First direct comparison between a graphite calorimeter and a water calorimeter in a 60 MeV proton beam

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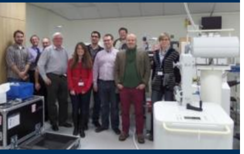
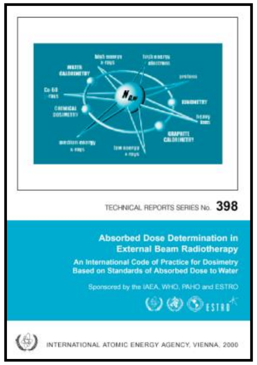
PPRIG Proton Therapy Physics Workshop

March 12-13, 2014



Motivations



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INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 2000

IAEA (2000) Code of Practice in terms of $N_{D,w}$

- Dose-to-water
- Reference conditions
- $D_{w,Q} = M_Q \, N_{D,w,Q_o} \, k_{Q,Q_o}$

The combined standard uncertainty for dosimetry under reference conditions < 2%

- High energy photon beams : 1.5%

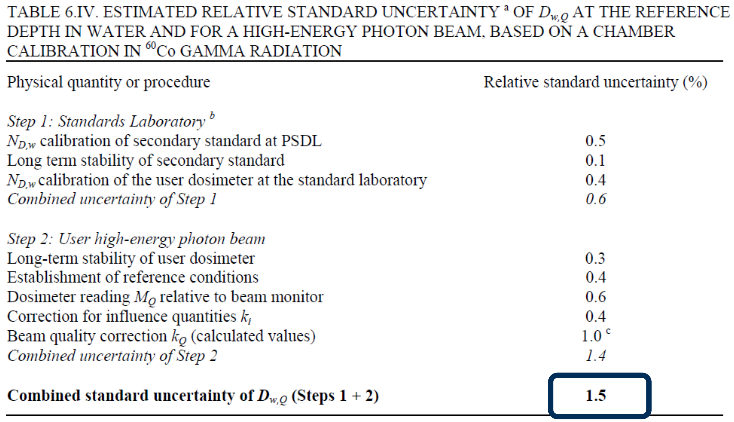
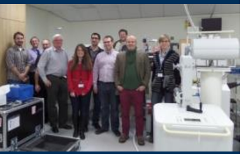
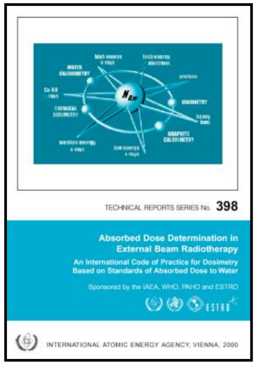


TABLE 6.IV. ESTIMATED RELATIVE STANDARD UNCERTAINTY [a] OF $D_{w,Q}$ AT THE REFERENCE DEPTH IN WATER AND FOR A HIGH-ENERGY PHOTON BEAM, BASED ON A CHAMBER CALIBRATION IN ^{60}Co GAMMA RADIATION

Physical quantity or procedure	Relative standard uncertainty (%)
Step 1: Standards Laboratory [b]	
$N_{D,w}$ calibration of secondary standard at PSDL	0.5
Long term stability of secondary standard	0.1
$N_{D,w}$ calibration of the user dosimeter at the standard laboratory	0.4
Combined uncertainty of Step 1	*0.6*
Step 2: User high-energy photon beam	
Long-term stability of user dosimeter	0.3
Establishment of reference conditions	0.4
Dosimeter reading M_Q relative to beam monitor	0.6
Correction for influence quantities k_i	0.4
Beam quality correction k_Q (calculated values)	1.0 [c]
Combined uncertainty of Step 2	*1.4*
Combined standard uncertainty of $D_{w,Q}$ (Steps 1 + 2)	$\boxed{\textbf{1.5}}$



