Dosimetric Issues Associated with Scanned Proton Beams

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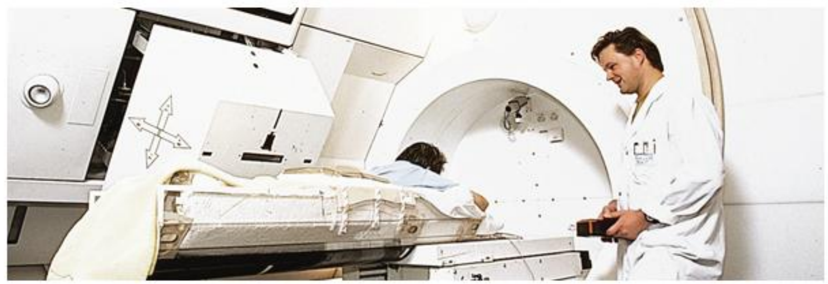
The Future of Proton Therapy

- The future of proton therapy will be scanned proton beams. There are many different types of scanned beams.
- Proton therapy is expensive, perhaps a factor of 25 greater than photon therapy.
- Proton therapy is less tolerant to the uncertainties of treatment than photon therapy.
- Photon therapy keeps improving, with IMRT including VMAT, SBRT and IGRT.
- IMPT should be better than IMXT in terms of overall dose to the non-target volumes of the patient.

Paul Scherrer Institute in Villigen, Switzerland 1984

Protontherapy



Proton therapy at PSI

The aim of radiation therapy at the Paul Scherrer Institute (PSI) is to use charged particles, known as protons, to destroy tumour tissue. Protons are especially suited for this purpose because they exert their greatest effect deep within the body, inside the tumour itself. The PSI has developed a unique radiation technique able to adapt the radiation dose extremely accurately to the shape of the tumor, which is usually irregular, thus protecting healthy tissue much better than with the most modern conventional radiation therapy techniques.

Current research at PSI aims at improving this radiation technique even more in order to be able to extend the treatment to movable tumors (e.g. breast and lung cancers) with high precision.

Suitable only for specific tumours

Proton therapy is used for the treatment of very specific tumors for which clinical studies can prove a substantial medical advantage.

PSI Gantry 2
Scanning Options

- 1. Basic discrete spot scanning – a step and shoot method
- 2. Intensity Modulated Scanning – continuously moving beam over a fixed pattern while intensity is changed
- 3. Intensity Modulated “Contoured-lines” scanning – an inward pattern along the BEV of the target.
- 4. Fast wobbling to simulate a scattered beam

Beam Delivery Nozzles (IBA)

- Single scatter: small fields
- Double scatter: large fields
- Uniform scanning: beam spot is moved by magnetic scanning and allows several mini-irradiations. Full modulation (non-rotating RMW), field uniformity, apertures.
- Pencil beam scanning: slice by slice irradiation of the target with millimeter precision (energy change upstream degrader). Primary advantages include: multiple fast repainting no use of aperture, no compensator devices, dose uniformity, IMPT and gating.
- Universal nozzle and dedicated pencil beam nozzle.

Varian Proton Product

- The ProBeam system incorporates Dynamic Peak integrated scanning technology, which paints a precise radiation dose on the target volume, enabling true intensity-modulated proton therapy. The system also incorporates proprietary pencil-beam scanning technology, which allows for precise dose distribution

Still River ProTom
Both Scanning Systems Soon

The Monarch250™ PBRT System

The implementation cost of current proton beam radiotherapy (PBRT) designs is $100 million and up which has limited the deployment of this Medicare-approved treatment modality to a handful of large institutions. In fact, only about twenty proton therapy centers have opened around the world.

Still River Systems is designing the Monarch^{250}™ PBRT System, a practical, cost-efficient, single-room PBRT system scaled for use at most cancer centers. Using state of the art engineering techniques and materials, the heart of the Monarch^{250} System will be a compact, superconducting high field magnet which directs a proton beam toward a precisely defined isocenter.

Included in the Monarch^{250} PBRT System will be a cyclotron, the proton beam delivery system, a treatment couch with pendant control, a radiographic patient positioning system, proton beam treatment planning, and a link to a treatment record and verify system.

"Proton beam radiation therapy is widely regarded as the optimal radiation treatment for a wide variety of cancers."

Ernest A. Bates, M.D., Chairman & CEO, ASHS.

The Radiance 330™

Advanced Treatment Delivery Tools

ProTom's system, the ***Radiance 330***™, offers next-generation proton therapy. It provides the most advanced delivery capabilities (proton beam scanning) in a small-footprint solution, providing superior treatment precision and enhancing patient throughput at substantially reduced capital and operating costs. The ***Radiance 330*** enables next-generation IMPT delivery techniques and is fully integrated with all necessary hardware and software components, with a variety of configuration options tailored to each site's specific requirements and clinical objectives.

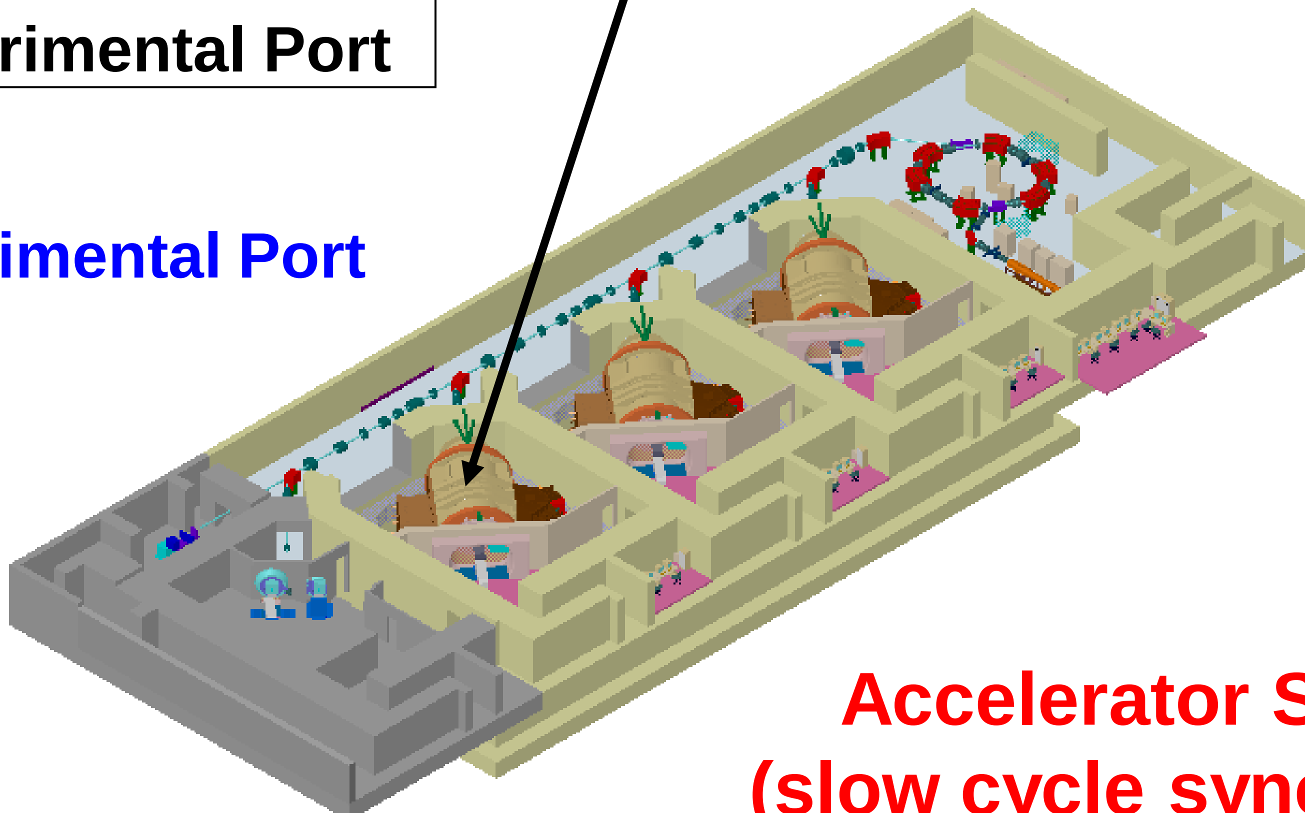
Proton Therapy Center - Houston

<u>PTC-H</u>
3 Rotating Gantries
1 Fixed Port
1 Eye Port
1 Experimental Port

Pencil Beam Scanning Port

Passive Scattering Port

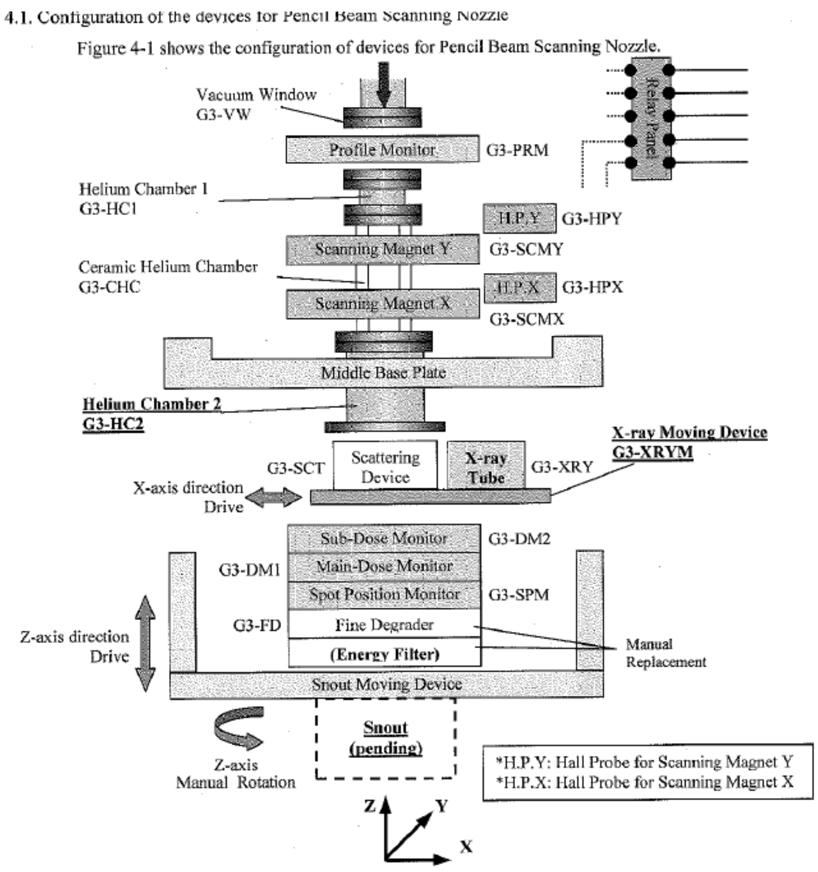
Experimental Port

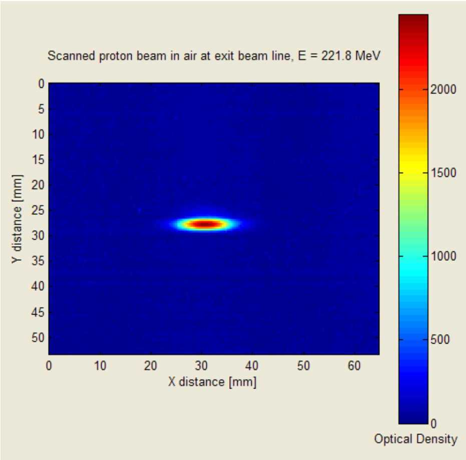


Accelerator System (slow cycle synchrotron)

Large Fixed Port **Eye Port**

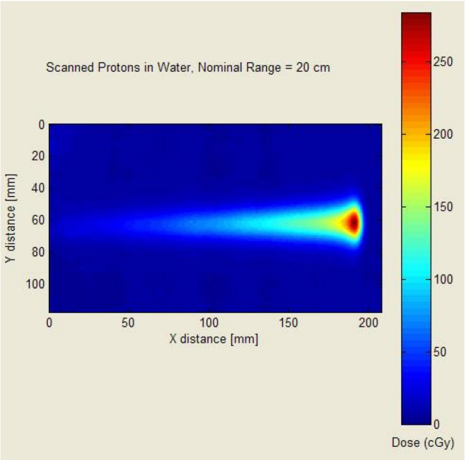
Spot Scanning
The Spot





Spot in air at nozzle entrance

BEV



Spot in water, range 20 cm

Side

View

Discrete Spot Scanning: Current Status

- 94 energies in clinical use with ranges from 4.0 cm to 30.6 cm
- Field sizes from 4 cm x 4 cm and greater
- 2+ years. 300 + patients A constraint is the Physics QA time of 1.25 hours/patient.
- Single field optimization (SFO) used for all patients.
- 38 out of 120 patients are being treated with the scanning beam in mid-October, 2010.
- As of March, 2010, TPS is Eclipse, V. 8.9, which has a double Gaussian in air spot model.
- Eclipse V 8.1, was the previous version (2008 to 2010). It uses a single Gaussian. MDACC in 2009 rejected V 8.2, 8.5, 8.6, and 8.8.

SFO vs. MFO IMPT

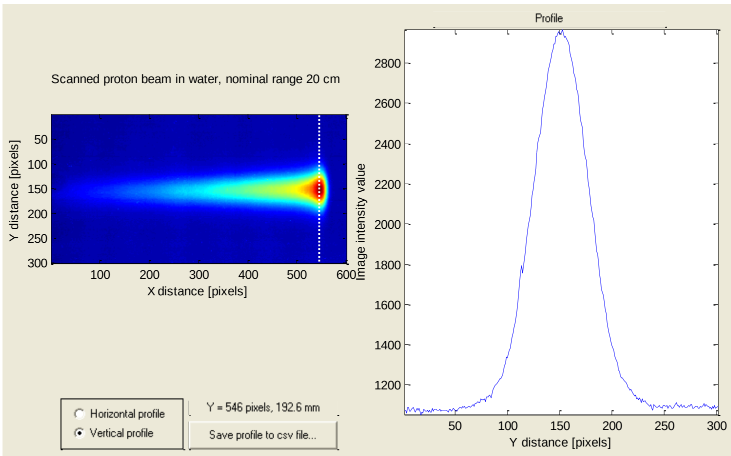
SFO

- “Open Field” for “simple” volume
- ‘Uniform’ dose distribution – boosts can be built in.
- Less sensitive to uncertainties
- Should use SFO plan if MFO plan is not significantly better

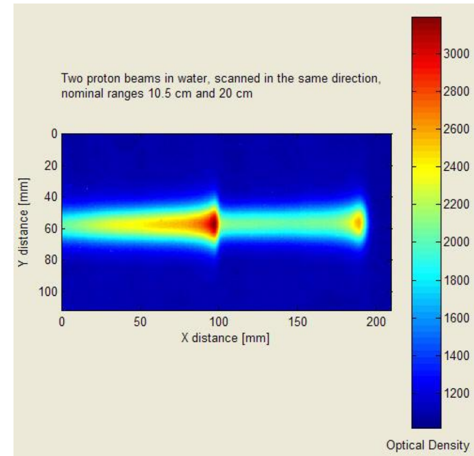
MFO

- “Patch Field” for complex volume
- More versatile to get a good plan
- More sensitive to uncertainties
- Robustness of MFO is important
- Currently we beginning to treat selected patients with MFO

Spot Scanning: Creating a 3D dose distribution by combining spot location, weight, and energies



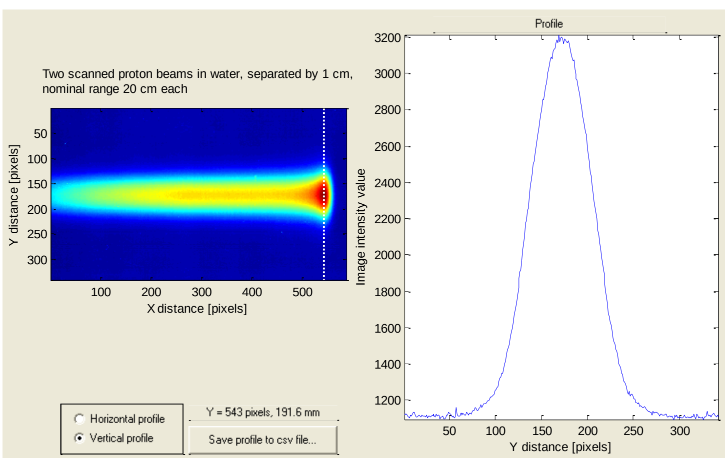
Single spot

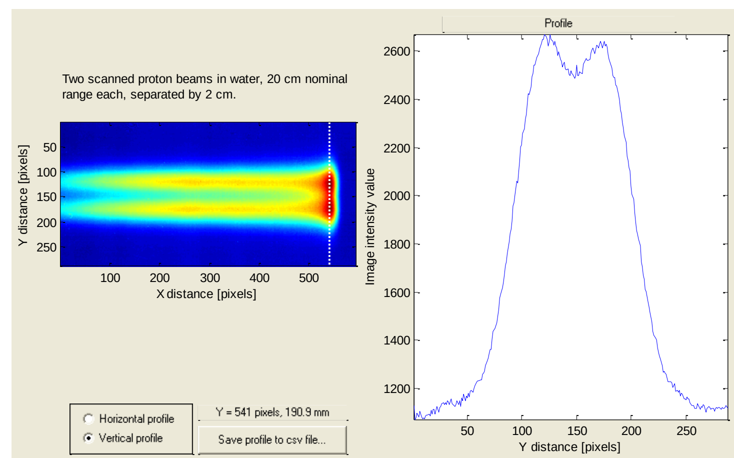


Two spots

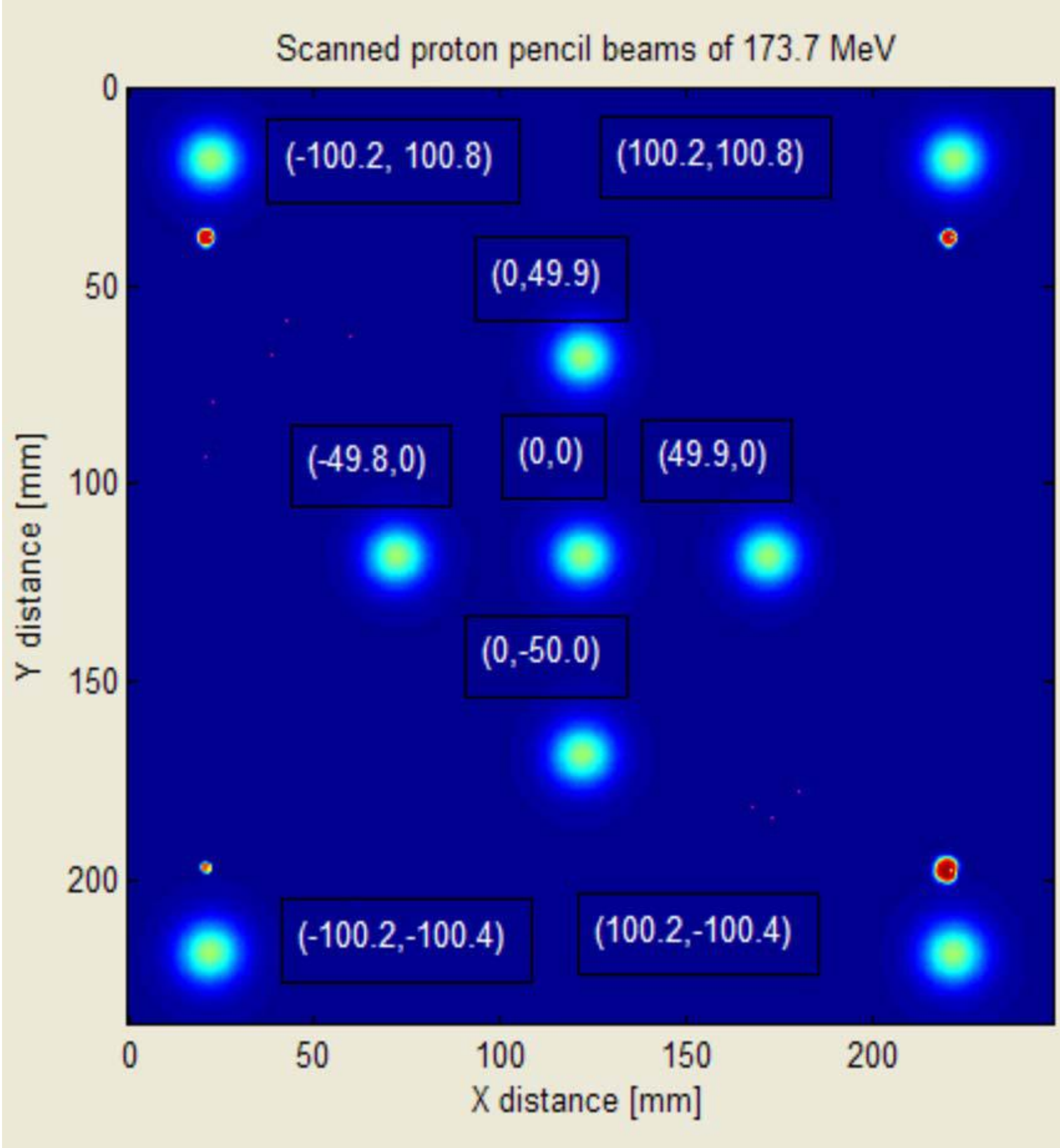
Different

Energies





Two spots separated by 1 cm and two spots separated by 2 cm.



Scanned proton pencil beams of 173.7 MeV
(-100.2, 100.8)
(100.2,100.8)
(0,49.9)
(-49.8,0)
(0,0)
(49.9,0)
(0,-50.0)
(-100.2,-100.4)
(100.2,-100.4)
Y distance [mm]
X distance [mm]
0
50
100
150
200

Calibration of Dose Monitor

- A MU is defined at the center of a 1 liter volume which is receiving a uniform dose,
  - Max range: 30.6 cm; Max Energy: 221.8 MeV
  - Min range: 21.0 cm; Min Energy: 178.6 MeV
  - Total 18 energies (18 layers)
  - Spot spacing: 8mm
  - Total spots: 6760
  - Total MU: 217.13
  - Dose at the isocenter: 217.13 cGy at the center of the volume

Scanning Beam: What does a MU mean?

Definition of charge per MU

The interaction of the protons with the air in the monitor chamber results in the production of ionic charges, which are collected by the chamber. For the scanning nozzle, after 2 10^{-12} C 2 pC have been collected, a count is created by an analog to digital converter in the main dose monitor. The precision of this converter is 1%. The system has been designed such that approximately 10 000 counts are set to be equal to one MU.

MU: An Arbitrary Tracking Method

- A single MU merely represents a certain amount of charge collected by the main dose monitor; its relation to dose distribution depends on the energies and locations of spots.
- The amount of charge in the main dose monitor, in terms of the number of counts defining a MU, was arbitrarily defined by using the reference conditions for the International Atomic Energy Agency IAEA TRS 398 protocol.

Independent Review of Calibration

- RPC TLD Report for G3, the scanned beam line.
- Generally, an ion chamber check of the output is performed before the TLD is irradiated.

RESULTS OF TLD CHECK OF PROTON BEAM

v8.0.2

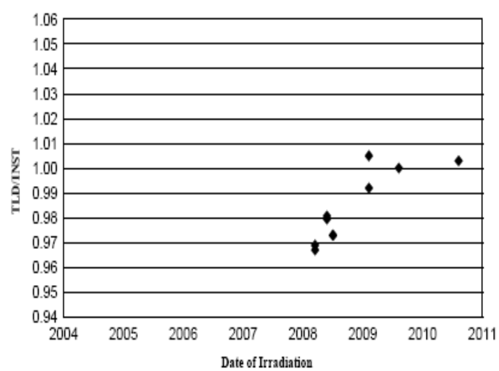
Institution:	M D Anderson Proton Center, Houston, TX
RTF Number:	3419
Person irradiating dosimeters:	Michael T. Gillin, Ph.D.
Radiation Machine:	Hitachi Proton (G3)
Distance from source to reference point:	267.0 cm

OUTPUT VERIFICATION:

Proton Energy	Date of Irradiation	Dose determined by RPC:*	Dose determined by institution:*	**Ratio of absorbed dose determined by RPC to that stated by institution: TLD/INST**
221 MeV	07/17/2010	218 cGy to water	217 cGy to water	1.00

Agreement within 5% is considered a satisfactory check. Dose prescription by cooperative trials is absorbed dose to muscle.

TLD RESULT HISTORY FOR THIS MACHINE



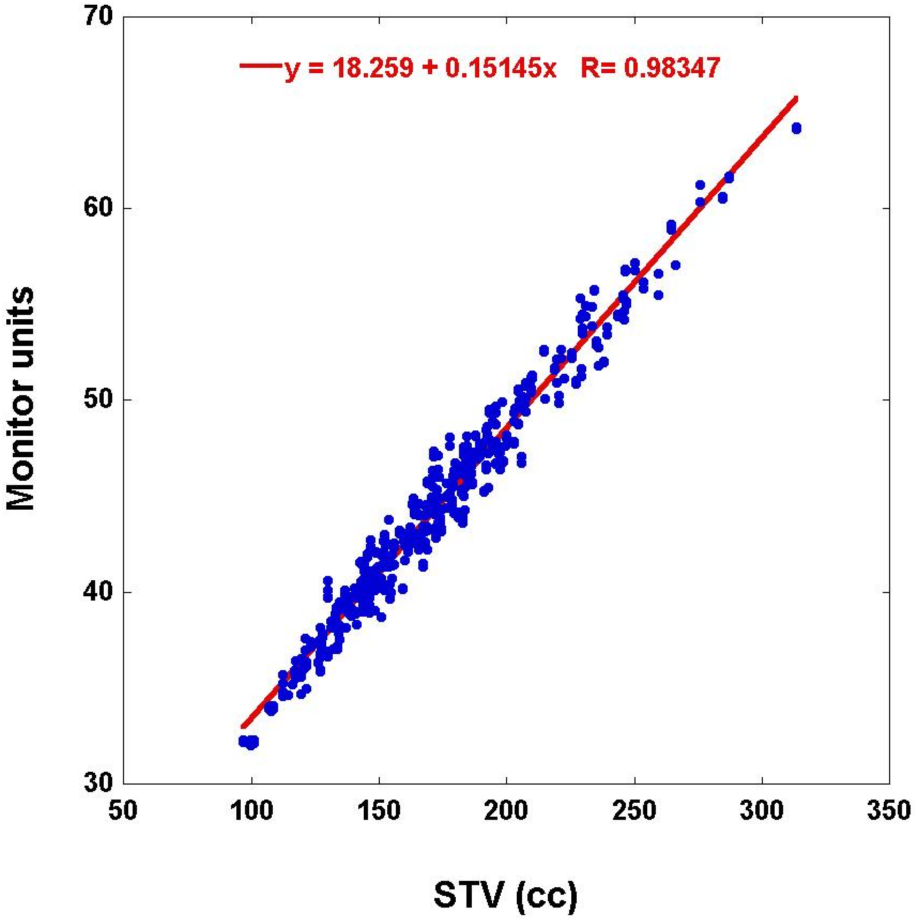
THIS INFORMATION SHOULD BE USED ONLY AS A CHECK OF MACHINE OPERATION AND NOT AS A MACHINE CALIBRATION, nor as an alternative to frequent calibration by a qualified physicist.

The TLD dose was evaluated using the AAPM TG-51 Dosimetry Calibration Protocol.

TLD read on:	04-Aug-2010
TLD read by:	Anju Tailor
Checked by:	Francisco Aguirre, M.S.

*The variance of the dose determined by a single TLD is less than 3%. The three TLD sample, therefore, has an uncertainty of 5% at a confidence level in excess of 90%. This analysis did not include uncertainties in the institutions' irradiation technique.

Geoffrey S. Ibbott
Director



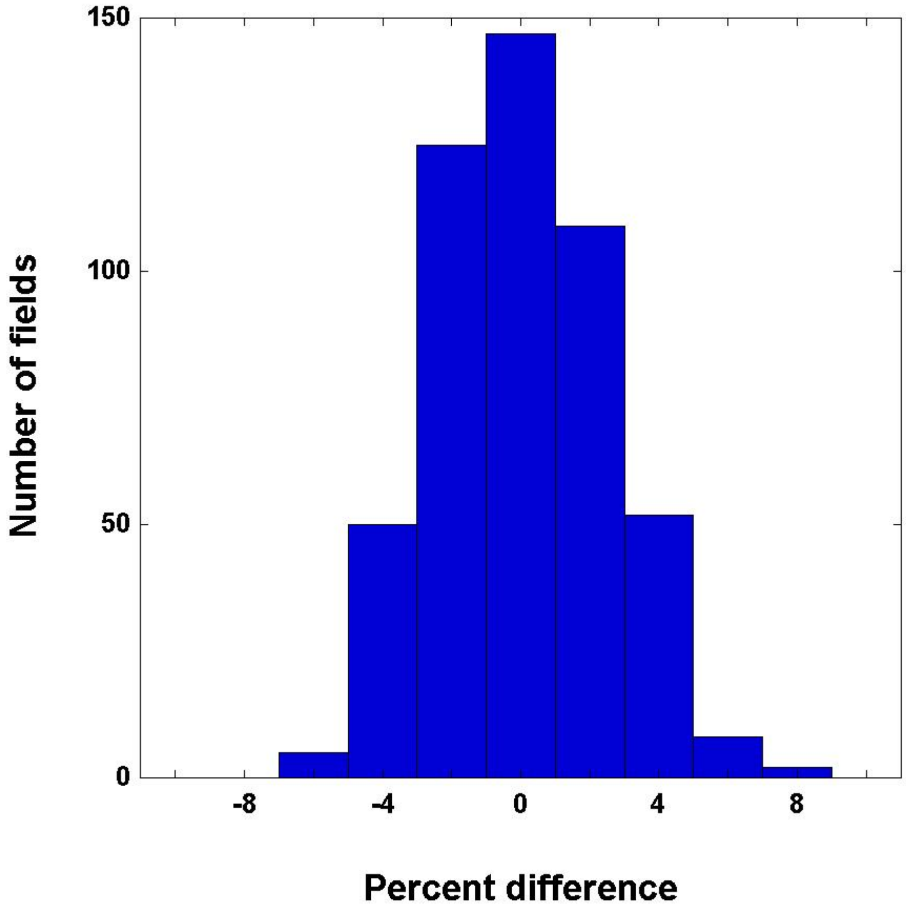
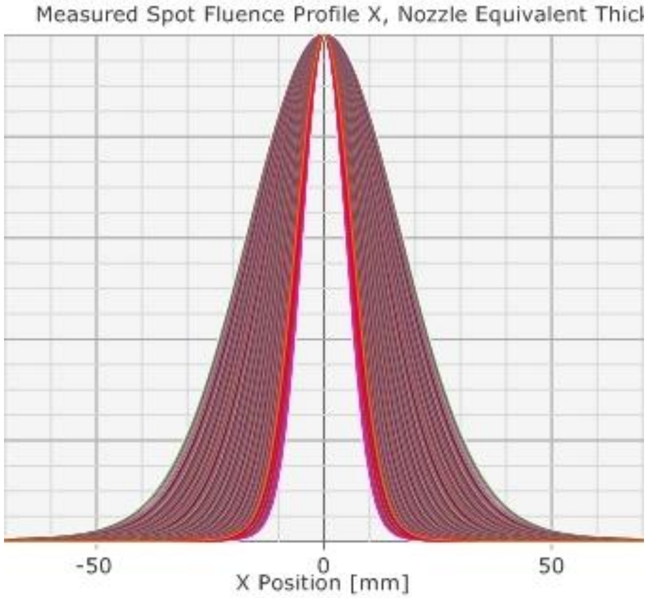


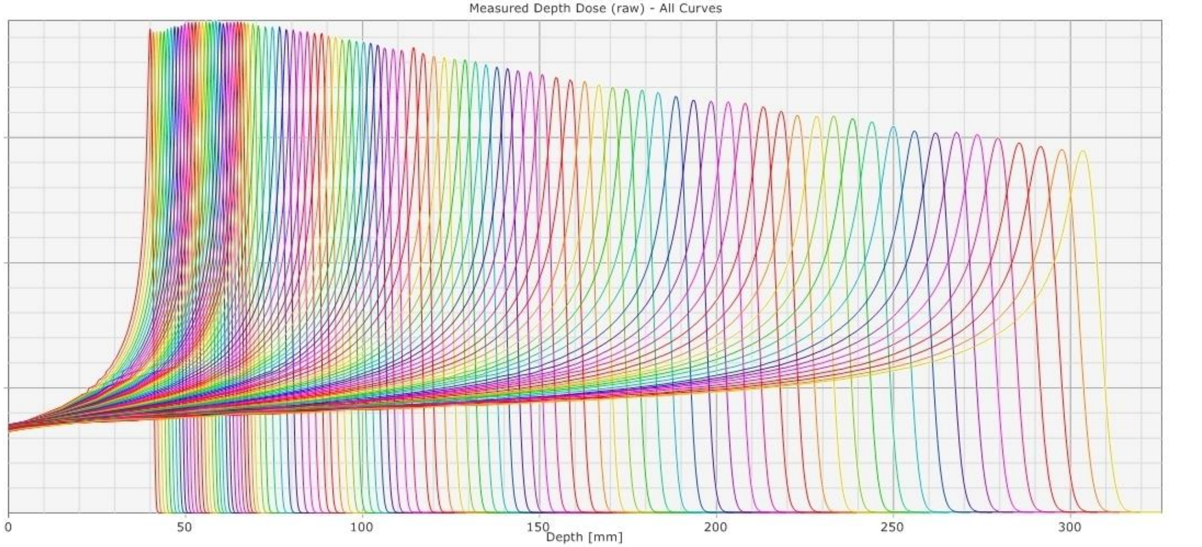
Fig. 3 (A) Monitor units vs. STV for 249 patients. Red line is the linear fit to the data.
(B) Histogram for the differences from the linear fit

There is a strong correlation between volume and MU's for the G3 prostate patients.

