
# Instrumentation for Verification of Dose

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## Goals

**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 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 light ion beams**

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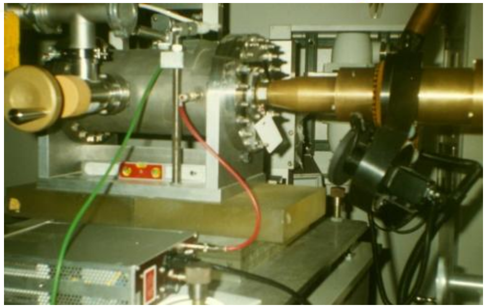
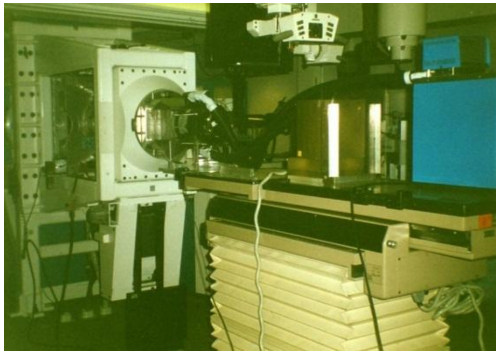
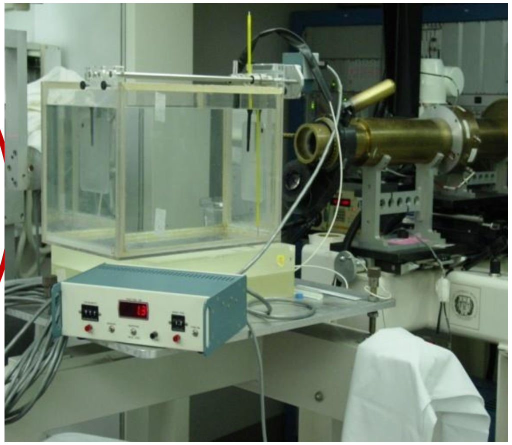
Faraday Cup



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

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

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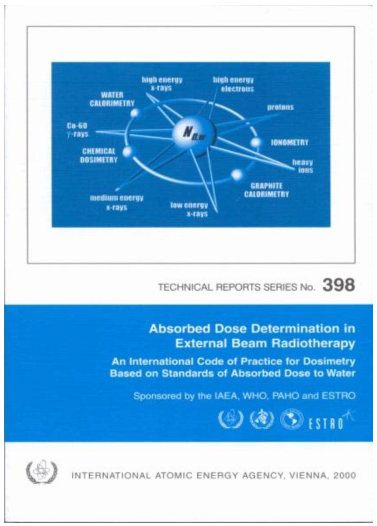
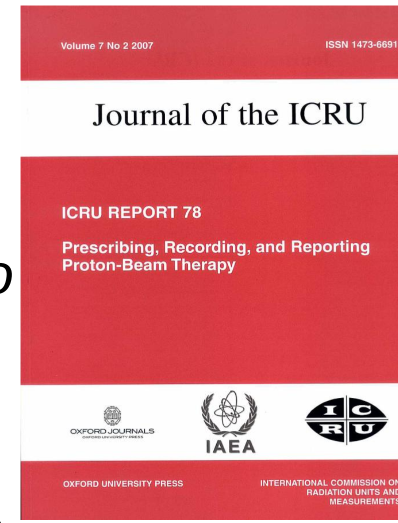
## $D_w(z_{ref})$ at <u>any</u> user quality $Q$ (photons, electrons, protons, heavier ions)




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




*corrected instrument reading at Q*

*calibration coefficient at $Q_o$*

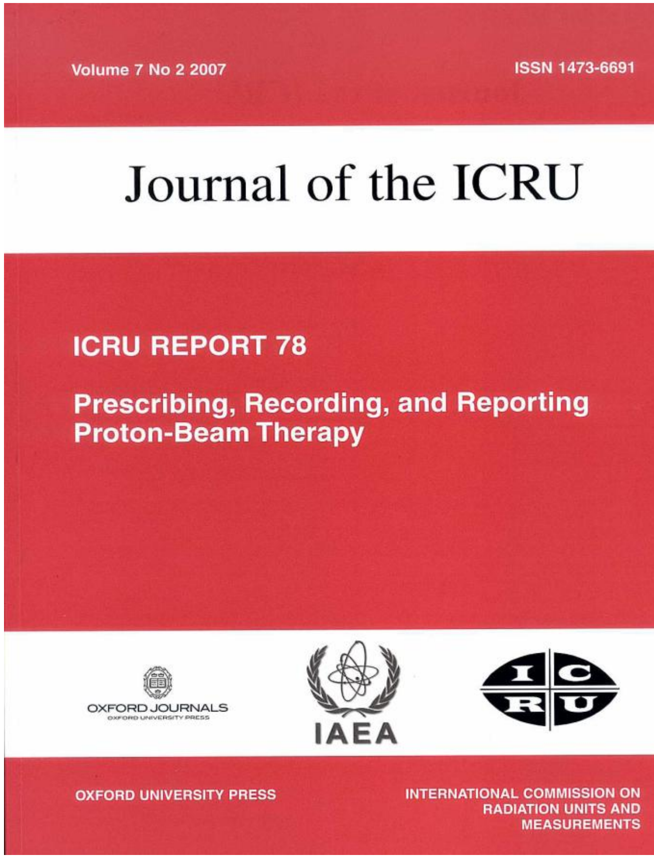
*beam quality factor*

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

$N_{D,w}$ approach would ultimately lead to a dosimetry system, where the dose applied to a patient is traceable to the dosimetry standards of the national PSDL.

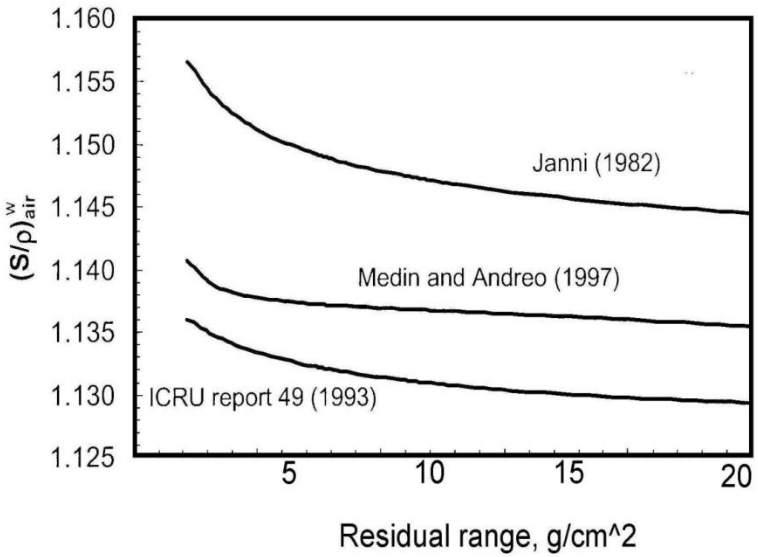
**=> $Q_o$ = $^{60}$Co**

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



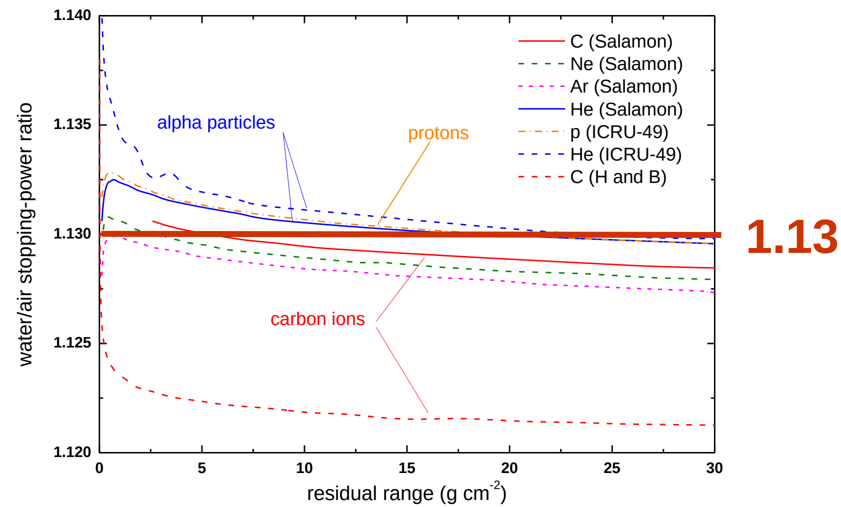
# Stopping powers

## Proton beams

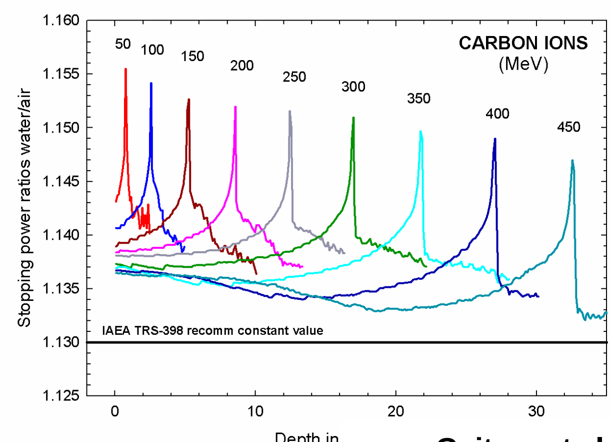



- **Basic proton stopping powers from ICRU 49**
- **Calculation using MC code PETRA following Spencer-Attix cavity theory**
- **Transport included secondary electrons and nuclear inelastic process**

