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IMPT Delivery Systems and Current Limitations

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AAPM Symposium
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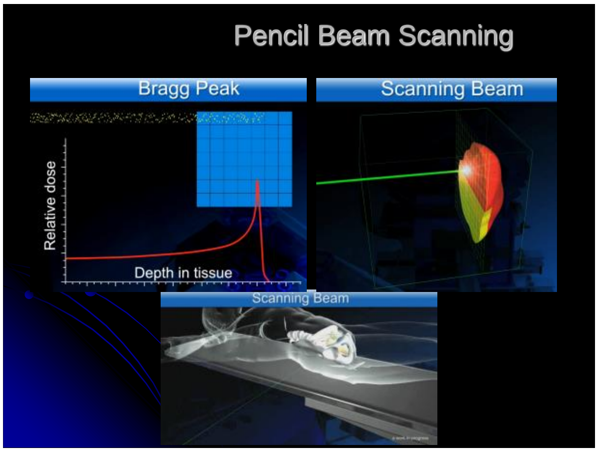
Disclosure

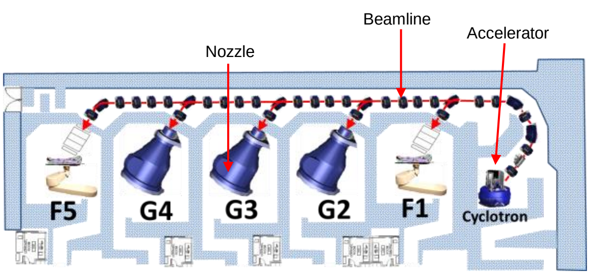
- Varian's ProBeam user

Goals

- To learn about typical components of IMPT delivery system
- To understand various potential limitations in treatment delivery and treatment planning

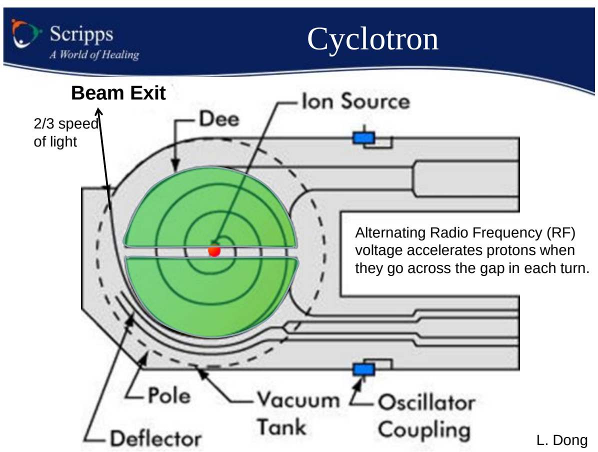


Scripps Proton Therapy Center Layout

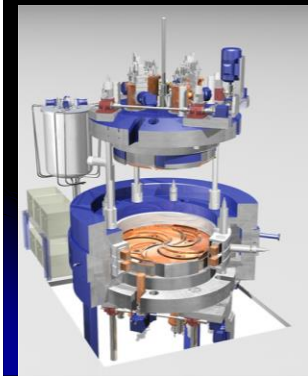


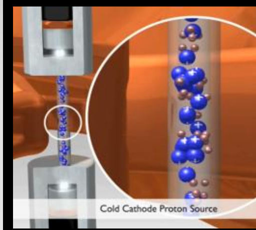
Five Treatment Rooms
3 – Isocentric Gantry Rooms
2 – Fixed beam rooms

Dong/SPTC



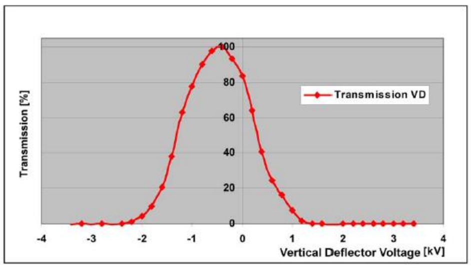
Varian/Accel's Superconducting Cyclotron





