Standards for proton and heavy ion beams

Ronald E. Tosh, PhD
Dosimetry Group
Radiation Physics Division
Physical Measurement Laboratory
National Institute of Standards and Technology
Gaithersburg, MD USA

NIST
National Institute of Standards and Technology
U.S. Department of Commerce

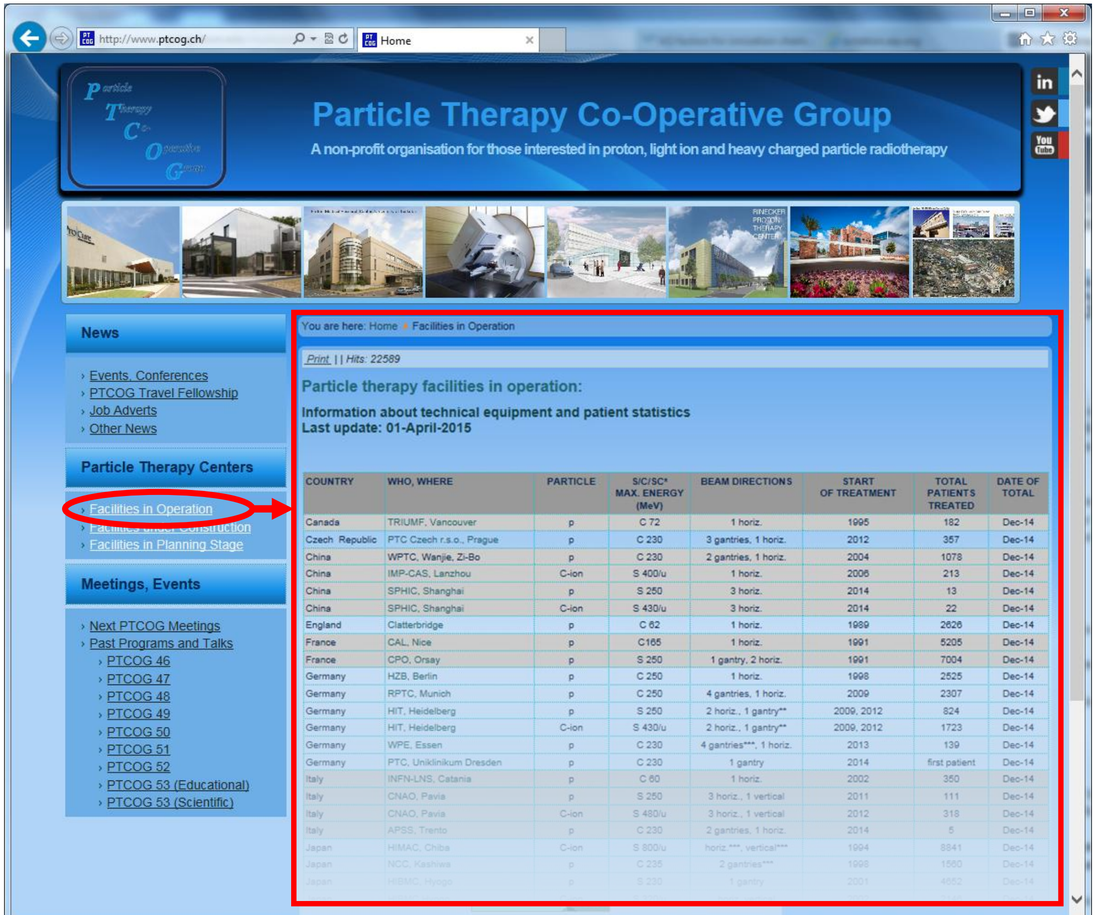
SAM – Reference Dosimetry for Beam Modalities other than MV Photons
57th Annual AAPM Meeting
Anaheim Convention Center, Anaheim, CA
Thursday, July 16, 2015, 1:15 p.m.
TH-E-304-2

Outline -

- **Traceability chain for proton and ion therapy beams**
  - Current and projected particle facilities
  - Traceability chain of protons and ions compared to Co-60
- **Primary standards for absorbed dose**
  - Physical basis of operation
  - Example development efforts
- **Effect on end-user dosimetry in the next 5-10 years**
  - Implications for protocols
  - How dissemination might work
  - Reductions in measurement uncertainty

Treatment modalities available in the clinic -

http://www.ptcog.ch



COUNTRY	WHO, WHERE	PARTICLE	S/C/SC* MAX. ENERGY (MeV)	BEAM DIRECTIONS	START OF TREATMENT	TOTAL PATIENTS TREATED	DATE OF TOTAL
Canada	TRIUMF, Vancouver	p	C 72	1 horiz.	1995	182	Dec-14
Czech Republic	PTC Czech r.s.o., Prague	p	C 230	3 gantries, 1 horiz.	2012	357	Dec-14
China	WPTC, Wanjie, Zi-Bo	p	C 230	2 gantries, 1 horiz.	2004	1078	Dec-14
China	IMP-CAS, Lanzhou	C-ion	S 400/u	1 horiz.	2006	213	Dec-14
China	SPHIC, Shanghai	p	S 250	3 horiz.	2014	13	Dec-14
China	SPHIC, Shanghai	C-ion	S 430/u	3 horiz.	2014	22	Dec-14
England	Clatterbridge	p	C 62	1 horiz.	1989	2626	Dec-14
France	CAL, Nice	p	C165	1 horiz.	1991	5205	Dec-14
France	CPO, Orsay	p	S 250	1 gantry, 2 horiz.	1991	7004	Dec-14
Germany	HZB, Berlin	p	C 250	1 horiz.	1998	2525	Dec-14
Germany	RPTC, Munich	p	C 250	4 gantries, 1 horiz.	2009	2307	Dec-14
Germany	HIT, Heidelberg	p	S 250	2 horiz., 1 gantry**	2009, 2012	824	Dec-14
Germany	HIT, Heidelberg	C-ion	S 430/u	2 horiz., 1 gantry**	2009, 2012	1723	Dec-14
Germany	WPE, Essen	p	C 230	4 gantries***, 1 horiz.	2013	139	Dec-14
Germany	PTC, Uniklinikum Dresden	p	C 230	1 gantry	2014	first patient	Dec-14
Italy	INFN-LNS, Catania	p	C 60	1 horiz.	2002	350	Dec-14
Italy	CNAO, Pavia	p	S 250	3 horiz., 1 vertical	2011	111	Dec-14
Italy	CNAO, Pavia	C-ion	S 480/u	3 horiz., 1 vertical	2012	318	Dec-14
Italy	APSS, Trento	p	C 230	2 gantries, 1 horiz.	2014	5	Dec-14
Japan	HIMAC, Chiba	C-ion	S 800/u	horiz.***, vertical***	1994	8841	Dec-14
Japan	NCC, Kashiwa	p	C 235	2 gantries***	1998	1560	Dec-14
Japan	HIBMC, Hyogo	p	S 230	1 gantry	2001	4652	Dec-14

Summary as of 01-April-2015

p, C^{+}, both

Location	Active	Construction
US	16	14
World	45, 4, 4	29, 2, 2

What is ‘traceability’?

