AAPM 49th Annual Meeting

CE - Therapy

PROTON THERAPY

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Topics Covered

- History of Proton Therapy
- Worldwide Facilities
- Rationale for Proton Therapy
- Physics of Proton Beams
- Treatment Delivery Techniques
- Proton Treatment Technology
- Clinical Commissioning
- Treatment Planning

History and Current Status

of

Proton Therapy

Abbreviated History of Protons

- 1919 Rutherford proposed existence of protons
- 1930 E. O. Lawrence built first cyclotron
- 1946 Robert Wilson proposed proton therapy
- 1955 Tobias et al treated patients at LBL
- 1961 Kjellberg et al treated patients at HCL
- 1972 MGH received first NCI grant for proton studies at HCL
- 1991 First hospital-based proton facility at LLUMC
- 2006 28 facilities worldwide treating patients; over 55,000 patients treated with protons.

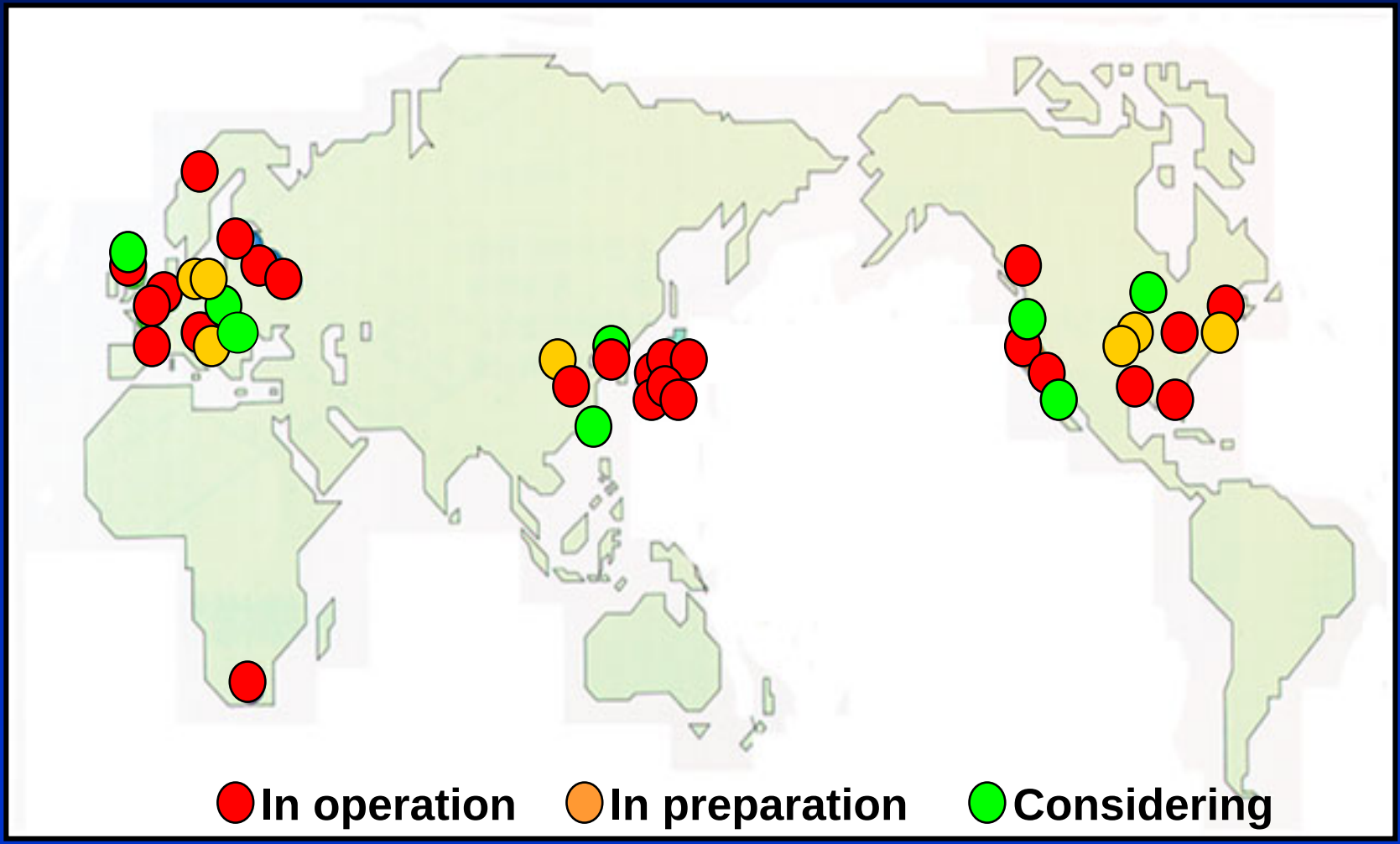
Charged Particle Therapy Facilities

25 facilities worldwide are treating patients.

- 6 in Japan (4 hospital-based)
  - Chiba, NCC East-Kashiwa, HIBMC-Hyogo, PMRC-Tsukuba, WERC-Wakasa, Shizuoka Cancer Center
- 6 in the United States (4 hospital-based)

  LLUMC, MGH, MDACC, Univ. of Florida, Univ. of Indiana, UC Davis
- 9 in Europe/Russia
- 4 Additional facilities (UK, China, Korea, South Africa)
- 15 additional institutions worldwide are either building a new facility or are seriously planning to have a particle therapy facility.

Particle Therapy Facilities Worldwide



Treating: Protons 25, Carbon ions 3

Courtesy of Takashi Ogino, MD, PhD, NCC Kashiwa, Japan

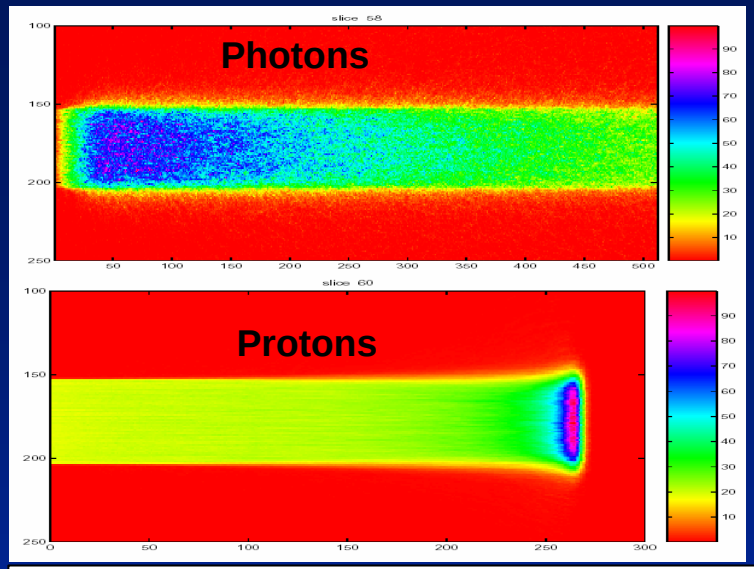
Rationale for Proton Therapy

Need for Improved Local Control in Cancer Treatment (selected sites)

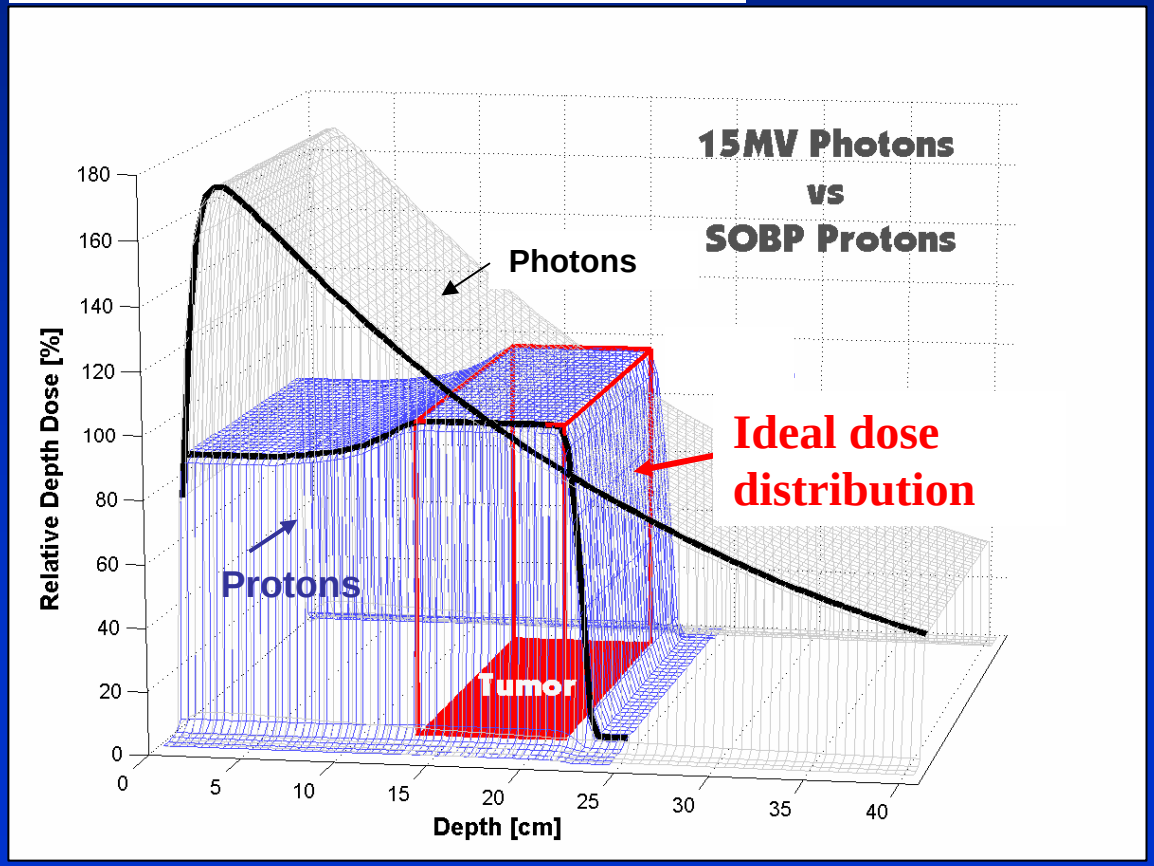
(all numbers are estimates)

Tumor Site	Deaths/ year	Deaths due to Local Failure
Head/Neck	22,000	13,200 (60%)
Gastrointestinal	135,000	54,000 (40%)
Gynecologic	28,000	14,000 (50%)
Genitourinary	55,000	27,500 (50%)
Lung	160,000	40,000 (25%)
Breast	41,000	4,920 (12%)
Lymphoma	20,000	2,400 (12%)
Skin, Bone, Soft Tissue	15,000	5,000 (33%)
Brain	12,000	10,800 (90%)
Total	488,000	171,820 (35%)

Over 1,350,000 new cancer patients per year in the US



Fundamental Things to Remember about Protons

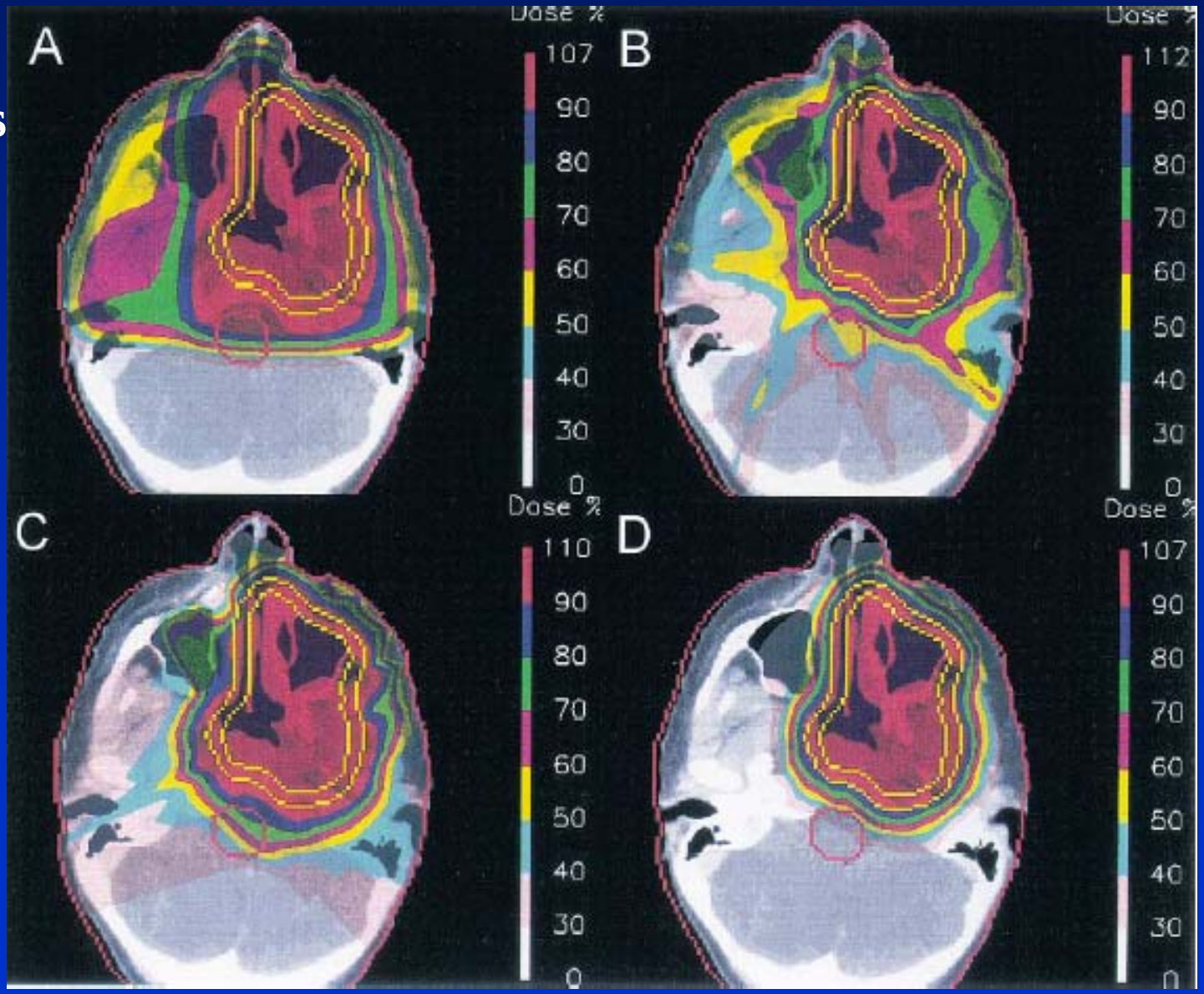


- Protons Stop!
- Photons don't stop.
- Proton dose at depth (target) is greater than dose at surface.
- Photon dose at depth (target) is less than dose at d_{max}.

Rhabdomyosarcoma of Paranasal Sinus (7 y old boy)

6 MV Photons (3 field)

160 MeV Protons (2 field)



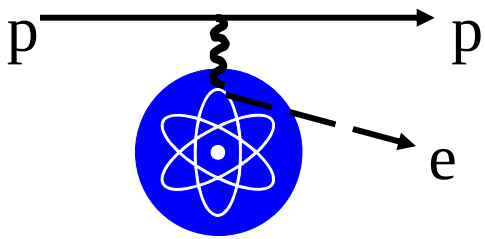
Photon IMXT (9 field)

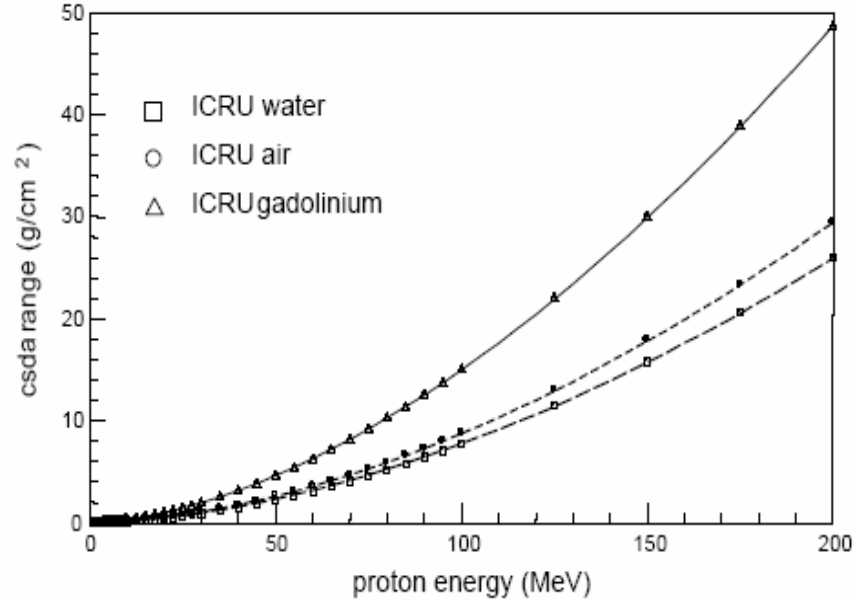
Proton IMRT (9 field)

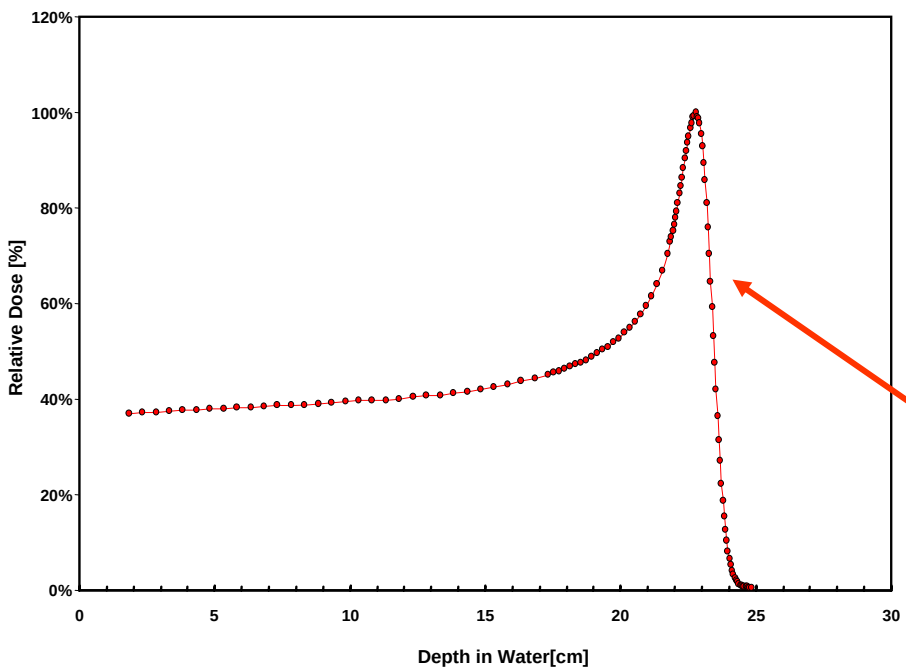
Proton Physics

- The physics of proton beams
- Passive scattering systems
- Pencil beam scanning systems

Electromagnetic energy loss of protons







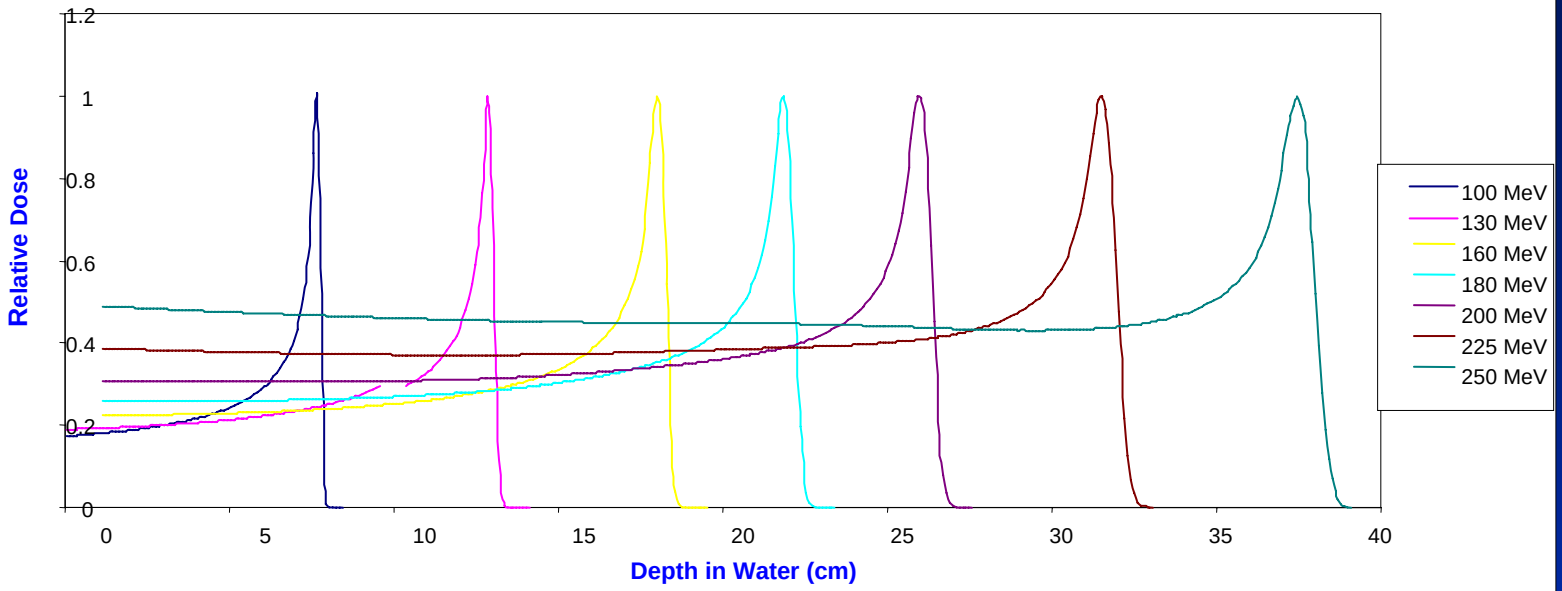
Mass Electronic Stopping Power is the mean energy lost by protons in electronic collisions in traversing the distance dx in a material of density ρ.

$$S/\rho = 1/\rho[dE/dx] \propto 1/v^2$$

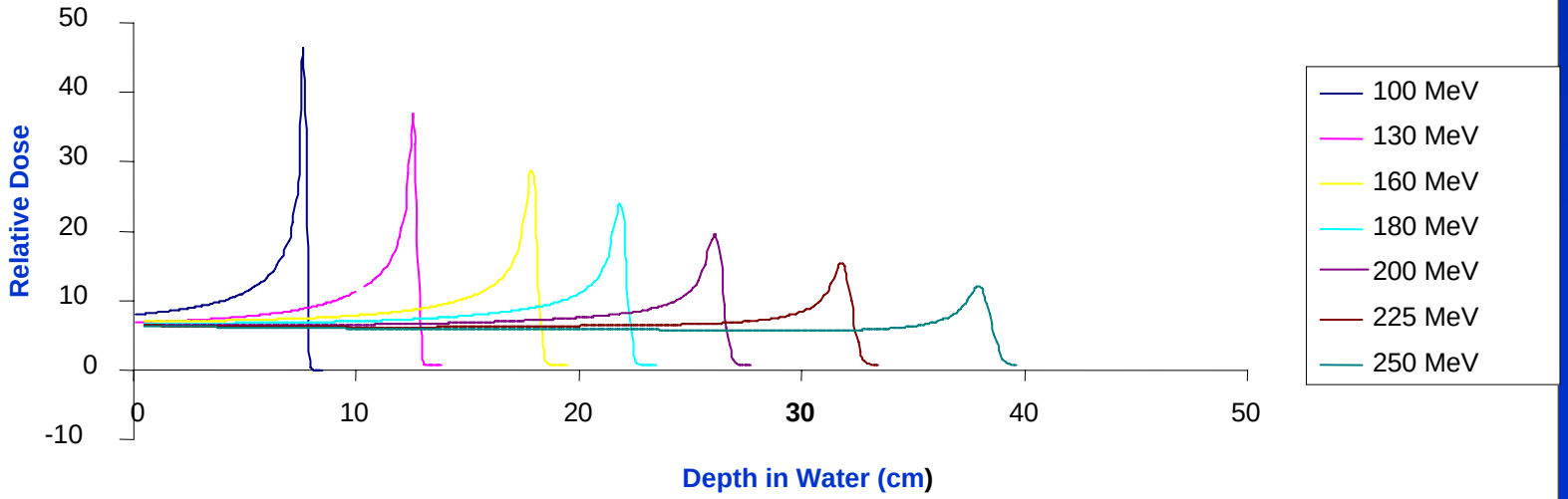
Where v = proton velocity

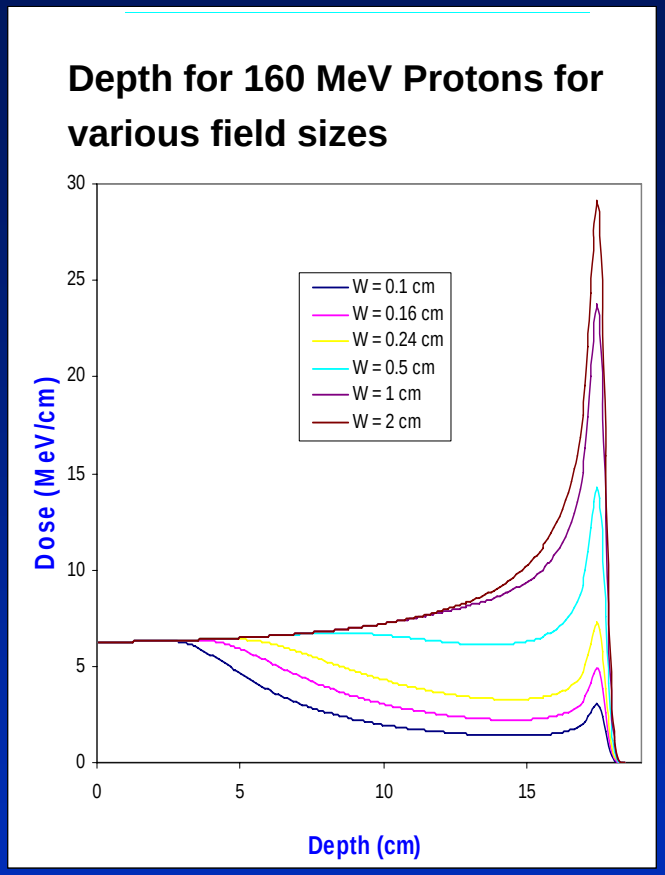
Normalized (at peak) Bragg Curves for Various Proton Incident Energies

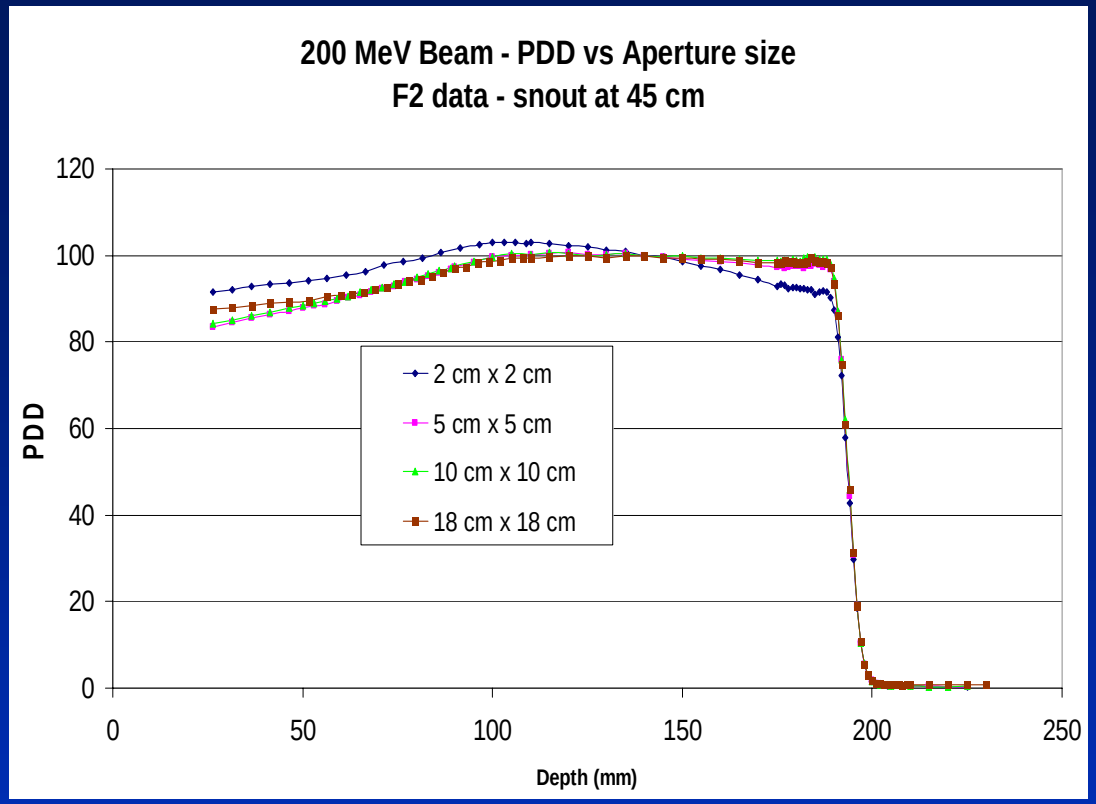
Range Straggling will cause the Bragg peak to widen with depth of penetration



Normalized (at entrance) Bragg Curves for Various Proton Incident Energies





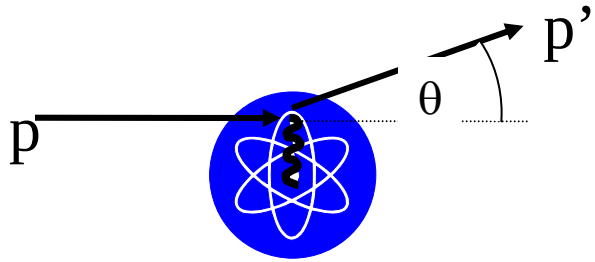


Loss of in-scattering (charged particle equilibrium) results in deterioration of Bragg peak and non uniformity of SOBP.