## Heavier ion beams




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




**Geitner et al 2006**

# Compilation of published data $I_{water}$

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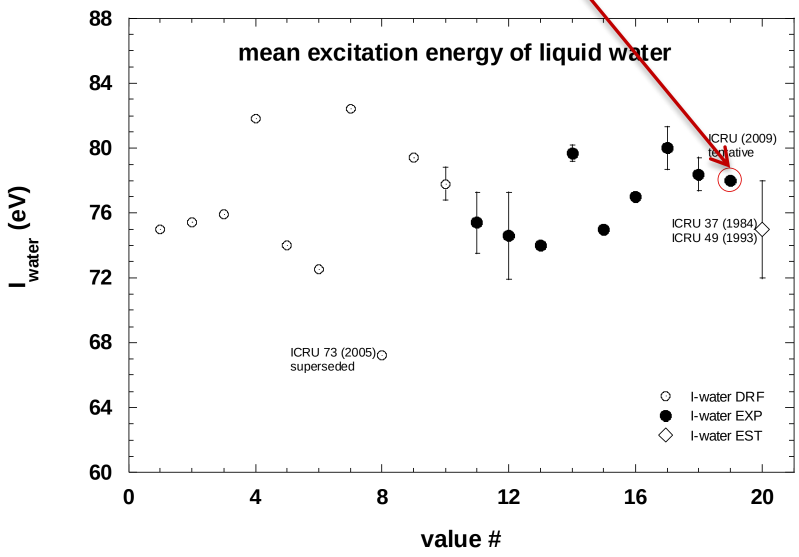
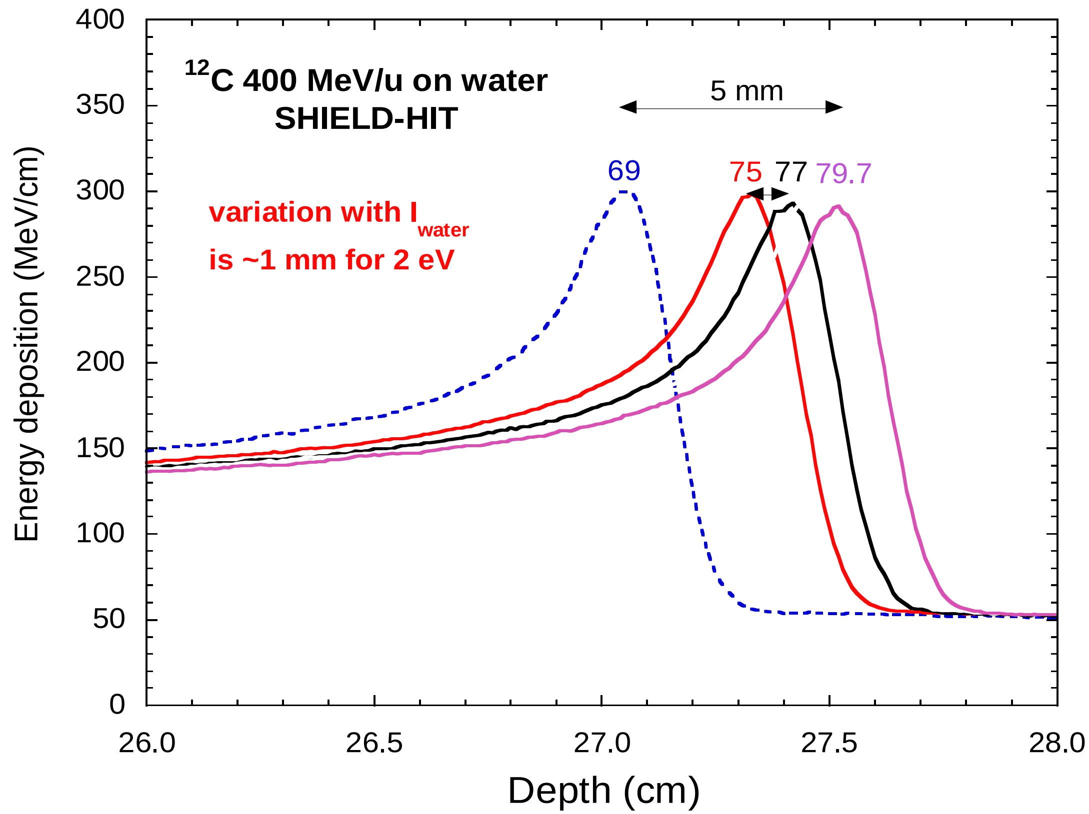
$I_{water}$ = 78 eV

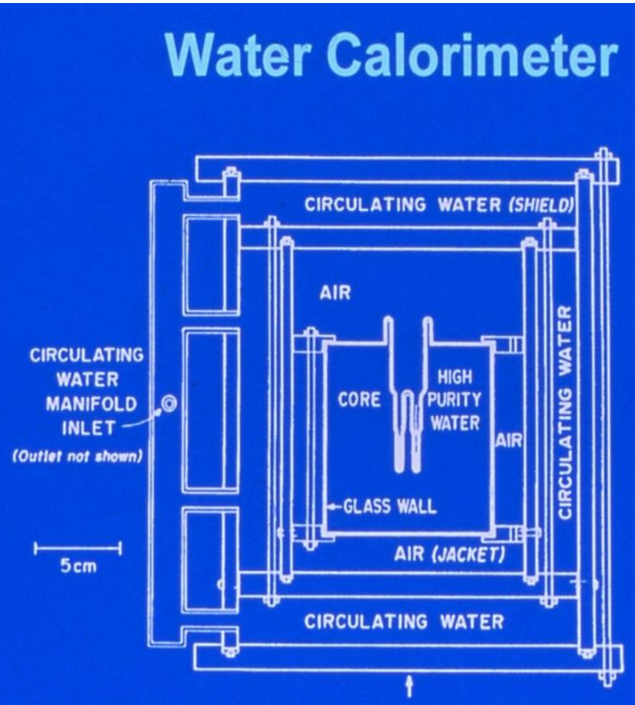


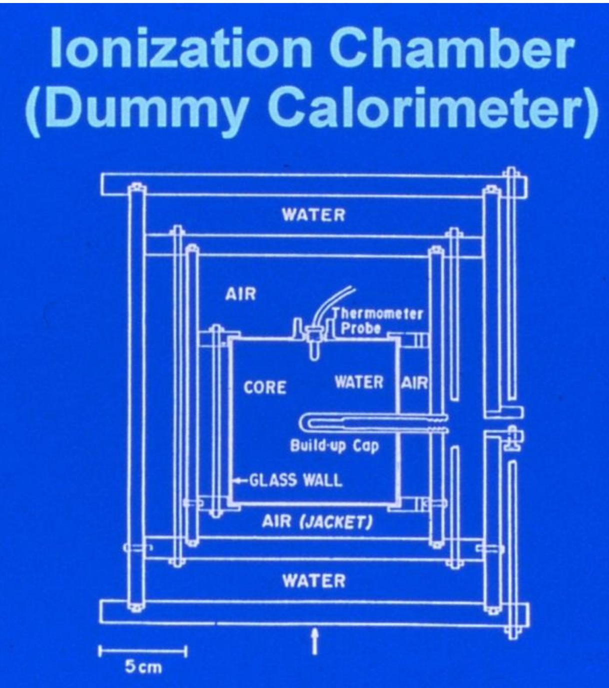



# Calorimetry-based determination of *W*-values

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

$$N_{D,w,c} = \frac{D_w(Q,cal)}{M^{corr}}$$

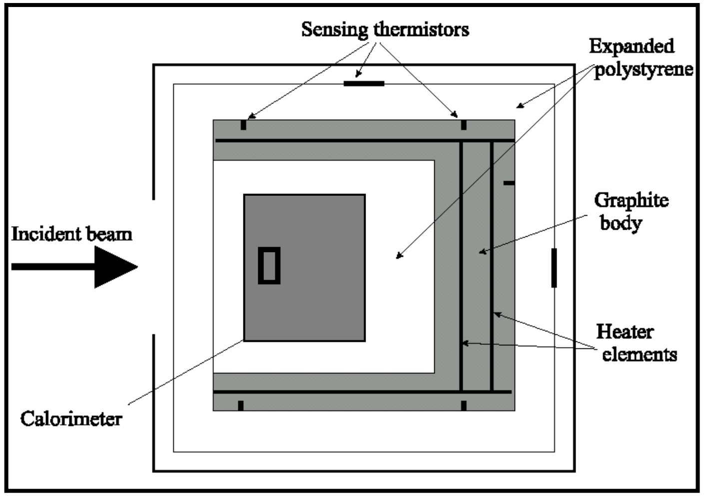


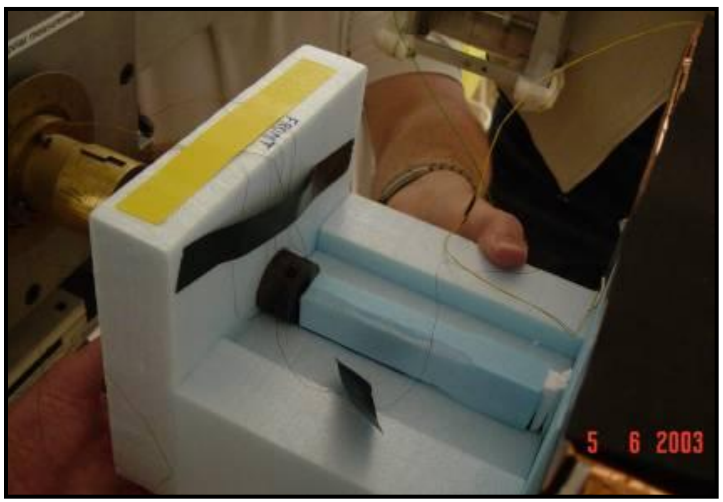




$$D_w(Q,cal) \qquad M^{cor} N_{D,w,{}^{60}Co} \frac{(S_{w,air})_Q}{(S_{w,air})_{{}^{60}Co}} \frac{(W_{air})_Q}{(W_{air})_{{}^{60}Co}} \frac{(p)_Q}{(p)_{{}^{60}Co}}$$

