# State-of-Art IMPT vs. IMRT

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Scripps
A World of Healing

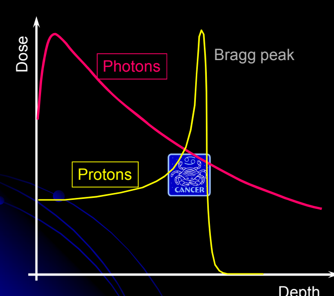
AAPM-Midwest Chapter,
Chicago, April 27, 2013

# Scripps Proton Therapy Center


# Goals

- Review proton therapy technologies and IMPT
- Compare differences between IMRT and IMPT
- Discuss challenges in using IMPT in clinical practice

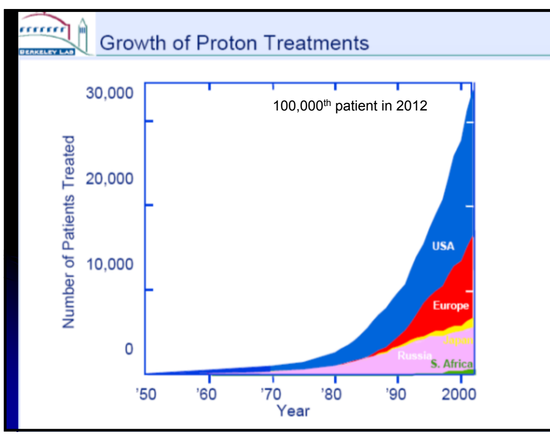
# Why protons?




**Other Factors**

- No. of beams
- Inverse planning
- Pencil beams
- PTV and size
- IGRT
- …

## Growth of Proton Treatments




# Proton Therapy Centers in US

Tim Williams – Economics of Proton Therapy

ASTRO 2007 Proton Panel

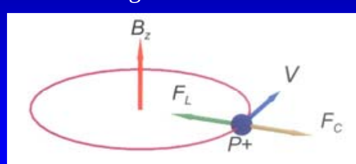
Reasons to Establish a Proton Center

- Belief in Clinical Efficacy
- Program Differentiator
- Revenue Generation
- Institutional Prestige
- Defensive Maneuver

What are different proton systems?

## Physics

- Requires higher energy: 250 MeV p+ ~ 30cm
- Requires magnetic field for beam acceleration and beam steering




Modified from Y. Jongen

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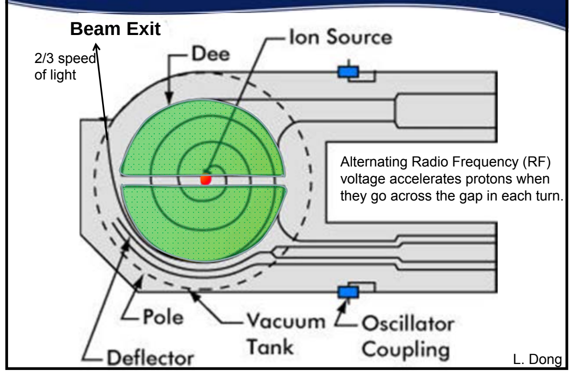
## Cyclotron




L. Dong

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## Cyclotron

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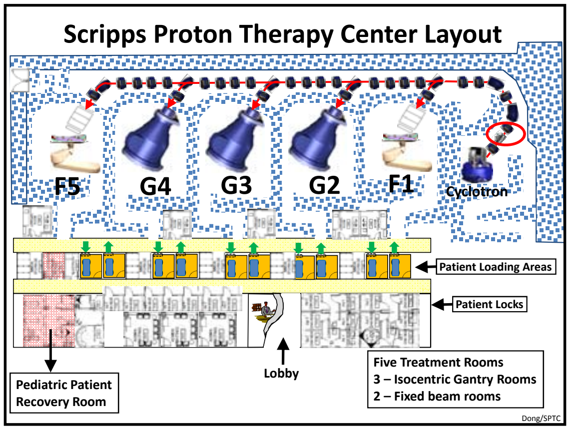
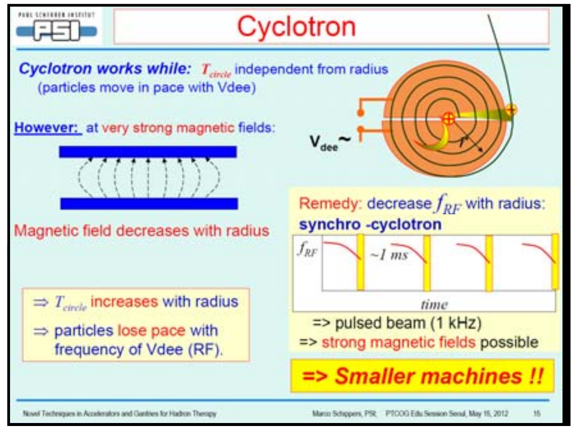
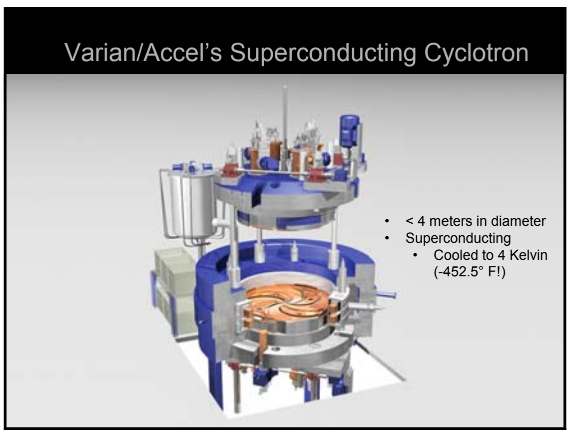
## Beam Transportation (Magnets)

12


Scripps Proton Therapy Center Layout
F5
G4
G3
G2
F1
Cyclotron
Patient Loading Areas
Patient Locks
Pediatric Patient
Recovery Room
Lobby
Five Treatment Rooms
3 – Isocentric Gantry Rooms
2 – Fixed beam rooms
Dong/SPTC


Cyclotron
Cyclotron works while: $T_{circle}$ independent from radius
(particles move in pace with Vdee)
However: at very strong magnetic fields:
$V_{dee}$ ~
Magnetic field decreases with radius
⇒ $T_{circle}$ increases with radius
⇒ particles lose pace with frequency of Vdee (RF).
Remedy: decrease $f_{RF}$ with radius:
synchro -cyclotron
$f_{RF}$
~1 ms
time
=> pulsed beam (1 kHz)
=> strong magnetic fields possible
=> Smaller machines !!
Novel Techniques in Accelerators and Gantries for Hadron Therapy
Marco Schippers, PSI; PTCOG Edu Session Seoul, May 15, 2012
15


Varian/Accel's Superconducting Cyclotron
< 4 meters in diameter
Superconducting
Cooled to 4 Kelvin (-452.5° F!)


