Particle Therapy (Technical) Approaches

PTCOG 47 Educational Sessions
Massachusetts General Hospital, Harvard Medical School
Francis H. Burr Proton Therapy Center

5/08
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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.

Range 32 cm

Field Size 30cmx40cm

Passive Scatt. Scanning

Beam Properties Appropriate

2Gy Rx Less than 1min

Change Energy < 2sec

Beam Loss

270 MeV

235 MeV + Wobbling

~215 MeV

~215 MeV

0.1-10nA

Fixed Energy Accelerator = 300nA

Paint 30 Layers < 1min

Beamline Beam Nozzle

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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

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

Biological
- Response time of Cell?

Examples:
- 100MHz rf ==> 1nsec / 10 nsec
- Rapid Cycling Synch ==> nsec/30 Hz

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Time Structure in Pencil Beam Scanning

Dose Driven “Spot” Scanning

Continuous Stable/Unstable. Pulsed Short or Long

Flanz – PTCOG 2008
Flexibility in Scanning?
Mixed Spot and Line / Optimization of Time & Position

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

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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. Grözinger¹, Q. Li², E. Rietzel¹, W. Becher¹, T. Haberer¹ and G. Kraft¹

¹GSI Darmstadt; ²IMP-CAS Lanzhou, China

Tests: 0.11Hz

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

Fig. 2: Test of lateral compensation accuracy. A homogeneous 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.

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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

Linac:
- Rf Linac
- CycLinac
- DWA

Cyclotron:
- Isochronous Cyclotron
- Synchro-Cyclotron
- CycFFAG

Synchrotron:
- Strong Focusing
- Weak Focusing
- Rapid Cycling
- FFA

Laser
Accelerator Development Now Underway

Why?

- Smaller
- Cheaper
- Faster
- Stronger
- Different Parameters !!!

-Proton Beam

Technovelgy.com

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**Acceleration Mechanism(s)**

\[ \mathbf{F} = q \mathbf{E} + q \mathbf{v} \times \mathbf{B} \]

- **Physics**: Anything that can create an electric Field which accelerates a charged particle in the direction of its motion.
  - \( E \sim dB/dt \) (changing magnetic field) (betatron)
  - \( E \sim \) Applied Voltage
    - DC Voltage
    - AC Voltage
  - “Create” an Electric Field

- **Engineering**: “Efficient use of Power”
  - One time through (Linac)
  - Reuse the Electric Field
**Acceleration Mechanism(s)**

\[ \vec{F} = q \vec{E} + q \vec{v} \times \vec{B} \]

\[ F = q \cdot (-\nabla \Phi - \frac{\partial A}{\partial t} + \vec{v} \times \vec{B}) \]

- **Physics**: Anything that can create an electric Field which accelerates a charged particle in the direction of its motion.
  - \( \vec{E} \propto \frac{dB}{dt} \) (changing magnetic field) (betatron)
  - \( \vec{E} \propto \) Applied Voltage
    - DC Voltage
    - AC Voltage
  - “Create” an Electric Field

- **Engineering**: “Efficient use of Power”
  - One time through (Linac)
  - Reuse the Electric Field
Scaling DOWN Cyclotrons - Quantitatively

US/Germany/??

Smaller / Cheaper

Scaling DOWN Cyclotrons - Quantitatively

Tons

IUCF, IThemba

IBA

Varian

Still River +

Others?

Other Places????

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Single room – Less ‘compact’

Comparing Apples with Apples

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

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Cyclotrons

- Magnetic Field
- Rf Frequency
- Energy Change
- Current
- Pulse Frequency
- Pulse Length
- Scanning Type
- Multi-Extraction

- Constant
- Constant
- Degrader (150ms – 1 sec)
- 100’s na / 100’s to 1 na
- Continuous (Rf) (~10ns) or X Hz
- Continuous (Rf) (~1ns)
- All ?
- 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

<table>
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<th>BINP</th>
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<td>FODB</td>
<td>BODO</td>
<td>OFOBDB</td>
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<tr>
<td>Total weight</td>
<td>~1</td>
<td>~1.5</td>
<td>~2</td>
<td>ton</td>
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</table>

|                  |        |          |        |
| 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        |        |

**2005**

Figure 1: Present ring layout.
The RCMS (p)
Rapid Cycling Medical Synchrotron
the second generation

Tandem pre-injector (AES)
Synchrotron accelerator
Gantries (ACCEL)
Horizontal & eye fixed lines
Research room line

China / US
Faster / Stronger

Peggs

Please Do Not Use without reference J. Flanz 2008
Balakin Device

ProTom

• Simple
• Light
• Inexpensive

Smaller / Cheaper

Scanning Optimized Synchrotron

All non-essential equipment minimized

RUSSIA

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Synchrotrons

- Magnetic Field
- Rf Frequency
- Energy Change
- Current
- Pulse Frequency
- Pulse Length
- Scanning Type
- Multi-Extraction

- Changing
- Changing
- Acceleration Cycle (or 30Hz~sec)
- <> nanoamps
- 0.5 Hz to 30 Hz + Rf
- ~ second(s) (or usec)
- Spot / (Depends?)
- 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!

