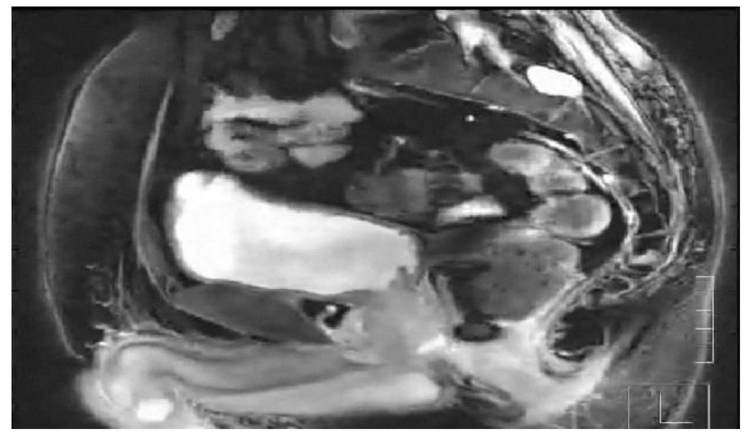
DVH comparison showing more uniform coverage and that the biggest differences in dose for the OARs are for the peripheral structures such as the cord and cochlea while the brainstem and chiasm are similar in the high dose region.



Prostate Motion and the Interplay Effect

- PBS delivers a plan spots by spots; layers by layers.
- Each Layer is delivered almost instantaneously.





- The switch (beam energy tuning) between layers takes about 10 seconds.
- Prostate motion during beam energy tuning causes an interplay effect.

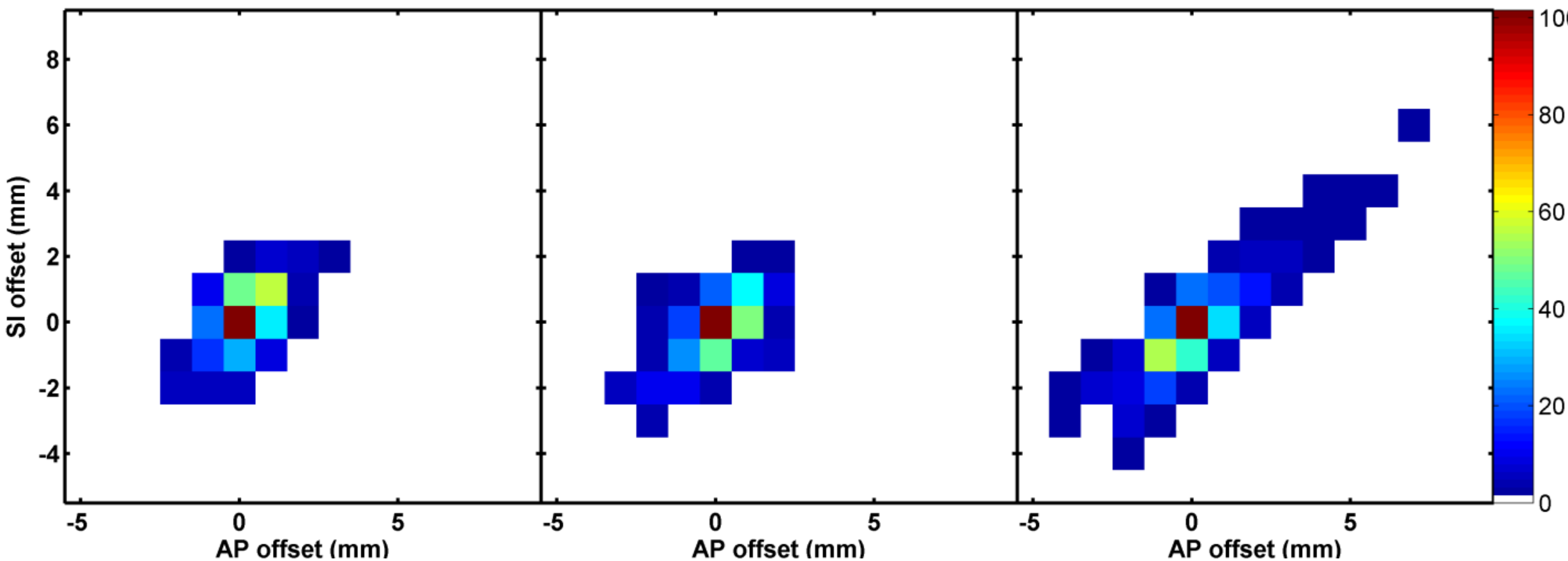
Evaluating Interplay Effect

Considerations:

- The lateral motion is negligible.*
- AP and SI motions are significant.*
- HUs of prostate and surrounding tissues are very close.
- The prostate motion determined by the Calypso log file (0.5s).
- The beam delivery log file determines the beam on and off time.
- The dose to CTV is re-calculated by considering prostate drifting.

