Dosimetry aspects of proton radiotherapy

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Content

- Introduction
- Reference dosimetry for proton beams
  Methods, detectors, protocols
- Dosimetry in non reference conditions for proton beams
  Methods, detectors
- Recommendations

about 25 treatment facilities are established

another 20 proton and light-ion centers are planned to be open in 5 years

Typical layout of charged-particle beam radiotherapy facility

Accelerator

Switchyard

Horizontal Beam delivery system

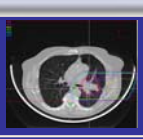
Gantry Beam delivery system

patient positioner

patient positioner

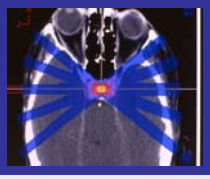
Main clinical applications for proton beams

treatment of large or deep seated tumours



treatment of ocular tumours

stereotactic radiosurgery (cross-fire technique)



Consistent and harmonized dosimetry guidelines

Accurate beam calibration

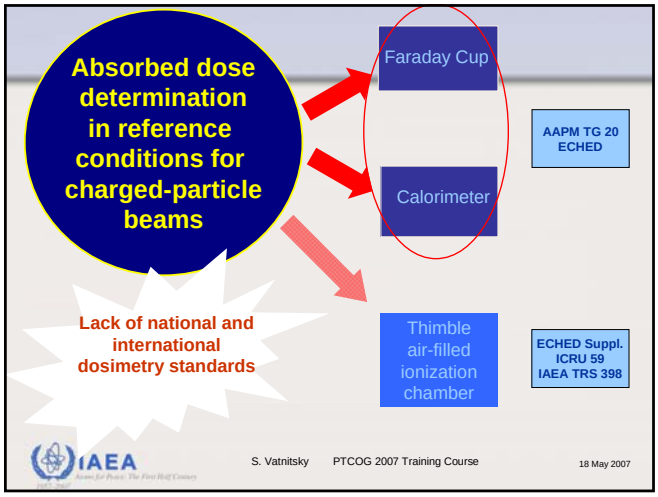
- Ensure exact delivery of prescribed dose
- Perform planning of high-precision conformal therapy
- Provide interchange of clinical experience and treatment protocols between facilities
- Provide standardization of dosimetry in radiobiology experiments

Dosimetry tasks in proton radiotherapy

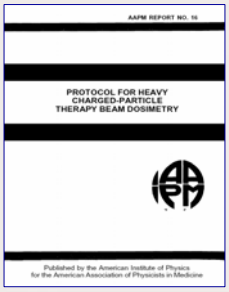
- **Acceptance testing and commissioning of treatment beam lines**
- **Commissioning of treatment planning system**
- **Periodic checks**
- **Verification of dose delivery**

Reference dosimetry

- **Basic output calibration of a clinical beam, is a direct determination of dose or dose rate in water under specific reference conditions, that is referred to as:**
  Reference dosimetry.
- **Reference dosimetry techniques for clinical proton beams:**
  - **Calorimetry**
  - **Faraday Cup**
  - **Ionization chamber dosimetry**



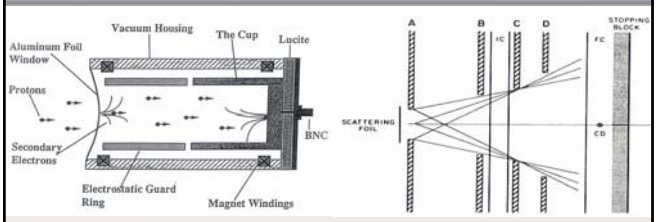
TG 20 Protocol for charged-particle therapy beam dosimetry



Reference instruments
- Faraday cup
- calorimeter

Ion chamber dosimetry
- A-150 walled with Nx calibration
- No beam quality specifier
- s/ρ for plateau and peak only

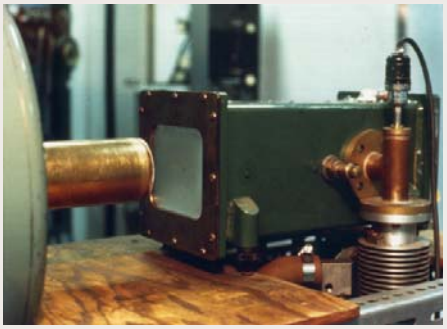
FC-based calibration of the ionization chamber



$D_w = (N/A)\,(S/\rho)_w * 1.602 \times 10^{-10}$

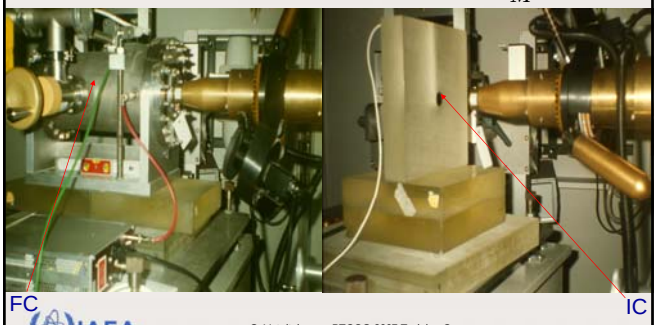
N : number of protons per MU collected in the FC
A : effective area of the beam
$(S/\rho)_w$: stopping power for water at the incident proton energy

