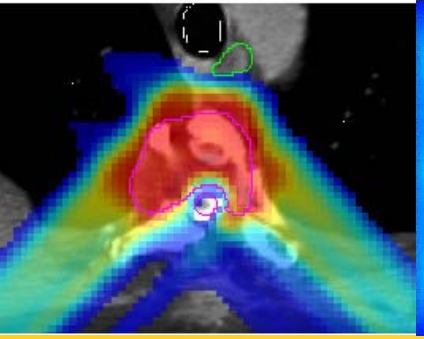
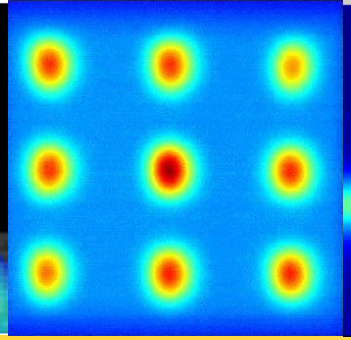
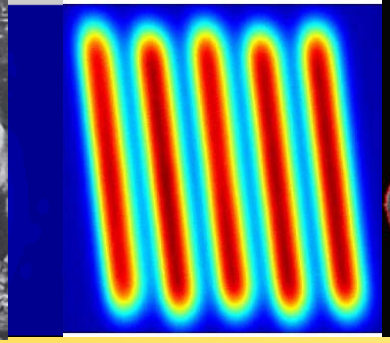
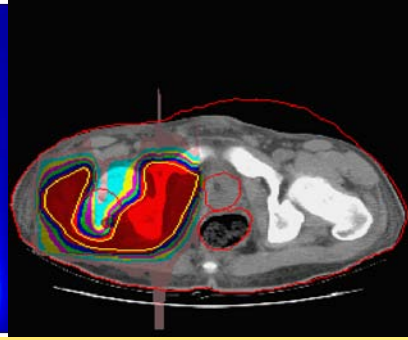



The CERN Accelerator School

Future (of)Synchrotrons for Particle Therapy

Where are we now?

Where do we need to go?

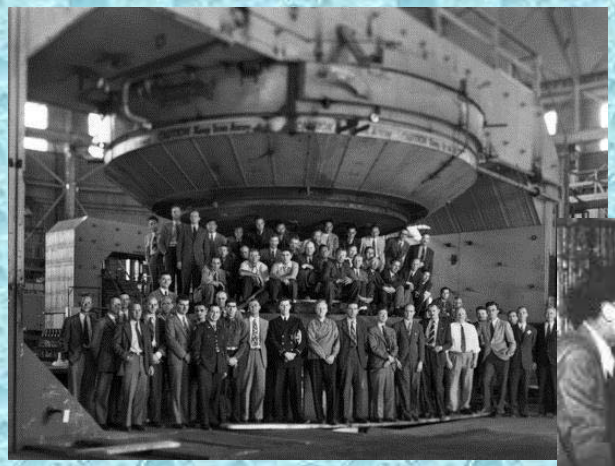
Jay Flanz

Technical Director, Burr Proton Therapy Center

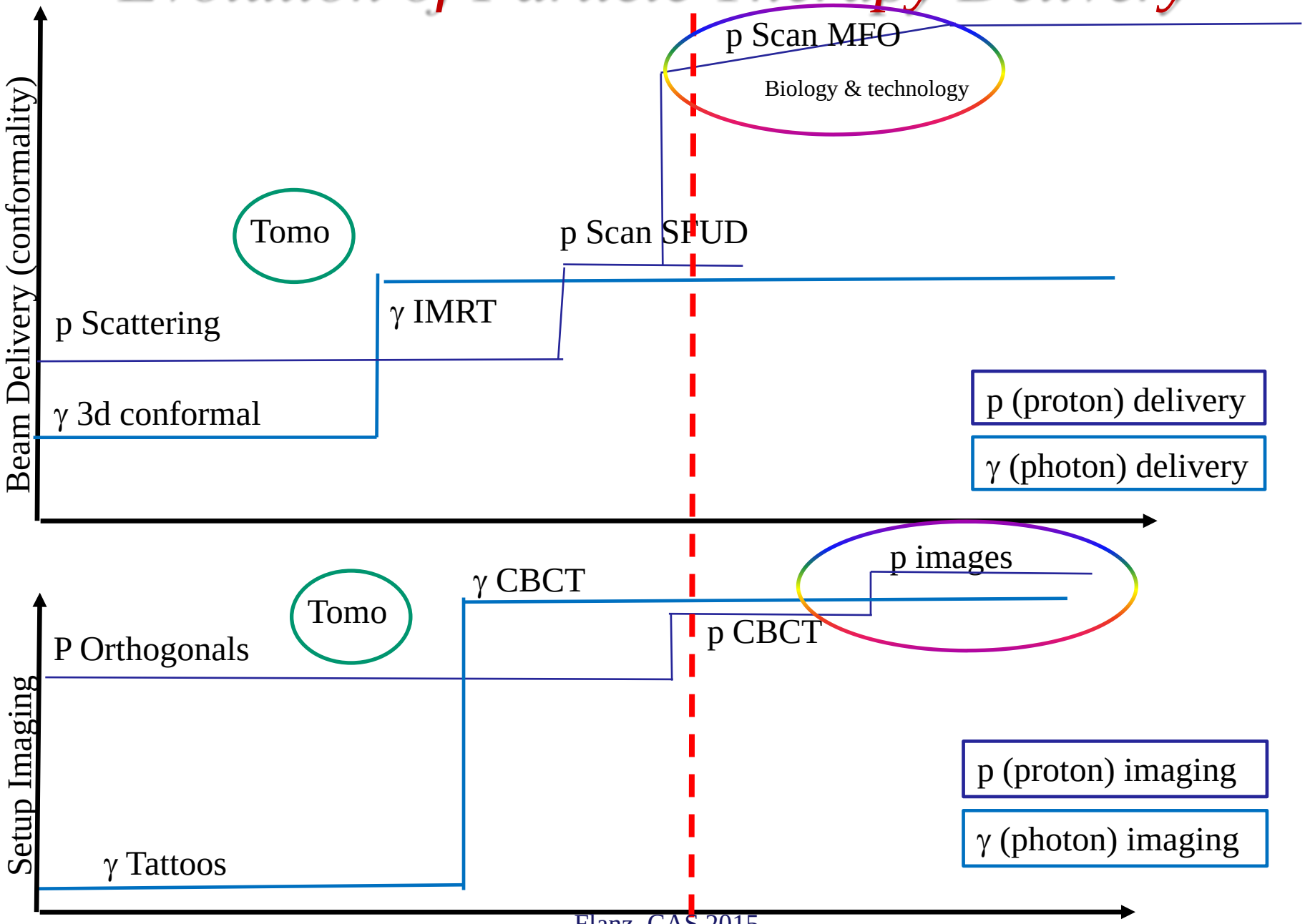
Assoc. Prof. Harvard Medical School

Berkeley: Start of Particle Therapy

184” Cyclotron to the Bevalac



Evolution of Particle Therapy Delivery



New/Ongoing Themes in Particle Therapy:

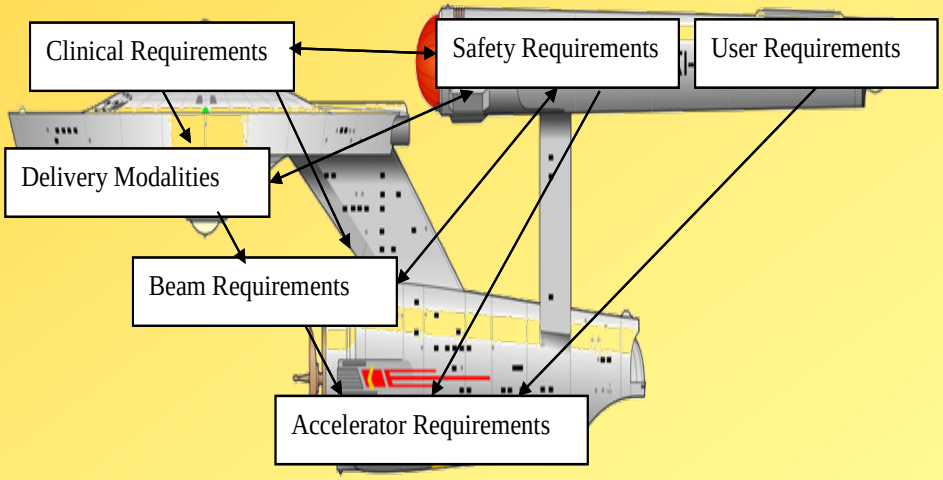
We are now in the 3rd Generation of Particle Therapy.
What does that mean? Size – Cost - Quality

1. *Beam Scanning (Pencil or Crayon) (PBS)*
   - Impact on: Beam Parameters from Accelerator + Delivery
     - Scanning "type"; Beam Size; etc.
2. *Image Guided Therapy (IGRT)*
   - Impact on: Imaging; Beam Alignment
     - e.g. PROTON Radiography/Tomography
3. *Organ Motion*
   - Impact on: Beam Parameter timing; Beam Tracking; Dose Rate
4. *Adaptive Radiotherapy*
5. *End of Range* ® - Proton Range vs. HU vs. Target du jour?
   - Detect Range relative to target and correct
6. *Field Directions*(θ,φ,ψ): How to treat specific sites?
7. *IONS: Designer Treatments with Radiobiology and multiple LETs*
8. *Increased Throughput*
   - Positioning, Aligning (IGRT), Field-to-field time, Irradiation time
9. *Lower Capital Costs \$\$\$*

Flow of System Requirements to the Accelerator

Goals of Radiotherapy

- Deliver the required dose
- Deliver that dose with the prescribed dose distribution, and
- Deliver that dose in the right place



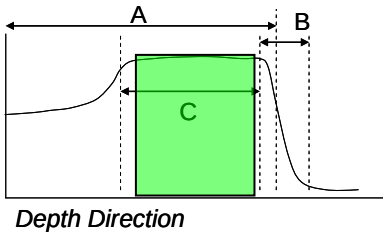
Clinical Parameter	Clinical Value	Beam Value	Accelerator Parameter
Dose Rate	1Gy/Liter/min	~100x10^9 protons/min	Beam Current
Range	32 cm (in water)	226.2 MeV	Beam Energy
Scan Beam Penumbra	80% to 20% fall off = 3.4mm	3mm sigma ($e^{-1/2}$) of a Gaussian beam)	Beam size, beam emittance

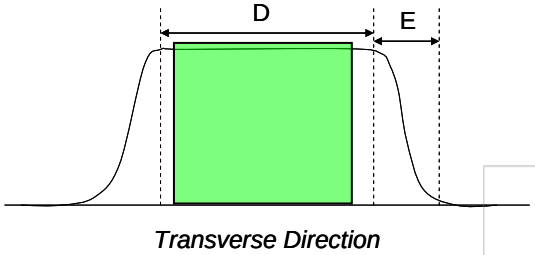
But specific 'parameter' solutions are BAD. Need System solutions for a real issue.

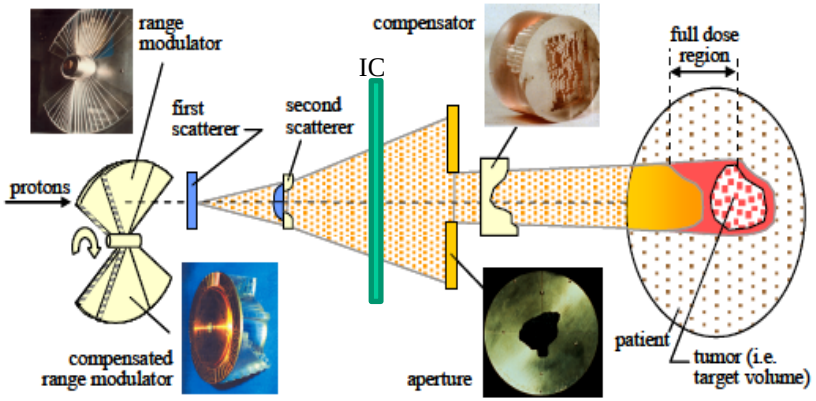
Scatter & Scan Differences

(Scattering)

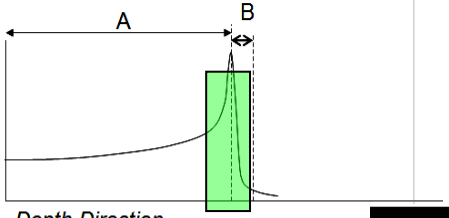
Dosimetric Regions of Interest

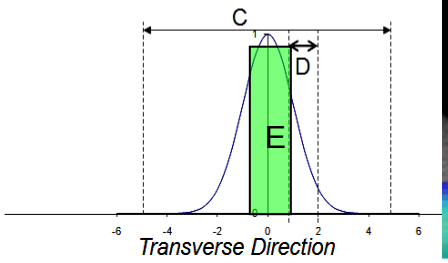


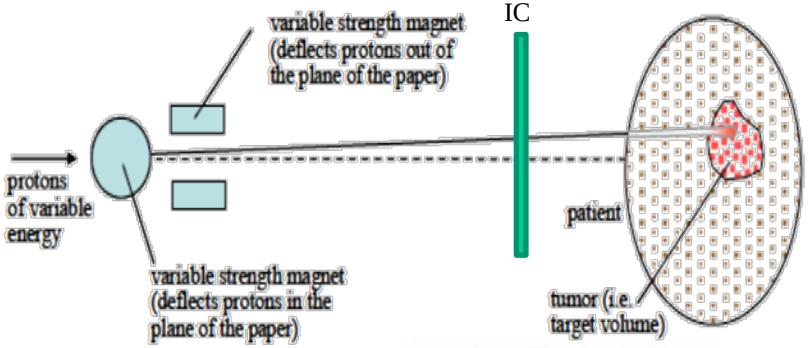


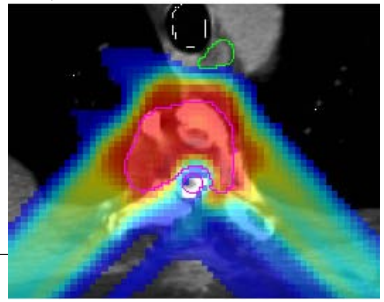


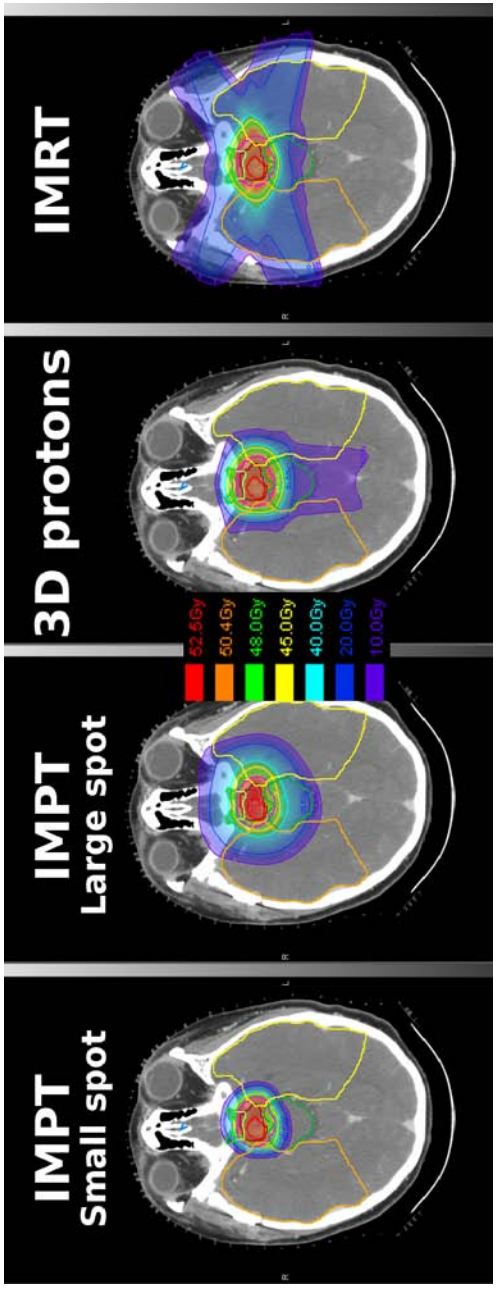
Dosimetric Regions of Interest (Scanning)



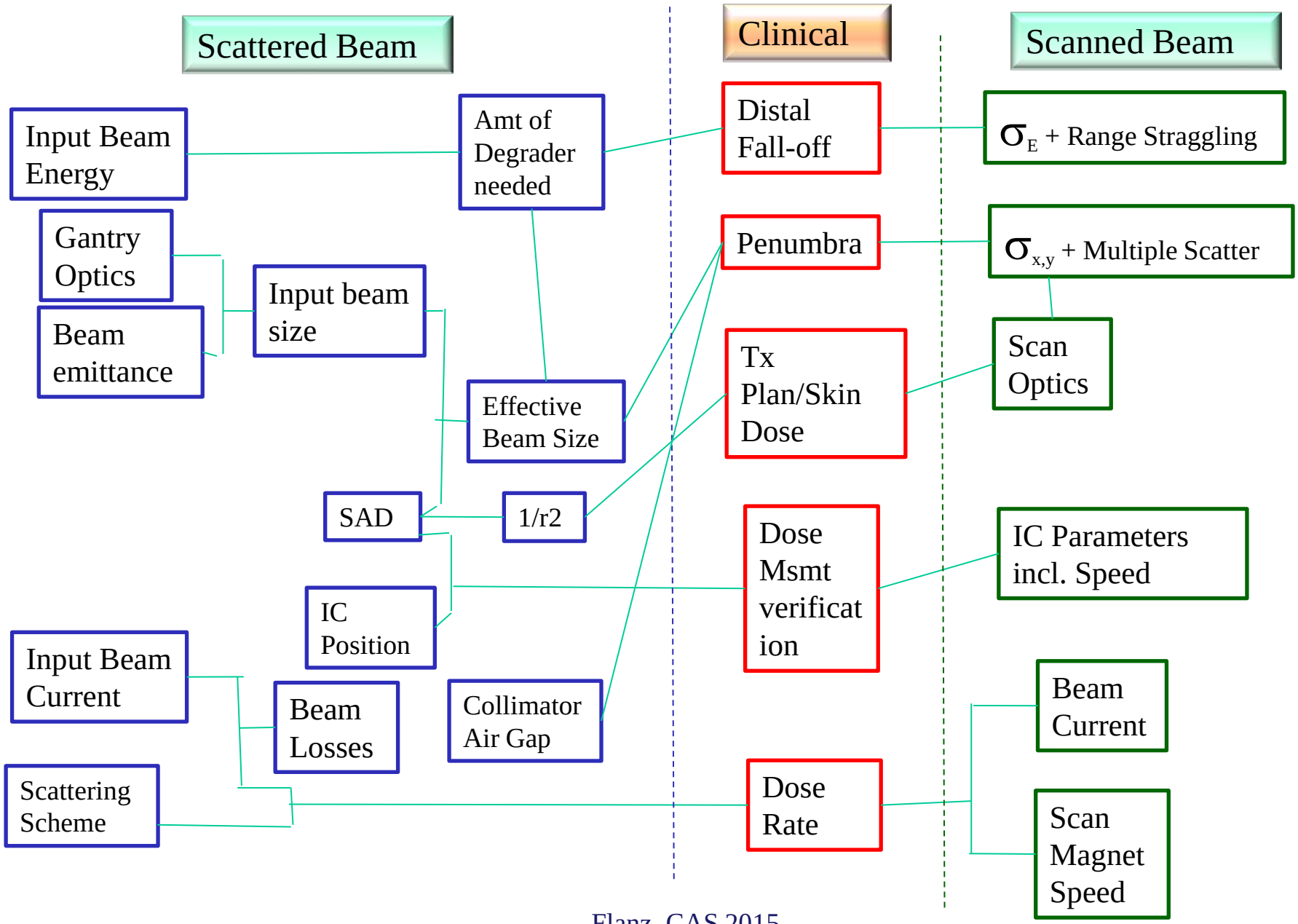






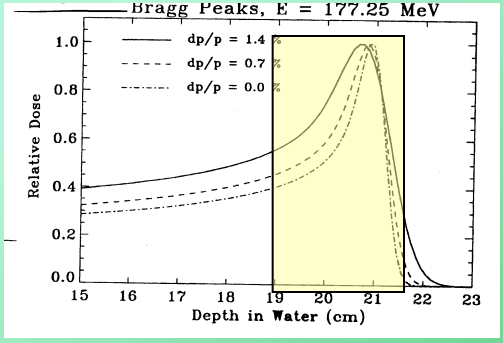


Clinical Parameter Dependences



Dose / Dose Rate (assume 1min?)