Monte Carlo

- Monte Carlo simulated data (Uwe Titt, Ph.D.) are used as input data for the planning system
  - Validated with limited number of energies
  - Integrated depth doses are in MeV/cm^3 and need to be converted to $(Gy/MU)mm^2$



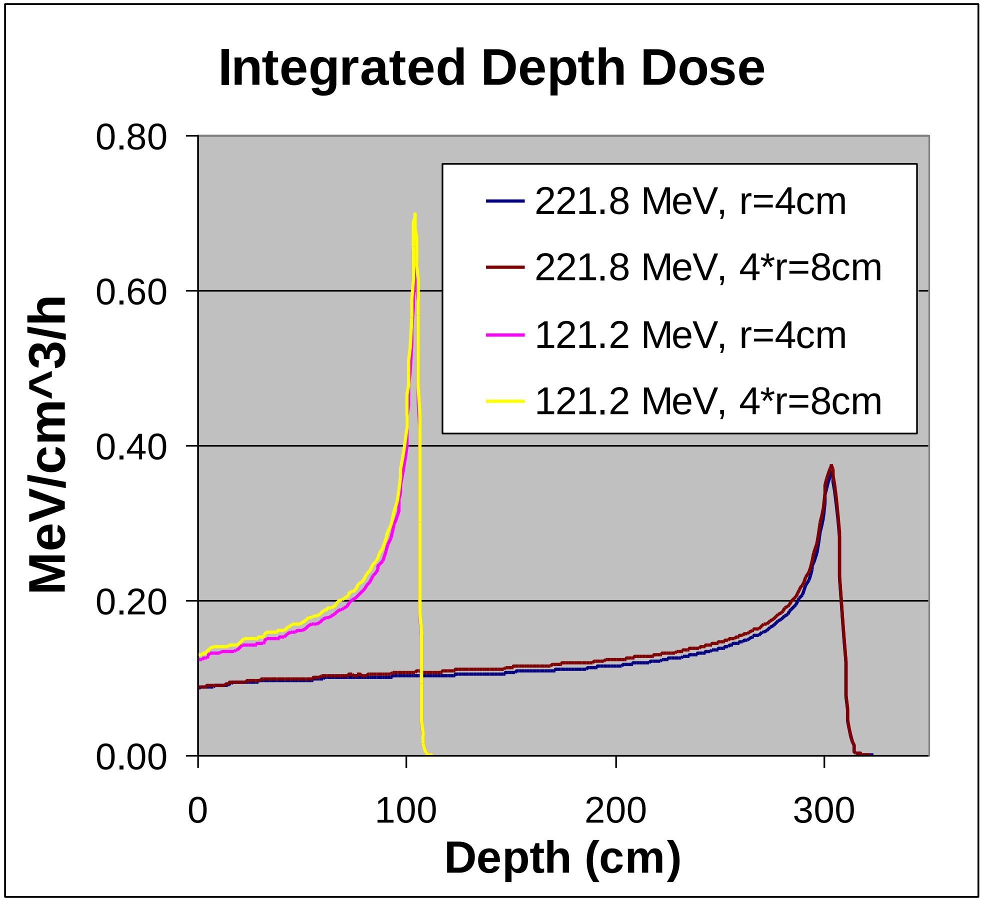


Basic Information about Bragg Peak Chamber

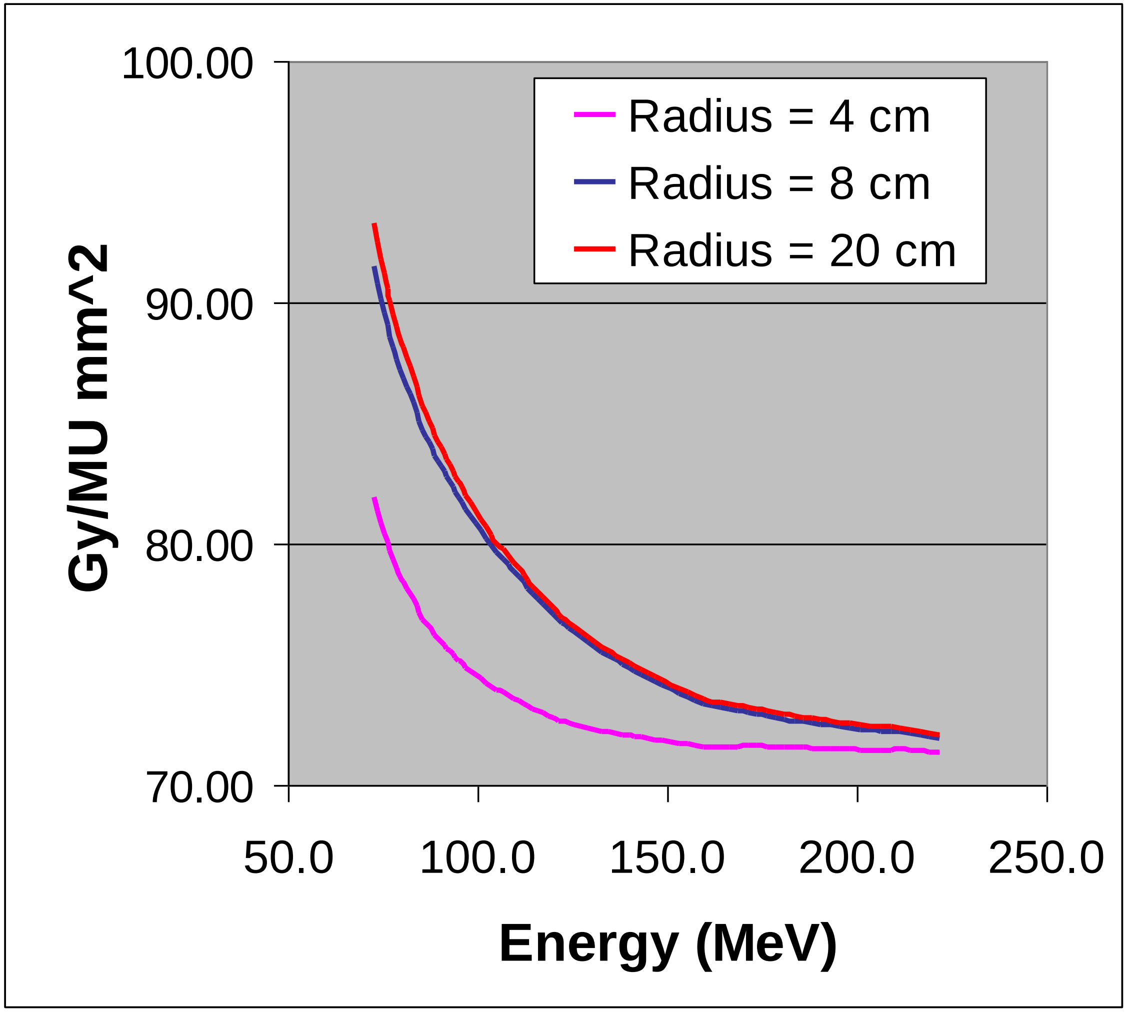
- Nominal sensitive volume: 10.5 cm^3.
- Sensitive volume: r = 42 mm, t = 2 mm.
- Nominal response: 325 nC/Gy.
- Reference point 3.5 mm front chamber surface.
- Entrance window: 3.47 mm PMMA.
- WET window: 4 mm.
- $N_{D,W}k_p = (3.181 \pm 0.023) \times 10^6$ Gy/C
  - Average 3 inter-comparison

Bragg Peak Chamber Large Enough?

- Monte Carlo integrated depth doses for all energies are available for detector radius of 4, 8 and 20 cm:
  - Differences between 4 and 8 cm results

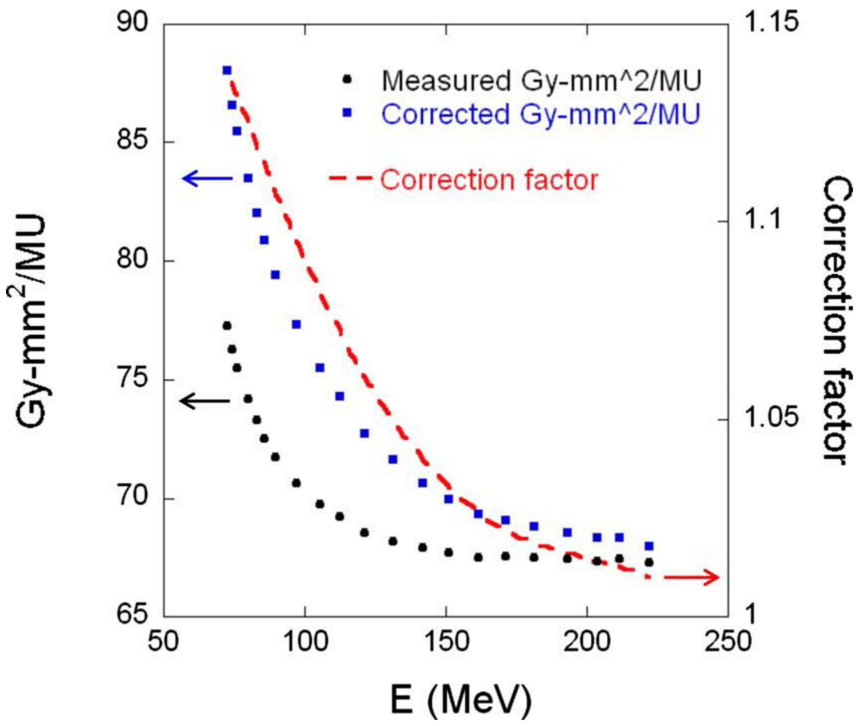


(Gy/MU)mm^2 at 2.0 cm

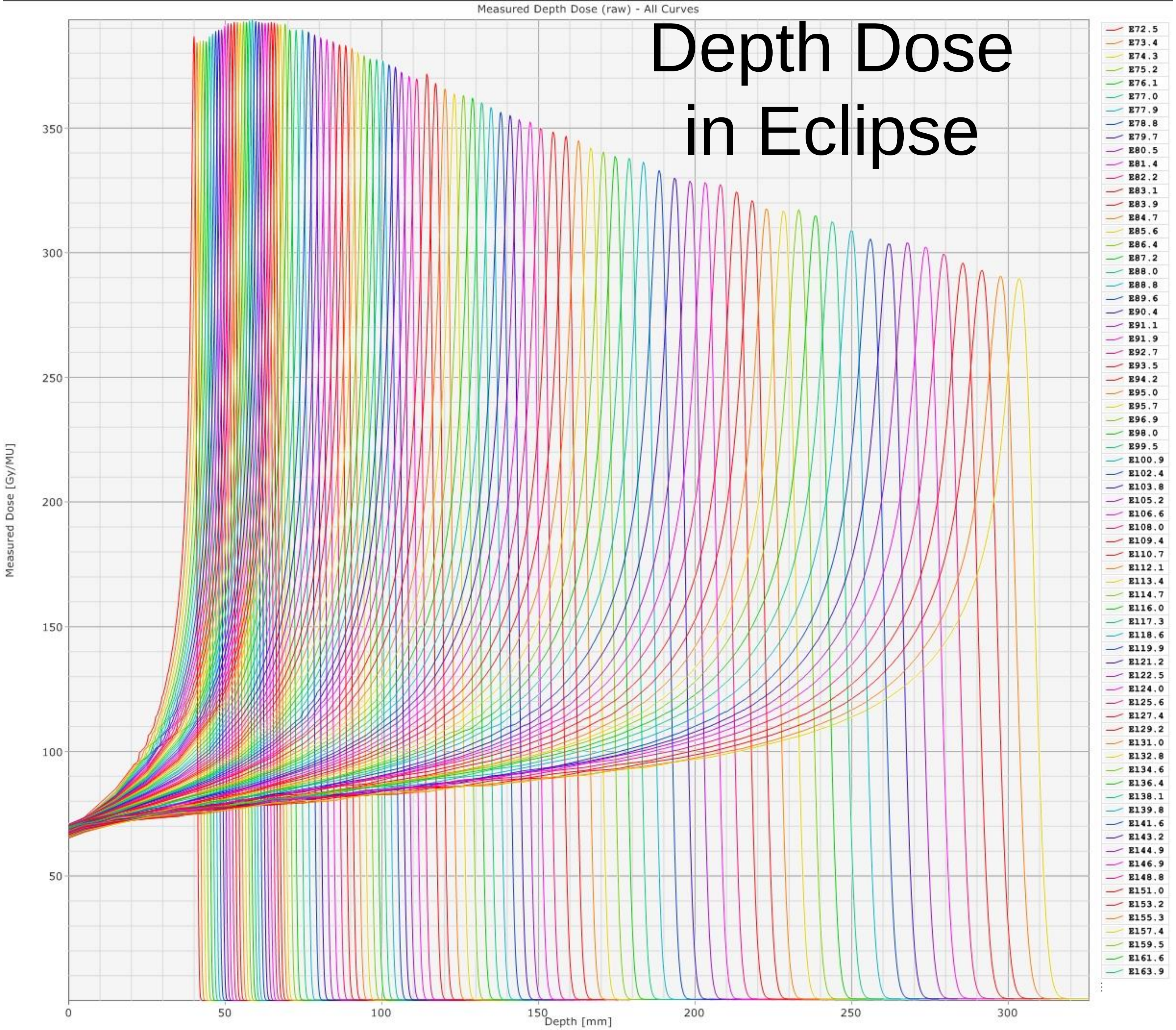


The normalization challenge to define the dose as the energy changes.

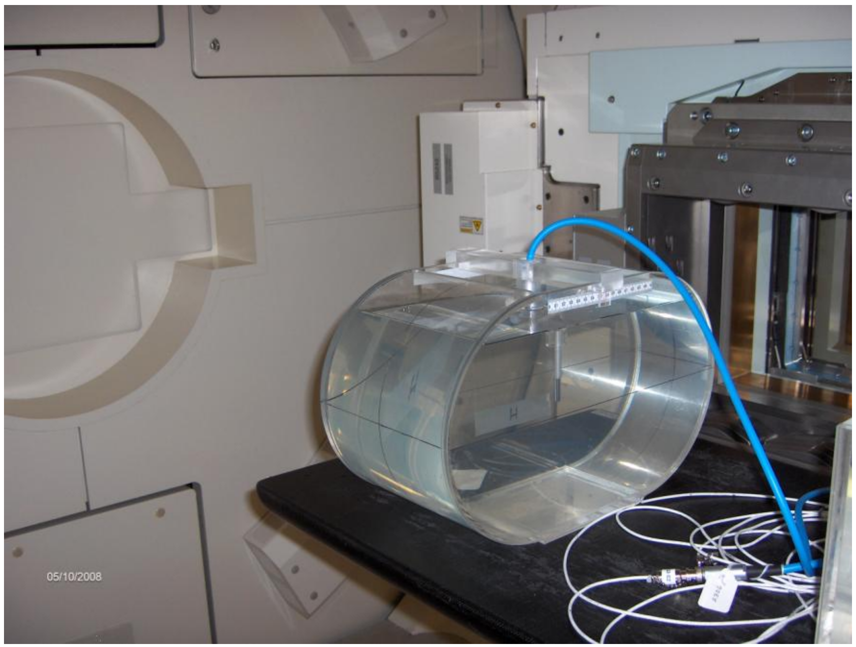
- Integral doses in Gy mm^2 /MU at the depth of 2 cm as a function of energy. Circles are measured integral doses; squares are corrected integral doses; and dashed line is the correction factors.

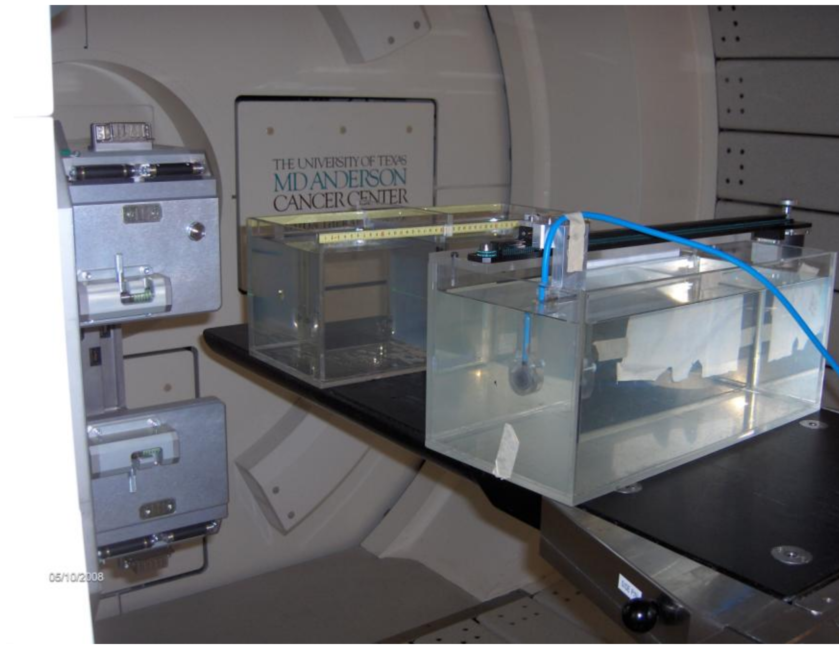


Depth Dose in Eclipse



Scanning Beam
Patient Specific QA



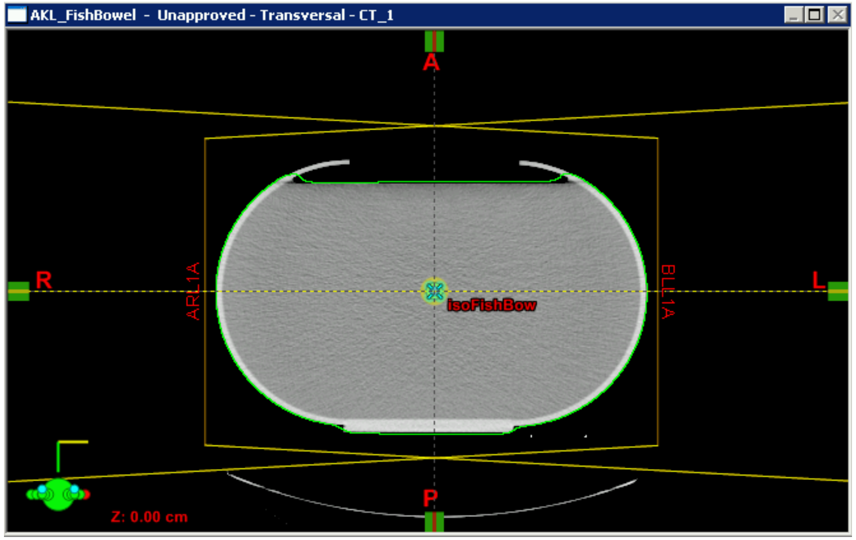


"Fish Bowl" Phantom

2 Identical phantoms: Ion chamber (right) and EBT film (left)

Absolute Dose Measurement in "Fish Bowl" Phantom

- Phantom filled with water was imaged.
- Verification plan was created in Eclipse
- A ion chamber was used to determine the absolute dose at gantry angle 270 and 90 degrees.

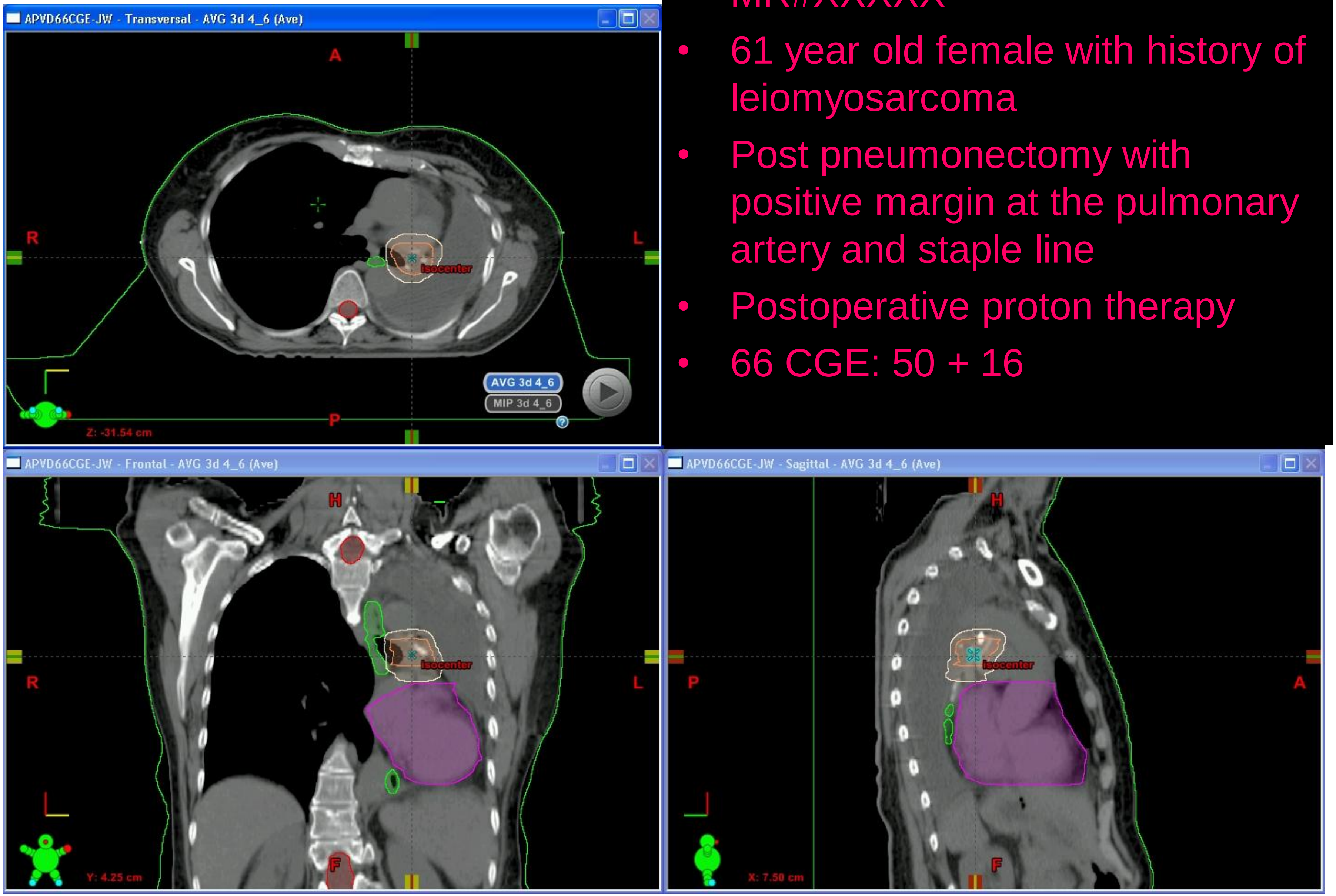


Dose is measured at the gantry angle used for treatment.

Current Patient Specific QA

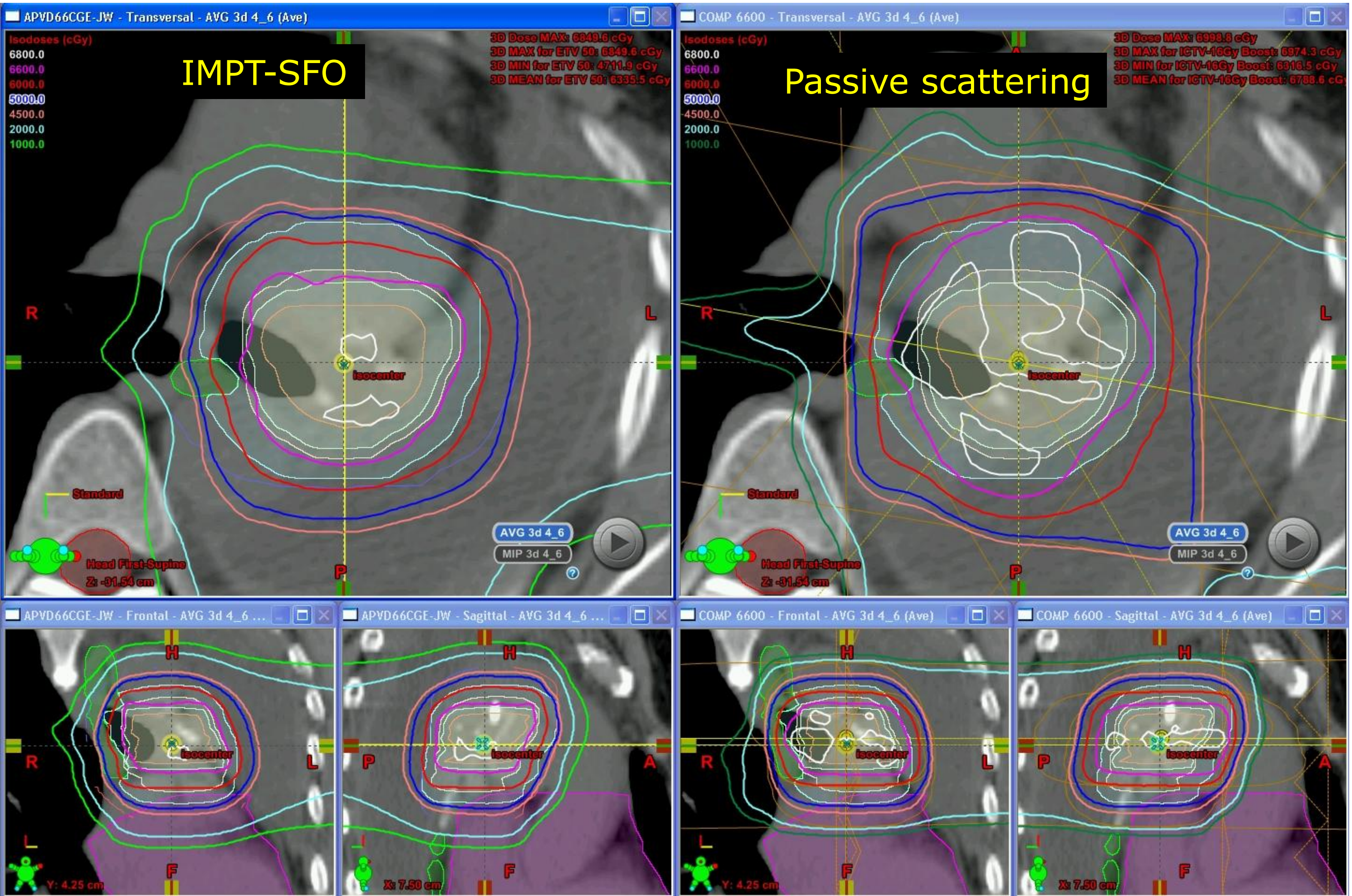
- Confirmation of MUs in “Fish Bowl” phantom
- Central Axis depth dose in a rectangular water phantom using a Markus chamber
- Previously EBT films at 2 different depths for each field in a water phantom. Now the Matrixx, a 2D ion chamber array is used instead of film.
- Total time per patient: 1 to 1.5 hours for each patient as three separate phantoms are used. Eventually we will decrease the measurements made for SFO plans.

Case 1



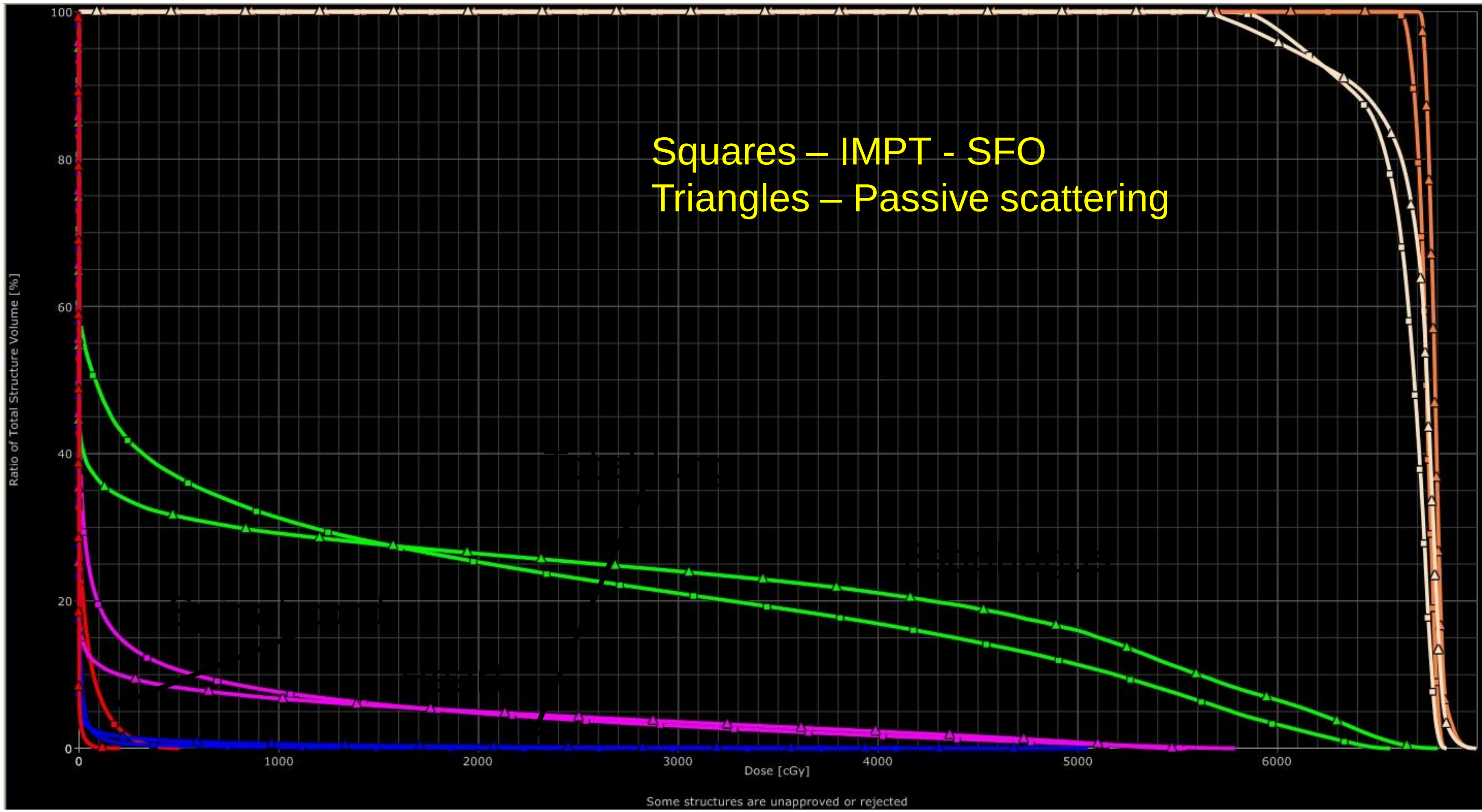
- MR#XXXXX
- 61 year old female with history of leiomyosarcoma
- Post pneumonectomy with positive margin at the pulmonary artery and staple line
- Postoperative proton therapy
- 66 CGE: 50 + 16

