Proton therapy: cobalt dose to water calibration protocols

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19 October 2010

Outline

- Current status of proton therapy in the US.
- Why and how of proton therapy.
- Dosimetry of proton beams.

There are eight high-energy proton facilities in the United States treating approximately 600 patients per day.

Between 5 and 15 others are currently under construction to some extent but it is hard to know how many of these will be completed.

University of Maryland to build proton cancer treatment center

$200 million project to open in 2014 at West Baltimore BioPark

October 14, 2010 | By Frank D. Roylance, The Baltimore Sun

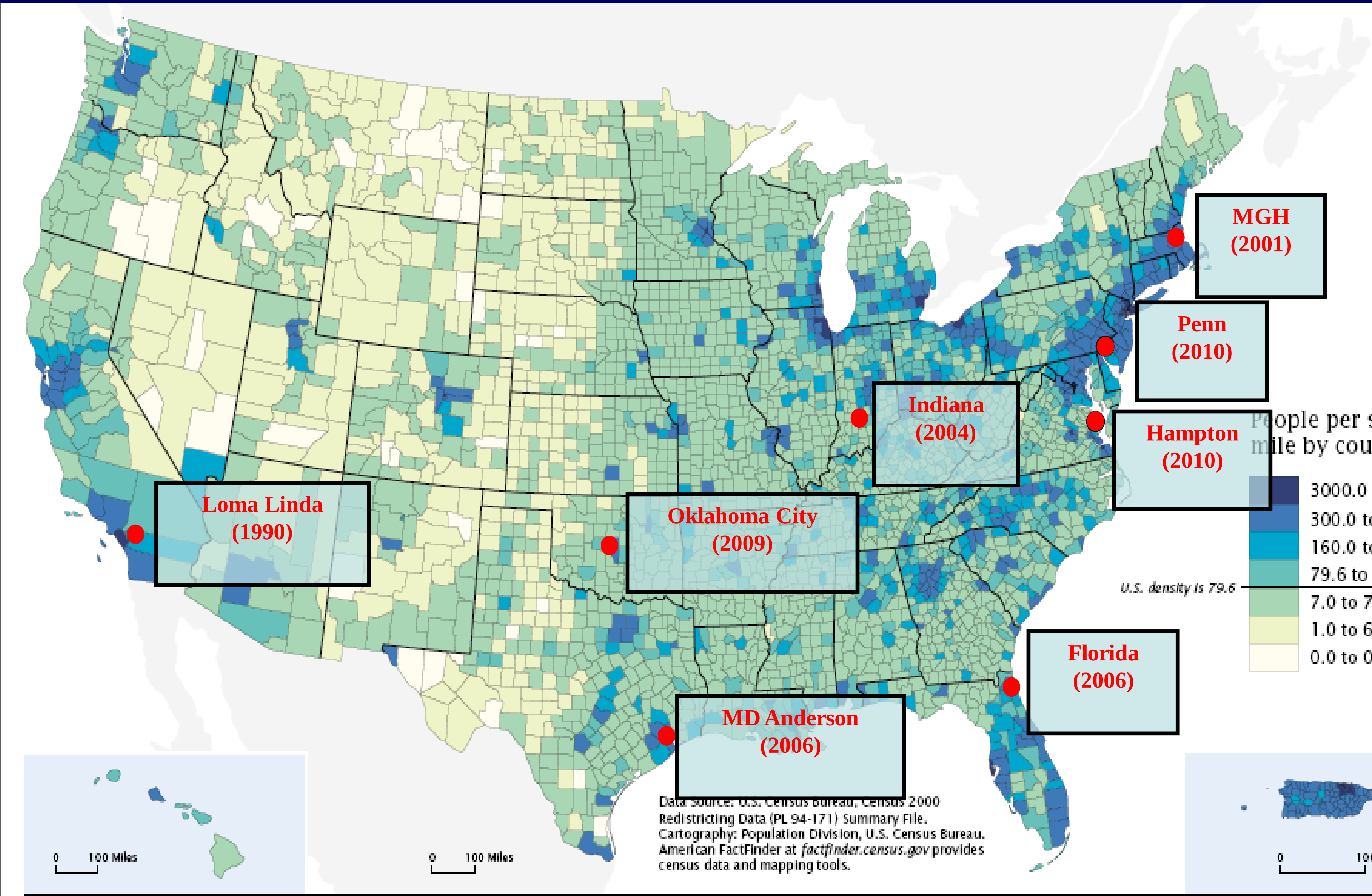
Kim Hairston, Baltimore Sun

The University of Maryland's growing BioPark in West Baltimore will get a $200 million boost from plans announced Wednesday by the School of Medicine to team with private partners on a state-of-the-art proton cancer treatment center.

Maryland Lt. Gov. Anthony G. Brown said the center would create 325 construction jobs, 110 permanent jobs and attract 2,000 patients a year. "It will also continue the state's and Baltimore City's investment in the communities of West Baltimore," he said

Slated for completion in 2014, the new therapy center would provide noninvasive outpatient treatment for a variety of cancers, with a promise of more precise radiation targeting of tumors and fewer side effects, especially for children.