Synchro-Cyclotron
8-10 T 250 MeV Synchro-cyclotron on a gantry
MEVION
First beam extracted in May 2010
Novel Techniques in Accelerators and Gantries for Hadron Therapy
Marco Schippers, PSI; PTCOG Edu Session Seoul, May 15, 2012
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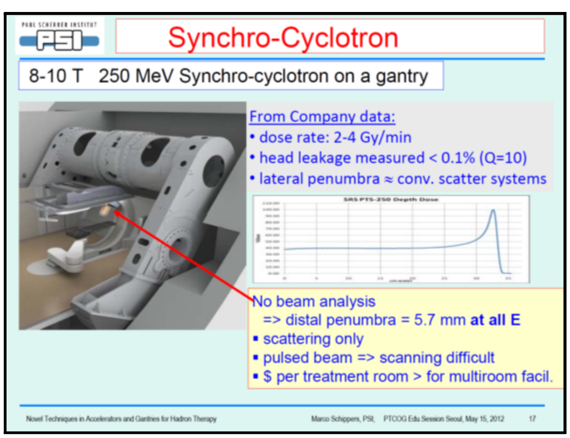
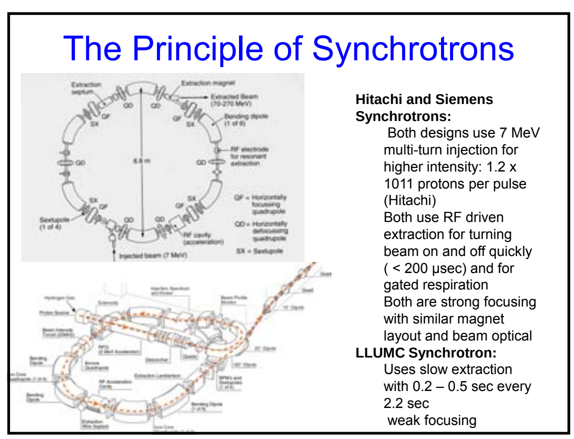

Synchro-Cyclotron
8-10 T 250 MeV Synchro-cyclotron on a gantry
From Company data:
• dose rate: 2-4 Gy/min
• head leakage measured < 0.1% (Q=10)
• lateral penumbra ≈ conv. scatter systems
No beam analysis
=> distal penumbra = 5.7 mm at all E
• scattering only
• pulsed beam => scanning difficult
• $ per treatment room > for multiroom facil.
Novel Techniques in Accelerators and Gantries for Hadron Therapy
Marco Schippers, PSI; PTCOG Edu Session Seoul, May 15, 2012
17

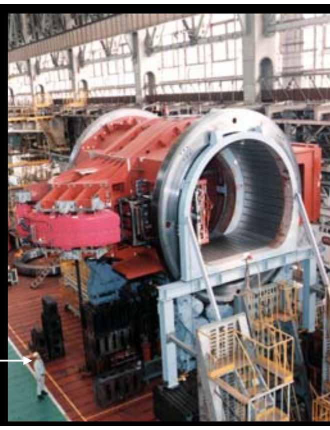

The Principle of Synchrotrons
Hitachi and Siemens Synchrotrons:
Both designs use 7 MeV multi-turn injection for higher intensity: 1.2 x 1011 protons per pulse (Hitachi)
Both use RF driven extraction for turning beam on and off quickly ( < 200 µsec) and for gated respiration
Both are strong focusing with similar magnet layout and beam optical
LLUMC Synchrotron:
Uses slow extraction with 0.2 – 0.5 sec every 2.2 sec
weak focusing

PTC-H 250 MeV Synchrotron Ring

## Beam Delivery System

- Gantry
  - Position beam in different angles (isocenttric)
  - Mounting of imaging systems
  - Lasers
- Fixed beam port (horizontal/inclined)
- Nozzle
  - Delivery the protons
  - Dose monitoring system
  - Beam shaping devices
  - Protect patient from unwanted radiation
  - Imaging (optional)

**A Proton Machine at 90 tons**



**Man**

## Multi-room Systems

- Hitachi — 270 MeV proton synchrotron
- IBA — 230MeV cyclotron
- Mitsubishi — 235 MeV proton synchrotron
- Mitsubishi* — 320MeV/u synchrotron (20 cm – $^{12}C$)
- Optivus — 250 MeV proton synchrotron
- ProTom — 330 MeV/u proton synchrotron
- Siemens * — 430 MeV/u synchrotron (30 cm – $^{12}C$)
- Varian — 250MeV superconducting cyclotron

* Proton and $^{12}C$

## Single Room Systems

- Mevion: — 250 MeV gantry mounted compact superconducting synchrocyclotron. In production.
- IBA — ProteusOne
- Tomotherapy — 250 MeV Dielectric Wall Accelerator. Compact linear accelerator. Feasibility testing.

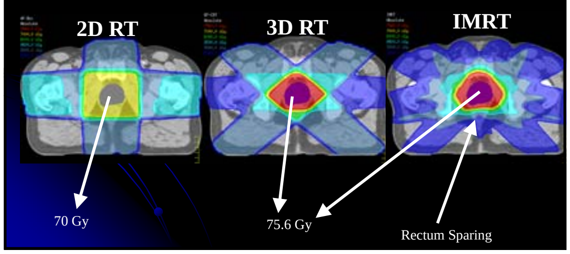
## From 2D to 3D

What have been changed?

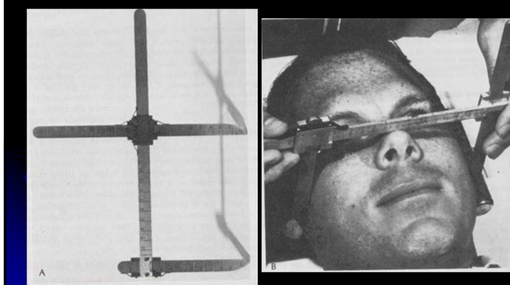
## Revolution in Radiotherapy

From 2D RT to the Current State of the Art

- 1980s - 2D RT
- 1990s - 3DCRT → IMRT
- 2000s - IMRT → IGRT → Particle Therapy

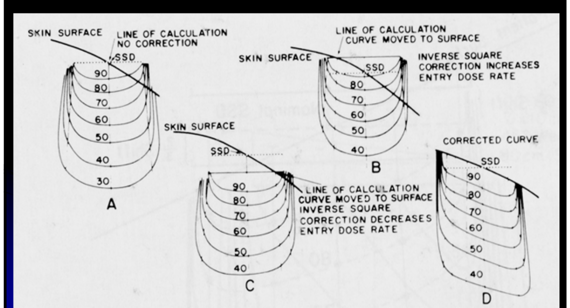



## Patient Model for Planning Treatment



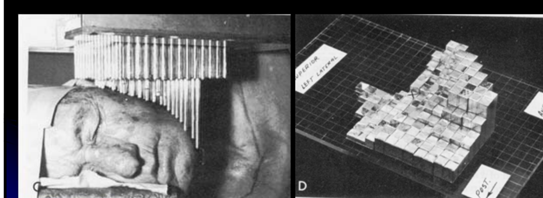
Fletcher's Textbook of Radiotherapy

## 2D Isodose Calculation




Fletcher's Textbook of Radiotherapy

## 2D Compensator



Fletcher's Textbook of Radiotherapy

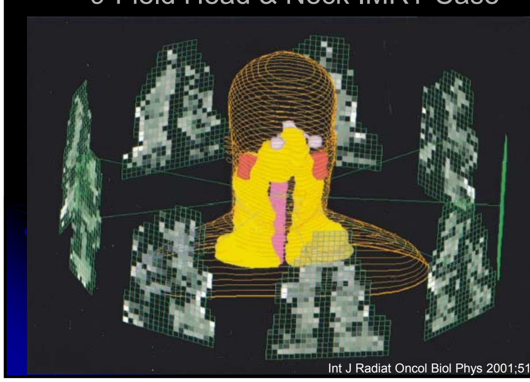
## What Is Intensity Modulated Radiation Therapy (IMRT)

An approach to deliver conformal therapy with optimized non-uniform beam intensities:

- Use computer mathematical scoring to design non-uniform radiation fields,
- Use dynamic motion of Multileaf Collimator to "paint" dose where desired - Intensity Patterns.