Motivations



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

The combined standard uncertainty for dosimetry under reference conditions < 2%

- High energy photon beams : 1.5%
- Electron beams: 2.1%

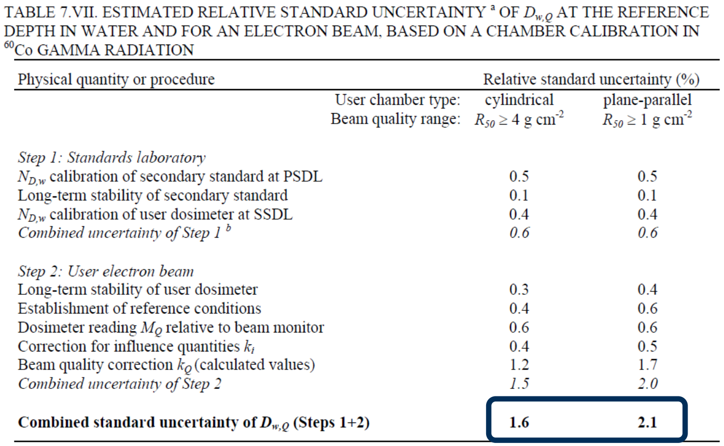
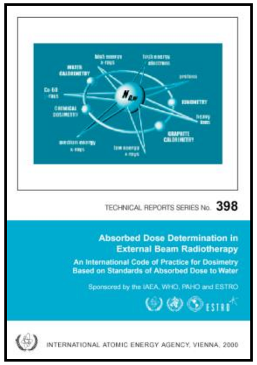


TABLE 7.VII. ESTIMATED RELATIVE STANDARD UNCERTAINTY [a] OF $D_{w,Q}$ AT THE REFERENCE DEPTH IN WATER AND FOR AN ELECTRON BEAM, BASED ON A CHAMBER CALIBRATION IN ^{60}Co GAMMA RADIATION

Physical quantity or procedure	Relative standard uncertainty (%)	
User chamber type:	cylindrical	plane-parallel
Beam quality range:	$R_{50} \geq 4$ g cm^{-2}	$R_{50} \geq 1$ g cm^{-2}
Step 1: Standards laboratory		
$N_{D,w}$ calibration of secondary standard at PSDL	0.5	0.5
Long-term stability of secondary standard	0.1	0.1
$N_{D,w}$ calibration of user dosimeter at SSDL	0.4	0.4
Combined uncertainty of Step 1 [b]	*0.6*	*0.6*
Step 2: User electron beam		
Long-term stability of user dosimeter	0.3	0.4
Establishment of reference conditions	0.4	0.6
Dosimeter reading M_Q relative to beam monitor	0.6	0.6
Correction for influence quantities k_i	0.4	0.5
Beam quality correction k_Q (calculated values)	1.2	1.7
Combined uncertainty of Step 2	*1.5*	*2.0*
Combined standard uncertainty of $D_{w,Q}$ (Steps 1+2)	**1.6**	**2.1**

Motivations



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- Dose-to-water
- Reference conditions
- $D_{w,Q} = M_Q \, N_{D,w,Q_o} \, k_{Q,Q_o}$

The combined standard uncertainty for dosimetry under reference conditions < 2%

- High energy photon beams : 1.5%
- Electron beams: 2.1%
- Proton beams: 2.3%

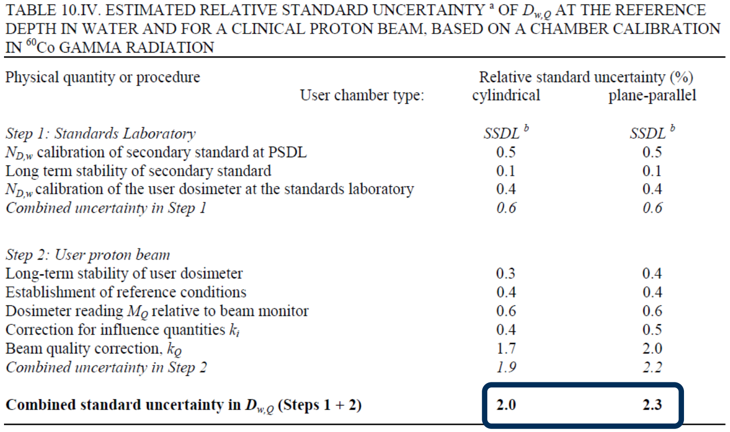
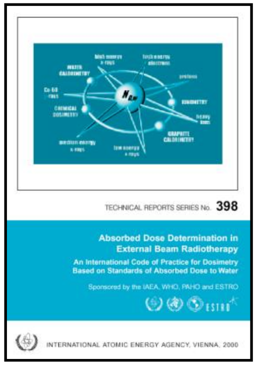


TABLE 10.IV. ESTIMATED RELATIVE STANDARD UNCERTAINTY [a] OF $D_{w,Q}$ AT THE REFERENCE DEPTH IN WATER AND FOR A CLINICAL PROTON BEAM, BASED ON A CHAMBER CALIBRATION IN ^{60}Co GAMMA RADIATION