FC-based calibration at HCL

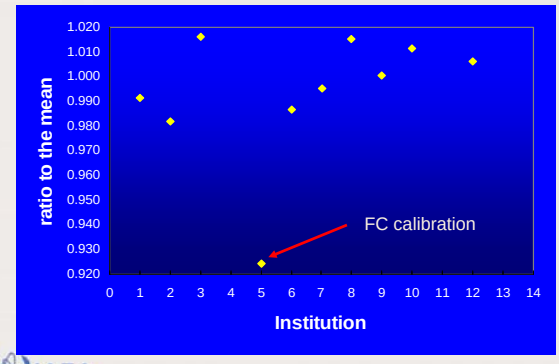


FC-based calibration of the ionization chamber at LLUMC

$$D_w(Q,FC) = \frac{N}{A} \times (S/\rho)_w \times 1.602 \times 10^{-10} \qquad N_{D,w,FC} = \frac{D_w(Q,FC)}{M^{corr}}$$



1995 PTCOG Dosimetry comparison Institution's statement of proton dose



Calorimetry-based calibration of the ionization chamber

- Calorimetry is the most fundamental of the three reference dosimetry techniques, since it relies on basic definition of either electrical energy or temperature.
  - In principle, calorimetric dosimetry is simple.
  - In practice, calorimetric dosimetry is very complex because of the need for measuring extremely small temperature differences.

Calorimetry-based calibration of the ionization chamber

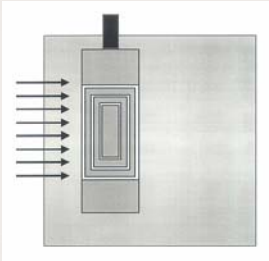
Main characteristics of calorimetry dosimetry:

- Energy imparted to matter by radiation causes an increase in temperature ΔT.
- Dose absorbed in the sensitive volume is proportional to ΔT.
- ΔT is measured with thermocouples or thermistors.
- Calorimetric dosimetry is the most precise of all absolute dosimetry techniques.

Calorimetry-based calibration of the ionization chamber

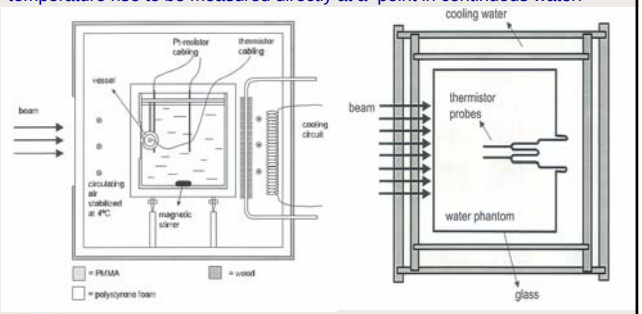
- Two types of absorbed dose calorimeter are used in charged particle beams:

In graphite calorimeters the average temperature rise is measured in a graphite body that is thermally insulated from surrounding bodies (jackets) by evacuated vacuum gaps.



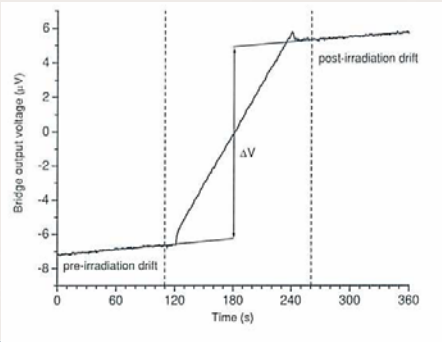
Calorimetry-based calibration of the ionization chamber

In sealed water calorimeters low thermal diffusivity of water enables the temperature rise to be measured directly at a point in continuous water.



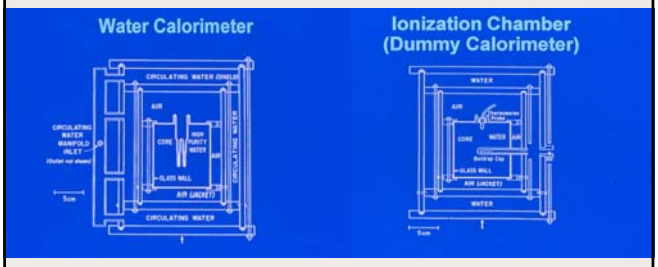
Calorimetry-based calibration of the ionization chamber

