Beam Requirements for Particle Therapy

or

What does an FFAG have to do to be considered for medical therapy application?

FFAG Workshop - 2006

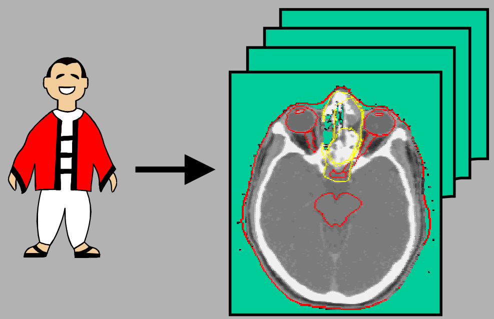
5/18/06

Jay Flanz

Massachusetts General Hospital

Overview of Radiation Therapy

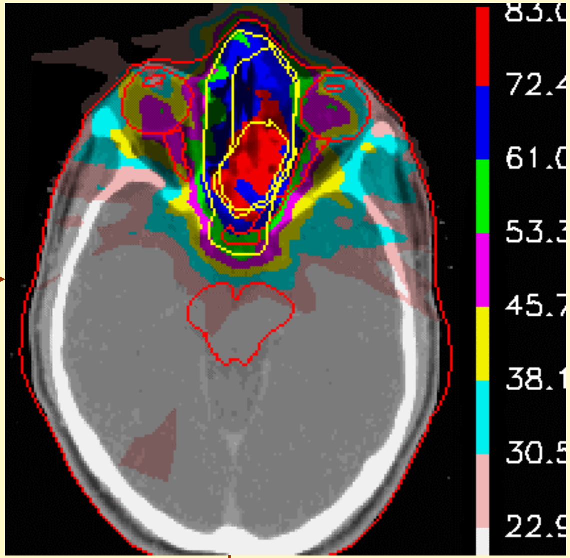
Identify the Target



•Imaging to localize and diagnose disease
- –High precision
- –Accurate 3D geometric model of patient
- –Permits accurate modeling of dose-effects

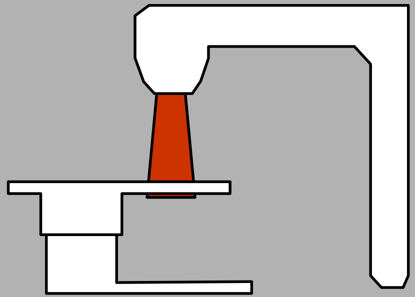
Simulation (virtual)

Dose distribution within patient



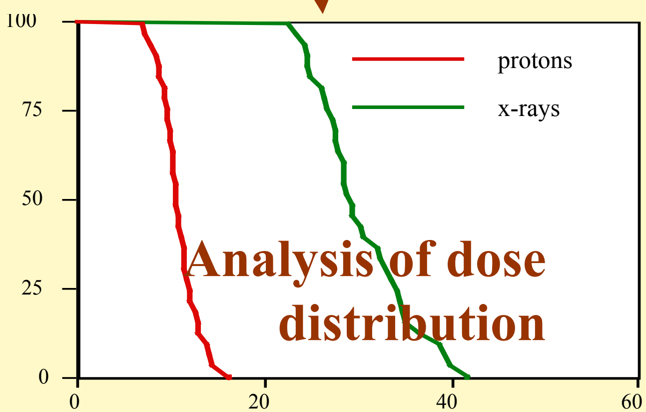
Plan & Evaluate

Chose the therapy equipment/modality



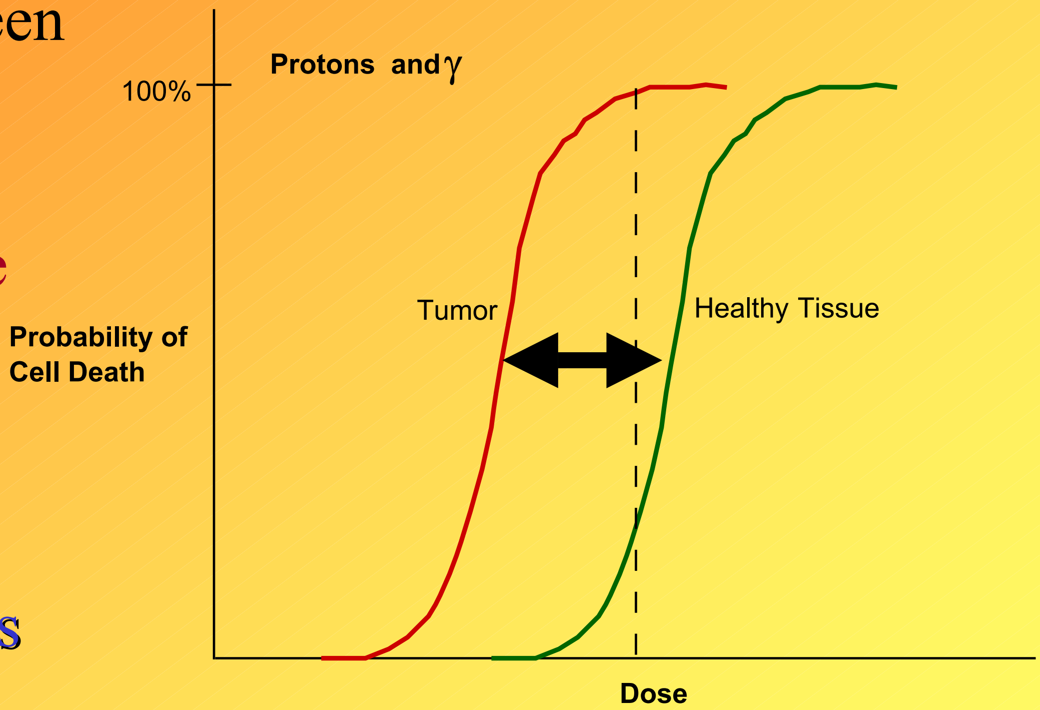
•Patient positioning (and tracking)
- –Control target and radiation field overlap

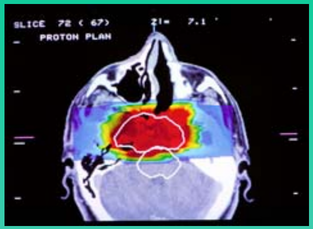
•Radiation
- –Treat diseased cells *but* spare normal cells



Why radiation works

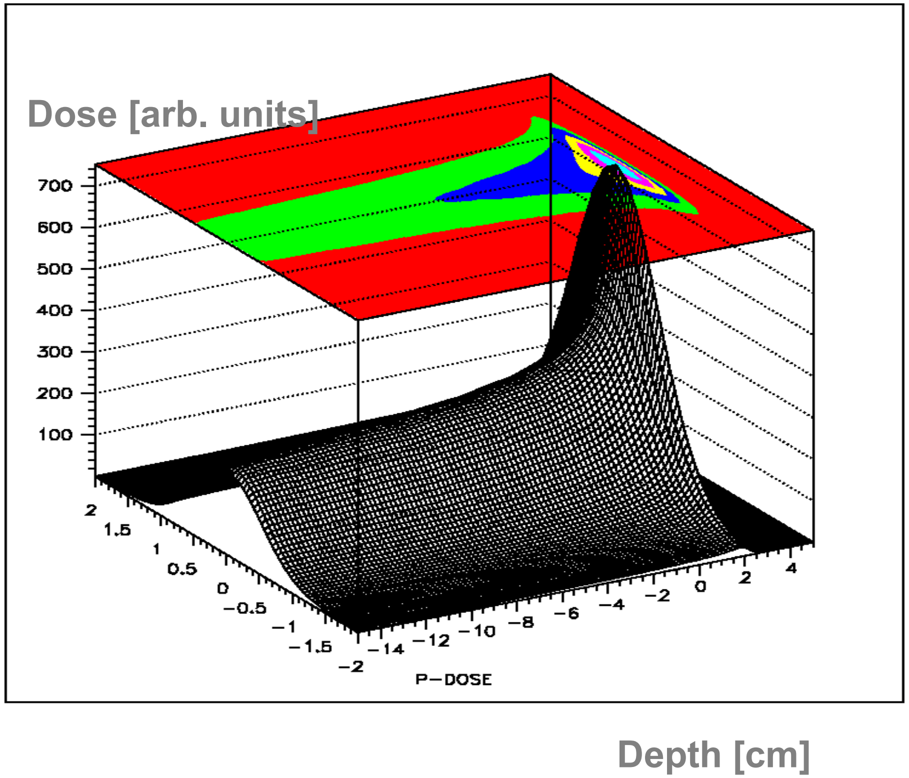
- Difference in repair ability between tumor and healthy cells
- Difference in damage between tumor and health cells
  - Healthy tissue tolerance limits treatment dose
  - One method is to geometrically confine dose to the tumor and minimize dose to tissues



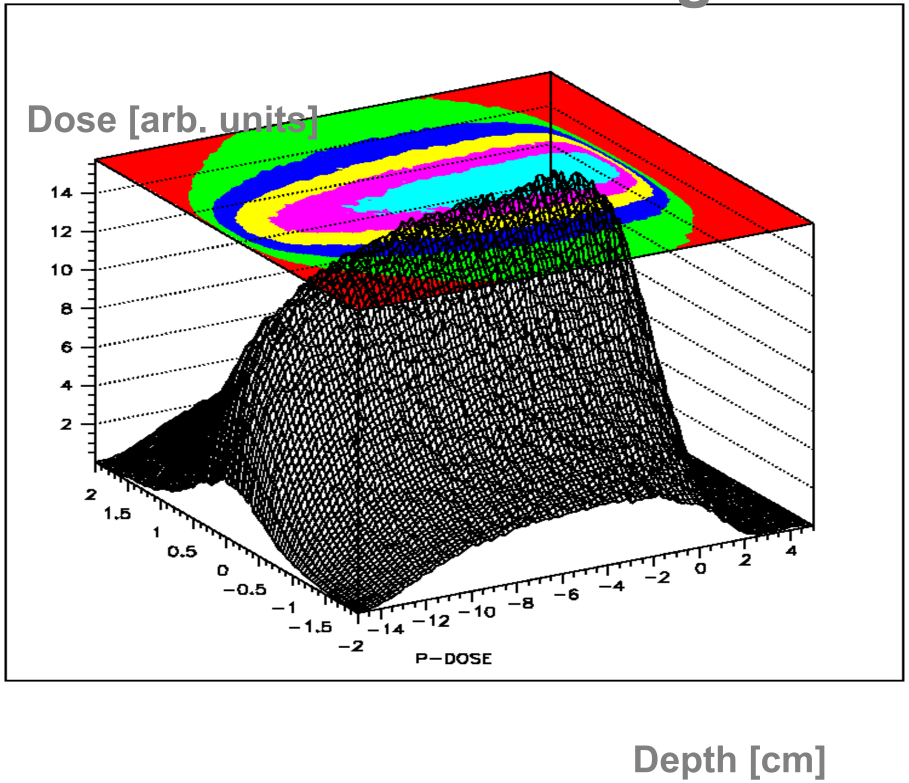


Dose; Protons and Nuclear Interactions Monte Carlo Studies (GEANT)

Primary Protons
Ionization (non-nuclear)



Secondary Protons
Proton Scattering



Dose in Water for a 160 MeV p beam

Harald Paganetti

Spread Out Bragg Peak

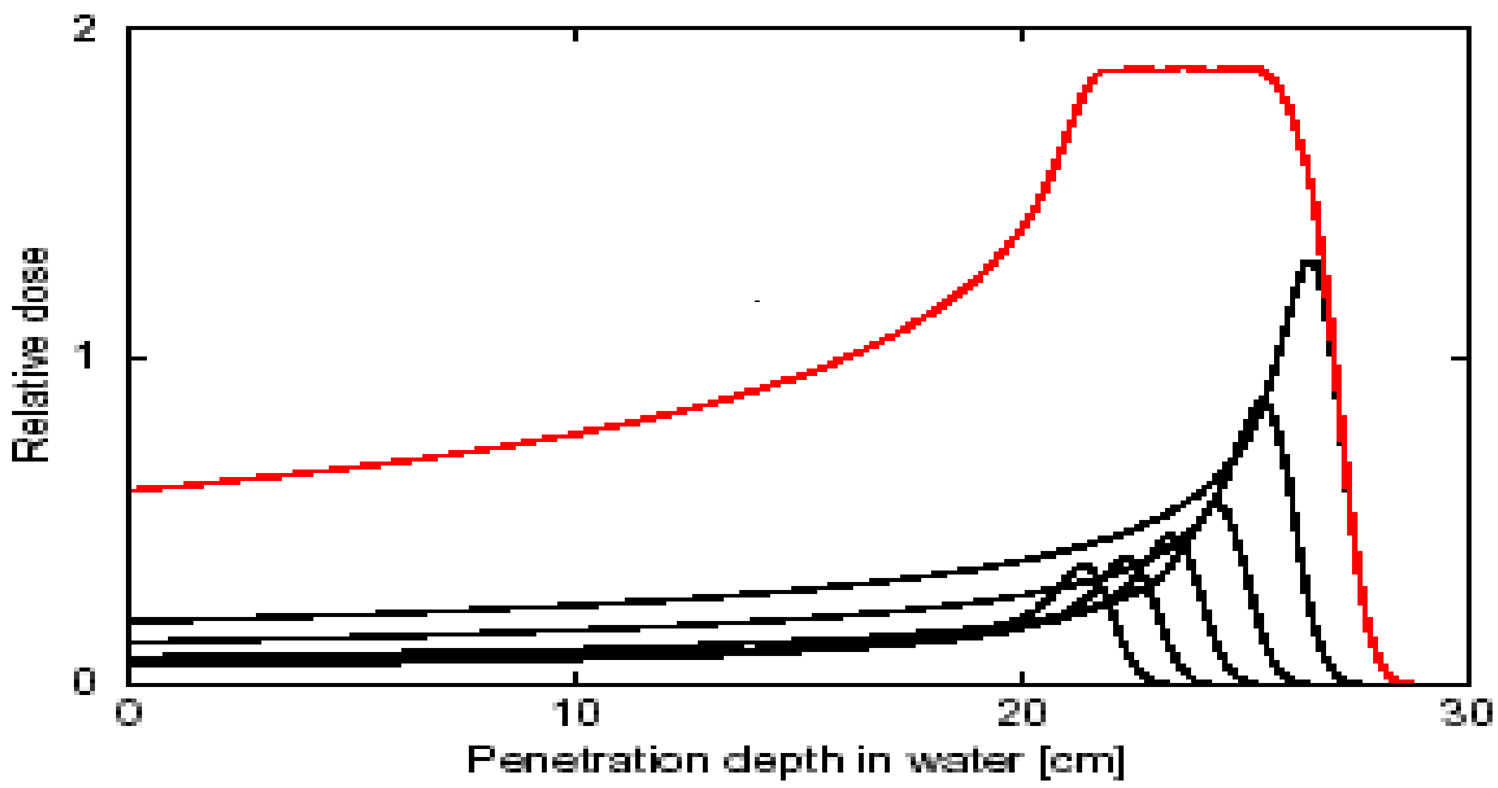
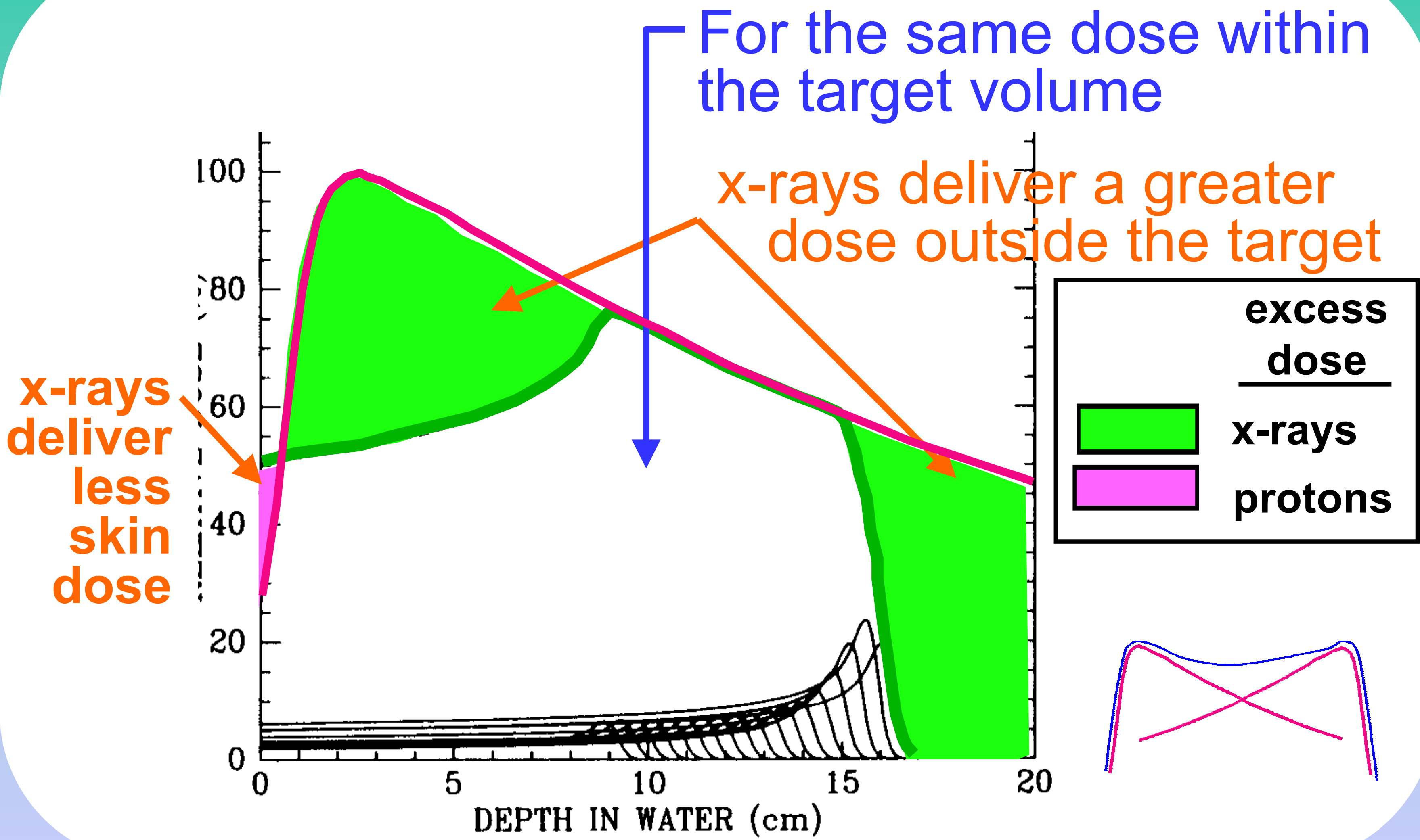


Figure 1: Spread out Bragg peak from 6 beam pulses.

