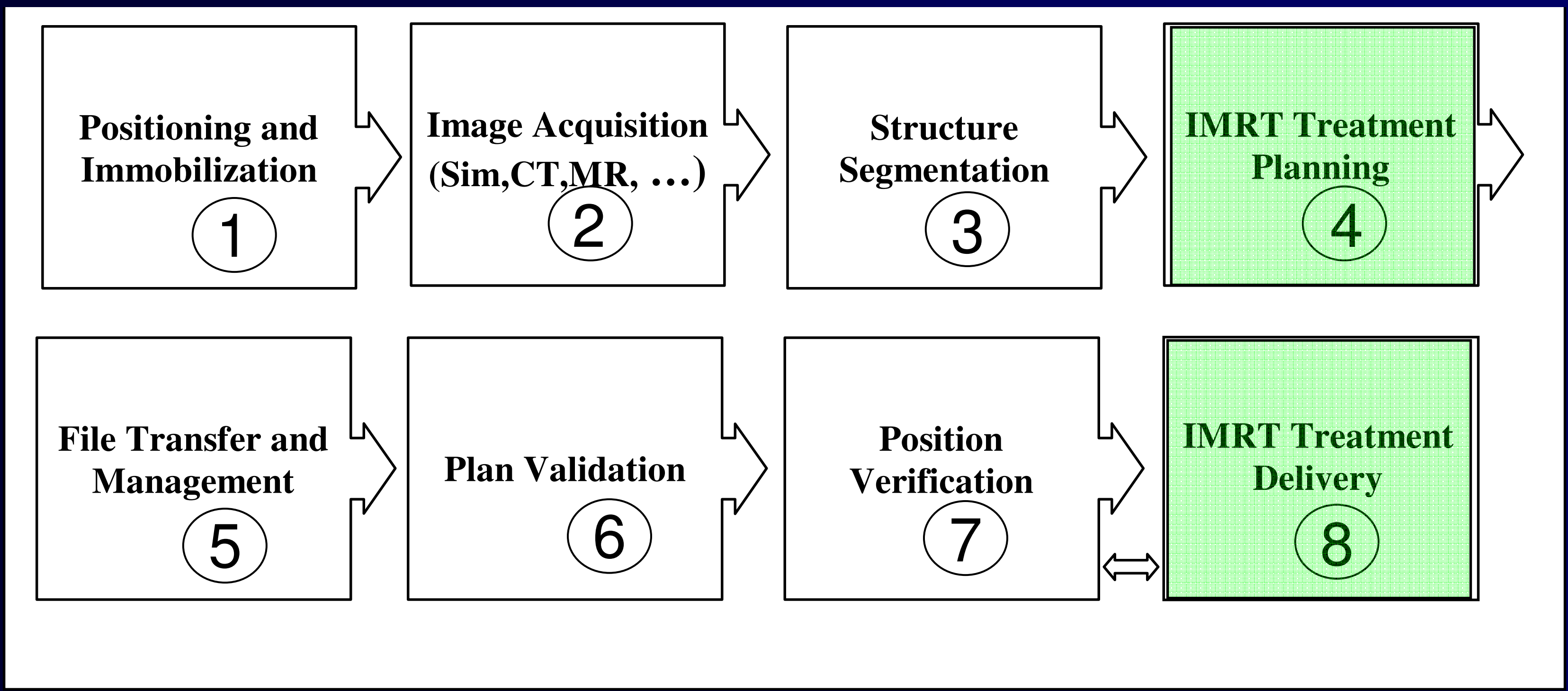
How do we decide on Tolerance Limits for IMRT QA?

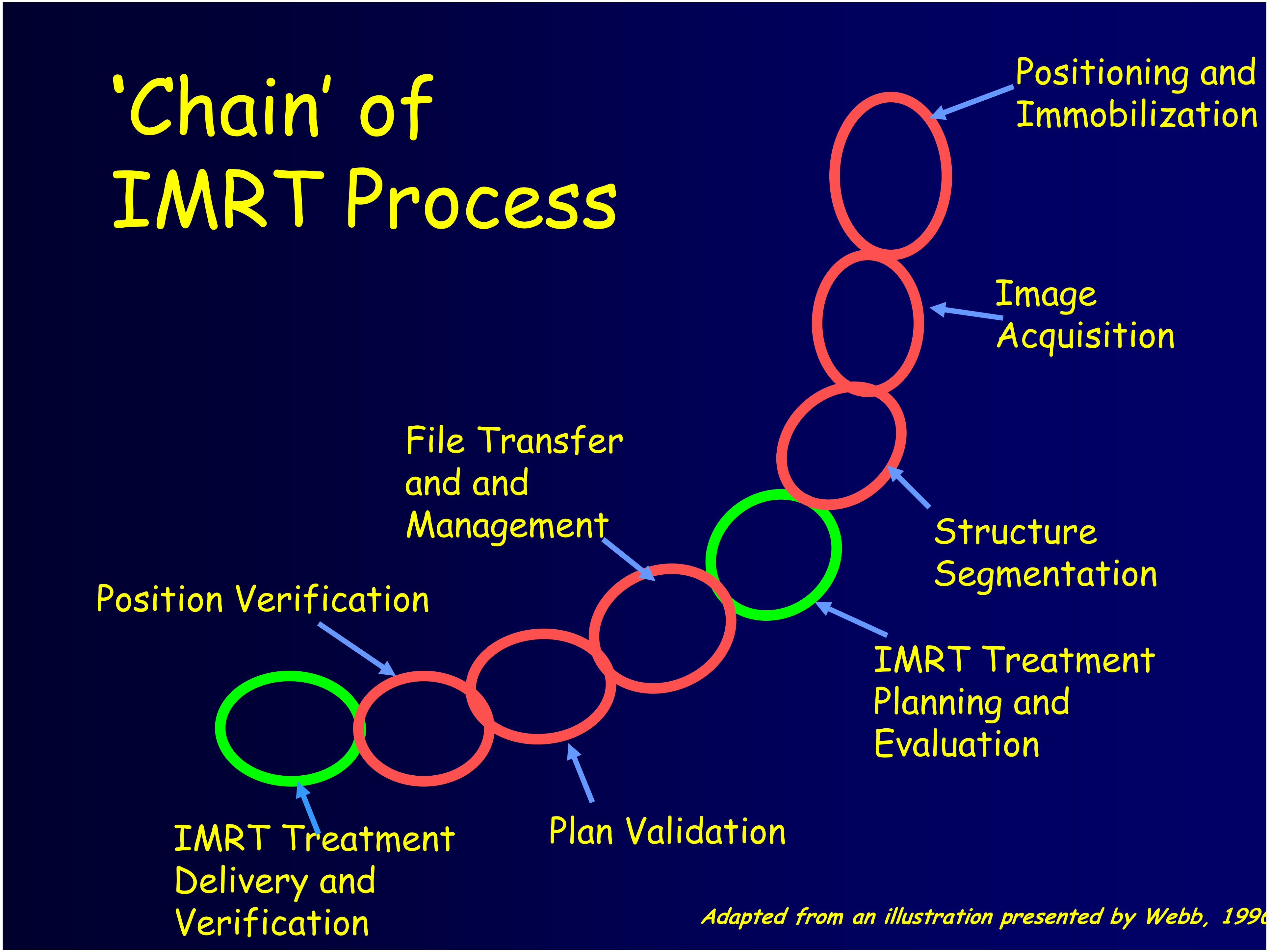
Jatinder R Palta, Ph.D
Siyong Kim, Ph.D.
Department of Radiation Oncology
University of Florida
Gainesville, Florida

Objectives

- Describe the uncertainties in IMRT Planning and Delivery
- Describe the impact of spatial and dosimetric uncertainties on IMRT dose distributions
- Describe the limitations of current methodologies of establishing tolerance limits for IMRT QA
- Describe a new method for evaluating IMRT QA measurements

The Overall Process of IMRT Planning and Delivery



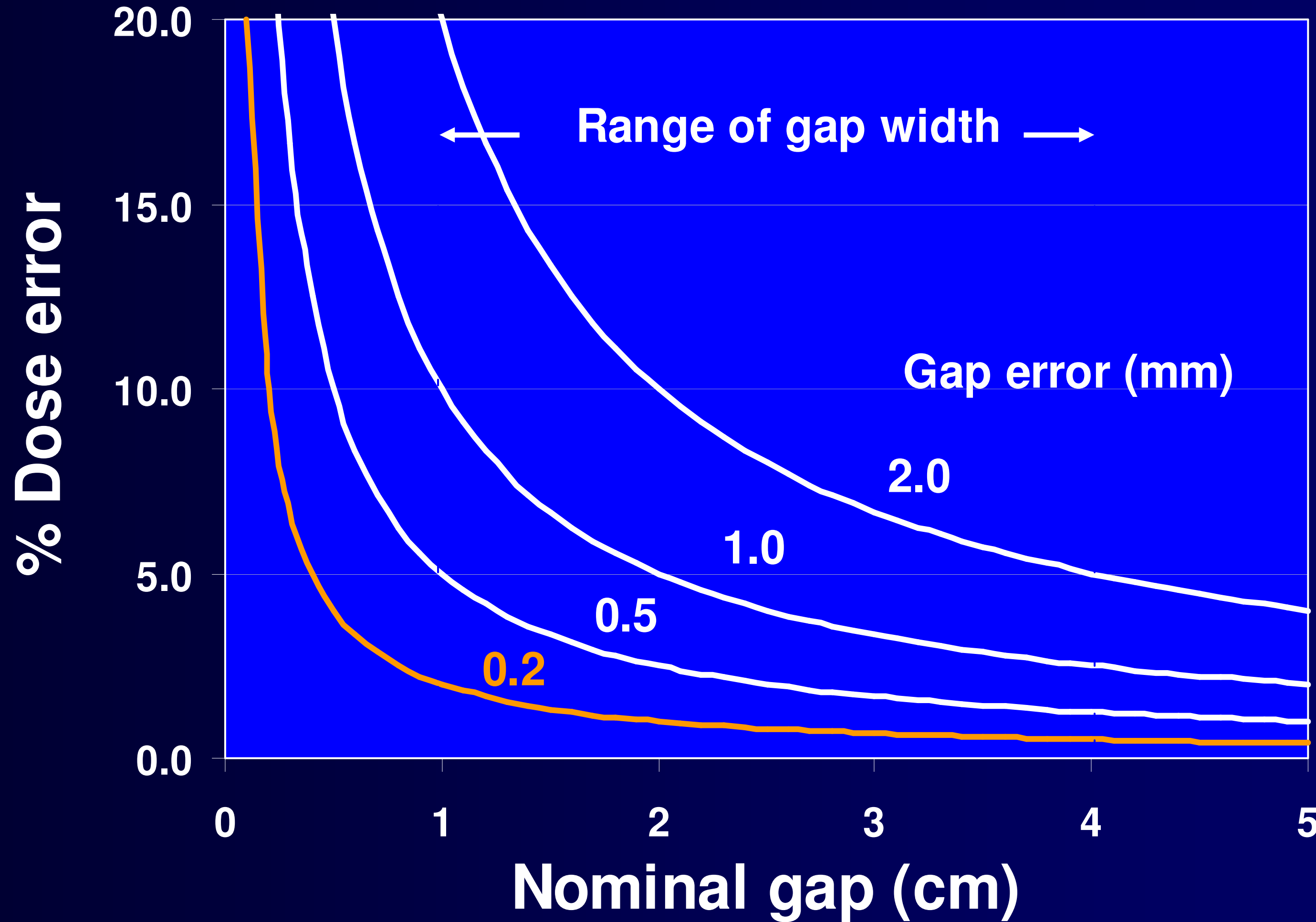

'Chain' of IMRT Process
Positioning and Immobilization
Image Acquisition
Structure Segmentation
IMRT Treatment Planning and Evaluation
File Transfer and and Management
Position Verification
Plan Validation
IMRT Treatment Delivery and Verification
Adapted from an illustration presented by Webb, 1996

Uncertainties in IMRT Delivery Systems

- MLC leaf position
- Gantry, MLC, and Table isocenter
- Beam stability (output, flatness, and symmetry)
- MLC controller

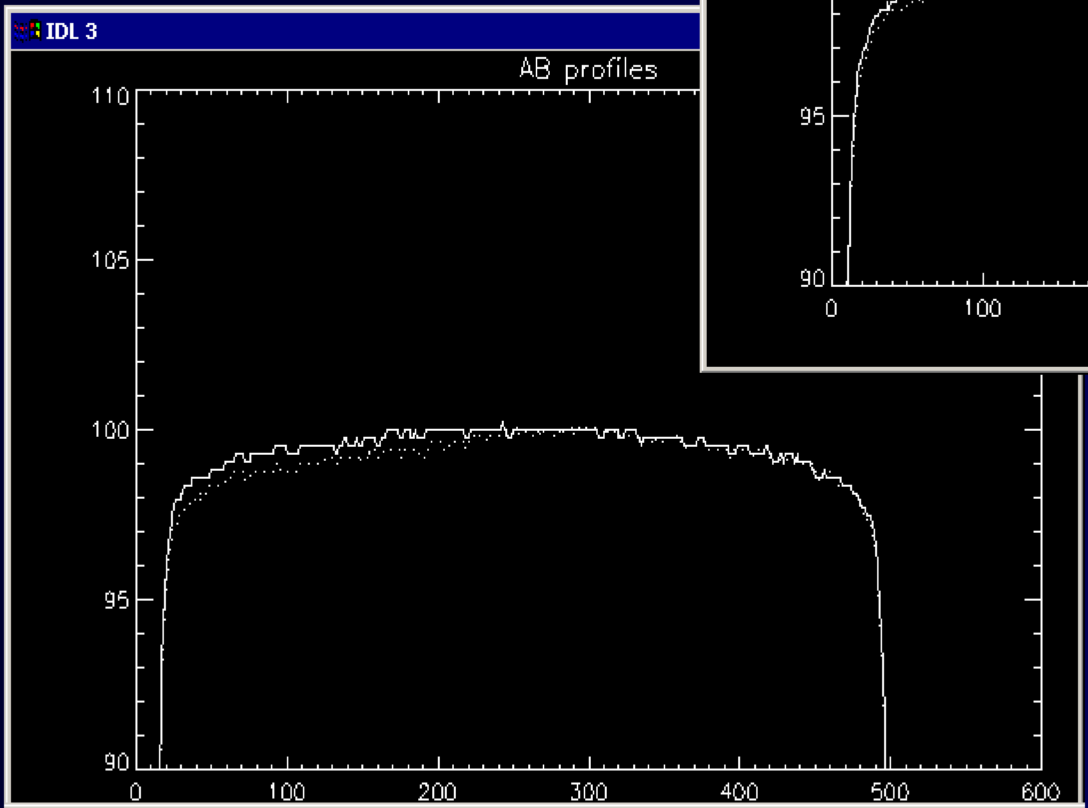
MLC Leaf Position

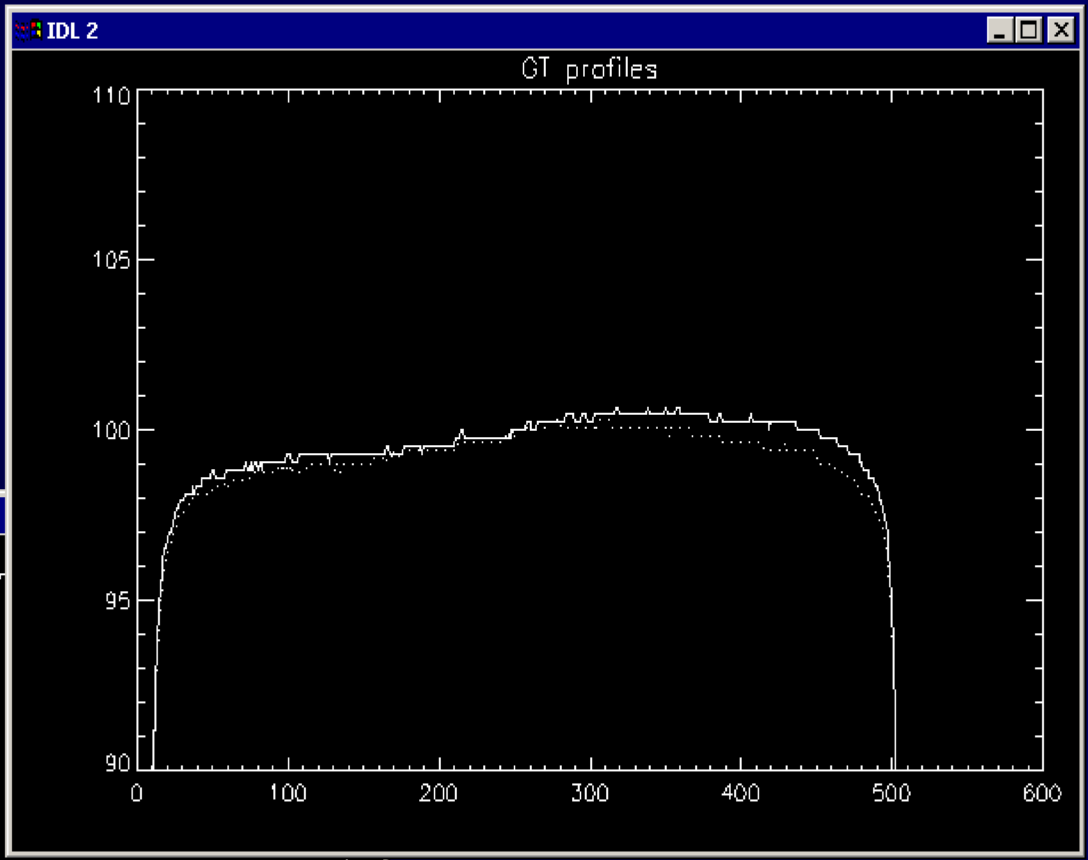
Gap error ⟶ Dose error



Data from MSKCC; LoSasso et. al.