$$D_w(Q,cal) = c \times \Theta \times \Delta V \times (1 + D_T)$$

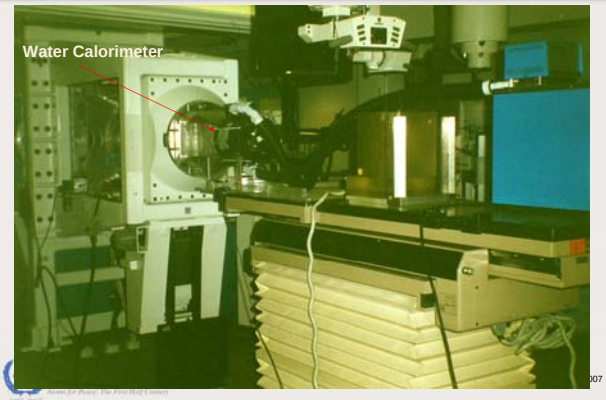


Calorimetry-based calibration of the ionization chamber

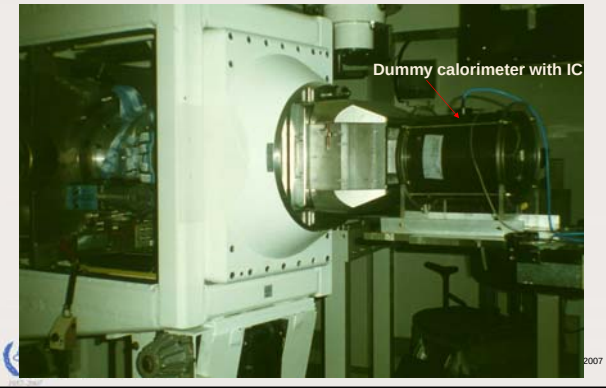
$$D_w(Q,cal) = c \times \Theta \times \Delta V \times (1 + D_T) \qquad N_{D,w,c} = \frac{D_w(Q,cal)}{M^{corr}}$$



Water calorimeter measurements in 250 MeV proton beam at LLUMC



Ionization chamber measurements (dummy calorimeter) in 250 MeV proton beam



Experimental calorimetry to ionometry ratios for clinical proton beams

	Energy, MeV	$D_{w,cal} / D_{w,ion}$	*CoP*
Schultz *et al*, 1990	160	0.99±0.01	TG 20
Vatnitsky & Siebers, 1994	180	0.978±0.005	ECHED
Palmans *et al*, 1996	85	0.974±0.009	ECHED
Delacroix *et al*, 1997	33-186	0.985±0.007	ECHED

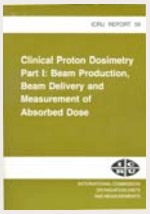
Absorbed dose determination in reference conditions for charged-particle beams

- Faraday Cup
- Calorimeter — AAPM TG 20, ECHED
- Thimble air-filled ionization chamber — ECHED Suppl., ICRU 59, IAEA TRS 398

Lack of national and international dosimetry standards

Ionisation chamber dosimetry protocol

- A dosimetry protocol provides the formalism and the data to relate a calibration of an ionization chamber at a standards laboratory to the measurement of absorbed dose to water under reference conditions in the clinical beam.
- Two types of dosimetry protocol are currently in use:
  - Protocols based on air kerma in air calibration coefficients.
  - Protocols based on absorbed dose to water calibration coefficients.



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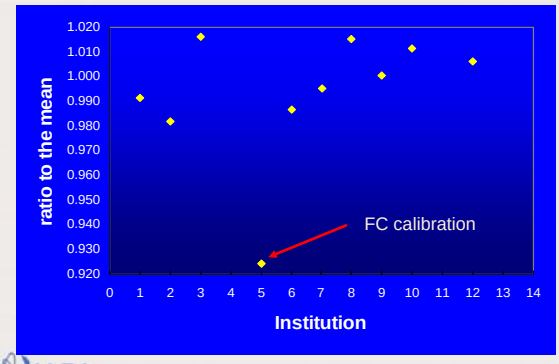
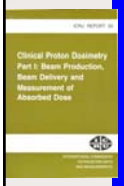
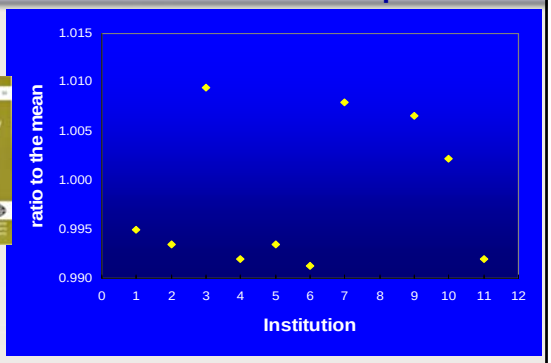


1999 PTCOG Dosimetry comparison ICRU 59 Institution's statement of proton dose





Ionisation chamber dosimetry protocol

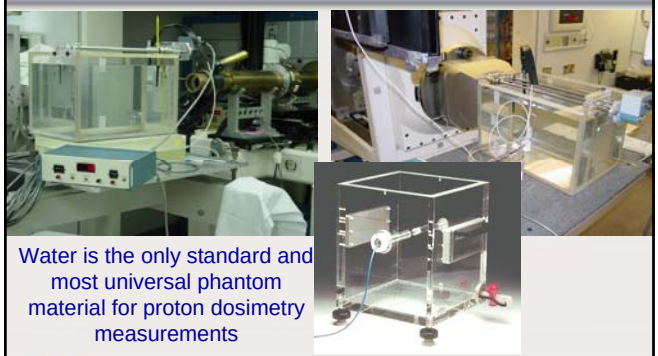
Dosimetry equipment

Ionization chambers

- Both cylindrical and plane-parallel chambers are recommended for reference dosimetry
- Plane-parallel chambers yield higher u_c in absolute D_w, though are better suited for relative dosimetry
- cylindrical chambers recommended for SOBP width≥2 cm
- For SOBP widths < 2 cm plane-parallel chambers must be used

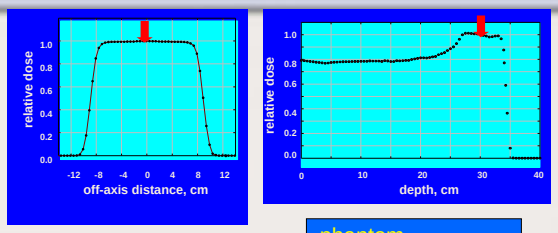
- Versatile electrometer with cable and connectors fitting to the electrometer and all chambers
- thermometer, barometer

