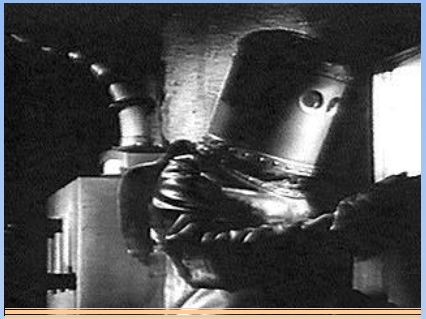
Particle Therapy *(Technical)* *Approaches*



Jay Flanz

PTCOG 47 Educational Sessions

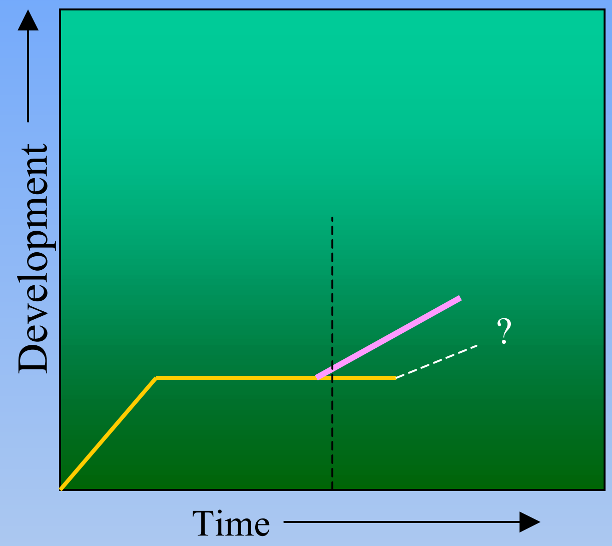
Massachusetts General Hospital, Harvard Medical School

Francis H. Burr Proton Therapy Center

5/08

Thanks to:

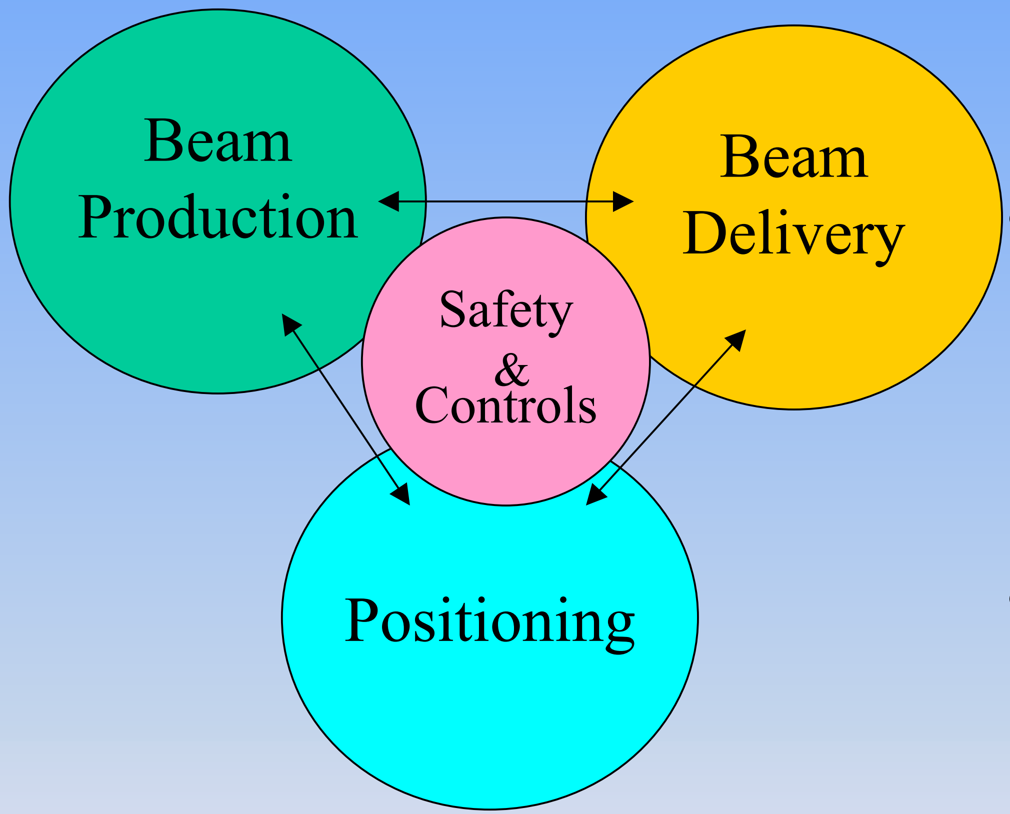
- Ugo Amaldi
- Regis Ferrand
- Yves Jongen
- Detlef Kirschel
- Gerhardt Krafft
- Charlie Ma
- Rock Mackie
- Yoshiharu Mori
- Niek Schreuder
- Steve Spotts
- Nancy Flanz
- etc…



There is a rich field of development starting again with collaborations forming.

Apologies to the developers of systems that I have not mentioned.

Technical Elements of a Particle Therapy *System*



- Beam Range Adjust
  - "electronic" (accelerator)
  - "mechanical" degrader
- Beam Delivery
  - Beam Spreading
  - Beam/Gantry Optics
  - Organ Motion
  - Pulsed or CW Beam
- Beam Alignment
  - Move Patient to Beam
  - Move Beam to Patient
- Positioning
  - Gantry or Not
  - Specialized or General

New/Ongoing Themes in ***Field*** of Particle Therapy

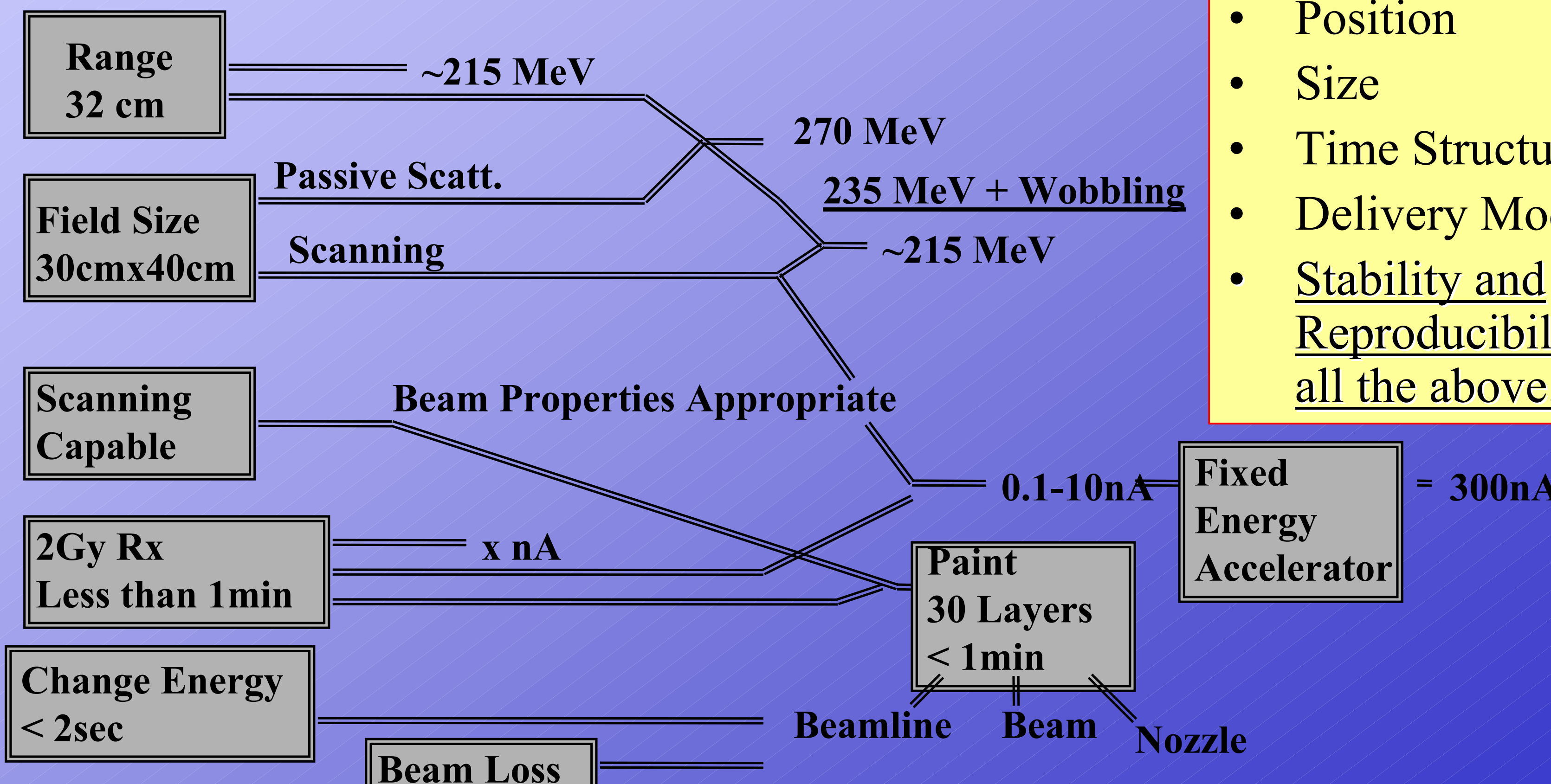
Examples for CONTEXT:

- Pencil Beam Scanning (PBS)
  - Impact on: Beam Parameters from Accelerator + Delivery
- Image Guided Therapy (IGRT)
  - Impact on: Imaging; Beam Alignment
- Organ Motion
  - Impact on: Beam Parameter timing; Beam Tracking
- Increased Throughput
  - Positioning, Aligning, Field-to-field time, Beam time

These may not be new concepts, but they are the current foci owing to the fact that the 'first' round of system specs have been satisfied. (i.e. the Berkeley/MGH report of 15 years ago.)

Clinical Specification to Implementation to Equipment Requirements!

- Beam Particle
- Energy
- Current
- Position
- Size
- Time Structure
- Delivery Modality
- Stability and Reproducibility of all the above.



System Solutions vs. Specifications

- How to deliver a Rx non-uniform dose distribution to a moving target with a desired conformance (Scanning):

  vs. Continuous Beam Scanning: with 3mm Sigma

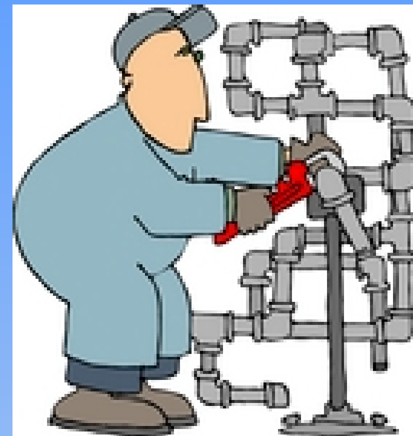
  – *This involves beam parameter TIMING issues, beam trajectory and range manipulation, etc.*

- How to deliver quality treatment to the maximum number of patients (Throughput)

  vs. Out of room setup; Energy Change in 2 seconds

  – *This involves automated remote operations*
    - *Imaging and Analysis and Correction of Position*
    - *Go from Field to Field without delays (e.g. Moving things remotely)*

- What should a 'customer' do?
  – Challenge Equipment Limitations - Give difficult Specs
  – Recognize Equipment Limitations - Give realistic Specs



The “Approach” you take:

Depends upon your equipment

and how you use it !

Or

The Equipment you select depends upon your approach

Particle Therapy Equipment "Complaints" and Tradeoffs

- Accelerator
  - Big and Expensive?
    - Dose Rate
    - Time Structure
    - Energy Switching
- Beam Line
  - Does one need them? (Multiple rooms)
  - Too Slow
    - Energy Switching
- Gantries
  - Big and Expensive?
    - Angles needed
    - Optics to support delivery systems
- Beam Delivery System
  - Want Scanning
    - (For all fields? Why?)
  - Change from field to field quickly
- Positioning
  - Not smooth or accurate or remote enough
  - Takes too long
- QA
  - QA Takes too long
  - End to End vs. Components

Modularity ?

Mix and Match ?

Particle Therapy Equipment Reactions/Approaches to Issues

- Accelerator
  - Smaller
  - Lower / Higher Dose Rates
- Beam Line
  - Single room facilities
- Gantries
  - Limited Range of Motion
- Beam Delivery System
  - Scanning with difficult Specs
  - Minimize Patient specific devices
  - Remote operation
- Positioning
  - Robots
  - External Alignment
- QA
  - Integrated/Automated/Faster
  - Component QA ?

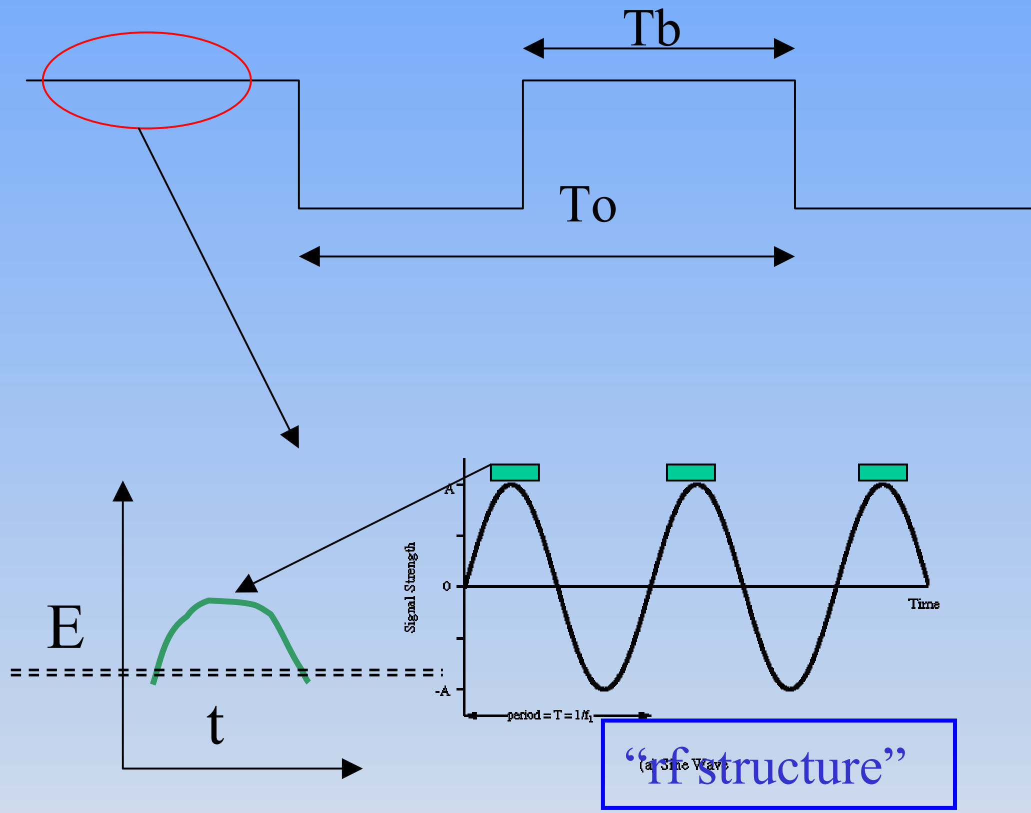
Modularity ?

Mix and Match ?

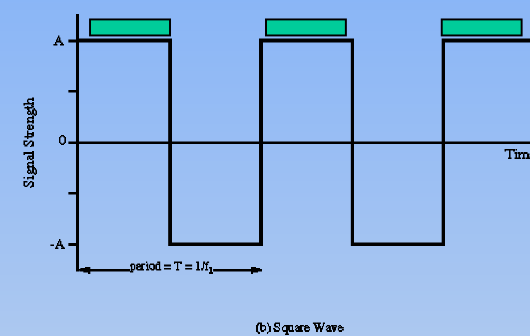
One Integrated System?