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“CycLinac” Concept

Faster / Stronger

Italy / England / IBA

IDRA - Institute for Diagnostic and Radiotherapy (Protons)

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

Ugo Amaldi

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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?).

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

“Macro Structure”

Or Constant
Proof of Principle Machine! 2000 KEK 500keV

(Remember when that was possible?)

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

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Proton Options

New **FFAG** Options

Proton energy 230MeV
Intensity >100nA
Rep. Rate 20-100Hz, respiration mode
Diameter ~8m
Extraction fast, multi-port
RACCCAM 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
Damienne Neuvéglise: SIGMAPHI
Jaroslaw Pasternak: LPSC
Thomas Planche (PhD): SIGMAPHI
Pascal Pommier (MD): Lyon Hospital

students
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.)

Grenoble, 8.04.2008
J. Pasternak, LPSC Grenoble
## FFAG

- Magnetic Field
- Rf Frequency
- Energy Change
- Current
- Pulse Frequency
- Pulse Length
- Scanning Type
- Multi-Extraction

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Magnetic Field</td>
<td>Constant</td>
</tr>
<tr>
<td>Rf Frequency</td>
<td>Varies (or Constant!)</td>
</tr>
<tr>
<td>Energy Change</td>
<td>Move Kicker</td>
</tr>
<tr>
<td>Current</td>
<td>&gt; 100 na</td>
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<tr>
<td>Pulse Frequency</td>
<td>100 Hz</td>
</tr>
<tr>
<td>Pulse Length</td>
<td>1 usec</td>
</tr>
<tr>
<td>Scanning Type</td>
<td>Spot</td>
</tr>
<tr>
<td>Multi-Extraction</td>
<td>Yes</td>
</tr>
</tbody>
</table>

- 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
**Physics**: Anything that can create an electric field which accelerates a charged particle in the direction of its motion.
- \( E \sim \frac{dB}{dt} \) (changing magnetic field) (betatron)
- \( E \sim \) 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
**DWA - Dielectric Wall Accelerator**

**How High Gradient Insulators Work**

Conventional Insulator

- Emitted electrons repeatedly bombard surface

High Gradient Insulator

- Emitted electrons repelled from surface

Floating conductors

**Smaller / Cheaper / Faster**

George Caporaso et. al., LLNL

Mackey, Caporaso et. al.
DWA supports a virtual traveling wave by continuous wall excitation* accelerator

Longitudinal Electric Field Plot

*patent pending

Mackey, Caporaso et. al.
Spot Scanning and DET

- SS Spot Locations (~300)
- DET Spot Locations (~20)

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

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)**

\[ \vec{F} = q \vec{E} + q \vec{v} \times \vec{B} \]

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

- **Physics**: Anything that can create an electric Field which accelerates a charged particle in the direction of its motion.
  - \( E \sim dB/dt \) (changing magnetic field) (betatron)
  - \( E \sim \) 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**

- Intense Laser Pulse ($10^{20}$ W/cm$^2$)  
  Femtosec --> 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 » à 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
System Design

Charlie Ma

Victor Malka

Please Do Not Use without reference J. Flanz 2008
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

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Beam Size, 3 m drift, From Gantry to Isocenter

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

$$X_{DIP}^2 \sim X_{ISO}^2 + L^2 \theta_{ISO}^2$$

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Issues:
- Injection Matching Optics
- Optics to Patient
- Scanning Implementation
- Other Constraints

Non-Scaling FFAG!

A lot of magnets, but VERY lightweight!

Trbojevic, BNL

Patient position

r = 3.263 m

0.6 m

+-3 mm

~1.2 m

~2.0 m
Reducing the Range of Delivery Angles

PROSCAN - PSI

Is this enough? Two Fixed Beamlines - ProCure

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

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Simple Planar System (SPS)
Marc Kats

MV
B<1.8T, Y'<=-60°
1.8m*1.36m*0.16m

SPS(60) GANTRY

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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

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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.

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BPTC Positioners

Please Do Not Use without reference J. Flanz 2008
A non-Gantry for Pediatric Treatments

J. Flanz
Patent Pend.

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Clinical Beam Parameters of "Importance"

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

Beam at Target (Not Accelerator)

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<th>Random</th>
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<tr>
<td>Sigma</td>
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<td>x</td>
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What is the Right Number?

Please Do Not Use without reference J. Flanz 2008
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

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Flanz