PROTONS MATCHED TO X-RAYS IN TARGET REGION

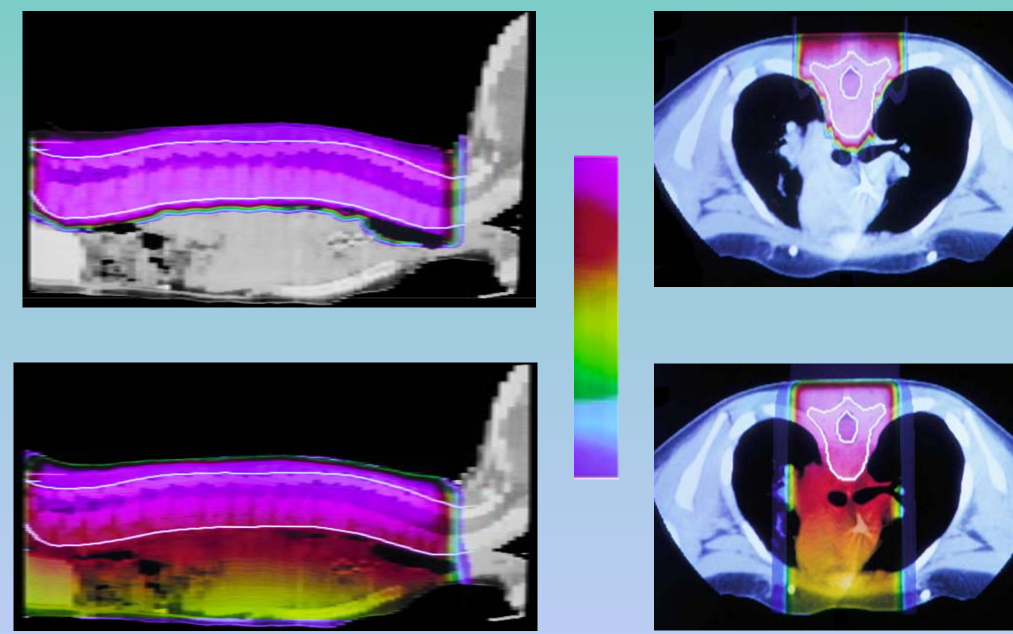


Example: Pediatric Tumors

– *Effects on growth, organ function, cognitive skills and secondary tumors are major limitations in pediatric radiation oncology*

Retinoblastoma

Medulloblastoma



What's Important here? Range, Coverage ON target.

Intensity Modulated Therapy

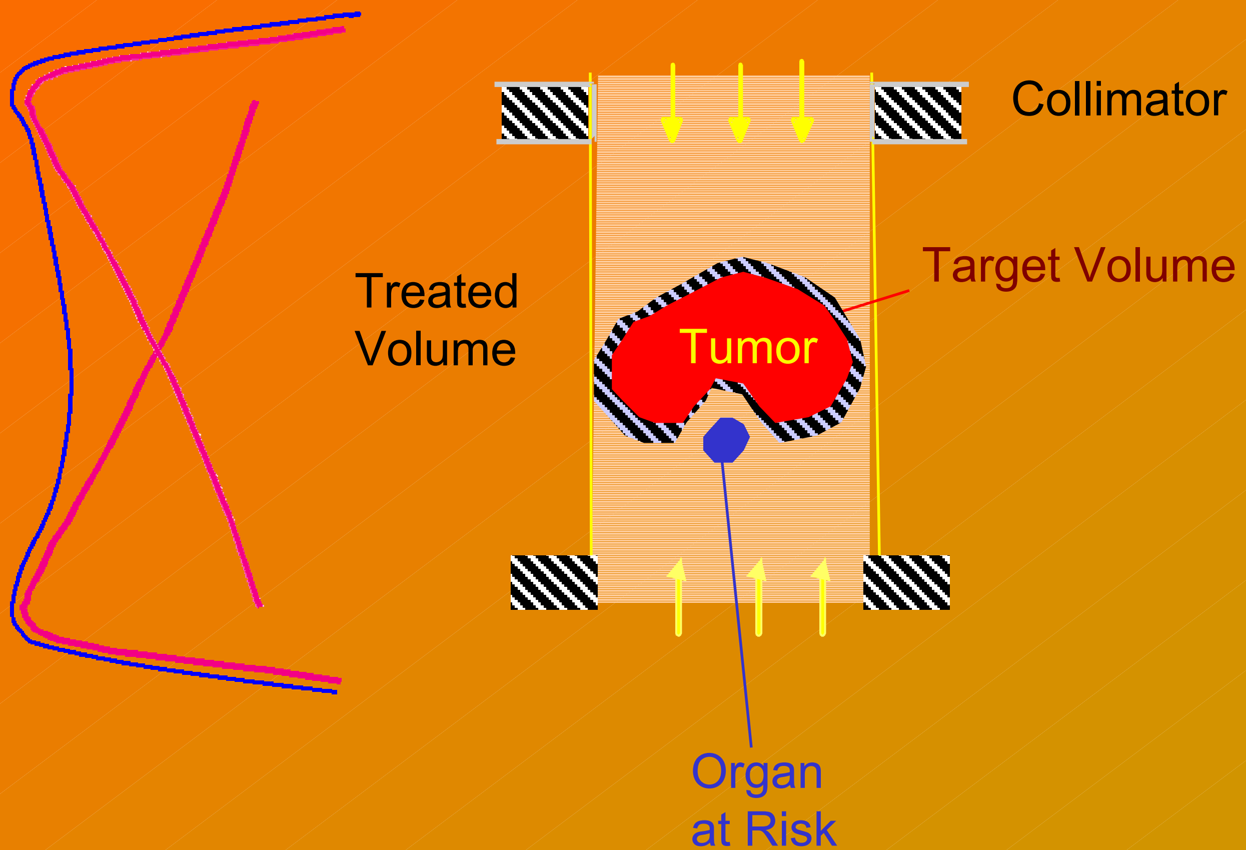
The Quest for *"Conformity"*

which is to say, for a Treatment Center

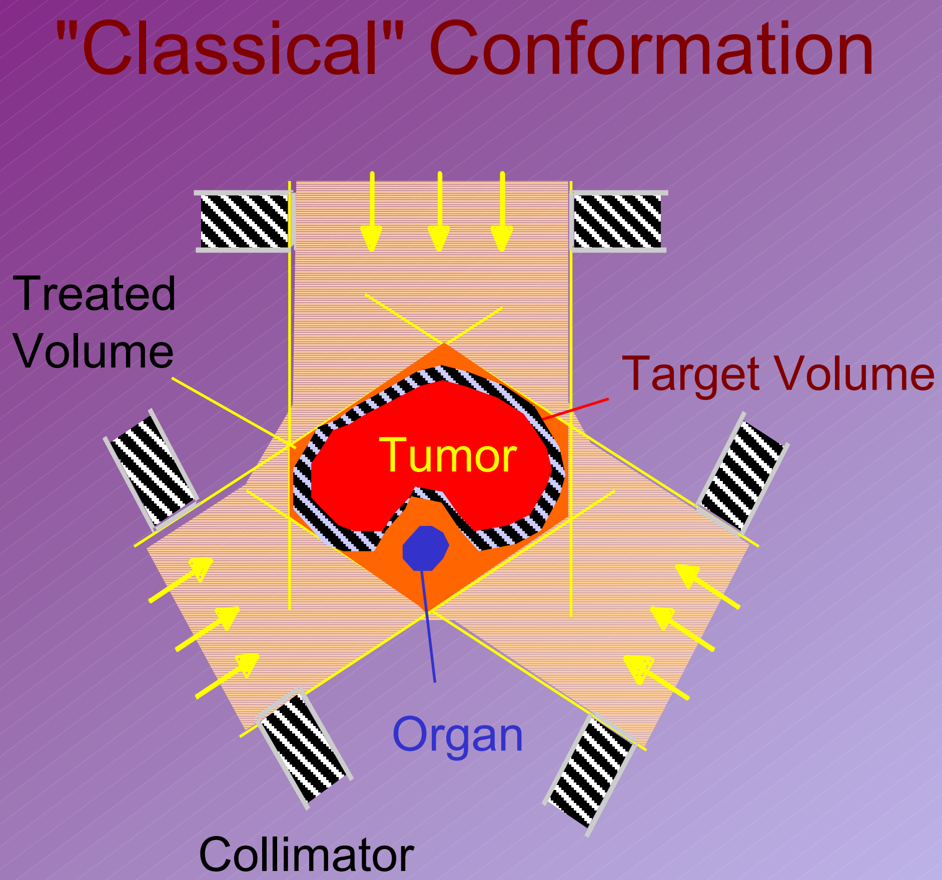
Not to be the same as the rest

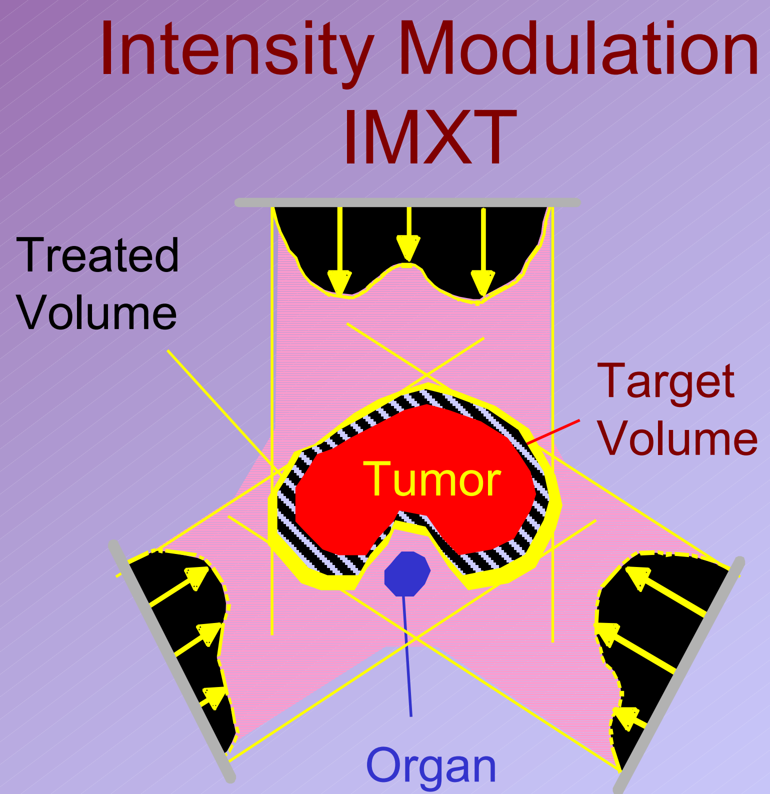
Improving Methods of Conformation to Target

"Classical" Non-Conformal Photon Radiation Therapy

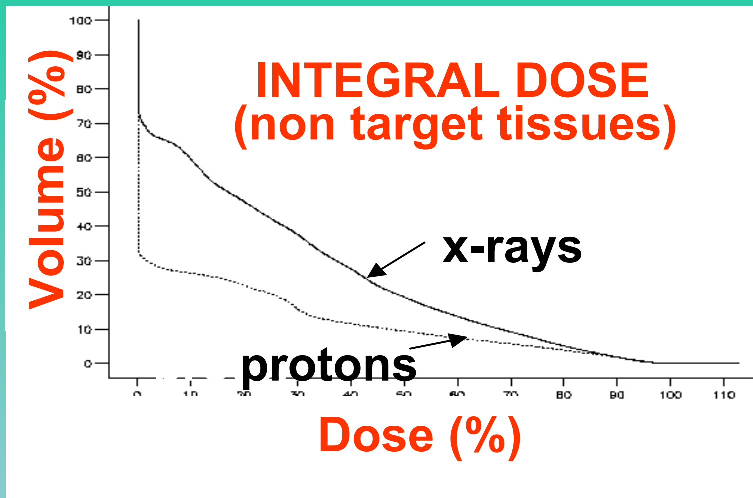


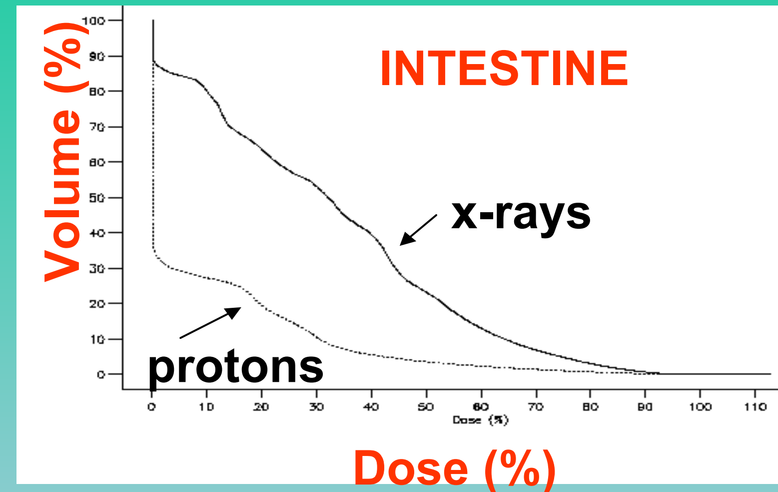
Improving Methods of Conformation to Target
Why Intensity Modulated Radiation Therapy (IMRT) (Photons) ?



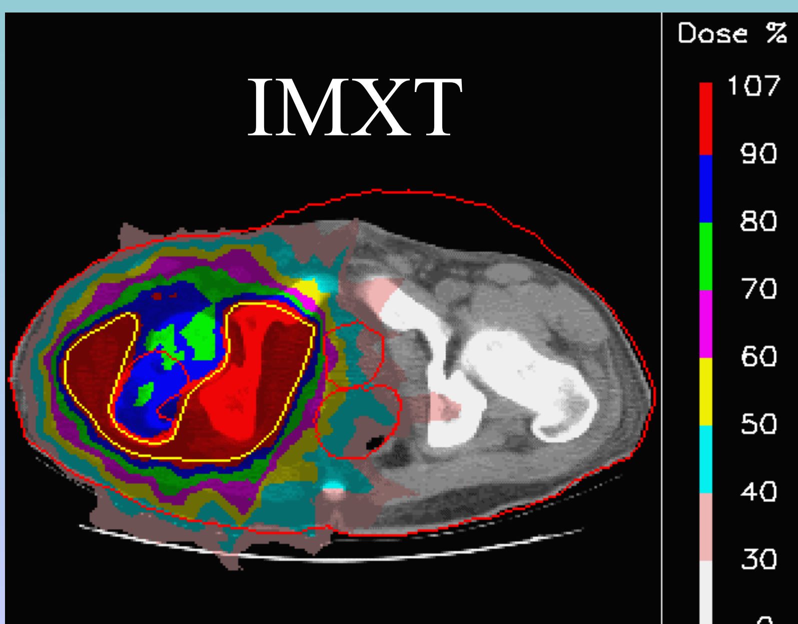


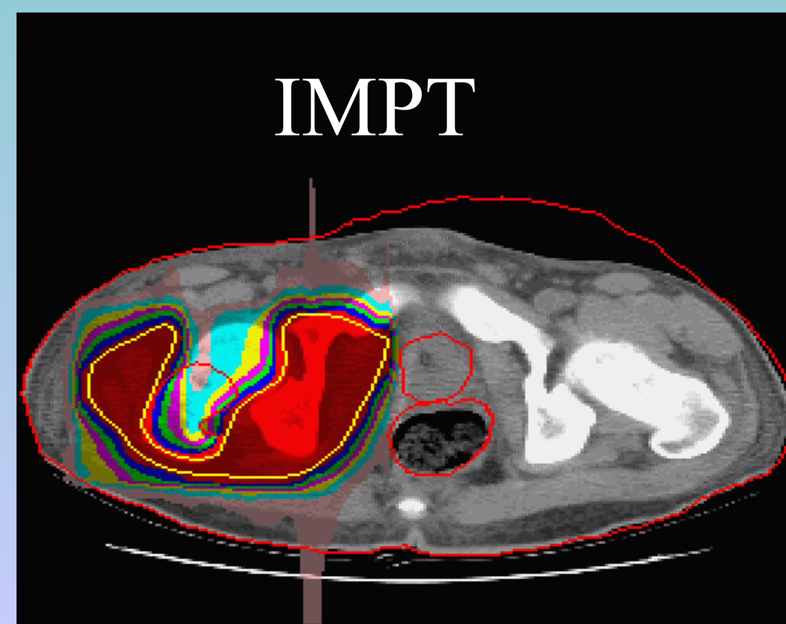
IM protons vs. IM x-rays: Ewing's Sarcoma





Proton integral dose is factor of 2 less than for x-rays





Beam Delivery

What should an FFAG be prepared to do?

Beam Delivery

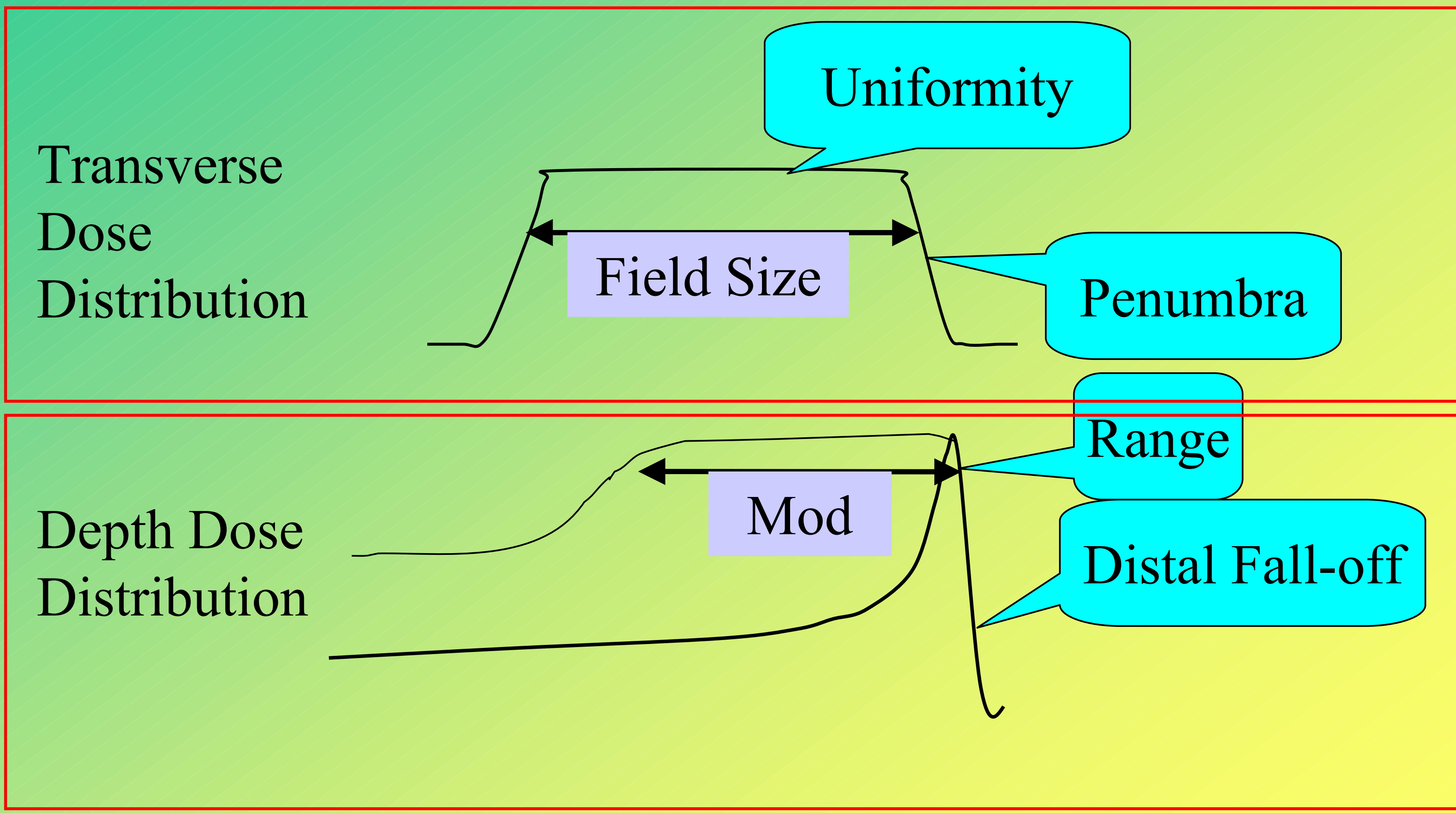
Accelerator → Transport → Beam Shaping

"Just give me an accelerator and I'll find a way to use it !"