Definitions of Time Structure:

DC; CW, Pulsed, Duty Factor



Duty Factor = Tb/To



Examples:

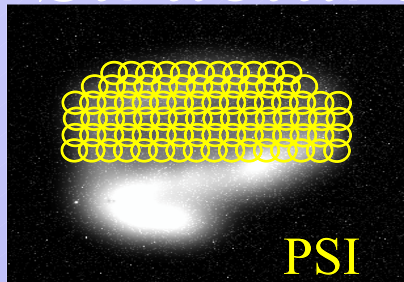
100MHz rf ==> 1nsec / 10 nsec

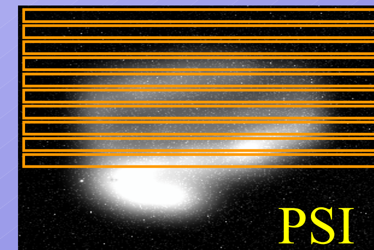
Rapid Cycling Synch => nsec/30 Hz

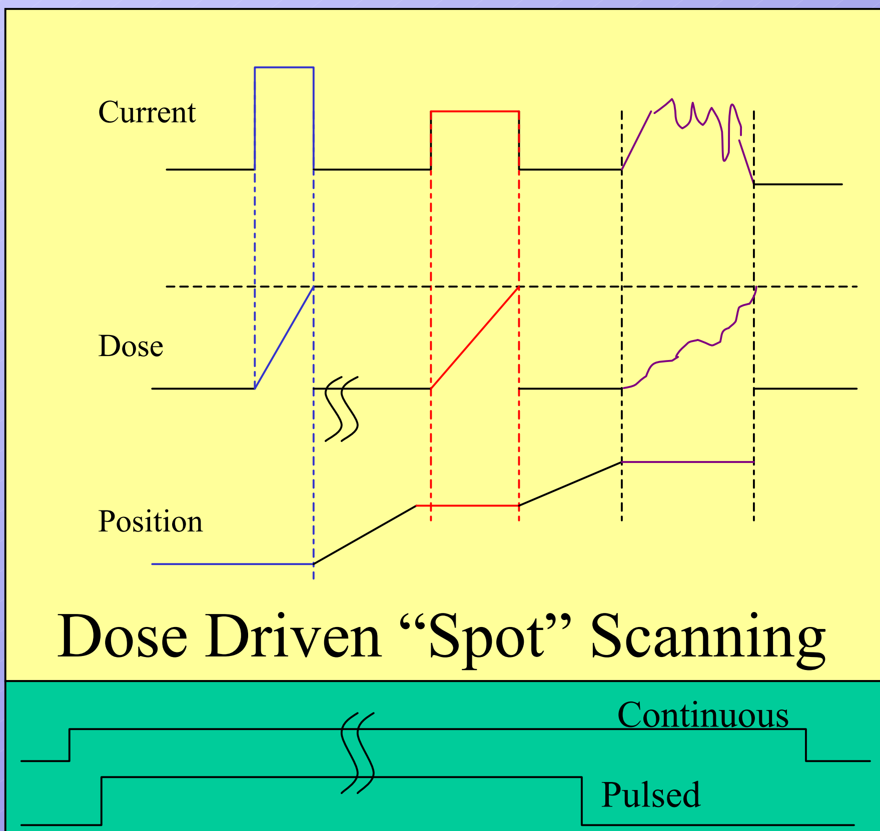
<u>Instrumentation Issues:</u>
- Response time of Detector
- Response time of Electronics
- Saturation / Recombination

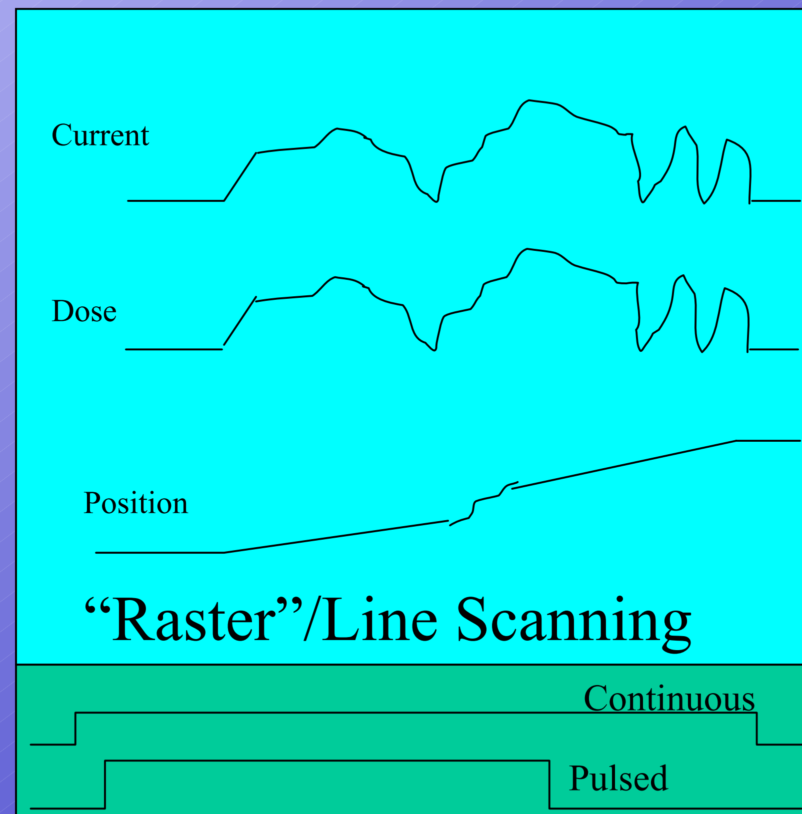
<u>Biological</u>
- Response time of Cell?

Time Structure in Pencil Beam Scanning





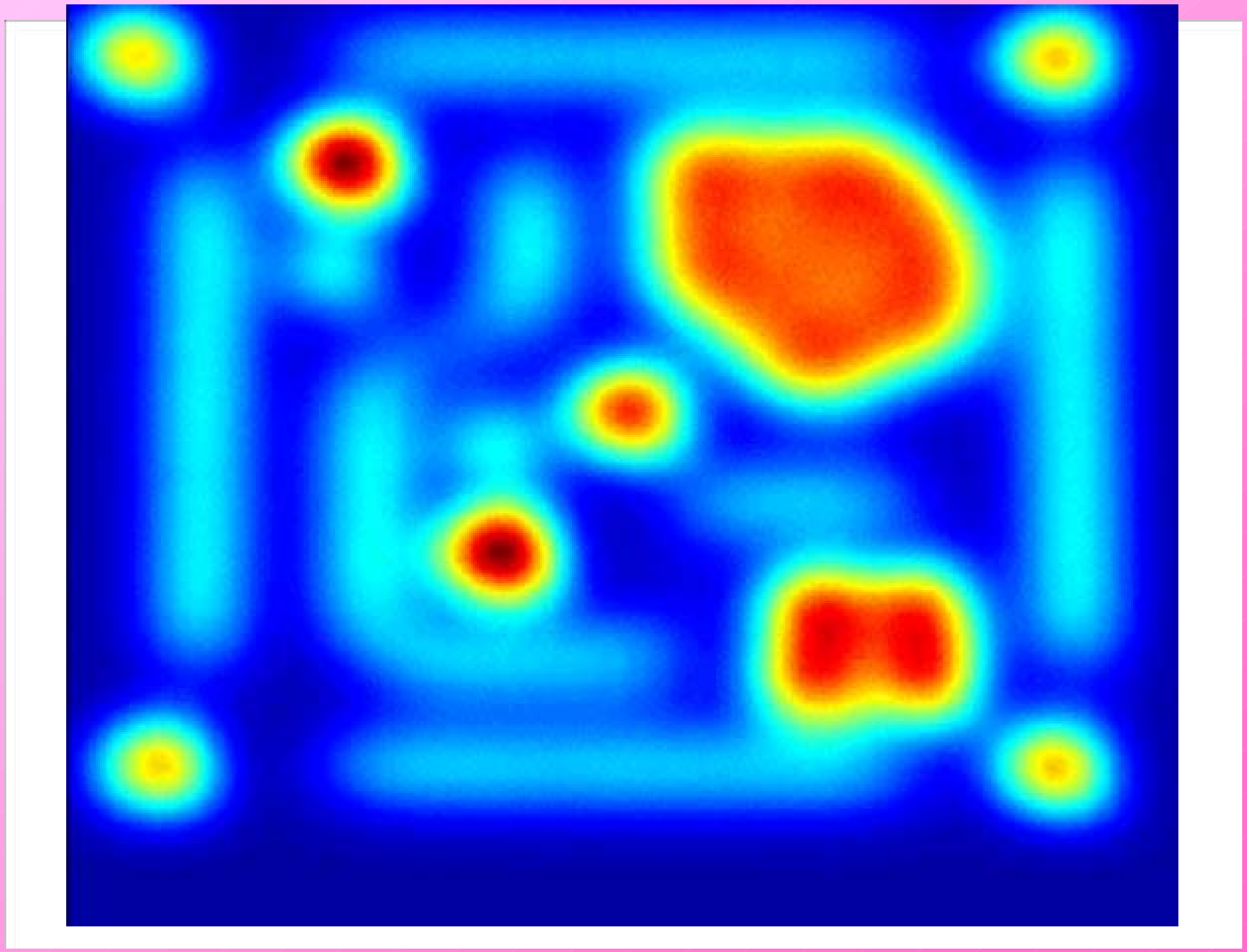




Continuous Stable/Unstable. Pulsed Short or Long

Flexibility in Scanning?
Mixed Spot and Line / Optimization of Time & Position

Scanning at MGH See my talk on Saturday
(postpone your flight!)



Unpaid Advertisement:

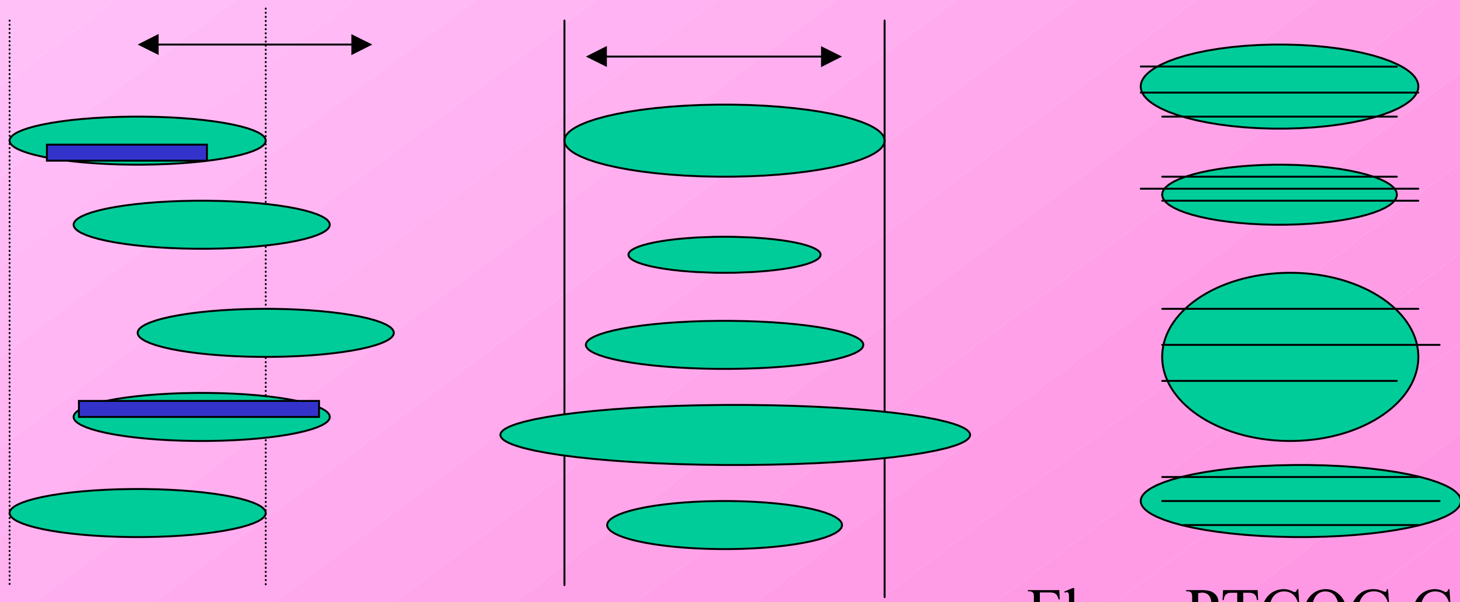
Among the many excellent Posters are the MGH/IBA/Pyramid contributions:

- **Experimental mapping of proton therapy system capability to pencil-beam scanning requirements**
- **Experimental comparison of pencil-beam scanning methods using the gamma-index criterion**
- **Quality Assurance test patterns for pencil beam scanning**
- **Determination of the dose equivalent near proton pencil beams**

Measurements, Clinical Relevance, Quality Assurance, Neutrons +

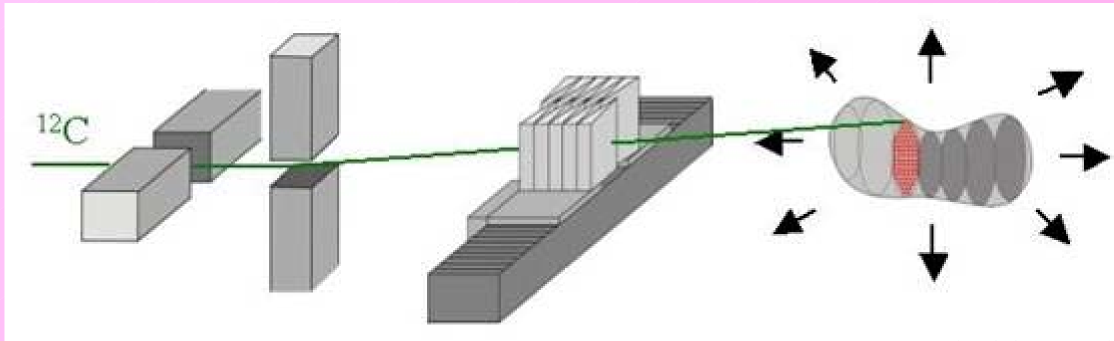
Target Motion – Tracking or Averaging

- Target Motion and Scanning – Time Scale?
  - Is scanning speed fast enough for tracking a target?
  - Is motion reproducible wrt respiration or body motion, or something?
  - What about range?
  - What about 'adaptive' TP with deforming (3D) targets.



3D Online Motion Compensation

S.O. Grözinger[1], Q. Li[2], E. Rietzel[1], W. Becher[1], T. Haberer[1] and G. Kraft[1]
[1]GSI Darmstadt; [2]IMP-CAS Lanzhou, China



"mechanical system"

magnetic scanner system

PMMA wedge system

suitable motion tracking system

dynamic treatment plan

Tests: 0.11Hz

a) static *b) no comp.* *c) with comp.*

Fig. 2: Test of lateral compensation accuracy. A homogenous pattern (a) is irradiated while an x-ray sensitive film is moved in a respiration-like 2D pattern. The strong motion effect (b) could automatically be compensated (c) by the prototype setup.

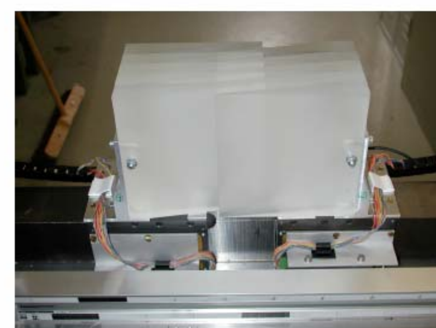


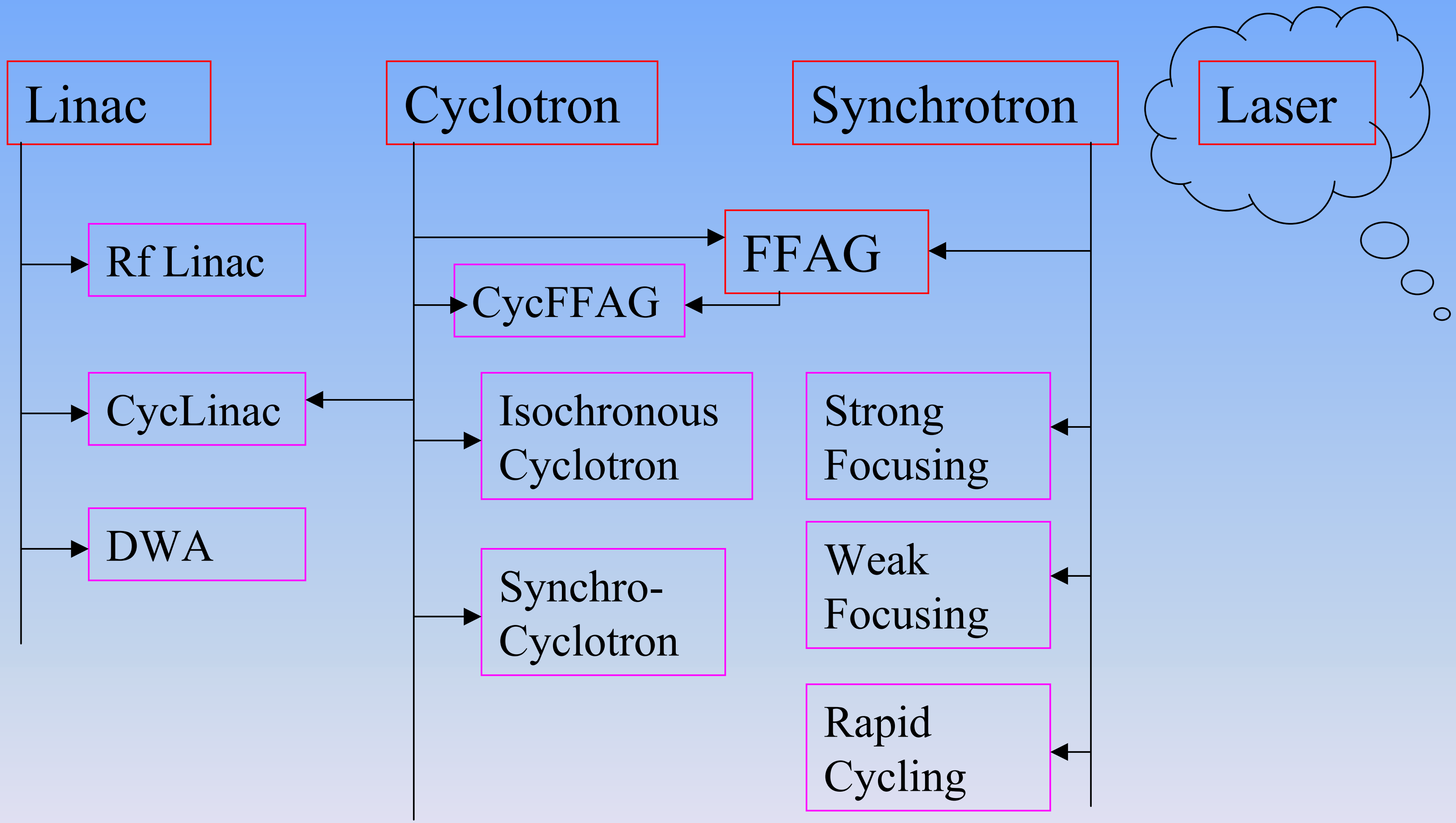
Fig. 1: Prototype of PMMA-wedge system for fast, passive energy modulation compensating the longitudinal component of target motion.

Preaching:

Pencil Beam Scanning is PBS

- *PBS is not "just" IMPT or compared with IMXT*
- *Intensity Modulation is required in PBS just to achieve a Single field with uniform dose.*
- *Additional modulation (of some sort, i.e. intensity, time, or velocity) is required to deliver a non-uniform dose.*
- *PBS Dose Distributions 'can' be better than IMXT*
- *Therefore: PBS is PBS and not IM anything.*
- *Therefore: We should Not use "IMPT"*
  - Use specific forms of PBS like:
    - *PBS/**SFUD** (Single Field Uniform Dose)*
    - *PBS/**NUD** (Non-Uniform Dose)*

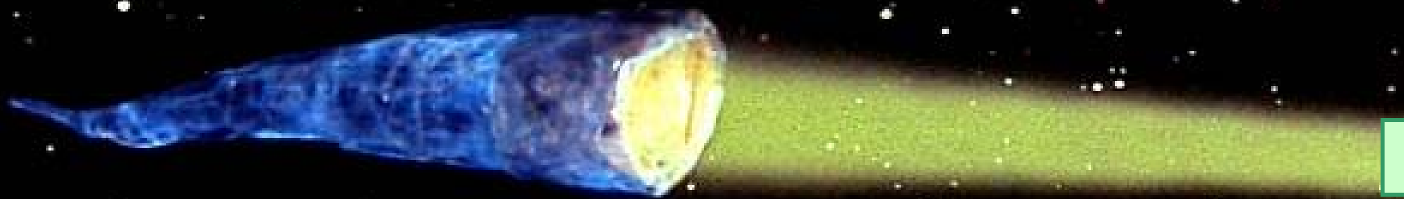
Subsystem: Types of Accelerators



Accelerator Development Now Underway Why?