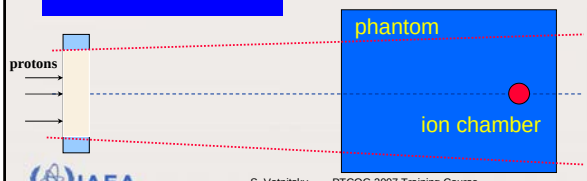
Water phantoms for reference dosimetry



Water is the only standard and most universal phantom material for proton dosimetry measurements

Reference geometry for proton beam calibration (passive beam modulation)





Basic formalisms used in ion chamber dosimetry of clinical proton beams

Air kerma – based

Absorbed dose to water– based

Air filled ionization chamber is considered as a Bragg-Gray cavity
Contributions to ionization by charged particles other than protons is neglected

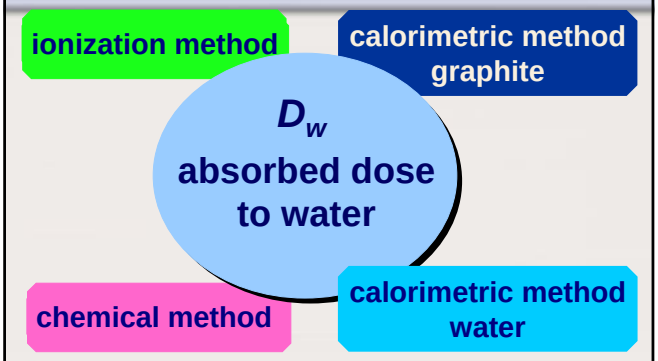
$$D_{w,p} = M_p^{corr} \cdot N_{D,g} \cdot C_p$$

$$C_p = (s_{w,air})_p \frac{(w_{air})_p}{(W_{air})_c}$$

$$D_{w,Q} = M_Q \cdot N_{D,w,Q_0} \cdot k_{QQ_0}$$

$$k_{QQ_0} = \frac{(s_{w,air})_Q \cdot (w_{air})_Q \cdot p_Q}{(s_{w,air})_{Q_0} \cdot (w_{air})_{Q_0} \cdot p_{Q_0}}$$

A robust system of D_w standards



Steps in the determination of D_w at the reference point using N_K-$N_{D,air}$ formalism and $N_{D,w}$-formalism

(1)	K_{air,Q_o}	D_{w,Q_o}
(2)	$N_{K,Q_o} = \dfrac{K_{air,Qo}}{M_{Q_o}}$	$N_{D,w,Q_o} = \dfrac{D_{w,Q_o}}{M_{Q_o}}$
(3)	$N_{D,air,Q_o} = \dfrac{\overline{D}_{air,Q_o}}{M_{Q_o}} = N_{K,Q_o}(1-g)k_{att}\,k_m\,k_{cel}$	
(4)	$N_{D,air,Q} = N_{D,air,Q_o}$	
(5)	$D_{w,Q} = \overline{D}_{air,Q}(s_{w,air})_Q\,p_Q$	
(6)	$D_{w,Q} = M_Q\,N_{D,air}\,(s_{w,air})_Q\,p_Q$	$D_{w,Q} = M_Q\,N_{D,w,Q_o}\,k_Q$

$N_{D,w}$ - based formalism - IAEA TRS-398

$D_w(z_{ref})$ at <u>any</u> user quality Q
(photons, electrons, protons, heavier particles)

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

corrected instrument reading at Q — *calibration coefficient at Q_o* — *beam quality factor*

Lack of standards for proton dosimetry => Q_o = ^{60}Co

$$k_Q = \frac{(s_{w,air})_Q}{(s_{w,air})_{^{60}Co}}\,\frac{(W_{air})_Q}{(W_{air})_{^{60}Co}}\,\frac{p_Q}{p_{^{60}Co}}$$

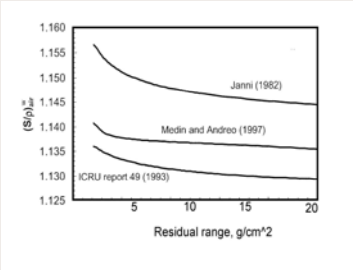
$$p_Q = p_{dis}\,p_{wall}\,p_{cav}\,p_{cel}$$

≈ 1 for protons

≠ 1 for ^{60}Co

Tabulated values of proton beam quality correction factors for various ionization chambers are given in TRS 398

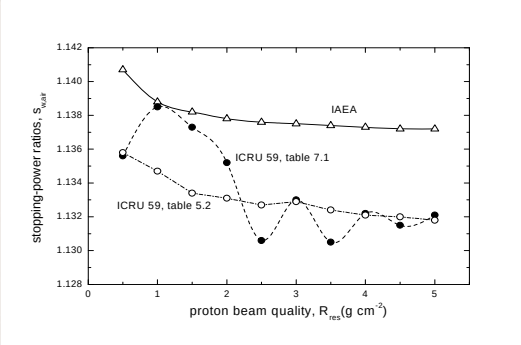
Stopping powers for for proton beams



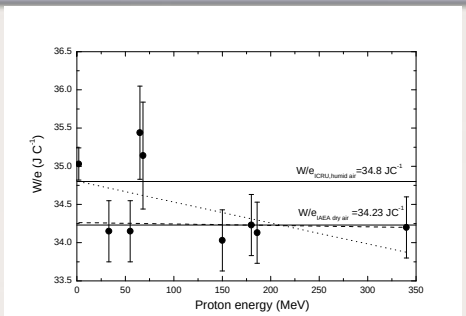
TRS 398

- **Basic proton stopping powers from ICRU 49**
- **Calculation using MC code PETRA following Spencer-Attix cavity theory**
- **Transport included secondary electrons and nuclear inelastic process**