Beam stability for low MU





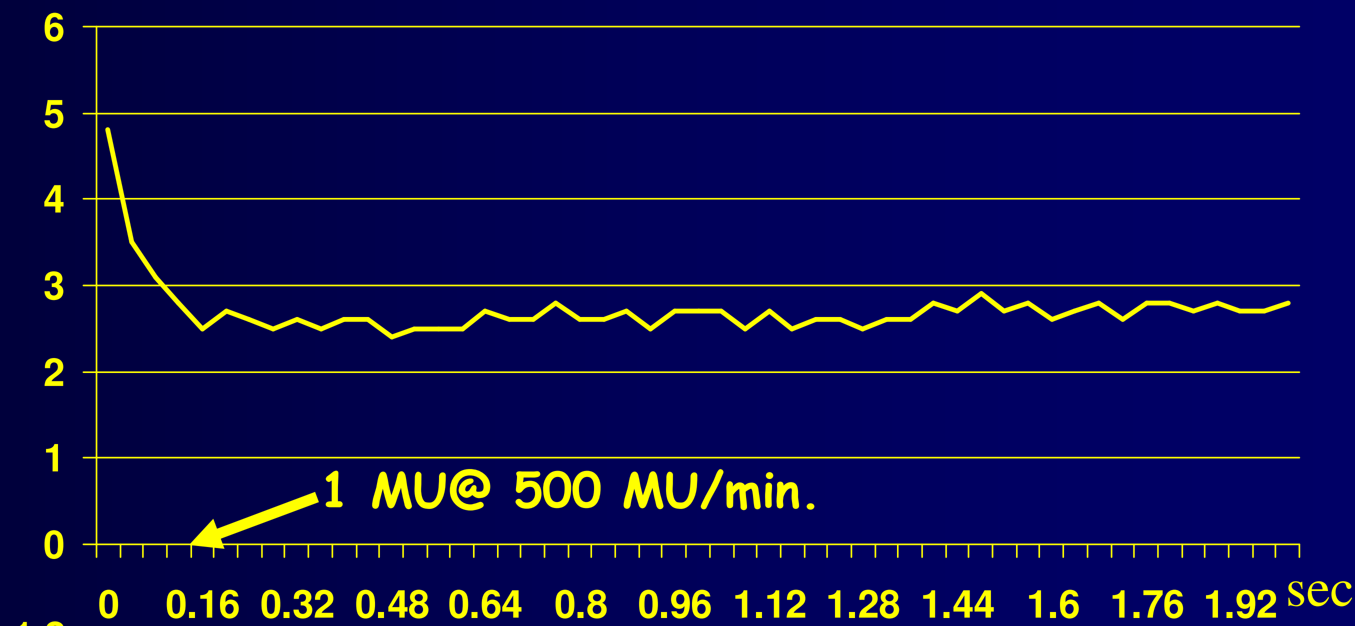
… 40 MU

____ 20x2 MU integrated

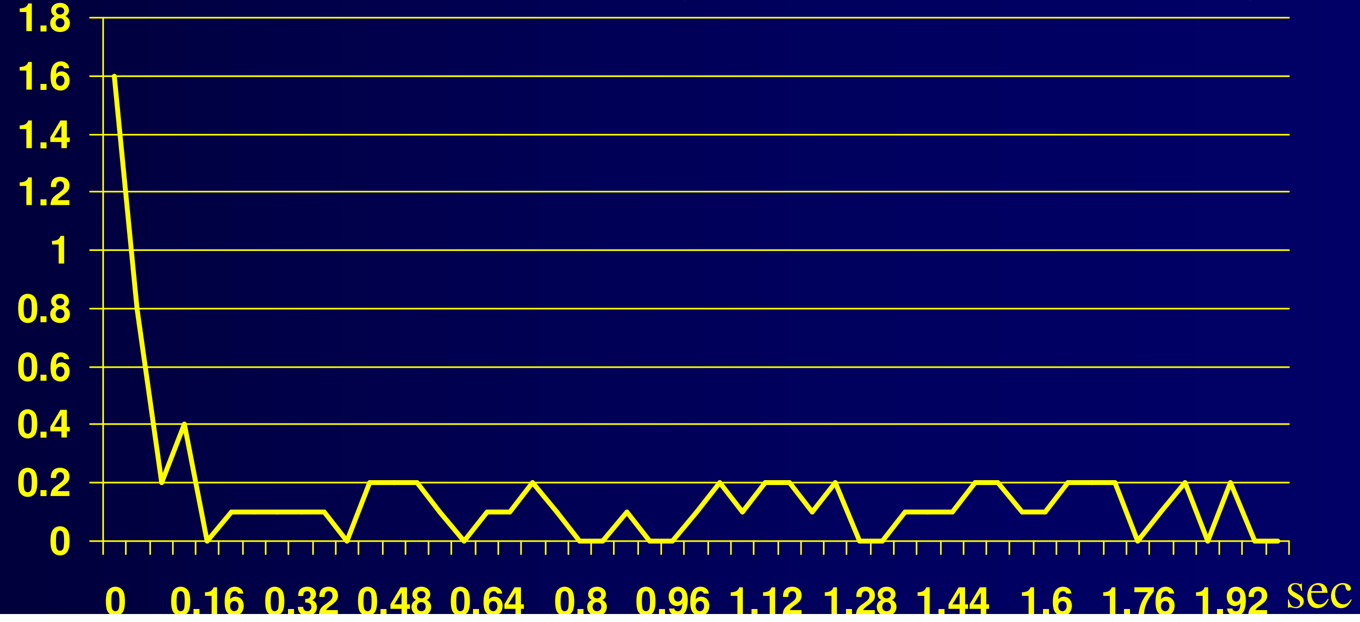
Courtesy Geoff Budgell, Christie Hospital

Beam Flatness and Symmetry for low MU

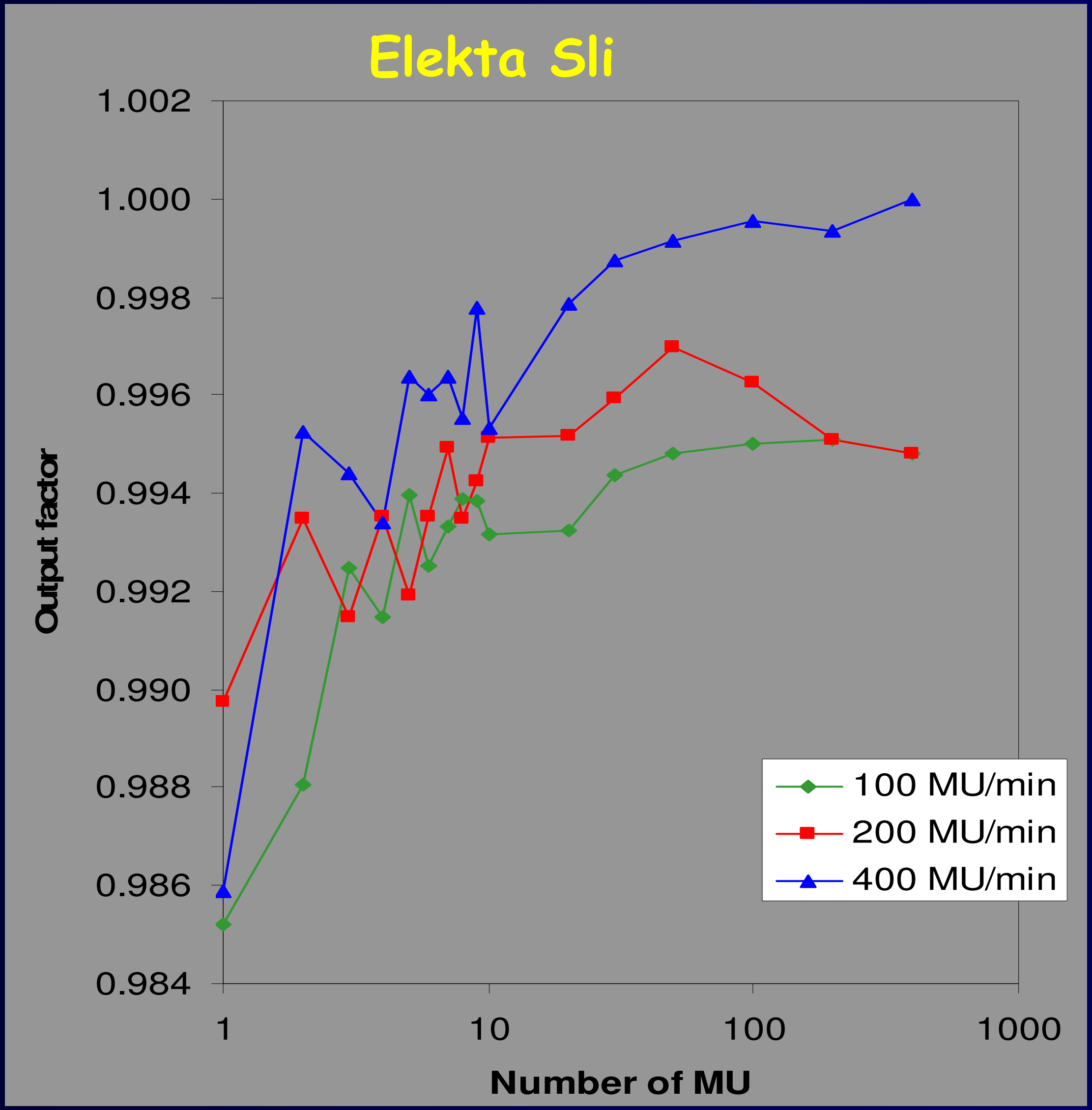
Flatness
versus time (s)
after beam on



Symmetry
versus time (s)
after beam on



Beam Stability: Output (cGy/MU)

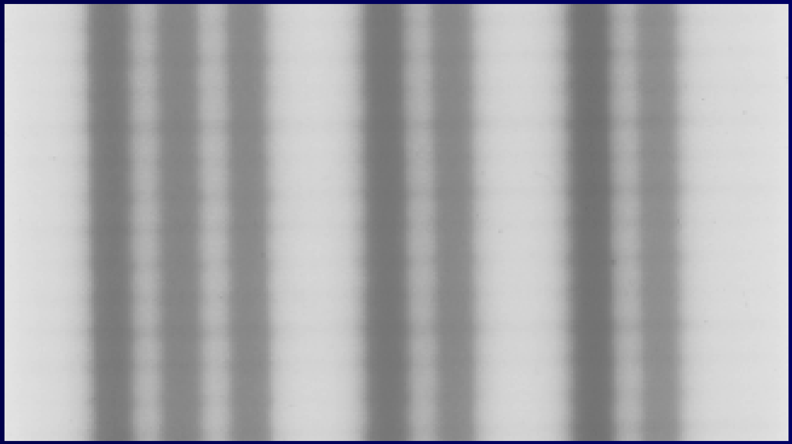


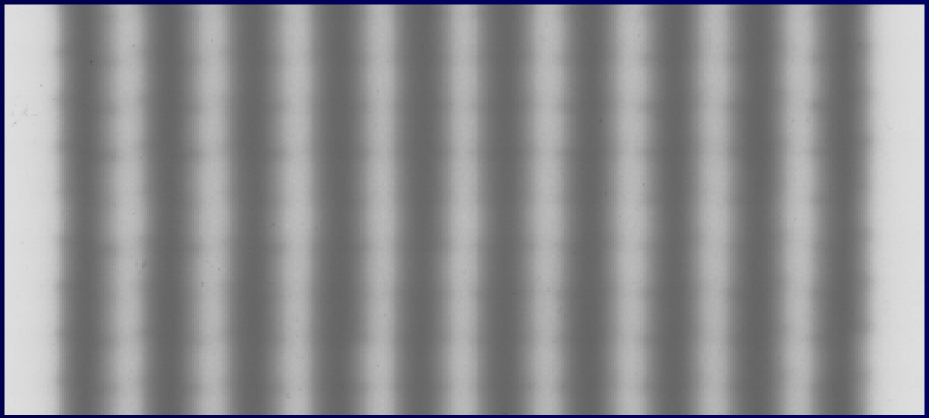
MLC Controller Issue

1 MU per strip

Dose Rate: 600 MU/min

Varian 2100 C/D





Dose Rate: 600 MU/min

Elekta Synergy

Film measurements of a 10-strip test pattern. The linacs were instructed to deliver 1 MU per strip with the step-and-shoot IMRT delivery mode for a total of 10 MU. The delivery sequence is from left to right.

Uncertainties in IMRT Planning

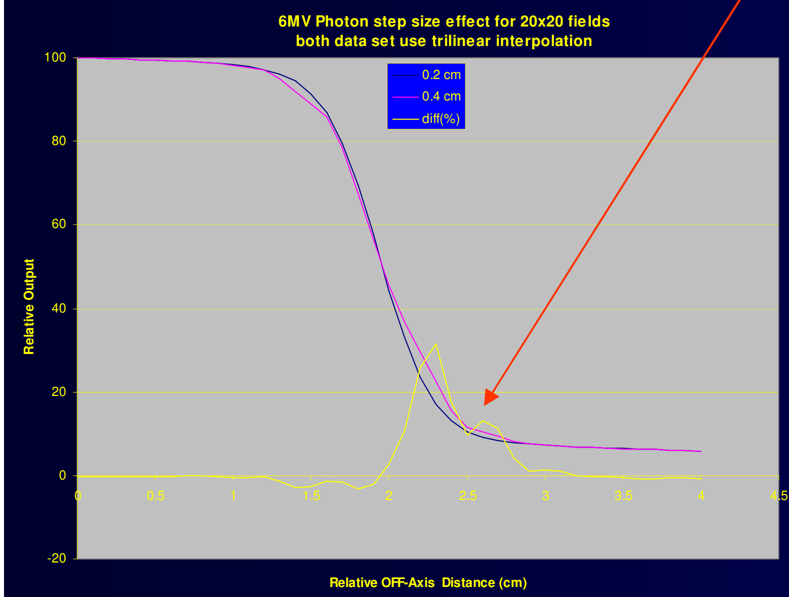
Can be attributed to:

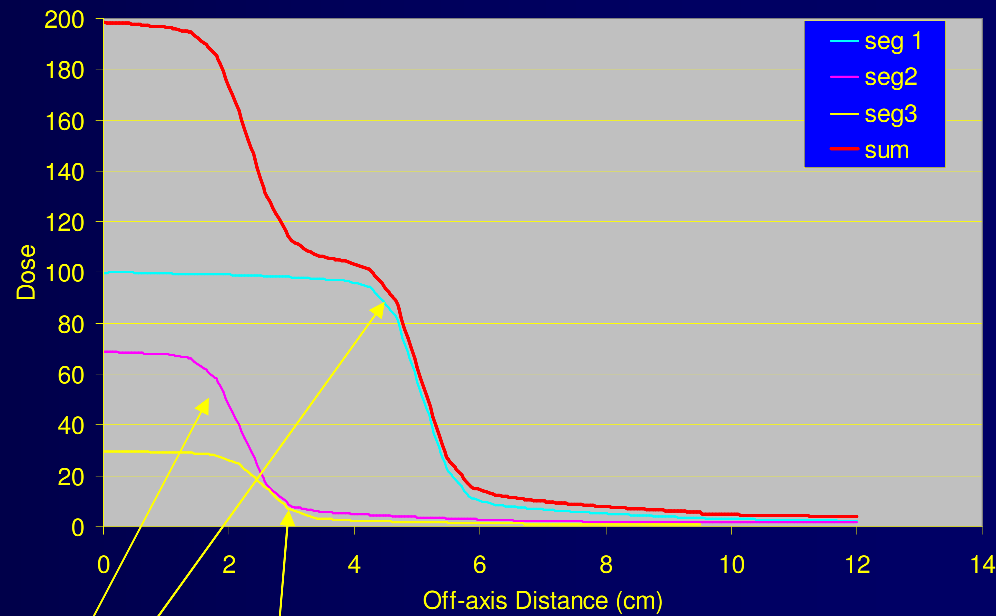
- Dose calculation grid size
- MLC round leaf end –none divergent
- MLC leaf-side/leaf end modeling
- Collimator/leaf transmission
- Penumbra modeling; collimator jaws/MLC
- Output factor for small field size
- PDD at off-axis points

The effect of dose calculation grid size at field edge

- Grid size becomes critical when interpolating high dose gradient.