- Power = Joules/sec = Energy * Current
  - e.g. → 150 MeV * 1 nA = *0.15 Watts*
- Dose = Joules/kg ≡ Gray (Gy)
  - Dose = (Power* seconds) /kg
  - e.g. → 150 MeV * 1 nA * **60 sec** = *9 Joules*
- Water → 1kg/1000cc = 1kg/liter
- Dose = 9 Joules /1kg (in a liter) = 9Gy
- ➔ 150 MeV, 1nA == 9 Gy in 1 liter in **1 minute**
- But not all energy goes into the target (see Bragg peak)→ *3-6 Gy in 1 liter in 1 minute*



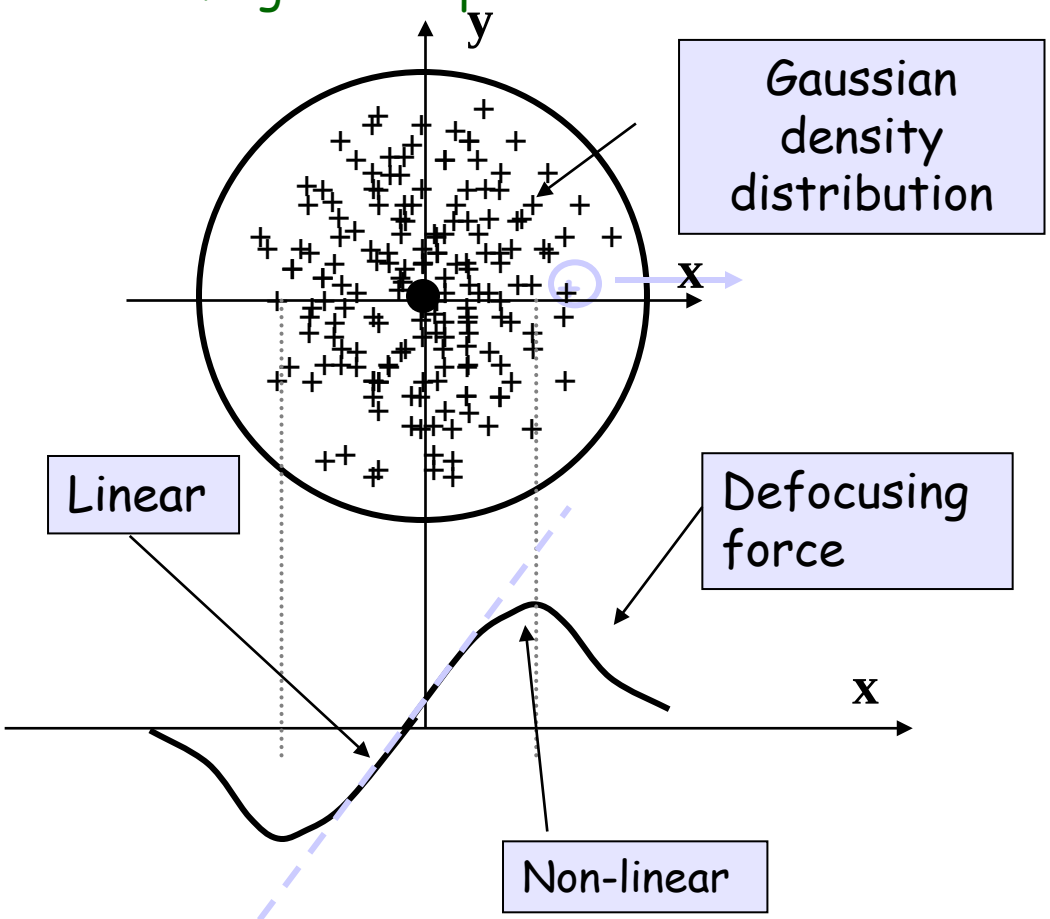
- *1nA in **60 seconds** ⇒ 60 x 10^{-9} coul ⇒ 3.7x10^{11} protons for 3Gy*
- *Therefore, for 1Gy in 1 liter we need ~ 120 GigaProtons (1.2x10^{11})*
  - *(120 GP/**min** ➔ ~ 0.3nA (averaged over a minute, but synchrotrons are cyclic…))*

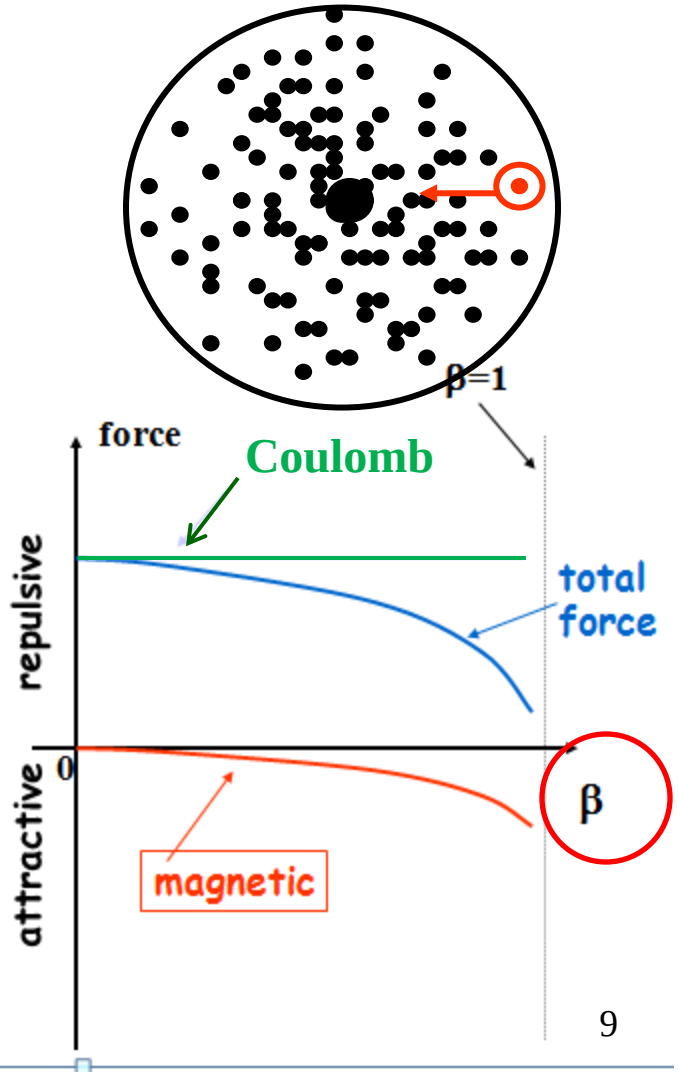
Accelerator Physics: Space Charge effects

How many protons can be stuffed into a Ring?

Charges ⇒ repulsion

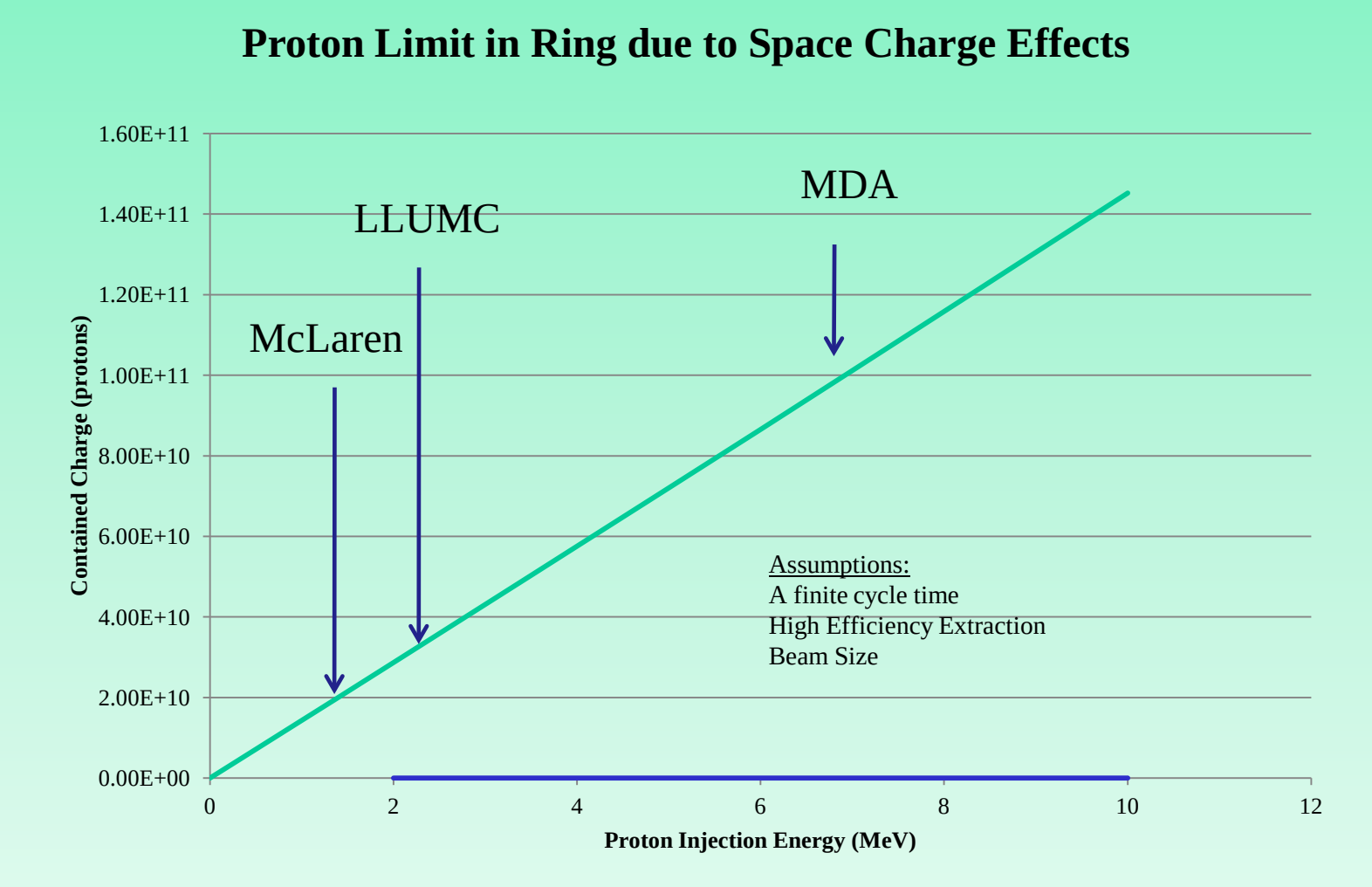
Parallel currents ⇒ attractive





How many protons can be stuffed in a ring?

How many are needed?



*Also 1Gy/**min** in a liter ➔ 120GigaProtons/**min** ➔ <4Gp/cycle (2 sec cycle)*

4Gp = $4x10^9$protons

Beam Current Issues

- Current needed (standard fractionation / 1minute Tx)
  - Scattering: nAs (tens or hundreds)
  - Scanning: tenths of nAs
- Hypofractionation
  - e.g. 2 Gy/min or 10 Gy/min or more
- Fraction delivered in time < motion (1sec?)
  - e.g. <1sec ⇒ Earlier current numbers x 60 ?
    - 0.3nA x 60 = 18nA ?? – NO !
  - $2x10^{10}$ ⇒ 120Gp in 12sec ⇒ *1.5nA*
    - Time limitation is dE or dx NOT nA in **SCANNING**
    - 1sec ⇒ 30msec/layer Total (assume 30 layers)
  - How to change energy very fast
    - Scattered beam delivery
    - e.g. RCS (Rapid Cycling Synchrotron)
    - or What if ALL charge in only ONE fill can be used
    - OR Just a few spills, but each layer fast AND synchronized (with motion)
- $? Cost of Charge in Ring

- Speed/Validity of Instrumentation
  - Spot
  - Continuous
  - Recombination/Linearity
- Dose Accuracy
  - Turn off the beam
  - Beam ‘reliability’
  - Beam Position

Acceleration process is cyclical
- There is a time dependence
  - It takes TIME to accelerate

What is Particle Beam Scanning (PBS)?

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

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.

Position (x,y)

Speed (v_x,v_y)

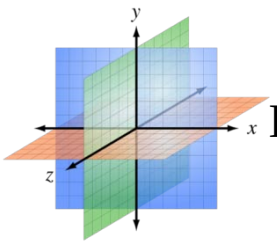
Energy (E)

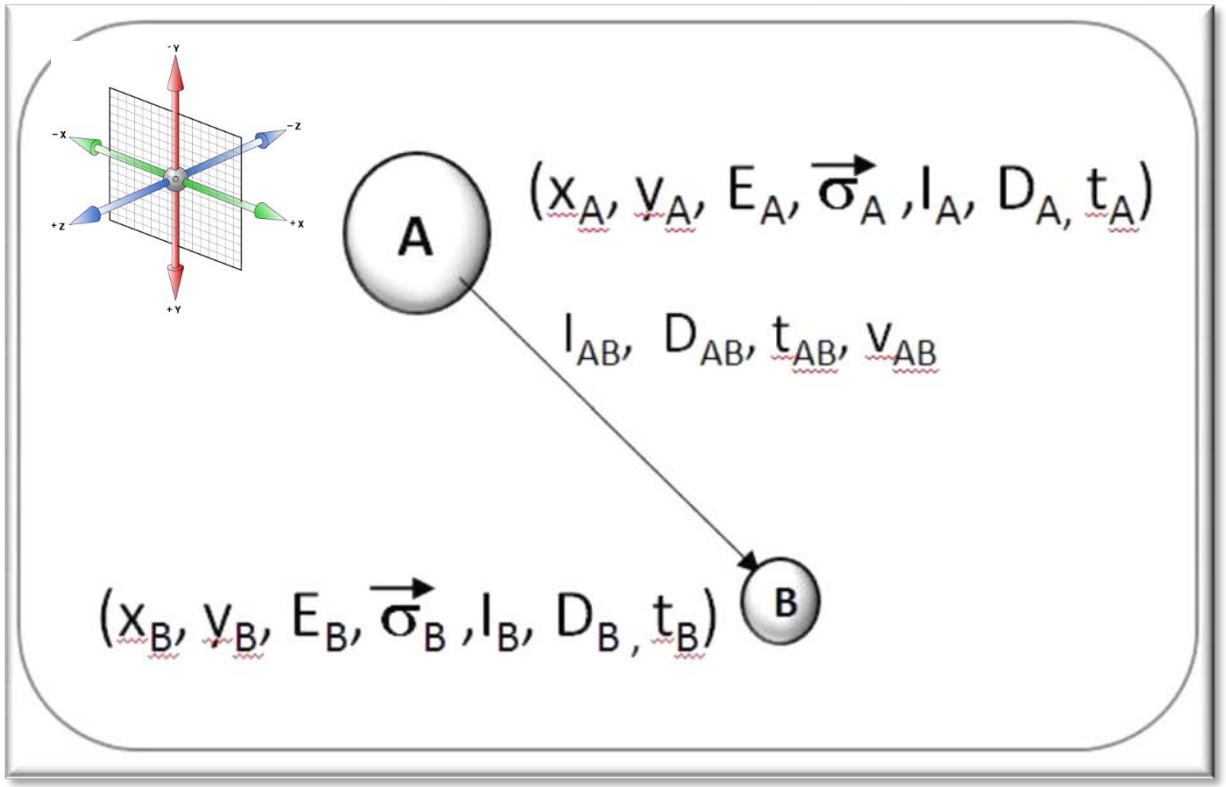
Time (t)

Intensity (I)

Size(σ)

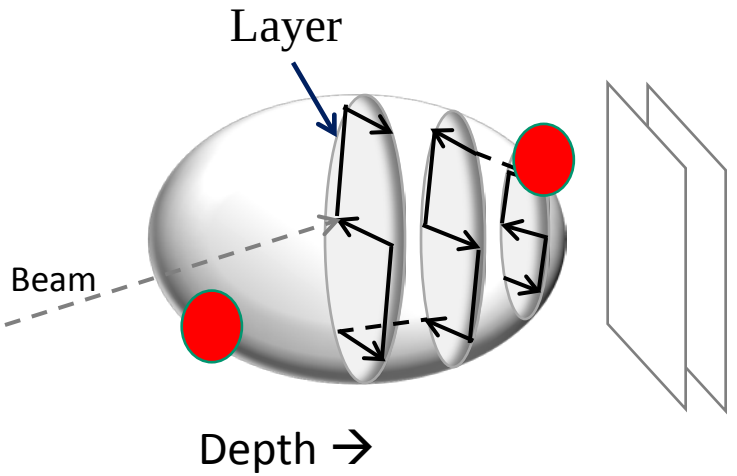
Dose (D)



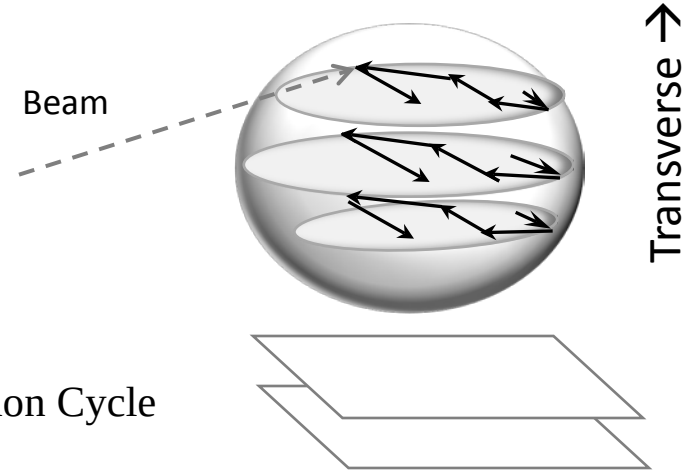


Scanning: spread out the beam (4-5d)

- Control the beam position transversely and in depth.
- Trajectory Optimization depends upon the many factors (e.g. speed…).
- At present, the Energy (Range) Change time is longer (e.g. 5 sec to 0.1sec (PSI)) vs. milliseconds (seconds) 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
  - ***0.03sec x 25 Layers = 0.75 seconds***
    - Organ motion ??