# Transportable graphite calorimeters

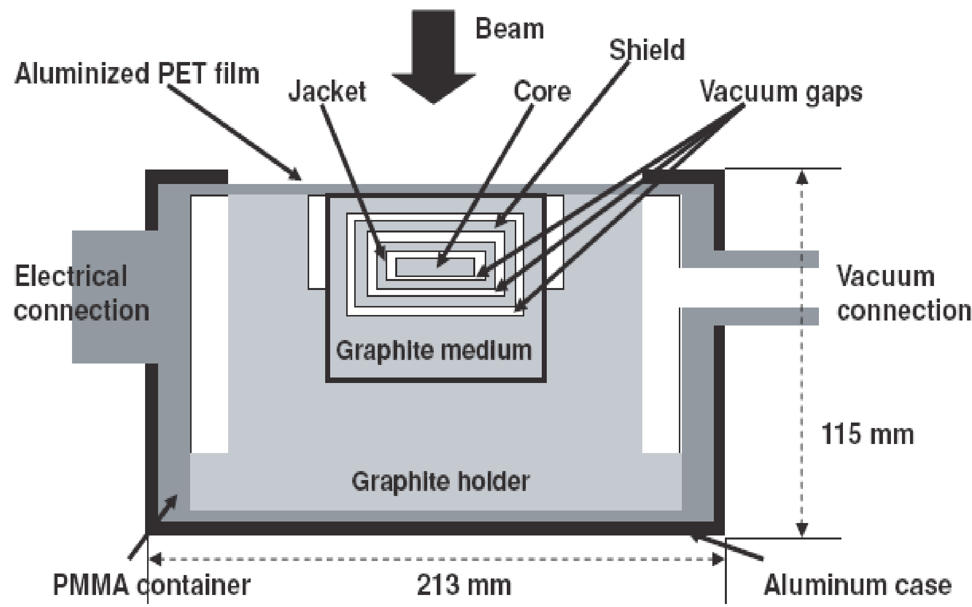
## NPL protons at CCO




**Palmans et al 2004**

## NIRS - carbon ions




**Sakama et al 2008**

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

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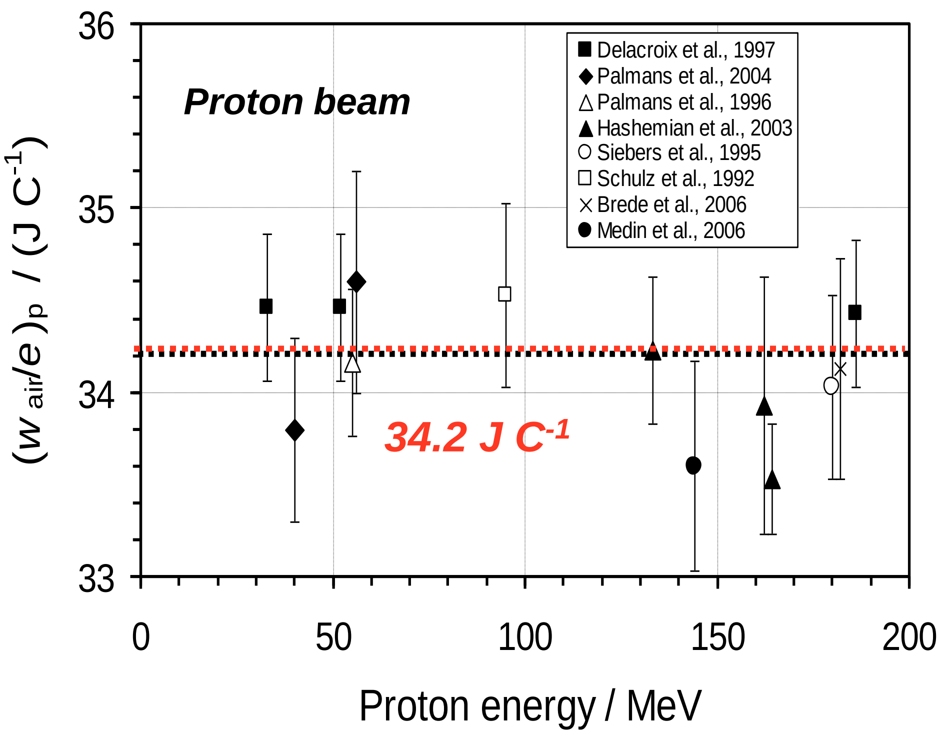
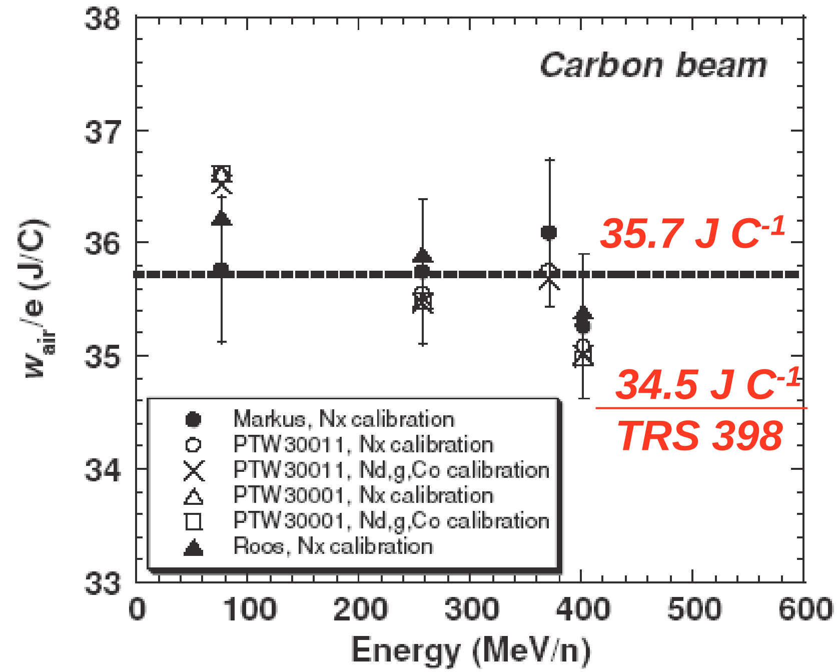


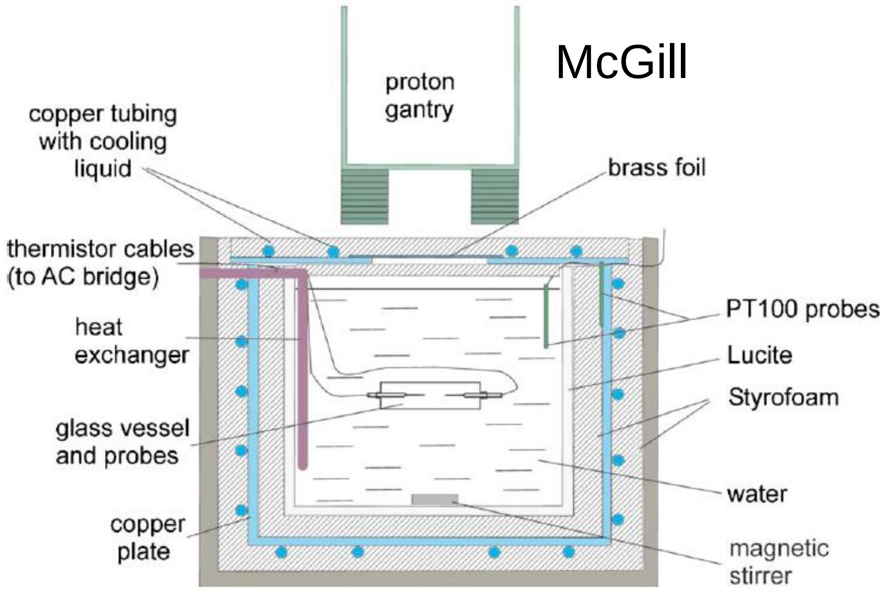

ICRU 78



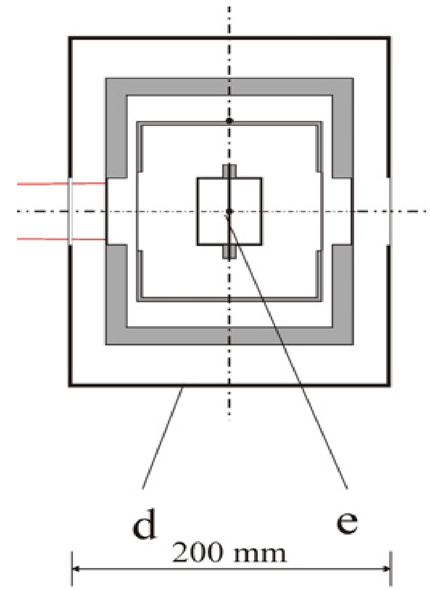

Sakama et al 2008

# Transportable water calorimeters

McGill




PTB




| Protons | Calorimetry Gy/MU | Ionometry Gy/MU | Difference % |
|---|---|---|---|
| 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