Wang, et. al. IJROBP, 11/2011

Motion in SI and AP for the Entire Course of Treatment (for One Patient)



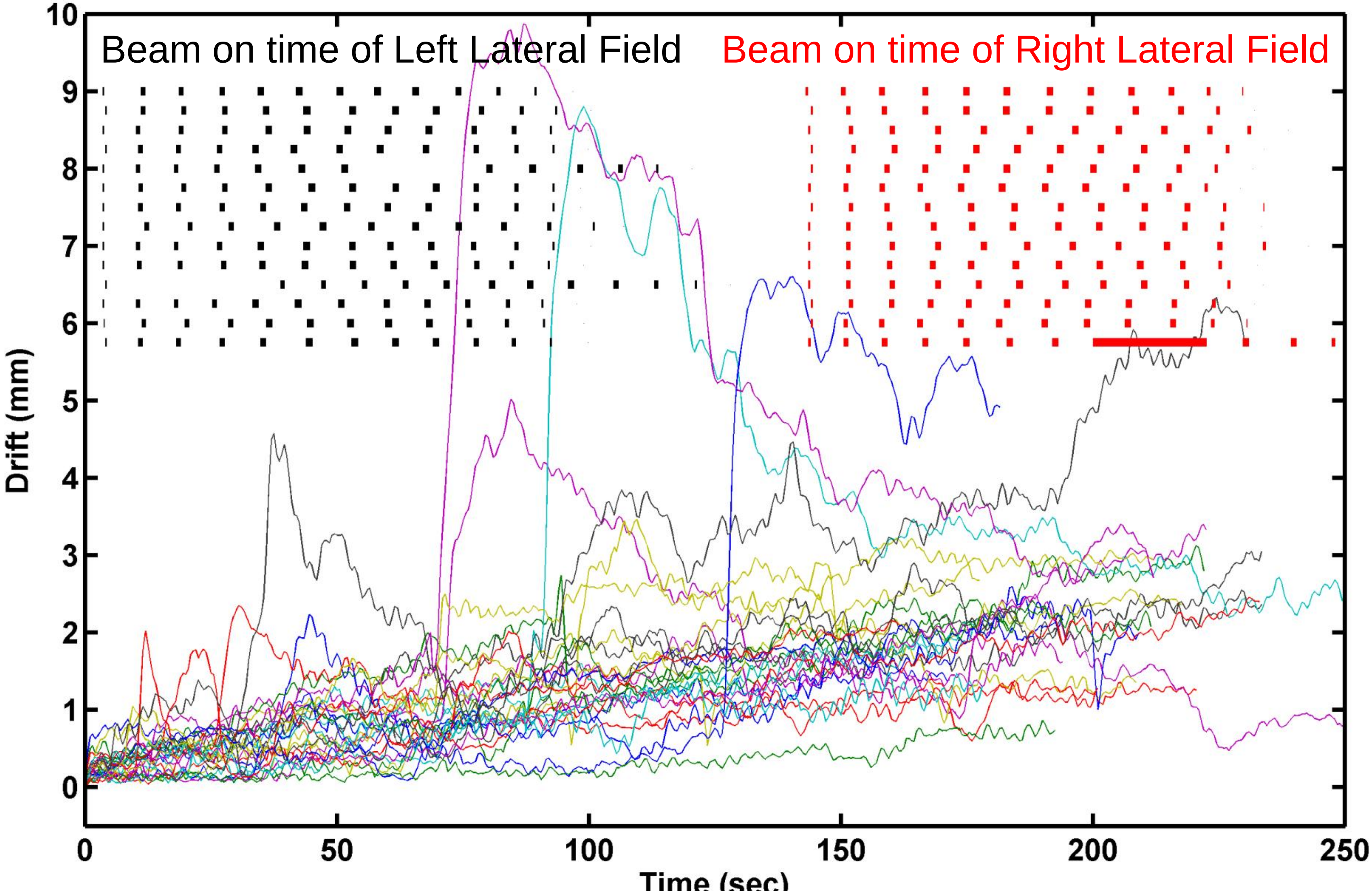
Best scenario

Intermediate scenario

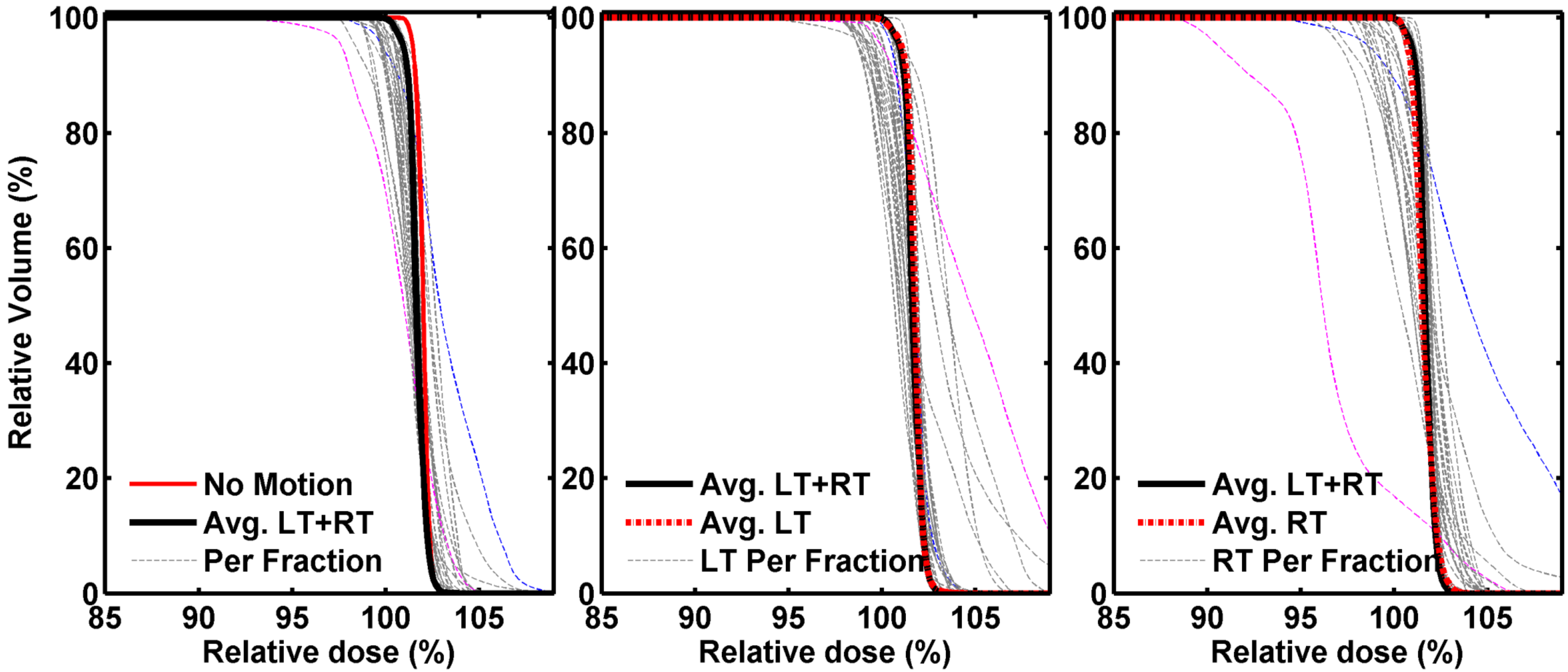