"I have an accelerator can you use it for medicine?"

What to control/measure?

Proton Beam Properties



Dose, Dose Rate

Longitudinal Beam Properties

“Depth Dose”

How to "Modulate" the Range - Requirement

1. Deliver Several different proton beam Energies

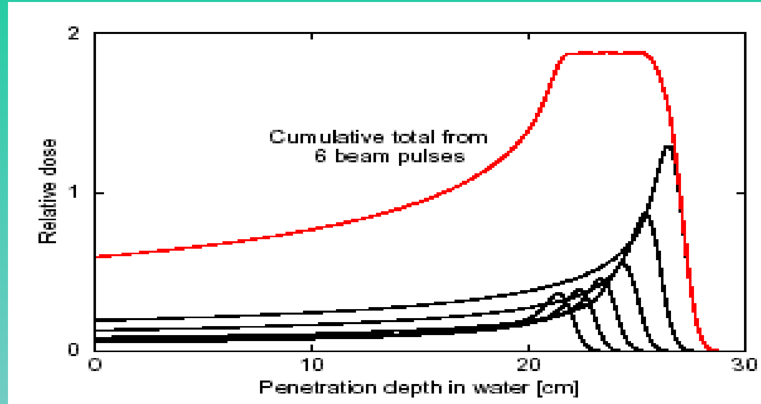


Figure 1: Spread out Bragg peak from 6 beam pulses.

Beam Requirements depend upon method !

2. Use a degrader with the appropriate 'weights'

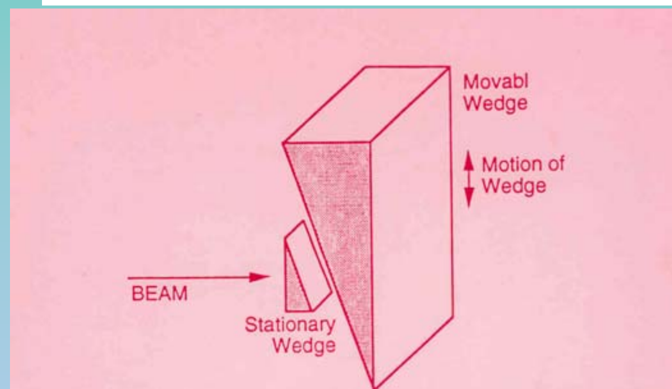


Fig. 18. Schematics of a double wedge system which is used to shift the range of the beam.

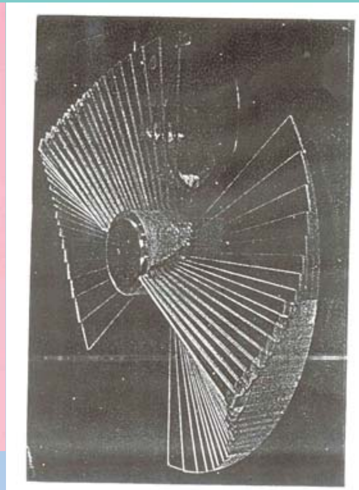
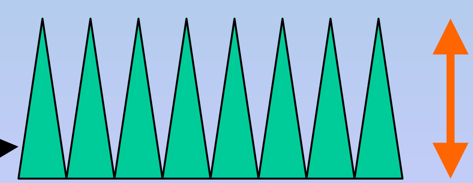
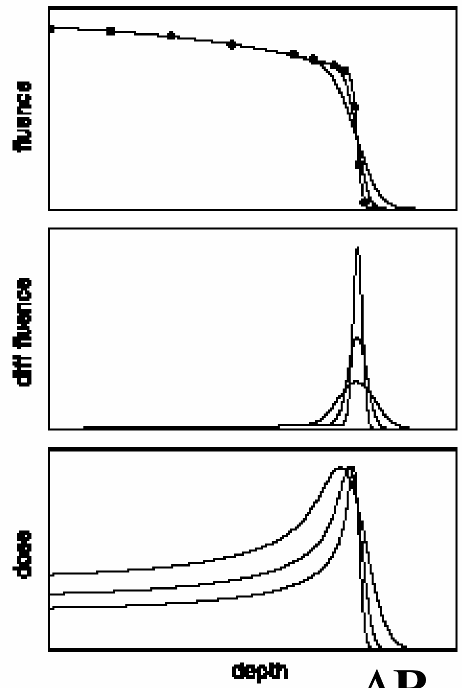


Fig. 3. Photograph of the 14.5 cm range modular wheel. The wheel is mounted onto the collimator for the large field proton beam. Diameter of the wheel is 82 cm. The circular beam defining aperture visible through the wheel is 27 cm diameter.

3. "Ridge Filter"



The Shape of the Bragg Peak One depends upon the energy spread



Distal Fall-off

$\Delta R_{80/20} \sim 1.3 * \sigma$

Figure 6.2: Fluence, differential fluence and dose as a function of depth for proton beams of a given range and different energy spreads, illustrating $r_0 = d_{80}$.

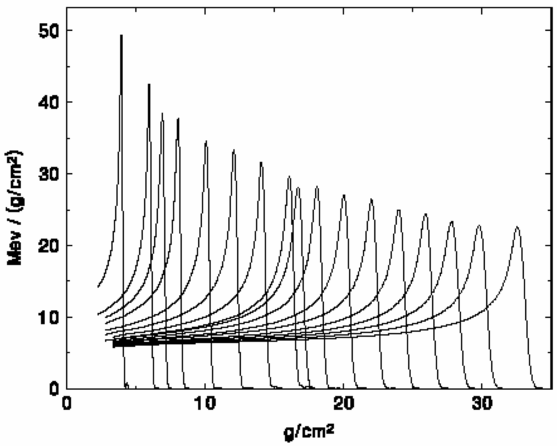
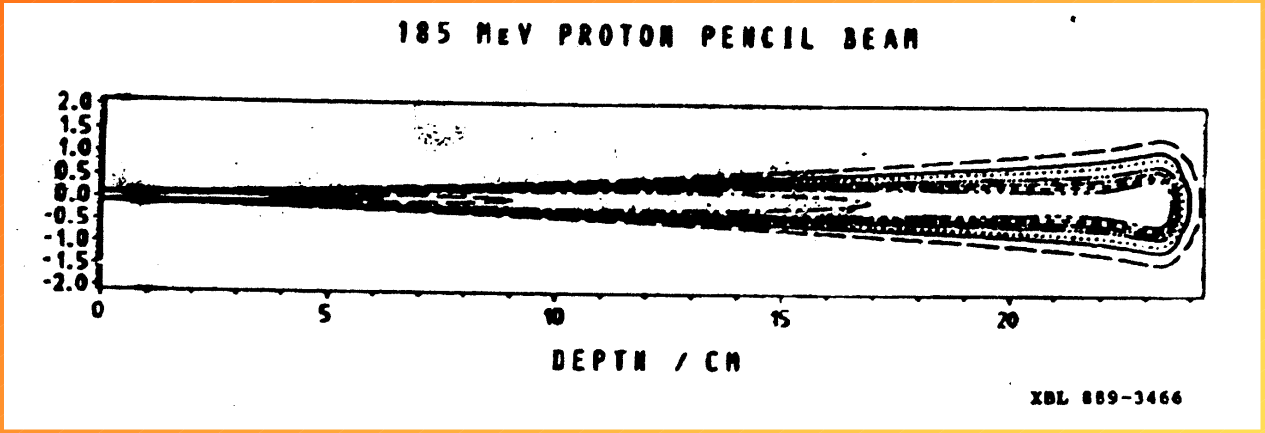


Figure 11.1: Measured Bragg peaks from 69 to 231 MeV.

***Also Range Straggling*: ΔR ~ 1.2% Range.**

Gottschalk

A Bragg Peak isn't always a Peak!



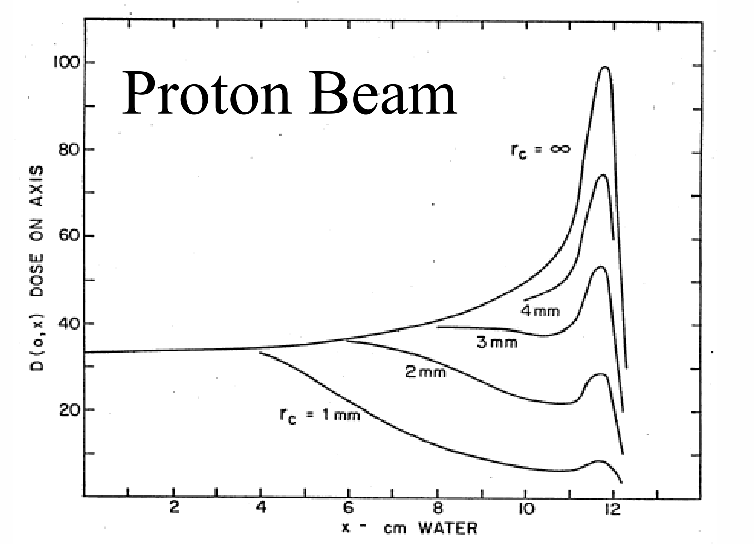


Figure 11.2: The relative dose on the axis of a uniform circular proton beam of initial range 12 cm of water and radius r_c at the collimator. The curve for $r_c = \infty$ is experimental, the others are calculated.

Therefore the range modulation parameters will be much different !

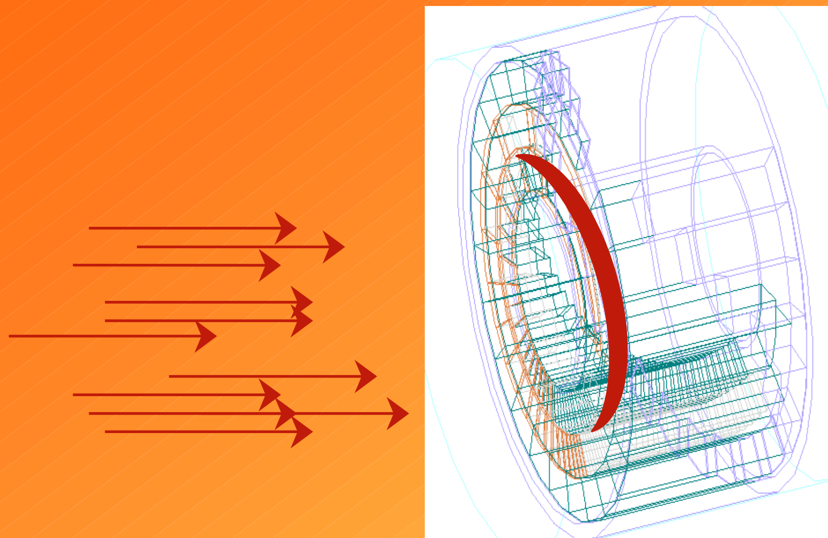
Does one have a different modulator for every conceivable case?

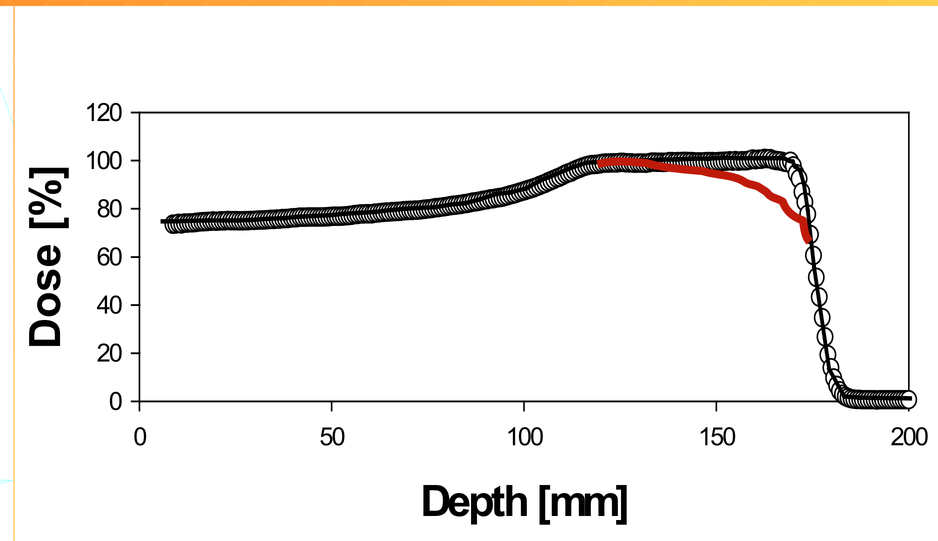
Gottschalk

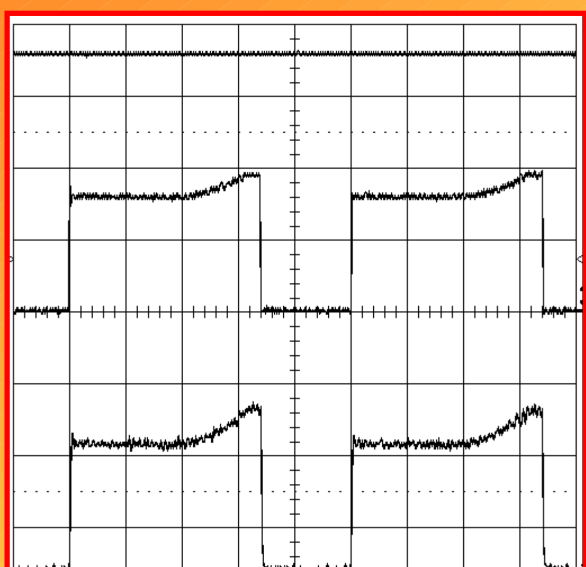
Current Modulation

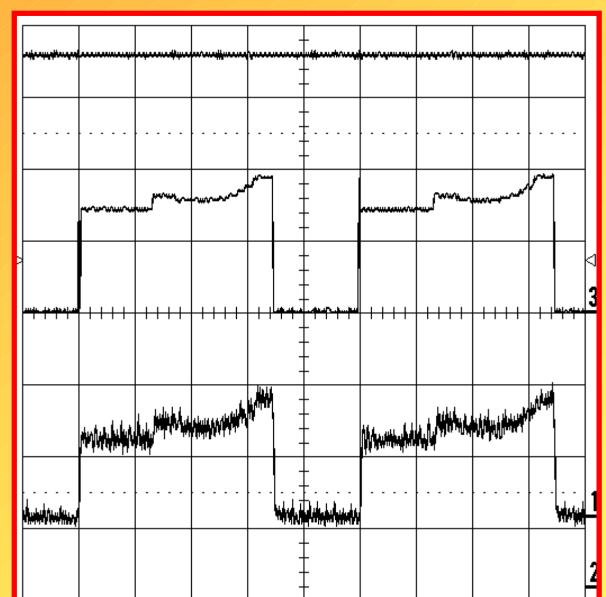
Harald Paganetti

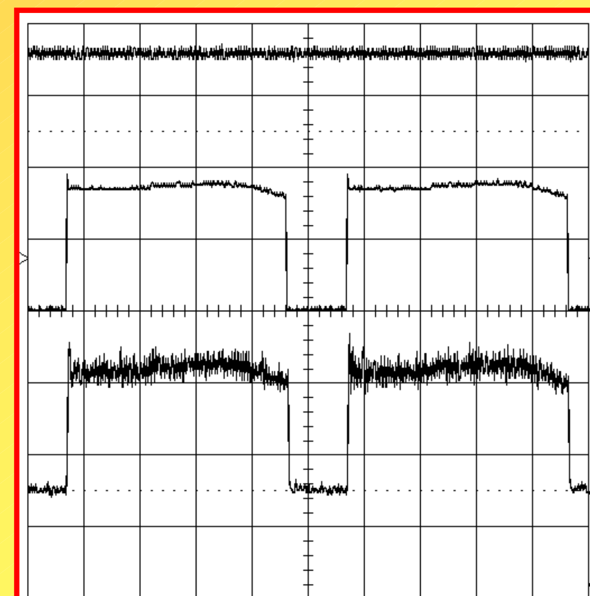
A **Requirement** of a Proton Therapy Accelerator



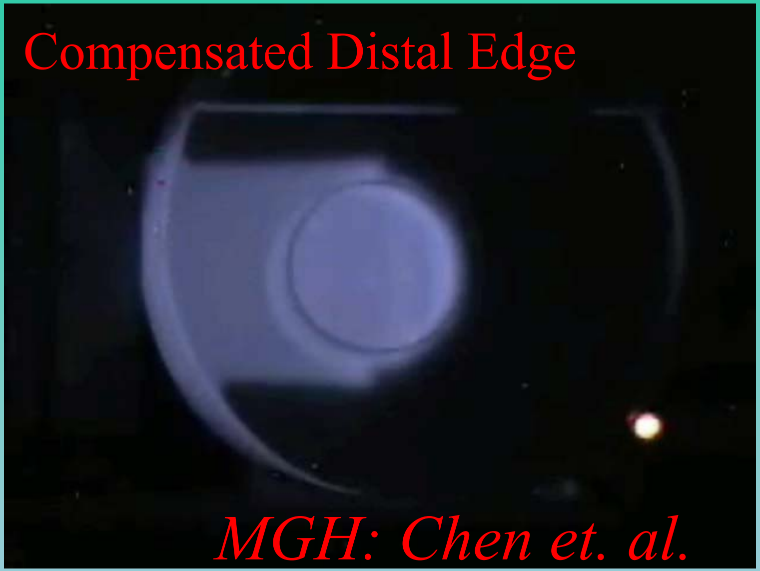








Modulating Proton Range



Longitudinal Properties of a Scattered Beam affected by:

- Beam Energy
- Beam Energy Spread
- Beam Current Time Structure/Modulation
  - Depends upon type of modulator
- Stuff in the Beam
- Stability of all the above

In the range of approximation of Proton Energies < few hundred MeV, a reasonable approximation is that the

mean **Range ~ (Incident Kinetic Energy)**$^{1.75}$

Therefore, $\mathbf{\Delta R/R \sim 1.75\ \Delta E_k/E_k}$ for not quite relativistic Particles