George Ciangaru

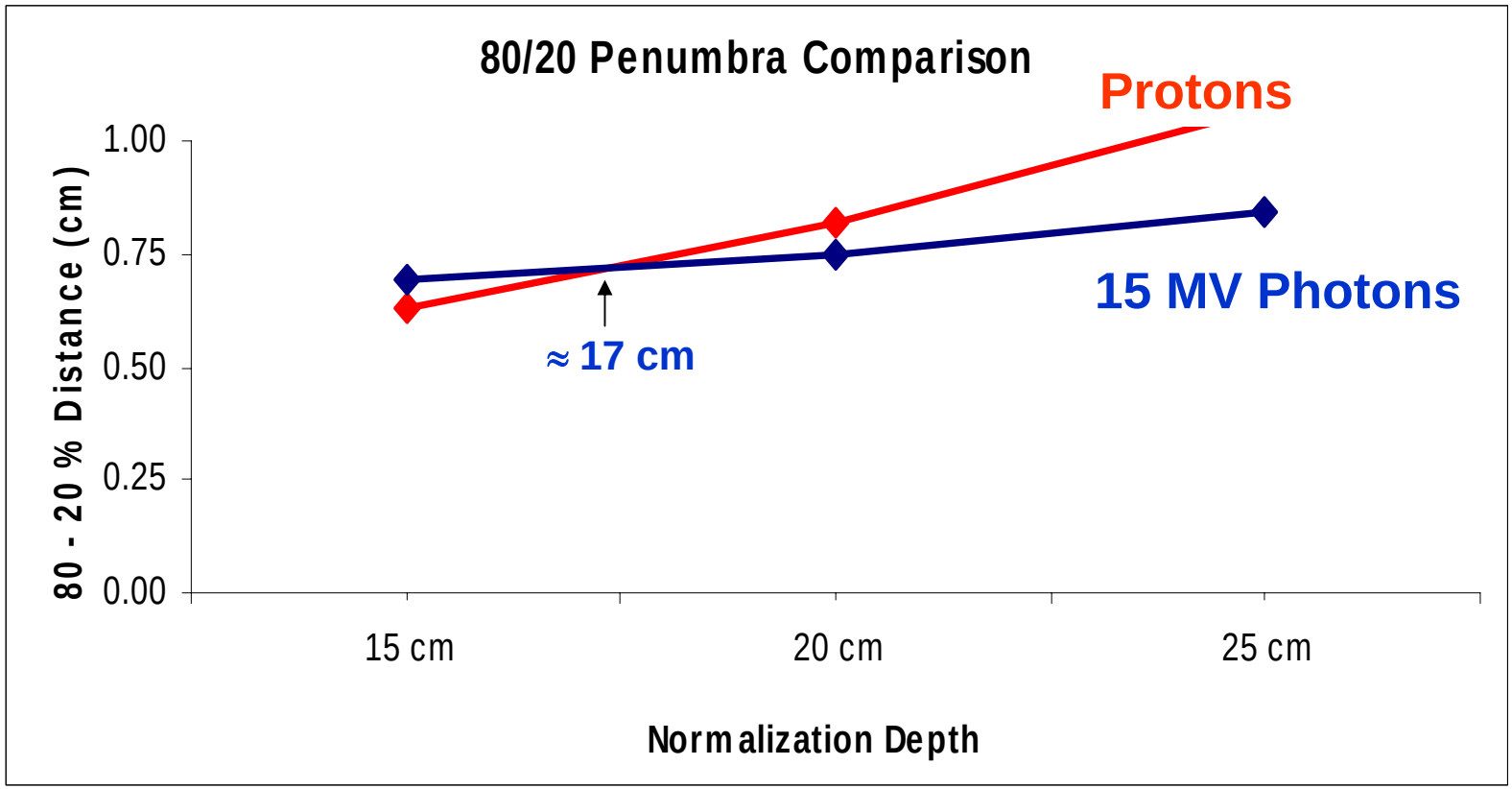
Narayan Sahoo

Multiple Coulomb Scattering

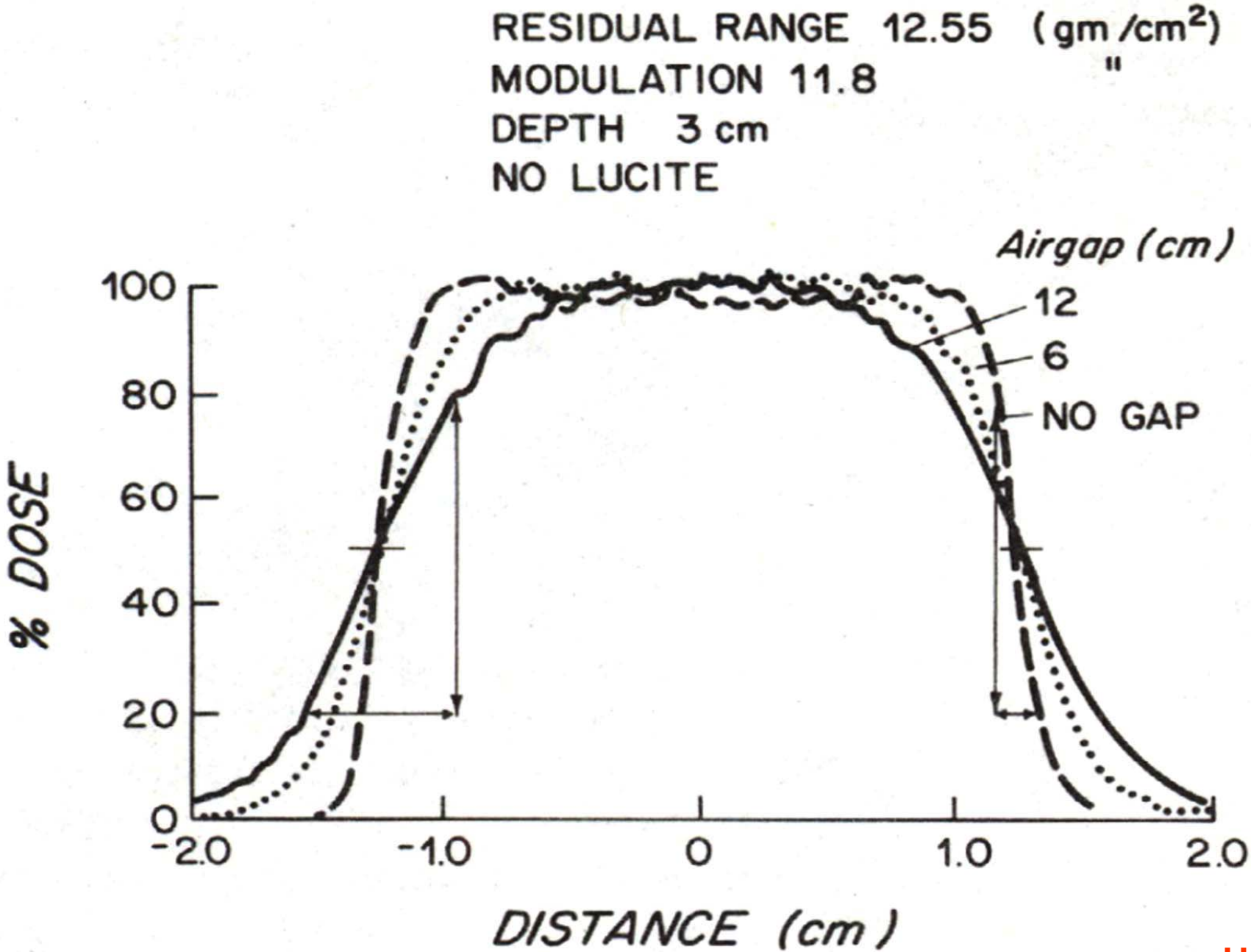


- Protons are deflected frequently in the electric field of the nuclei
- Beam broadening can be approximated by a Gaussian distribution

Lateral dose fall-off: Protons vs. Photons

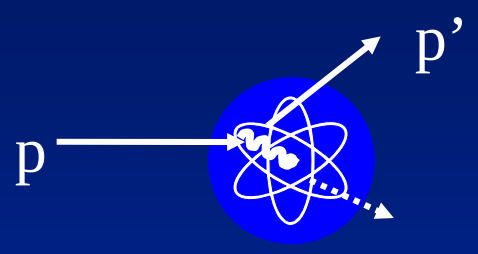


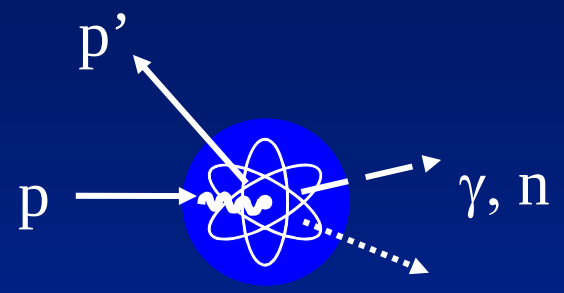
Paganetti


RESIDUAL RANGE 12.55 (gm/cm²)
MODULATION 11.8 "
DEPTH 3 cm
NO LUCITE
Airgap (cm)
12
6
NO GAP
100
80
60
40
20
0
% DOSE
-2.0
-1.0
0
1.0
2.0
DISTANCE (cm)

Urie

Nuclear interactions of protons

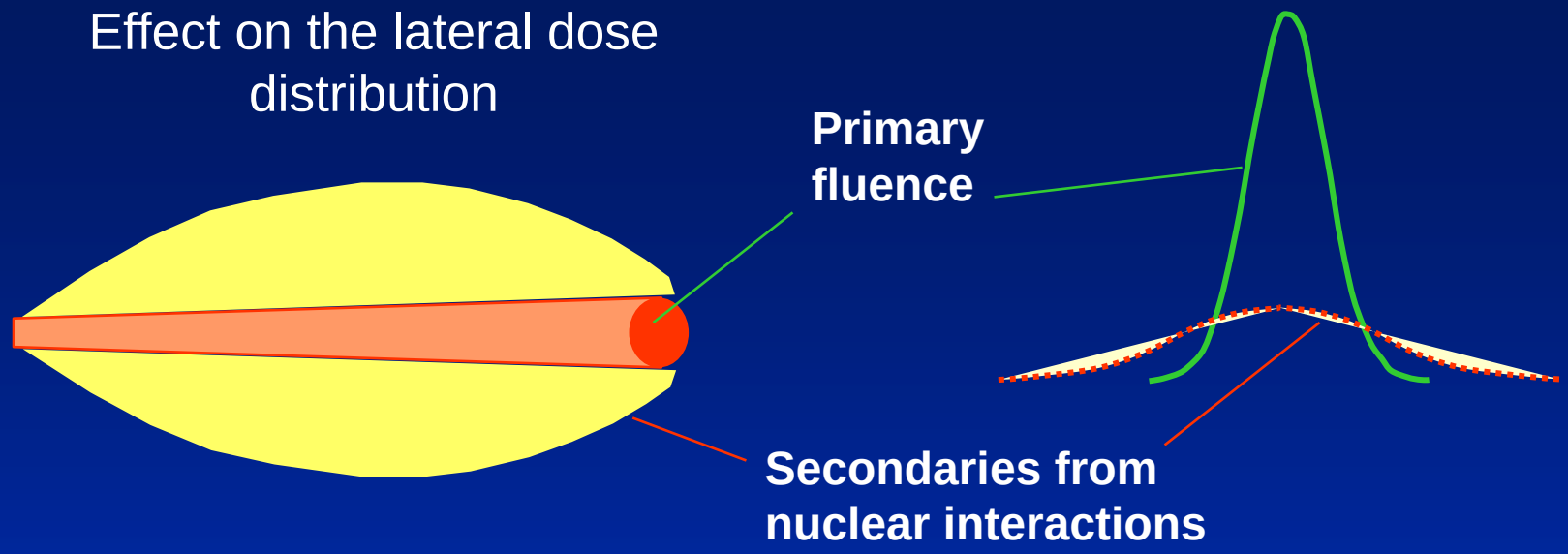


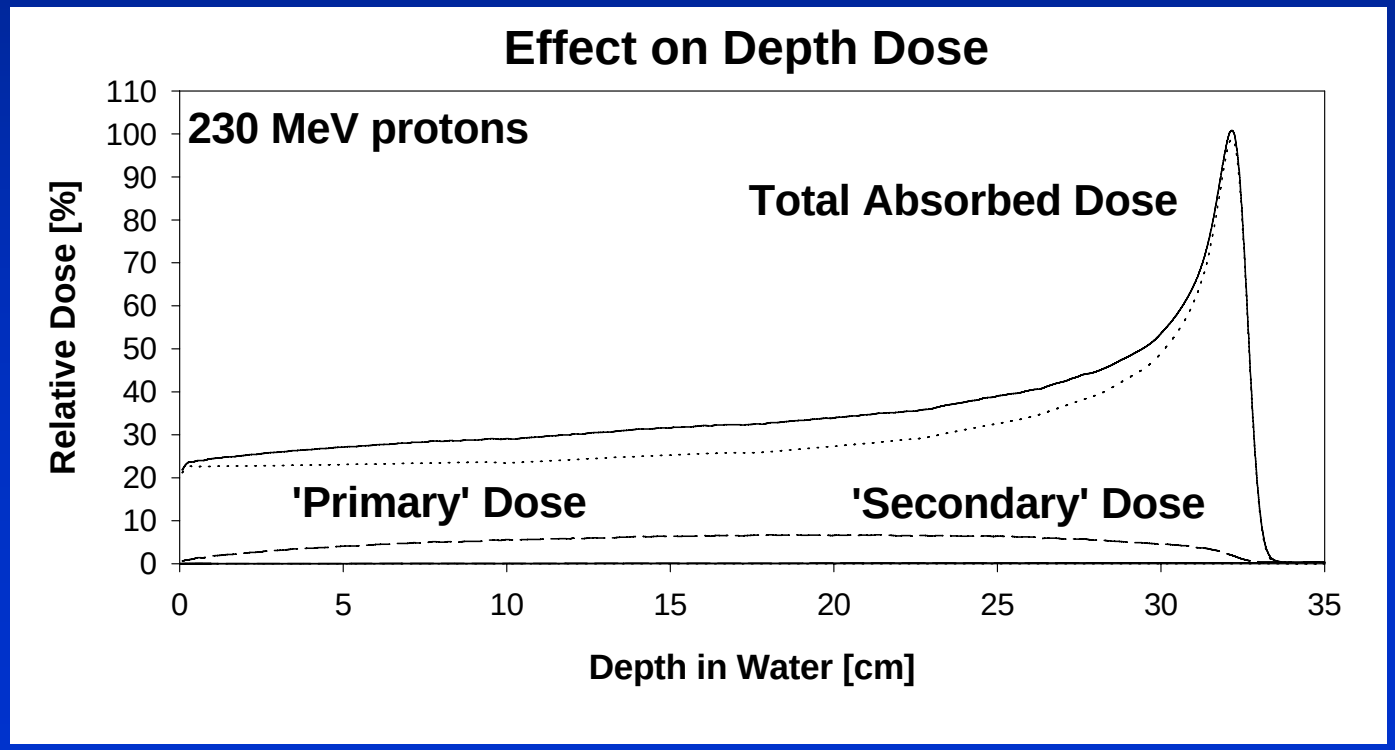


- **A certain fraction of protons undergo nuclear interactions, mainly on ^{16}O**
- **Nuclear interactions lead to secondary particles and thus to local and non-local dose deposition (neutrons!)**
- **In passive scattering systems neutrons are produced in the first and second scatterers, modulation wheel, aperture, range compensator in addition to those produced in the patient.**

Pedroni et al PMB, 50, 541-561, 2005

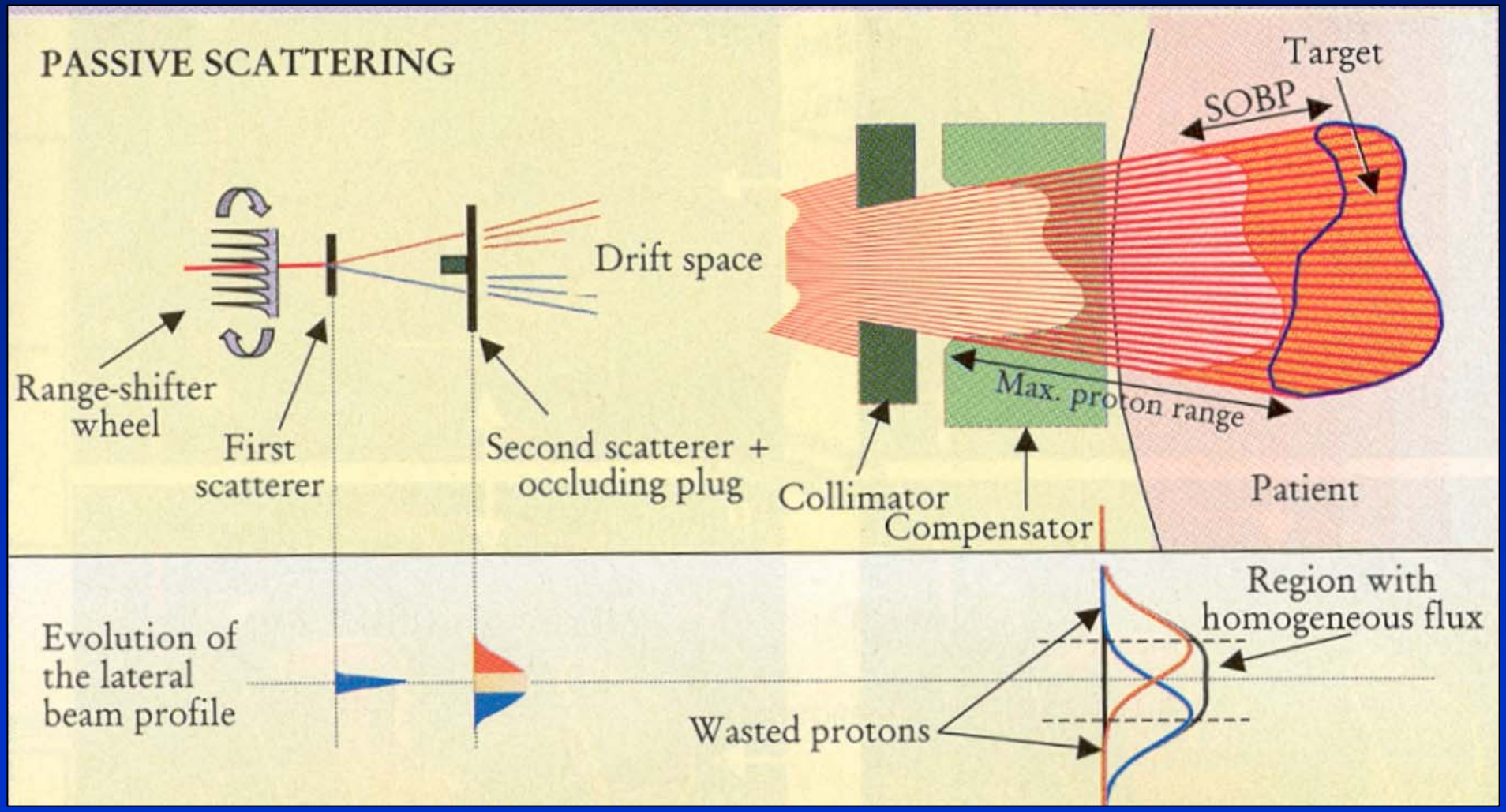
Effect on the lateral dose distribution





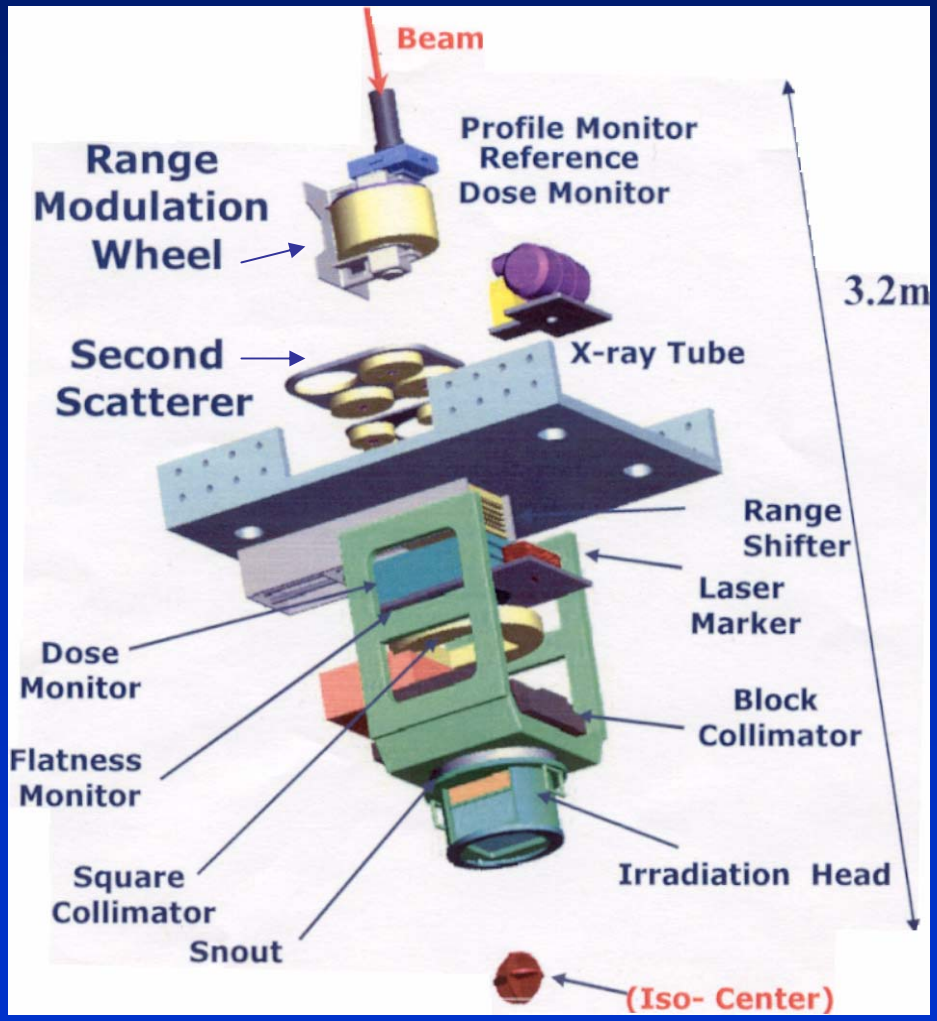
Proton Therapy
Beam Delivery Technology

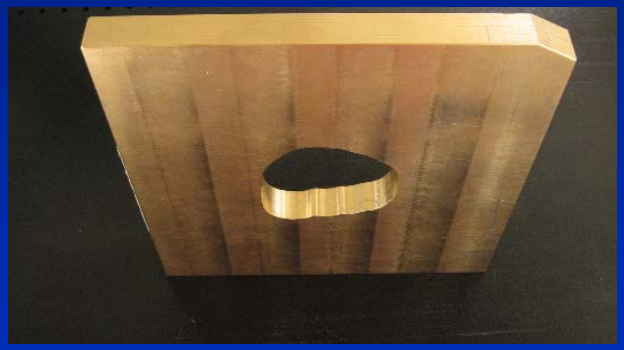
Physics of the Passive Scattering Mode of Proton Beam Delivery

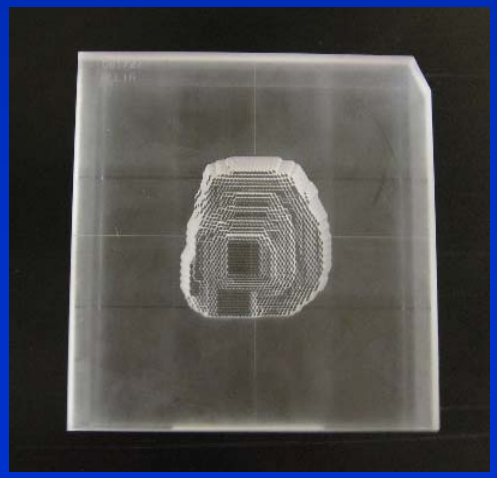


Goitein, Lomax, Pedroni - Med. Phys.

Passive Scattering Nozzle with Range Modulation Wheel

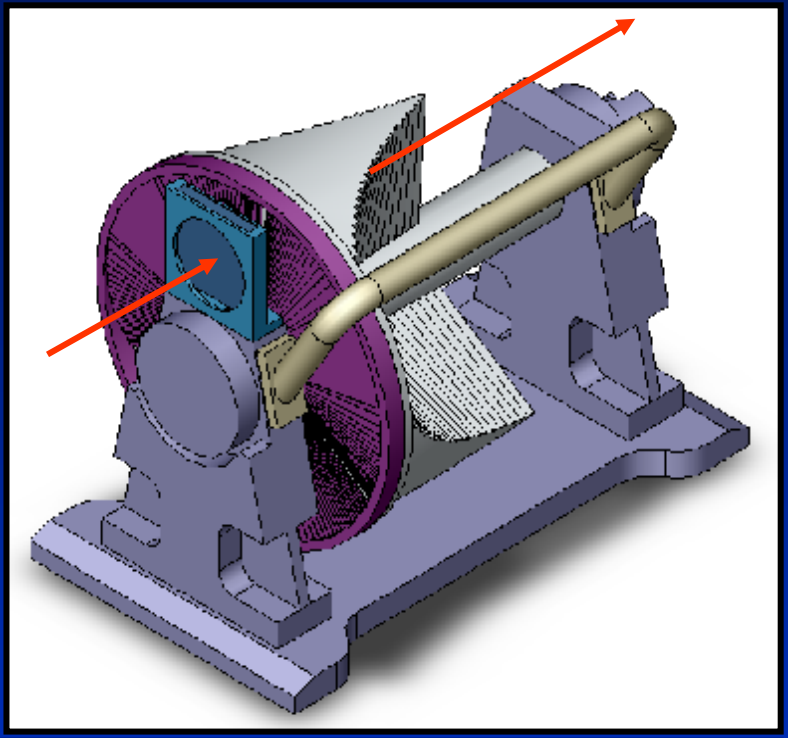


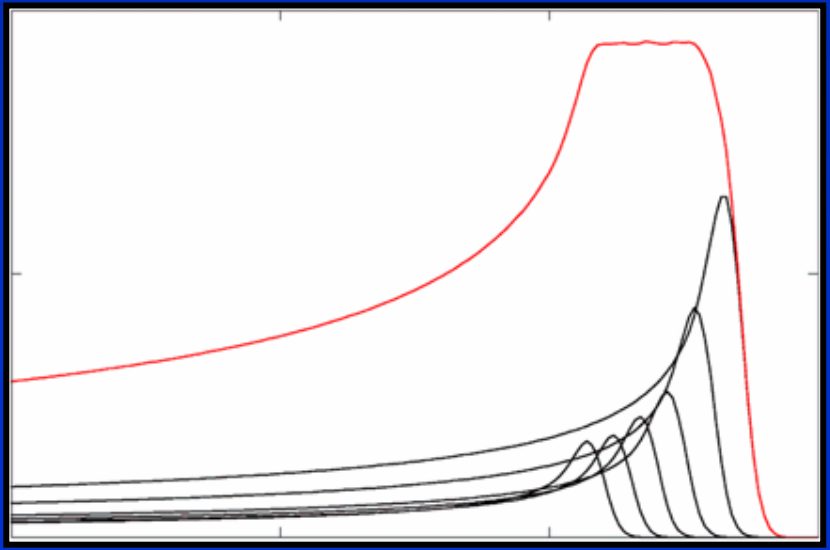


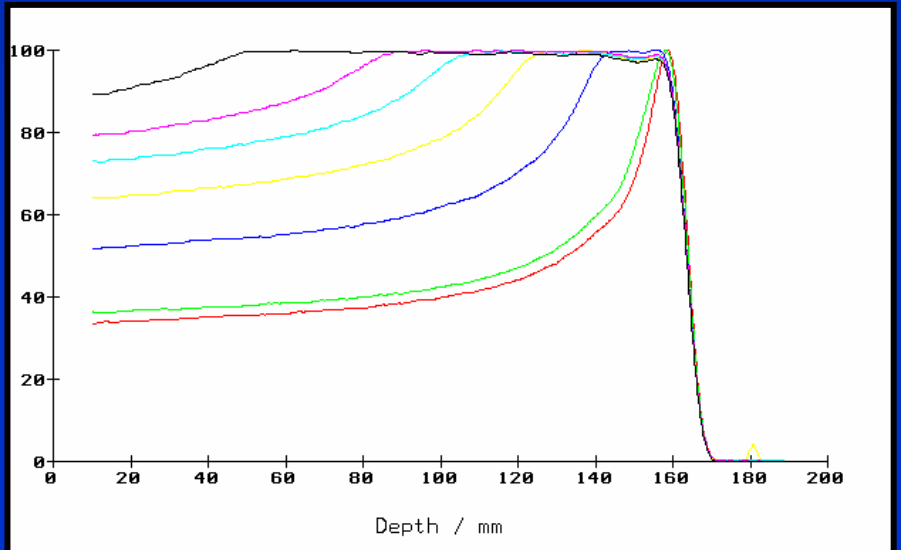


How a Spread Out Bragg Peak (SOBP) is formed.