Worst scenario

Both, et. al. IJROBP, 12/2011

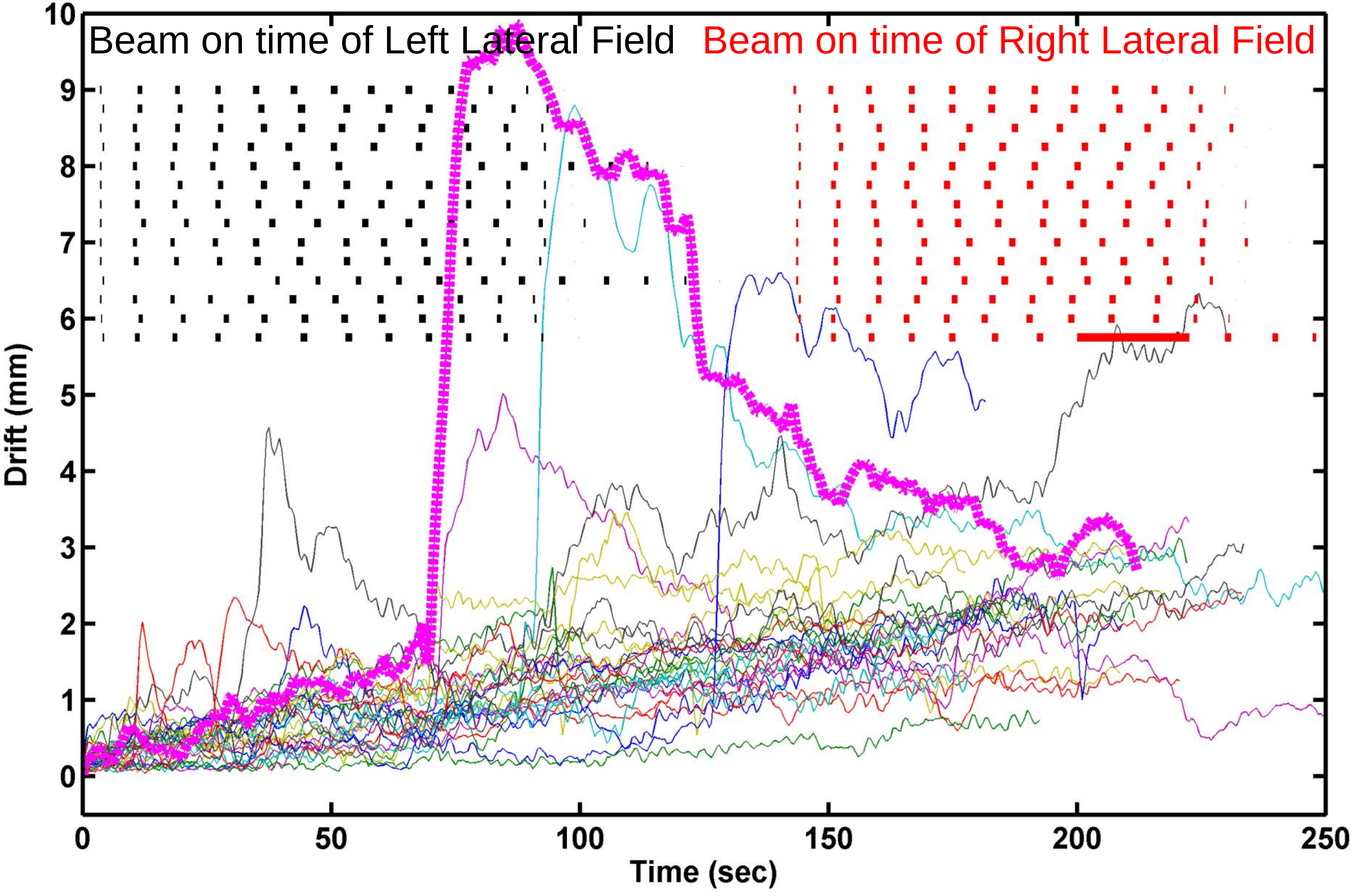
Prostate Drifting and Beam on Time



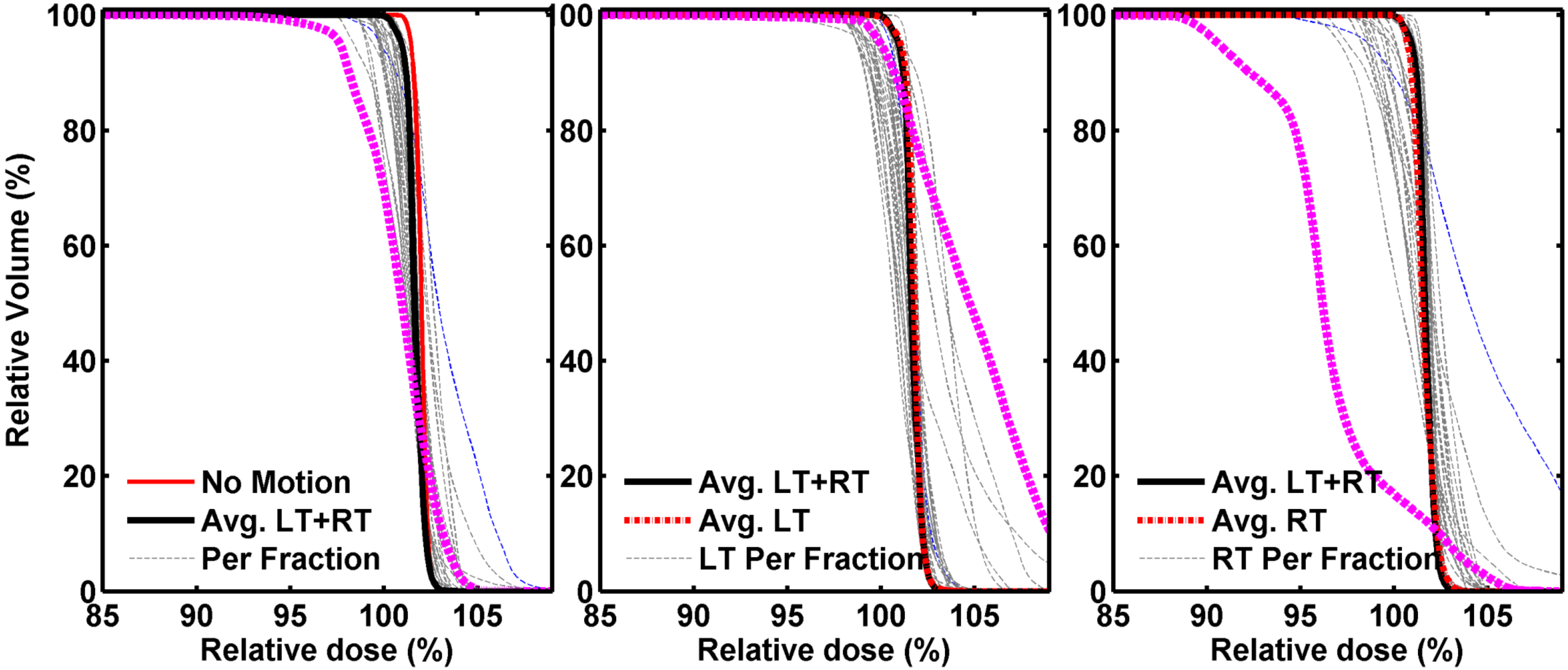
DVH of SFUD Plan