- Smaller
- Cheaper

Xtreme-Accelerators?



-Proton Beam

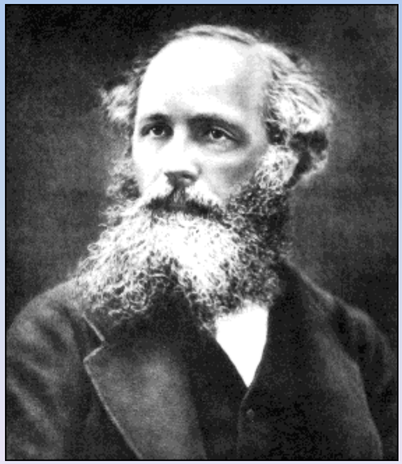
- Faster
- Stronger
- ***Different Parameters !!!***

Acceleration Mechanism(s)

$$\vec{F} = q\,\vec{E} + q\,\vec{v} \times \vec{B}$$

$$\mathbf{F} = q \cdot \left(-\nabla\Phi - \frac{\partial \mathbf{A}}{\partial t} + \mathbf{v} \times \mathbf{B}\right),$$

- ***Physics***: Anything that can create an electric Field which accelerates a charged particle in the direction of its motion.
  - E ~ dB/dt (changing magnetic field) (betatron)
  - E ~ Applied Voltage
    - DC Voltage
    - AC Voltage
  - "Create" an Electric Field
- ***Engineering:*** "Efficient use of Power"
  - One time through (Linac)
  - Reuse the Electric Field



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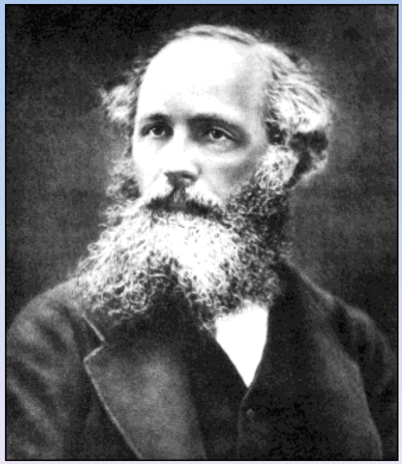
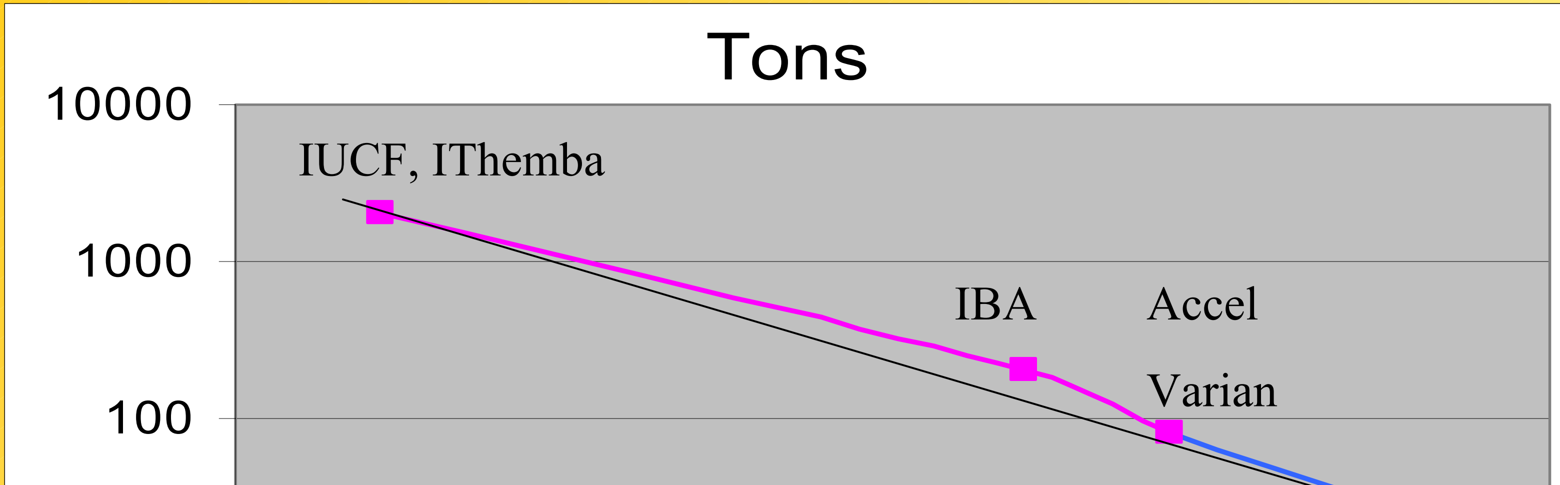
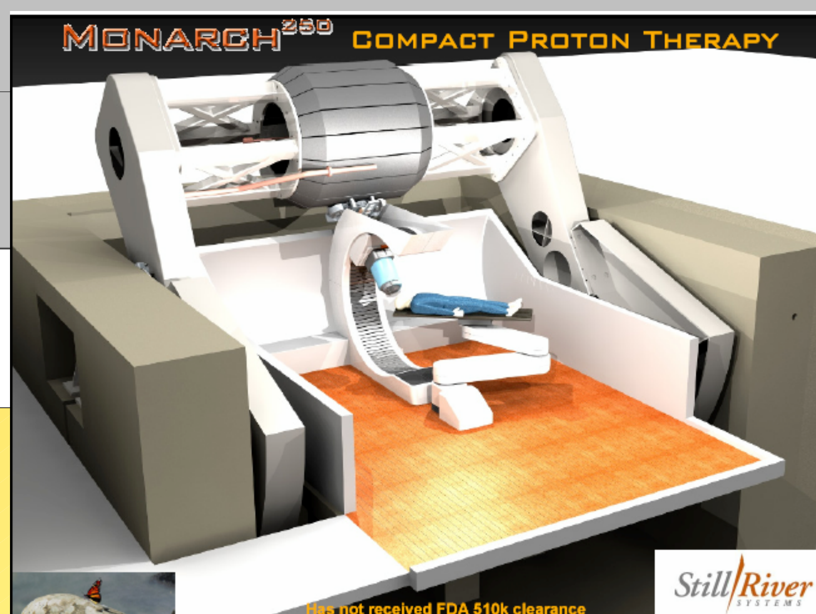


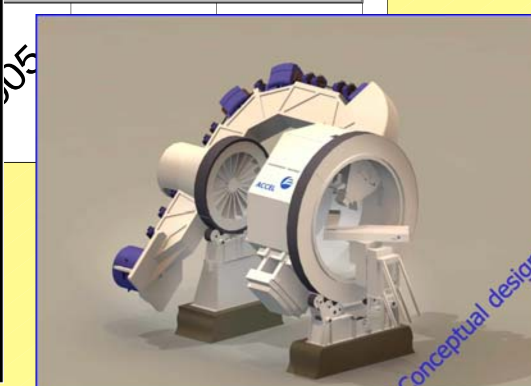
US/Germany/??

Smaller / Cheaper

Scaling DOWN Cyclotrons - Quantitatively







Other Places????

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Belgium

Cheaper

Single room – Less 'compact'

Comparing Apples with Apples

$20M should NOT be compared with $140M !!!!

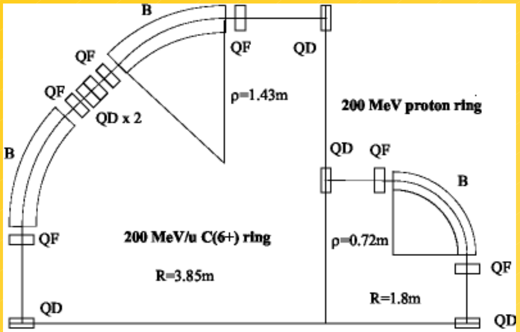
Cyclotrons

Magnetic Field………	Constant
Rf Frequency………..	Constant
Energy Change………	Degrader (150ms – 1 sec)
Current………………	100's na / 100's to 1 na
Pulse Frequency……..	Continuous (Rf) (~10ns) or X Hz
Pulse Length………..	Continuous (Rf) (~1ns)
Scanning Type………	All ?
Multi-Extraction…….	May be possible

- Lot's of Current at High Energy, but only Fixed energy cyclotron need it.
- Beam always available when you need it - Scanning / Organ Motion
  - (Different for SynchroCyclotrons)
- High Emittance - Gantries (if using a beam transport system)
- Energy Change speed limits (mechanical/magnetic)?

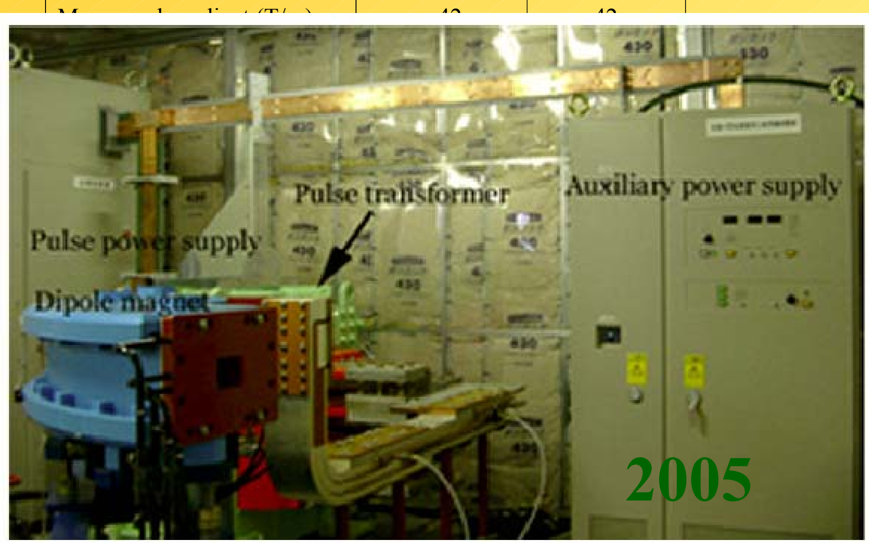
TABLE-TOP PROTON SYNCHROTRON RING FOR MEDICAL APPLICATIONS

K. Endo, K. Mishima S. Fukumoto and S. Ninomiya, KEK, Tsukuba, Japan
G. Silvestrov, BINP, Novosibirsk, Russia



	BINP	Frascati	KEK	unit
Max. energy	200.0	200.0	200.0	MeV
Inj. energy	1.0	12.0	2.0	MeV
Circumference	4.7	6.4	10.5	m
Av. diameter	1.5	2.0	3.3	m
Bending radius	0.43	0.54	0.72	m
Max. dipole field	5.0	4.0	3.0	T
Period	4	4	4	
Tune, ν_x/ν_y	1.4/0.45	1.42/0.54	1.4/0.75	
Max. dispersion	0.4	0.63	1.0	m
Cell structure	FODB	BODO	OFOBDB	
Total weight	~1	~1.5	~2	ton

Ring	Proton	C_{6+} ion
Max. energy (MeV/u)	200	200
Injection energy (MeV/u)	2	1
Max. dipole field (T)	3	3
Length of dipole (m)	1.126	1.126
Bending radius (m)	0.7165	1.4331
Number of dipoles	4	8
[illegible]	[illegible]	[illegible]



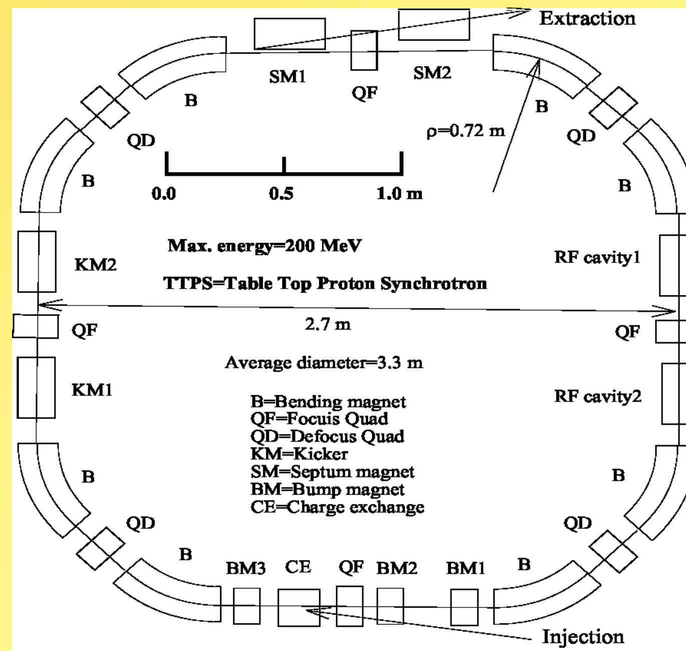
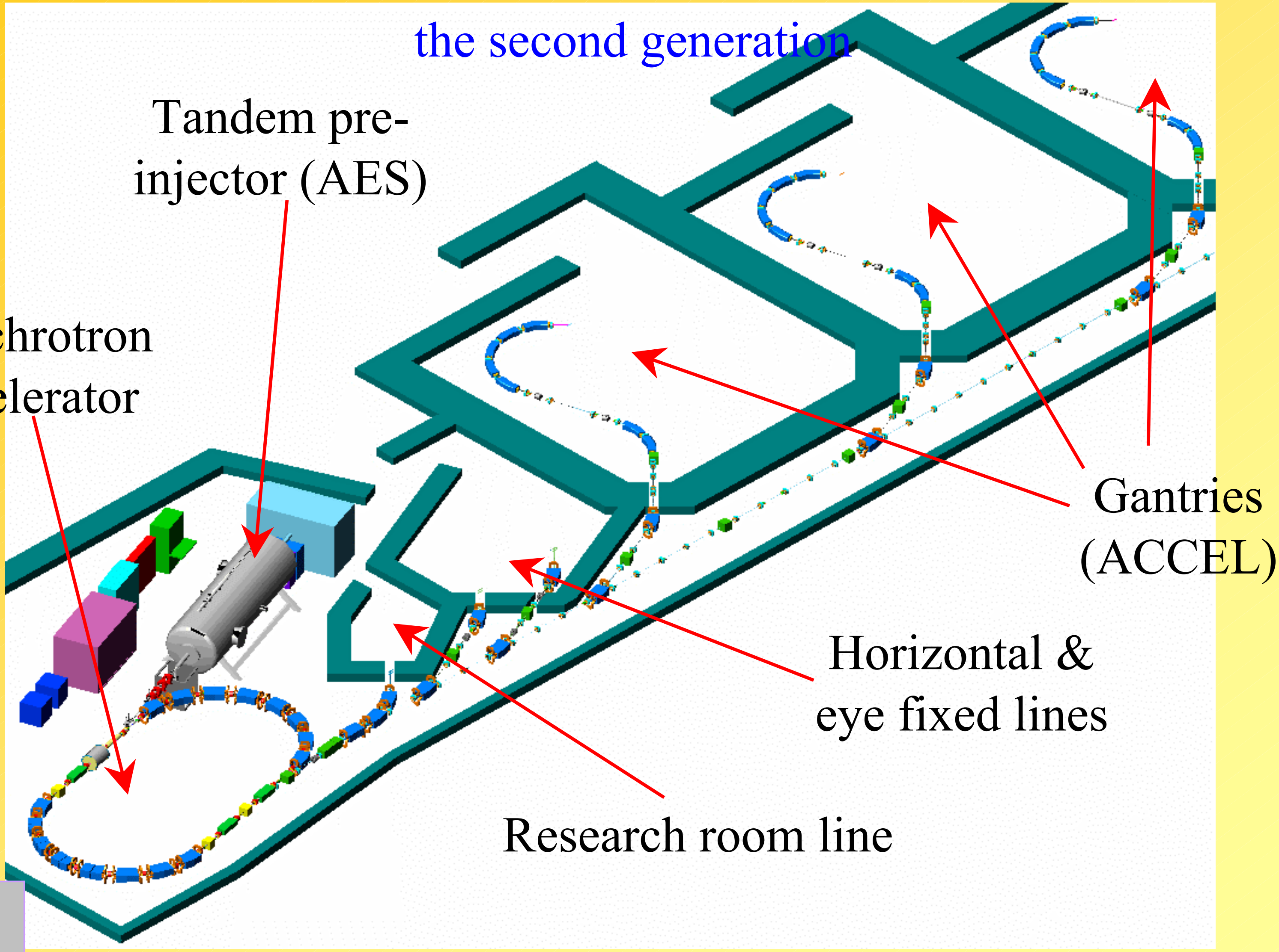


Figure 1: Present ring layout.