LD 01/02

## 9-Field Head & Neck IMRT Case



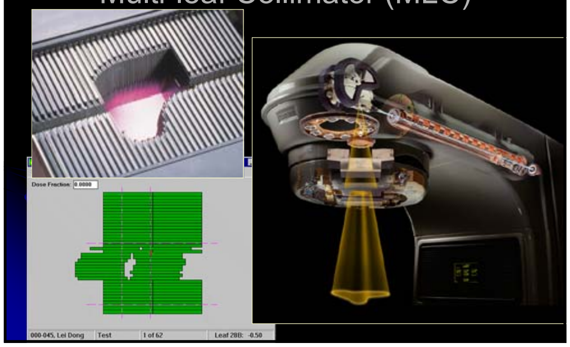
Int J Radiat Oncol Biol Phys 2001;51:880-9

## Why is IMRT Possible Today?

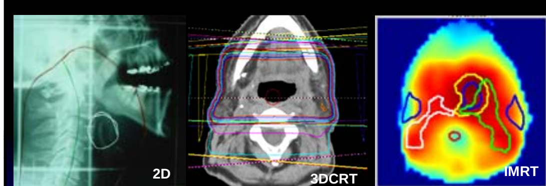
- Computer power sufficient to calculate plans in reasonable amount of time
- Linear Accelerators are computer -controlled
- Automated methods of machine setup and setup verification are convenient and commonplace
- Multileaf collimators have good mechanical precision and reliability

LD 03/03

## Computerized Treatment System Multi-leaf Collimator (MLC)

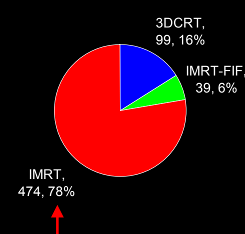


## From 2D to 3D to IMRT




## New H&N Cases at MDACC (2007)

- IMRT was the major treatment choice.
  - 3DCRT: conventional RT
  - FIF: manual field-in-field IMRT
  - IMRT: computer-optimized IMRT

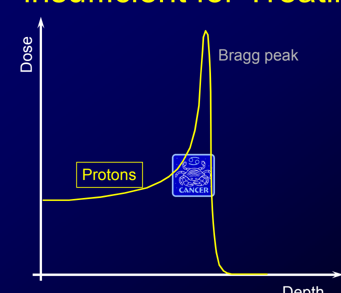


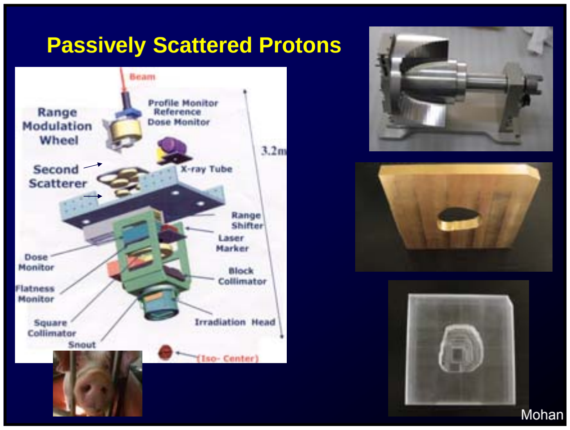

Lei Dong 2/29/2008

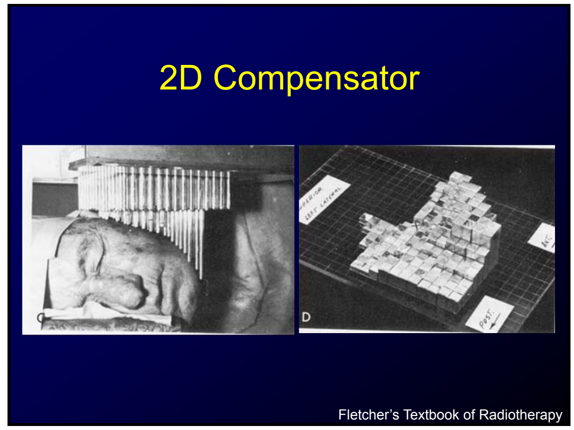
Technology Evolution in Proton Therapy

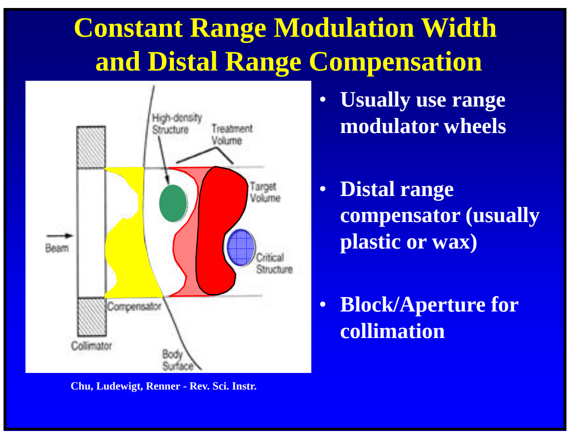
## From Scatter to Scanning

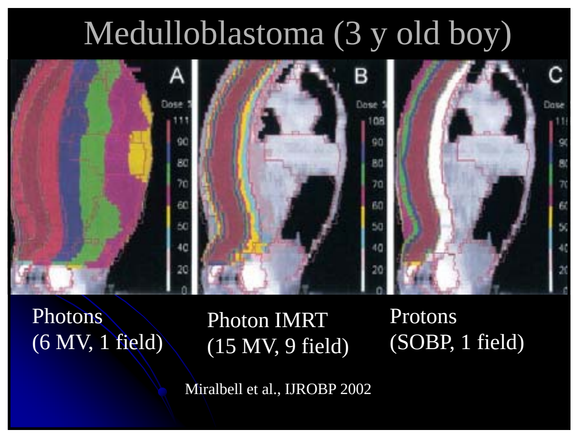
## Single Pencil Beam is insufficient for Treating Tumor

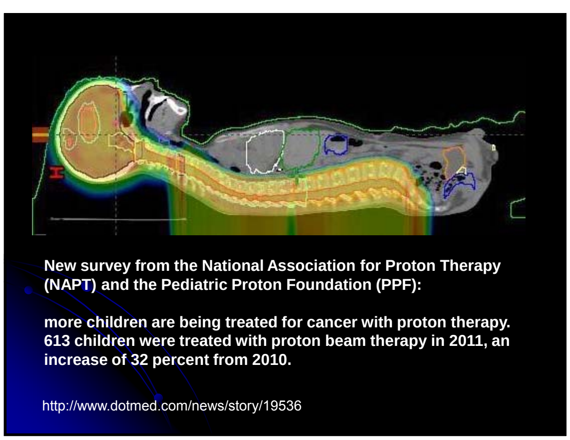


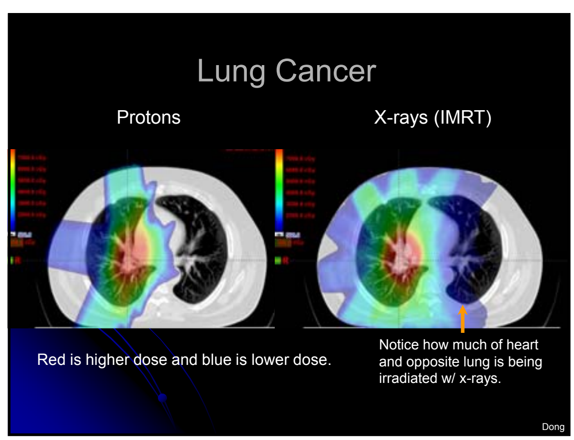

Passively Scattered Protons
Beam
Range Modulation Wheel
Profile Monitor
Reference Dose Monitor
3.2m
Second Scatterer
X-ray Tube
Range Shifter
Laser Marker
Dose Monitor
Block Collimator
Flatness Monitor
Square Collimator
Irradiation Head
Snout
(Iso- Center)
Mohan