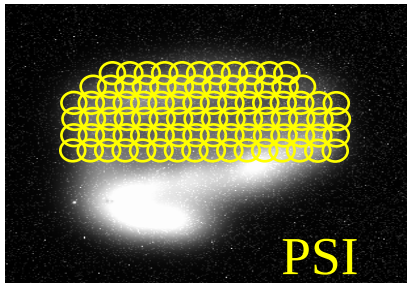
Two extreme examples

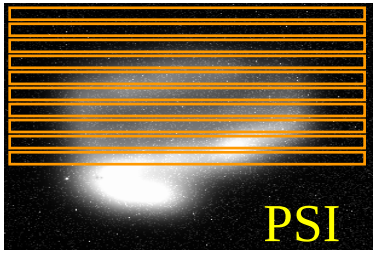


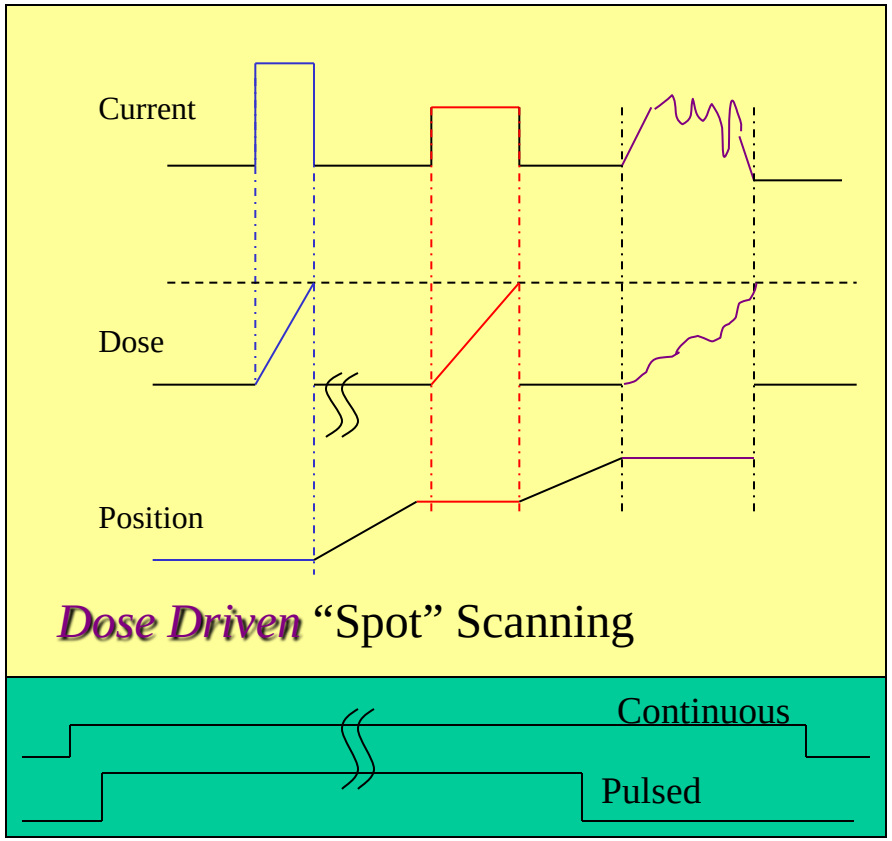
Transverse Conformity, Width, Transverse Fall-off

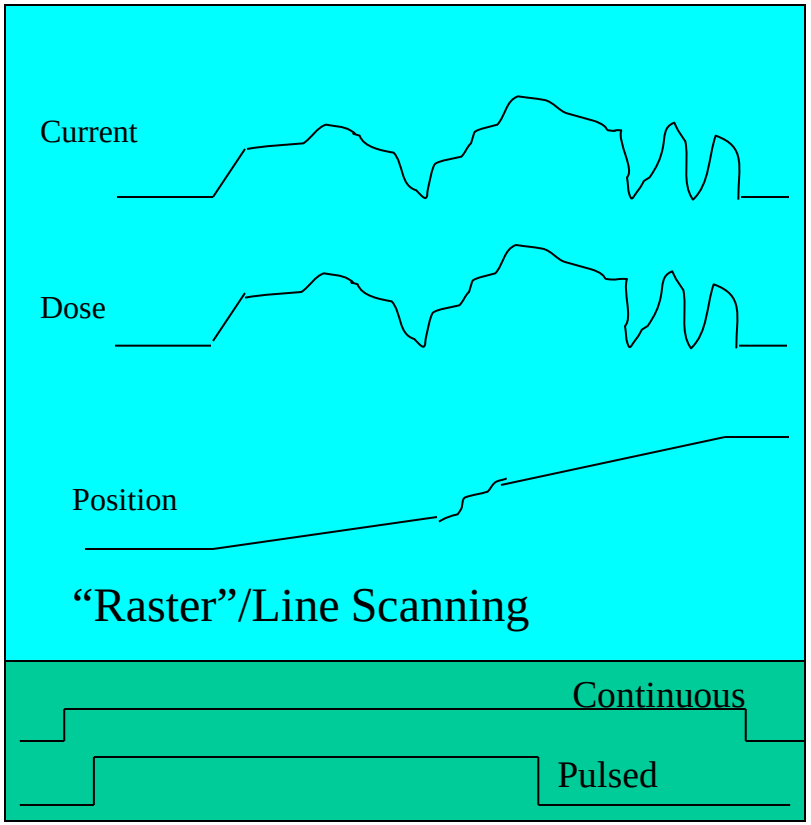
Longitudinal Conformity, Width Distal Fall-off

Time Structure in Pencil Beam Scanning









Continuous Stable/Unstable. Pulsed Short or Long

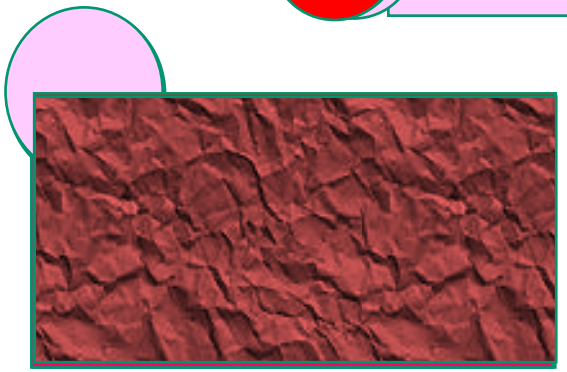
Scanning: Timing & Transverse Dose Distribution

- Dose Driven Scanning: *Dose at a spot determines what to do next (not time).*
  - 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

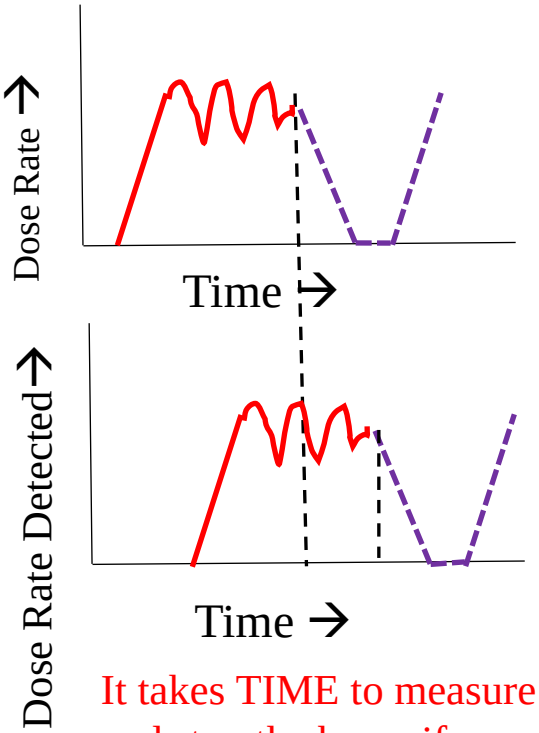
Raster

Continuous



Many Spots = Anything ?

Continuous:
Dose distribution sensitive to Dose Rate (Time dependent)

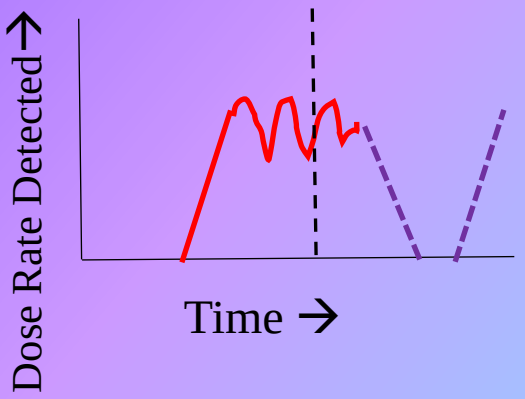


It takes TIME to measure and stop the beam if something is wrong. ➔ Dose Rate LIMIT

Transverse Conformity Width, Transverse Fall-off

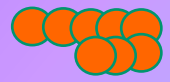
Turn off time effects…

- Dose smoothness/stability/predictability
  - Contributions to turn-off delay
    - Detection
    - Calculation
    - Beam Reaction
      - Excitation (Rf KO or resonance)
      - Closed Orbit Bump?



  - Uncertainty of Dose (smoothness of extraction)
    - Spot scan – dose accuracy questions
      - Is beam current and turn-off time predictable?
        - » do you believe it and check after?
      - High dose region vs. Low(er) dose region (e.g. dose modulation)
        - » % tolerance depending upon relative weight of spot
        - » (MGH separate code for error tolerance/spot)
    - Continuous – Position Accuracy & Dose Accuracy

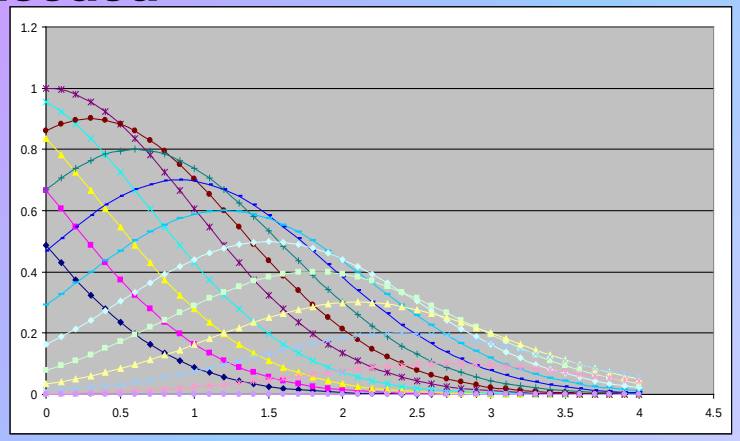
Some numbers …

- Deliver 100 Gp for desired total dose
- ≈ 40% in distal layer (if SOBP like) = 40Gp
  - Want 2% accuracy ⇒ within $8x10^8$ p
  - Assume 10cm x 10cm with 5mm beam spot 
    - 20x20 spots = 400 spots ⇒ 8 x 10^8 / 400 per spot
      - = 2 x 10^6 protons = TOLERANCE
  - If it takes 100usec to respond (TOTAL) *(Some places longer)*
    - 2 x 10^6 protons / 100 usec = 3.2 na ($1.6x10^{19}$ coul/p; 1A=coul/sec)
    - Or if ±100% current uncertainty ⇒ 1.6nA MAXIMUM current
      - vs. 0.3nA earlier for 1min Tx, vs. 1.5nA - vailable from the lowest current synchrotron discussed earlier
  - Note if $1x10^{10}$ per spill ⇒ ~1sec to use up protons (but MORE than one layers worth of protons AND too fast for instruments)
- If faster detection/turnoff…

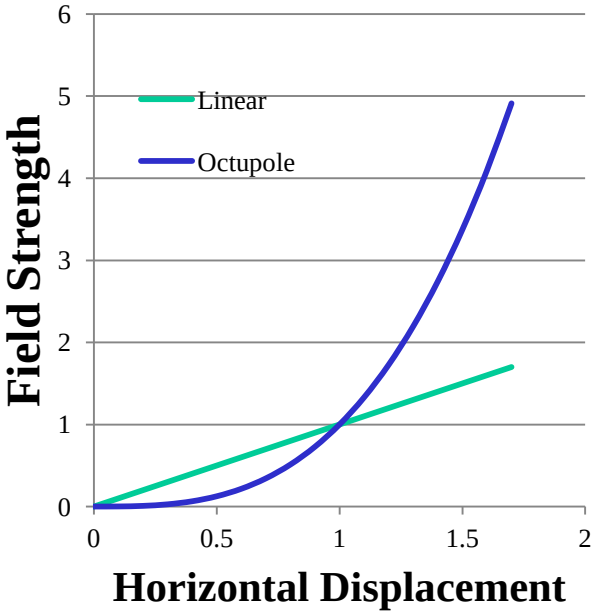
Some more numbers …

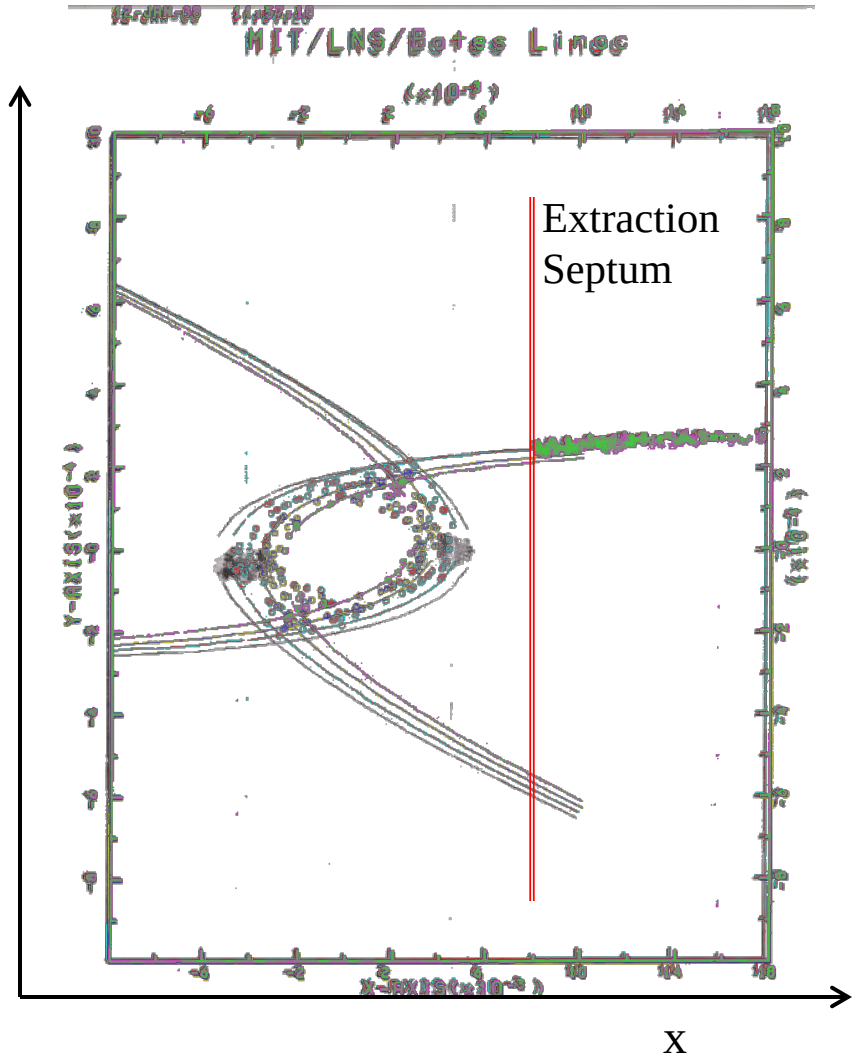
Moving beam

- 30 Hz @ 30cm
  - 33msec period or 16.5msec for 30cm
    - 18,000 mm/sec (Across meeting room in 1 second)
  - If 100usec turn off time
    - Beam will move 1.8mm (36% of 5mm beam) Too big
      - Or Maybe it is just a Penumbra increase – depends how much
    - Need about 50usec (for 30Hz) (TOTAL!!)
    - If 100Hz then 17usec timing is needed
  - Change Beam Intensity?
    - ~ beam size sigma
    - ⇒ 100usec (1.8mm) for 30Hz



Resonant Extraction (one method)





- The process is partly stochastic (uncorrected time structure is not smooth)and
- The extracted beam phase space is NOT Gaussian in the extraction plane (depending on the type of extraction).

SIMULATIONS OF HALF AND THIRD INTEGER RESONANT EXTRACTION FROM A ONE-GEV PULSE STRETCHER RING

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MIT-Bates Accelerator Center
Middleton, MA 01949-2846 USA

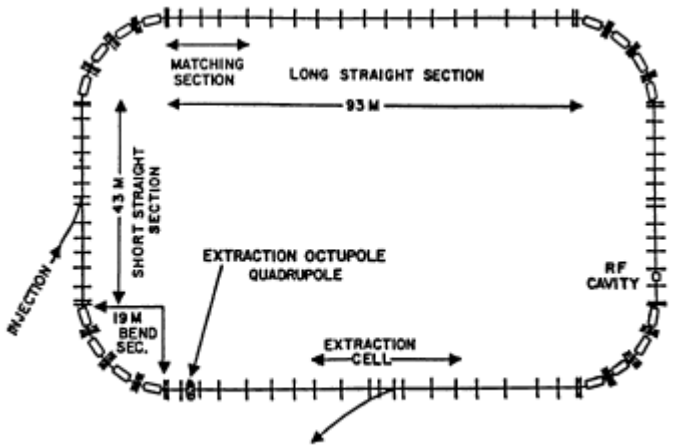
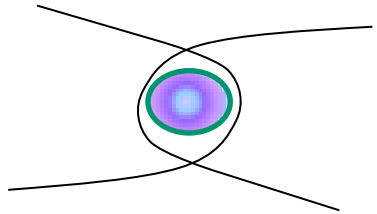


Figure 1. Layout of PSR components

Note the spiral effect and gaps evident near the fixed point vertices. This results from the tune dependence of a particle's position in phase space. The resulting output intensity is shown in Figure 4. The time structure is due to the time it takes for a particle in phase space to travel to the fixed point, or roughly $1/(2\Delta Q)$ turns.

In order to optimize the resulting duty factor, it is beneficial to introduce an additional tune spread in the beam, in such a way as to not increase the non-linearity of the extraction process. A useful method is to use the energy spread in the beam and couple it with a finite chromaticity producing a tune spread. With this technique, the output time dependence improves.



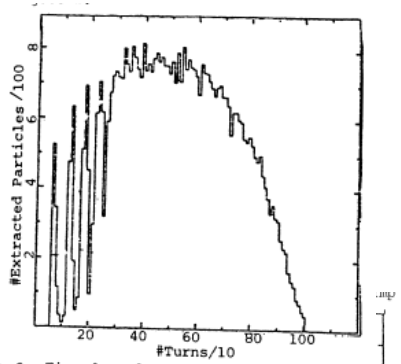


Fig. 2. Time dependence of Extracted Beam

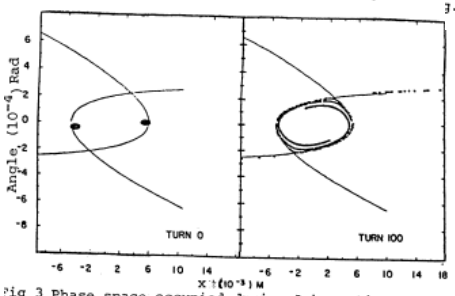


Fig 3 Phase space occupied during Achromatic Extraction

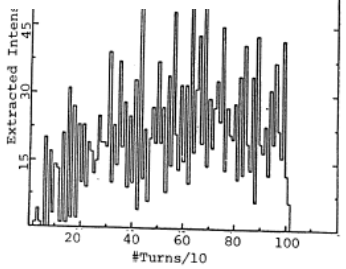


Fig. 4. Time dependence of Extracted Beam

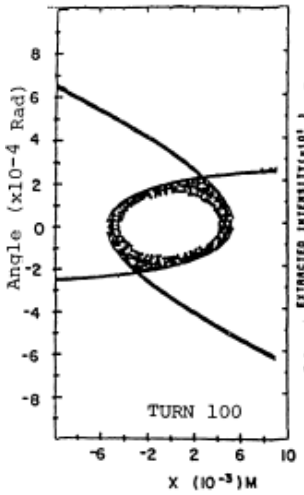


Fig. 5. Phase space for Chromatic Extraction

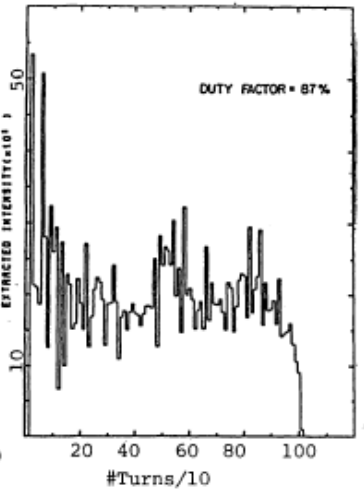
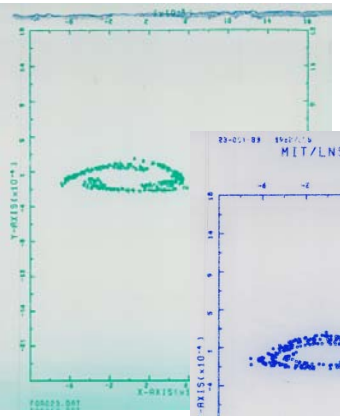


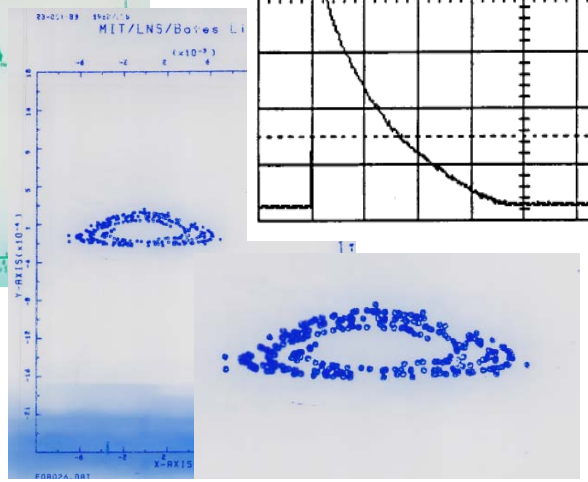
Fig. 6. Time dependence of Chromatic Extraction

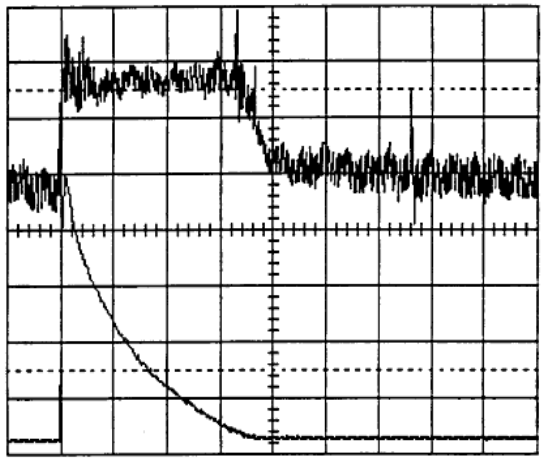
Idiosyncrasies of Resonant Extraction

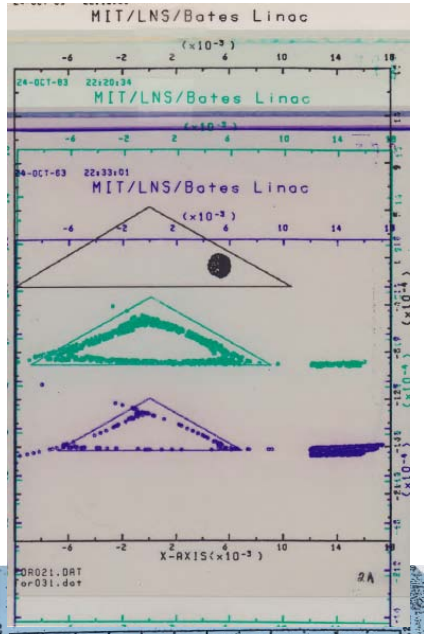
Note the spiral effect and gaps evident near the fixed point vertices. This results from the tune dependence of a particle's position in phase space. The resulting output intensity is shown in Figure 4. The time structure is due to the time it takes for a particle in phase space to travel to the fixed point, or roughly $1/(2\Delta Q)$ turns.

