Instrumentation for Verification of Dose

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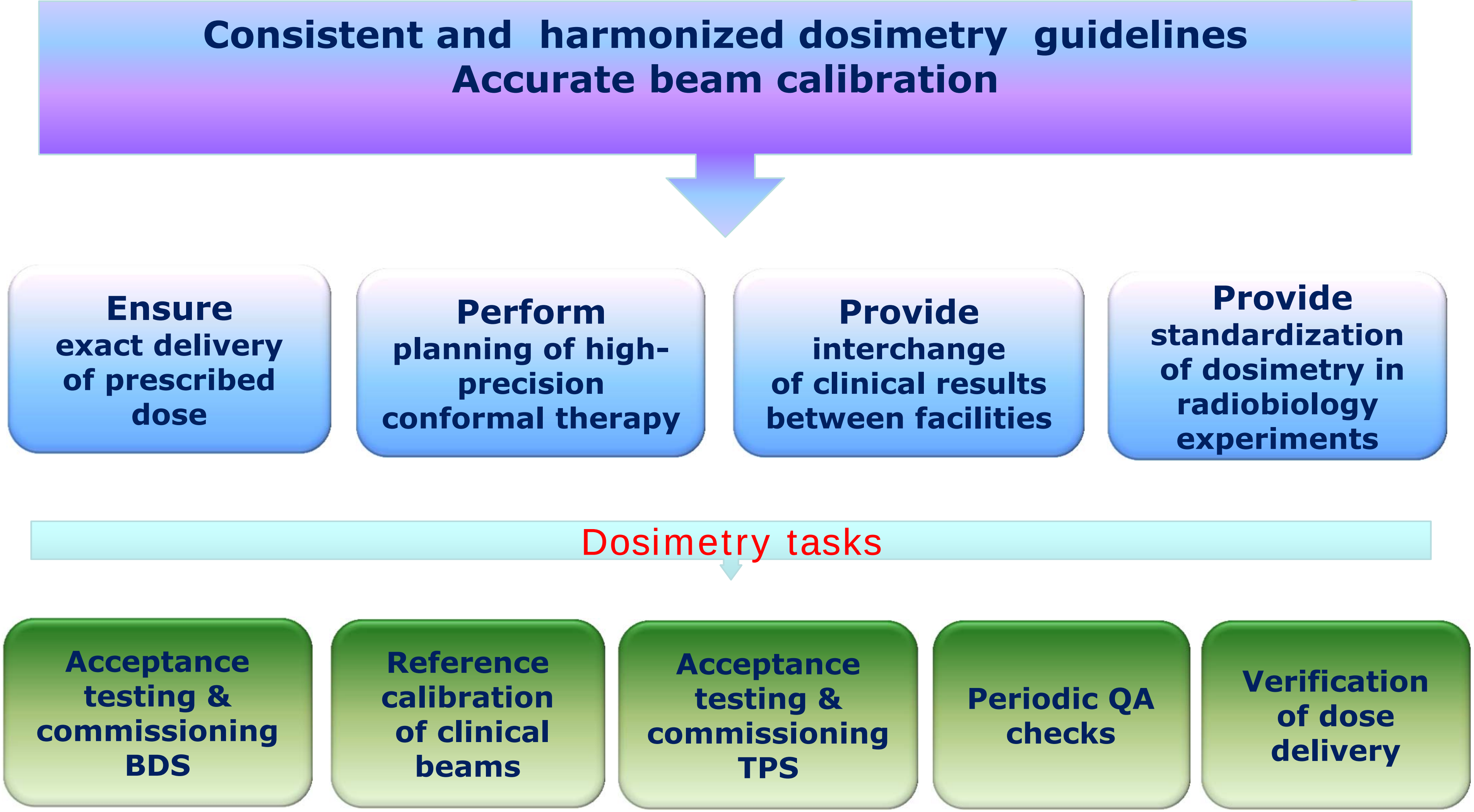
Presented to: Educational Workshop PTCOG 54
San Diego, USA, May 18-20, 2015



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 results between facilities
- **Provide** standardization of dosimetry in radiobiology experiments

Dosimetry tasks

- Acceptance testing & commissioning BDS
- Reference calibration of clinical beams
- Acceptance testing & commissioning TPS
- Periodic QA checks
- Verification of dose delivery

Absorbed dose determination in reference conditions for protons and heavier ion beams

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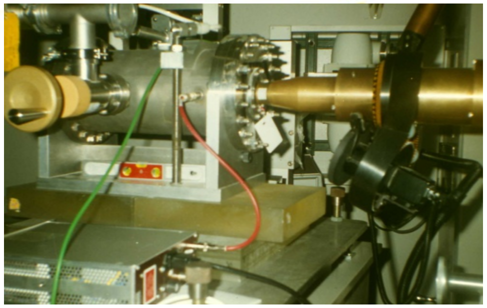
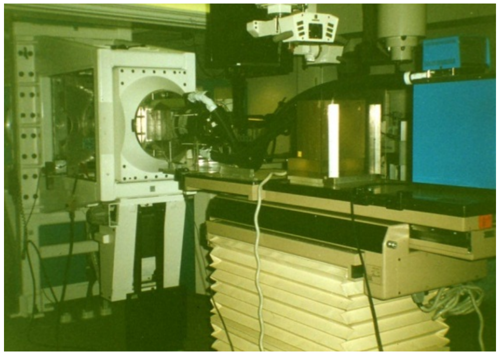
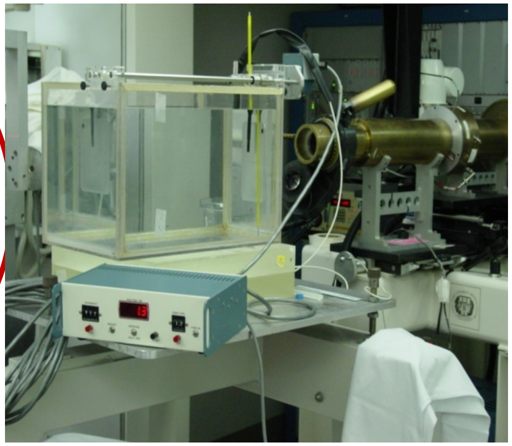
Faraday Cup



Calorimeter



Thimble air-filled ionization chamber



Lack of national and international dosimetry standards

Protocols/COP for proton and heavier ion beam dosimetry

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AAPM REPORT NO. 16

PROTOCOL FOR HEAVY
CHARGED-PARTICLE
THERAPY BEAM DOSIMETRY

Published by the American Institute of Physics
for the American Association of Physicists in Medicine

ICRU REPORT 59

Clinical Proton Dosimetry
Part I: Beam Production,
Beam Delivery and
Measurement of
Absorbed Dose

INTERNATIONAL COMMISSION
ON RADIATION UNITS
AND MEASUREMENTS

TECHNICAL REPORTS SERIES No.

Absorbed Dose Determinati
External Beam R diothe
A International Code of Pra ice for Dos
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Sponsored by th IAEA, WHO, PAHO and

INT NATIONAL ATOMIC ENERGY AGENCY, VIENNA

Volume 7 No 2 2007
ISSN 1473-6691

Journal of the ICRU

ICRU REPORT 78

Prescribing, Recording, and Reporting
Proton-Beam Therapy

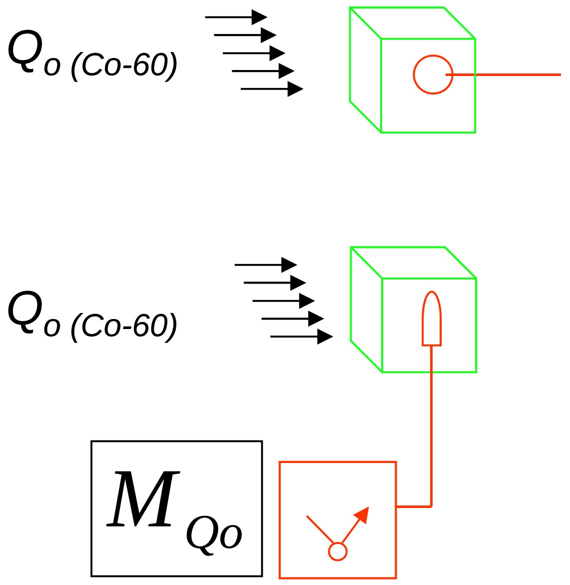
OXFORD JOURNALS
IAEA

OXFORD UNIVERSITY PRESS
INTERNATIONAL COMMISSION ON
RADIATION UNITS AND
MEASUREMENTS

Only a Protocol based on standards of absorbed dose to water is being recommended by ICRU/IAEA Reports for protons and heavier ions

Absorbed dose determination in reference conditions for light ion beams: **Step one**

At the standards laboratory ionization chamber is provided with a calibration factor in terms of the radiation quantity *S* in a beam of quality $Q_o : N_{S,Q_o}$



$\boxed{S}$

No national and international dosimetry standards for protons and heavier ions

$$N_{S,Q_o} = \frac{S}{M_{Q_o}} \quad \rightarrow \quad N_{D,w,Q_o}$$

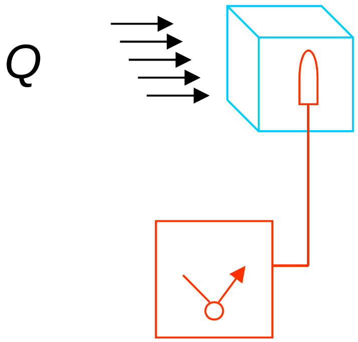
reference conditions: $P, T, h, \dot{S}, etc$

Q_o *(proton beam)*
calorimeter →

$$N_{D,w,p} = \frac{D_{w,p}(cal)}{M^{corr}}$$

Absorbed dose determination in reference conditions for light ion beams: **Step two**

The ionization chamber is then subsequently placed at a reference depth in water in the user's beam, of quality *Q*.



$$D_{w,Q} = M_Q \, N_{S,Q_o} \, f_{Q,Q_o}^{D,S}$$

M_Q	is the instrument reading in the user's beam, suitably corrected to the reference conditions for which N_{S,Q_o} is valid
$f_{Q,Q_o}^{D,S}$	is any ***overall*** factor necessary to convert both from the calibration quantity *S* to dose *D* and from the calibration quality Q_o to the user's quality *Q*

$N_{D,w}$ - based formalism: IAEA TRS-398/ICRU 78

$D_w(z_{ref})$ at any user quality Q (photons, electrons, protons, heavier ions)

TECHNICAL REPORTS SERIES No. 398

Absorbed Dose Determination in External Beam Radiotherapy

An International Code of Practice for Dosimetry Based on Standards of Absorbed Dose to Water

Sponsored by the IAEA, WHO, PAHO and ESTRO

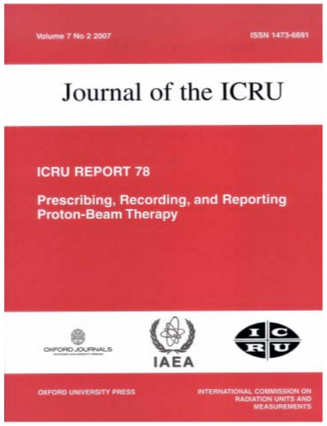
INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 2000

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

corrected instrument reading at Q

calibration coefficient at Q_o

beam quality correction factor



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IAEA

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INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS

Q_o (proton beam)
calorimeter

$$\longrightarrow \quad D_{w,Q} = M_Q \, N_{D,w,p} \, k_{Q,p}$$

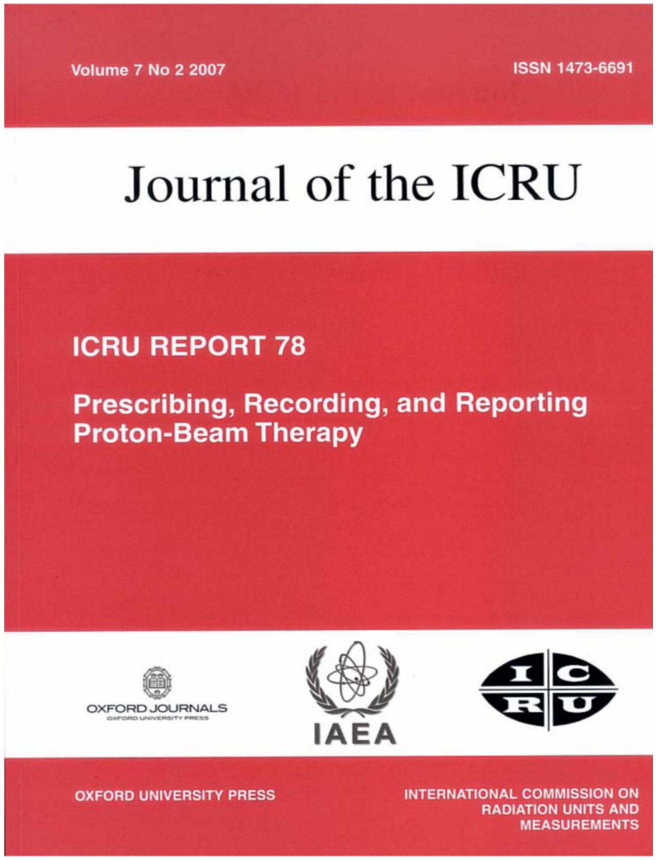
$N_{D,w}$ - based formalism: IAEA TRS-398/ICRU 78

=> Q_o = ^{60}Co

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

=> Q_o = proton beam

$$k_{Q,p} = \frac{\left(s_{w,air}\right)_Q}{\left(s_{w,air}\right)_p}$$



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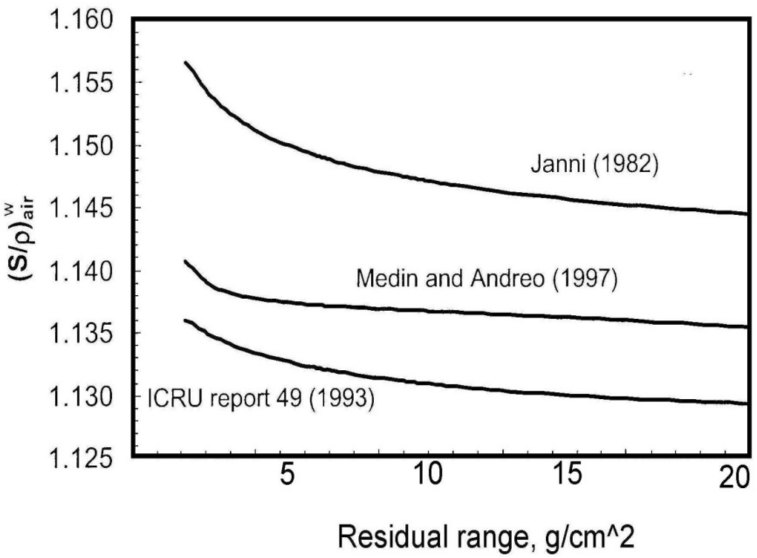
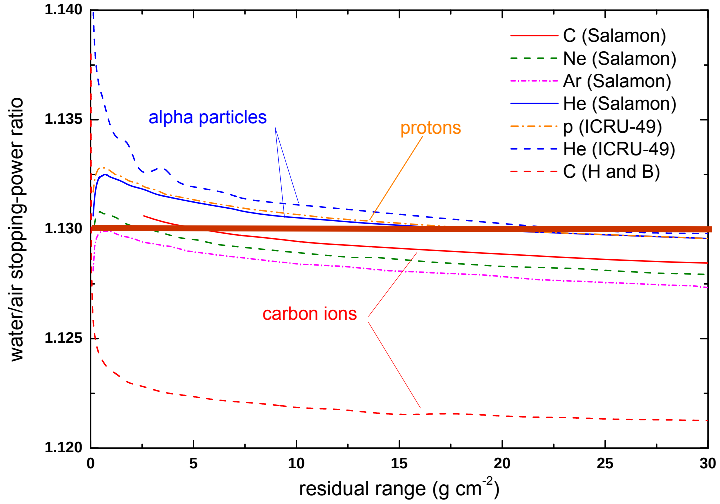
Stopping powers

Proton beams



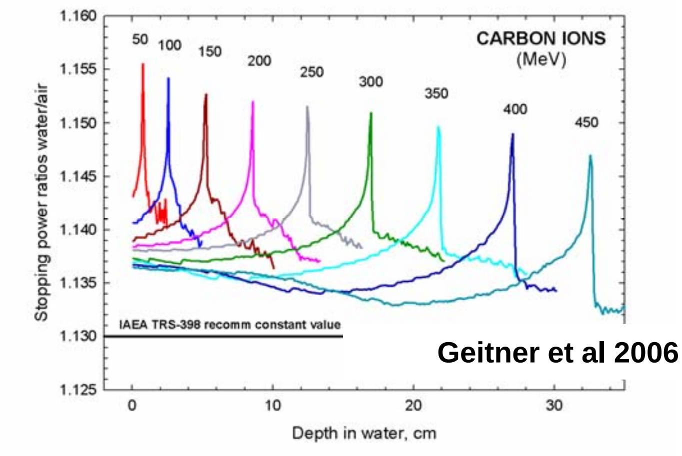
- **Basic proton stopping powers from ICRU 49**
- **Calculation using MC code PETRA following Spencer-Attix cavity theory**
- **Transport included secondary electrons and nuclear inelastic process**

Heavier ion beams



1.13

A constant value of $s_{w,air}$ = 1.13 adopted in TRS 398 (ignores fragments)



Geitner et al 2006

Calorimetry-based determination of *W*-values and comparison of calorimetry and ionometry

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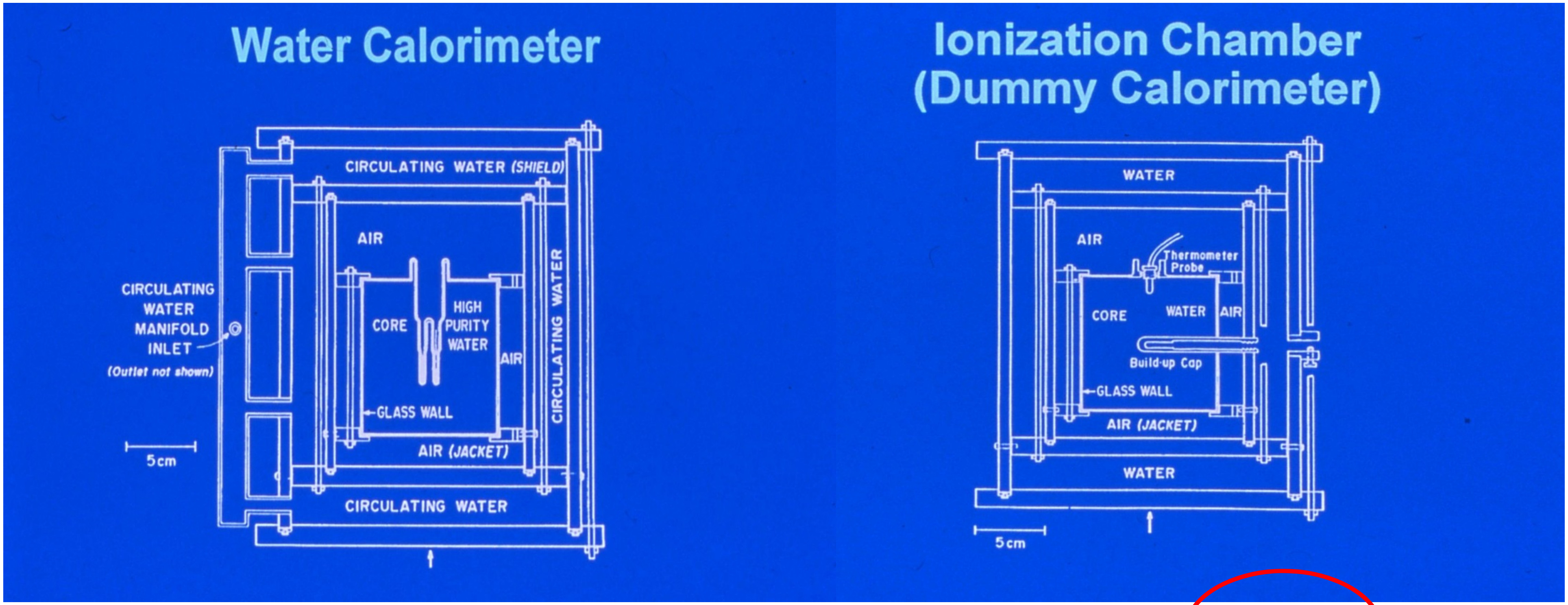
$$D_w(Q,cal) = c \times \Theta \times \Delta V \times (1 + D_T)$$



$$D_w(Q,cal) \qquad M^{cor} N_{D,w,{}^{60}Co} \frac{(S_{w,air})_Q}{(S_{w,air})_{{}^{60}Co}} \frac{(W_{air})_Q}{(W_{air})_{{}^{60}Co}} \frac{(p)_Q}{(p)_{{}^{60}Co}}$$

