Dosimetry and beam calibration

Hugo Palmans\textsuperscript{1,2} and Stanislav Vatnitksy\textsuperscript{1}

\textsuperscript{1} EBG MedAustron GmbH, Wiener Neustadt, Austria
\textsuperscript{2} National Physical Laboratory, Teddington, UK
Overview - Learning objectives

• What are potential primary standard instruments for proton dosimetry, how do they work specifically for protons.

• The principles of reference dosimetry using calibrated ionization chambers

• Dosimetry protocols and data

• Reference dosimetry of small and scanned beams

• Instruments for micro- and nano-dosimetry
Calorimetry

Radiation energy turns into heat

heat is tiny, but measurable – our primary standards for absorbed dose are calorimeters
Calorimetry: principle

\[ D_{med} = c_{med} \Delta T \frac{1}{1 - h} \Pi k_i \]

\[ \frac{\partial T}{\partial t} = \alpha \nabla^2 T + \frac{\partial D}{c \partial t} \]

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>\Delta T/D</th>
<th>\alpha</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(j.,kg^{-1}.k^{-1})</td>
<td>(mk.,Gy^{-1})</td>
<td>(m^2.s^{-1})</td>
</tr>
<tr>
<td>water</td>
<td>4182</td>
<td>0.24</td>
<td>1.44x10^{-7}</td>
</tr>
<tr>
<td>graphite</td>
<td>704</td>
<td>1.42</td>
<td>0.80x10^{-4}</td>
</tr>
</tbody>
</table>
Water calorimeter - phantom & enclosure

Beam

Air

4°C

Cooling fluid
Water calorimetry - heat conduction

![Graphs showing relative excess heat over time for photons and protons, with categories: Total, Field, Cylinder, Probe.](image)
Water calorimetry - scanned protons

Water calorimetry - scanned protons

Fig. 3. The temperature rise signal of two thermistors for 4.5 Gy 8 cm proton box.

Gagnebin et al. (2010) *Nucl Instrum Meth B* 268:524-528
Water calorimeter – chemical heat defect

\[
\begin{align*}
H_2O^+ + e^- & \rightarrow H_2O^* \\
H_3O^+ + e_{aq}^- & \rightarrow H\cdot OH\cdot + (10^{-7} s) \\
H_2 & \rightarrow H_2O_2 + OH^- 
\end{align*}
\]
Water calorimetry / chemical heat defect protons

**Experiment**

- H$_2$O/Ar
- H$_2$O/H$_2$
- H$_2$O+NaCOOH/O$_2$

**Simulations**

- Graph showing LET (keV·mm$^{-1}$) vs. G (100 eV$^{-1}$) for various charged particles:
  - $^{60}$Co (100 MeV)
  - (1 MeV) protons
- Graph showing t (s) vs. G (100 eV$^{-1}$) for various compounds:
  - H$_2$O
  - H$_2$O$_2$
  - OH$^-$
  - OH$^-$ e$^-_{aq}$
  - H$^+$
  - H$^+$ e$^-_{aq}$
Water calorimetry / chemical heat defect protons

Water calorimetry / chemical heat defect ions

**Chemical heat defect - scanned beams**


---

**Figure 13.** Calculated increase of the chemical energy per mass element as a function of time for four different LET values (a) for an N$_2$-saturated system. At low LET values, the system reaches a stationary state (b, c), while at higher LET values it does not. The irradiation cycle (120 s beam on time, 300 s beam off time), dose rate and aqueous system used for this simulation were the same as for figures 11 and 12.
# Water calorimetry - uncertainty

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Type A</th>
<th>Type B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermistor calibration</td>
<td>—</td>
<td>0.20</td>
</tr>
<tr>
<td>Repeatability</td>
<td>0.15</td>
<td>—</td>
</tr>
<tr>
<td>Specific heat capacity</td>
<td>—</td>
<td>0.05</td>
</tr>
<tr>
<td>Cond. heat loss correction</td>
<td>—</td>
<td>0.15</td>
</tr>
<tr>
<td>Field perturbation correction</td>
<td>—</td>
<td>0.02</td>
</tr>
<tr>
<td>Profile uniformity, $k_{dd}$ ($k_r$)</td>
<td>—</td>
<td>0.02</td>
</tr>
<tr>
<td>Positioning</td>
<td>—</td>
<td>0.10</td>
</tr>
<tr>
<td>Water density</td>
<td>—</td>
<td>0.02</td>
</tr>
<tr>
<td>Non-reference condition</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Heat defect ($h$)</td>
<td>—</td>
<td>0.30</td>
</tr>
<tr>
<td>Quadratic summation</td>
<td>0.15</td>
<td>0.41</td>
</tr>
<tr>
<td>Combined relative standard</td>
<td>0.15</td>
<td>0.43</td>
</tr>
<tr>
<td>uncertainty in $D_w$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Seuntjens and Duane 2009 Metrologia 46:S39
Graphite calorimetry
Graphite calorimetry