Case 1

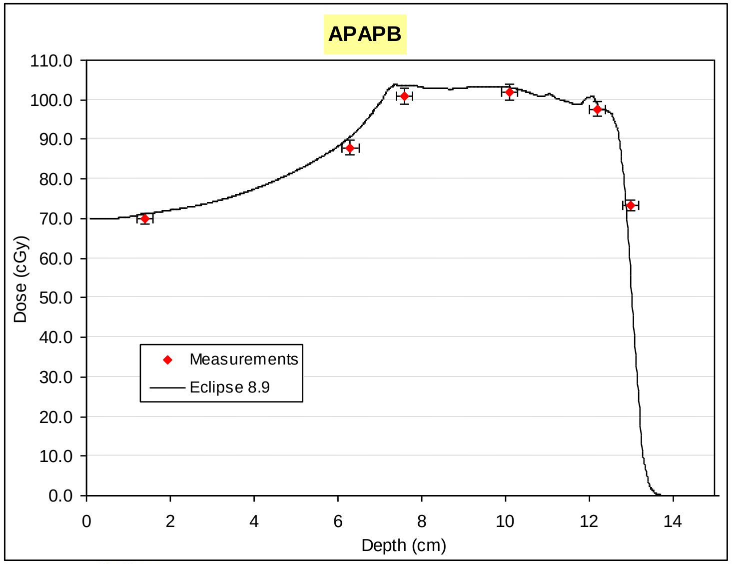


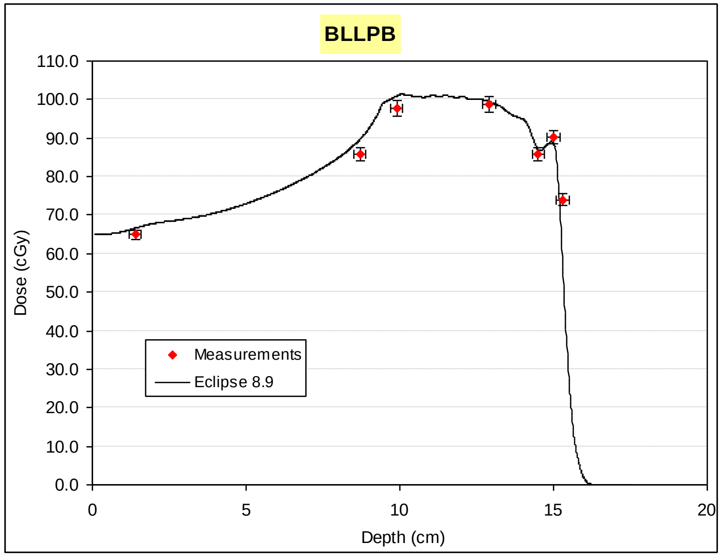
APVD66CGE-JW - Transversal - AVG 3d 4_6 (Ave)
Isodoses (cGy)
6800.0
6600.0
6000.0
5000.0
4500.0
2000.0
1000.0
IMPT-SFO
3D Dose MAX: 6849.6 cGy
3D MAX for ETV 50: 6849.6 cGy
3D MIN for ETV 50: 4711.9 cGy
3D MEAN for ETV 50: 6335.5 cGy
isocenter
Standard
Head First-Supine
Z: -31.54 cm
AVG 3d 4_6
MIP 3d 4_6
COMP 6600 - Transversal - AVG 3d 4_6 (Ave)
Passive scattering
3D Dose MAX: 6998.8 cGy
3D MAX for ICTV-16Gy Boost: 6974.3 cGy
3D MIN for ICTV-16Gy Boost: 6316.5 cGy
3D MEAN for ICTV-16Gy Boost: 6788.6 cGy
APVD66CGE-JW - Frontal - AVG 3d 4_6 ...
APVD66CGE-JW - Sagittal - AVG 3d 4_6 ...
COMP 6600 - Frontal - AVG 3d 4_6 (Ave)
COMP 6600 - Sagittal - AVG 3d 4_6 (Ave)
Y: 4.25 cm
X: 7.50 cm

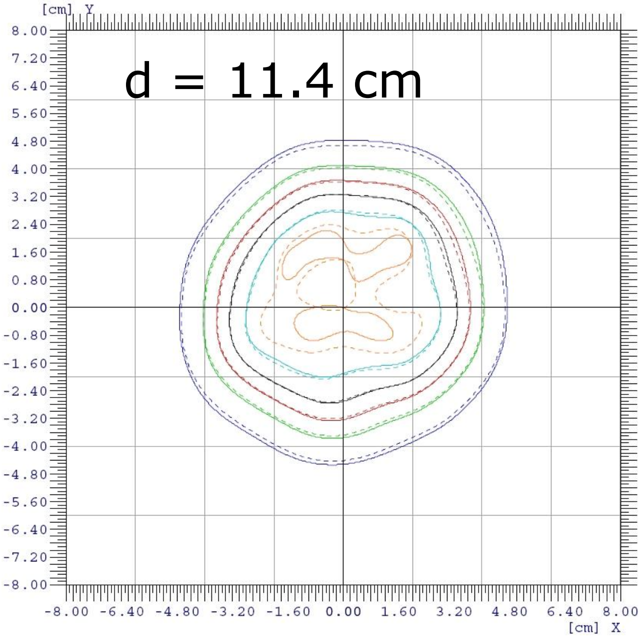
Case 1

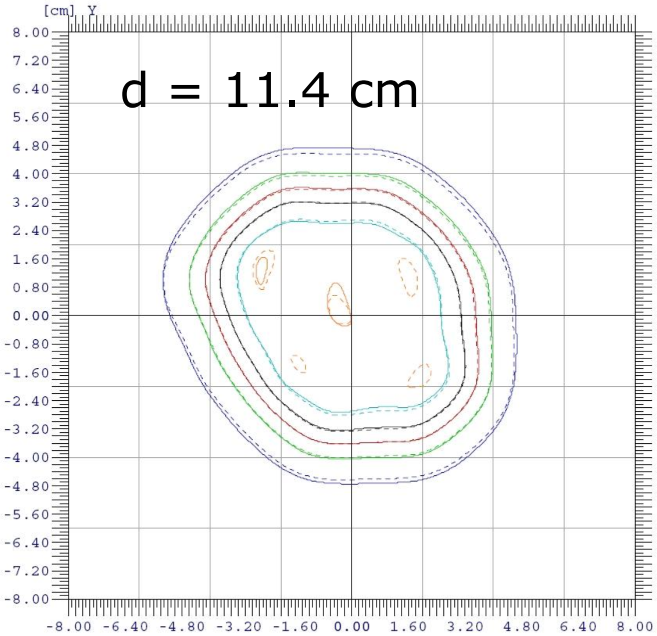

Squares – IMPT - SFO
Triangles – Passive scattering
Ratio of Total Structure Volume [%]
100
80
60
40
20
0
0
1000
2000
3000
4000
5000
6000
Dose [cGy]
Some structures are unapproved or rejected

Case 1 – QA Results - Primary

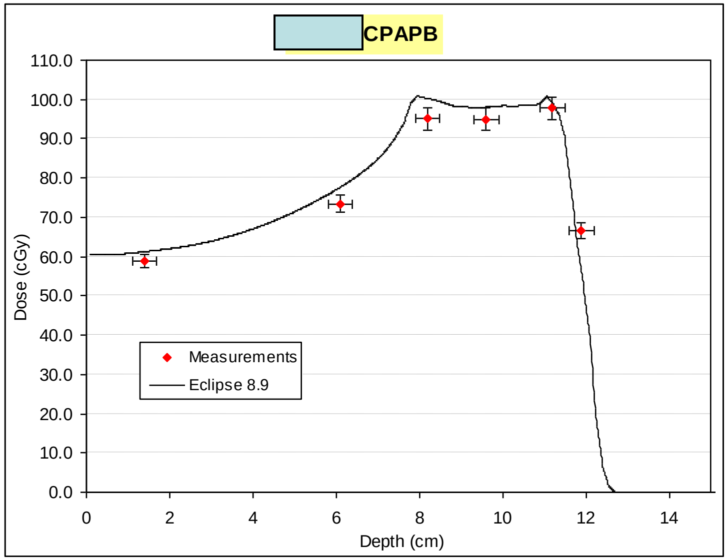


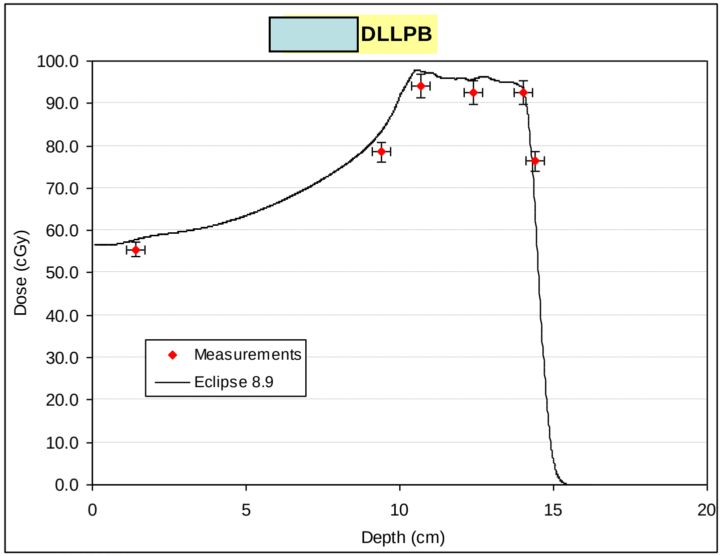


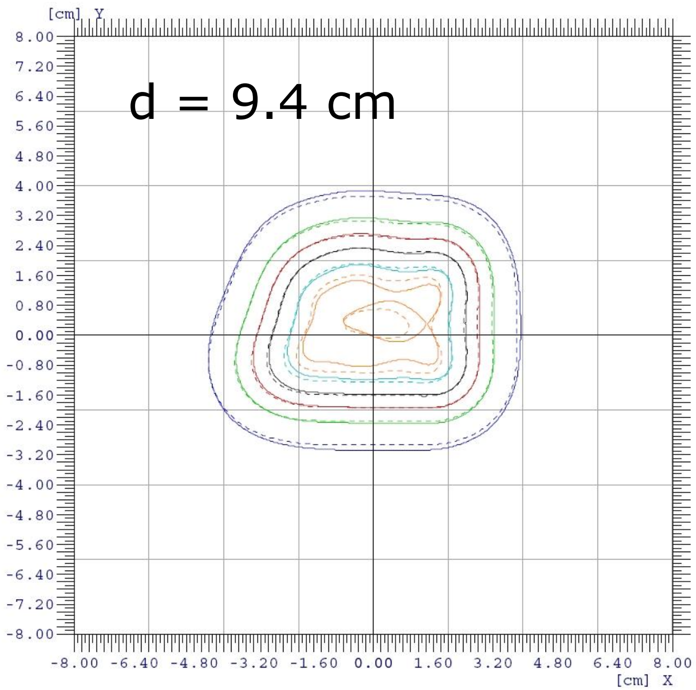


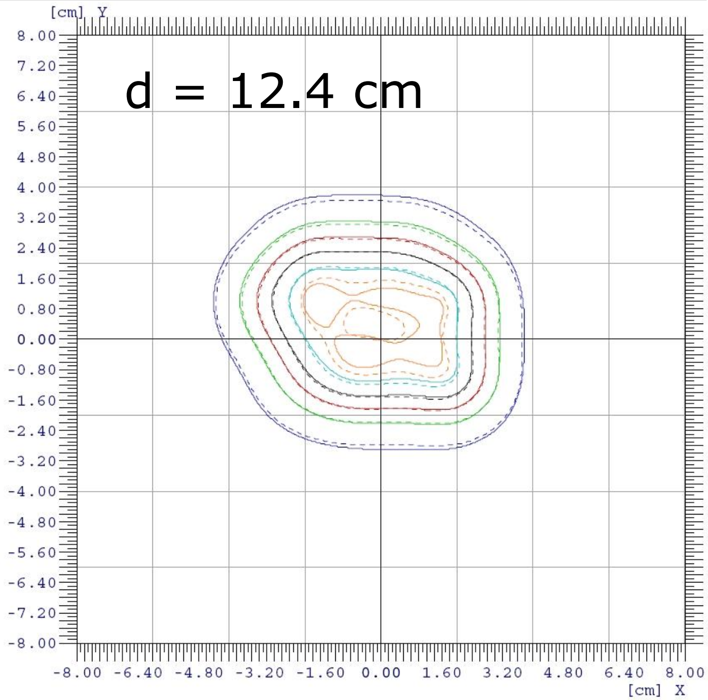


Case 1 – QA Results - Boost

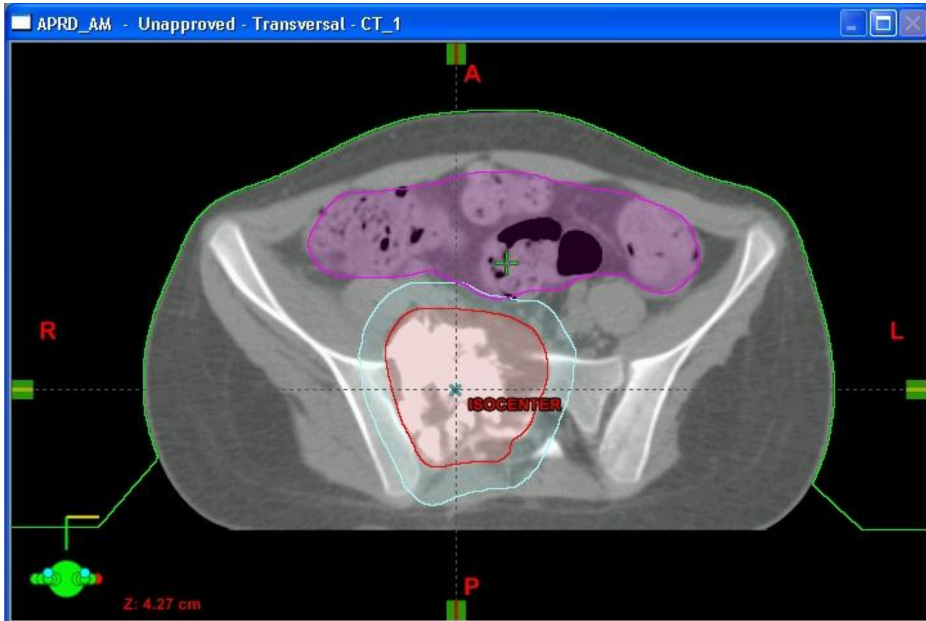






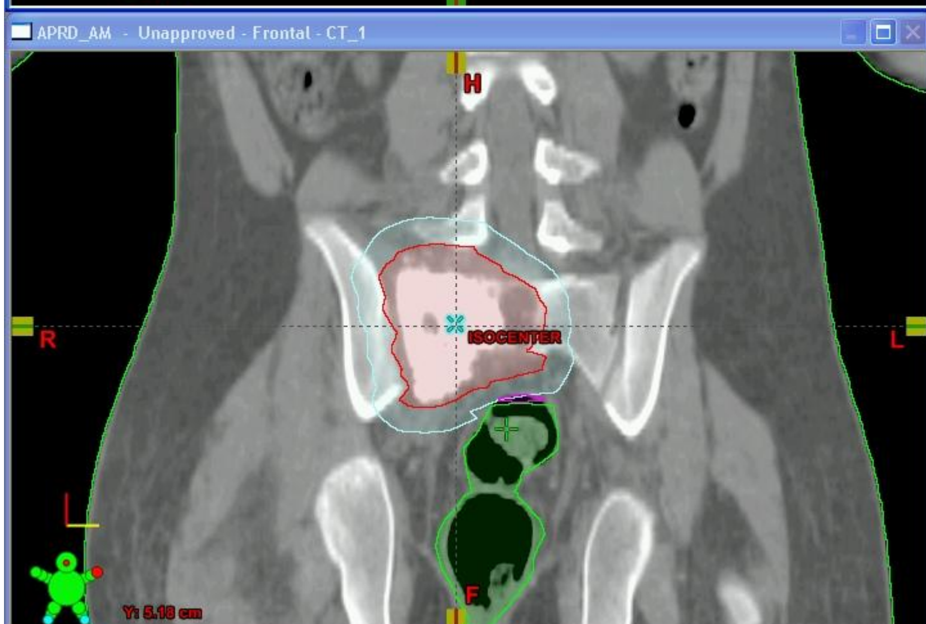


Case 2

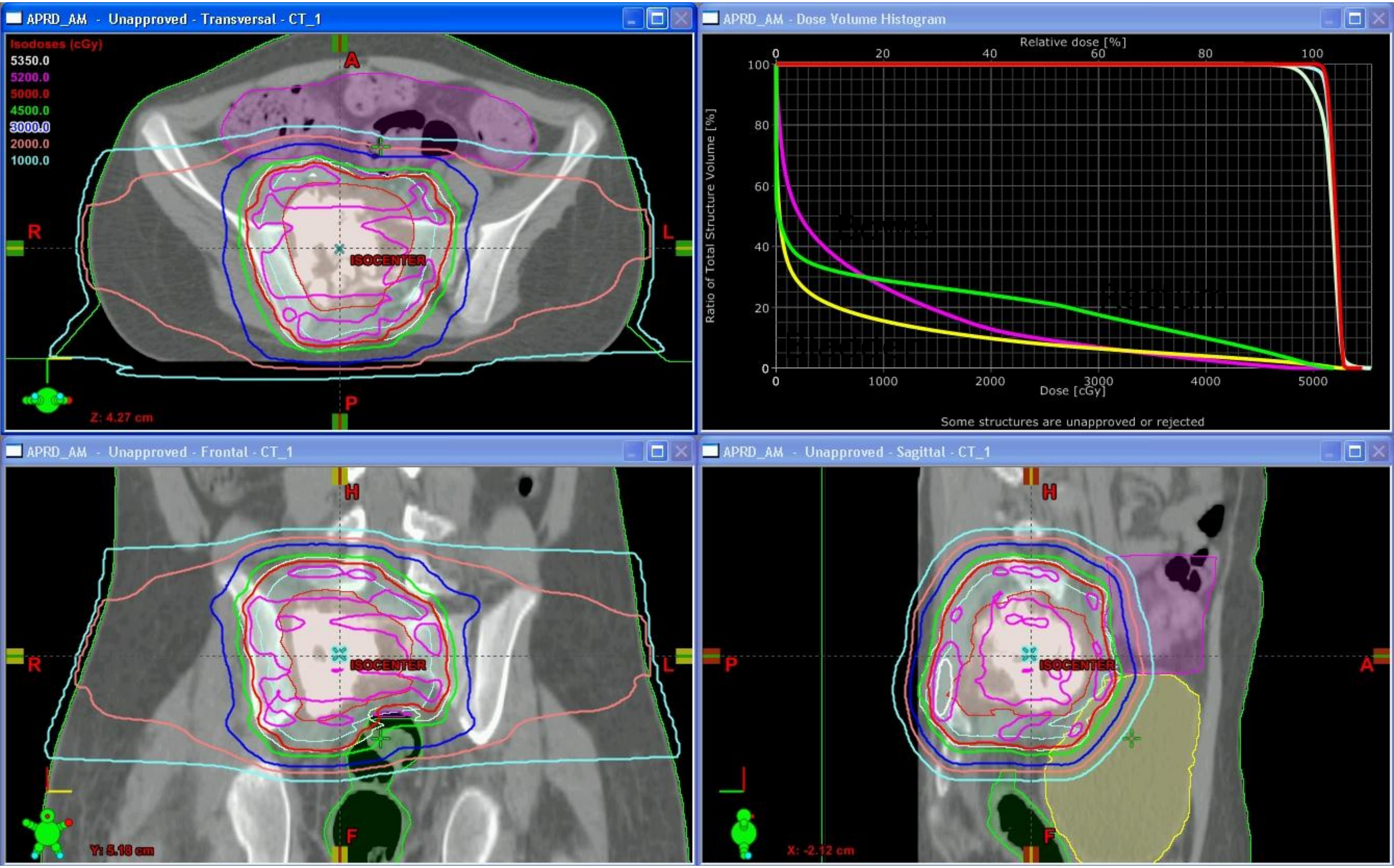


MR#XXXXX

- 14-yr-old boy
- Osteosarcoma right sacrum
- 50 CGE

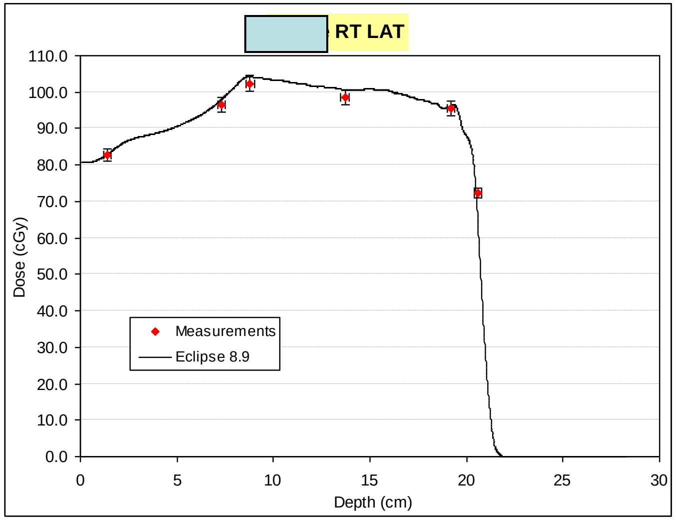


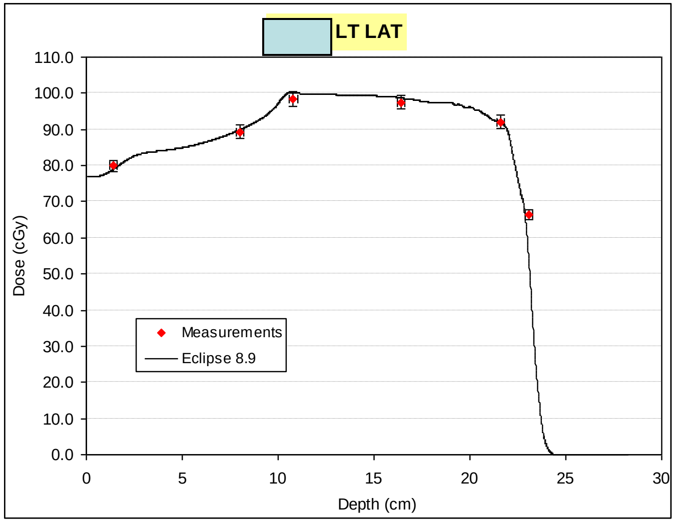
Case 2

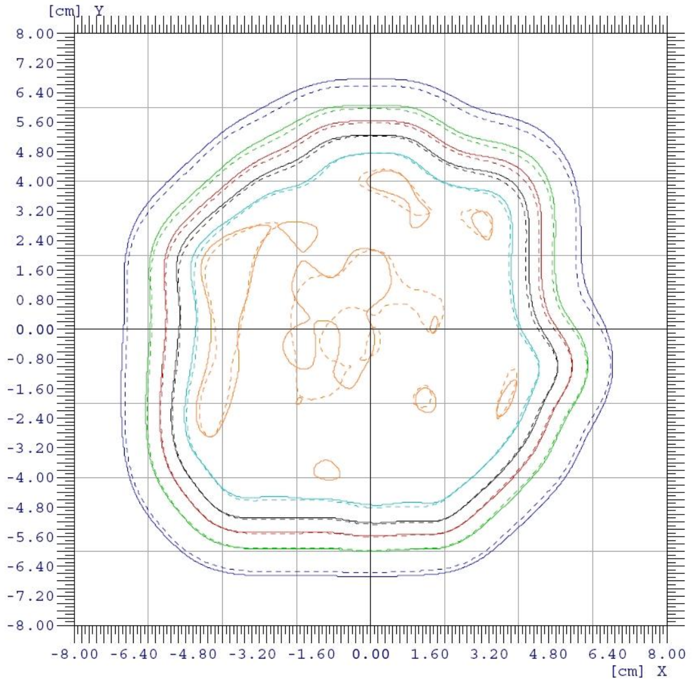


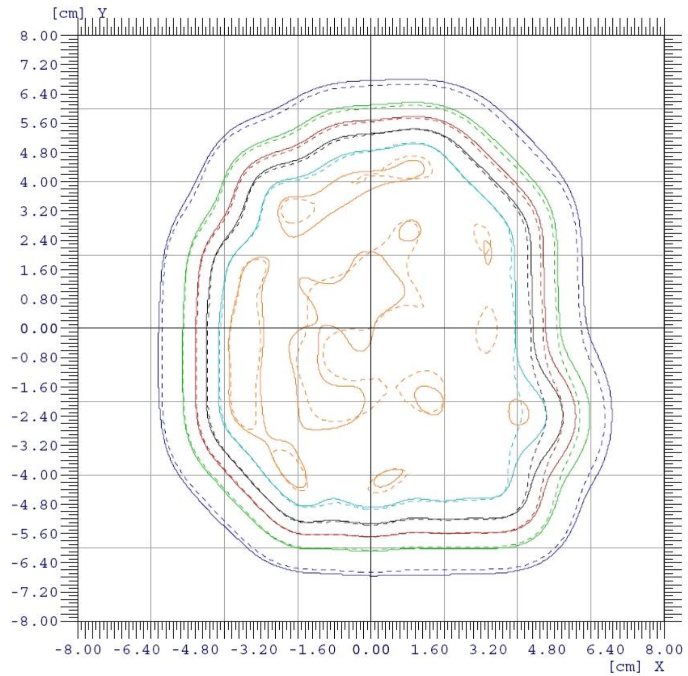
APRD_AM - Unapproved - Transversal - CT_1
Isodoses (cGy)
5350.0
5200.0
5000.0
4500.0
3000.0
2000.0
1000.0
A
R
L
P
ISOCENTER
Z: 4.27 cm
APRD_AM - Dose Volume Histogram
Relative dose [%]
0
20
40
60
80
100
Ratio of Total Structure Volume [%]
100
80
60
40
20
0
Bowel
Rectum
Bladder
0
1000
2000
3000
4000
5000
Dose [cGy]
Some structures are unapproved or rejected
APRD_AM - Unapproved - Frontal - CT_1
H
R
L
ISOCENTER
F
Y: 5.18 cm
APRD_AM - Unapproved - Sagittal - CT_1
H
P
A
ISOCENTER
F
X: -2.12 cm

Case 2 – QA results







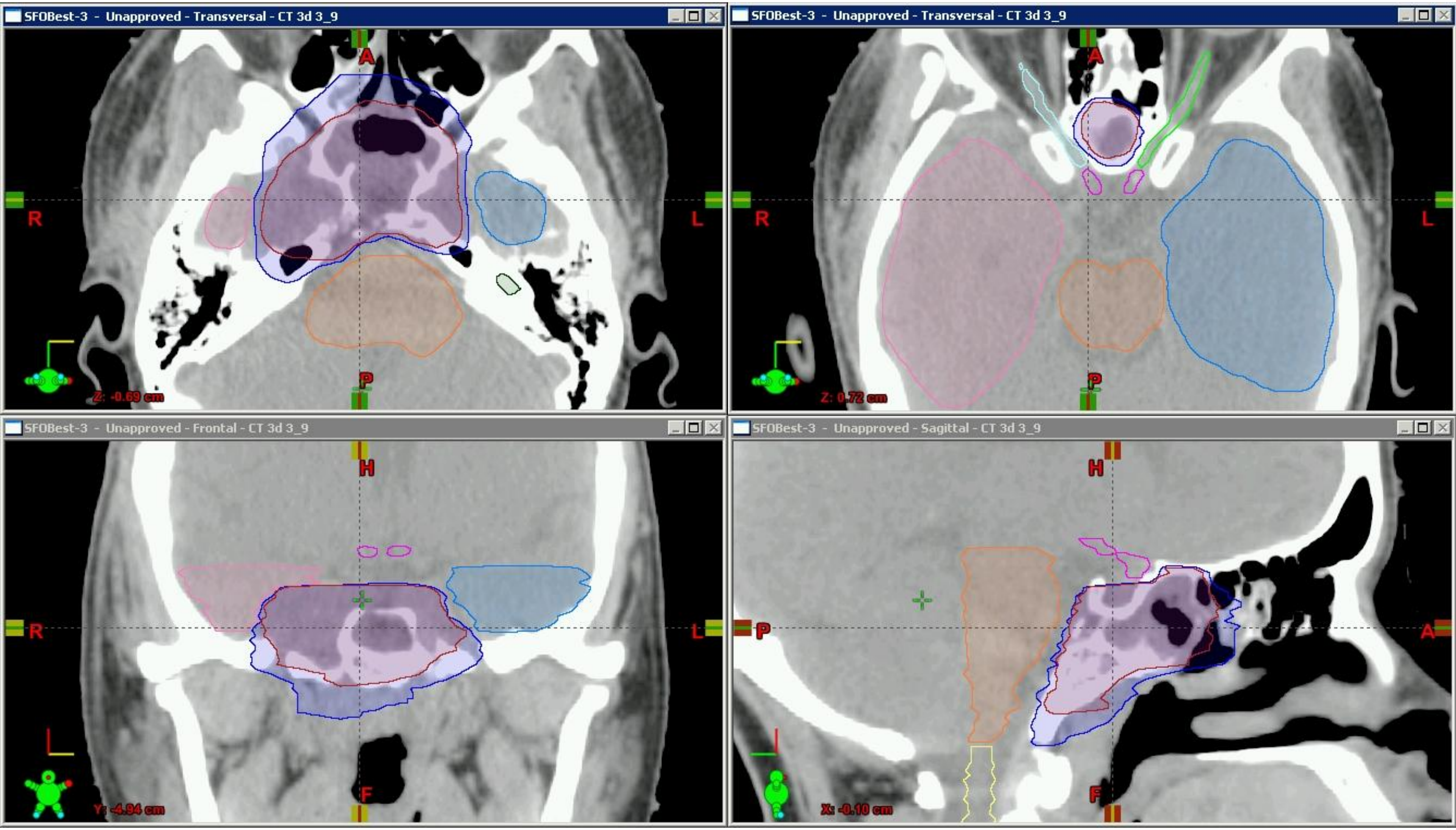


Case 3

- A 39 yr old female (MR#XXXXXX)
- Chondrosarcoma of the base of skull

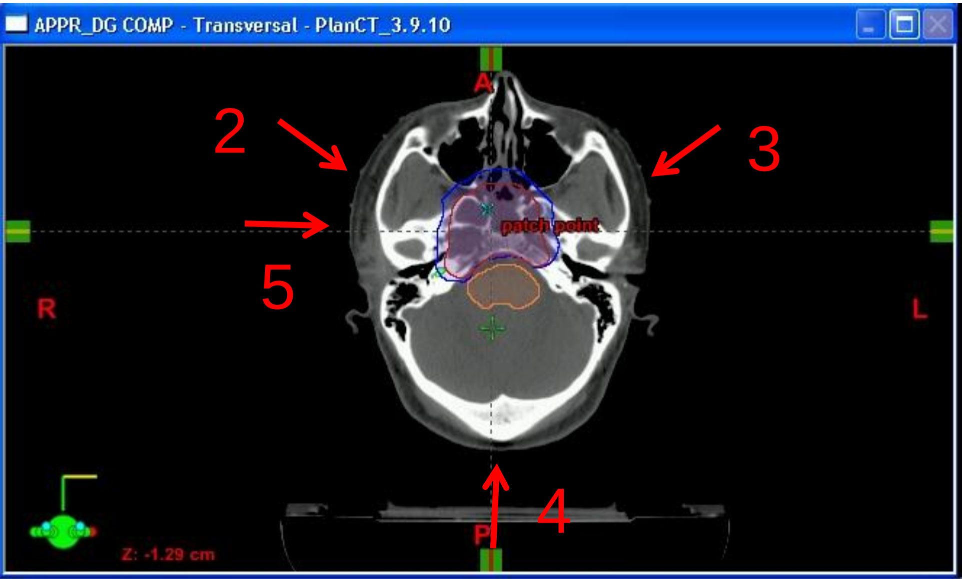
- Planning objectives:
  - CTV: 70 Gy
  - Brain stem: < 1 cc > 60 Gy
  - Optical nerves and chiasm: < 58 Gy
  - Temp lobes: < 1 cc > 70 Gy
  - Others: cochleas, spinal cord, hippocampuses, eyes, and lenses

Anatomy



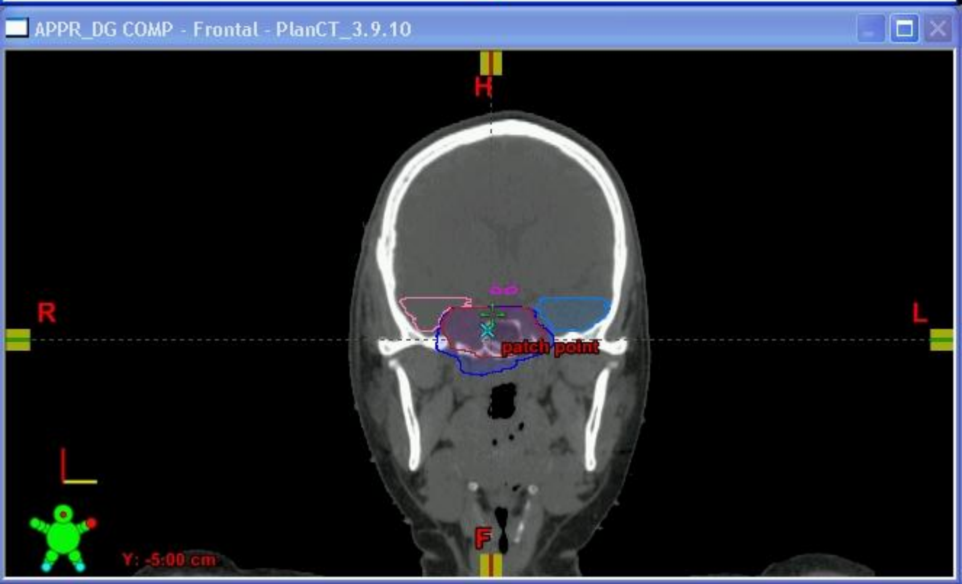
SFOBest-3 - Unapproved - Transversal - CT 3d 3_9
SFOBest-3 - Unapproved - Transversal - CT 3d 3_9
SFOBest-3 - Unapproved - Frontal - CT 3d 3_9
SFOBest-3 - Unapproved - Sagittal - CT 3d 3_9
Z: -0.69 cm
Z: 0.72 cm
Y: -4.94 cm
X: -0.10 cm