Current US Facilities

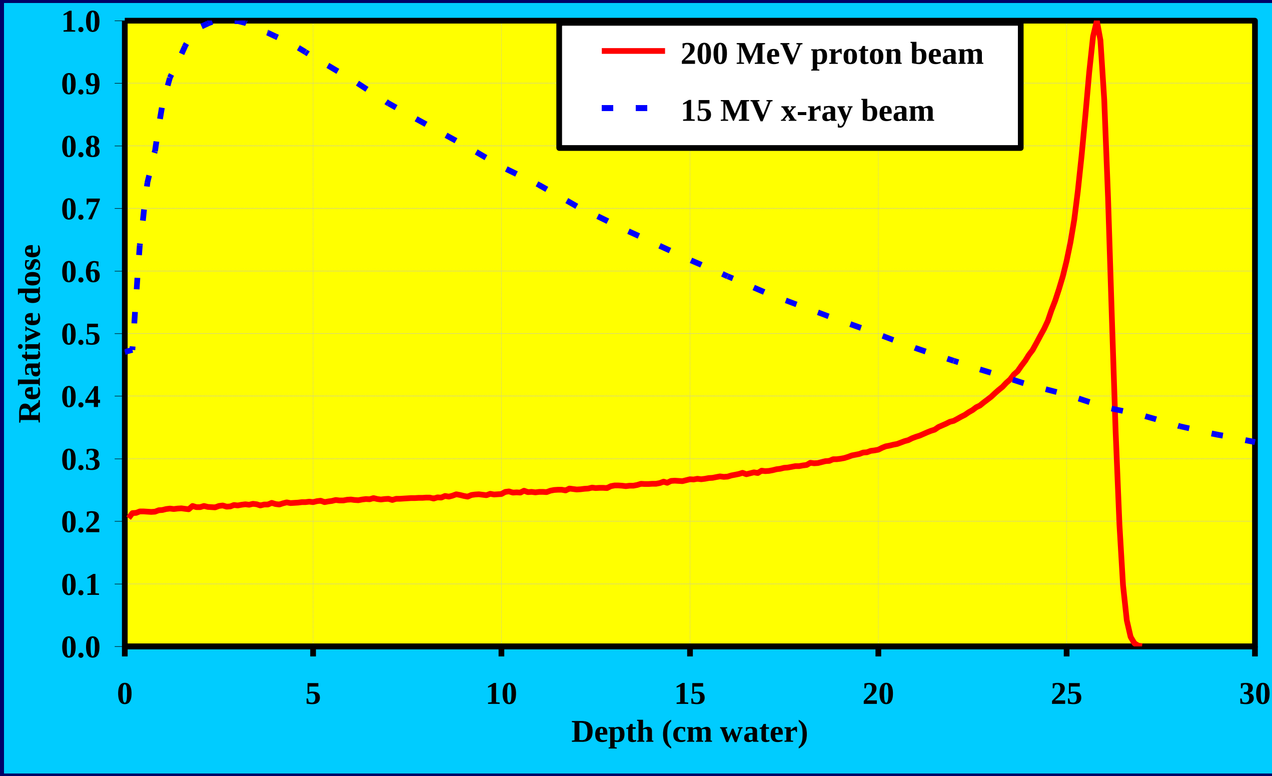


Why protons?

Energy Loss by charged particles (Bethe-Bloch equation)

$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

The collision mass stopping power is proportional to the inverse-square of the velocity of the incident particle.



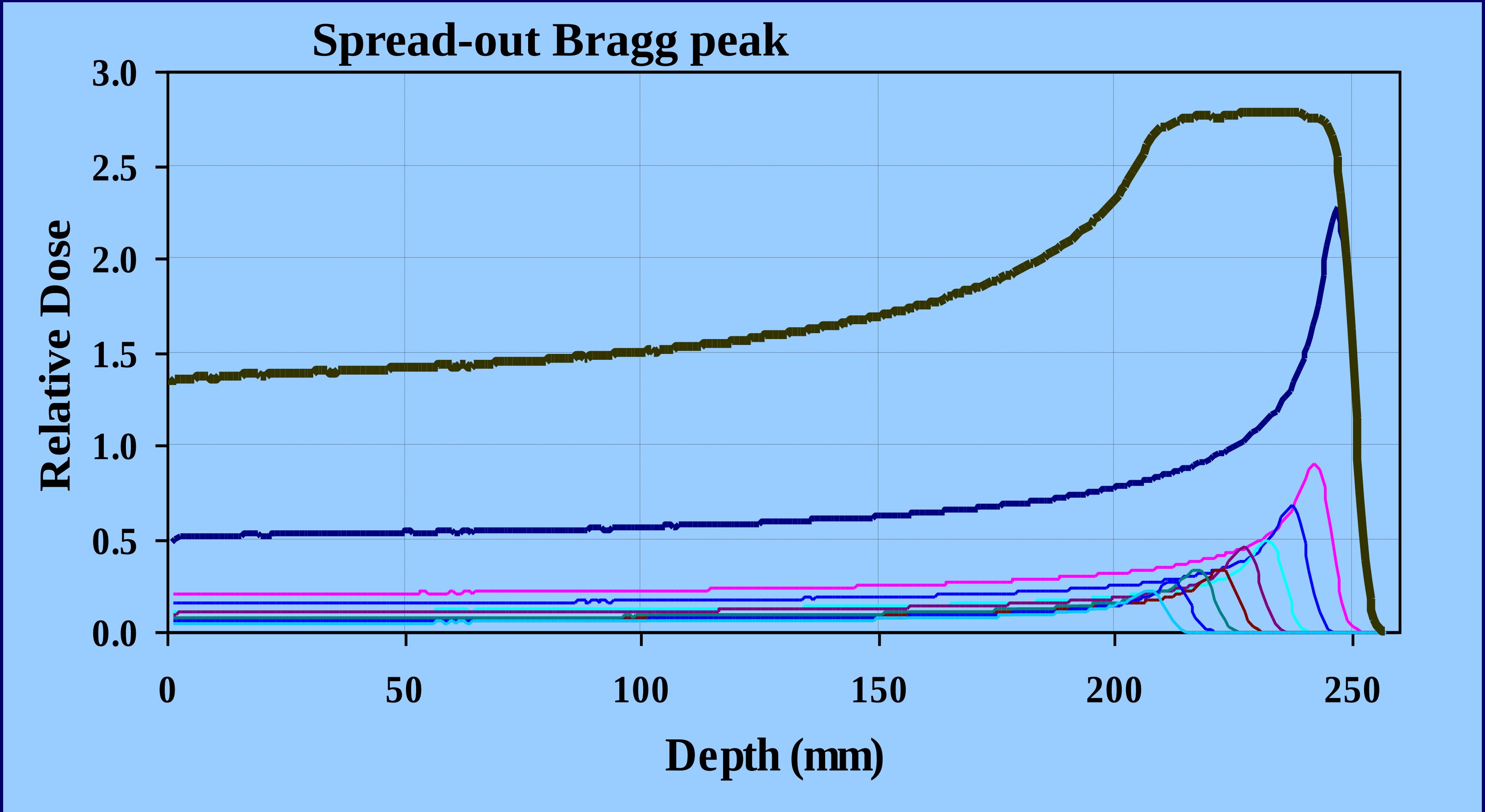
To use the proton beam for treatments it must be spread-out in the lateral and depth directions. There are several ways to do this:

Depth

- **Passive** using Modulator wheels or Ridge filters
- **Active** by bringing in different energy protons

Transverse

- **Passive** using double scatterers
- **Active** by magnetically steering the protons across the target



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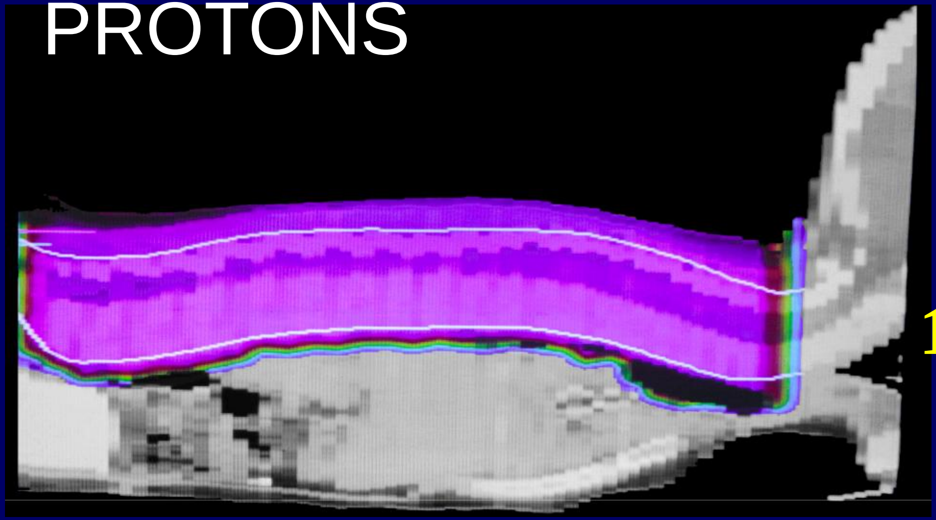
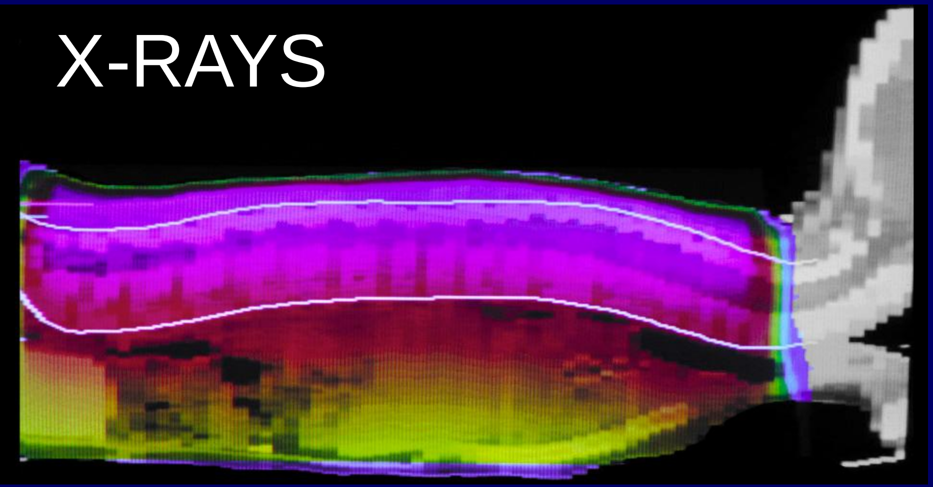
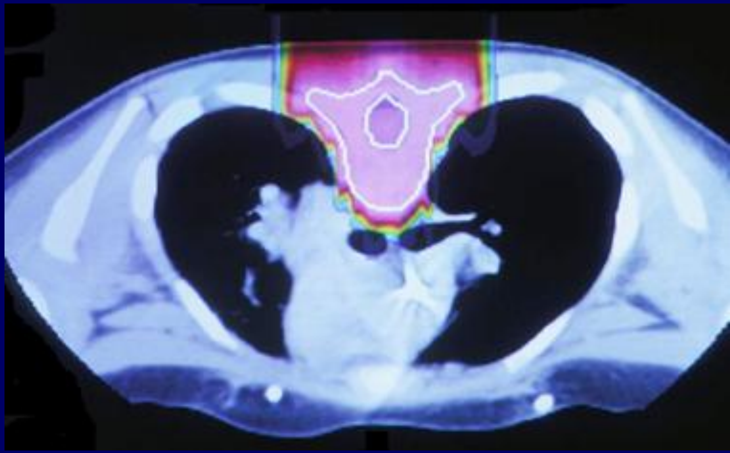