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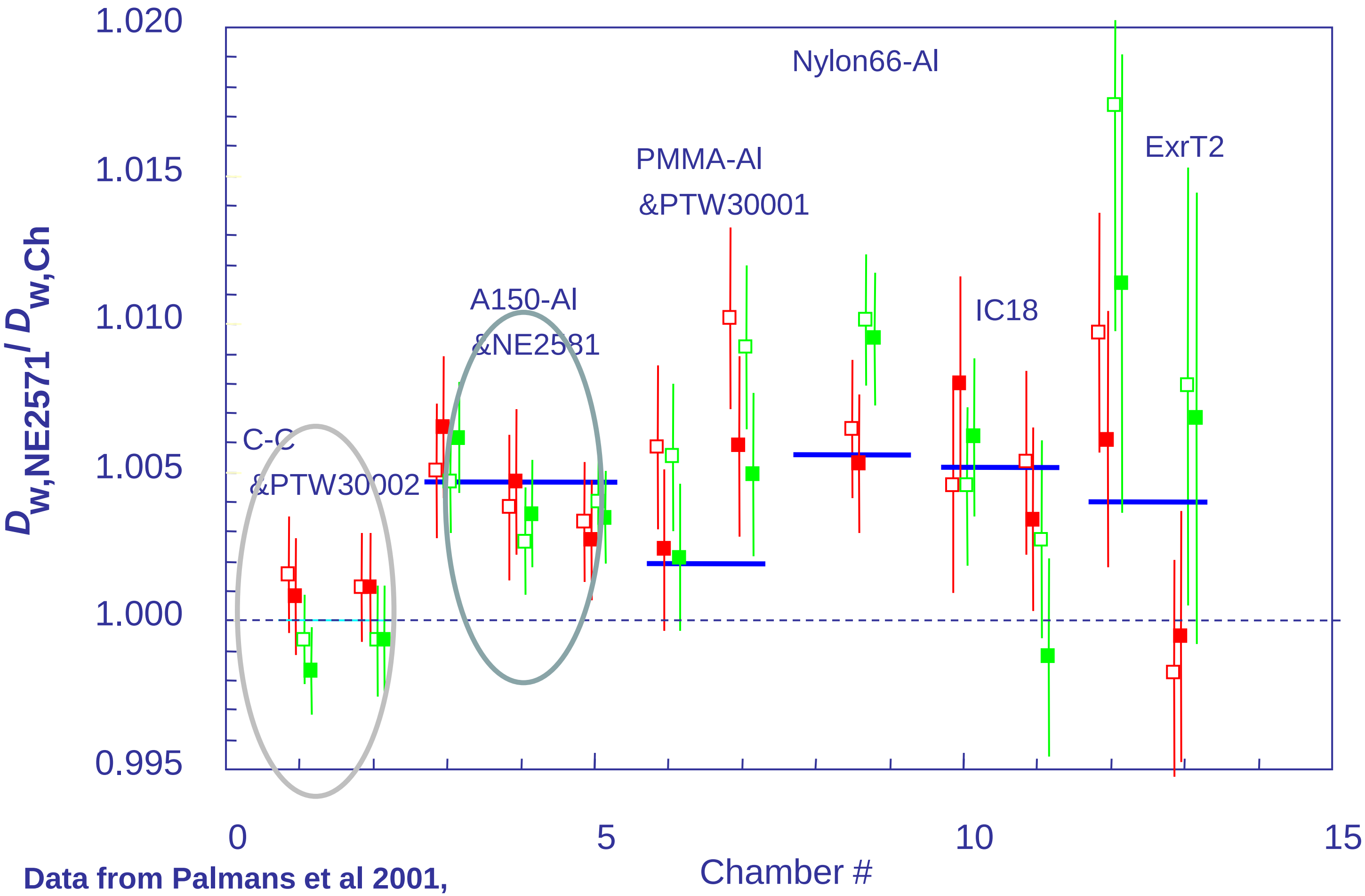
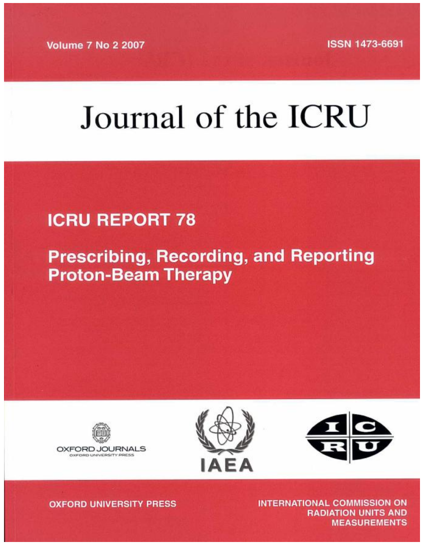
$$k_Q = \frac{\left(s_{w,air}\right)_Q}{\left(s_{w,air}\right)_{^{60}Co}} \frac{\left(W_{air}\right)_Q}{\left(W_{air}\right)_{^{60}Co}} \frac{p_Q}{p_{^{60}Co}}$$




≈ 1 for protons and ions

≠ 1 for $^{60}$Co

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

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

(results presented by P. Andreo at ESTRO 2013)

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- 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 $W_{air,protons}$ - increase of 0.6% i.e.

$W_{air,protons}$ = *34.44 eV (current value 34.23 eV)*

***CONCLUSION: the net effect of all the changes***

***leaves current calculated kQ values unaltered***

# Recombination corrections for protons and heavier ions

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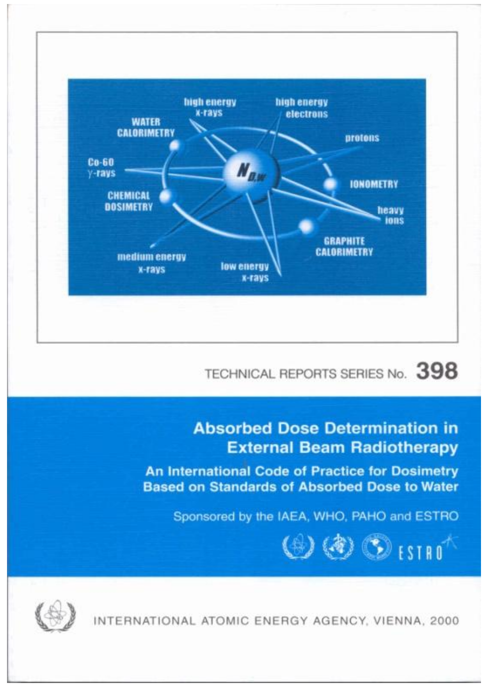
**Protons and heavier Ion beams:**

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




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

**Not all beams are pulsed for determination of recombination**

**Two-voltage method**

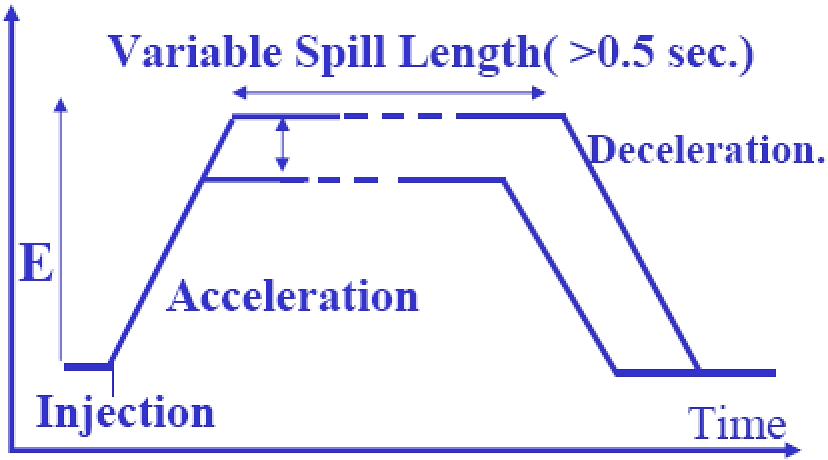
$$k_s = a_o + a_1\left(\frac{M_1}{M_2}\right) + a_2\left(\frac{M_1}{M_2}\right)^2$$

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

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

Ion collection time of ion chamber shorter compared to pulse duration

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

**continuous beam**

**Scanned continuous beam**

The user should verify recombination corrections against independent method

# Reference calibration: reference conditions

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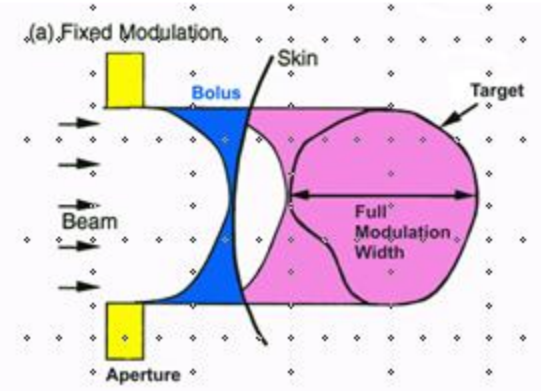
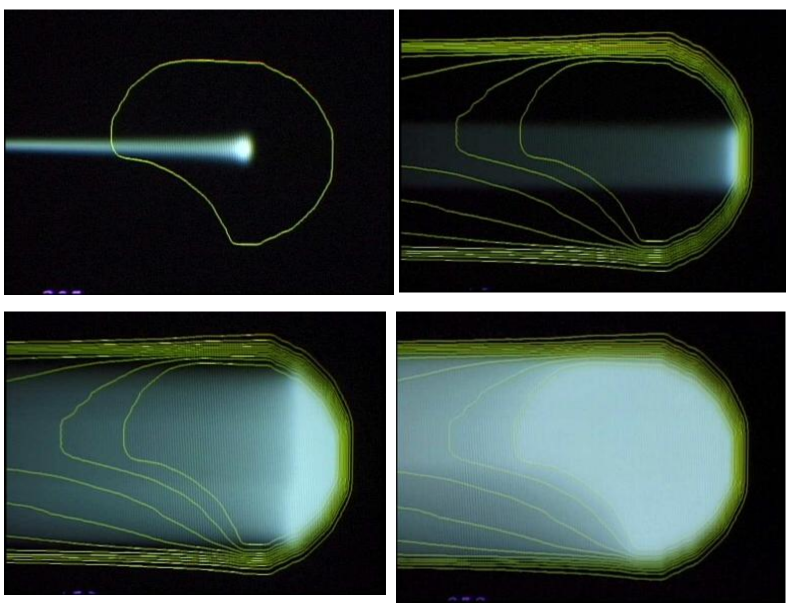



**Passive Scattering protons, carbon ions** → Calibration at SOBP



**( Pedroni *et al*)**

**Reference conditions are facility specific**

Protons spot scanning → Calibration at 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