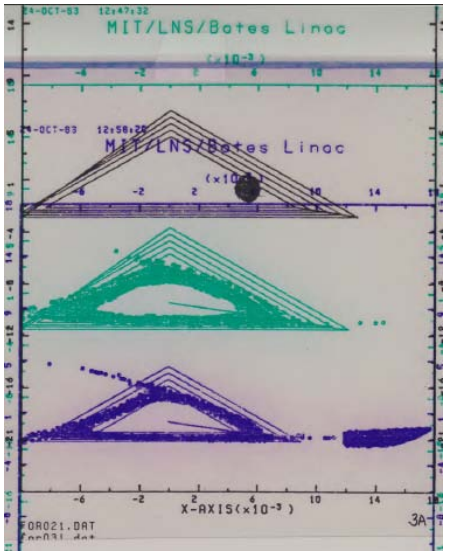
In order to optimize the resulting duty factor, it is beneficial to introduce an additional tune spread in the beam, in such a way as to not increase the non-linearity of the extraction process. A useful method is to use the energy spread ir
with a finite chromaticity pro
With this technique, the outpu

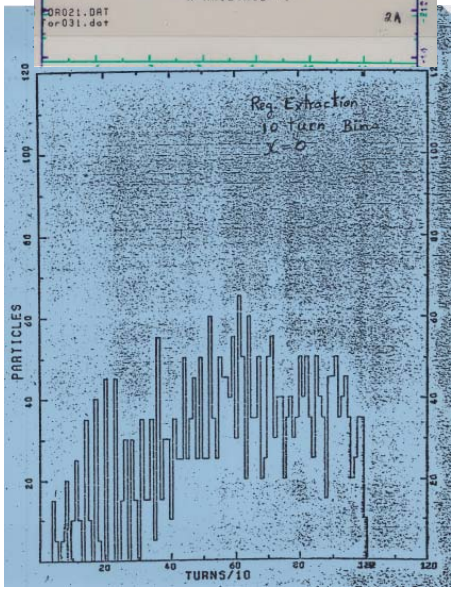


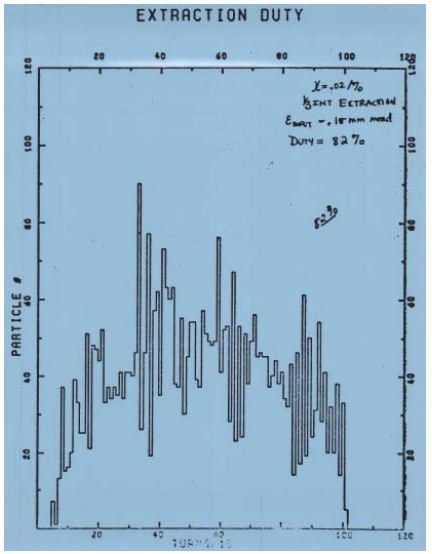






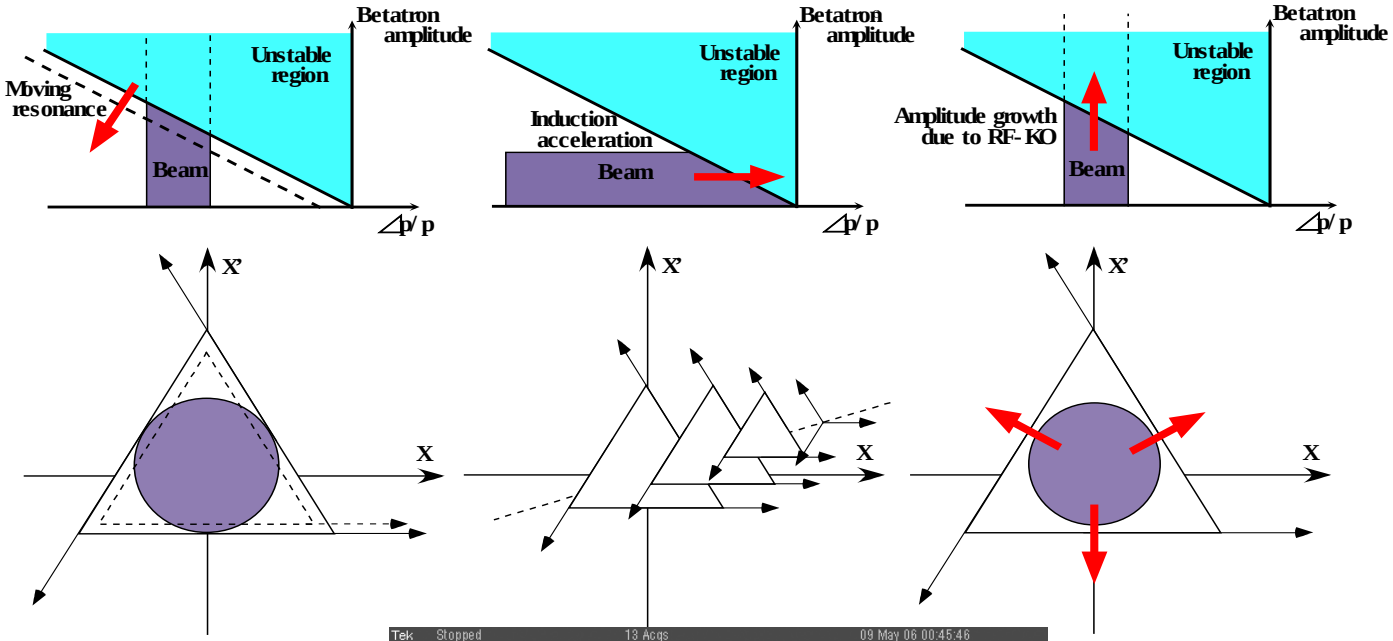


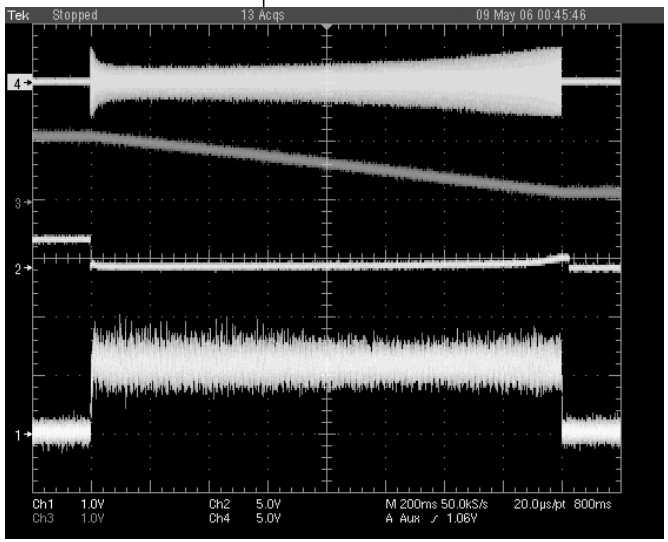




Slow Extraction

NODA



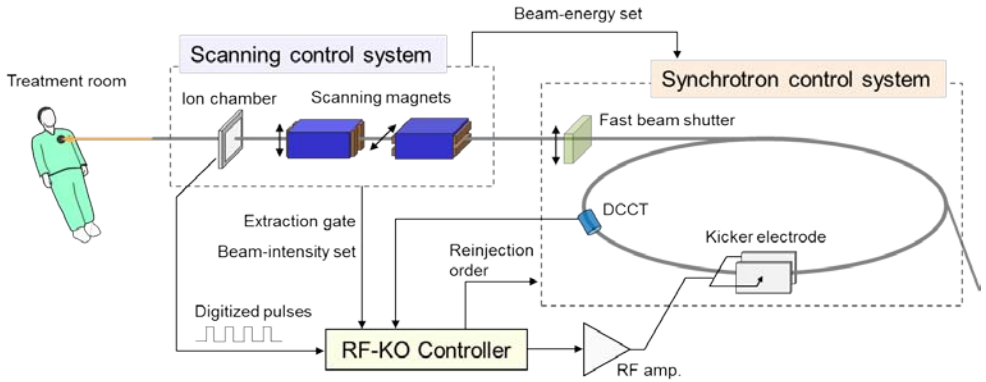


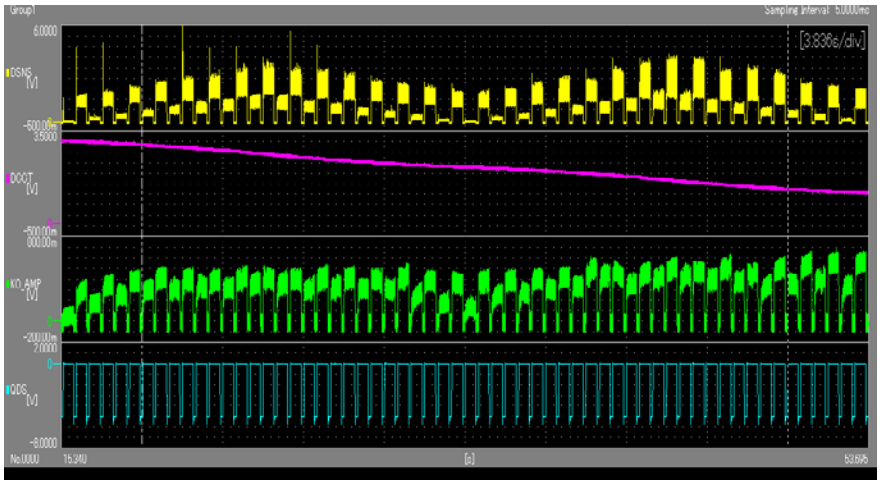
Response of dose rate control

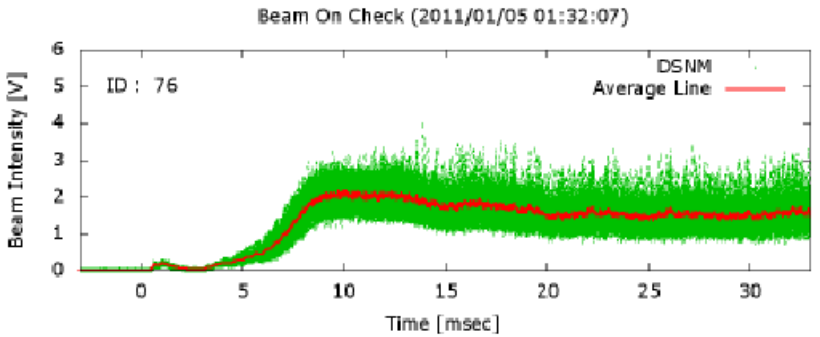
NODA

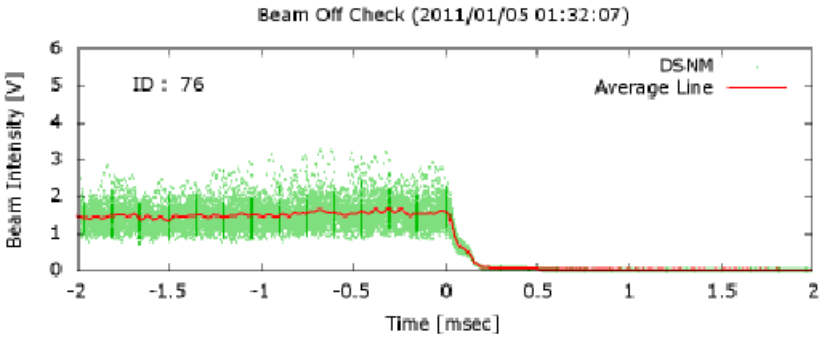
Development of synchrotron extraction control

Intensity and Beam on/off



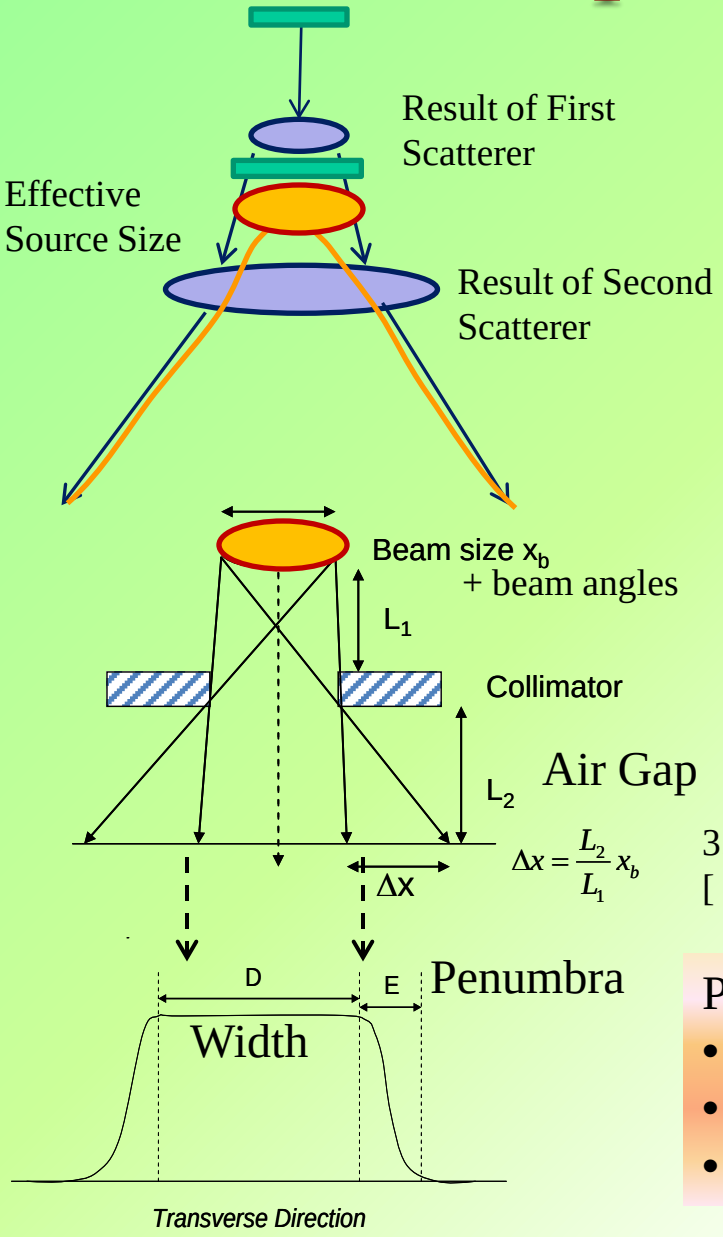


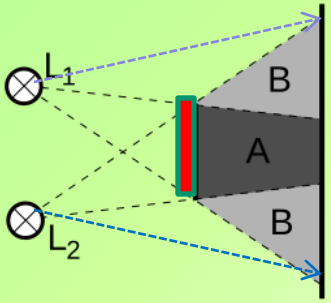




Dynamic range of modulation ~ 30

Beam Shape: Scattering: Penumbra





L_1 only - Penumbra

Neither L_1 OR L_2

L_2 only - Penumbra

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

Multiple sources above, vs. Extended source to the left.

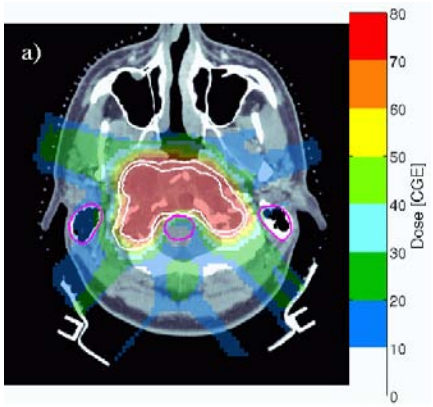
3.8mm=
[25cm/200cm]*3cm

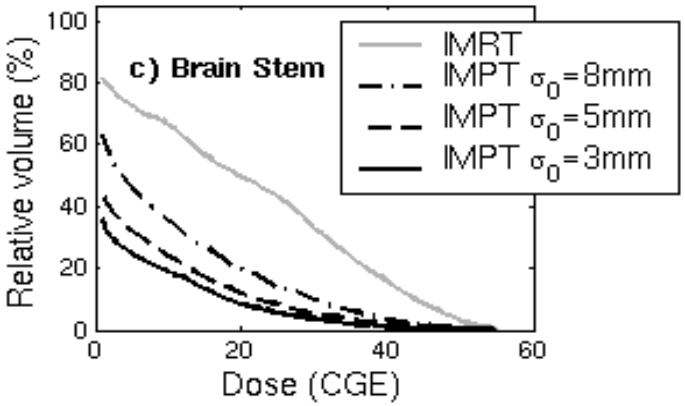
Parameters Created in this Method:

- Width (50% - 50% ?)
- **Uniform** Region (At ONE depth)
- Penumbra (80% - 20%) (Varies with Depth)

Transverse Uniformity, Width, Transverse Fall-off

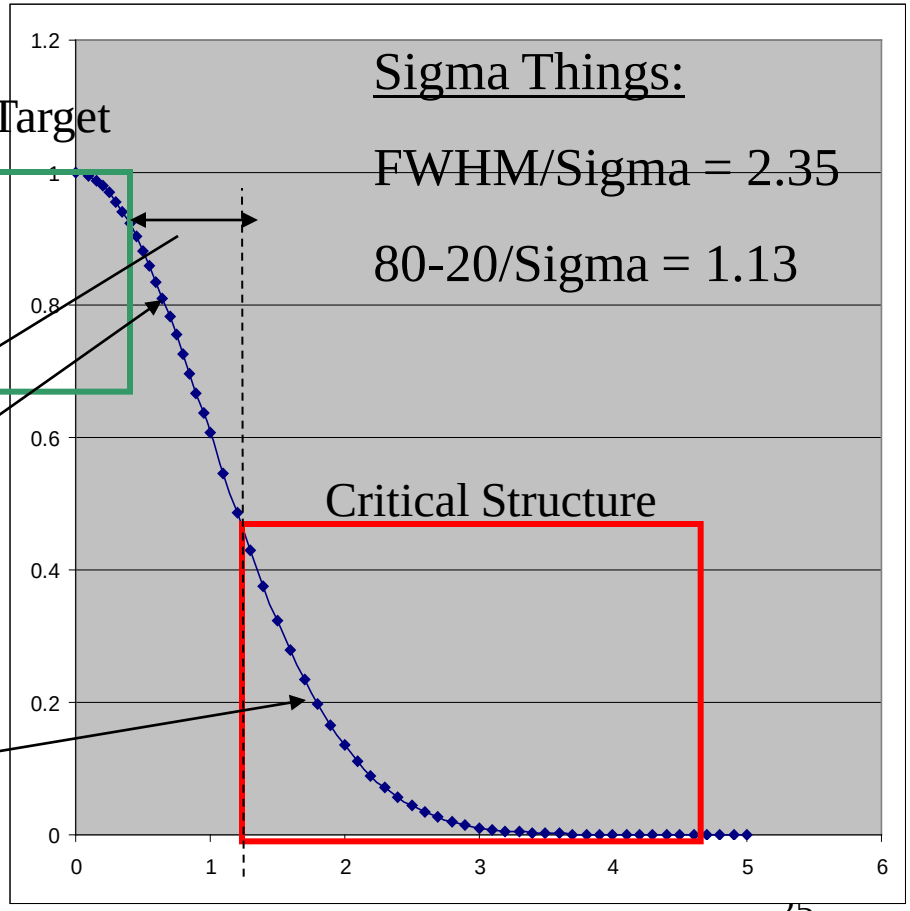
Beam Shape: Scanning: What is the Penumbra?





