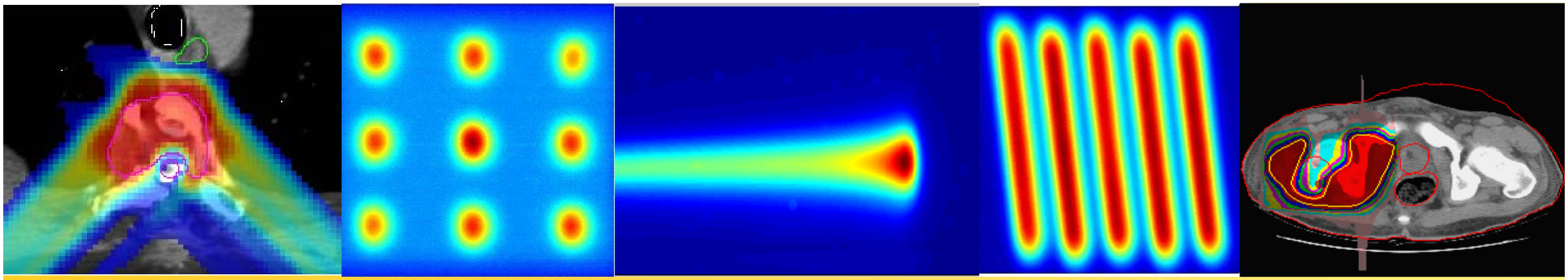


Beam Spreading Methods

PTCOG 52

J. Flanz, Ph.D.
Massachusetts General Hospital
Harvard Medical School

Goals of Radiotherapy

- *Deliver the Prescribed Dose.*
  - *What is Dose? How does a Dose get delivered?*
- *Deliver the Prescribed Dose Distribution.*
  - *What physical principles allow one to create a Distribution?(Spread out in a volume with the correct dose.)*
- *Deliver Dose to the Target.*
  - *How to position the relative relationship between the beam and the target.*

What do we know this morning?

We know enough about the particles to understand how to accomplish the above.

We need to know how to use the physical properties of these particles and which tools are needed to accomplish the above

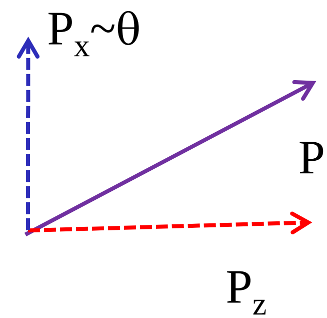
Some Goals of a Beam Delivery System

- Dose Distribution:
  - Direct the beam to the target and with the desired dose distribution
- Unwanted Dose:
  - Minimize Dose outside the target area (from any particle- e.g. neutrons) (*Penumbra, Distal Falloff,* …)
- Treatment Time:
  - Allow for a Clinically Effective and efficient treatment
- Sensitivities
  - Use realistic tolerances of the incoming beam parameters (position, angle, timing)
- Implement a Operational Efficiency & low Cost
  - Patient Specific Hardware
  - Number of fields required
  - QA

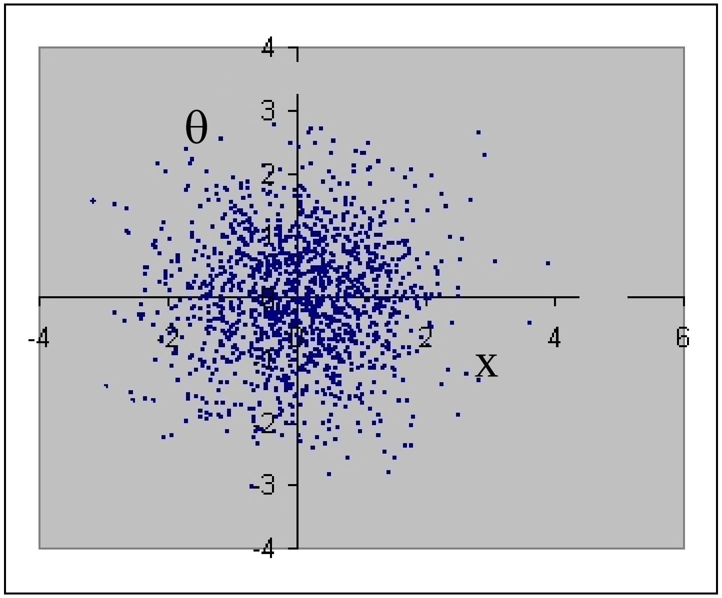
What is a Beam?

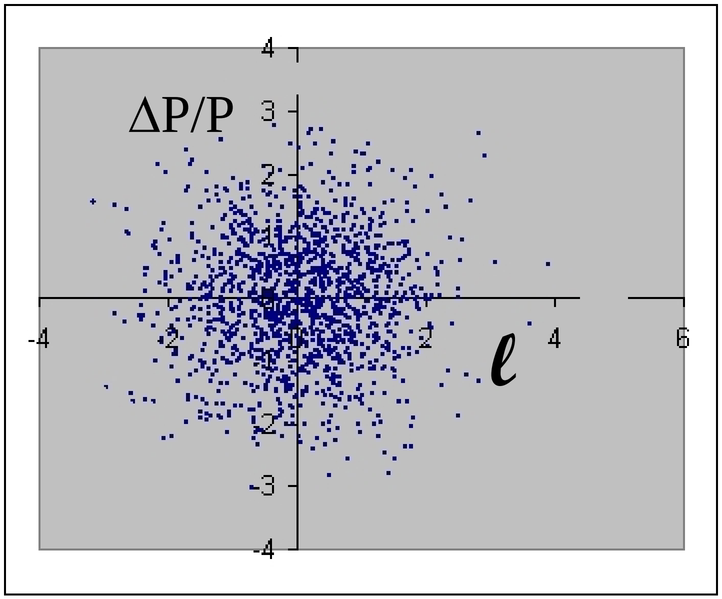
- A beam is a collection of many particles all of whose <u>longitudinal</u> and <u>transverse</u> momenta are close enough and remain more or less close to each other.

One characterizes the <u>Transverse</u> properties of a beam by plotting the phase space diagram below in which the *transverse particle position* and *transverse momentum* of each particle in the beam is plotted.

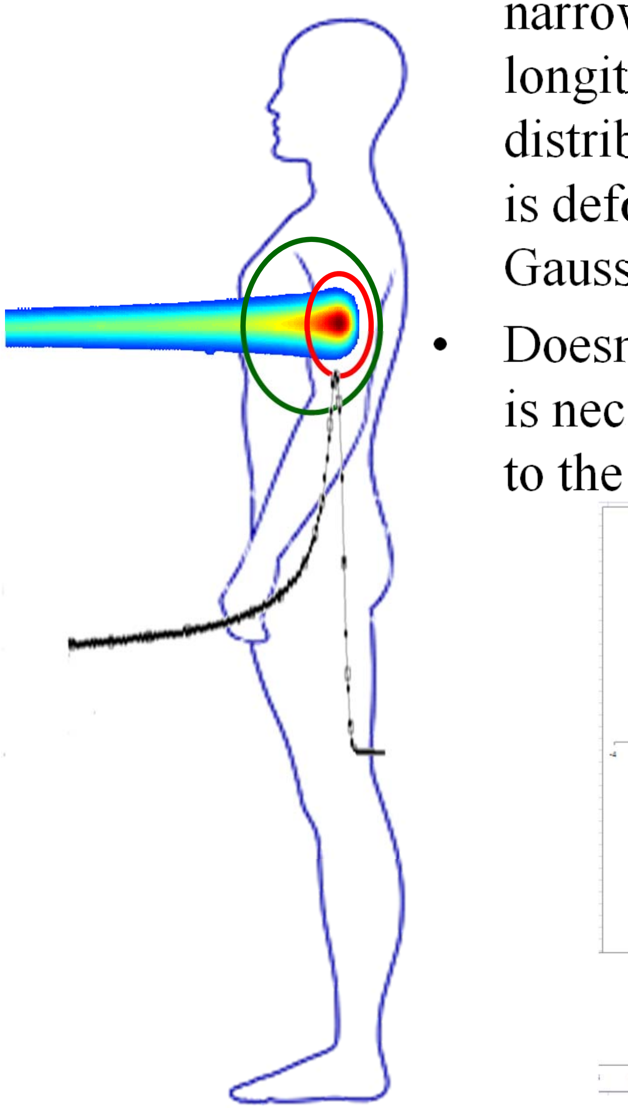


One can characterize the <u>Longitudinal</u> properties of a beam, similarly by considering the *longitudinal momenta* in the beam and the *length* of the beam.

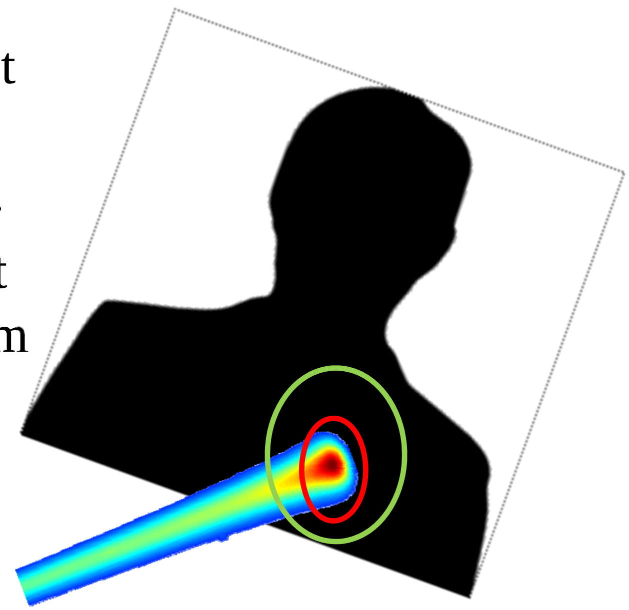


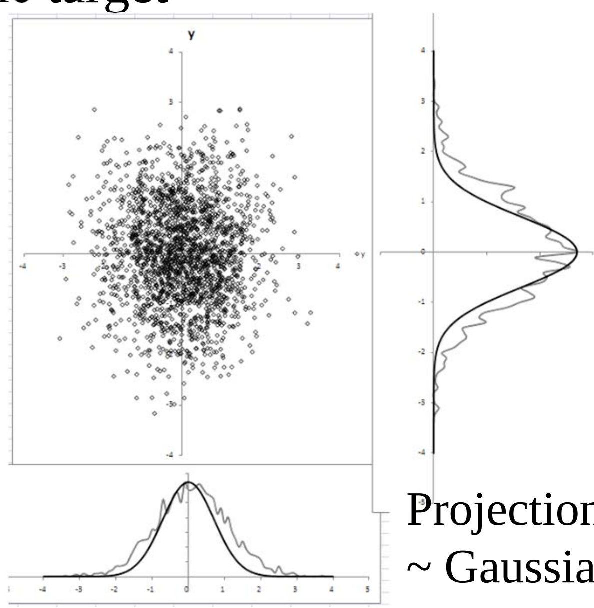


The need to "spread" a beam



- The beam from an accelerator is narrow (transversely and longitudinally) (a "Pencil") –The distribution of that beam, even if it is defocused transversely is Gaussian, not conformal to an Rx.
- Doesn't match the target shape. It is necessary to spread it to conform to the target





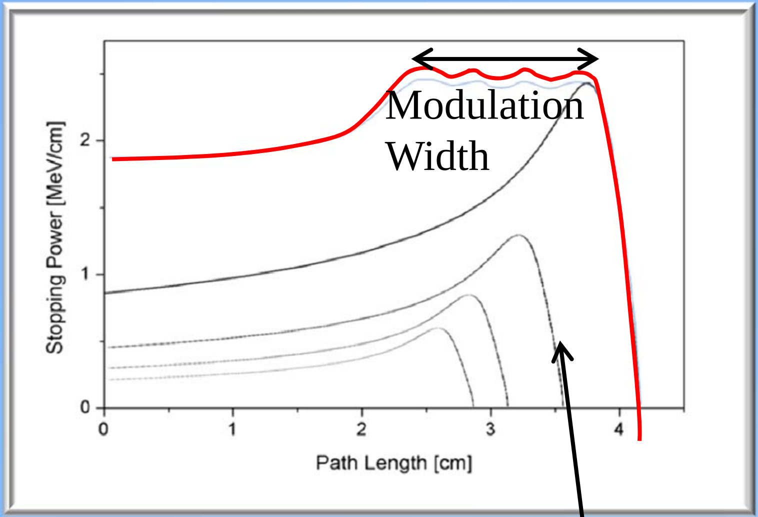
Projection is
~ Gaussian Distribution

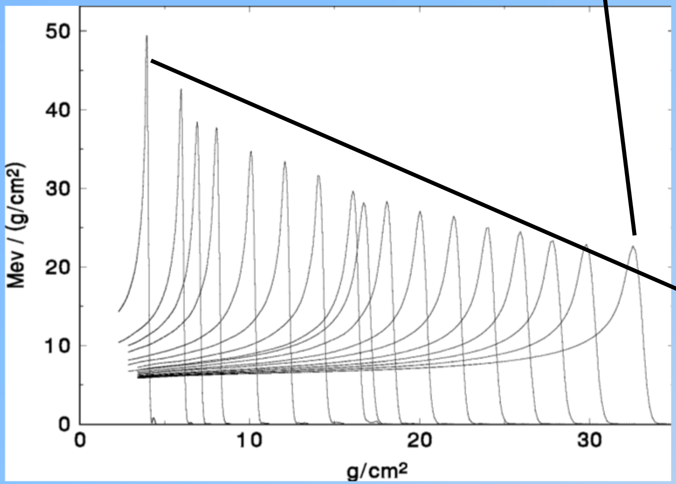
Flanz 2013; PTCOG Educational

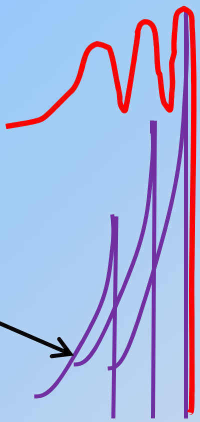
Longitudinal Spreading Options

- Passive (do nothing) Spreading
  - Ridge Filter
- Active (do something) Spreading
  - Range Modulator Wheel
  - Energy Stacking
    - Beam
    - Mechanical

Spread out Longitudinally (Spread Out Bragg Peak - SOBP)







- Spread out Bragg Peak
  - Sum up Bragg Peaks spaced apart
  - Adjust the relative amplitudes to create the desired SOBP (Does NOT have to be FLAT!)
  - The Bragg Peaks are NOT Gaussian and therefore the spacing is fairly sensitive.
  - Sensitivity is further enhanced at Low Energy! (It's harder to smoothly attach Sharp peaks.)

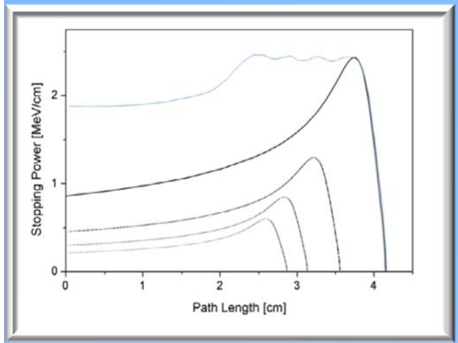
    Reduced straggling

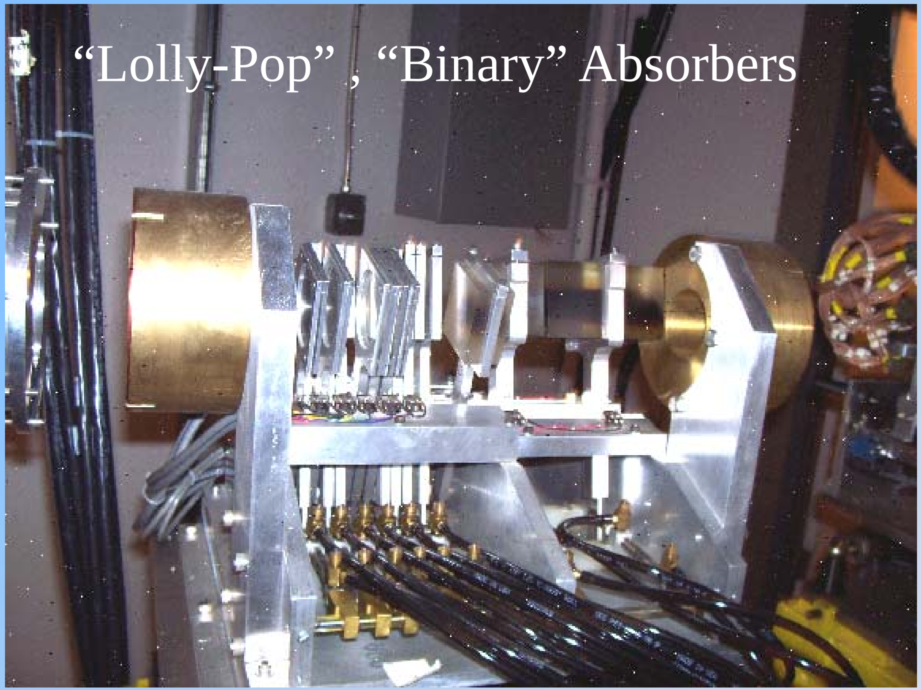
    Reduced absolute energy spread (constant momentum fraction)

    If one pulls back a higher energy peak, the initial energy spread is included and the peak is less sharp + more straggling

How to change the beam energy?