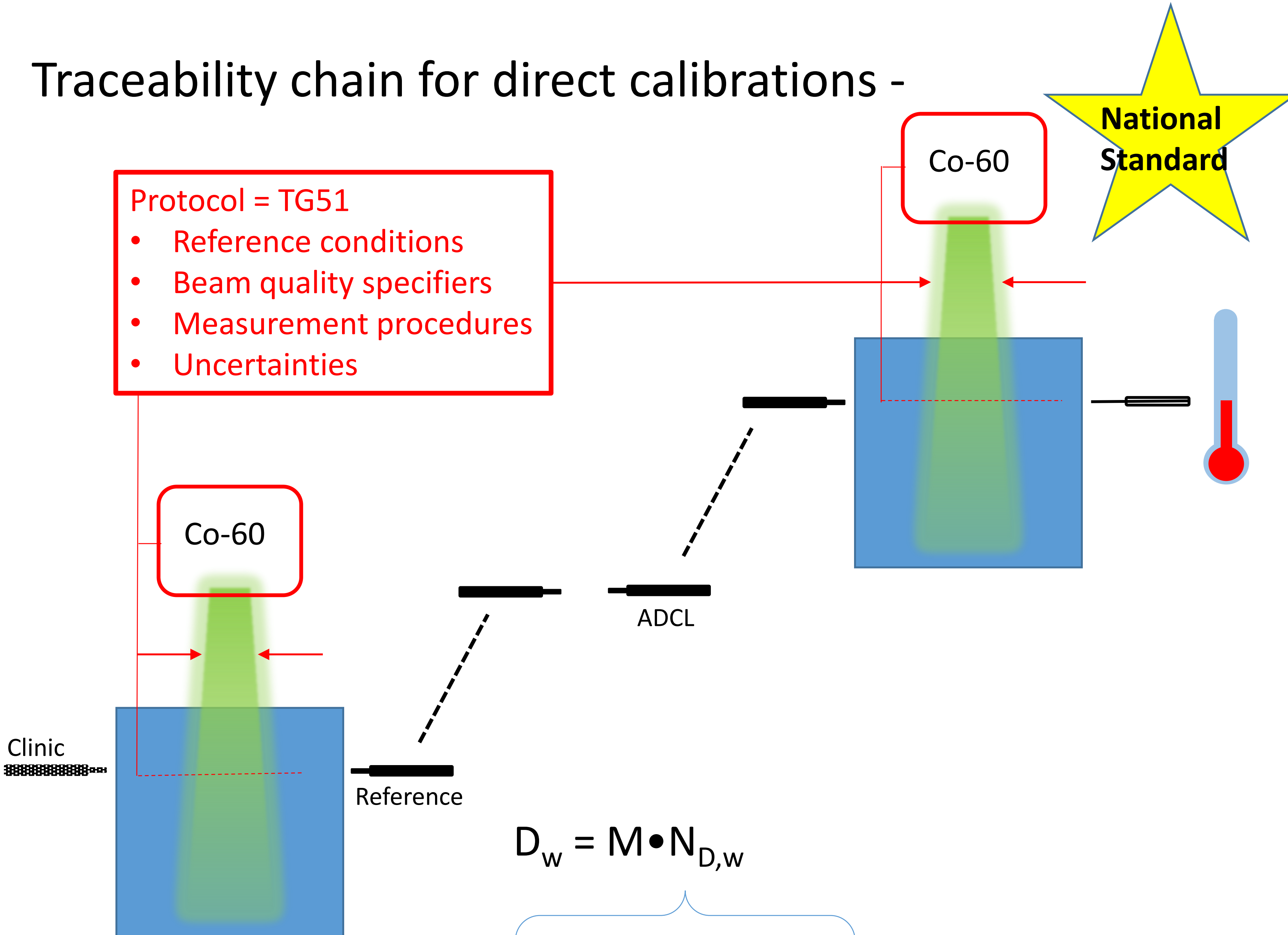
- *Traceability is a **property** of a dose **measurement**! It ensures that the **measurement** can be related to the **national dose standard “D_w”** maintained by a **PSDL** through a documented unbroken chain of calibrations, each contributing to the **measurement** uncertainty.*
    - **PSDL**: Primary Standards Dosimetry Laboratory
        - e.g. NIST, NRCC, …

- *The national dose standard Dw is realized at the PSDL using a **primary instrument**.*
    - **Primary instrument:** for direct realization of absorbed dose
        - e.g. calorimeter, Fricke solution, ionization chamber, Faraday cup, …

What is ‘traceability’? (continued)

- *The relationship (or cross calibration) between the measurement and the national standard for dose, Dw, is done by following accepted* ***protocols.***
  - **protocol**: prescribes reference beam conditions, procedures for conducting and correcting measurements, …
    - e.g. AAPM TG-51, IAEA TRS-398, …
- Traceability can be **direct** or **indirect** …