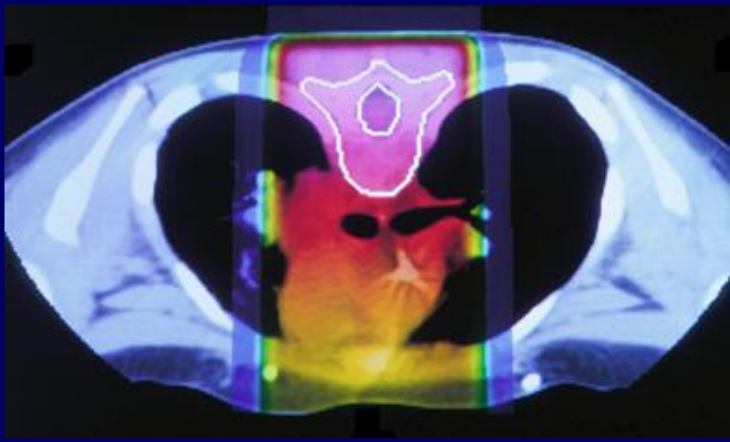


100

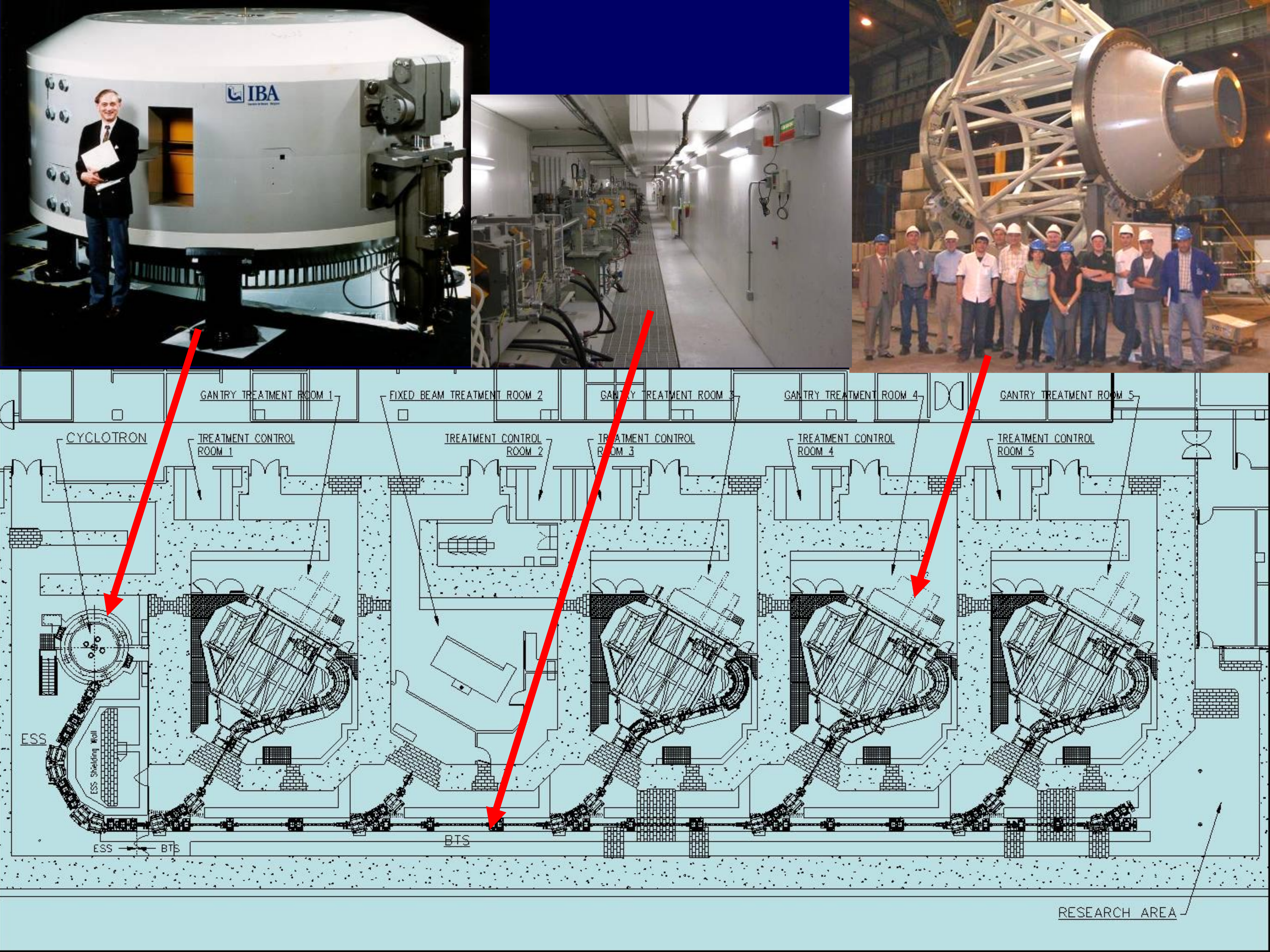
60

10





Slide courtesy of A. Smith, MGH



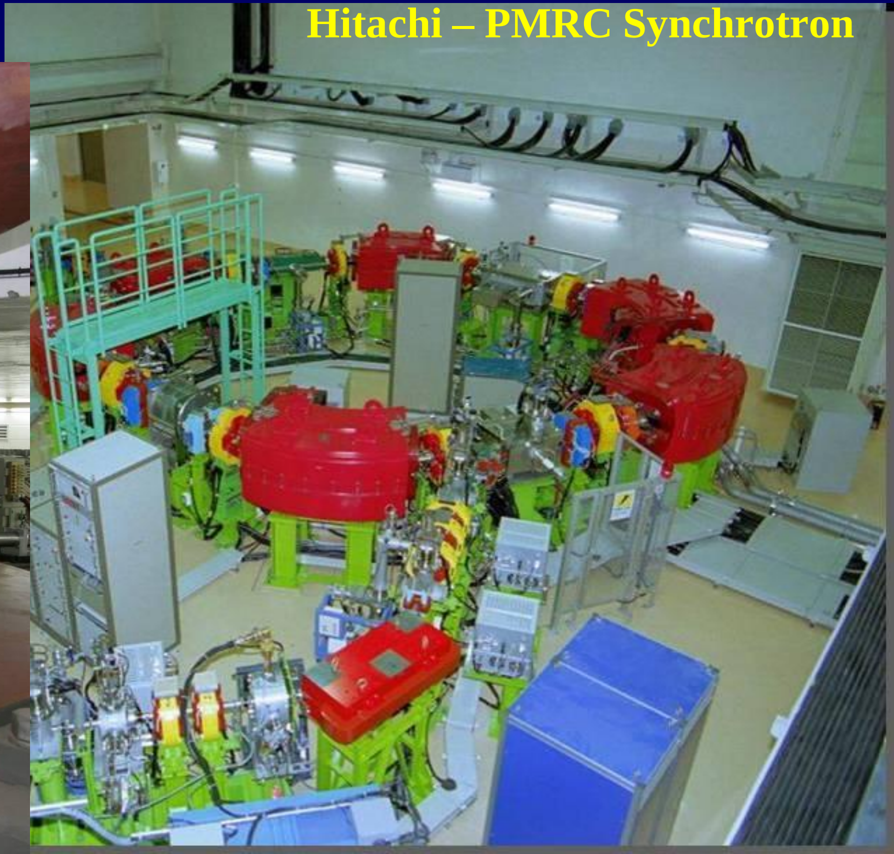
IBA
GANTRY TREATMENT ROOM 1
FIXED BEAM TREATMENT ROOM 2
GANTRY TREATMENT ROOM 3
GANTRY TREATMENT ROOM 4
GANTRY TREATMENT ROOM 5
CYCLOTRON
TREATMENT CONTROL ROOM 1
TREATMENT CONTROL ROOM 2
TREATMENT CONTROL ROOM 3
TREATMENT CONTROL ROOM 4
TREATMENT CONTROL ROOM 5
ESS
ESS Shielding Wall
ESS
BTS
BTS
RESEARCH AREA