Current Modulation

Vertical Deflector Transmission curve



ProNova

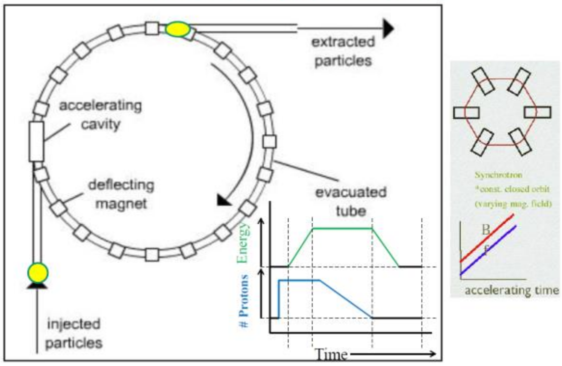
Cyclotrons for Hadron Therapy

Machine	Man'f	Type	Energy	Size	Power	Intensity	Peak B field
C230	IBA, Also Sumitomo	NC Iso	230 MeV	220 t 4.3 m	320 kW	Up to 300 nA CW	Up to 2.2 T
SC Proton Cyclotron	Varian	SC Iso	250 MeV	90 t 3.1 m	155 kW	Up to 800 nA CW	< 4 T
IUCF Main stage	Indiana University	NC Iso	208 MeV	2,000 T > 9 m	900 kW	Up to 500 nA CW	< 2.25 T
S250	MEVION	SC Syn	250 MeV	20 T 1.8 m	- ?	500 Hz period	~ 9 T
S2C2	IBA	SC Syn	230 MeV	<50 T 2.5 m	- ?	1 kHz period	~ 6.56 T
C400	IBA	SC Iso Light Ion	250 MeV (p) 400 MeV/u	700 T 6.6 m	200 kW for RF	8 nA	2.5 T - 4.5 T

Iso = Isochronous   Syn = Synchrocyclotron

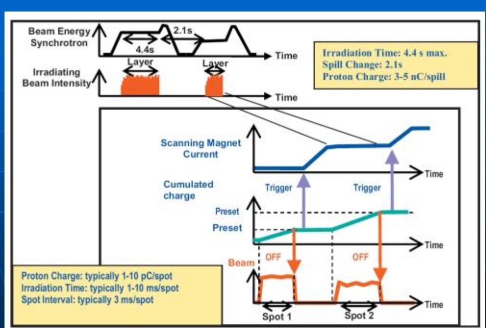
3 - August - 2013   AAPM Proton Symposium   Particle Beam Technology – Cyclotrons
Laddie (Vladimir) Derenchuk

What is a Synchrotron?



Flanz 2013; AAPM Symposium

Scanning beam timing chart



Smith *et al*. Med Phys 2009

AAPM 2010 Abstract

What is the maximum number of beam spots deliverable within one gating window for synchrotron based scanning proton beam therapy of lung cancer?

Yoshikazu Tsunashima[1], Sastry Vedam[2], Lei Dong[2], Masumi Umezawa[3], Xiaodong Zhang[2], Peter Balter[2] and Radhe Mohan[2]

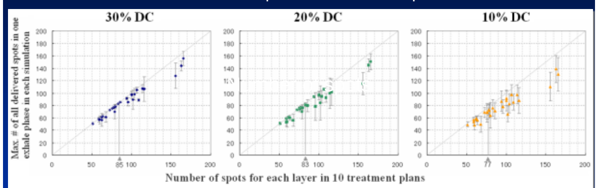
1. Graduate School of Biomedical Sciences, University of Texas at Houston
2. Department of Radiation Physics, MD Anderson Cancer Center
3. Hitachi Ltd., Energy and Environmental Systems Laboratory

THE UNIVERSITY OF TEXAS MD Anderson Cancer Center Making Cancer History

HITACHI Inspire the Next

Key Result

Number of spots (average) delivered within one expiration phase from simulation results vs. Number of spots from treatment plan



Maximum number of spots/layer whose plot within σ from the line

- 85 spots 30 %DC threshold
- 83 spots 20 %DC threshold
- 77 spots 10 %DC threshold

Cyclotron vs. Synchrotron

Cyclotron

- Energy:
  - Degrader
  - 70 – 250 MeV
- Energy resolution:
  - ~ 0.1 MeV
- Beam current
  - 300 – 800 nA
- Intensity Modulation
  - Vertical deflector
- Cycle time
  - Continuous (50 MHz)

Synchrotron

- Energy:
  - On-demand acceleration
  - 70 – 250 MeV
- Energy resolution:
  - ~ 0.1 MeV (94 energies)
- Beam current
  - 300 – 800 nA
- Intensity Modulation
  - Modulated @ 1000 Hz; duty cycle 0.2%
- Cycle time
  - ~ 2 seconds