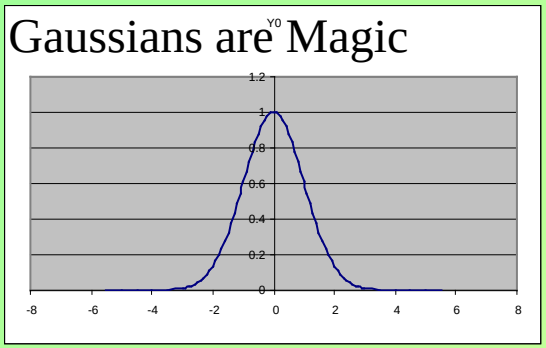
If we have a 5mm spacing, we need a beam sigma of 7mm

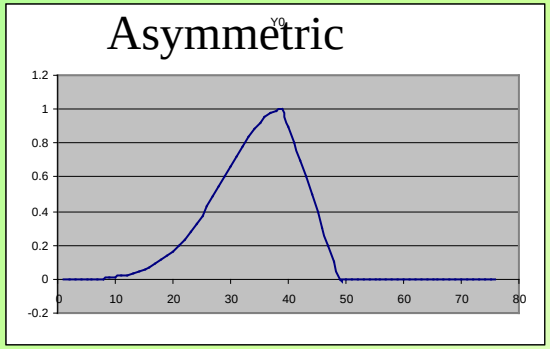
(Penumbra ~ 8mm)

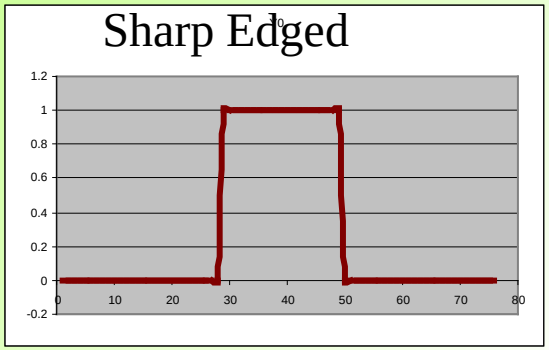


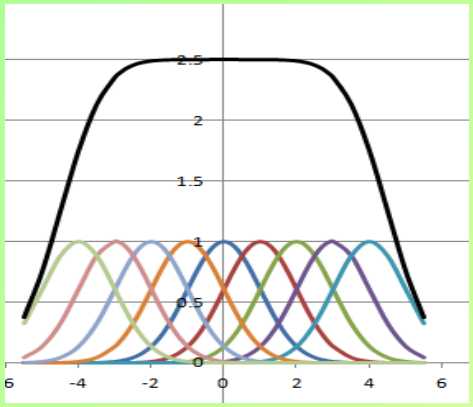
Transverse Fall-off

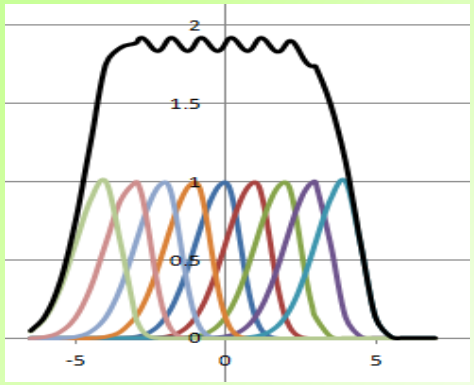
Spread out Transverse Dose with Scanned beam spots

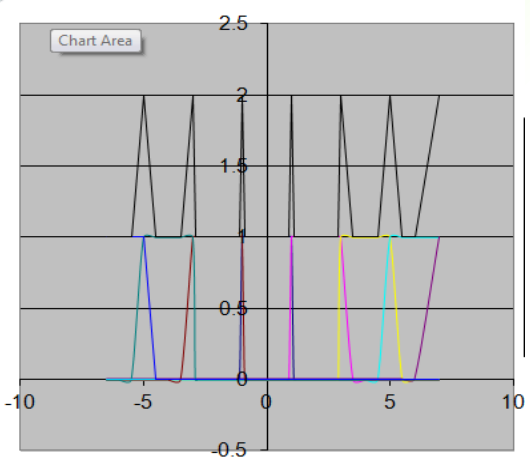


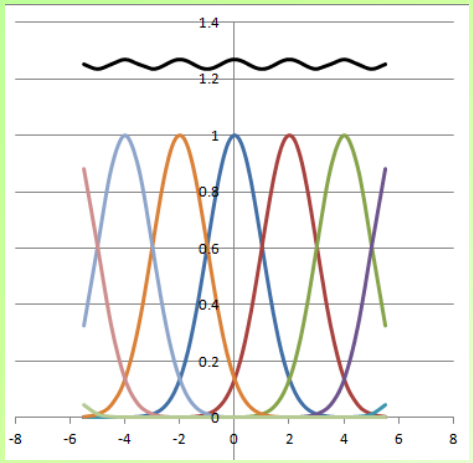




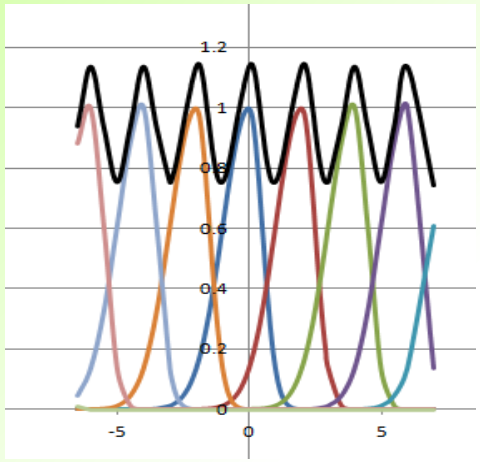








Spacing: 2 sigma 1 sigma



Transverse spreading using superposition of unmodified beams.

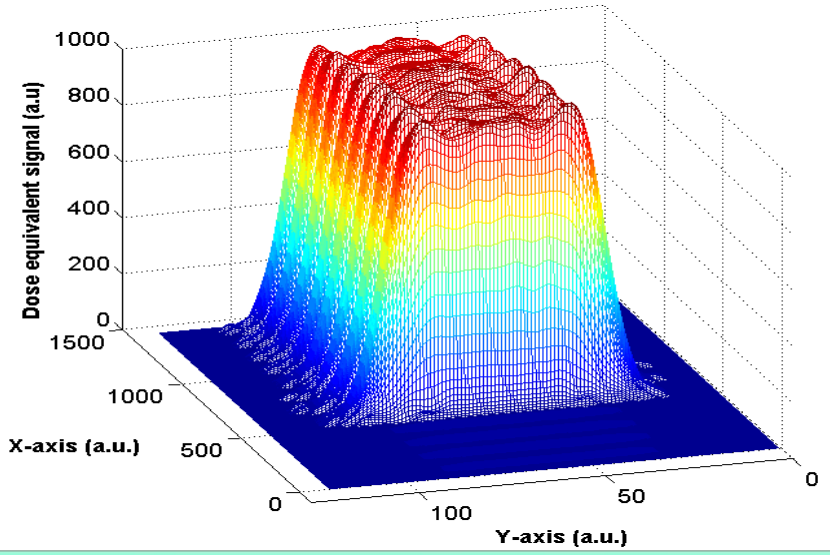
Uniform dose scenario.

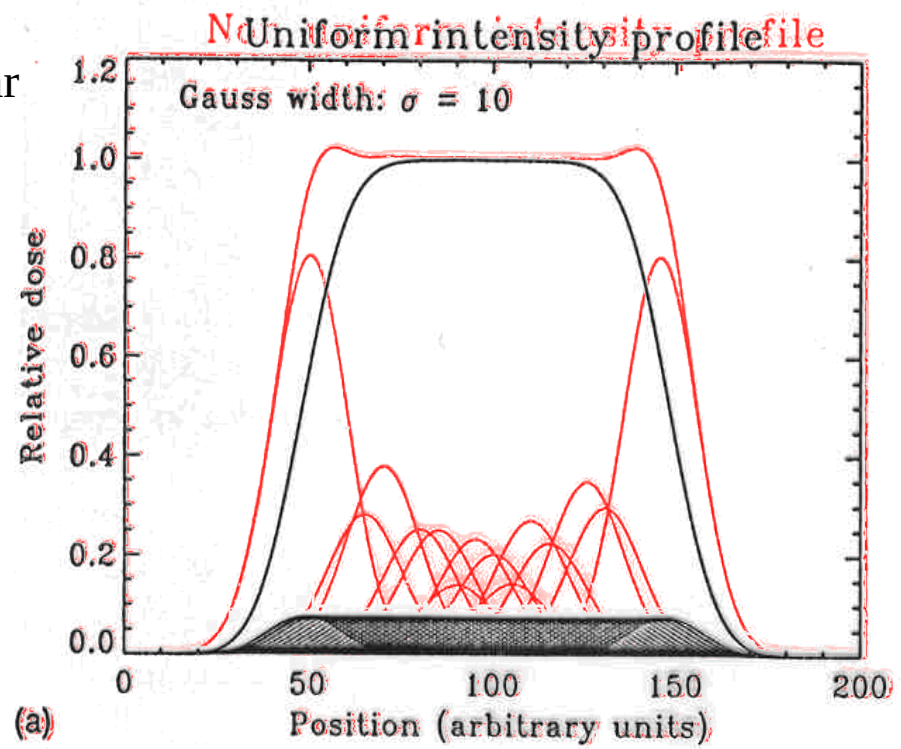
Beam Shape: Scanning : Penumbra Optimization

- Penumbra Optimization (Originally identified by PSI & Berkeley)
  - This results in a balance between penumbra and overall uniformity. (There will be ears.)
  - In this technique the dose delivered ACROSS the field varies – in a way similar to that used for SOBP optimization.

• Simple addition of Gaussians widens the Penumbra
• Apply same techniques as SOBP to sharpen the Penumbra

Pedroni et. al.



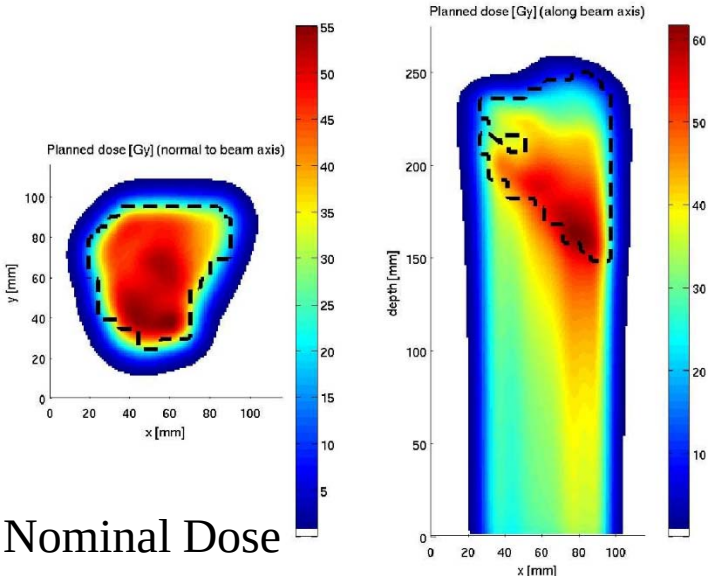


Therefore "Fluence Modulation" is required even for optimized Single Field Uniform Dose ! (Is Beam current modulation required?)

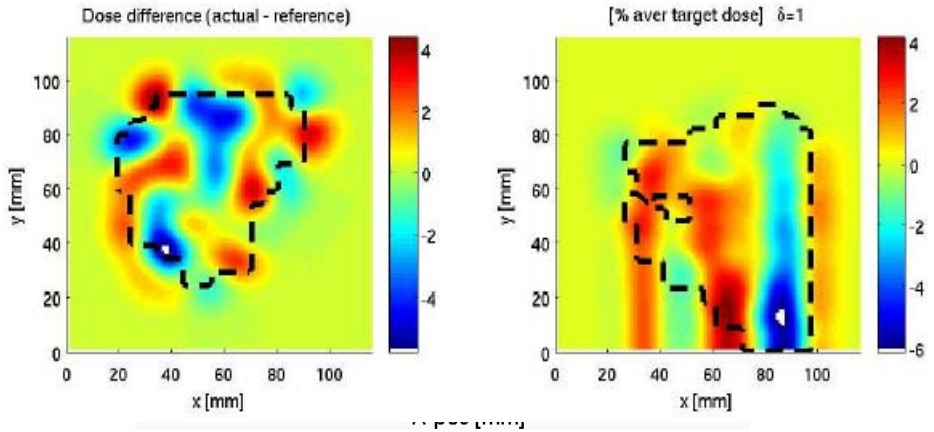
Transverse Fall-off

Beam Position Tolerances

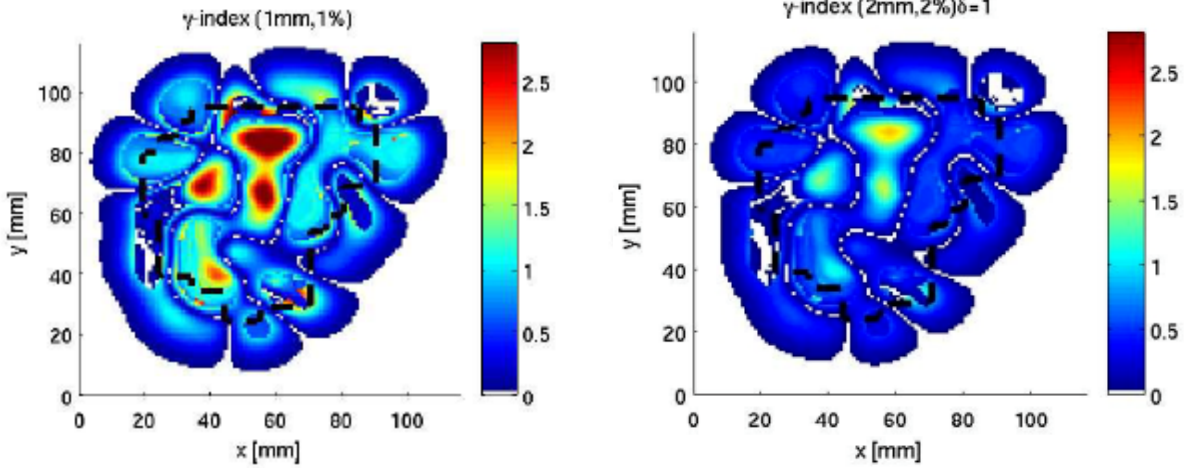
Prostate, Right Lateral



Nominal Dose



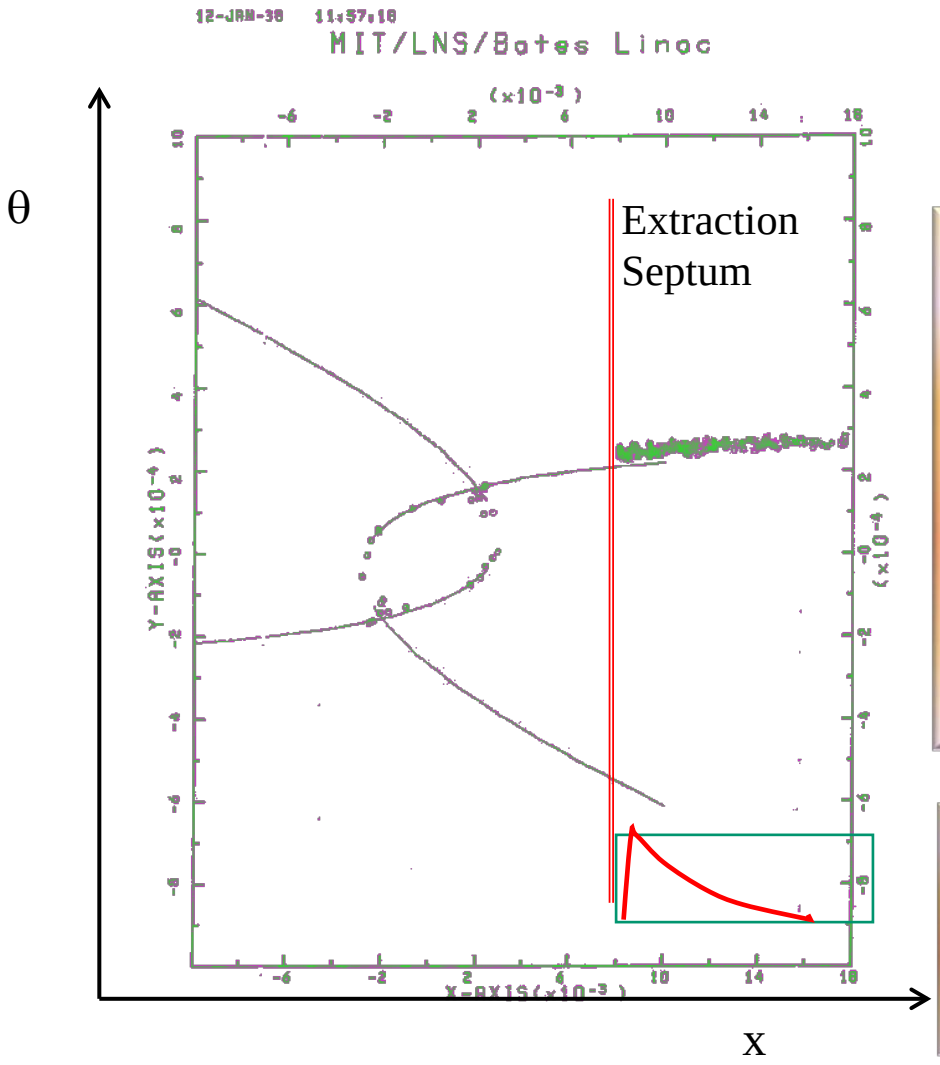
Difference Dose (position 1mm rms)



Gamma Map (1%, 1mm) (2%, 2mm)
(position 1mm rms)

Beam Shape: From a Synchrotron?

Extracted Beam from Resonant Extraction (one method)

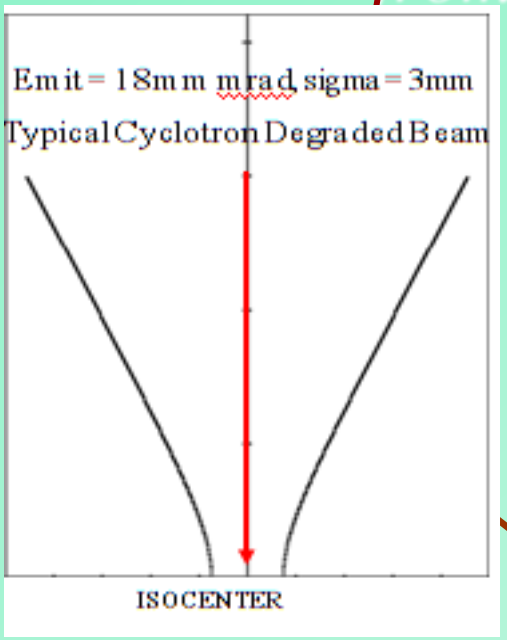


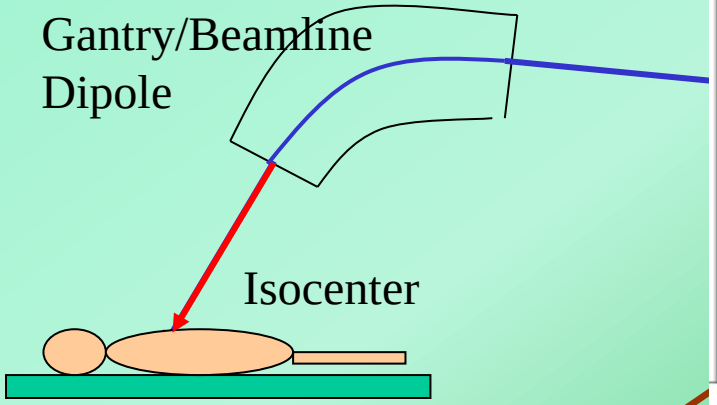
Beam Angle (position) is NOT constant, unless you do something.
-Adjust separatrix so it is ANGLE – easy to correct.
- Hardt condition
-…

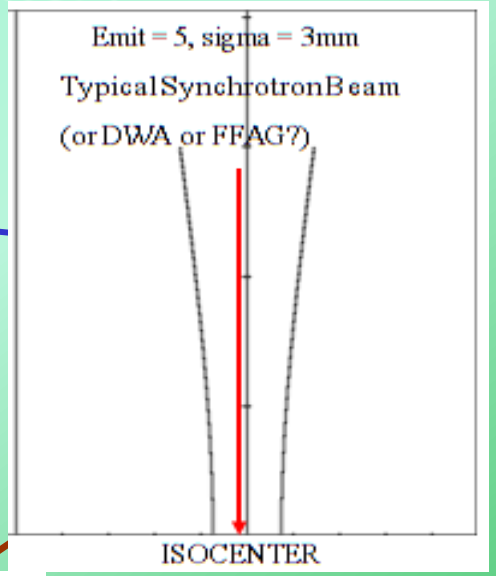
Extracted distribution is NOT Gaussian unless one does something

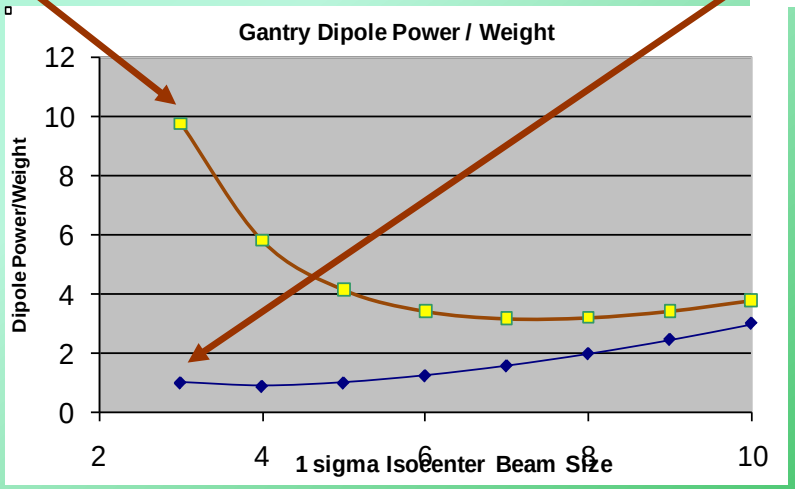
Beam size Issues: Cost

from the last magnet to Isocenter?