Cyclotron or Synchrotron?

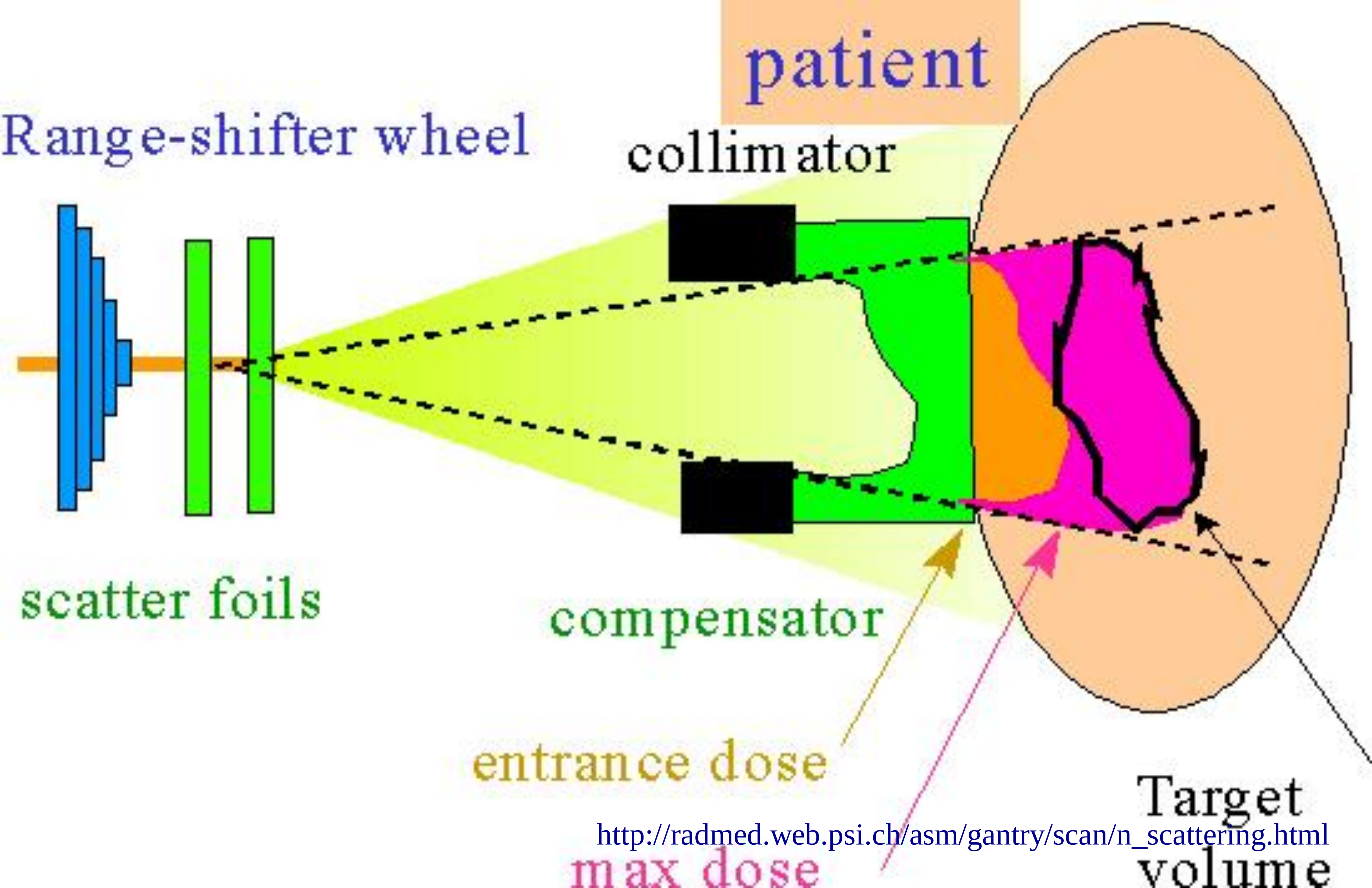
- Cyclotrons have fixed energy but high intensity. They are somewhat simpler because the magnetic field and RF frequency are constant.
- Synchrotrons have selectable energy but lower intensity. High energy can be reached & shielding around the accelerator is easier.