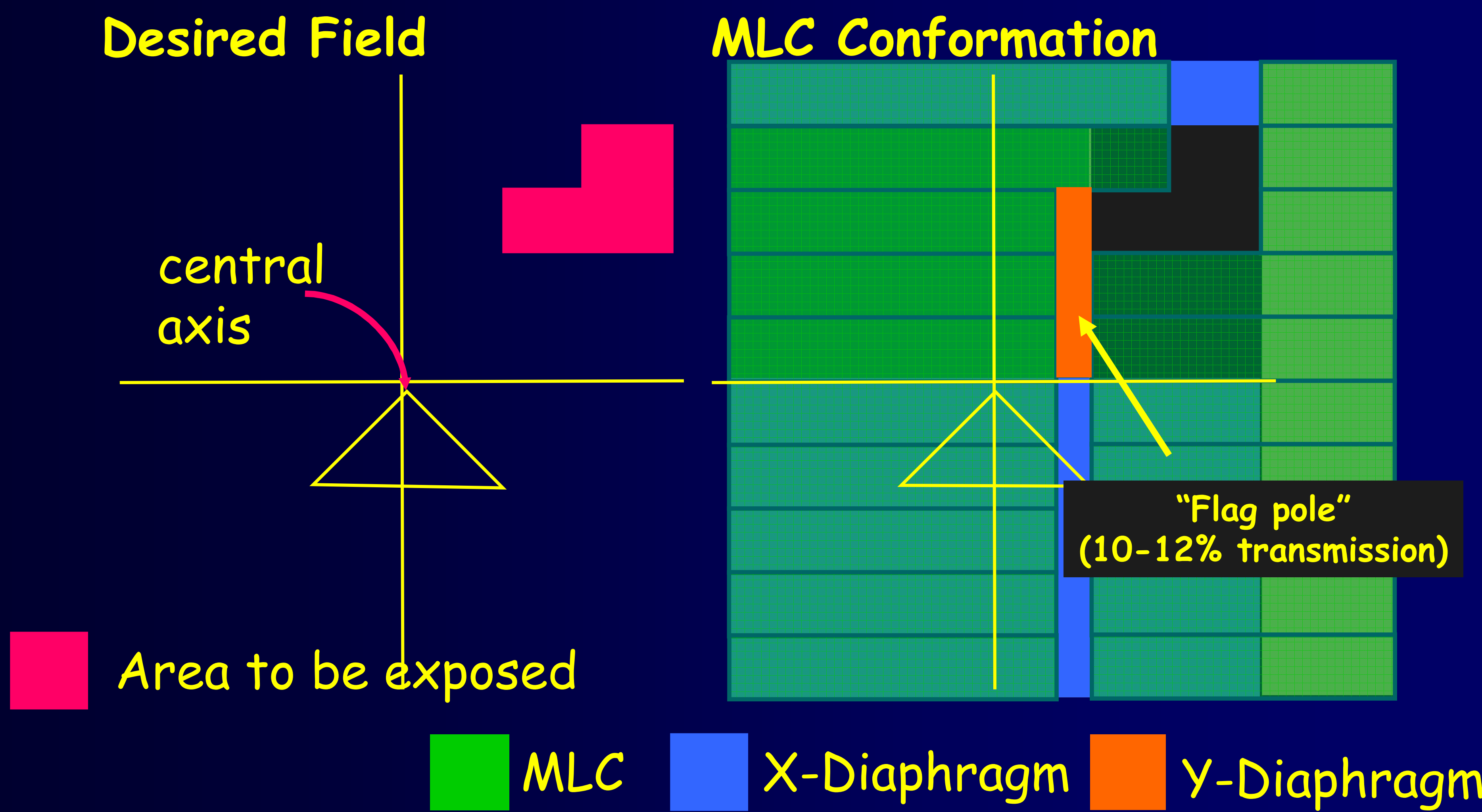
Can result in large errors





Fine grid size is needed for interpolation

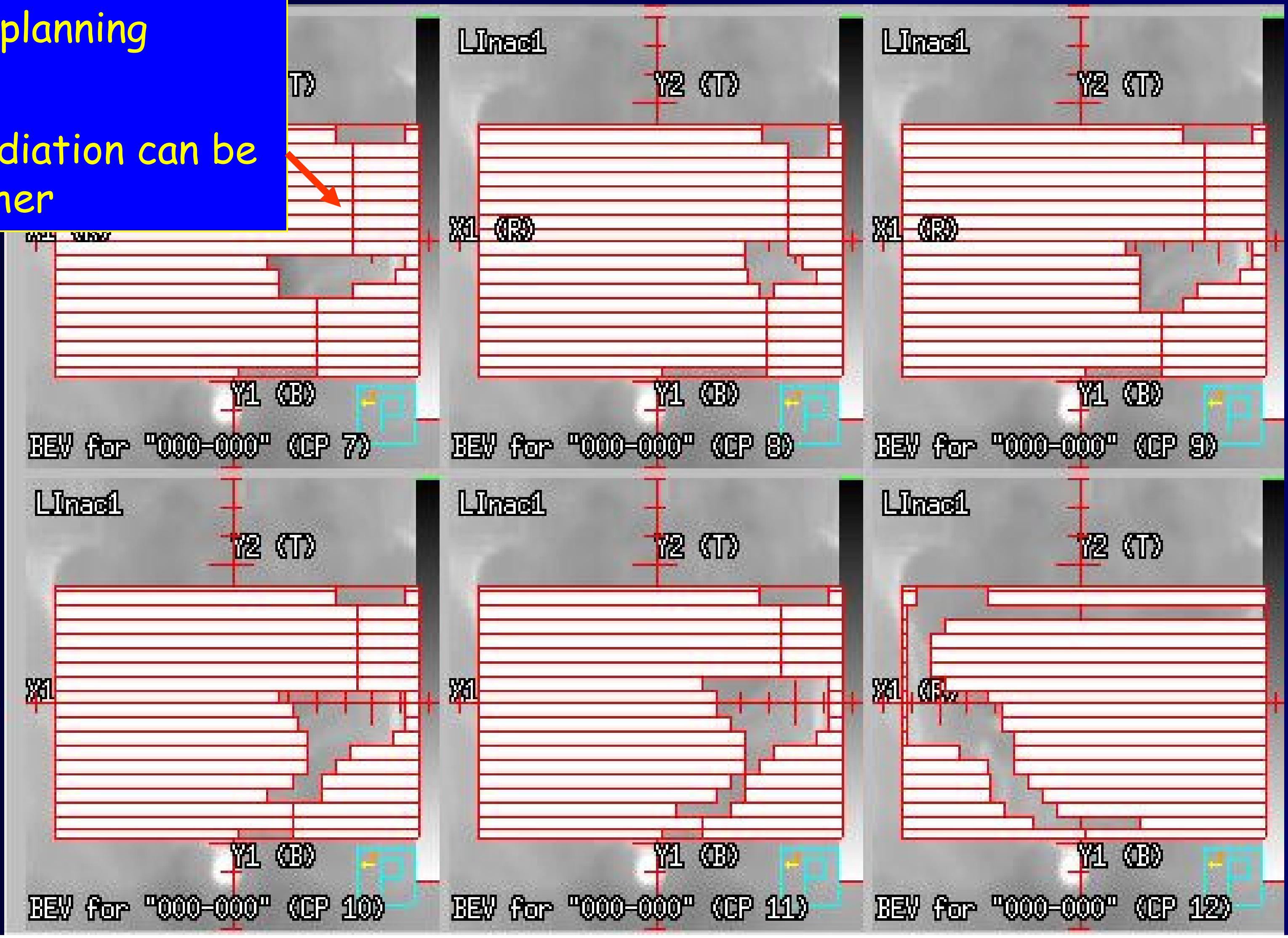
Minimum Leaf Gap Requirement



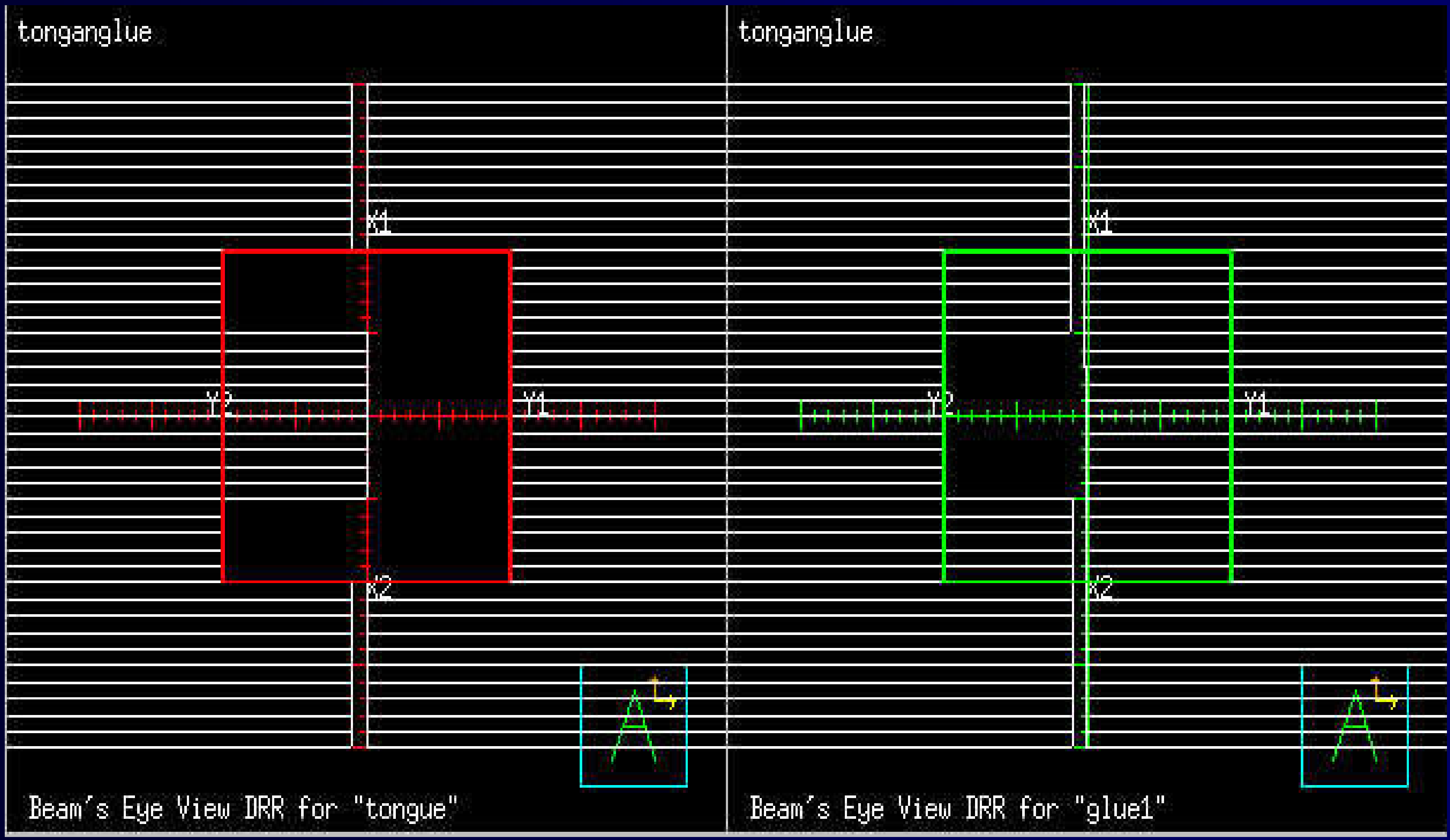
Closed Leaf Position

May not be accurately accounted for in the treatment planning system

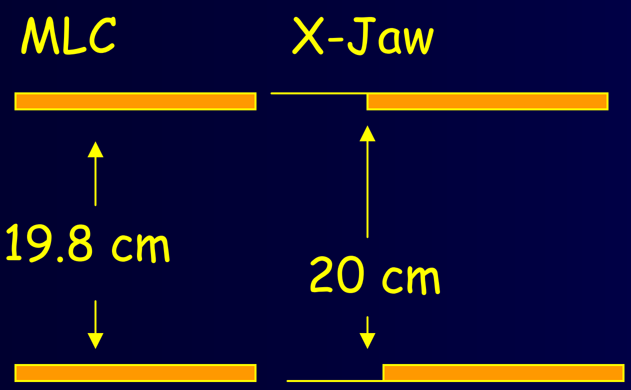
Leakage radiation can be 15% or higher

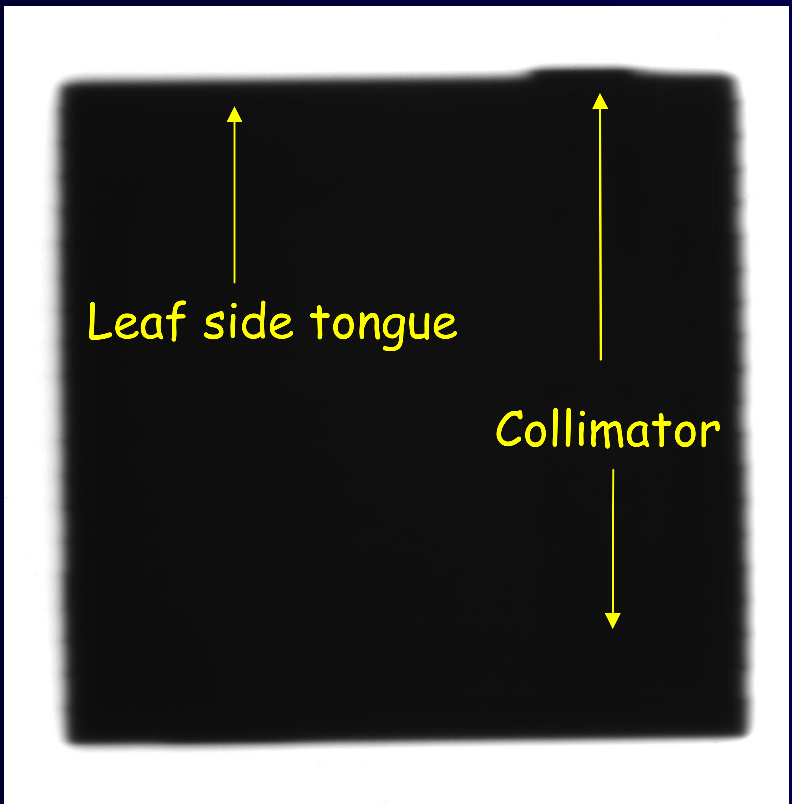


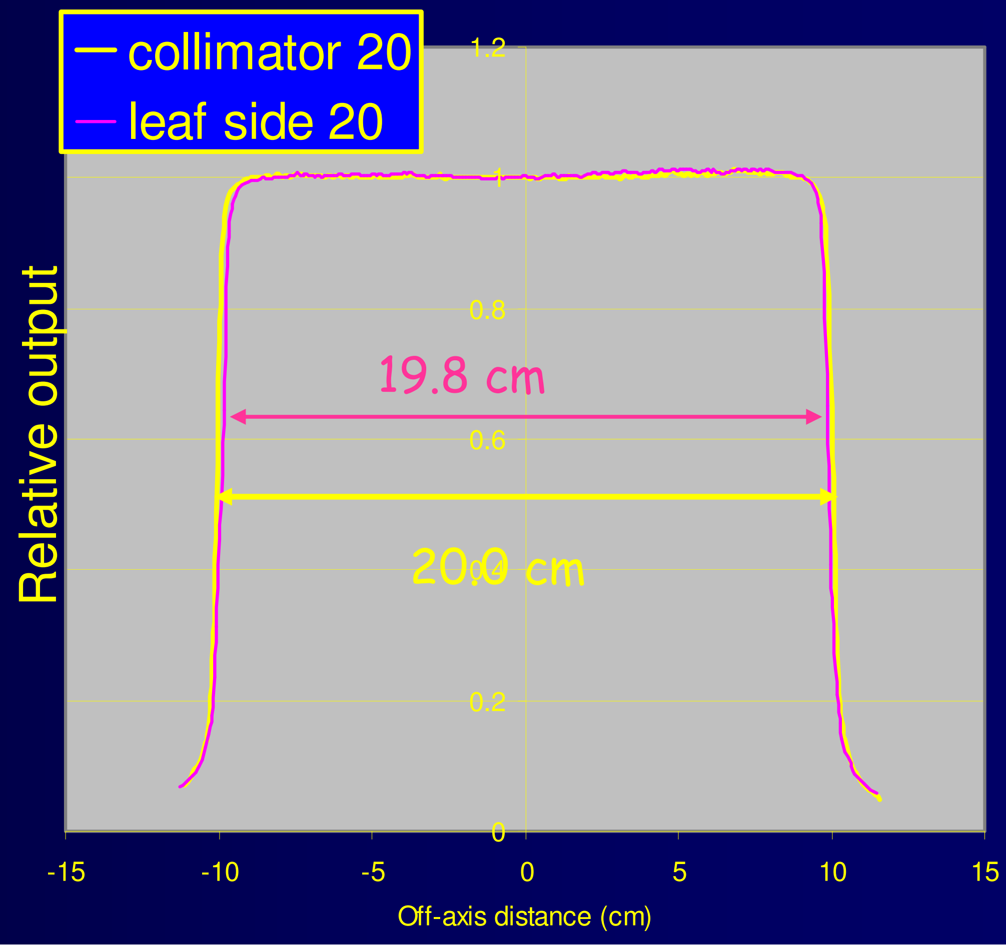
Tongue-and-groove effect



Leaf-side effect

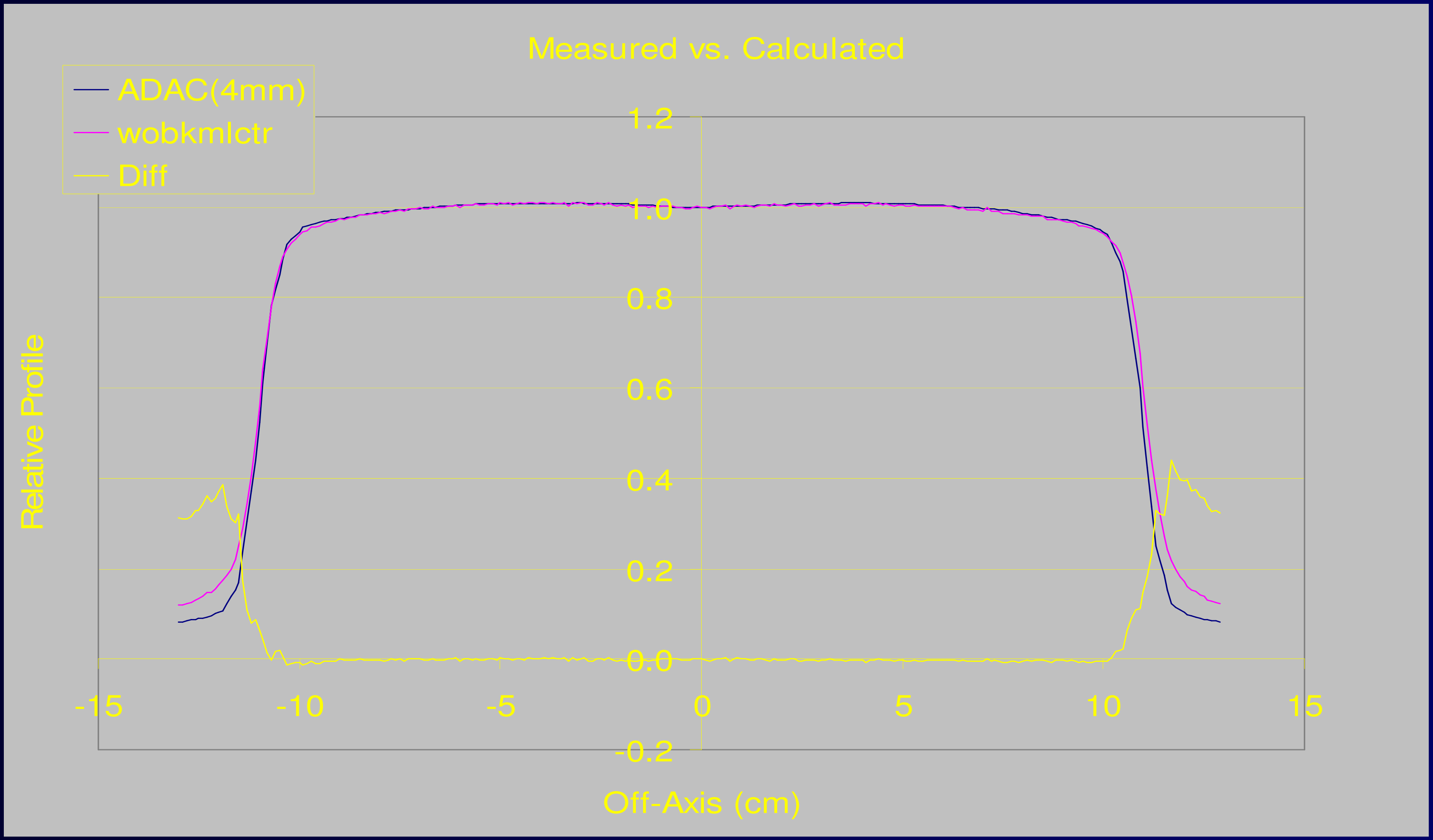






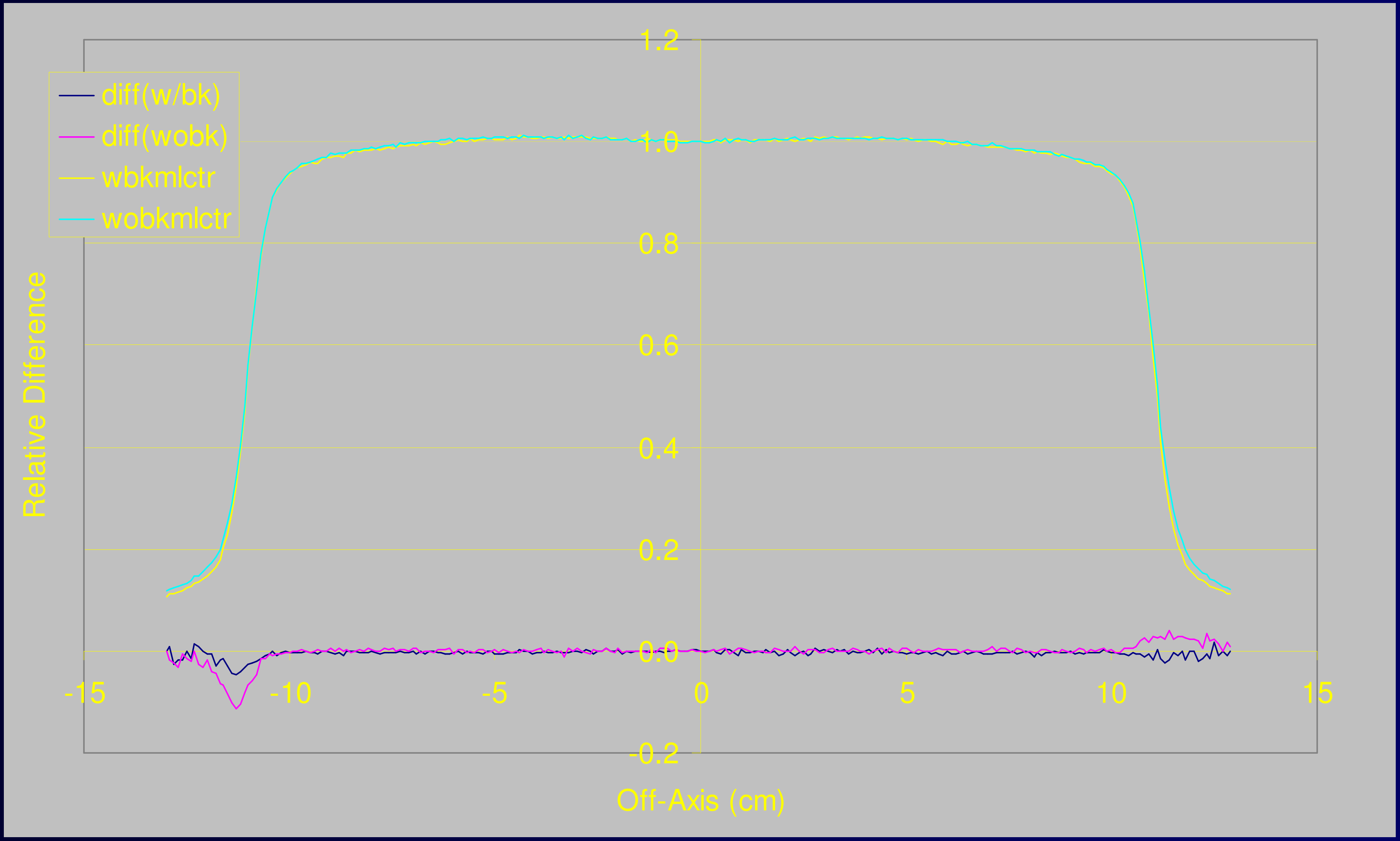
Beam Modeling

(Cross beam profile with inappropriate modeling of extra-focal radiation)



Beam Modeling

(Cross beam profile with appropriate modeling of extra focal radiation)



What should be the tolerance limits and action levels for delivery systems for IMRT?

Segmental Multileaf Collimator (SMLC) Delivery System

	Tolerance Limit	Action Level
MLC*		
Leaf position accuracy	1 mm	2 mm
Leaf position reproducibility	0.2 mm	0.5 mm
Gap width reproducibility	0.2 mm	0.5 mm
Gantry, MLC, and Table Isocenter	0.75 mm radius	1.00 mm radius
Beam Stability		
Low MU Output (<2MU)	2%	3%
Low MU Symmetry (<2MU)	2%	3%

** Measured at all four cardinal gantry angles*

Dynamic Multileaf Collimator (DMLC) Delivery System

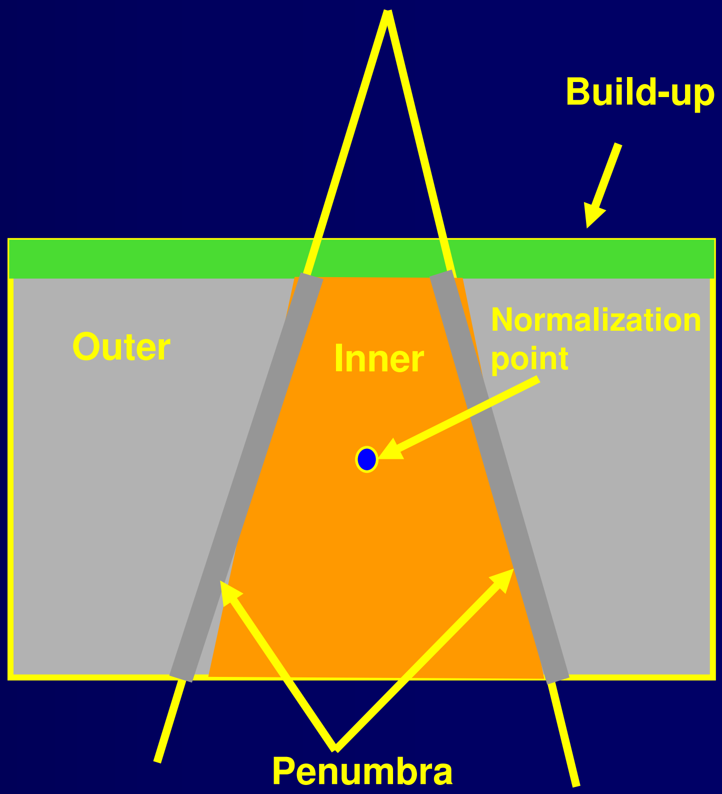
	Tolerance Limit	Action Level
MLC*		
Leaf position accuracy	0.5 mm	1 mm
Leaf position reproducibility	0.2 mm	0.5 mm
Gap width reproducibility	0.2 mm	0.5 mm
Leaf speed	±0.1 mm/s	±0.2 mm/s
Gantry, MLC, and Table Isocenter	0.75 mm radius	1.00 mm radius
Beam Stability		
Low MU Output (<2MU)	3%	5%
Low MU Symmetry (<2MU)	2%	3%

What should be the tolerance limits and action levels for IMRT Planning?