Traceability chain for direct calibrations -



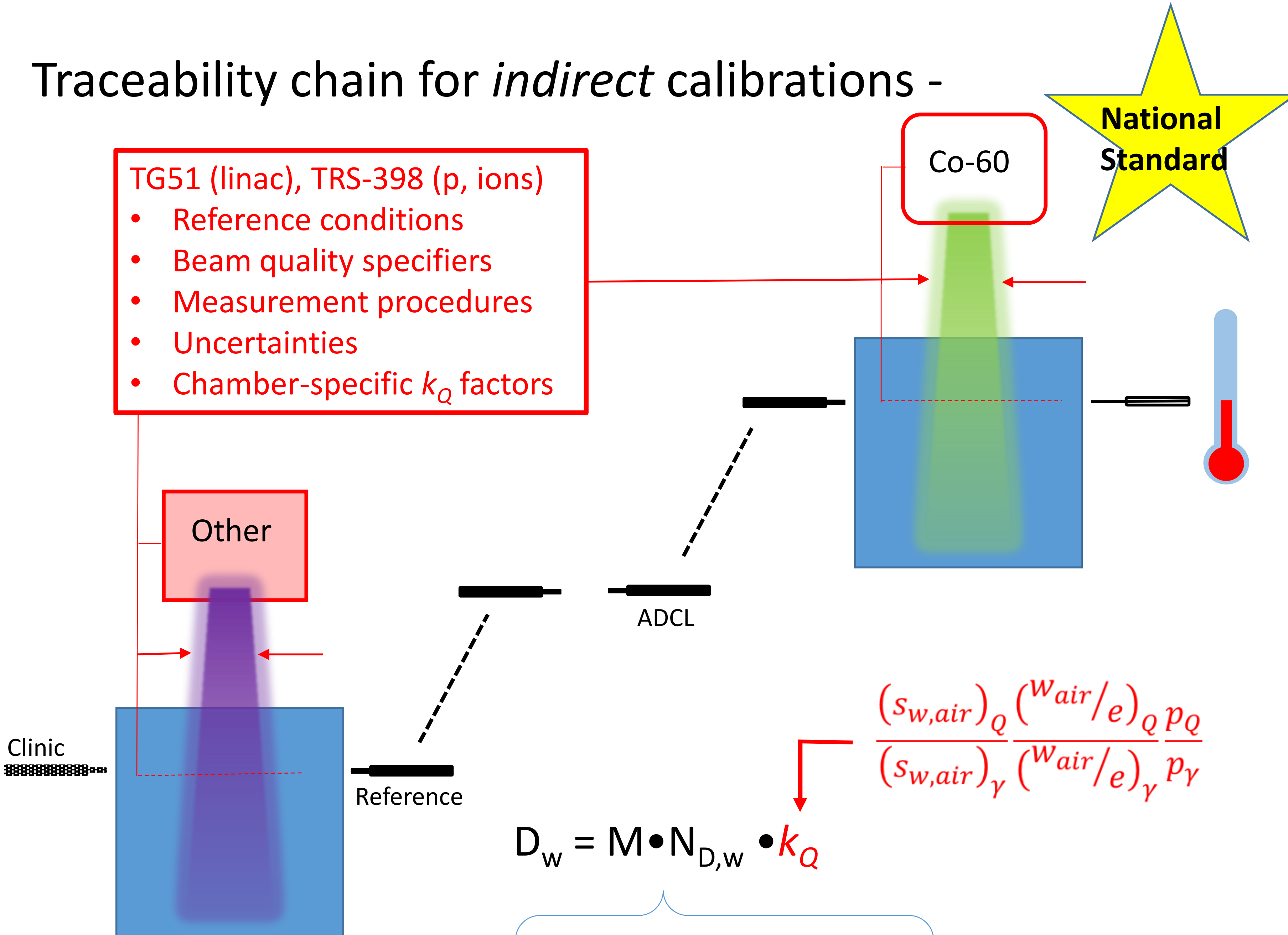
$$D_w = M \bullet N_{D,w}$$

$$\pm \sigma_{clinic} \pm \sigma_{ADCL} \pm \sigma_{NIST}$$

Traceability chain for *indirect* calibrations -

TG51 (linac), TRS-398 (p, ions)

- Reference conditions
- Beam quality specifiers
- Measurement procedures
- Uncertainties
- Chamber-specific k_Q factors



$$\frac{\left(s_{w,air}\right)_Q}{\left(s_{w,air}\right)_\gamma}\frac{\left(W_{air}/e\right)_Q}{\left(W_{air}/e\right)_\gamma}\frac{p_Q}{p_\gamma}$$

$$D_w = M \bullet N_{D,w} \bullet k_Q$$

$$\pm\,\sigma_{clinic} \pm \sigma_{ADCL} \pm \sigma_{NIST} \pm \sigma_{kQ}$$

Dosimeter calibration for p and light-ion beams -

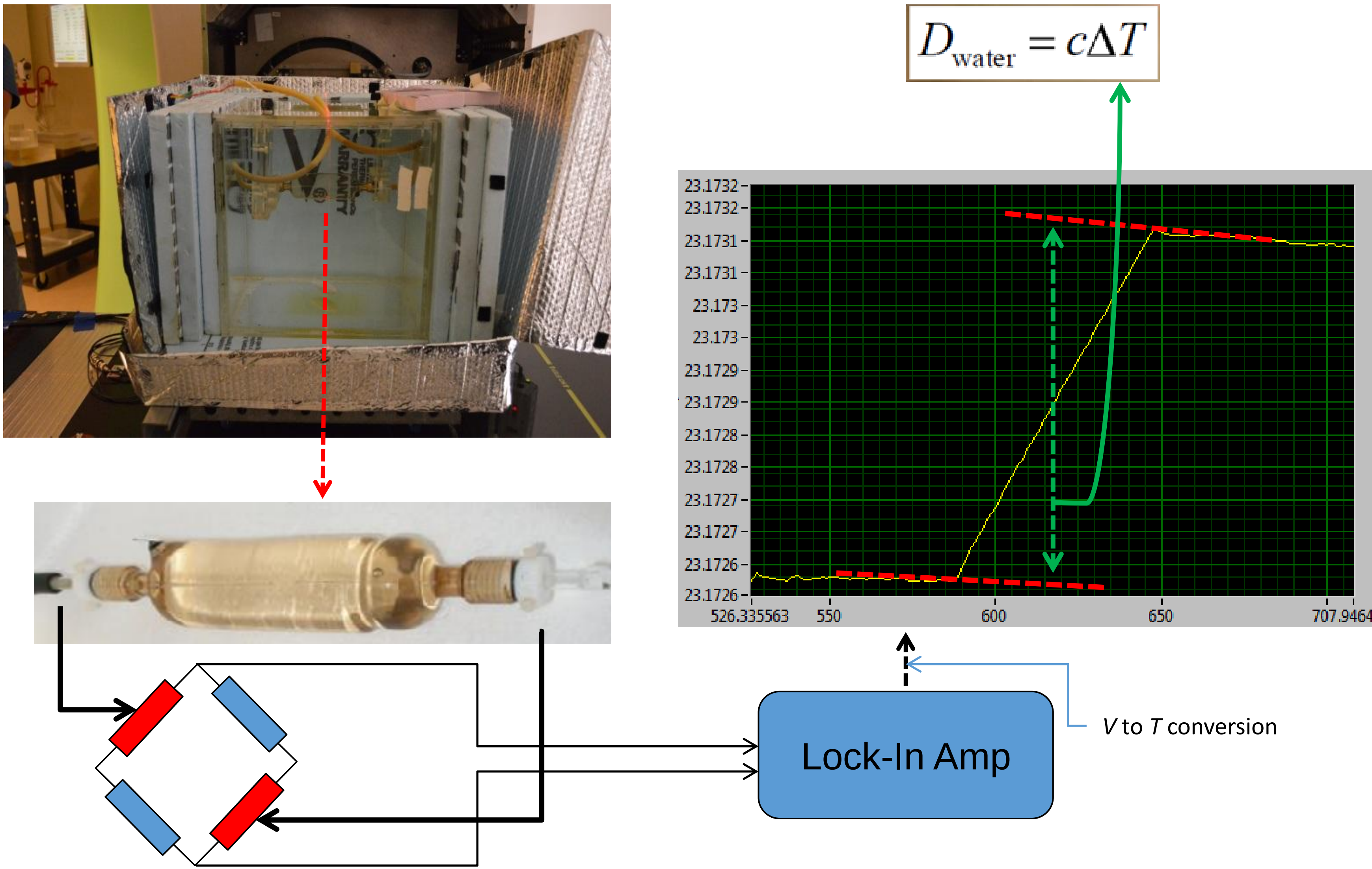
- Need an appropriate absolute dosimeter[1]
  - Faraday cups used in the early days
  - Other options include: Fricke dosimetry, ionization chambers, carbon activation, calorimetry
  - ICRU 78 (2007) → calorimetry, *when available…*