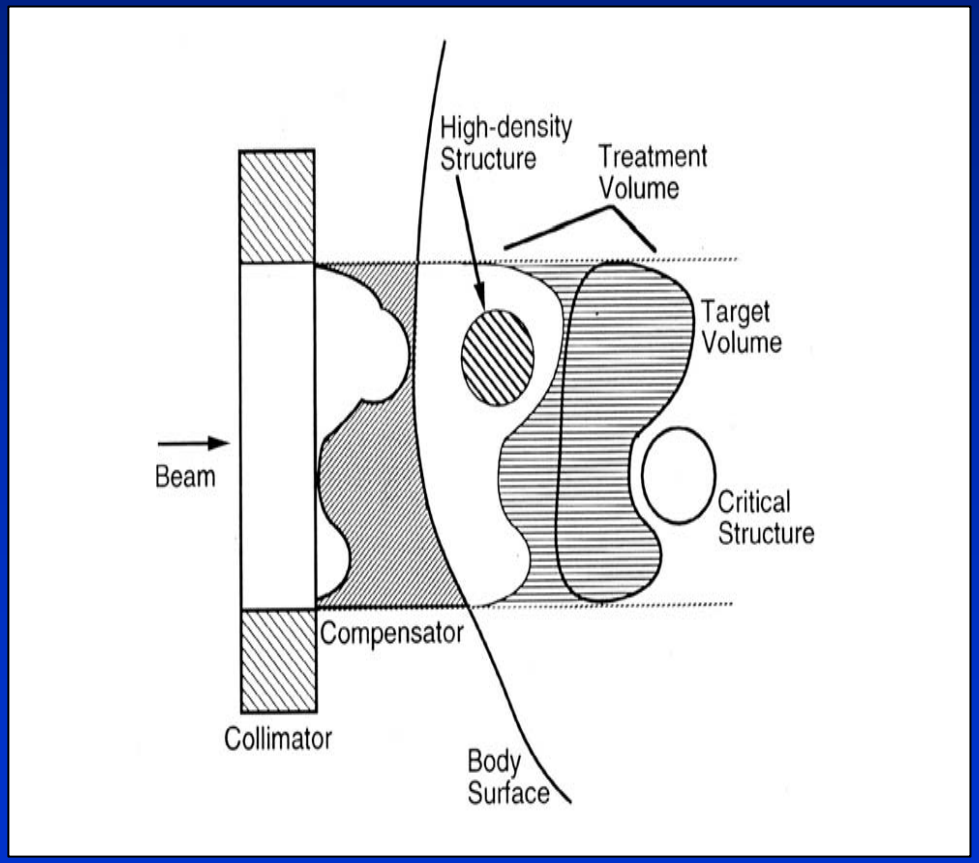
- Modulation wheel rotates in the beam.
- Pull-back (energy shift) determined by height of step.
- Weight determined by width of step.
- Multiple SOBPs can be obtained by gating beam.







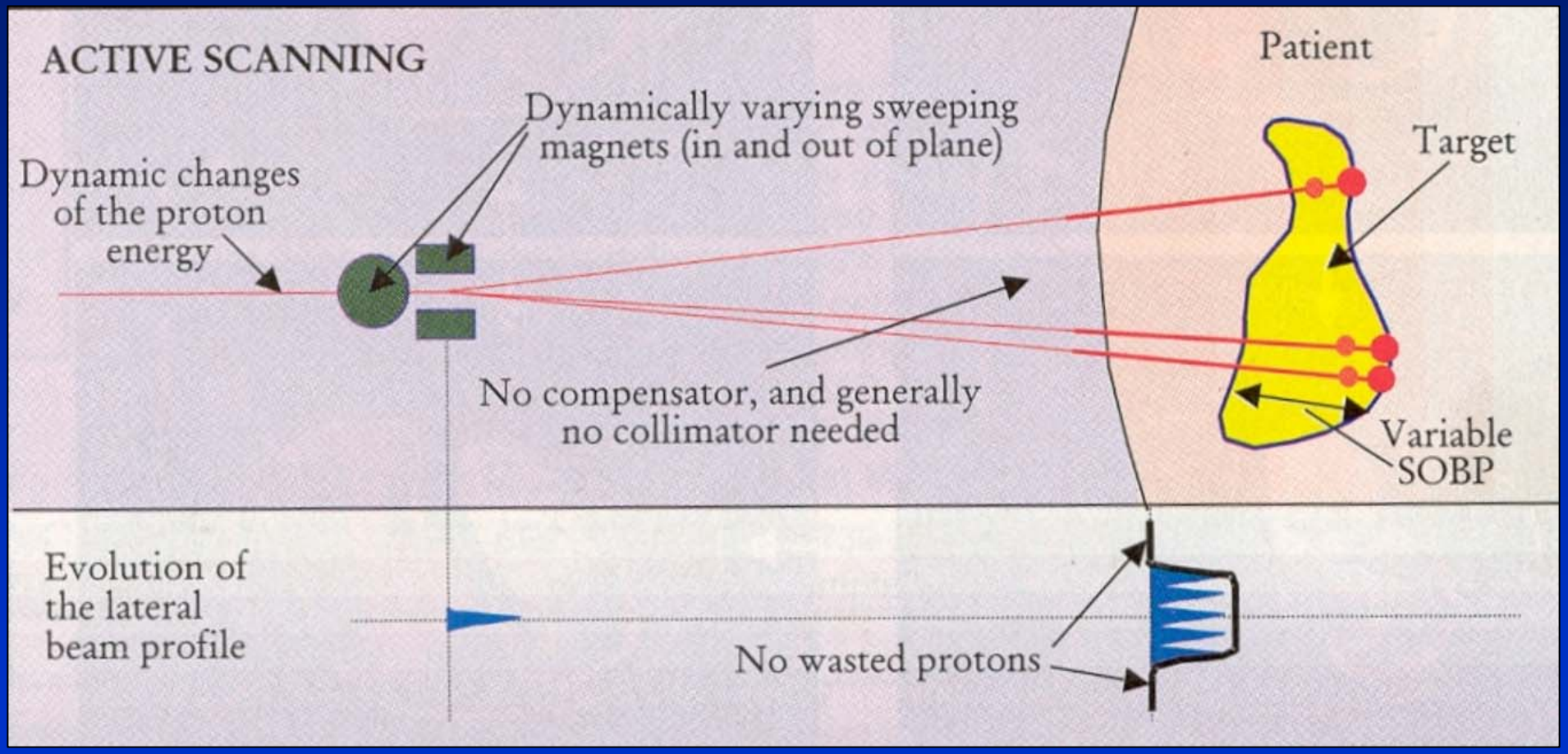
Deficiencies of Proton Passive Scattering Techniques



- Uniform SOBP - excess normal tissue dose.
- Requires custom aperture and compensator
- Inefficient - high proton loss produces activation and neutron production.

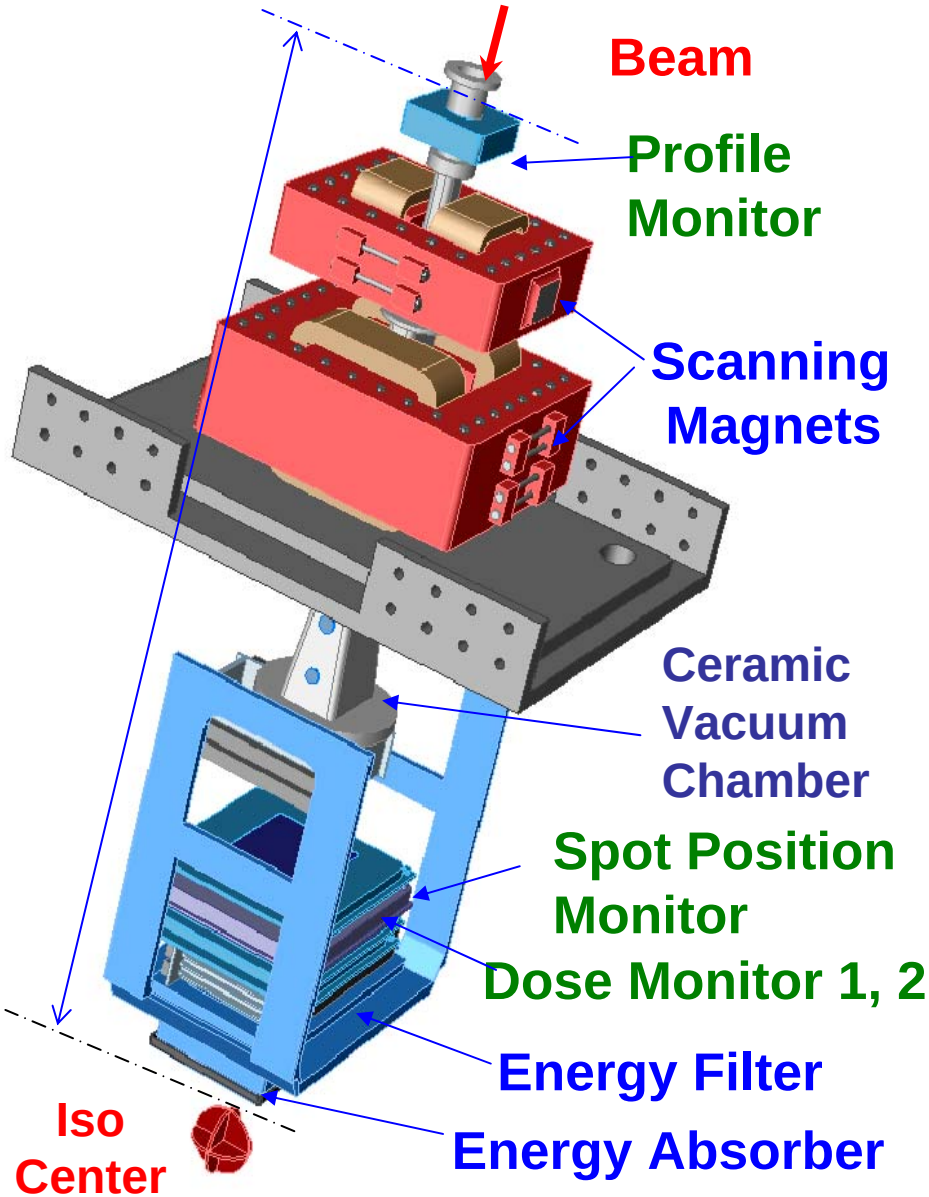
Chu, Ludewigt, Renner - Rev. Sci. Instrum.

The Pencil Beam Scanning Mode of Proton Beam Delivery



Goitein, Lomax, Pedroni - Med. Phys.

Pencil Beam Scanning Nozzle



Performance

Range	4 – 36 g/cm^2
Adjustability	0.1 g/cm^2
Max. field size	30 x 30 cm
Beam size in air	6 – 10mm σ
SAD	> 2.5 m
Dose compliance	+/- 3% (2 σ)
Irradiation time	< 2 min to deliver 2 Gy to 1 liter

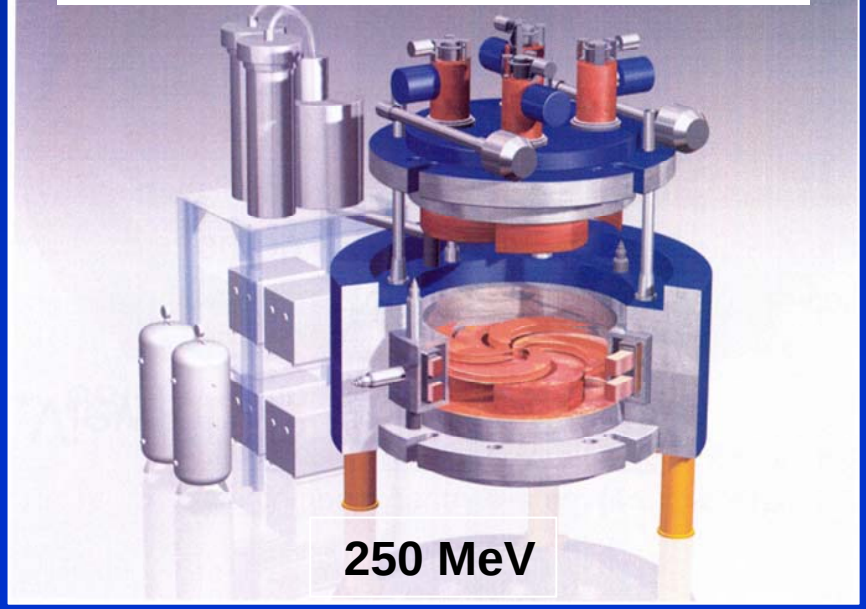
Proton Accelerators
Isocentric Gantries
Typical Facility

Typical Accelerators used in proton therapy facilities

Hitachi 250 MeV synchrotron ring
7 MeV Linac injector

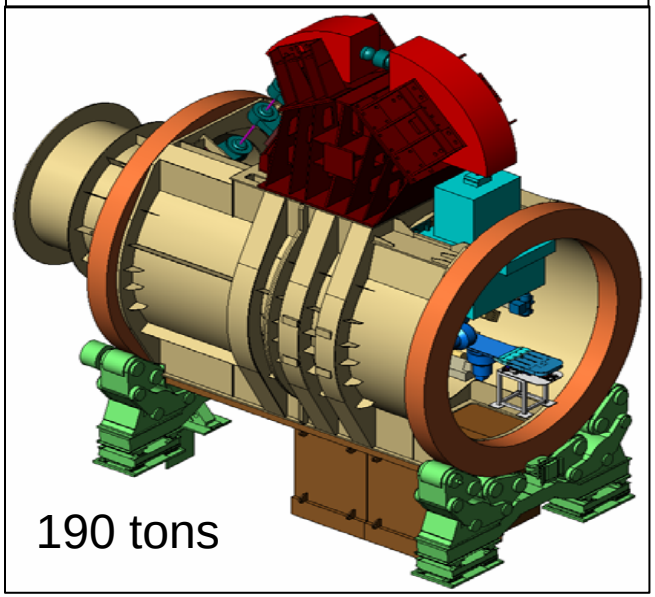
IBA 230 MeV Cyclotron

ACCEL Superconducting Cyclotron

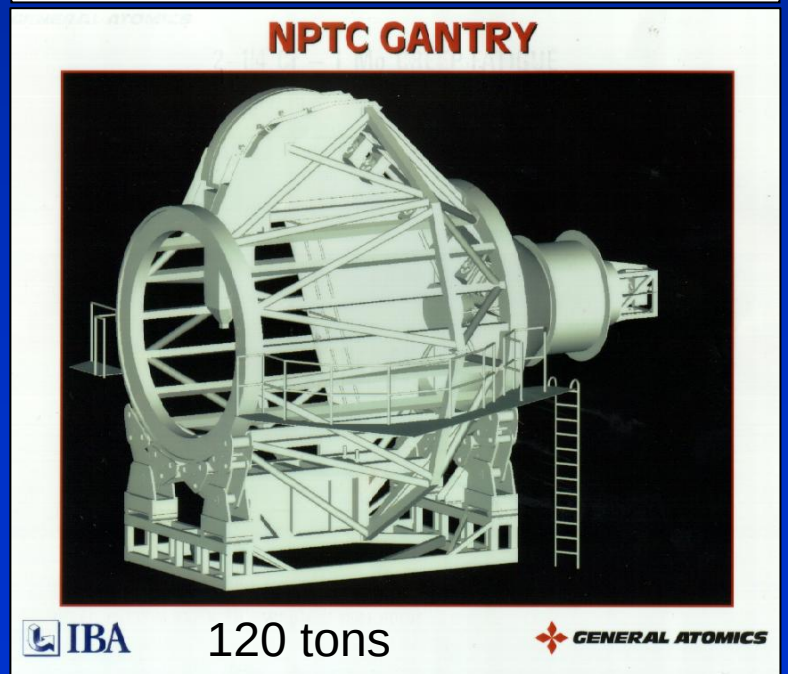


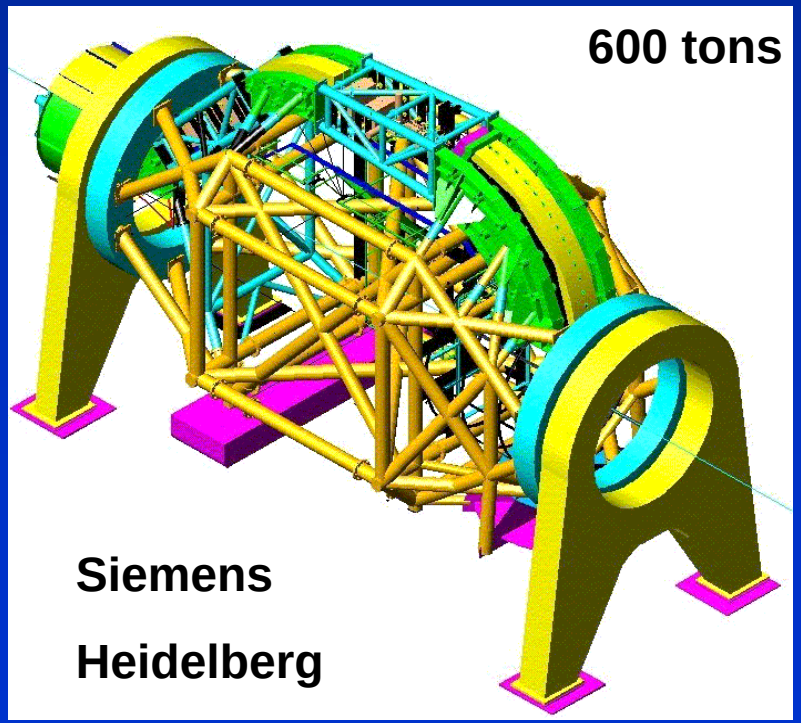
250 MeV

Proton and Carbon Ion Gantries



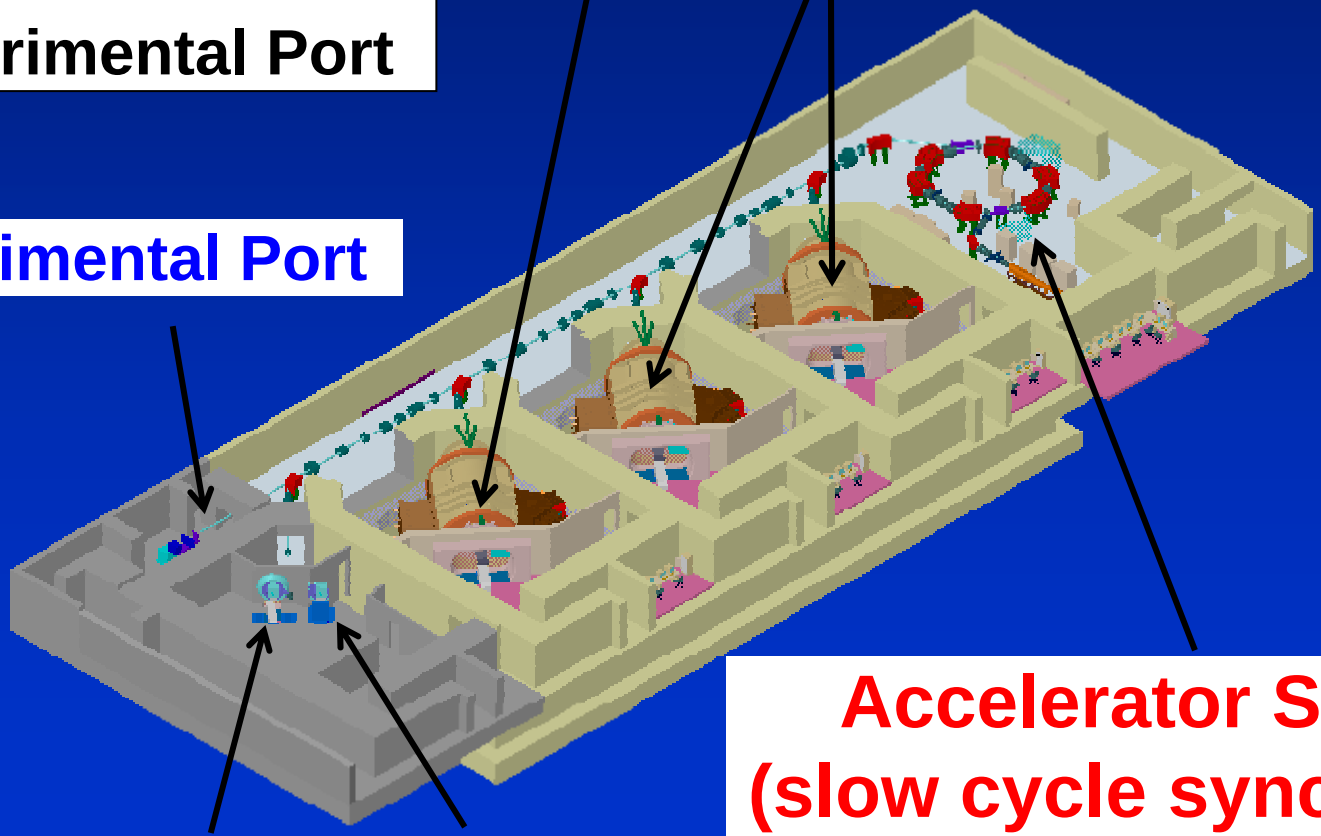
Hitachi





Proton Therapy Center - Houston

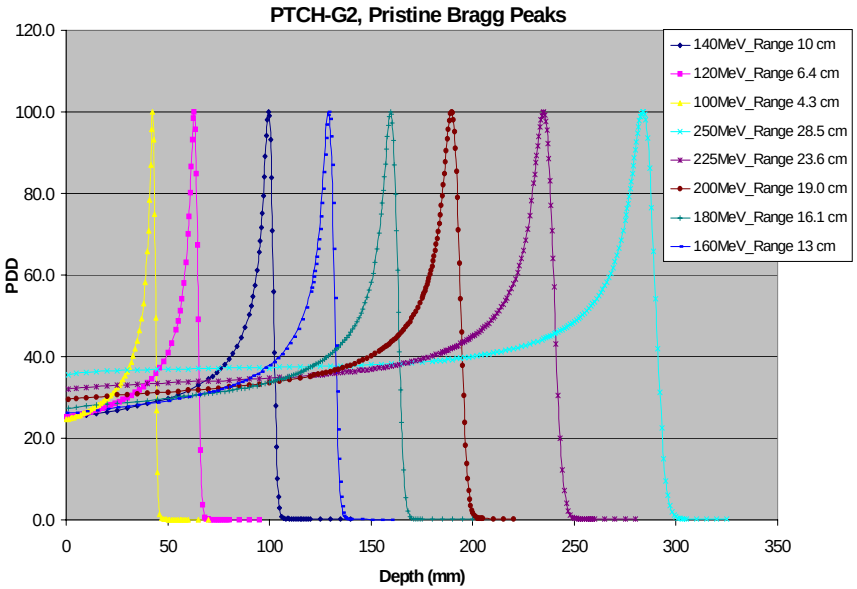
PTC-H
3 Rotating Gantries
1 Fixed Port
1 Eye Port
1 Experimental Port



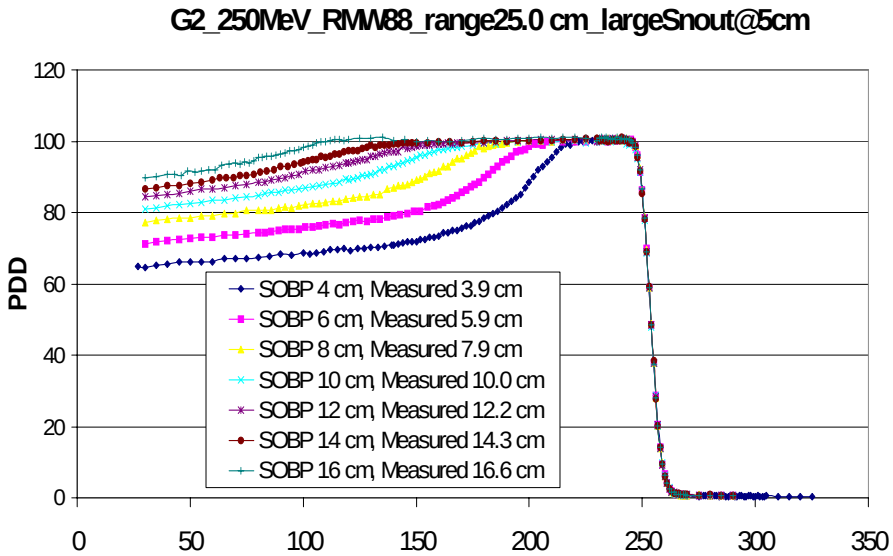
Clinical Commissioning

- Tests for system functionality and safety
- Treatment Planning System commissioning
  - Collection of data for input to planning system
  - Validation of planning system output
- Beam calibration
  - Calibration of transmission ionization chambers
  - Measurement of dependence of dose on range modulation, field size, etc.
- Patient treatment and machine QA

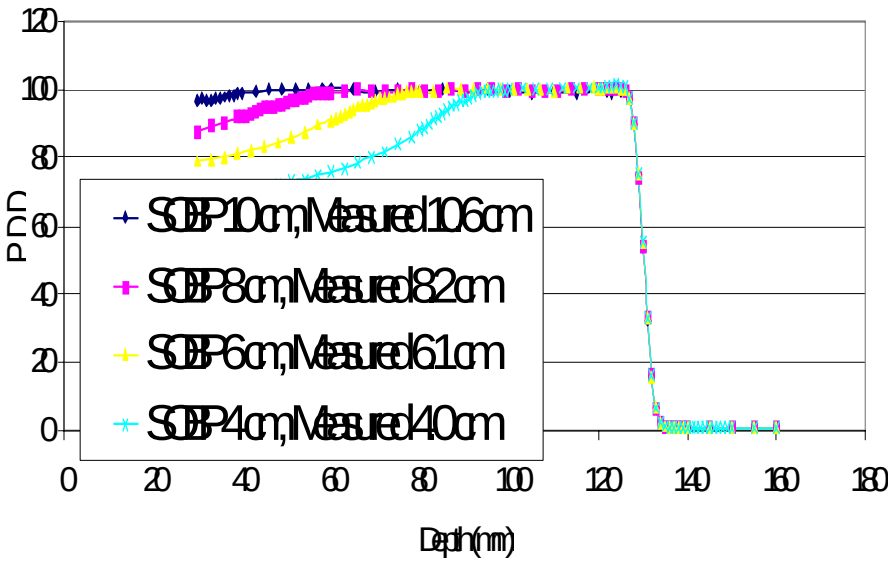
Pristine Bragg Peaks



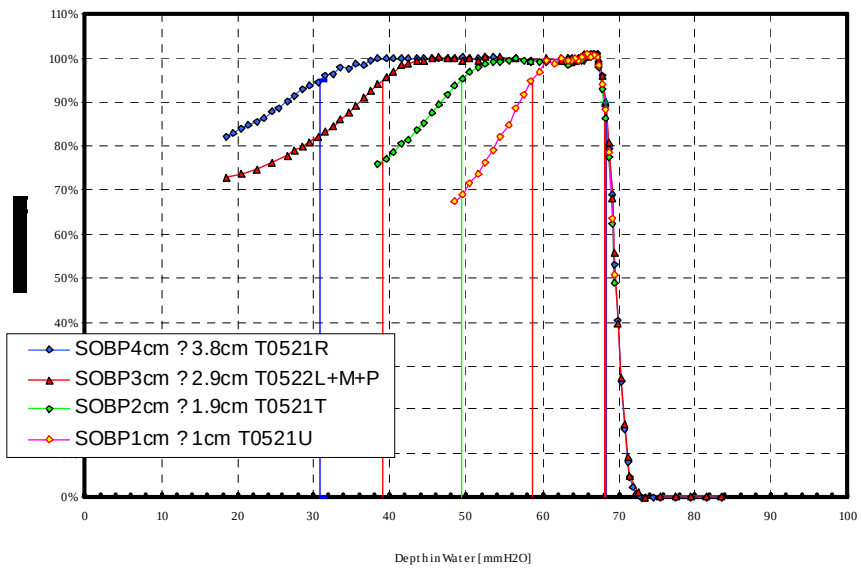
250 MeV



160 MeV

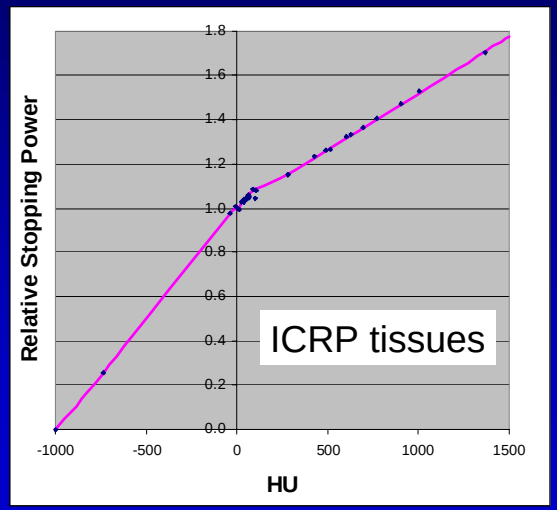


120 MeV



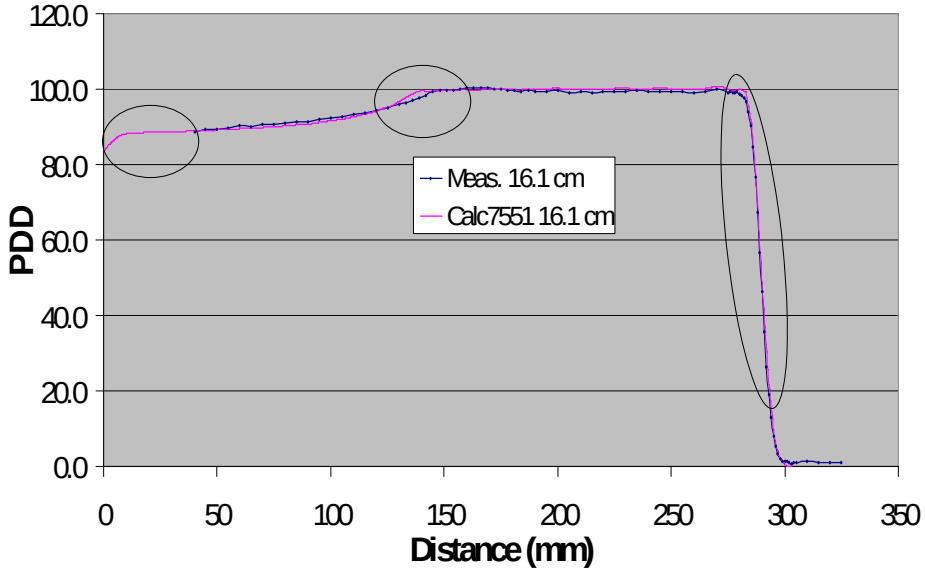
The CT scanner used to acquire treatment planning images should be calibrated.