Physical quantity or procedure		Relative standard uncertainty (%)	
	User chamber type:	cylindrical	plane-parallel
Step 1: Standards Laboratory		*SSDL* [b]	*SSDL* [b]
$N_{D,w}$ calibration of secondary standard at PSDL		0.5	0.5
Long term stability of secondary standard		0.1	0.1
$N_{D,w}$ calibration of the user dosimeter at the standards laboratory		0.4	0.4
Combined uncertainty in Step 1		*0.6*	*0.6*
Step 2: User proton beam			
Long-term stability of user dosimeter		0.3	0.4
Establishment of reference conditions		0.4	0.4
Dosimeter reading M_Q relative to beam monitor		0.6	0.6
Correction for influence quantities k_i		0.4	0.5
Beam quality correction, k_Q		1.7	2.0
Combined uncertainty in Step 2		*1.9*	*2.2*
Combined standard uncertainty in $D_{w,Q}$ (Steps 1 + 2)		**2.0**	**2.3**

Motivations

IAEA (2000) Code of Practice in terms of $N_{D,w}$



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- Dose-to-water
- Reference conditions
- $D_{w,Q} = M_Q \, N_{D,w,Q_o} \, k_{Q,Q_o}$

The combined standard uncertainty for dosimetry under reference conditions < 2%

- High energy photon beams : 1.5%
- Electron beams: 2.1%
- Proton beams: 2.3%
- Heavy-ion beams: 3.4%

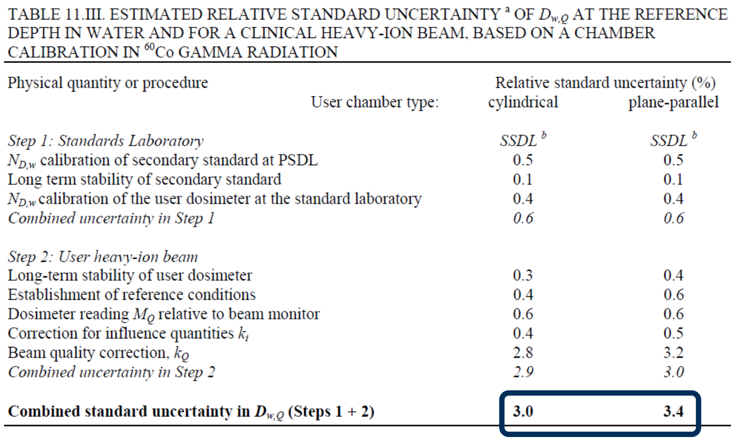
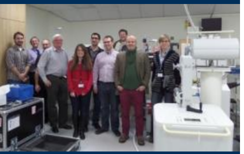


TABLE 11.III. ESTIMATED RELATIVE STANDARD UNCERTAINTY [a] OF $D_{w,Q}$ AT THE REFERENCE DEPTH IN WATER AND FOR A CLINICAL HEAVY-ION BEAM, BASED ON A CHAMBER CALIBRATION IN ^{60}Co GAMMA RADIATION

Physical quantity or procedure	Relative standard uncertainty (%)	
User chamber type:	cylindrical	plane-parallel
Step 1: Standards Laboratory	*SSDL* [b]	*SSDL* [b]
$N_{D,w}$ calibration of secondary standard at PSDL	0.5	0.5
Long term stability of secondary standard	0.1	0.1
$N_{D,w}$ calibration of the user dosimeter at the standard laboratory	0.4	0.4
Combined uncertainty in Step 1	*0.6*	*0.6*
Step 2: User heavy-ion beam		
Long-term stability of user dosimeter	0.3	0.4
Establishment of reference conditions	0.4	0.6
Dosimeter reading M_Q relative to beam monitor	0.6	0.6
Correction for influence quantities k_i	0.4	0.5
Beam quality correction, k_Q	2.8	3.2
Combined uncertainty in Step 2	*2.9*	*3.0*
Combined standard uncertainty in $D_{w,Q}$ (Steps 1 + 2)	**3.0**	**3.4**