NPL primary standard level proton calorimeter under development:
# Graphite calorimetry

<table>
<thead>
<tr>
<th>Operational mode</th>
<th>Measurand</th>
<th>Primary expression</th>
<th>Corrections</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quasi-adiabatic radiation</td>
<td>( \frac{E_{\text{rad}}}{m_{\text{core}}} )</td>
<td>( = c_p \Delta T_{\text{core}} )</td>
<td>(- \frac{\Delta E_{\text{transfer}}}{m_{\text{core}}} )</td>
</tr>
<tr>
<td>Quasi-adiabatic electrical</td>
<td>( c_p \Delta T_{\text{core}} )</td>
<td>( = \frac{\Delta E_{\text{elec}}}{m_{\text{core}}} )</td>
<td>(+ \frac{\Delta E_{\text{transfer}}}{m_{\text{core}}} )</td>
</tr>
<tr>
<td>Isothermal</td>
<td>( \frac{E_{\text{rad}}}{m_{\text{core}}} )</td>
<td>( = - \frac{\Delta E_{\text{elec}}}{m_{\text{core}}} )</td>
<td>(+ c_p \Delta T_{\text{core}} - \frac{\Delta E_{\text{transfer}}}{m_{\text{core}}} )</td>
</tr>
</tbody>
</table>

Graphite calorimetry - operation modes

**Quasi-adiabatic mode**

\[ D_m = c_{p,m} \Delta T \ k \]

**Isothermal mode**

\[ D_m = \frac{E_m}{m_m} \ k \]
Graphite - heat defect?


graphite:

\[ k_{HD} = 1.004 \pm 0.003 \]

A150:

\[ k_{HD} = 1.042 \pm 0.004 \]
Dose conversion graphite calorimetry

\[ D_w(z_w) = D_g(z_g) \cdot \left( \frac{S}{\rho} \right)_g^w \cdot k_{fl} \]

- Stopping power ratio
- Total non-elastic absorption
- Emitted protons
- Emitted deuterons
- Emitted alpha particles
Dose conversion graphite calorimetry – stopping power ratio

$S_{w,g}$ vs $z_{w-eq} / g \text{ cm}^{-2}$

- Geant4
- ICRU49
- Burns & Paul
Dose conversion graphite calorimetry – fluence correction factor

\[ z_{\text{w-eq}} / \text{g cm}^{-2} \]

\[ K_{\text{fl}} \]

60 MeV

200 MeV
Step aside – $k_{fl}$ other low-Z materials

Geant4 simulations

<table>
<thead>
<tr>
<th>$k_{fl}$</th>
<th>$k_{fl}$</th>
<th>$k_{fl}$</th>
<th>$k_{fl}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.020</td>
<td>1.04</td>
<td>1.04</td>
<td>1.04</td>
</tr>
<tr>
<td>1.015</td>
<td>1.03</td>
<td>1.03</td>
<td>1.03</td>
</tr>
<tr>
<td>1.010</td>
<td>1.02</td>
<td>1.02</td>
<td>1.02</td>
</tr>
<tr>
<td>1.005</td>
<td>1.01</td>
<td>1.01</td>
<td>1.01</td>
</tr>
<tr>
<td>1.000</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>0.995</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>0.990</td>
<td>0.98</td>
<td>0.98</td>
<td>0.98</td>
</tr>
</tbody>
</table>

230 MeV

depth / cm
Graphite calorimetry within core
### Graphite calorimetry - uncertainty