Comparison of stopping power ratios, $s_{w,air}$, for proton dosimetry: ICRU-59 *versus* IAEA TRS-398



Comparison of W_{air}/e for proton beam dosimetry: ICRU-59 *versus* IAEA TRS-398

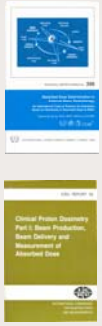


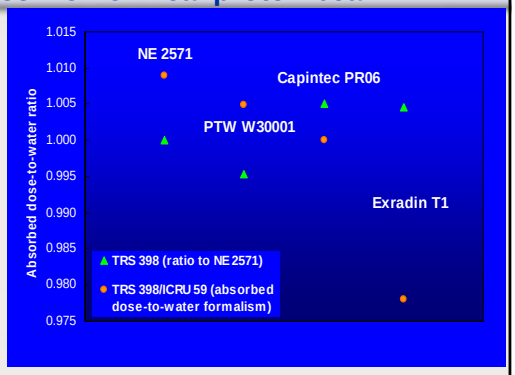
W_{air}/e for ^{60}Co: IAEA 33.97 JC^{-1} (dry air) ICRU 33.77 JC^{-1} (humid air)

Standard uncertainties in D_w

$u(N_{D,w}^{SSDL}) = 0.6$	SSDL k_Q calc
Co-60 gamma-rays	0.9
High-energy photons	1.5
High-energy electrons	1.4-2.1
Low energy X-rays	2.2-4.0
Medium energy X-rays	1.9-3.4
Proton beams	2.0-2.3
Heavy ions	3.0

Comparison results from measurements in a 155 MeV clinical proton beam





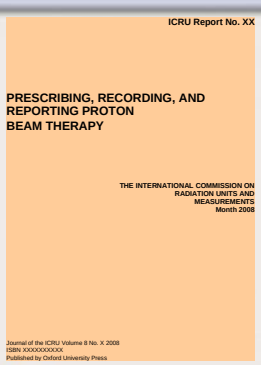
Main features of current CoPs for dosimetry of clinical proton beams

	ICRU 59	TRS 398
Particle type	Protons	Protons, ions
Phantom material	water	water
Reference dosimeter	IC thimble	IC thimble or pp
Calibration quality	Co-60 beam	Co-60 beam
IC calibration Factor	N_X ,N_K , $N_{D,w}$	$N_{D,w}$

Main features of current CoPs for dosimetry of clinical proton beams

	ICRU 59	TRS 398
IC wall material	No restriction	No restriction
Energy specifier	Effective energy	Residual range
Stopping powers	ICRU 49	ICRU 49 based
W_{air}	34.8±2%	34.2±0.4%(p) 34.5±1.5%(i)
$U(D_w)$, 1 σ	2.8%	2.0%(p) 3.0%(i)

New ICRU Report on proton therapy (2007)


ICRU Report No. XX

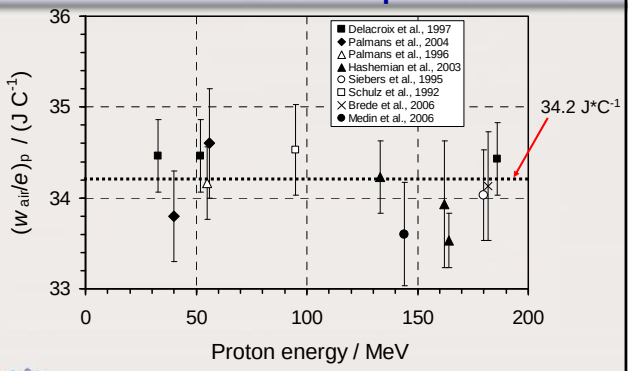
PRESCRIBING, RECORDING, AND REPORTING PROTON BEAM THERAPY

THE INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS
Month 2008

Journal of the ICRU Volume 8 No. X 2008
ISBN XXXXXXXXXX
Published by Oxford University Press

- Recommendations and guidelines of IAEA TRS 398
- **$(w_{air})_p$** and **(S/ρ)w,air** are established as in TRS 398
- Additional recommendations for scanned beams

$(w_{air}/e)_p$ as determined from calorimetry measurements in clinical proton beams



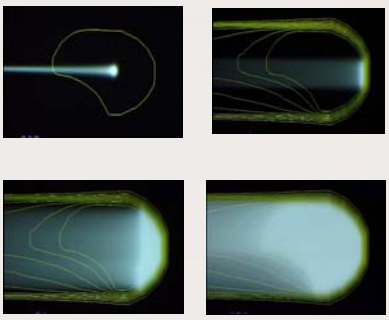
A calibration procedure for beam monitors in a scanned beam of heavy charged particles