Relative Stopping Power & Calibration Curve



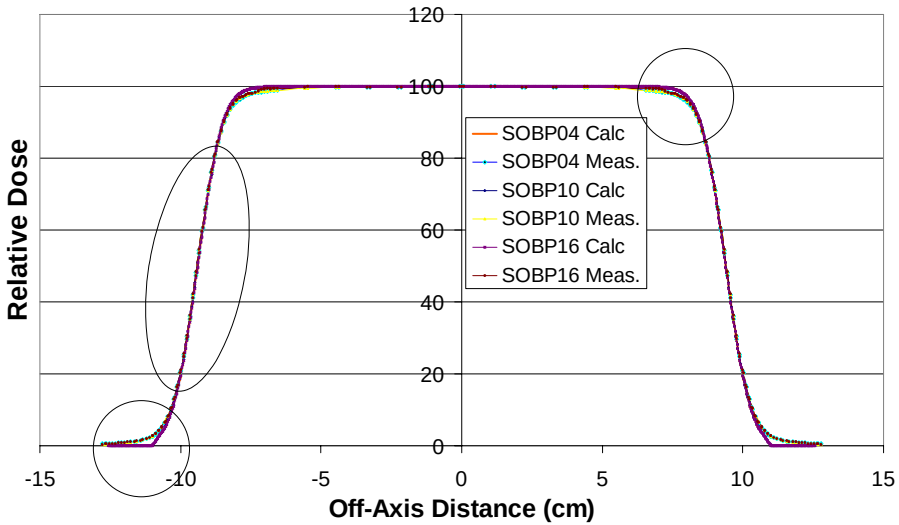
Comparison of measurements with treatment planning calculations

250 MeV, Range 28.5 cm, SOBP Width 16 cm



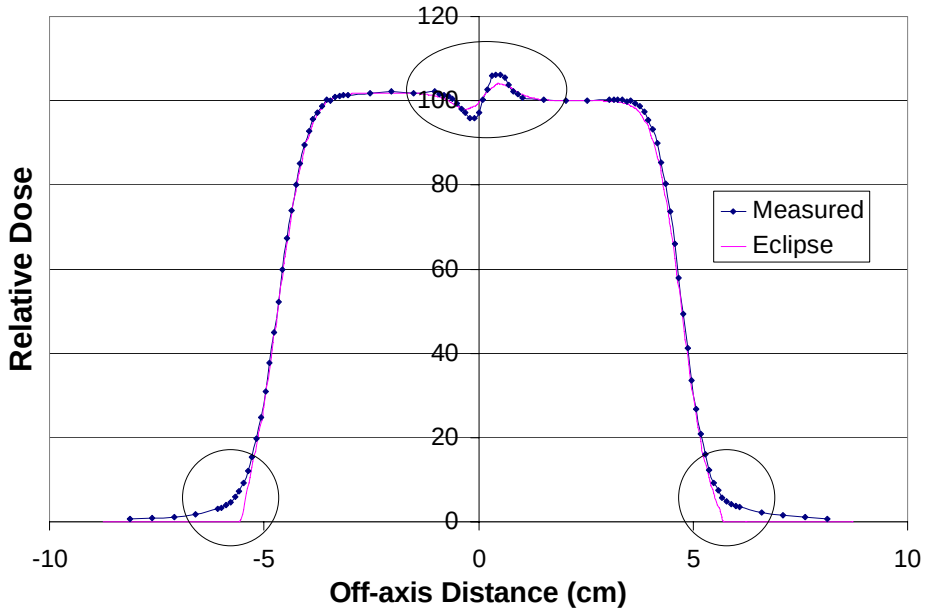
Comparison of measurements with treatment planning calculations

250 Mev, depth = 23.3 cm, Cross Plane Scan

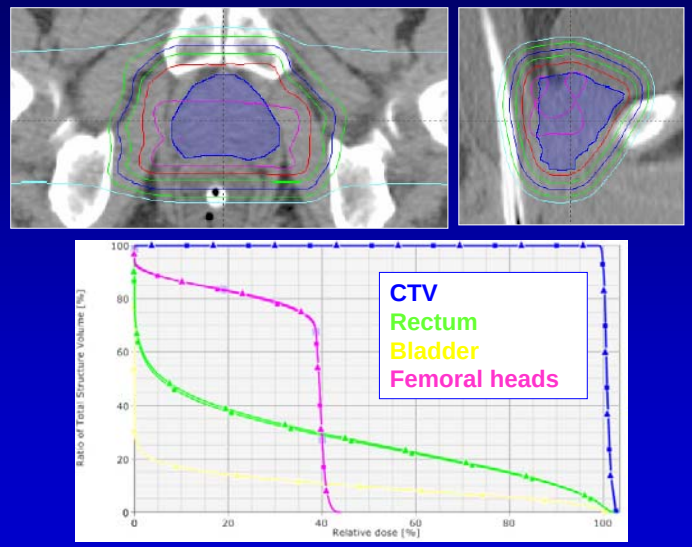


Comparison of Measurements and Treatment Planning Calculations

Bone-Water Interface Profile, 250 MeV, Depth = 17.9 cm

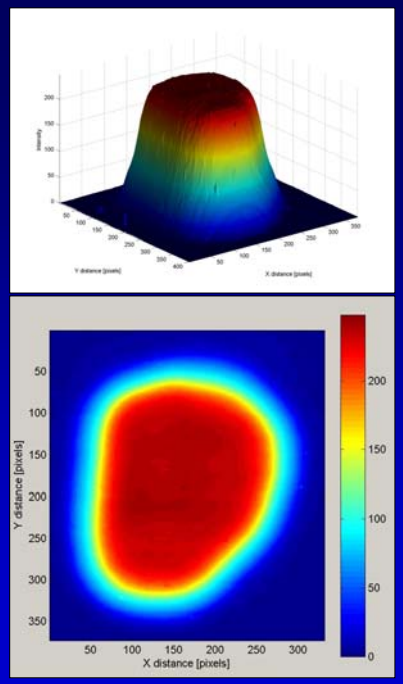


Prostate Patient Treatment Plan

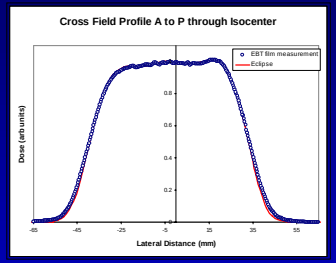


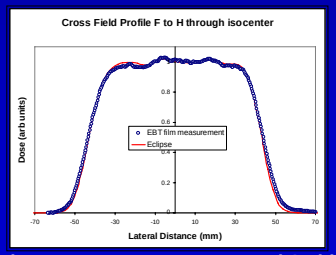
QA of Prostate Treatment using patient treatment parameters/appliances and EBT film in water phantom.

Treatment plan on CT anatomy converted to dose distribution in water phantom.



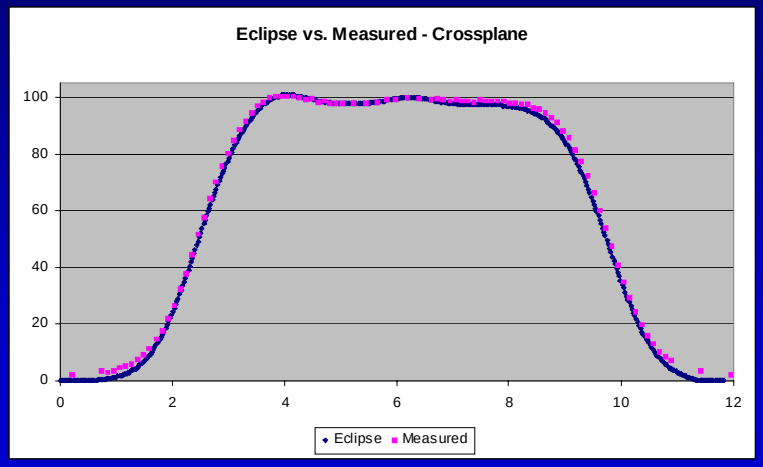
Measurements in water phantom using EBT film, patient aperture, and range compensator





Patient Treatment QA – Measurements compared with treatment planning calculations converted to water phantom.

Data measured in water phantom using Pin-Point ion chamber. Treatment aperture and range compensator were both inserted.



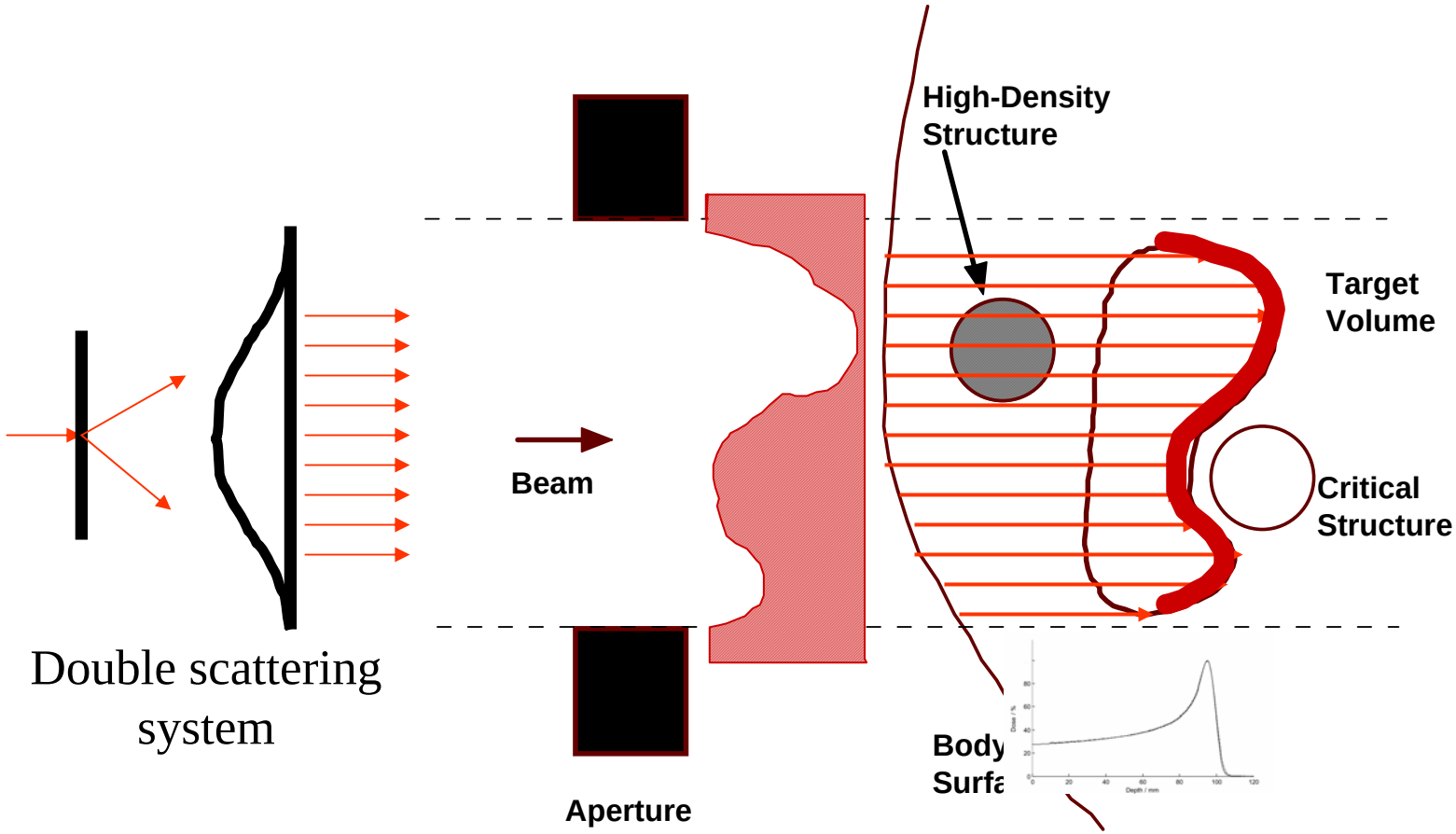
Treatment Planning

- Acquisition of imaging data (CT, MRI)
- Conversion of CT values into stopping power (not electron density)
- Delineation of regions of interest
- Selection of proton beam directions
- Optimization of the plan

Treatment Planning

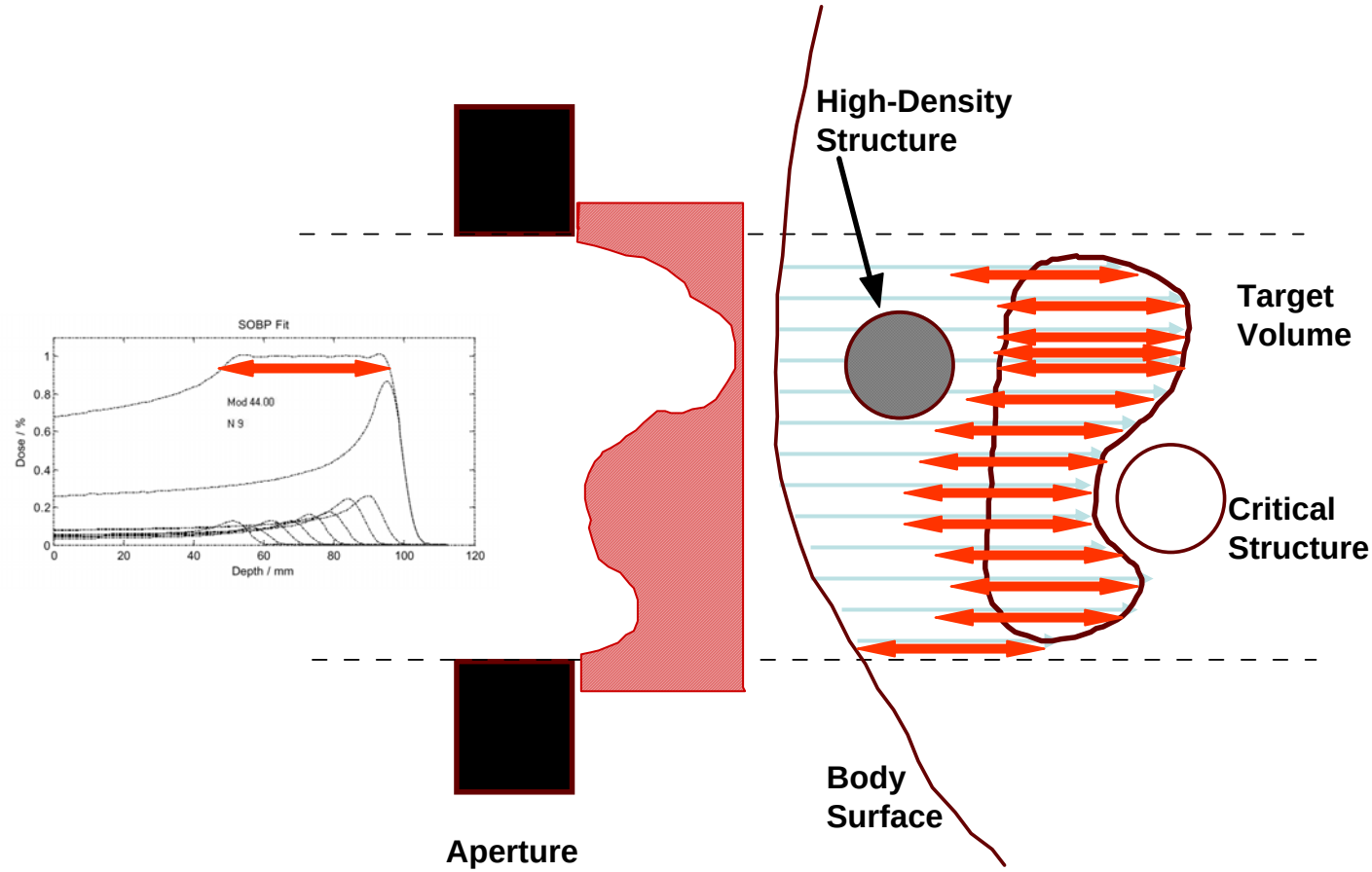
- Passive scattered proton beams
- Scanned Proton Beams
- Intensity modulated proton beams
- Comparative Treatment Plans

Dose shaping: Range compensator



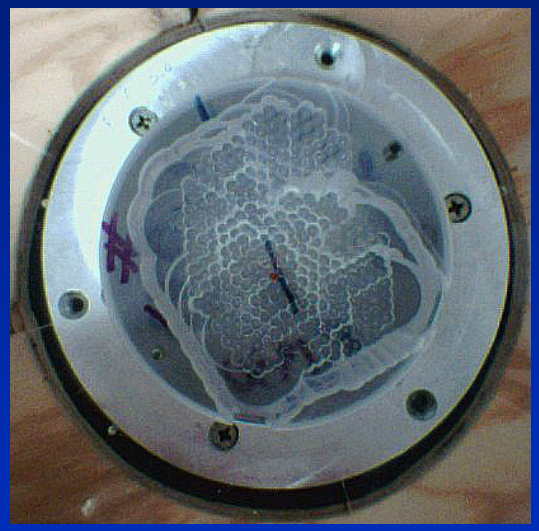
Double scattering system

SOBP Modulation



Aperture and Range Compensator

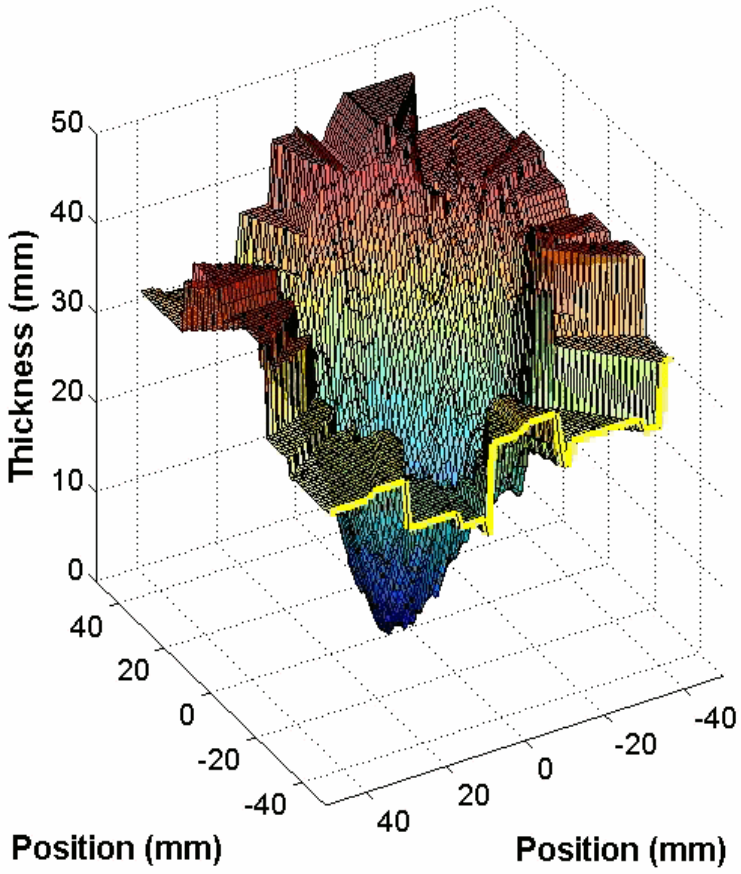
+

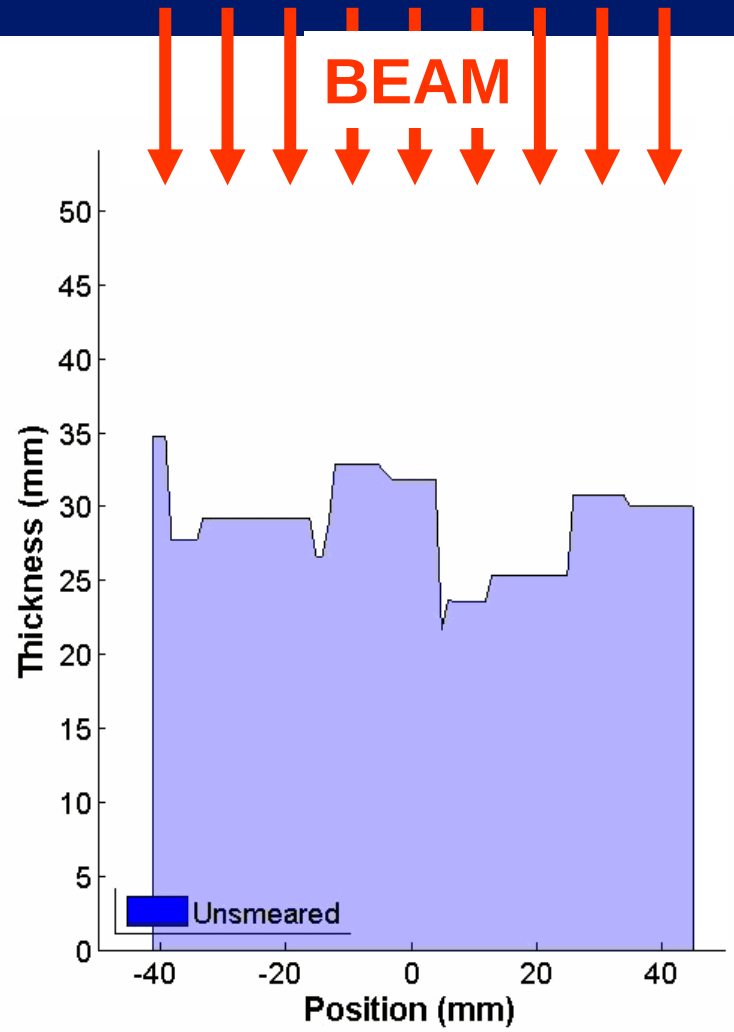


=

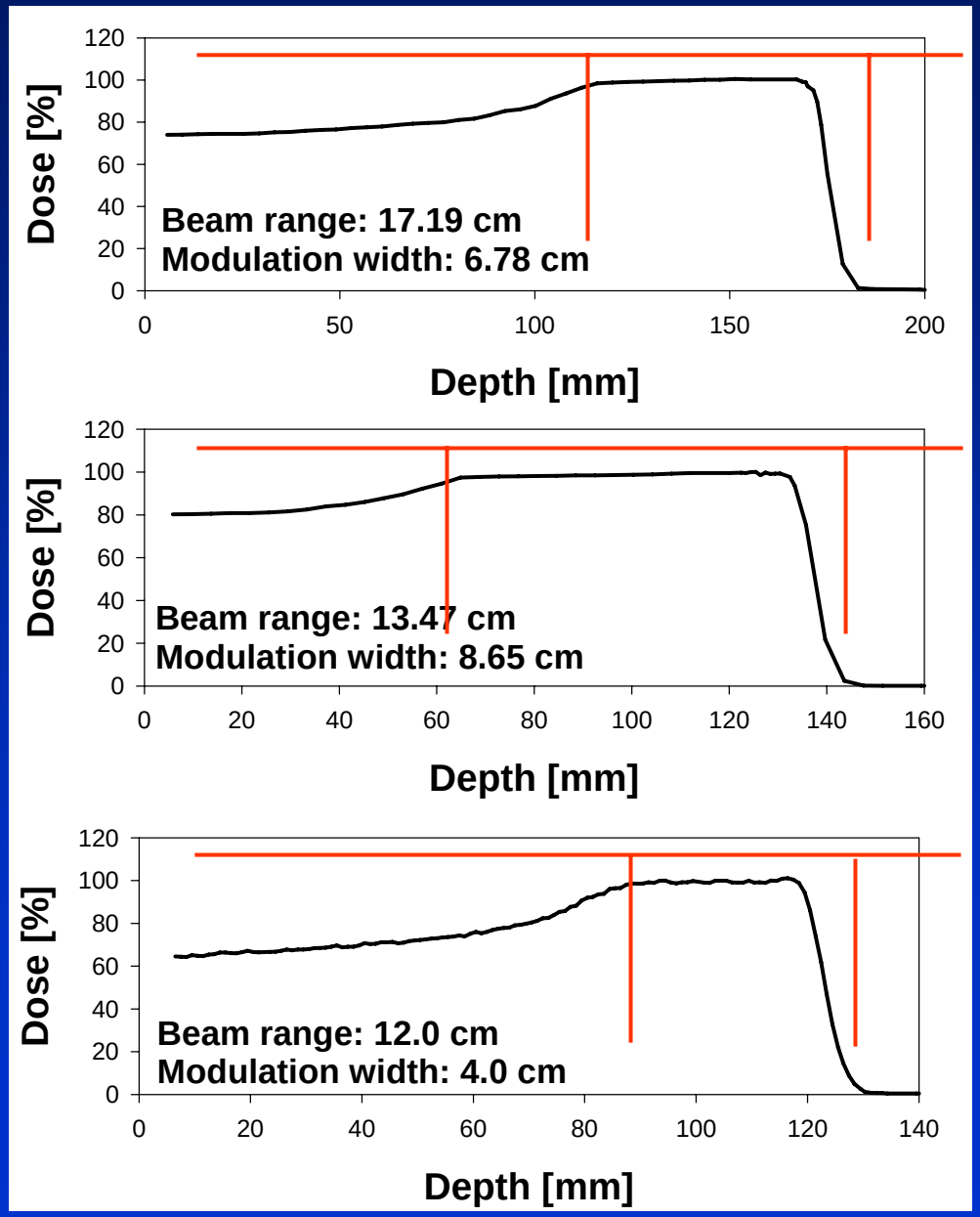
To be ‘designed’ by the planning system !