Seuntjens and Duane 2009 Metrologia 46:S39

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Type A</th>
<th>Type B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat transfer correction</td>
<td>—</td>
<td>0.10</td>
</tr>
<tr>
<td>Repeatability</td>
<td>0.05</td>
<td>—</td>
</tr>
<tr>
<td>Electrical power</td>
<td>—</td>
<td>0.14</td>
</tr>
<tr>
<td>Core mass</td>
<td>—</td>
<td>0.05</td>
</tr>
<tr>
<td>Gap effect correction</td>
<td>—</td>
<td>0.13</td>
</tr>
<tr>
<td>Graphite depth</td>
<td>—</td>
<td>0.17</td>
</tr>
<tr>
<td>Distance from source</td>
<td>—</td>
<td>0.10</td>
</tr>
<tr>
<td>Radial non-uniformity</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Quadratic summation</td>
<td>0.05</td>
<td>0.30</td>
</tr>
<tr>
<td>Combined relative standard uncertainty in $D_g$</td>
<td>0.30</td>
<td></td>
</tr>
</tbody>
</table>

$s_{w,\text{air}}$ & 1.0 \\
$k_{fl}$ & 0.5 \\
$D_w$ & 1.2

(remember water calorimetry: 0.4%)
Absolute dosimetry – Fluence based methods

\[ D_{med} = \frac{N}{A} \cdot \left( \frac{S}{\rho} \right)_{med} \]
Absolute dosimetry - Faraday cup

N protons

- entrance window
- housing
- collecting electrode
- guard
- winding

Absolute dosimetry – Activation measurement

$^{12}\text{C}(p,\text{pn})^{11}\text{C}$ reaction

$4\pi \beta\gamma$-coincidence counting

(Nichoporov 2003, Med Phys 30:972-8)
Graphite calorimetry - dose-area-product

Calorimeter: DAP(z_{ref})

Large area ion chamber: pdd(z)
Faraday cup: N/MU
S/\rho: DAP(z_0 \text{ or } z_{ref})
Integrate lateral dose profiles over all spots
Dose determination with ion chamber

\[ D_w = D_{\text{air}} \cdot S_{w,\text{air}} \cdot \rho \]

\[ D_{\text{air}} = \frac{Q}{m_{\text{air}}} \cdot W_{\text{air}} = \frac{Q}{\rho \cdot V_{\text{air}}} \cdot W_{\text{air}} \]

\( Q \): charge produced in the air of the chamber
\( W \): mean energy required to produce an ion-pair in air

Unfortunately, for commercially available chambers, the volume \( V \) is not known with the necessary accuracy (would otherwise be a primary standard!).

We have to rely on methods other than “first principles”, which involve the use of ion chamber calibration factors

(courtesy Pedro Andreo)
Simple absorbed dose protocol

\[ D_{w,Q} = M_Q N_{D,w,Q} \]

But we have \( N_{D,w,Q_0} \) with \( Q_0 \neq Q \) →

\[ D_{w,Q} = M_Q N_{D,w,Q_0} k_{Q,Q_0} \]

This is formalism of IAEA TRS-398 and ICRU Report 78
Derivation $k_{Q,Q_0}$

\[ D_{w,Q_0} = D_{\text{air},Q_0} \quad (s_{w,\text{air}})_{Q_0} p_{Q_0} \]

\[ D_{w,Q} = D_{\text{air},Q} \quad (s_{w,\text{air}})_Q p_Q \]
Derivation \( k_{Q, Q_0} \)

\[
D_{w, Q_0} = M_{Q_0} N_{D, air, Q_0} \left( s_{w, air} \right)_{Q_0} p_{Q_0} \text{ with } N_{D, air, Q_0} = \frac{(W_{air})_{Q_0}}{\rho_{air} V}
\]

\[
D_{w, Q} = M_{Q} N_{D, air, Q} \left( s_{w, air} \right)_{Q} p_{Q} \text{ with } N_{D, air, Q} = \frac{(W_{air})_{Q}}{\rho_{air} V}
\]

\[
k_{Q, Q_0} = \frac{N_{D, w, Q_0}}{N_{D, w, Q_0}} = \frac{D_{w, Q}/M_{Q}}{D_{w, Q_0}/M_{Q_0}} = \frac{N_{D, air, Q} \left( s_{w, air} \right)_{Q} p_{Q}}{N_{D, air, Q_0} \left( s_{w, air} \right)_{Q_0} p_{Q_0}}
\]