2D Compensator
D
Fletcher's Textbook of Radiotherapy

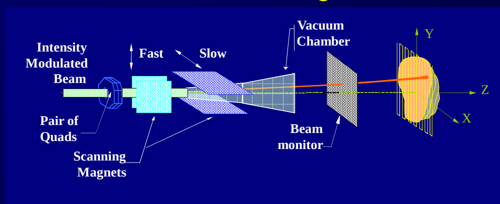

Constant Range Modulation Width and Distal Range Compensation
High-density Structure
Treatment Volume
Target Volume
Beam
Critical Structure
Compensator
Collimator
Body Surface
Chu, Ludewigt, Renner - Rev. Sci. Instr.
• Usually use range modulator wheels
• Distal range compensator (usually plastic or wax)
• Block/Aperture for collimation


Medulloblastoma (3 y old boy)
A
B
C
Photons (6 MV, 1 field)
Photon IMRT (15 MV, 9 field)
Protons (SOBP, 1 field)
Miralbell et al., IJROBP 2002


New survey from the National Association for Proton Therapy (NAPT) and the Pediatric Proton Foundation (PPF):
more children are being treated for cancer with proton therapy. 613 children were treated with proton beam therapy in 2011, an increase of 32 percent from 2010.
http://www.dotmed.com/news/story/19536

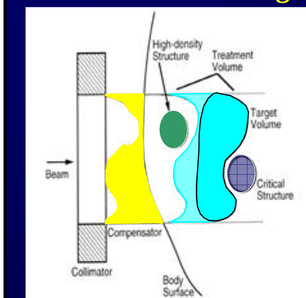

Lung Cancer
Protons
X-rays (IMRT)
Red is higher dose and blue is lower dose.
Notice how much of heart and opposite lung is being irradiated w/ x-rays.
Dong

## Pencil beam scanning nozzle




- Layer-by-layer scanning (changing energy is not easy)
- Spot scanning or raster scanning
- Max patient field (40x30) cm$^2$

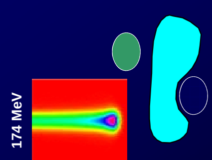
## Constant Range Modulation Width and Distal Range Compensation




Chu, Ludewigt, Renner - Rev. Sci. Instr.

- **Usually use range modulator wheels**
- **Distal range compensator (usually plastic or wax)**
- **Block/Aperture for collimation**

## Pencil Beam Scanning is Simplyer




- **Variable energy to treat tumor at different depth**
- **Dose conformality for both distal and proximal surfaces**
- **Sharp pencil beam to replace aperture**

## 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
- Scanning nozzle ( ~ MLC)

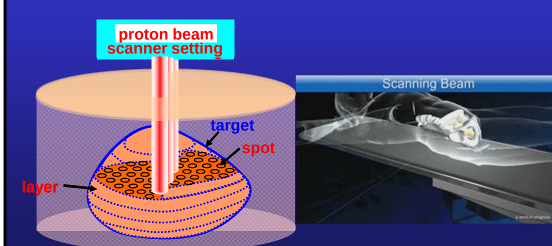
LD 04/13

## Advantages for using Pencil Beam Scanning

- Fewer neutrons
- No physical compensator or aperture
- Sparing of healthy tissues proximal to the target
- Large treatment field
- Intensity and energy modulated proton therapy (IMPT)
  - Inverse planning
  - Dynamic dose painting (control points)

## Step-and-shoot delivery of proton beam scanning

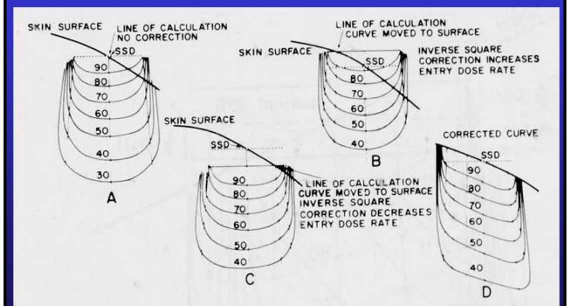
*Discrete spot scanning method*




Modified from Martin Bues, PhD,

From Varian

## 2D Isodose Calculation




Fletcher's Textbook of Radiotherapy

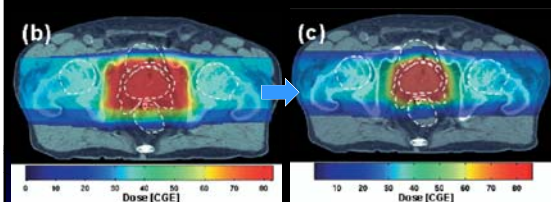
## Proton Beam Delivery Mode

- Passive Scatter (PS)
  - Use scatter technique to create a large treatment field
  - Range modulation is required
- Uniform Scanning (US)
  - Pre-programmed PBS with beam aperture (more tolerant of motion)
- Pencil Beam Scanning (PBS)
  - Use magnetic field to scan the treatment field
  - High intensity modulation (better plans)
  - Energy (range) can be changed spot-by-spot

## Raster Scan vs. Spot Scan

- Intensity modulation is much higher in spot scanning technique, which leads to better treatment plans
- Raster scanning may be more tolerant for organ motion

## Evolution of Proton Therapy

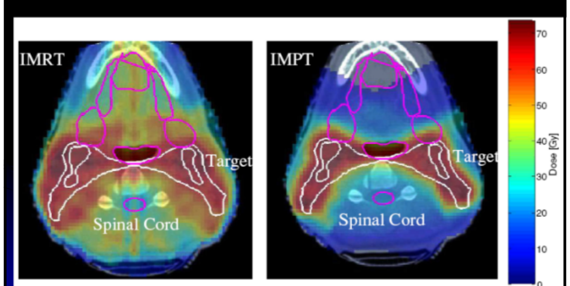



Conventional PT

PBS (Pencil Beam Scanning) /IMPT (Intensity Modulated Proton Therapy)

Trofimov et al. IJROBP 69(2): 444-453. (2007)

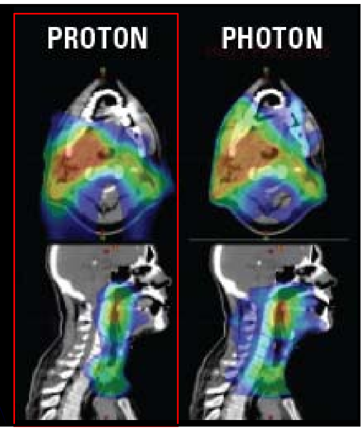
## Photons vs. Future Protons




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

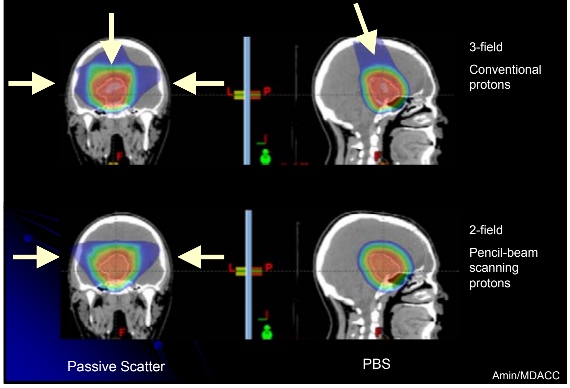
IMRT

IMPT (big spot size)




MD Anderson

PBS has better conformality and allows fewer fields




Amin/MDACC

## IMRT vs. IMPT

- IMPT typically use fewer beams
  - 2-3 (IMPT) vs. 5-9 (IMRT)
- Range uncertainties – PTV concept
- CT image quality is important
  - Metal artifacts
  - Patient scatter
- Normal tissue motion is important
- IGRT
  - CBCT is lacking in proton therapy centers (today)