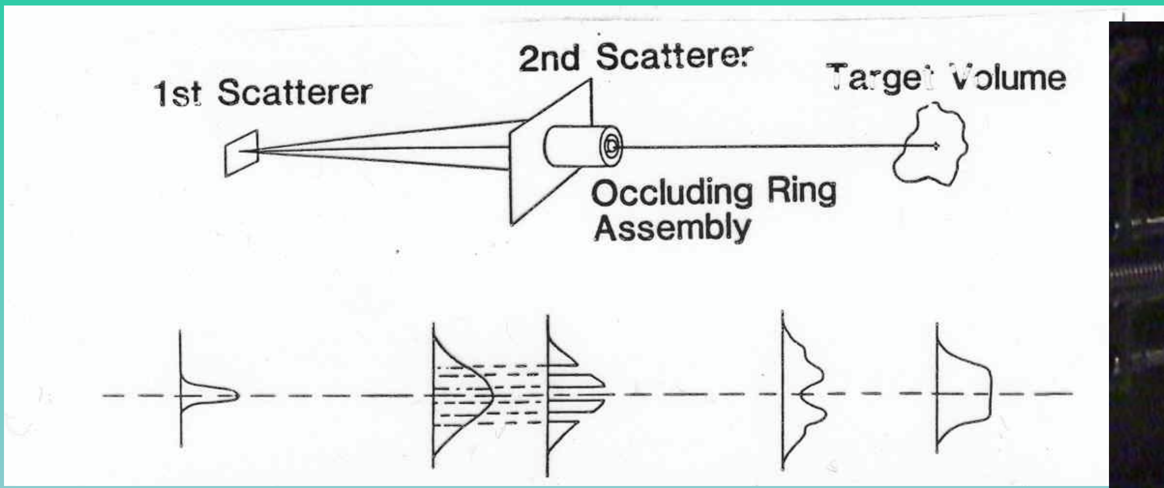
Transverse Beam Properties

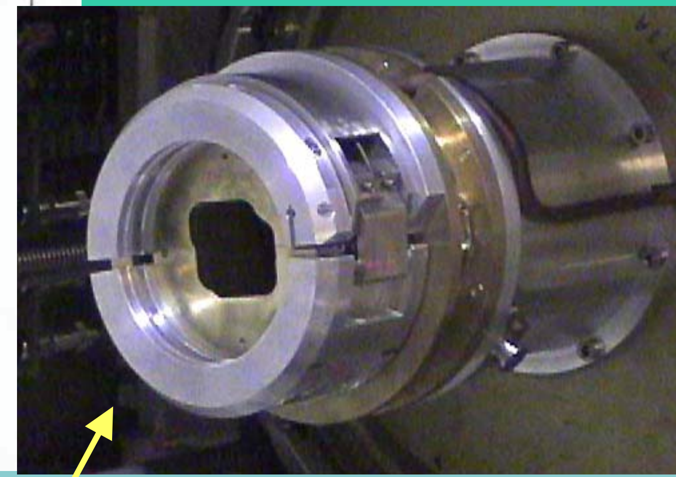
"Uniformity and Penumbra"

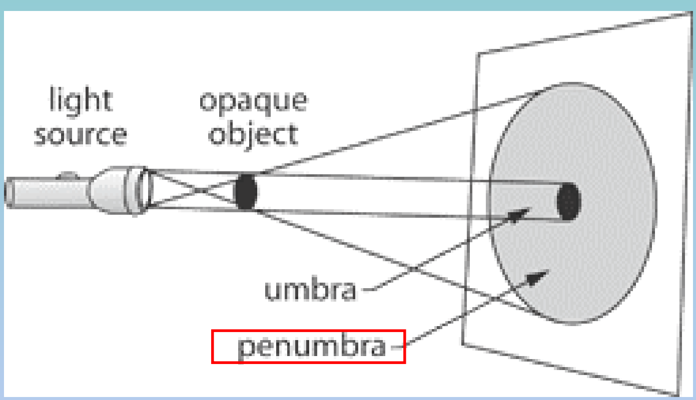
and

How to Spread the beam to match the target?

Passive Scattering (Single and Double)







A) Source Size

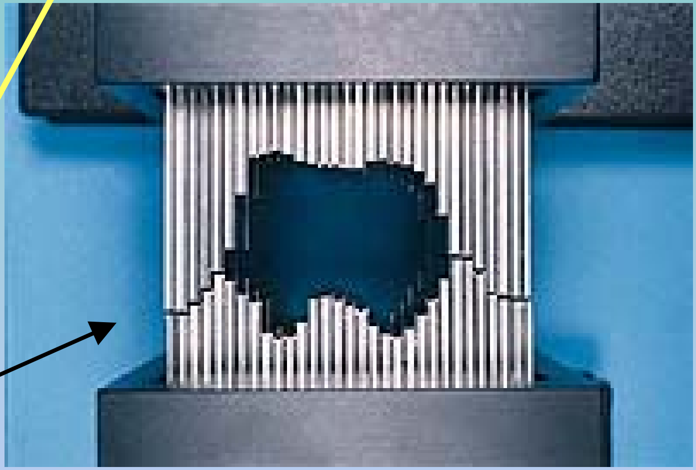
B) Distance (SAD)

1. Spreading Technique

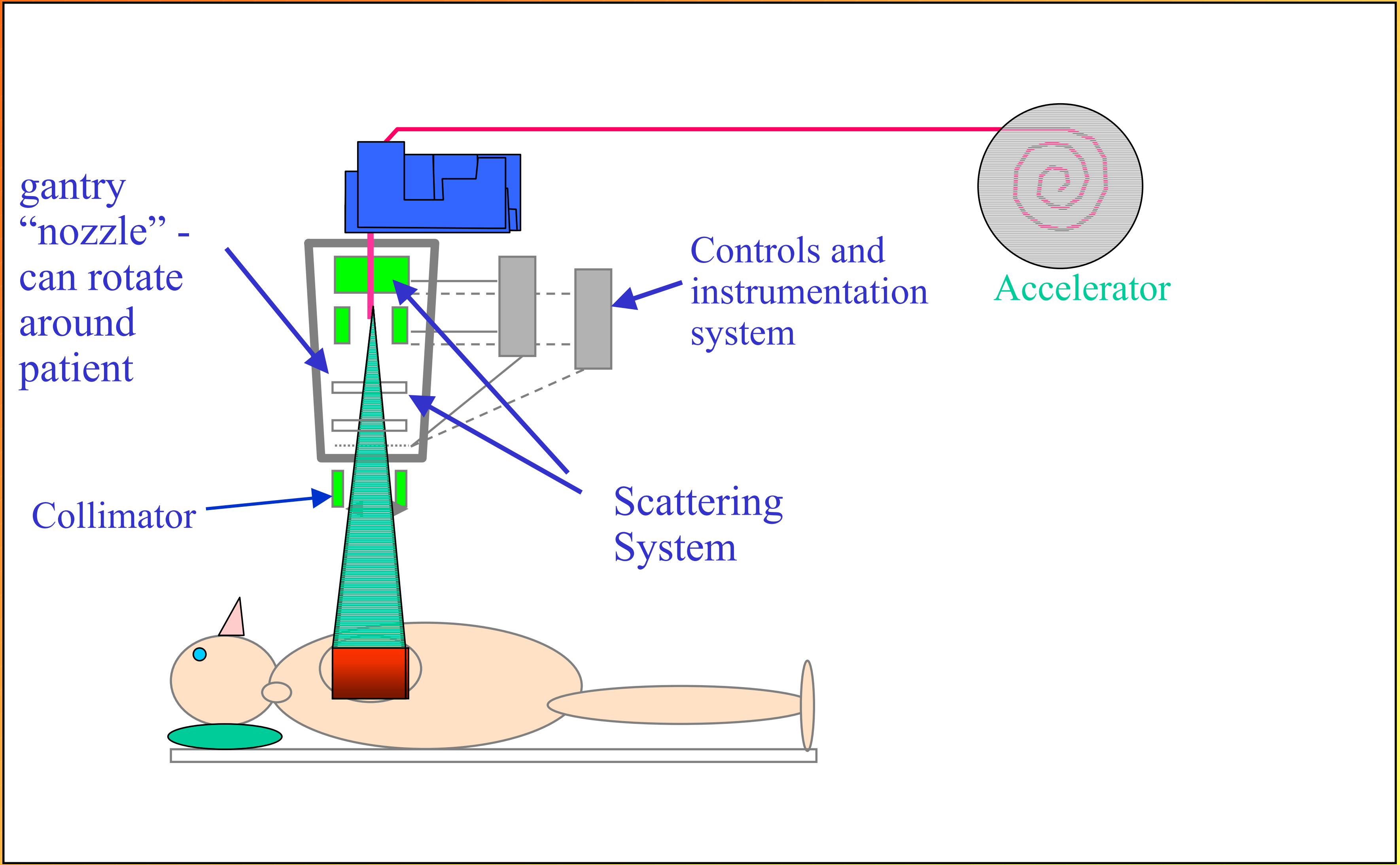
2. Shaping

a) Fixed Aperture

b) MLC



Proton Therapy implementation at the NPTC
Beam Delivery with Double Scattering



Transverse Properties of a Scattered beam affected by:

- Scatterers in the Beam
- Beam Size
- Energy

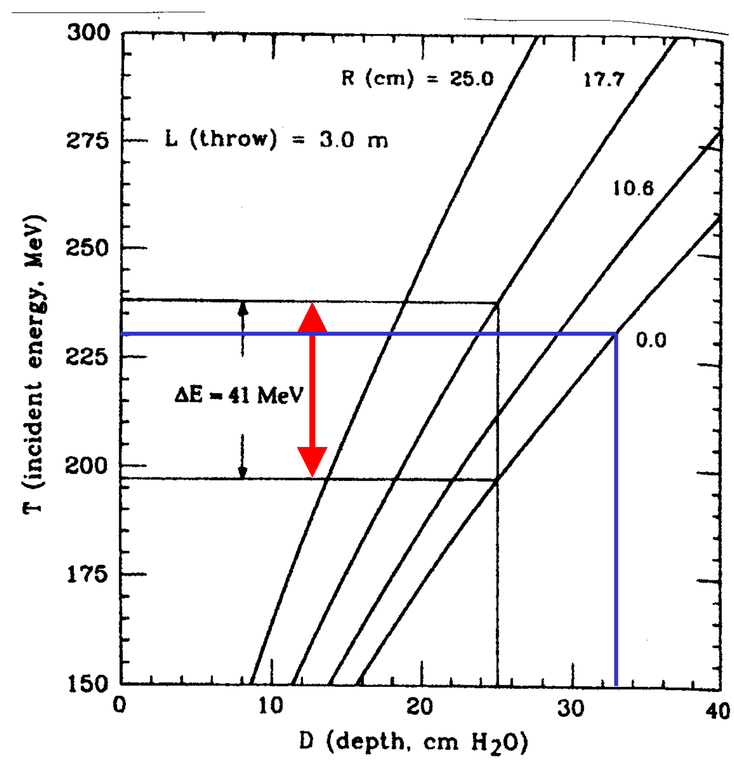


FIG. 3. Energy of the beam incident on the first scatterer versus penetration depth in water, for a 3-m throw, different field radii *R*, and a contoured second scatterer.

Gottschalk

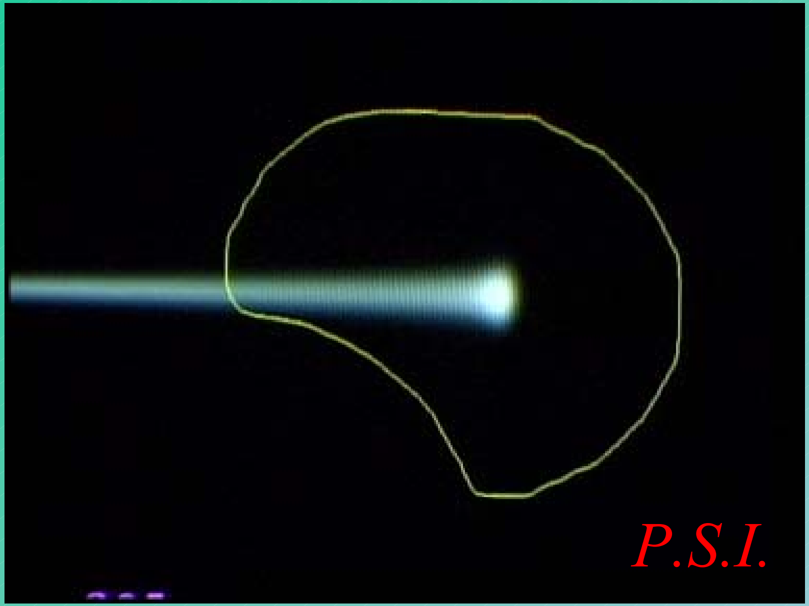
Dose Rate:

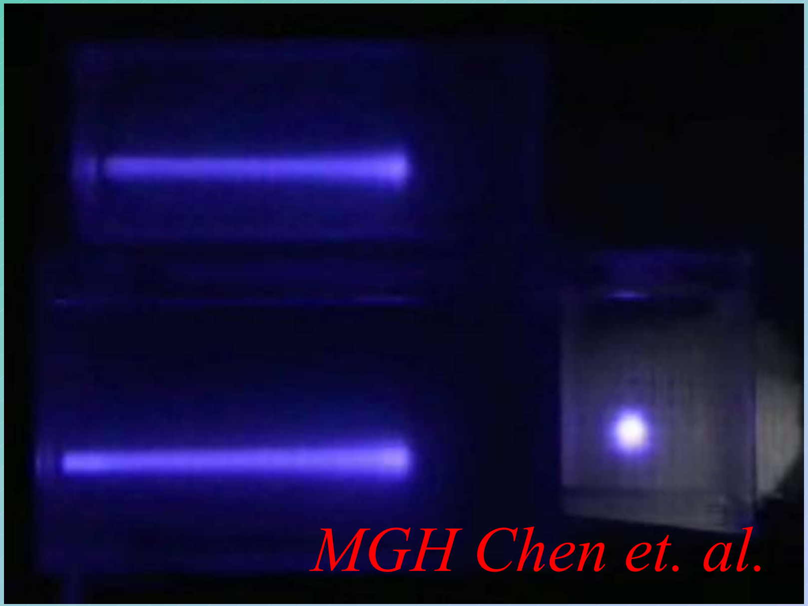
- Beam Current AT PATIENT

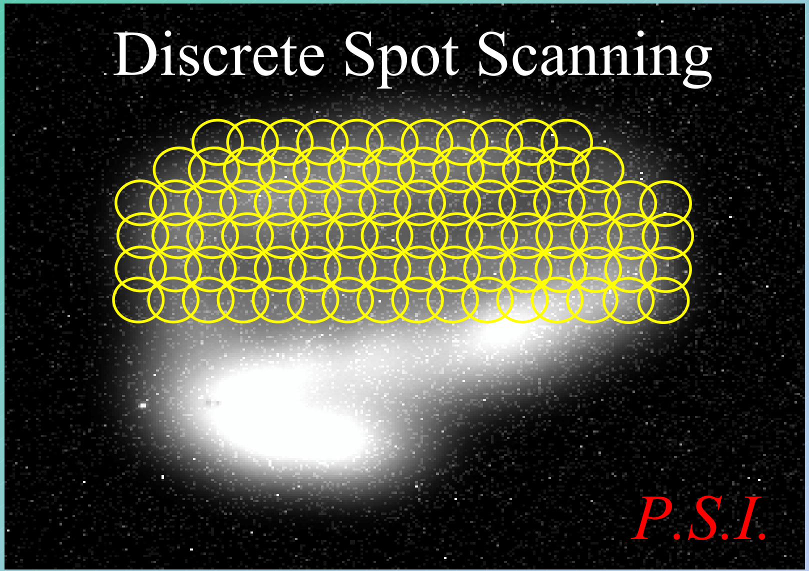
Dose Rate (Gy/min) $\approx$ S(MeV/g/cm2) * i(nA) * 60 / Area (cm2)

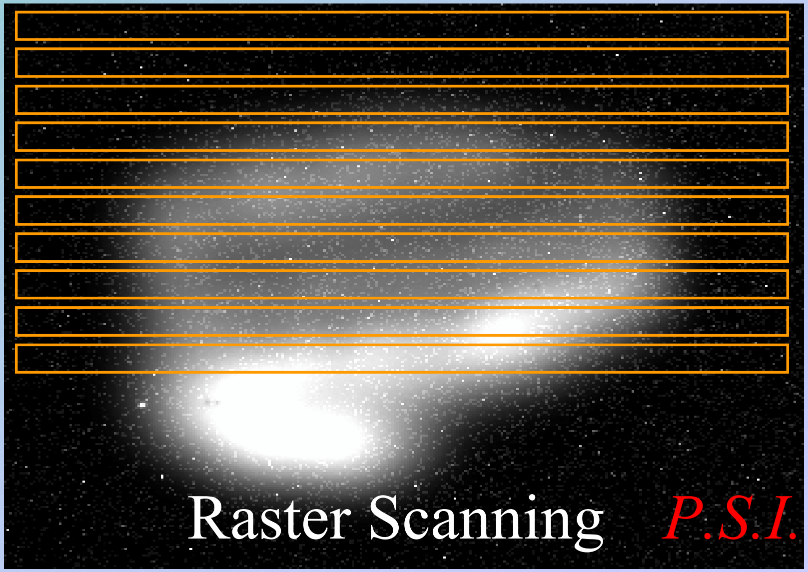
- vs. Beam Current from Accelerator,
  - Efficiency of Beam Line, Scattering from Stuff in Beam - Efficiency of Delivery System

"*Pencil*" *Beam Scanning*





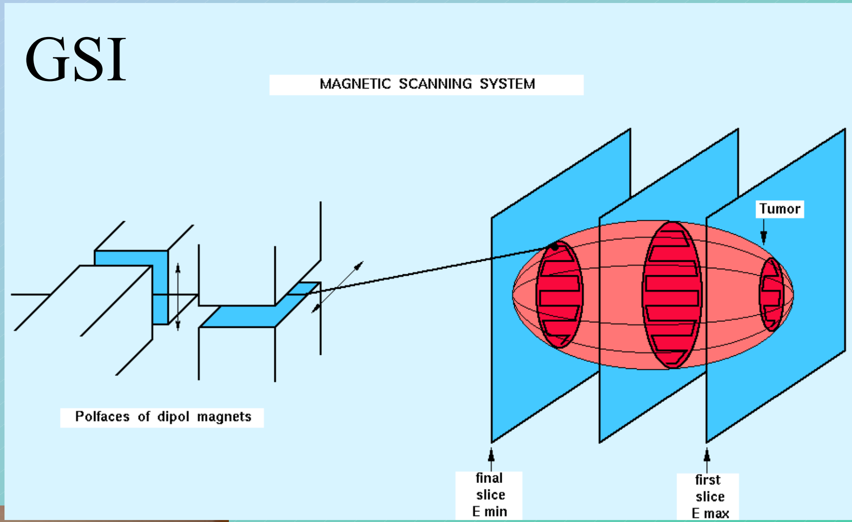




How, physically, to scan…
Two is not always better than one!