Transportable graphite calorimeters

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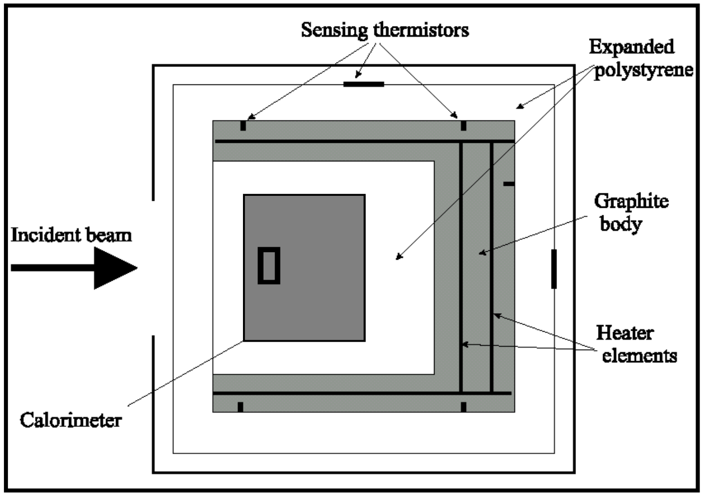
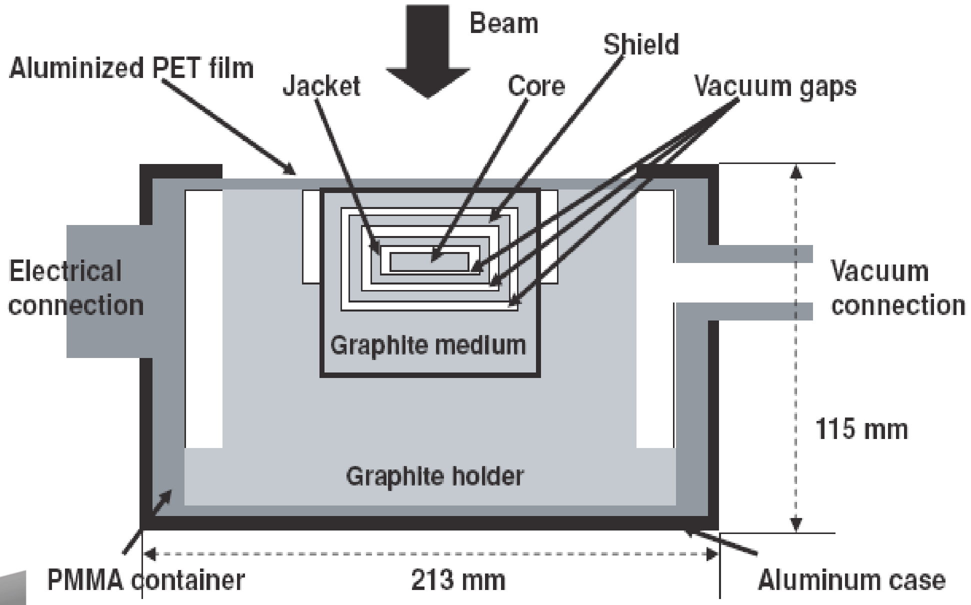
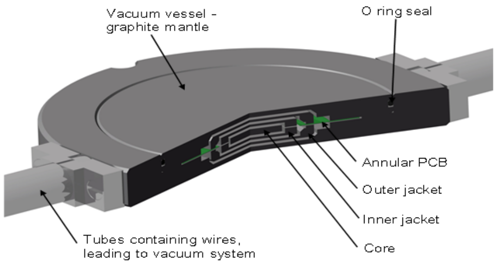
NPL protons at CCO (2004)



NIRS - carbon ions

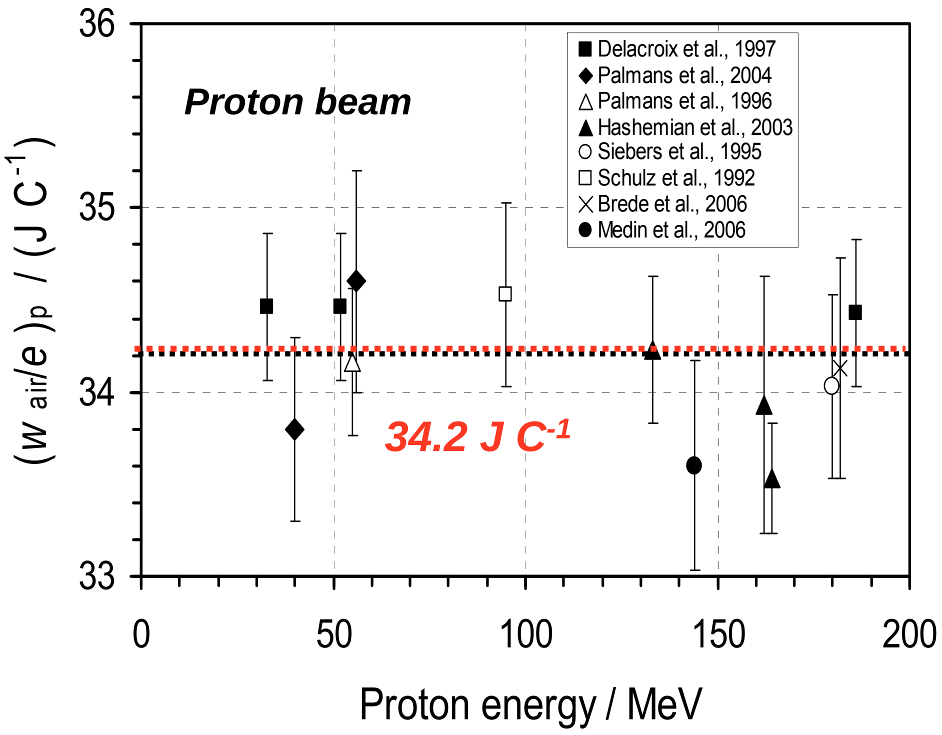


Sakama et al 2008

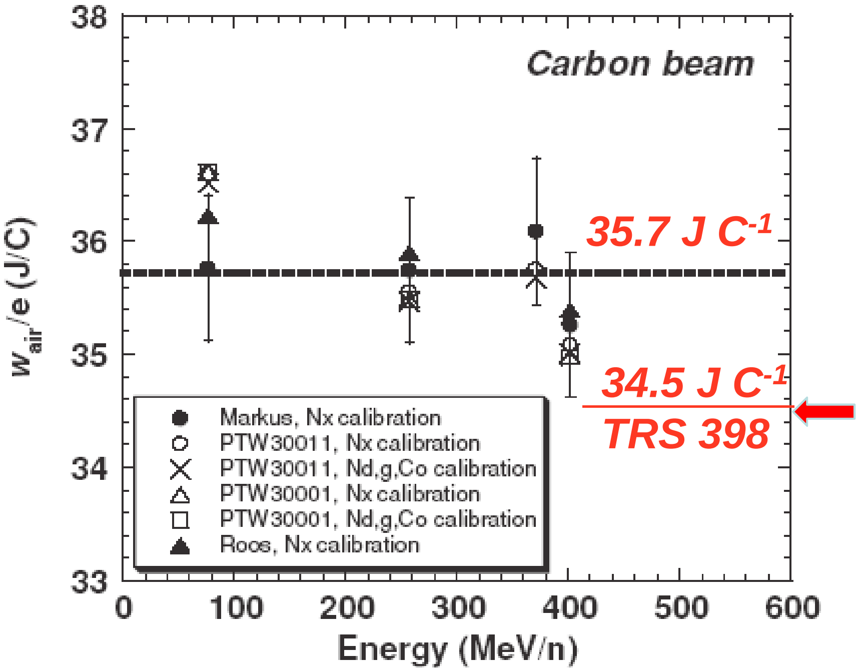


Palmans et al 2012

Values of *W*/*e* for protons and carbon ions deduced from comparison of IC and calorimeter measurements



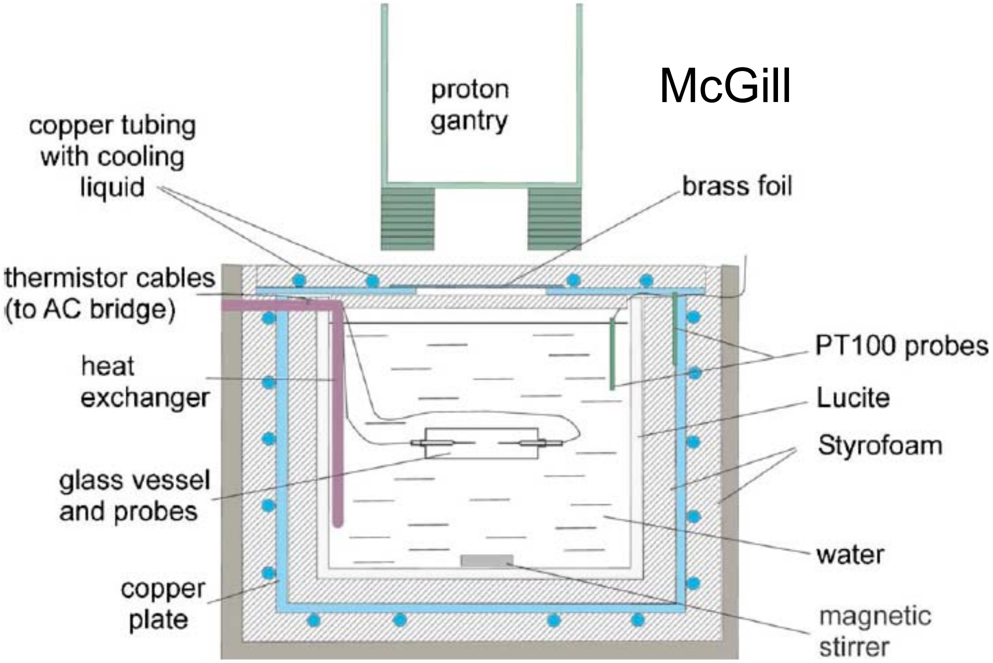
ICRU 78



Sakama et al 2008

Transportable water calorimeters

McGill



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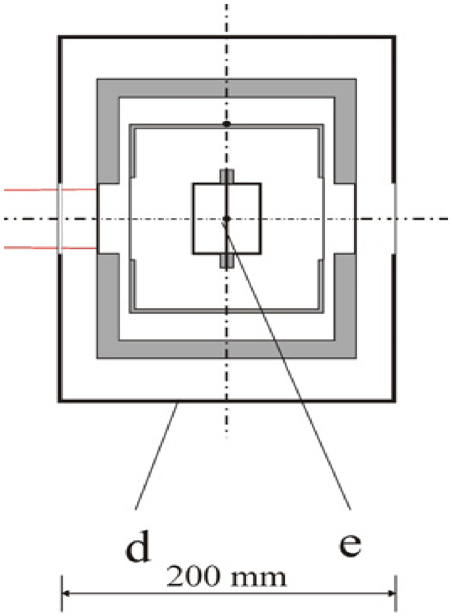