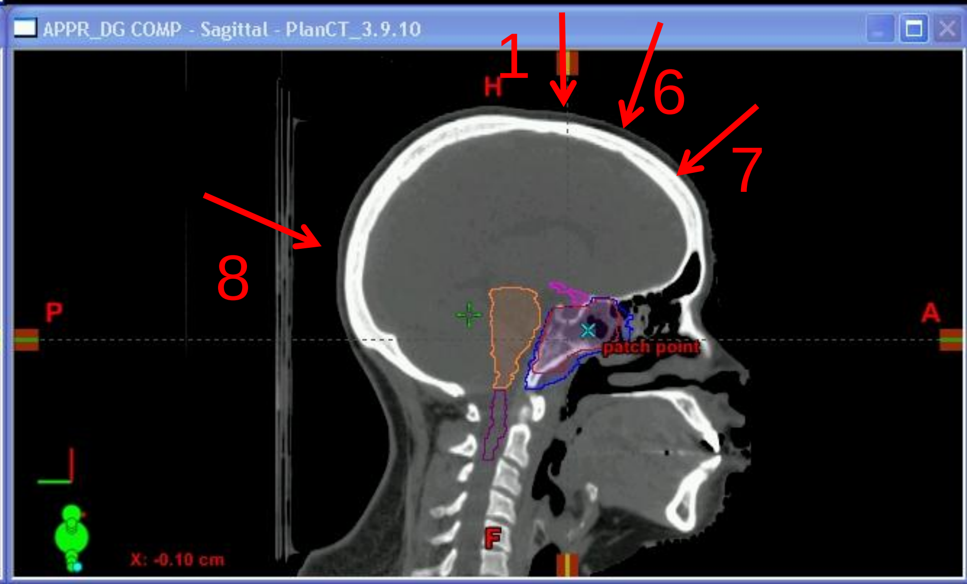
Beam angles - MFO



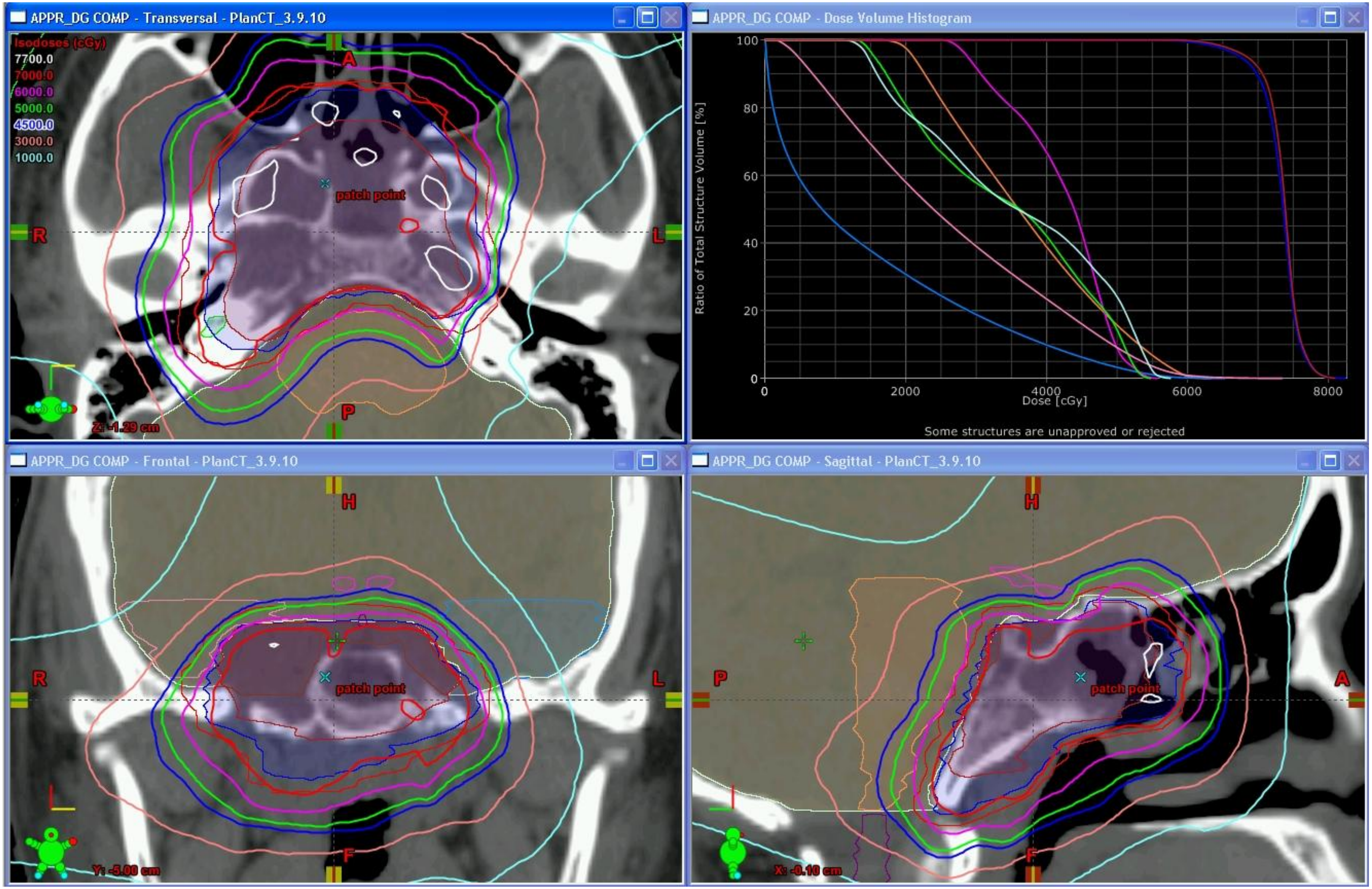
Two plans to improve robustness

- Each has 4 fields
  - 1-4
  - 5-8

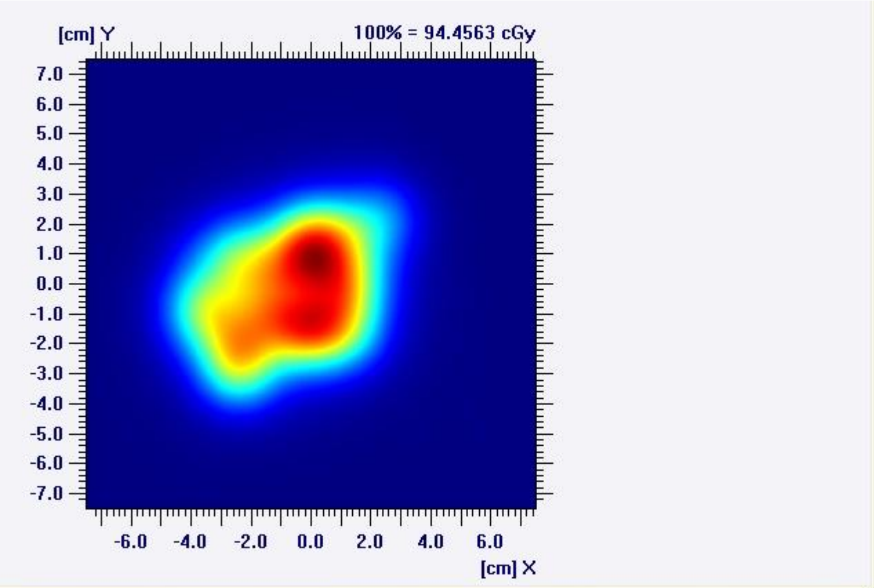


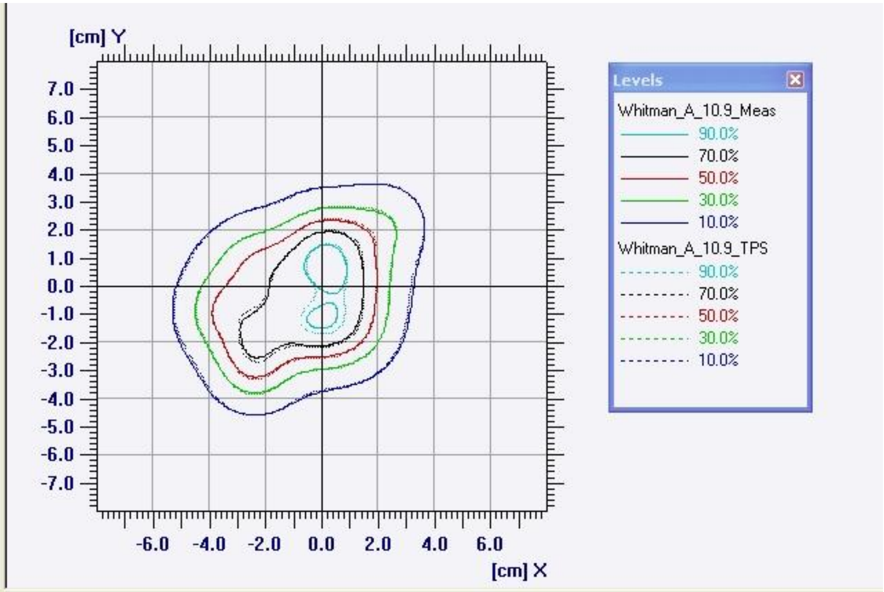


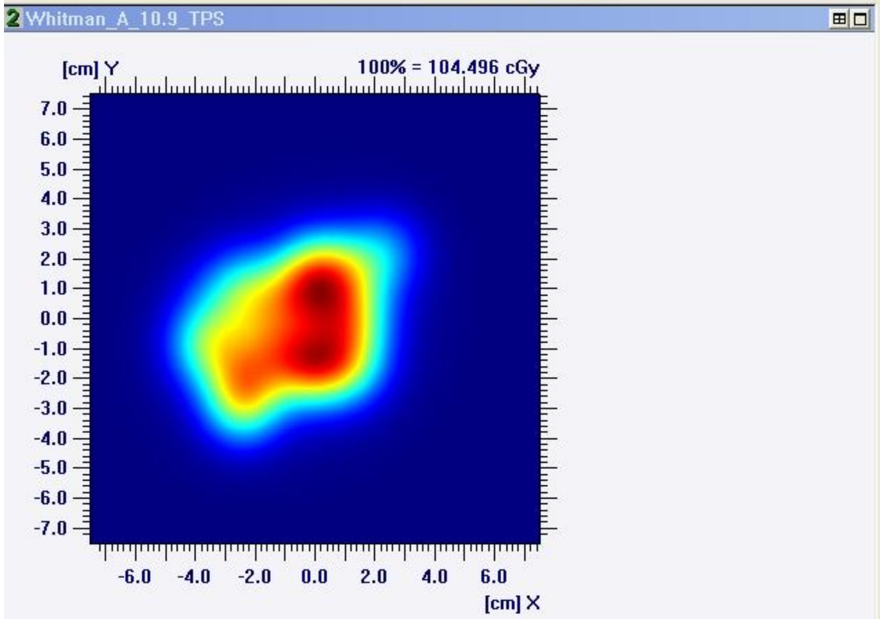
Plan results - MFO

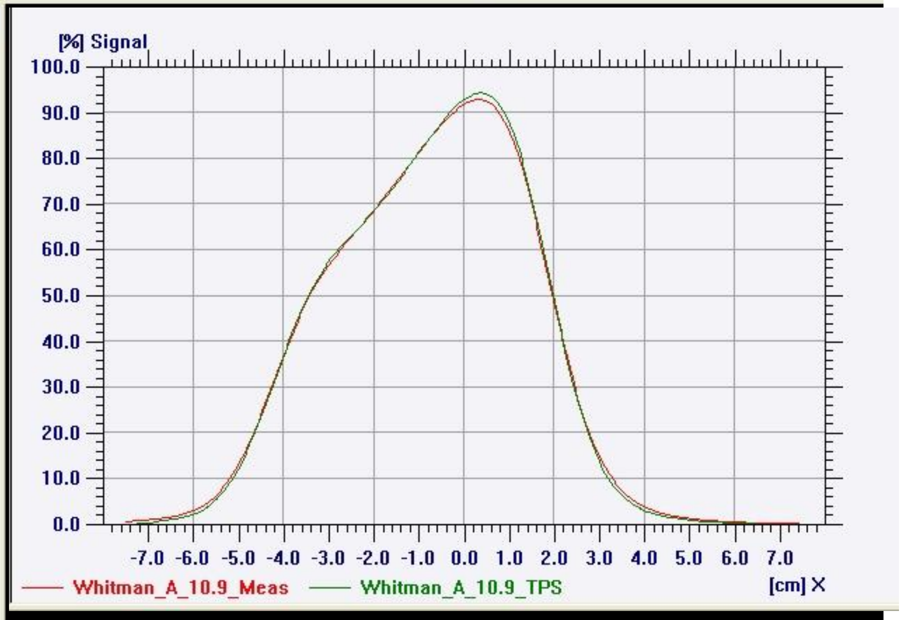


MFO – Field 1   d = 10.9 cm

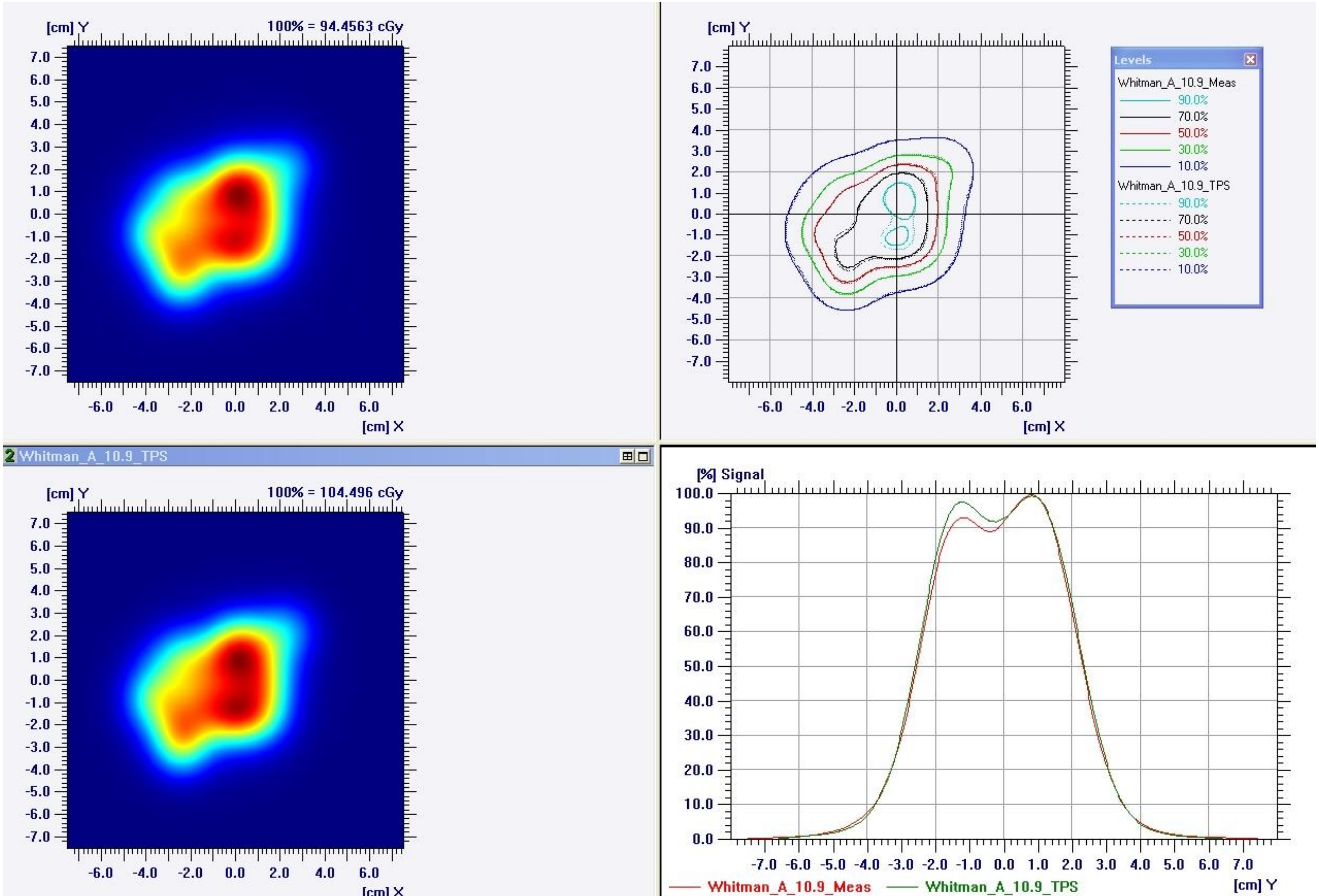




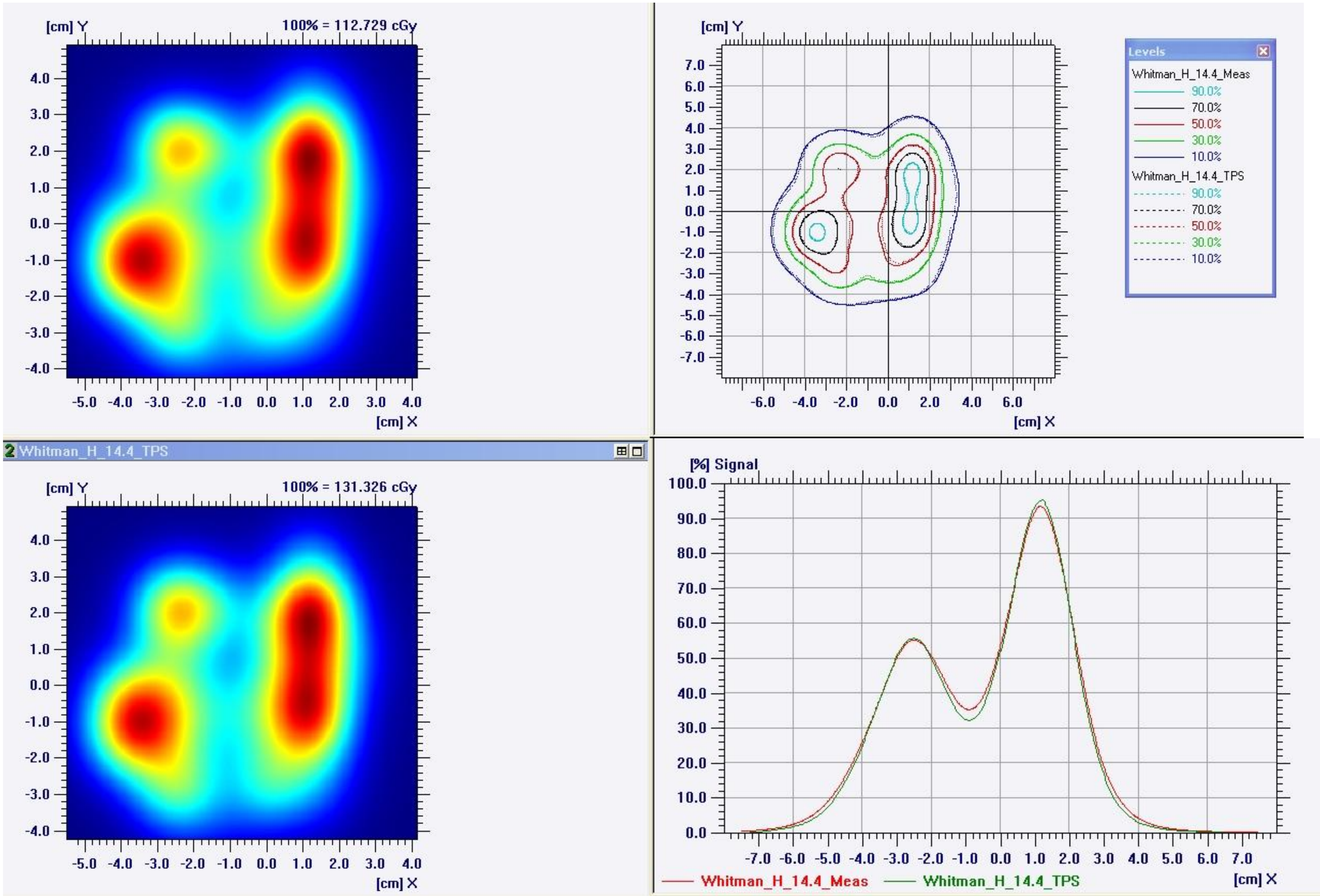




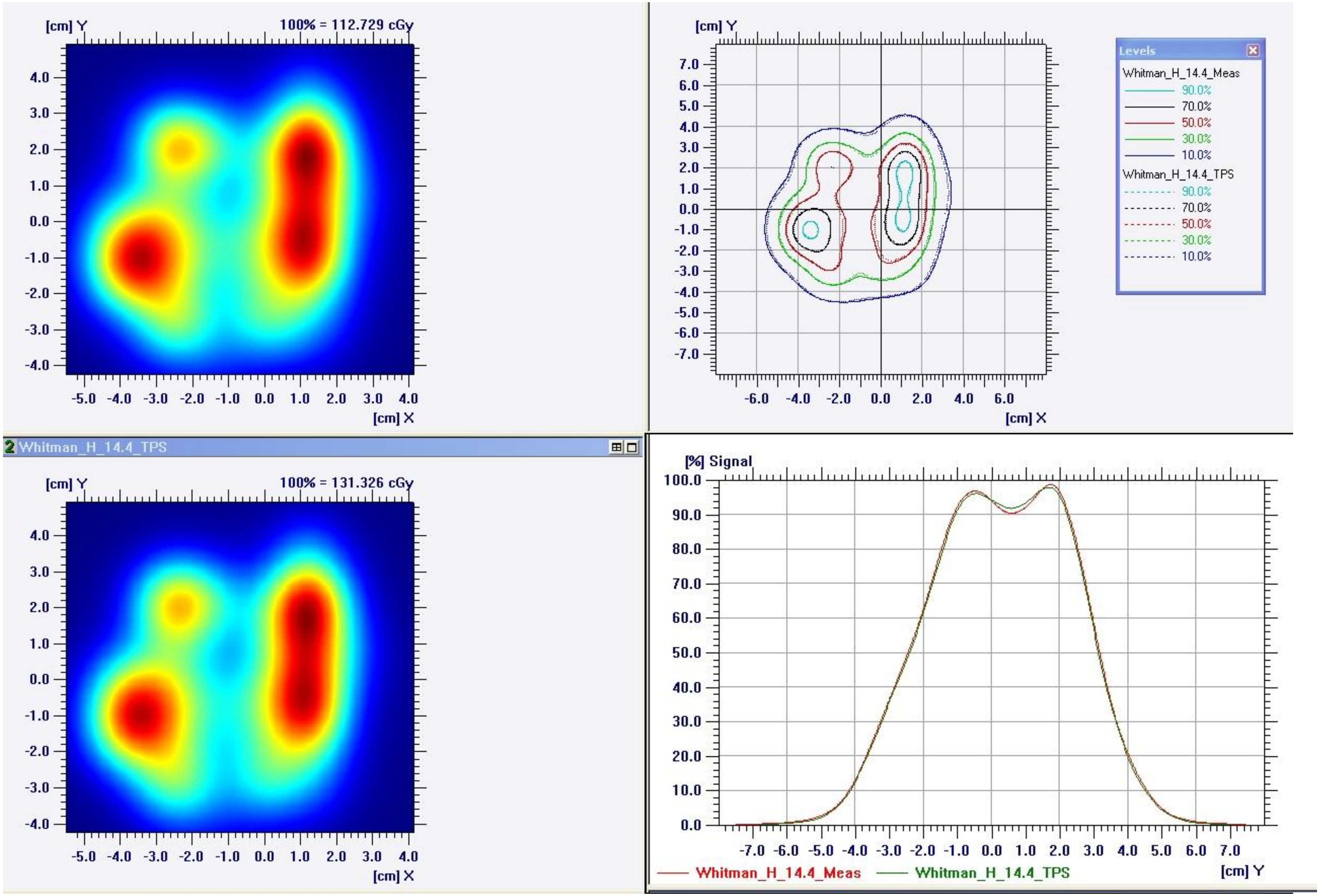
MFO – Field 1   d = 10.9 cm



MFO – Field 8   d = 14.4 cm



MFO – Field 8   d = 14.4 cm



Comparison of Normalization Dose

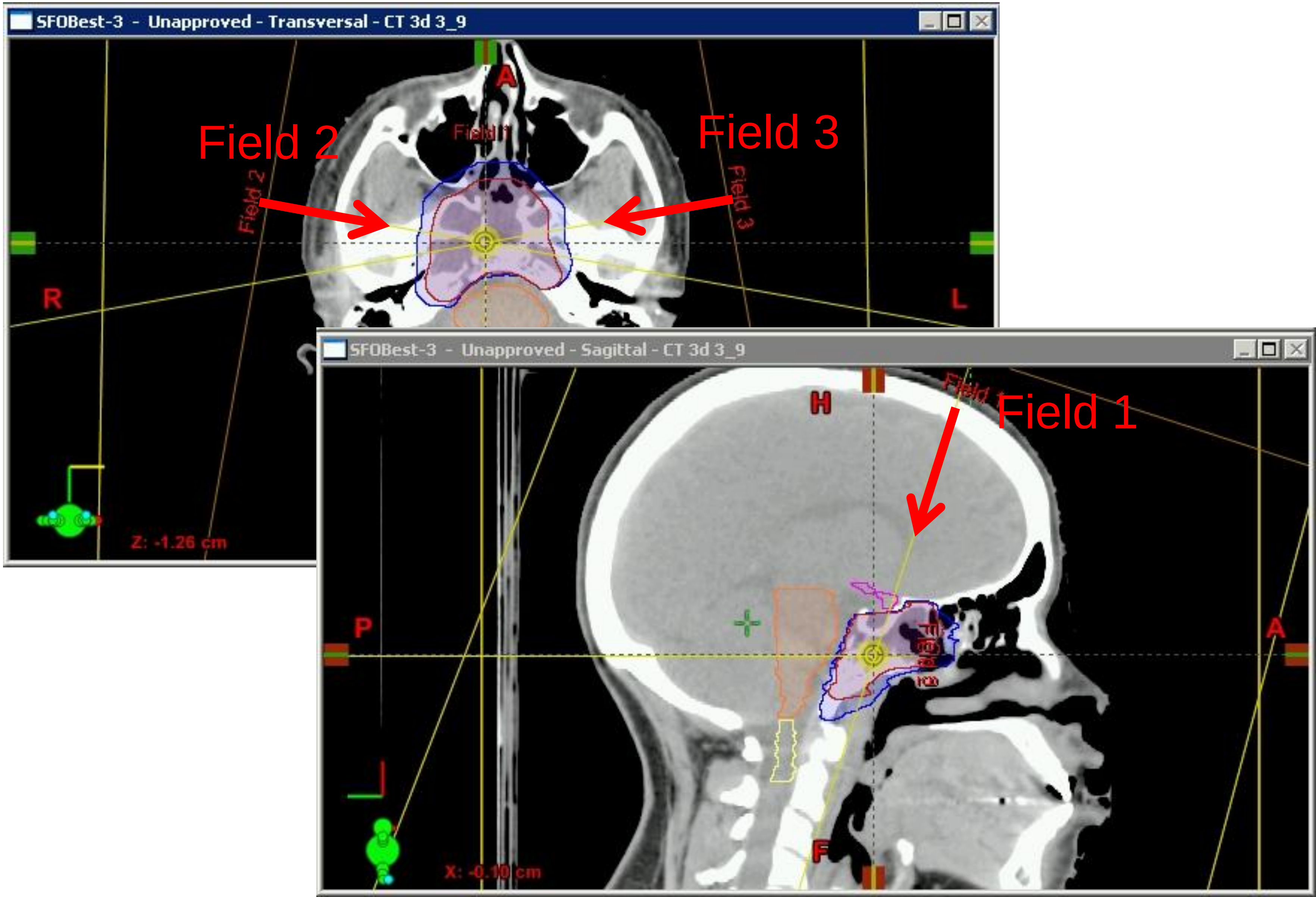
Field	Depth (cm)	Eclipse (CcGE)	Eclipse (cGy)	Meas (cGy)	Diff (%)
1	9.9	102.8	93.5	91.8	1.8%
1	10.9	104.5	95.0	94.5	0.6%
1	14.4	24.5	22.3	20.6	8.1%
3	3.9	105.2	95.6	90.6	5.6%
3	6.4	169.9	154.5	147.1	5.0%
4	5.4	101.2	92.0	88.6	3.8%
4	9.9	132.0	120.0	114.3	5.0%
5	5.4	135.7	123.4	120.0	2.8%
5	10.9	194.6	176.9	167.8	5.4%

Comparison of Normalization Dose

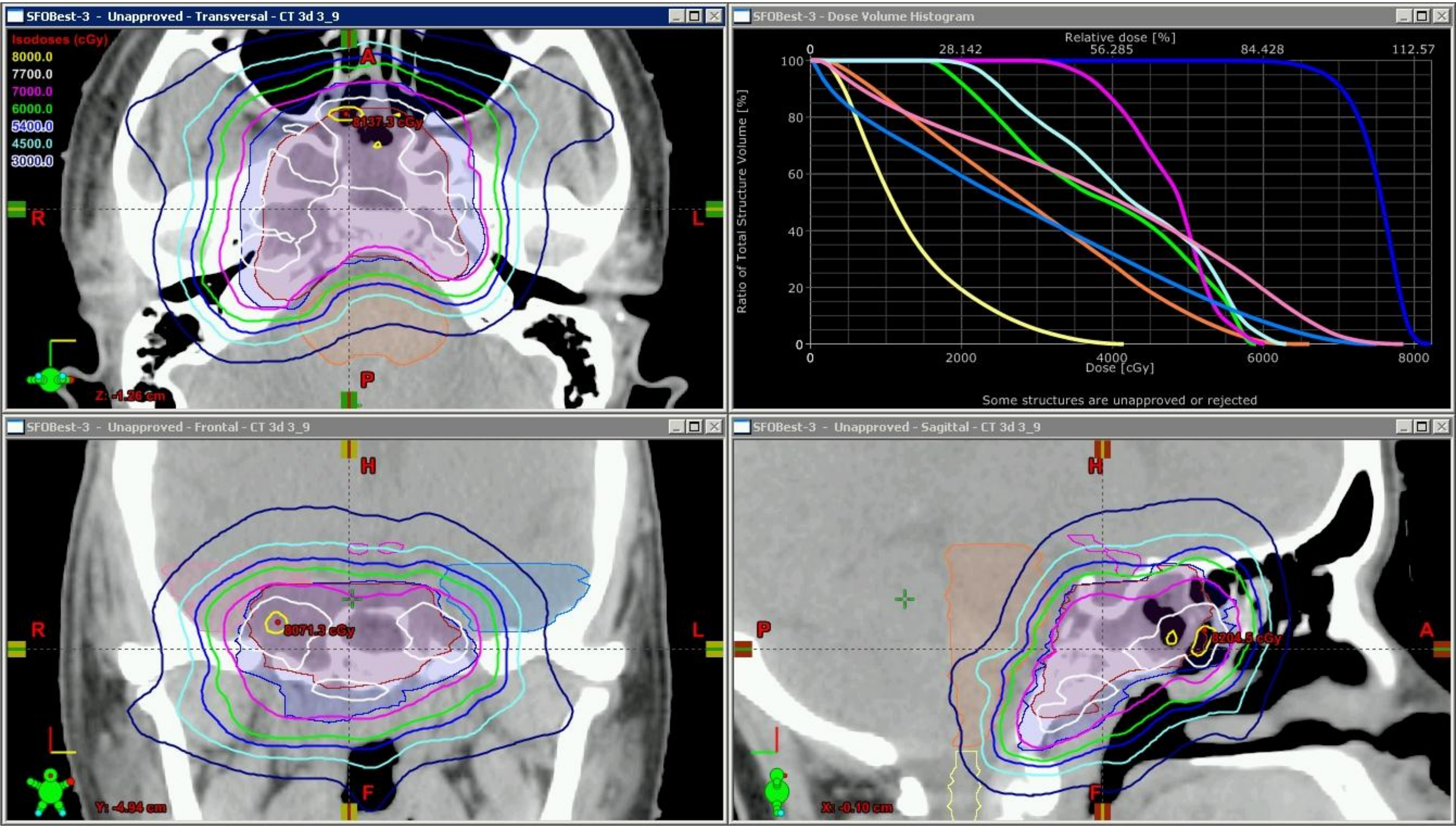
Field	Depth (cm)	Eclipse (CcGE)	Eclipse (cGy)	Meas (cGy)	Diff (%)
6	5.4	58.7	53.4	51.2	4.2%
6	8.9	103.4	94.0	91.0	3.3%
7	5.4	39.1	35.5	33.5	6.1%
7	9.9	105.7	96.1	91.0	5.6%
7	14.9	83.1	75.5	69.8	8.2%
8	5.4	85.7	77.9	75.1	3.7%
8	14.4	131.3	119.4	112.7	5.9%
				Avg =	4.7%
				Stdev =	2.1%
				Min =	0.6%
				Max =	8.2%

Physics recommended that this plan NOT be used.