PS Current ~ Gap (2.1 sigma)
Magnet weight ~ gap ^{2}
Power ~ Current ^{2} ~ gap ^{2}

Energy desired is directly extracted

- No degrader ⇒ No increase in emittance
- THIS HAS BIG (small) IMPLICATIONS

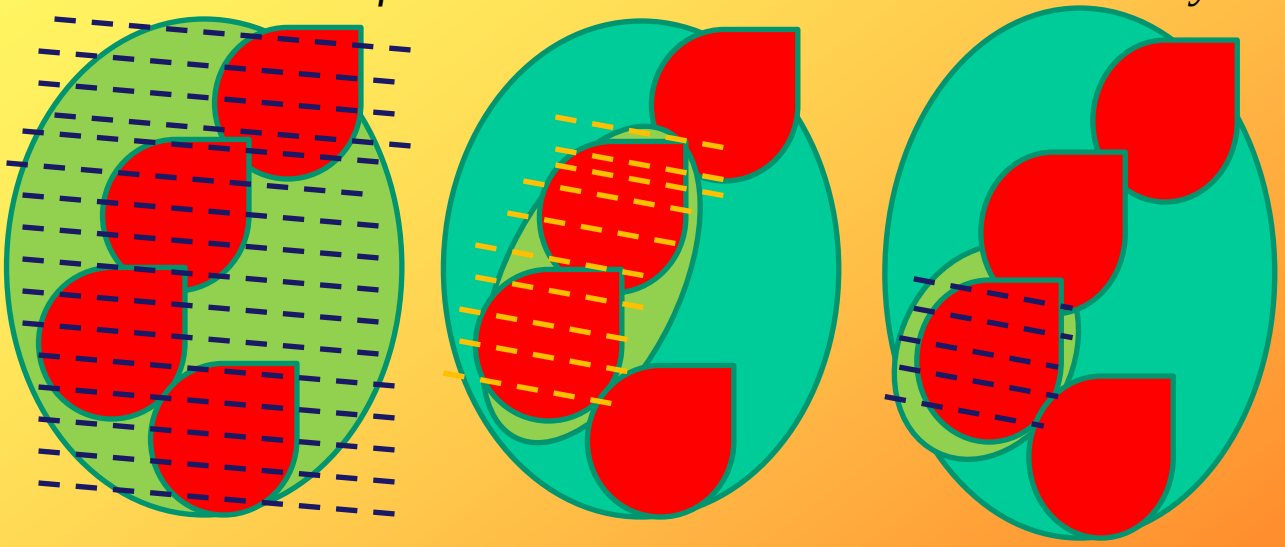
Organ Motion

- Time scale of organ motion
  - Respiration – seconds
  - Heart - < 1 second
- Methods
  - Respiration Gating
  - Tracking
  - Fast Whole Volume Irradiation (<1 sec)
    - 1000msec/30 = 30 msec energy change
    - 1-2 % accuracy dose delivery
    - 0.1 sec/energy x 30 layers = 3 seconds: No good for this purpose? Good for overall time reduction.

Scattering: Motion Mitigations: Nothing/Gate & ITV

NO Time Dependence of Beam Delivery

- **Choosing the target to Irradiate?**
  - 1. Define a ITV that is large enough to include entire motion volume and keep delivering dose until Target is uniformly irradiated.
  - 2. Define a smaller ITV and continue irradiating, until Target has passed through that region enough and is uniformly irradiated.
  - *Which of the above two cases results in less healthy tissue dose?*



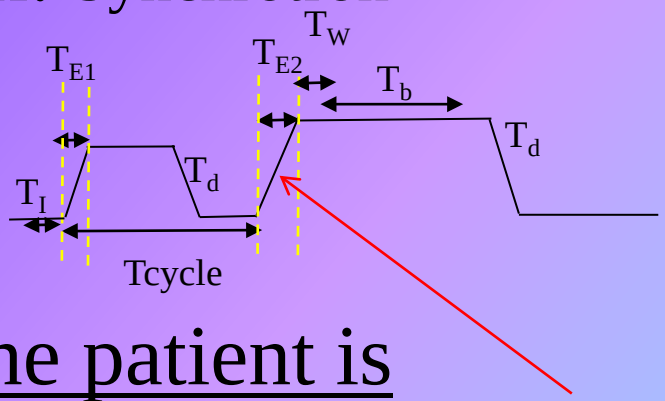
3. Gate the beam on, when the target is in the right location.

Maybe it would be nice to see a DVH as a function of the ITV and motion effects???

CTV - Clinical Tumor Volume
GTV - Gross Tumor Volume
PTV - Planning Tumor Volume
ITV – Internal Tumor Volume
(GTV <= CTV <= PTV<=ITV)

Treatment Beam Time Contributions

Longer Pulse Extraction: Synchrotron



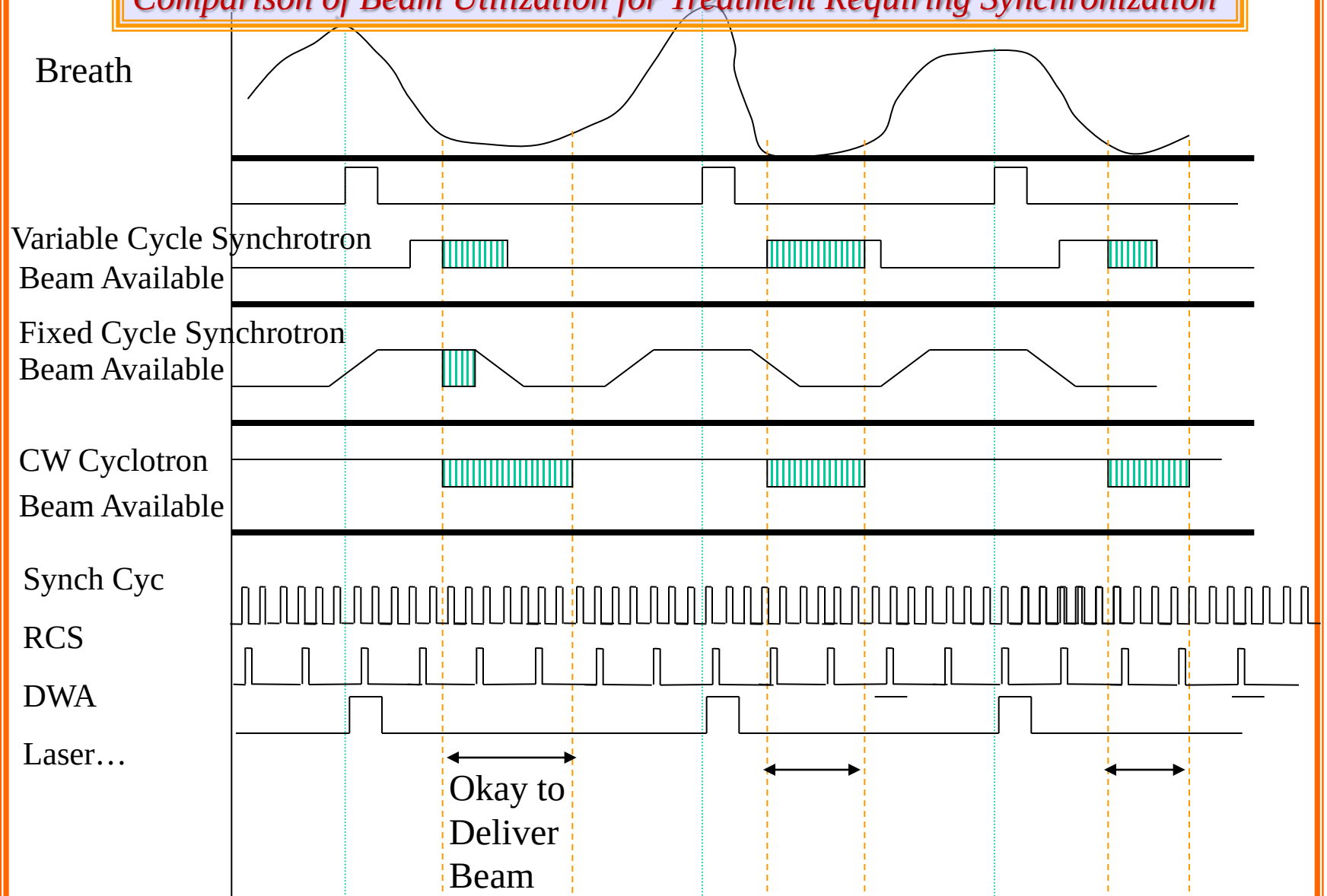
- Time to Inject: T_I
- Time to Accelerate: T_{En}
- Time needed to <u>wait until the patient is ready</u> for particles (e.g. gating): T_W
- Time needed to extract particles: T_b
  - Instrumentation will only allow a finite number of particles per unit time
- Time needed to Decelerate: T_d

If more particles are needed or change energy

V=L dI/dt
?Limit?

<u>Additional 'cycle' times</u> are needed if there are not enough protons in the ring to deliver the required dose at a given range.

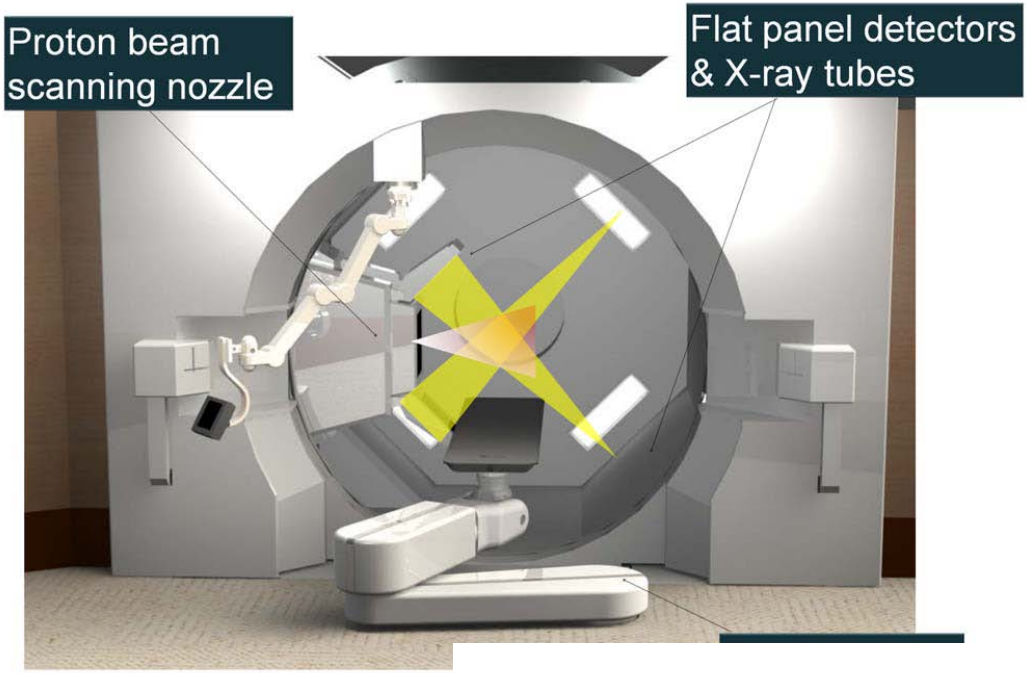
Comparison of Beam Utilization for Treatment Requiring Synchronization

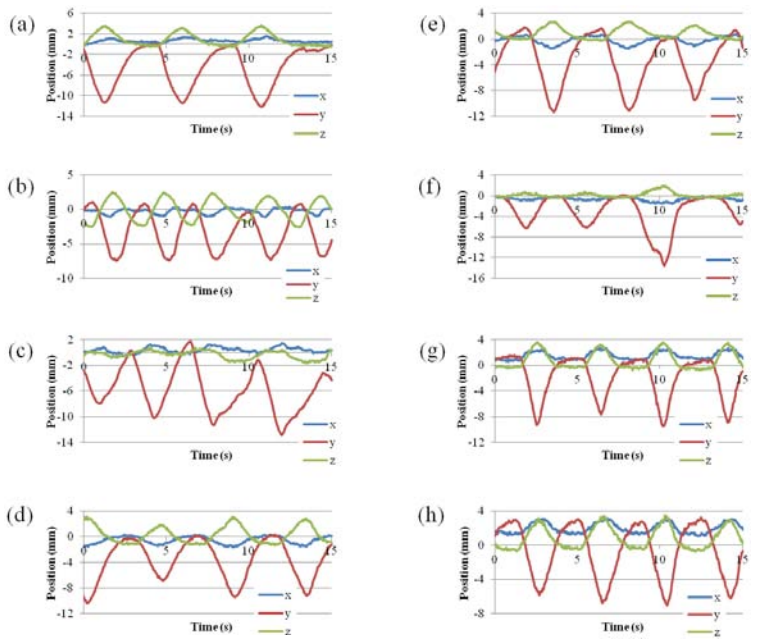


1. Efficiency of Beam Utilization
2. What needs to be done with the beam when it's okay to deliver? e.g. usec vs. sec

On-line motion management

Hitachi @ Hokkaido





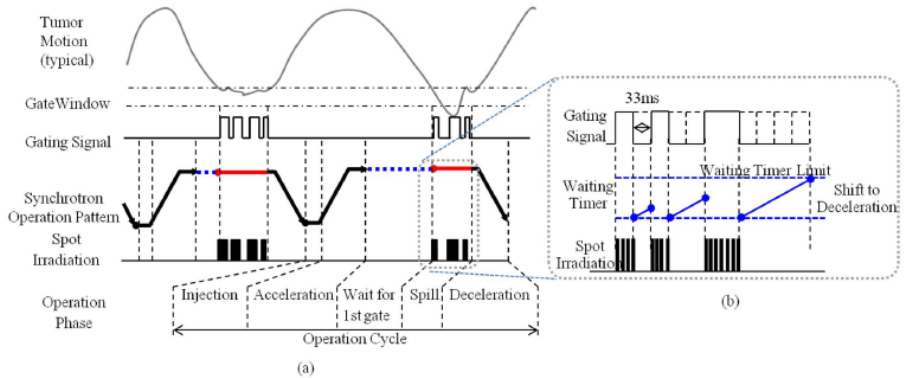
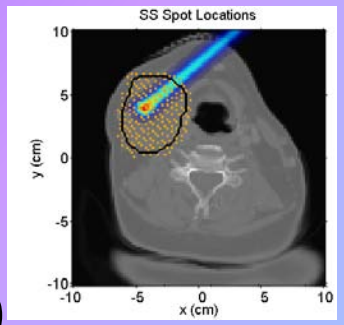


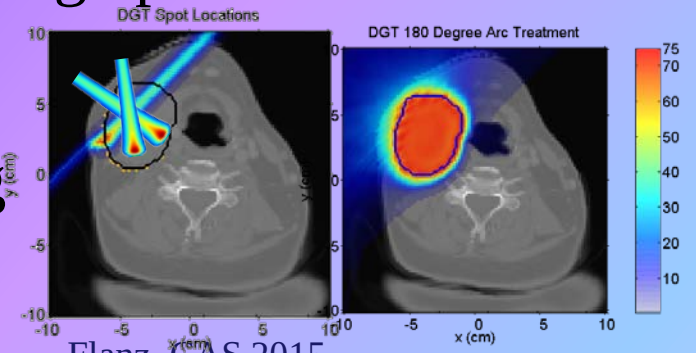
Figure 5. Diagram of the (a) synchrotron operation and (b) beam waiting function. The operation cycle of the synchrotron varies approximately from 2 to 7 s. The flat top length which consists of wait for the first gate and extraction time has a maximum of 5 s. During extraction, beam waiting function enables to irradiate proton beam to the multiple gates per operation cycle.
doi:10.1371/journal.pone.0094971.g005

Short Pulse beam timing?

No organ motion considerations here.

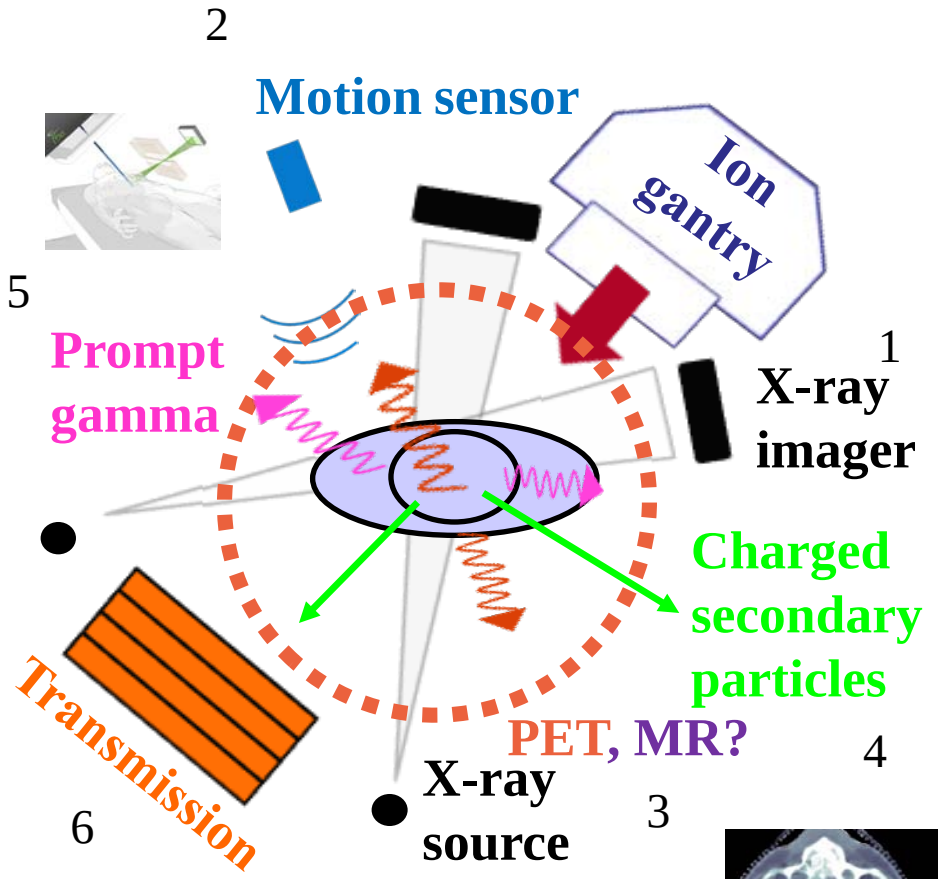
- Accelerator Timing is very important when considering SCANNING beam delivery
- For example
  - 30cm x 30cm with a **10**mm beam ➔ 1000 spots/layer
  - For 30 layers ➔ 30,000 spots
  - 30Hz delivery ➔ 1,000 seconds/irradiation (16.7 min!)
  - AND THIS ASSUMES 1 PULSE/Spot
  - Try 3 pulses/spot ➔3,000 sec (50min)
  - Therefore to reduce to 1 min, need 50 x 30Hz = 1500Hz
- IBA, for example, has chosen 1kHz (*2x pulse/spot*) rep rate for their synchro-cyclotron with multiple pulses at successively reduced charge/pulse to achieve the desired dose accuracy
- OR – Use DISTAL-Edge Tracking

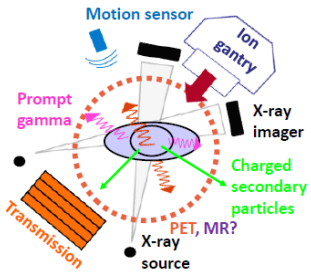


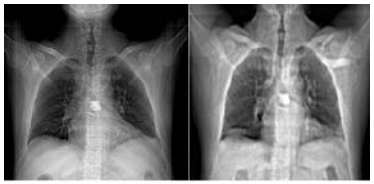


Implications of Imaging ?