O. Jäkel,[a] G. H. Hartmann, C. P. Karger, and P. Heeg
Deutsches Krebsforschungszentrum Heidelberg, Division for Medical Physics (E040), Heidelberg, Germany
S. Vatnitsky
International Atomic Energy Agency, Division of Human Health, Dosimetry and Medical Radiation Physics Section, Vienna, Austria

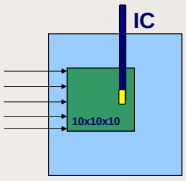
1009 Med. Phys. 31 (5), May 2004

- TRS-398 needs to be extended by explicit recommendations for the beam monitor calibration and dose verification in charged-particle beams.
- These recommendations should then distinguish systems using static and dynamic beams.
- This would ultimately lead to a dosimetry system, where the dose applied to a patient is traceable to the dosimetry standards of the national PSDL.

Reference dosimetry of spot scanning at PSI

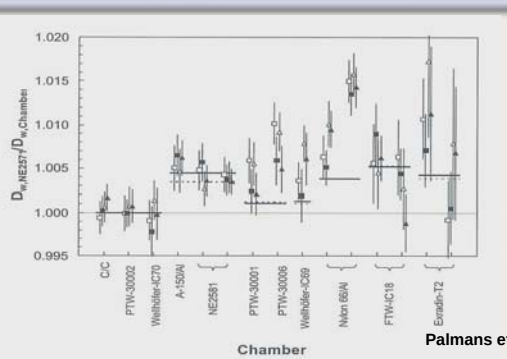


- dose model predicts IC the number of protons/Gy
- 10x10x10 cm box is filled in with homogeneous dose distribution to a dose of 1Gy

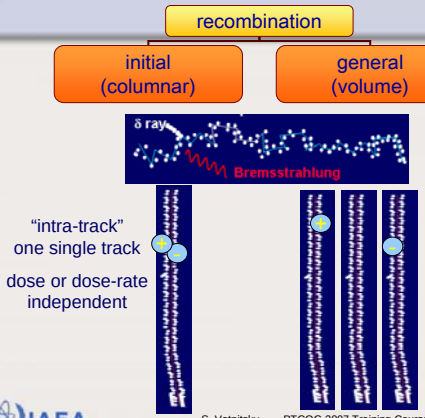


(Pedroni et al)

Perturbation factors



Palmans et al.



Courtesy of P. Andreo

Guidelines for absorbed dose determination in reference conditions for charge -particle beams

- Large and small fields: high-energy proton and ion beams
- Small fields: low energy proton beams
- Narrow beams for stereotactic radiosurgery: Cross-fire technique

Dosimetry in non-reference conditions

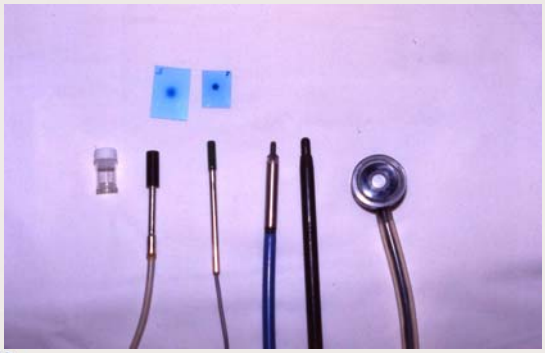
Relative dose measurements require no detector calibration other than verification of linearity of response within assumed dynamic range of measurement conditions

- Routine daily clinical physics activity
- Beam line commissioning
- Collecting data for TPS
- Periodic QA

Beam characteristics

✓ Depth dose
✓ Lateral profiles
✓ Output factors

Detectors for measurements in non reference conditions in clinical proton beams



Plastic phantoms

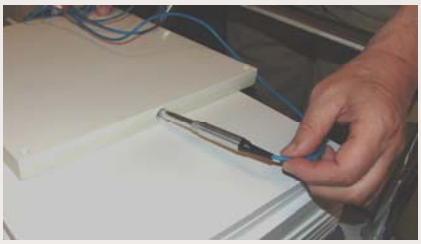
For ionometric and film measurements a polystyrene or water equivalent plastic phantom is convenient.

Plastic phantoms for ionization chambers

A second block should be machined to place the entrance window of a parallel plate chamber at the level of one surface of the block. This arrangement allows measurements with the parallel plate chamber with no material between the window and the radiation beam.

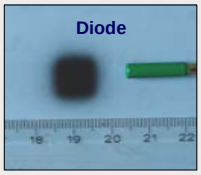
Plastic phantoms for ionization chambers

One block should be drilled to accommodate an ionization chamber with the center of the hole, 1 cm from one surface.



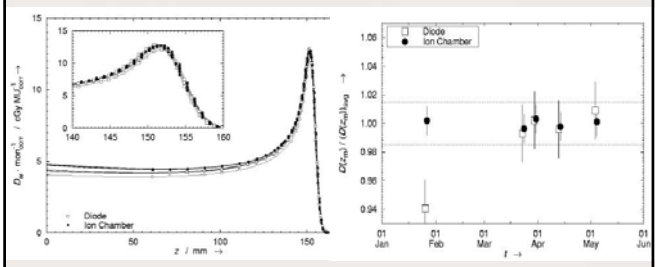
Diodes for characterization of small proton beams

- Because of their small size silicon diodes are convenient for profile measurements and characterization of small proton beams.