NIST, 2011

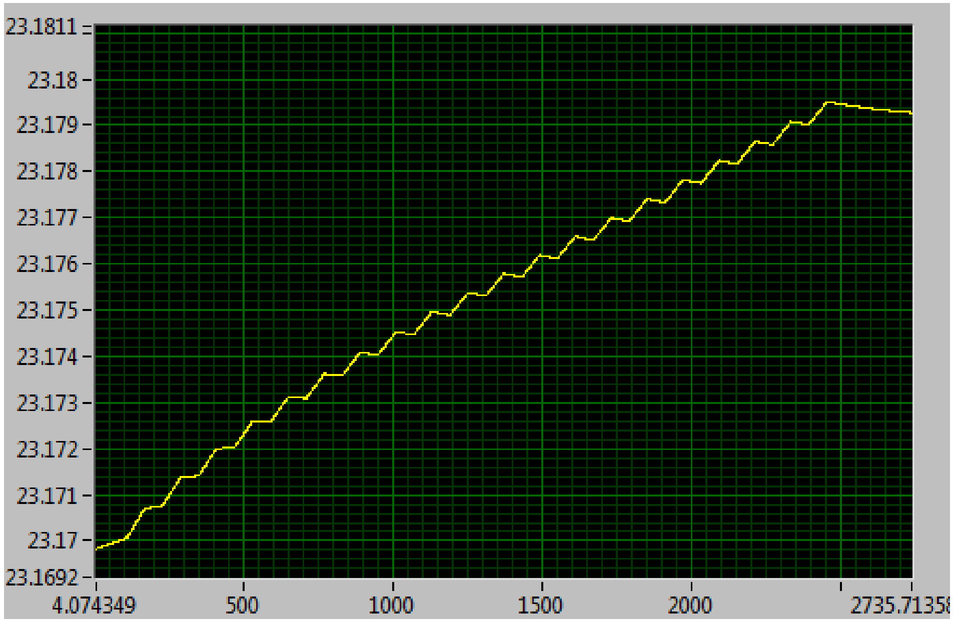
HUPTI, 2012 – *photo credit: M.A. Moyers*

[1]Moyers, M.A. and Vatnitsky, S.M., "Practical Implementation of Light Ion Beam Treatments", Medical Physics Publishing, Madison, WI, 2012, p. 24.

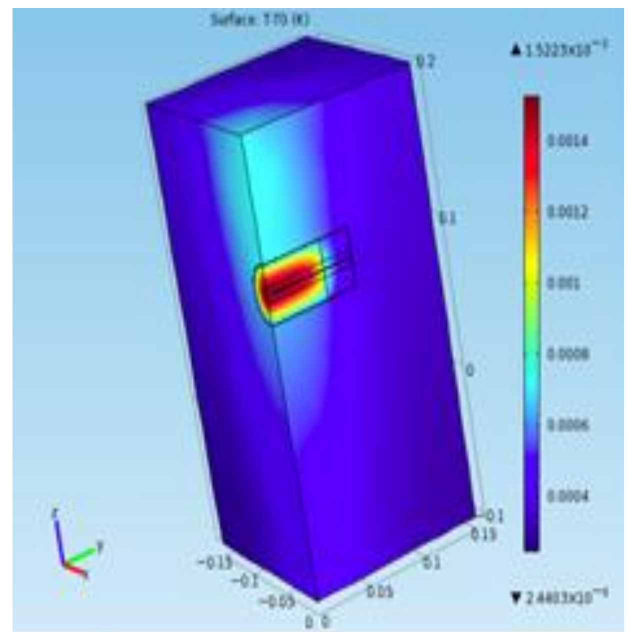
Water calorimetry – basis of operation



Water calorimetry corrections: heat transfer (ht)



The cumulative effect of thermal gradients within the device distorts the waveform (drift segments not parallel) and introduces a systematic uncertainty into ΔT.



Modeling the effect with finite-element analysis is straightforward, enabling the determination of a correction factor $\mathbf{k_{ht}}$.

Water calorimetry corrections: heat defect (HD)

A much larger systematic effect is attributable to photolytic reactions induced by radiation.

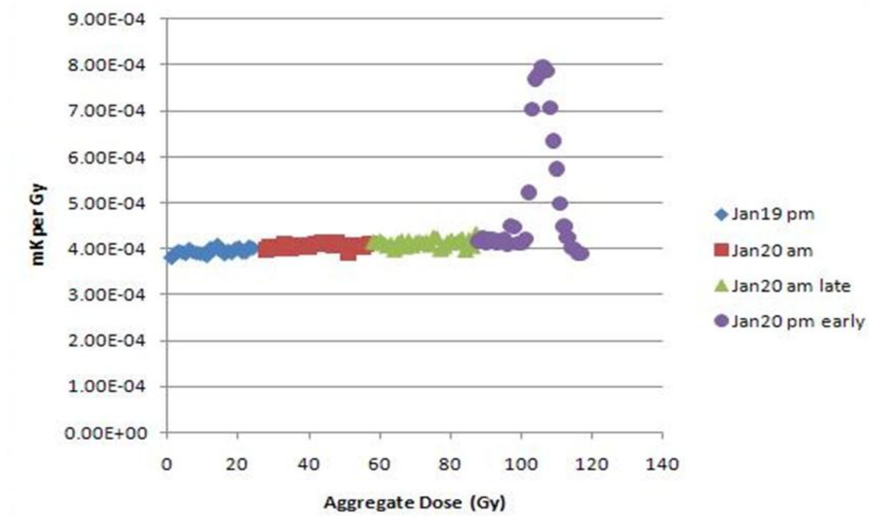


Table 1. Model IIIR: reactions and rate constants (4 °C)