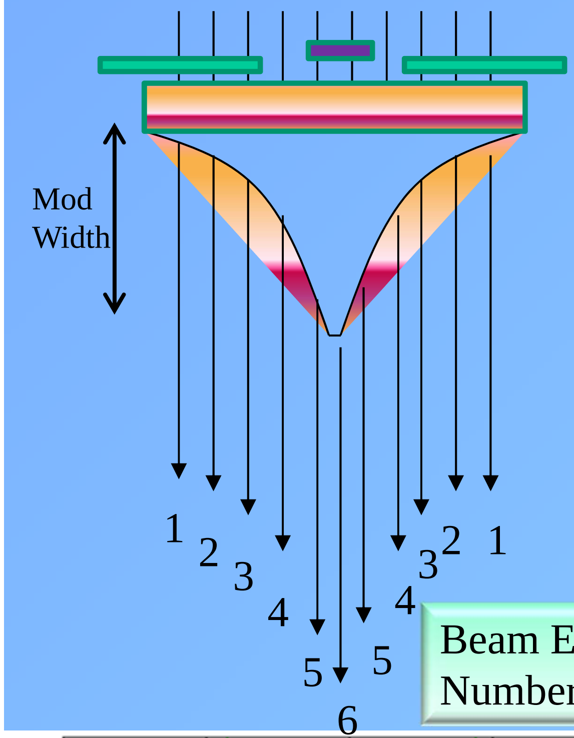
1. From the Accelerator (Before the Nozzle)
2. AFTER the accelerator (Degrader in Nozzle)
   – Binary Absorber

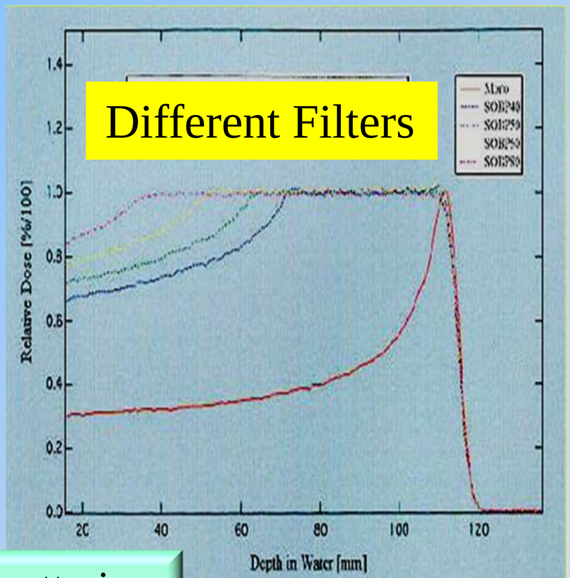




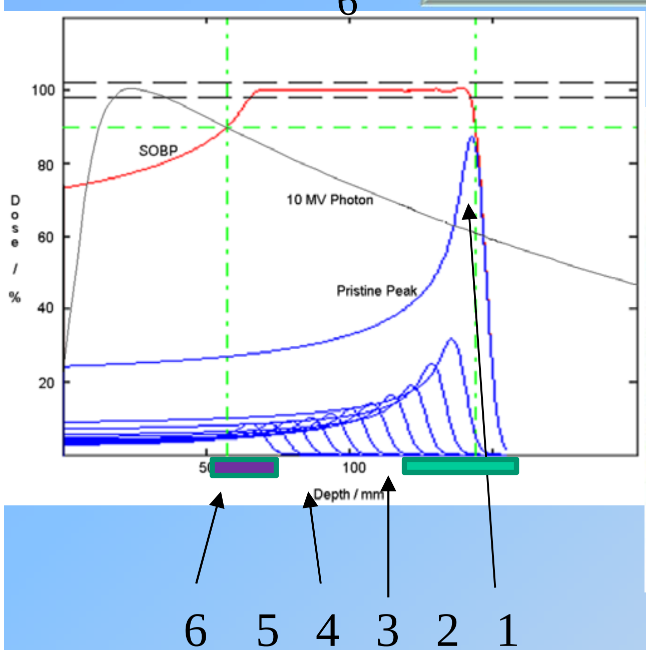
Control the NUMBER of Ions that enters the target at a given Energy

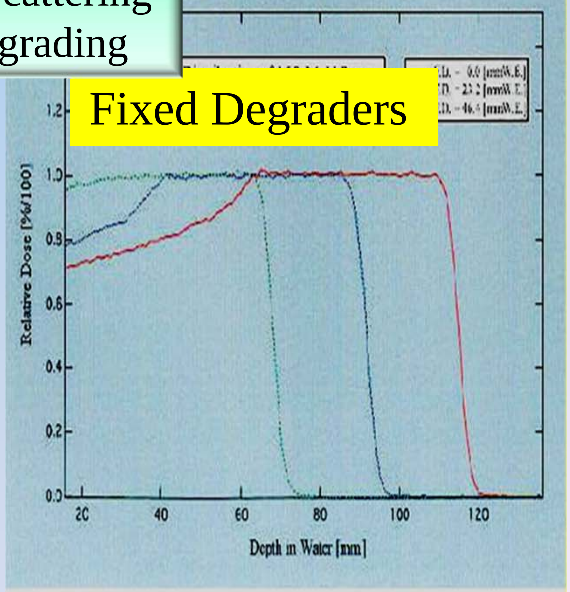
- Ridge Filter





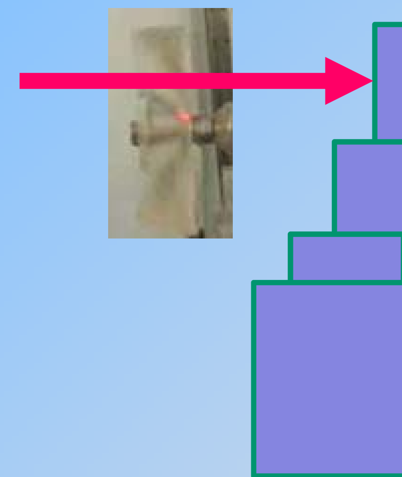
Beam Energy Variations is Mixed Transversely via Scattering
Number of Protons controlled by length of region degrading





NCC Kashiwa

- *Range Modulator Wheel*



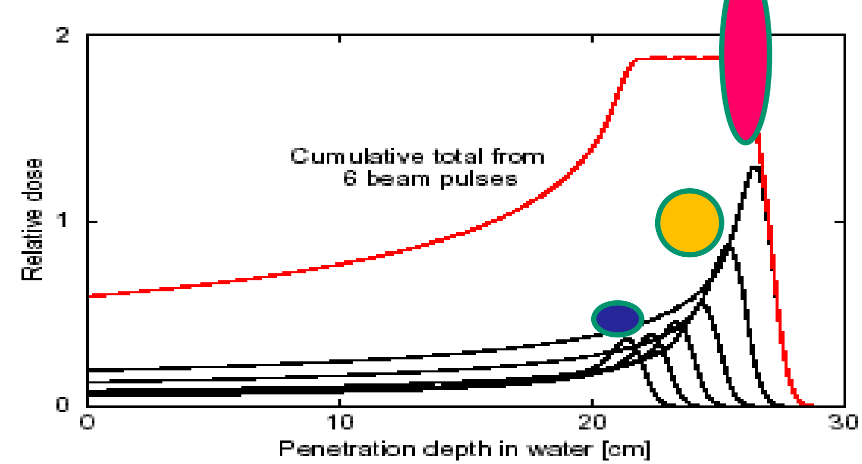


Figure 1: Spread out Bragg peak from 6 beam pulses.

-Control the number of protons getting through at a given energy with the geometry

-<u>Proton Rate x Time = # Protons</u>

 -Assume proton rate constant

 -Assume rotation rate constant

- 360 degrees in e.g. 0.1 sec (600rpm)

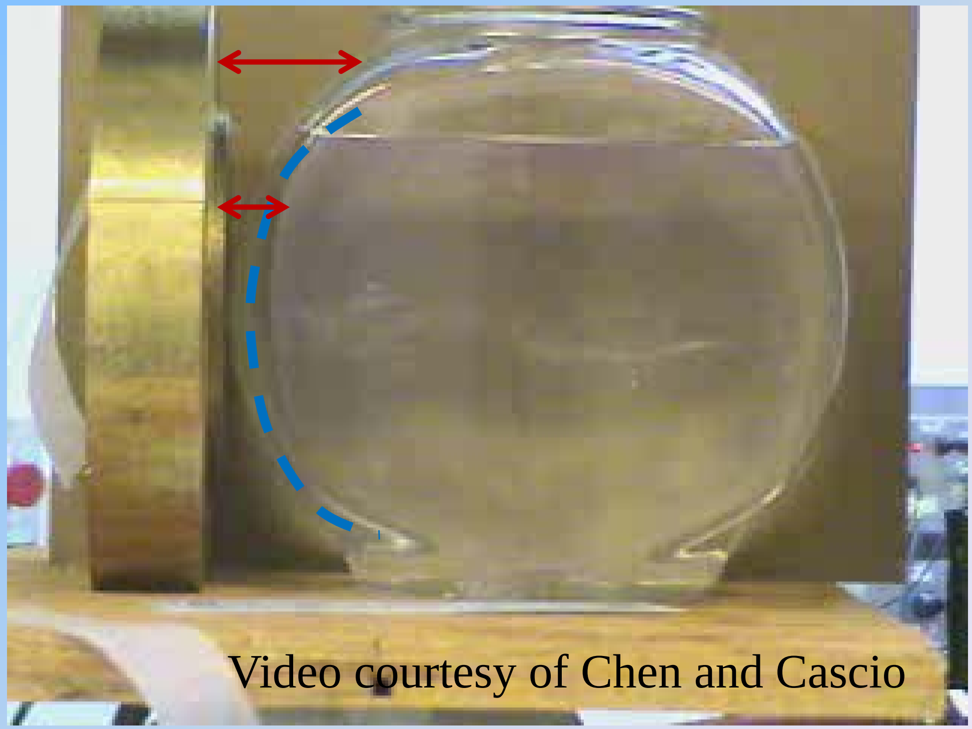
- NO Degradation >1/3 of the time ➔ More of the beam at higher energy

Range Modulating Wheel

Visualize the Proton Range using liquid scintillating material in a fish tank + Slower wheel.

Beam

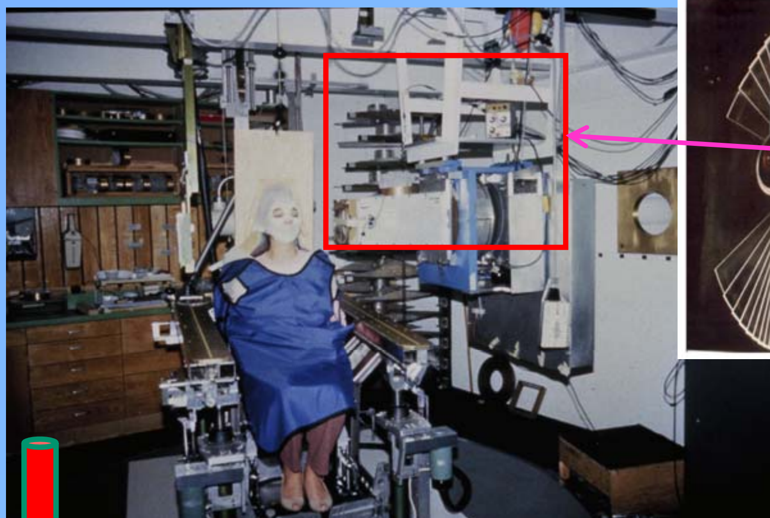
Propeller
Multiple thicknesses of plastic

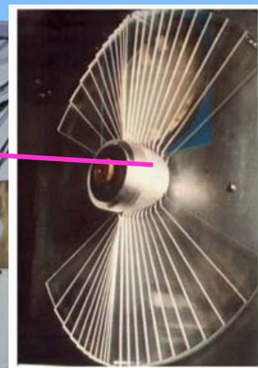


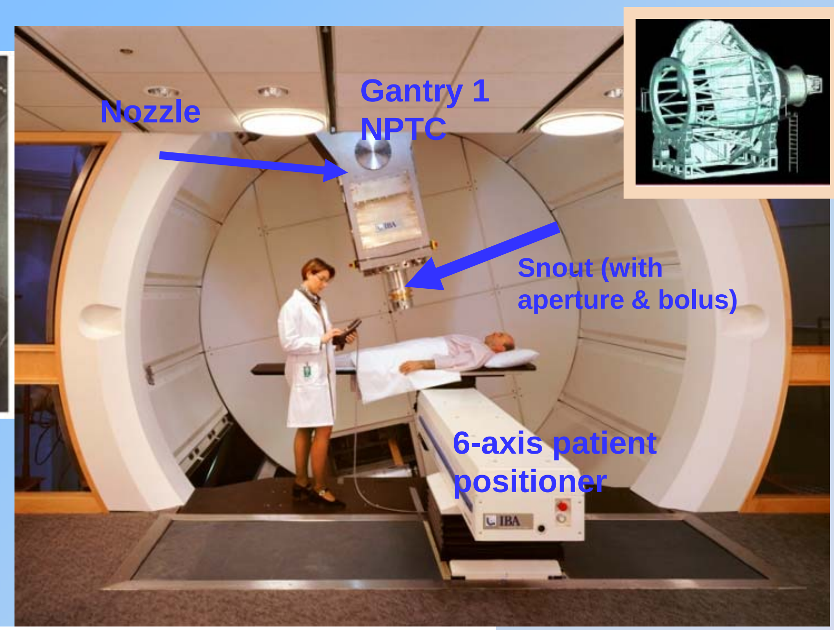
Aperture + Fish Tank with Scintillating Fluid

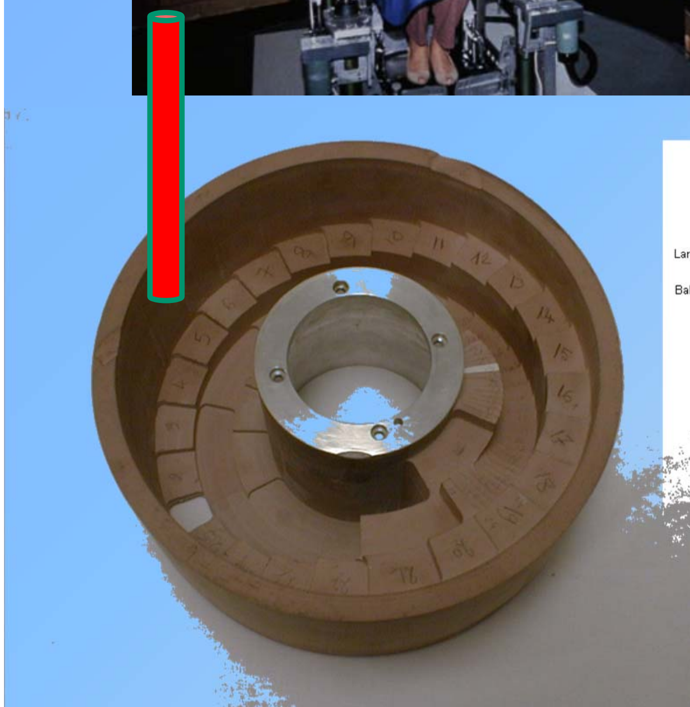
Evolution of Range Modulation

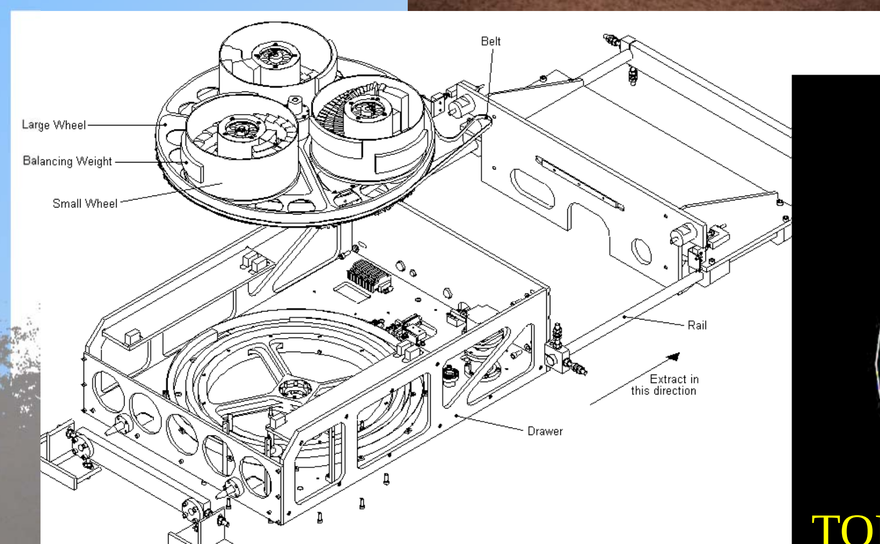
MOD WHEELS ON THE WALL



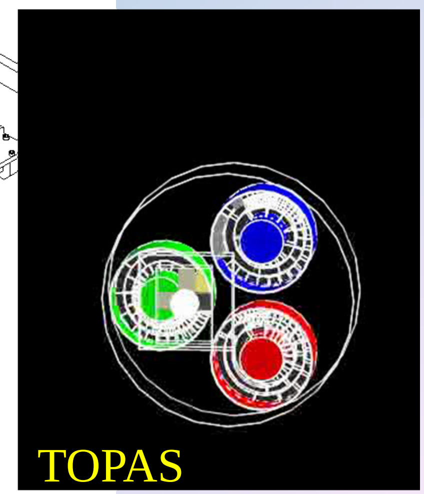








IBA/MGH Implementation



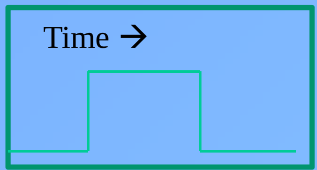
MOD WHEELS IN THE DRAWER

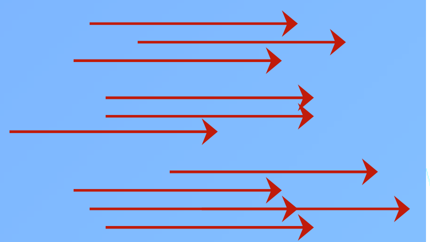
Flanz 2013; PTCOG Educational

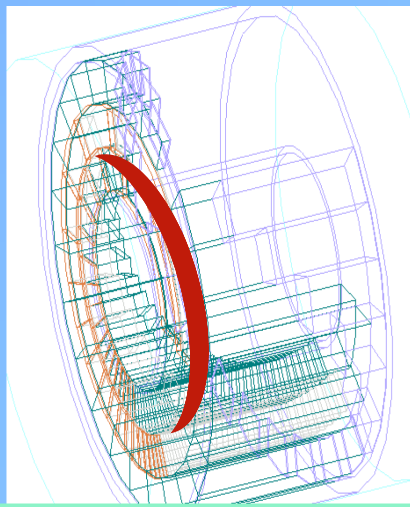
Courtesy: Paganetti

Current Modulation

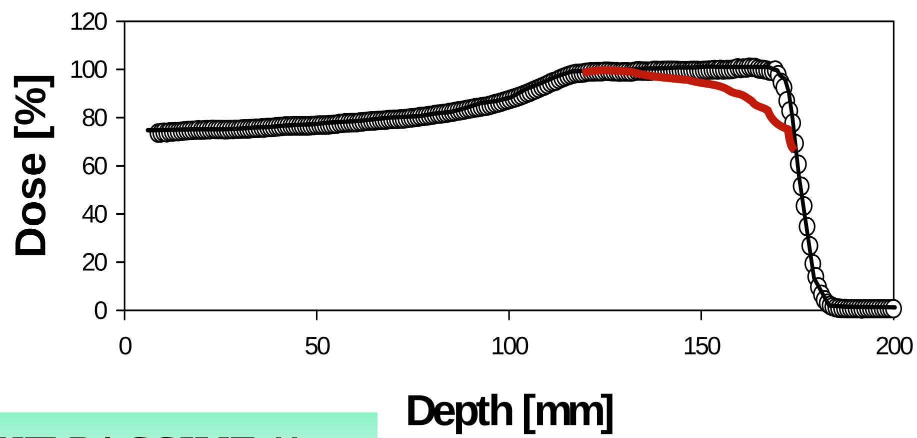
A **Requirement** of a multi-use Mod wheel based Proton Beam Delivery System