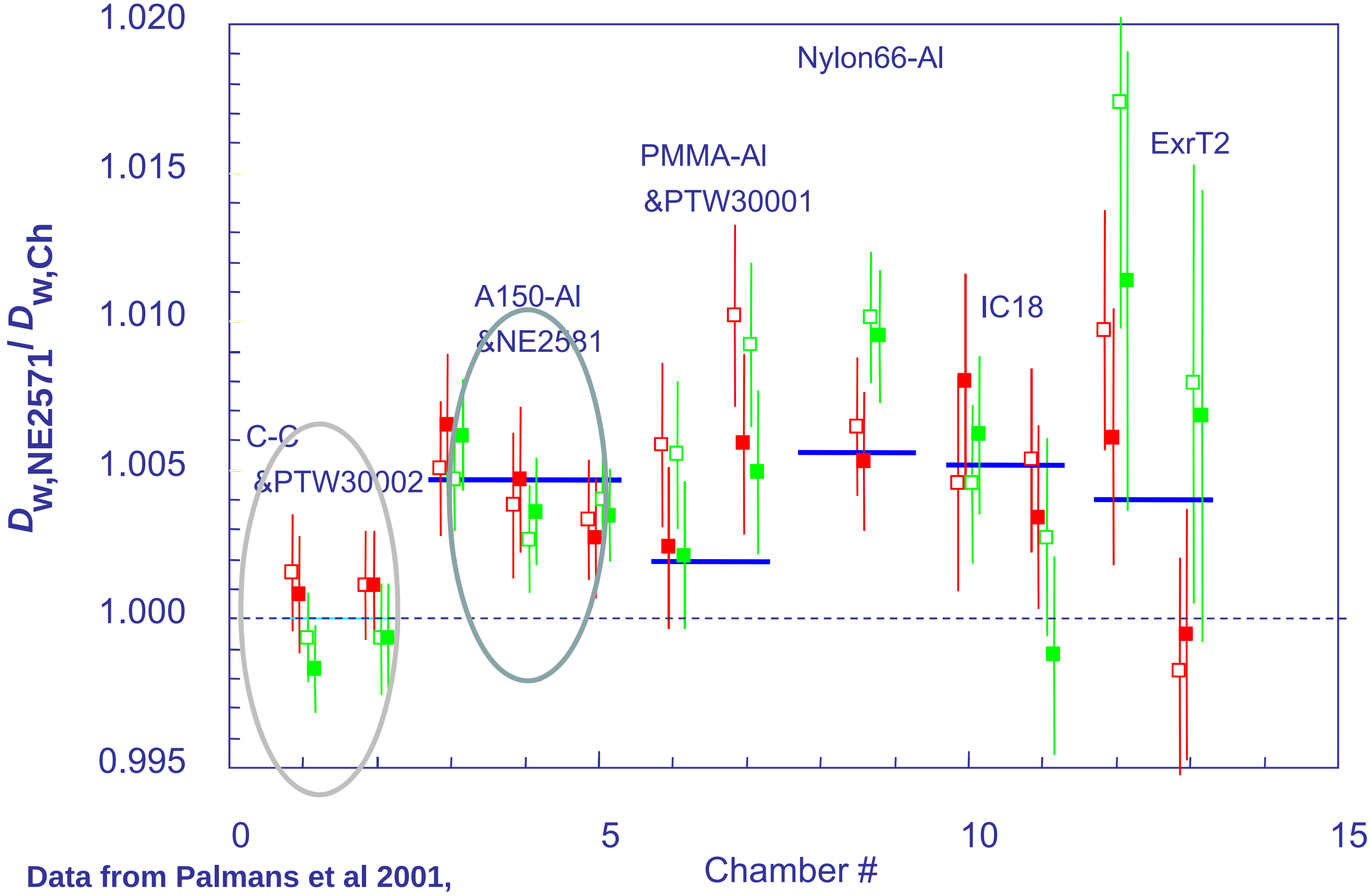
	Calorimetry Gy/MU	**Ionometry Gy/MU**	**Difference %**
Protons **Scattering**	**$9.087*10^{-3}$**	**$9.118*10^{-3}$**	**0.34**
Scanning	**$1.198*10^{-3}$**	**$1.203*10^{-3}$**	**0.42**

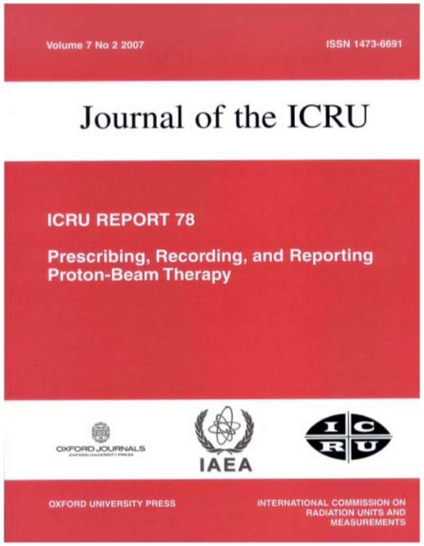
Sarfehnia et al., 2010

	Calorimetry Gy/MU	**Ionometry Gy/MU**	**Difference %**
Protons 182 MeV	**2.95±0.04**	**2.97±0.09**	**+0.7**
C^{12} 430 MeV/u	**2.77±0.05**	**2.69±0.08**	**- 3.0**

Brede et al., 2006

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

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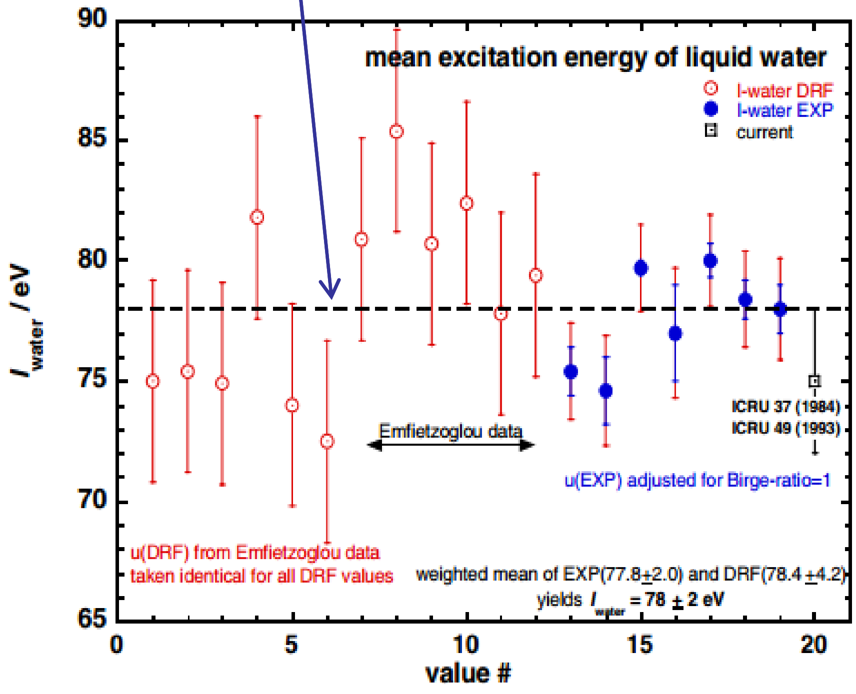
≈ 1 for protons and ions

≠ 1 for ^{60}Co

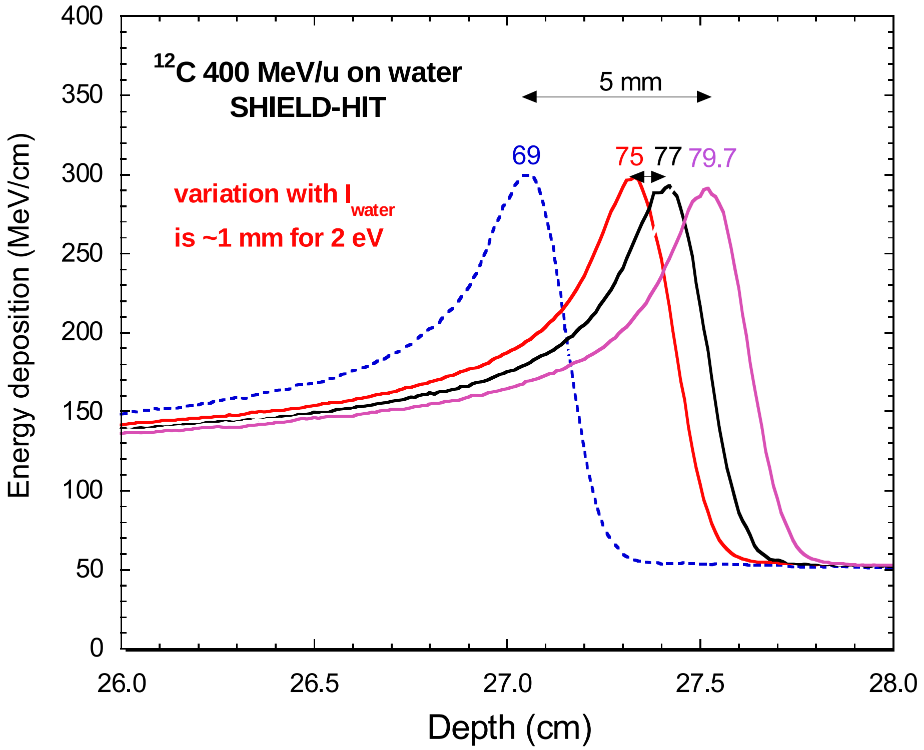
Data from Palmans et al 2001,
and Palmans and Verhaegen, Montreal workshop 2001

Compilation of published data for I_{water}

I_{water} = 78±2eV

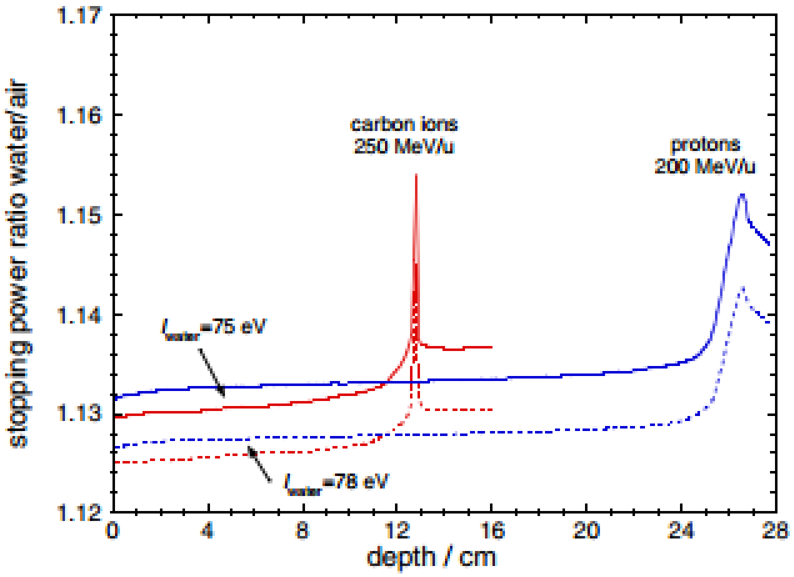


P. Andreo et. al., 2013



Influence of a change in the I_{water} and $I_{graphite}$ values on basic dosimetry data and k_Q values

- Decrease of 0.6% in $S_{w,air}$ for Co-60
- Decrease of 0.4% in $S_{w,air}$ for protons and heavier ions
- Net change in $W_{air,p}$ - increase of 0.6% i.e. $W_{air,p}$ = *34.44 eV (current - 34.23 eV)*



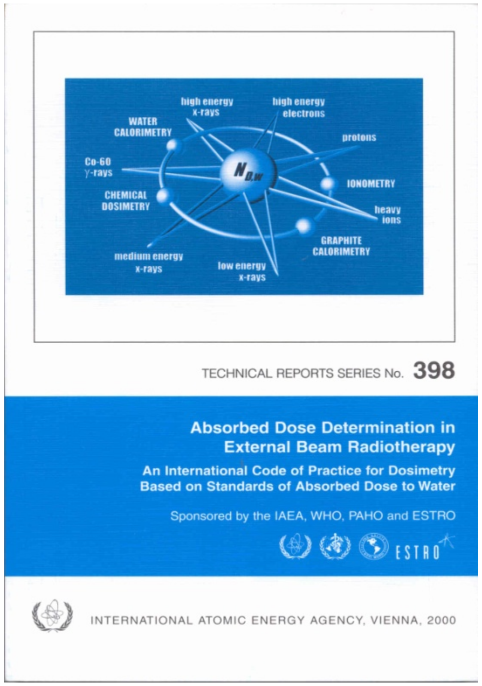
CONCLUSION: the net effect of all the changes leaves current calculated k_Q values <u>unaltered</u>

(P. Andreo et al., 2013)

Recombination corrections for protons and heavier ions

Protons and heavier Ion beams:

- Pulsed (passive) or pulsed scanned (active) beams,
- no continuous beams !