## Image Guidance in New Systems

## Image Guidance

- X-ray source to axis distance = 2 meters
- Detector to axis distance = 1 meter

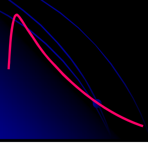
Courtesy of Varian

## Robotic Couch

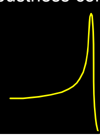
## Challenges

## Inverse Planning Challenges

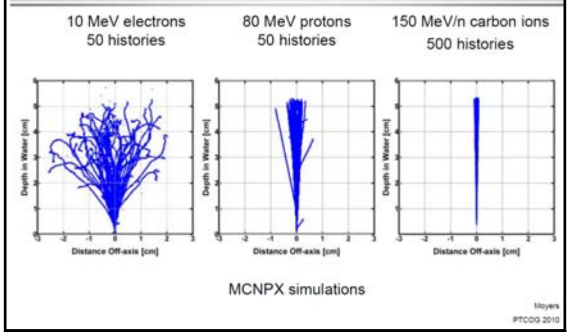
**IMRT**
- Beam angle
- Pencil beam position
- Pencil beam intensity

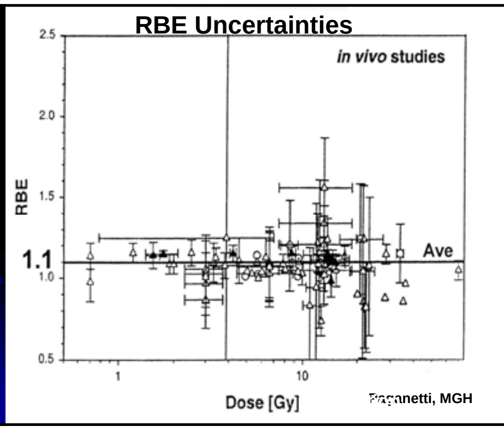


**IMPT**
- Beam angle
- Pencil beam position
- Pencil beam intensity
- Pencil beam energy
- Pencil beam spacing f(E)
- Robustness considerations



## Straggling from Multiple Particle Paths



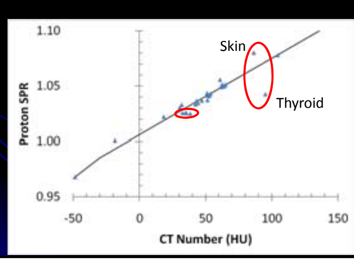




## CT Number Uncertainties

Leading to errors in predicted proton range in patient

## CT number to Proton Stopping Power

- Degeneracy problem
  - HU ($\rho_1$, $Z_1$) = HU ($\rho_2$,$Z_2$)
  - SPR($\rho_1$, $Z_1$) ≠ SPR($\rho_2$,$Z_2$)

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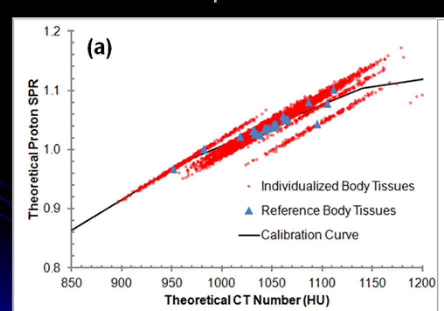
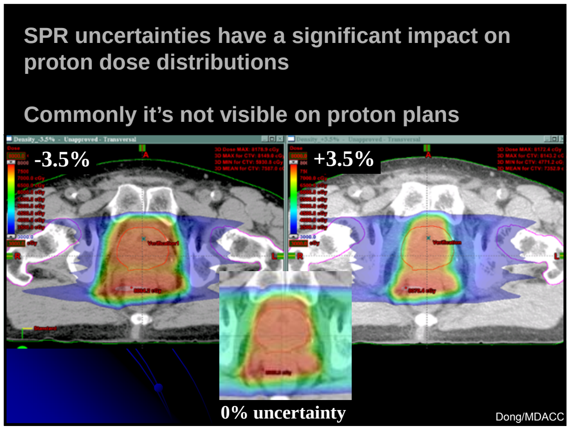
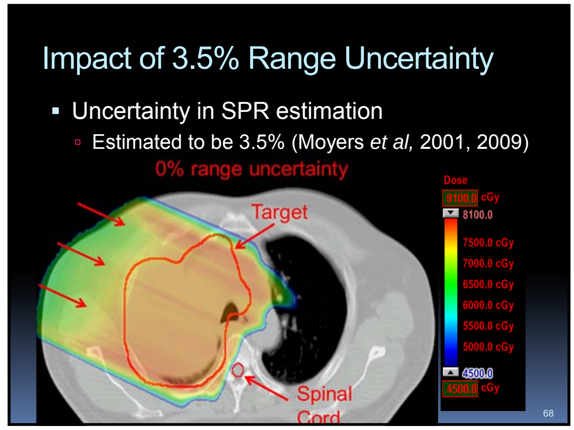
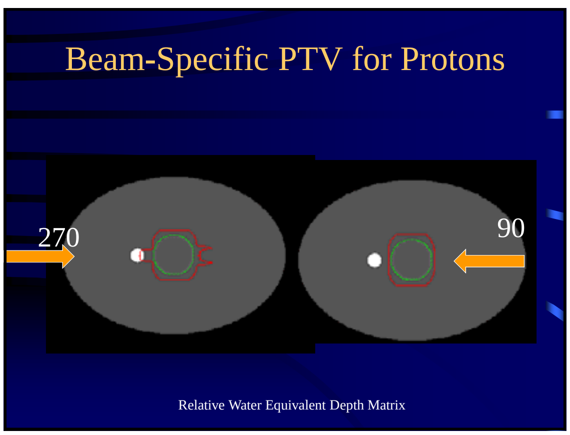
## Variations in Human Tissue Composition

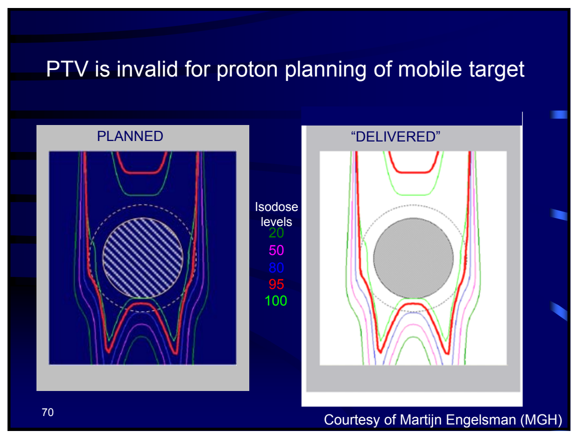


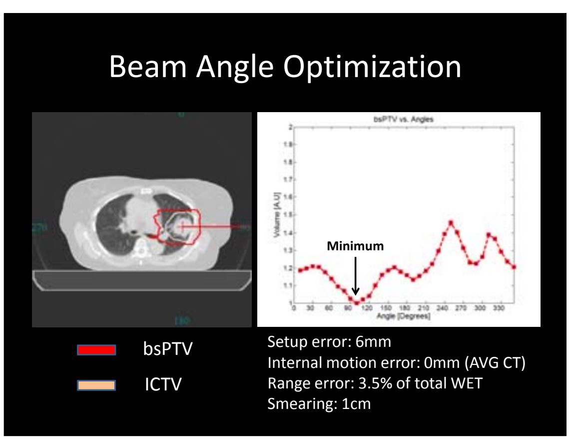

Yang M.