IBA Cyclotron

Hitachi – PMRC Synchrotron



Double- scattered beam with aperture and compensator

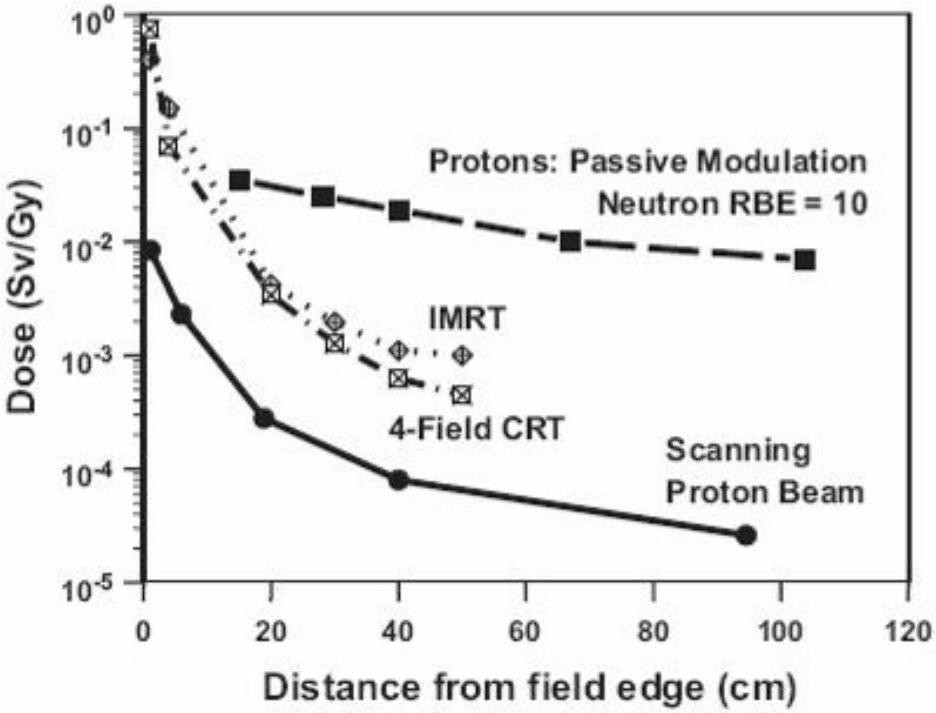


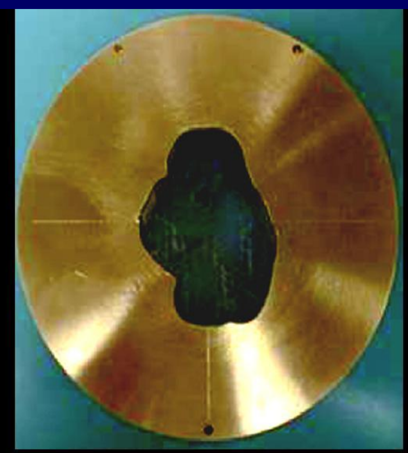
http://radmed.web.psi.ch/asm/gantry/scan/n_scattering.html

There are several disadvantages using scattered beams:

- Neutrons are produced by the scatterers and apertures.
- The scatterers reduce the proton energy (and maximum range).
- The compensator can conform the dose to the target in either the distal or proximal side but not both.
- Apertures and compensators must be machined and QA'ed for each field.
- Penumbra can be poor if aperture is not close to patient.

IMRT, protons, and the risk of second cancers
EJ Hall, Red Journal 65.





MGH aperture and compensator

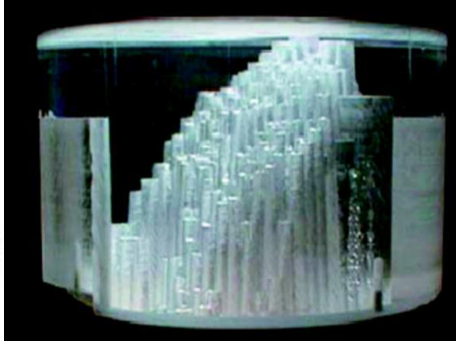
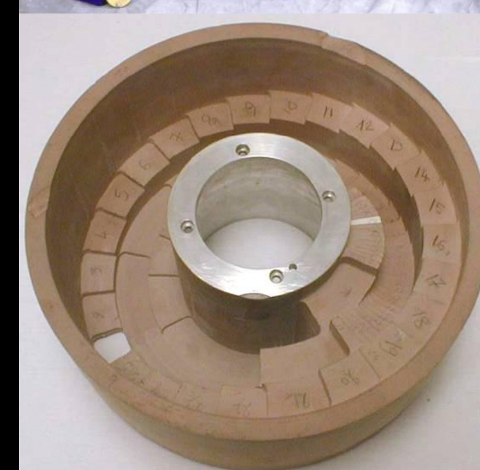


Image courtesy LLUMC



IBA modulator wheel

Alternatives to scattered beams:

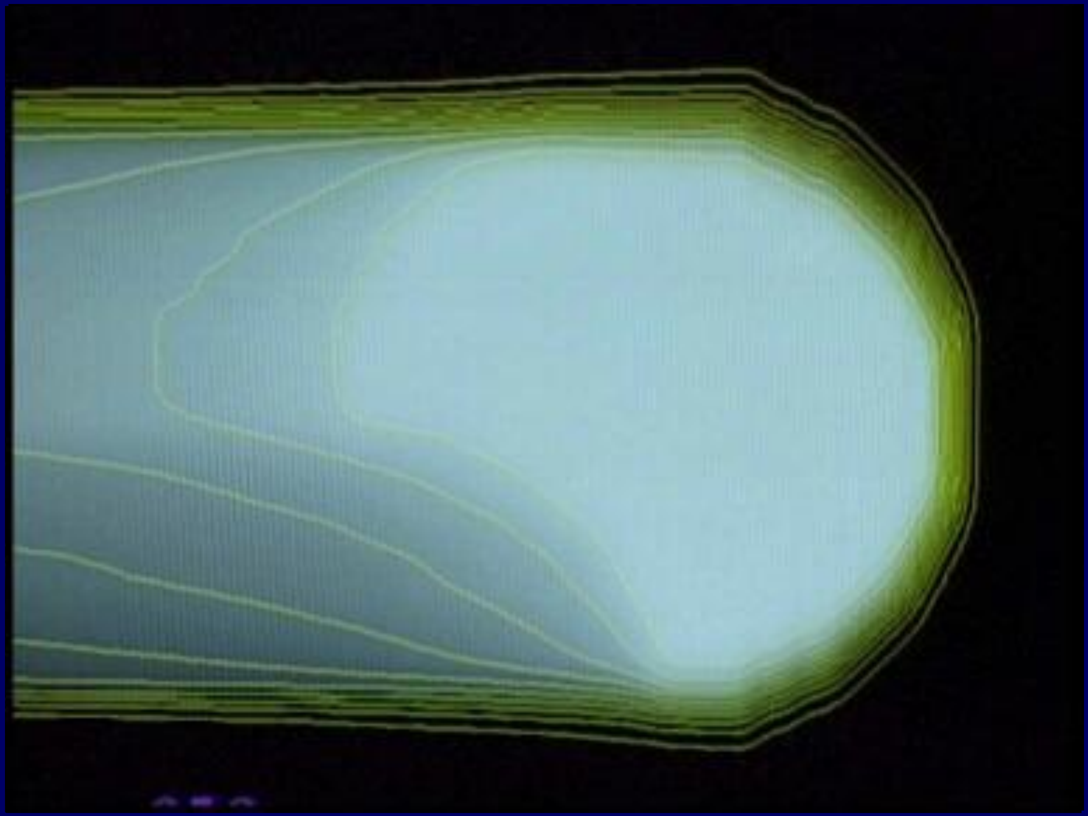
• Uniform Scanning (formerly known as wobbling) uses magnets to steer a large (~5 cm) spot across the field instead of using a second scatterer. Aperture and compensator are still needed. Penumbra is better than with scattered beam and neutron production is lower