Compensator smearing to account for uncertainties

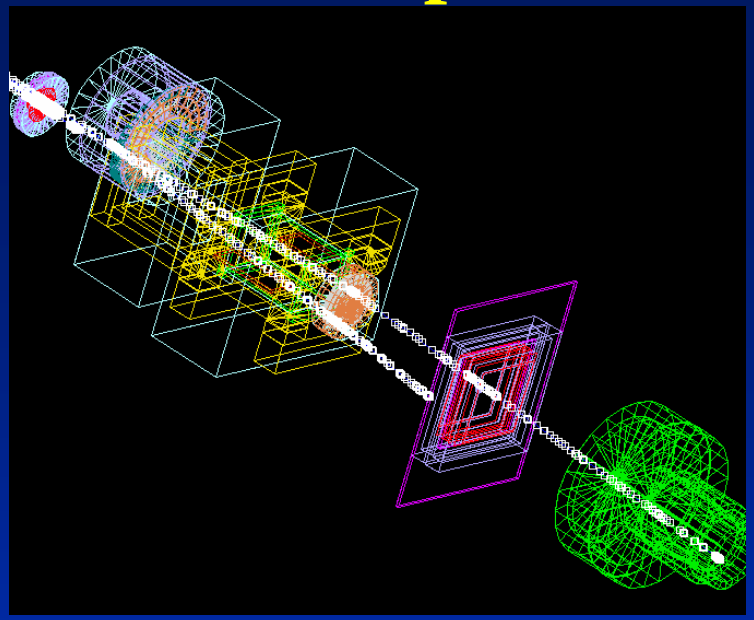


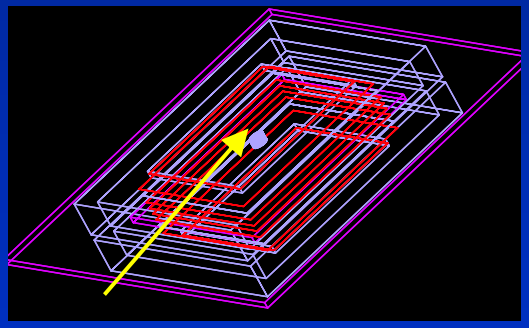


Dosimetry and QA for SOBP proton fields



Field dependent (!) absolute dosimetry

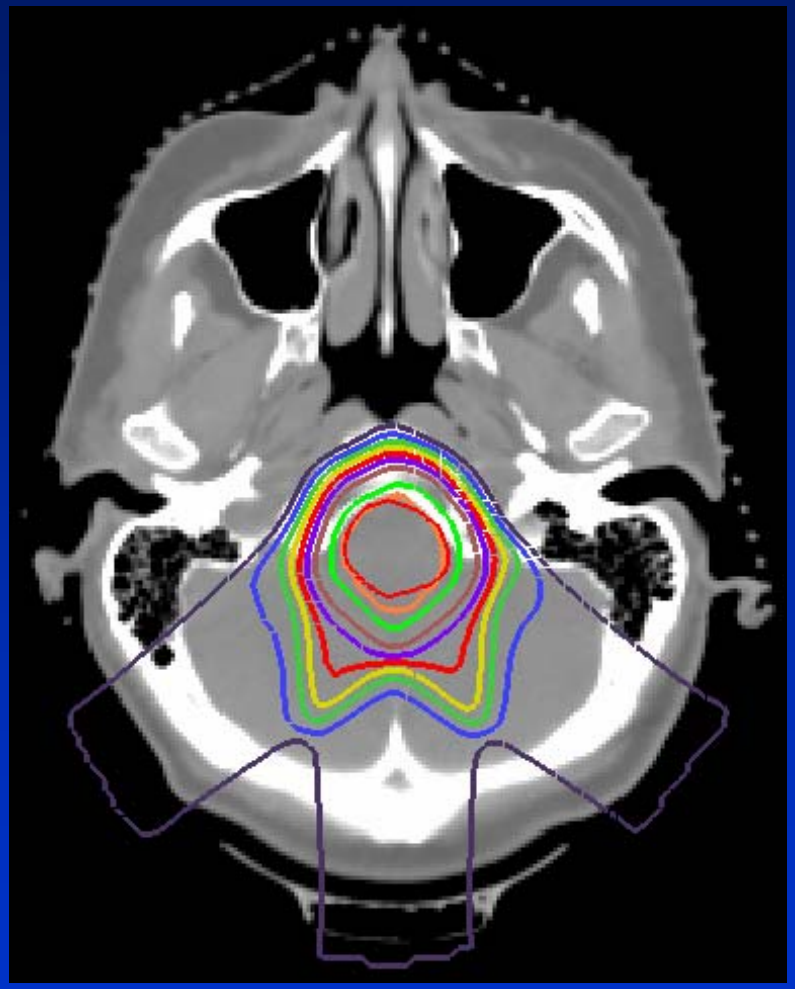


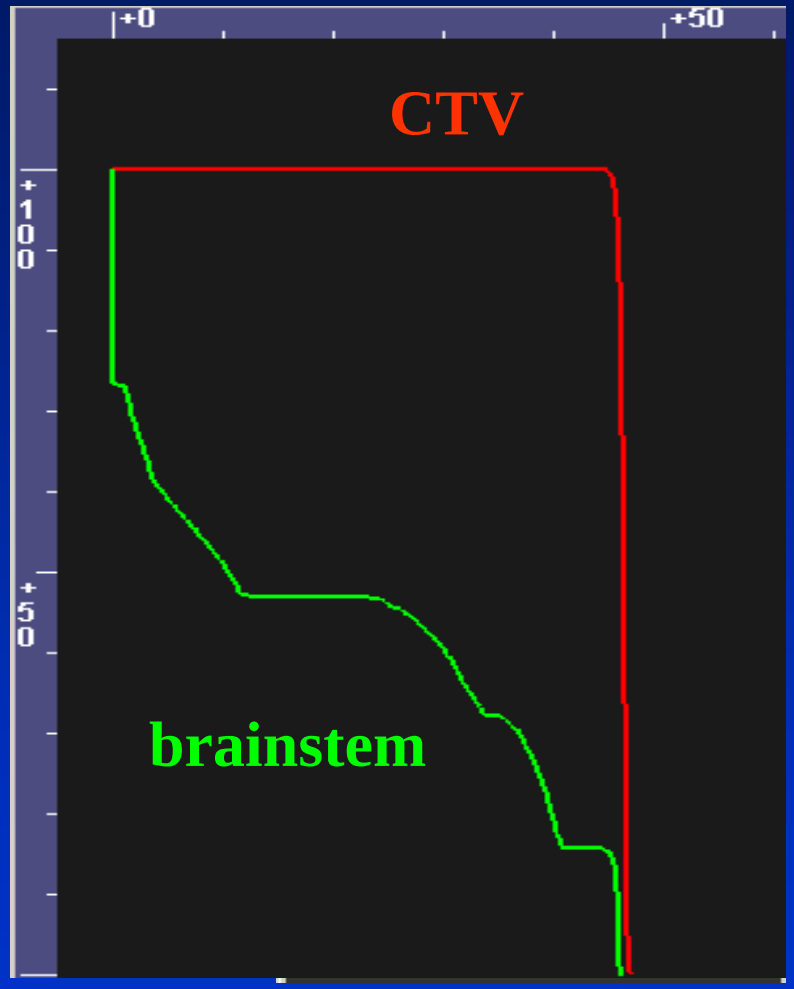


Volume for absolute dosimetry

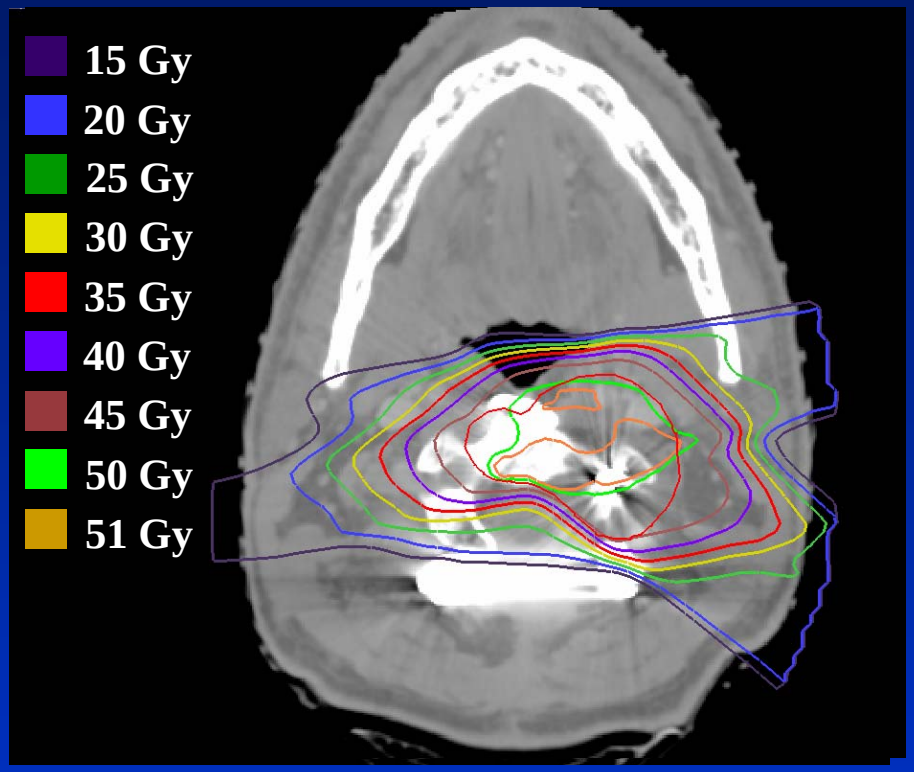
$$Output - Factor \cong \frac{D_{cal}}{i_{ic}} \left[cGy / MU \right]$$

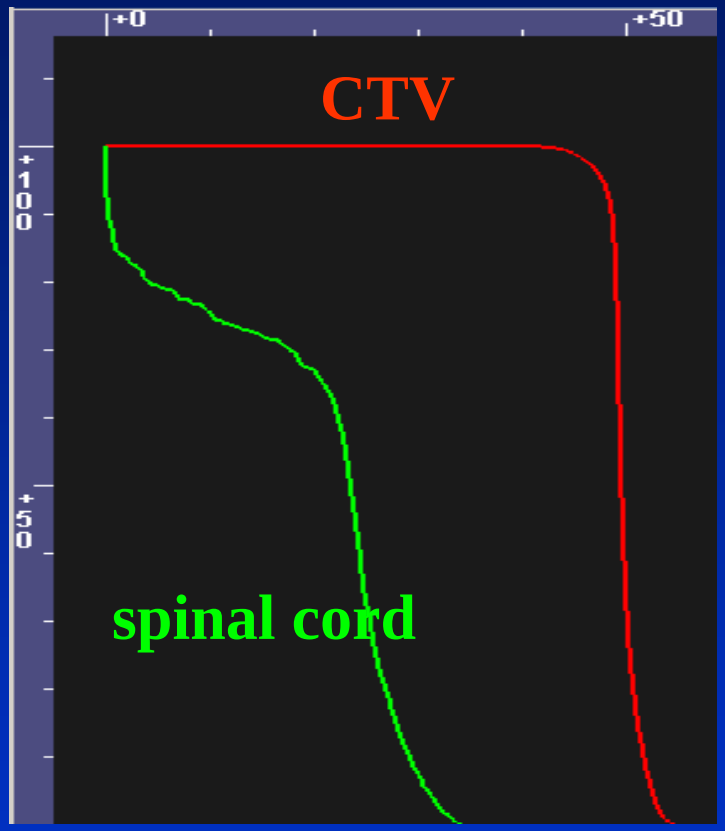
EXAMPLE 1: Para-spinal case using 3 fields



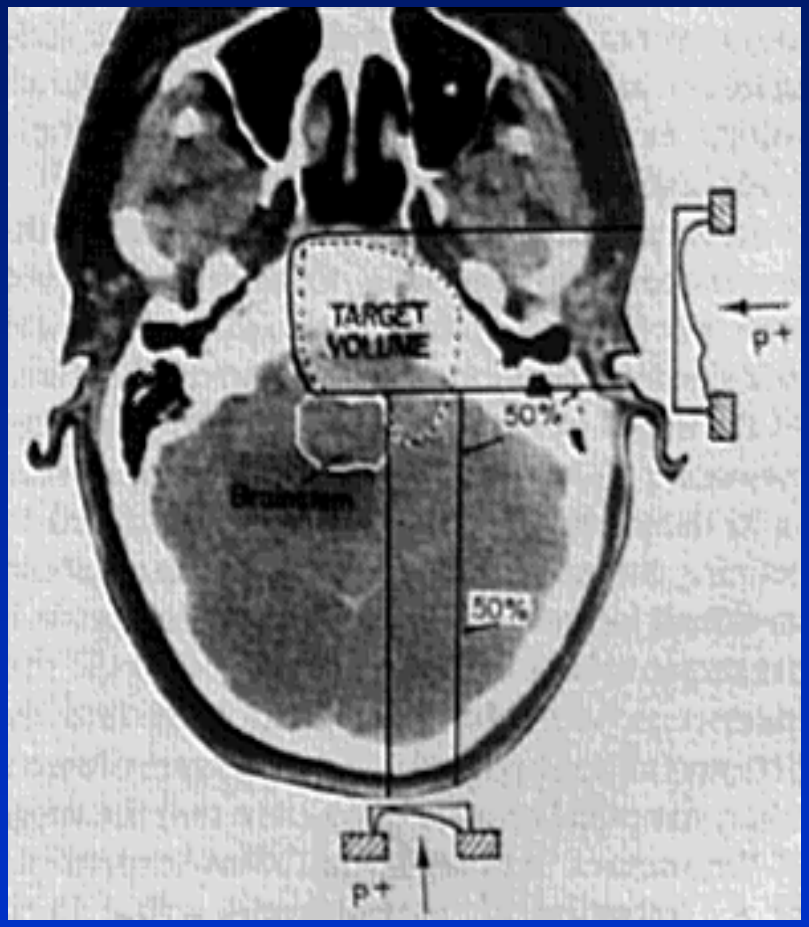


EXAMPLE 2: Para-spinal case using 6 fields (involves metal CT artifacts)





Field Patching

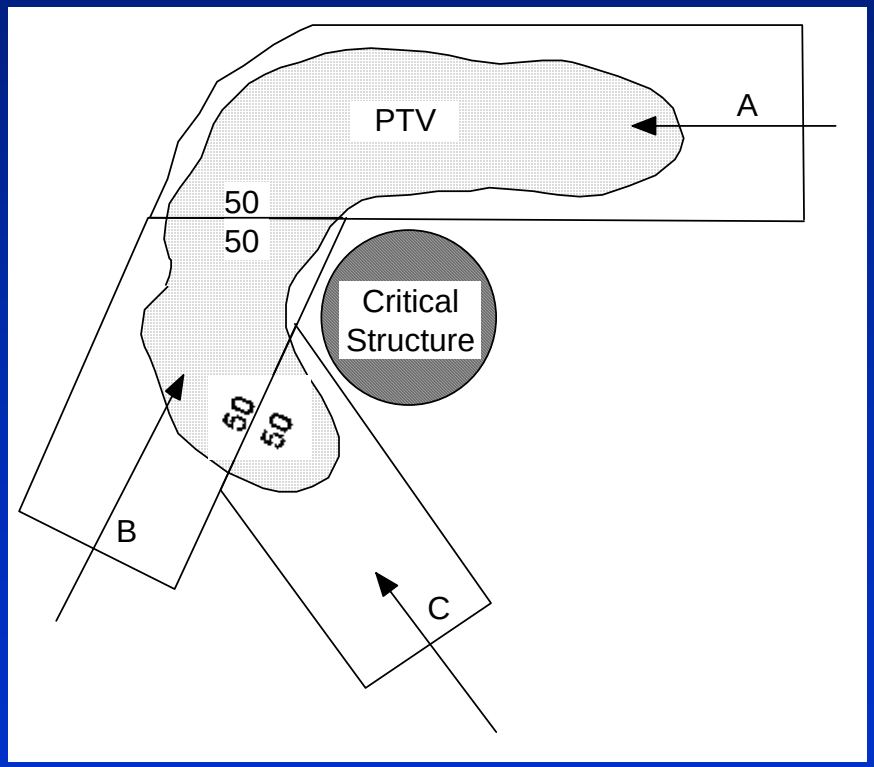


Urie M. M. et al (1986), Med Phys. 13, 734.

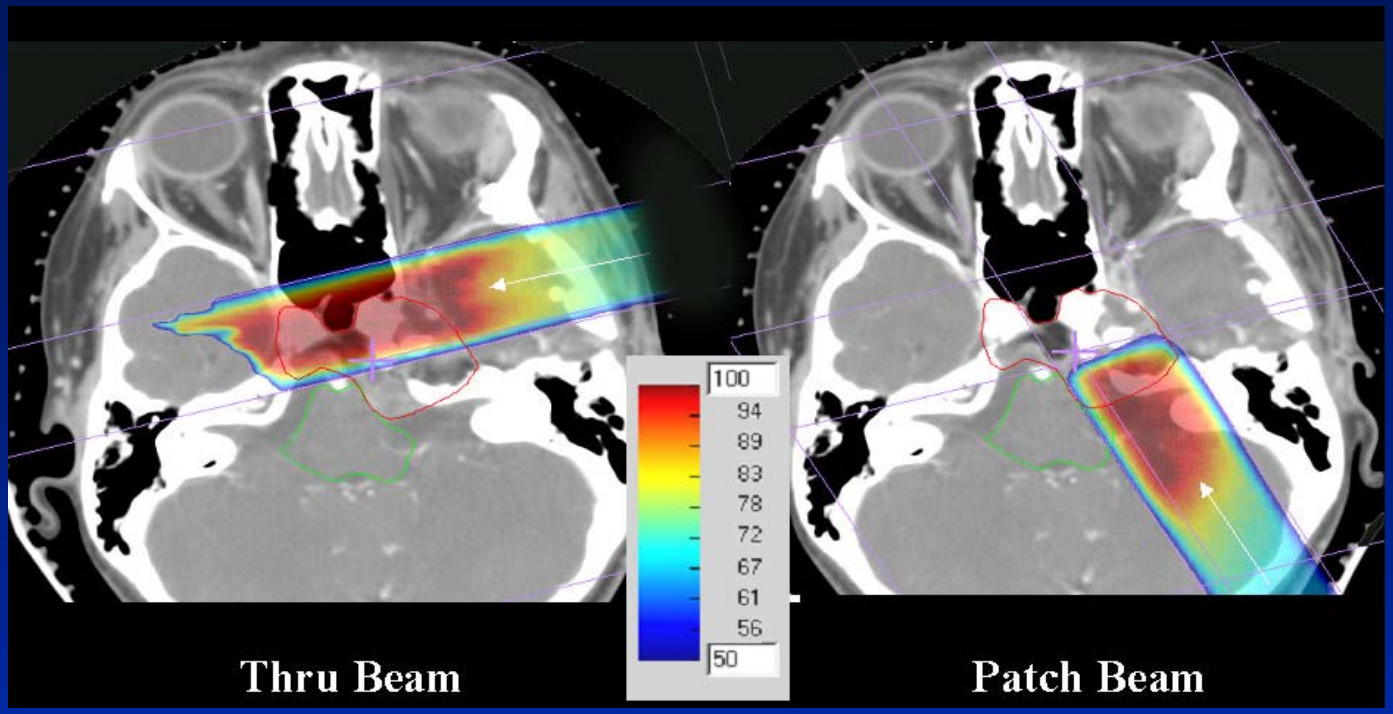
- Abutting the distal dose edge of one field to the dose boundary of other field(s).
- Useful if target is close to critical structures
- Not necessarily homogeneous dose to the target for each beam (IM!)
- Range an penumbra uncertainties need to be considered

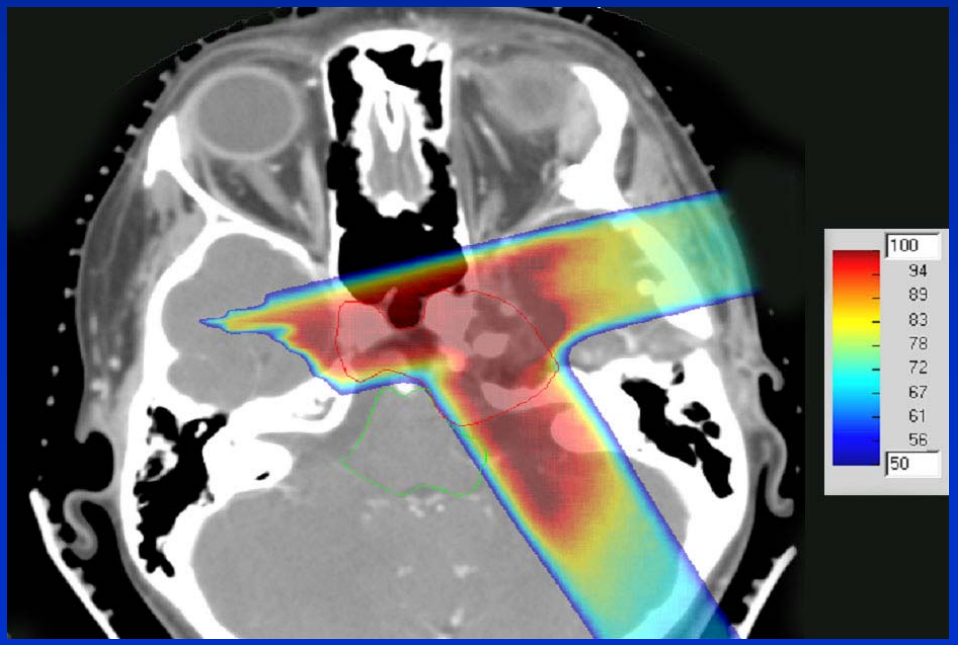
Field Patching

"THROUGH" Field A
followed by
"PATCH" field B,
followed by
"PATCH" field C

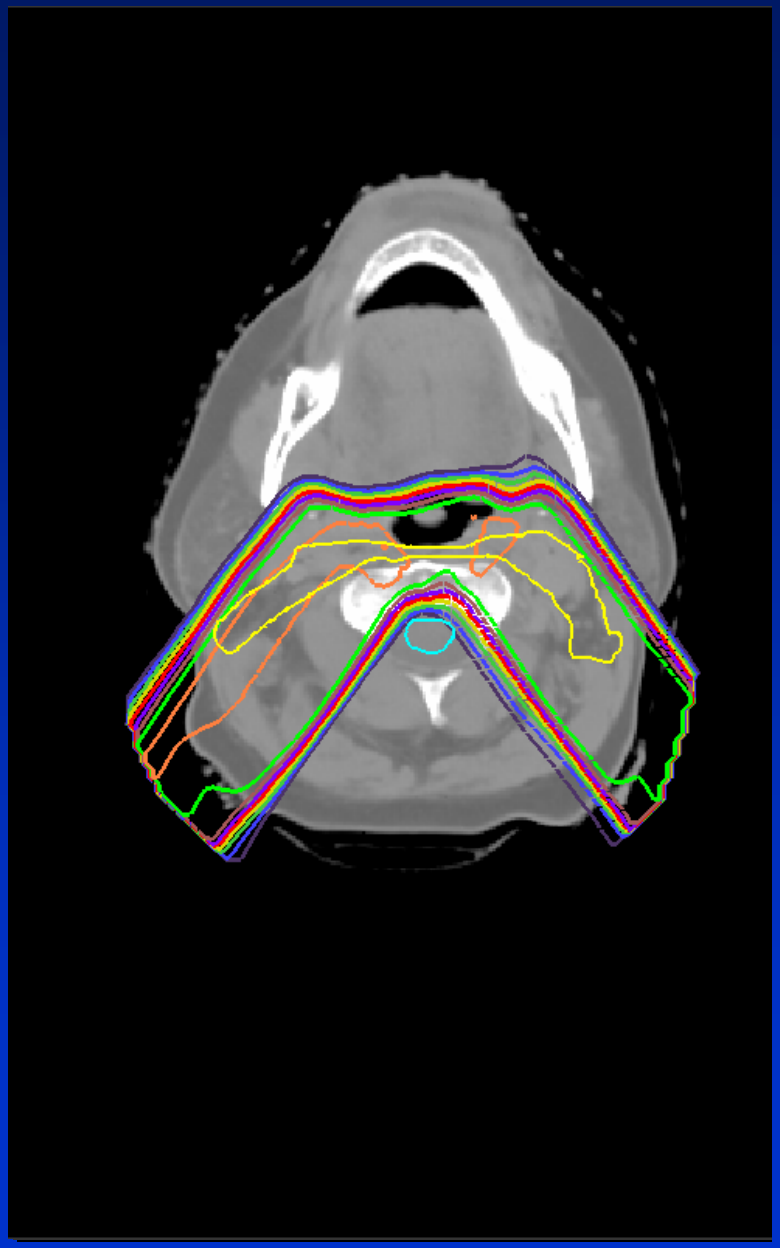


Match at 50% isodose,
lateral + distal, levels



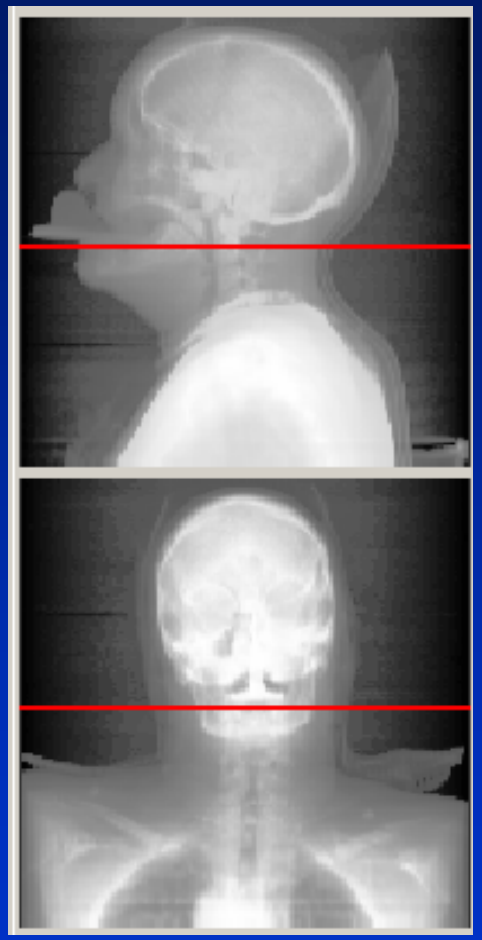


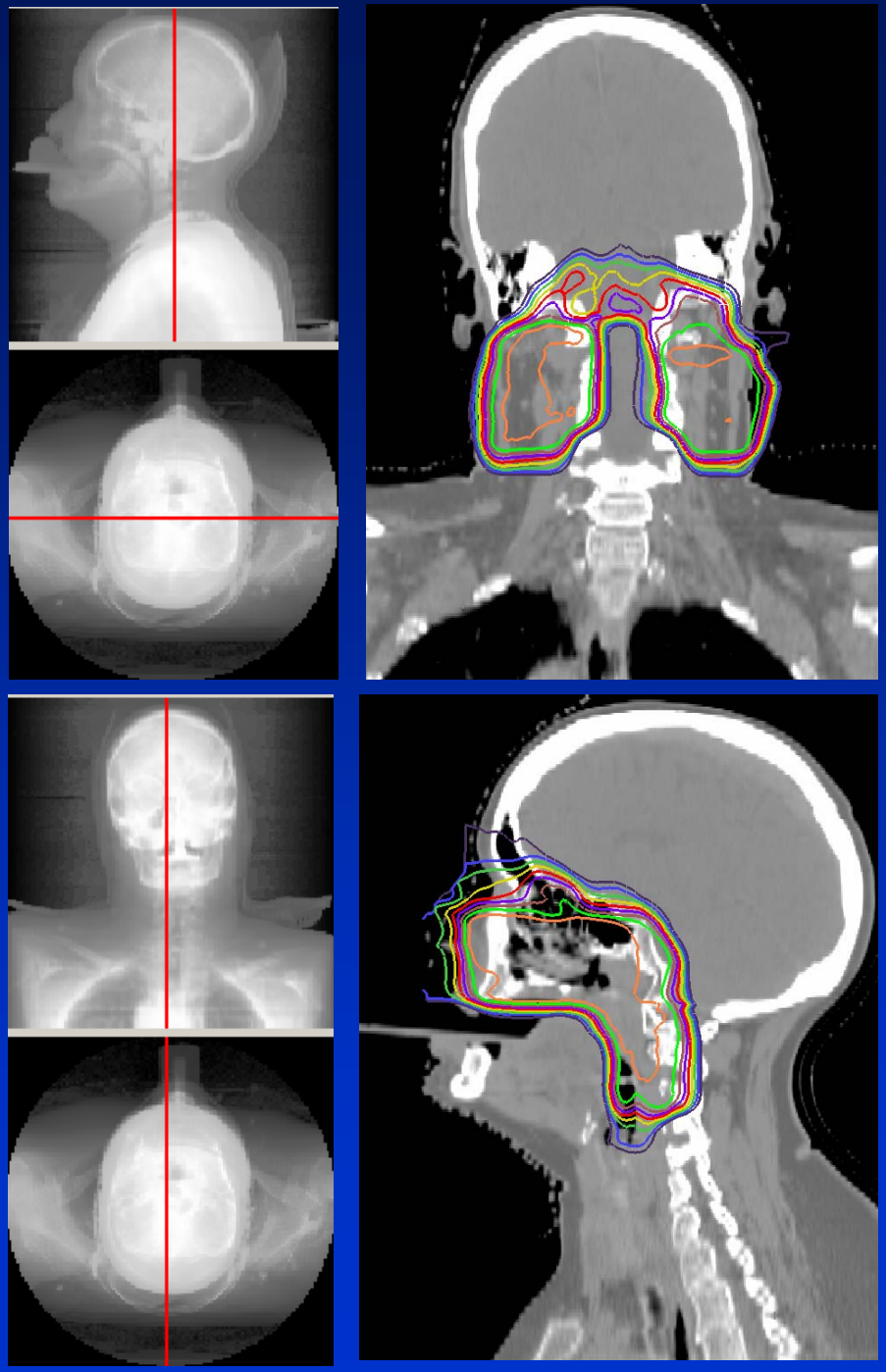
EXAMPLE 3: Nasopharynx case using 14 fields (plus additional photon fields to the lower neck)

