Comparison of ionometric and calorimetric determination of absorbed dose to water for cobalt-60 gamma rays

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W/e = (33,97 +- 0,05) J/C

Boutillon and Perroche-Roux (1987)

This value is mainly based on the calorimetric and ionometric determination of the Co-60 absorbed dose to graphite at the same depth in a graphite phantom, published by Niatel *et al* in 1985, which yielded the product

$$(W/e)\bar{s}_{c,a} = 34{,}07\ J/C \pm 0{,}24\%$$

The evaluation of *W/e* from this result is based on the calculated ratio

$$\bar{s}_{c,a} = 1{,}003(1)$$

An important parameter for the calculation of collision stopping power values is the mean excitation energy of the absorber, called *I*-value. In ICRU 37, I_C=78 eV was chosen for graphite. This value has an uncertainty of 7 eV. However, Bichsel *et al* (1992) published a value of I_C=86,9 eV with a much lower uncertainty of 1,2 eV.

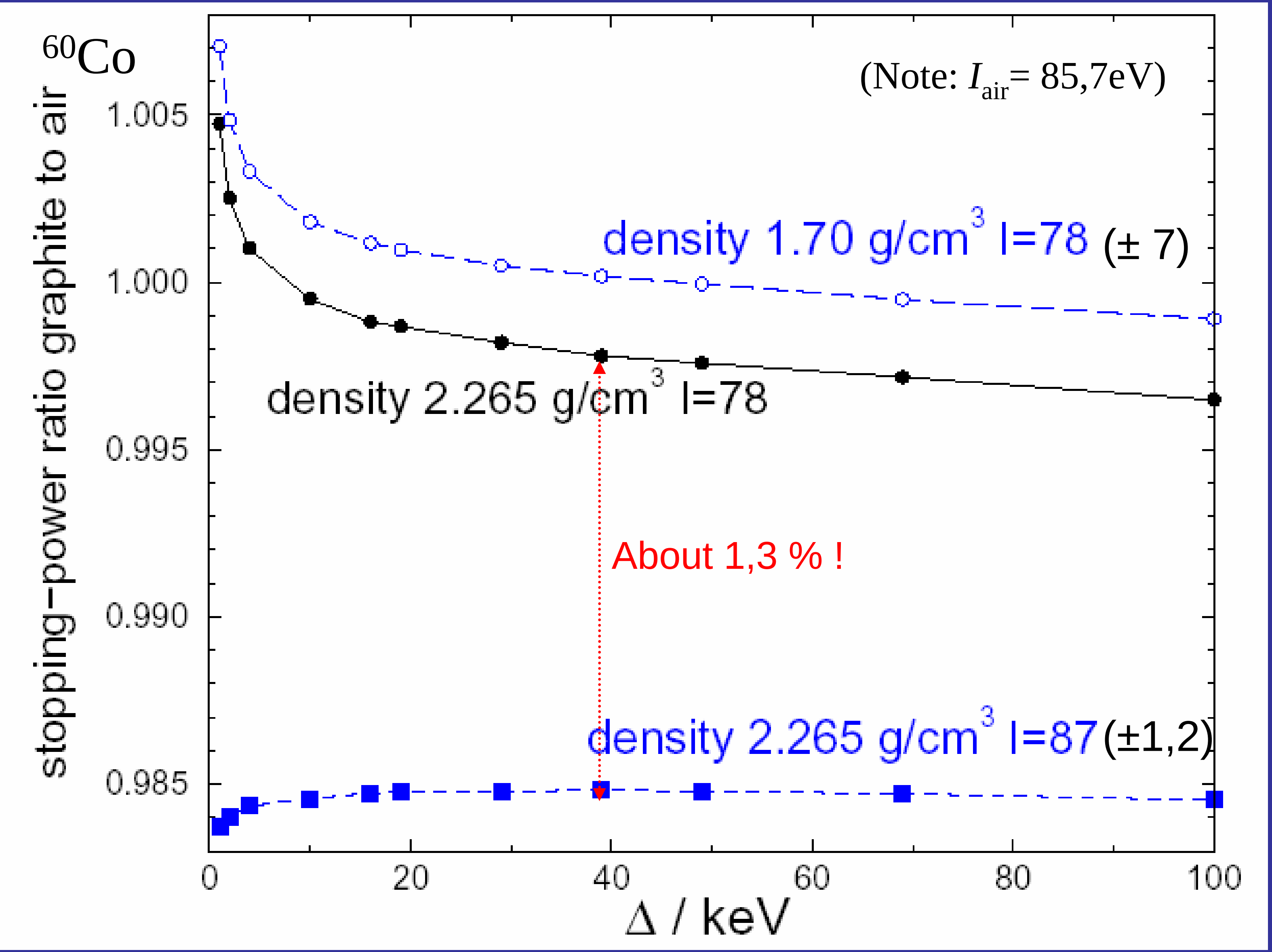
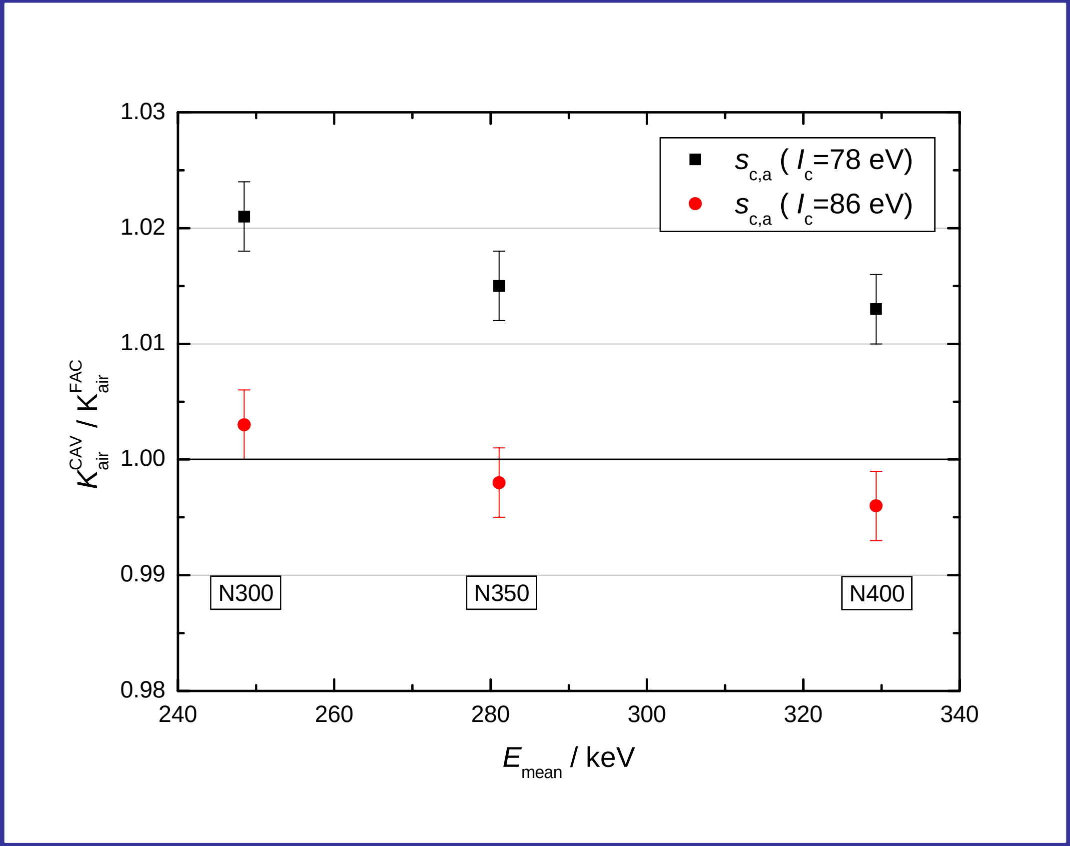