	Reactions[a]			Rate constants[b]
1	$e^-_{aq} + e^-_{aq}$	→	$H_2 + OH^- + OH^-$	3.48×10^9
2	$e^-_{aq} + H$	→	$H_2 + OH^-$	1.73×10^{10}
3	$e^-_{aq} + OH$	→	OH^-	2.38×10^{10}
4	$e^-_{aq} + H_2O_2$	→	$OH^- + OH$	8.84×10^9
5	$e^-_{aq} + O_2$	→	O_2^-	1.16×10^{10}
6	$e^-_{aq} + O_2^-$	→	$HO_2^- + OH^-$	8.48×10^9
7	$e^-_{aq} + HO_2$	→	HO_2^-	8.48×10^9
8	$H + H$	→	H_2	3.44×10^9
9	$H + OH$	→	H_2O	1.21×10^{10}
10	$H + H_2O_2$	→	$OH + H_2O$	3.18×10^7
11	$H + O_2$	→	HO_2	9.58×10^9
12	$H + HO_2$	→	H_2O_2	7.24×10^9
13	$H + O_2^-$	→	HO_2^-	7.24×10^9
14	$OH + OH$	→	H_2O_2	3.76×10^9
15	$OH + H_2$	→	$H + H_2O$	2.40×10^7
16	$OH + H_2O_2$	→	$H_2O + H_2O$	1.79×10^7
17	$OH + HO_2$	→	$H_2O + O_2$	9.08×10^9
18	$OH + O_2^-$	→	$OH^- + O_2$	7.89×10^9
19	$HO_2 + HO_2$	→	$H_2O_2 + O_2$	3.72×10^5
20	$HO_2 + O_2^-$	→	$H_2O_2 + O_2 + OH^-$	5.84×10^7
21	H_2O	→	$H^+ + OH^-$	2.22×10^{-6}
22	$H^+ + OH^-$	→	H_2O	7.23×10^{10}
23	H_2O_2	→	$H^+ + HO_2^-$	1.34×10^{-2}
24	$H^+ + HO_2^-$	→	H_2O_2	3.13×10^{10}
25	$H_2O_2 + OH^-$	→	$HO_2^- + H_2O$	7.56×10^9
26	$HO_2^- + H_2O$	→	$H_2O_2 + OH^-$	5.45×10^5
27	H	→	$e^-_{aq} + H^+$	8.83×10^{-3}
28	$e^-_{aq} + H^+$	→	H	1.88×10^{10}
29	$e^-_{aq} + H_2O$	→	$H + OH^-$	5.08×10^0
30	$H + OH^-$	→	$e^-_{aq} + H_2O$	7.77×10^6
31	OH	→	$H^+ + O^-$	1.34×10^{-2}
32	$H^+ + O^-$	→	OH	3.13×10^{10}
33	$OH + OH^-$	→	$O^- + H_2O$	7.56×10^9
34	$O^- + H_2O$	→	$OH^- + OH$	5.45×10^5
35	HO_2	→	$O_2^- + H^+$	4.21×10^5
36	$O_2^- + H^+$	→	HO_2	3.13×10^{10}
37	$HO_2 + OH^-$	→	$O_2^- + H_2O$	7.91×10^9
38	$O_2^- + H_2O$	→	$HO_2 + OH^-$	1.94×10^{-2}
39	$O^- + H_2$	→	$H + OH^-$	7.95×10^7
40	$O^- + H_2O_2$	→	$O_2^- + H_2O$	3.44×10^8
41	$OH + HO_2^-$	→	$OH^- + HO_2$	5.17×10^9
42	$OH + O^-$	→	HO_2^-	6.02×10^9
43	$e^-_{aq} + HO_2^-$	→	$O^- + OH^-$	2.19×10^9
44	$e^-_{aq} + O^-$	→	$OH^- + OH^-$	1.82×10^{10}
45	$O^- + O_2$	→	O_3^-	2.63×10^9

Computational modeling of this effect also is straightforward, but requires adequate models of the reaction system (e.g. at left) and G-values (average photolytic production yield, #/100 eV) for production of reactant species by the radiation beam. The associated correction factor is designated $\mathbf{k_{HD}}$.

N.V. Klassen and Carl K. Ross, J. Res. Natl. Inst. Stand. Techol. **107**, 171-178 (2002).

Water calorimetry overview cont'd …

$$D_w = \Delta T_w \cdot c_w \cdot k_{HD} \cdot k_{ht} \cdot k_{dd} \cdot k_p$$

k_{HD} - correction for the heat defect, h, due to radiation-induced chemical reactions, where $k_{HD} = (1\text{-}h)^{-1}$. It is considered here to be unity, with an appropriate uncertainty;