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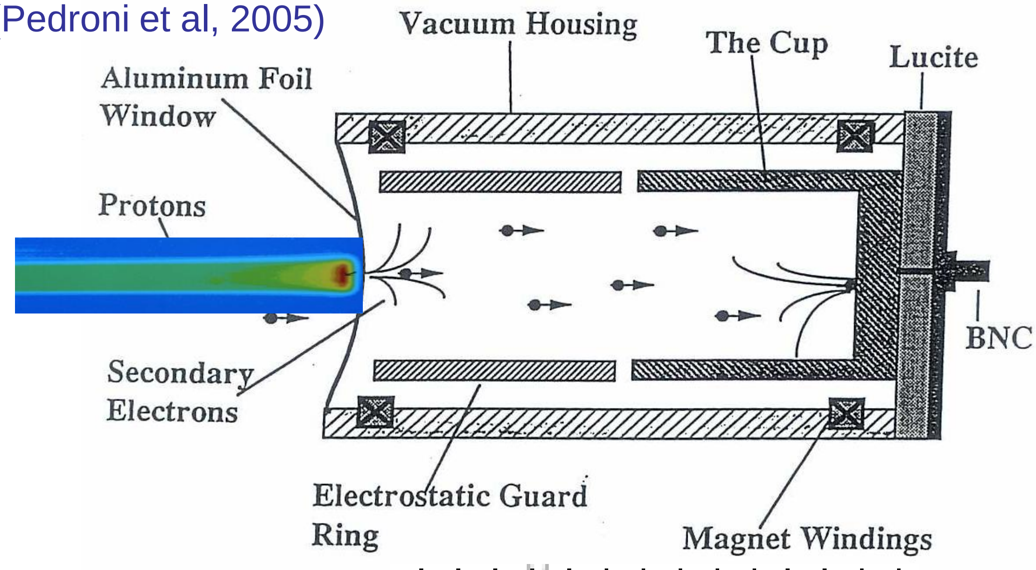
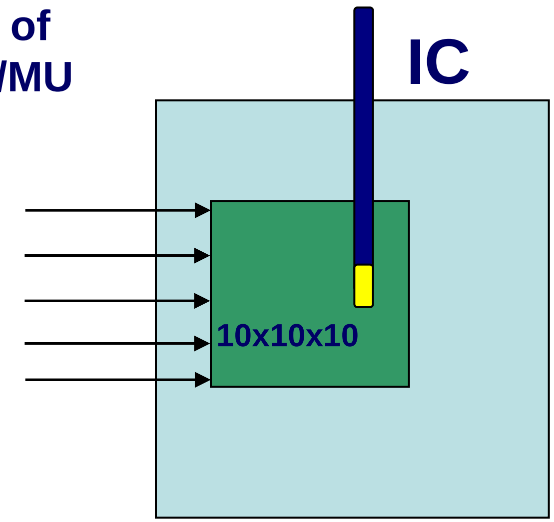
## PSI

(Pedroni et al, 2005)




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

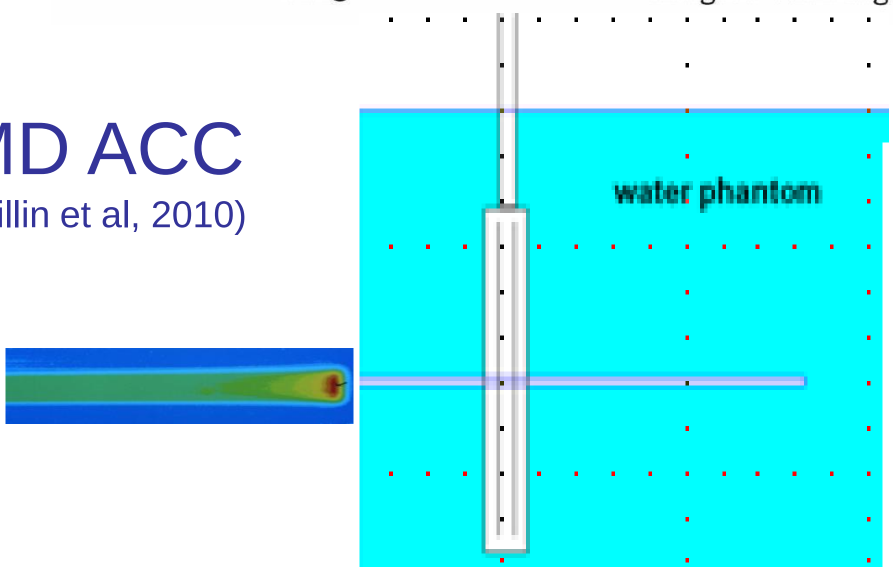
**Number of protons/MU**

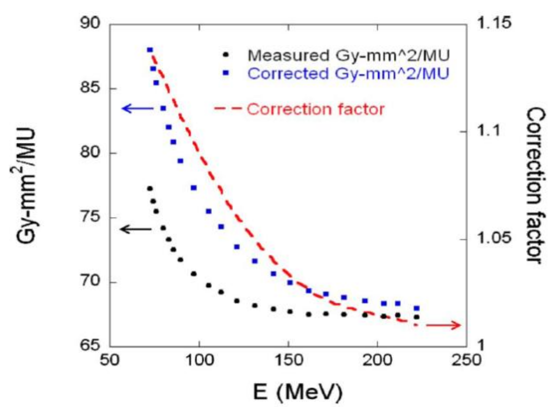



**Dose/MU**

## MD ACC

(Gillin et al, 2010)



# Standard uncertainties in $D_w$ (*TRS 398*, *ICRU 78*)

| | |
|---|---|
| $u(N_{D,w}^{SSDL}) = 0.6$ | $k_Q$ calc |
| **Co-60 gamma-rays** | **0.9** |
| **High-energy photons** | **1.5** |
| **High-energy electrons** | **1.4-2.1** |
| **Proton beams** | **2.0-2.3** |
| **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

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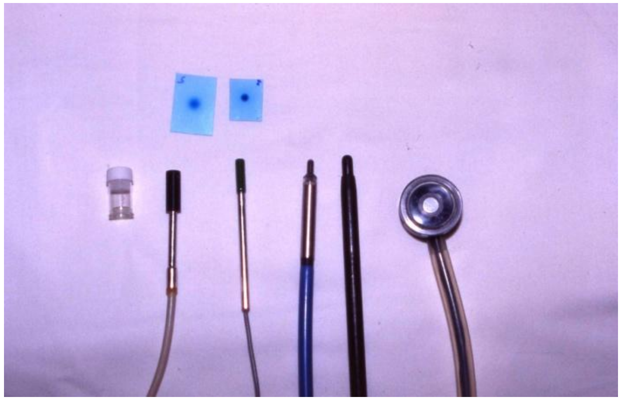
Active detectors:

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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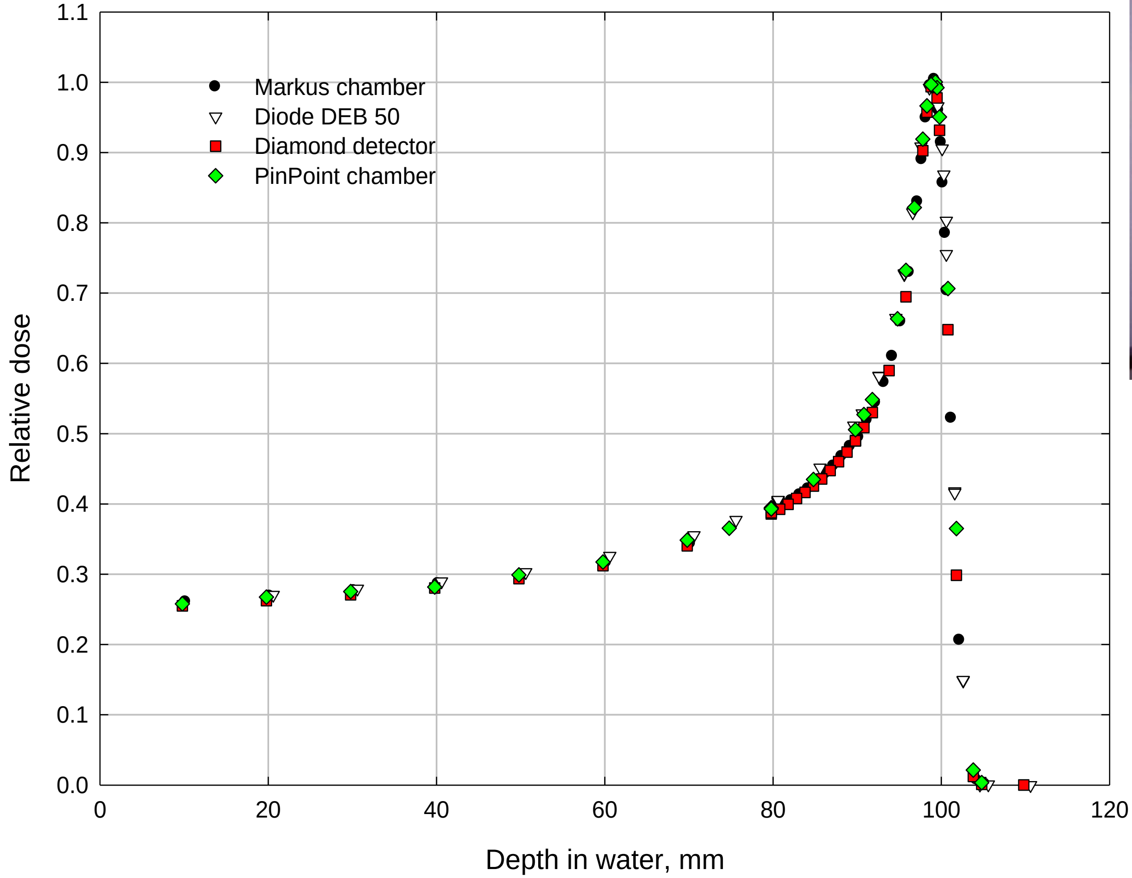
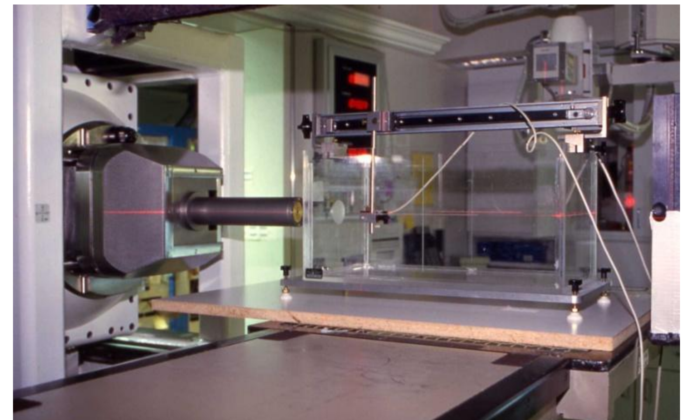
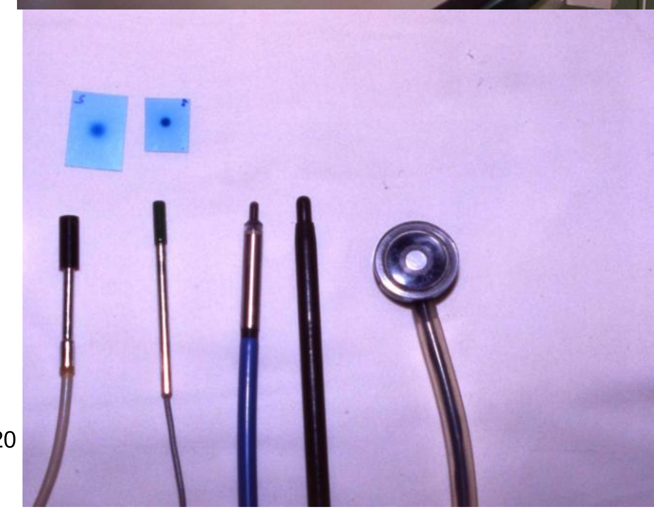
126 MeV protons, collimator 30 mm, no modulation