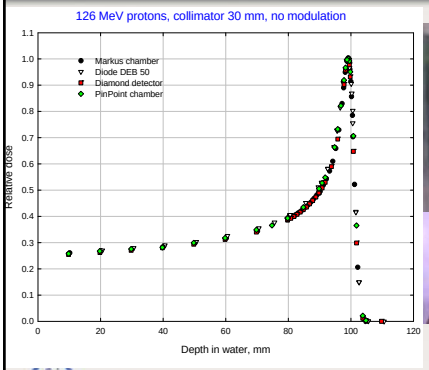
- Note:
  The response of diodes must always be checked against ionometric measurements before use.

Diodes for characterization of proton beams

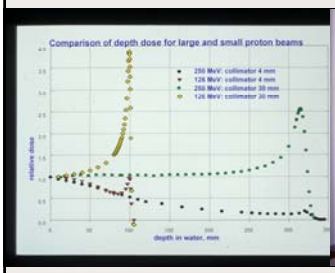


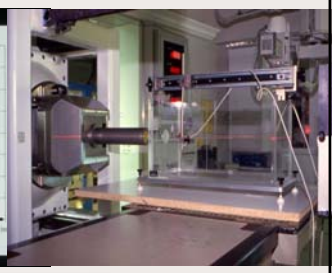
Newhauser et al, 2003

Characterization of small proton beams

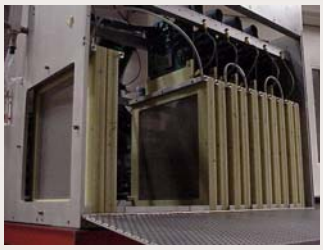


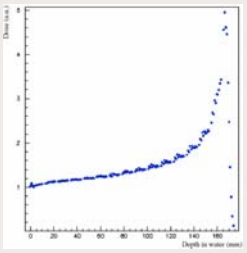
Characterization of small proton beams



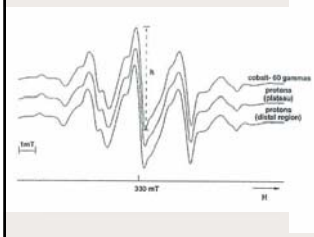


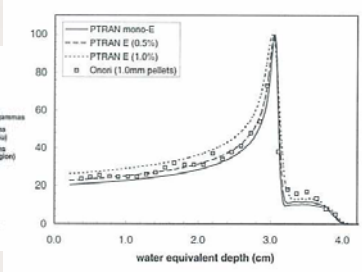
Magic Cube: multi-wire ionization chamber