The RCMS (p)

Rapid Cycling Medical Synchrotron



RUSSIA

Smaller / Cheaper

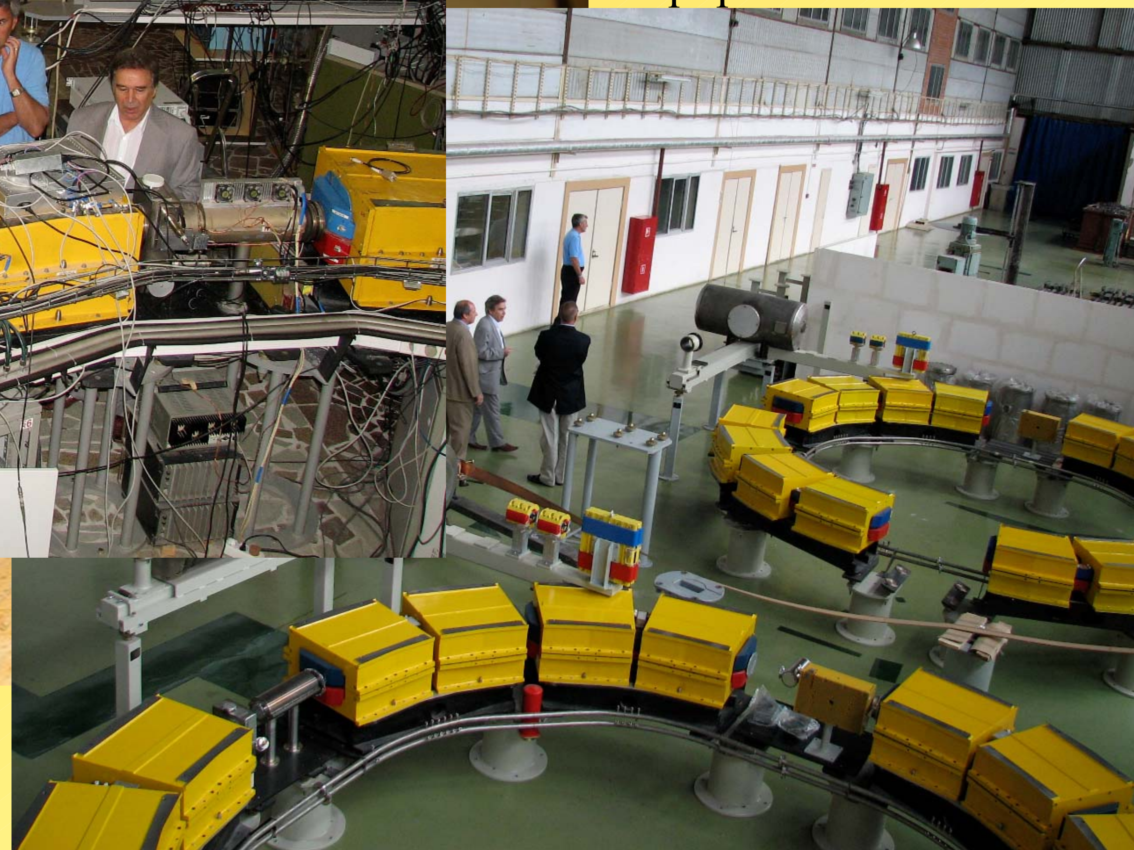
Balakin Device

ProTom

Scanning Optimized Synchrotron

All non-essential

equipment minimized



- Simple
- Light
- Inexpensive

Synchrotrons

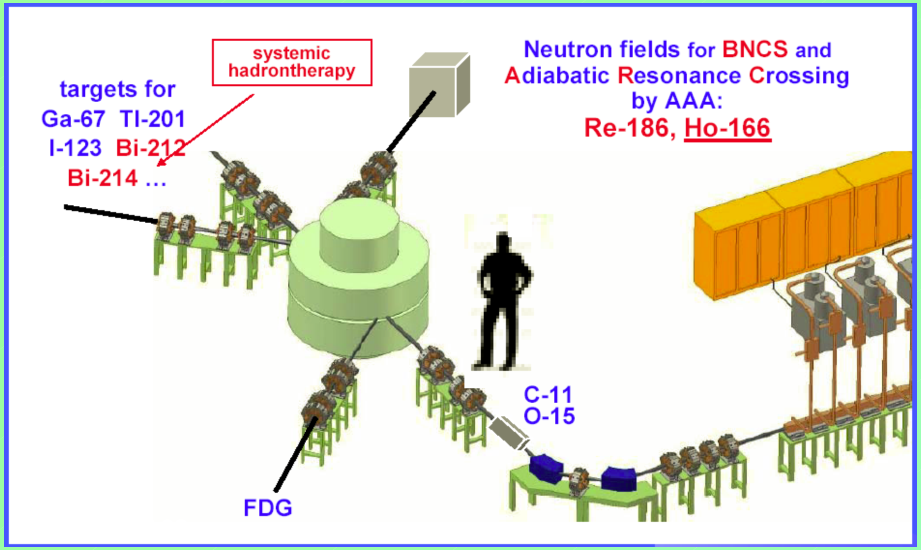
Magnetic Field………	Changing
Rf Frequency………..	Changing
Energy Change………	Acceleration Cycle (or 30Hz~sec)
Current……………….	< > nanoamps
Pulse Frequency……..	0.5 Hz to 30 Hz + Rf
Pulse Length………...	~ second(s) (or usec)
Scanning Type………	Spot / (Depends?)
Multi-Extraction…….	Not Easy (No)

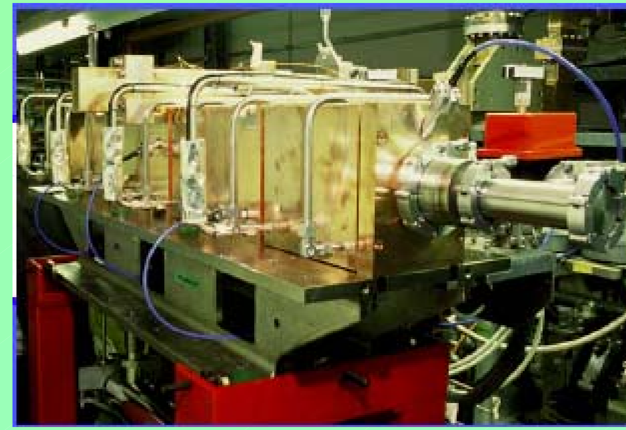
- Enough Current.
- Beam Time Structure (maybe) - Scanning (not line?) / Organ Motion
- Lower Emittance - Gantries (if beam transport is used)
- Energy Change time linked to acceleration time.
- (RPM) At 30 Hz in 120 sec ==> 3600 pulses !

Italy /England /IBA

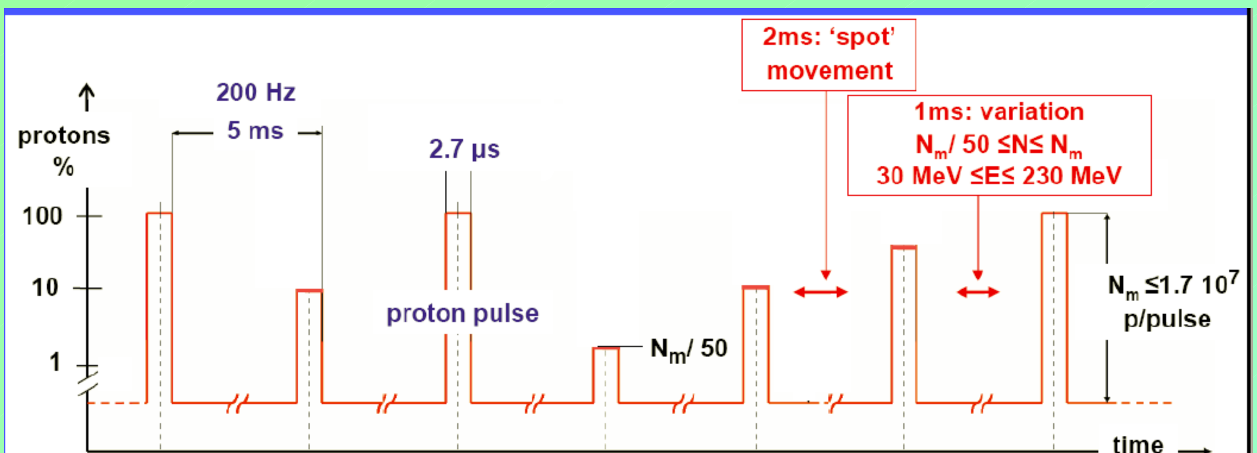
"CycLinac" Concept

Faster / Stronger





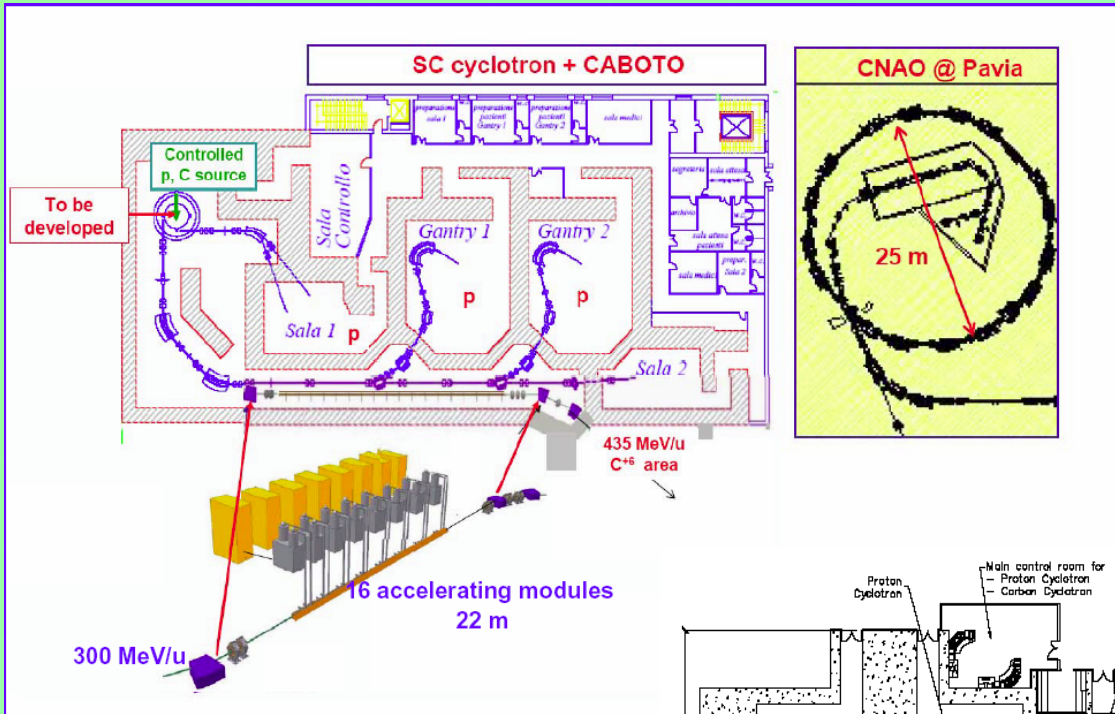
IDRA- *Institute for Diagnostic and RAdiotherapy (Protons)*



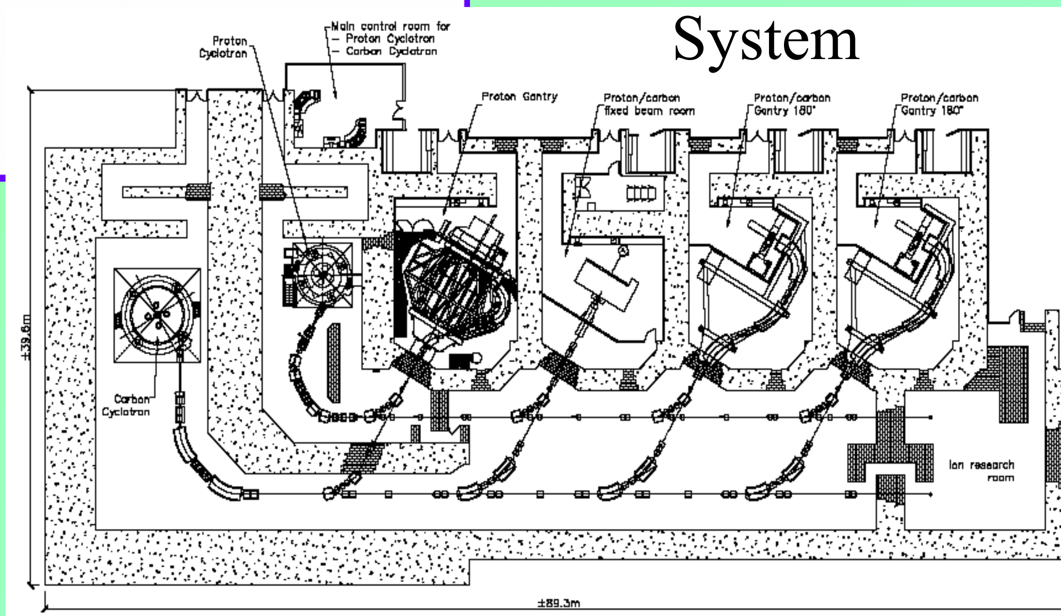
- Collaboration to build LIBO (***LI***nac ***BO***oster)
  - –TERA, CERN, INFN (Milan and Naples)
  - 3 GHz!,
  - 15.7 MV/m; tested with 62MeV beam from LNS (INFN) cyclotron,
  - 80kW (Modest Power),
  - small gap (8mm)

Ugo Amaldi

CABOTO- *CArbon BOoster for Therapy in Oncology*



IBA Multi Particle System



Ugo Amaldi

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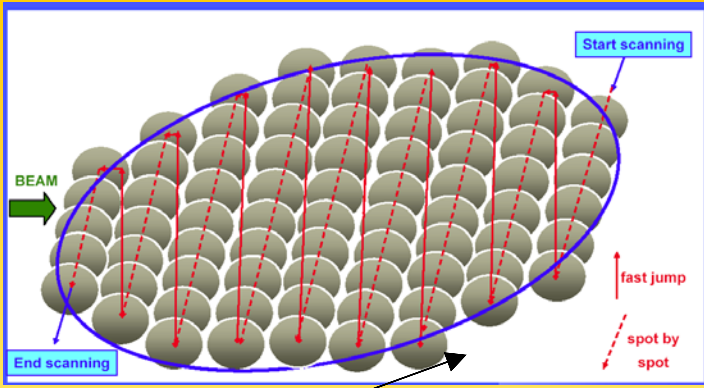
CycLinac



- Magnetic Field……… • Constant
- Rf Frequency……….. • Constant
- Energy Change……… • Linac Modules (200 Hz) (Beamline?)
- Current………………. • ~na
- Pulse Frequency…….. • 200 Hz (5msec)
- Pulse Length……….. • usec
- Scanning Type……… • Spot
- Multi-Extraction……. • Yes

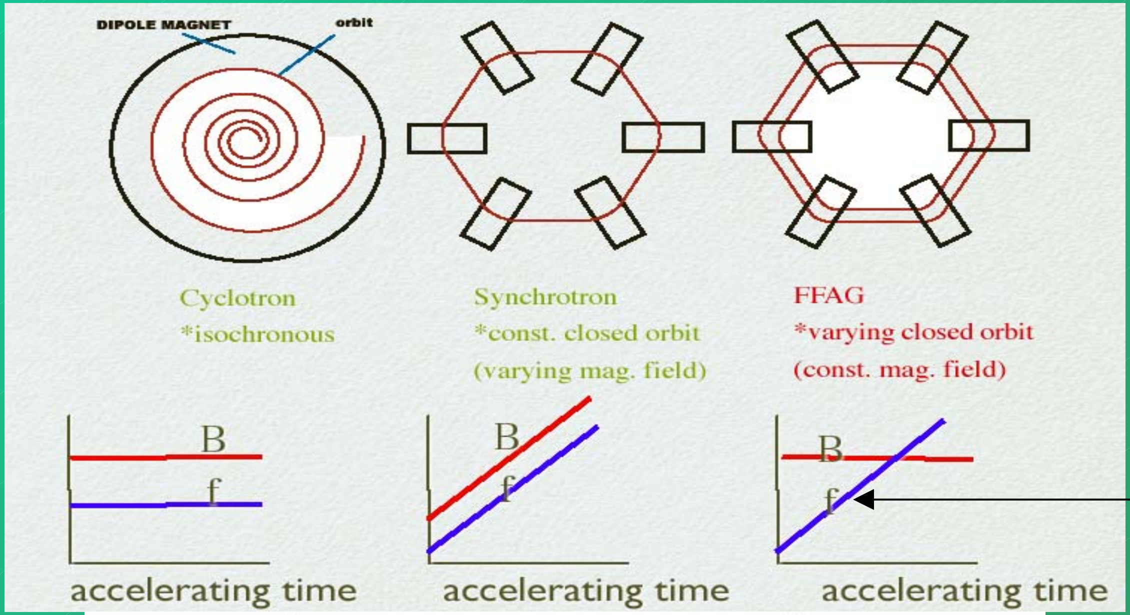
- Maybe enough Current.
- Beam Time Structure (usec pulses) - Instrum / Scan (not line) / Organ Motion
- Lower Emittance - Gantries
- Energy Change time linked to fast Rf pulses (and Beamline?).

Fixed Field Alternating Gradient - FFAG

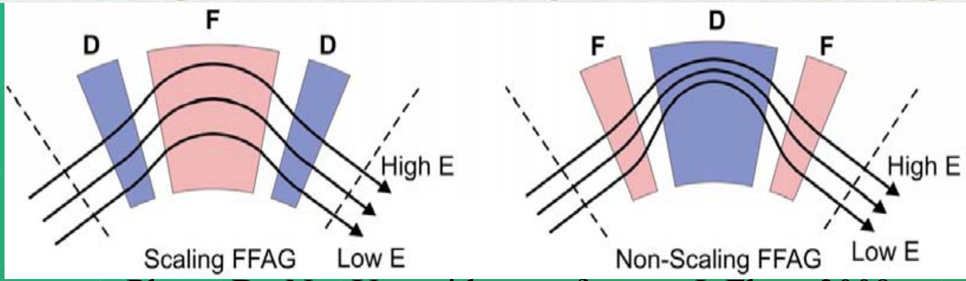
- Strong Focusing – Alternating Gradient Cells
- A Ring of Magnets like a Synchrotron, BUT Fixed Field like a Cyclotron.
- Beam Orbit moves within the magnets, but a very small amount, allowing small, light magnets to be used, over a wide range of momentum.
- Fast Acceleration, Variable Energy

"Macro Structure"

- High Average Current (Possible large rep rate, short injection pulse)



Or Constant



Mori

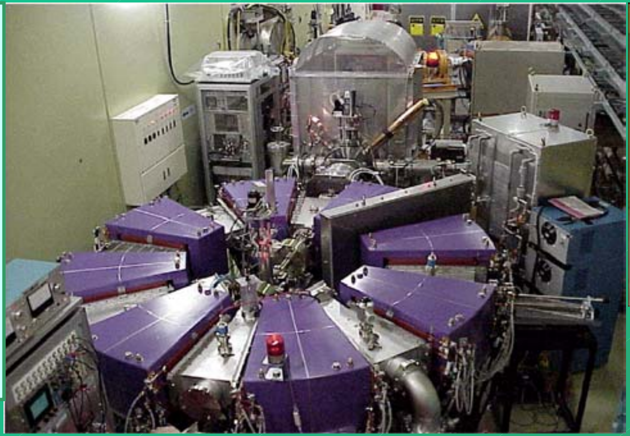
Japan/France/UK/ US (FNAL)

Faster / Smaller

FFAG – Fixed Field Alternating Gradient

Proof of Principle Machine ! 2000 KEK 500keV

(Remember when that was possible?)