Motivations

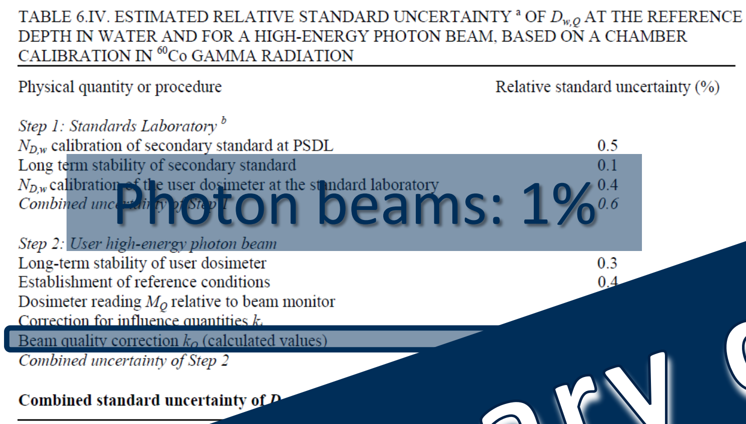


TABLE 6.IV. ESTIMATED RELATIVE STANDARD UNCERTAINTY [a] OF $D_{w,Q}$ AT THE REFERENCE DEPTH IN WATER AND FOR A HIGH-ENERGY PHOTON BEAM, BASED ON A CHAMBER CALIBRATION IN ^{60}Co GAMMA RADIATION

Physical quantity or procedure	Relative standard uncertainty (%)
Step 1: Standards Laboratory [b]	
$N_{D,w}$ calibration of secondary standard at PSDL	0.5
Long term stability of secondary standard	0.1
$N_{D,w}$ calibration of the user dosimeter at the standard laboratory	0.4
Combined uncertainty of Step 1	*0.6*
Step 2: User high-energy photon beam	
Long-term stability of user dosimeter	0.3
Establishment of reference conditions	0.4
Dosimeter reading M_Q relative to beam monitor	
Correction for influence quantities k_i	
Beam quality correction k_Q (calculated values)	
Combined uncertainty of Step 2	
Combined standard uncertainty of D	

Photon beams: 1%

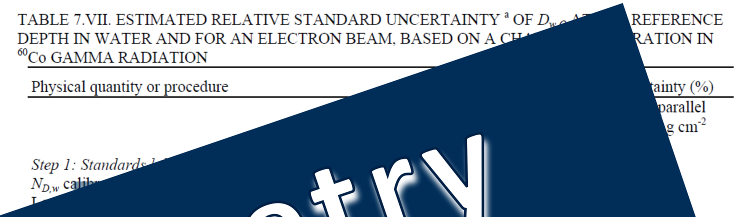


TABLE 7.VII. ESTIMATED RELATIVE STANDARD UNCERTAINTY [a] OF $D_{w,Q}$ AT ... REFERENCE DEPTH IN WATER AND FOR AN ELECTRON BEAM, BASED ON A CH... RATION IN ^{60}Co GAMMA RADIATION

Physical quantity or procedure ... tainty (%)

parallel

g cm^{-2}

Step 1: Standards

$N_{D,w}$ calib

Primary dosimetry method: calorimetry

Ste

$N_{D,w}$

Long

$N_{D,w}$ c

Combi

Step 2: U

Long-term

Establishme

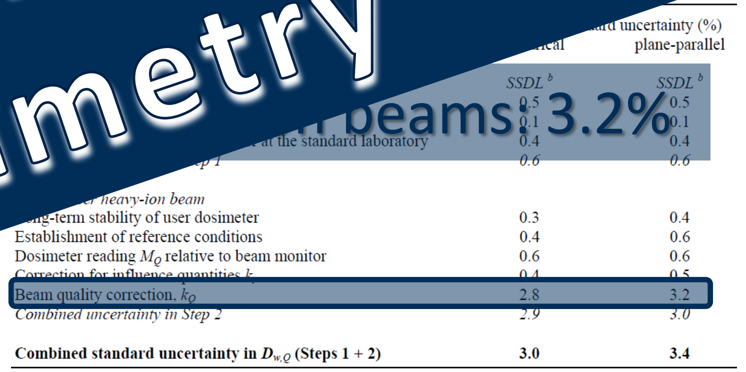
Dosimeter re

Correction fo

Beam quality ... 2.0

Combined unce ... *2.2*

Combined stand ... **2.0** **2.3**



	...ical	plane-parallel
	SSDL [b]	*SSDL* [b]
	0.5	0.5
	0.1	0.1
... at the standard laboratory	0.4	0.4
...ep 1	*0.6*	*0.6*
...er heavy-ion beam		
...ng-term stability of user dosimeter	0.3	0.4
Establishment of reference conditions	0.4	0.6
Dosimeter reading M_Q relative to beam monitor	0.6	0.6
Correction for influence quantities k_i	0.4	0.5
Beam quality correction, k_Q	2.8	3.2
Combined uncertainty in Step 2	*2.9*	*3.0*
Combined standard uncertainty in $D_{w,Q}$ (Steps 1 + 2)	**3.0**	**3.4**

...n beams: 3.2%

Dominant uncertainty: k_Q-value

How reduce the uncertainty ?