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Sponsored by the IAEA, WHO, PAHO and ESTRO

ESTRO

INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 2000

Two-voltage method

$$k_s = a_o + a_1\left(\frac{M_1}{M_2}\right) + a_2\left(\frac{M_1}{M_2}\right)^2$$

Not all beams are pulsed for determination of recombination

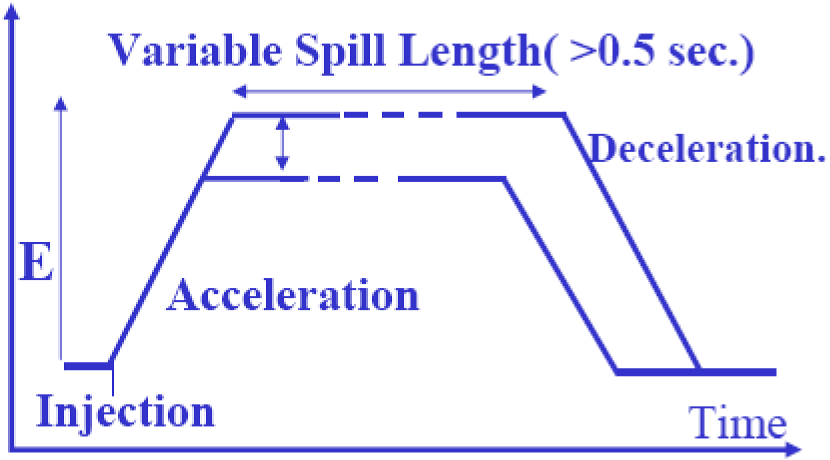
$$k_s = a_o + a_1\left(\frac{M_1}{M_2}\right) + a_2\left(\frac{M_1}{M_2}\right)^2$$

$$1/M = 1/M_\infty + b/V$$

General recombination

Recombination corrections for proton beams – ICRU 78

Synchrotrons (Repetition < 0.5 Hz, Acceleration 0.5 – 1s)



Cyclotrons (small pulses, high repetition, high dose per pulse)

- dose per pulse (0.2 Gy)
- pulse length 400μs
- maximum transit time for the ionization chamber 152 μs (300 V) and 76 μs (600 V) **Lorin et al, 2008**

Effective pulse duration is long compared to ion collection time of ion chamber

$$k_s = \frac{(V_N/V_L)^2 - 1}{(V_N/V_L)^2 - (M_N/M_L)}$$

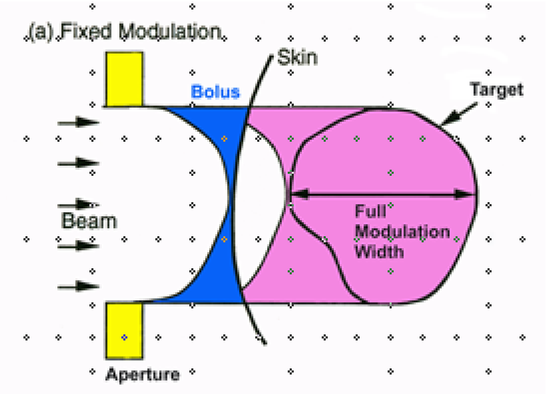
Ion collection time of ion chamber shorter compared to pulse duration

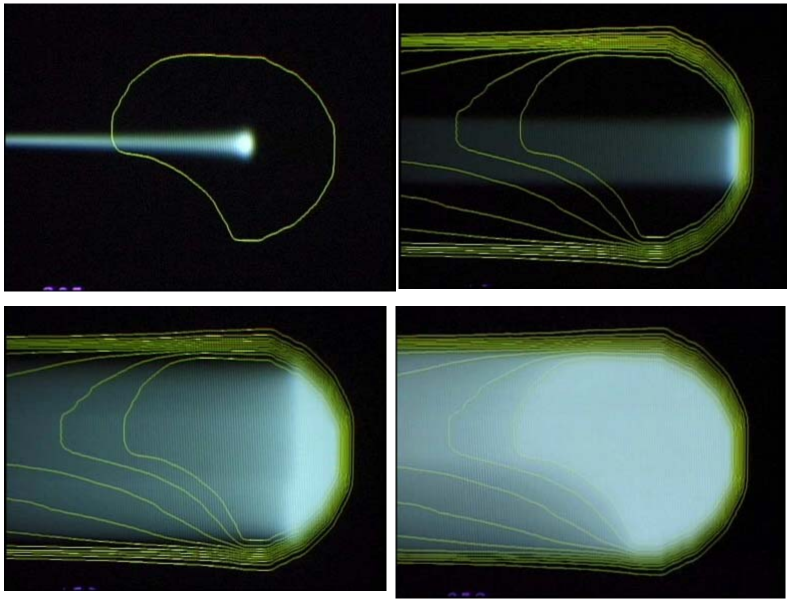
continuous beam

Scanned continuous beam

The user should verify recombination corrections against independent method

Reference calibration: reference conditions





(Pedroni *et al., 2001*)

Passive Scattering protons, carbon ions → Calibration at SOBP

Reference conditions are facility specific

Protons spot scanning → Calibration at plateau/SOBP

Carbon ions spot scanning → Calibration at plateau

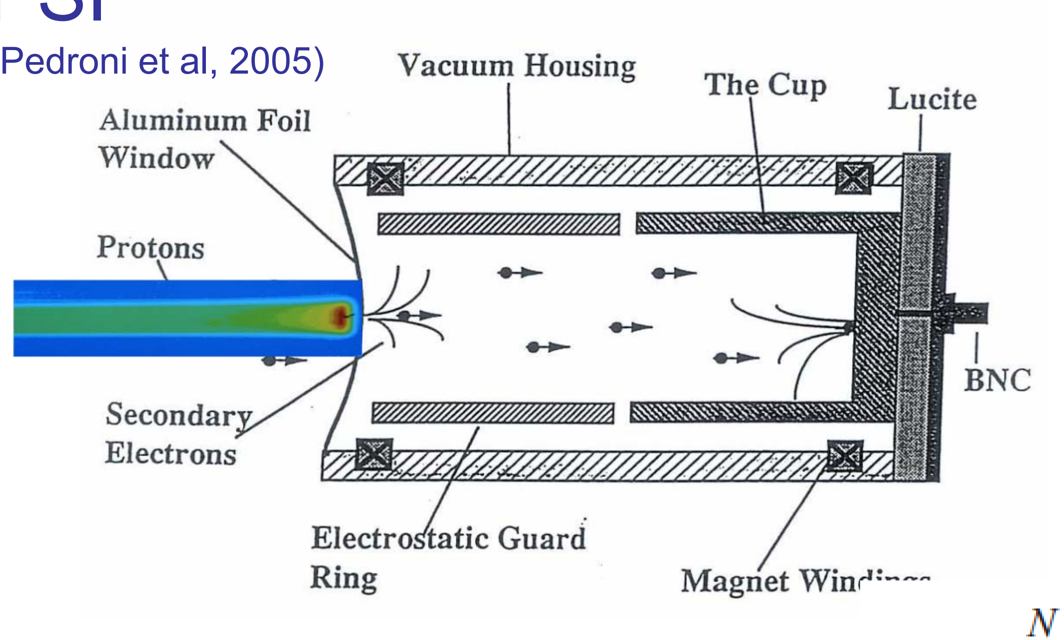
Plateau versus SOBP:

- **superposition of beams with different intensities**
- **not continuous and reproducible**
- **mix of particles with high and low LET**
- **fluence corrections are small**

Proton spot scanning calibration

PSI

(Pedroni et al, 2005)



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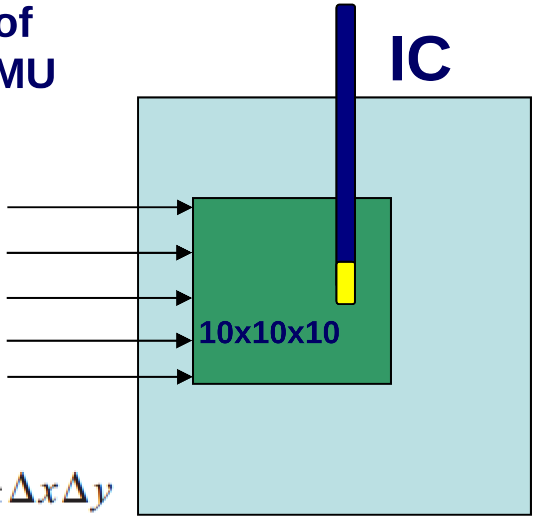
$$D_w = (N/A)\,(S/\rho)_w * 1.602 \times 10^{-10}$$

Number of protons/MU

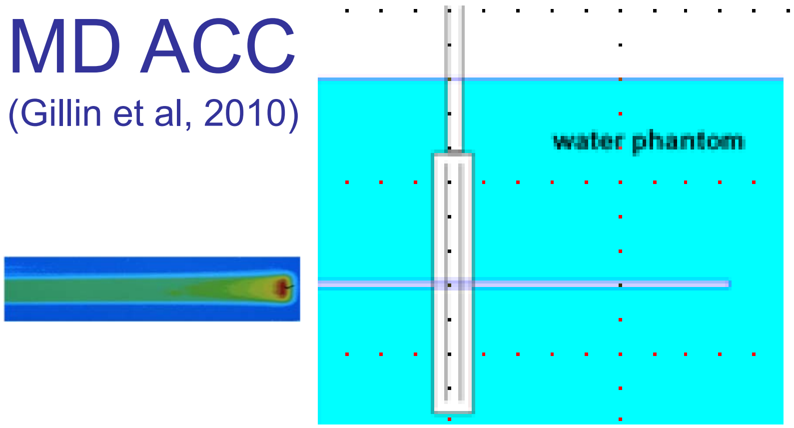


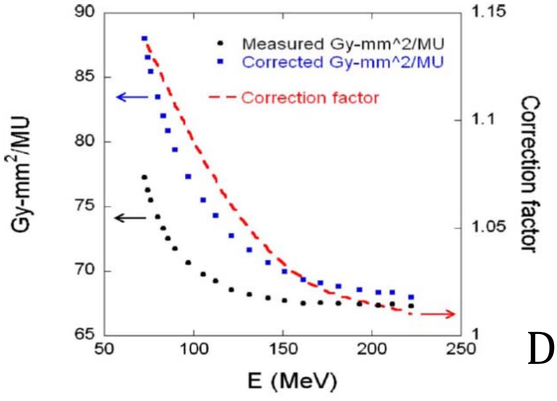
$$K(E)=\frac{N}{\mathrm{MU}}=\frac{D_{\mathrm{meas}}}{S_E(x)\mathrm{MU}}\Delta x\Delta y$$

Dose/MU

MD ACC

(Gillin et al, 2010)





$$N \approx \frac{\mathrm{DAP}_w}{(S/\rho)_w}$$

$$\mathrm{DAP}_{w,Q}^{A} = M_Q N_{\mathrm{DAP},w,Q_0} \kappa_{Q,Q_0}$$

Standard uncertainties in determination of D_w *(TRS 398, ICRU 78)*

$u(N_{D,w}^{SSDL}) = 0.6$

	k_Q calc	$k_{Q,p}$
Co-60 gamma-rays	**0.9**	
High-energy photons	**1.5**	
High-energy electrons	**1.4-2.1**	
Proton beams	**2.0-2.3**	**1.2**
Heavier ions	**3.0-3.4**	