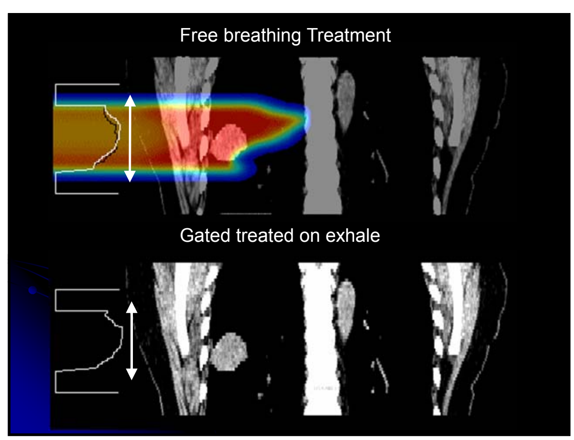

SPR uncertainties have a significant impact on proton dose distributions
Commonly it's not visible on proton plans
-3.5%
+3.5%
0% uncertainty
Dong/MDACC

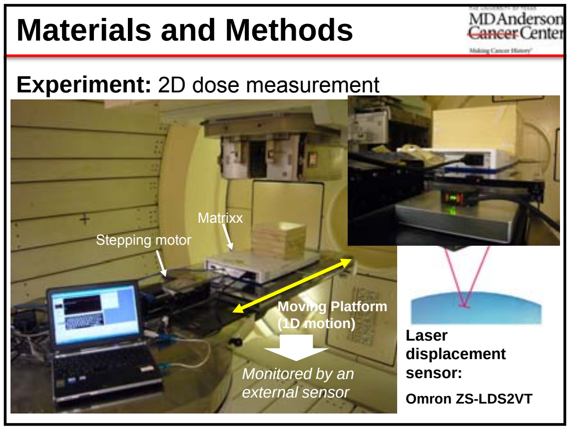

Impact of 3.5% Range Uncertainty
Uncertainty in SPR estimation
Estimated to be 3.5% (Moyers et al, 2001, 2009)
0% range uncertainty
Target
Spinal Cord
Dose
8100.0 cGy
7500.0 cGy
7000.0 cGy
6500.0 cGy
6000.0 cGy
5500.0 cGy
5000.0 cGy
4500.0 cGy
68

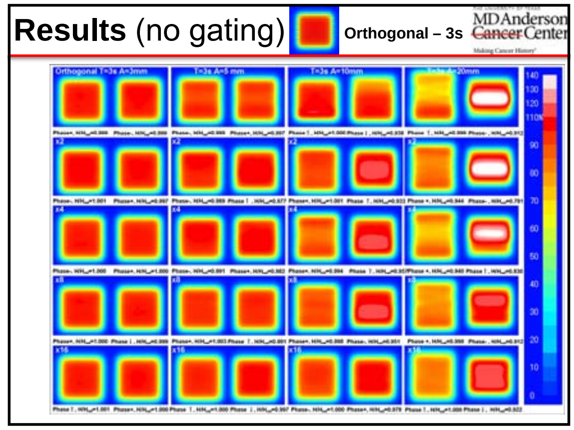

Beam-Specific PTV for Protons
270
90
Relative Water Equivalent Depth Matrix

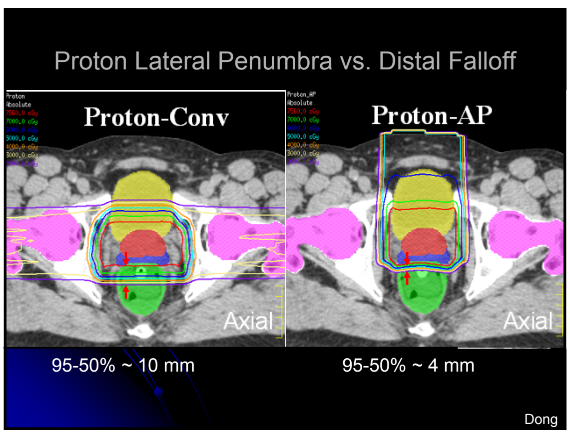

PTV is invalid for proton planning of mobile target
PLANNED
"DELIVERED"
Isodose levels
20
50
80
95
100
70
Courtesy of Martijn Engelsman (MGH)

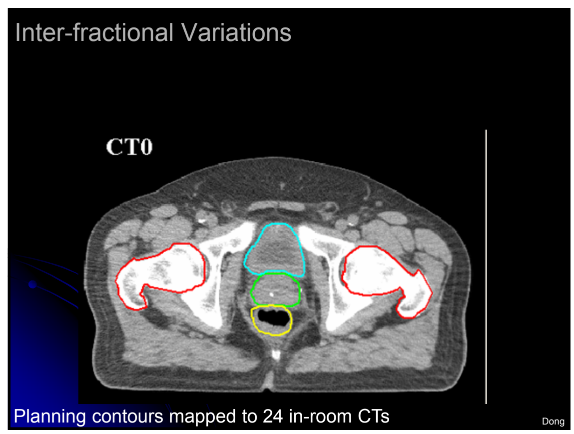

Beam Angle Optimization
bsPTV vs. Angles
Minimum
Angle [Degrees]
bsPTV
ICTV
Setup error: 6mm
Internal motion error: 0mm (AVG CT)
Range error: 3.5% of total WET
Smearing: 1cm

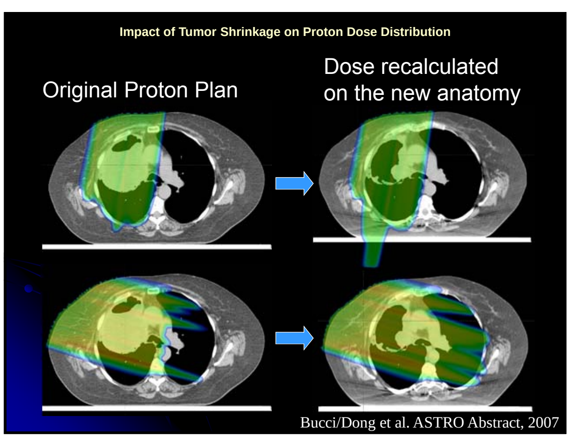

Free breathing Treatment
Gated treated on exhale

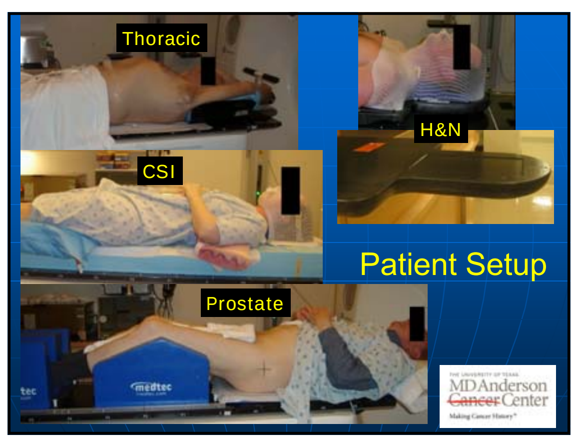

Materials and Methods
MDAnderson Cancer Center
Experiment: 2D dose measurement
Matrixx
Stepping motor
Moving Platform (1D motion)
Monitored by an external sensor
Laser displacement sensor:
Omron ZS-LDS2VT