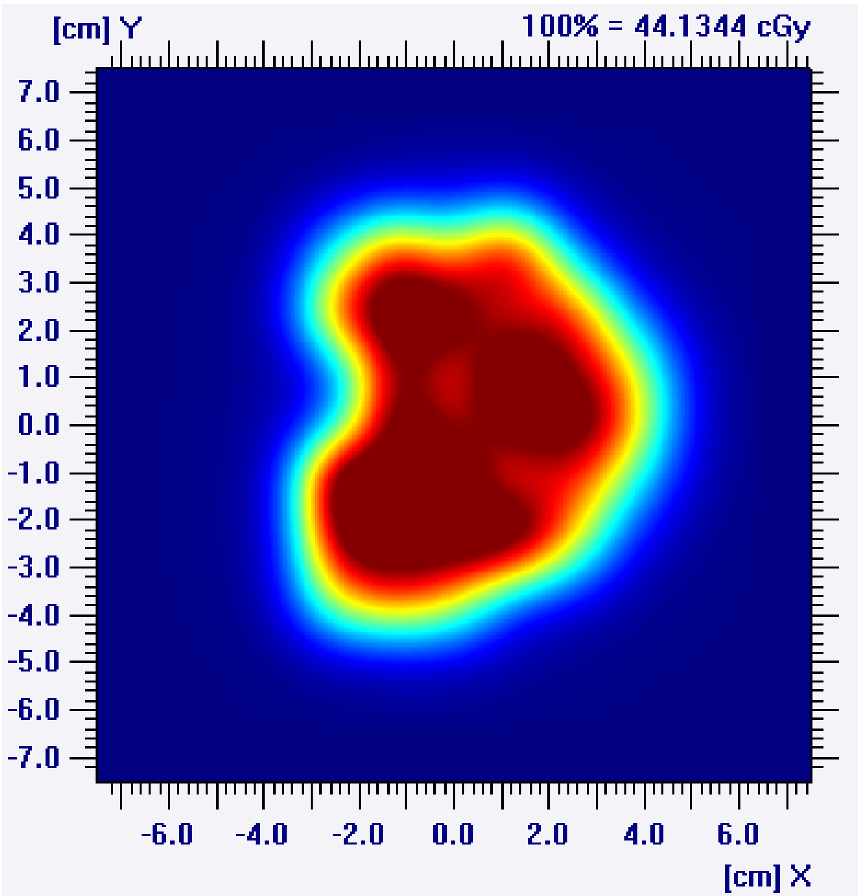
Beam angles - SFO

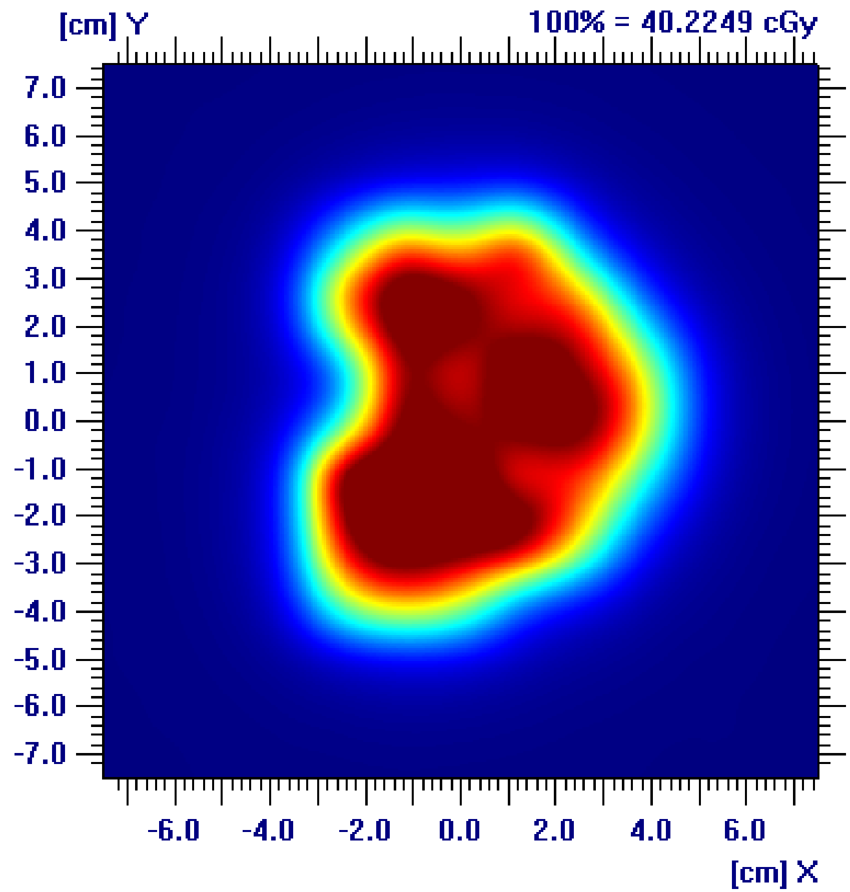


Plan results - SFO



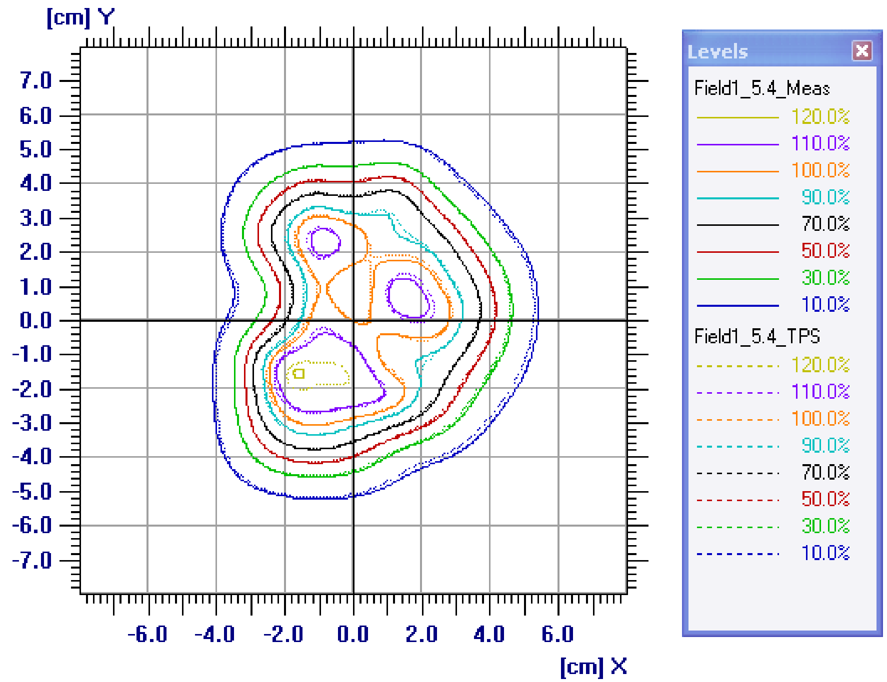
SFO - Field 1   d = 5.4 cm

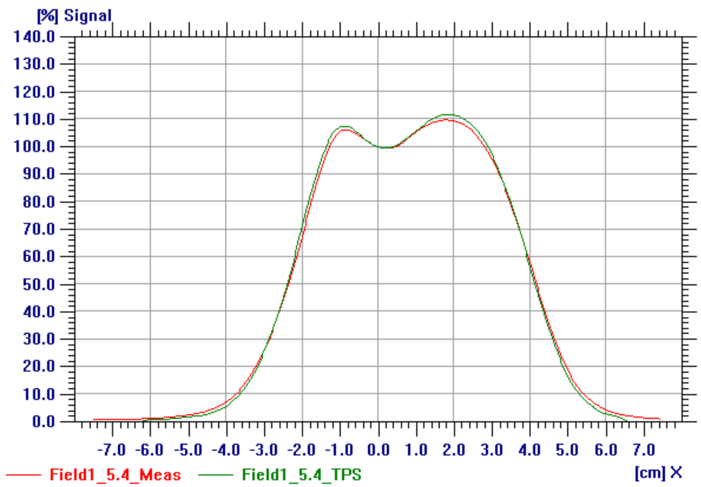


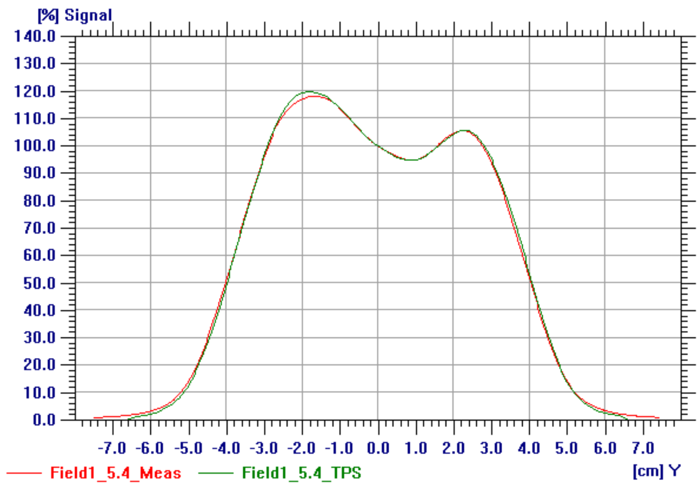


Difference in normalization = -0.3%

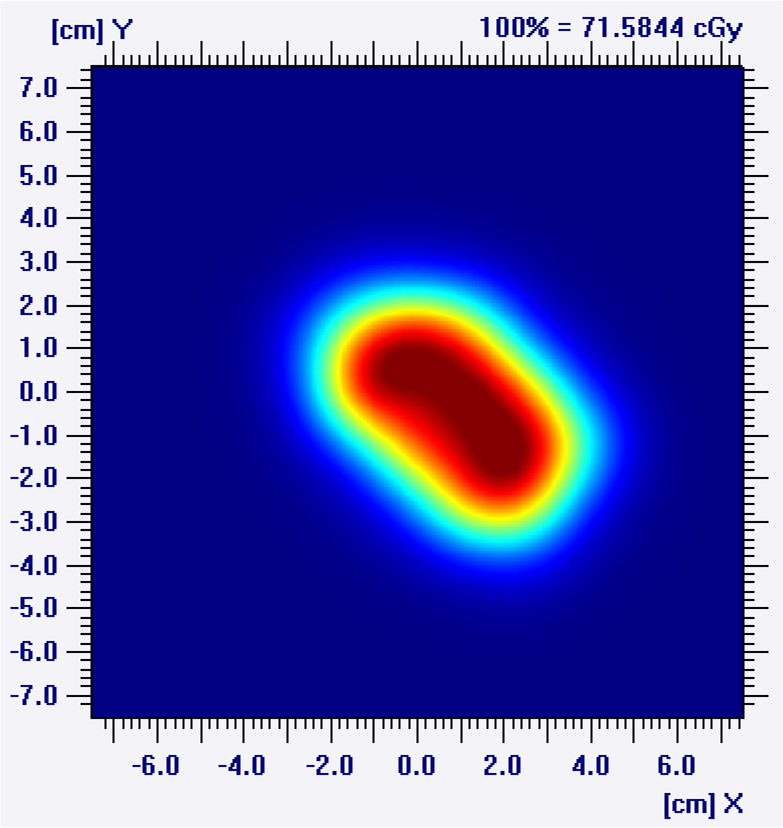
SFO - Field 1   d = 5.4 cm

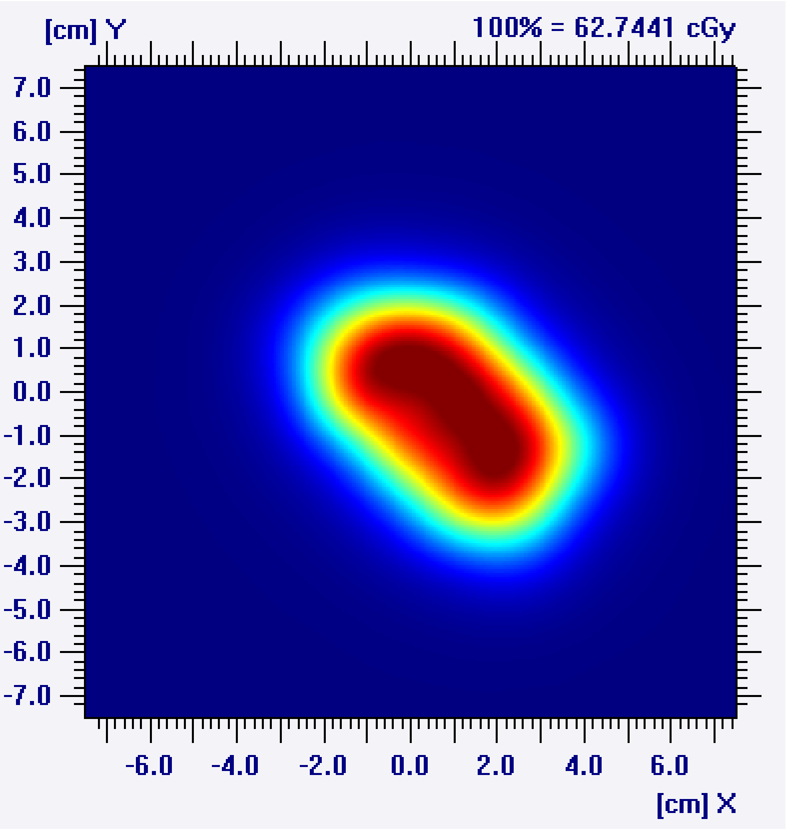






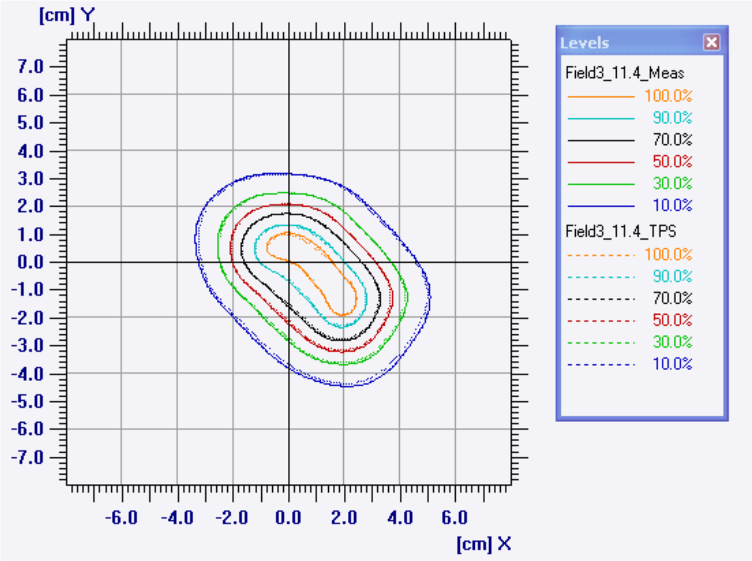
SFO - Field 3   d = 11.4 cm



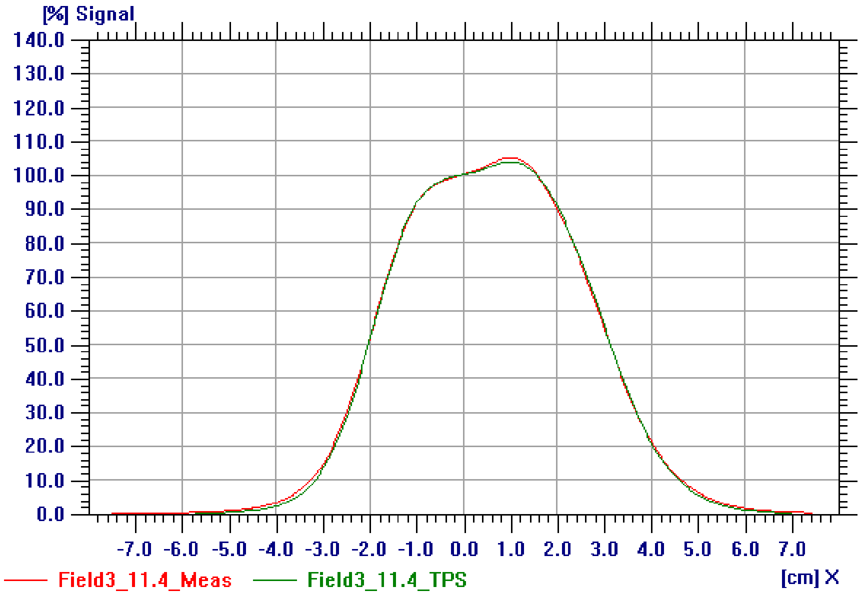


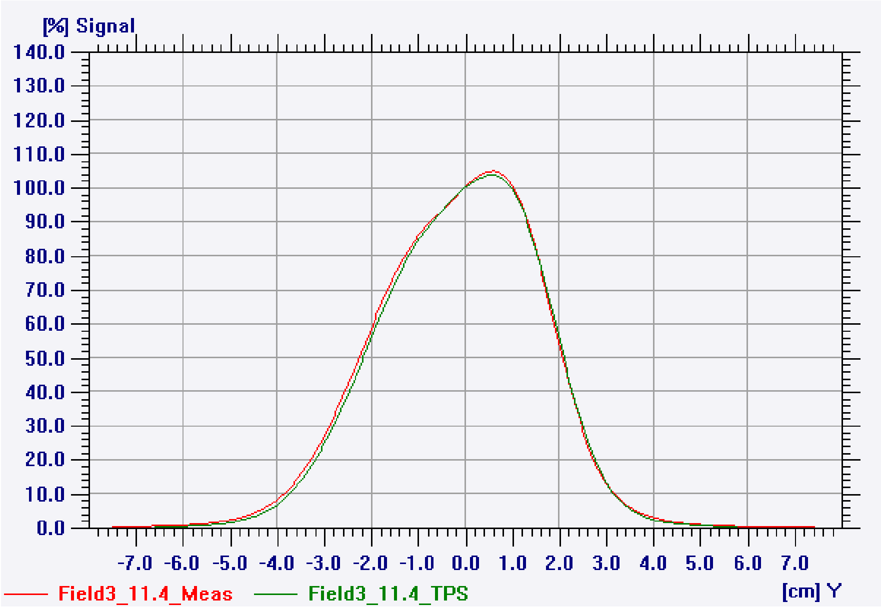
Difference in normalization = 3.7%

SFO - Field 3   d = 11.4 cm



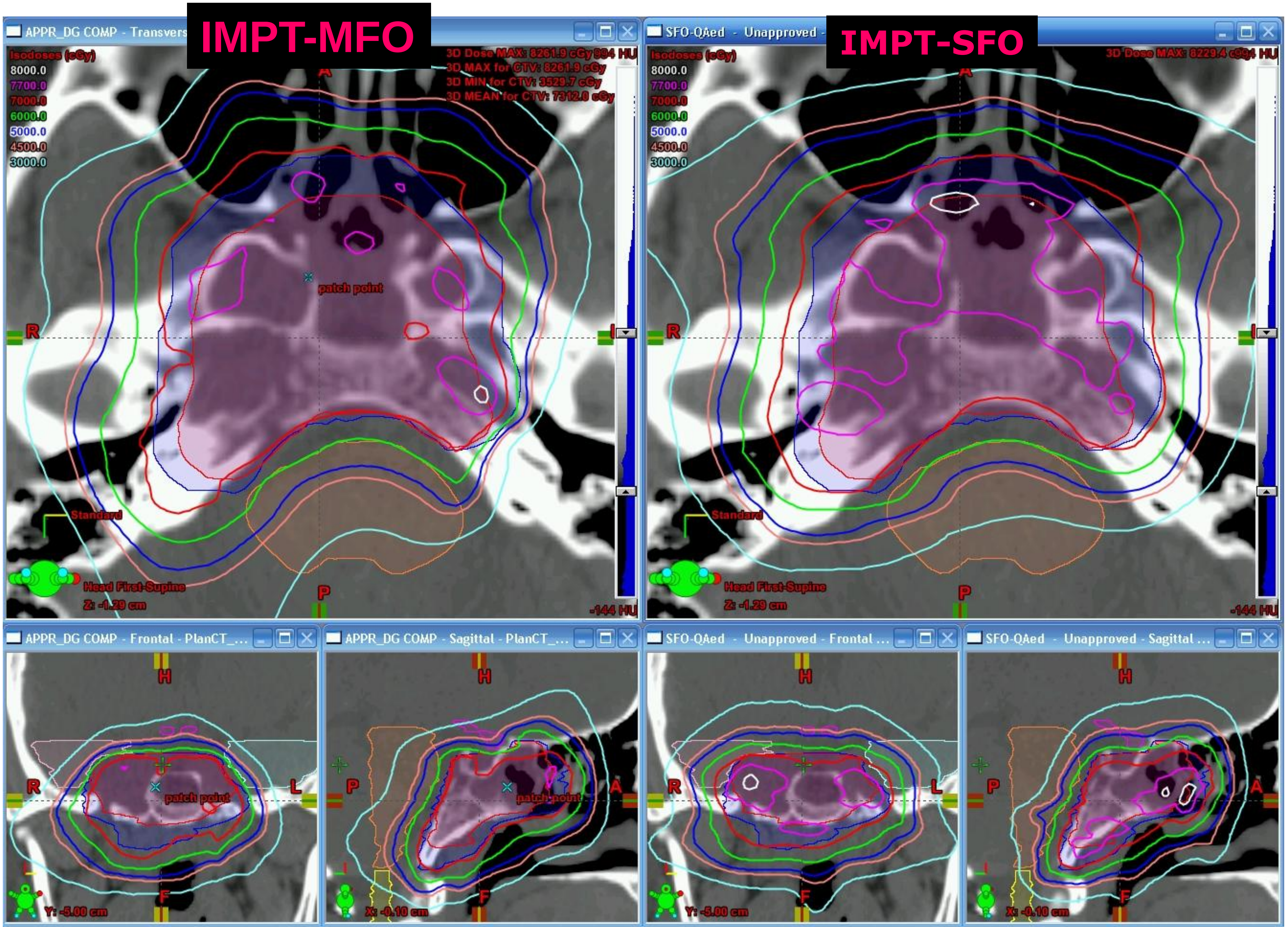
Avg =	2.0%
Stdev =	1.4%
Min =	-0.3%
Max =	3.7%





Comparison of Normalization Dose

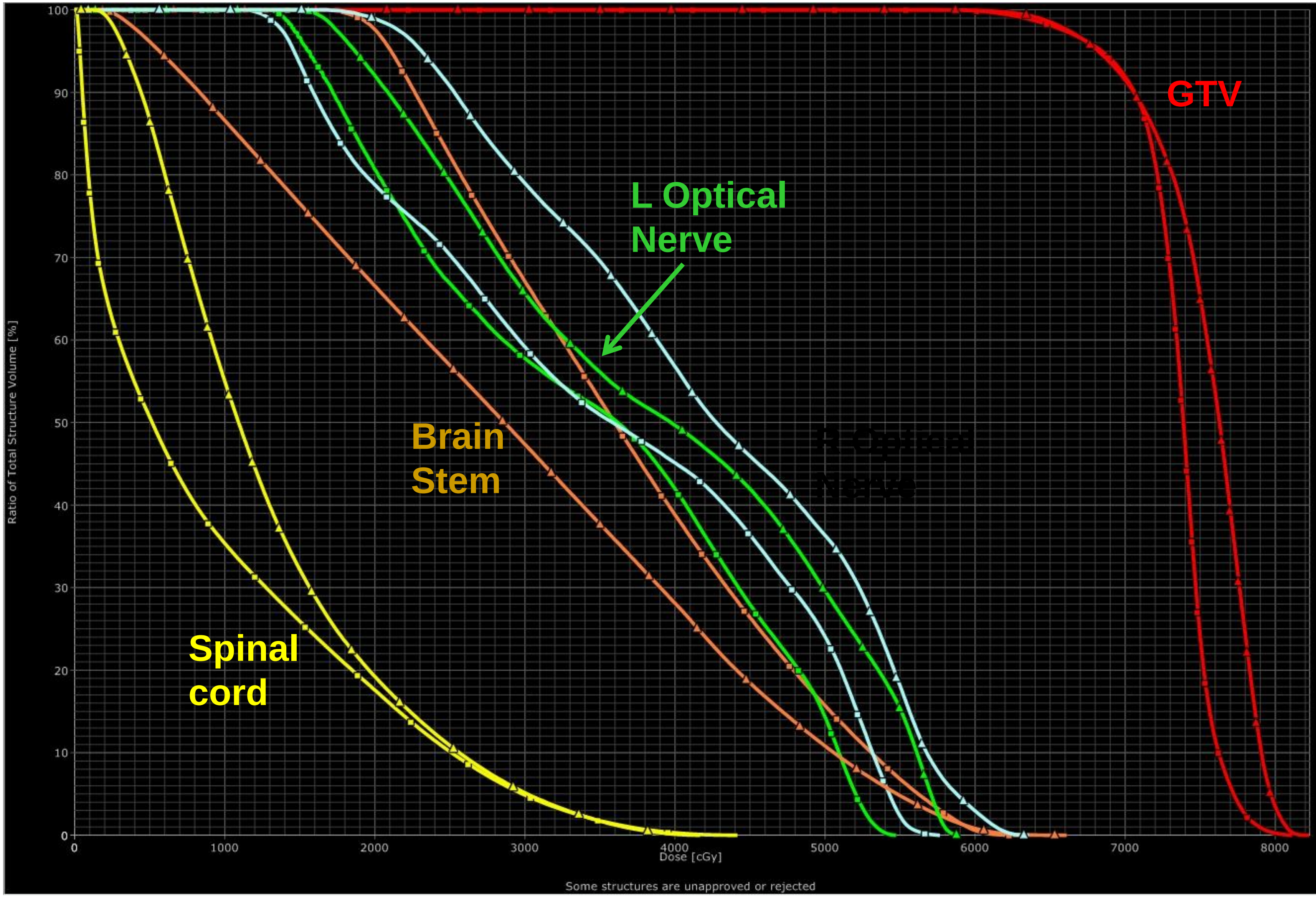
Field	Depth (cm)	Eclipse (CcGE)	Eclipse (cGy)	Meas (cGy)	Diff (%)
1	5.4	44.1	40.1	40.2	-0.3%
1	11.4	64.2	58.4	57.0	2.4%
1	13.4	71.4	64.9	64.3	0.9%
2	5.4	72.8	66.2	65.2	1.6%
2	11.4	74.3	67.5	65.1	3.7%
3	5.4	67.3	61.2	60.1	1.9%
3	11.4	71.6	65.1	62.7	3.7%
				Avg =	2.0%
				Stdev =	1.4%
				Min =	-0.3%
				Max =	3.7%



IMPT-MFO
IMPT-SFO
APPR_DG COMP - Transvers
Isodoses (cGy)
8000.0
7700.0
7000.0
6000.0
5000.0
4500.0
3000.0
3D Dose MAX: 8261.9 cGy 994 HU
3D MAX for CTV: 8261.9 cGy
3D MIN for CTV: 3529.7 cGy
3D MEAN for CTV: 7312.0 cGy
patch point
Standard
Head First-Supine
Z: -1.29 cm
-144 HU
SFO-QAed - Unapproved
3D Dose MAX: 8229.4 c994 HU
APPR_DG COMP - Frontal - PlanCT_...
APPR_DG COMP - Sagittal - PlanCT_...
SFO-QAed - Unapproved - Frontal ...
SFO-QAed - Unapproved - Sagittal ...
Y: -5.00 cm
X: -0.10 cm

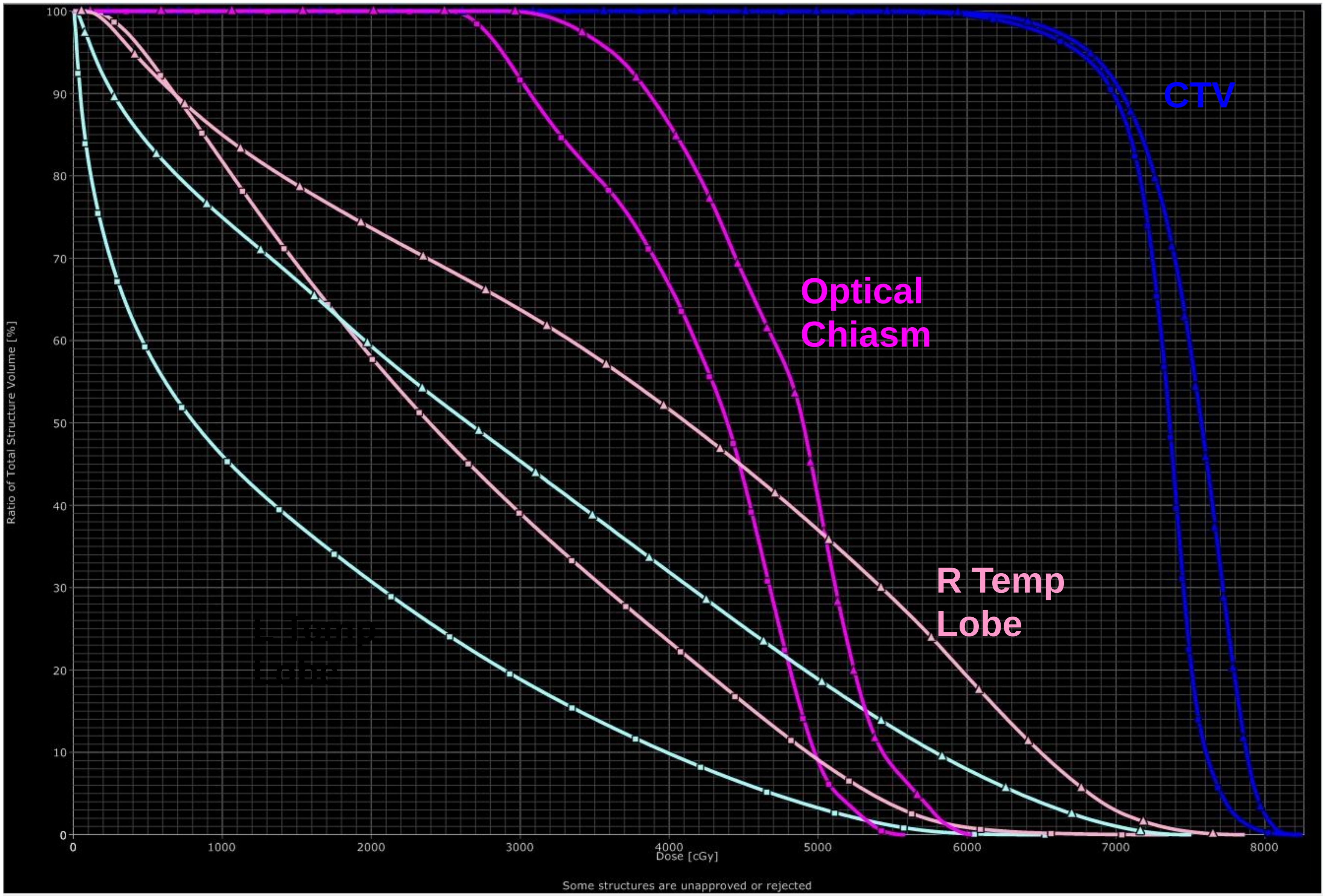
DVH Comparison: MFO vs. SFO

Squares - MFO
Triangles - SFO



DVH Comparison: MFO vs. SFO

Squares - MFO
Triangles - SFO



Patient 3 Summary

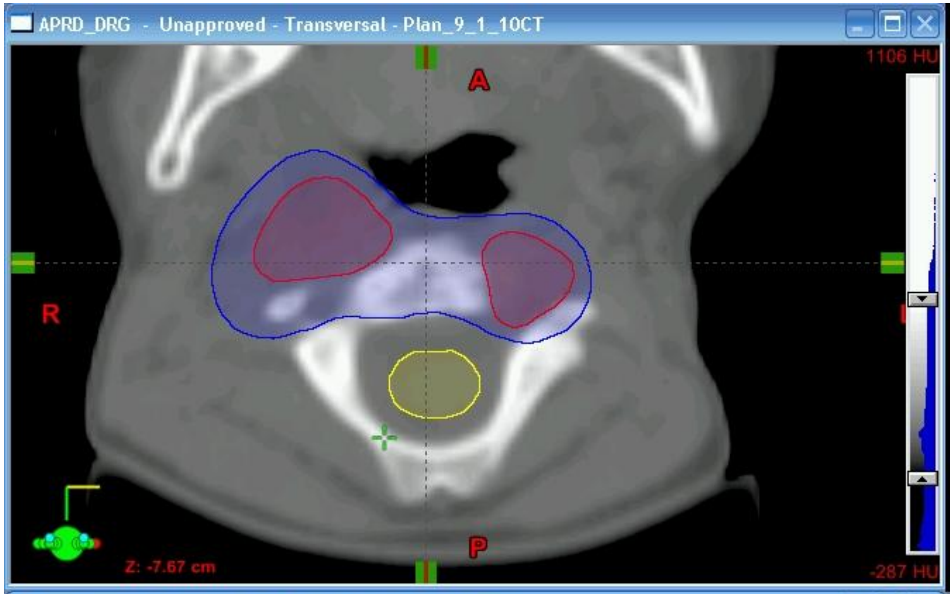
- This patient was not treated with discrete spot scanning. A combination of x-rays and scattered protons were used.
- Physics concerns include the widely modulated, high dose, small volume dose distribution.
- It was an interesting learning experience, which was good preparation for the challenges of MFO IMPT.