"CycFFAG" - 2006 KEK
150 MeV / 100Hz at
/ 90% extraction efficiency

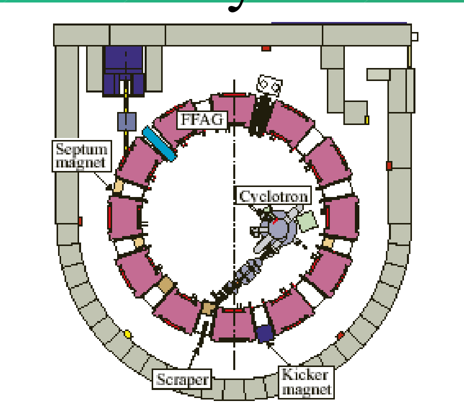
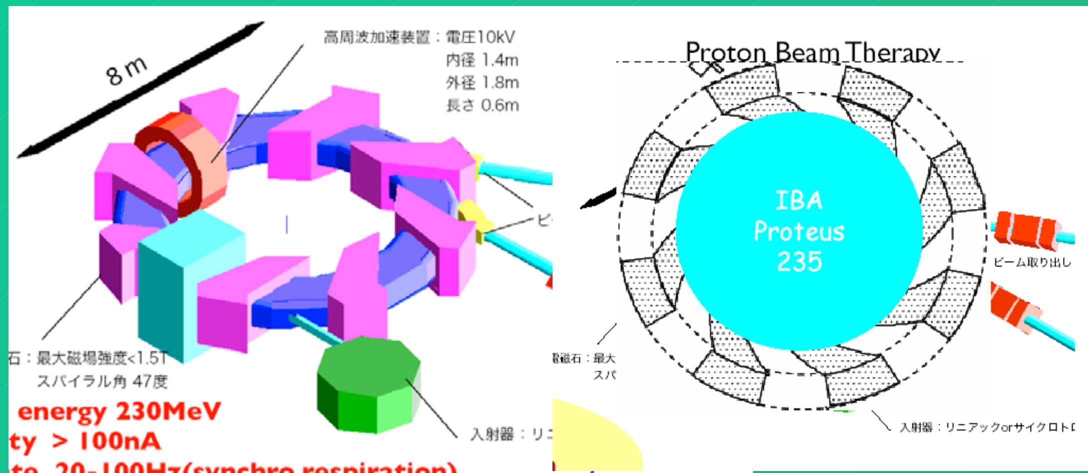
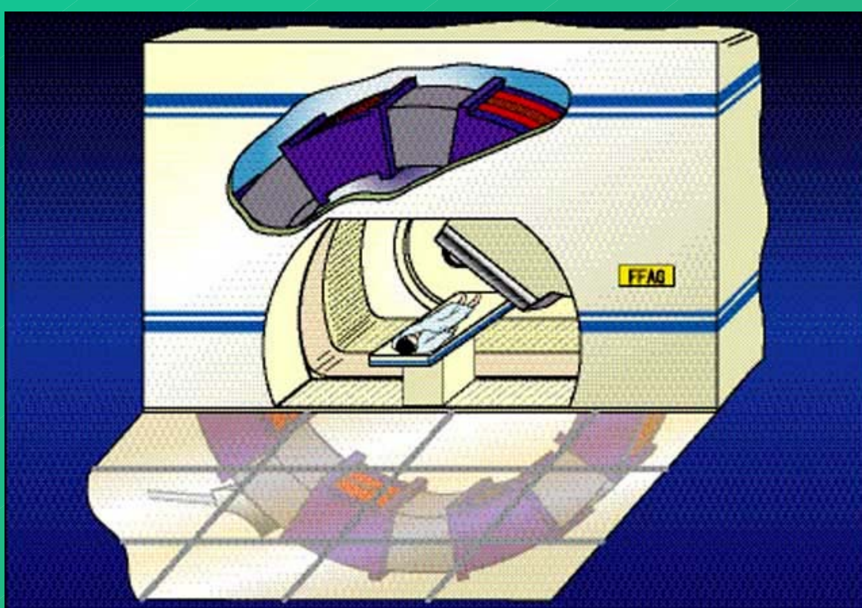
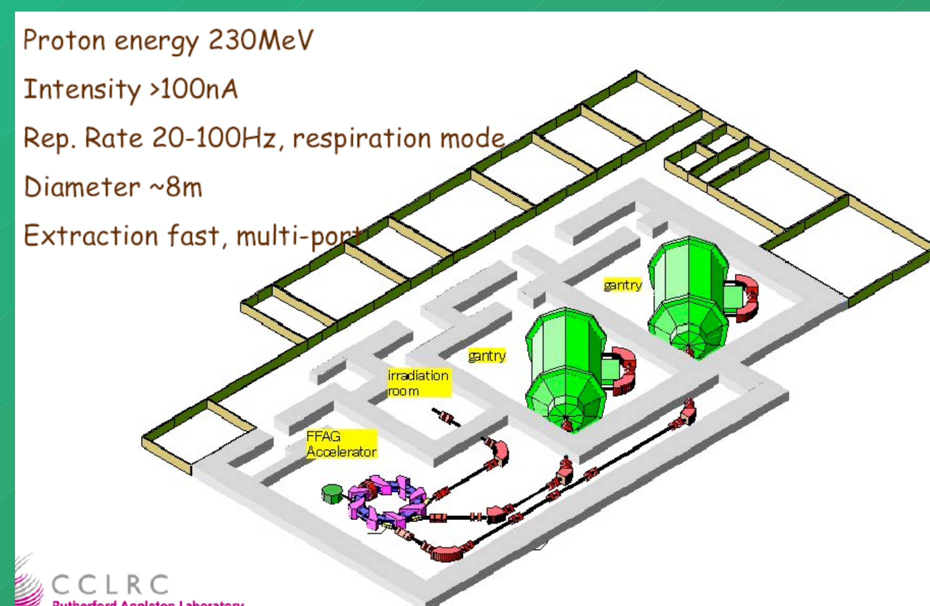


Fig 1. Layout of extraction devices.

Proton Options New *FFAG* Options







RACCAM Project - ANR Contract
(Recherche en ACCélérateur et Applications Médicales)

Bruno Autin	LPSC, collaborator
Jacques Balosso (MD)	Gren. Hospital
Johann Collot	LPSC
Joris Fourrier (PhD)	LPSC
Emmanuel Froidefond	LPSC
Franck Lemuet	CEA & CERN
François Méot	CEA & LPSC
Damiene Neuvéglise	SIGMAPHI
Jaroslaw Pasternak	LPSC
Thomas Planche (PhD)	SIGMAPHI
Pascal Pommier (MD)	Lyon Hospital
students	
Florence Martinache	ENSPG (2006)
Abdulhamed Chaikh	Medical Phys., Gren.
Matthias Grimm	Munich Univ.
Jean-Baptiste Lagrange	ENSPG

Collaboration:
AIMA, IBA

Project goals:
- Design medical installations based on FFAG principle
- Build magnet prototype
- Participate in ongoing global FFAG effort (EMMA, NuFact, etc.)

FFAG

Magnetic Field………	Constant
Rf Frequency………..	Varies (or Constant!)
Energy Change………	Move Kicker
Current……………….	> 100 na
Pulse Frequency……..	100 Hz
Pulse Length………..	1usec
Scanning Type………	Spot
Multi-Extraction…….	Yes

- Plenty of current (more than needed?)
- Beam Time Structure (usec pulses) - Instrum / Scanning / Organ Motion
- Lower Emittance - Gantries
- Energy Change time may be an issue

Acceleration Mechanism(s)

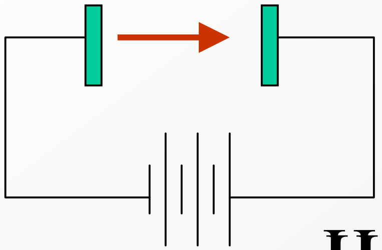
$$\vec{F} = q\,\vec{E} + q\,\vec{v} \times \vec{B}$$

- ***Physics***: Anything that can create an electric Field which accelerates a charged particle in the direction of its motion.
  - ~~E ~ dB/dt (changing magnetic field) (betatron)~~
  - E ~ Applied Voltage
    - DC Voltage
    - AC Voltage
  - "Create" an Electric Field
- ***Engineering:*** "Efficient use of Power"
  - One time through (Linac)
  - Reuse the Electric Field
    - Cyclotron
    - Synchrotron
    - FFAG

US (LLNL/Tomo)

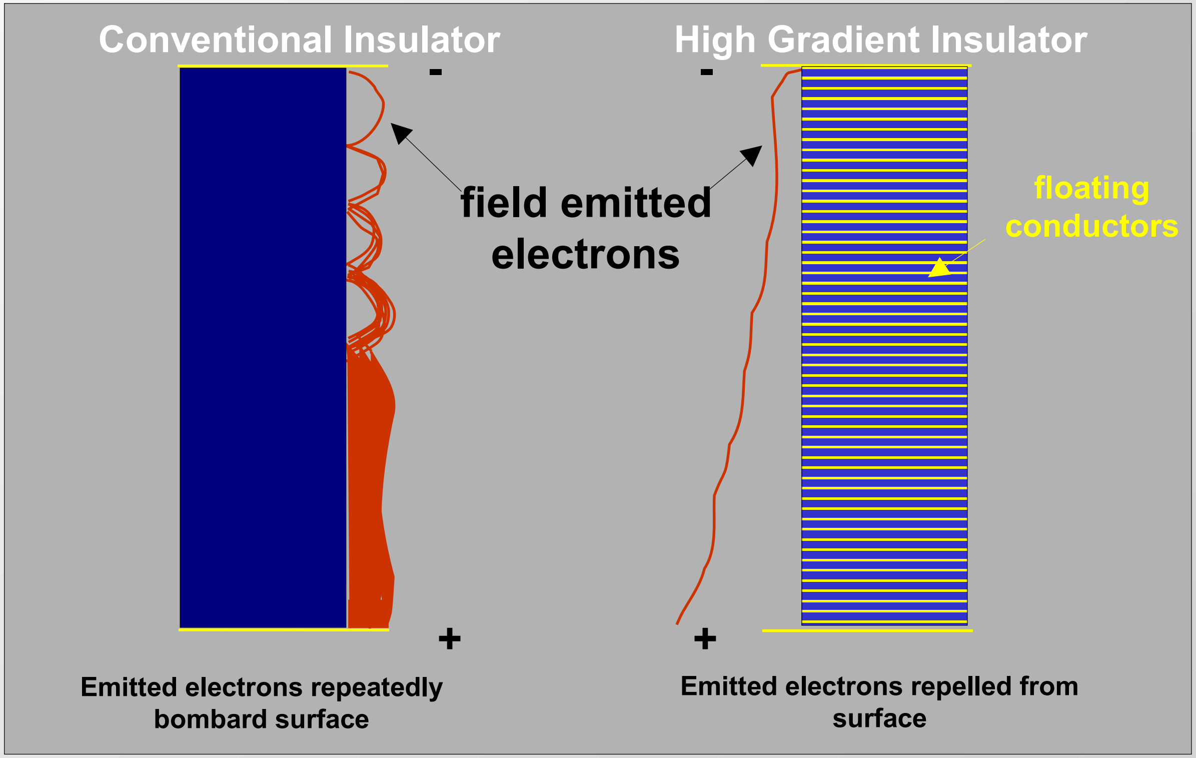
Smaller / Cheaper / Faster

DWA - Dielectric Wall Accelerator



George Caporaso et. al., LLNL

How High Gradient Insulators Work



Mackey, Caporaso et. al.

`

DWA supports a virtual traveling wave by continuous wall excitation accelerator*

Longitudinal Electric Field Plot

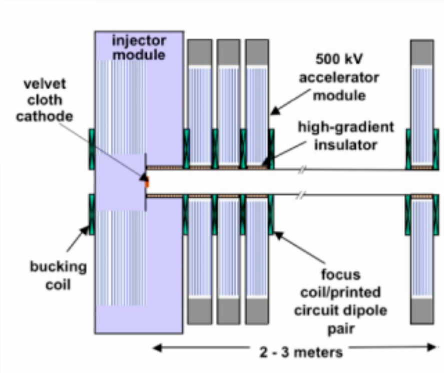
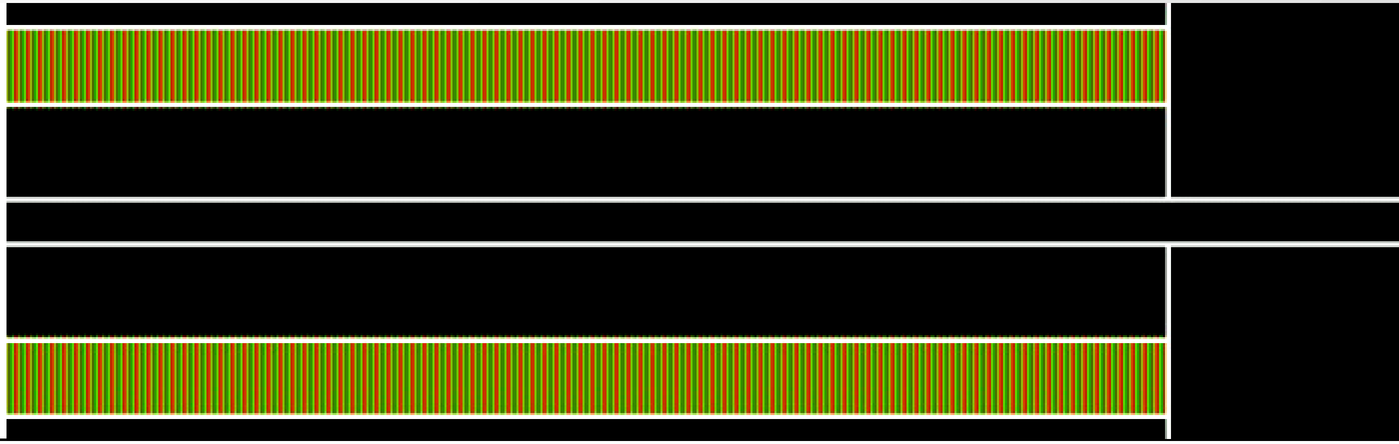
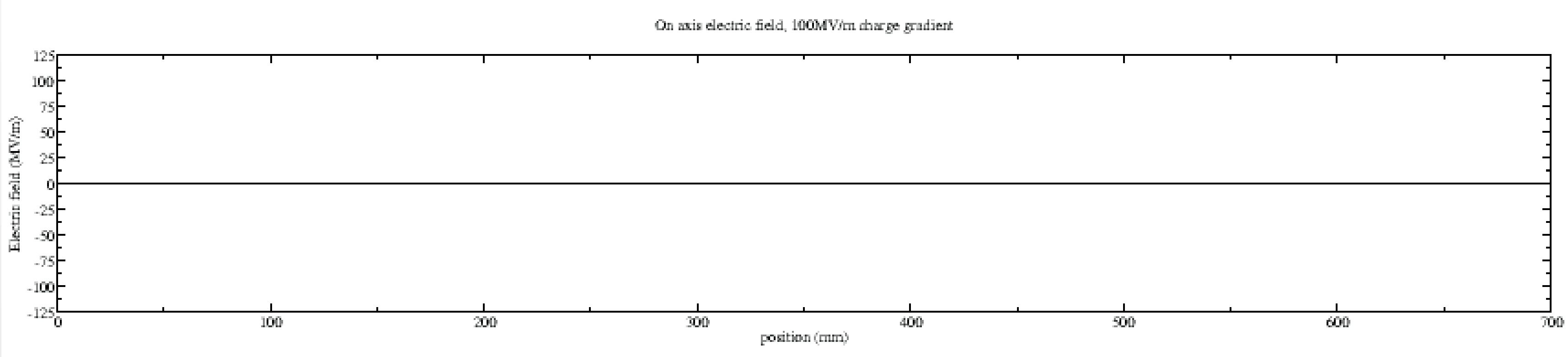


Figure 1: Dielectric wall induction accelerator configuration.





***patent pending**

Mackey, Caporaso et. al.