Results (no gating)
Orthogonal – 3s
MDAnderson Cancer Center

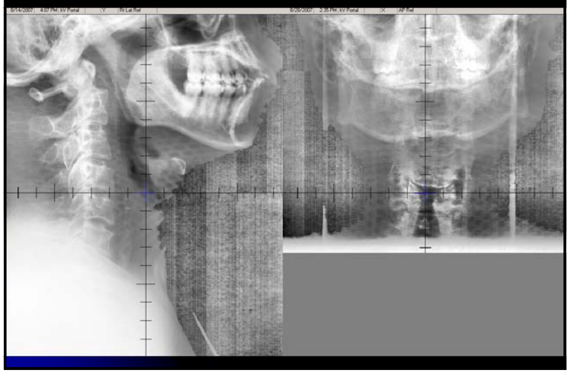

Proton Lateral Penumbra vs. Distal Falloff
Proton-Conv
Proton-AP
Axial
Axial
95-50% ~ 10 mm
95-50% ~ 4 mm
Dong


Inter-fractional Variations
CT0
Planning contours mapped to 24 in-room CTs
Dong

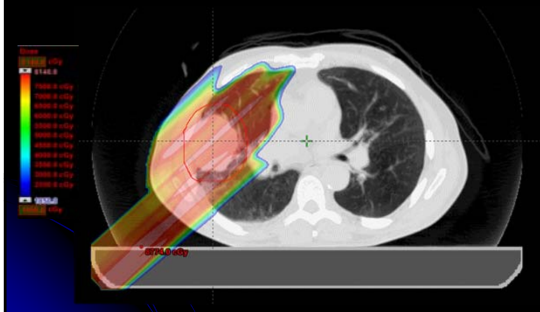

Impact of Tumor Shrinkage on Proton Dose Distribution
Original Proton Plan
Dose recalculated on the new anatomy
Bucci/Dong et al. ASTRO Abstract, 2007


Thoracic
H&N
CSI
Patient Setup
Prostate
MDAnderson Cancer Center

## Setup Error and Positional Variation of Immobilization Device

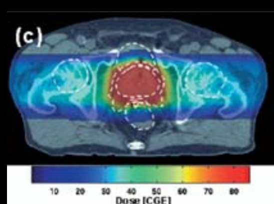


## Couch Edge Effect



H. Yu et al.

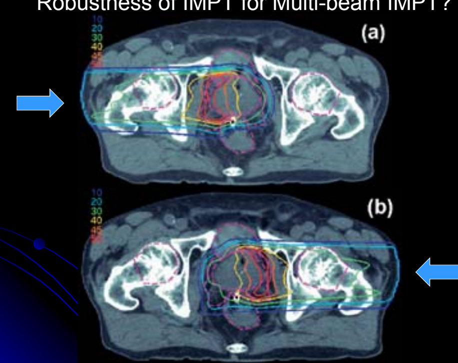
## IMPT Planning




PBS (Pencil Beam Scanning) /IMPT (Intensity Modulated Proton Therapy)

Trofimov et al. IJROBP 69(2): 444-453. (2007)

## Robustness of IMPT for Multi-beam IMPT?

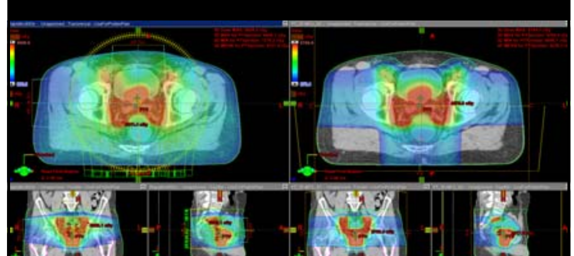



Trofimov et al. IJROBP 69(2): 444-453. (2007)

## SFO vs. MFO

- Single-Field Optimization
  - Treat the entire target from one beam
  - Less normal tissue sparing
  - Relatively more robust for range uncertainties
- Multi-Field Optimization
  - Simultaneous optimization of multiple beams for one or more targets
  - Better plan (on paper) and more tissue sparing
  - Sensitive to range uncertainties and organ motion