Alanine ESR dosimetry

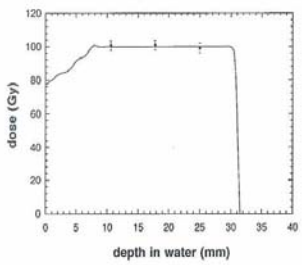




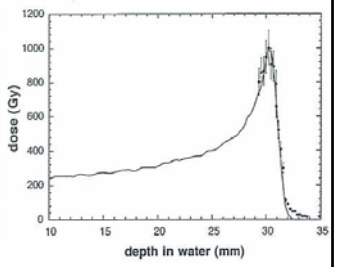
Onori et al, 2000

Alanine ESR dosimetry

pellets

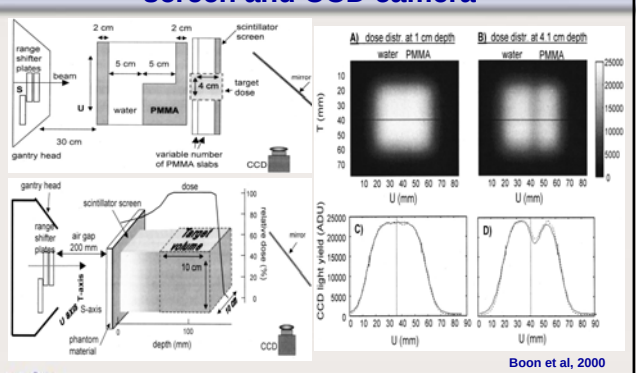


films



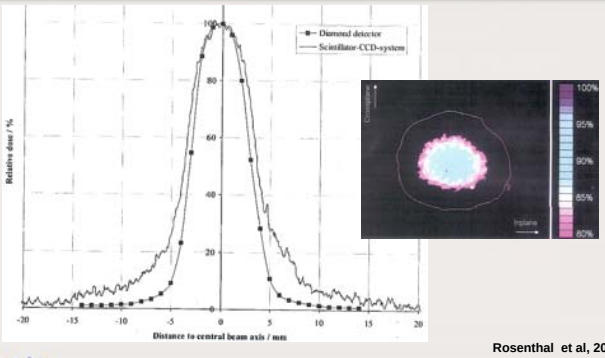
Onori et al, 2000

Two dimensional dosimetry with fluorescent screen and CCD camera



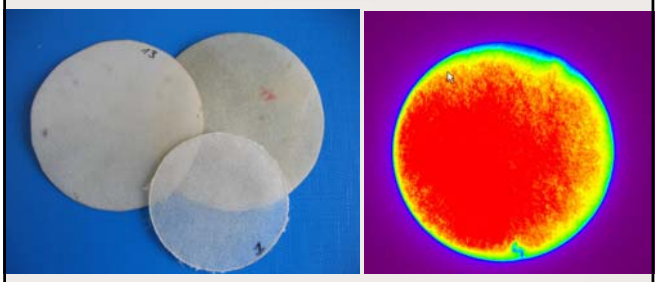
Boon et al, 2000

Two dimensional dosimetry with fluorescent screen and CCD camera



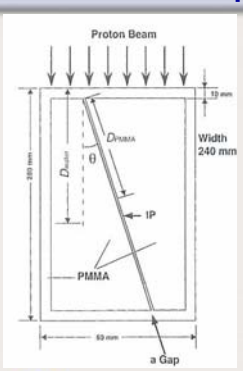
Rosenthal et al, 2004

2D TLD film for characterization of proton beams

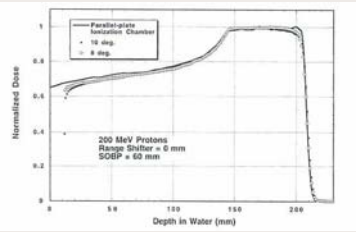


Olko et al, 2004

Imaging plate for depth dose measurements in proton beams



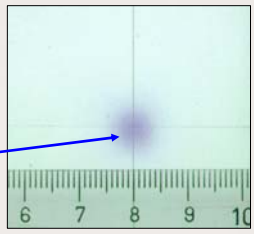
IP utilizes a photostimulable phosphor of BaFBr:Eu^{2+} and latent images are created by proton beam
Latent images are scanned by stimulating laser beam and are read as PSL



Nohotomi et al, 2003

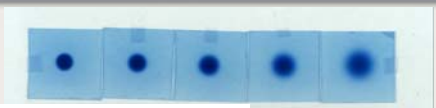
Radiochromic film for characterization of clinical proton beams

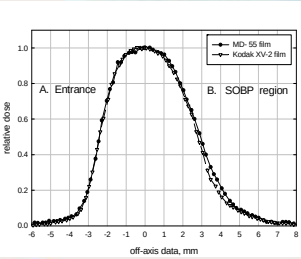
radiochromic film is **self-developing**, requiring neither developer nor fixer

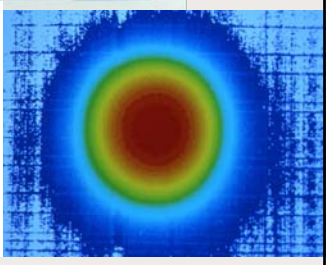


Principle:
Radiochromic film contains a special dye that is polymerized and develops a blue color upon exposure to radiation.

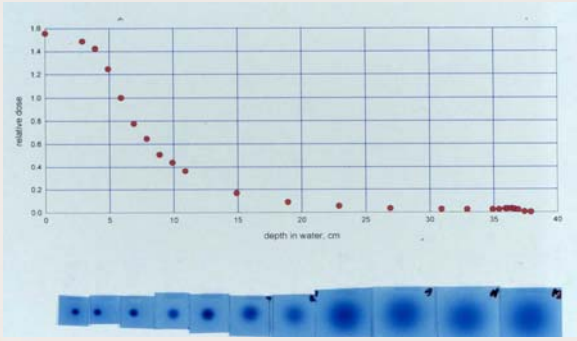
Radiochromic film for characterization of clinical proton beams



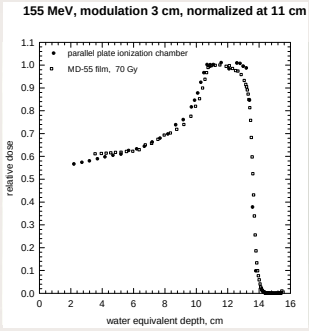




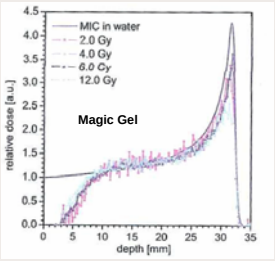
Measured depth dose for 250 MeV proton beam with ∅ 2.5 mm

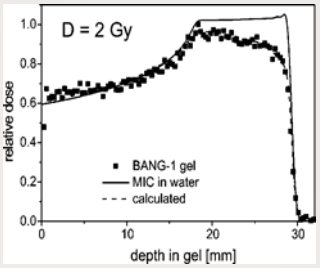


Radiochromic film dosimetry of proton beams



3D Gel dosimetry for characterization of proton beams





Heufelder et al, 2003

Current status of charged-particle dosimetry:

Implementation of IAEA TRS 398 and new ICRU Report

→ harmonize clinical dosimetry at charged-particle beam facilities

→ provide a level of accuracy comparable to that in calibration of photon and electron beams

Current status of charged-particle dosimetry:

Protons and ions: passive range modulation → TRS 398 (center of SOBP)

Protons and ions: active range modulation → TRS 398 (plateau region)

Protons and ions radiosurgery (narrow beams) → Special methods (MC)

Take home message

Reference dosimetry

- TRS 398
- ICRU xx 2007
- Ionization chamber
- Water phantom

Dosimetry in non-reference conditions

Depth dose

- small volume ion chamber
- other detectors can be used when the response was verified versus ion chamber
- Water or Plastic phantoms

Lateral profiles

- Diode, diamond, CCD, TLD, film etc.
- Water or Plastic phantoms