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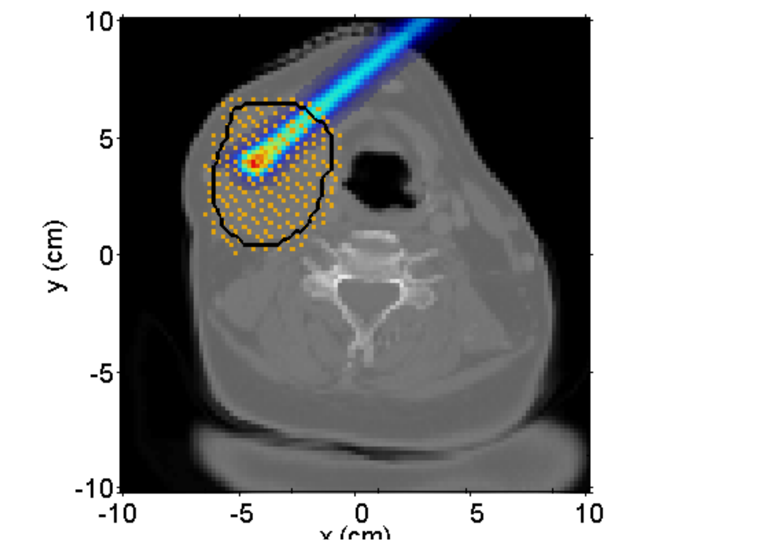
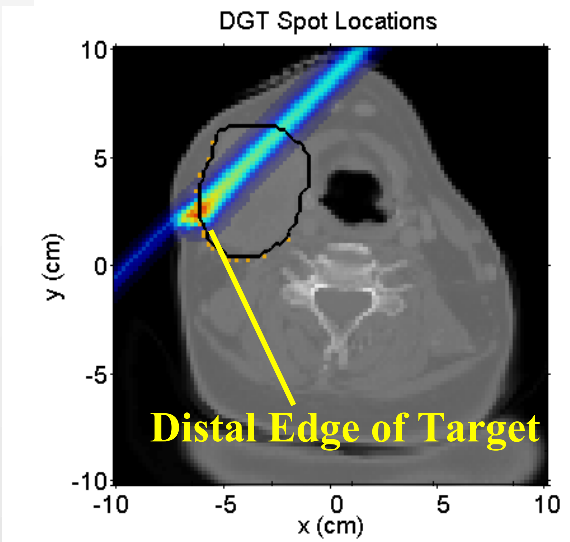
Spot Scanning and DET

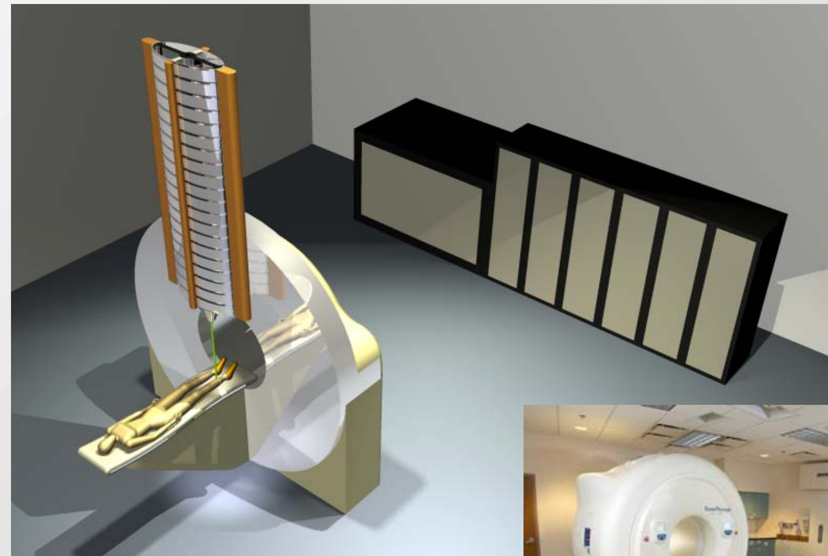
SS Spot Locations (~300)



DET Spot Locations (~20)



TomoTherapy
Next Generation



- **For DET multiple directions or arc therapy and intensity modulation required to obtain uniform dose distributions.**

Please Do Not Use without reference

Mackey, Caporaso et. al.

DWA

• Magnetic Field………	• Constant
• Rf Frequency………..	• n/a, DC timed field
• Energy Change………	• Pulse to Pulse
• Current………………	• ?
• Pulse Frequency……..	• 10's Hz
• Pulse Length………..	• nsec
• Scanning Type………	• Distal Edge Tracking
• Multi-Extraction…….	• No

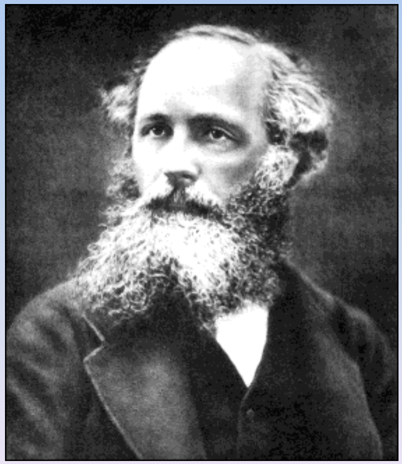
- Current?
- Beam Time Structure (nsec pulses) - Instrum / Scanning / Organ Motion
- Pulse to Pulse change of Energy, Beam Size, Current
- At 100sec/10Hz = 1000 pulses. (Distal Edge Tracking uses less spots.)

Acceleration Mechanism(s)

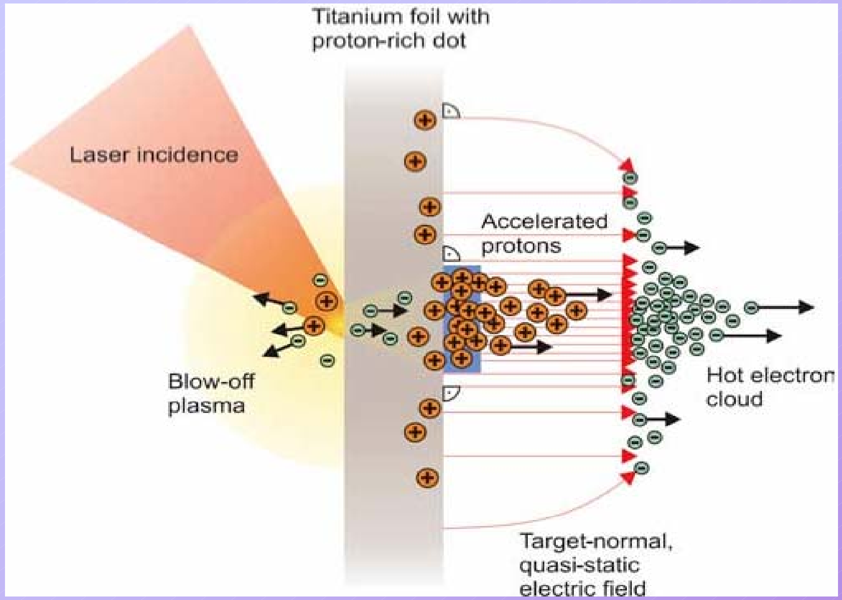
$$\vec{F} = q\,\vec{E} + q\,\vec{v} \times \vec{B}$$

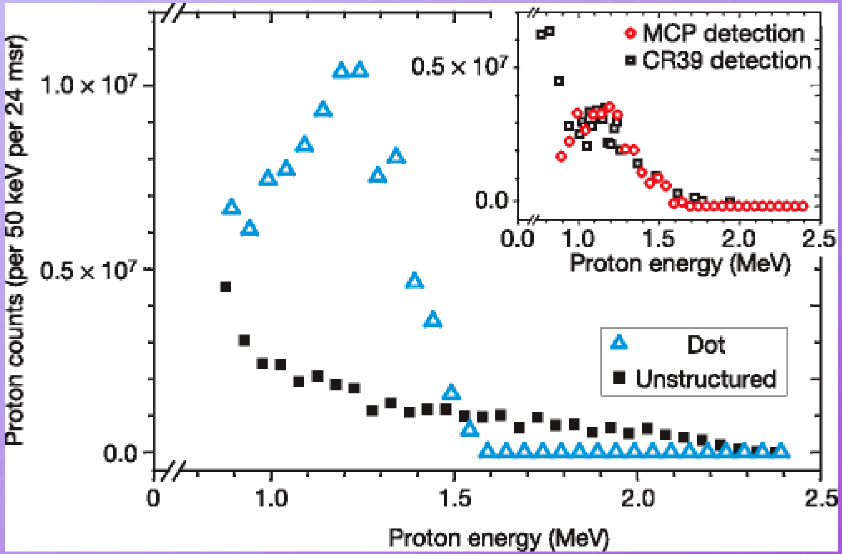
$$\mathbf{F} = q \cdot \left(-\nabla\Phi - \frac{\partial \mathbf{A}}{\partial t} + \mathbf{v} \times \mathbf{B}\right),$$

- ***Physics***: Anything that can create an electric Field which accelerates a charged particle in the direction of its motion.
  - E ~ dB/dt (changing magnetic field) (betatron)
  - E ~ Applied Voltage
    - DC Voltage
    - AC Voltage
  - "Create" an Electric Field
- ***Engineering:*** "Efficient use of Power"
  - One time through (Linac)
  - Reuse the Electric Field



Laser Acceleration Mechanism





Energy Spectrum Measurement

- Intense Laser Pulse (10^{20} W/cm^2)
  Femptosec --> Picosec
- Plasma is created which accelerates electrons OUT of the target.
- Protons from a proton rich deposit follow, being accelerated by the large Electric field generated (10^{12} V/m)
- Energy Gain of several tens of MeV, depends upon intensity of laser pulse, target capability…
- e.g. theoretical example:
  - Laser = 10^{21} W/cm^2, 30 fs pulse
  - Target 2μm
  - ➔ 180 MeV

Vol 439 26 January 2006/nature04492

H. Schwoerer

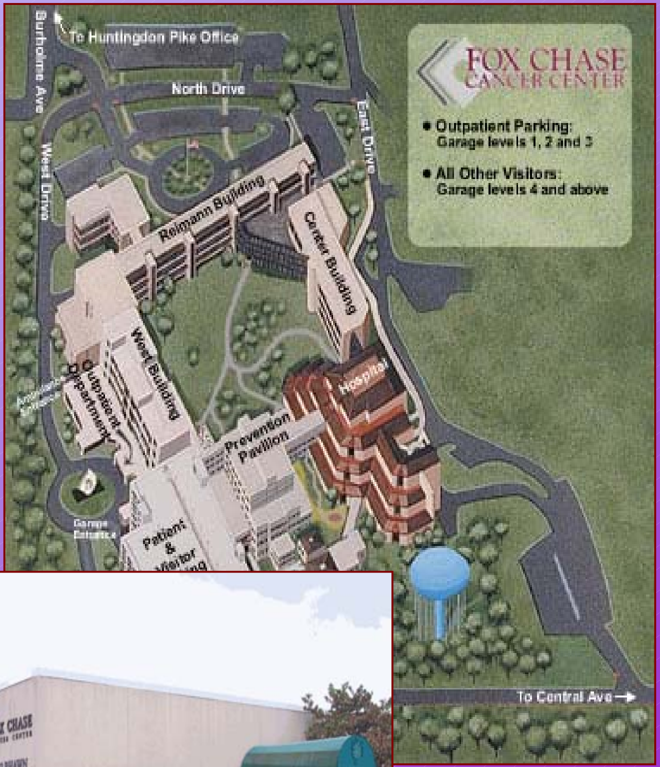
Liste des projets

1- Projets de développement d'équipements laser pour la protonthérapie

- **Projet Fox Chase Center (USA)**
  - Equipement : laser femtoseconde de 20 TW (laser de 100 TW en développement)
  - Résultats actuels : production de protons de 6 MeV (spectre maxwellien) avec le 20TW
- **JAERI (Japon): « Medical laser Vallet »**
  - Equipement : Lasers 10 TW et 30 TW fonctionnant très bien
  - Résultats actuels : Beaucoup de résultats très intéressants à 5 MeV.
- **Strathclyde (Ecosse)**
  - Equipement : laser 20 TW qui sera « boosté » a 200 TW
- **Dresden (Allemagne)**
  - Equipement : laser 150 TW
- **Sherbrooke (Canada)**
  - Equipement : laser 200 TW, évolution vers le petawatt
- **Propulse (France)**
  - Equipement : laser 100 TW puis évolution rapide vers 200 et 500 TW

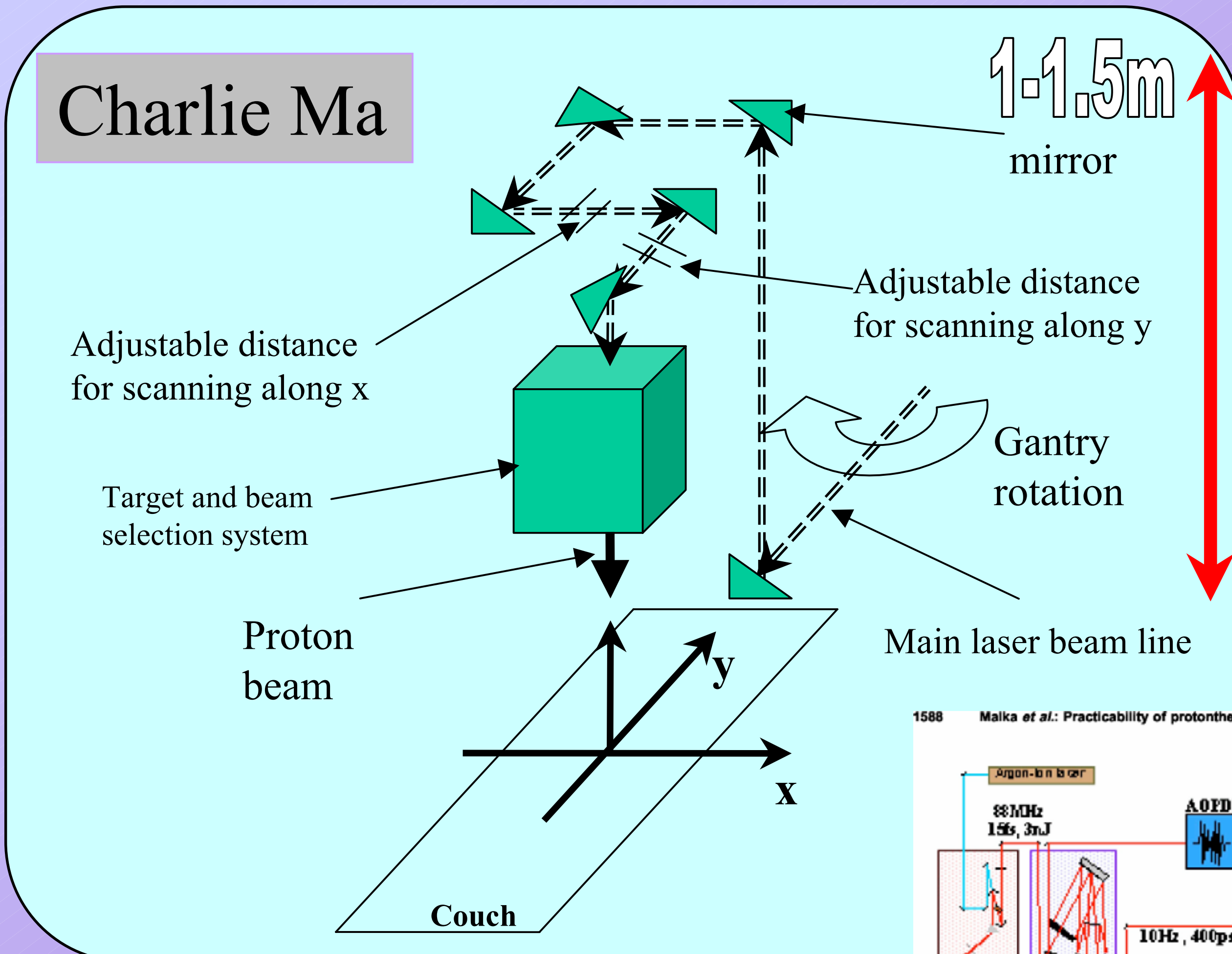
The Laser-Proton Facility

- Renovation completed in June 2005
- An off-campus facility for experimental studies
- Laser/target chamber/shielding installed/commissioned in Sept 2006
- Research laser-proton accelerator license granted by the State



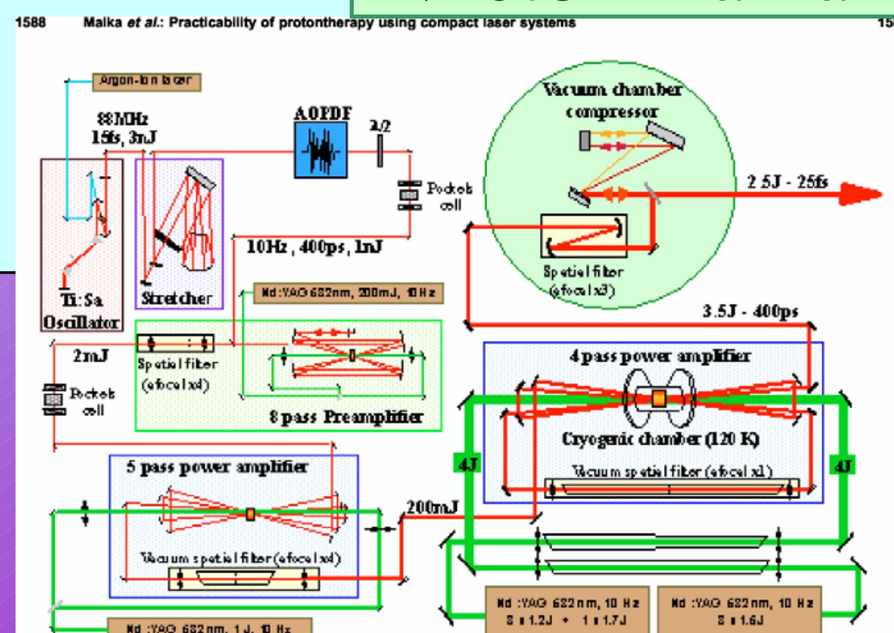
Charlie Ma

Charlie Ma



System Design

Victor Malka



Phys Rev:(Linz and Alonso)

Laser

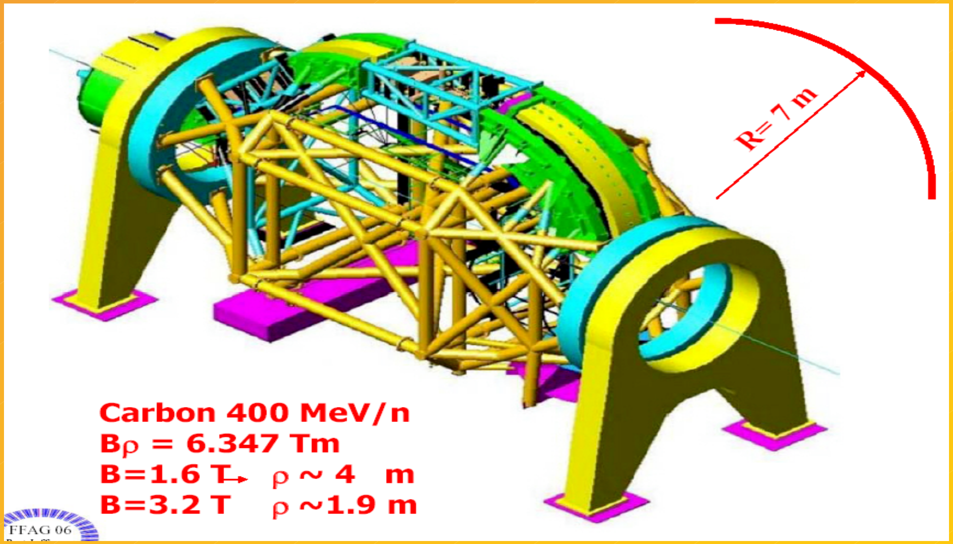
• Magnetic Field………	• n/a
• Rf Frequency………..	• n/a, Pulsed Laser
• Energy Change………	• Pulse to Pulse (so far 58MeV (kJoules; ps)
• Current……………….	• .01na --> ??
• Pulse Frequency……..	• (10Hz?)
• Pulse Length………..	• psec
• Scanning Type………	• Spot, Distal edge ?
• Multi-Extraction…….	• No

- Current? , Neutrons?
- Beam Time Structure (nsec pulses) - Instrum / Scanning / Organ Motion
- Pulse to Pulse change of Energy, Beam Size, Current
- Emittance 1um x 23 degrees - small but challenging
- 1 liter volume at 1cm spots = 1000 spots. At 100sec/10Hz = 1000 pulses.