\[
k_{Q, Q_0} = \frac{(W_{air})_{Q} \left( s_{w, air} \right)_{Q} p_{Q}}{(W_{air})_{Q_0} \left( s_{w, air} \right)_{Q_0} p_{Q_0}} \text{ note that in AAPM notation } s_{w, air} = \left( \frac{L}{\rho} \right)^{w}_{air}
\]
Factorisation

\[ D_{w,Q} = [M_Q] \left[ \frac{1}{\rho_{air} V_{cav}} \right] [(W_{air})_Q (s_{w,air})_Q p_Q] \]

Helpful to compare codes of practice:

e.g. TRS-398: \[ \left[ \frac{1}{\rho_{air} V_{cav}} \right] = \frac{N_{D,w,Q_0}}{(W_{air})_Q (s_{w,air})_Q p_{Q_0}} \]

ICRU 59: \[ \left[ \frac{1}{\rho_{air} V_{cav}} \right] = \frac{N_K(1-g)A_{wall}A_{ion}}{(W_{air})_c s_{wall,g} (\mu_{en}/\rho)_{air,wall} K_{hum}} \]
$W_{\text{air}} / \text{protons}$

TRS-398

$W_{\text{air,p}} / \text{eV}$

Energy / MeV

Average

Median: IAEA TRS-398
$W_{\text{air}} / \text{protons}$

Calorimetry data Jones 2006 Rad Phys Chem 75:541 + more recent
Ion chambers: water to air stopping power ratio

![Graph showing the relationship between $E_{eff}$ (MeV) and $(S/\rho)_air$ for different studies.]

- Janni (1982)
- Medin and Andreo (1997)
- ICRU report 49 (1993)
Ion chambers – perturbation correction factors for proton beams

Overall perturbation correction factor

\[ p_Q = 1 \] assumed in IAEA TRS-398 and ICRU 78

Gradient correction factors

\[ p_{\text{dis}} = 1 \] assumed in SOBP or plateau

Secondary electron correction factors

ignored in IAEA TRS-398 and ICRU 78
Gradient corrections for cylindrical ionization chambers

**Figure 2.** Measured (□) and calculated (broken line) increase of the relative dose as a function of wall thickness for an NE2571 chamber in a PMMA phantom in the 75 MeV non-modulated beam at a residual range of 2.65 cm.
Ion chambers - cavity theory for $p_{cav}$

$$D_{med} = D_{air} \cdot \left( \frac{S^{SA}}{\rho} \right)_{med} \cdot \left( \frac{S}{\rho} \right)_{air} \cdot p_{cav,e}$$

$$p_{cav,e} = \left( \frac{S^{SA}}{\rho} \right)_{med} / \left( \frac{S}{\rho} \right)_{air}$$
Compared with Medin and Andreo (1997)

The graph shows the comparison between the cavity model monoE and the data from Medin and Andreo (1997). The y-axis represents the pressure or flow rates ($p_{cav} \text{ or } s_{w,\text{air}}$), and the x-axis shows the log of the effective energy ($\log(E_{\text{eff}})$). The data from Medin and Andreo (1997) is depicted as black squares, while the cavity model monoE is shown as a green line. The graph includes a plateau at $0.97 \times 10^{-3}$.
Ion chambers - cavity theory for $p_{\text{wall}}$

\[ D_{\text{med}} = D_{\text{air}} \cdot \left( \frac{S_{\text{SA}}}{\rho} \right)_{\text{wall}} \cdot \left( \frac{S}{\rho} \right)_{\text{med}} \]

\[ = D_{\text{air}} \cdot \left( \frac{S_{\text{SA}}}{\rho} \right)_{\text{med}} \cdot p_{\text{wall, e}} \]

\[ p_{\text{wall, e}} = \left( \frac{S}{\rho} \right)_{\text{med}} \cdot \left( \frac{S_{\text{SA}}}{\rho} \right)_{\text{wall}} \div \left( \frac{S_{\text{SA}}}{\rho} \right)_{\text{air}} \]
Secondary electron $\rightarrow \rho_{\text{wall}}$ and $\rho_{\text{cel}}$