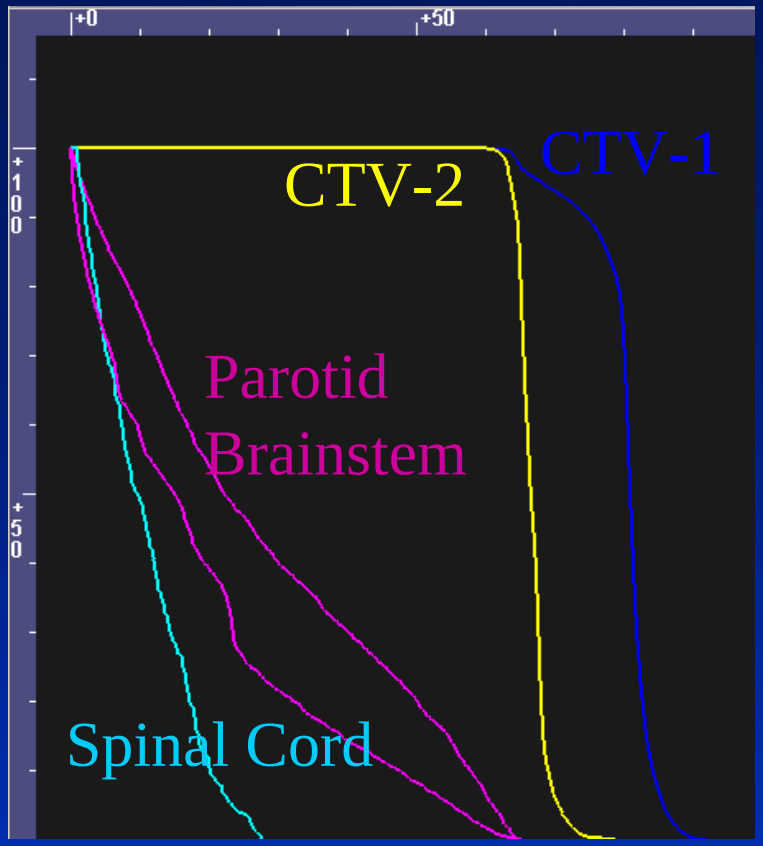


CTV-2

- 25 Gy
- 30 Gy
- 35 Gy
- 40 Gy
- 45 Gy
- 50 Gy
- 55 Gy
- 60 Gy
- 67 Gy





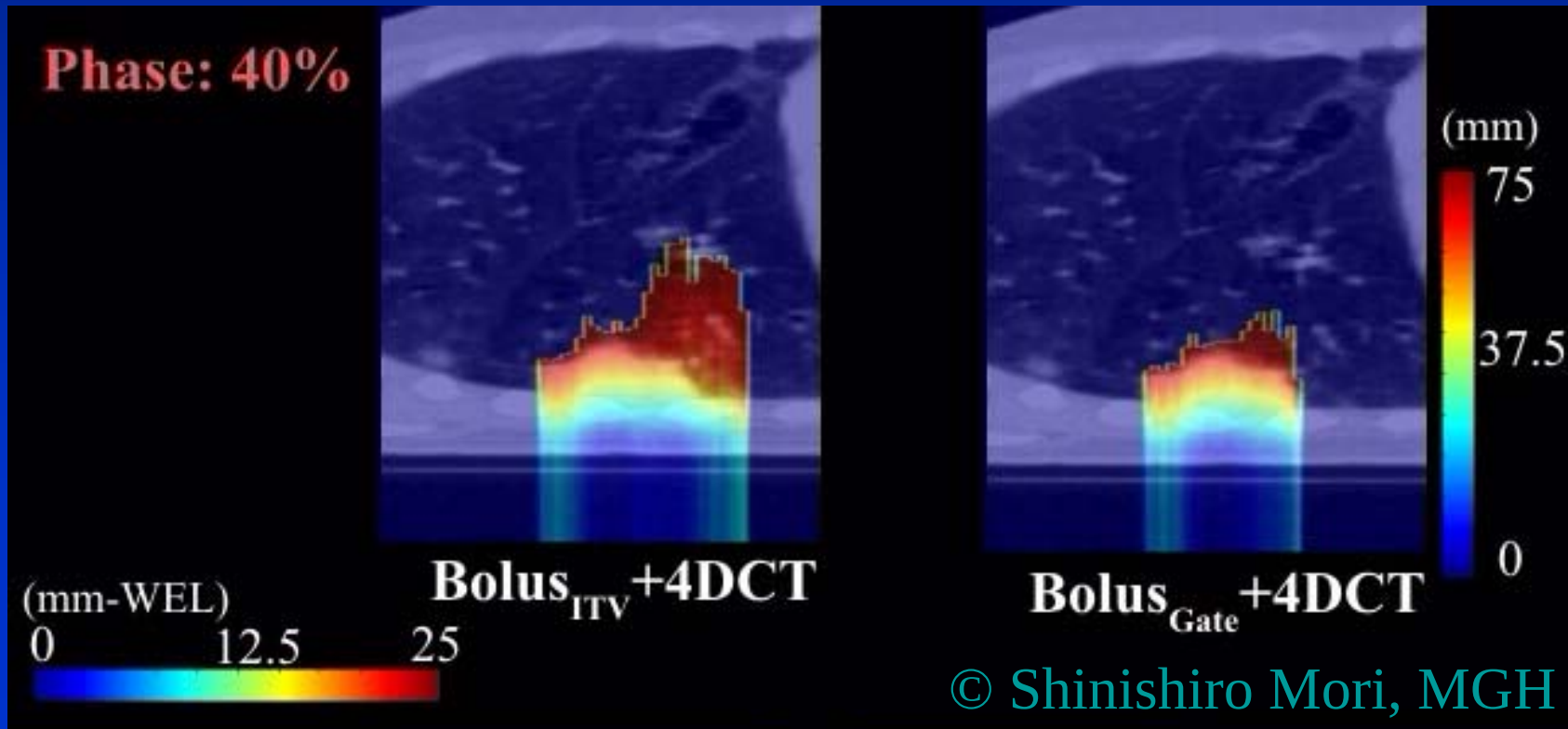


- GTV 76 Gy
  - CTV1 60-66 Gy
  - CTV2 60 Gy
- Nodes 54 Gy

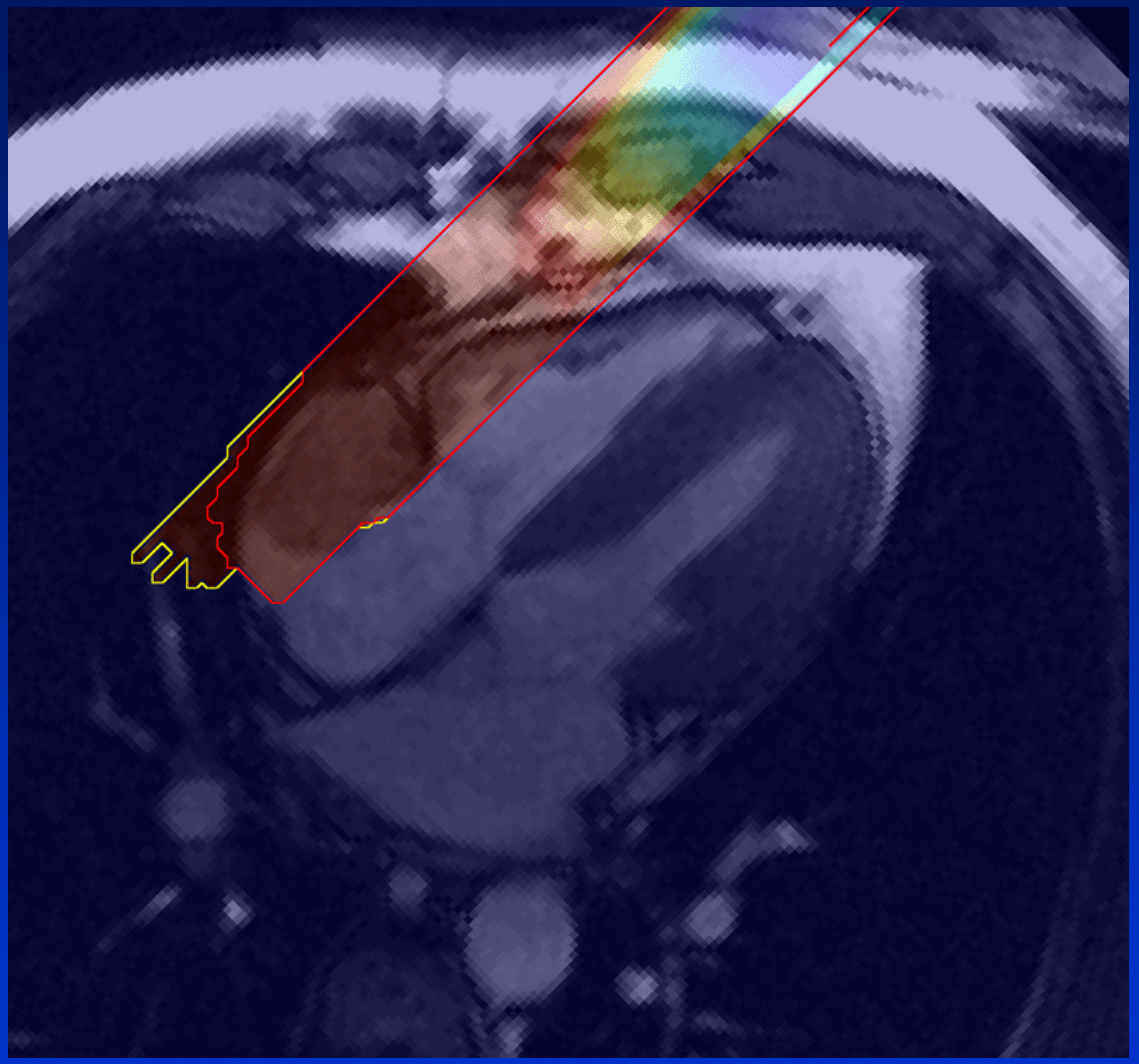
Treating moving targets with protons

Effect of respiration on dose

Range fluctuations due to respiration in the lung



Effect of respiration on dose



Range Fluctuation on Cardiac MRI

Burr Proton Therapy Center (2001-)

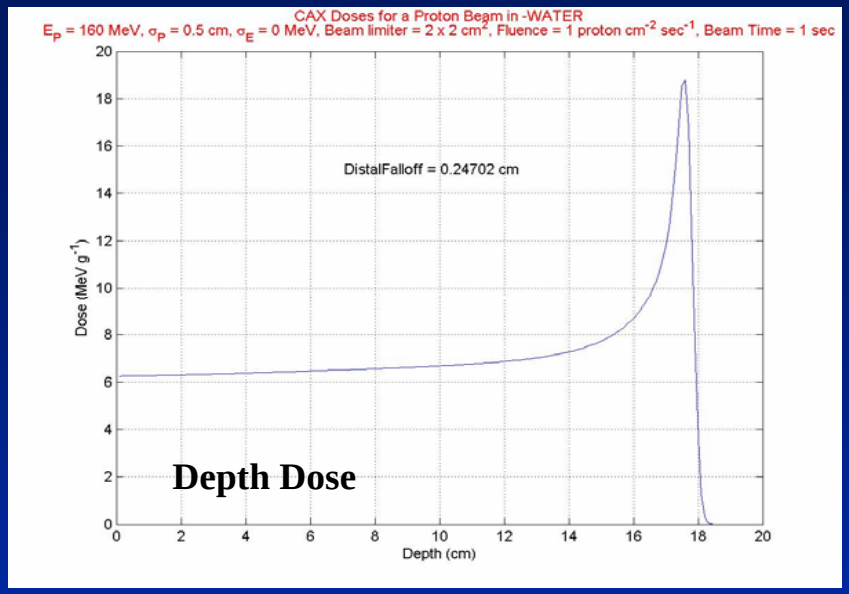
Patient Population

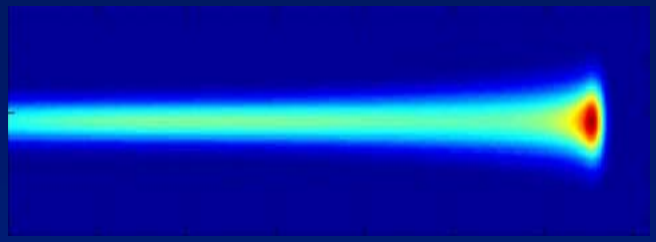
- Brain 32%
- Spine 23%
- Prostate 12%
- Skull Base 12%
- Head & Neck 7%
- Trunk/Extremity Sarcomas 6%
- Gastrointestinal 6%
- Lung 1%

In general, 1-3 fields / day

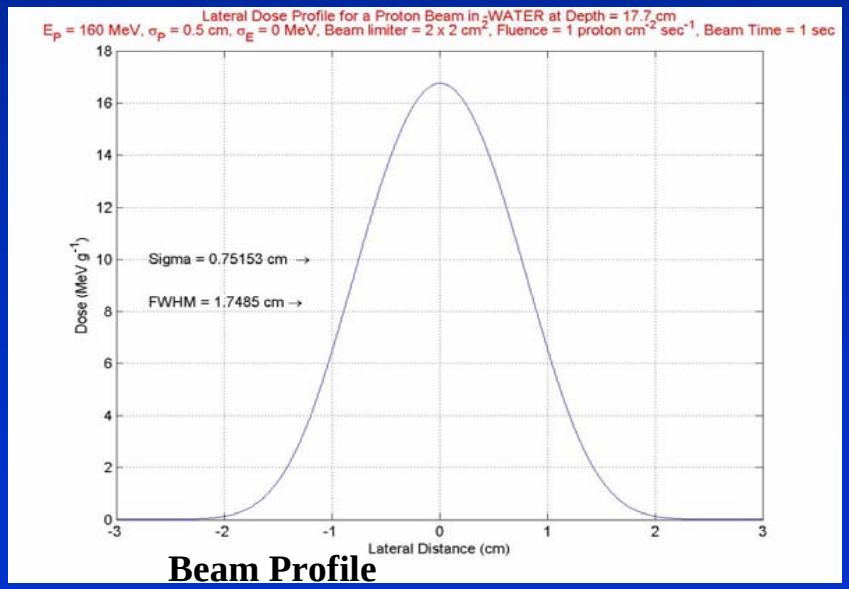
Treatment Planning

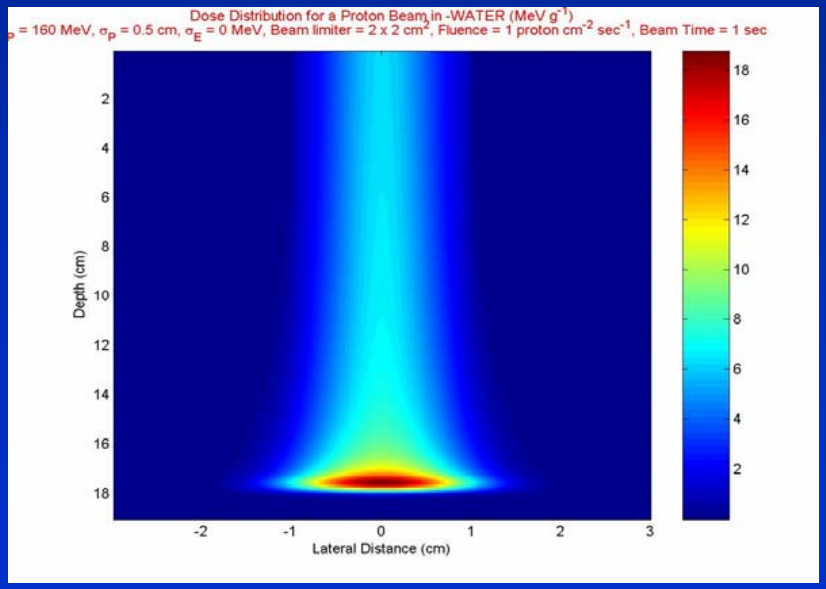
- Passive scattered proton beams
- Scanned Proton Beams
- Intensity modulated proton beams
- Comparative Treatment Plans



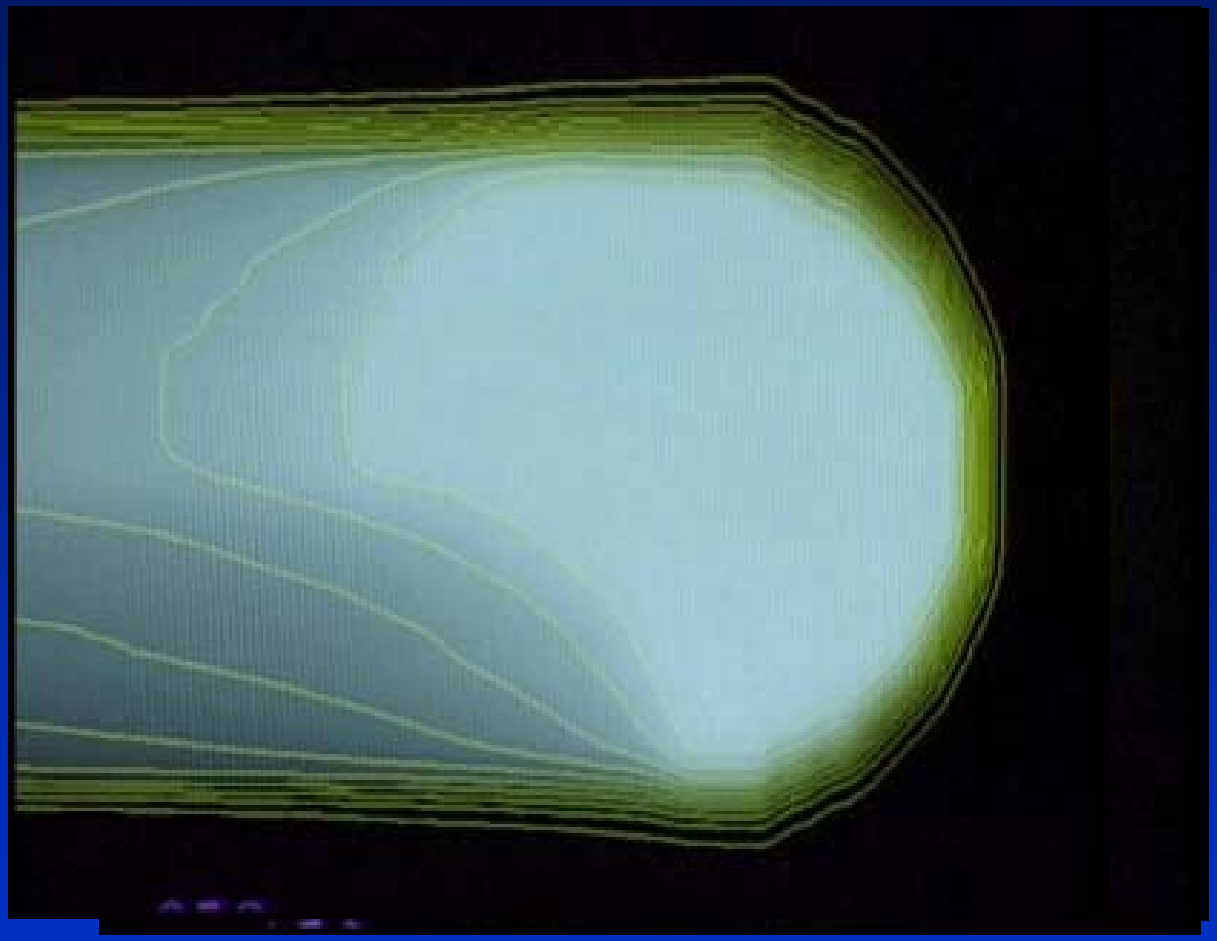


Typical Spot Beam in Water





Beam Scanning



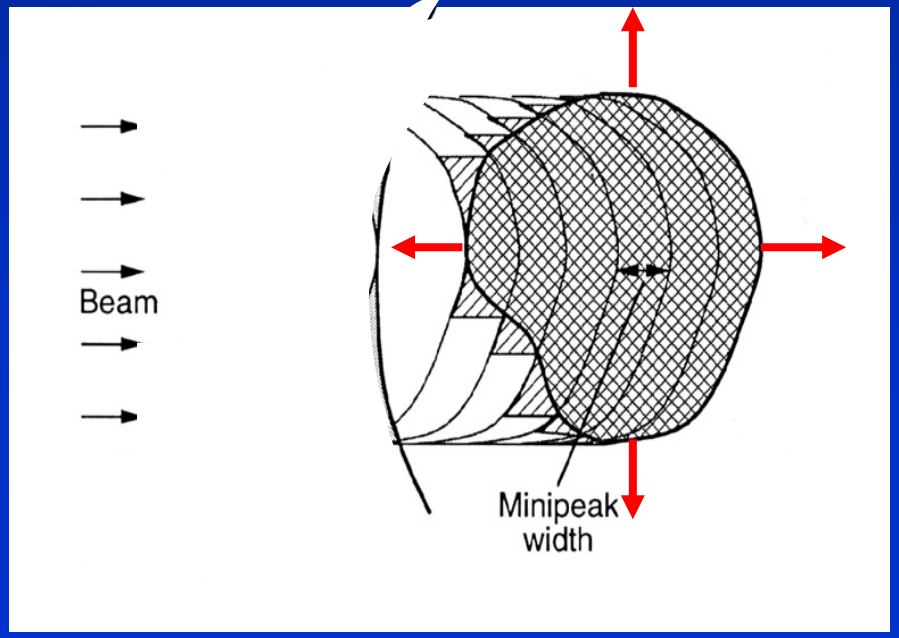
No compensator, no aperture, no scattering system required

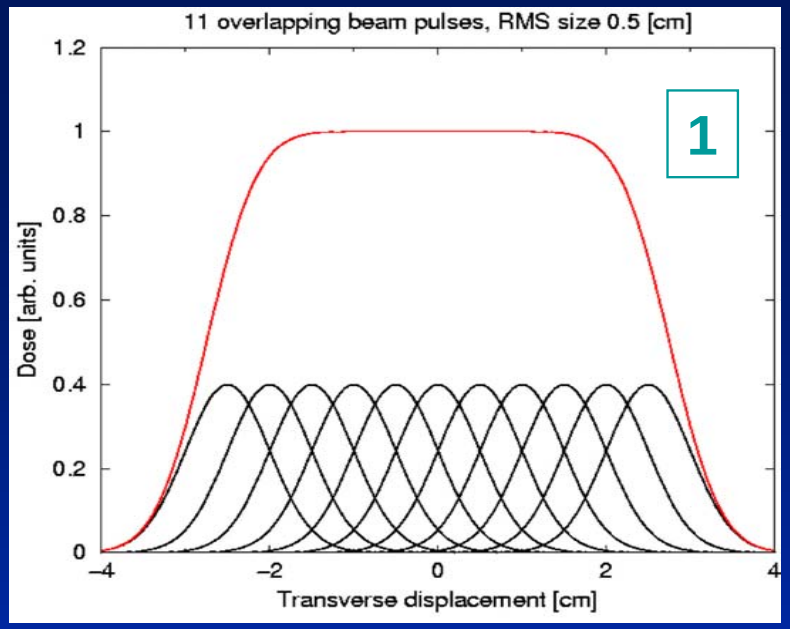
A major problem with spot scanning:

The target can move !

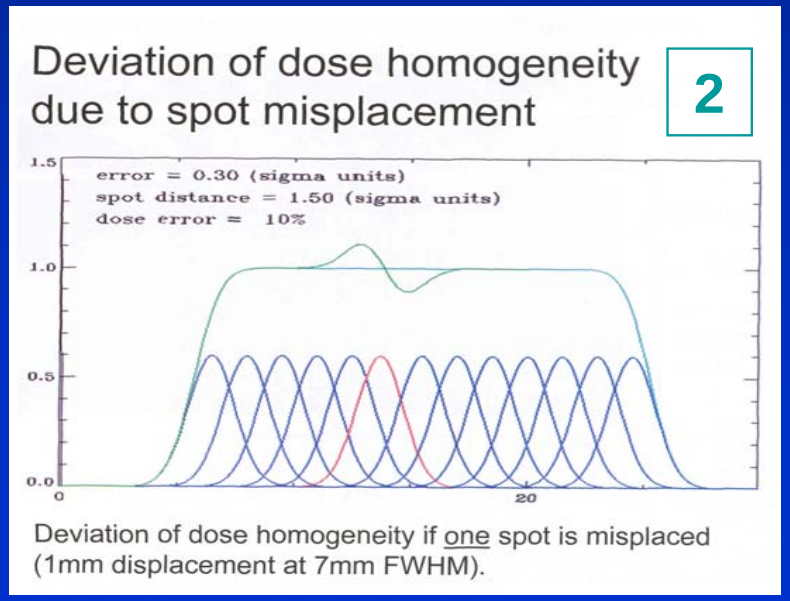
Remedies:

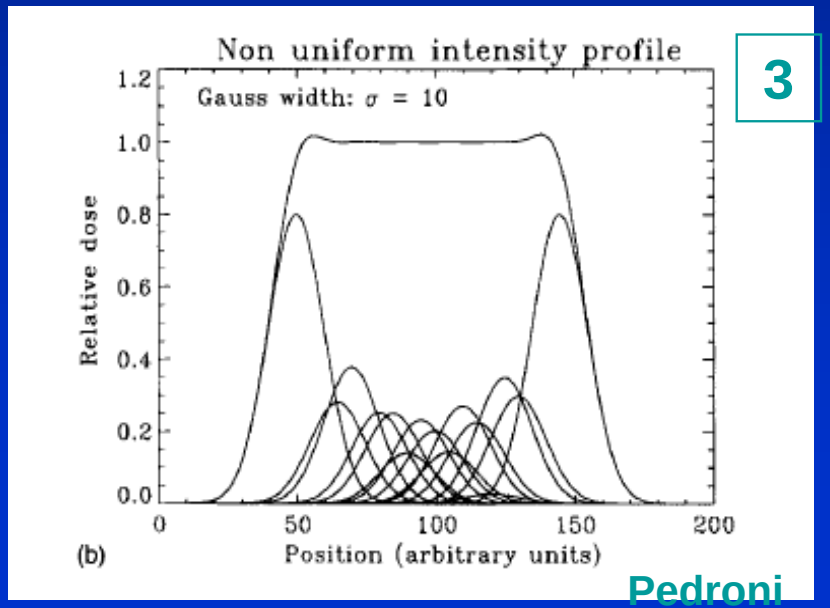
- **Rescanning**
- **Beam Gating**
- **Real time tumor tracking with markers**





1. Evenly spaced/weighted spots to achieve uniform field
2. 1mm spot error due to delivery error or patient motion.
3. Optimum spacing/weighting to achieve sharper penumbra



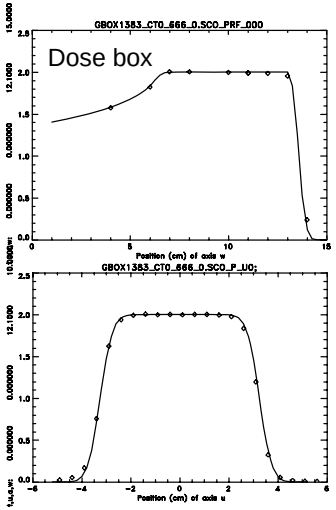


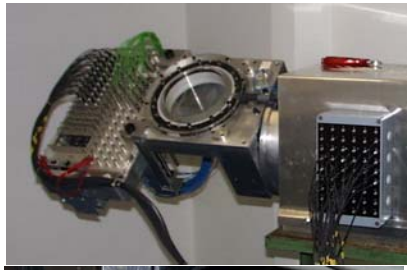
Dosimetry and QA of pencil beams

- Energy/Range
  - large number of energies required.
  - energy spacing must provide dose uniformity over all depths
- Spot size and shape
  - spot size/shape dependence on energy
  - spot orientation as a function of gantry angle
- Spot position accuracy
- Validation of treatment planning calculations
- Validation of treatment delivery
- Measurements require methods for rapid collection large amounts of data
- <u>Real-time beam information</u>