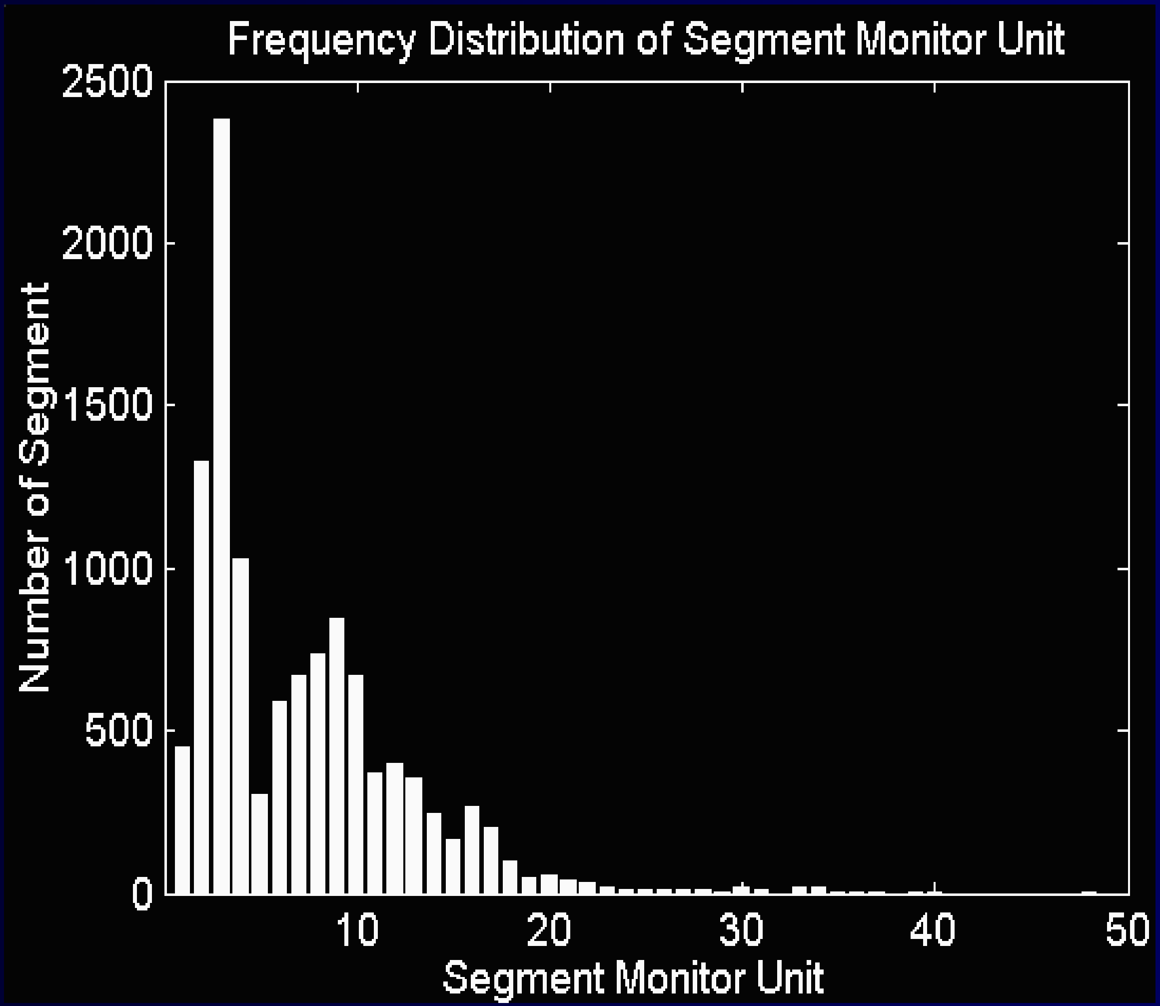
Are TG53 recommendation acceptable for IMRT TPS?

Absolute Dose @ Normalization Point (%)	1.0
Central-Axis (%)	1.0 - 2.0
Inner Beam (%)	2.0 - 3.0
Outer Beam (%)	2.0 - 5.0
Penumbra (mm)	2.0 - 3.0
Buildup region (%)	20.0 - 50.0

TG 53 Recommendation for 3DRTPS



Probably not!!!!

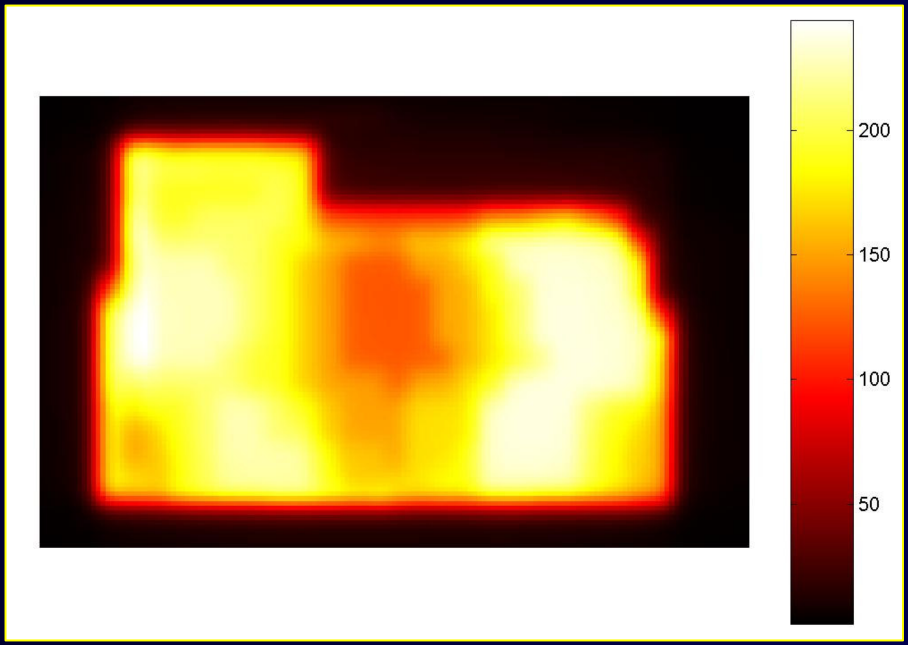


- Most sub-fields have less than 3 MU

(Data from 100 Head and Neck IMRT patients treated at UF)

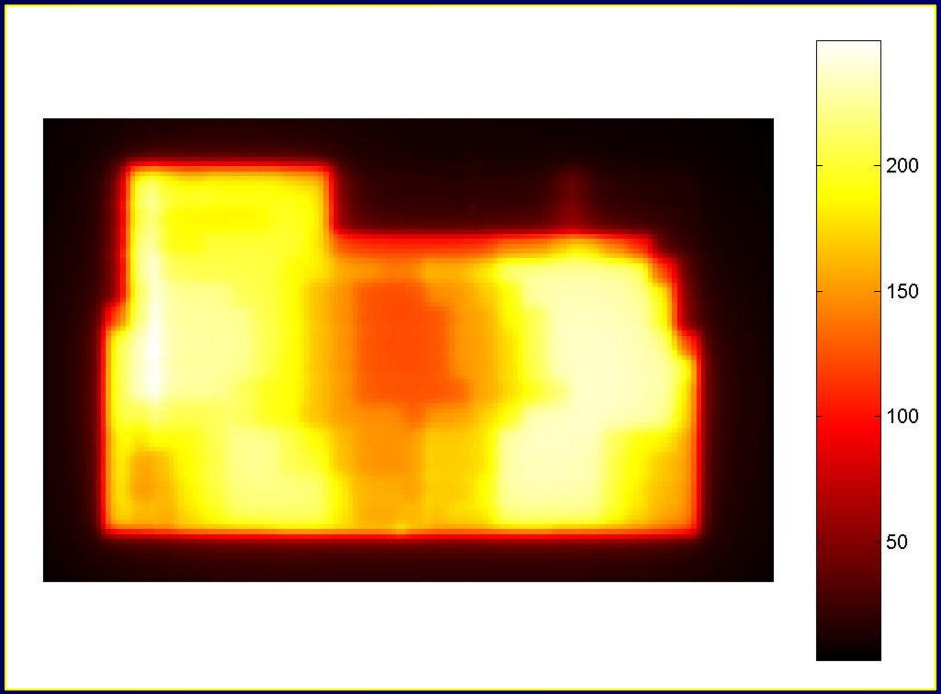
Need 2D/3D analyses tools……

How to quantify the differences?



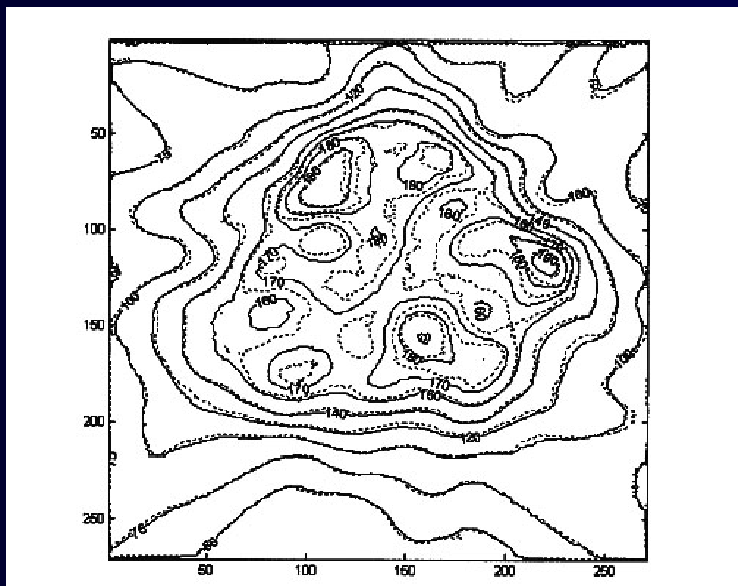
Calculation

Measurement

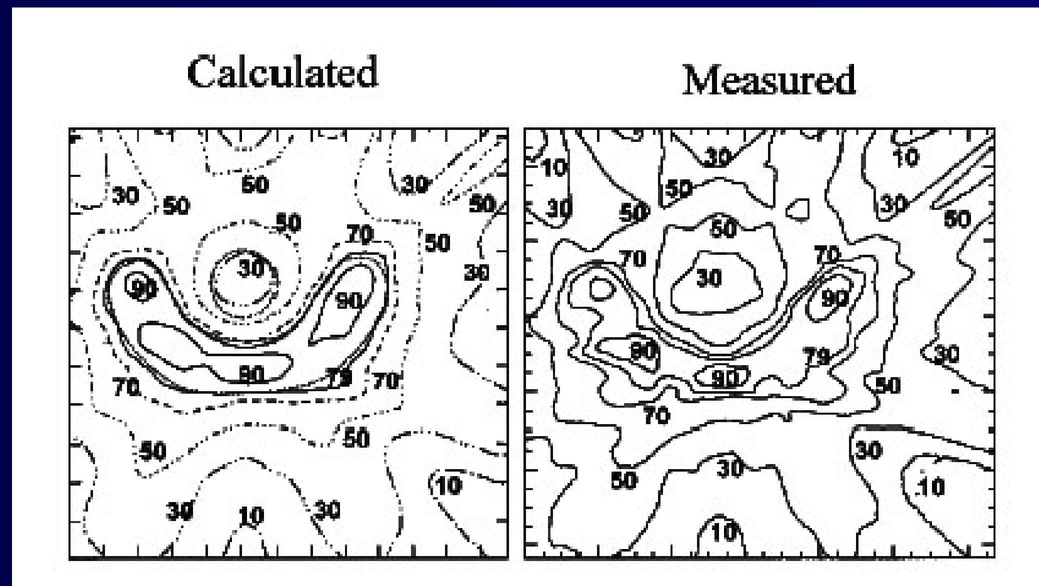


Methods (1)

- **Qualitative**



Overlaid isodose plot

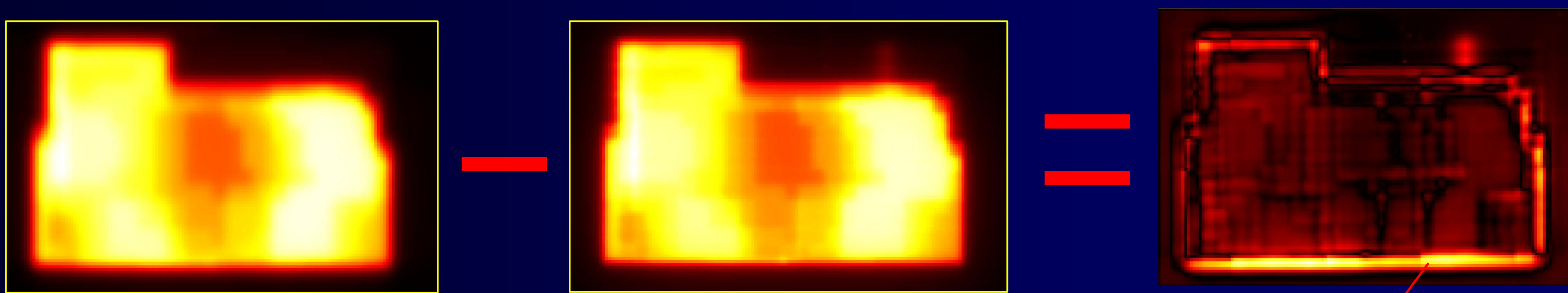


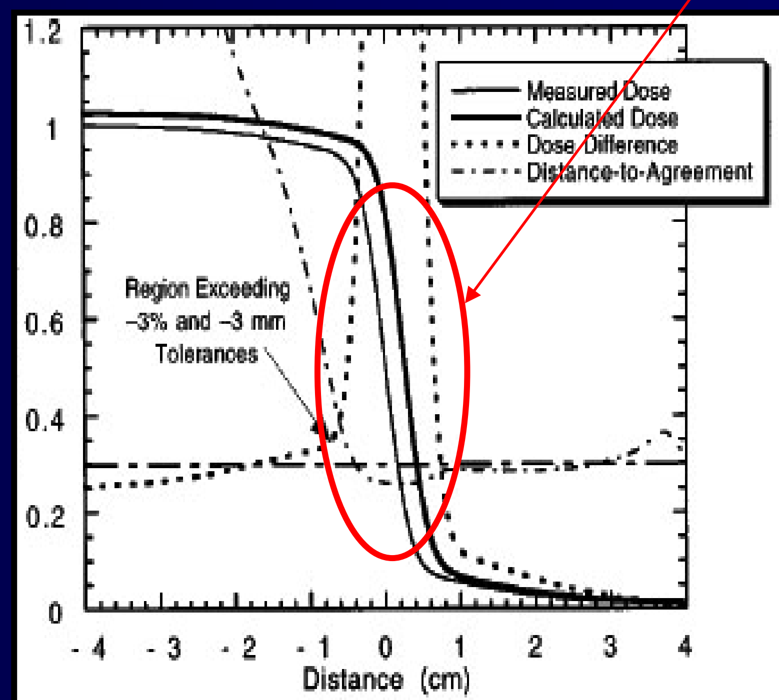
visual comparison

- Adequate for ensuring that no gross errors are present
- evaluation influenced by the selection of isodose lines; therefore it can be misleading……

Methods (2)

- **Quantitative methods: Dose Difference**

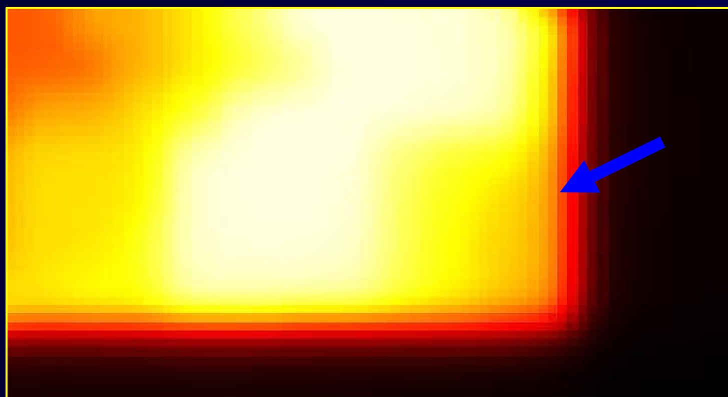


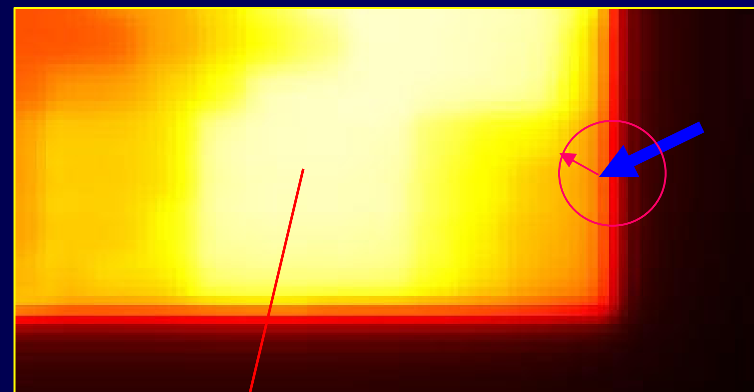


- Possible to quickly see what areas are significantly hot and cold; however, large errors can exist in high gradient regions

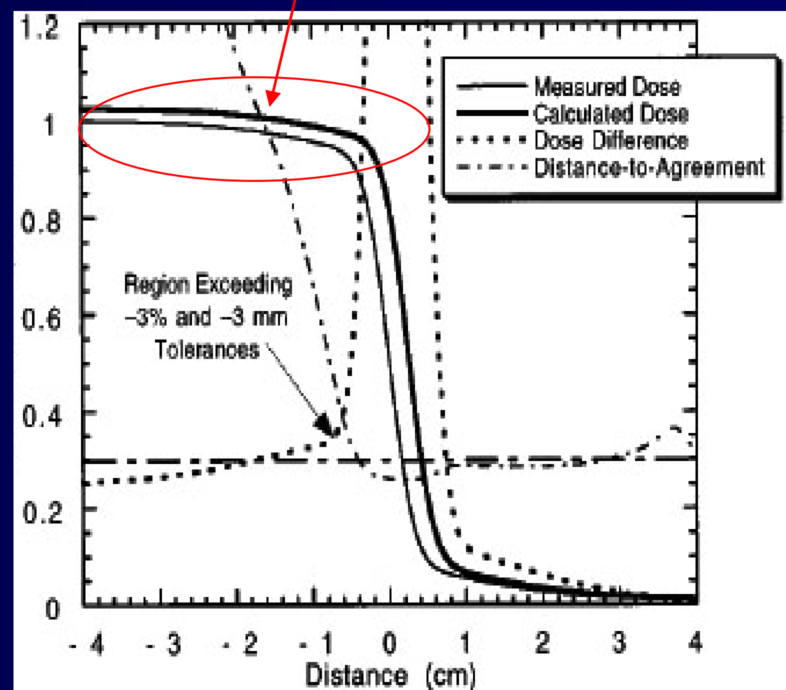
Methods (3)