Palmans 2011, IDOS

![Graph showing the relationship between proton energy and $\rho_{\text{wall}}$ and $\rho_{\text{cel}}$. The graph includes different materials such as A150, graphite, and aluminium.](attachment:graph.png)
Ionization chamber perturbations

D_{W,NE2571}/D_{W,Ch}

Nylon66-Al
PMMA-Al & PTW30001
ExrT2
A150-Al & NE2581
C-C & PTW30002
IC18

Chamber #
In summary: $k_{Q,Q_0} - Q_0$ is $^{60}\text{Co}$

Palmans 2012, Dosimetry, In: Proton Therapy Physics / Paganetti
In summary: $k_{Q,Q_0} - Q_0$ is a proton beam for ALL chambers !!!
Influence quantities

Pressure, temperature, humidity

Polarity effects

Ion recombination
Initial recombination
Volume recombination
Volume recombination - continuous radiation - plane-parallel chamber

\[ k_s = 1 + \frac{m^2 g}{V^2} i_{sat} \]

\[ k_s = \frac{(\frac{V_1}{V_2})^2 - 1}{(\frac{V_1}{V_2})^2 - \frac{M_1}{M_2}} \]

\[ \rightarrow \text{2-voltage: quadratic} \]
Volume recombination - pulsed radiation - plane-parallel chamber

\[ k_s = \frac{u}{\ln(1 + u)} \]

\[ \approx 1 + \frac{u}{2} \]

\[ u = \frac{\alpha}{e(k^- + k^+)} \frac{r d^2}{V} \]

-> 2-voltage: linear
Ion recombination in ionization chambers

Dose rate (Gy s\(^{-1}\))

Time (in 1/8 revolutions)

z = 23 mm
z = 20 mm
z = 10 mm
surface

Equation (1)
Pulsed (Boag)
Markus 1
Markus 2
Ion recombination for time-dependent spatial ionisation distribution in cavity

Similar as for IMRT deliveries [4], in the near saturation regime:

\[ p_{ion} = \frac{i_{sat}}{i_V} \approx 1 + \frac{A}{V} + \frac{B}{V^2} \int \int \lambda_{sat}^2(z, t) \, dz \, dt \]

where \( V \) is the polarizing voltage, \( \dot{\lambda}_{sat}(z) \) is the linear ionization rate density, \( A \) is an initial recombination parameter and \( B \) a volume recombination parameter.
Cumulative recombination patterns and voltage-dependence

continuous

pulsed

250 μs pulse
Volume recombination vs pulse length

![Graph showing the relationship between volume recombination and pulse length](image-url)

- Pulsed
- Continuous
- Pulse 100us
- Pulse 150us
- Pulse 250us
- Pulse 500us
Volume recombination vs pulse length

![Graph showing volume recombination vs pulse length](chart)
Volume recombination vs pulse length

\[ k_{ion} = 1 + a \frac{V \exp(-0.0023T_{pulse})}{V^2} \]
Beam monitor calibration of scanned beams
Reference dosimetry scanned beams

Gillin et al 2010
Med Phys 37:154

\[ D_{AP}^{BP}_{w,Q} = M_{Q}^{BP} N_{DAP,w,Q_{0}}^{BP} \kappa_{Q,Q_{0}}^{BP} \]

\[ N = \frac{D_{AP}^{\infty}_{w,Q}}{(S/\rho)_{w}} = \frac{D_{AP}^{BP}_{w,Q}}{(S/\rho)_{w}} \times CF \]
Reference dosimetry scanned beams

Gillin et al 2010
Med Phys 37:154

Fig. 5. Integral doses in Gy mm²/MU at the depth of 2 cm as a function of energy. Circles are measured integral doses; squares are corrected integral doses; and dashed line is the correction factors.
Large-area chamber - cross calibration

\[ N_{\text{DAP},w,Q_{\text{cross}}} = \frac{[M_{Q_{\text{cross}}} N_{D,w,Q_0} k_{Q_{\text{cross}},Q_0}]_{\text{REF}}}{[M_{Q_{\text{cross}}}]_{\text{BP}}} \times \int\int_A \text{OAR}(x,y)\,dx\,dy \]
Calculation $\kappa_{Q,Q_0}$

$$\kappa_{Q,Q_0} = \frac{(W_{\text{air}})_Q(s_{w,\text{air}})_Q p_Q}{(W_{\text{air}})_{Q_0}(s_{w,\text{air}})_{Q_0} p_{Q_0}}$$