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

Dosimetry tasks

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

Beam characteristics

✓ Depth dose

✓ Lateral profiles

✓ Output factors

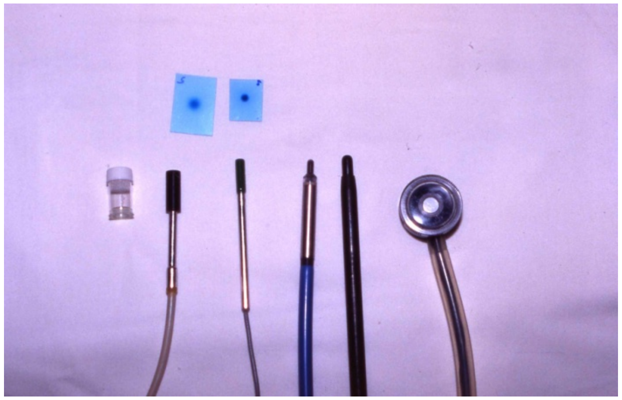
Detectors for measurements in non-reference conditions

Active detectors:

Ion chambers, diodes, diamond detector, scintillators

(single and multiple)

Direct display of the current dose rate or the accumulating dose



Passive detectors:

Destructive – TLD
Non-destructive – Films, alanine

Probe accumulates the dose during irradiation. The value of dose is obtained after irradiation with read-out device

Characterization of small proton beams

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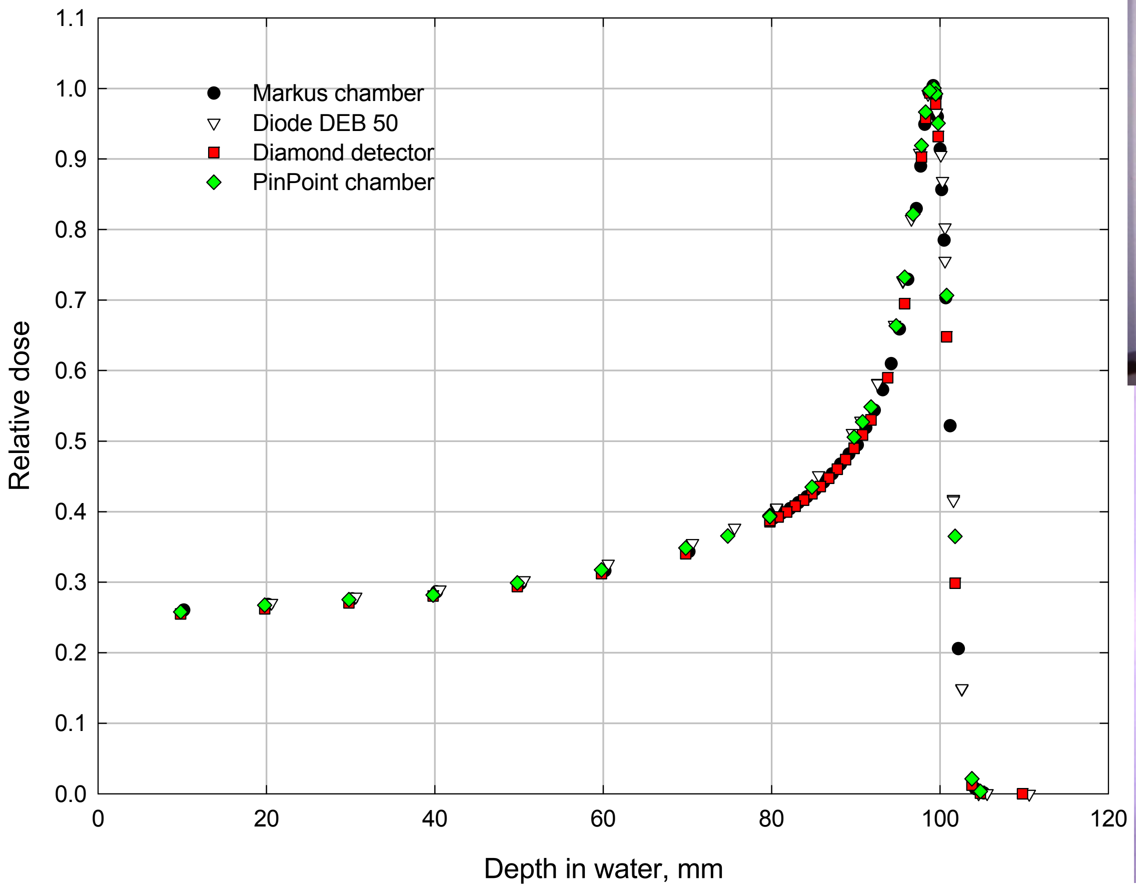
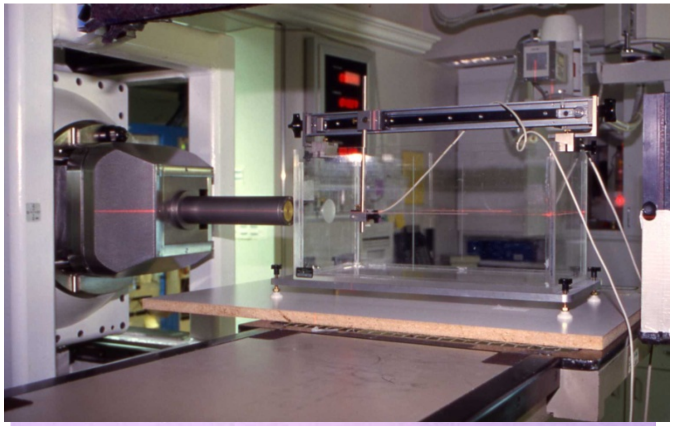
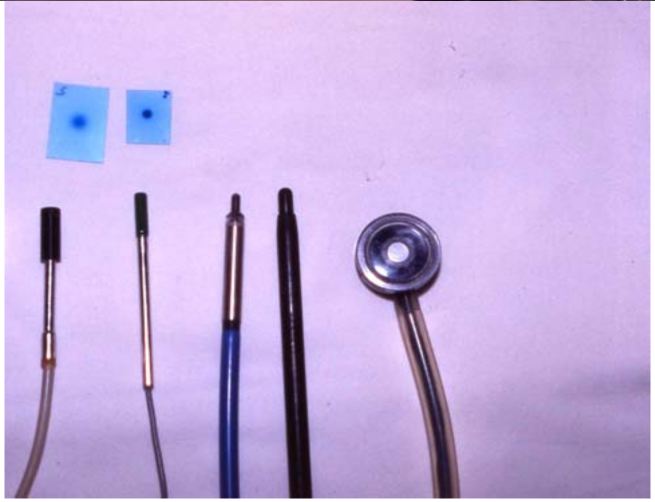
126 MeV protons, collimator 30 mm, no modulation







The user should carefully select detectors depending on beam size

Characterization of scanned proton pencil beams

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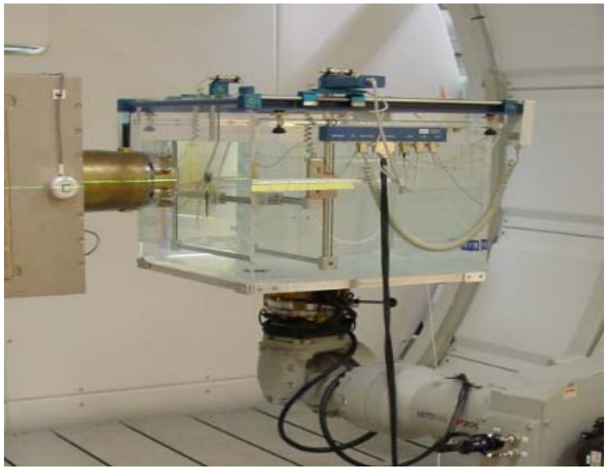
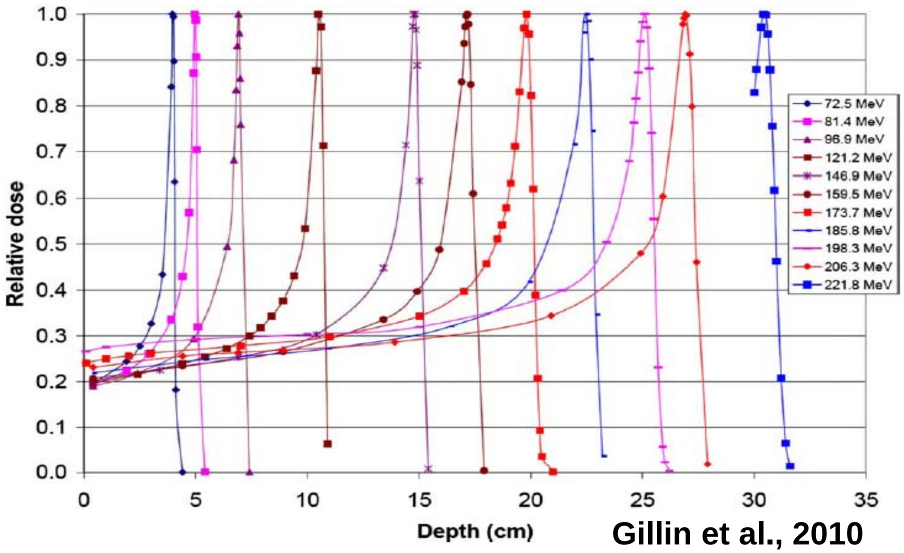
courtesy by PTW