Other Subsystems:
Positioning (incl. Gantries), Beam Delivery Systems

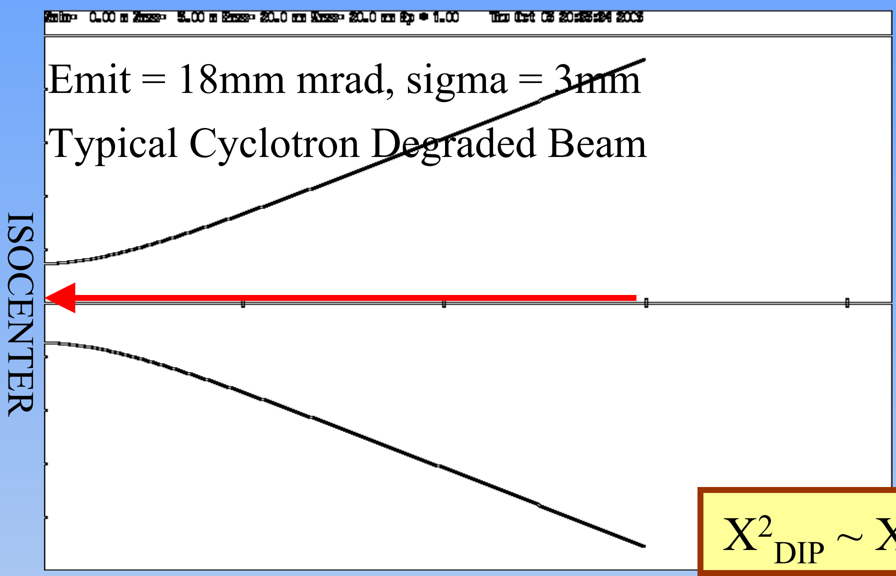
100-200 Tons

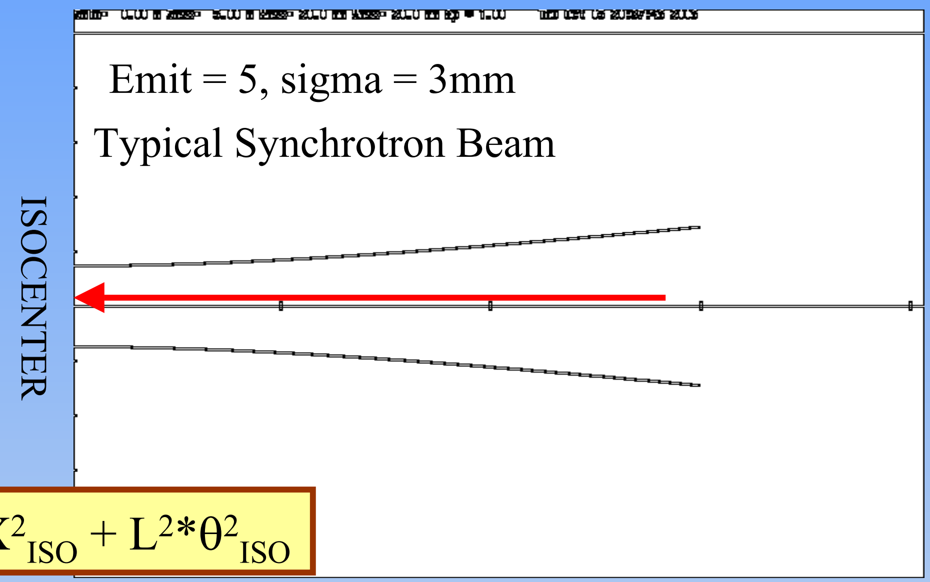
In-plane Gantry Color Choices



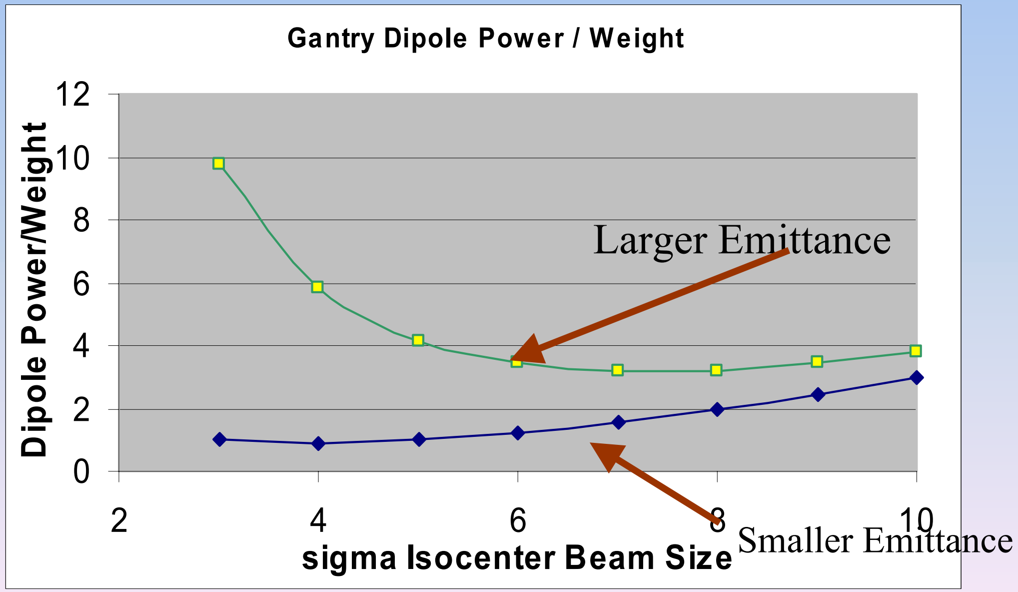
630 Tons

Beam Size, 3 m drift, From Gantry to Isocenter





$X^2_{DIP} \sim X^2_{ISO} + L^2 * \theta^2_{ISO}$



The emittance of the Beam Transported will affect the Gantry Design. (Not including Scattering)

FFAG Gantry Implementation

Patented !

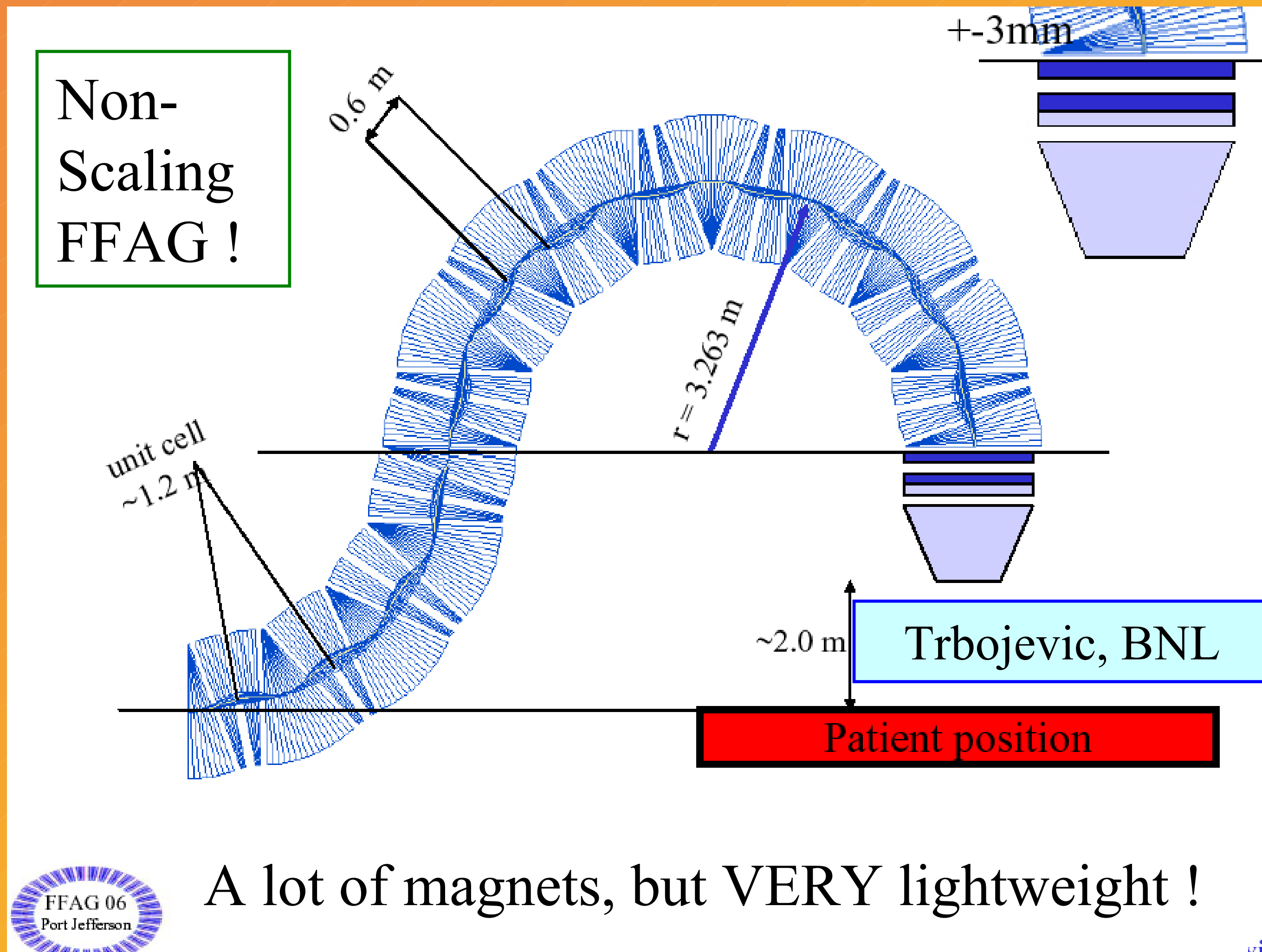
Issues:

Injection Matching Optics

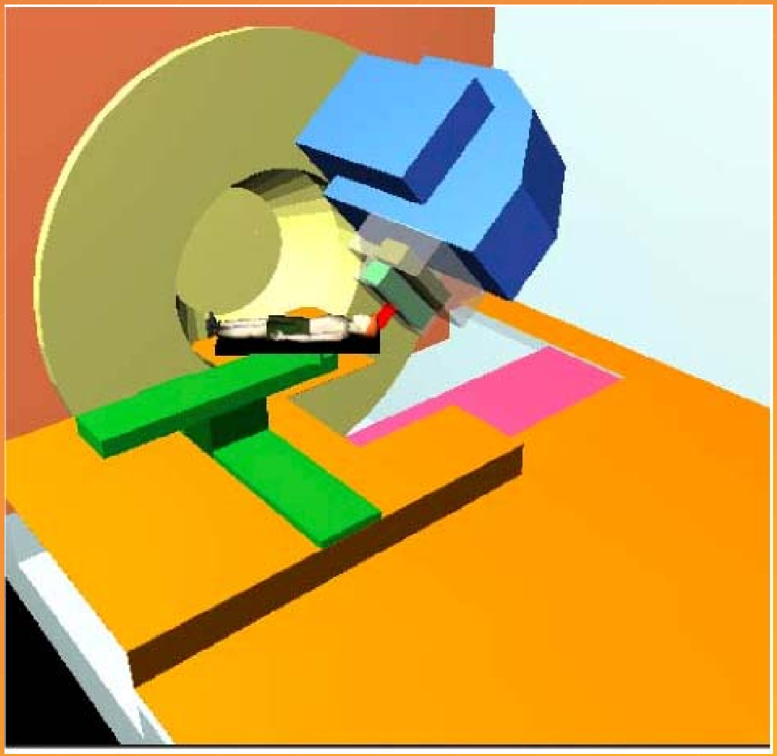
Optics to Patient

Scanning Implementation

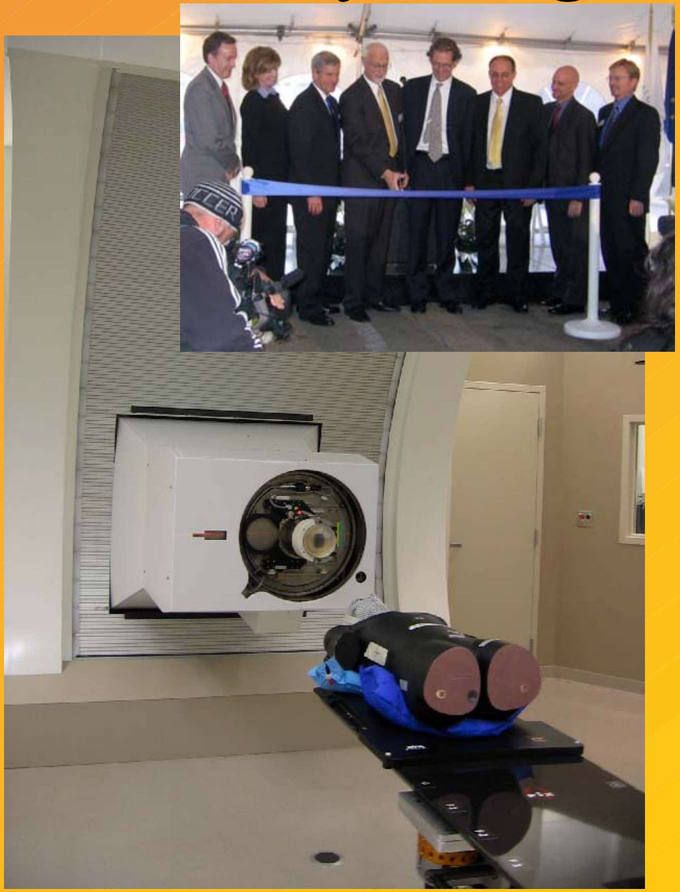
Other Constraints



Reducing the Range of Delivery Angles



PROSCAN - PSI

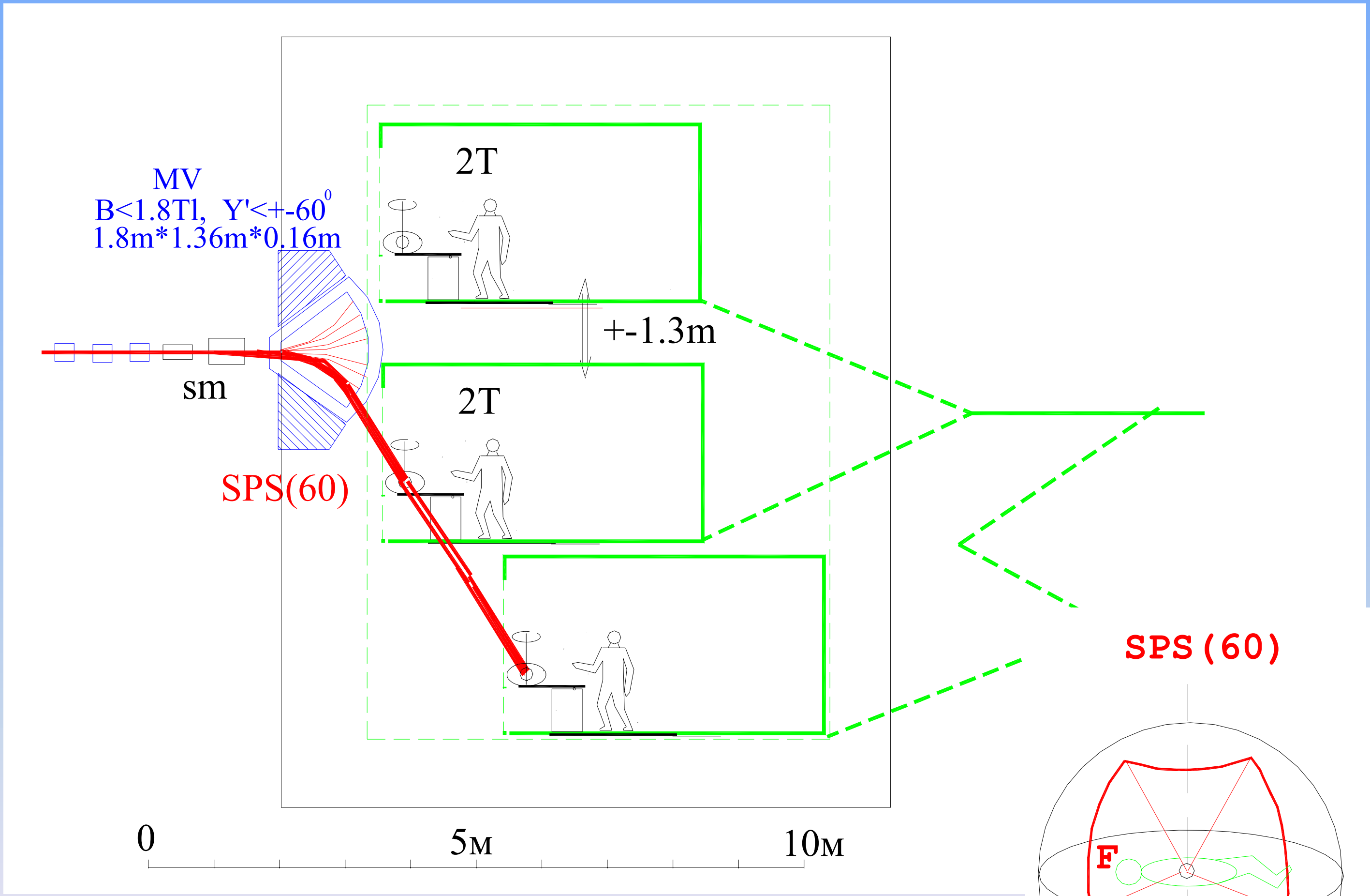


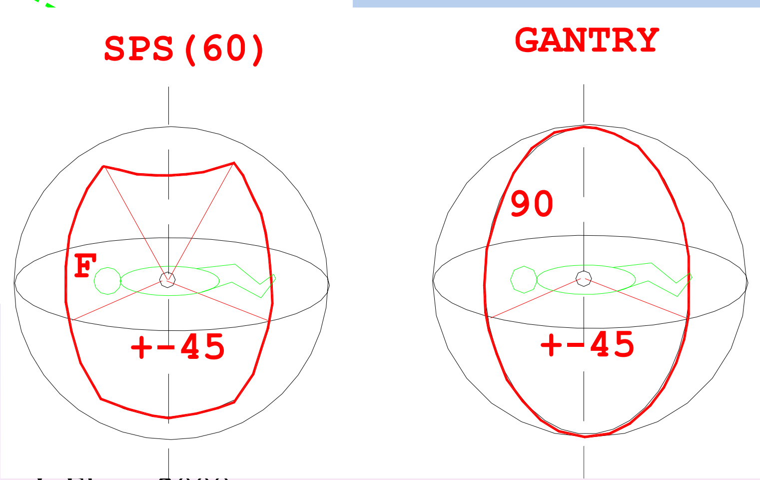
Is this enough?