The user should carefully select detectors depending on beam size

# Characterization of scanned proton pencil beams

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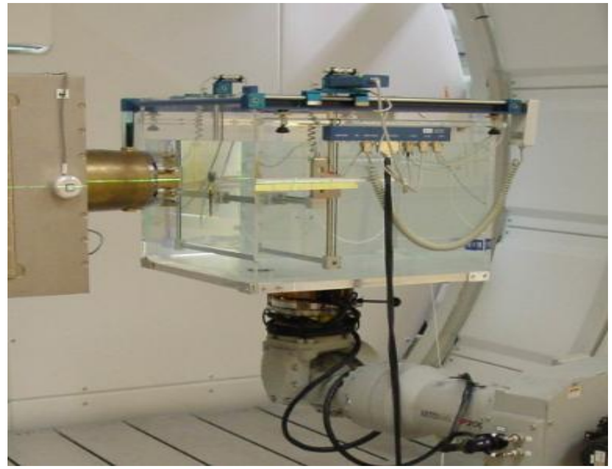
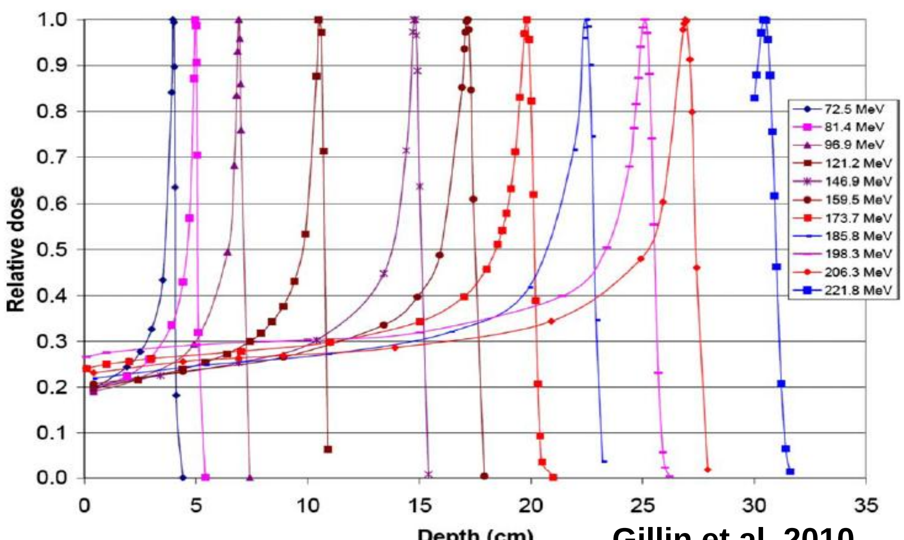
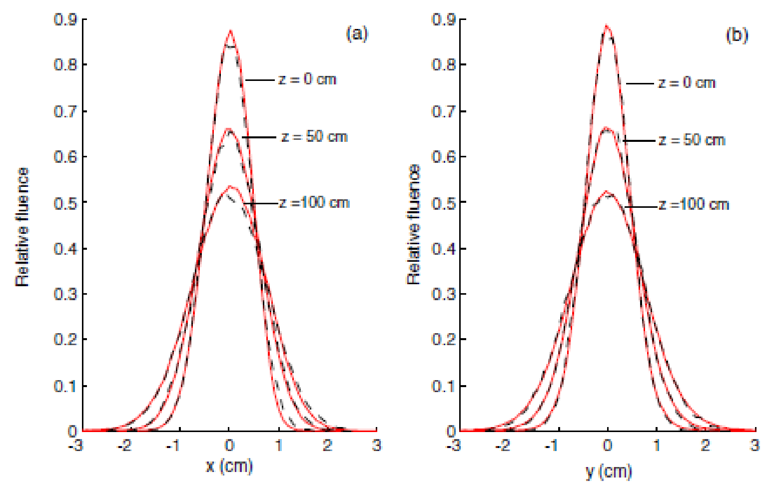


**Depth dose distribution**



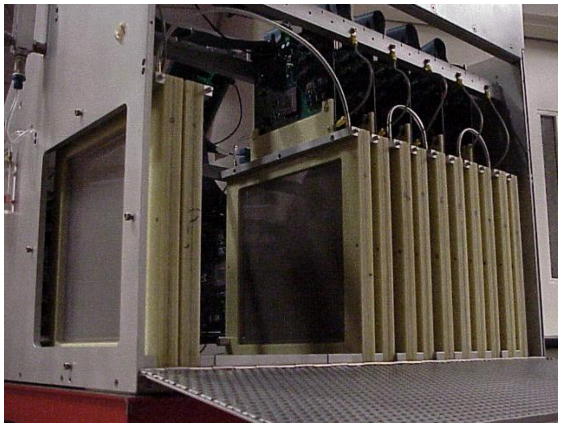

**Gillin et al, 2010**

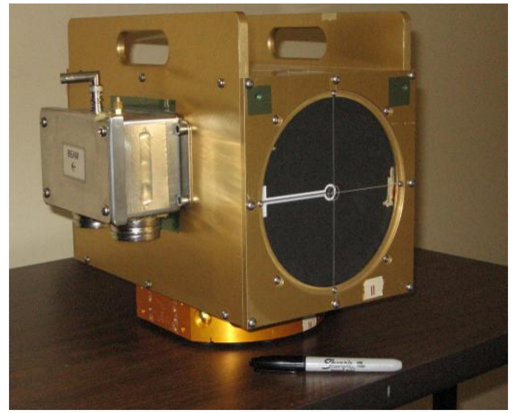
**Dose profiles**

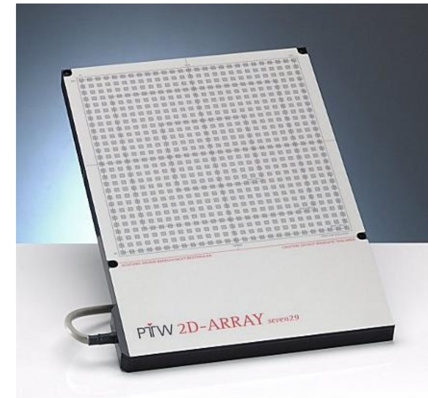



**Kimstrand et al. 2007**

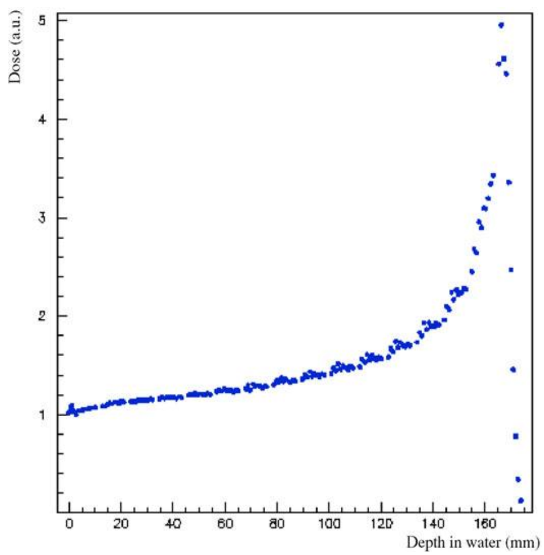
# Multi-detector systems
## for characterization and QA of proton and carbon beams



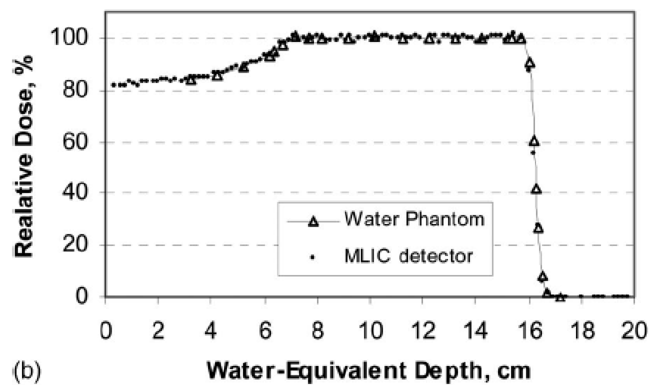





**courtesy by PTW**




**Cirio *et al.* 2004**

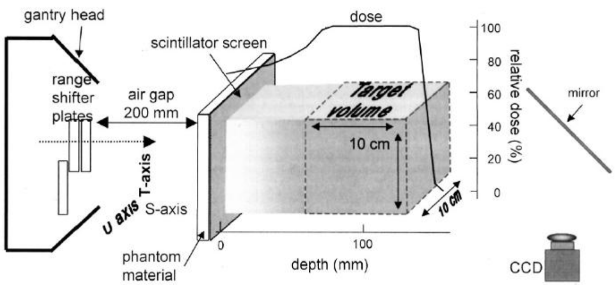



(b)