Calorimetry

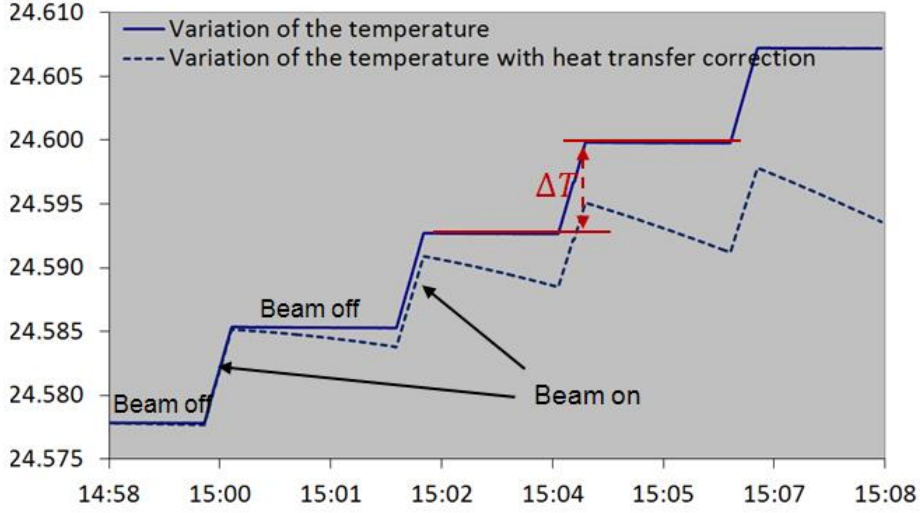
A **calorimeter** can be a **primary standard instrument** to determine **the absorbed dose** from its definition (i.e. a measure of the energy deposited in a medium by ionizing radiation per unit mass).

Graphite calorimeter (GCal) or water calorimeter (WCal) ?

	$c_{p,m}$ [J/K kg]	$\Delta T/D_m$	α [m²/s]	k_h	
water **liquid**	4180	0.24 **sensitivity**	$1.44 \,.\, 10^{-7}$	0.96-1.02 **heat defect**	dose to water
graphite	710	1.41	$0.80 \,.\, 10^{-7}$	1.000	dose to graphite **conversion**

Each system has advantages and disadvantages: heat defect, dose conversion, ease of operation ...

Calorimetry: 2 operation modes

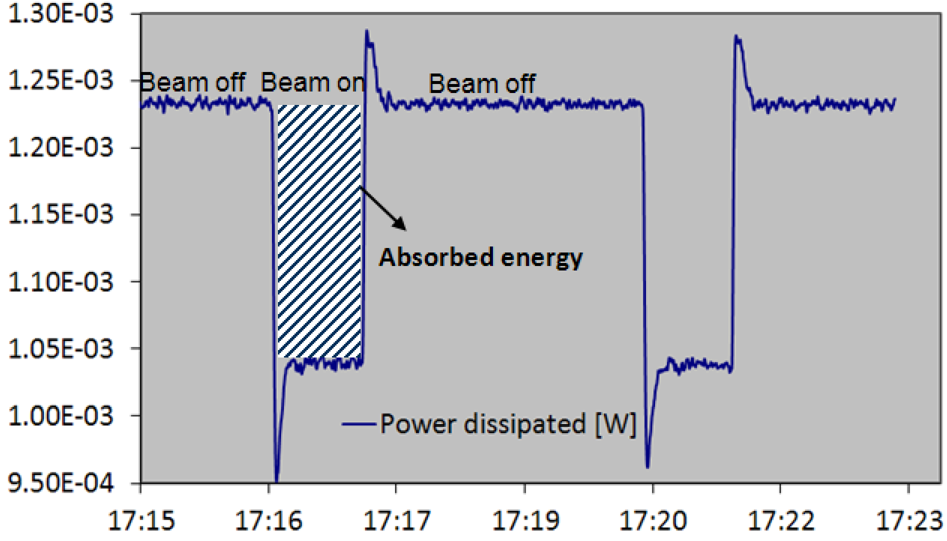


Quasi-adiabatic mode

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

Isothermal mode

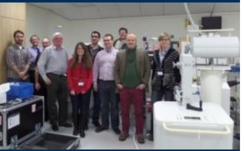
$$D_m = {}^{E_m}\!/_{m_m}\;k$$



$c_{p,m}$: specific heat capacity
m_m: mass of the medium
k: correction
E_m: energy absorbed in the medium
ΔT : temperature rise