Figure 11 in Rogers and Kawrakow (*Med Phys* 30, 521-532, 2003):
Monte Carlo calculated correction factors for primary standards of air-kerma

Comparison of air kerma rates measured with free-air and graphite cavity ionization chambers
(Büermann et al, 2006, ISRP 10, Coimbra, accepted for publication in NIM A)

$$\dot{K}_{air}^{FLK} = (I/m)^{FLK}(W_{air}/e)K^{FLK}$$

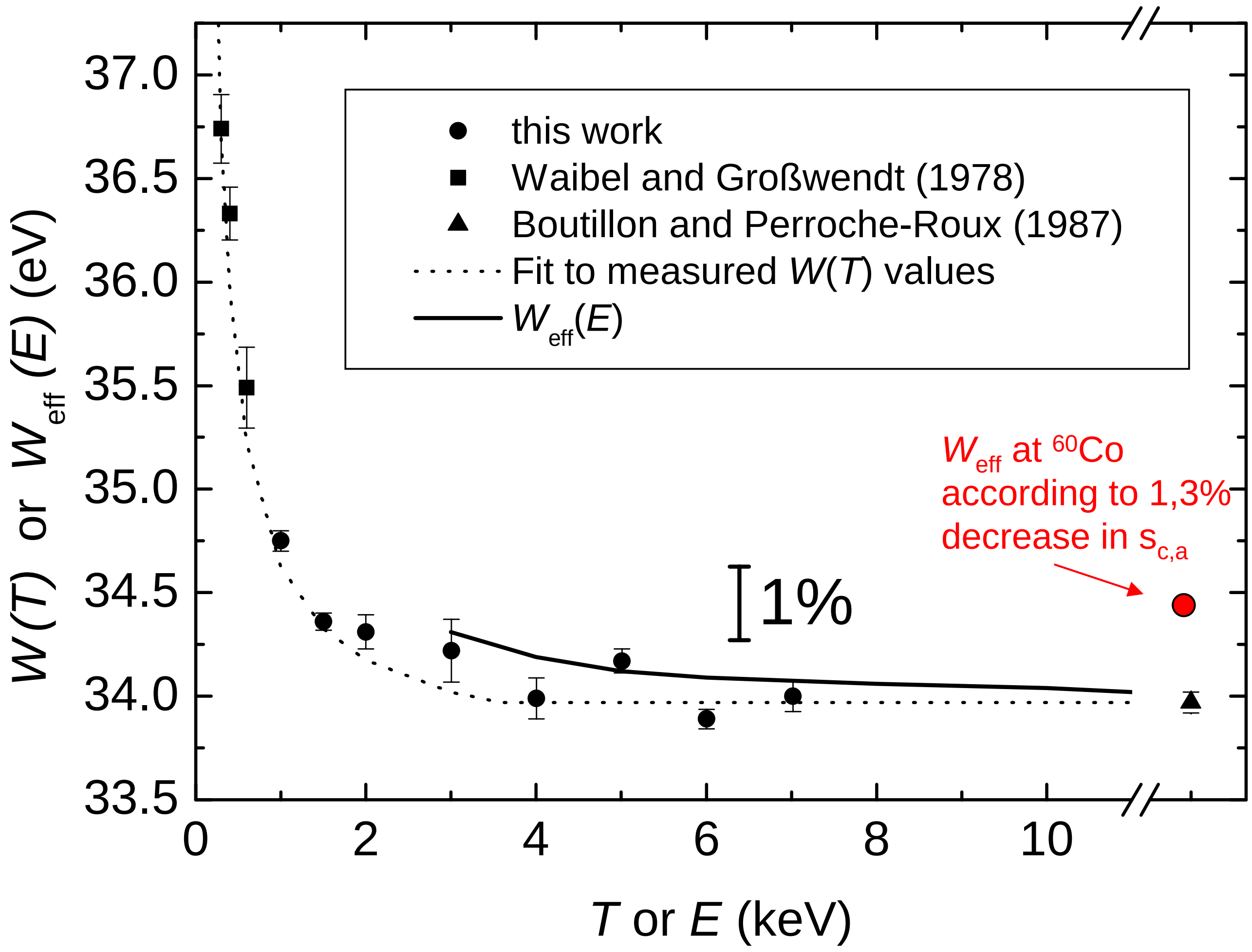
$$\dot{K}_{air}^{BG} = (I/m)^{BG}(W_{air}/e)(\overline{\mu}_{en}/\rho)_{a,c}\,\overline{s}_{c,a}K^{BG}$$



Value of *W/e* cancels out in this ratio, if equal numbers are assumed for free-air and cavity ionization chambers!

Supports graphite stopping power values based on Bichsel's I_C=86,9(1,2) eV.

Figure 3 in Büermann *et al*, PMB**51** (2006) 5125-5150



Supports W_{air} = (33,97 +- 0,05) eV, which is currently in use

Comparison of ionometric and calorimetric determination of absorbed dose to water for cobalt-60 gamma rays

Usual method:

$$D_{\mathrm{W}}^{\mathrm{ion}} = (I/m)(W/e)\bar{s}_{\mathrm{c,a}} \prod k_i = D_{\mathrm{W}}^{\mathrm{cal}}$$

Method used here:

$$D_{\mathrm{w}}^{\mathrm{ion}} = D_{\mathrm{CAV}}\, f$$

where *f* is a calculated factor to convert D_{cav} into D_w. Among other parameters, *f* will depend on the graphite stopping power used in the calculation.

Steps:

1. Measurement of the ionization current, I_{CAV}, of a graphite cavity ionization chamber with known cavity volume, V_{CAV}, at the reference depth in a water phantom.