Main problem is $p_{Q_0}$

Same assumptions for photon and electrons as pp chambers
Reference dosimetry scanned beams

Jaekel et al Phys Med Biol 2004

$$D_{w,Q}^{cyl} = M_Q^{cyl} N_{D,w,Q_0}^{cyl} k_{Q,Q_0}^{cyl}$$

$$N = \frac{D_{w,Q}^{cyl} \Delta X \Delta Y}{(S/\rho)_w}$$
# Uncertainty of $DAP_w$ determination

<table>
<thead>
<tr>
<th>Contribution</th>
<th>BP xcal in $^{60}$Co</th>
<th>BP xcal in 200 MeVp</th>
<th>FA cal in $^{60}$Co</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{D,w,Q_0}^{FA}$</td>
<td>0.55</td>
<td>0.55</td>
<td>0.55</td>
</tr>
<tr>
<td>$k_{Q,Q_0}^{FA}$</td>
<td></td>
<td></td>
<td>1.70</td>
</tr>
<tr>
<td>uniformity $\Delta x \Delta y$</td>
<td></td>
<td></td>
<td>0.50</td>
</tr>
<tr>
<td>$k_{Q_{cross},Q_0}^{FA}$</td>
<td></td>
<td>1.70</td>
<td></td>
</tr>
<tr>
<td>$k_{Q,Q_{cross}}^{BP}$</td>
<td>1.60</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>$(k_{ion})_Q^{FA}$</td>
<td></td>
<td></td>
<td>0.50</td>
</tr>
<tr>
<td>$DAP_{w,Q}^{\infty}$</td>
<td>1.7-1.8</td>
<td>1.8-1.9</td>
<td>2.0</td>
</tr>
<tr>
<td>$(S/\rho)_w$</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>$N = \frac{DAP_{w,Q}^{\infty}}{(S/\rho)_w}$</td>
<td>2.6-2.7</td>
<td>2.7</td>
<td>2.8</td>
</tr>
</tbody>
</table>
Microdosimetry
Mini-TEPC

Davide Moro, INFN-LNL

Aluminium
Rexolite®
Sensitive Volume: 0.9x0.9 mm²

Cathode (A-150 plastic)

Gas In
Gas Out

Rollet et al 2010, Rad Prot Dosim 143:445
Si-microtelescope

Andrea Pola, Politecnico di Milano

Agosteo et al 2010
Radiat Meas 45:1284
Microcalorimetry

Sebastian Galer PhD:


![Graph and AFM image of a submicron SQUID loop with schematic indication of a rectangular submicron thin-film absorber deposited in the center (the SQUID)](image-url)
Nanodosimetry
Shchemelinin et al 1997 In: Proc MicroDos 12
PTB: Hilgers et al Rad Prot Dosim 126:467
LLU: Schulte et al 2008 Z Med Phys 18:286
Schulte et al 2011 AIP Conf Proc 1345:249
Jet Counter

Bantsar et al 2004 Rad Prot Dosim 110:845
Schulte et al 2011 AIP Conf Proc 1345:249
Fig. 5. Measured and calculated cluster size distributions of 20 MeV protons at an impact parameter of 2.7 nm (see text).
Conclusions – take home messages

• Calorimeters and calibrated ionization chambers established for proton beam reference dosimetry; main uncertainties:
  - water calorimetry: heat defect
  - graphite calorimetry: conversion $D_g \rightarrow D_w$
  - ionometry: product $(W_{air})_Q(s_{w,air})_Q + ^{60}\text{Co data}$

• Factorisation $D_{w,Q} = [M_Q] \left[ \frac{1}{\rho_{air}V_{cav}} \right] [(W_{air})_Q(s_{w,air})_Q p_Q]$ allows easy comparison between codes of practice

• Advantage of calibrations in proton beams
• Issues scanned beams (DAP vs N, ion recombination)
• Some examples microdosimetry & nanodosimetry instruments
Reading


H. Palmans, “Monte Carlo for proton and ion beam dosimetry,” In: Monte Carlo Applications in Radiation Therapy, Ed. F. Verhaegen and J Seco, (London: Taylor & Francis), 2013, pp. 185-199