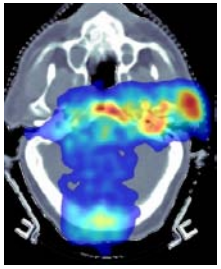
1. On-line: Adapt Position
   - Timing (on/off)
2. On-line: Adapt Position
   - Timing (on/off)
3. In-beam maybe:
   - Beam on/off fast
4. n/a
5. Low background;
6. Fast energy change; Low current; High energy





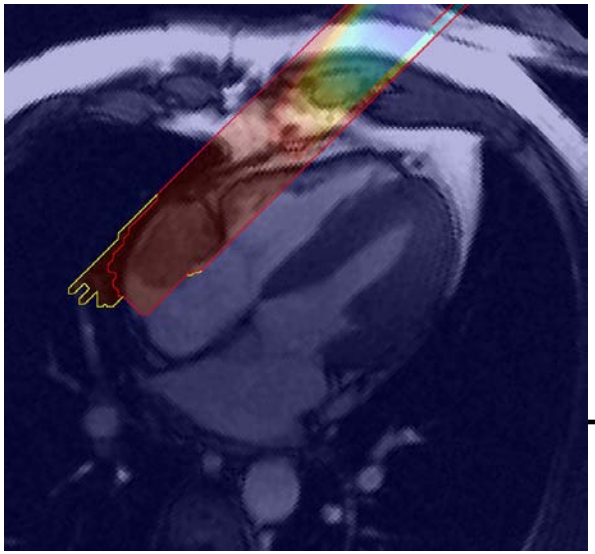


Parodi, CAS 2015

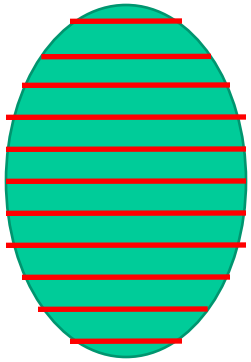


Flanz_CAS 2015

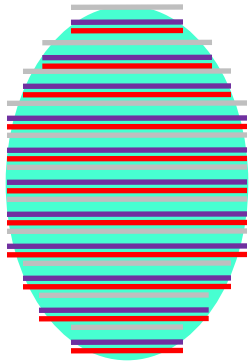
Scanning Timing: Motion "Interplay"



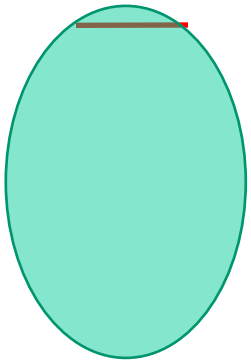
Fast Two Dimensional Beam Delivery NOT Time dependent:



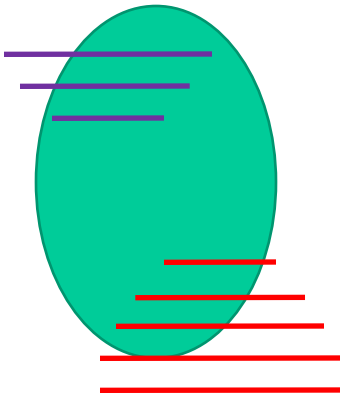
Final Result



Real Two Dimensional Scanning Beam Delivery IS Time dependent (if the time it takes to delivery the dose to the volume is a significant part of the time that the target is moving. (AS it is today))



Final Result

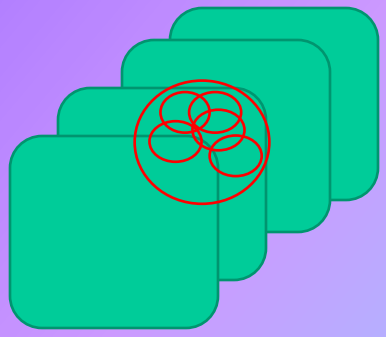


Motion Mitigations: Gating, Larger ITV and Repainting

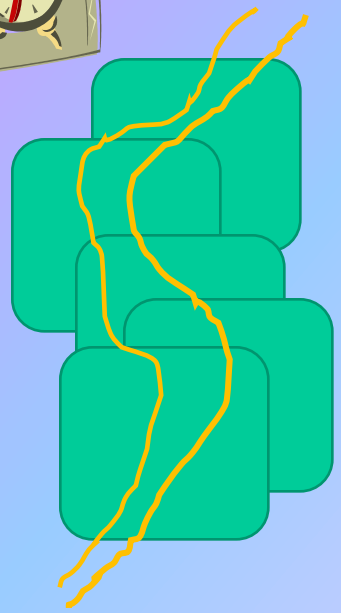
Transverse Conformity;Width

Motion Timeframe

- Breathing motion (*rigid body* approximation)
  - Cycle about 2-3 seconds (without arresting respiration)
  - Motion amount from 3mm to 1cm (conservative – not extreme)
  - Position Tolerance (depends on sigma) from 0.3mm to 3.0mm.
  - Therefore, for the WHOLE transverse scan:
    - Fastest Motion (Worse case): 10mm/2sec = 5 mm/sec (100?)
  - Tolerances gives the time required for irradiation (Freeze Layer(s)?)
    - Worst Case I: 0.3mm/(5mm/sec) = 0.06 sec (60 msec) (16 Hz)
    - Best Case I: 3.0 mm/ (5mm/sec) = 0.6 sec (600 msec)
  - What can be done in this timeframe – (remember instruments)
- TRANSVERSE (e.g. spot scanning):
  - 10cm x 10cm; 3mm beam ~1000 spots
  - 1000 spots in 60msec = 60usec/point** (vs. 50us turn off time before)
  - ** This includes response time of instrumentation and beam on/off (if needed)
- DEPTH:
  - Need same time frame as above if do NOT want to buy EASYTRACK®
  - e.g. 1 seconds =0.05sec*20 layers which is < respiration cycle ∴motion !!
  - Therefore we can complete one respiration phase if energy change is this fast. Otherwise we would have to go faster or follow more phases
- *Heartbeat timing; e.g. 80 beats/minute (0.75 sec/cycle)*



Fast or Not Moving

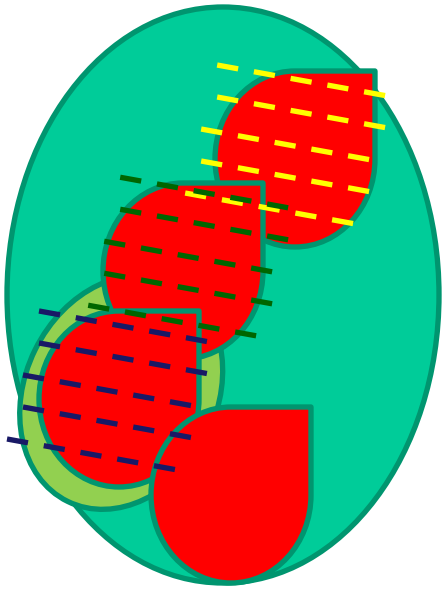


Position then Energy or Energy then Position or Mixed? Can we do faster than 0.1 sec??

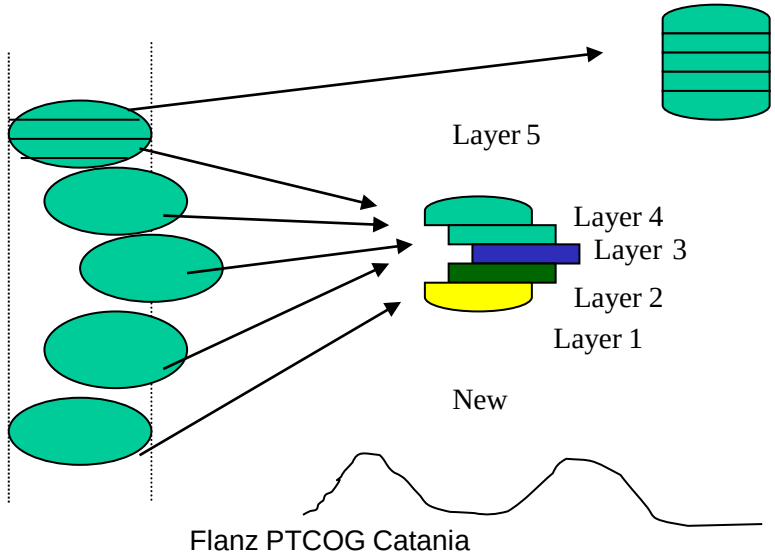
Moving, Size Changing Density Changing

Gating with EasyTrack®

- Multiple Phase Gating (*EasyTrack ® V1*)
  - Same as above (**Speed** and **Assumptions**), however prepare for irradiations during multiple phases
  - Preparation involves "**Known**" positions AND DEPTHS. Wait for target to be at those positions before delivering the beam (and do it fast).
  - **Time:** How many breathing cycles does it take to complete this irradiation? (e.g. 5 times faster in this case)



ONE treatment plan, just parts of it delivered at different positions. Position is phase dependent.



Motion Mitigation with Scanning: Super ® Track

- **Tracking of a Rigid Body:**

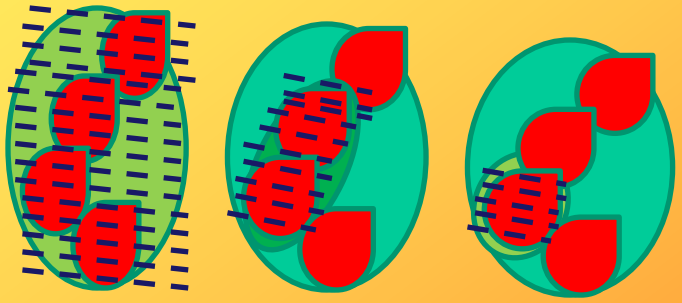
  One phase per respiration cycle

  Assumption: that during a particular phase of the cycle, the target has the same parameters

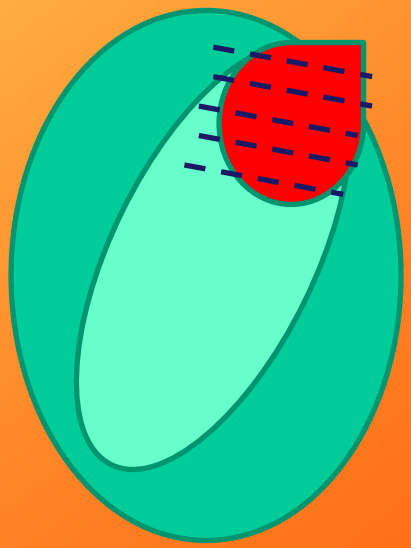
  - Depth/Density
  - Other moving organs in the way or not are repeatable
  - Size and Shape
  - Transverse Position

  Speed of Delivery: It doesn't matter if you're tracking a rigid body

  Time: It doesn't matter if you're tracking a rigid body



NO 'effective' Time Dependence of Beam Delivery



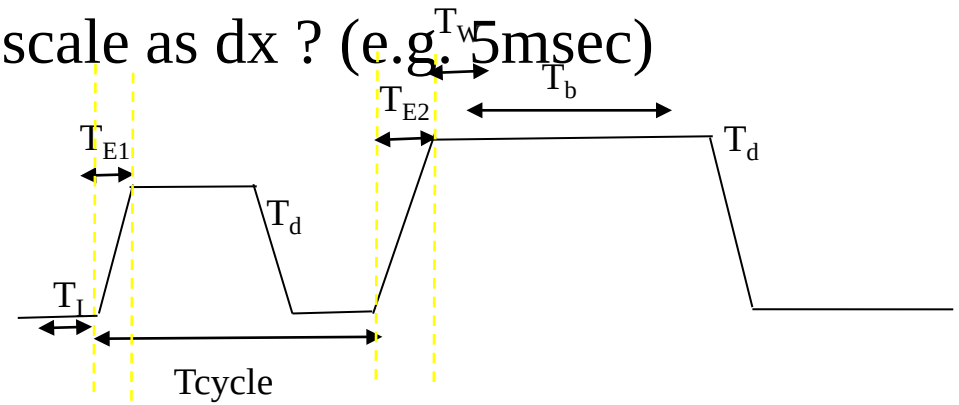
Transverse Conformity Width

Timing Lessons

- Scattered beams are delivered in a volume almost instantaneously relative to human motion.
  - But Scattered beam distribution cannot easily be changed quickly (e.g. MLC)
- Scanned beam timing is challenging with the present technology and is a factor in delivering dose to moving targets.
  - But scanned beam potential for tracking (if there is a signal that can be used) is great.
  - The start of real-time adaptive therapy??

Beam Range and Range Changes

- Range:
  - Therapeutic Energy only OR
  - Energy Required for Particle Imaging (Higher)
  - Lower (70 MeV? – why) Is there an extraction dependence on Energy? (emittance/vacuum windows…)
- Scanning delivery layer by layer due to time to change layers. Much has been said about this in this talk. Reduce that time.
  - dE on same time scale as dx ? (e.g. 5msec)
    - Spill by spill
    - Interspill

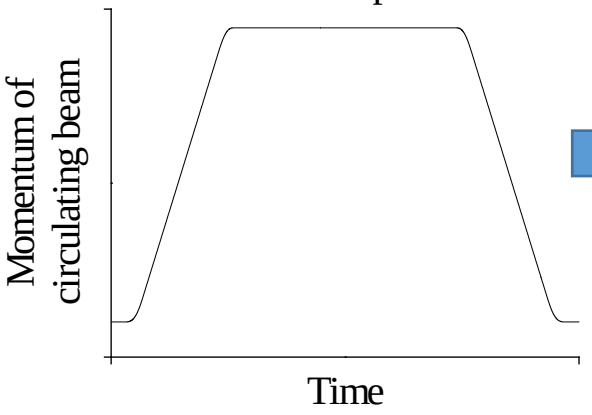


Variable Energy Operation & Intensity Modulation

Noda

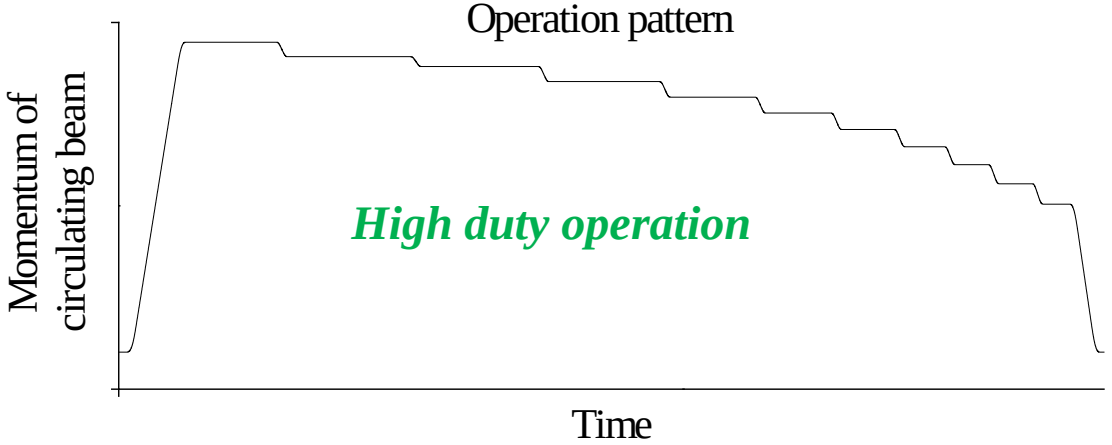
Standard Operation

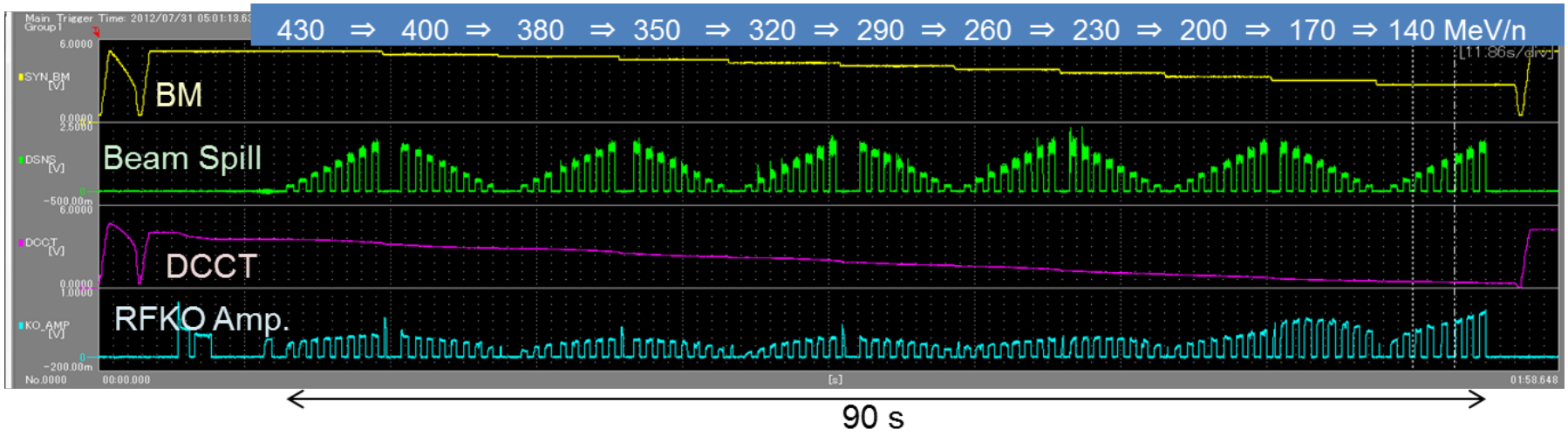
Reference pattern



Multiple Energy Operation

Operation pattern

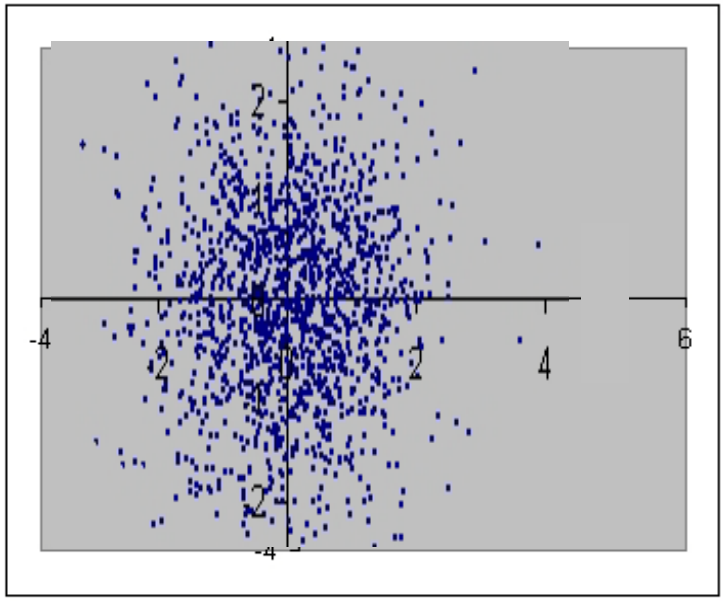


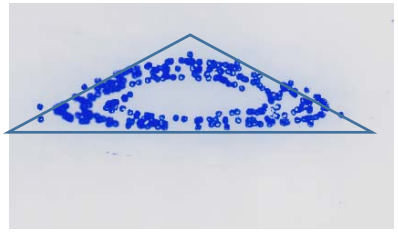


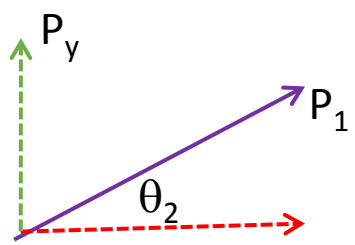
Decelerating a Beam

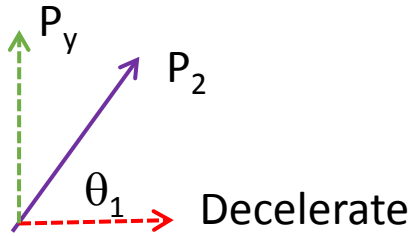
• A beam is a collection of many particles all of whose longitudinal and transverse momenta are close enough and remain more or less close to each other.