LBL

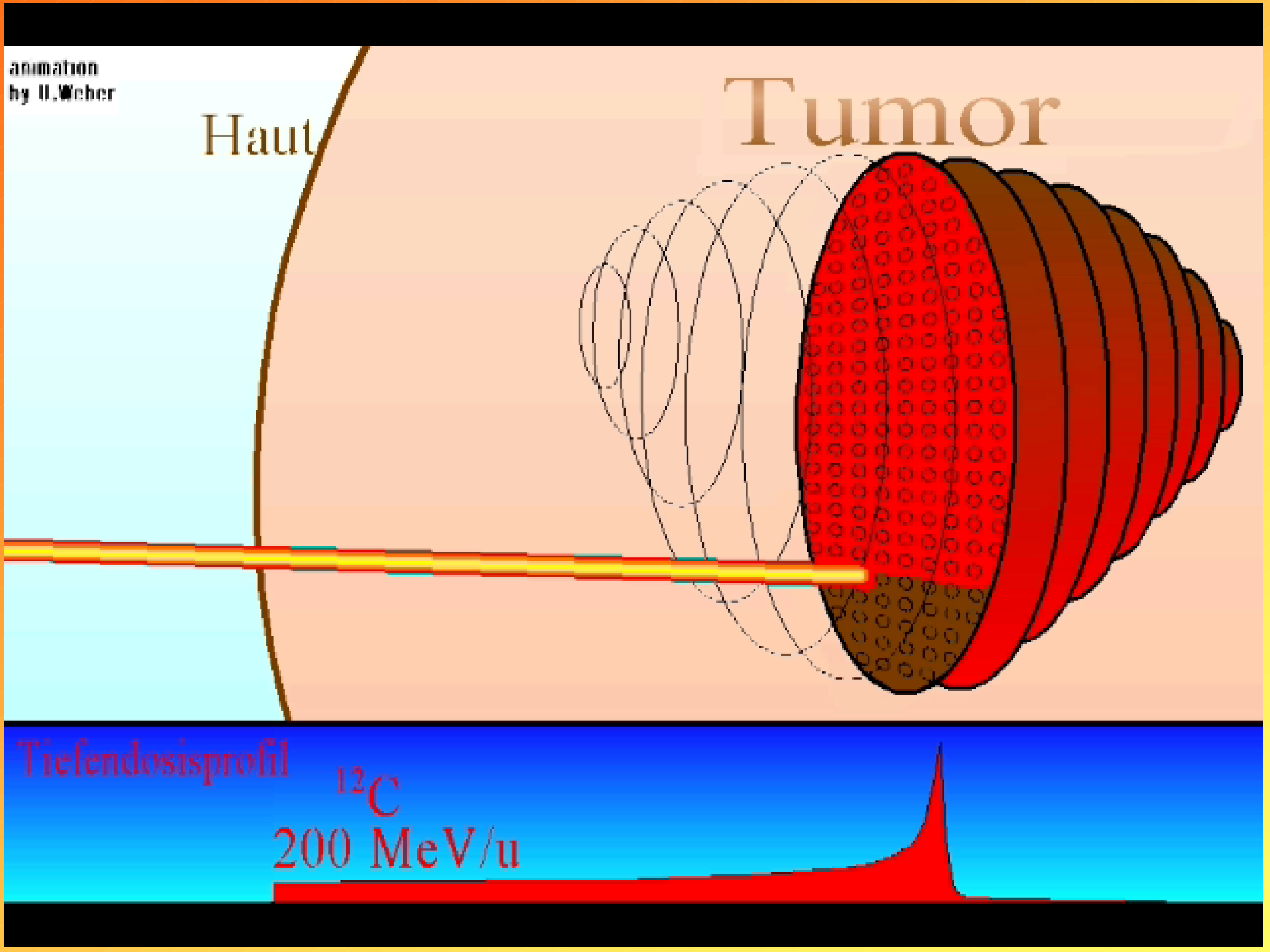
GSI



IUCF: Anferov

- Equal SADs
- Saves Space
- Maybe more useful in existing systems without specific optics for two magnets.

Scanning by Layers



Edge Effects with Scanning Beams

Modeling and System Specifications for an Integrated 3-D Proton Treatment Delivery System*

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volume while maximizing the lateral and distal falloffs. We have used an optimization procedure developed by Brahme[2] and by Lind[3]. The function F is approximated through an iteration process

$$F_0 = D_0$$

$$F_{n+1} = C[F_n + a(D_0 - F_n \otimes P)].$$

Here, D_0 is the desired dose distribution, C is a constraint operator guaranteeing non-negative occupation function amplitude, and a is a convergence speed parameter.

This method of determining the occupation function F has two advantages over other optimization methods:

- F is non-negative,
- D is never smaller than the desired dose D_0 within the treatment volume at the scanned points.
- The dose outside the treatment volume is minimized.

The function F is the irradiation or Bragg peak density defined throughout the volume and describes the amount of beam deposited in the volume with the center of the Bragg peak at a particular location. F can also be viewed as a beam occupation distribution which can be directly used to control a voxel scanning system.

As an illustration, a one-dimensional example is given. A gaussian beam irradiates a line segment to give a uniform dose for $0 \le x \le 50$ and no dose for $50 < x \le 100$. Figure 2 shows the beam half-profile (dashed) and the occupation function (solid line), the time spent along the line segment by the beam, the inverse of the scanning velocity, as it sweeps. Note that the occupation function has a peak at the edge and oscillates within the dose area. This occupation function assures that full dose (dot-dash) is given inside the required dose volume, and the width of the fall-off is minimized.

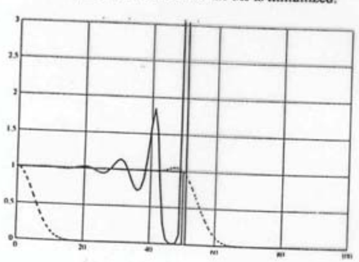


Figure 2. Dose, Occupation Function

We have simulated a raster scanner scanner system in which each layer of target volume is transversely scanned as shown in Figure 3.

The idealized dose distribution ...

turn-around points. The accelerator and beam transport system energy is changed for each layer. Typically, layers are separated in range by 5 mm and as many as 60 layers may be used.

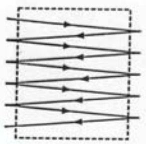


Figure 3.

The sweep velocity is modulated to vary the pixel dose. The raster pattern is conserved by keeping the ratio of the horizontal and vertical sweep velocities constant. This pattern requires the smallest slew rate to cover the dose area. The maximum slew rate requirement of the scanning magnets is specified at 10 times the average, with no lower limit to provide high dose capability to selected pixels, particularly at the edges.

For simulation of the raster scan the density function F is defined along the zig-zag scan lines only and is determined by an iteration procedure as described above. The linear sweep velocity is the inverse of the occupation function F for each voxel on the scan line. The calculations were done on a 1 mm transverse grid with a 5 mm longitudinal spacing. About 20 iterations are necessary for F to converge.

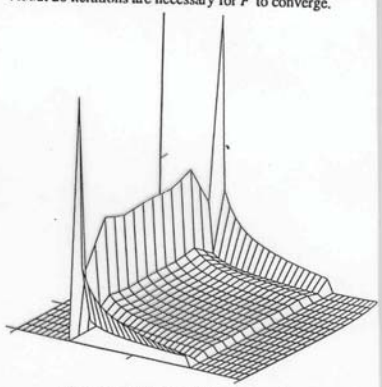


Figure 4. Bragg Peak Density Function F

Figure 4 shows the optimized Bragg peak density function on a plane perpendicular to the scan plane and through the central axis of the radiation field.

IV. SENSITIVITY TO FLUCTUATIONS

The goal of this study is to evaluate the dose distribution subject to imperfections in the scanned beam such as ...

The 200-MeV proton therapy project at the Paul Scherrer Institute: Conceptual design and practical realization

Eros Pedroni, Reinhard Bacher,[a] Hans Blattmann, Terence Böhringer, Adolf Coray, Antony Lomax, Shixiong Lin, Gudrun Munkel, Stefan Scheib, Uwe Schneider, and Alexander Tourovsky[b]
Department of Radiation Medicine, Paul Scherrer Institute, CH-5232 Villigen PSI, Switzerland

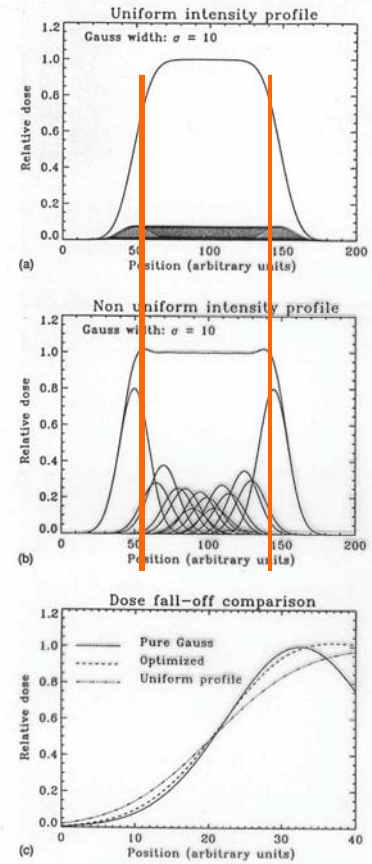


FIG. 6. (a) Dose profile created through the superposition of uniformly closely spaced Gaussians ("collimator" case). (b) "Optimized" distribution for a discrete scanned beam. More dose is deposited at the edge of the field, still maintaining a reasonable homogeneity at the interior of the field. (c) Comparison of the falloff of the original Gaussian used in the superposition with the "optimized" field and with the "collimator" case.

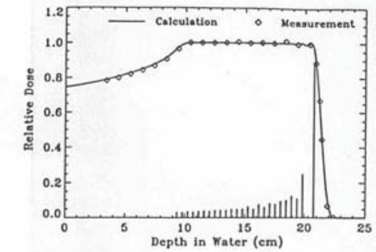


FIG. 7. Typical experimental result obtained in the beam period of summer 1992. Comparison of calculated (line) and measured (symbols) spread-out-Bragg-peak (SOBP) dose distributions. The vertical lines represent the relative dosage applied to each spot as a function of the number of range-shifter plates inserted in the beam displayed at the corresponding Bragg peak positions. A separate report on these experiments is in preparation (Ref. 23).

The dose application system was steered according to a sequence of commands to produce a complex shaped target volume in water (only the "active" system was used here). Figure 7 shows as an example the comparison between measured and calculated dose profiles for a spread-out Bragg peak in water. A detailed report on the experimental work performed in the horizontal beam line in 1992 is in preparation.

At the end of September 1992 the experimental apparatus was completely removed from the horizontal beam line in the proton therapy room and the activities for the installation of the compact PSI gantry were started.

IV. THE PSI COMPACT GANTRY

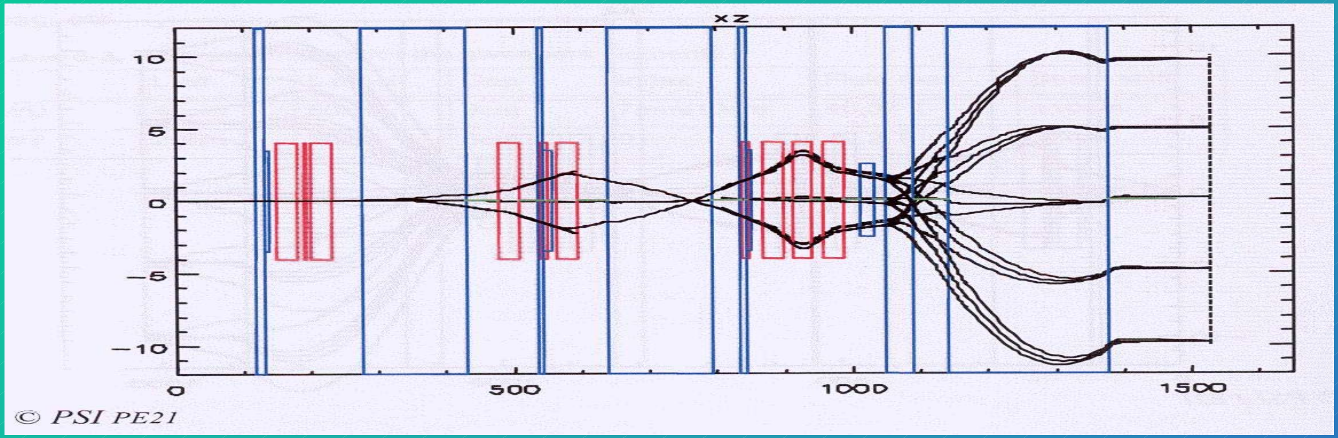
A. The gantry layout

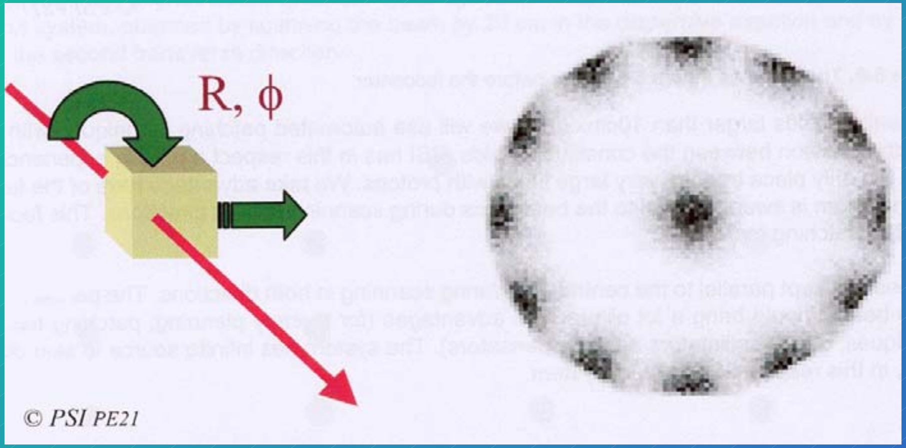
Figure 8 shows the layout of the PSI gantry. The compact gantry has been designed exclusively for the spot-scanning technique in order to achieve a very compact rotating structure. The PSI gantry spans a diameter of only 4 m, which is determined solely by the space occupied by the 90° bending magnet, by the nozzle (with monitor and range shifter system), and by the patient table. No drift space is used between bending magnet and patient.

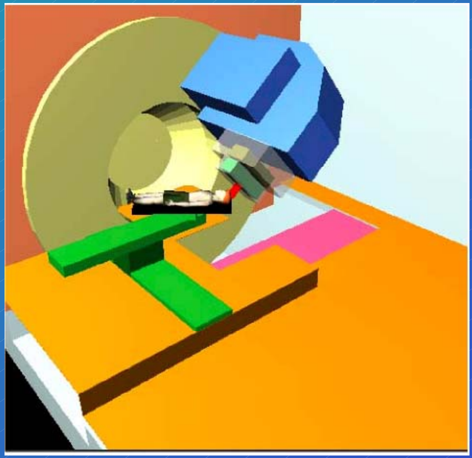
The scanning devices will be mounted on the gantry exactly as for the horizontal setup (the arrangement of Fig. 4). The sweeper magnet will be mounted in front of the 90° bending magnet. The only difference with the horizontal setup is the replacement of the straight vacuum beam pipe between sweeper and monitor system with the curved ...

Penumbra given by Beam Sigma Directly + Scattering in Patient.

Or the sharpness of the edge !







PSI: Pedroni et. al. Use of Gantry Optics (Spectrometer Quality) to allow upstream edge collimation !

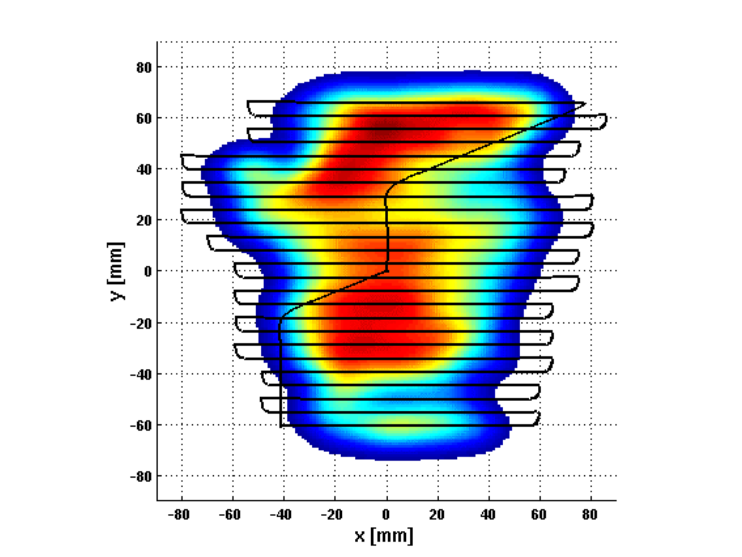
Time to deliver the beam: Equipment Comfort

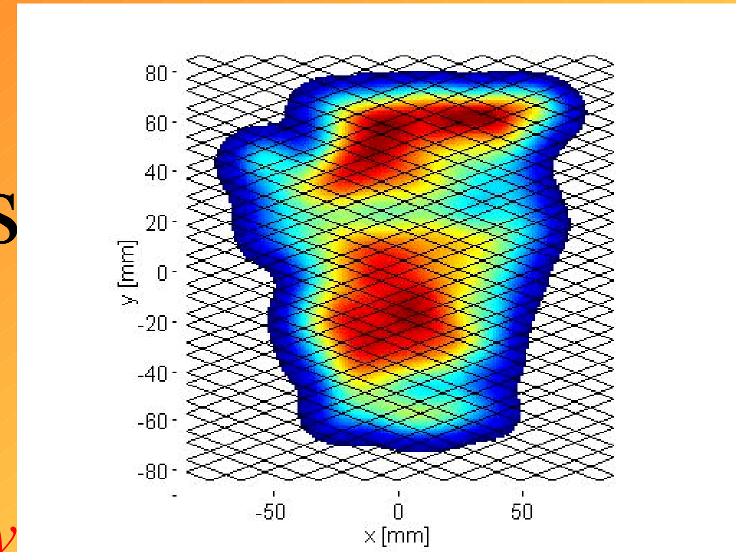
- Time to move the beam
- Time to change Energies
  - Accelerator ?
  - Other Methods?
- Time to turn beam on/off
  - Accelerator? / Source?
- Time to read instrumentation
- …