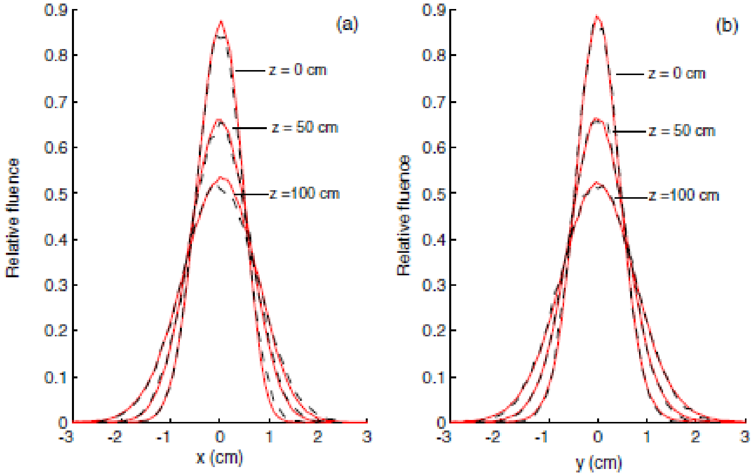
courtesy by PTW

Depth dose distribution



Gillin et al., 2010

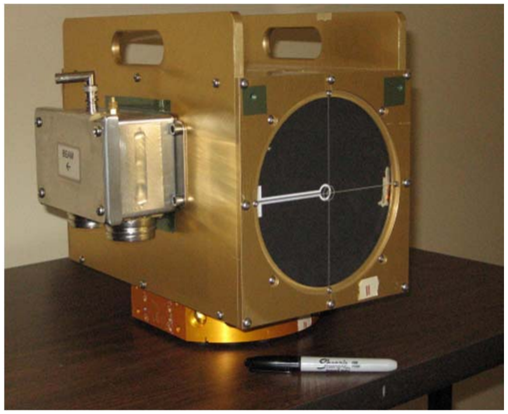
Dose profiles



Kimstrand et al., 2007

Multi-detector systems
for characterization and QA of proton and carbon beams

MedAustron



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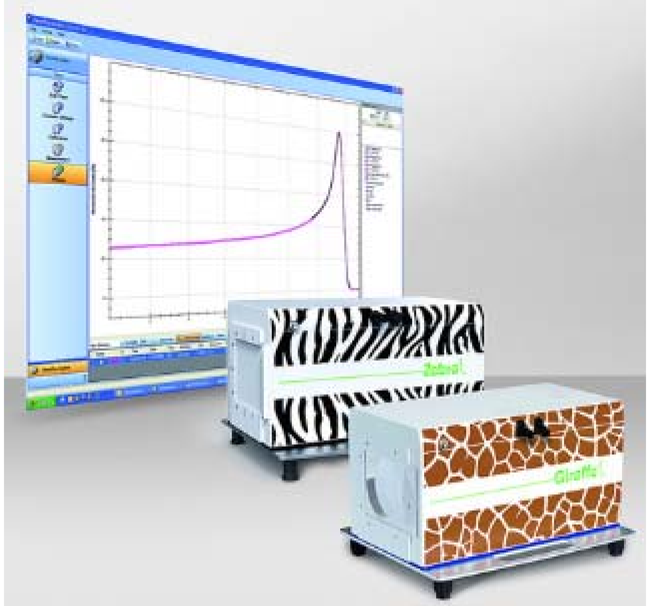
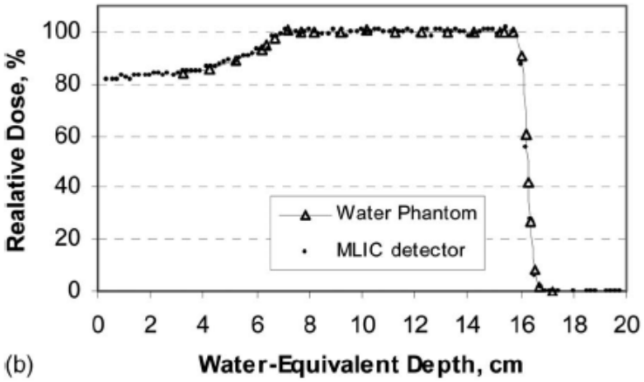


courtesy by IBA

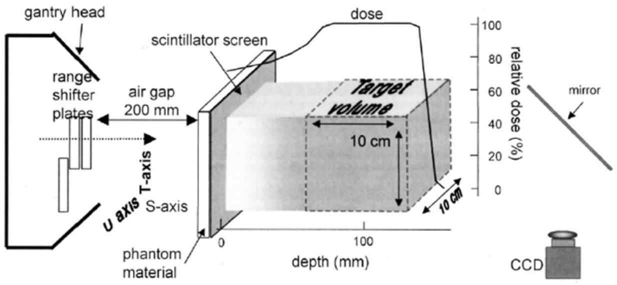


Nichiporov *et al*. 2007

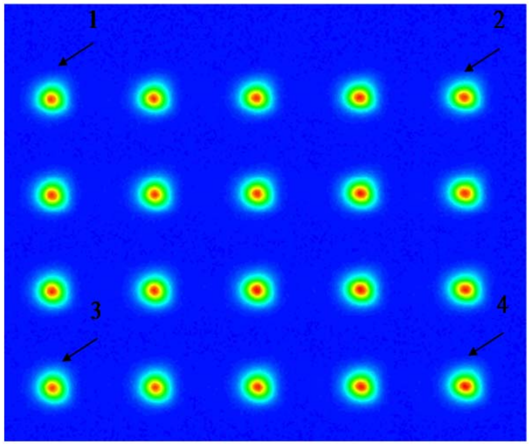
courtesy by IBA

2-D dosimetry: fluorescent screen and CCD camera

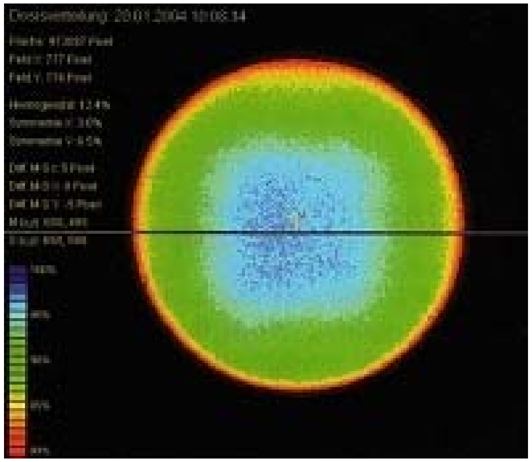
MedAustron

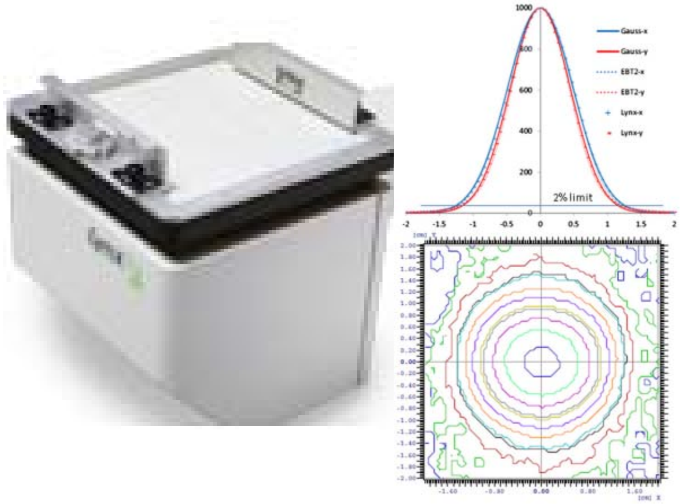


Boon et al 2000

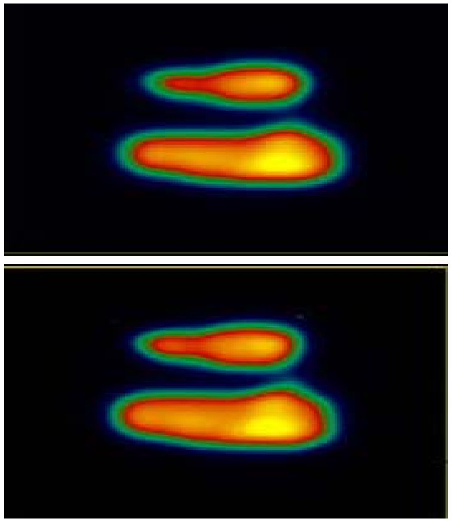


Courtesy CMS

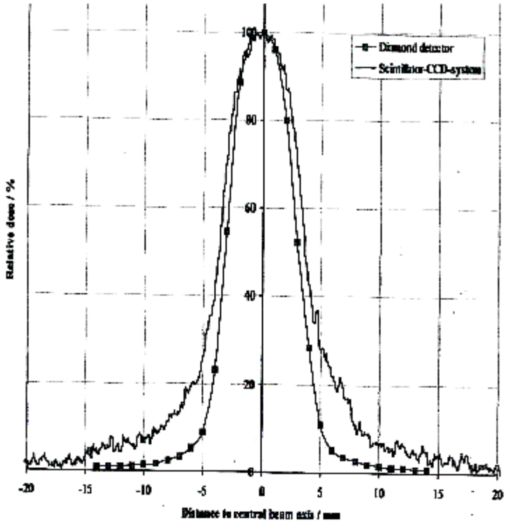




Lin et al., 2013



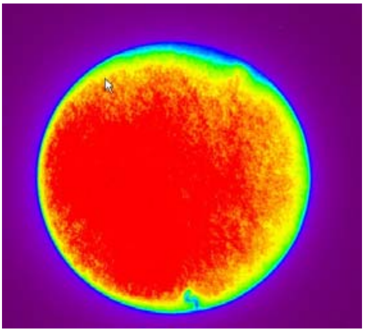
E. Pedroni *et al.*, 2005

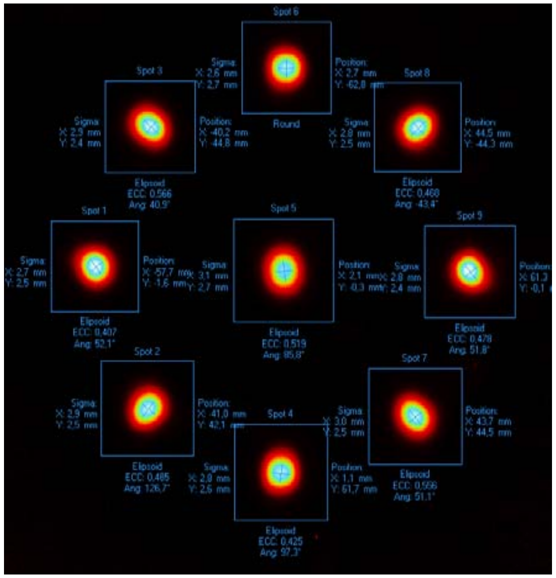


Rosenthal *et al.*, 2004

2-D dosimetry:

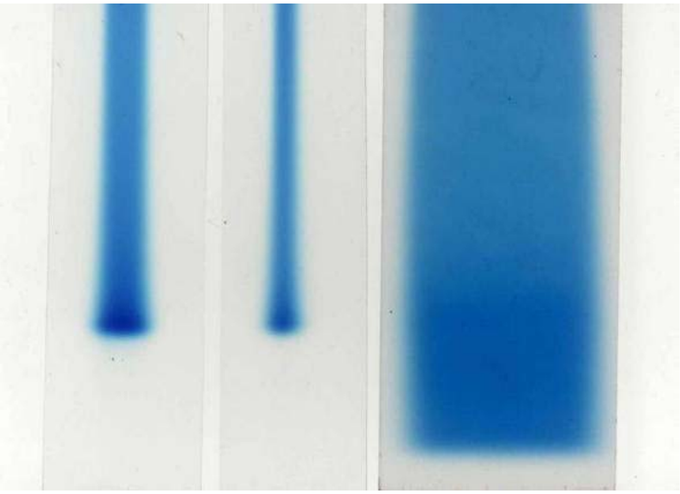
TLD

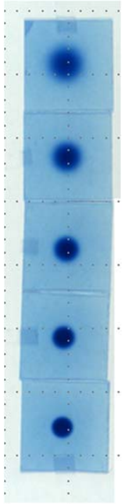


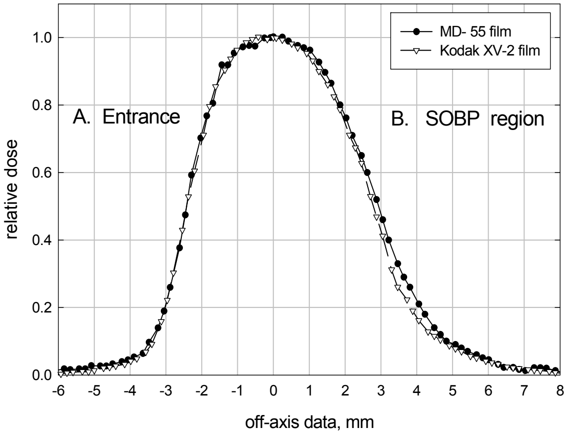


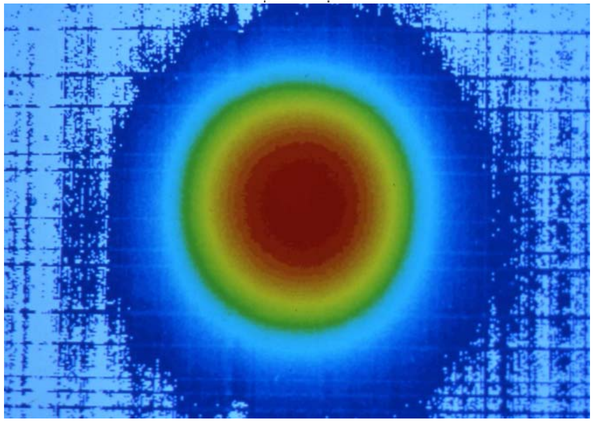
(courtesy of P. Olko).