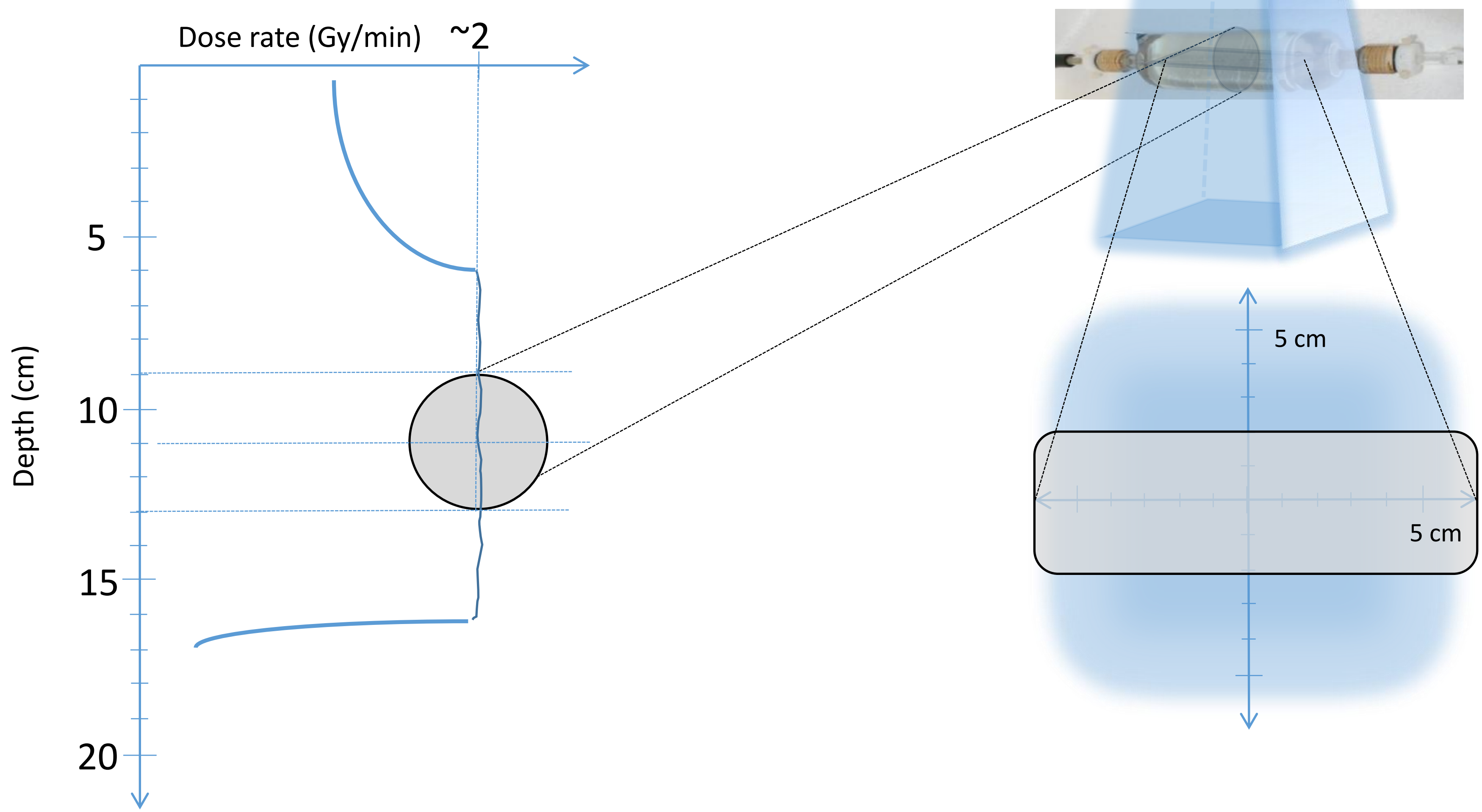
k_{ht} - correction for heat transfer due to thermal gradients generated within the vessel;

k_{dd} - correction for the non-uniformity of the lateral dose profile between the thermistor beads and the centre of the field;

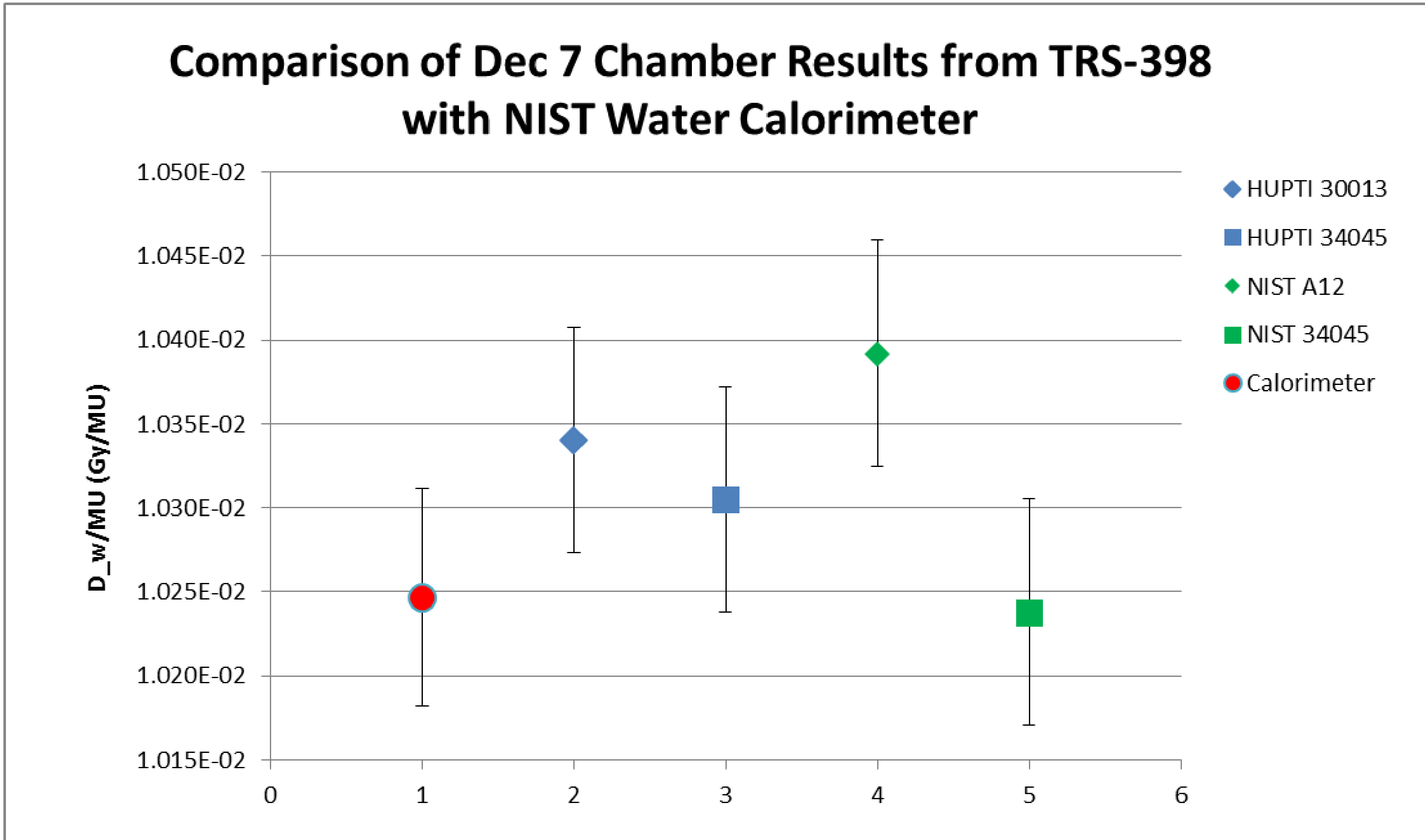
k_p - correction of the perturbation of the radiation field due to attenuation and scattering by the thermistor probes and glass vessel, determined from ionization chamber measurements and Monte Carlo simulations.

NIST at HUPTI (Hampton, VA, 2012)

With the NIST calorimeter in place, HUPTI generated a treatment plan with a 10 cm by 10 cm field, with a range of 16 cm and a modulation of 10 cm. This placed the calorimeter thermistor probes inside the vessel at an 11 cm depth, precisely in the middle of the uniform dose region. Chambers were positioned at the same depth for comparison measurements.