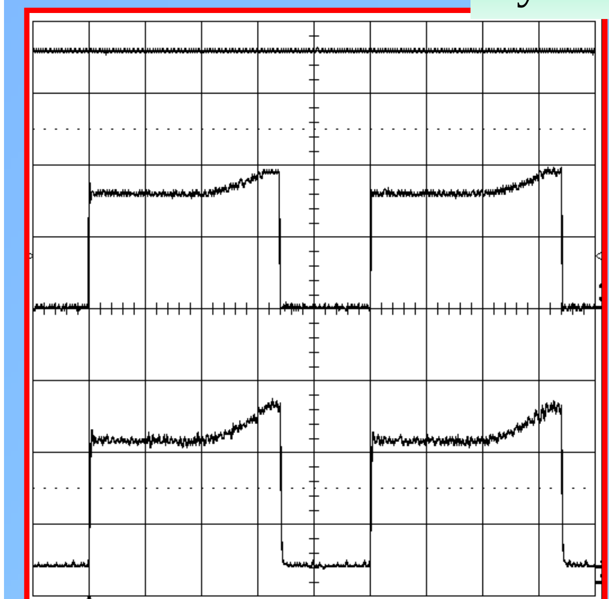


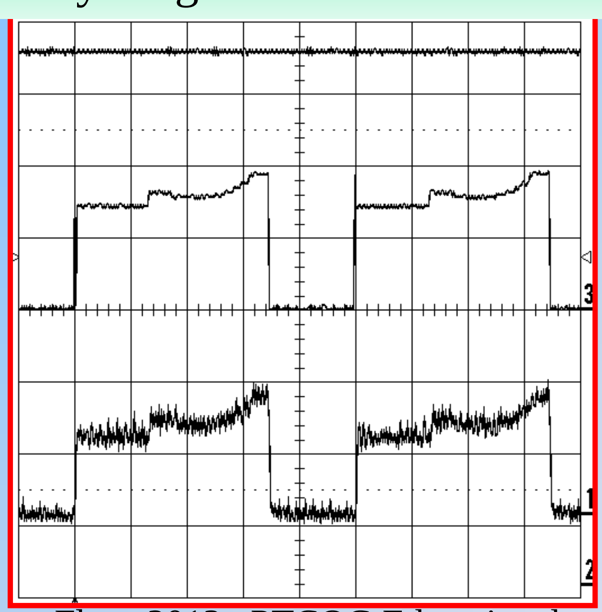


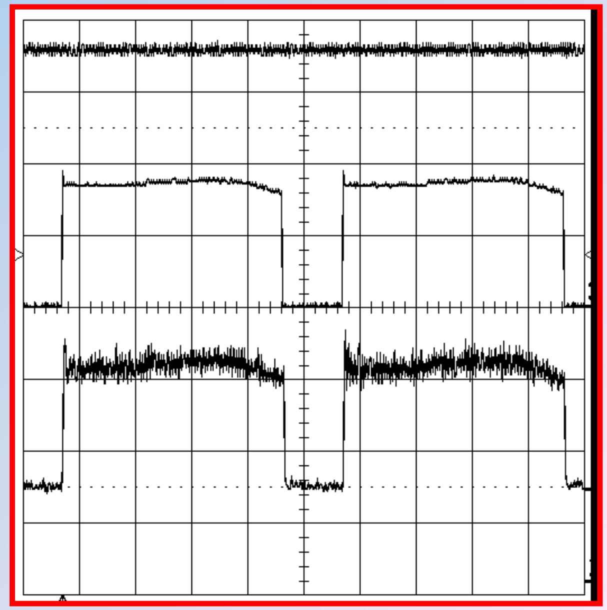
Harald Paganetti



System is anything **BUT** PASSIVE !!

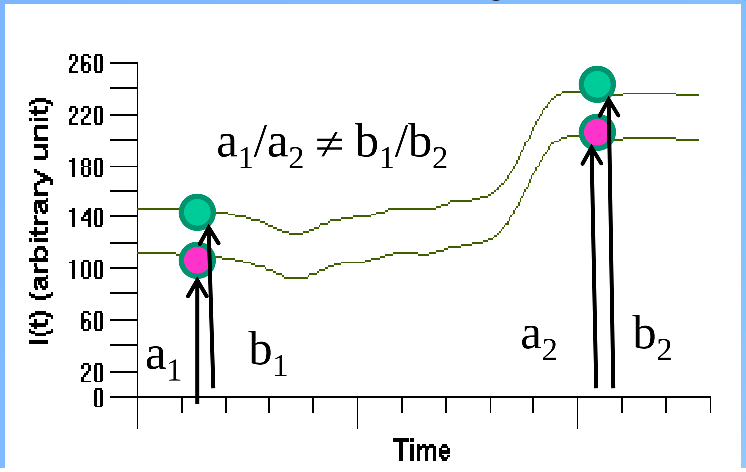


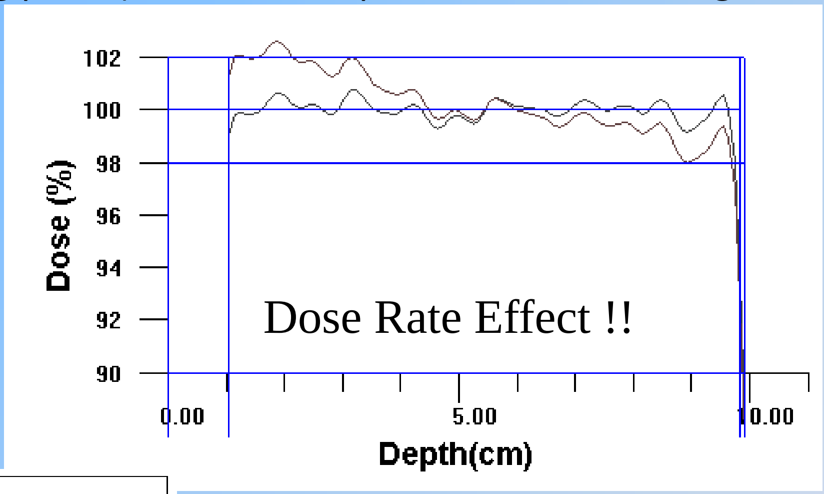


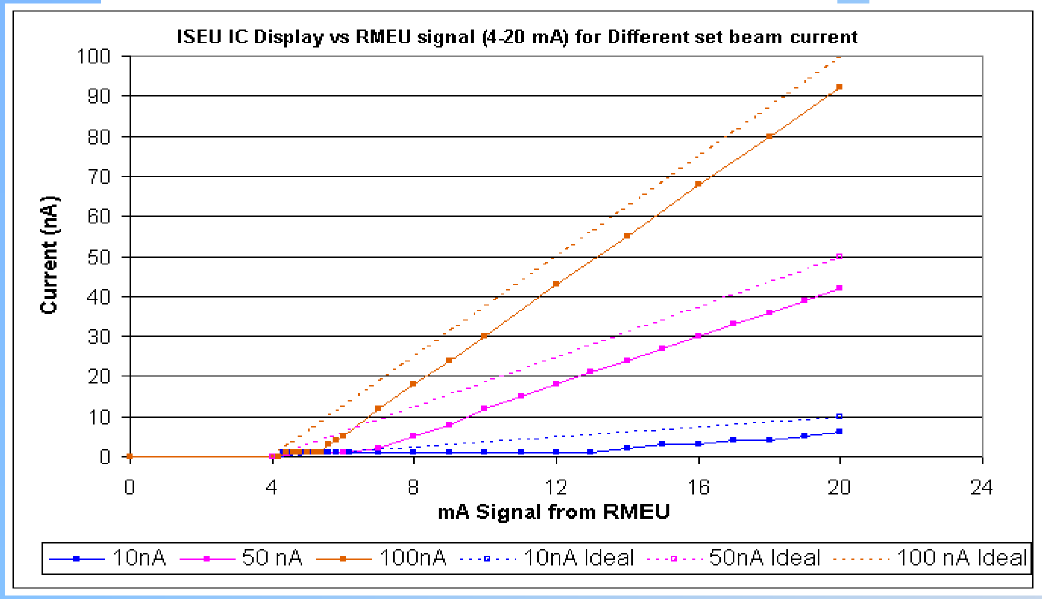


Sensitivity: Current Modulation

If BCM current is shifted by a fixed amount, the ratio of the current from one time to another during a cycle will be different (and the relative weights of the Bragg peaks) AND the shape of SOBP will change.





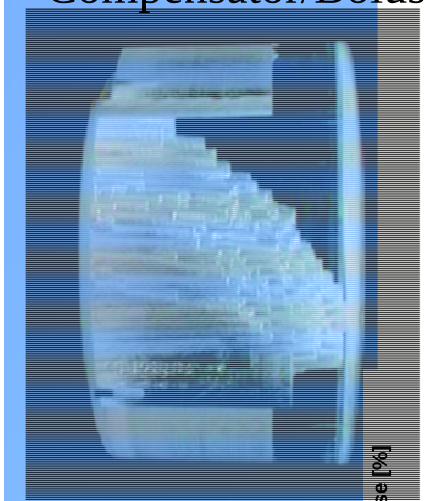


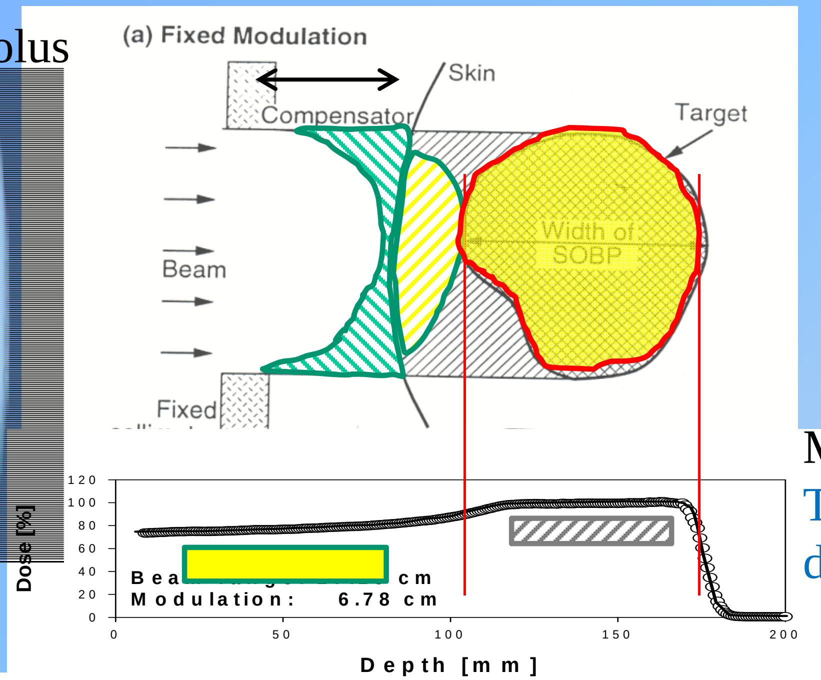
We experienced lack of issues with the SOBP flatness in the beginning, until we investigated thoroughly and found (and FIXED) <u>an offset in the requested vs. delivered current</u>.

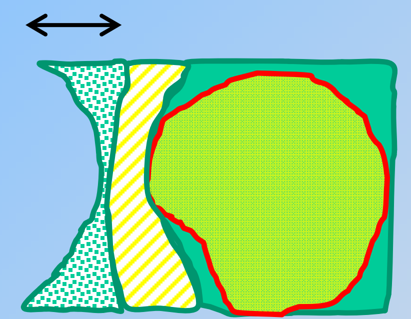
Hsaio-Ming Lu, Robert Brett, Martijn Engelsman, Roelf Slopsema, Hanne Kooy, and Jay Flanz, "Sensitivities in the Production of a Spread-Out Bragg Peak", Med Phys 34 (10), 3844, 2007

Distal Edge Conformation

Compensator/Bolus

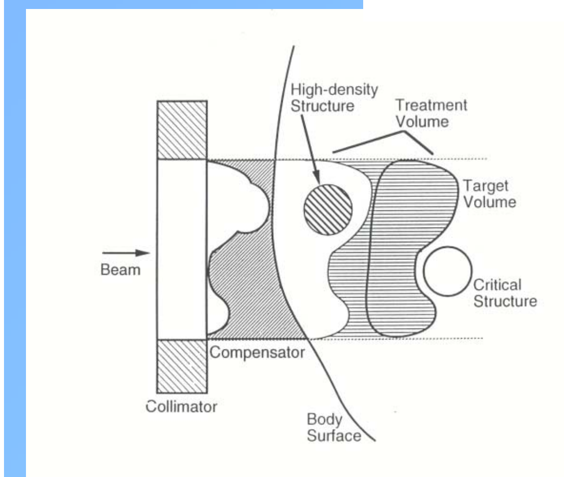




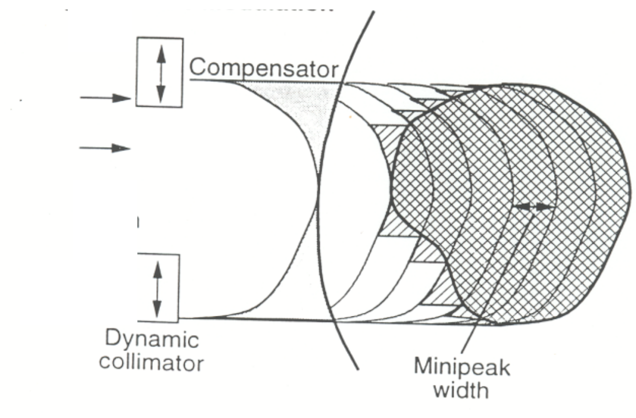


Mod Width **Fixed** ACROSS target !!

Thickness of Compensator determines Bragg peak "pull back"



Energy Stacking with Variable Collimation + Compensator



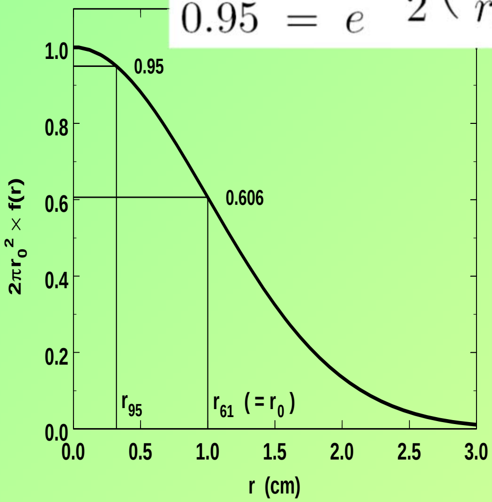
Flanz 2013; PTCOG Educational

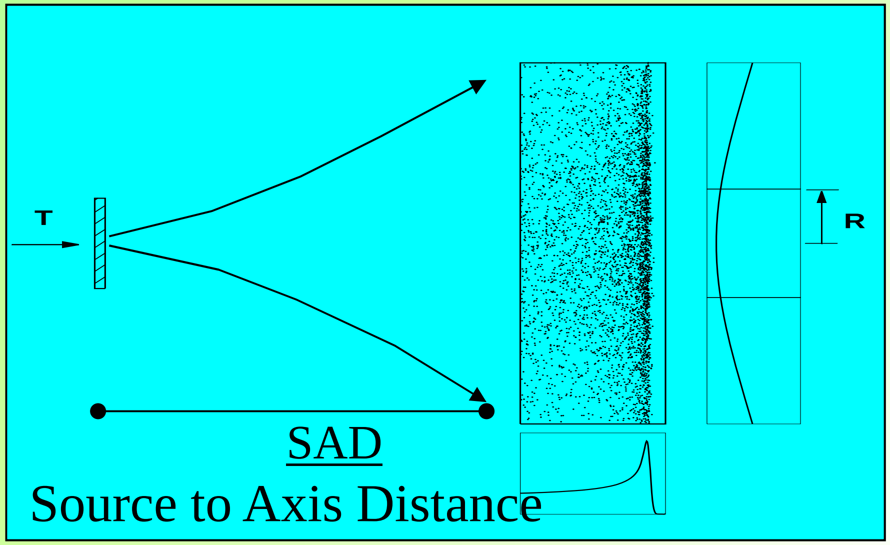
Transverse Spreading Options

- Passive Scattering
  - Single Scattering
  - Double Scattering
- Wobbling (Beam Scanning with Scattered beam)
- Pure Magnetic Scanning
- Combined Magnetic and Mechanical Scanning
  - Moving Magnet
  - Moving Patient

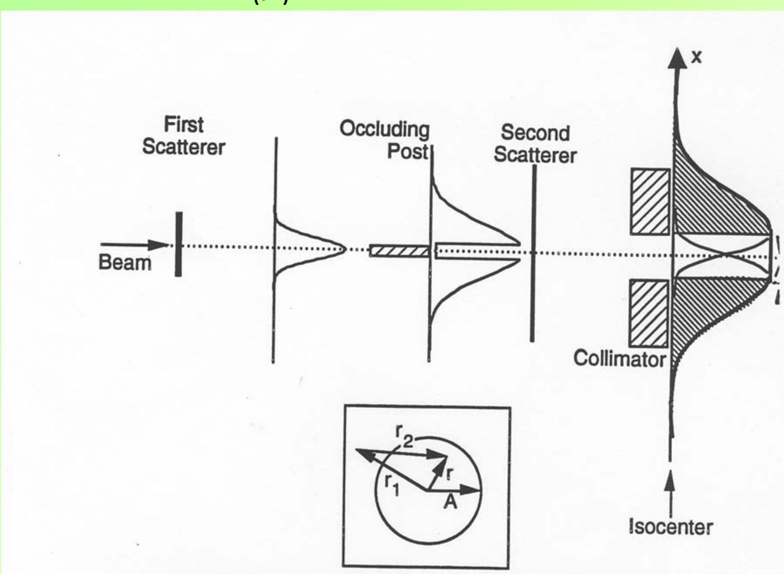
Scattering – Start with Gaussian Beam

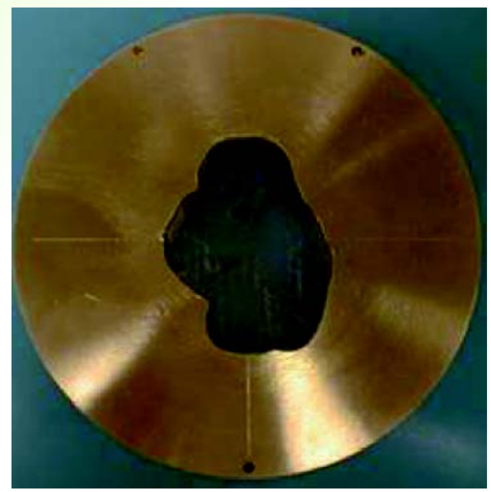
$$0.95 = e^{-\frac{1}{2}\left(\frac{r_{95}}{r_0}\right)^2}$$