Beam Characteristics and Tolerances for IMPT Beam Delivery

Scan Patterns

IBA





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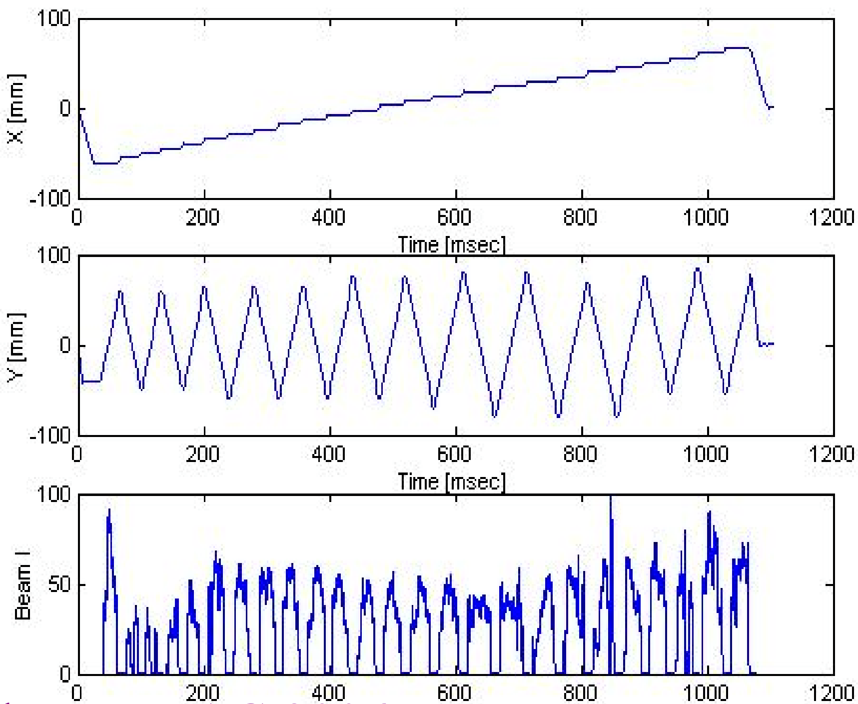
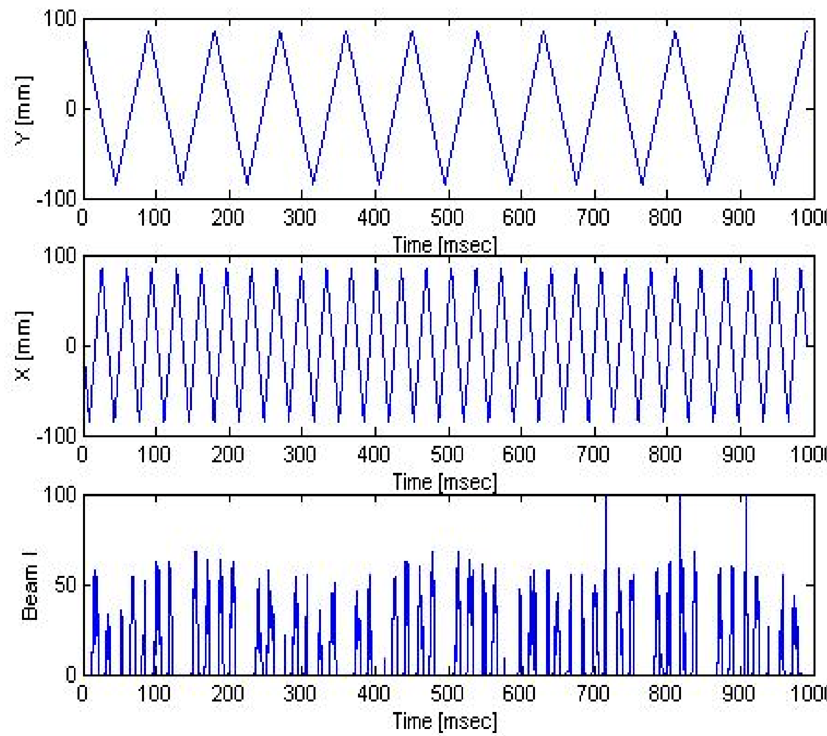
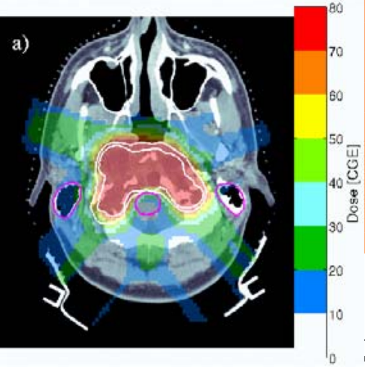
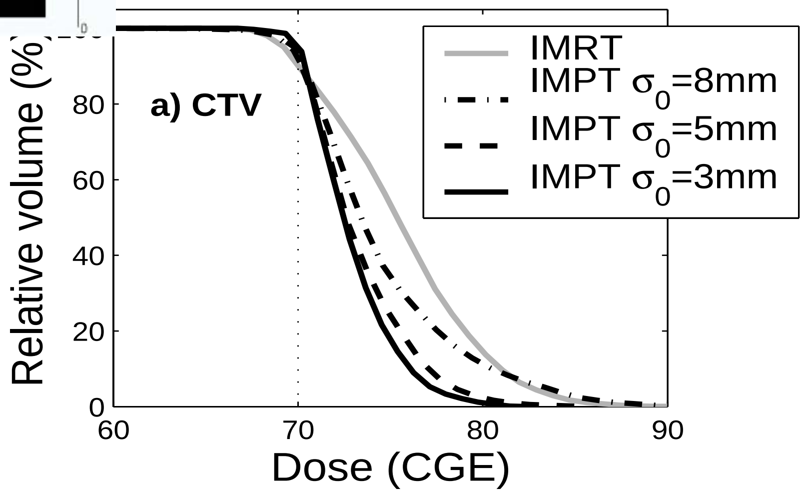
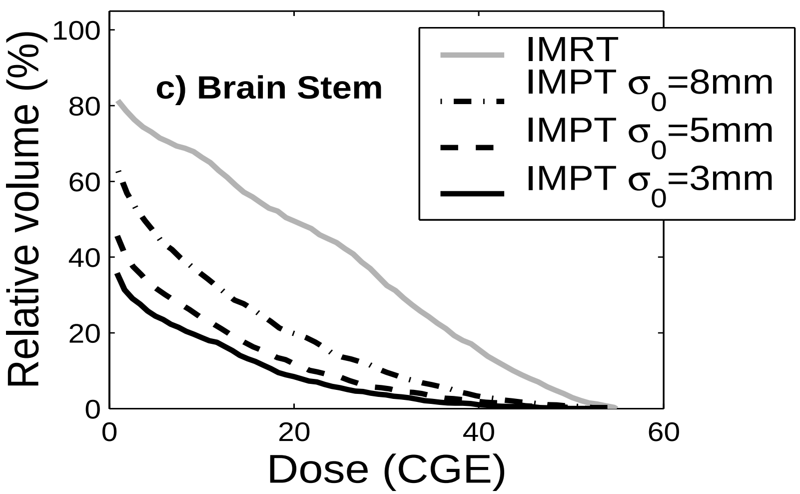


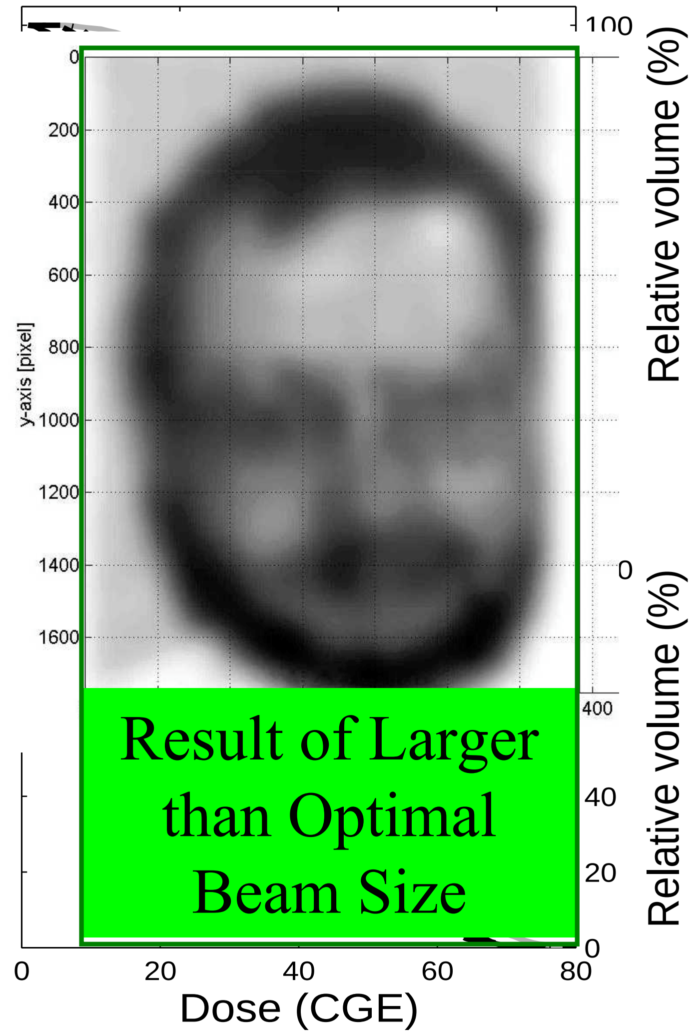




Choice of beam sigma: head&neck case (TCRT-03)







Result of Larger than Optimal Beam Size

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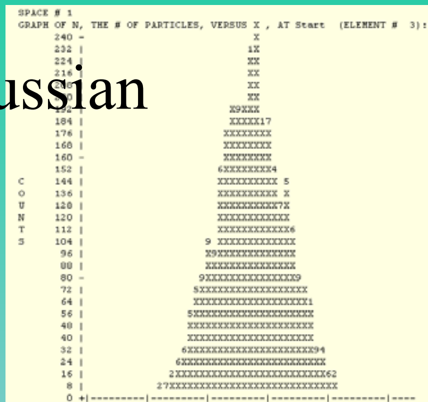
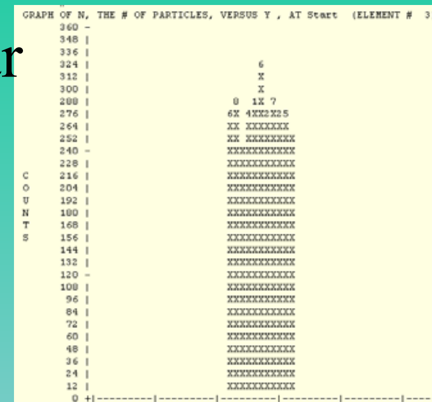
Comparison with Gaussian - Where is 'small' beam important?

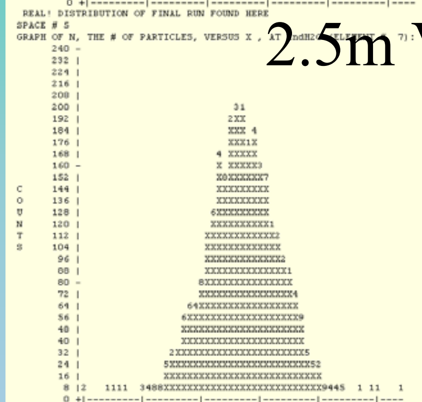
Gaussian

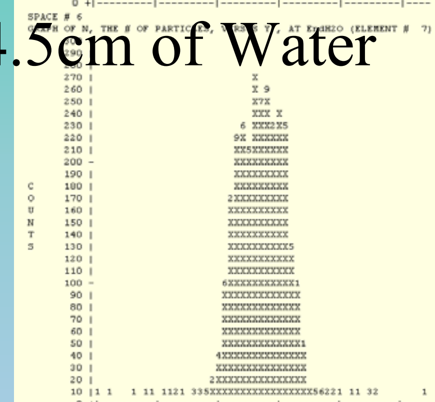


Rectangular

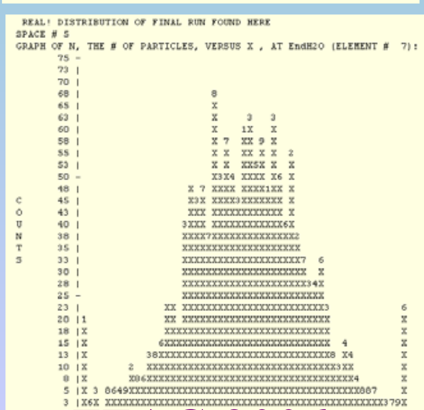


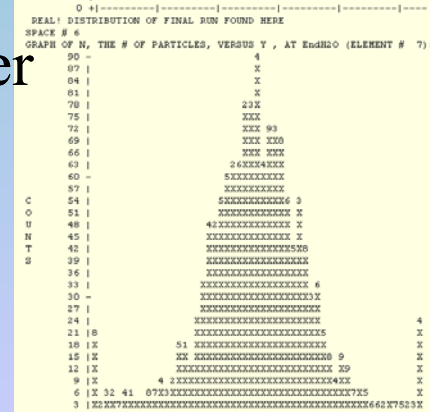
2.5m Vacuum and 4.5cm of Water

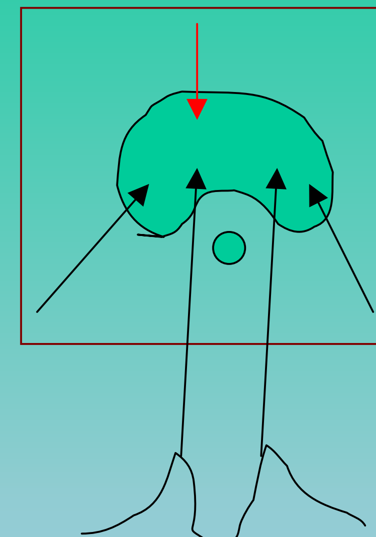


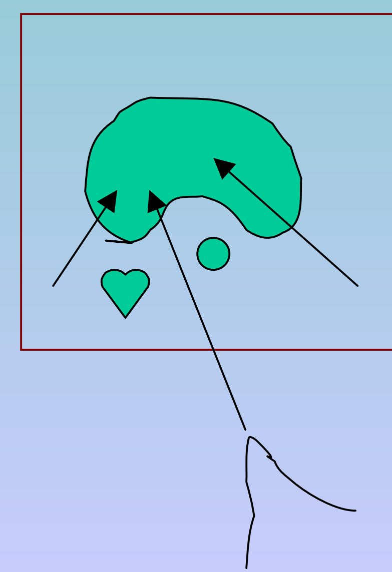


18cm of Water





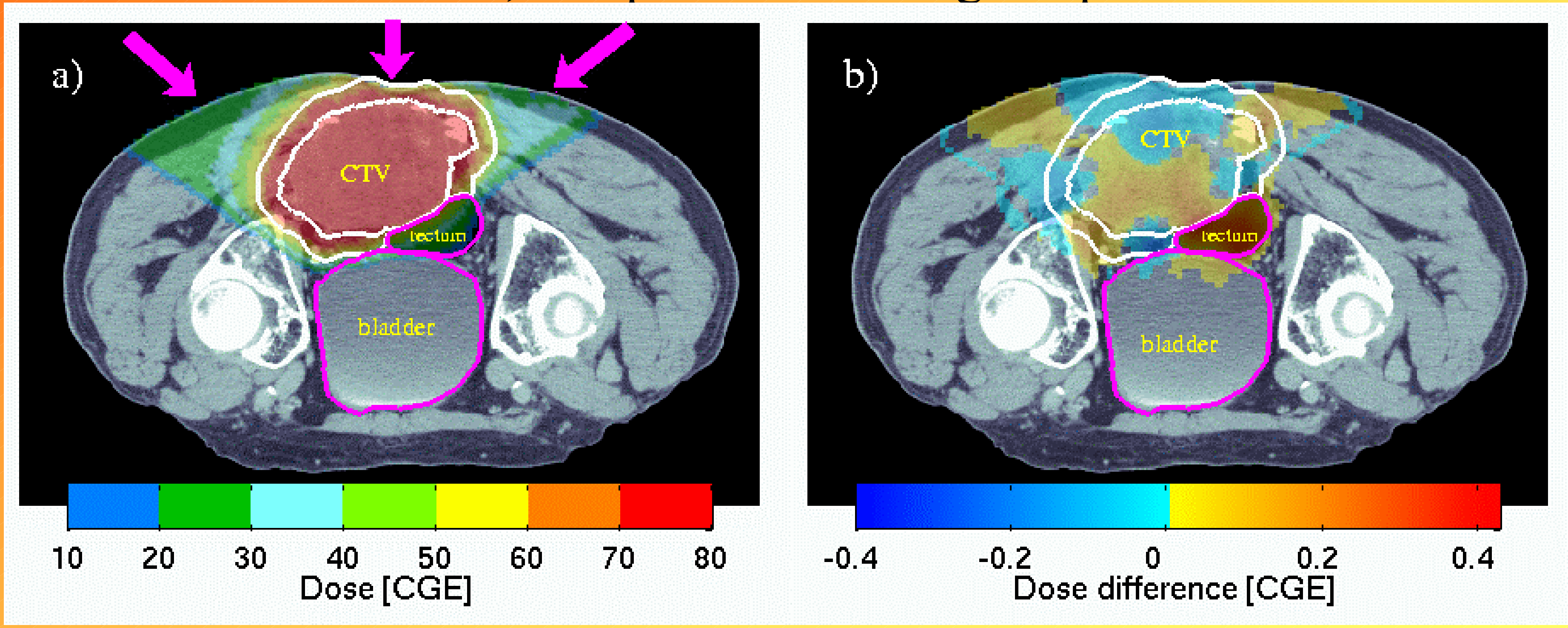




Intensity -- dynamic range

Treatment planning study:

TPS beam weights were discretized (averaged) into 10-100 levels.
Doses recalculated, compared to the original plan



original plan

dose difference for 50 levels

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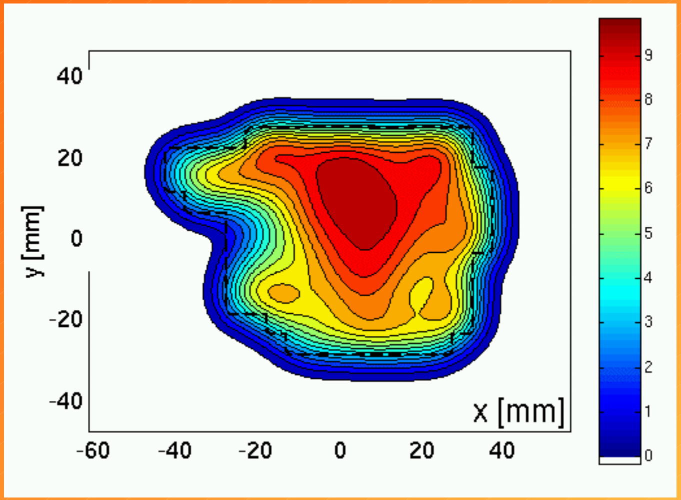
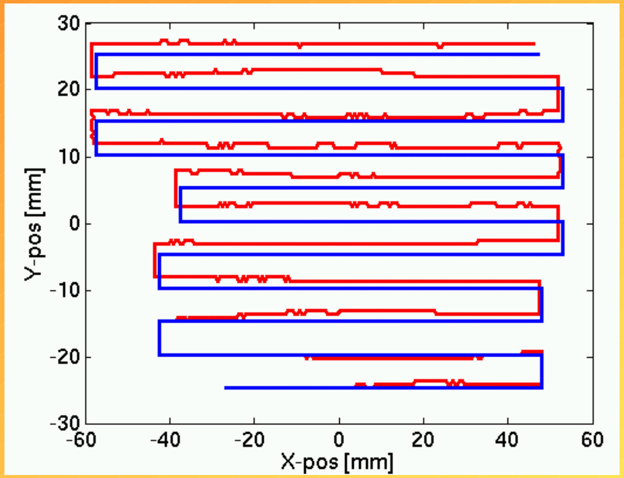
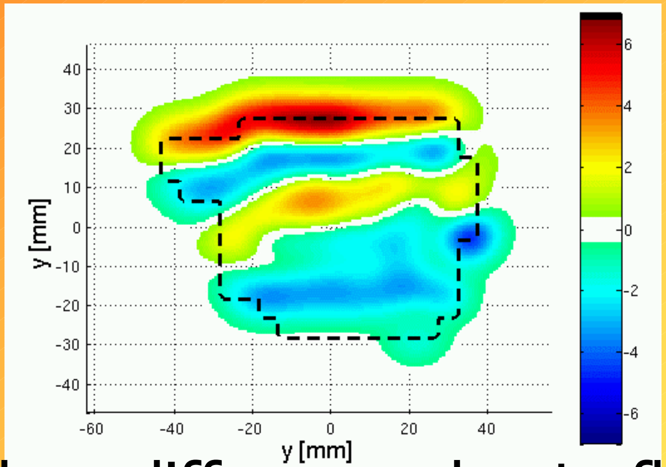
Estimate the effect on the dose distribution using realistic IMPT beam fluence maps