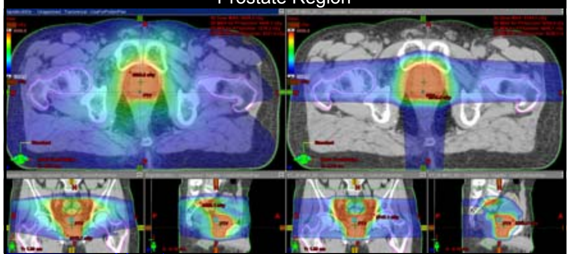
## IMRT vs. IMPT Example



RapidArc™ 3F IMPT

## IMRT vs. IMPT Example

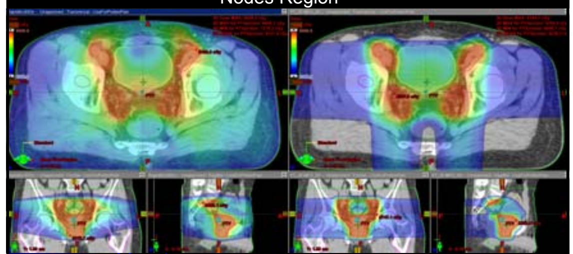
Prostate Region



RapidArc™ 3F IMPT

## IMRT vs. IMPT Example

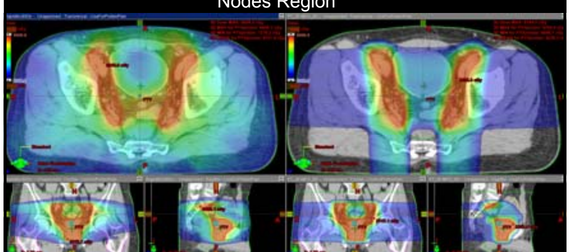
Nodes Region



RapidArc™ 3F IMPT

## IMRT vs. IMPT Example

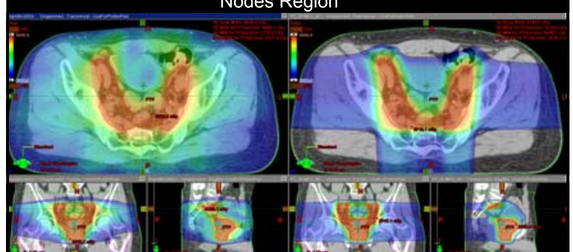
Nodes Region



RapidArc™ 3F IMPT

## IMRT vs. IMPT Example

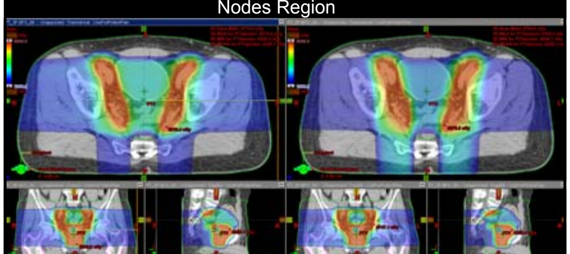
Nodes Region



RapidArc™ 3F IMPT

## SFO vs. MFO (IMPT)

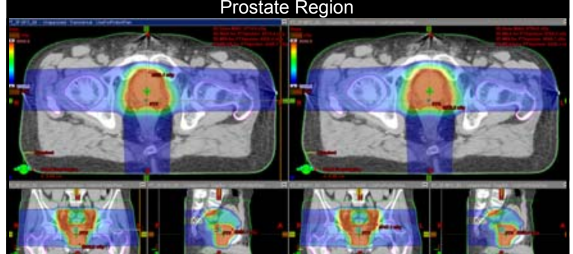
Nodes Region



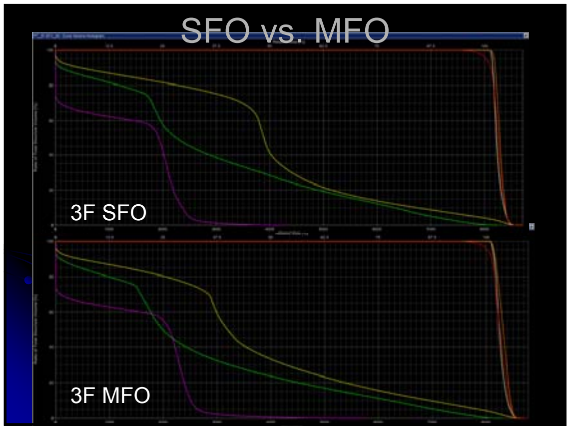
3F SFO 3F MFO

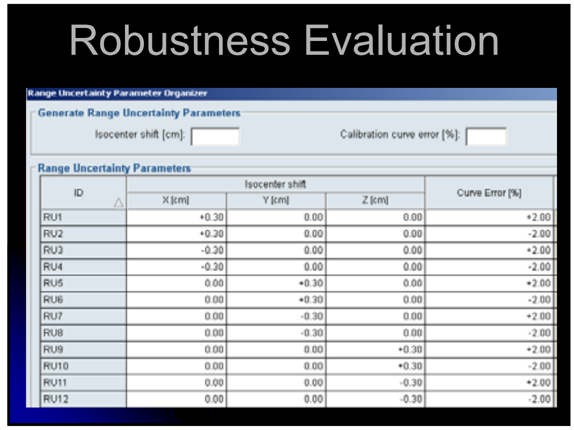
## SFO vs. MFO (IMPT)

Prostate Region

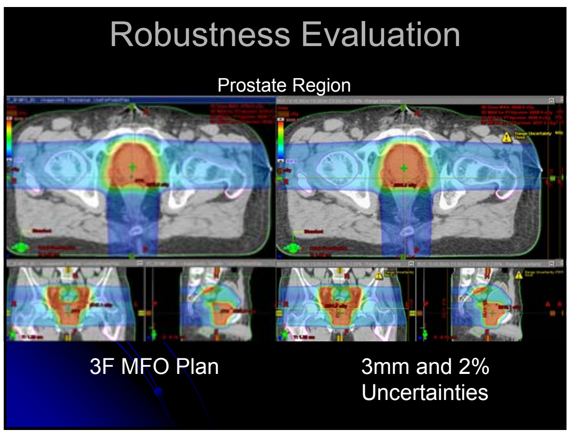


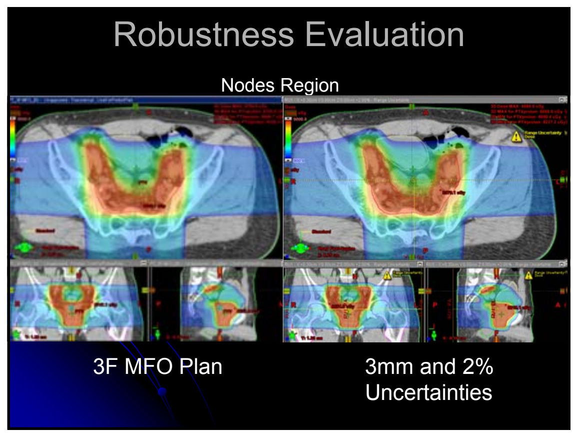
3F SFO 3F MFO

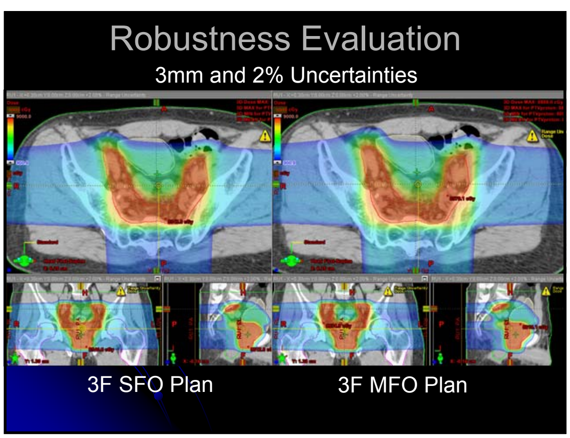


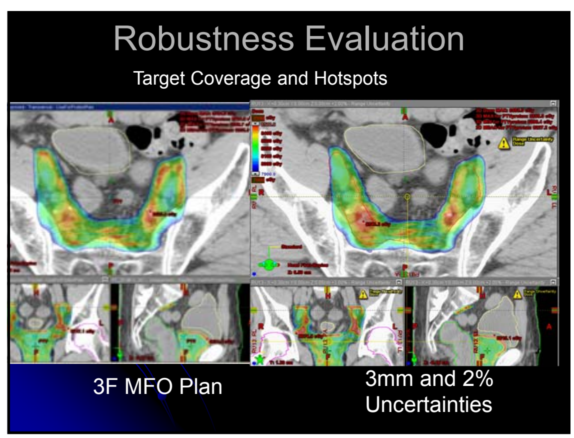




| ID | Isocenter shift | | | Curve Error [%] |
|---|---|---|---|---|
| | X [cm] | Y [cm] | Z [cm] | |
| RU1 | +0.30 | 0.00 | 0.00 | +2.00 |
| RU2 | +0.30 | 0.00 | 0.00 | -2.00 |
| RU3 | -0.30 | 0.00 | 0.00 | +2.00 |
| RU4 | -0.30 | 0.00 | 0.00 | -2.00 |
| RU5 | 0.00 | +0.30 | 0.00 | +2.00 |
| RU6 | 0.00 | +0.30 | 0.00 | -2.00 |
| RU7 | 0.00 | -0.30 | 0.00 | +2.00 |
| RU8 | 0.00 | -0.30 | 0.00 | -2.00 |
| RU9 | 0.00 | 0.00 | +0.30 | +2.00 |
| RU10 | 0.00 | 0.00 | +0.30 | -2.00 |
| RU11 | 0.00 | 0.00 | -0.30 | +2.00 |
| RU12 | 0.00 | 0.00 | -0.30 | -2.00 |

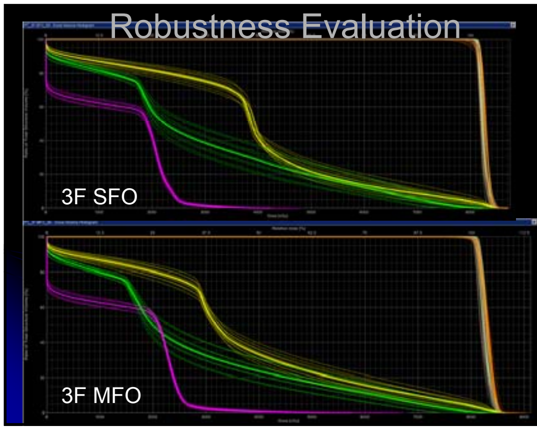


## Robustness Evaluation




## Summary

## Challenges

- Development and optimal use of IMPT
- Measurement dosimetry
- In vivo range verification
- Robustness plan evaluation
- Robust plan optimization
- Motion management strategies
- Dose-guided setup and adaptive RT
- Workflow optimization and efficiency
  - Auto-segmentation
  - Workflow assessment and optimization
  - Setup outside of treatment room

## Opportunities

- Development and optimal use of IMPT
- Measurement dosimetry
- In vivo range verification
- Robustness plan evaluation
- Robust plan optimization
- Motion management strategies
- Dose-guided setup and adaptive RT
- Workflow optimization and efficiency
  - Auto-segmentation
  - Workflow assessment and optimization
  - Setup outside of treatment room

## Future Proton Therapy Machines will be Different from Today!

What is IMRT?

**I'M R**eally **T**ired

What is IMPT?

**I'M P**ainfully **T**ired

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