Case 7 - MFO

- A 10 yr old boy (MR#XXXXXX)
- Recurrent extrarenal rhabdoid tumor

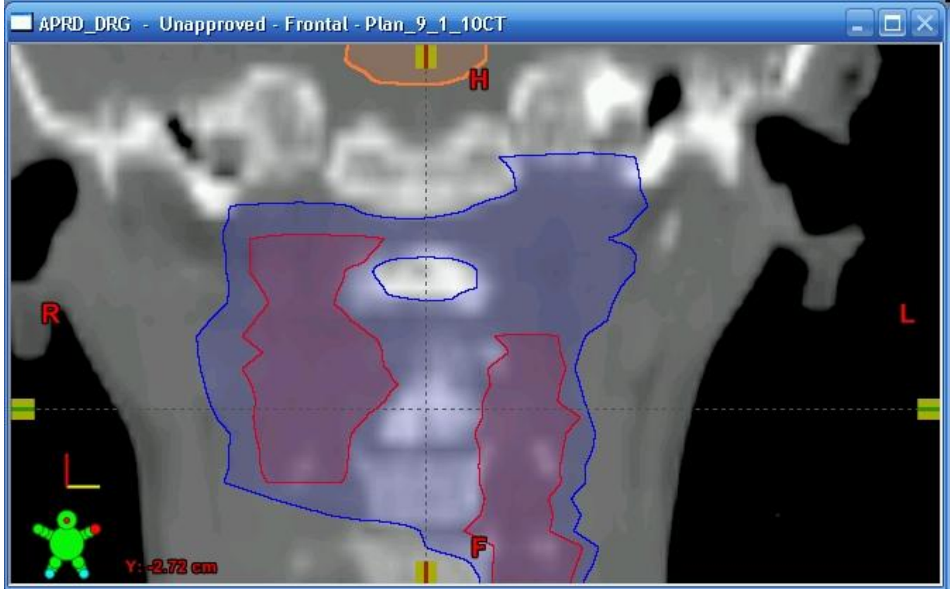
- Planning objectives:
  - CTV: 50.4 Gy
  - Spinal cord: < as low as possible
  - Brain Stem: < as low as possible

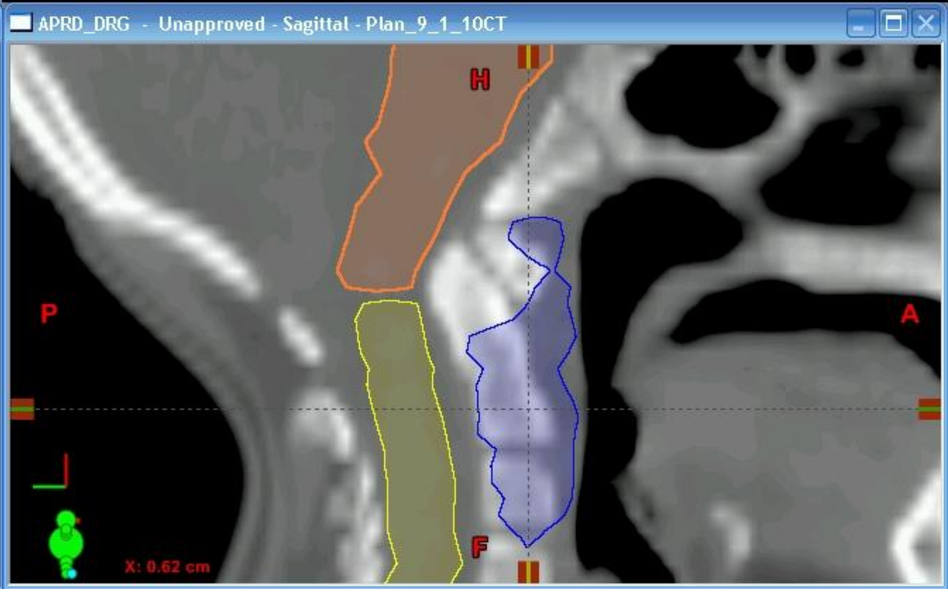
Case – 7 IMPT - MFO



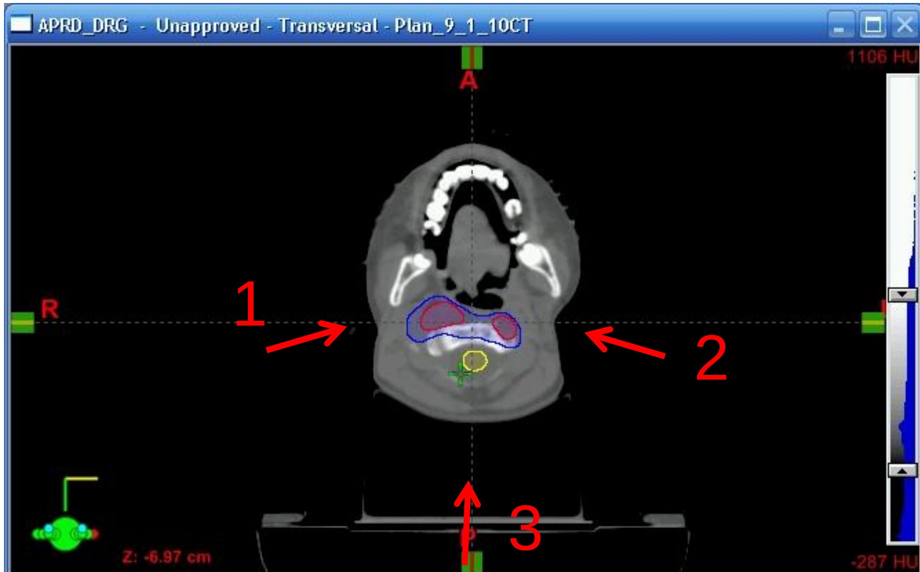
- A 10 yr old boy (MR#XXXXXX)
- Recurrent extrarenal rhabdoid tumor

- Planning objectives:
  - CTV: 50.4 Gy
  - Spinal cord & Brain Stem ALAP





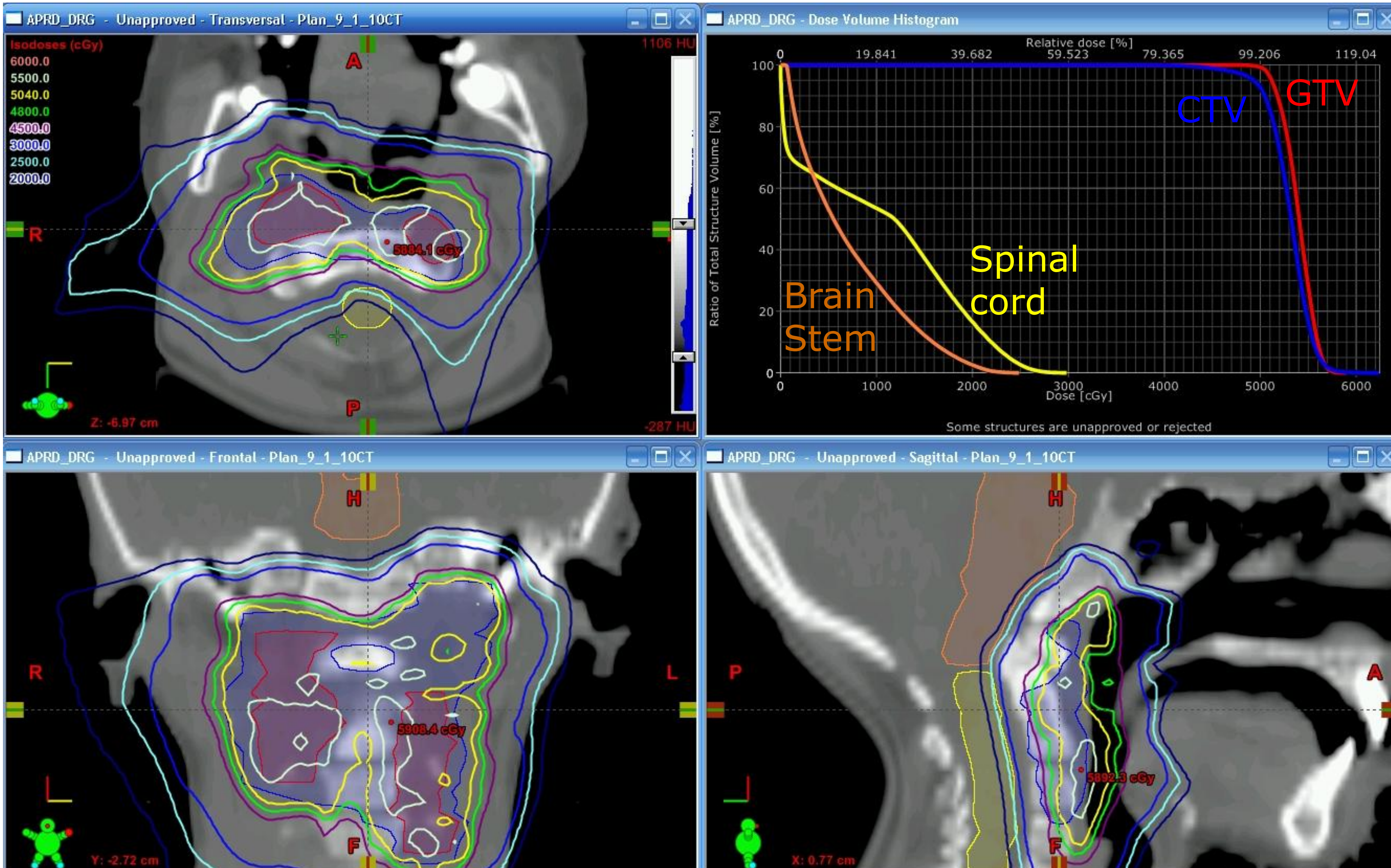
Beam angles - MFO



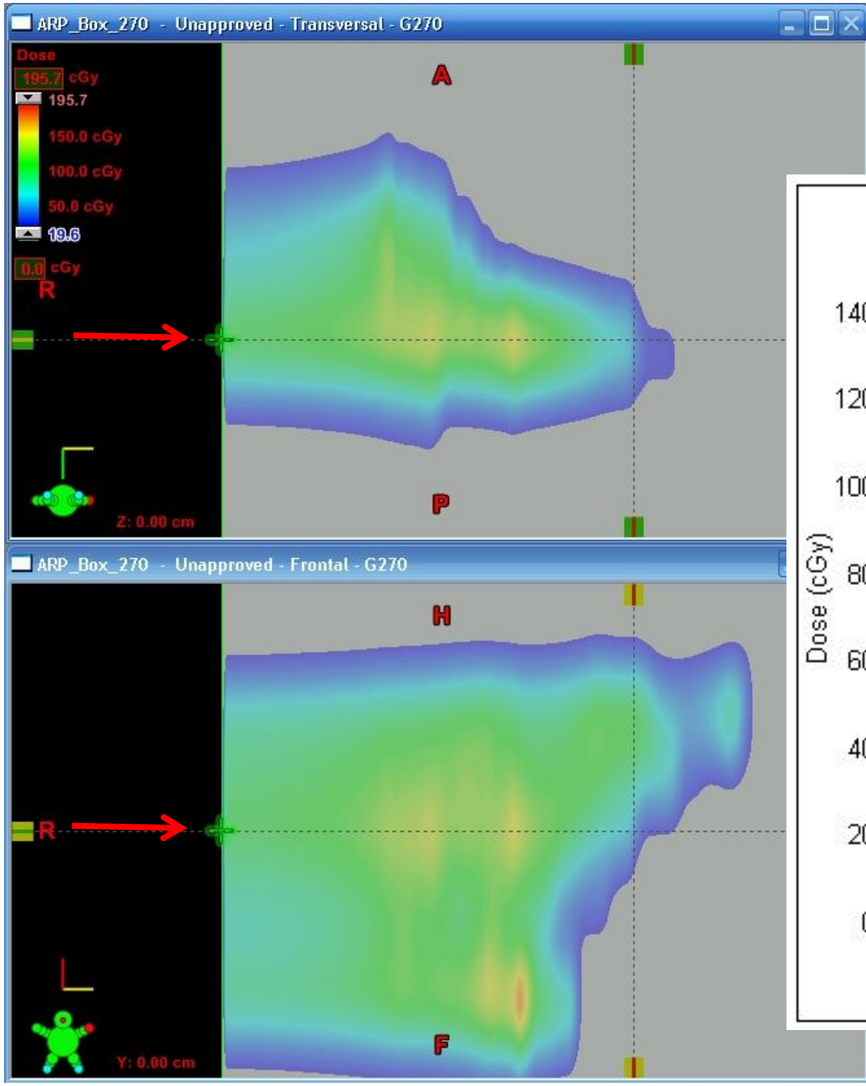
Three field plan

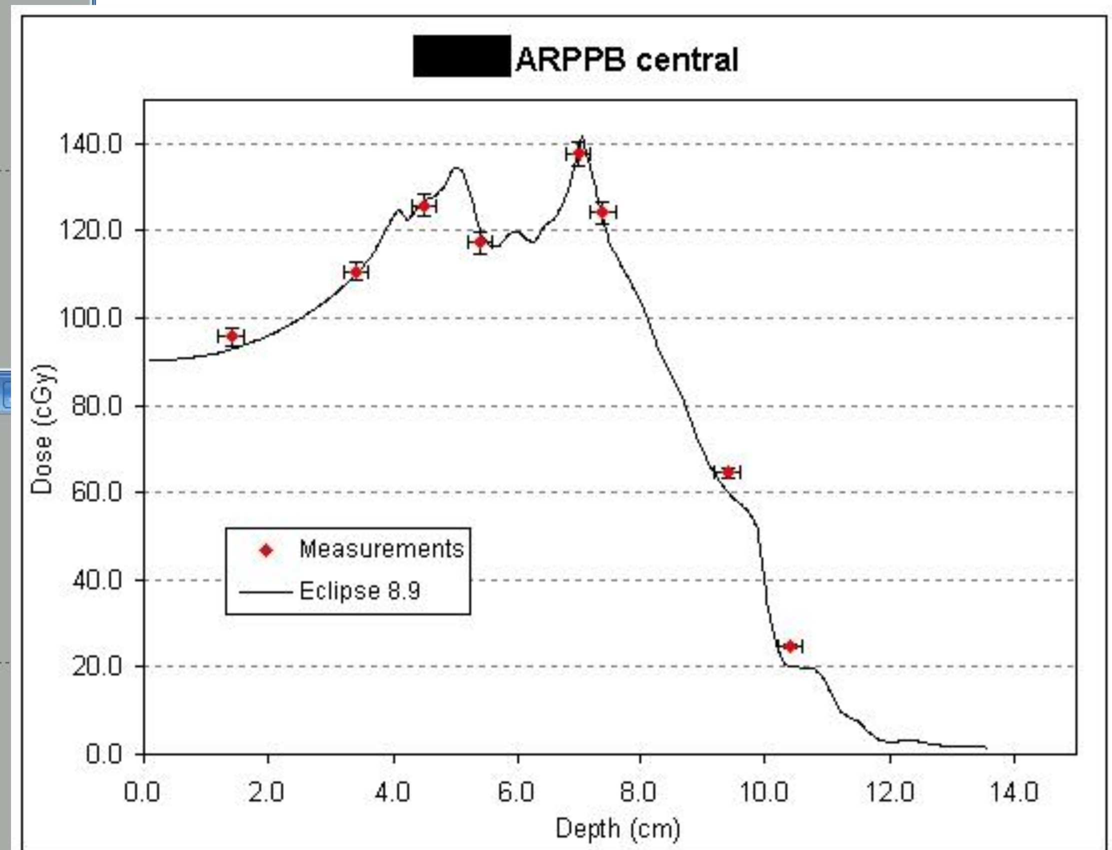
- Two posterior oblique
- One Posterior anterior

Plan results - MFO

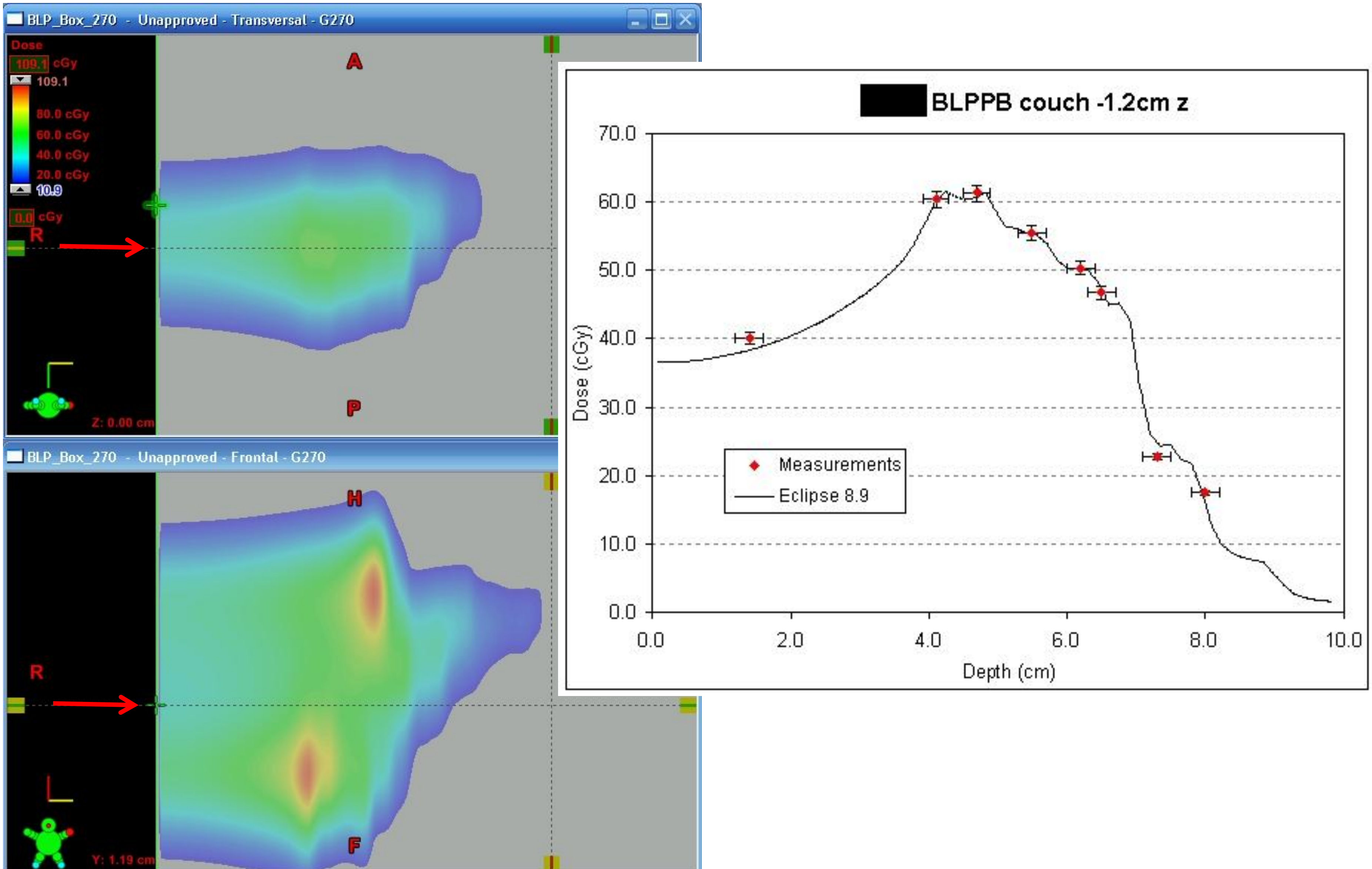


MFO - Field 1 Depth Dose

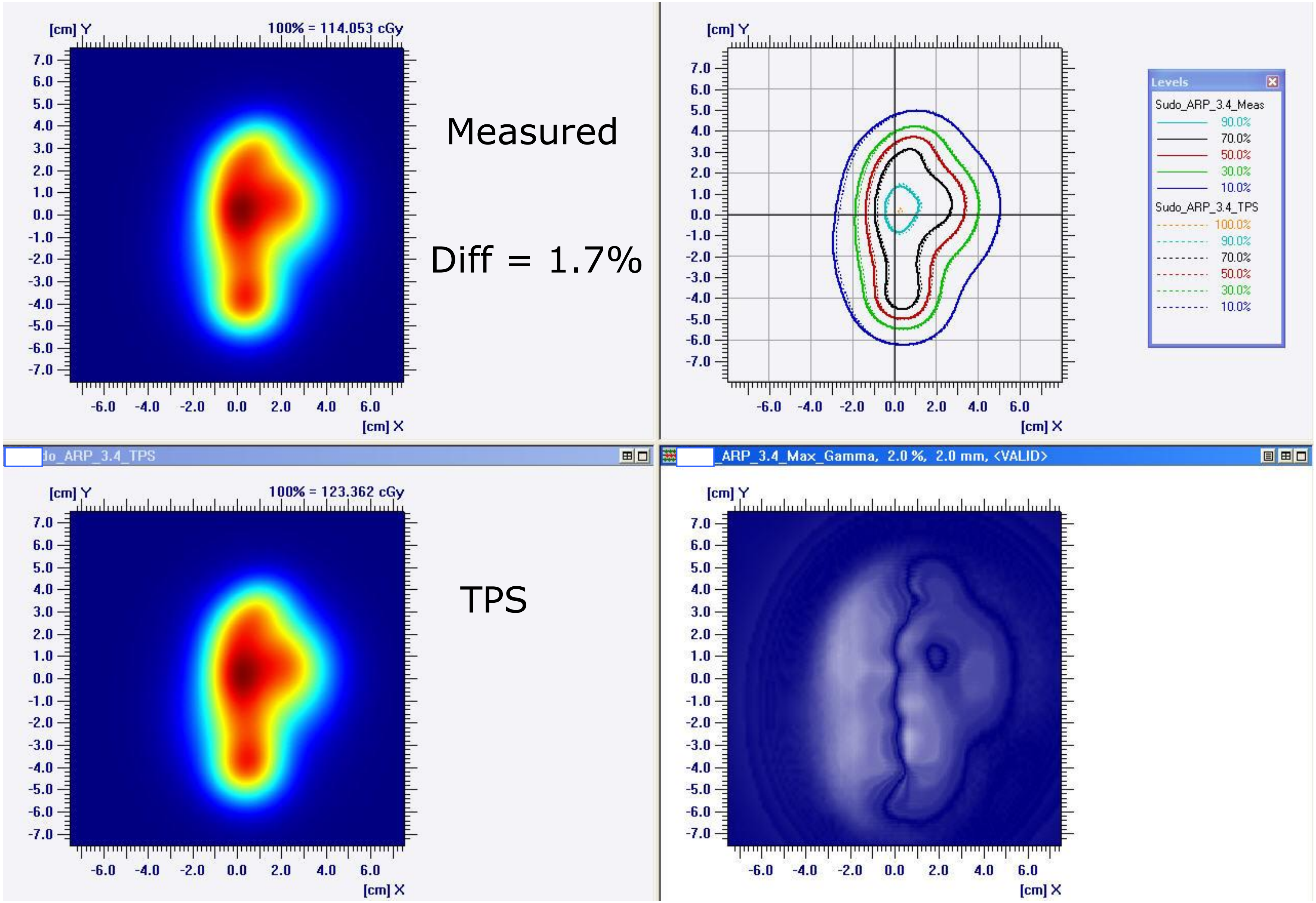




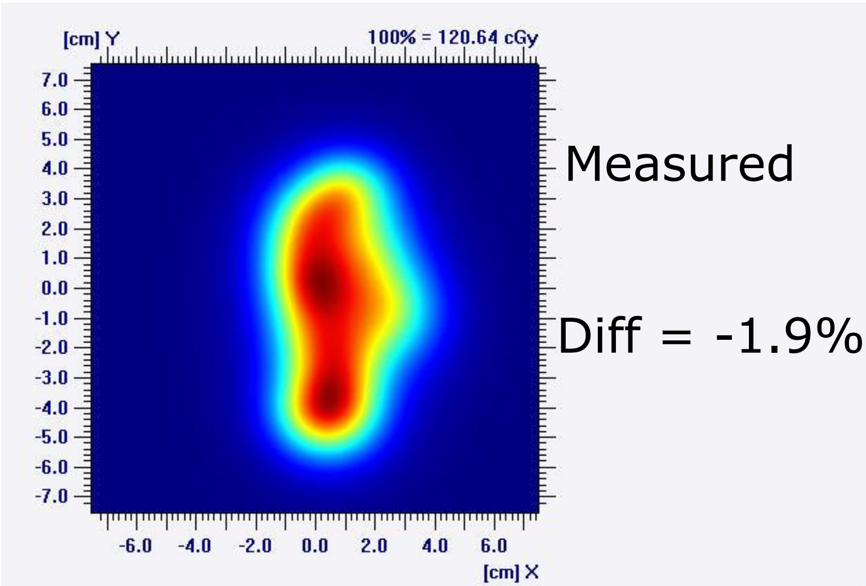
MFO - Field 2 Depth Dose

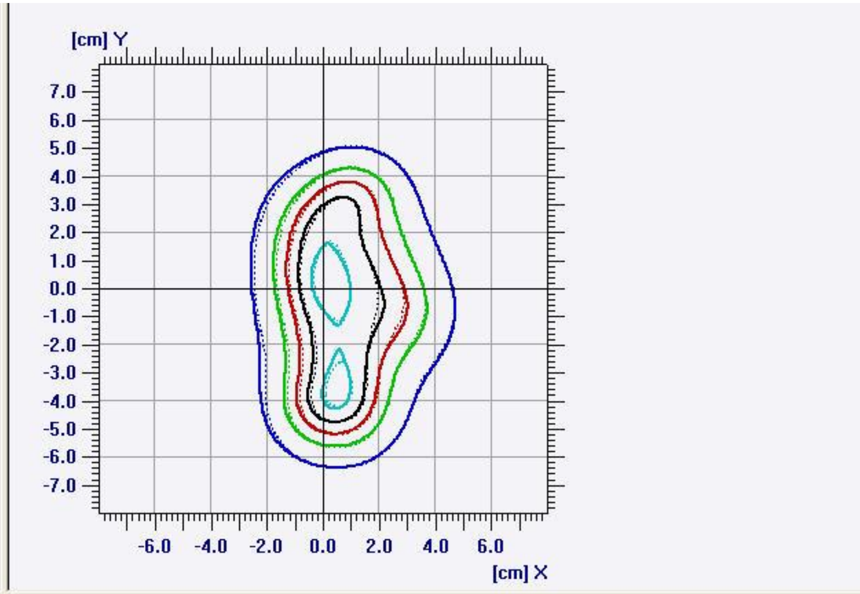


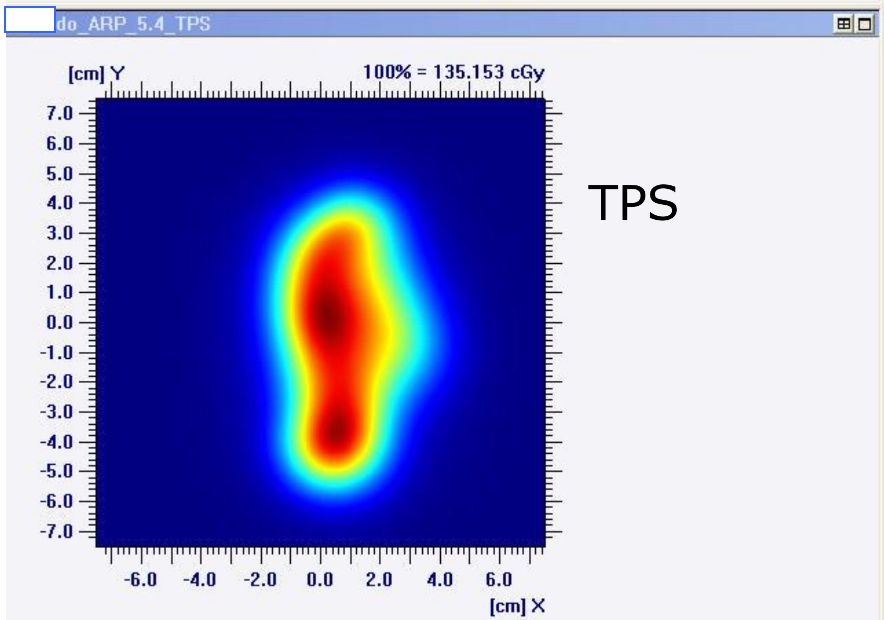
MFO - Field 1 Depth = 3.4 cm

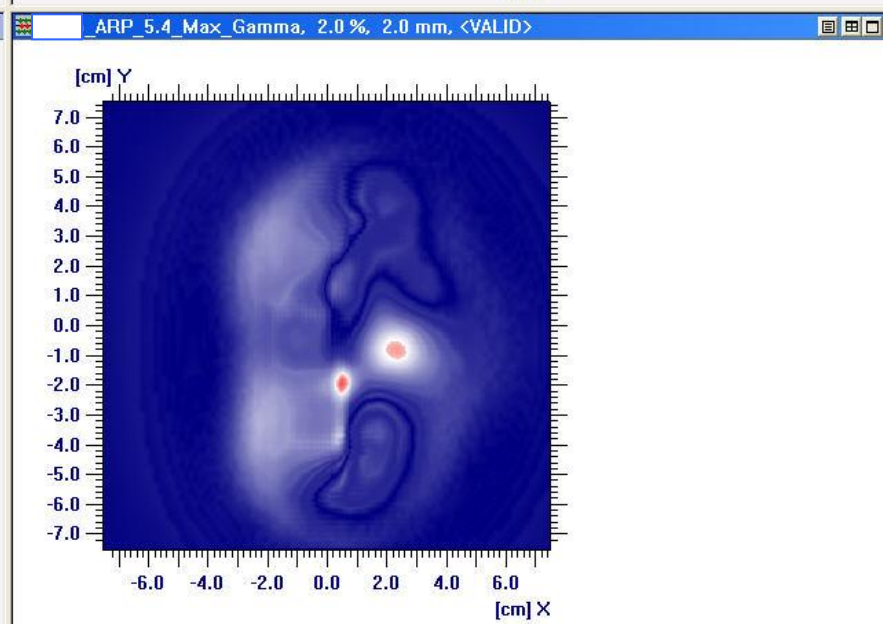


MFO - Field 1   Depth = 5.4 cm

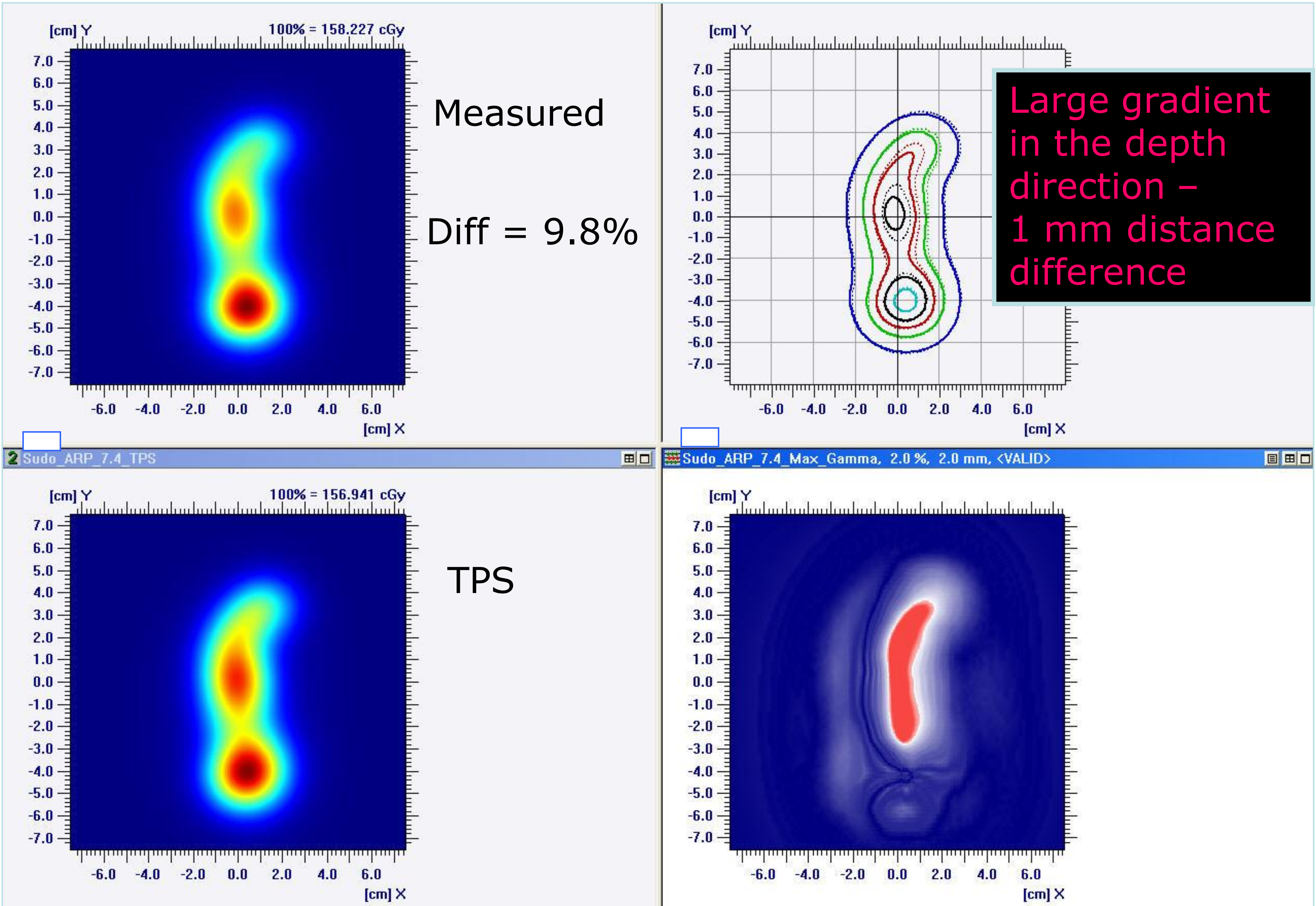








MFO - Field 1   Depth = 7.4 cm



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- Dynamic beam scanning systems can be used to achieve the desired lateral dose distribution at specific depths by magnetically deflecting the beam across the target. Several different techniques can be used to change the beam penetration depth. The advantages of beam scanning are flexibility (no patient-specific devices required), IMPT can be undertaken, there is better dose conformation to the target volume, and the background dose to the patient and the activation of beam line elements are reduced.
- However, there are specific problems related to the patient and organ motion, which can be minimized by multiple “repainting” of the target volume.
- Scanning beams are not suitable for treating small lesions.