Radiochromic film









Radiochromic films and gels for characterization of clinical proton beams

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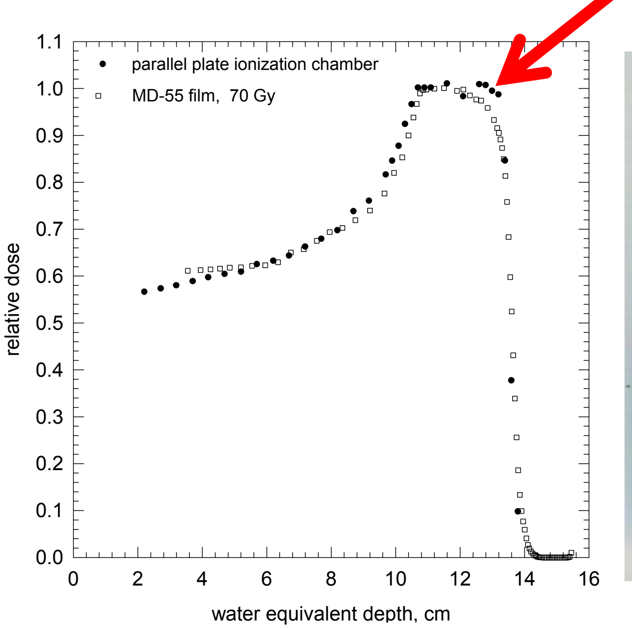
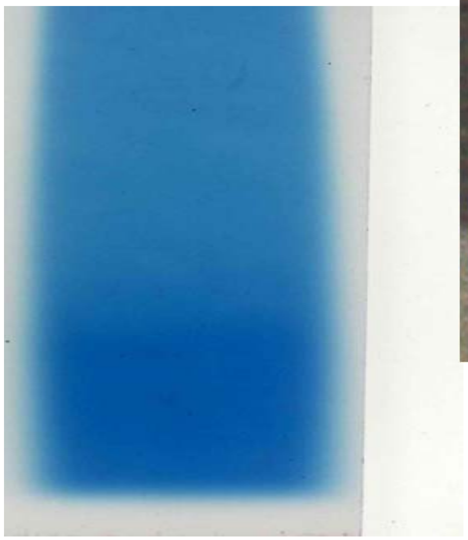
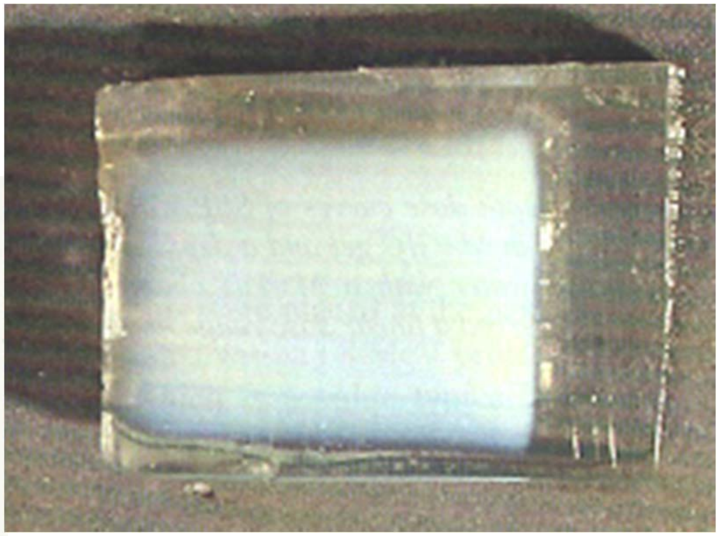
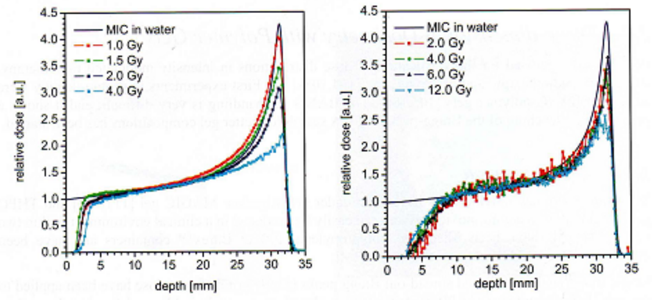
155 MeV, modulation 3 cm, normalized at 11 cm

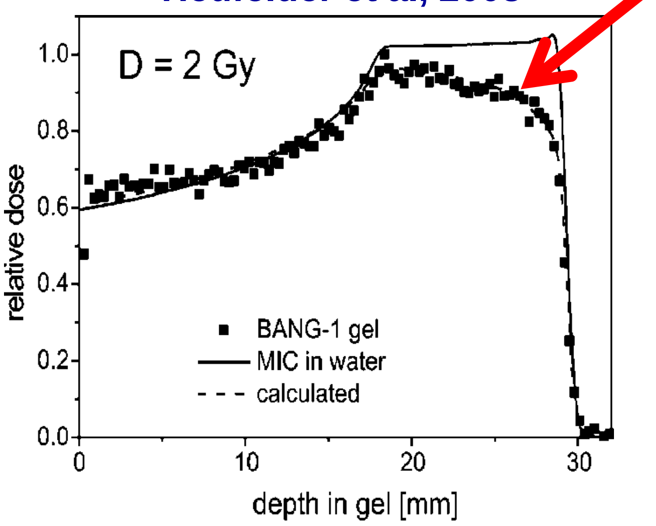




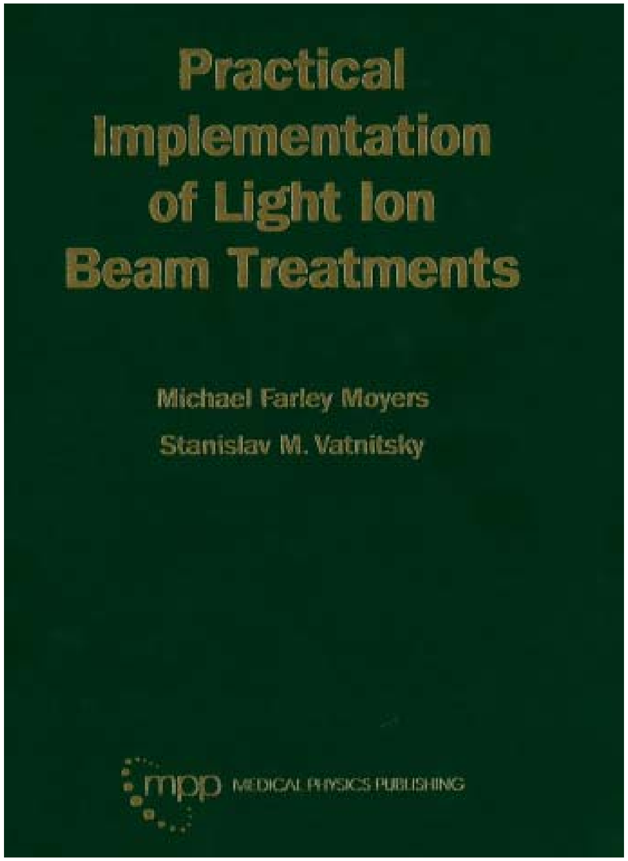




Heufelder et al, 2003



Additional reading



Practical Implementation of Light Ion Beam Treatments

Michael Farley Moyers

Stanislav M. Vatnitsky

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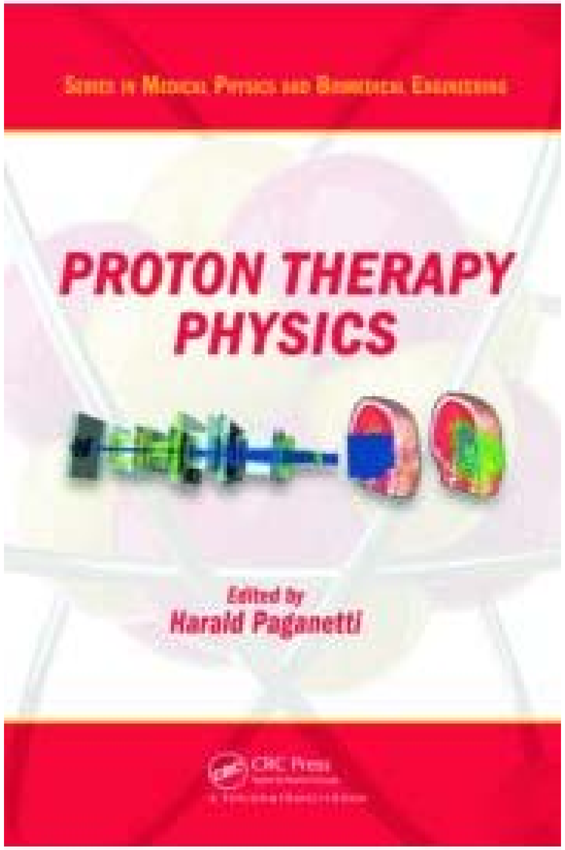

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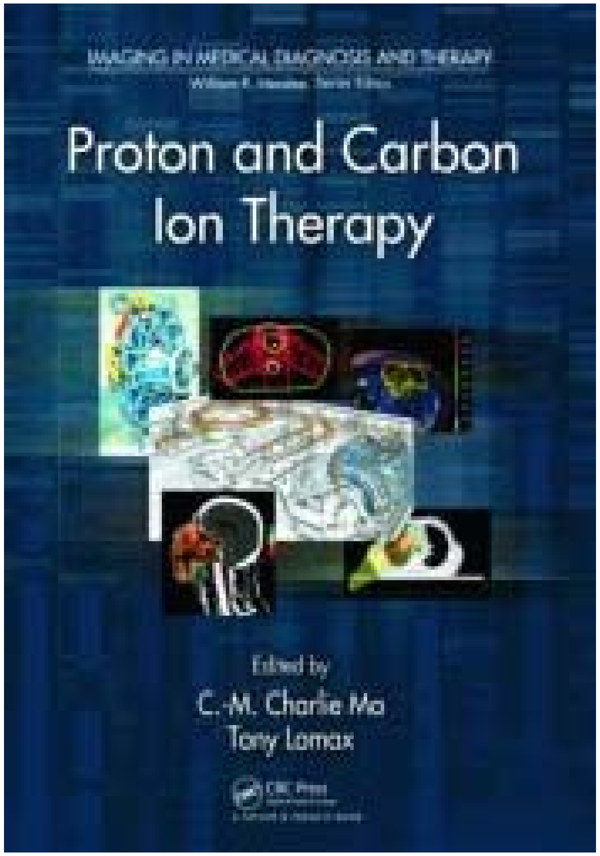

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Take home message

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Implementation
of ICRU Report 78
IAEA TRS 398

harmonize clinical dosimetry
at proton and heavier
ion beam facilities

Traceability audits:
Dose /MU review of proton
facilities: Moyers et al 2014
$N_{D,w}$ (ICRU 78): 0.997±0.016

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

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- O. Jäkel and colleagues at HIT
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Thank you for your attention!