NIST/HUPTI – 2012, cont'd…



McGill University/MGH – 2010 (Sarfehnia, Seuntjens – McGill)

Direct absorbed dose to water determination based on water calorimetry in scanning proton beam delivery

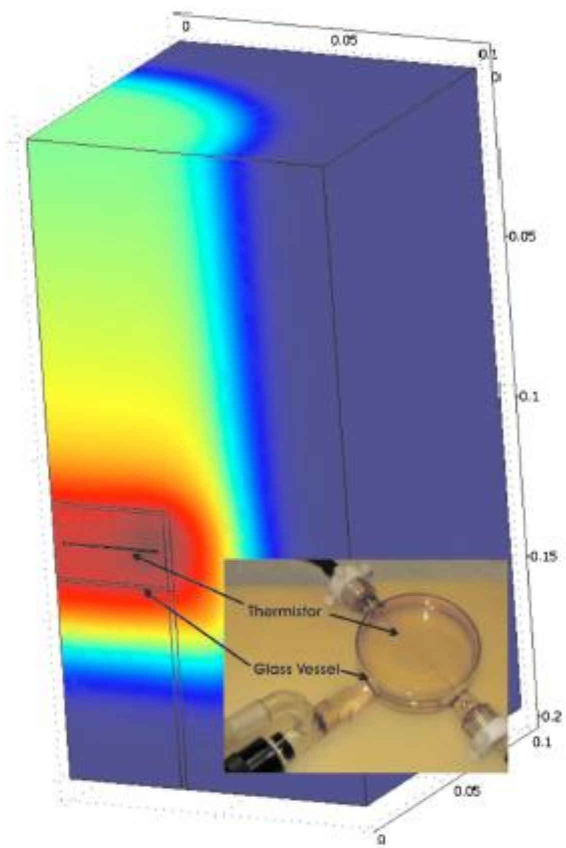


FIG. 2. The COMSOL temperature distribution results inside a geometrical model of our setup. Only one quarter of the entire geometry has been modeled due to symmetry. A picture of the parallel plate vessel (with two thermistors positioned inside) is also included.

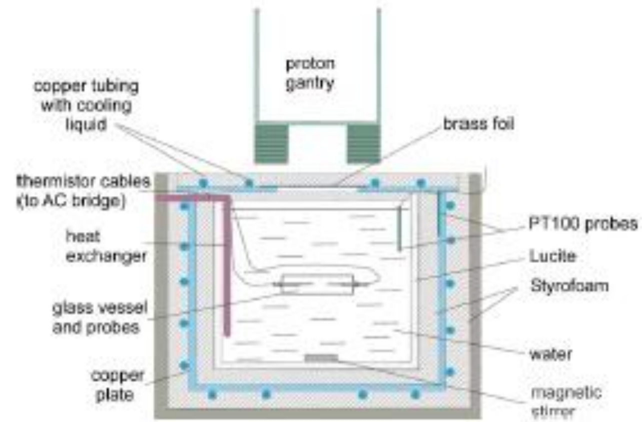


FIG. 1. A schematic diagram of the McGill in-house built transportable water calorimeter positioned below a proton gantry.

TABLE V. The final dose measurement results and comparison between the primary water calorimetry and reference T1 mini-Shonka (based on a pulsed beam ion recombination criterion).

	k_{ht}	Calorimetry (Gy/MU)	T1 Chamber (Gy/MU)	% difference
Scattering	0.996	9.087×10^{-3}	9.118×10^{-3}	0.34
Scanning	0.953	1.198×10^{-3}	1.203×10^{-3}	0.42

Medical Physics, Vol. 37, No. 7, July 2010

METAS/PSI - 2006

Water calorimetry with scanned proton beam, showing response of each thermistor

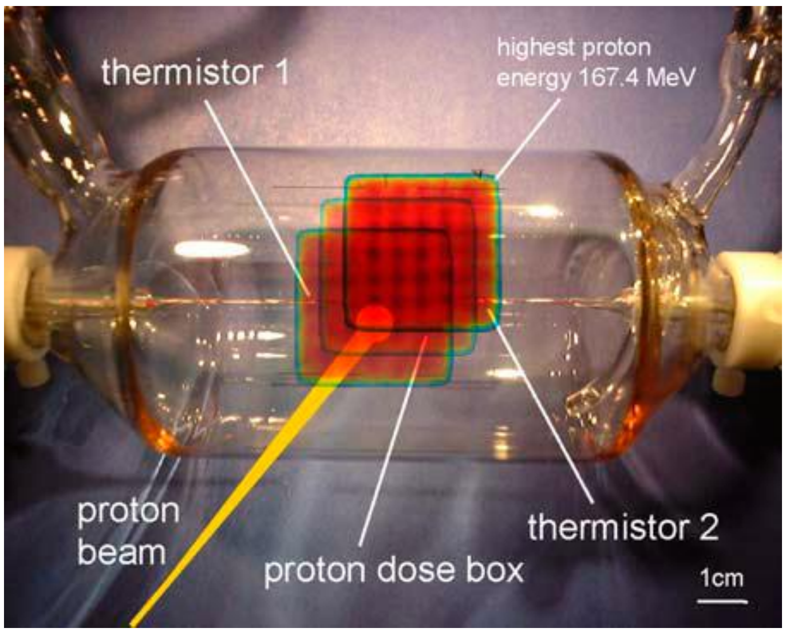


Figure 1: The sealed vessel of the water calorimeter with two thermistors separated by 1 cm. Superimposed is a schematic scanned proton dose profile.

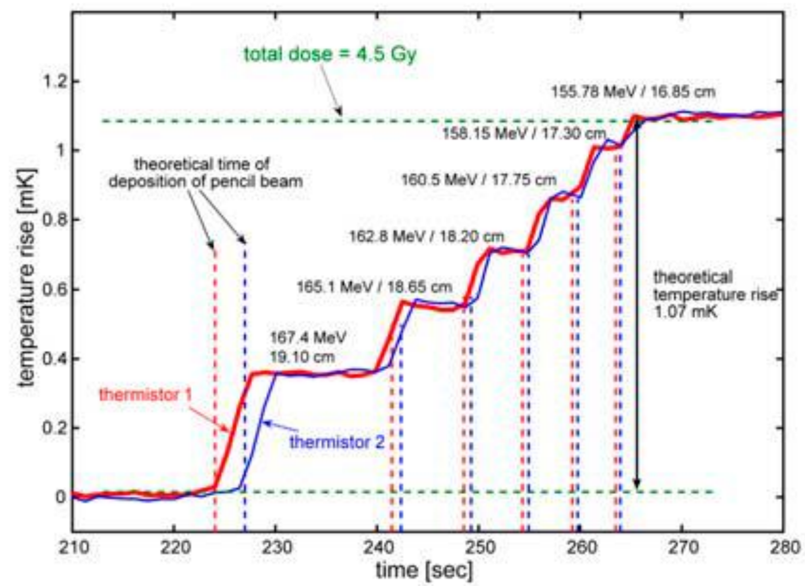


Figure 3: The temperature rise signal of the two thermistors for the cubic dose distibution of 4.5 Gy.

http://metascms01.admin.ch/metasweb/Fachbereiche/Ionisierende_Strahlung_und_Radioaktivitaet/IS%20PDF%20Dateien/Protonkalorimeter_METAS_PSI_Jahresbericht.pdf

Work of Gagnebin et al.