•Phase space diagram highlighting the canonical variables









$P_{z\,2}$ $P_{z\,2}$

Why not Accelerate?????

Compact and Low(er) Cost

Compared to what?

- Linac ≅ $3M
  - Equipment Only
  - Replacement (Lifetime?) = 10 years
- Proton ≅ $100M ??
  - Equipment for 3 rooms ≅ $40 M
  - Equipment per Tx room ≅ $13 M
  - Lifetime ~ 30 years ⇒ $4 M per 10 years
- ONE Room System (In an existing bldg?)
  - $25M? / what should it be?

Small ?

- Size = Cost ???
  - Equipment costs
  - Building costs
- How to make smaller?
  - High Field
    - Special Steel
      - Harder to make
    - Superconductivity
      - Field Changing is hard (slower)
  - No magnets?
  - Reduce ‘unneeded’ Space
    - Define ‘needed’
    - Design by “Accelerator Physics” vs. Other

Your choice of Synchrotron Colors

Proton

Hitachi 1

Hitachi 2

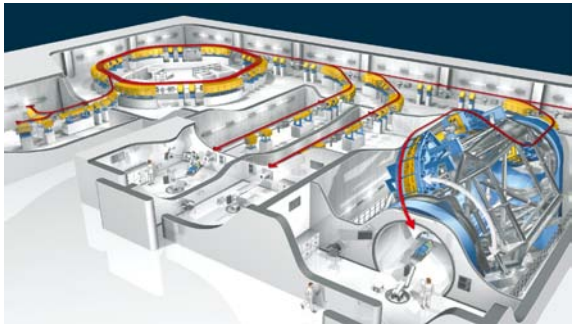
ProTom

Mitsubishi

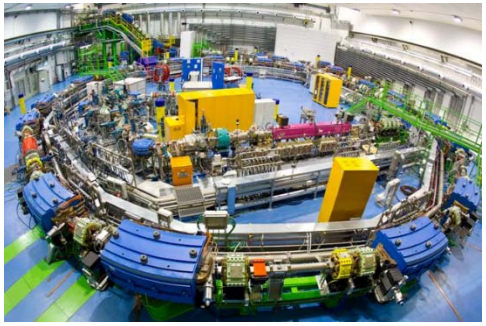
One of these is not like the others?

Heavier Ions

Heidelberg



CNAO



Mitsubishi

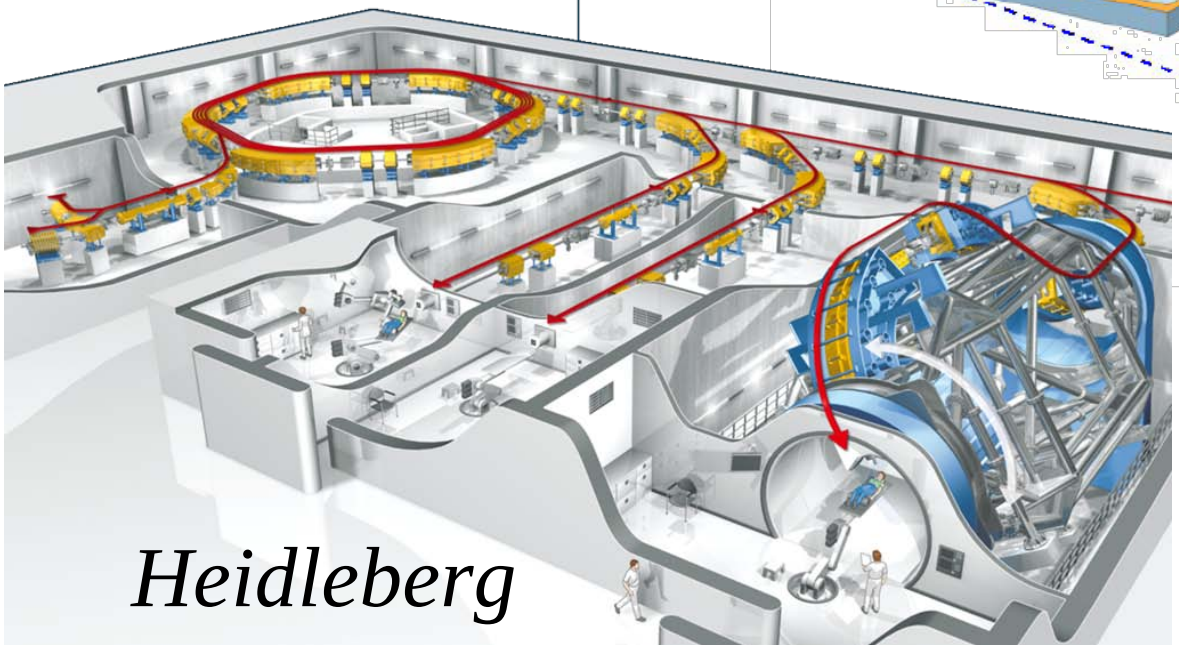
This is NOT include all synchrotrons ! I apologize for the omissions.

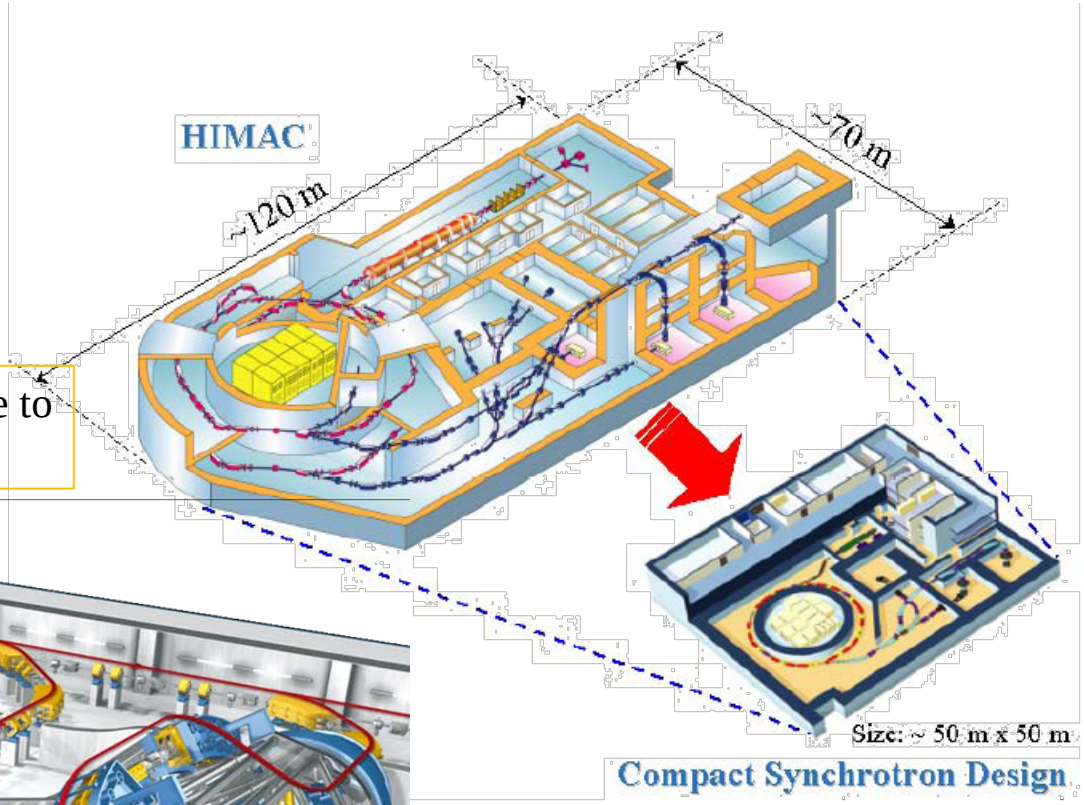
Heavy Ion Accelerators and Facilities - Conventional

Remember:
400MeV/nucleon:

Could be big and (Expensive)!
But they are shrinking also !

Multiple Ions – NIRS Pulse to Pulse using 2 synchrotrons



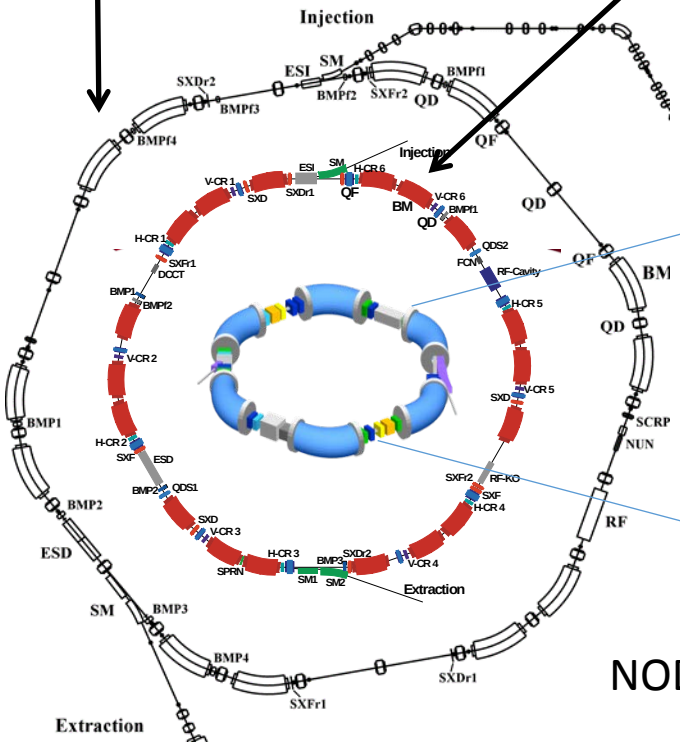


NIRS Japan

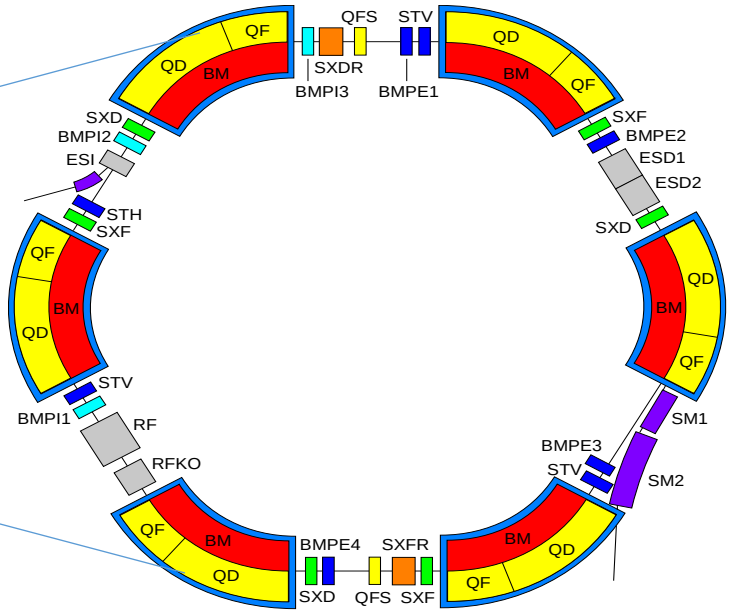
Further Reducing the HI Synchrotron Size

HIMAC Exsiting: Super cell structure of HIMAC synchrotron:
Two FODO cells contain two dipole magnets C=129.6m

Super cell structure of compact synchrotron:
Two FODO cells contain three dipole magnets



Super Minimac C=31.88m



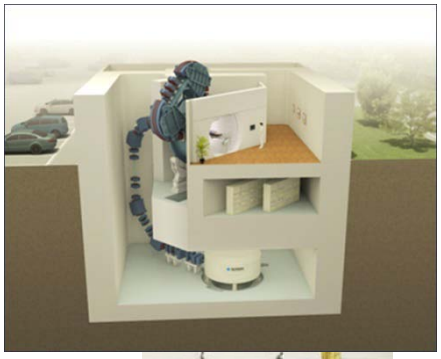
NODA

Injection Energy	**4 – 8 MeV/n**
Extraction Energy	**430–60 MeV/n**
Tune(Q_x,Q_y)	**(1.68, 1.13)**
Field Strength	**~3.4 T**

$

Scaling Down Systems (Gen 3) *(straightforward extensions?)*

IBA



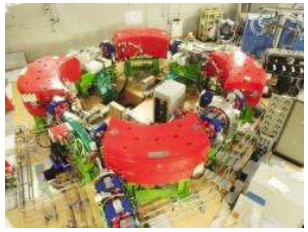
Sumitomo

Axially
Shorter

MEVION medical systems

180°
Half
Width

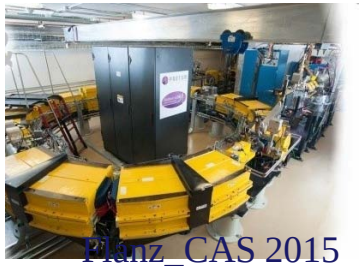
HITACHI
Inspire the Next



ProNova

Axially
Shorter

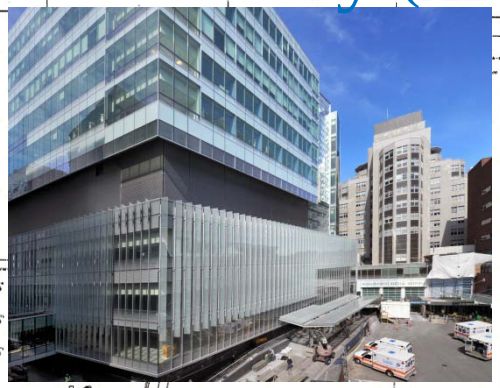
PROTOM proton therapy technologies

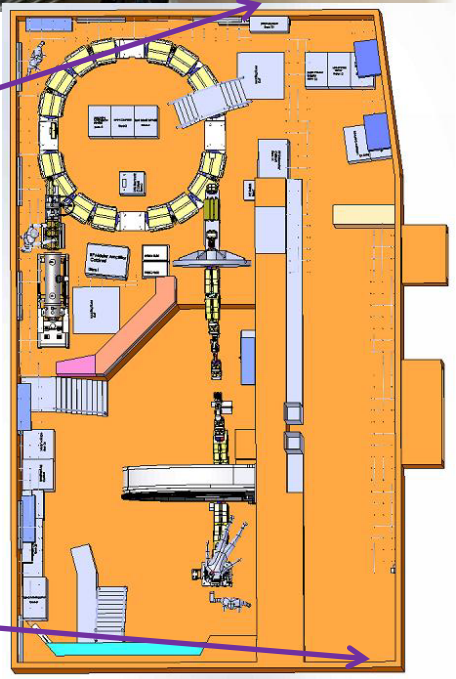


180°
Half
Width

Future (?) Challenge: Install within an existing Radiotherapy Department (4th Gen?)

MGH new proton facility (*ADD* not Replace)





Okay – we added a pit

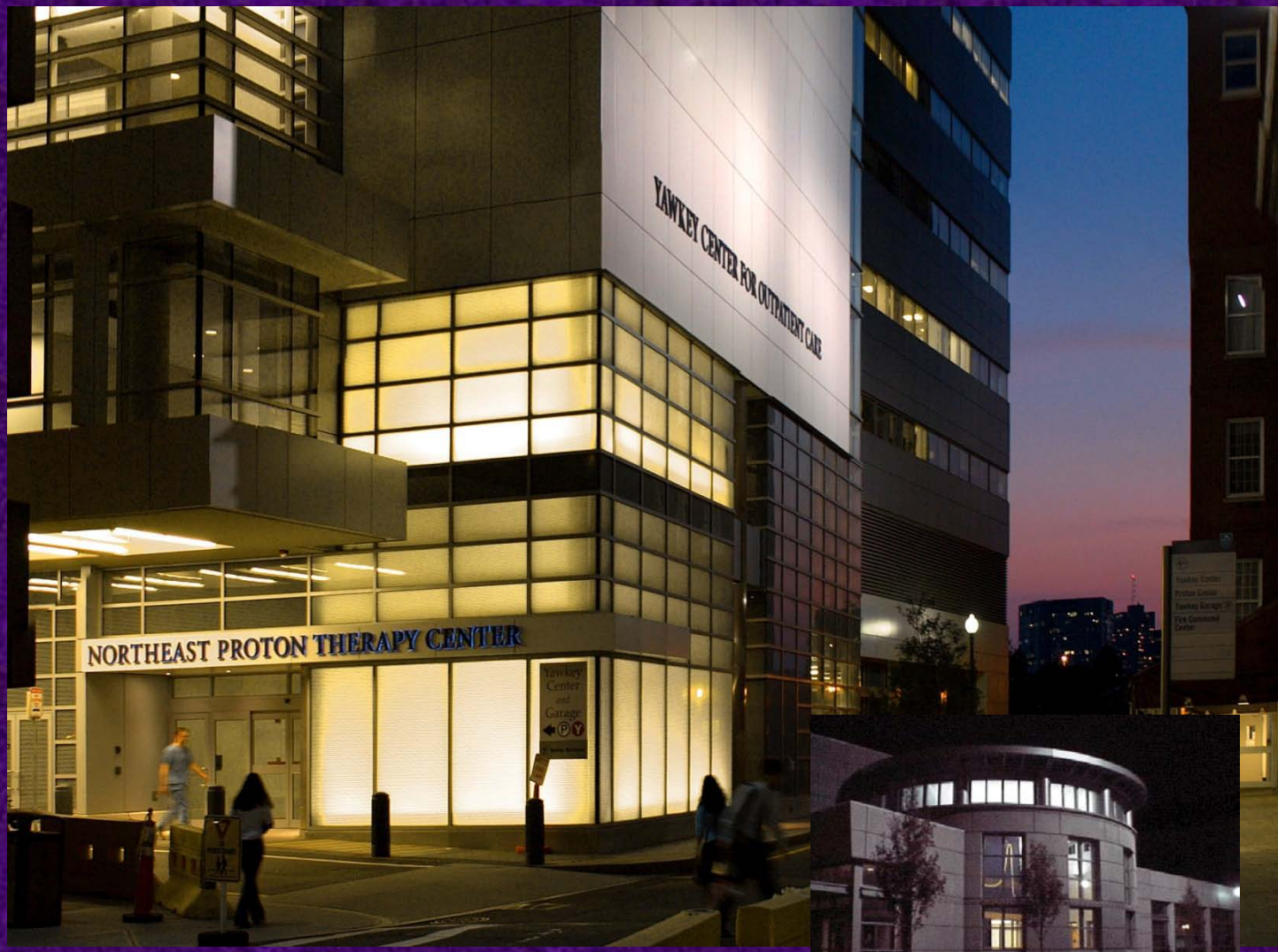
Issues for Future consideration:

- Cost:
  - Size vs. Superconducting
  - Injector energy
- Intensity
  - Injector energy vs. Cost
- Energy
  - Therapeutic only vs. Imaging vs. Low
- Energy change speed
  - Superconductivity
  - Beam storage stability
- Turn off time
  - Instrumentation detection time
  - Calculation Time
  - Extraction control parameters
- Irradiation Time (e.g. motion)
  - Full volume irradiation in ONE spill
    - In a time less than motion relevance

"Full Volume Irradiation in ONE cycle < 1 second"

"Fit in an existing Hospital Infrastructure"

The Francis H. Burr Proton Therapy Center



Thank You !

Relationship of Themes to Beams

	Delivery Time vs. Dose Rate	Range	Range Change	Beam Size	Beam Position	Beam Shape	Ion Species
Scanning (no motion)							
IGRT							
Organ Motion							
Adaptive Radiotherapy							
End of Range							
Field Directions							
Capital Costs							
Throughput							
Hypofraction							
Maximal Spec	HIGH Deliver <1 sec	IMAGING Range	Consistent with Delivery Time	2mm – 8mm at high Energy	10% of size	Gaussian (almost)	??

Now (P*) vs. Future (F, FF*) (2)

	Small	Low Cost	Fast dE	High E	Enough Q	Stable Ext	Sync Timing
Super Mimiac							
RCMS							
Hitachi							
Mitsubishi							
ProTom							
HIMAC							
CNAO							
MedAustron							
HIT							

P = Happening Presently in clinical use
F = Future, now working on it
FF = Farther Future, needs development

Fast dE vs.
Superconductivity (Small)

Not ALL Synchrotrons are here and I don't know all the parameters. Apologies