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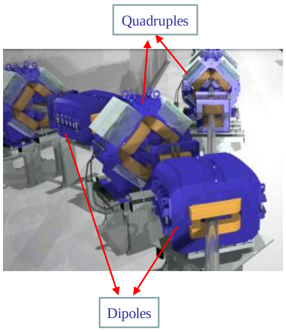
Beam Steering by Magnetic Fields

- Dipoles: for bending the beam
- Quadruples: focusing the beam
- Vacuum pumps to keep beamline under very high level of vacuum (think about outer space)
- Beam profile monitors to measure beam along the central tube



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Beamline

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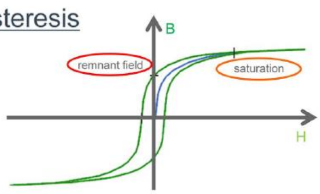
Changing Field Strength and Managing Residual Magnetic Field

Magnetic Hysteresis

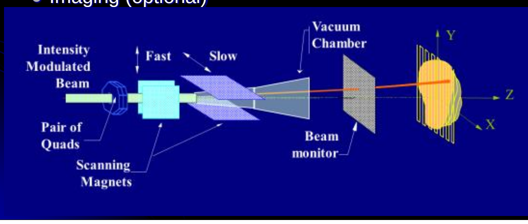


Compensation:

- Degaussing → Switching dipoles (MFCS)
- Initial Saturation → Quads & remaining Dipoles

Beam Delivery System

- Nozzle
  - Lateral scanning system
  - Position monitoring system
  - Dose monitoring system
  - Accessory holders (range shifter and aperture)
  - Imaging (optional)



Scanning System Challenges

- Power requirements
  - Faster scans and large fields require high power (>1000A)
  - Raster vs. Spot Scanning
- High precision is required for magnetic field
- Gantry dependence
- Position monitoring at low dose rate
- Preferred fast scan direction to minimize breathing motion

Variations in proton scanned beam dose delivery due to uncertainties in magnetic beam steering

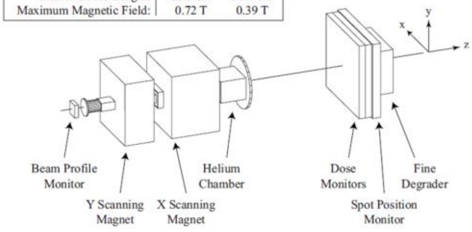
Stephen Peterson and Jerimy Polf et al.

Variations in Magnetic field Strength ΔB → (Analytical) → Displacement of spot lateral positions: Δs → (Empirical) → Dose delivery Uncertainties in Patient: ΔD

Med. Phys. 36 (8), 2009

- Variations in magnetic field strength leads to fluctuations in the steering of the pencil beams to their intended final position.

Scanning Magnet Specifics	Y Magnet	X Magnet
Distance to Isocenter:	263.85 cm	211.30 cm
Effective Pole Length:	23.3 cm	38.4 cm
Maximum Magnetic Field:	0.72 T	0.39 T



Analytical formula between magnet strength and lateral spot position

Magnetic steering beam position relationship: physics

Find the function mapping magnet strength to beam position: $s_{Ymag} = f(By)$

Lorentz and centripetal force:

$$F = qvB_Y = \frac{mv^2}{r_{Ymag}} \Rightarrow r_{Ymag} = \frac{mv}{qB_Y}$$

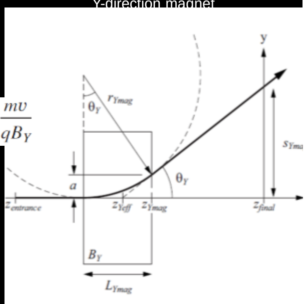
Relativity effect:

$$E = \gamma m_o c^2, \quad \text{where} \quad \gamma = \frac{1}{\sqrt{1-(v/c)^2}}$$