• Modulated Scanning (sometimes called spot scanning or pencil beam scanning) uses magnets to steer a small (<1cm) beam using a step-and-shoot approach. No scatterers, modulator wheels, compensators, or apertures are required.

• Raster Scanning is a version of modulated scanning that uses magnets to steer a small (<1cm) beam by continuously sweeping the beam. Again no scatterers, modulator wheels, compensators, or apertures are required. It should be faster than the step-and-shoot approach.

Spot scanning - The principle

The dynamic application of scanned and modulated proton pencil beams



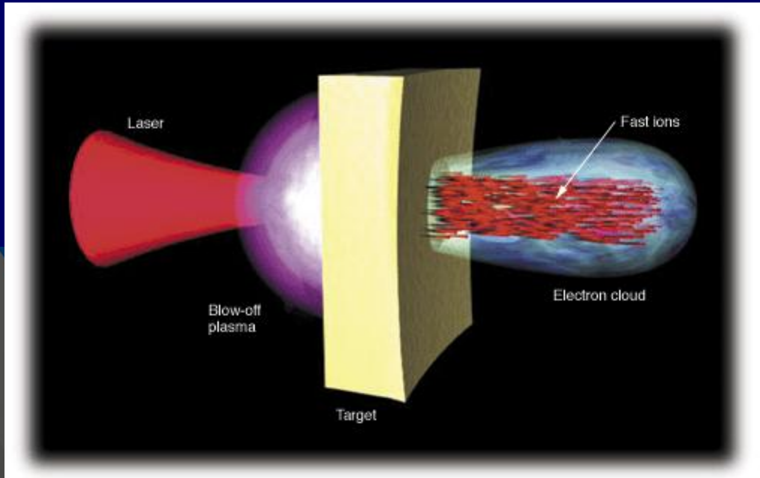
A full set, with a homogenous dose conformed distally *and* proximally

Images courtesy of E Pedroni and T Lomax, PSI

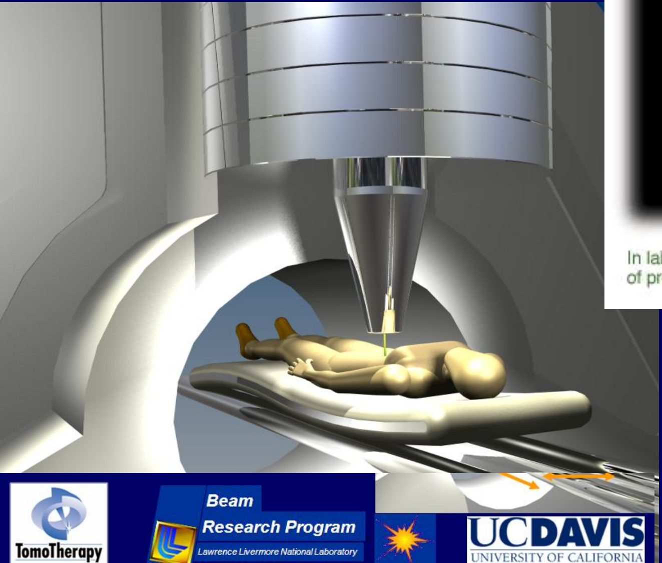
Non-Traditional Proton Therapy

There are plans to develop single room facilities with limited options to reduce costs. Three are:

- **Superconducting synchro-cyclotron mounted in the gantry**
- **Dielectric wall accelerator**
- **Laser acceleration of protons**



In laboratory experiments, the Petawatt laser's tremendous power produced intense beams of protons, proving the laser to be a powerful ion accelerator.



Calibration Protocols

In 1995, thirteen institutions participated in a proton dosimetry intercomparison (Vatnitsky, et al; Radiotherapy and Oncology 41 (1996) 169-177). At that time calibrations were performed using calorimeters, Faraday cup dosimeters, or by following one of two protocols {AAPM TG-20 1986 or ECHED 1991, 1994} **using ion chambers calibrated in a Co-60 beam.**

The results indicated agreement to within 3% of the mean for the Co-60 based calibrations.

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In 1999, another intercomparison was done; this time based on the 1998 ICRU-59 protocol (also Co-60 based) .

Those results indicated a maximum difference of 2.9%.

Calibration Protocols (con't)

In 2000, the IAEA published TRS-398 "Absorbed Dose Determination in External Beam Radiotherapy: An International Code of Practice for Dosimetry based on Standards of Absorbed Dose to Water".

The proton component of this protocol was similar to ICRU-59 but differed in some key areas such as the water-to-air stopping power ratio and the energy deposition required to produce an ion pair.

In 2007, ICRU-78 "Prescribing, Recording, and Reporting Proton-Beam Therapy" recommended that the protocol in IAEA TRS-398 be used for proton calibration.