Ionization Chamber Array

Water column with 26 small ionization chambers of 0.1 cm^3

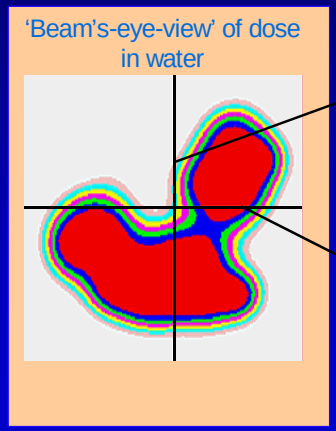


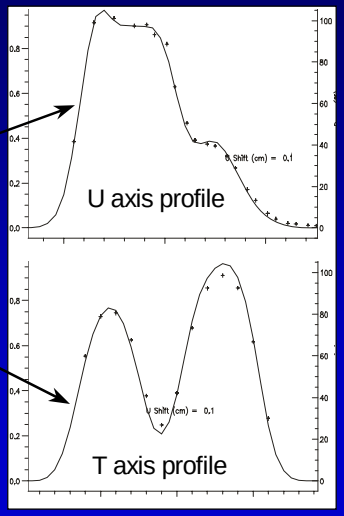


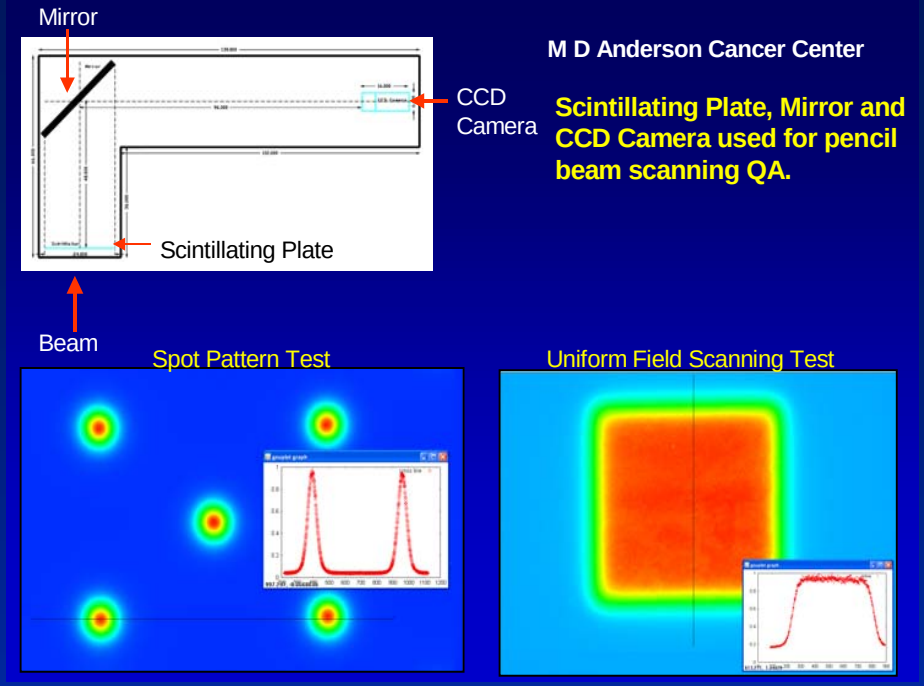
Pedroni, PSI, Switzerland

Pedroni, PSI, Switzerland

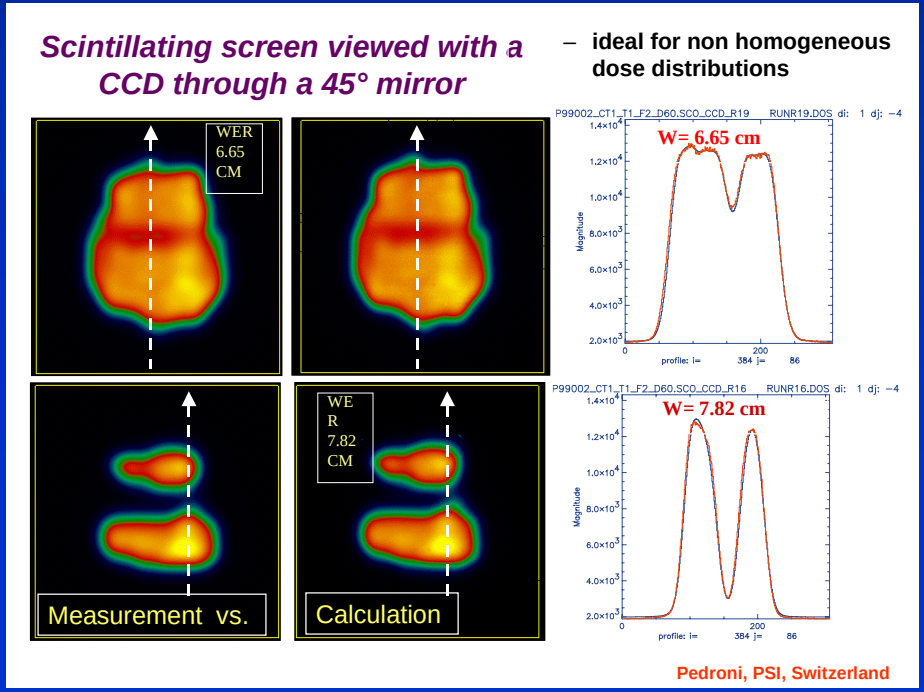
Orthogonal IC array measurements performed at different water depths using a computer controlled water column and compared with calculations.







© Martin Bues, MDACC

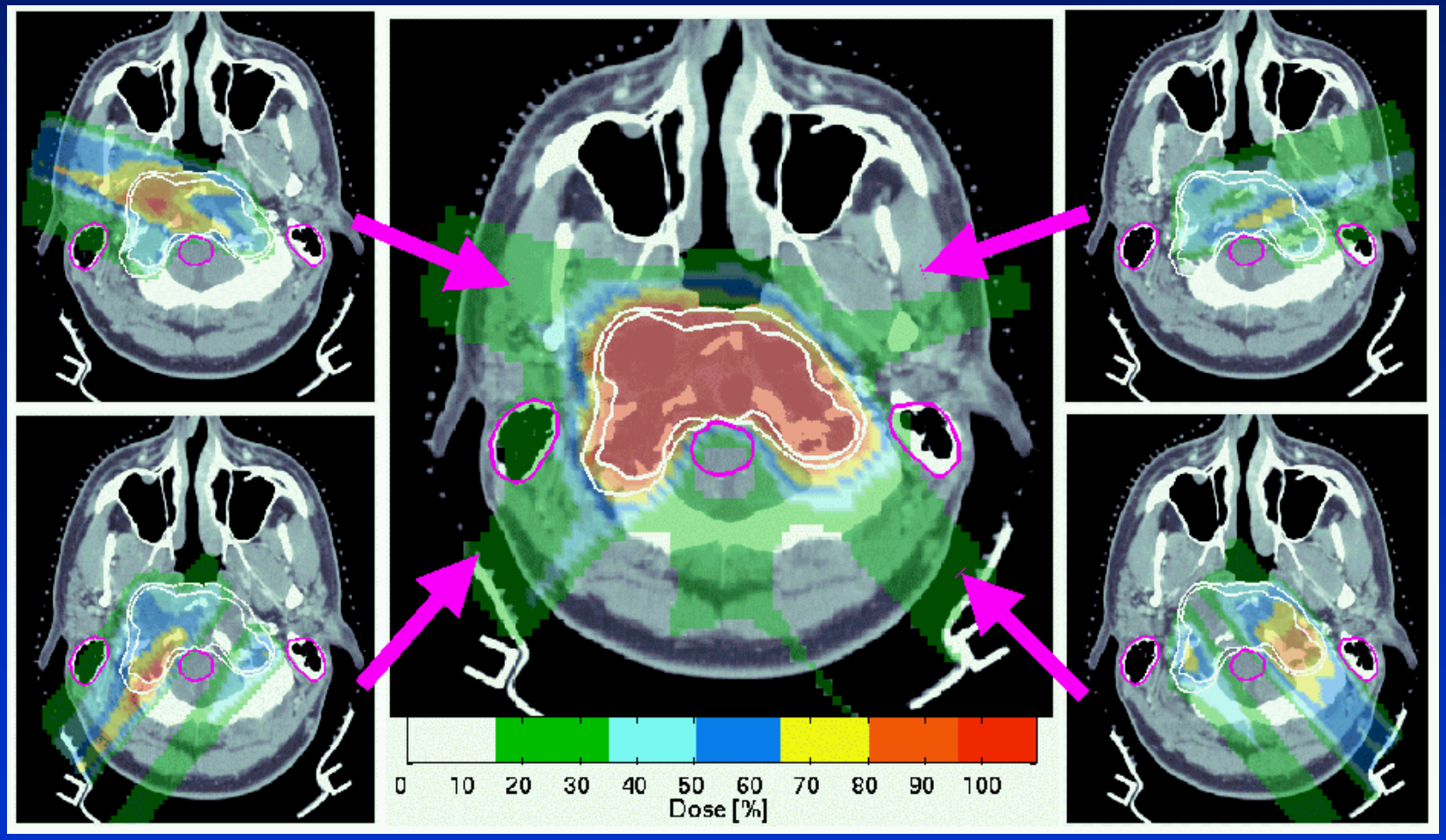


© Eros Pedroni, PSI

Treatment Planning

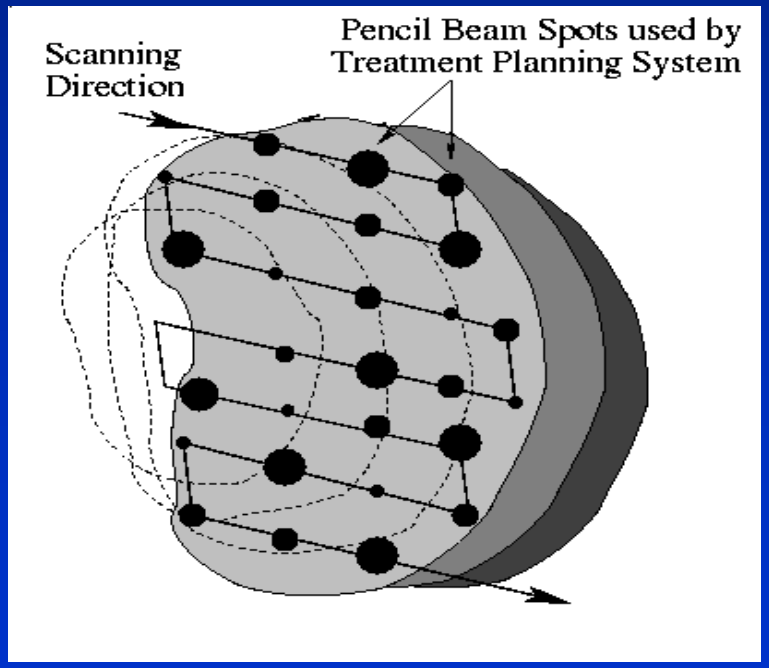
- Passive scattered proton beams
- Scanned Proton Beams
- Intensity modulated proton beams
- Comparative Treatment Plans

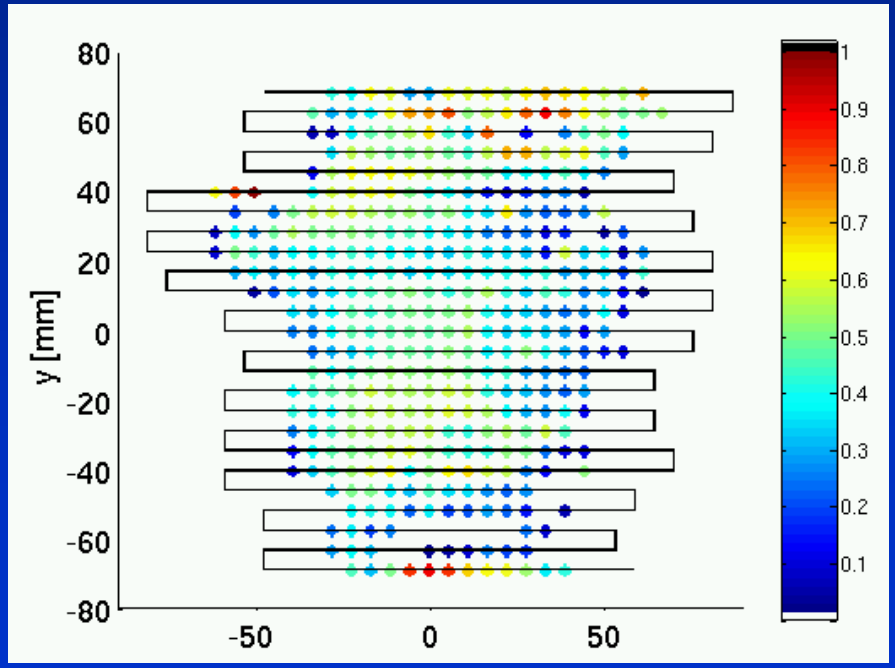
Intensity-Modulated Proton Therapy–IMPT



IMPT Treatment Planning

- Bragg peaks of pencil beams are distributed throughout the planning volume
- Pencil beam weights are optimized for several beam directions simultaneously (inverse planning)

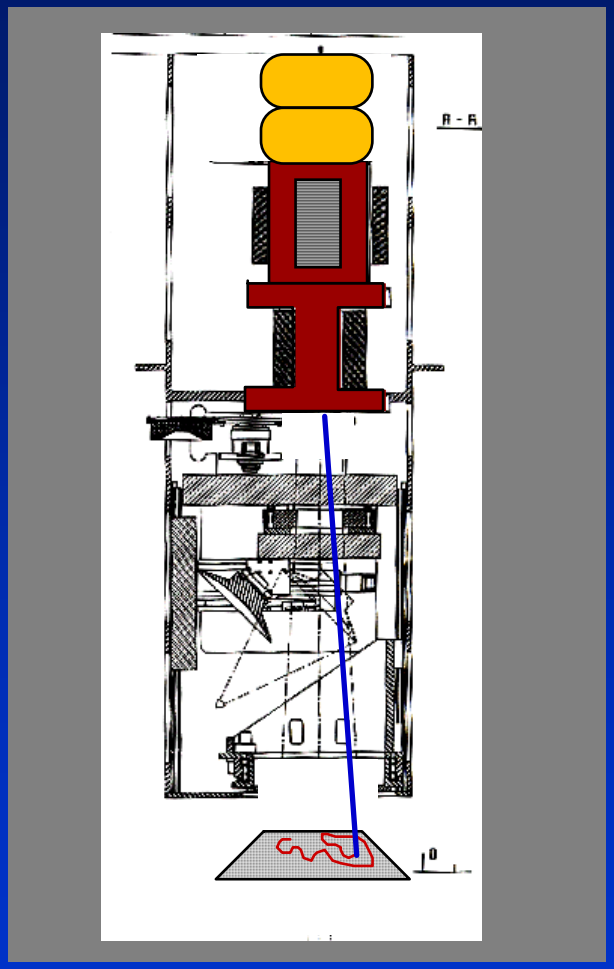




IMPT Delivery

Spot scanning at PSI (Switzerland)

IMPT Delivery



- Built-in magnets for IMPT
- Two (red) “dipole” magnets to deflect the beam in X and Y respectively
- Two (yellow) “quadrupole” magnets to focus the beam in X and Y respectively

IMPT in clinical practice

+ great flexibility and variability
+ no need for apertures/compensators
+ easy delivery of large fields
+ beamlet optimization routines

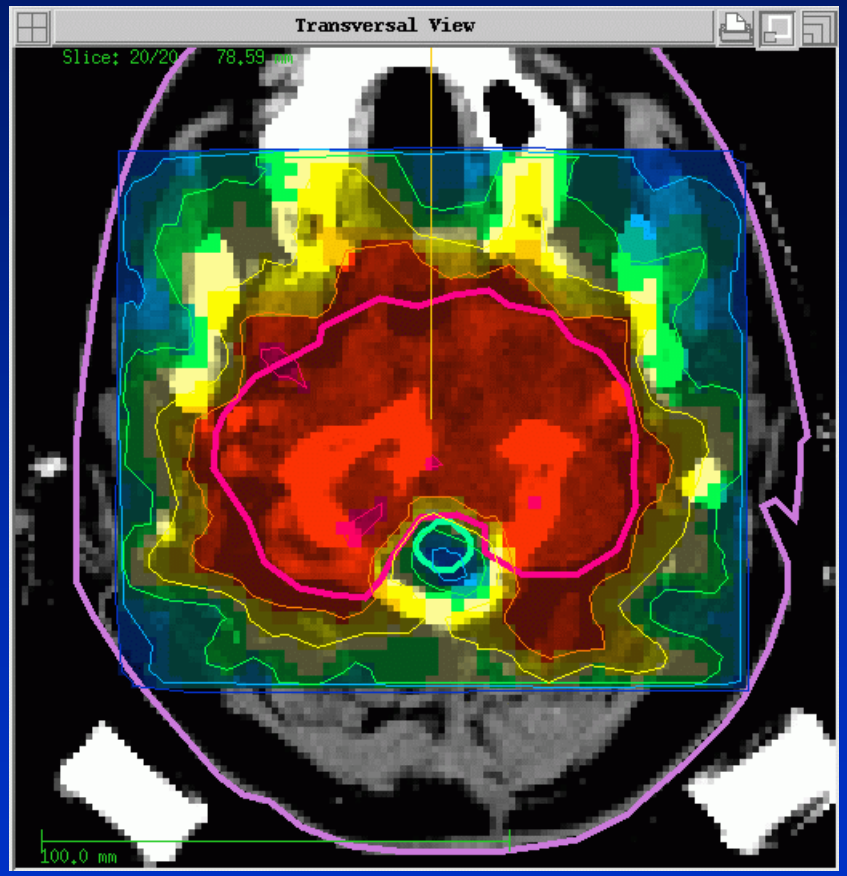
- requires very high degree of precision

Treatment Planning

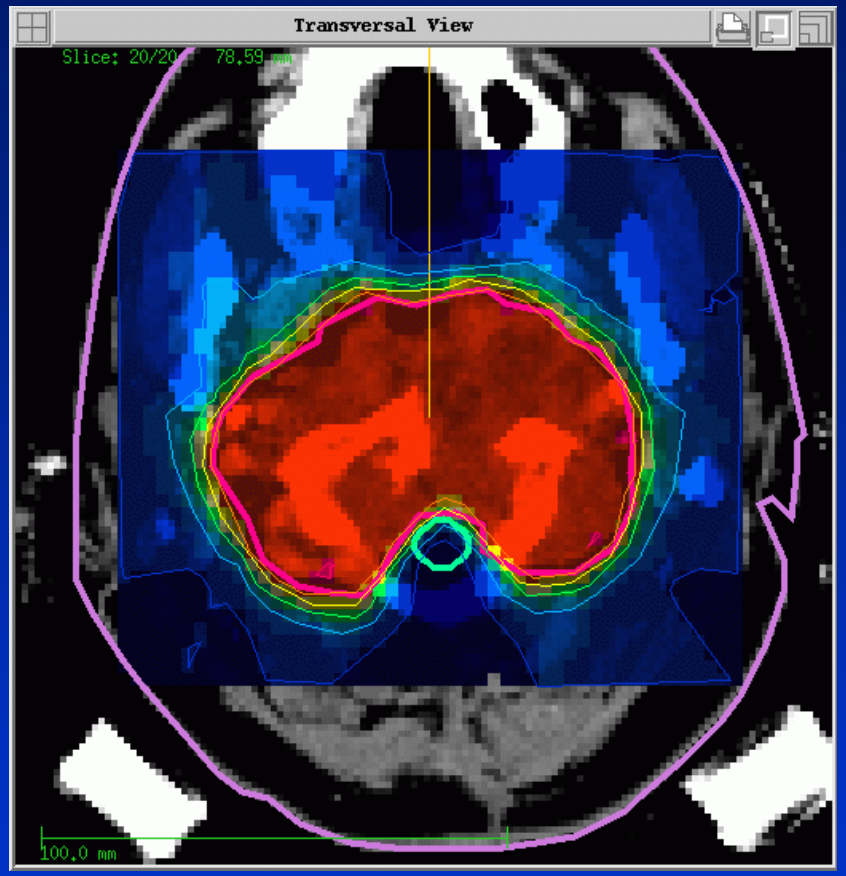
- Passive scattered proton beams
- Scanned Proton Beams
- Intensity modulated proton beams
- Comparative Treatment Plans

Example
(IM protons vs. IM photons)

Photon IMRT



Proton IMPT

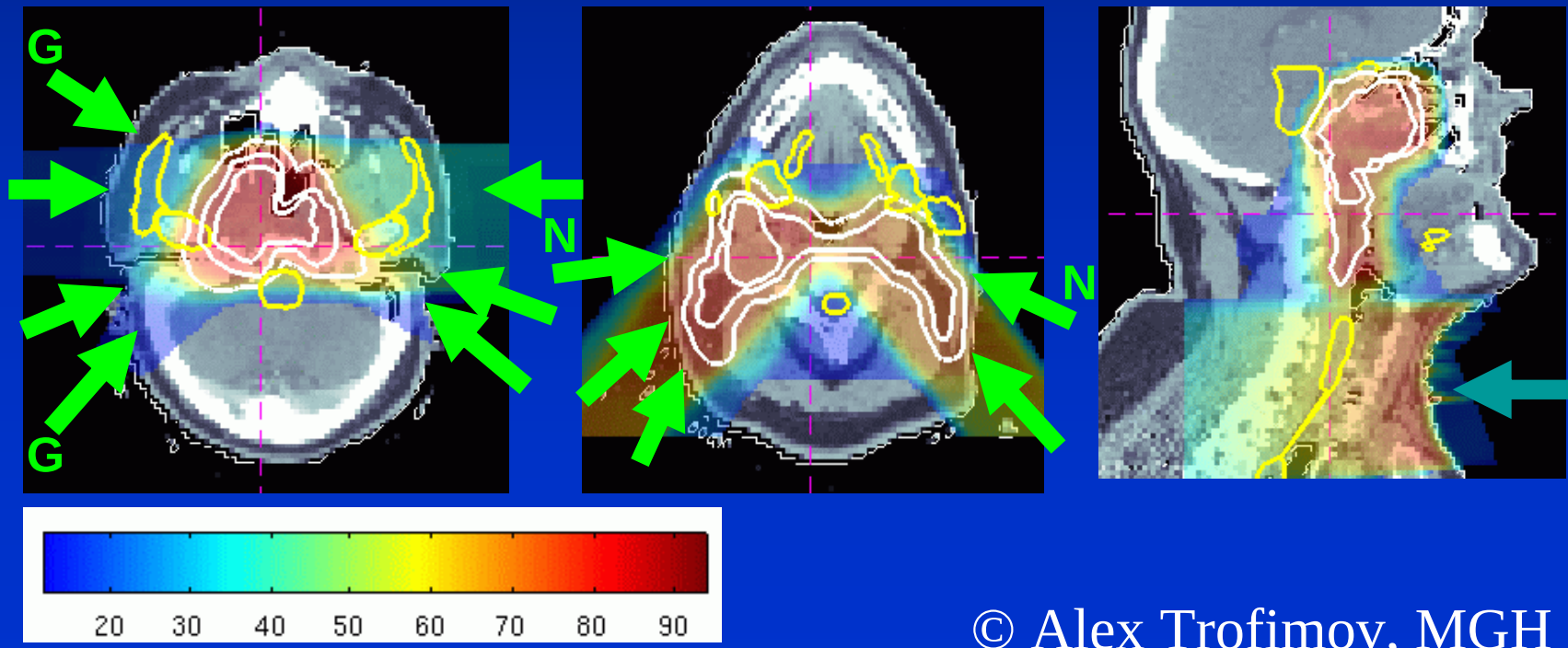


Example
(protons vs. IM photons)

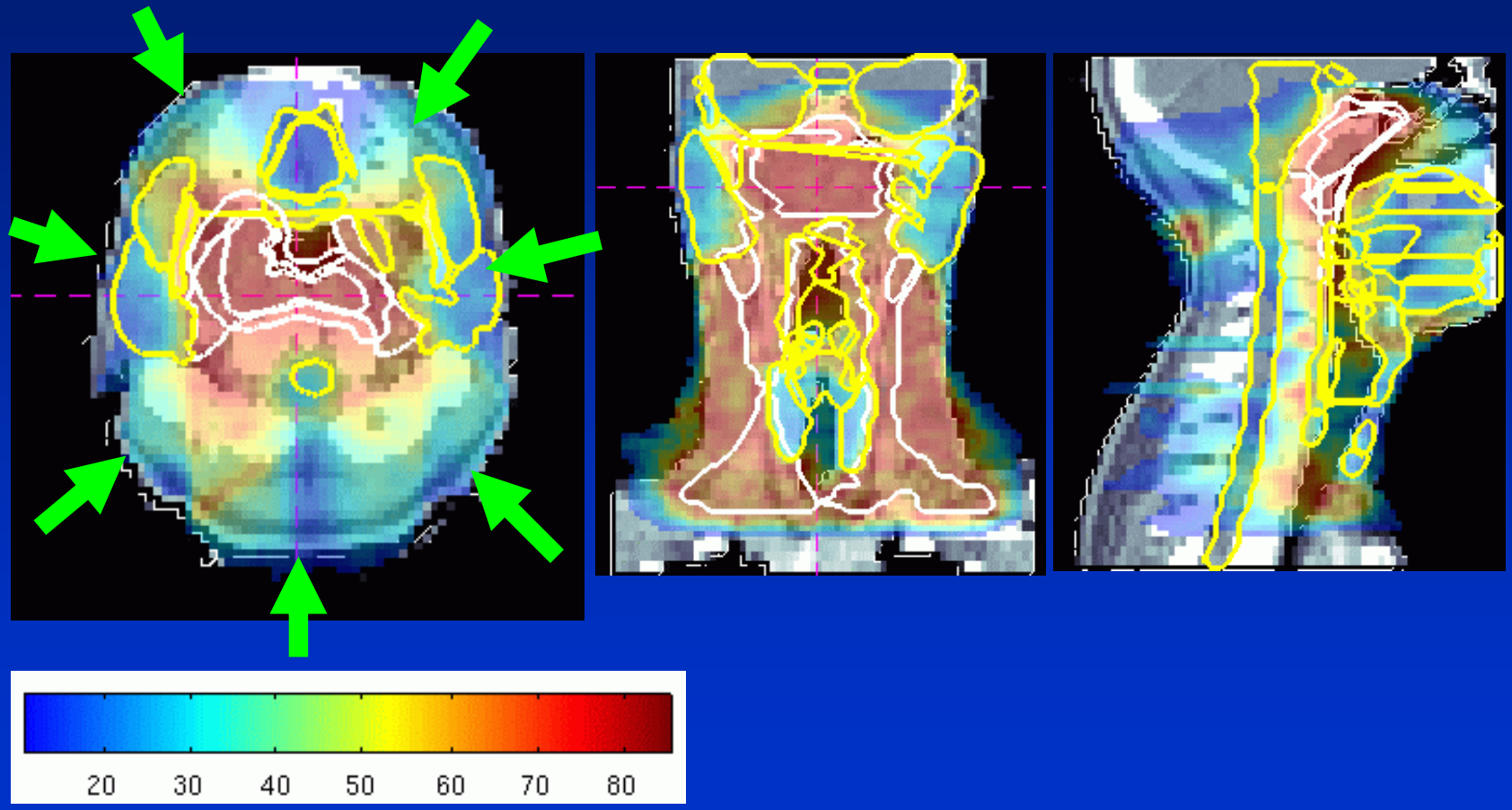
Nasopharynx
(case shown earlier)

A Composite plan
(14 proton fields, 4 photon fields)