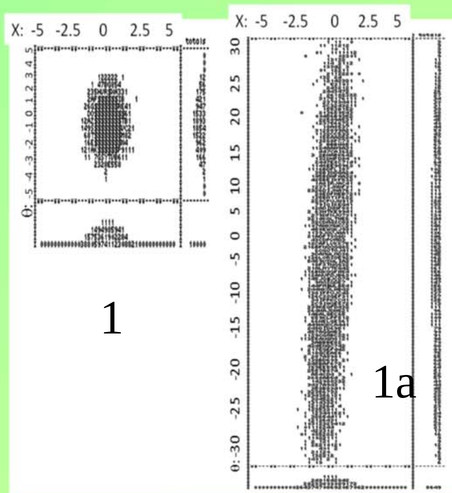
Single Scattering

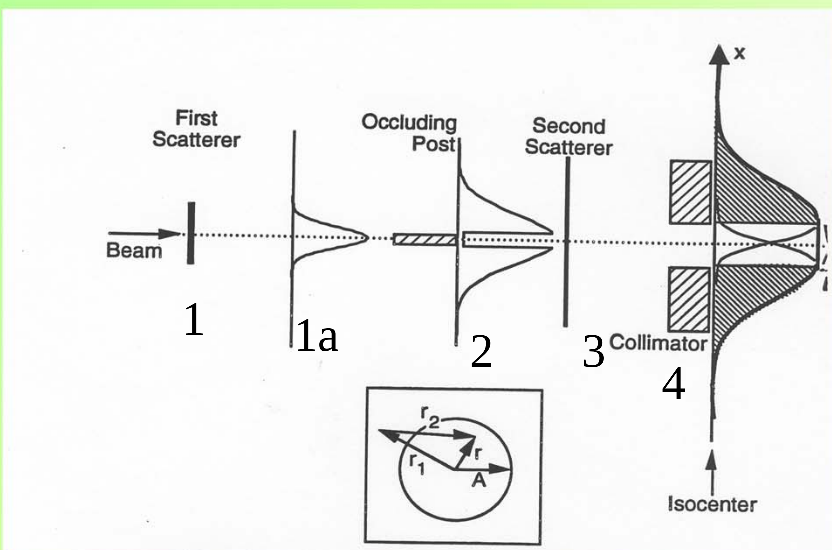


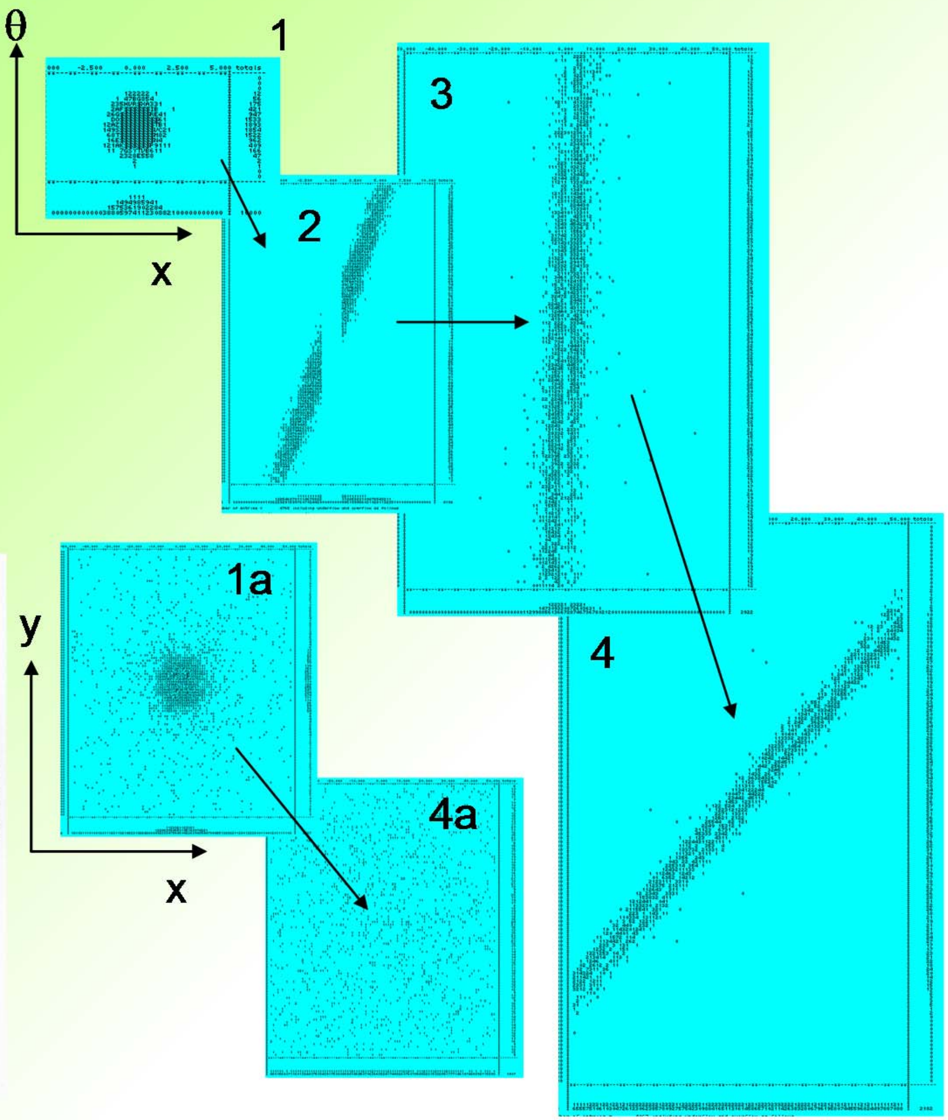


Simple form of Double Scattering

Double Scattering – The real story







Flanz 2013; PTCOG Educational

Combined First Scatterer and Range Modulator

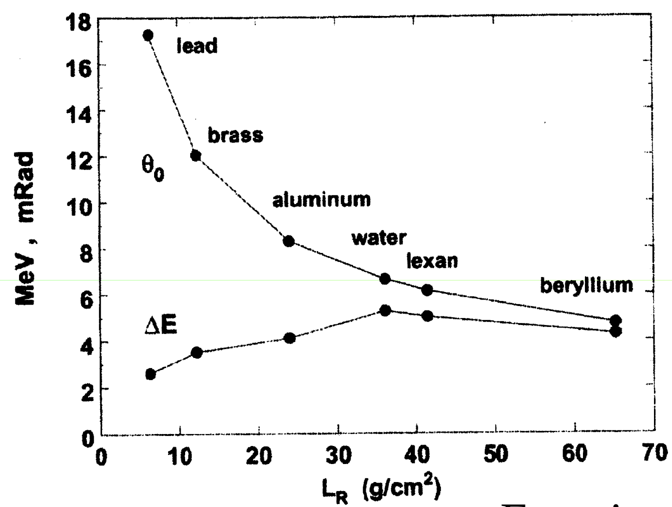
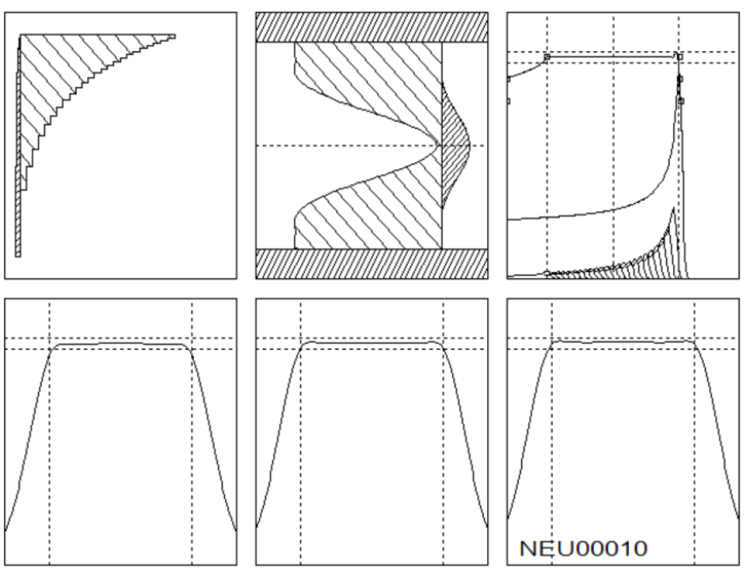


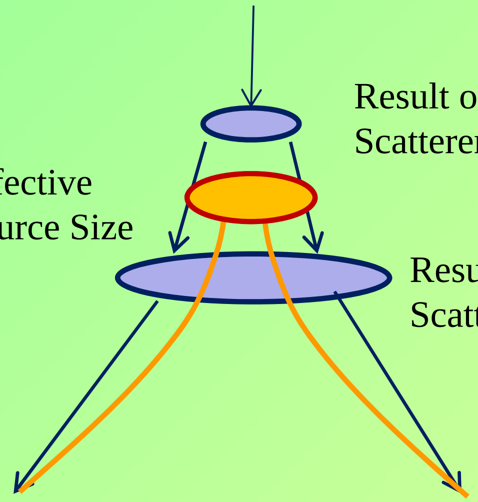
Figure 9.1: Scattering and stopping in various materials.

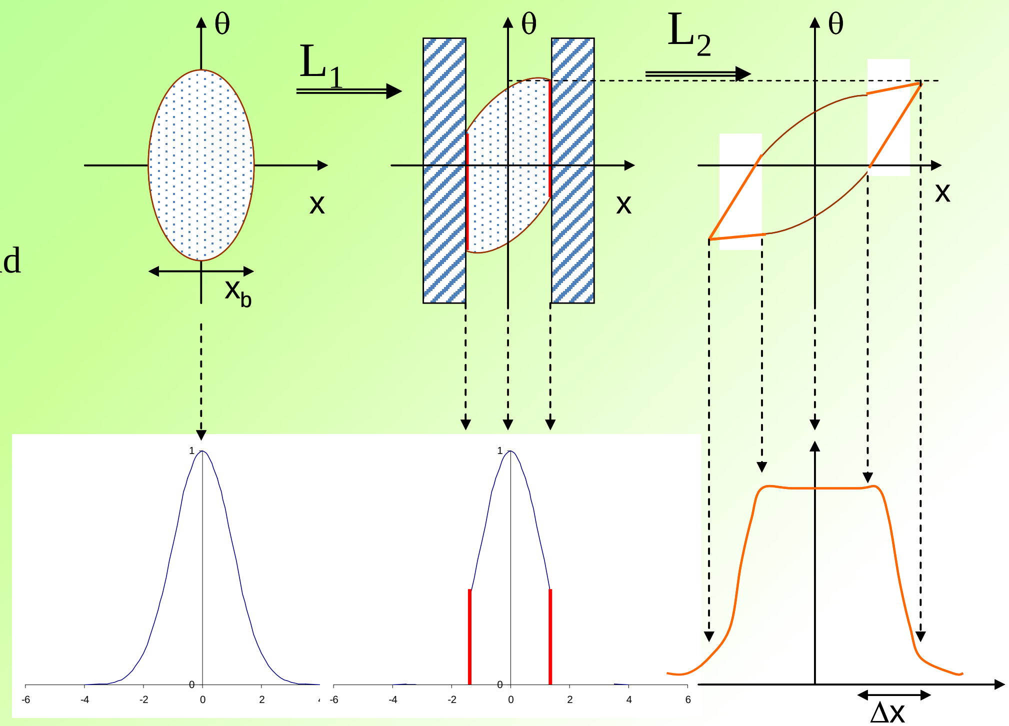
Function of A and Z



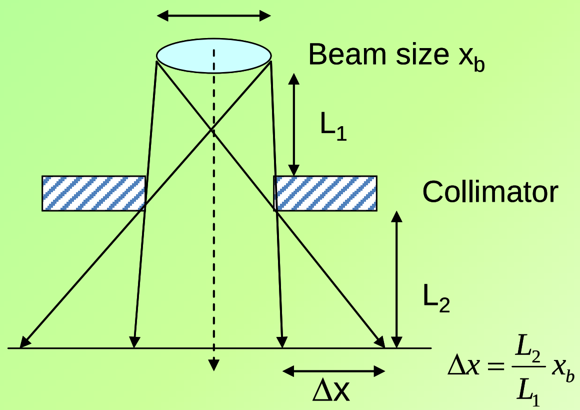
- Combining what we've learned about the Energy Loss and Multiple Scattering …

Penumbra

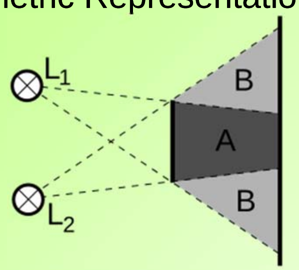




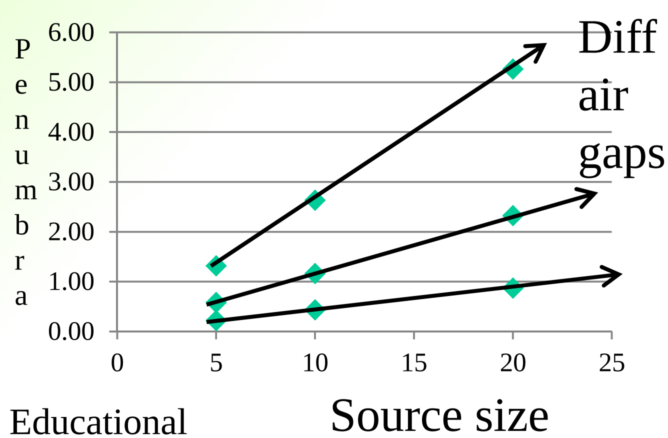
Optical Representation of Collimation



Geometric Representation of Collimation

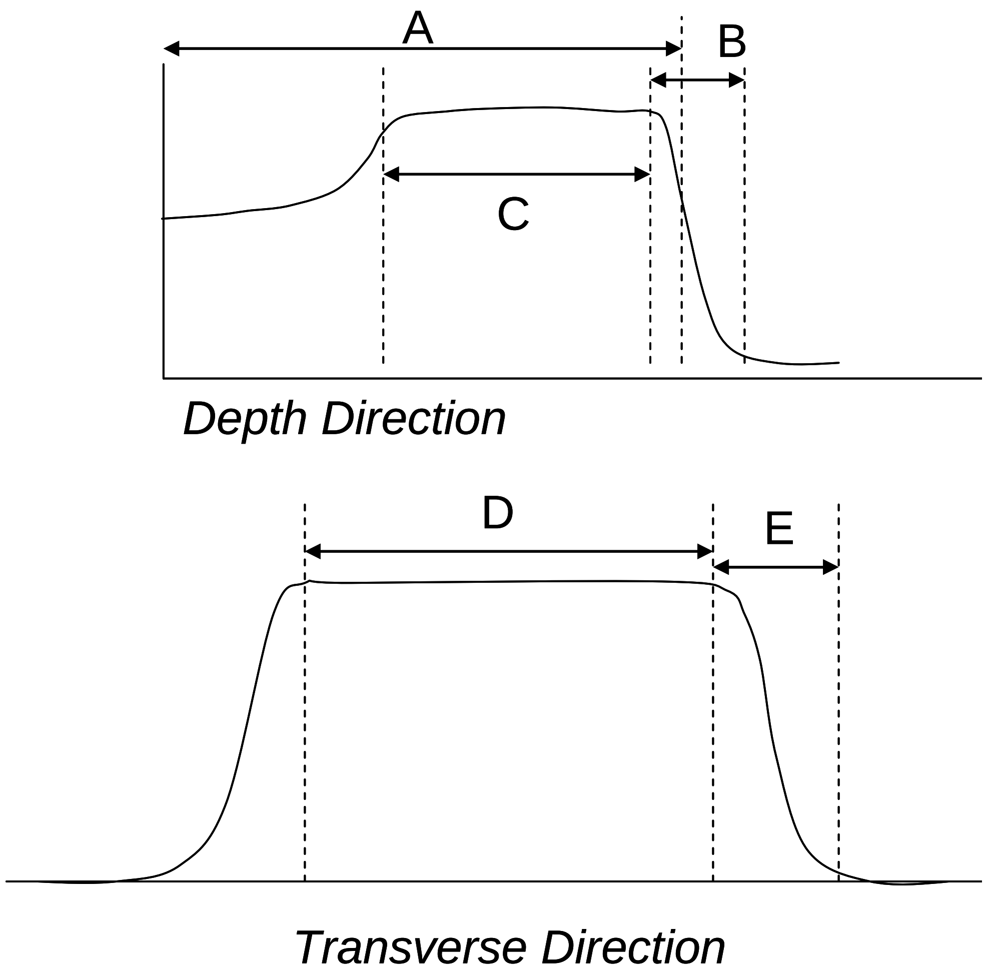


The **umbra**, **penumbra** and **antumbra** are the names given to three distinct parts of a shadow, created by any light source after impinging on an opaque object. For a point source only the umbra is cast.Umbra (A) and penumbra (B)



Flanz 2013; PTCOG Educational

Dosimetric Regions of Interest for Scattering



A. Range (95%?)
B. Distal Fall off (80%-20%)
C. SOBP Width (95-98?)
D. Lateral Width (50%)
   Uniformity(95%?)
E. Penumbra (80-20%)

Not everyone uses the same Definitions?

Flanz 2013; PTCOG Educational

Particle Beam Scanning: Developing Frontier

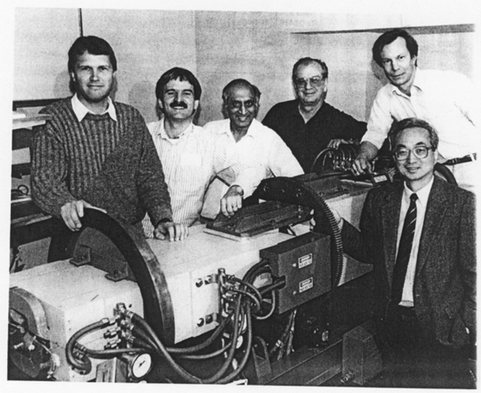
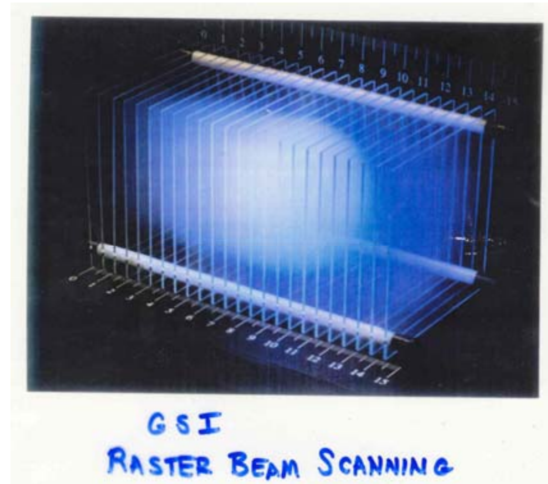


Fig. 4. Raster scanning system shown with its development team of Drs Chu, Renner and Ludewi engineers Nyman, Singh and Stradtner.



30 Years

Technology?
Clarity?
Vision?

- 1978-9: Spot Scanning at NIRS - 30 Patients
  - Range Modulator (Fast) + Lateral 2d Spot
- 1992 ish: B&W Scanning at BNL
- mid 1990's: Spot Scanning at PSI
- mid 1990's: Scanning at GSI

- 2008: Scanning at MDA (with Hitachi)
- 2008: Scanning at MGH (with IBA)
- Renniker (RPTC) (with Varian)
- Upenn (with IBA)
- …Others

HITACHI Inspire the Next

iba

VARIAN medical systems

MITSUBISHI ELECTRIC Changes for the Better

PROTOM

Sumitomo Heavy Industries, Ltd.

What is Particle Beam Scanning (PBS)?

The idea is to SPREAD the beam with a dose distribution that conforms to the prescription.