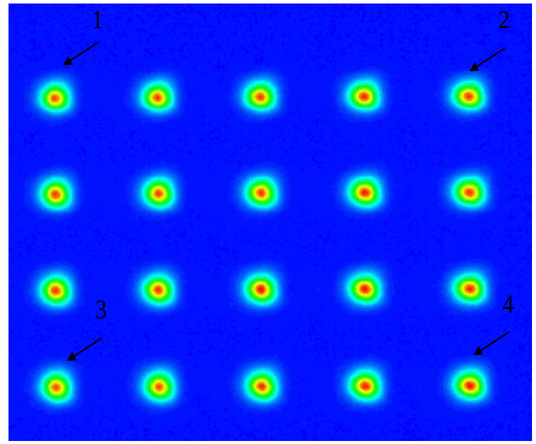
**Nichiporov *et al.* 2007**

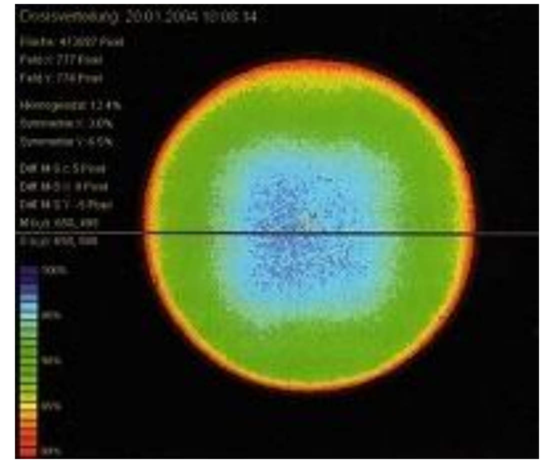

**courtesy by IBA**

# 2-D dosimetry: fluorescent screen and CCD camera

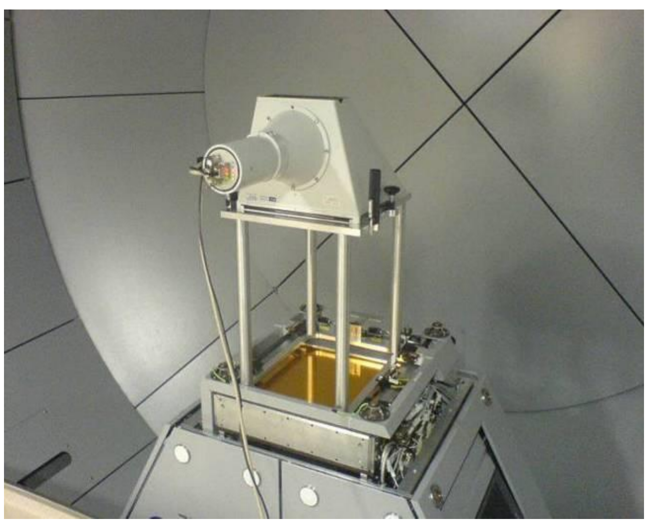



**Boon et al 2000**

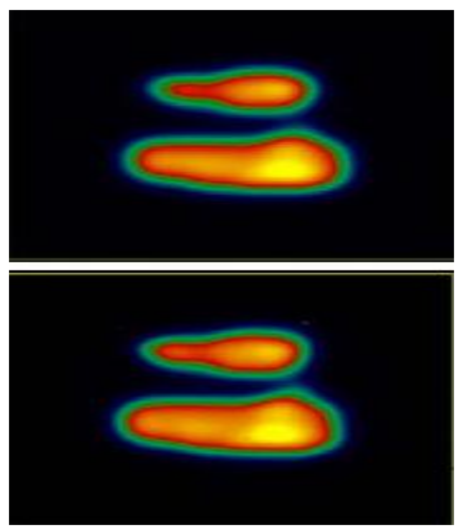


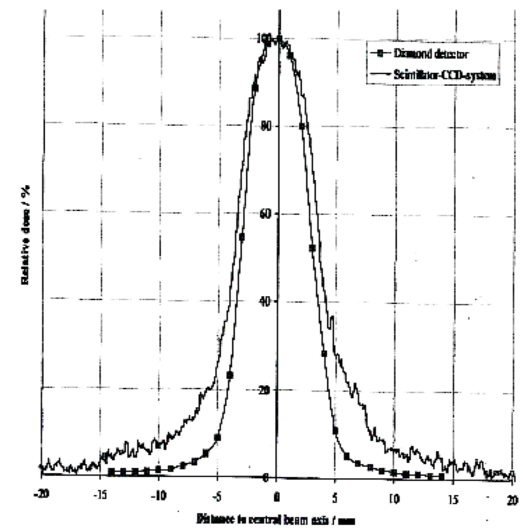
**Courtesy CMS**



**Courtesy of J. Heese**

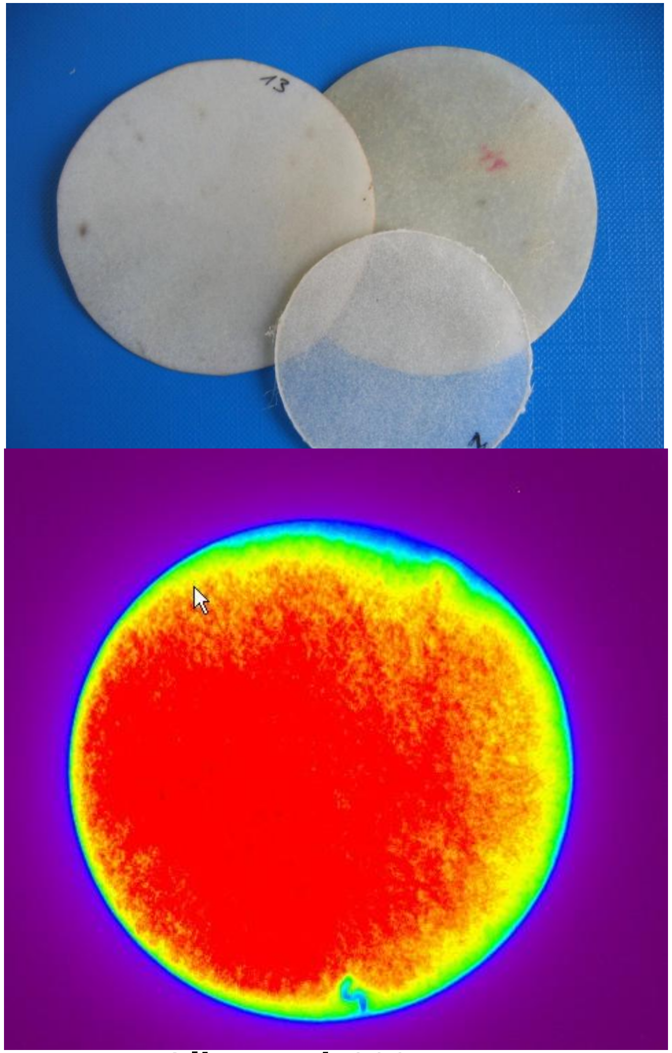


**E. Pedroni *et al.* 2005**



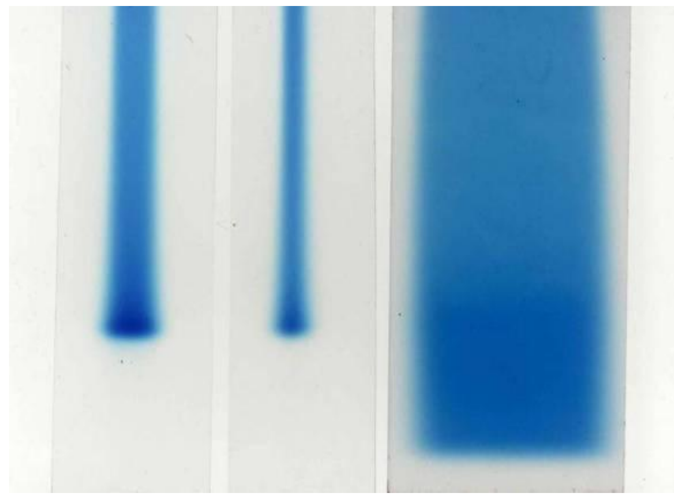

**Rosenthal *et al.* 2004**

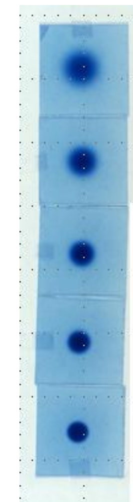
# 2-D dosimetry: TLD

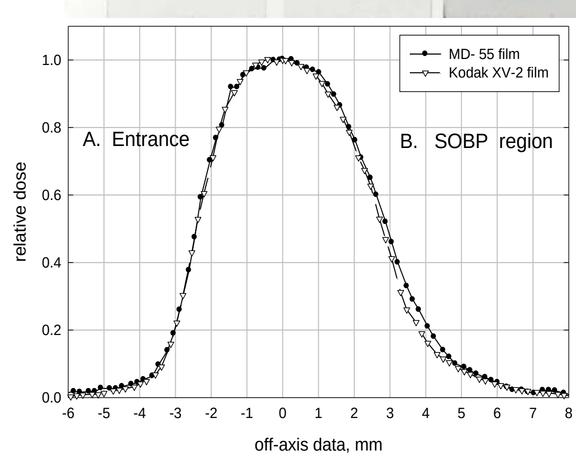


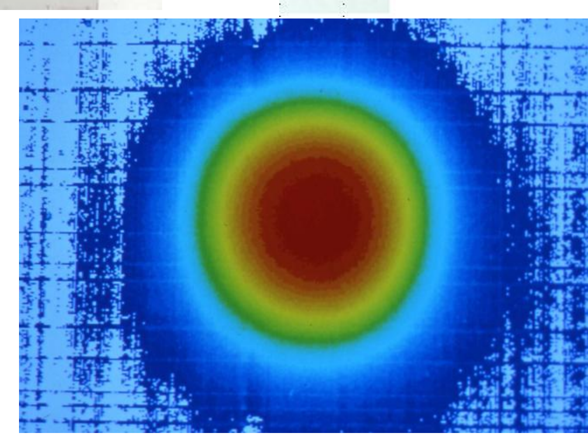
Olko *et al*. 2004

## Radiochromic film



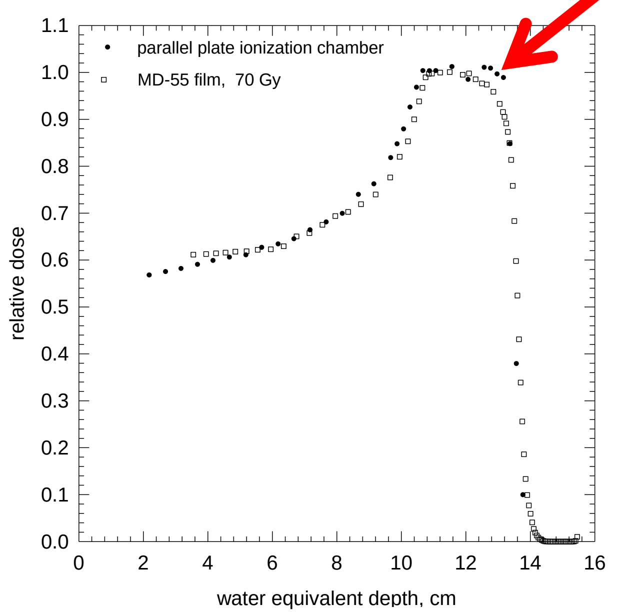


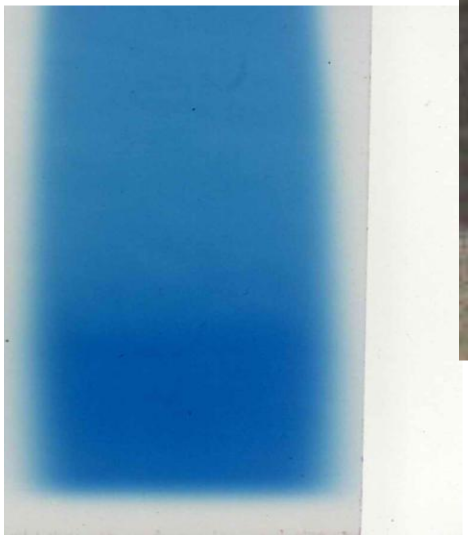