Summary

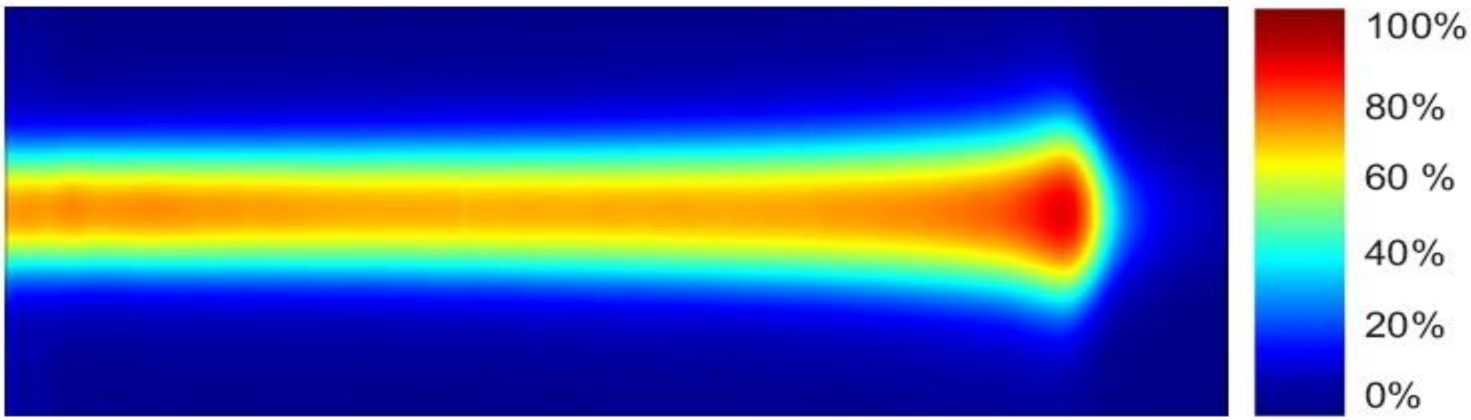
- The planning systems are behind the delivery systems. Is what you see, what you get?
- A good 3D dosimetry system would be very helpful, as opposed to the 1D or 2D systems which we are using.
- Current challenges include small highly modulated fields, motion management, and shallow depths, which may be helped by the use of an Energy Absorber.
- MDACC will treat at least one MFO patient by the end of the year 2010 with agreement between calculated and measured dose within 5%.

Acknowledgements

- The entire proton clinical physics staff, including Ron, Narayan, Falk, Jim Lii, Richard Amos, Richard Wu, Kazumichi, the physics proton fellows, the physics assistants and the post-docs.
- The support fro Gabriel, Dr. U. Titt, Dr. Mohan, and others on the main campus.
- Varian Medical Systems who continues to work with us to provide a TPS which meets our expectations and who supported this presentation.

The Discrete Spot

30 cm x 30 cm field at isocenter
94 different energies
2.1 sec between energies



Gillin *et al*. Med Phys 2010

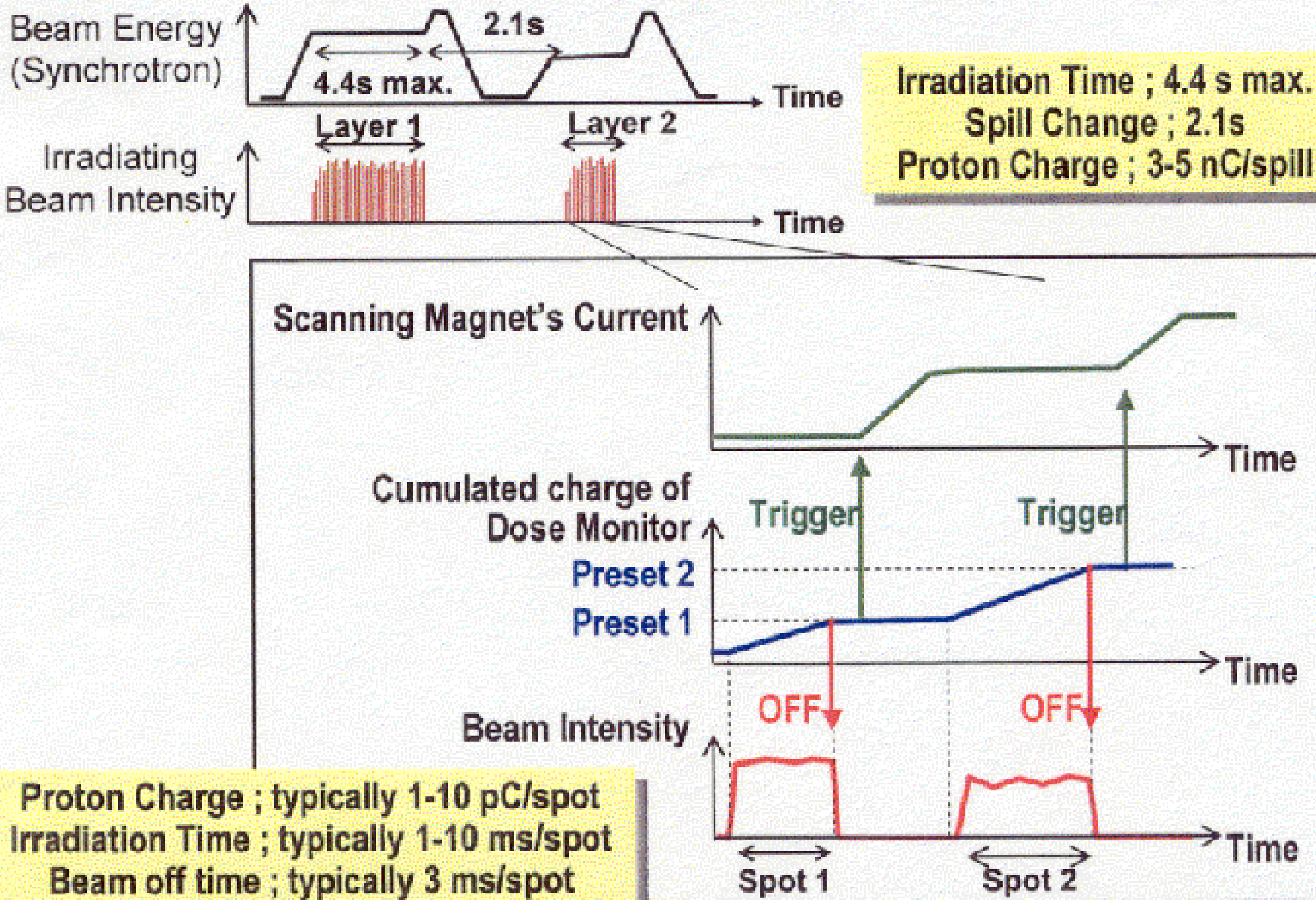
Input Data Requirements by the Treatment Planning System

- Integrated depth dose:
  - Eclipse requires depth dose to be measured with a large p-p chamber,

$$R = 3\sigma_{spot} = \sqrt{\sigma^2_{fluence} + 2\left(0.0307 \times Range\right)^2}$$

  - The measured depth dose should be multiplied by the area of the detector and the integrated dose should be in unit of Gy/MUmm^2.

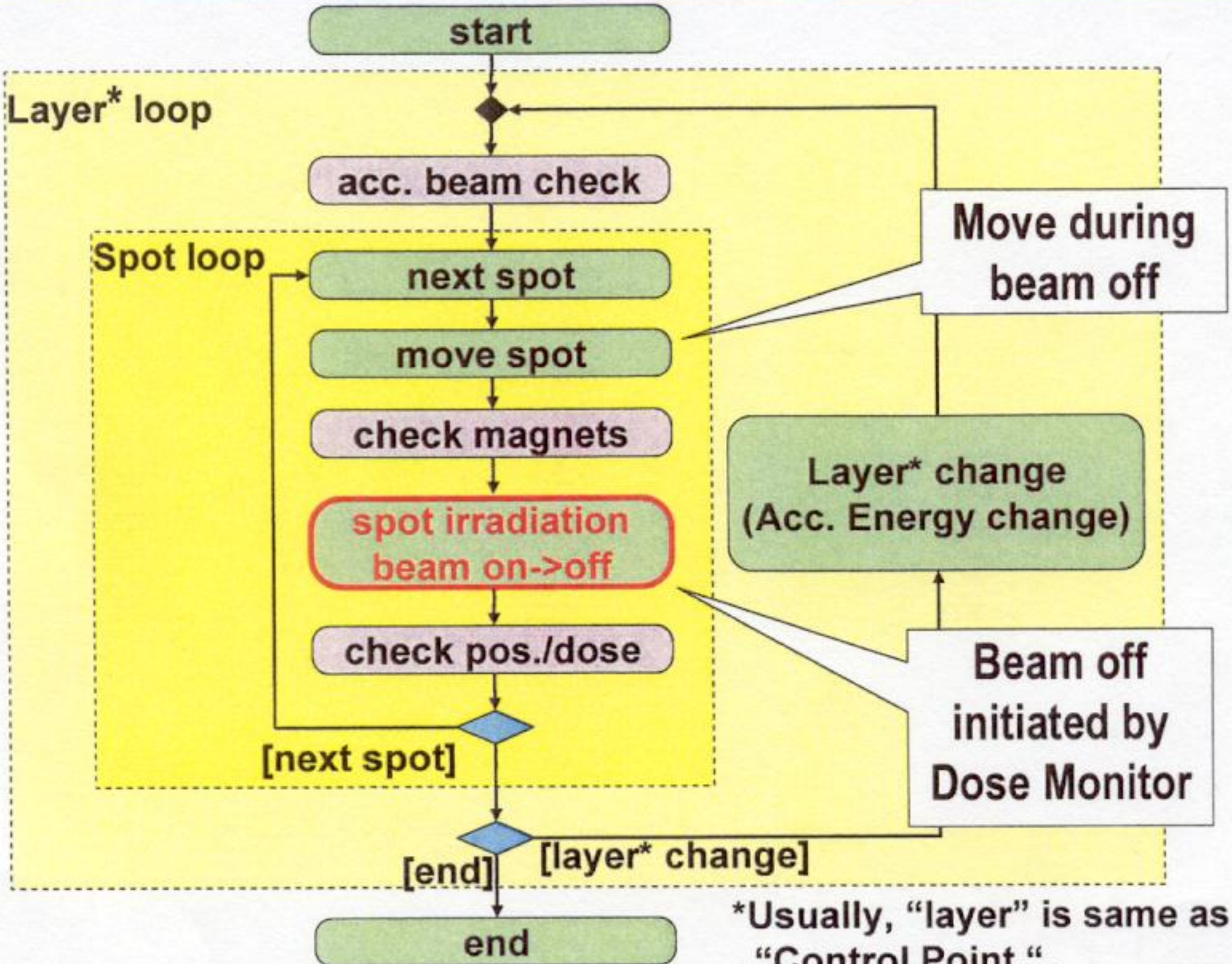
Scanning Timing Chart



Irradiation Time ; 4.4 s max.
Spill Change ; 2.1s
Proton Charge ; 3-5 nC/spill

Proton Charge ; typically 1-10 pC/spot
Irradiation Time ; typically 1-10 ms/spot
Beam off time ; typically 3 ms/spot

Flow Chart



*Usually, "layer" is same as "Control Point ".

Max. MU
per spot:
.04

Min. MU
per spot:
.005

Dose per spot

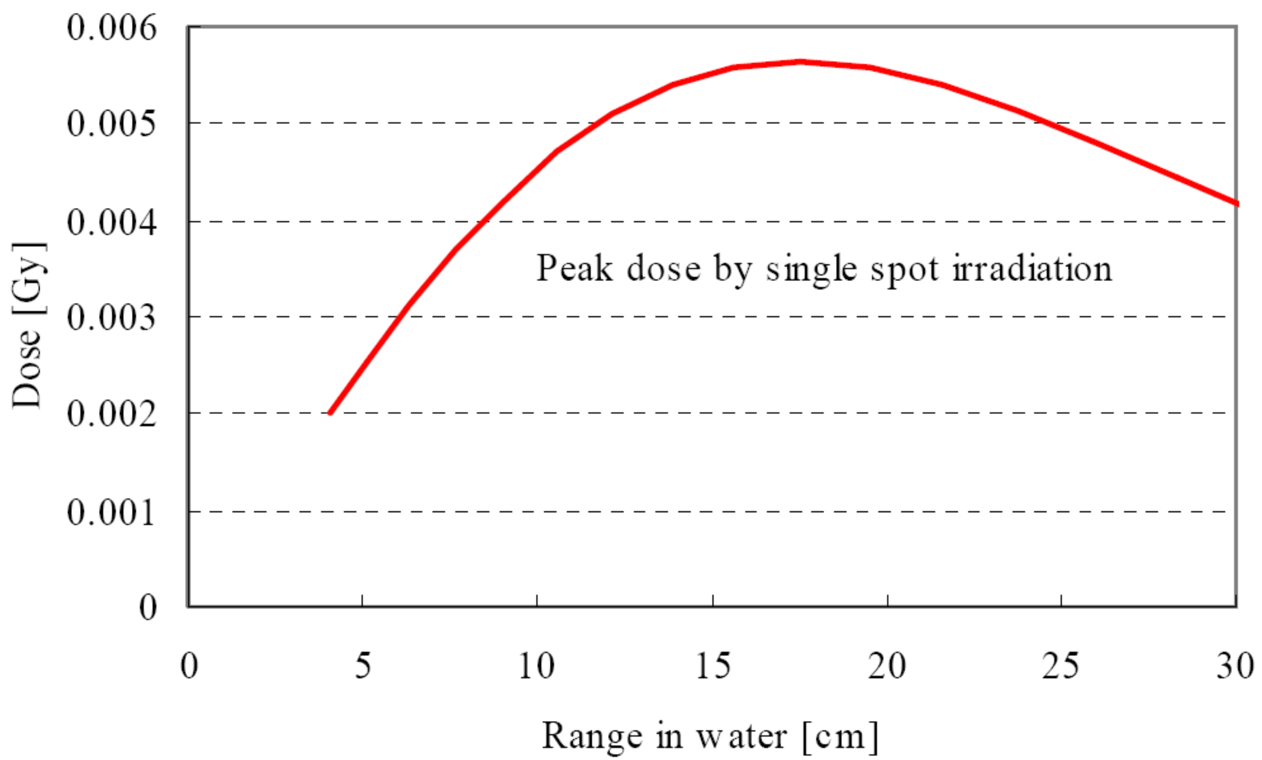
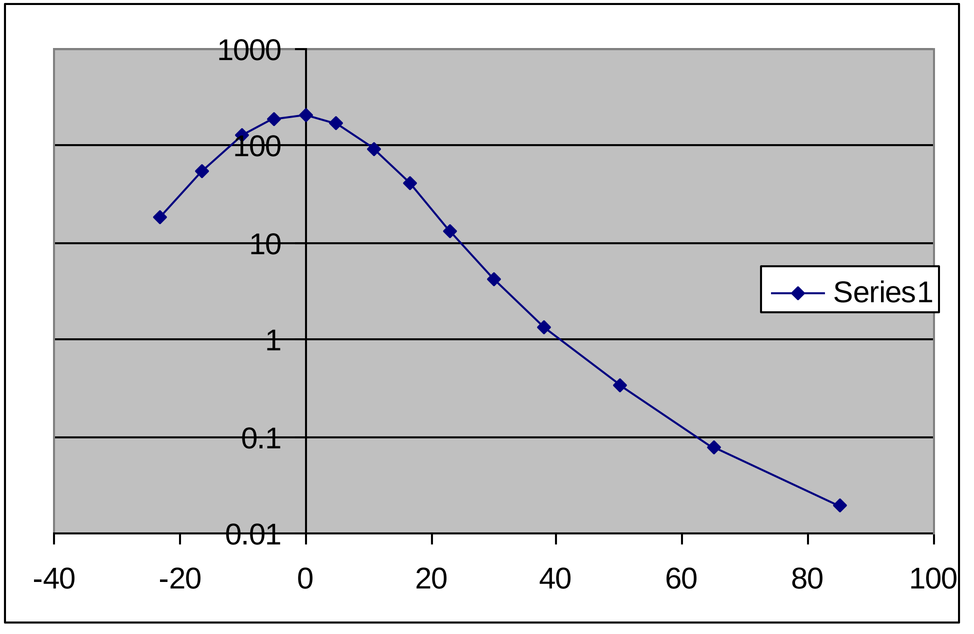


Figure 2 Dose at Bragg Peak delivered by irradiation with spot dose of 100 pC

- Peak ~ 160 MeV
- 110 cGy/MU
- 0.57 cGy/Spot at Min MU 0.005
- 4.6 cGy/Spot at Max MU 0.04

Range 11.0 cm Profile in water



Ion Chamber: One point at a time

Semi-log scale: There is a small dose contribution far from the spot.

Pencil Beam Scanning Nozzle

Profile monitor

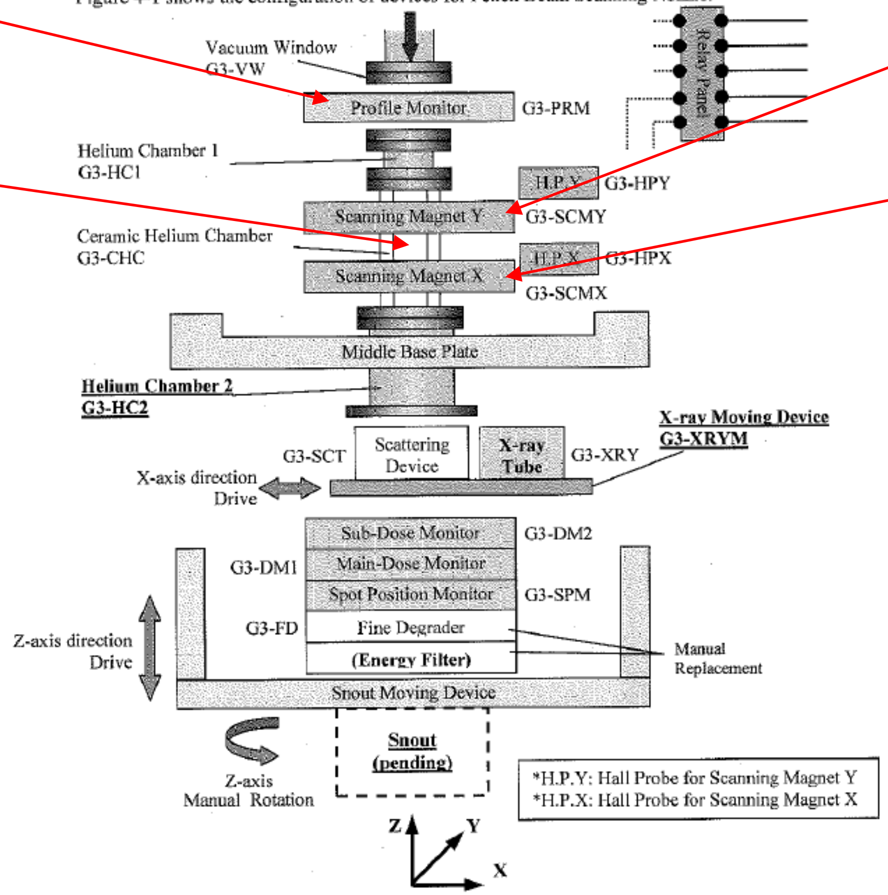
4.1. Configuration of the devices for Pencil Beam Scanning Nozzle

Figure 4-1 shows the configuration of devices for Pencil Beam Scanning Nozzle.

Y scanning magnet

Helium chamber

X scanning magnet



Spot position monitor

Main and sub-dose monitor

Input Data Requirements by the Treatment Planning System

- In air profiles:
  - At 3 to 5 different positions from isoceter (e.g., ±200, ± 00, and ±0 mm) for every 10-20 MeV in both directions.
  - If a range shifting device is used, 2~3 complete data sets for 2~3 different thicknesses.

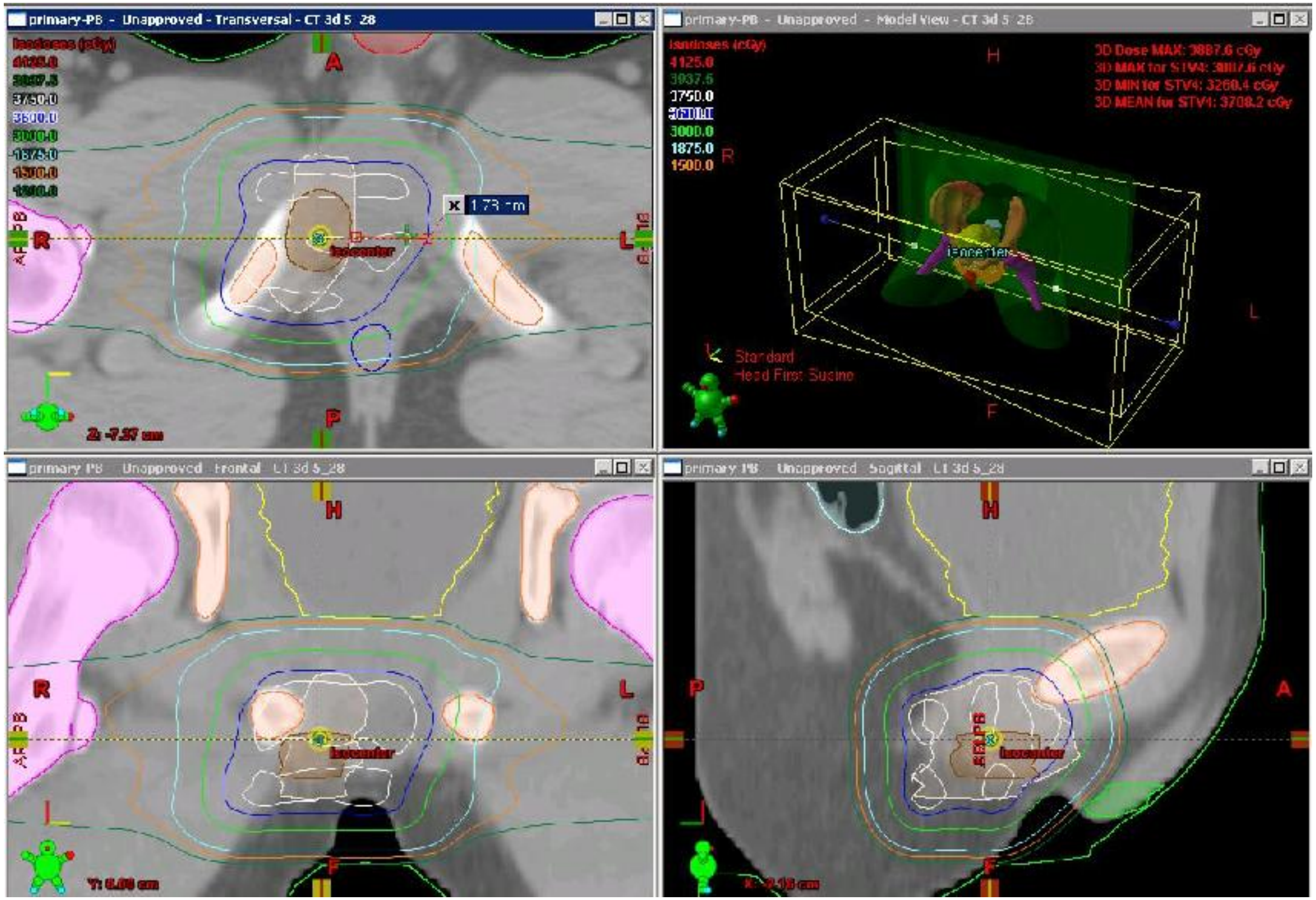
Scanning Beam
9 YO Recurrent
Rhabdomyosarcoma JL

- Ranges 12 cm to 19 cm
- 20 layers 652 spots R and 17 layers 642 spots L
- TPS dose 88.8 cGy – 20.1 MU
- Treatment delivery time: < 1 minute

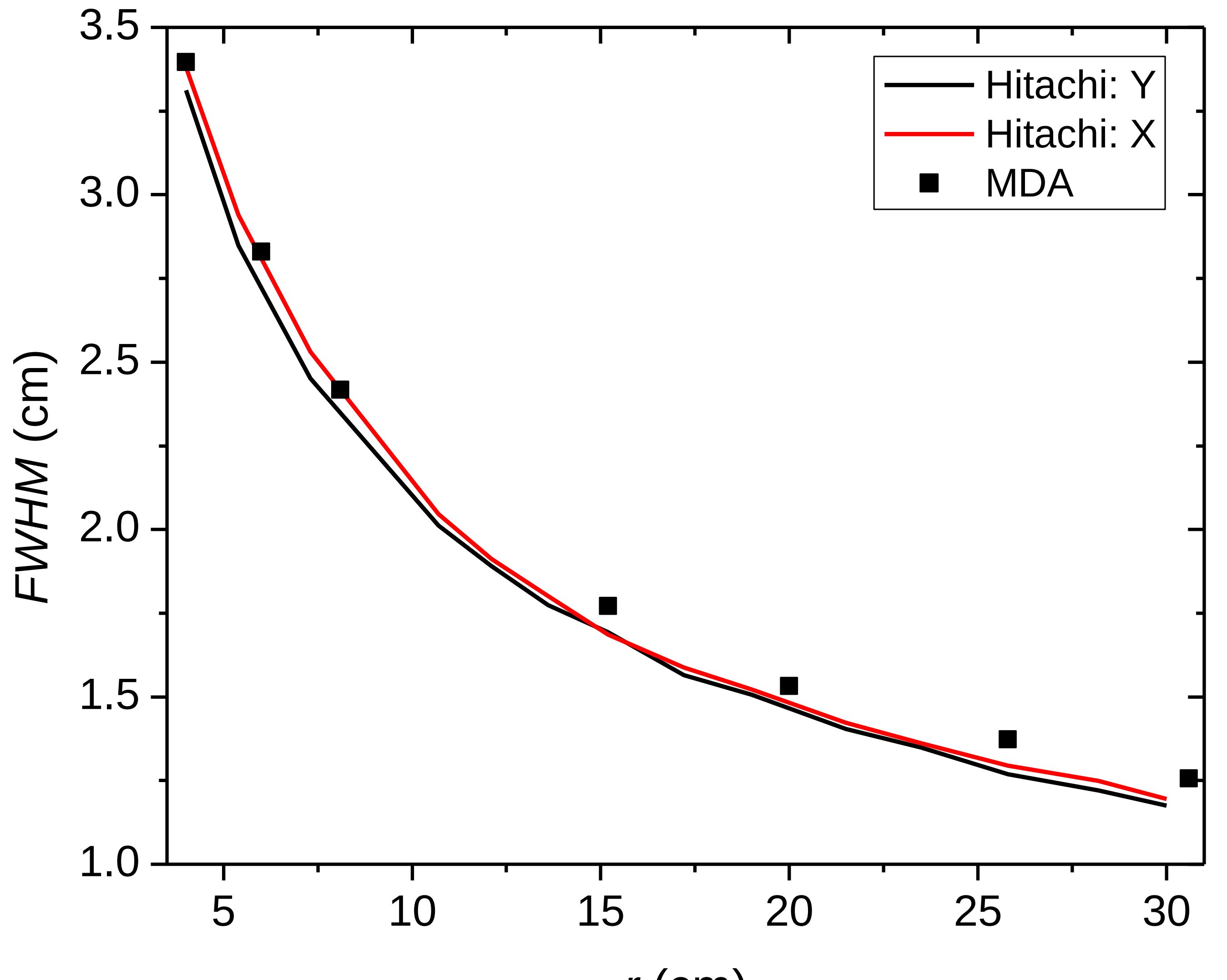
BLLPB Field 17 CP JL

CP	Spot	Energy (MeV)	Weight
0	30	178.6	0.057048
1	37	176.2	0.068263
2	69	173.7	0.129447
3	82	171.3	0.148287
4	53	168.8	0.084155
5	53	166.2	0.086347
6	61	163.9	0.098074
7	48	161.6	0.065658
8	50	159.5	0.068745
9	40	157.4	0.050372
10	37	155.3	0.045654
11	31	153.2	0.038943
12	22	151.0	0.024910
…			
17	3	143.2	0.003271

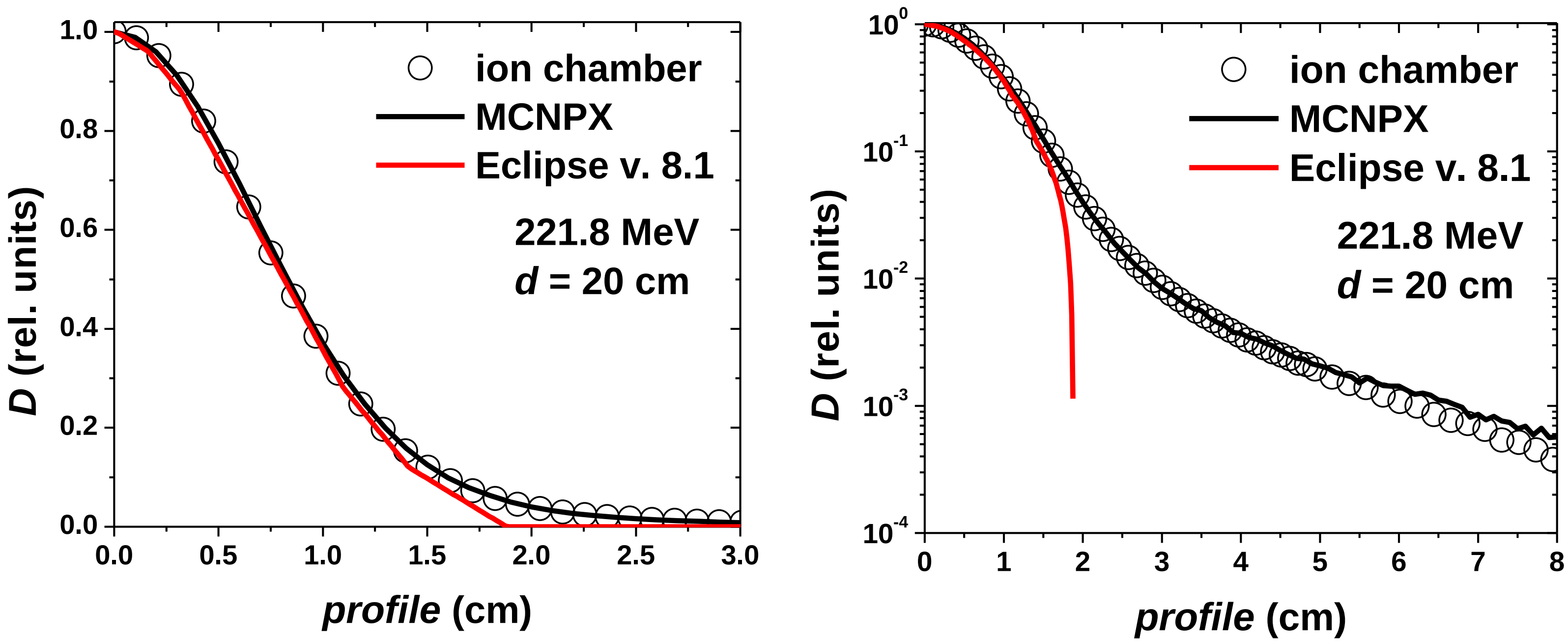
Recurrent Rhabdomyosarcoma
9 YO Male Scanning Beam