<u>Beam scanning can be defined as the act of moving a charged particle beam ('relative to the target') of particular properties and perhaps changing one or more of the properties of that beam for the purpose of spreading the dose deposited by a beam throughout the target volume.</u>

Position (x,y)

Speed (v_x,v_y)

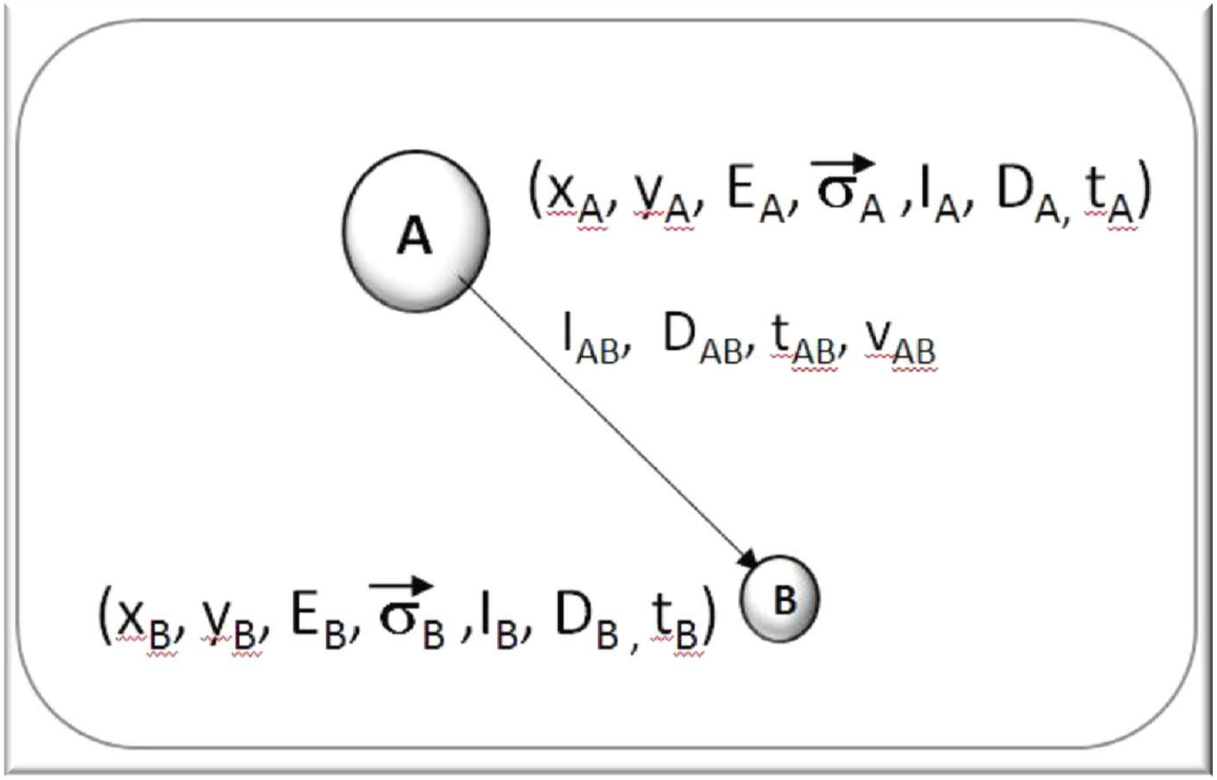
Energy (E)

Time (t)

Intensity (I)

Size(σ)

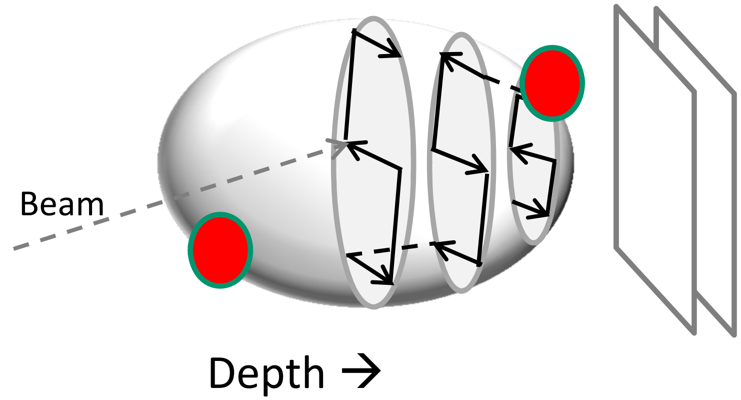
Dose (D)



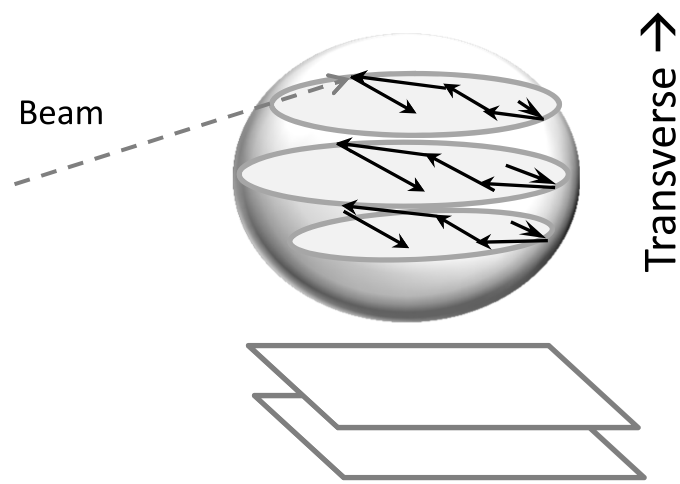
Flanz 2013; PTCOG Educational

How to spread out the beam (3d)?

- To deliver a conformal dose one must control the beam position transversely and in depth.
- Which combination of directions depends upon the many factors (e.g. speed…).
- Usually the Energy (Range) Change time is longest (e.g. 5 sec to 0.1sec (PSI)) vs. milliseconds transversely.
  - Scattering techniques cover the 3D volume either instantly (Ridge filter) or at most over about a 0.1 second time interval.
  - *Normally, Scanning starts at one position and irradiates 'sequentially' taking time to reach the last 3D position. (All things being equal (in time) one could do it diff)*
  - *5 sec x 25 Layers = 125 sec (2 min)*
  - *0.1sec x 25 Layers = 2.5 seconds* ~ Respiration Cycle
    - Organ motion can be an issue



Two extreme examples



Flanz 2013; PTCOG Educational

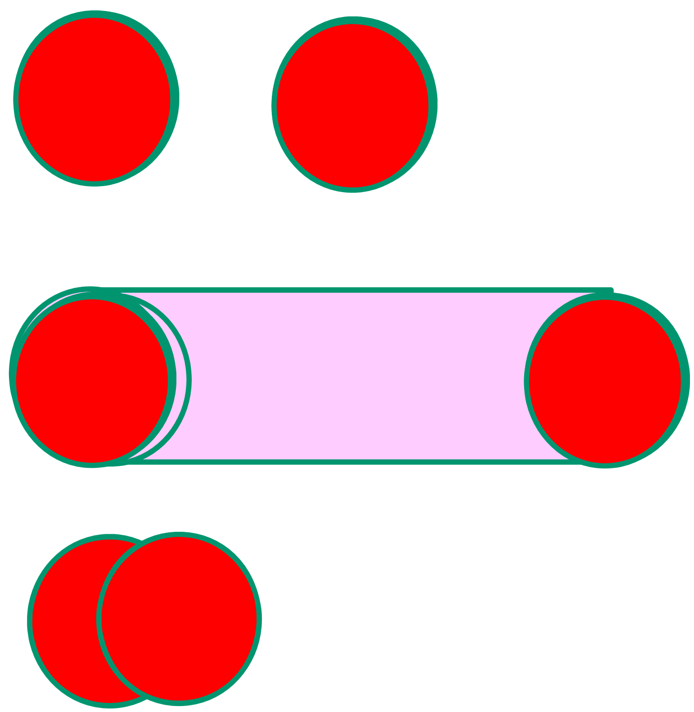
What Names are used? (Technology)

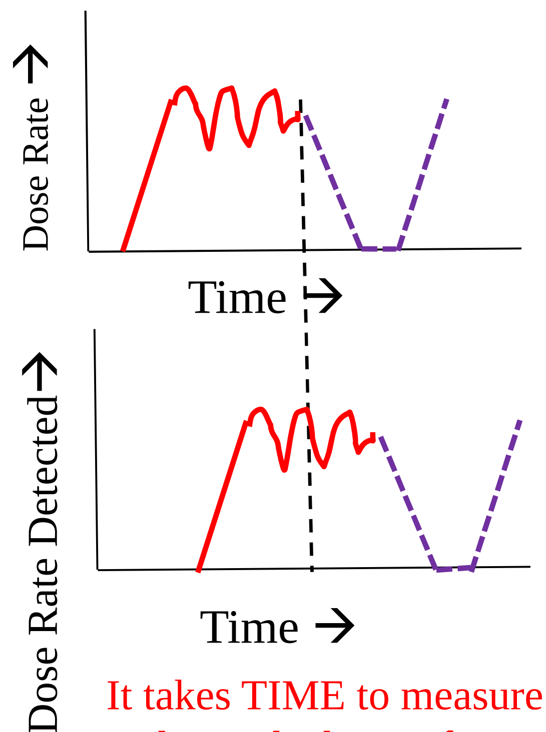
- Dose Driven Scanning: *Dose at a spot determines what to do next.*
  - Spot Scanning: Irradiate one “spot” at a time. Stop the beam while moving to the next spot. Dose at a spot determines when to move. (LCD/LED TV)
  - Raster Scanning: Irradiate one “spot” at a time (mostly). Move the beam to the next spot while the beam is on.

Spot

Raster

Many Spots = Anything ?





It takes TIME to measure and stop the beam if something is wrong. → Dose Rate LIMIT

What Names are used? (Technology)

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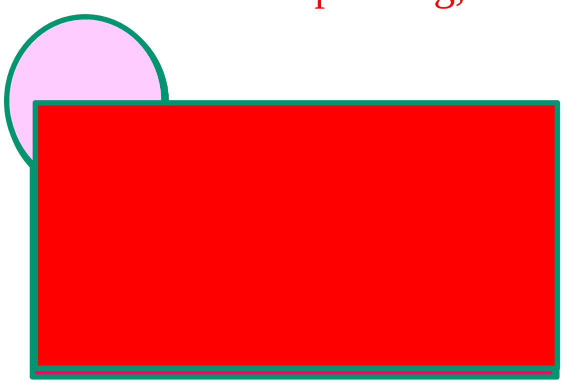
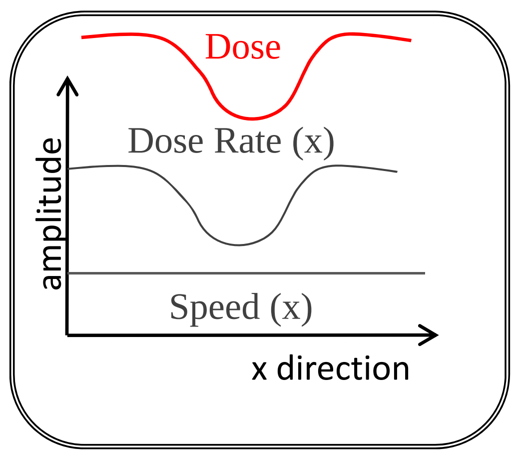
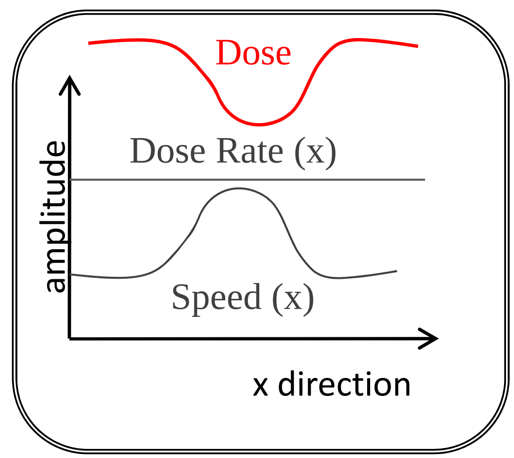
- Time Driven Scanning: *Time and intensity determines the dose at a location.*
  - Same as above (Spot & Raster)but wait a certain time rather than Dose (If linked).
  - Continuous/Line/Raster… Scanning: Irradiate while the beam is moving. Intensity or speed of beam can vary to determine the dose at a given location.
    - It takes TIME to measure and stop the beam if something is wrong. ➔ Dose Rate LIMIT
    - ➔ Repainting, even if you don't want to







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What Names are used? (Technology)

Particle Beam Scanning

- Dose Driven Scanning: *Dose at a spot determines what to do next.*
  - Spot Scanning: Irradiate one "spot" at a time. Stop the beam while moving to the next spot. Dose at a spot determines when to move. (LCD/LED TV)
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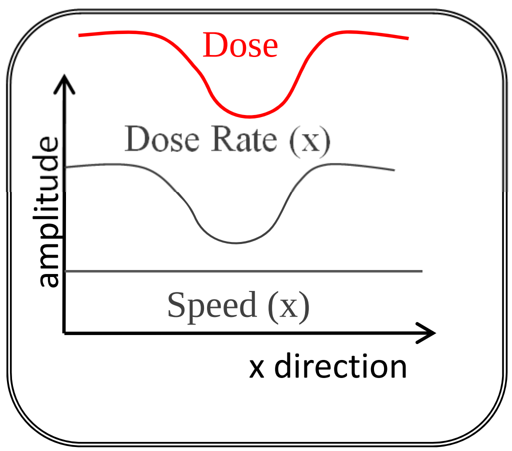
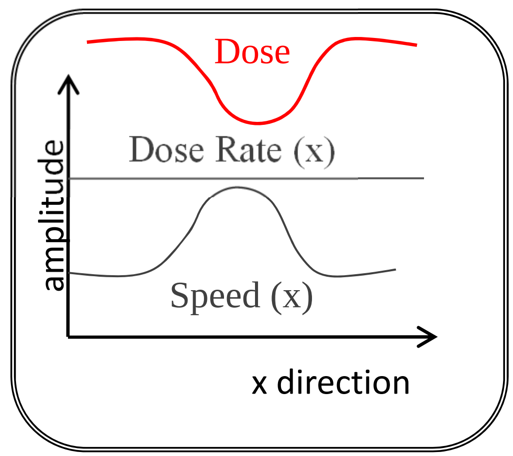
- Time Driven Scanning: *Time and intensity determines the dose at a location.*
  - Same as above (Spot & Raster)but wait a certain time rather than Dose.
  - Continuous/Line/Raster… Scanning: Irradiate while the beam is moving. Intensity or speed of beam can vary to determine the dose at a given location.
- Uniform Scanning: "Constant" Speed and Current; Simulate Scattering

- **Pencil Beam Scanning:** Implies a very small transverse beam size (pencil point)
- Crayon Beam Scanning: Not so small as a pencil
- Others:
  Mechanical Motion, Ribbon Scanning (with Variable Collimators),…





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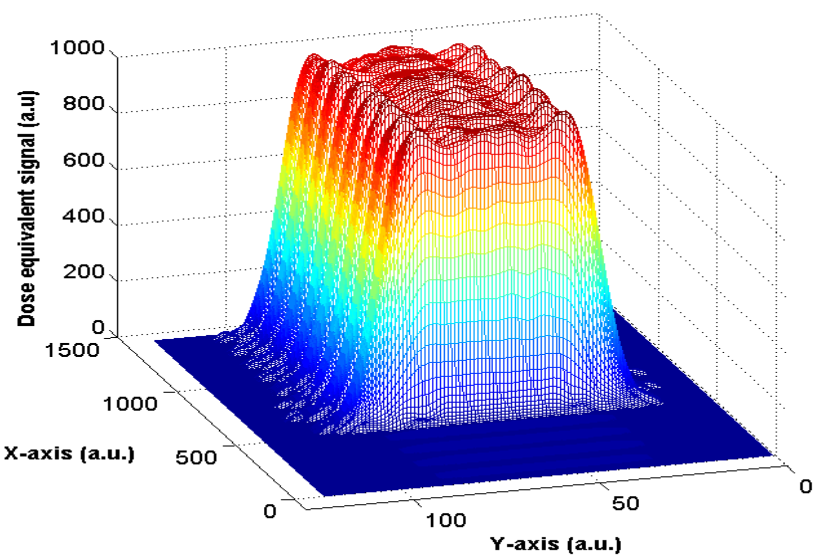
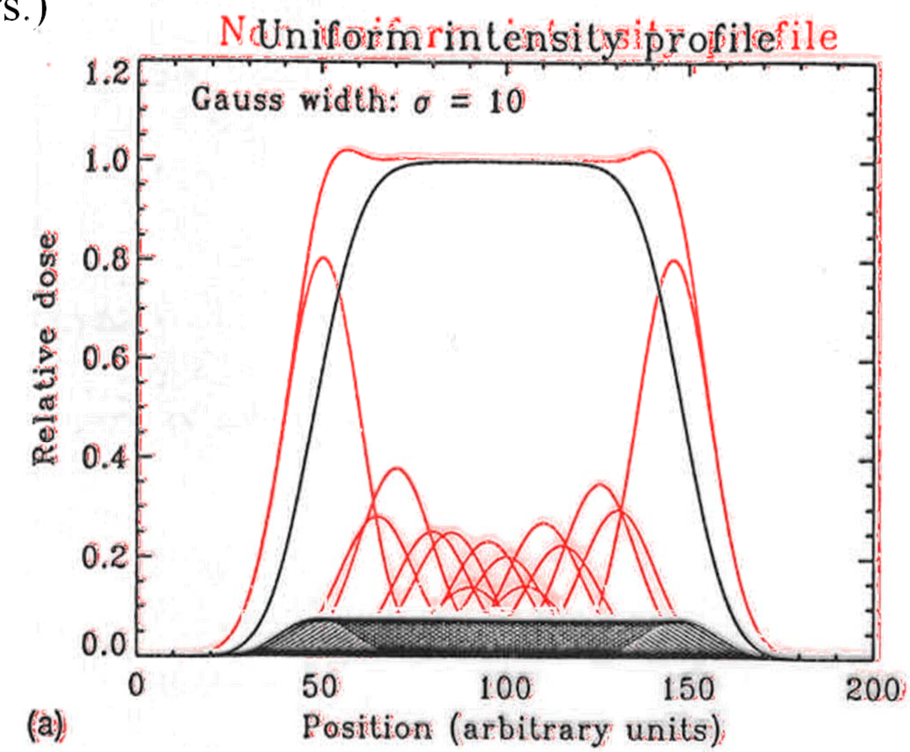
Idiosyncrasies of Scanning: e.g. Penumbra Optimization

- Penumbra Optimization (ala PSI/Berkeley)
  - This results in a balance between penumbra and overall uniformity. (There will be ears.)
  - TPS provides the map which must be compared with the measurement



Pedroni et. al.