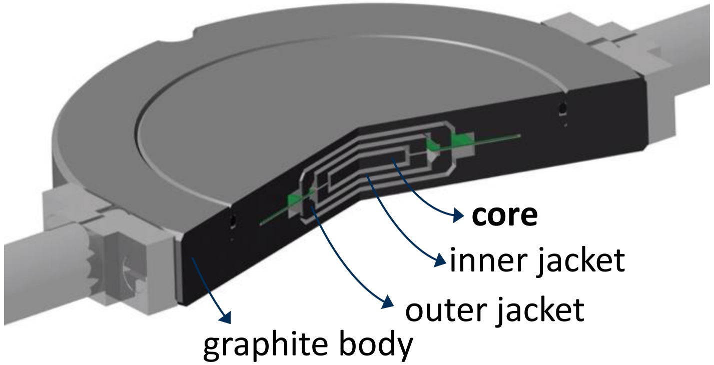




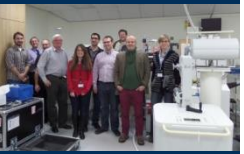
Calorimeters used in this work

1. A new portable **graphite calorimeter** for hadron beams developed by the National Physical Laboratory (UK)
   - Operation modes: quasi-adiabatic and isothermal mode
   - Absorbed dose to graphite measured in the core (diameter of 16 mm, thickness of 2 mm)

Internal structure of the GCal

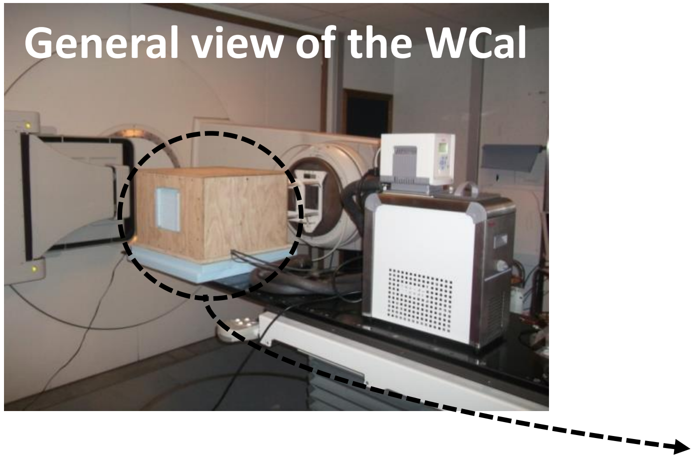


General view of the GCal



Calorimeters used in this work

1. A NPL portable **graphite calorimeter** for hadron beams
2. A **water calorimeter** for low-energy hadron beams developed by McGill University (Canada) in collaboration with Université catholique de Louvain (Belgium):
   - Operation mode: quasi-adiabatic mode
   - Absorbed dose to water measured in the McGill vessel by 2 thermistors (window thickness of 1.2 mm)

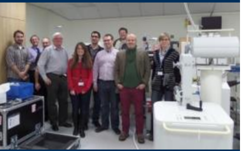


General view of the WCal

Internal view

McGill vessel

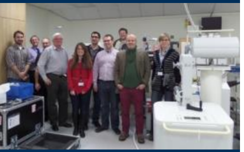
Experimental campaign



Beams: modulated and non-modulated, low-energy (60 MeV) passive scattered clinical proton beams at the *Clatterbridge Cancer Centre* (UK)

Objectives:

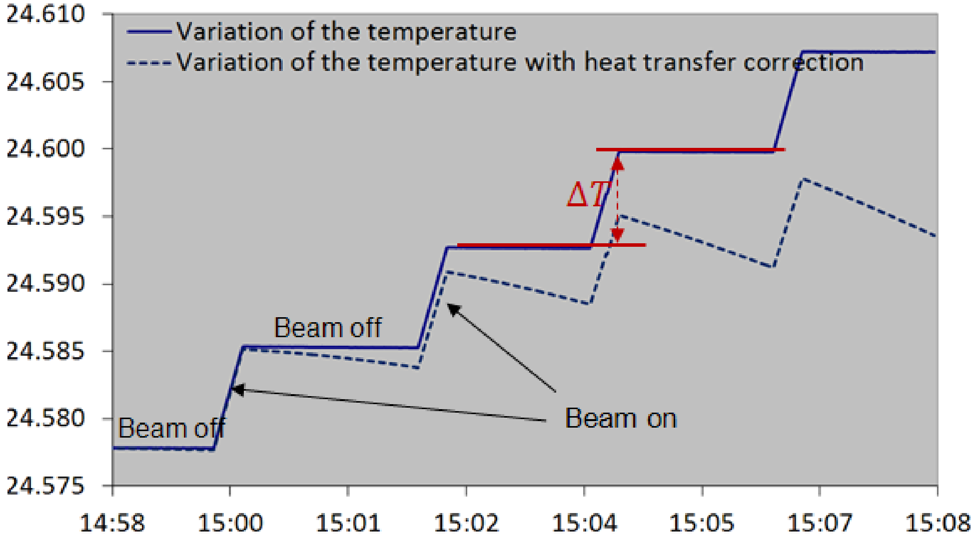
1. Direct comparison between 2 independent calorimeters ➡ confirmation of the dose conversion procedure used for the graphite calorimeter to determine the dose-to-water in proton-therapy.
2. Experimental determination of k_{Q,Q_0}-values

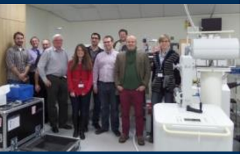


Corrections

GCal system:

1. **Heat transfer** between different parts of the calorimeter





Corrections

GCal system:

1. Heat transfer between differen
2. **Conversion** from dose to grap *et al.* Phys Med Biol 58(10): 3481-99 (2013)].
    1. the **water-to-graphite stoppi**
    2. a **fluence correction factor** :
        1. 0.998 ± 0.002 non-modu
        2. 1.000 ± 0.002 modulatec

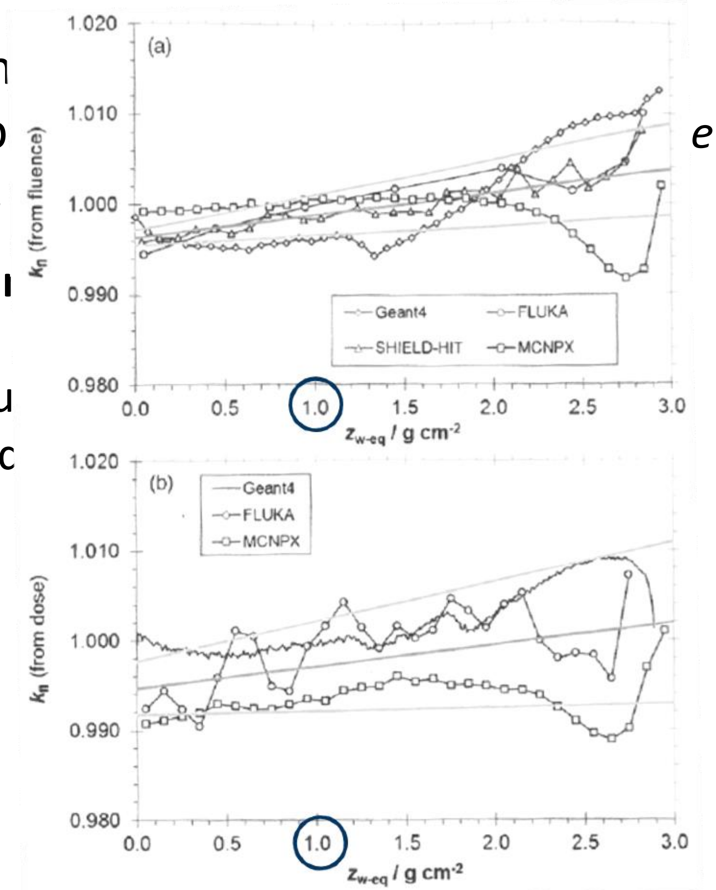
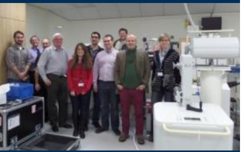


Figure 8. Results from four codes for k_{fl} (a) from equation (6) and from three codes (b) from equation (10) for 60 MeV mono-energetic protons. The orange lines (central grey lines in the printed version) are linear fits to the average of the three curves from the surface to a depth of 2.7 g cm^{-2} while the pink lines (upper and lower grey lines in the printed version) represent a 2σ interval of uncertainty estimates based on linear fits to the root mean square deviations from the mean values.