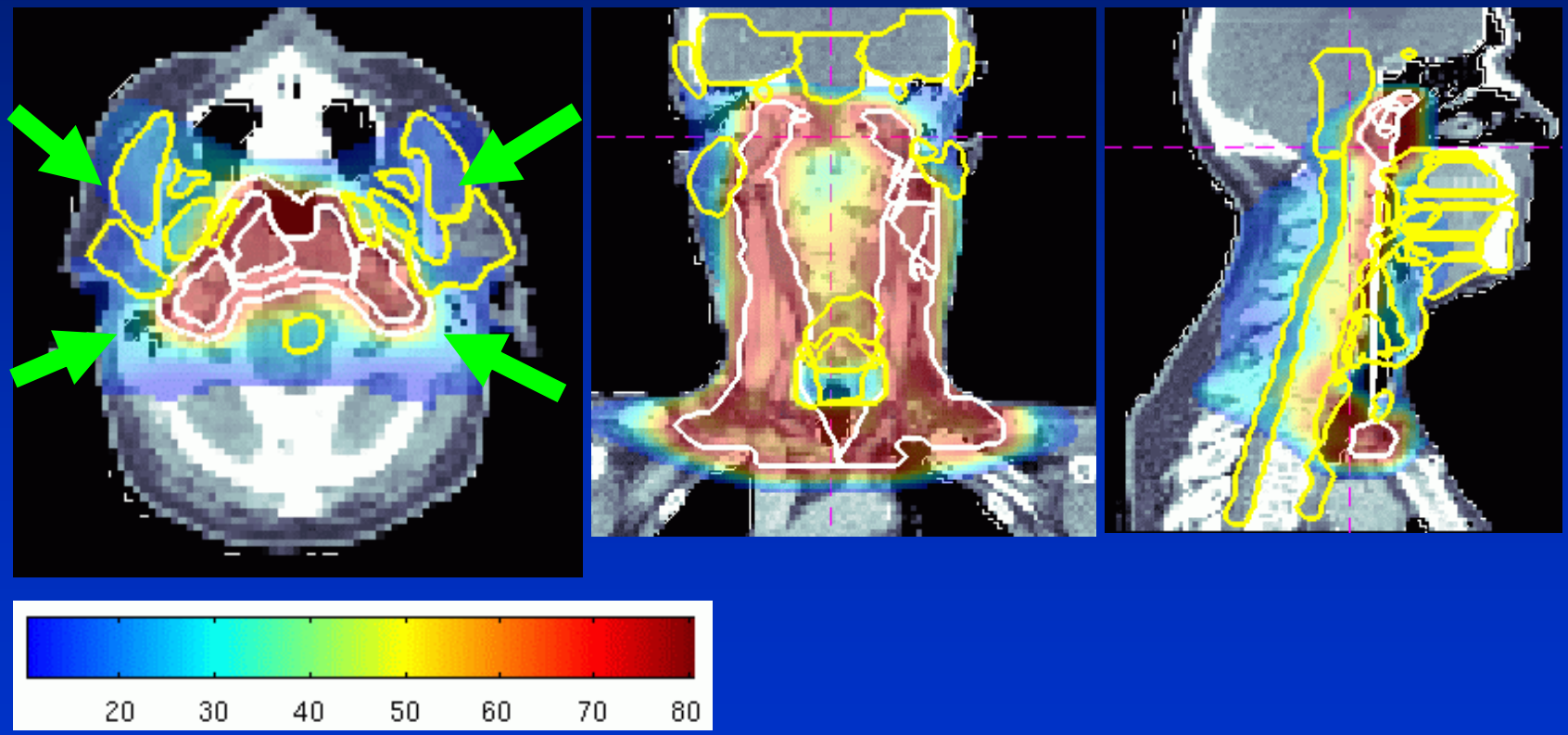
- proton fields
  CTV to 59.4 GyE (33 x 1.8 Gy)
  GTV to 70.2 GyE (+ 6 x 1.8 Gy)
- Photon fields
  lower neck, nodes to 60 Gy



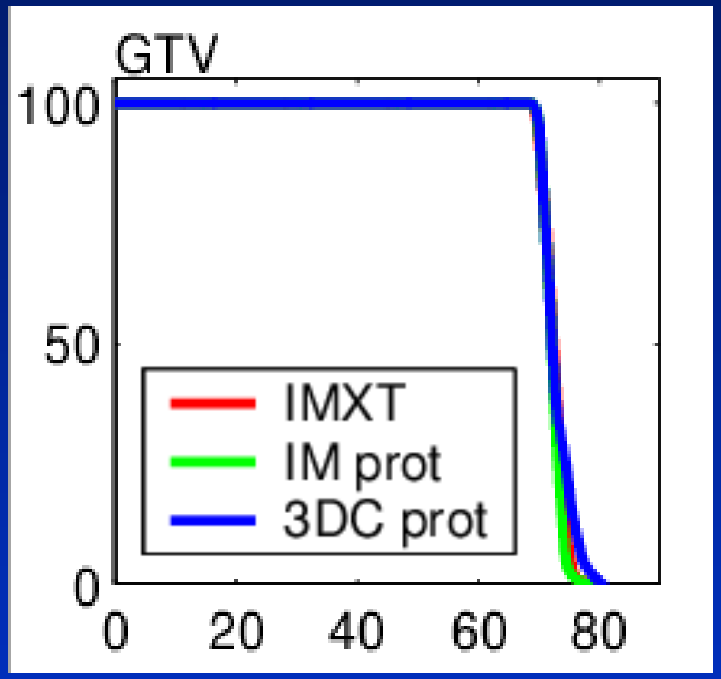
B IMXT plan
(7 coplanar photon beams)

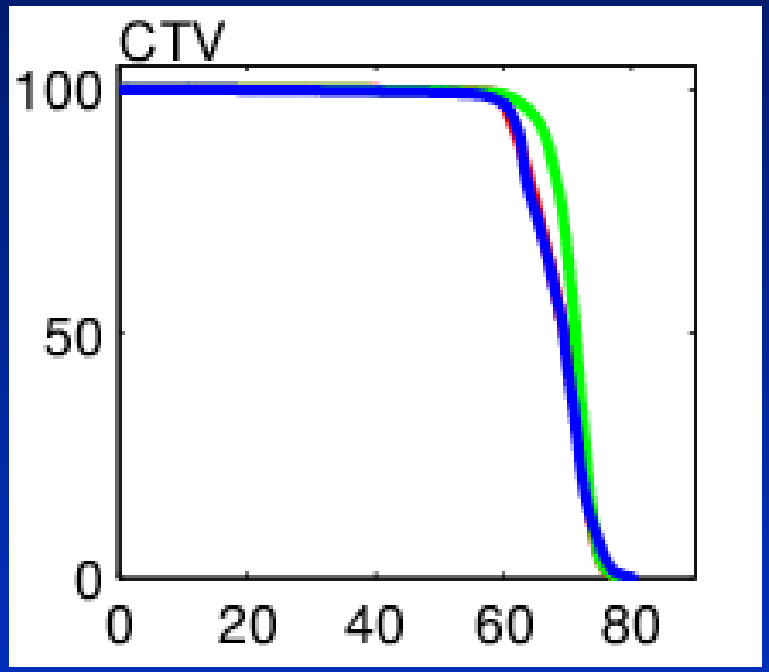


C IMPT plan
(4 coplanar photon beams)



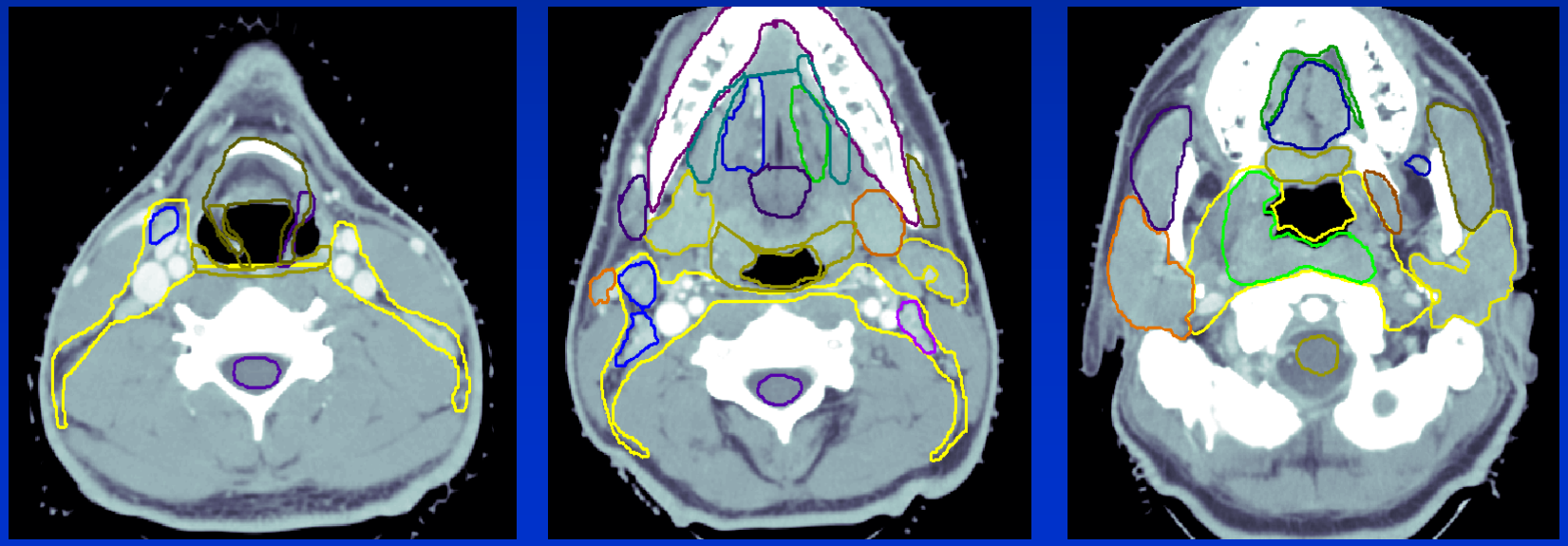
DVH for target structures



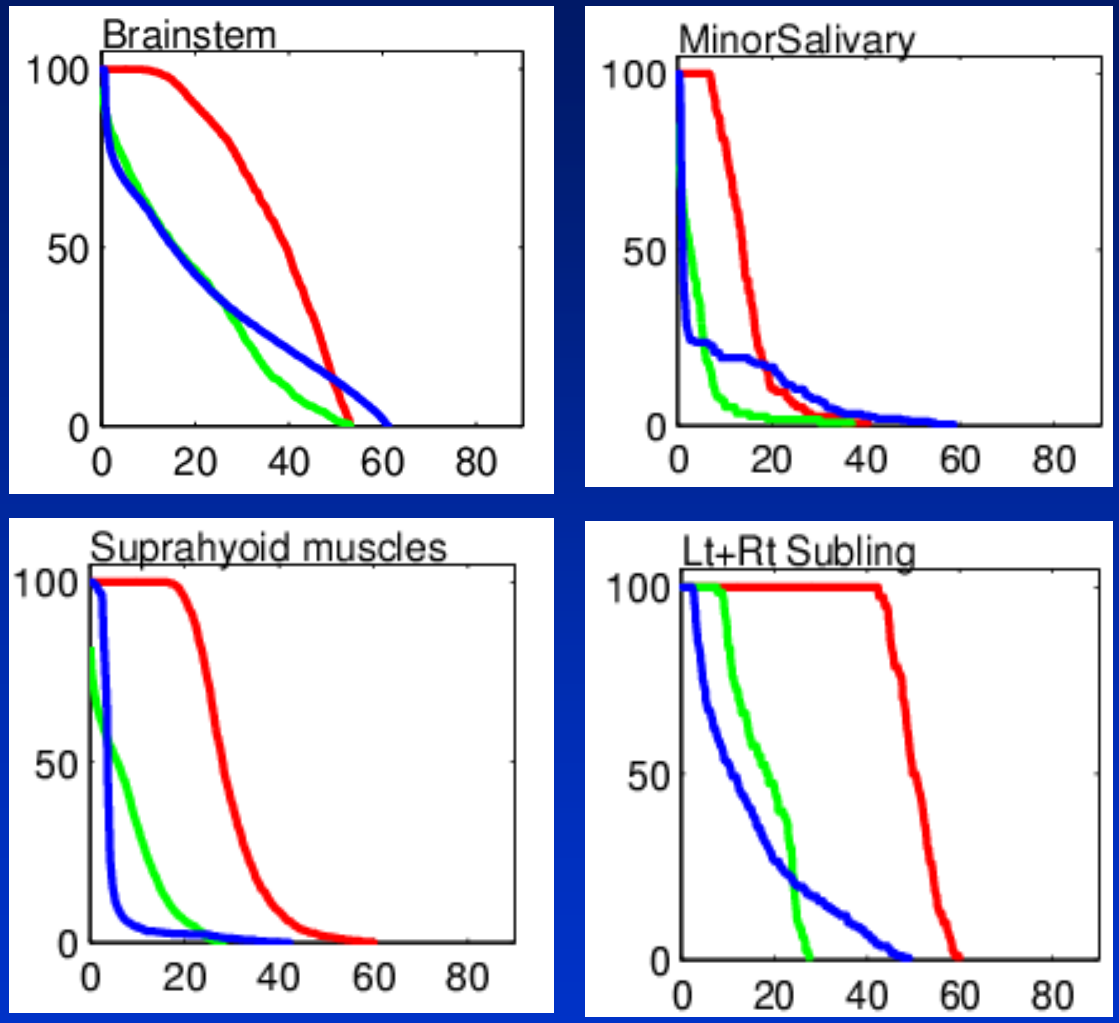


Comparable target coverage

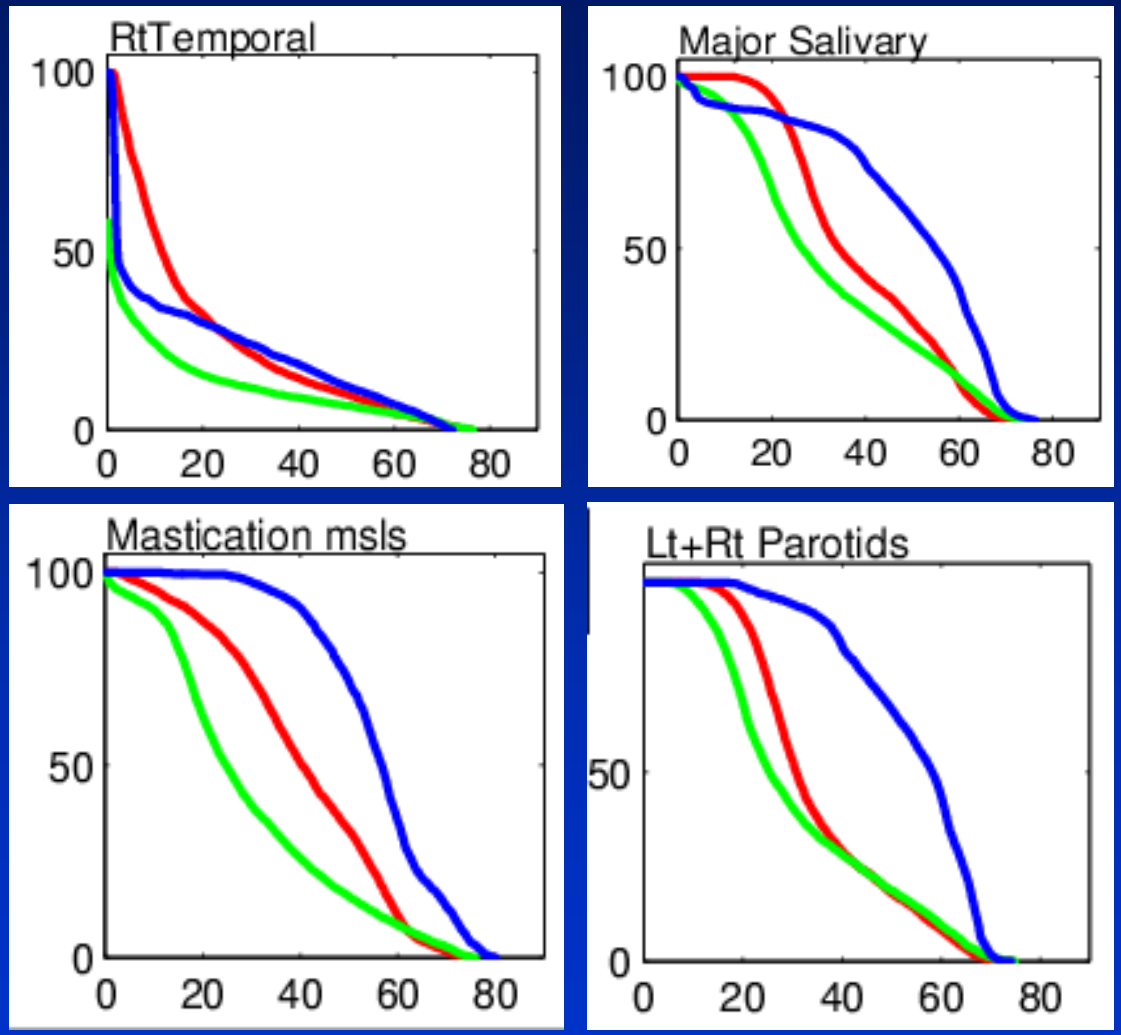
- Critical normal structures (always outlined):
  - brain stem, spinal cord, optic structures
  - parotid glands, cochlea
- ‘Extra’ structures were outlined on 3 data sets
  - esophagus, base of tongue, larynx
  - minor salivary, sublingual and submand. glands
  - mastication and suprahyoid muscles



DVH for some critical structures



DVH for some critical structures



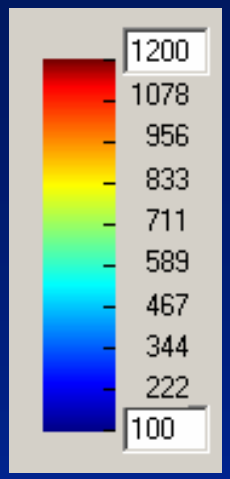
Example
(standard protons vs. photons)

Medulloblastoma

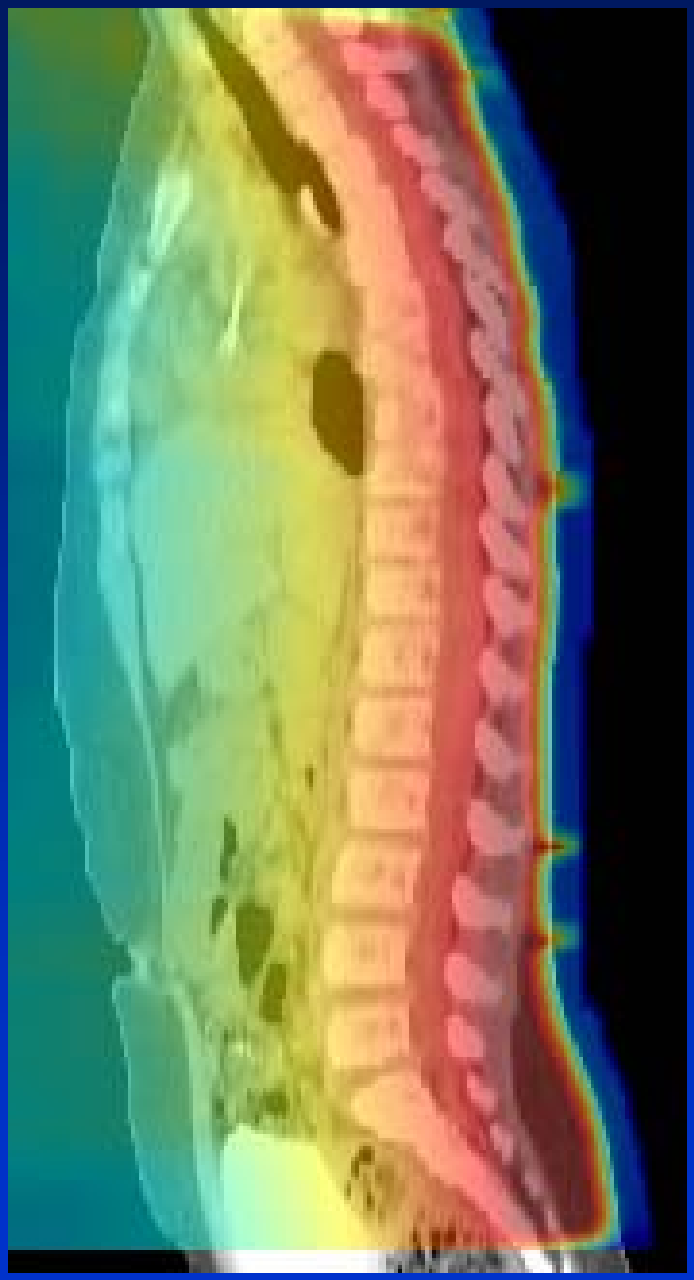
Medulloblastoma

- Irradiation of the whole cranium and spinal axis
  - Low Risk – 23.4 CGE
  - High Risk – 36.0 CGE
  - Spine
    - Include Vertebral Body
  - Cranium
    - Constrain Auditory System < 40 CGE
    - Pituitary / Hypothalamus ~ 45 CGE
- Posterior Cranial Fossa Boost
  - Total 54 CGE

Protons



Photons



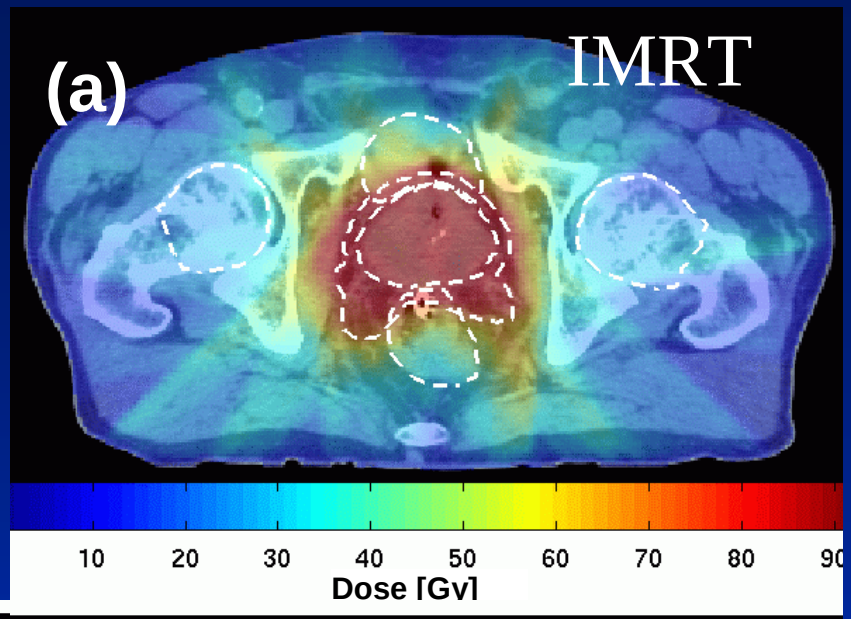
Example
(protons vs. IM photons)

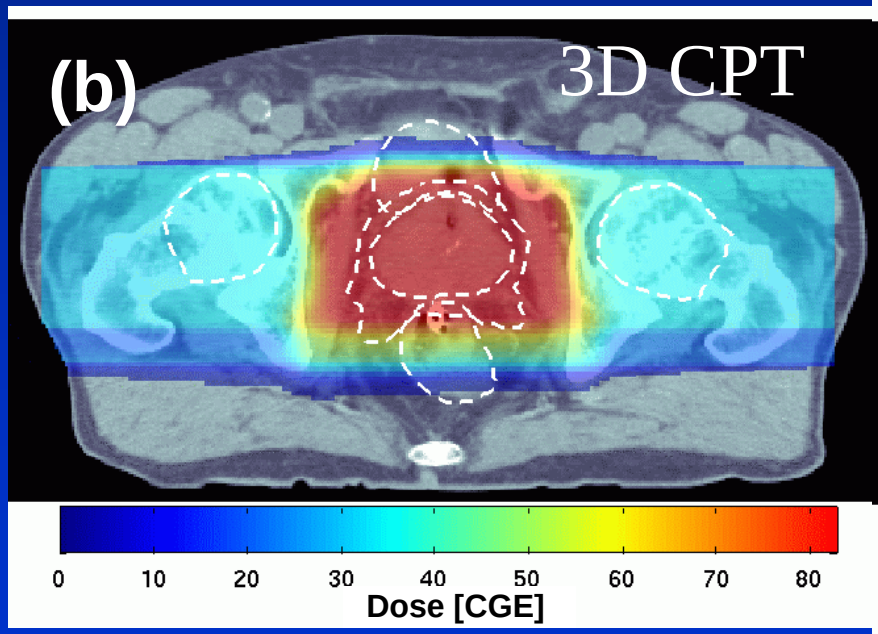
Prostate

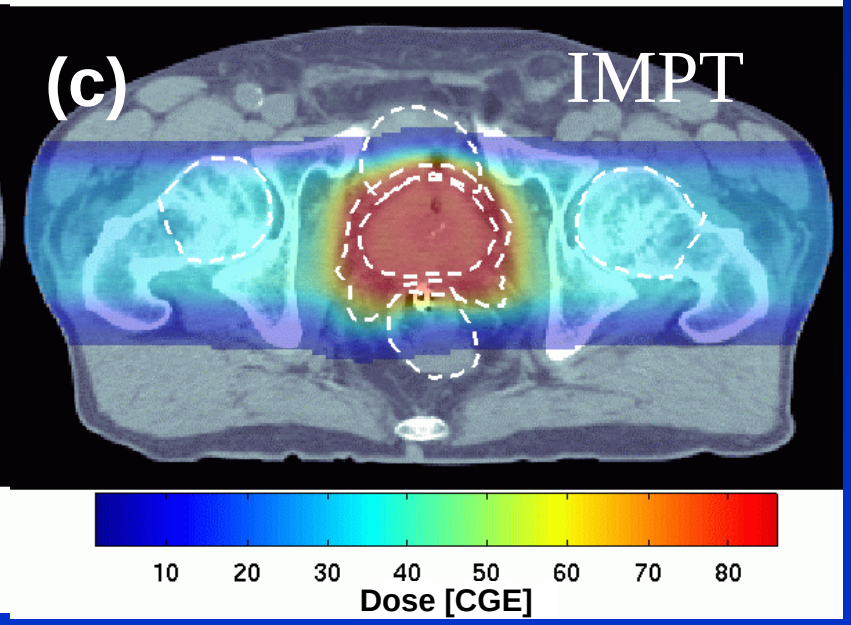
Prostate carcinoma:

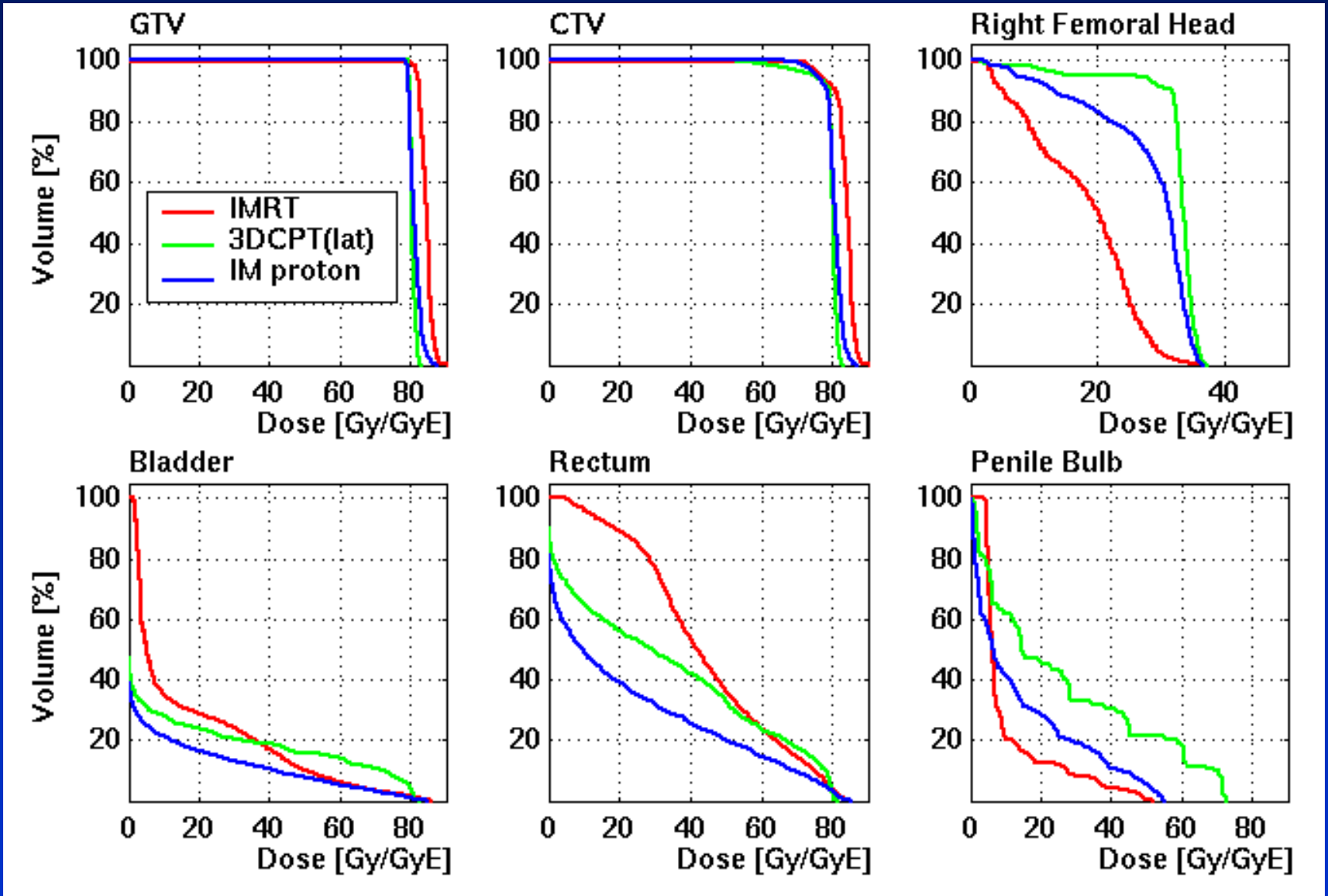
(GTV + 5mm) to 79.2 Gy

(CTV + 5mm) to 50.4 Gy









Summary

- Proton planning offers more options in terms of beam directions and field shaping than photon planning
- For specific sites IMRT and protons can be comparable in terms of dose conformality
- Protons are able to reduce the dose to most critical structures compared to photons
- Proton therapy is able to reduce the integral dose compared to photons by up to a factor of 3
- IMPT is the method of choice

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