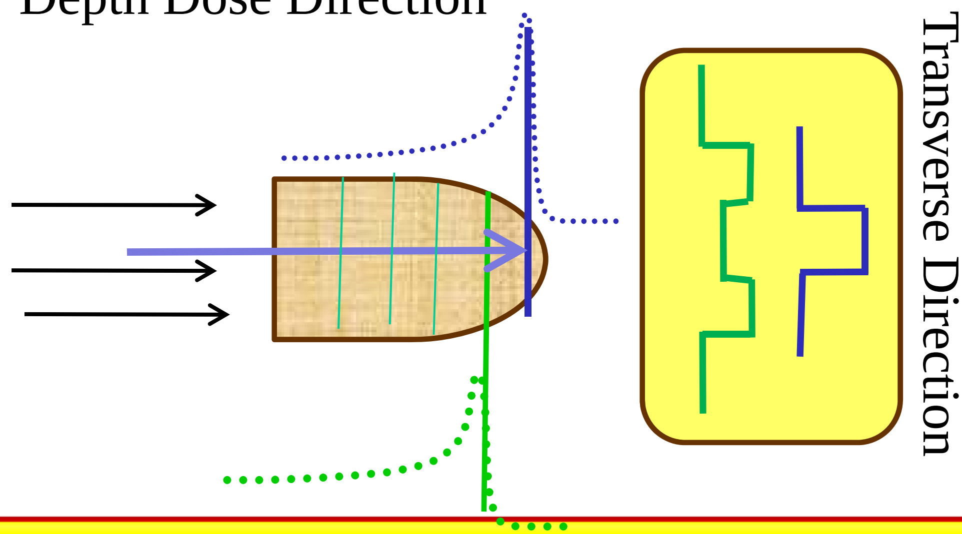


Therefore "Fluence Modulation" is required even for optimized Single Field Uniform Dose !

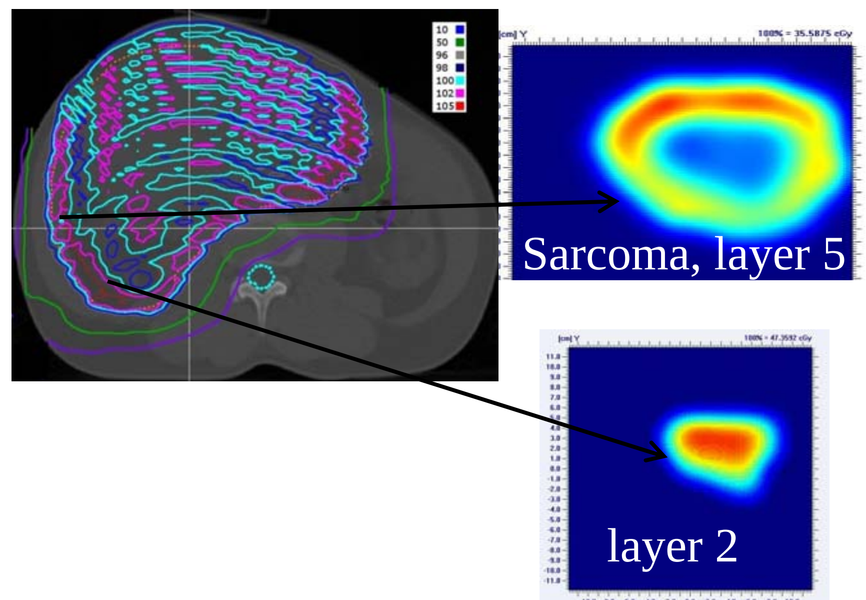
Names for Scanning (Delivery)

- SFUD: Single Field Uniform Dose
  - Deliver a dose distribution with a scanning beam. At the **end of one field** the dose to the target should be uniform. (*Note that this says NOTHING about the distribution of any given **subset of that dose**.*)

Depth Dose Direction



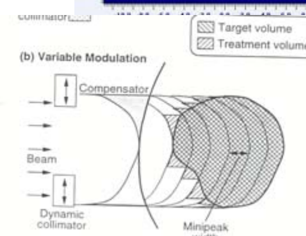
MGH 1st Patient Treatment – 4 liter Sarcoma



SFUD REQUIRES <u>Dose Modulation</u>

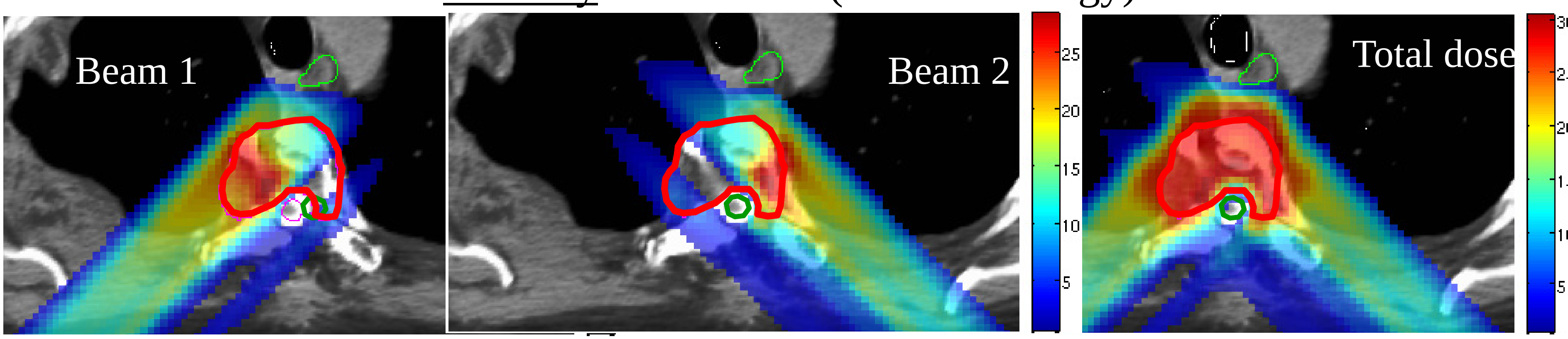
<u>Why not a **BOOST** in a single field?</u>

Without a Compensator
Can Consider WITH a Compensator



Names for Scanning (Delivery)

- SFUD: Single Field Uniform Dose
- IMPT: ~~Intensity~~ Modulated Particle Therapy
  - Deliver a dose distribution with a scanning beam. At the end of one field the dose to the target may NOT be uniform. Multiple fields will create a uniform or prescribed distribution. (In this case it takes Multiple Fields for Uniform Dose not a Single Field)
  - The number of protons deposited at a location MAY HAVE NOTHING to do with the Intensity of the beam (see Technology).



These names IMPLY the RESULT of a SINGLE field! There is NO difference between SFUD and IMPT/MFUD in the delivery technology (**unlike** 3DConformal vs. IMXT) but there could be a big difference in the character of IMXT and so-called IMPT.

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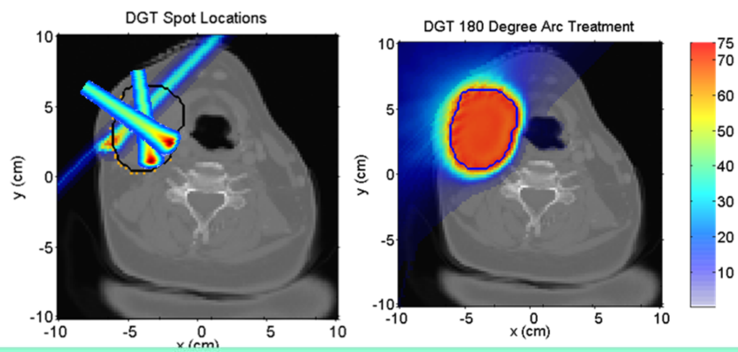
  - The number of protons deposited at a location MAY HAVE NOTHING to do with the <u>Intensity</u> of the beam (see Terminology).
- DET: Distal Edge Tracking
  - Deliver beam around the target through to the distal edge of the target (!!! Angles, End of Range?)

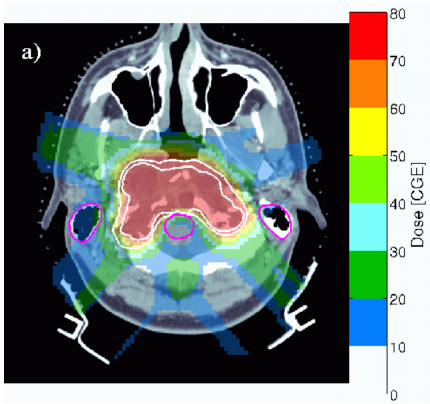
PBS

Particle Beam Scanning



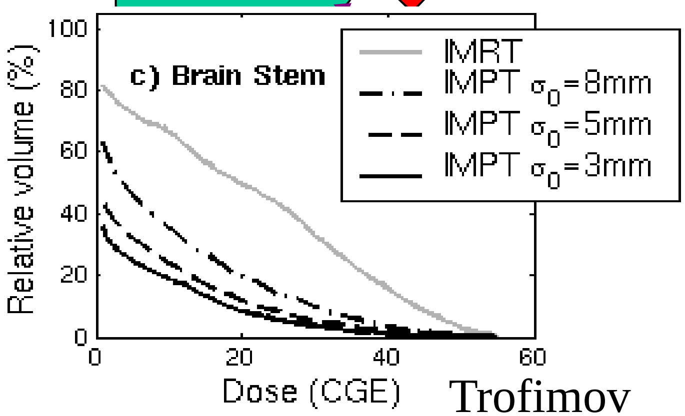
These names IMPLY the RESULT of a SINGLE field! There is NO difference between SFUD and IMPT/MFUD in the delivery technology (**unlike** 3DConformal vs. IMXT) but there could be a big difference in the character of IMXT and so-called IMPT.

Beam Sigma or Penumbra or Edge ?

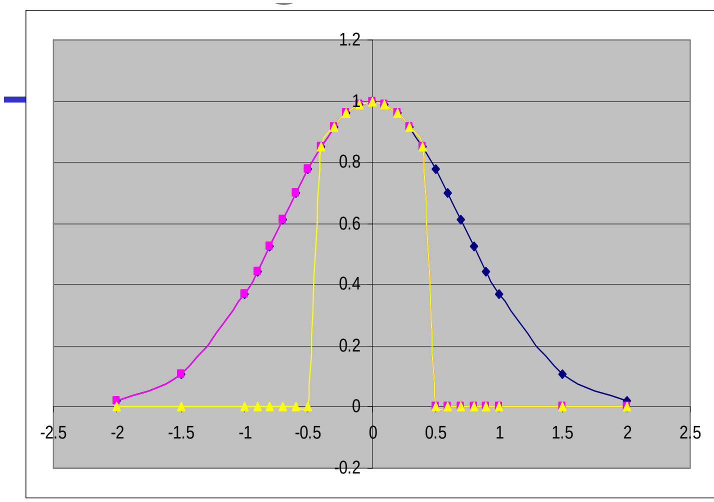


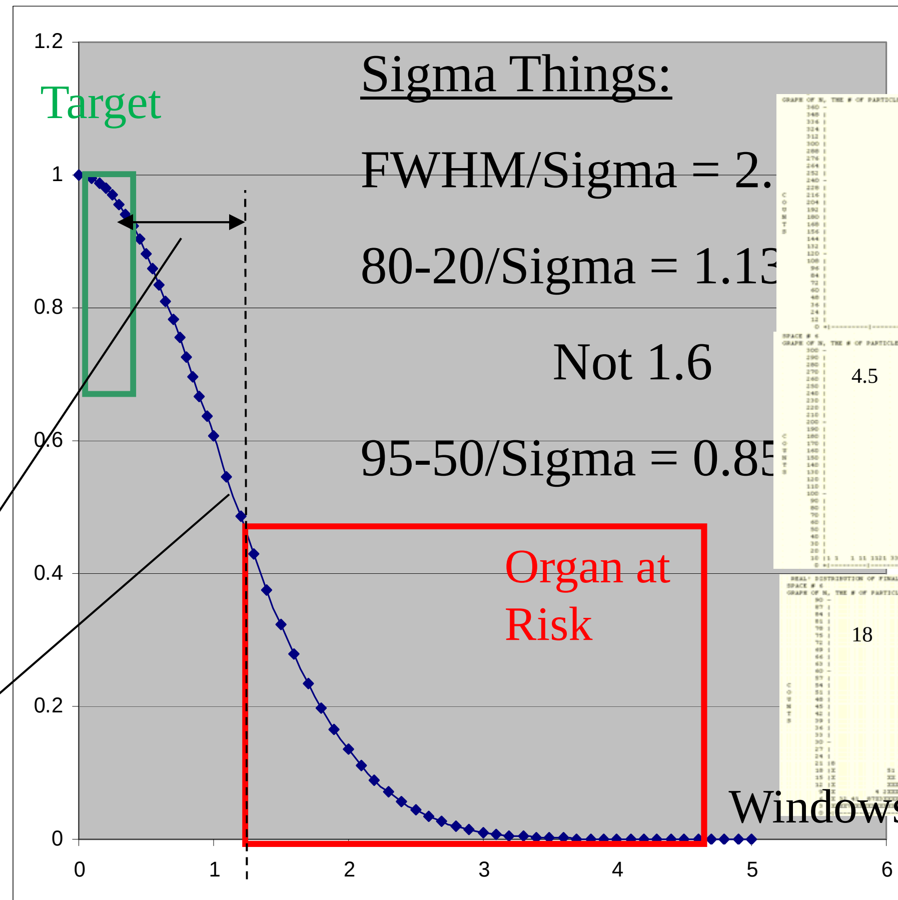
$$y = e^{-\frac{1}{2}\left(\frac{x}{\sigma}\right)^2}$$

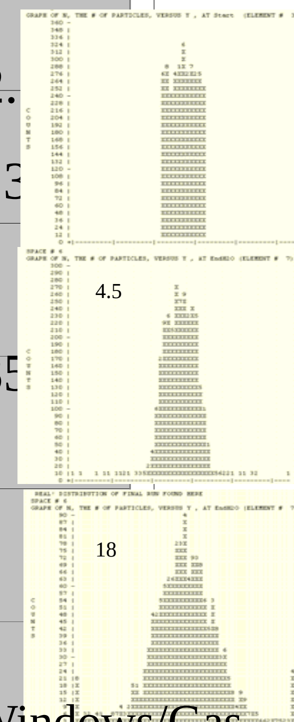
Assume: Dose to Target within +/- 2.5% and Organ at Risk < 50%



Trofimov





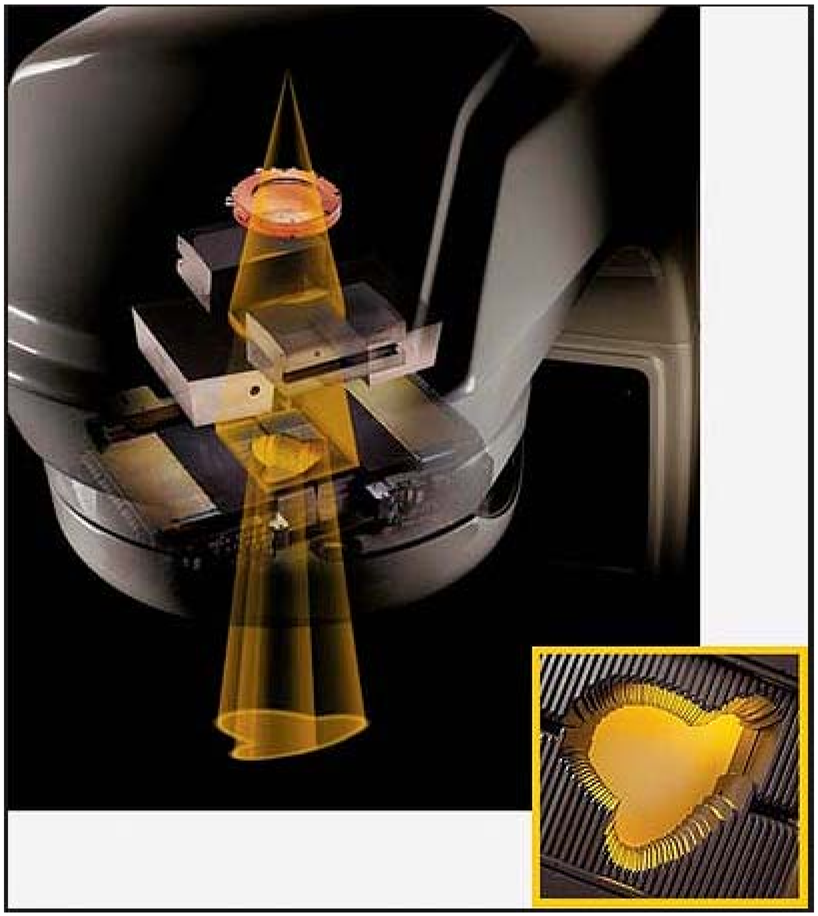


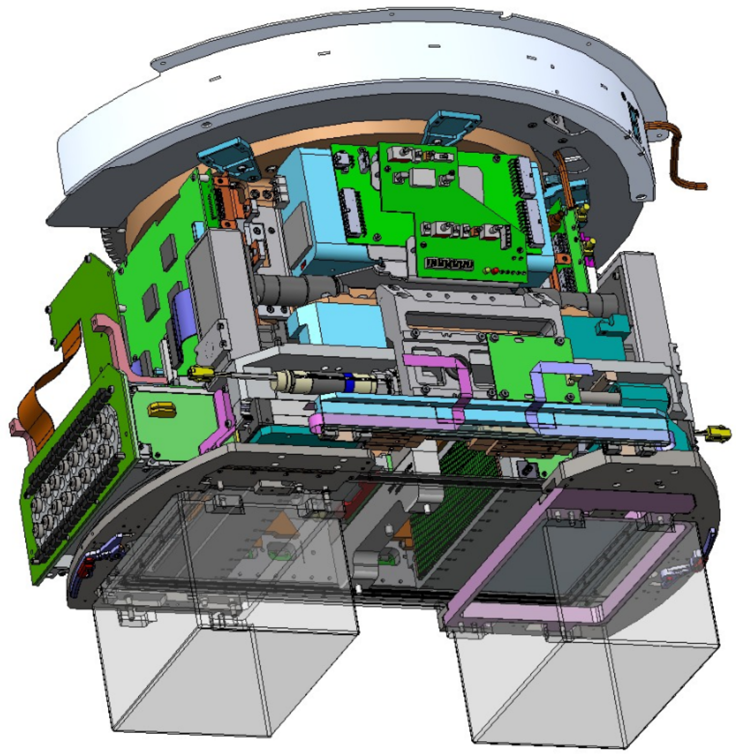
Windows/Gas…

Not efficient to always use small beam !