FWHM of a single spot in air for protons with ranges of 4 cm to 30.6 cm

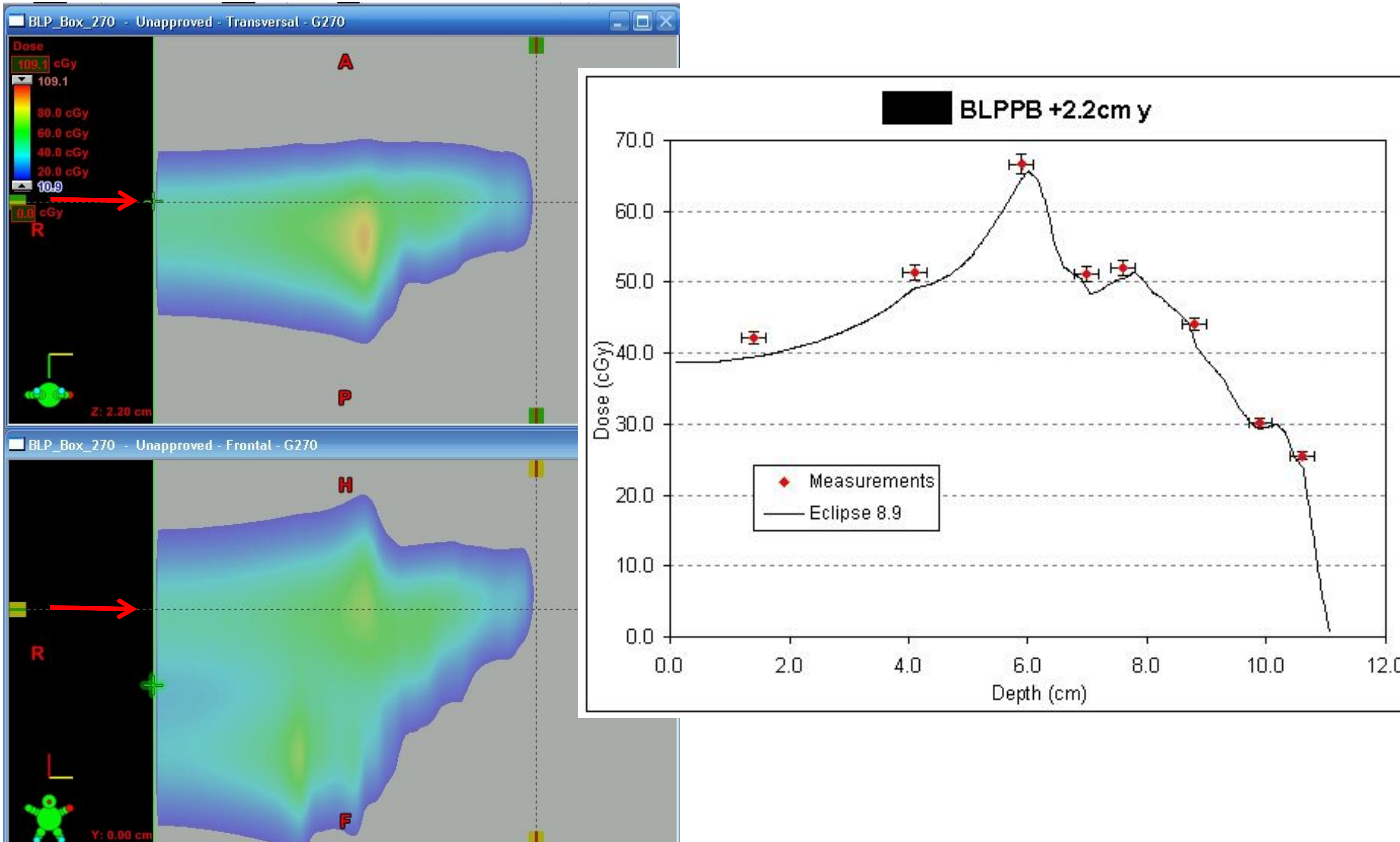


Lateral profiles in water at 20 cm for 221.8 MeV

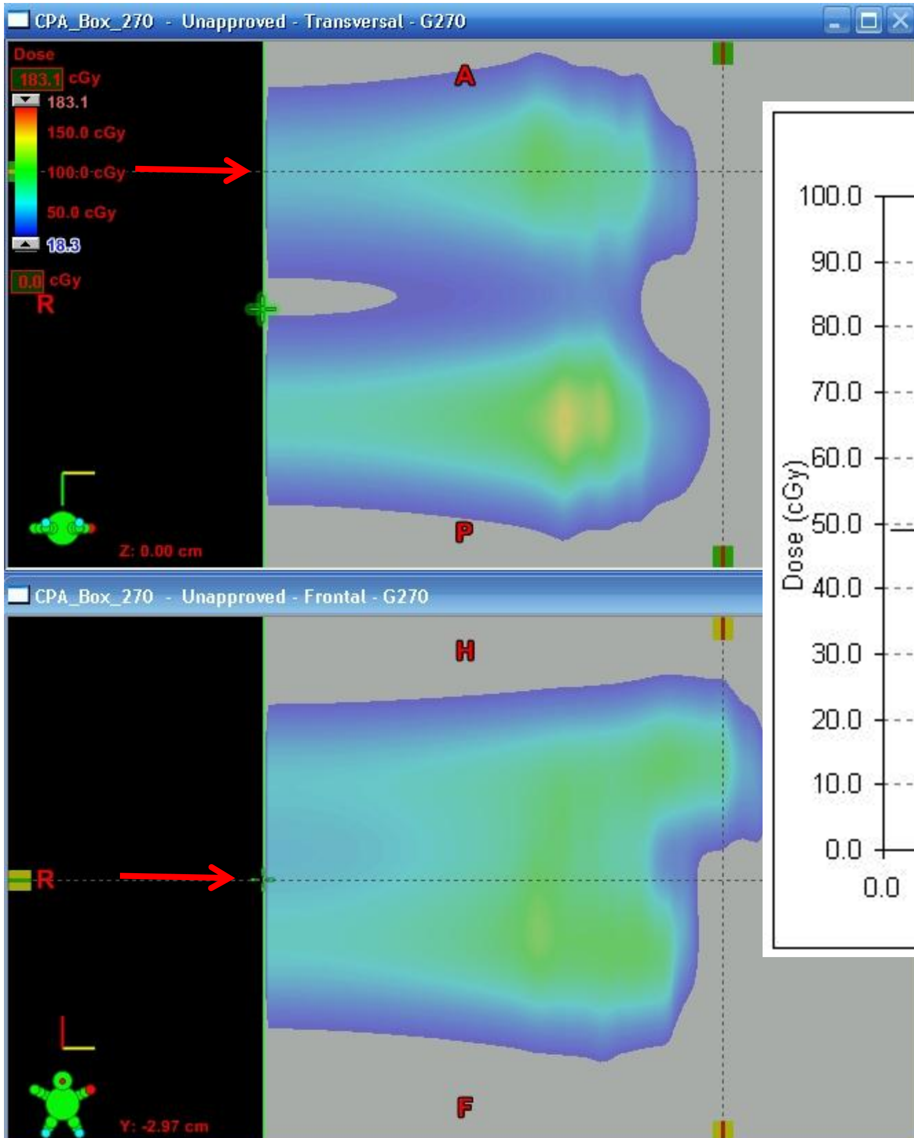


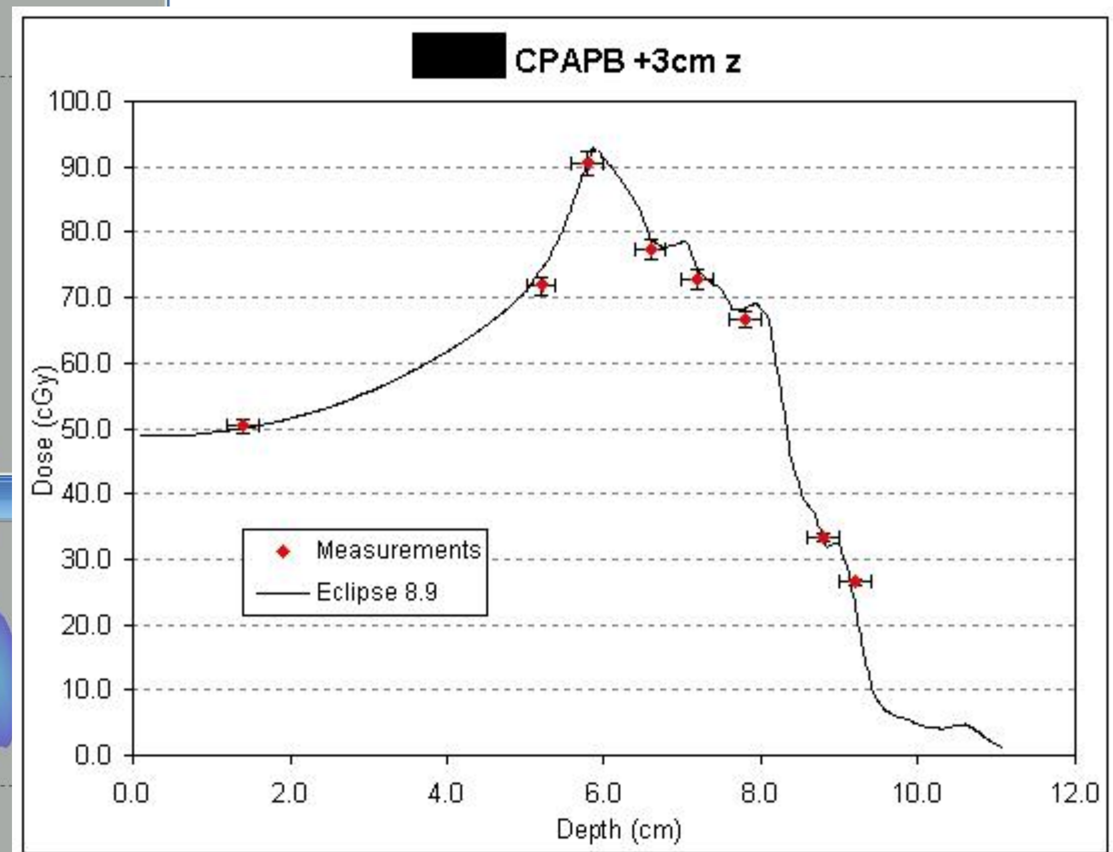
Courtesy: G. O. Sawakuchi, PhD.

MFO - Field 2   Depth Dose

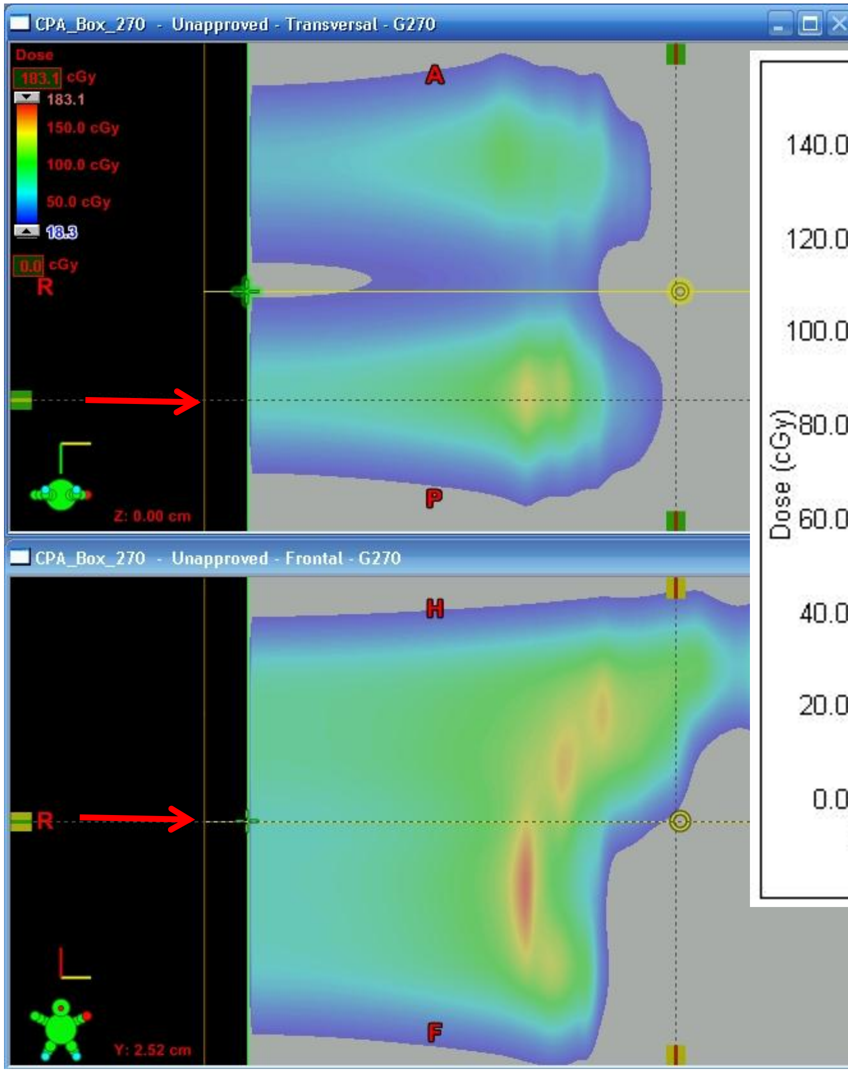


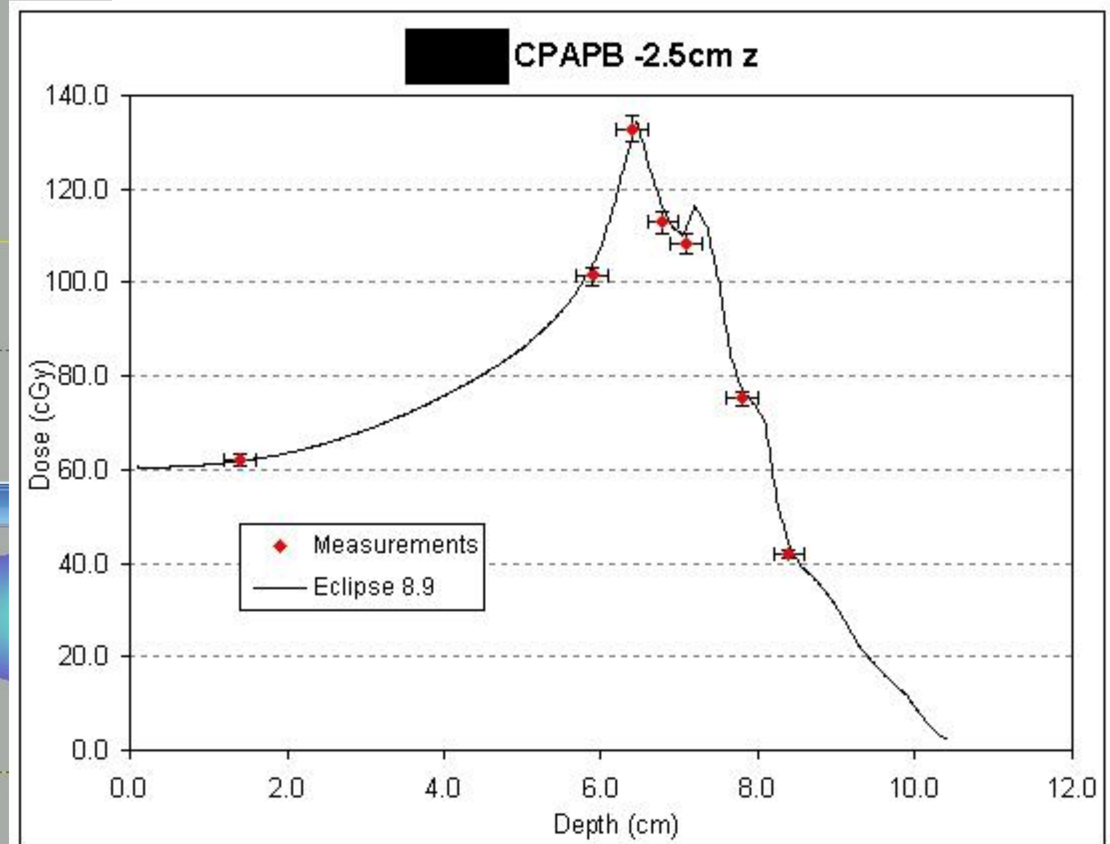
MFO - Field 3   Depth Dose



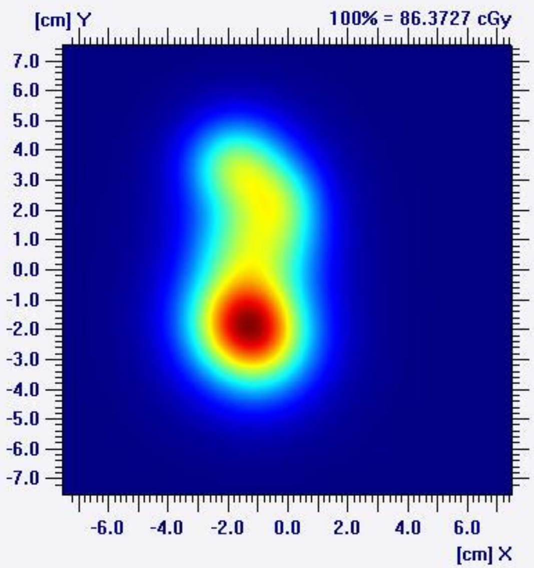


MFO - Field 3 Depth Dose



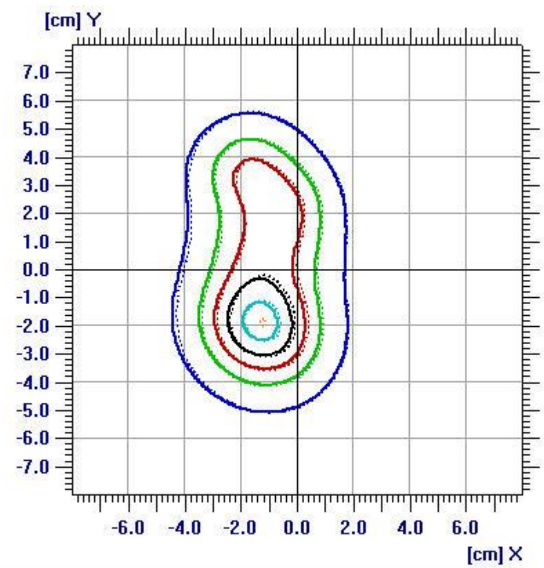


MFO - Field 2 Depth = 3.9 cm

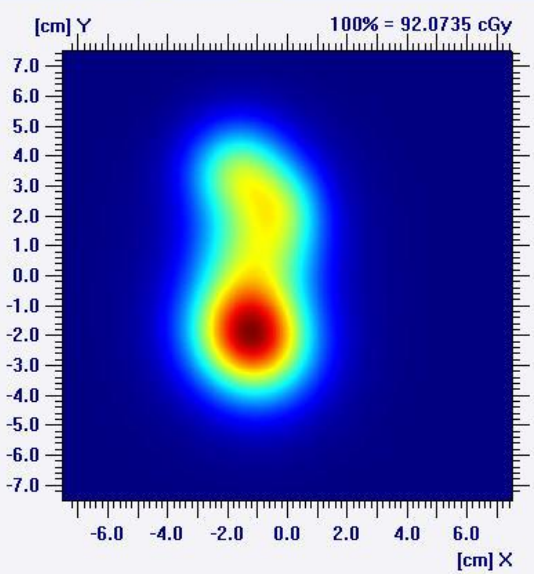


Measured

Diff = 3.1%

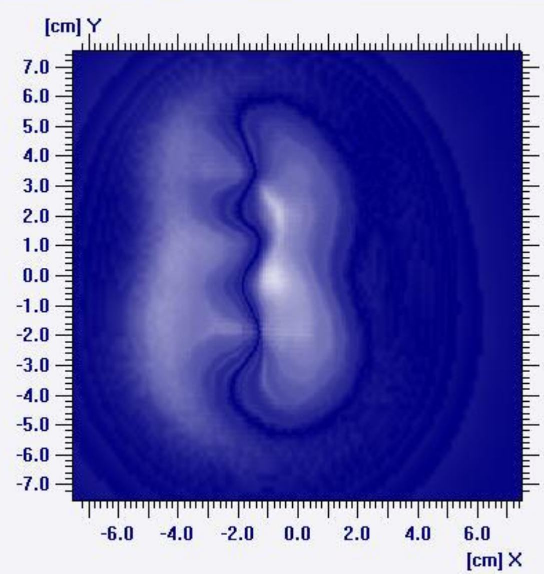


BLP_3.9_TPS

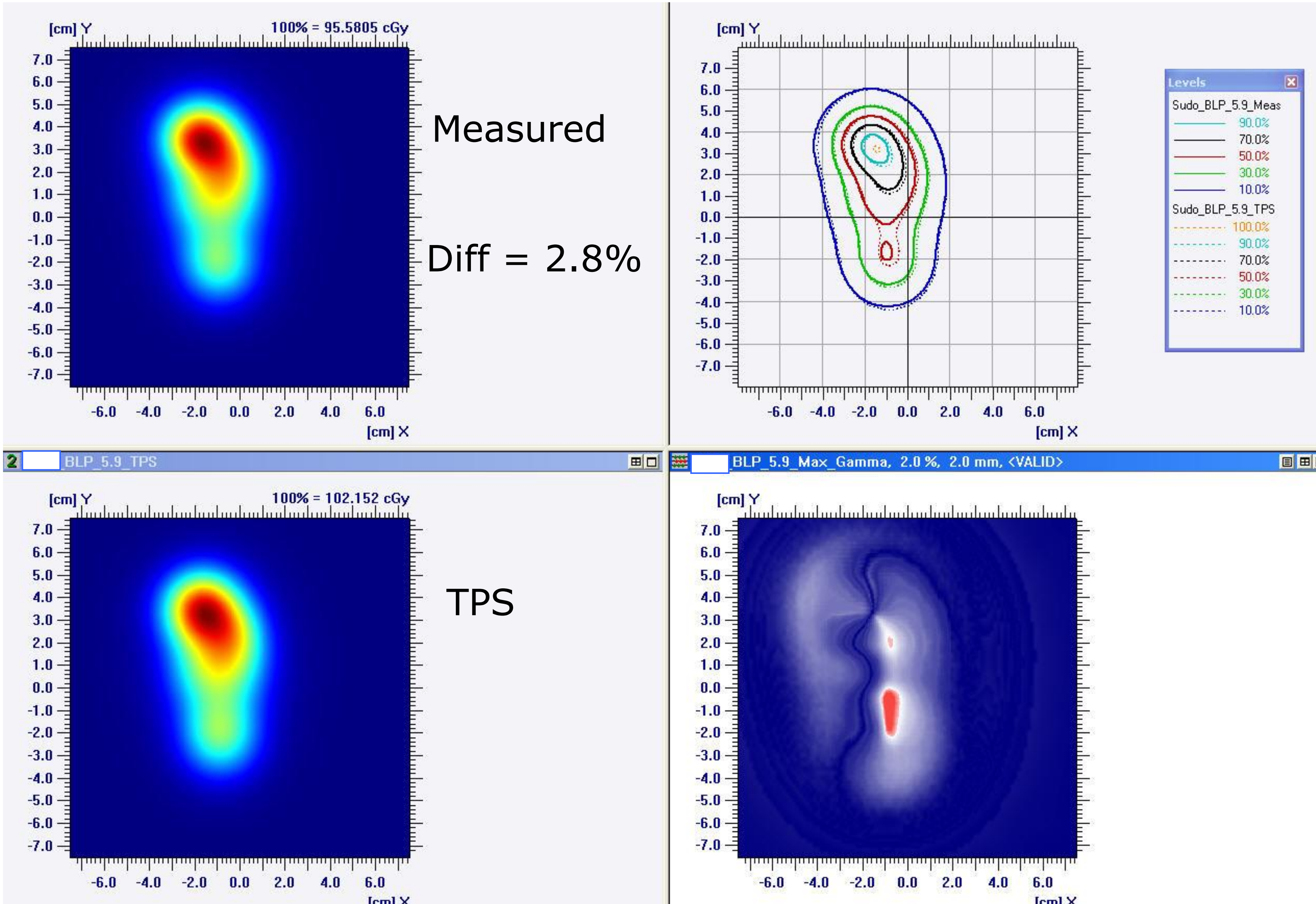


TPS

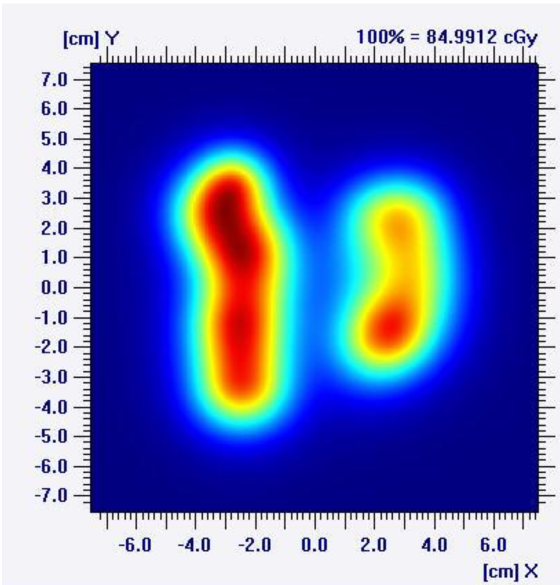
BLP_3.9_Max_Gamma, 2.0 %, 2.0 mm, <VALID>



MFO - Field 2   Depth = 5.9 cm

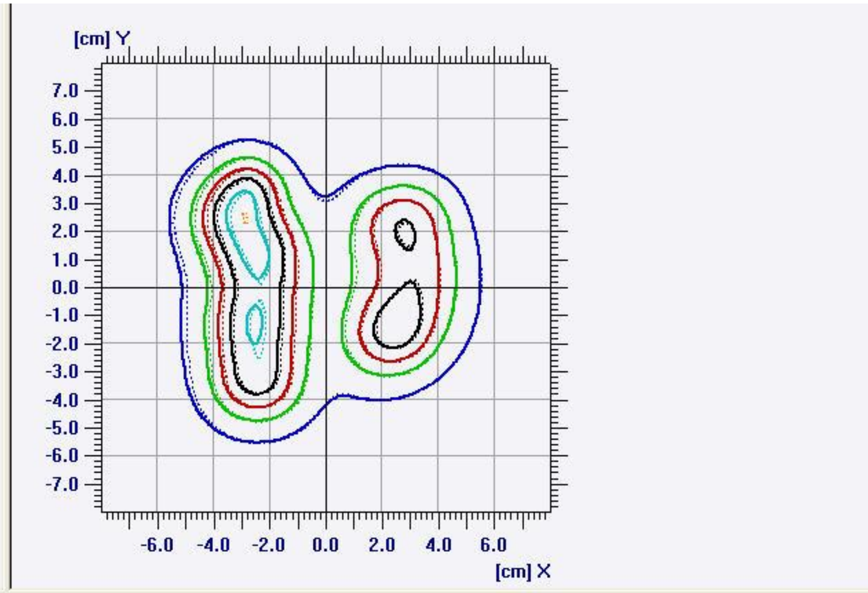


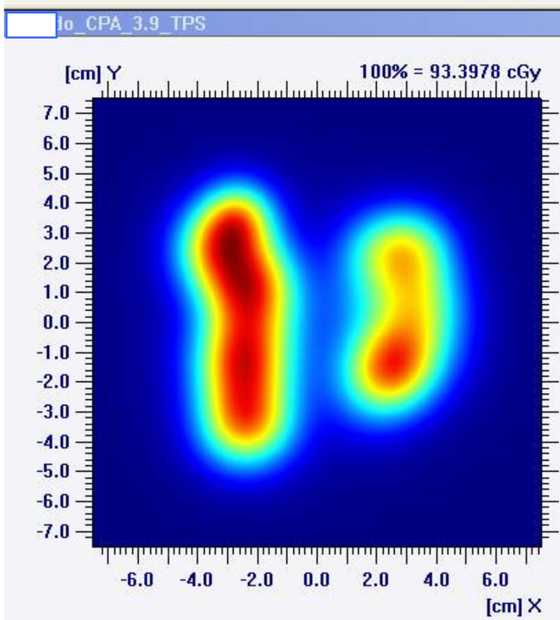
MFO - Field 3   Depth = 3.9 cm



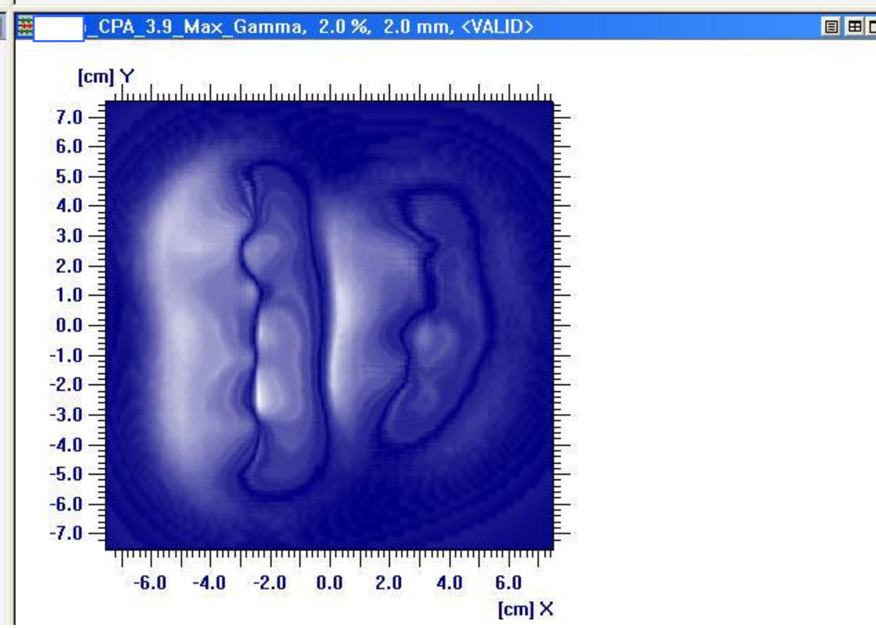
Measured

Diff = 0.1%

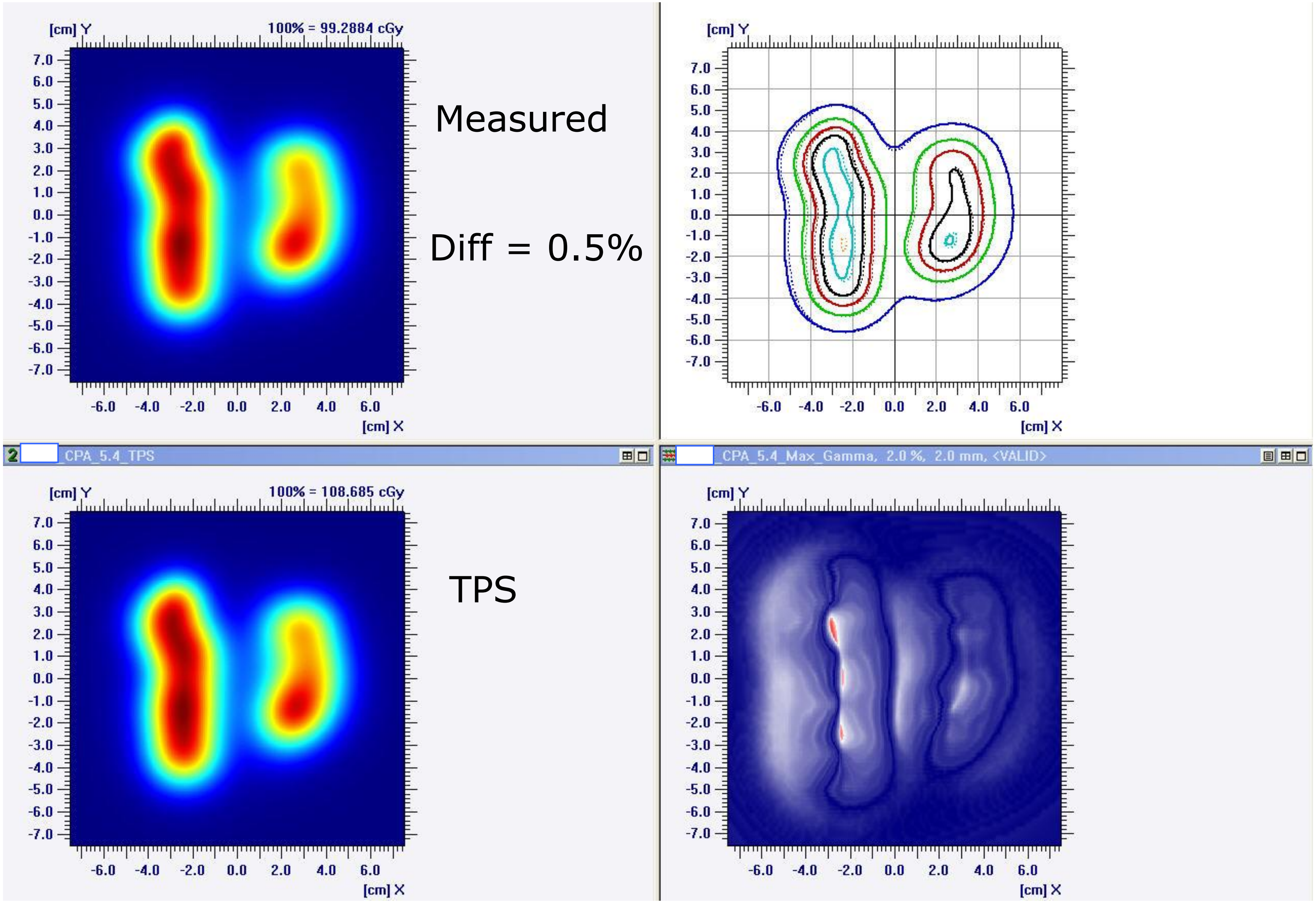




TPS



MFO - Field 3 Depth = 5.4 cm



MFO - Field 3 Depth = 6.9 cm