Two Fixed Beamlines - ProCure

Why not have everything? Size, Cost, Access to Patient …

Simple Planar System (SPS)
Marc Kats





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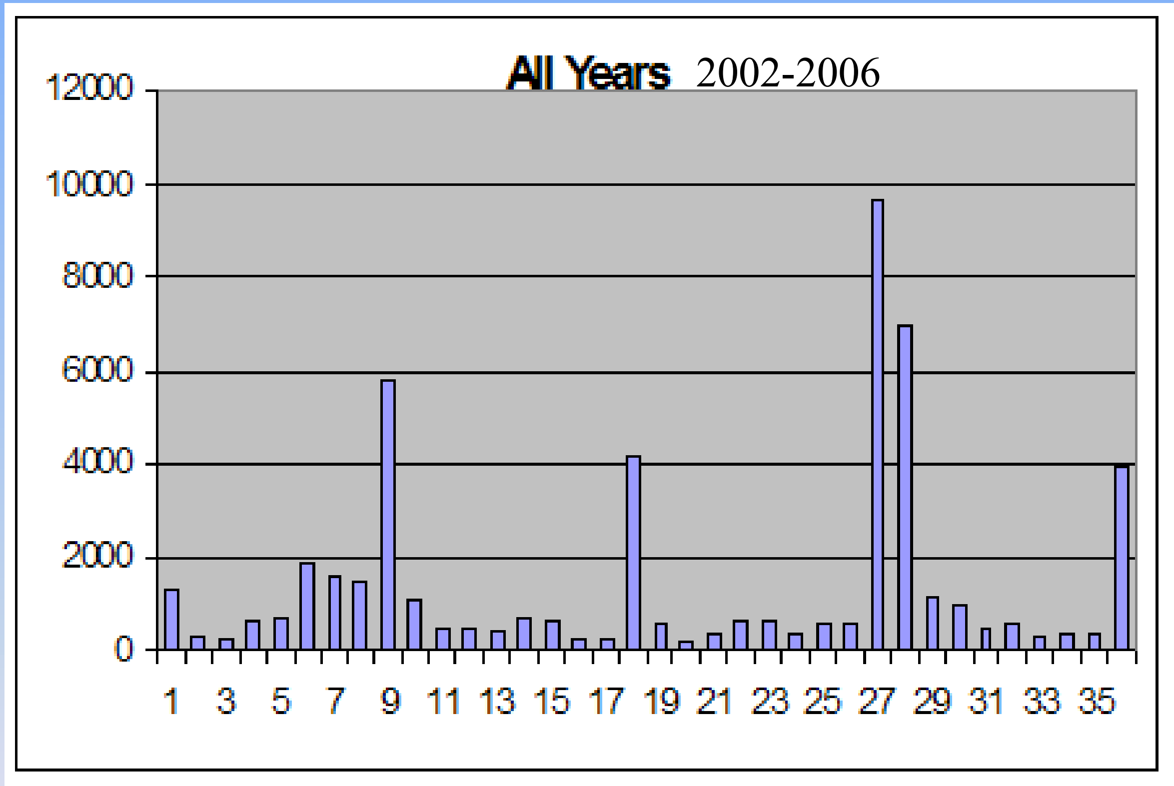
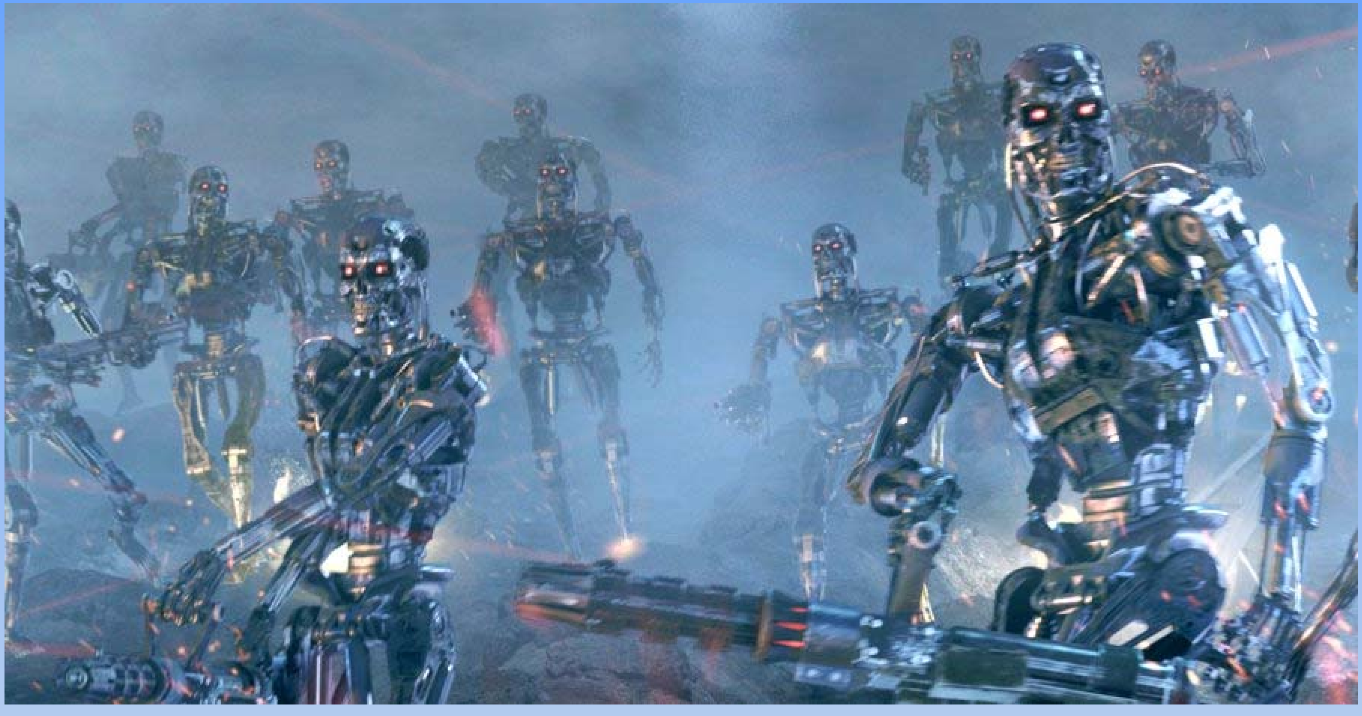
BPTC Gantry Angle Summary



Over 60% of all fields were delivered within +/- 10 degrees of cardinal angles.

Gantry Summary

- Gantry is expensive
  – Size and Weight
- Convenience of all Angles is seductive
  – But is is necessary
- It is advantageous to minimize the motion of a patient? (What does that mean?)
- Gantry Beam Optics is linked to Beam Scanning Capability
- Reliability and Maintenance



Positioning

The Rise of the Robot

Special Purpose Niches?

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The new Robots

Smooth, Fast, Reproducible, Safe,

(Move with beam on?) Change the Field Size spec??

NAC, Orsay, Siemens, Optivus, MGH, etc.

BPTC Positioners

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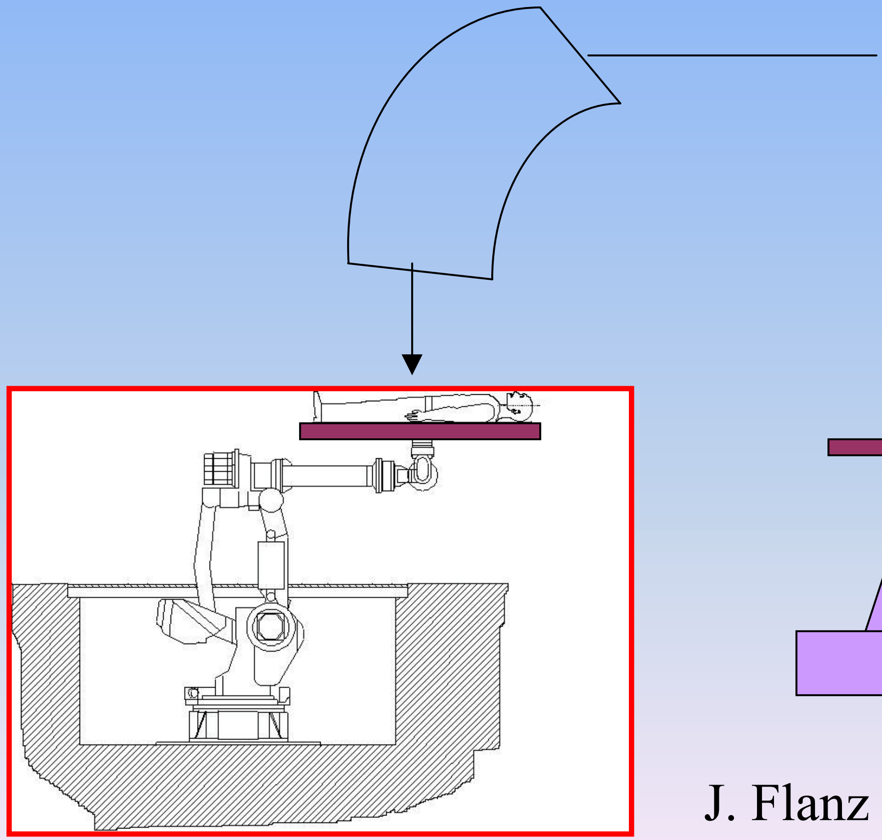
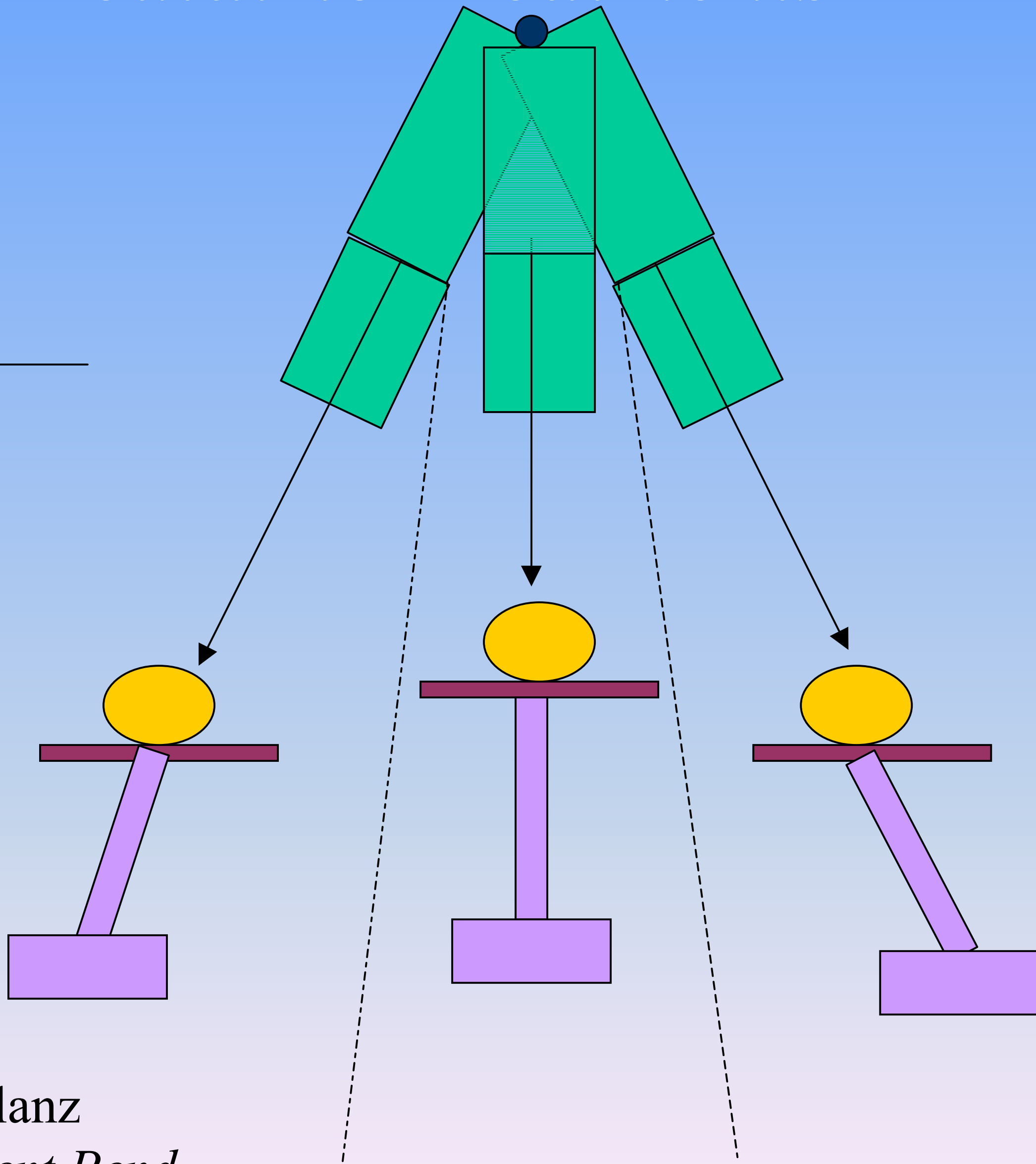
A non-Gantry for Pediatric Treatments





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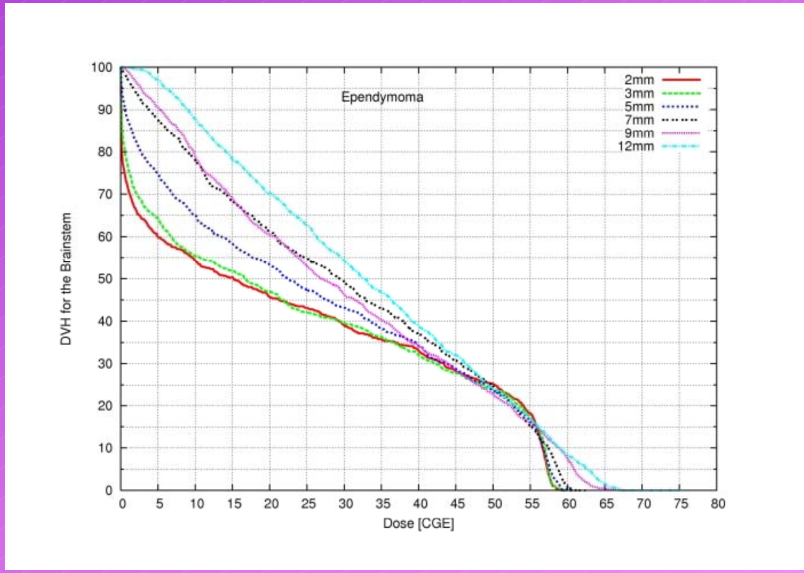
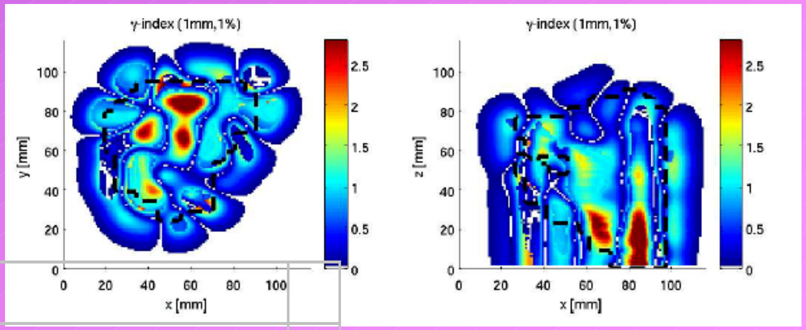
Patent Pend.

Clinical Beam Parameters of "Importance"

- Clinical
  - Patient Related
  - Dosimetry Related
- e.g.
  - Dose Volume Histogram
  - Gamma Index





Beam at Target (Not Accelerator)

Sigma =	5mm			
		Random	Random	Technical
	Systematic	Once	Repainting	
Sigma	**0.2mm**	**0.25mm**	**0.75mm**	**Quad field ~ 0.4%**
Position	**x**	**0.2mm**	**0.6mm**	**Dipole field ~ 0.05%**
Gradient	**4%**	**5%**	**15%**	**200 usec / 4%**
Dynamic Range				**50:1**
Range	**0.75mm**	**x**	**x**	**Dipole field ~ 0.14%**

What is the Right Number?

Conclusions?

- *Treating with particles requires a system approach.*
- *The various subsystems interact with each other and depend upon each others capabilities.*
- *Trade-offs include size, speed, intensity, of everything, (equipment, beam etc.)*
- *New Approaches are being fueled by both accelerator interests, and by the more and more demanding requirements of particle therapy.*

End Slides

PTCOG 47

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