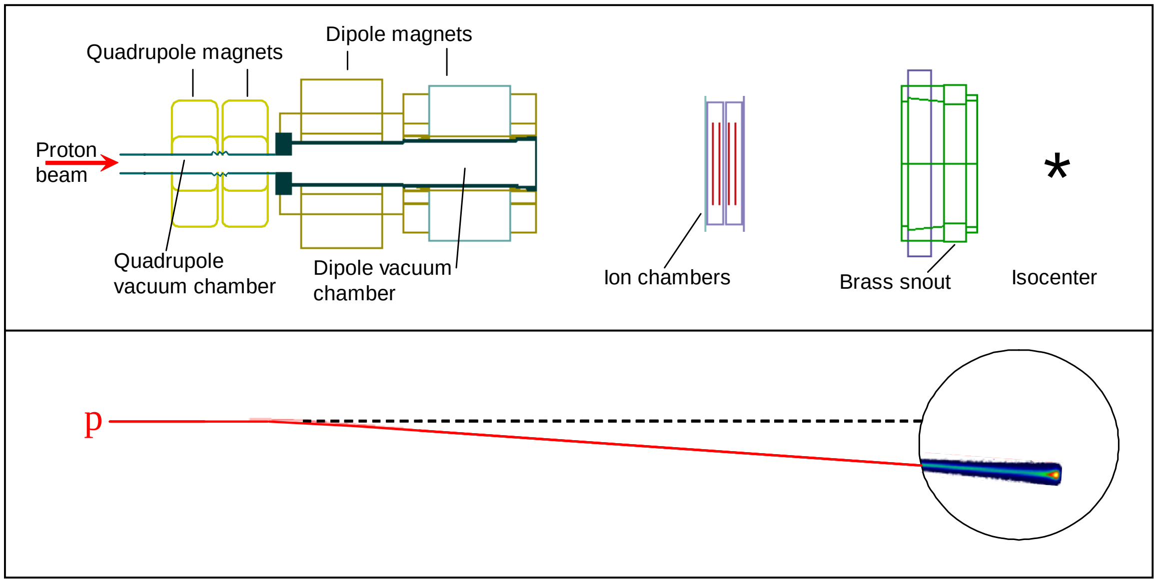
Multi-Leaf Collimator for Protons

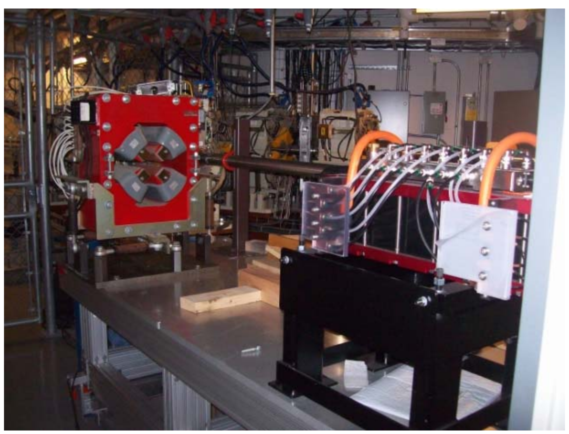
(UPenn/Varian + Sumitomo)

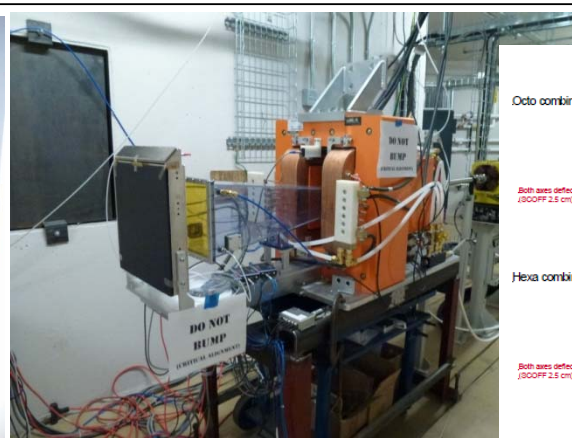




Magnetic Scanning Implementation







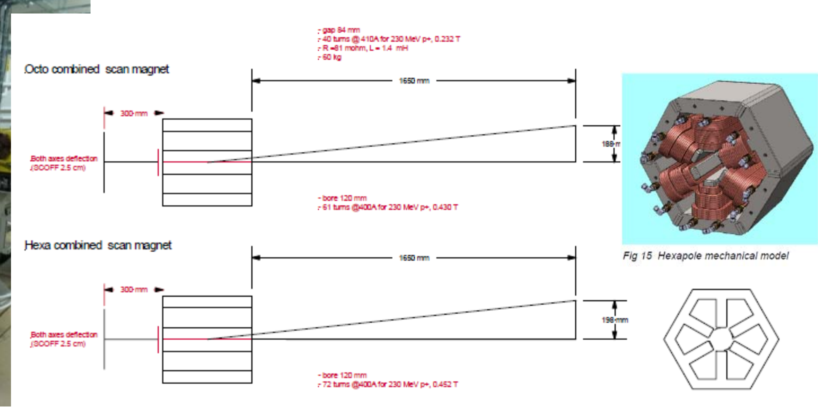
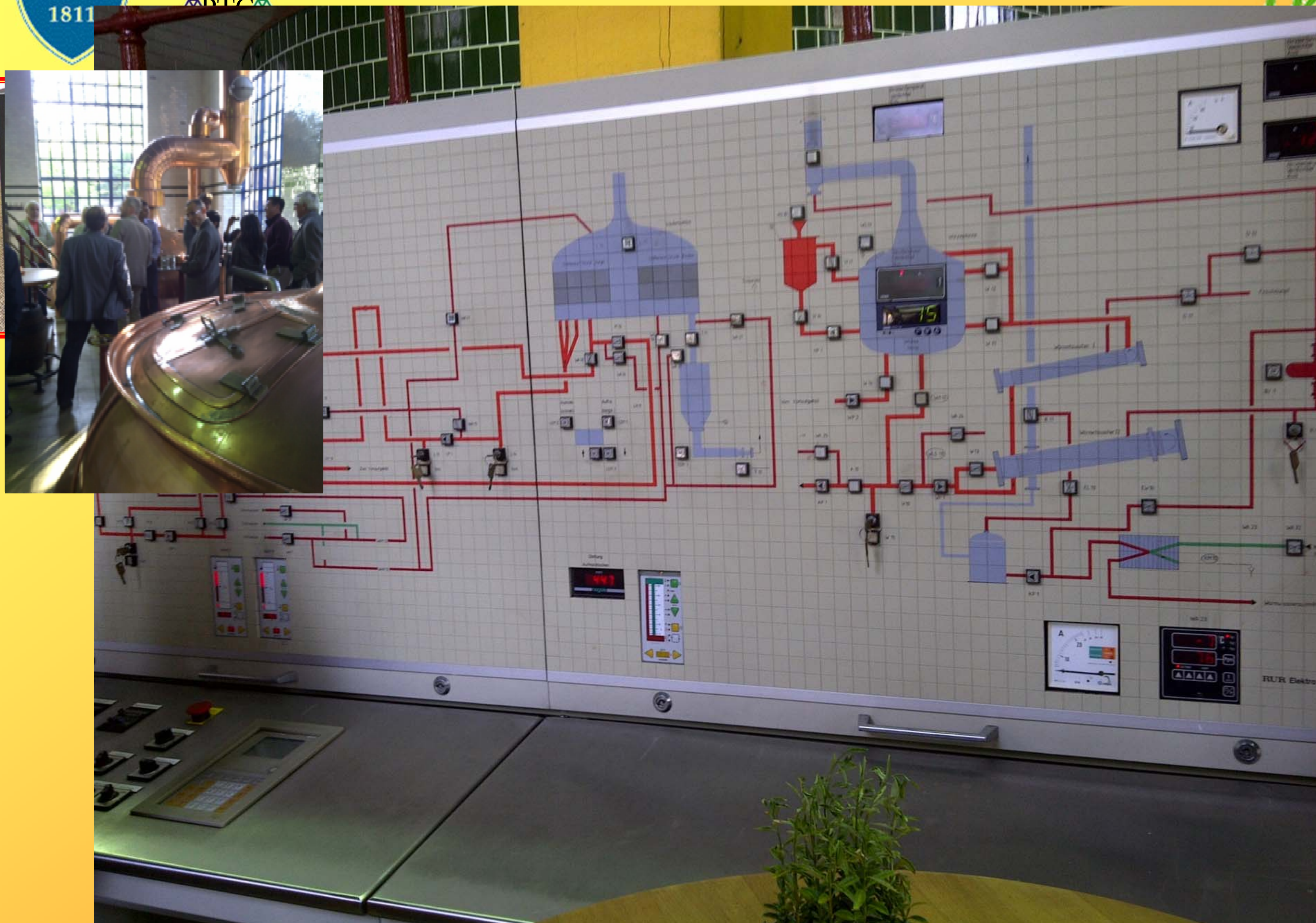


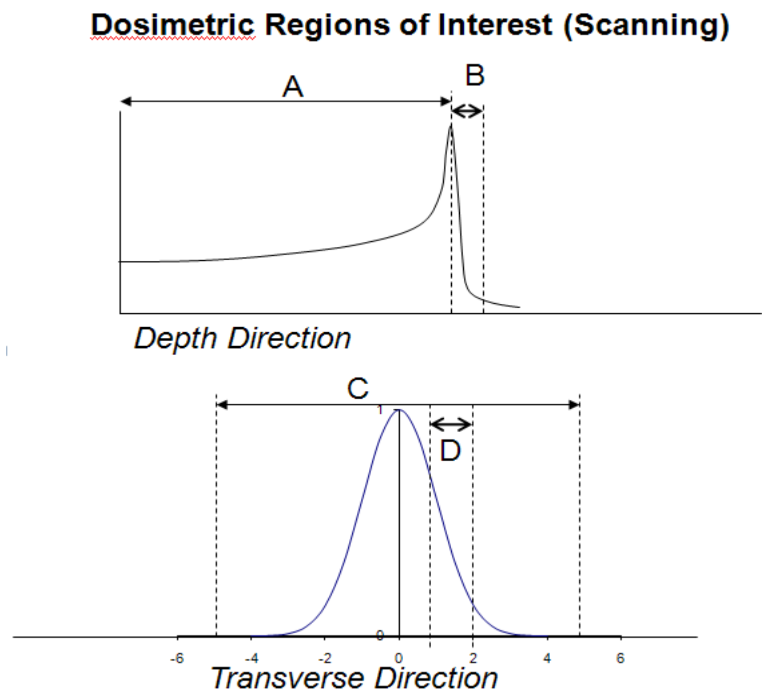
Fig 14 Deflection in multipole magnets combined-function magnet

See Poster Session !

Scanning Controls



Dosimetric Quantities for Scanning



A. Range
B. Distal Fall off
C. Field Size
D. Penumbra

- *Reduce* # fields for a uniform Dose Delivery (Clinical effects?).
- *Reduce* unwanted Dose (e.g. Proximal Primary Dose)
- *Reduce* the need for Patient Specific Equipment
  - Apertures
  - Compensators
- *Reduce* radiation from primary beam intercepting machine components (n)
- *Allow* a non-uniform Dose Delivery

Comparison - Time

Scattering

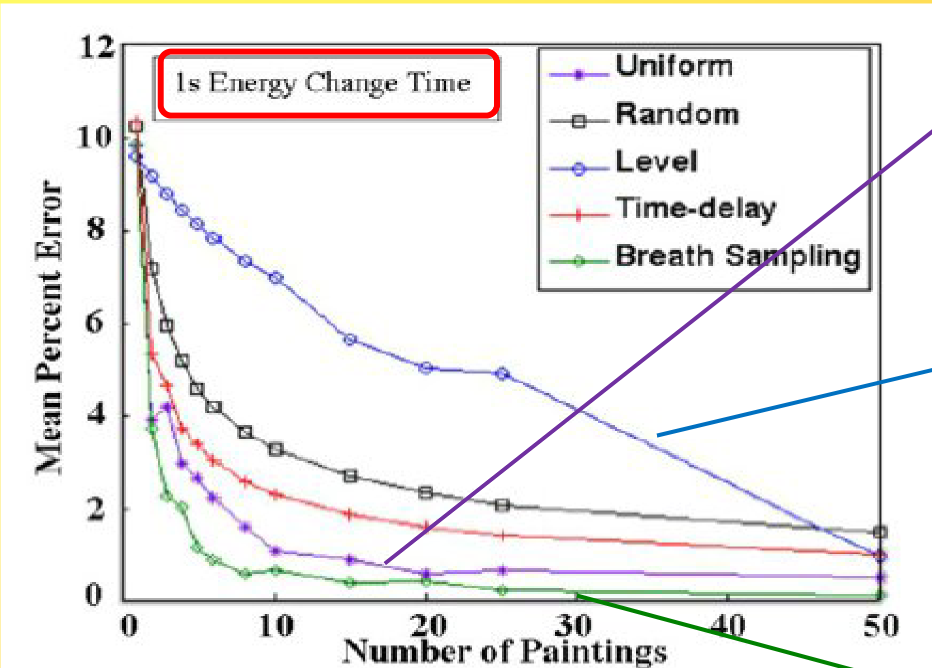
- Time to spread out in depth
  - Ridge Filter - 0
  - Mod Wheel – 0.1sec
  - Layer Stacking (Mechanical)
    - <1sec/layer
  - Energy Change
    - 5 sec to 0.1 sec
- Time to spread out x&y - 0

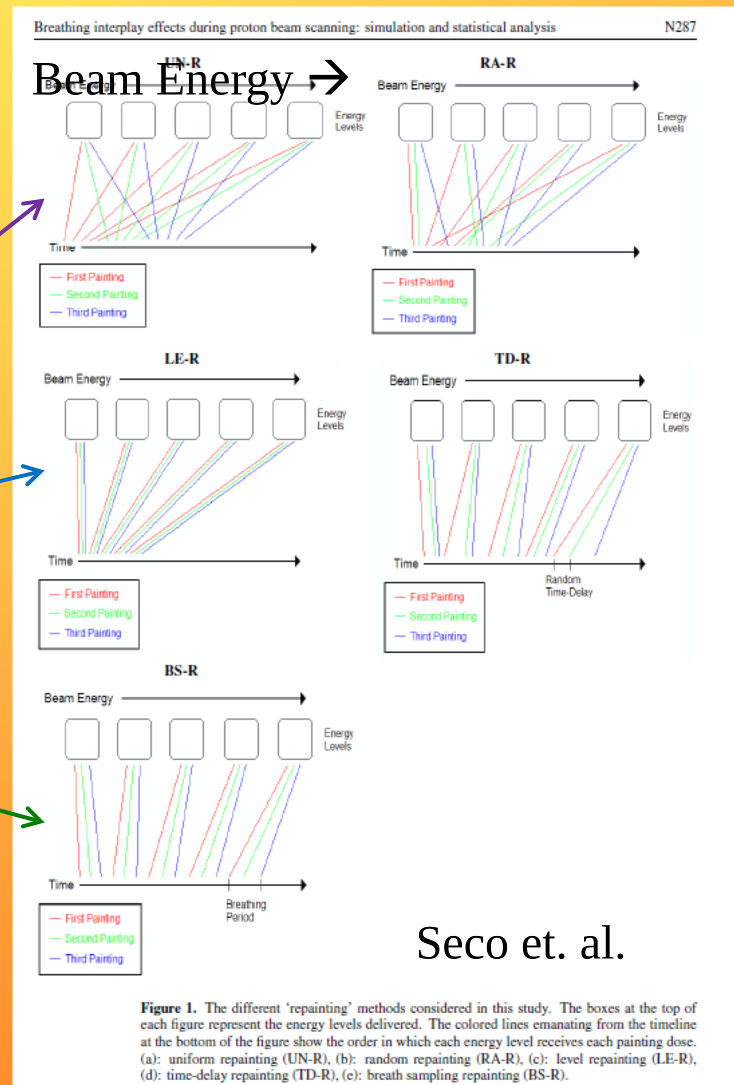
Scanning

- Time to spread out in depth
  - Energy Change
    - 5 sec to 0.1 sec
- Time to spread out x&y
  - Spot scanning vs. Raster
  - Big Spots vs. Little Spots
  - >0.2sec slew time

Time Dependence of Repainting

Repainting helps to average out errors due to timing effects - Later



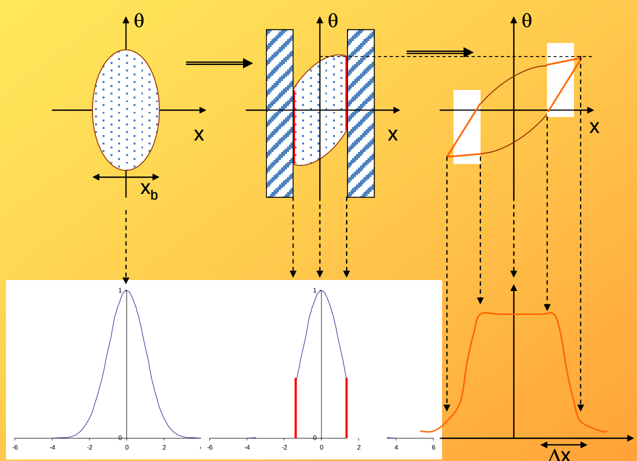


Therefore: Fast repaintings of a layer (e.g. continuous scanning) may not be better than slower. Must redo this for diff dE times!

Comparison - Penumbra

Scattering

- Source Size
  - Single Scattering
  - Double Scattering
- Aperture
  - Must be used
- Distances

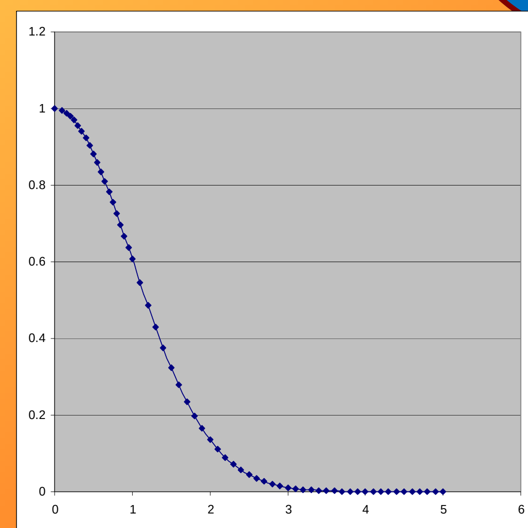


Optical Representation of Collimation

Depends upon Equipment/Hardware !

Scanning

- Beam size = Source Size
  - Energy Change – Size dependence
- Aperture
  - CAN be used
- OTHER parameters…



Depends upon Beam !