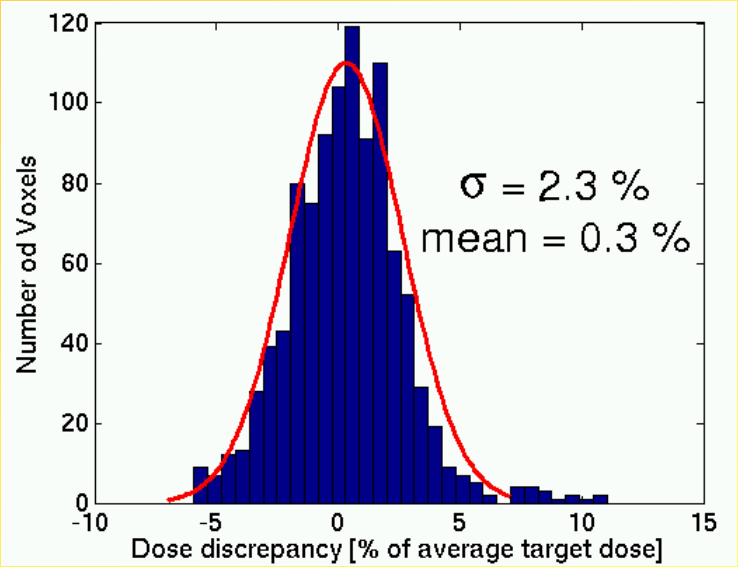
planned dose distr





dose difference due to fluct's

The distribution of point dose discrepancies is shown for the beam σ = 5 mm, fluctuation RMS = 0.25 mm



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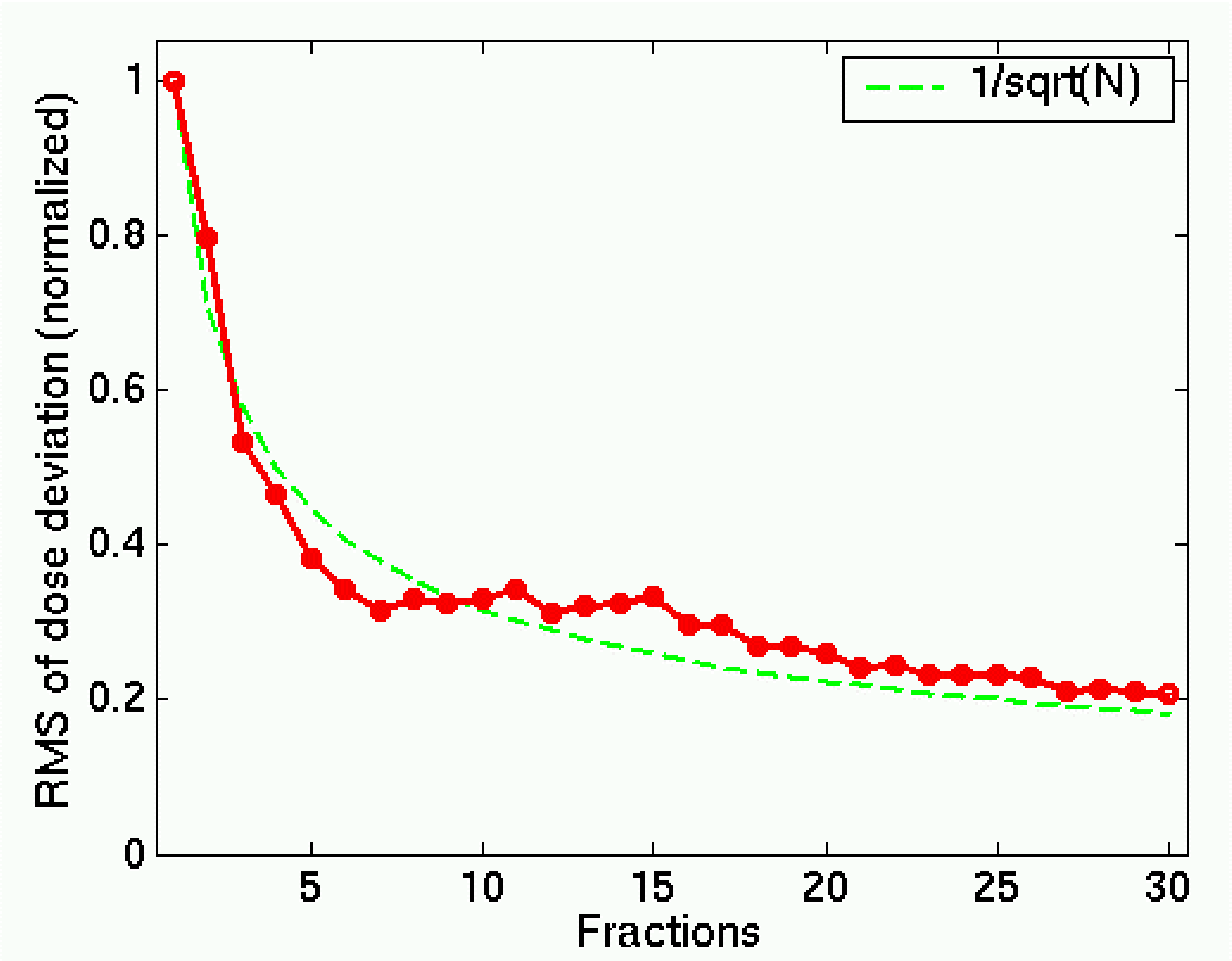
Dose deviation RMS and mean are reduced with multiple layer rescanning, treatment fractionation



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IMPT Characteristics affected by:

- Dose Dynamic Range - 50:1
- Beam size choice and stability
- Gradient – Current change speed + Scan Acceleration (depends upon scan speed e.g. 30Hz @ 40cm
  - ~ 1/2 sigma = 2.5mm ==> 100 usec
- For a single scan, to keep the dose within 5% of prescription,
  - fluctuation in beam position should be less than 10% of the nominal beam size *(e.g. 0.5mm for 5mm);*
  - beam intensity 5-10%
  - and size fluctuations should be < 5% of average *(e.g. 0.25mm for 5mm)*

- The effect on dose is reduced if treatment is delivered in multiple (N_p) “paintings” (scales as 1/sqrt(N_p))
- With energy layer scanning, dose discrepancy is reduced due to partial mutual cancellation of contributions from different layers

MGH - BPTC Specifications

Clinical Specifications

Range In Patient	32 g/cm2 Maximum 3.5 g/cm2 Minimum
Range Modulation	Steps of < 0.5g/cm2
Range Adjustment	Steps of < 0.1g/cm2
Average Dose Rate	25cmx25cm modulated to depth of 32 g/cm2. Dose of 2Gy in < 1min
Spill Structure	Scanning Ready
Field Sie	Fixed > 40x40cm Gantry > 40x30cm
Dose Uniformity	2.5%
Effective SAD	> 2.5 meters
Distal Dose Falloff	< 0.1g/cm2
Lateral Penumbra	< 2mm

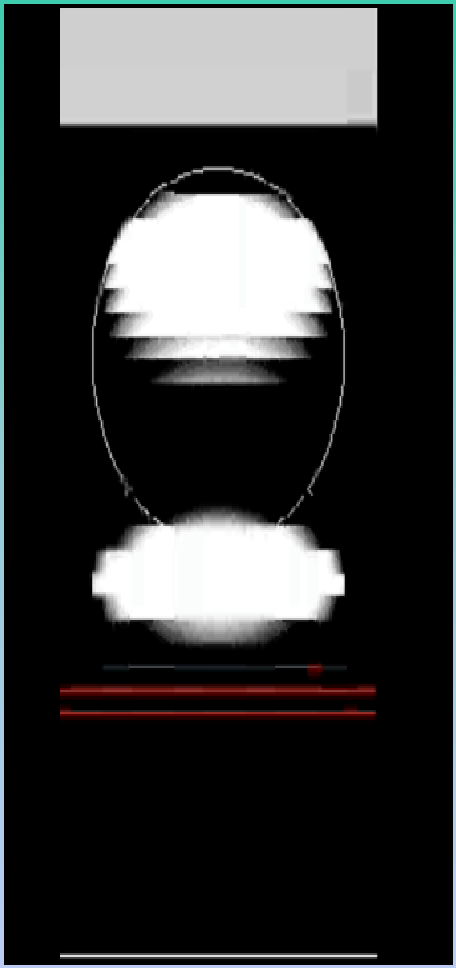
Facility Specifications

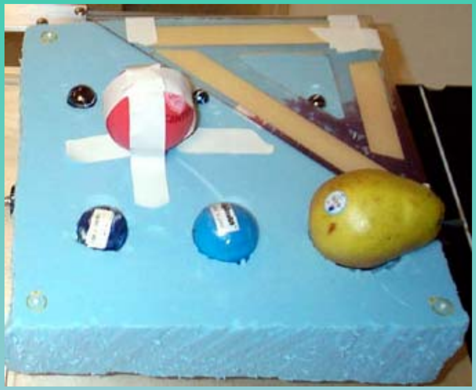
Time for Startup from Standby	< 30min
Time for Startup from cold system	< 2hours
Time for Shutdown to Standby	< 10min
Time for Manual Setup in one Room	< 1min
Time for Automatic Setup in one room	< 0.5min
Availability	> 95%
Dosimeter Reproducibility	1.5% (day) 3.0% (week)
Time to switch Rooms	< 1min
Time to Switch Energy in one Room	< 2 sec
Radiation Levels	ALARA

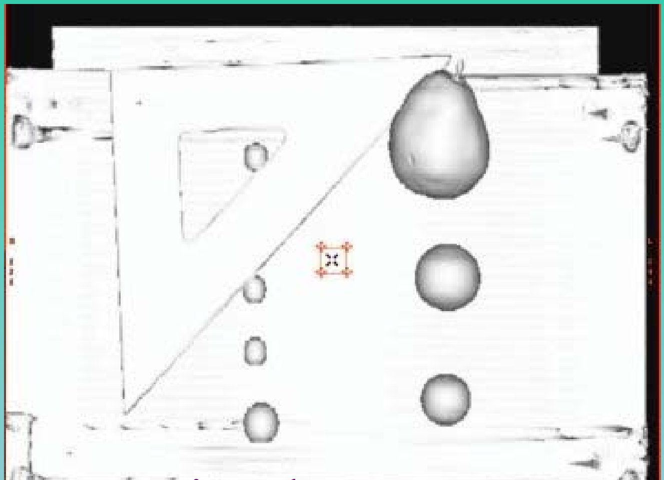
Time Dependence, Speed of Current Change (Scan Speed)

What does the ‘Target’ look like?

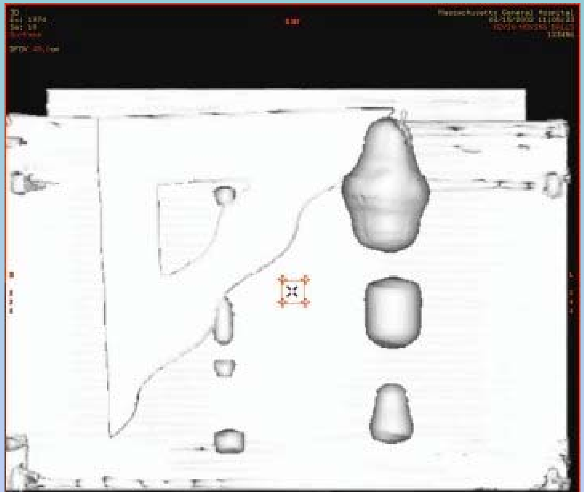
What does the 'Target' look like?







Static Phantom

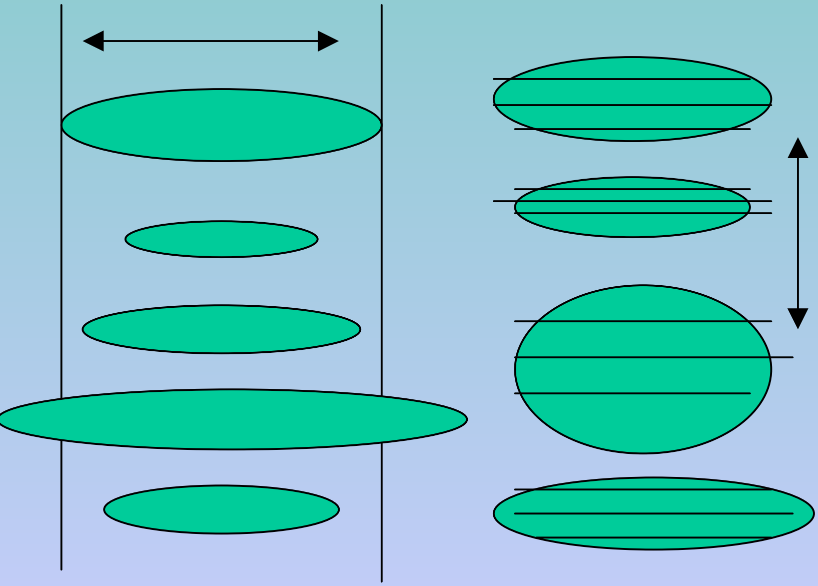


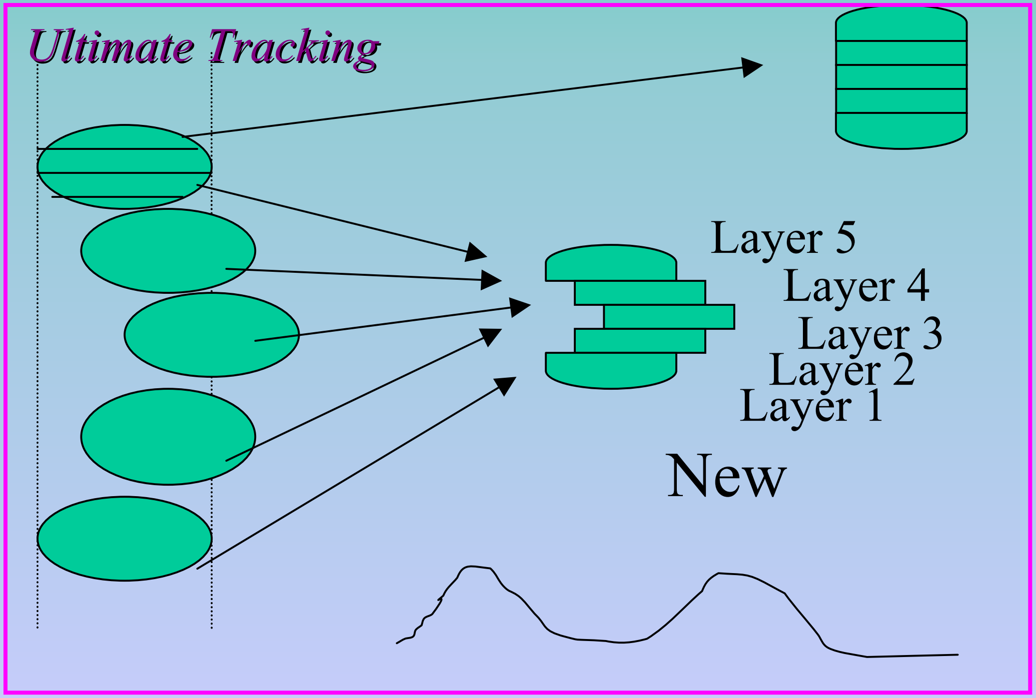
Breathing Phantom

MGH: Chen et. al.

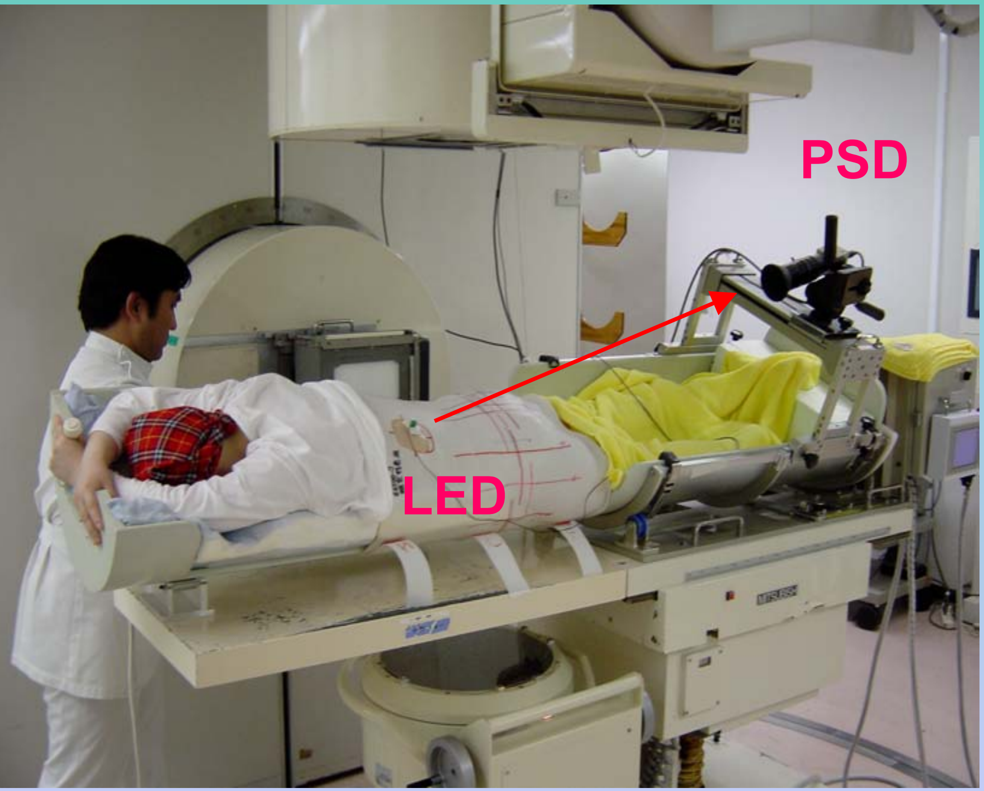
What to do about Target Motion

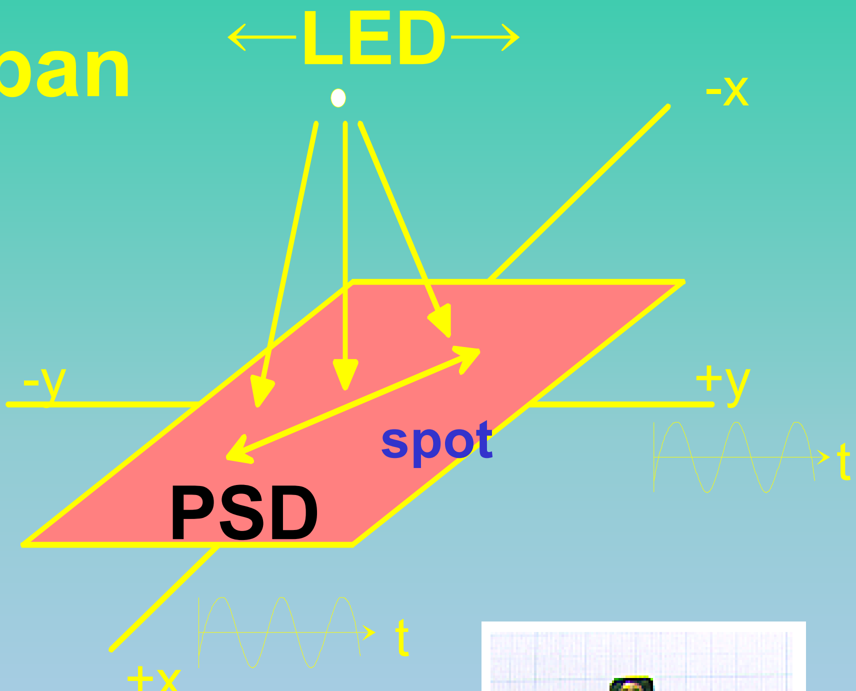
- Target Motion - What can we do about it?
- What kind of scanning is best?
- Time of motion?
  - Is a 200msec window fast enough for locating a target's edges?
  - Is motion reproducible wrt respiration or body motion, or something?