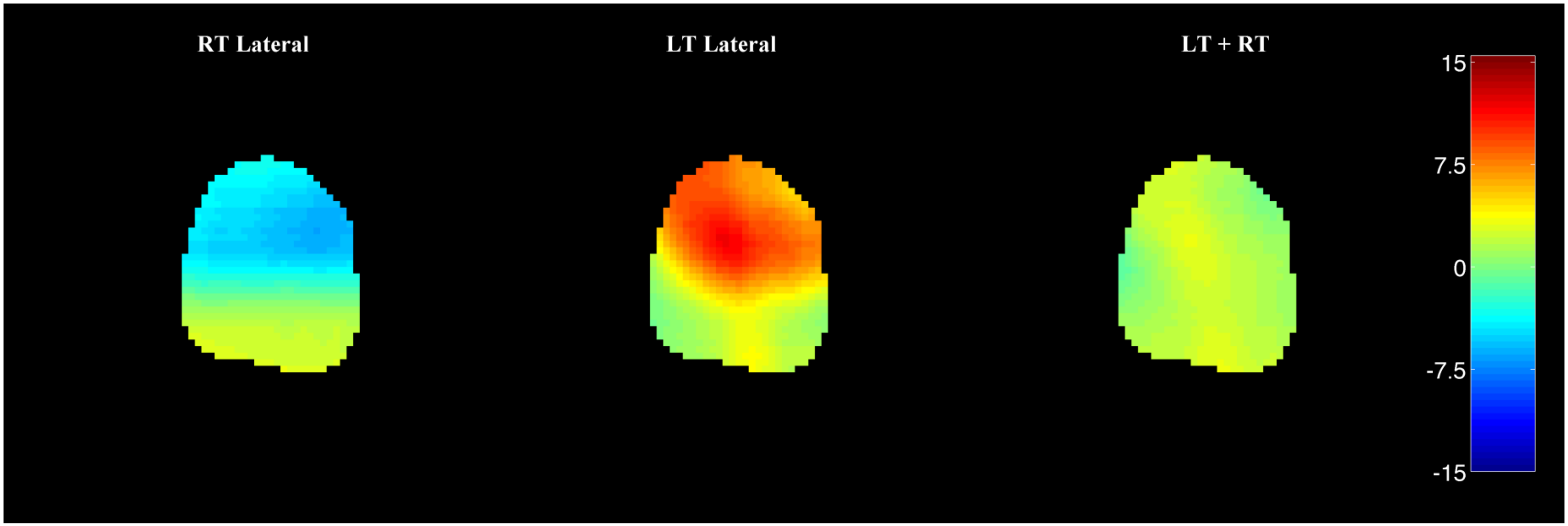
Prostate Drifting and Beam on Time



DVH of SFUD Plan

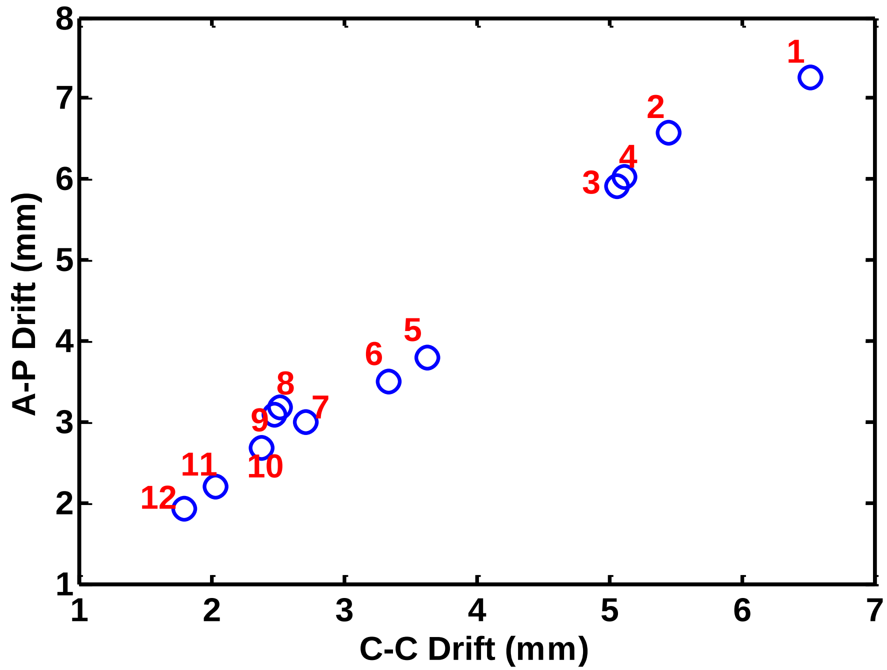


Interplay Effect on Dose Distribution

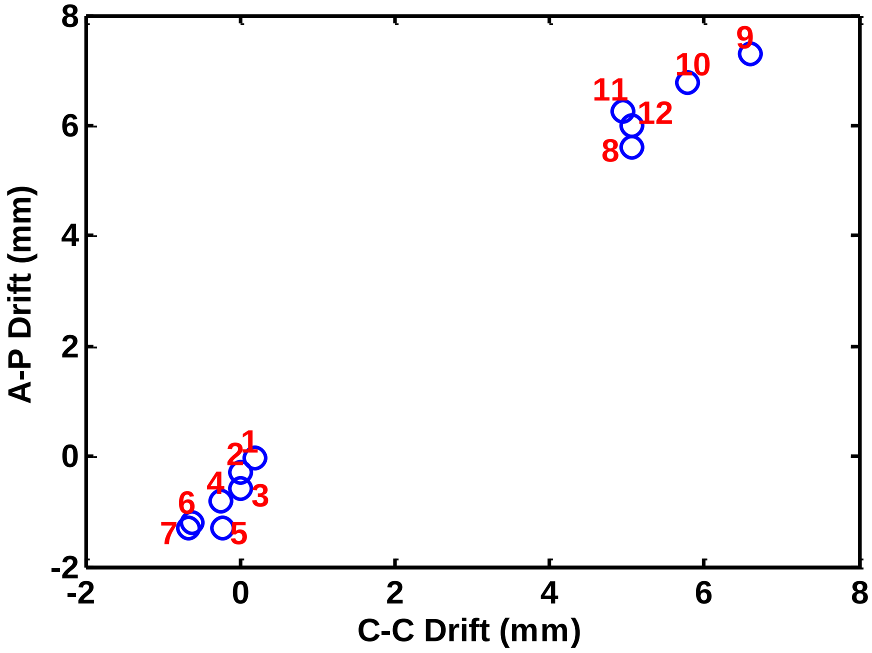