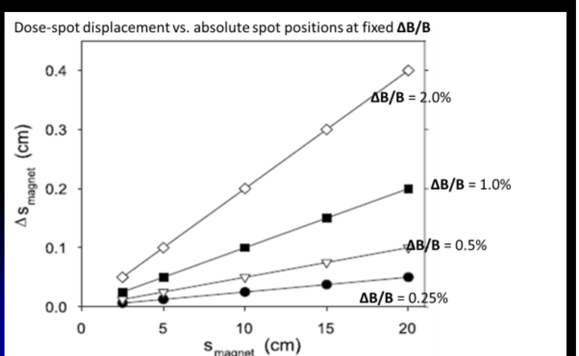
$$\Rightarrow v = c\sqrt{1 - \frac{1}{(1+E/m_o c^2)^2}}$$

Relativistic mass: $m = \gamma m_o$

Y-direction magnet

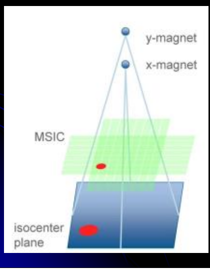


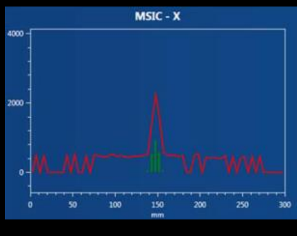
Results



Position Monitor

- Multi Strip Ionization Chamber (MSIC) or two-dimensional multi-wire system is used to monitor spot position and spot shape





Minimum MU per Spot

- To accurately measure spot position and shape
- Delayed charge – delay of the beam termination
- Beamline activation at high energy
- (MDACC) Upper limit: Safety consideration – limit the maximum dose per spot

Impact of Scan Direction

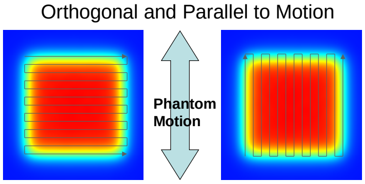
MD Anderson Cancer Center

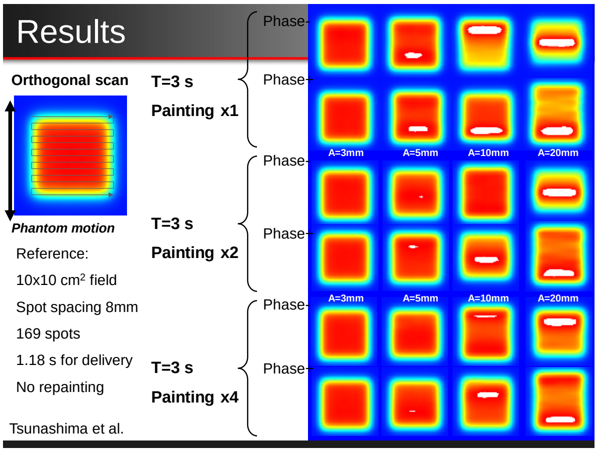
Experiment

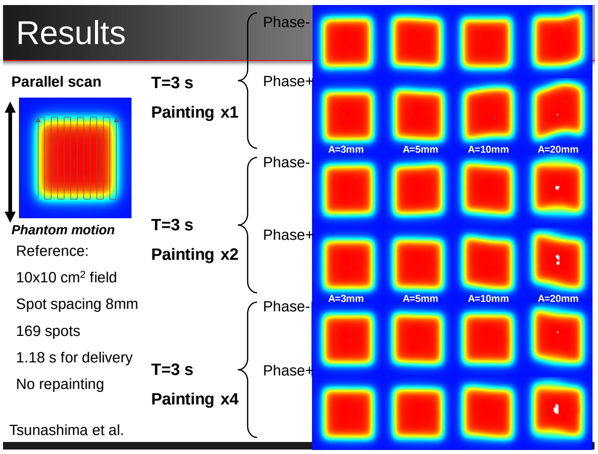
Tsunashima et al.

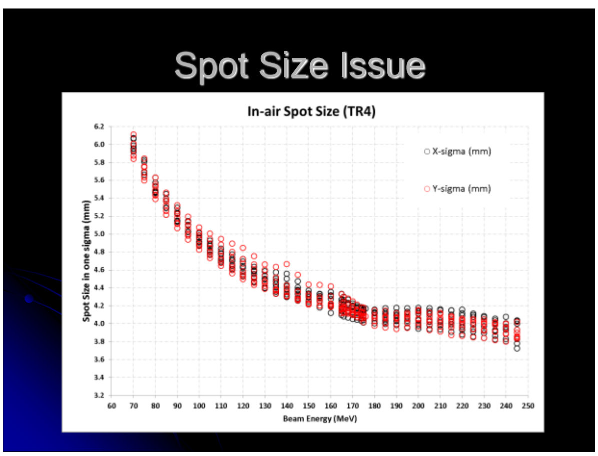
Beam delivery

• Field	10cm x10cm field
• Spot spacing	8mm (x and y direction)
• Number of spot	13 x 13=169 spots (≡one painting)
• Spot duration time	7ms/spot (4ms delivery+3ms moving)
• One layer time	169x7ms=1.2 s (one painting)
• Scan directions	Orthogonal and Parallel to Motion