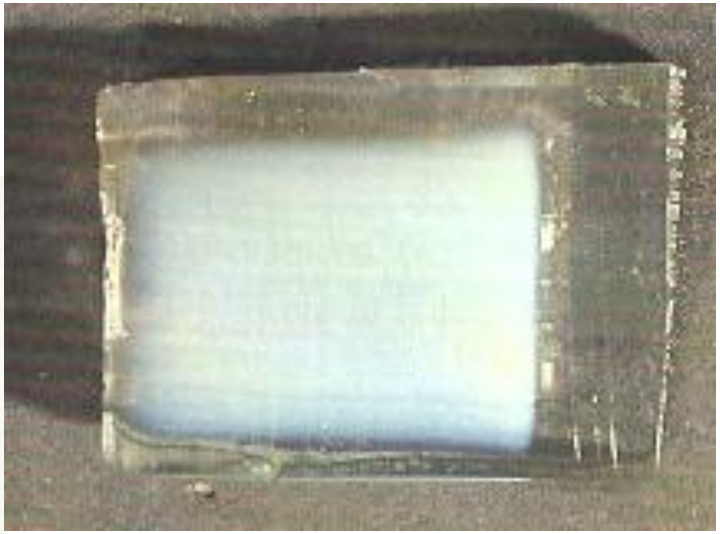



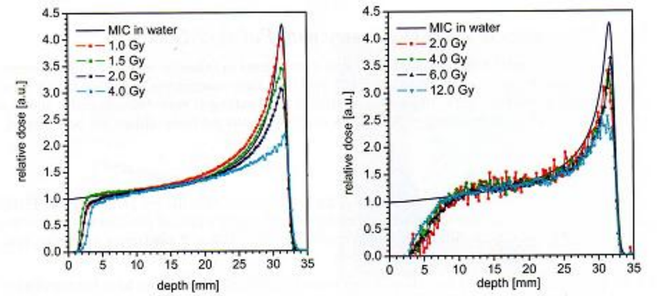
# Radiochromic films and gels for characterization of clinical proton beams

**155 MeV, modulation 3 cm, normalized at 11 cm**

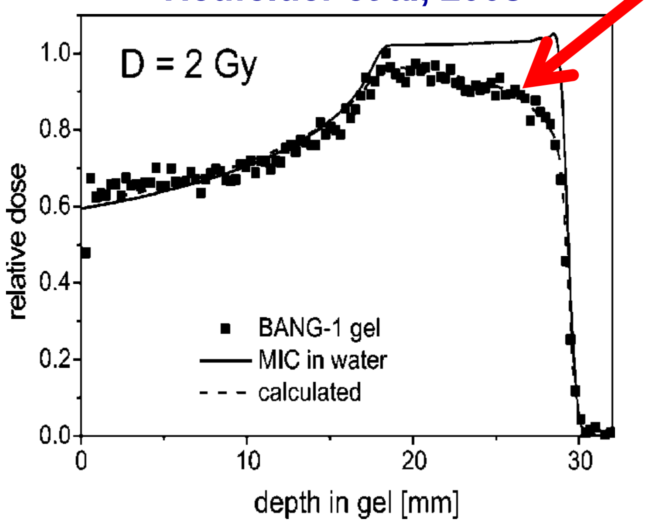







**Heufelder et al, 2003**



# Additional reading

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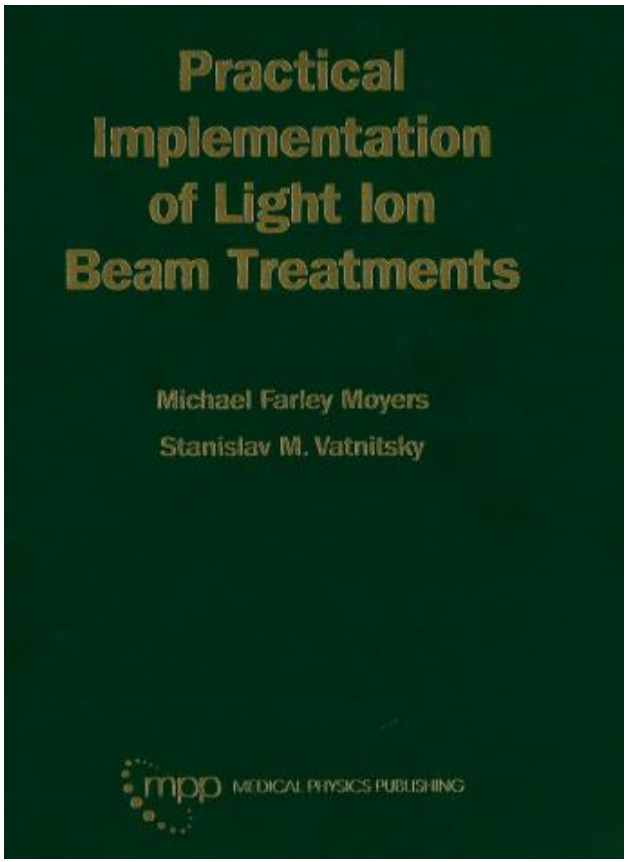


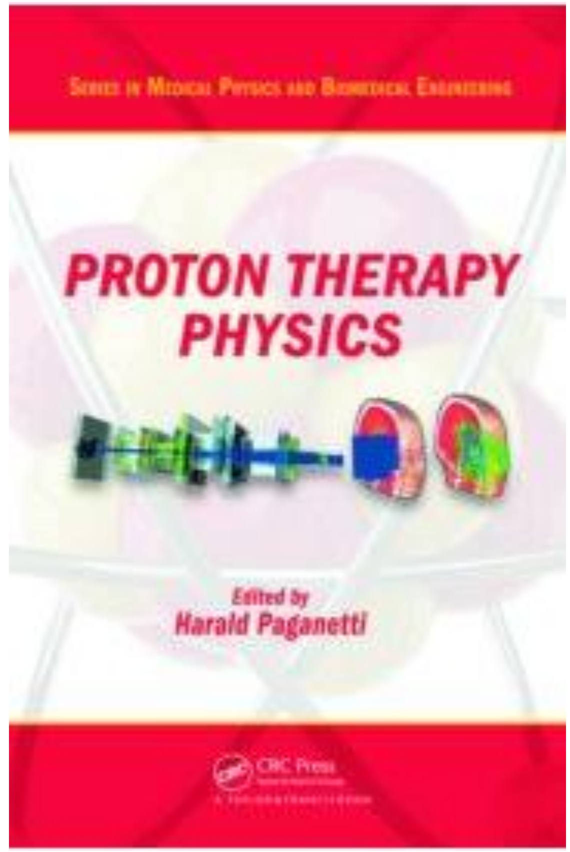


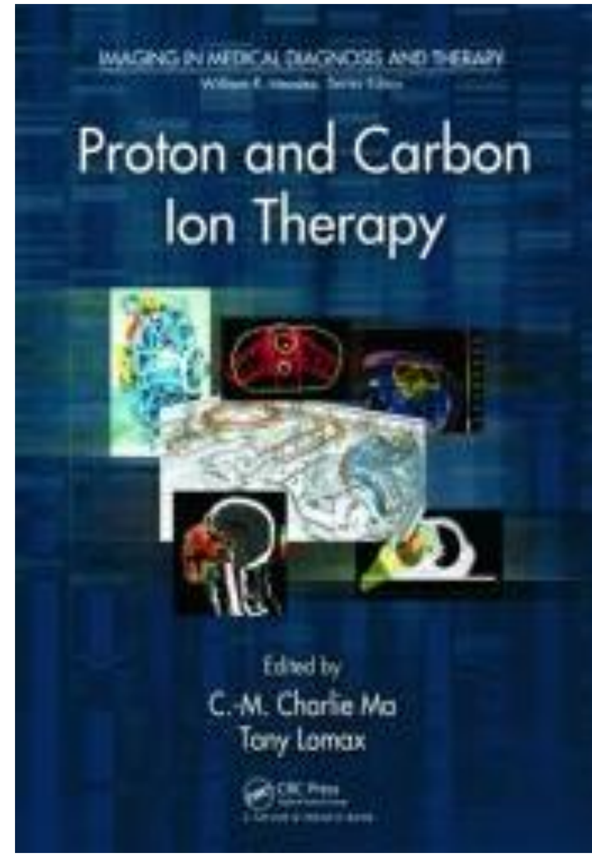

# Conclusion

MedAustron

Implementation of
ICRU Report 78
IAEA TRS 398

harmonize clinical dosimetry
at proton and heavier
ion beam facilities

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

# Acknowledgements


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