NPL – 2004 (to present)

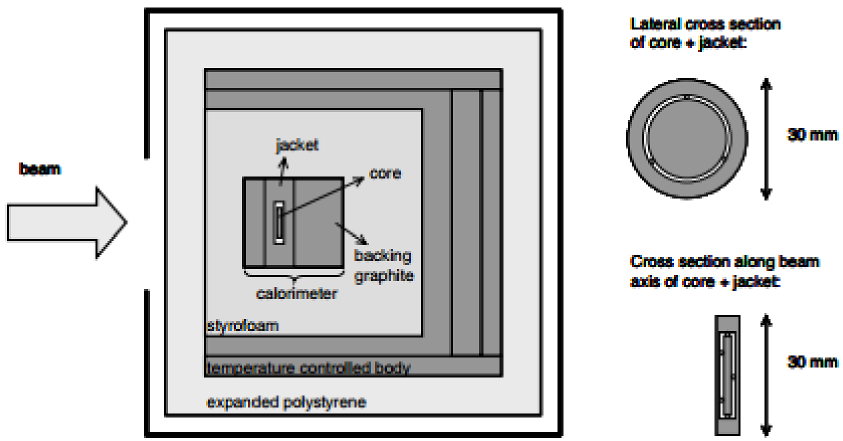


Figure 3. Schematic diagram of the small-body portable graphite calorimeter (left, not to scale, adapted from McEwen and Duane (2000)) and cross sections of the core and the jacket (right, approximately to scale).

http://metascms01.admin.ch/metasweb/Fachbereiche/Ionisierende_Strahlung_und_Radioaktivitaet/IS%20PDF%20Dateien/Protonkalorimeter_METAS_PSI_Jahresbericht.pdf
Work of Palmans et al.

Design of the graphite calorimeter for primary dosimetry in proton and ion beams

http://www.npl.co.uk/news/from-graphite-to-water

General views of the assembled electron/photon therapy level absorbed-dose graphite calorimeter (foreground), and the proton and light ion calorimeter, now being commissioned

http://www.npl.co.uk/upload/pdf/graphite-calorimeters-absorbed-dose.pdf

Graphite vs. water calorimetry

- Requires conversion from dose-to-graphite to dose-to-water
- Heat capacity of graphite is lower (ΔT/Gy higher)
- Choice of passive (quasi-adiabatic) or active (isothermal) modes of operation
- Heat conductivity of graphite is higher
- Absorber medium is a solid (no buoyant convection)
- Heat defect involves crystal dislocations

⋮

Effect on end-user dosimetry in 5-10 years

If…

- **Protocols are worked out**
  - beam quality specifiers (e.g. reference depths, …)?
  - Scattered and scanned?
- **Dissemination difficulties addressed**
  - Onsite calibrations by NMIs without calibration ranges (e.g. along the lines of the BIPM K6 Key Comparison?)

Then…

- **Reductions in measurement uncertainty**
  - Combined standard uncertainty for $N_{D,w,Co\text{-}60}$ = 0.47% [1]
  - " for k_Q in proton beams = 1.7% [2]
  - " for k_Q for ion beams = 2.8% [3]

[1]NIST Special Publication 250-74, p. http://nist.gov/calibrations/upload/sp250-74.pdf

[2,3]IAEA Technical Report Series No. 398, pp. 194, 197, respectively, http://www-pub.iaea.org/mtcd/publications/pdf/trs398_scr.pdf

Acknowledgments

- Malcolm McEwen, PhD, NRCC
- Arman Sarfehnia, PhD, Sunnybrook Health Sciences Centre

- NIST
  - Heather Chen-Mayer, PhD
  - Ronnie Minniti, PhD
  - Fred Bateman, PhD
  - Michael Mitch, PhD

Primary dose standards for therapy beams of protons …

4%
a. cannot be realized within the same instrument that would be used for C^{+} ions.

18%
b. will be most beneficial for the determination of chamber k_Q factors.

7%
c. should be built with a Faraday cup, because it is the best established technique.

11%
d. will be built with graphite because of its relatively low heat defect.

61%
e. will likely involve calorimetry, according to recommendations in ICRU Report 78.

Primary dose standards for therapy beams of protons …

1. Primary dose standards for therapy beams of protons …

(a) cannot be realized within the same instrument that would be used for C+ ions.
(b) will be most beneficial for the determination of chamber kQ factors.
(c) should be built with a Faraday cup, because it is the best established technique.
(d) will be built with graphite because of its relatively low heat defect.
(e) will likely involve calorimetry, according to recommendations in ICRU Report 78.

Answer: e - will likely involve calorimetry, according to recommendations in ICRU Report 78.

Ref: Moyers, M.A. and Vatnitsky, S.M., "Practical Implementation of Light Ion Beam Treatments", Medical Physics Publishing, Madison, WI, 2012, p. 24.

Within the US, traceability to national standards for dosimetry of proton and ion beams …

37% a. requires the commissioning of a national primary standard for proton absorbed dose.

46% b. necessarily involves Co-60 as the reference beam quality.

14% c. awaits acquisition of suitable particle beam facilities by NIST.

0% d. is feasible for double-scattered beams only.

3% e. entails formal recognition by the BIPM.

Within the US, traceability to national standards for dosimetry of proton and ion beams …

2. Within the US, traceability to national standards for dosimetry of proton …

(a) requires the commissioning of a national primary standard for proton absorbed dose.
(b) necessarily involves Co-60 as the reference beam quality.
(c) awaits acquisition of suitable particle beam facilities by NIST.
(d) is feasible for double-scattered beams only.
(e) entails formal recognition by the BIPM.

Answer: b – necessarily involves Co-60 as the reference beam quality.

Ref: Moyers, M.A. and Vatnitsky, S.M., “Practical Implementation of Light Ion Beam Treatments”, Medical Physics Publishing, Madison, WI, 2012, p. 29.

Ref: “Absorbed Dose Determination in External Beam Radiotherapy: An International Code of Practice for Dosimetry Based on Standards of Absorbed Dose to Water, IAEA Technical Report Series TRS-398 (2000), p. 135, 151.