- **Quantitative methods: Distance-to-agreement (DTA)**





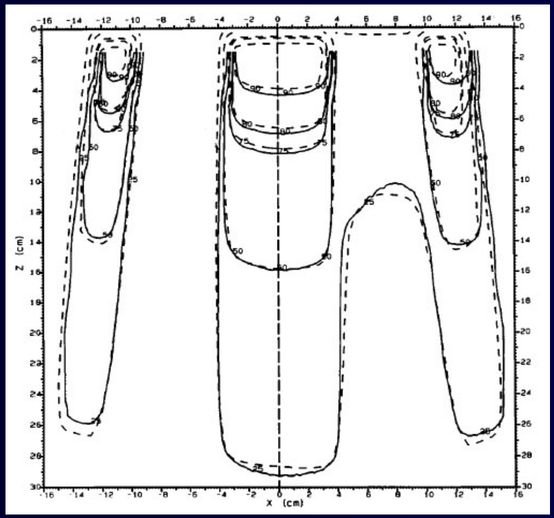
- Distance between a measured dose point and the nearest point in the calculated distribution containing the same dose value
- More useful in high gradient regions; however, overly sensitive in low gradient regions



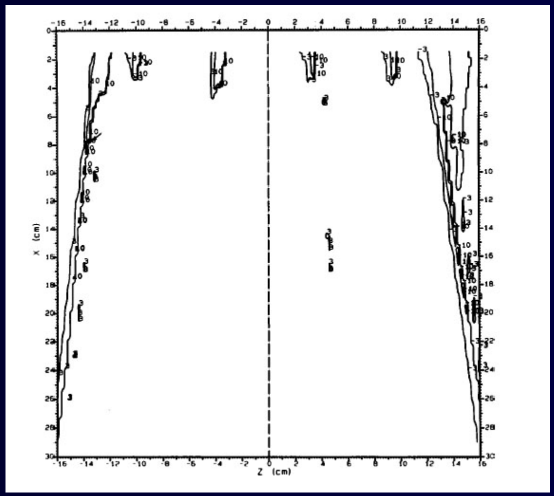
Hogstrom et .al. IJROBP., 10, 561-69, 1984

Methods (4)

- **Quantitative methods: Composite distribution**



Overlaid isodose distribution



Composite distribution

- A binary distribution formed by the points that fail both the dose-difference and DTA criteria

$\Delta D > \Delta D_{tol}$ $\quad$ $B_{DD} = 1$

$\Delta d > \Delta d_{tol}$ $\quad$ $B_{DTA} = 1$

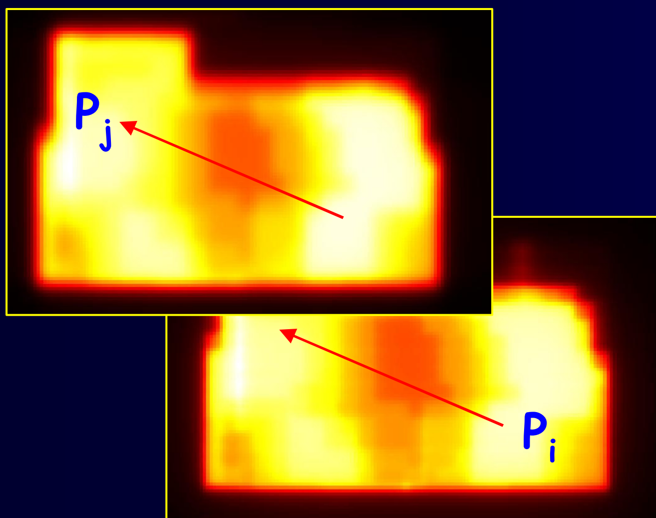
$B = B_{DD} \times B_{DTA}$

- **Useful in both low- and high- gradient areas** to see what areas are off
- **However, No unique numerical index**-that enables the analysis of the goodness of agreement

Harms et .al. Med. Phys., 25, 1830-36,1998

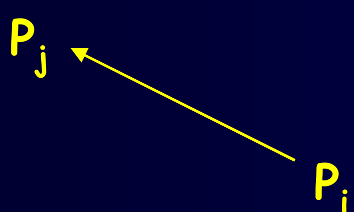
Methods (5)

- **Quantitative methods: Gamma index distribution**



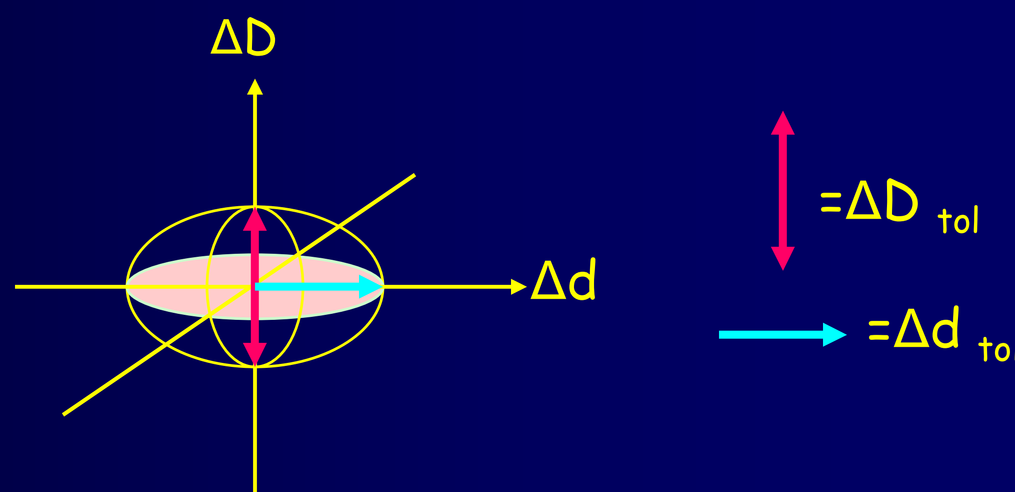
$$\gamma_i = \min\left[\sqrt{\left(\frac{\Delta d}{\Delta d_{tol}}\right)^2 + \left(\frac{\Delta D}{\Delta D_{tol}}\right)^2}\right]_{\forall j}$$

$\gamma \leq 1$, calculation passes, and
$\gamma > 1$, calculation fails



distance, Δd
dose-difference, ΔD

- **Combined ellipsoidal dose-difference and DTA test**



Low et .al. Med. Phys., 25, 656-61,1998

Methods (6)

- Quantitative methods: Normalized Agreement Test (NAT)

$\Delta D < \Delta D_{tol}$, NAT = 0

$\Delta d < \Delta d_{tol}$, NAT = 0

$\%D < 75\%$ & $D_{meas} < D_{cal}$, NAT = 0

Otherwise, $NAT = D_{scale} \times (\delta - 1)$

Try to quantify how much off overall

Where,

$D_{scale}^{i} = \text{larger}[D_{cal}, D_{meas}]^{i} / \max[D_{cal}]$

$\delta^{i} = \text{smaller}[(\Delta D/\Delta D_{tol}), (\Delta d/\Delta d_{tol})]^{i}$

$$\text{NAT index} = \frac{\text{Average NAT value}}{\text{Average of the } D_{scale} \text{ matrix}} \times 100$$

Childress et.al. IJROBP 56, 1464-79,2003

Tolerance limits based on statistical and topological analyses

Region	Confidence Limit* (P=0.05)	Action Level
δ_1 (high dose, small dose gradient)	3%	5%
δ_1 (high dose, large dose gradient)	10% or 2 mm DTA	15% or 3 mm DTA
δ_1 (low dose, small dose gradient)	4%	7%
$\delta_{90-50\%}$ (dose fall off)	2 mm DTA	3 mm DTA

* Mean deviation used in the calculation of confidence limit for all regions is expressed As a percentage of the prescribed dose according to the formula,

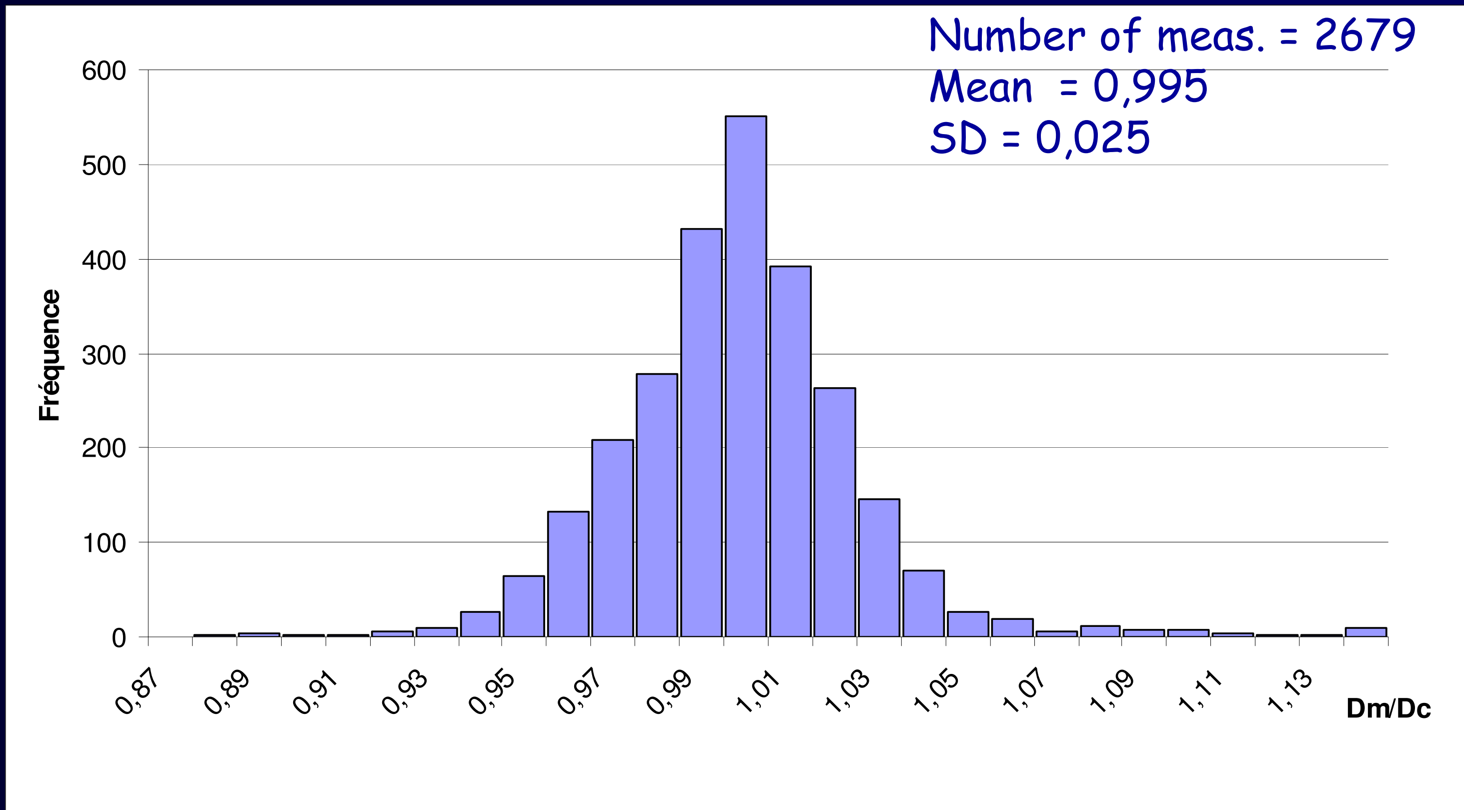
$\delta_i = 100\% \text{ X } (D_{calc} - D_{meas.}/D_{prescribed})$

Palta et.al. AAPM Summer School, 2003

Are there any limitations of current methodologies of establishing tolerance limits for IMRT QA????

Radiotherapy Oncology Group for Head &Neck

12 Centres- 118 patients



Recommandations for a Head and Neck IMRT Quality Assurance Protocol: 8 (2004), Cancer/Radiothérapie 364-379, M. Tomsej et al.

IMRT QA Outliers

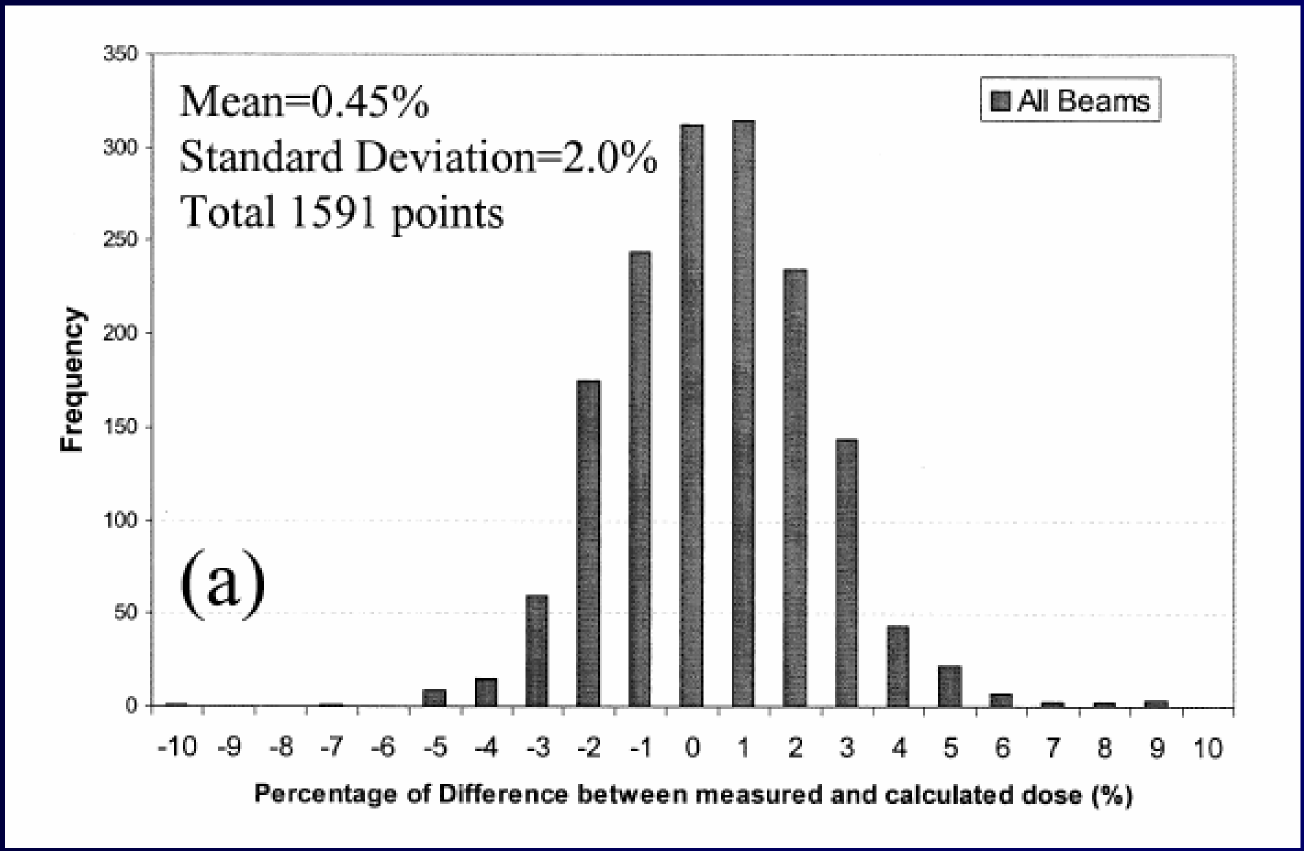
Surely there is something systematic at work in some cases................

7 Points outside 4σ

In 1600 observations

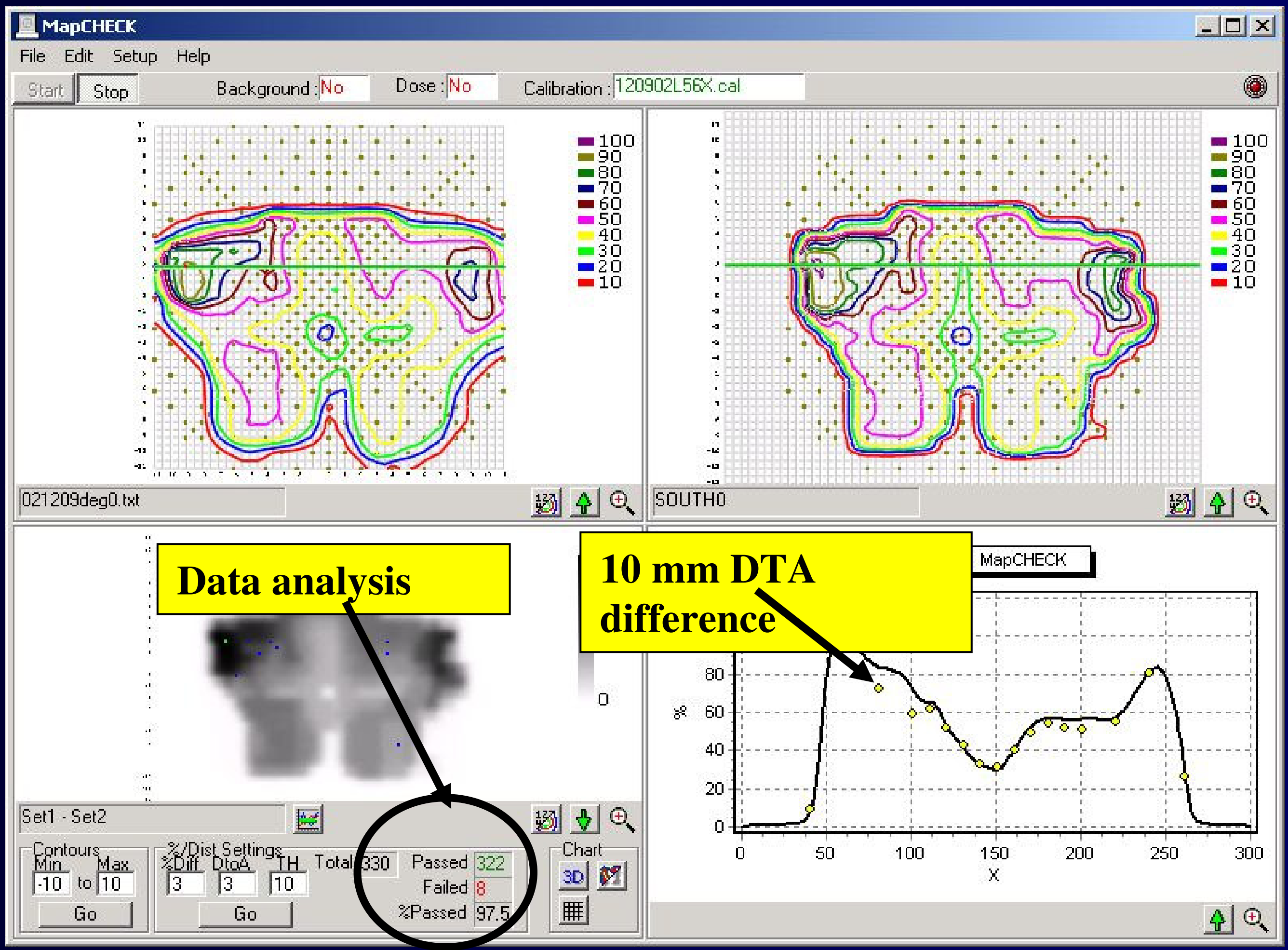
99.994% C.L.