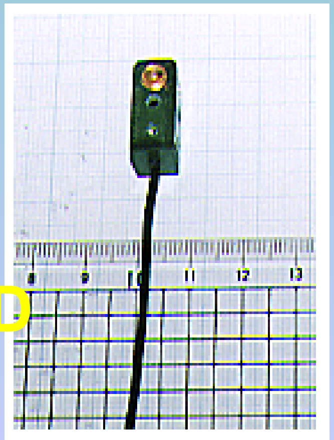




Respiratory Gating Irradiation System using LED and PSD - NIRS, Japan

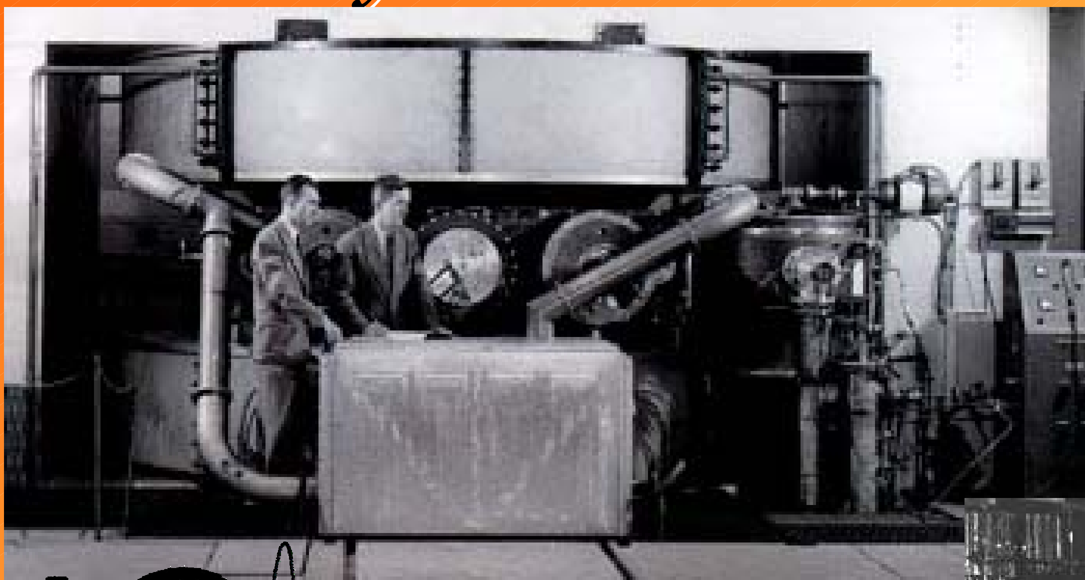






Infra-red LED

Accelerators - Cyclotrons, Synchrotrons and Others



Bevalac 1950 - 1993

1949 - 2001

Cyclotrons come with Action Figures!!

MIT-Bates South Hall Ring 1990

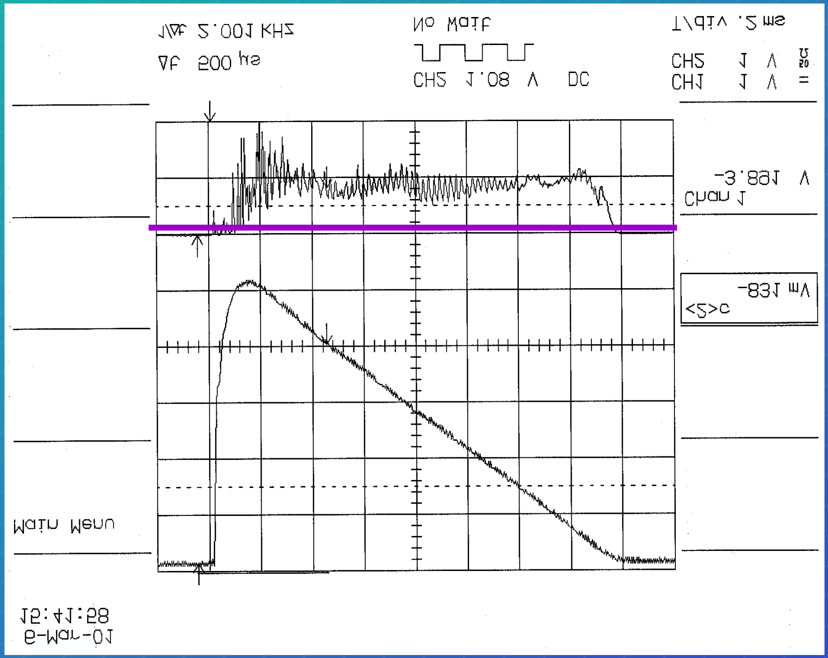
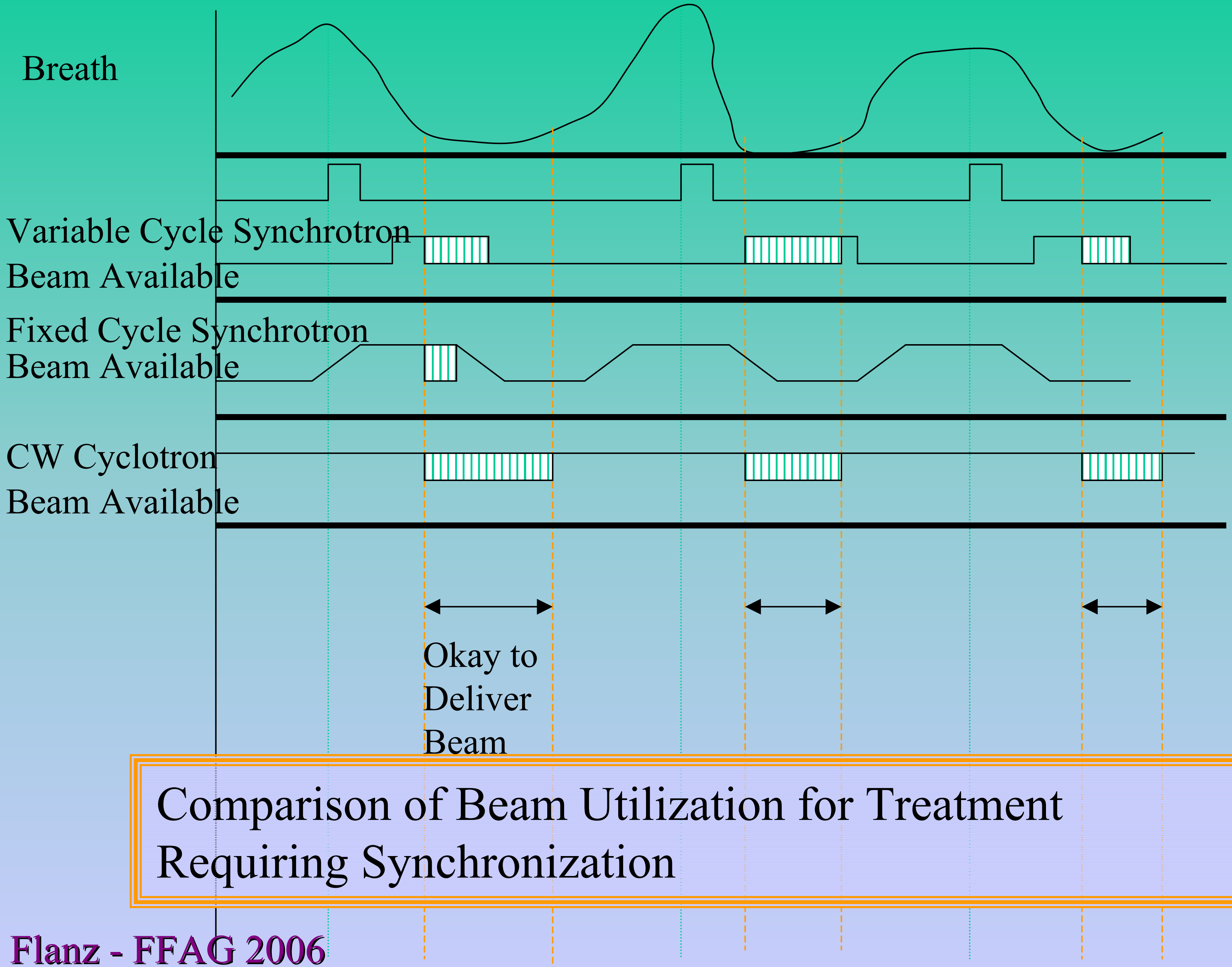


FIGURE 4. One extraction cycle. Top: stored beam current, 5 mA/div. Bottom: beam current to the experiment. Increasing current is down for both traces.

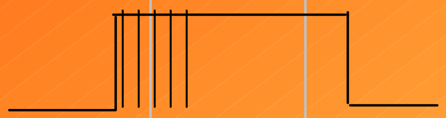
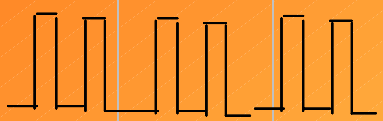
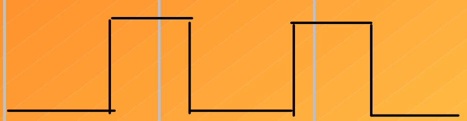
K. Jacobs, et. al.

J. Flanz, et. al.

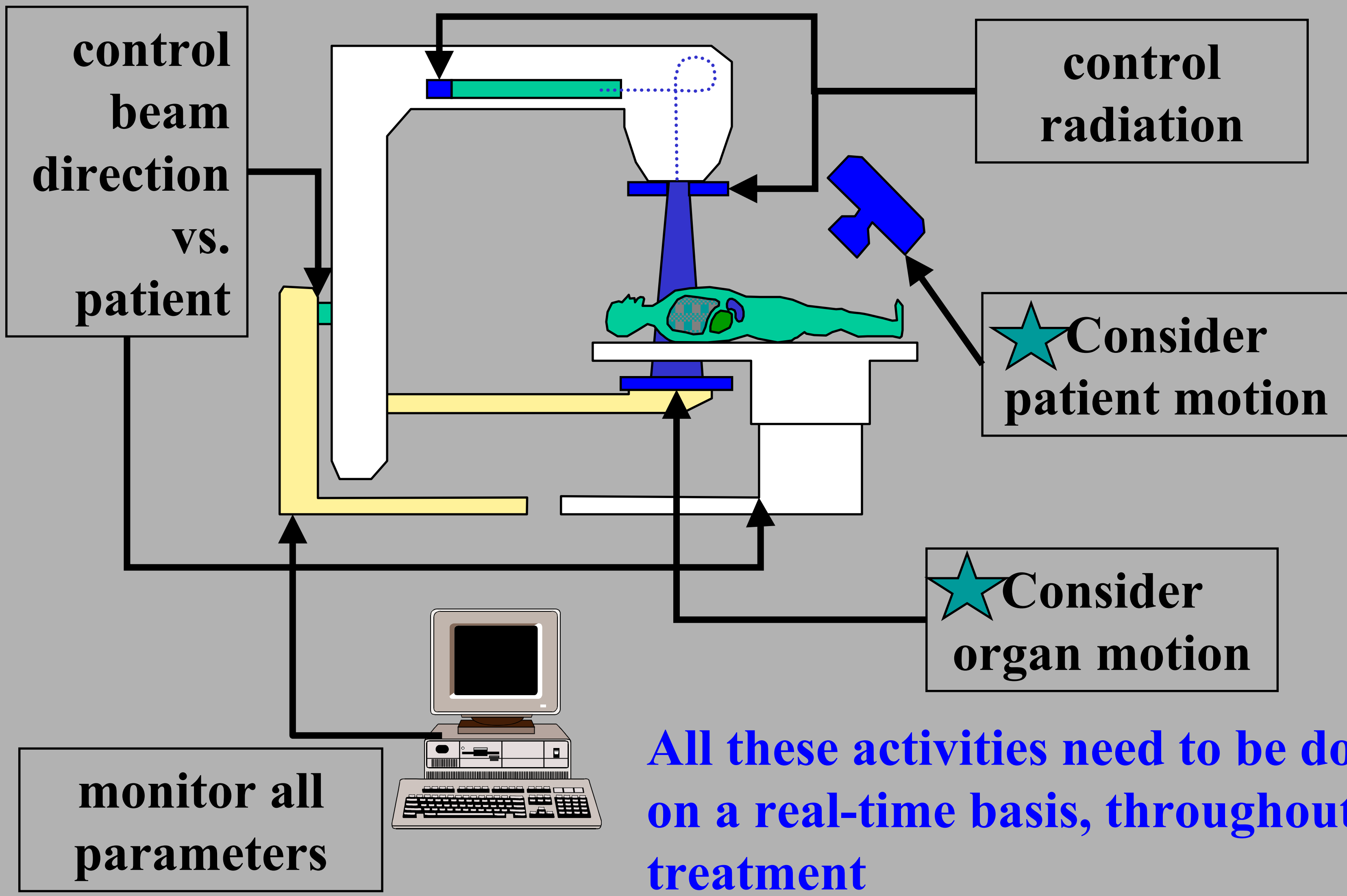


Comparison of Beam Utilization for Treatment Requiring Synchronization

Time Structure of Beam?

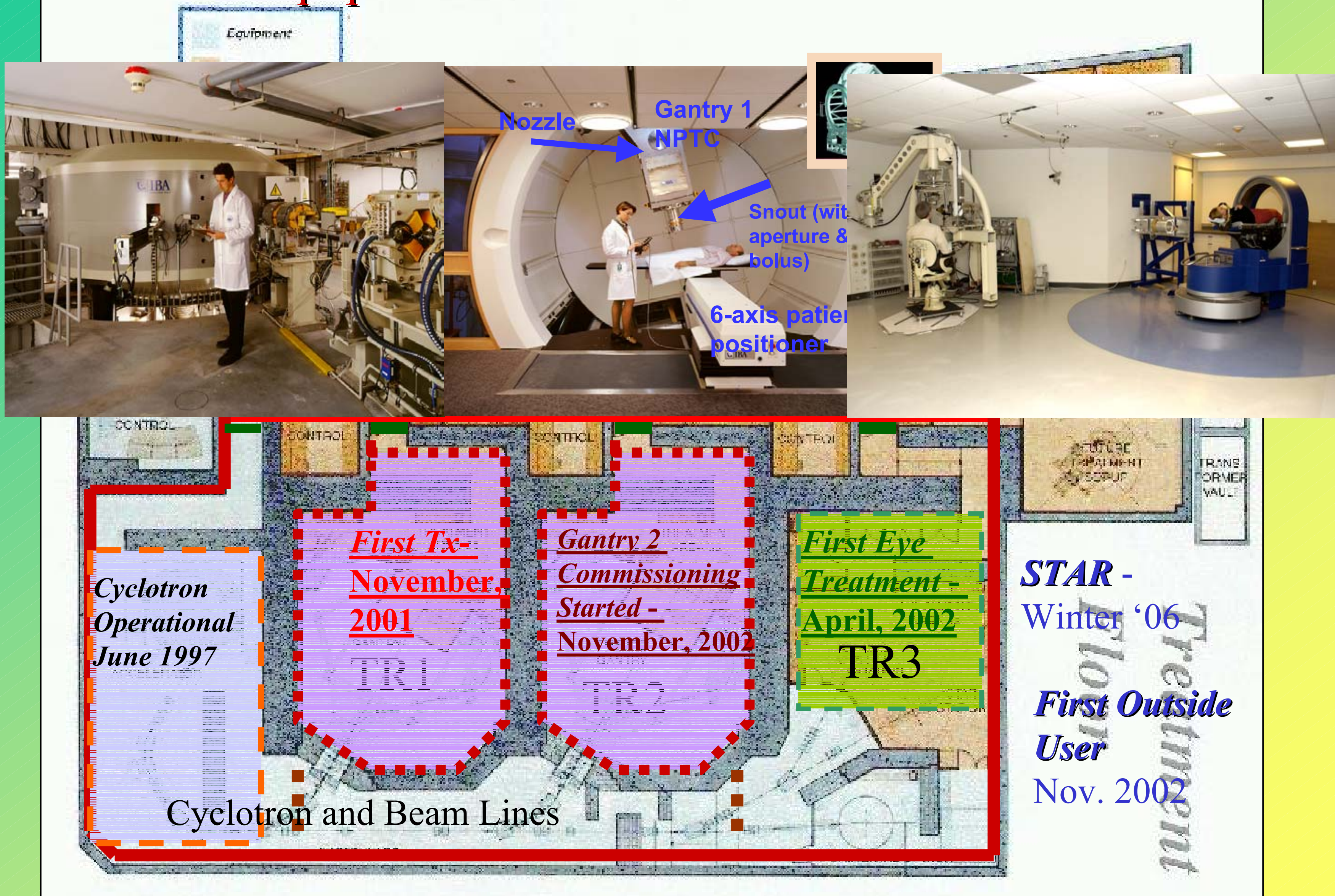
				Gating	Targeting				
			Describe	eg Organ Motion		Spot	Raster	Instrumentation	
			CW (Rf)	Good	Good	Good	Good	Good	
			10's msec?	Okay	Good	Good	If time << Spot Size (200 usec)	????	
			Seconds	Slower	Okay	Good	Marginal (depends on IM and Pulse length)	Okay	

What to Consider during the Delivery of Treatment



All these activities need to be done on a real-time basis, throughout treatment

NPTC Equipment Areas - And Related Milestones



Flanz - FFAG 2006 *Full HCL Patient Load at NPTC* - April, 2002

Summary: Some of What the accelerator has to do.

- General Beam Requirements
  - Safety (Dose Rate, Prevent Overdose - Turn off Beam (~100 us)
  - Patient Comfort - Irradiation < 1-2 minutes
- Beam Requirements (for specific clinical cases) (see previous slide for others)
  - Range ~32 cm (wet); Beam Energy ~ 230 MeV - ??? MeV Depends upon mode
  - Beam Energy Spread ~ <1%
  - Beam Current Time Structure/Modulation
  - Depends upon type of modulator (Passive Scattering)
  - Depends upon Scan Technique (Spot/Raster)
  - Beam Size - For Scanning 3mm - 5mm Depending upon religion (Sharp Edges)
  - Dose Dynamic Range (Beam Current + Scan Speed) 50:1
  - Gradient – Current change speed + Scan Acceleration (100 us or .5 sigma??)
- Stability Parameters of all the above (e.g. for a 5mm sigma)
  - Depends upon Repainting, Scan or Modulation Pattern
  - Beam Size ~ ± 0.25mm (single painting)
  - Beam Position ~ ± 0.5mm (single painting)
- Ability to Repaint to mitigate errors [ ] Time for a layer 2min/(5-10 repaintings)
- Time to switch Energy, (< 1sec?)

For a specific Clinical Site !

Some Non-Beam Requirements !

- Sized to fit in Therapy Center
- Availability - 99%
- Maintainability
- Cost
- Throughput

An Assortment of Accelerators

- Cyclotrons
  - Will Compact Cyclotron Work?
  - Superconducting vs. Room Temperature?
- Synchrotrons with Injectors
  - Can they be used for scanning?
    - Slow, Uniform, Controlled, Extraction?
  - Beam Gating?
  - Dose Rate ?
- FFAG
  - What are the beam properties (including time parameters)?
  - What is the cost and size?
- Others
  - Dielectric Wall
  - Laser Acceleration
  - Linacs

End Slides

jbf