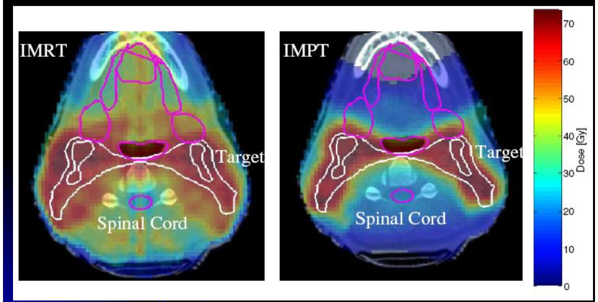



Results
Orthogonal scan
Phantom motion
Reference:
10x10 cm² field
Spot spacing 8mm
169 spots
1.18 s for delivery
No repainting
Tsunashima et al.
T=3 s
Painting x1
T=3 s
Painting x2
T=3 s
Painting x4
Phase-
Phase+
Phase-
Phase+
Phase-
Phase+
A=3mm
A=5mm
A=10mm
A=20mm


Results
Parallel scan
Phantom motion
Reference:
10x10 cm² field
Spot spacing 8mm
169 spots
1.18 s for delivery
No repainting
Tsunashima et al.
T=3 s
Painting x1
T=3 s
Painting x2
T=3 s
Painting x4
Phase-
Phase+
Phase-
Phase+
Phase-
Phase+
A=3mm
A=5mm
A=10mm
A=20mm

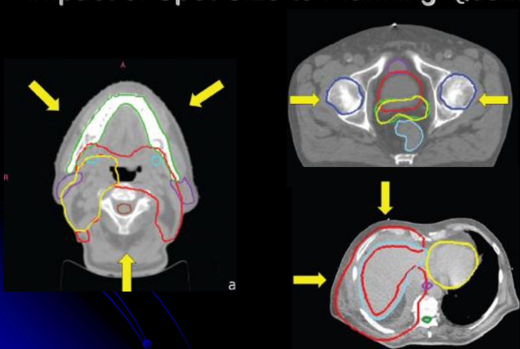

Spot Size Issue
In-air Spot Size (TR4)
X-sigma (mm)
Y-sigma (mm)
Spot Size in one sigma (mm)
Beam Energy (MeV)

Photons vs. Future Protons



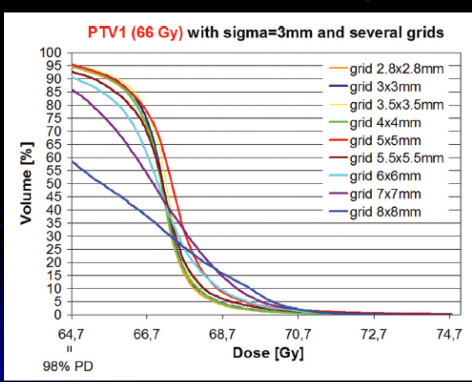
Bortfeld T. IMRT: "A review and a preview", Phys. Med. Biol. 51(13), 2006.

Impact of Spot Size to Planning Quality



Widesott et al. Med. Phys. 39 (3) 2012

H&N PTV 66 Gy



Conclusions

We determined the dependence of the maximum σ that obtains comparable target coverage and sparing of OARs to advanced photon techniques for three clinical cases. σ must be ≤ 4 mm for the head and neck cancer, ≤ 3 mm for the prostate cancer and ≤ 6 mm for the malignant pleural mesothelioma. Furthermore, the spot spacing was optimized for

Summary: Why is PBS Possible Today?

- Better power supply for magnets (dipole; quadruple; fast scanning coils)
- More advanced accelerator technology
  - More efficient accelerator
  - Better beam optics (smaller spots)
  - Fast energy change and current modulation
  - Automatic beam tuning and control system
  - Better and faster electronic circuits

LD 04/13