~Same odds as wining Power ball Multi-state Lotto 4 times



Dong *et al.* IJROBP, Vol. 56, No. 3, pp. 867-877, 2003

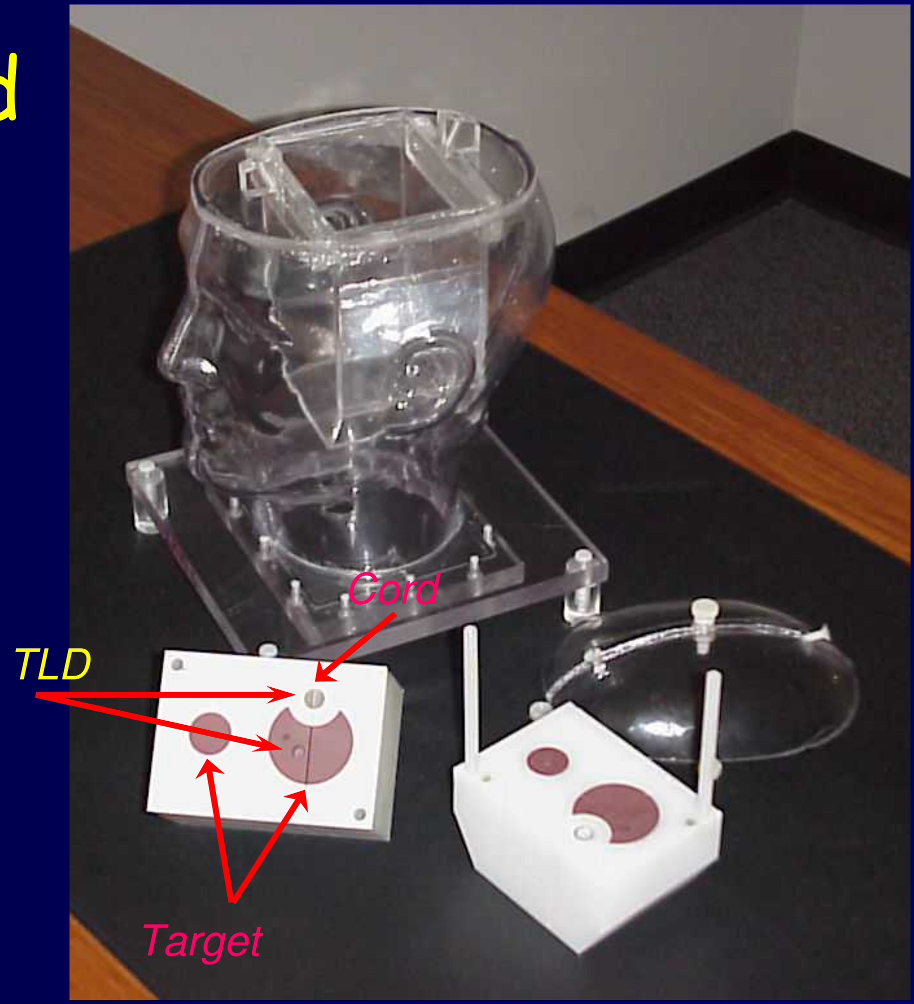
Comparison of Measured and Calculated Cross Plot



Measured with a diode-array (Map Check; Sun Nuclear Corp.)

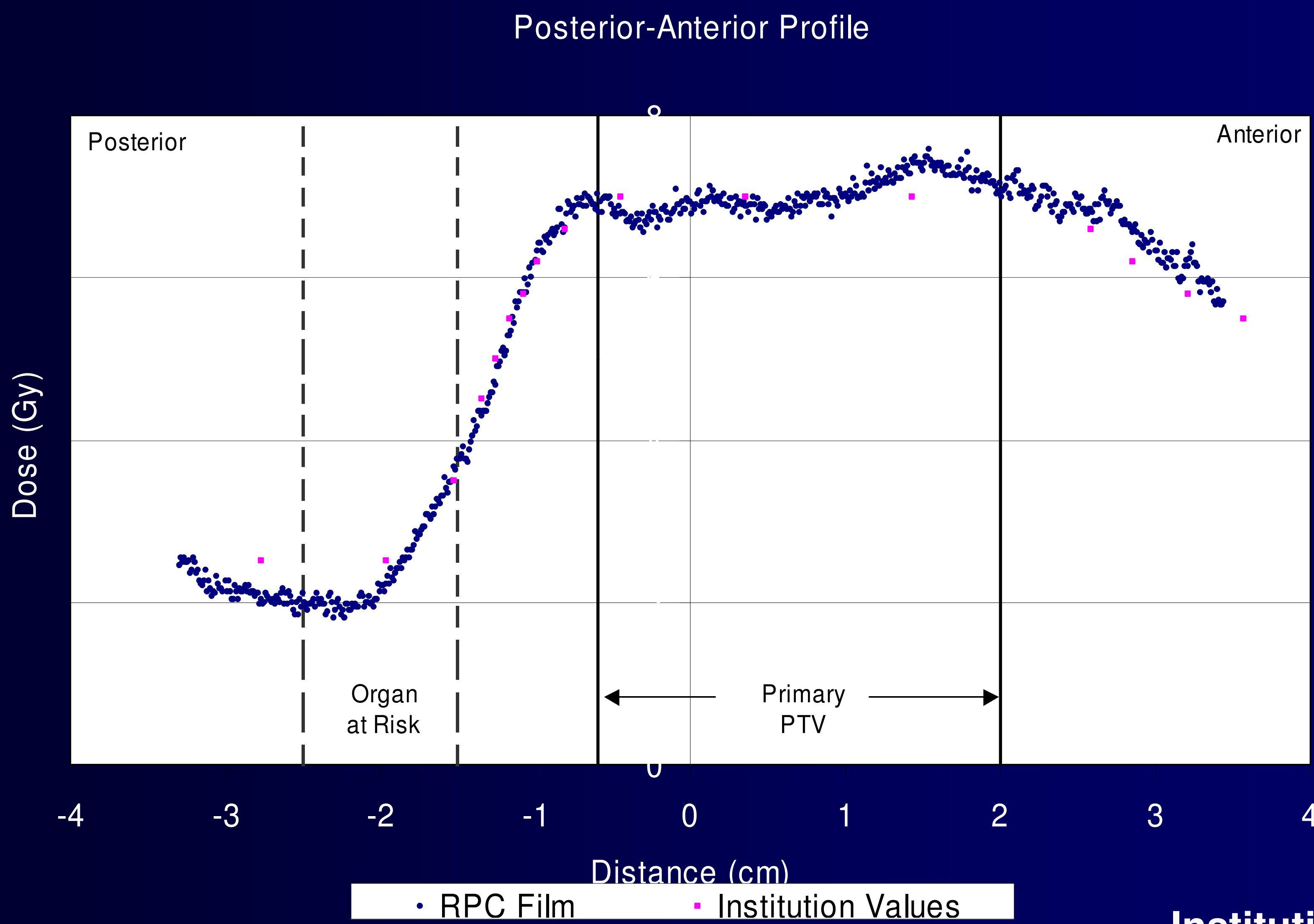
RPC Credentialing: IMRT

- RPC IMRT Head and Neck Phantom
- TLD in the Target and Organ-at-risk volumes
- Orthogonal Radiochromic films



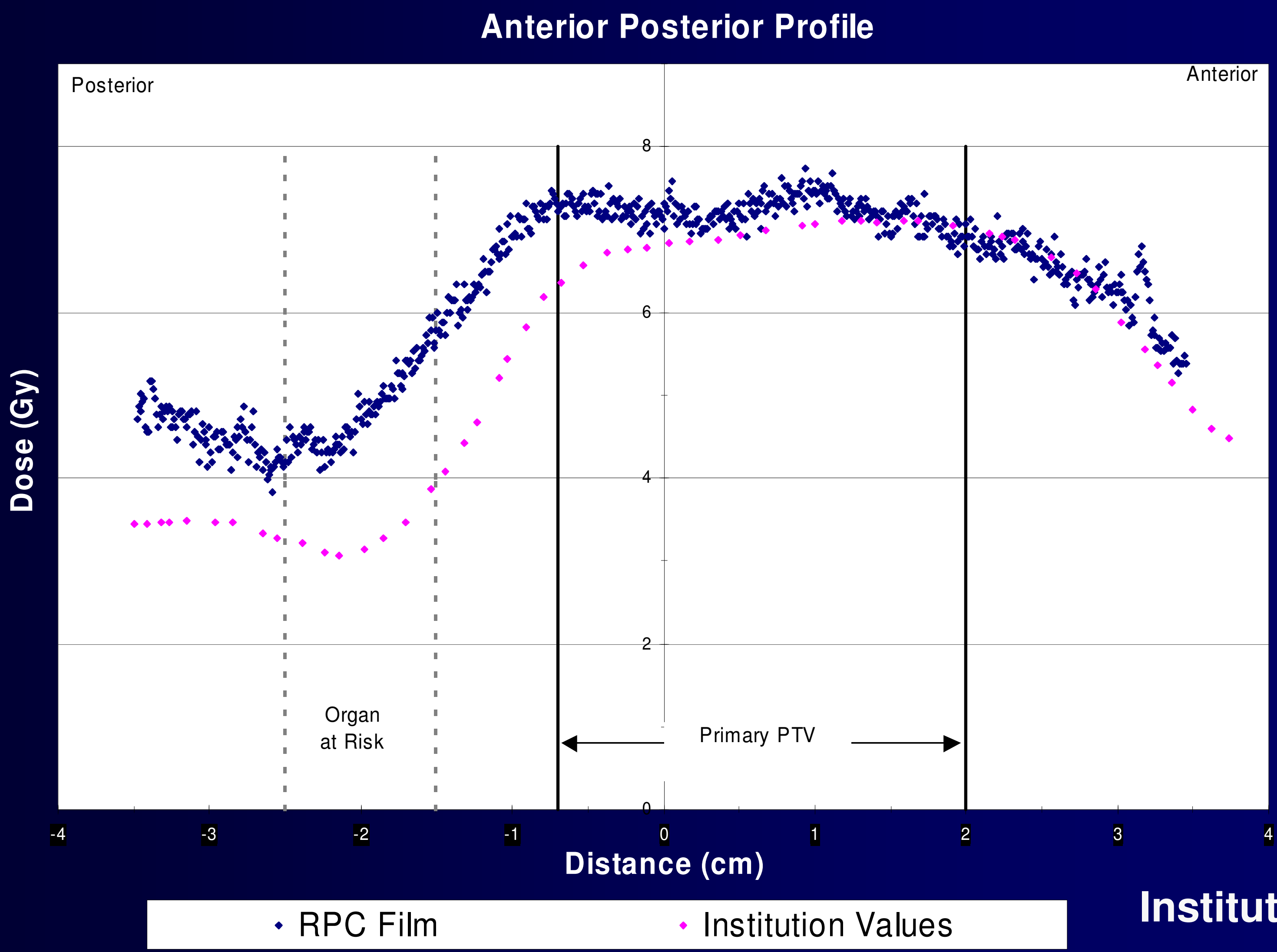
RPC criteria of acceptability:
7% for Planning Target Volume
4 mm DTA for the Organ-at-Risk

RPC IMRT Phantom Results



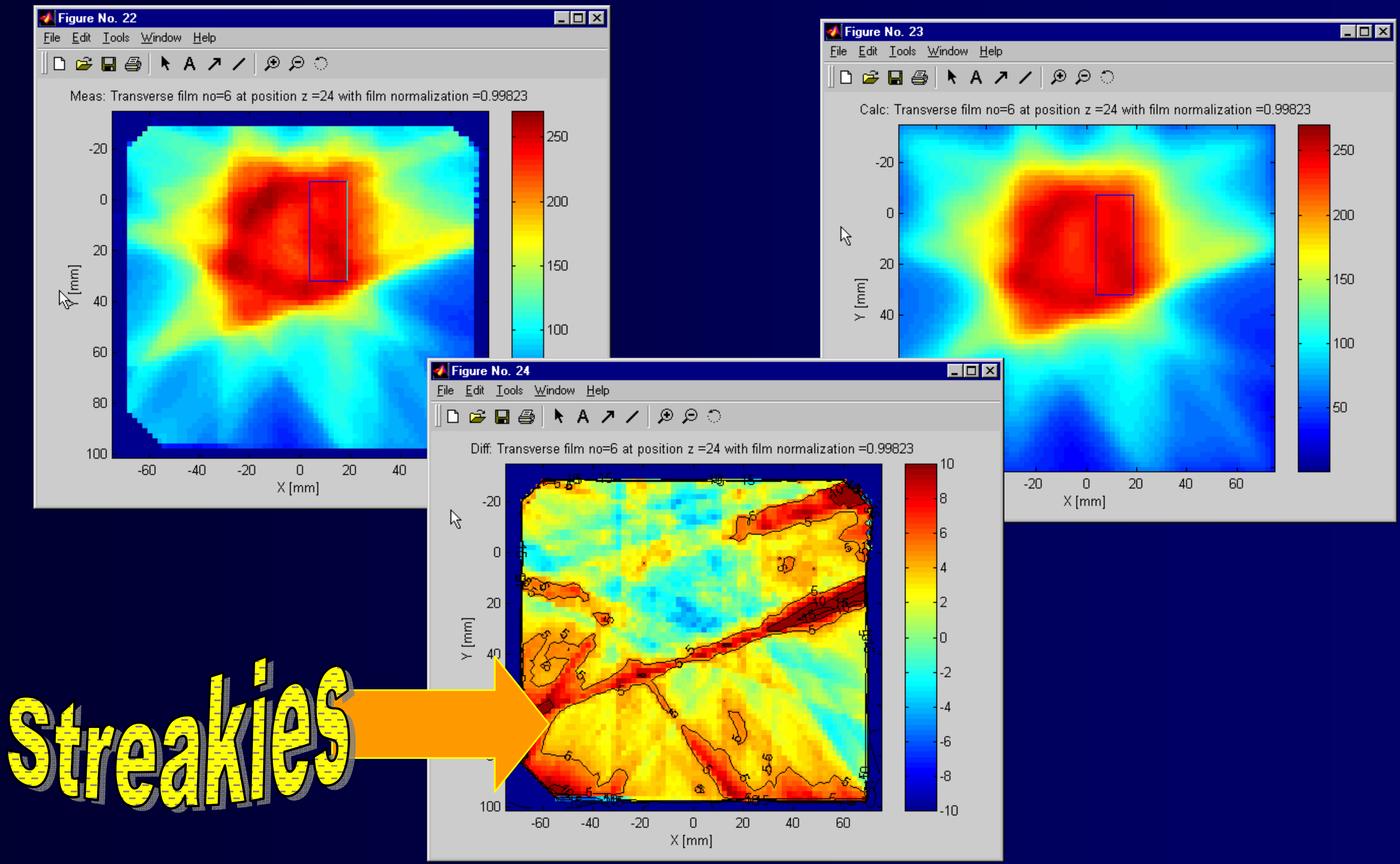
Institution A

RPC IMRT Phantom Results

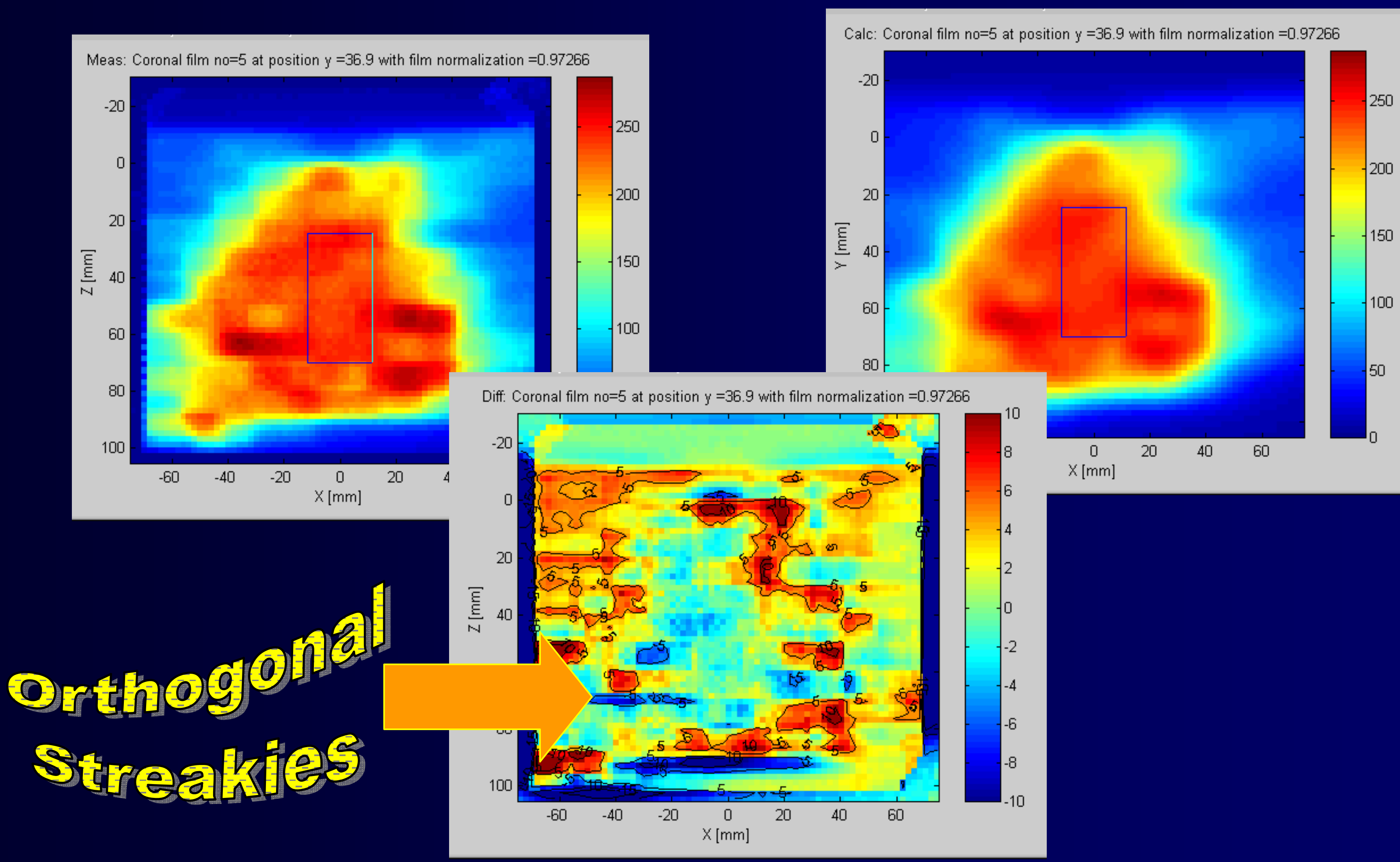


Institution B

Radiographic Film Dosimetry for Patient Specific QA: Axial Planes



Radiographic Film Dosimetry for Patient Specific QA: Coronal Planes



Evidence That Something Could Be Amiss…

What could be the reason???