Effects of Air gap and Range Shifter

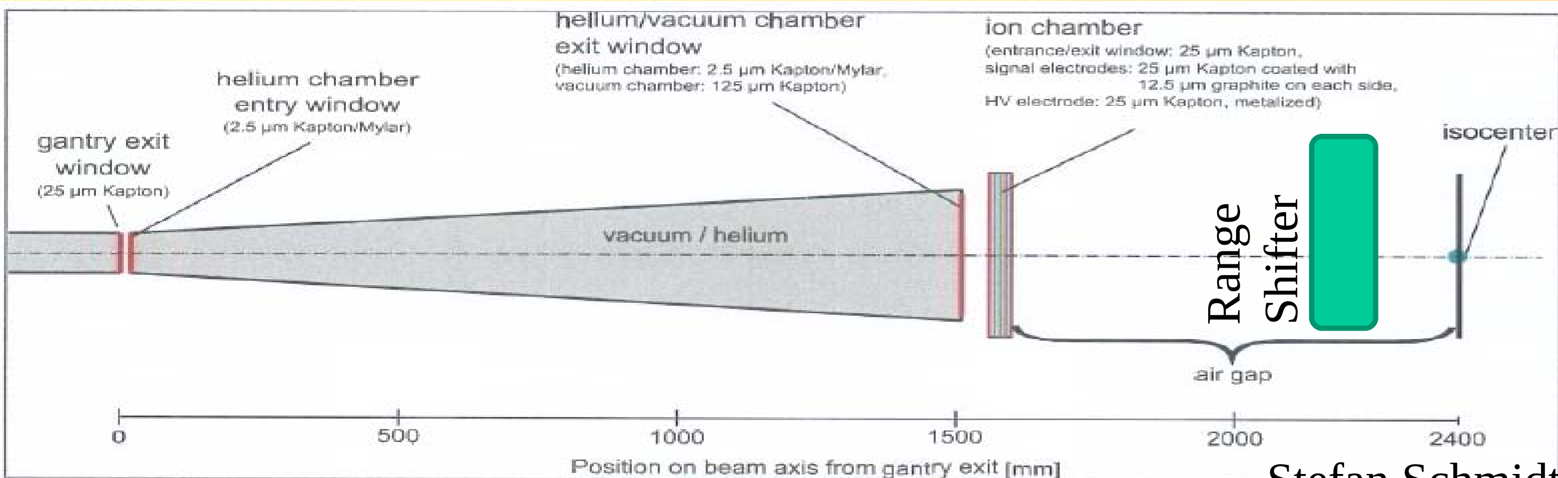


Figure 1: Nozzle geometry

Stefan Schmidt

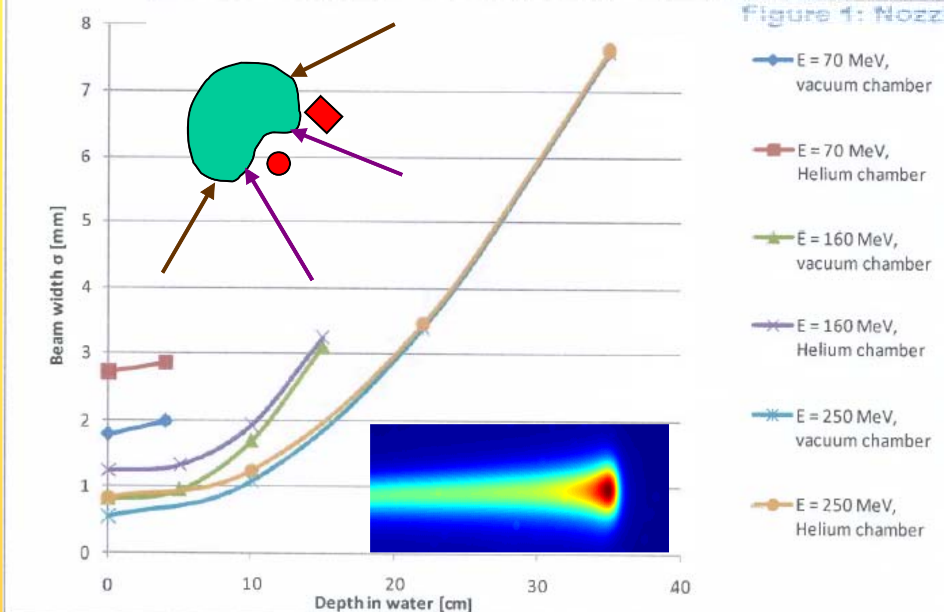
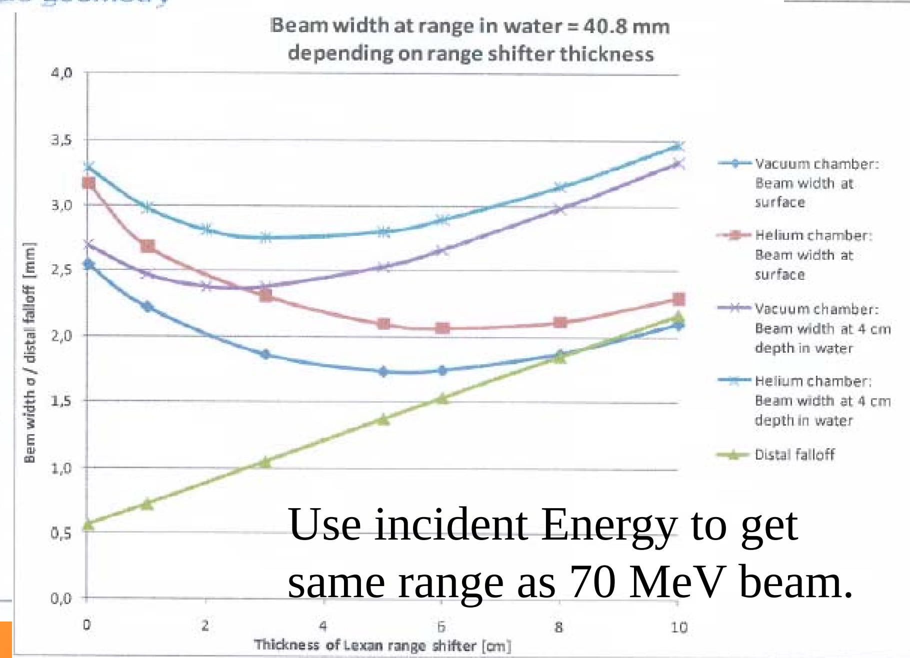


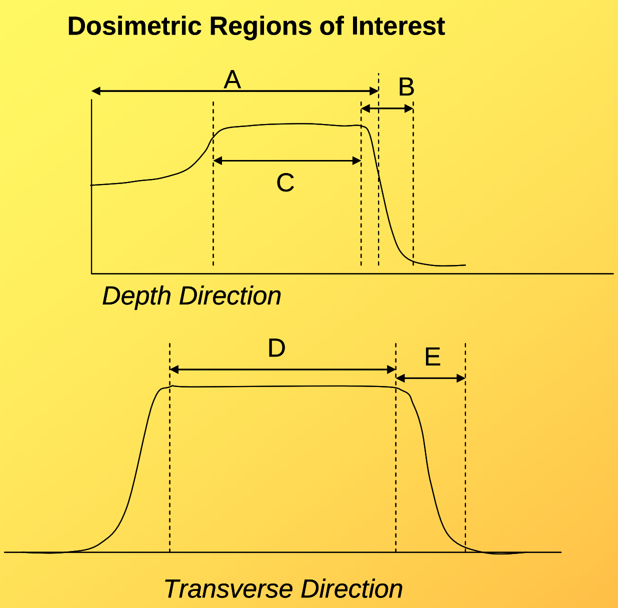
Figure 7: Beam width in water for 80 and 60-cm air gap



Use incident Energy to get same range as 70 MeV beam.

Comparison - QA

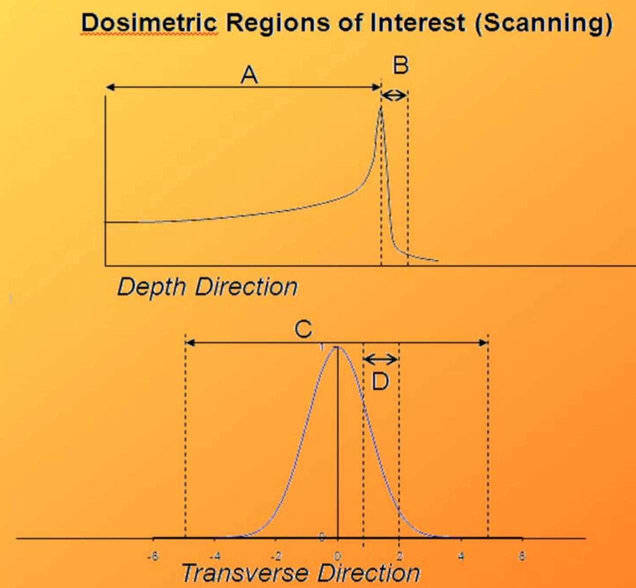
Scattering



A. Range
B. Distal Fall off
C. SOBP Width
D. Lateral Width/Uniformity
E. Penumbra

Depends upon
Equipment/Hardware !

Scanning



A. Range
B. Distal Fall off
C. Field Size
D. Penumbra

Depends upon Beam !

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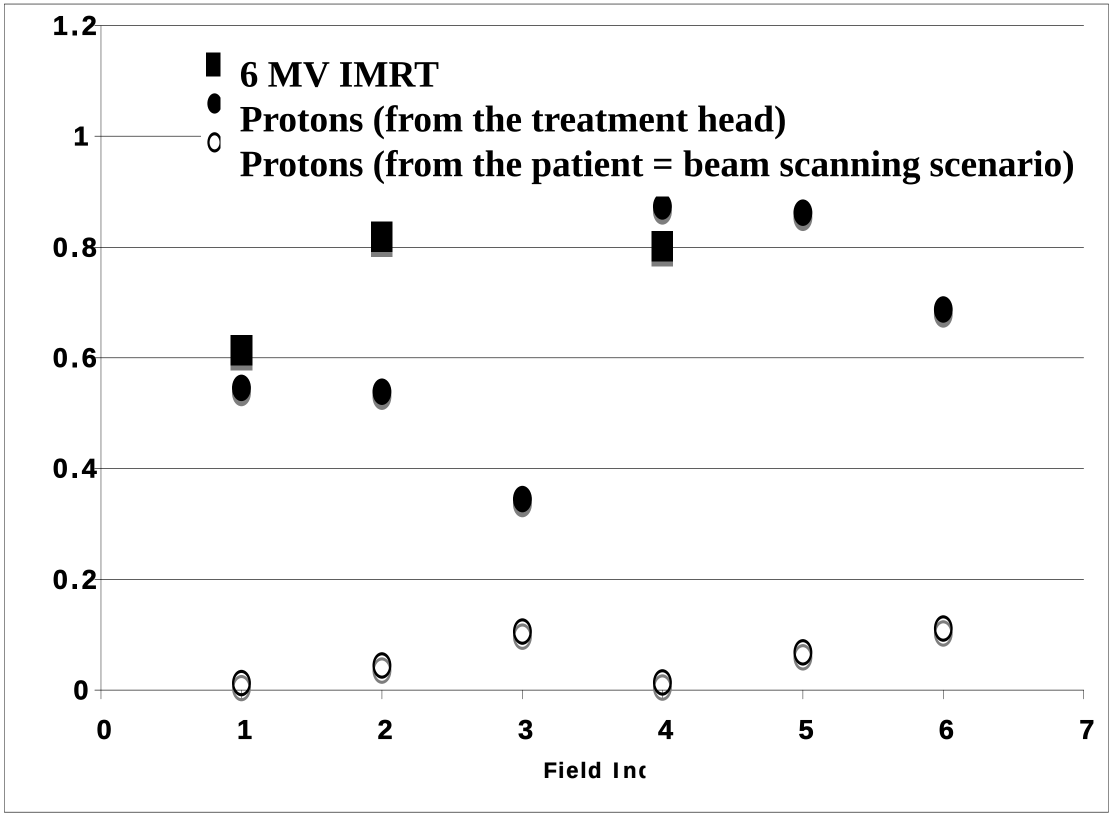
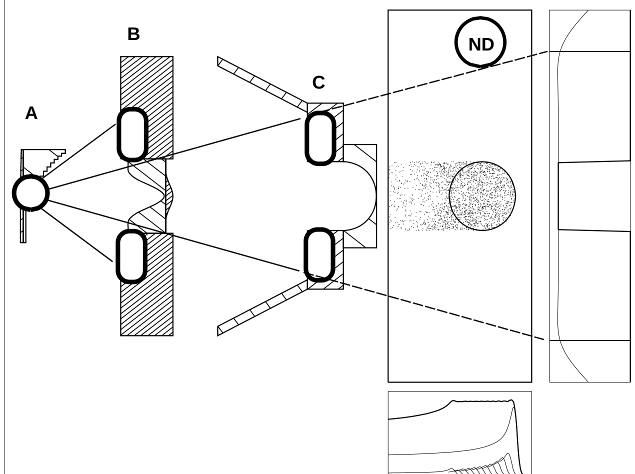
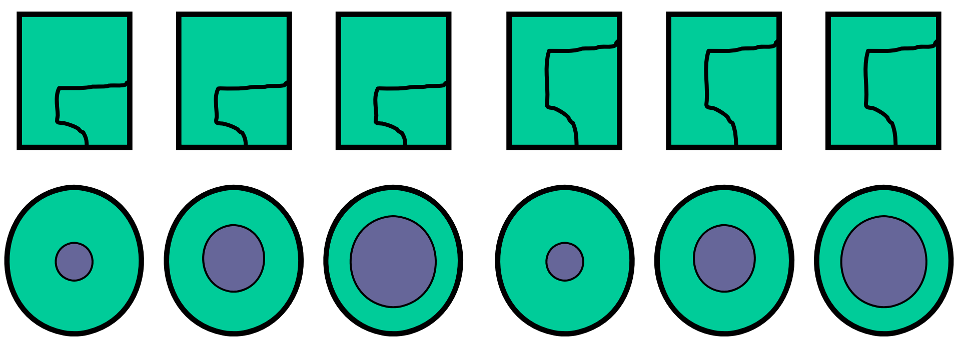
IMRT and proton therapy / spine fields





Gottschalk



Photon and neutron equivalent doses as a function of field index

Paganetti

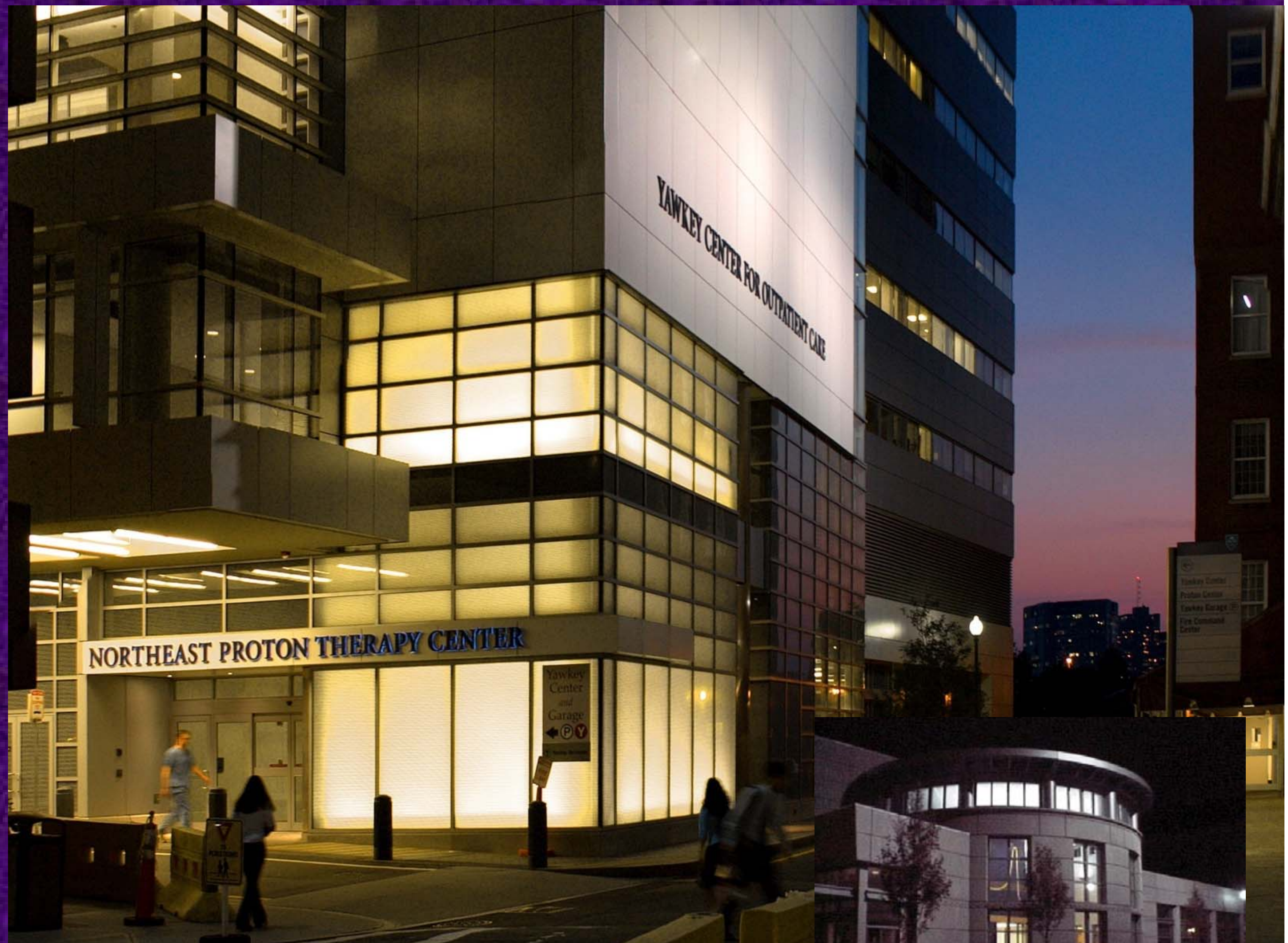
Innovations in Particle Therapy
Enabled by OR Required by Scanning !

- ***Image Guided Therapy (IGRT)***
  - *Need for more accurate alignment*
  - *Possibility to use proton Imaging*
- ***Hypofractionation***
  - *Need better conformality*
- ***Adaptive Therapy***
  - *Image; Re-Plan (Deformable registration); Treat*
    - *No patient specific Equipment*
- ***Organ Motion***
  - *Beam timing; Beam Tracking; Flex-Plan*
- ***End of Range Accuracy***
  - *Use of DET,*
  - *Simpler Plans*
- ***Increased Throughput***
  - *Less patient hardware (Field to field time)*
- ***Lower Cost (vs. Better Parameters)***

Summary

- The basic principles to modify raw beam to deliver a uniform dose to a target, have been described. Basic physical principles of the interaction of ions with matter is the basis of the optimization of these methods.
- Scattering
  - *Sometimes the term "passive" scattering has been misused. Most modern scattering systems require synchronization of the beam with a moving device, either a wheel or paddles. In some cases, the beam current is further modulated.*
  - *Single scattering provides the smallest penumbra, but is very inefficient in terms of beam usage and can result in secondary radiation produced*
  - *Double scattering is more efficient, in some cases up to 40%.*
- Scanning
  - *Scanning has the promise for the most conformal treatment, but is also most sensitive to organ motion.*
  - *Beam scanning is essentially 100% efficient and minimizes the secondary radiation delivered to the patient.*
  - *A scanned beam delivery may provide the most efficient treatment scenario. Deliver multiple fields without entering the room.*
  - *Scanning may not provide the best penumbra . Creating a very small beam is very difficult and expensive and can lead to longer treatment times (under some conditions), and it may be worth considering some cases for which lightweight apertures can produce an advantage.*
  - *There may be some situations in which the use of a range compensator is useful to minimize the beam-on delivery time.*
- Many thousands of patients have been successfully treated using most of these techniques.

The Francis H. Burr Proton Therapy Center



Thank You !