The Worst Fraction

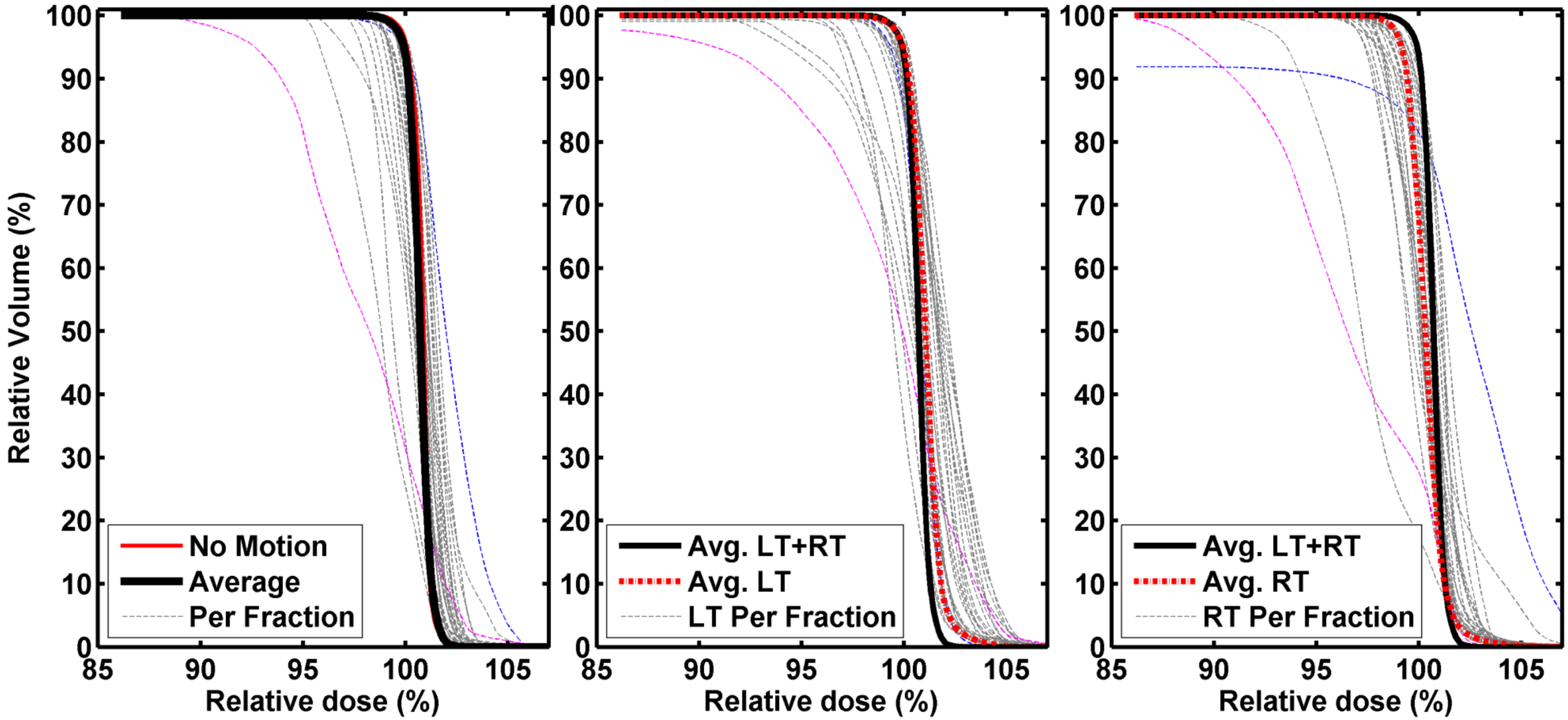
During Right Lateral Beam Delivery



During Left Lateral Beam Delivery



DVH of IMPT Plan



Summary

- Automated processes may improve proton therapy
- MLC may be implemented for PBS and PS in TPS
- PBS spot size may be preserved minimizing the air gap and the quantity of material in the beam
- Motion effects may be addressed by quick delivery, rescanning, organ motion management, etc.

Acknowledgments

Zelig Tochner

Neha Vapiwala

Paul James

Maura Kirk

Shikui Tang

Christopher Ainsley

Liyong Lin

James McDonough

Richard Maughan

Thank you.