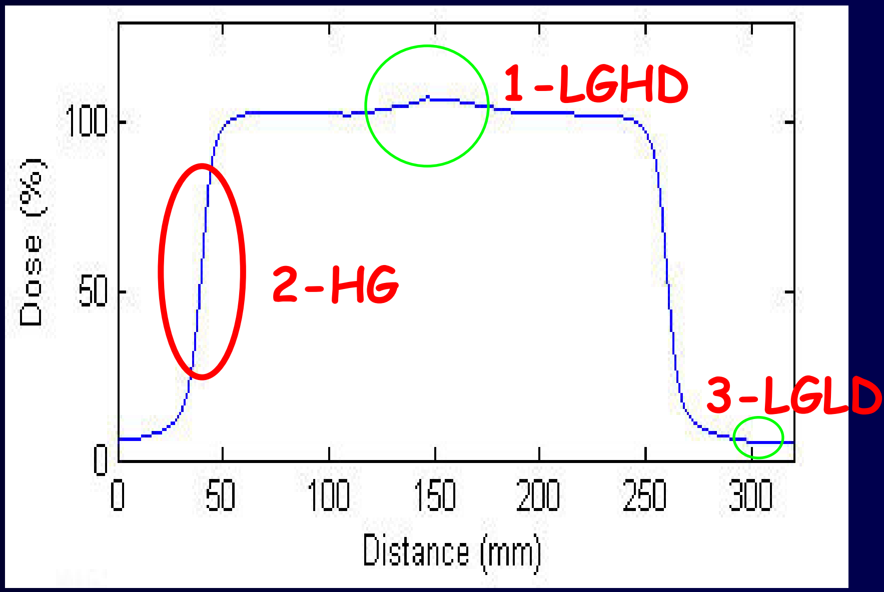
- It could be delivery error
  - Mechanical Errors?
    - MLC Leaf Positioning
  - Fluence and Timing?
    - Orchestration of MLC and Fluence
- It could be dosimetry artifacts
  - Some measurement Problem?
- It could be algorithmic errors
  - Source Model, Penumbra, MLC Modeling

More than likely a conspiracy of effects, each with it own uncertainty……

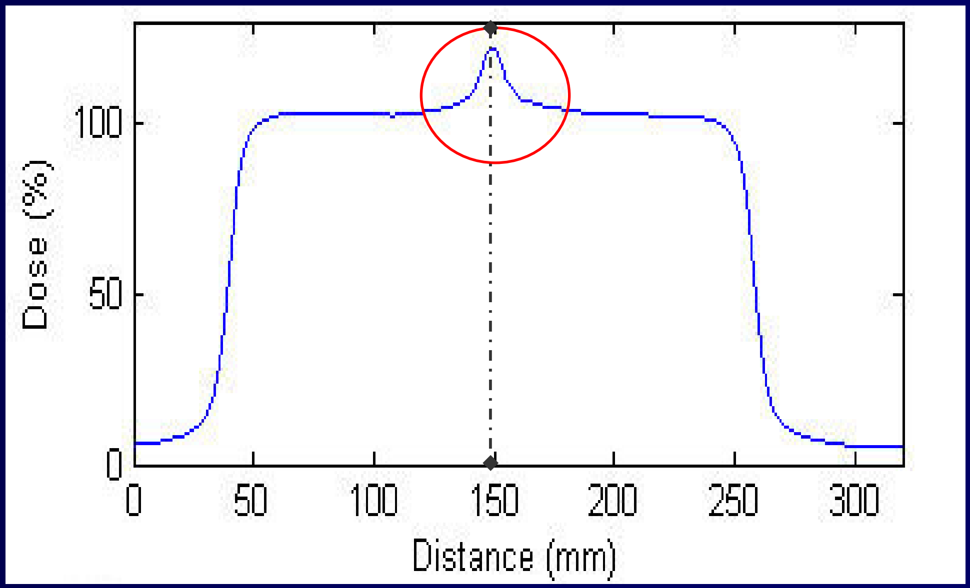
A new method for evaluating IMRT QA measurements……

Based on space-specific uncertainty information

1-D Example



Calculated dose

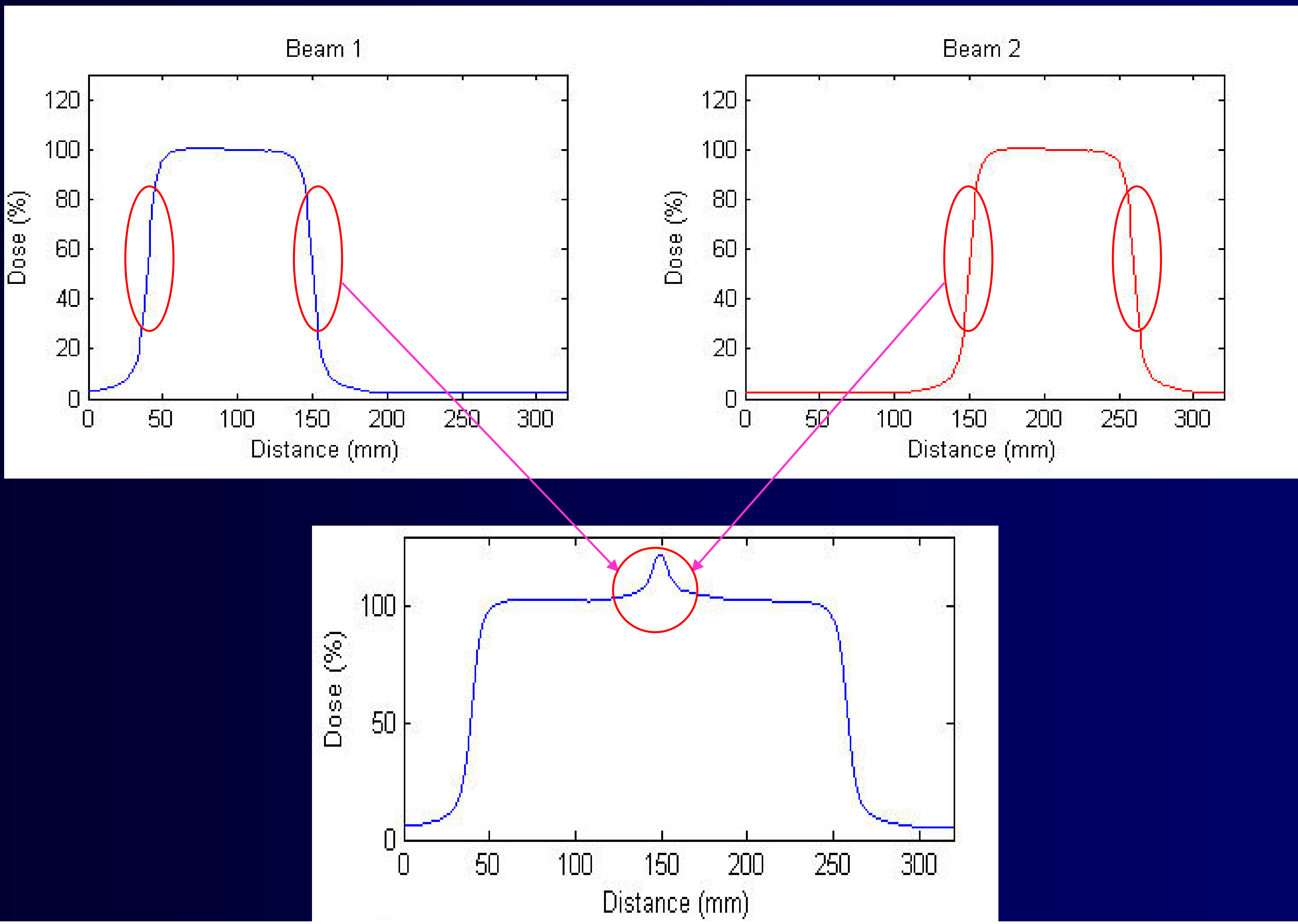


Measured dose

Possible Conclusion…….

Measured dose outside the criterion of acceptability

1-D Example : 2 Adjacent Fields



Uncertainty in dose calculation and measurement

$$D(r) = D_c(r) \pm k.\sigma(r) + \varepsilon$$

D(r), measured dose
Dc(r), calculated dose

k, confidence level
σ(r), standard deviation
ε, detectable systematic error

$k \cdot \sigma$	Probability
1 σ	68.26 %
1.96 σ	95 %
2 σ	95.44 %
2.58 σ	99 %
3 σ	99.74 %

Assumptions

Dose Uncertainty $(\sigma^2 = \sigma_{ns}{}^2 + \sigma_s{}^2)$

Non-spatial

Relative uncertainty σ_r: inversely proportional to the level of Dose

$$\sigma_r \propto \frac{\sigma}{D} = \frac{\sqrt{D}}{D} = \frac{1}{\sqrt{D}}$$

$$\sigma_{ns} = \sigma_{r_O} \sqrt{DD_o}\,(cGy)$$

Spatial

proportional to the gradient of Dose

$$\sigma_s = \left| \vec{G}(\vec{r}) \bullet \Delta\vec{r} \right| (cGy)$$

Uncertainty Model

Dose Uncertainty at a point, i from a field, j

$$\sigma^{i,j} = \sqrt{{\sigma_{ns}^{i,j}}^2 + {\sigma_s^{i,j}}^2}$$

With multiple fields,

$$\sigma^{i} = \sqrt{\sum_j {\sigma^{i,j}}^2}$$

Verification of the model (1-D Simulation)

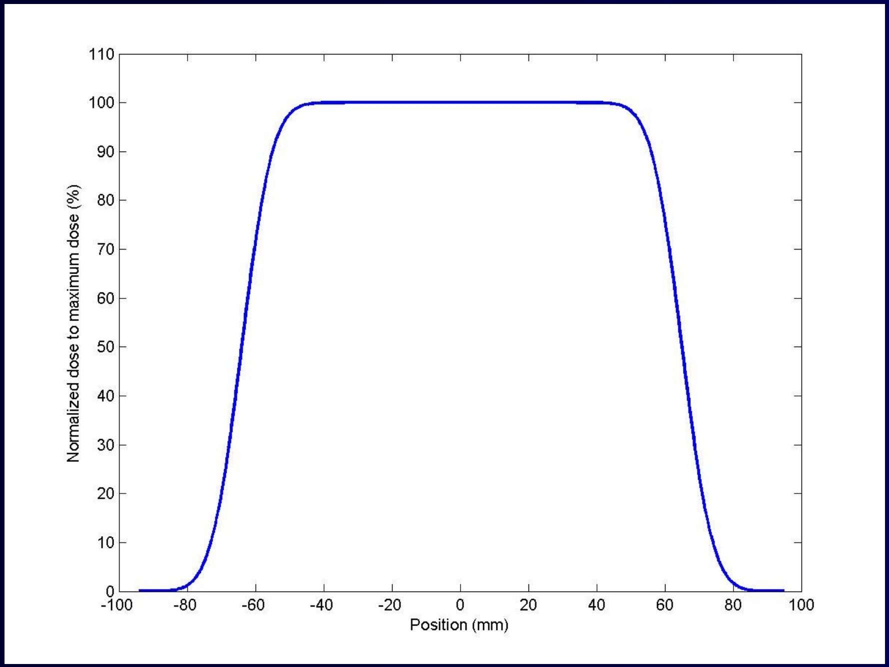
- Gaussian distribution of σ_{ns} and σ_s

with

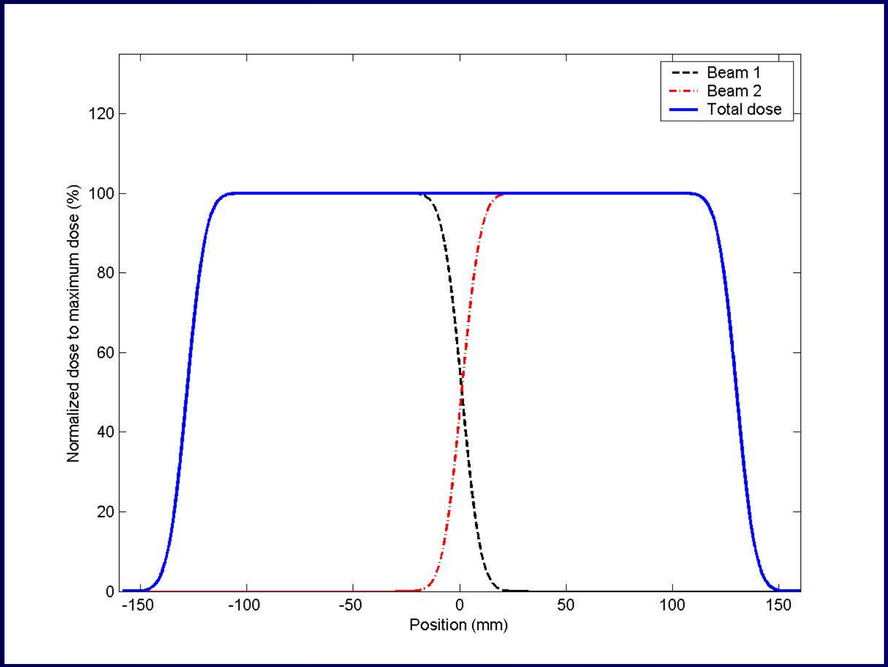
σ_{ns} = 1% at D_{max} (or Prescribed dose),
Δx = 1 mm for σ_s

1-D Simulation

Single Field (case 1) &
Two Adjacent Fields (case 2)

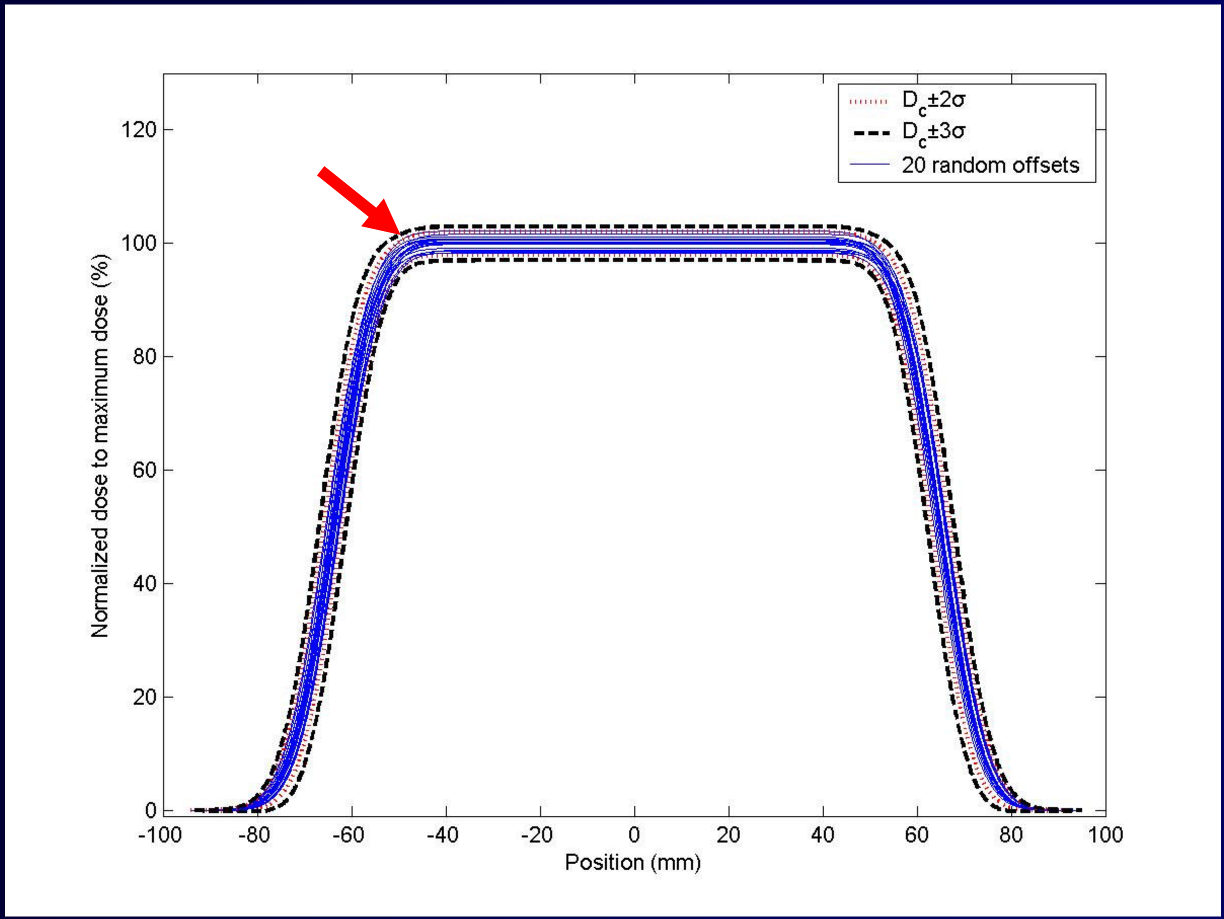


Single Field



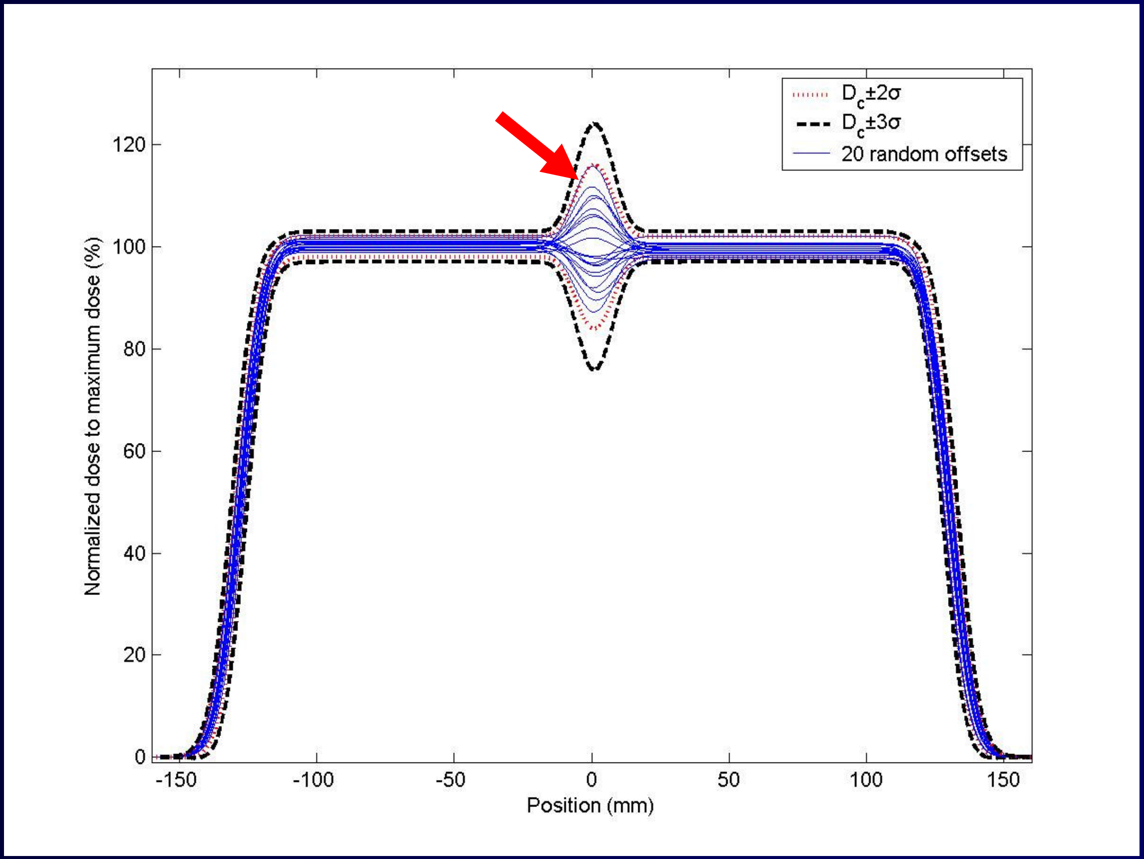
Two Adjacent fields

Results (1-D : 1 Field)



-2σ bound (95.44%): 1 out of 20 random offsets is out of the bound.
-3σ bound (99.74%): contains all the random offsets.

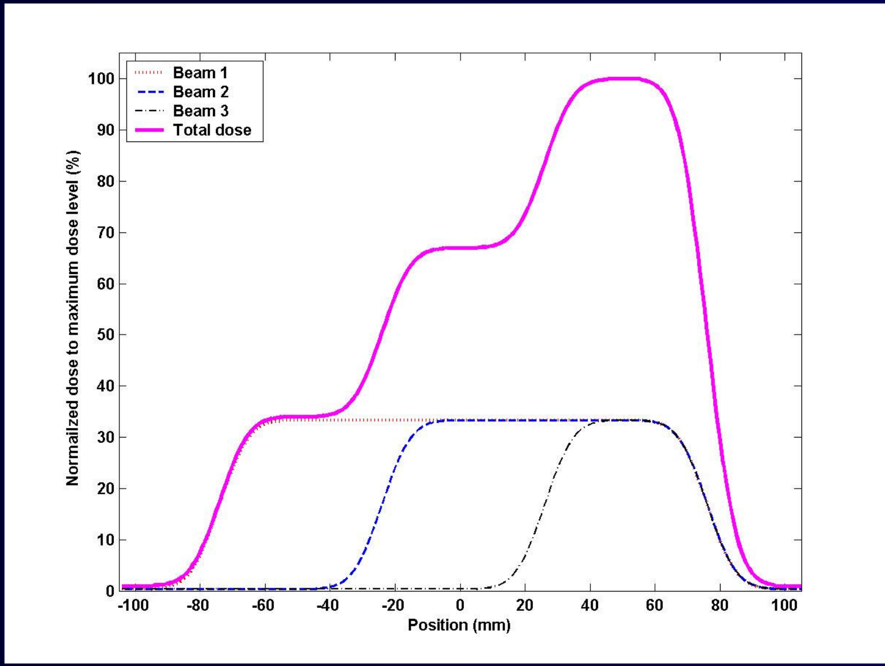
Results
(1-D : 2 Adjacent fields)



-2σ bound (95.44%): 1 out of 20 random offsets is out of the bound.
-3σ bound (99.74%): contains all the random offsets.