Corrections

GCal system:

1. Heat transfer between different parts of the calorimeter
2. Conversion from dose to graphite to dose to water

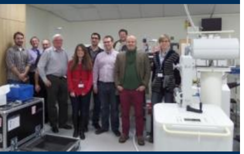
WCal system:

1. **Chemical heat defect**

Hydrogen saturated high purity water ⇒ heat defect assumed to be zero







Corrections

GCal system:

1. Heat transfer between different parts of the calorimeter
2. Conversion from dose to graphite to dose to water

WCal system:

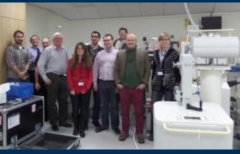
1. Chemical heat defect
2. Heat loss ⇒ a detailed modelisation with COMSOL (to do)

Ionisation chamber:

1. environmental conditions
2. recombination (0.4%) [Palmans et al., Phys Med Biol 51(4):903-17 (2006)]

Beam instability and output variation

Differences in the positioning of both calorimeters and ionisation chambers



Preliminary results

Comparison of GCal and WCal

The preliminary ratios of the graphite to water calorimetry dose are **0.995 and 0.987 for the modulated and non-modulated beam**, respectively, with an uncertainty of 1.2%.

WCal		GCal	
repeatability	0.16	repeatability	0.02
thermistor calibration	0.10	thermistor calibration	0.10
RTDs calibration	0.04	core specific heat capacity	0.10
specific heat capacity	0.03	core mass	
chemical heat defect	0.30	dose conversion	1.07
drift of the beam	0.10	linear interpolation / B	0.02
heat transfer correction		drift of the beam	0.10
position for probe in the vessel		heat transfer correction	
linear interpolation		teral beam no-uniformity	
lateral beam no-uniformity			
u_{WCal}	**0.4**	**u_{GCal}** (absorbed dose to water)	**1.1**
		u_{GCal} (absorbed dose to graphite)	**0.2**

Uncertainty budget in %. Overall standard relative uncertainties are shown, some still under investigation. Except for the repeatability, all are type B.

Preliminary results

$k_{Q,Q0}$-factor for a IBA PPC40 Roos chamber (beam quality R_{res}=2 g.cm^{-2})

- TRS-398: k_{Q,Q_0}= 1.004 with an uncertainty of 2.1%
- $k_{Q,Q0}$-factor = 0.998 and 1.011, with a uncertainty of 1.4% and 0.9% when the dose is based on the GCal and the WCal, respectively

WCal		**GCal**		**$k_{Q,^{60}Co}$-factor**	
repeatability	0.16	repeatability	0.02	repeatability	0.03
thermistor calibration	0.10	thermistor calibration	0.10	electrometer calibration	0.20
RTDs calibration	0.04	core specific heat capacity	0.10	p_{ion}	0.10
specific heat capacity	0.03	core mass		p_{TP}	0.05
chemical heat defect	0.30	dose conversion	1.07	drift of the beam	0.10
drift of the beam	0.10	linear interpolation / B	0.02	ND,w value	0.80
heat transfer correction		drift of the beam	0.10	positioning	
position for probe in the vessel		heat transfer correction		teral beam no-uniformity	
linear interpolation		teral beam no-uniformity			
lateral beam no-uniformity					
u_{WCal}	**0.4**	**u_{GCal}** (absorbed dose to water)	**1.1**	**$u_{k_{Q,60Co}}$** based on WCal	**0.9**
		u_{GCal} (absorbed dose to graphite)	**0.2**	**$u_{k_{Q,60Co}}$** based on GCal	**1.4**

Uncertainty budget in %. Overall standard relative uncertainties are shown, some still under investigation. Except for the repeatability, all are type B.

Conclusions/Perspectives

Conclusions (scattered proton beam)

- The possibility to determine $k_{Q,Q0}$-values with a lower uncertainty than specified in the TRS-398 ⇒ reduction of the uncertainty on absorbed dose-to-water.
- The agreement between calorimeters confirms the possibility to use GCal or WCal as primary standard. Because of the dose conversion, the use of GCal may lead to slightly higher uncertainty, but is, at present, considerably easier to operate.

Perspectives: use of both calorimeters in carbon ion beams

- Study of ion recombination mechanism in a scattered carbon ion beam at *NIRS* (Japan) – June 2014.
- An experimental campaign in an 80 MeV/n carbon ion beam with the WCal at *INFN-LNS*; experiments with GCal are done – end of 2014 (?)
- An experimental campaign in a scattered clinical carbon ion beam at *GHMC* (Gunma, Japan) - July 2014