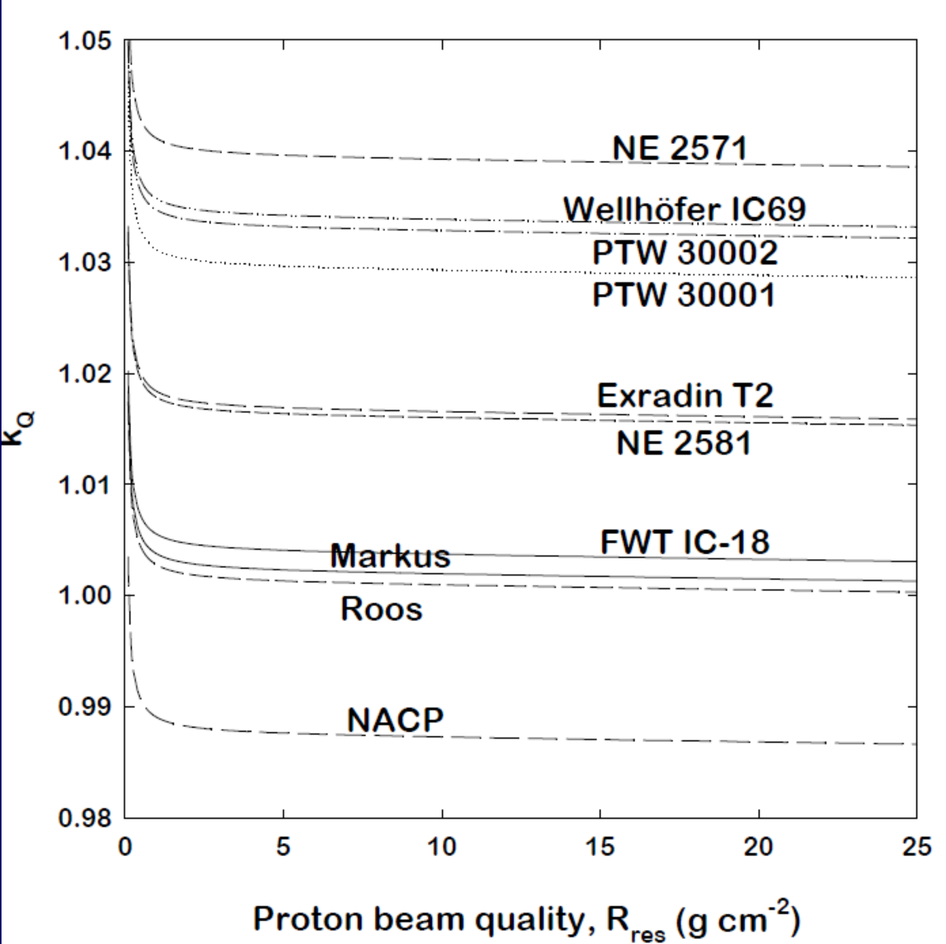
Comparing ICRU-59 & TRS-398

	ICRU-59	TRS-398
Phantom	Water or plastic	Water
Calibration coefficient	N_K or N_X or $N_{D,w}$	$N_{D,w}$
Stopping Powers	ICRU	PETRA Monte Carlo
$(w_{air})_{proton}$ (J/C)	34.8 +- 0.7	34.23 +- 0.13
$(w_{air})_{cobalt}$ (J/C)	33.77 +- 0.05	33.97 +- 0.07
Chamber	Cylindrical	Cylindrical and pp
Relative uncertainty (1 sigma)	2.6%	2.0% (cylindrical) 2.3% (parallel-plate)

Formalism of TRS-398

$$D_{w,Q} = M_Q N_{D,w,Q_o} k_{Q,Q_o}$$

$$k_{Q,Q_o} = \frac{\left(s_{w,air}\right)_Q}{\left(s_{w,air}\right)_{Q_o}} \frac{\left(W_{air}\right)_Q}{\left(W_{air}\right)_{Q_o}} \frac{p_Q}{p_{Q_o}}$$



Uncertainties in TRS-398

TABLE 10.IV. ESTIMATED RELATIVE STANDARD UNCERTAINTY [a] OF $D_{w,Q}$ AT THE REFERENCE DEPTH IN WATER AND FOR A CLINICAL PROTON BEAM, BASED ON A CHAMBER CALIBRATION IN ^{60}Co GAMMA RADIATION

Physical quantity or procedure	Relative standard uncertainty (%)	
User chamber type:	cylindrical	plane-parallel
Step 1: Standards Laboratory	*SSDL* [b]	*SSDL* [b]
$N_{D,w}$ calibration of secondary standard at PSDL	0.5	0.5
Long term stability of secondary standard	0.1	0.1
$N_{D,w}$ calibration of the user dosimeter at the standards laboratory	0.4	0.4
Combined uncertainty in Step 1	*0.6*	*0.6*
Step 2: User proton beam		
Long-term stability of user dosimeter	0.3	0.4
Establishment of reference conditions	0.4	0.4
Dosimeter reading M_Q relative to beam monitor	0.6	0.6
Correction for influence quantities k_i	0.4	0.5
Beam quality correction, k_Q	1.7	2.0
Combined uncertainty in Step 2	*1.9*	*2.2*
Combined standard uncertainty in $D_{w,Q}$ (Steps 1 + 2)	**2.0**	**2.3**

[a] See ISO Guide to the expression of uncertainty [32] or Appendix D. The estimates given in the table should be considered typical values; these may vary depending on the uncertainty quoted by standards laboratories for calibration factors and on the experimental uncertainty at the user's institution.

[b] If the calibration of the user dosimeter is performed at a PSDL then the combined standard uncertainty in Step 1 is lower. The combined standard uncertainty in D_w should be adjusted accordingly.

Concluding remarks

Penn Medicine

- Few patients are currently treated using proton beams but the number is growing rapidly & there is a great need for clinical trials to determine which disease sites are best treated with proton beams.

- The dosimetry is in very good shape but there are many new delivery systems & methods that will present new challenges.