1-D Simulation

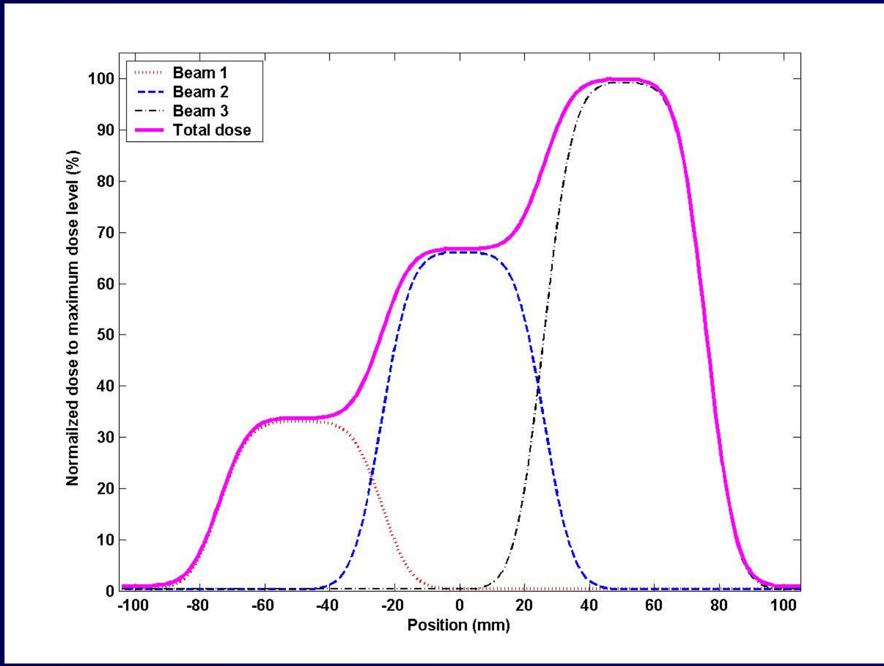
3-Segmented IMRT Field (case 3)



Beam set 1

Different beam width

Same beam fluence

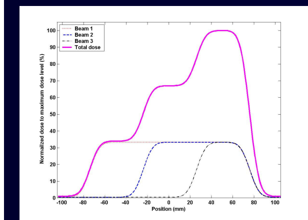


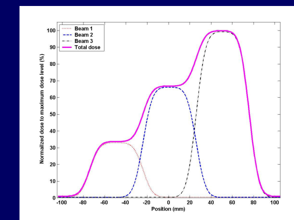
Beam set 2

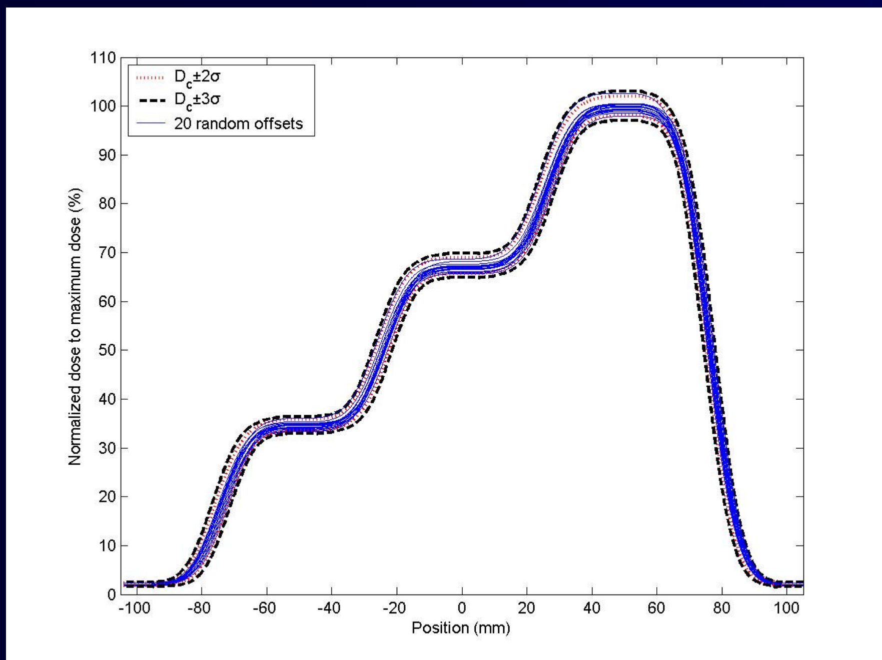
Same beam width

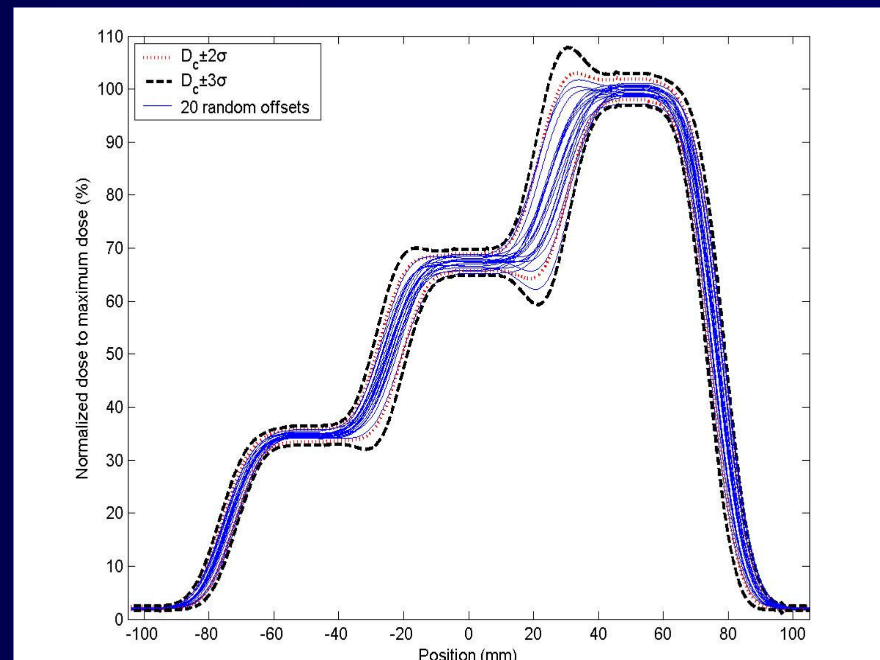
Different beam fluence

Results (1-D: 3 IMRT Beam Fields)









Beam set 1

Different beam widths

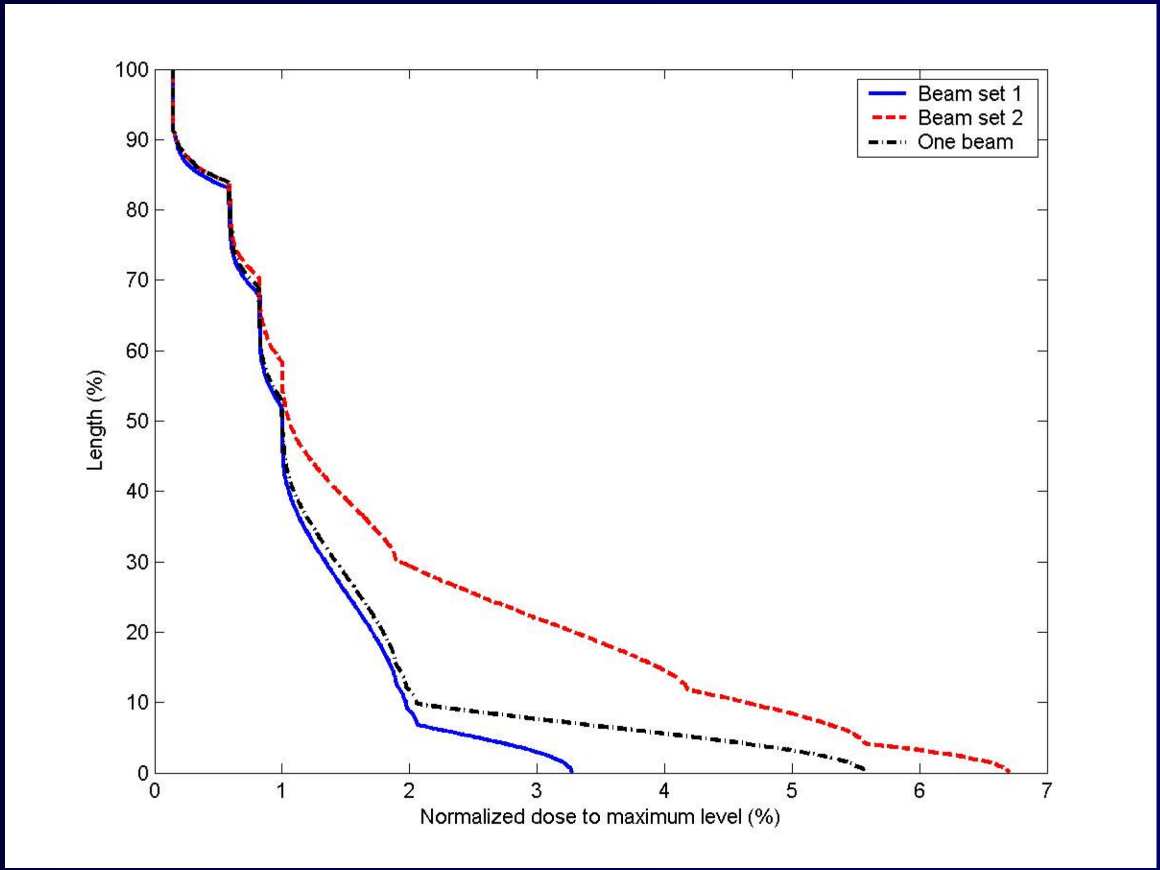
Same beam fluences

Beam set 2

Same beam widths

Different beam fluences

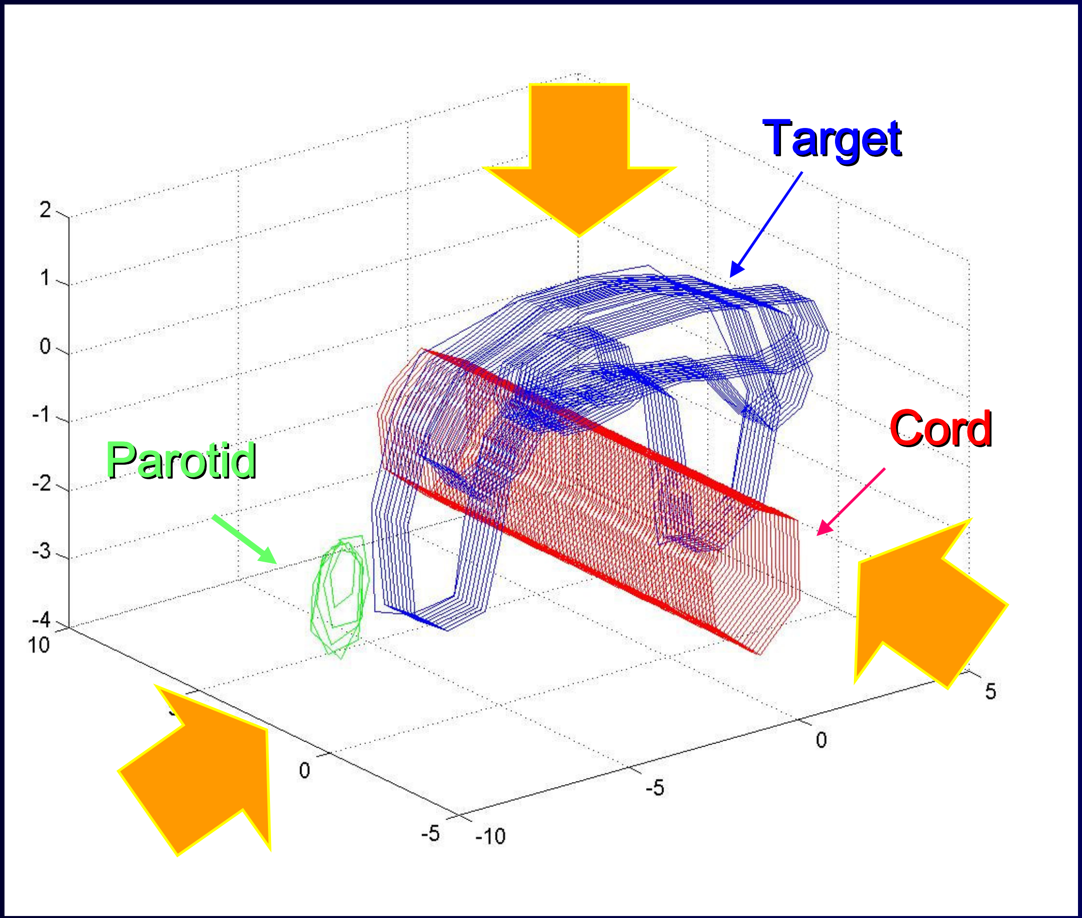
1-D ULH: Uncertainty Length Histogram



Beam set 1 is the best plan in terms of dose uncertainty.

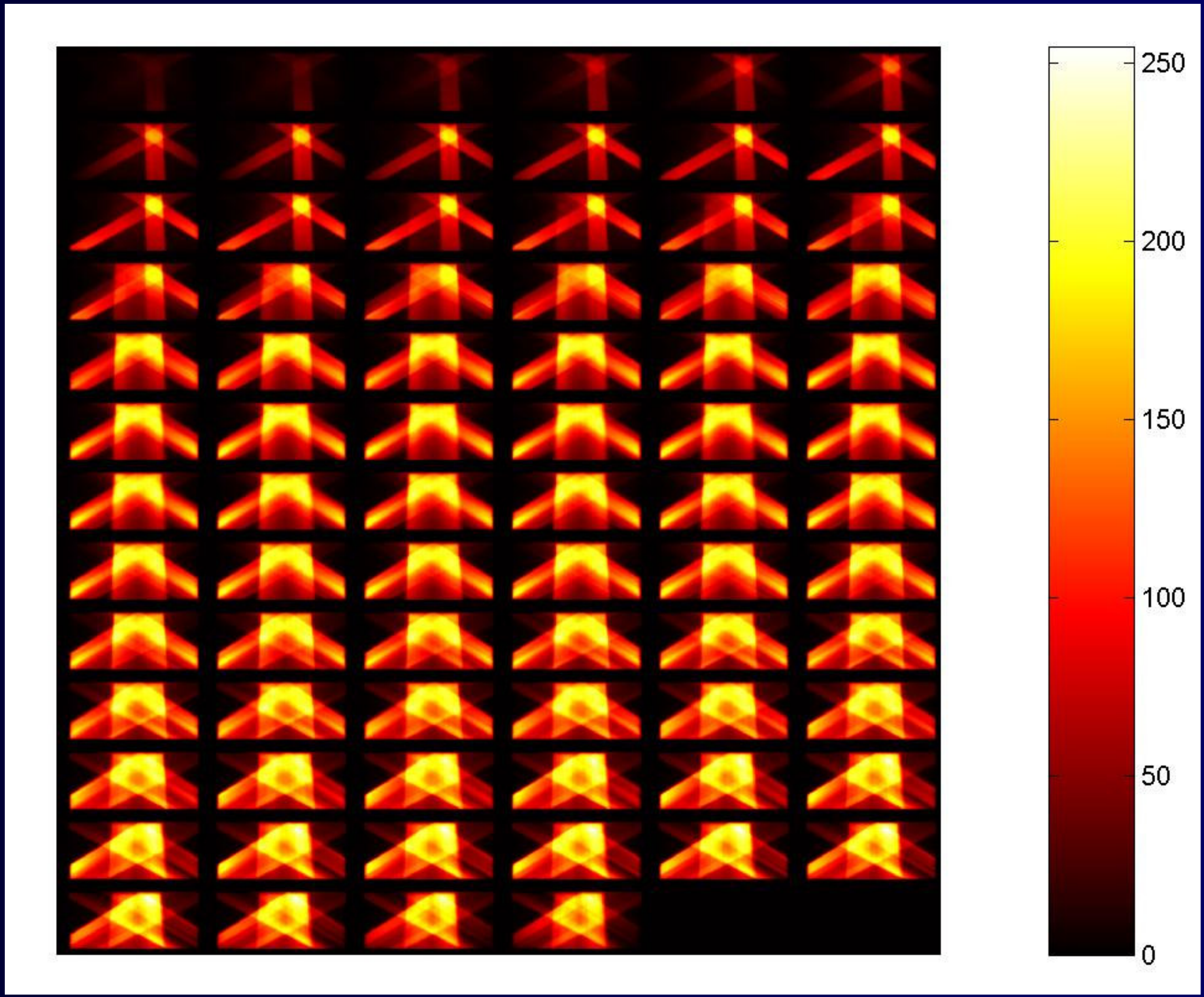
➡ **Useful for plan evaluation**

3-D Phantom Study



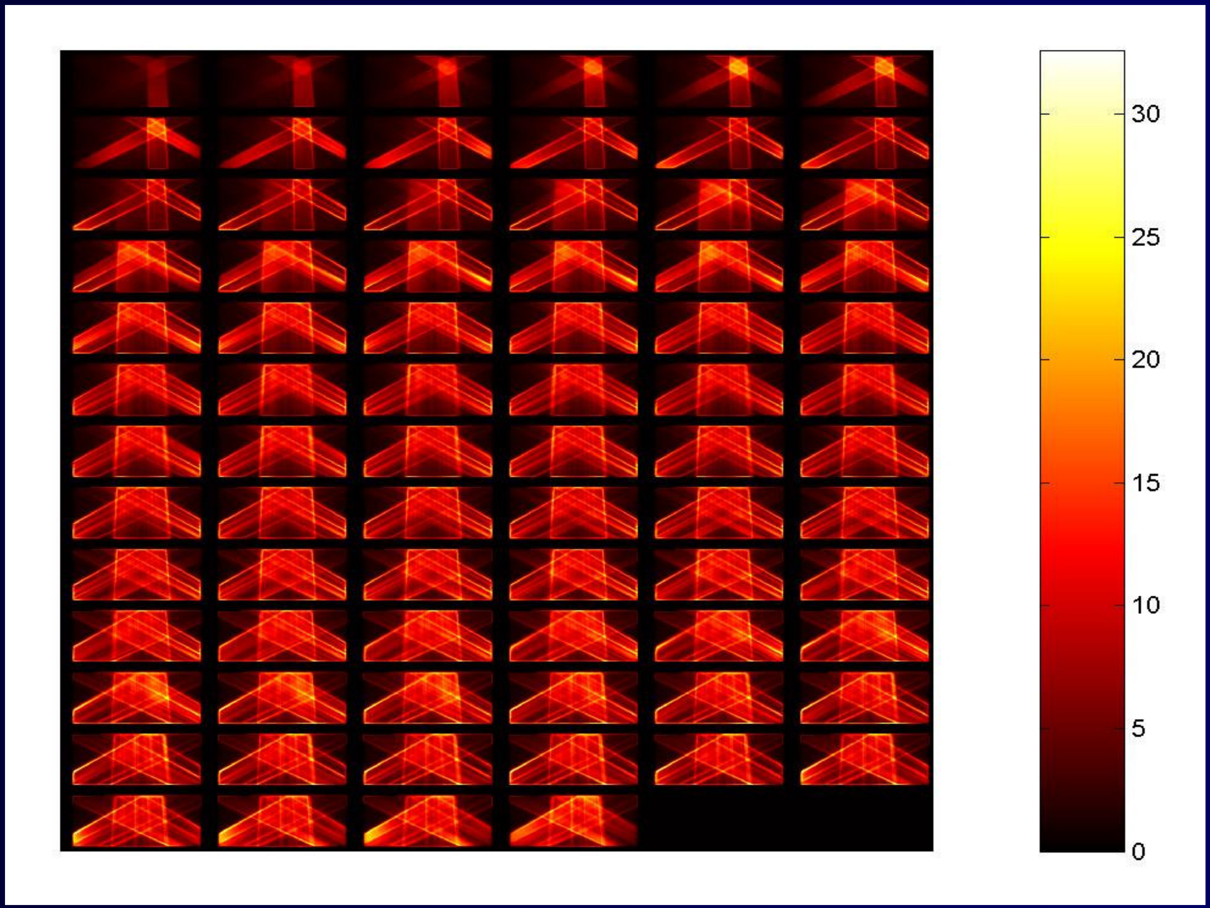
-H&N IMRT case
-3 Angles (Pinnacle)
(0°, 120°, and 240°)
-Prescription: 200 cGy/fx
-Fraction: 30 fxs
-Total dose: 60 Gy
-# of Beam segments
0° beam: 11 segments
120° beam: 9 segments
240° beam: 14 segments
-EDR2 Film irradiated at d=6 cm and compared with dose bound ($D_c \pm k\sigma$).

3-D Phantom Study



ADAC (Pinnacle) Dose Calculation

3-D dose uncertainty (U^D) map (1σ)



With σ_{ns}= 1% at $D_{prescription}$, Δr = 1 mm for σ_s ($\Delta x = \Delta y = \Delta z = \frac{1}{\sqrt{3}}$)

This is the world's first 3-D dose uncertainty map !!!

Summary

- ✓ The tolerance limits and action levels proposed in this presentation for the IMRT delivery system QA have justifiable scientific rationale
- ✓ The tolerance limits and action levels proposed in this presentation for the IMRT planning and patient specific QA also have justifiable scientific rationale.
  - ✓However, all commonly used metrics (ΔD, binary difference, gamma index etc.) for dose plan verification have limitations in that they do not account for space-specific uncertainty information
- ✓ The proposed plan evaluation metrics will incorporate both spatial and non-spatial dose deviations and will have high predictive value for QA outliers