2. Calculation of the absorbed dose rate to the air cavity according to:

$$\dot{D}_{\mathrm{CAV}} = \frac{I_{\mathrm{CAV}}}{m_{\mathrm{CAV}}} \frac{W}{e} \quad \left[\frac{\mathrm{A}}{\mathrm{kg}} \frac{\mathrm{J}}{\mathrm{As}} = \frac{\mathrm{Gy}}{\mathrm{s}} \right]$$

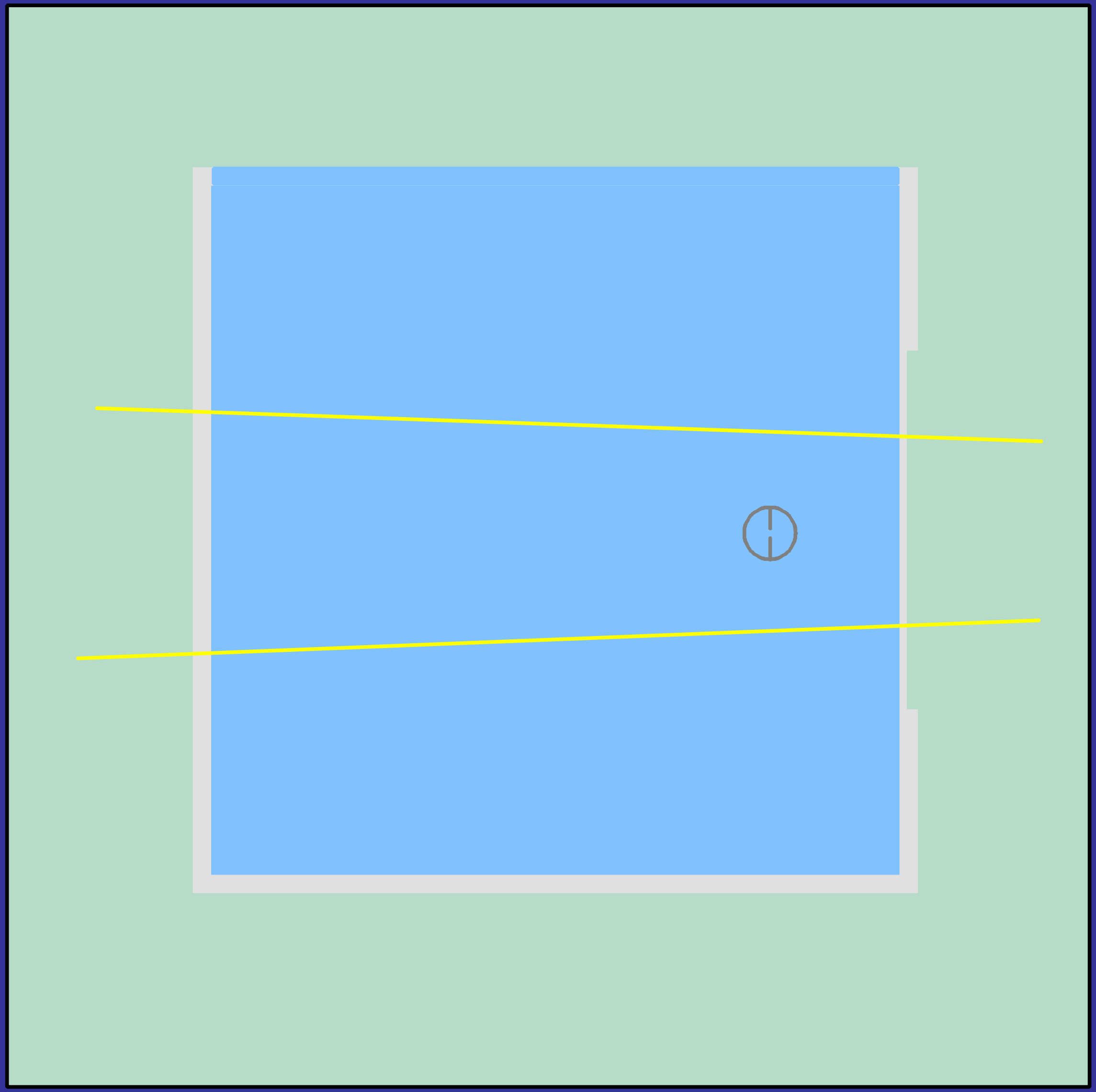
3. Calculation of the absorbed dose rate to water according to:

$$\dot{D}_{\mathrm{W}} = \dot{D}_{\mathrm{CAV}}\, f$$

Where f is a calculated factor to convert the absorbed dose rate to the cavity into the absorbed dose rate to water according to

$$f = \left[\frac{D_{\mathrm{W}}}{D_{\mathrm{CAV}}} \right]_{\mathrm{MC}}$$

PTB water calorimeter

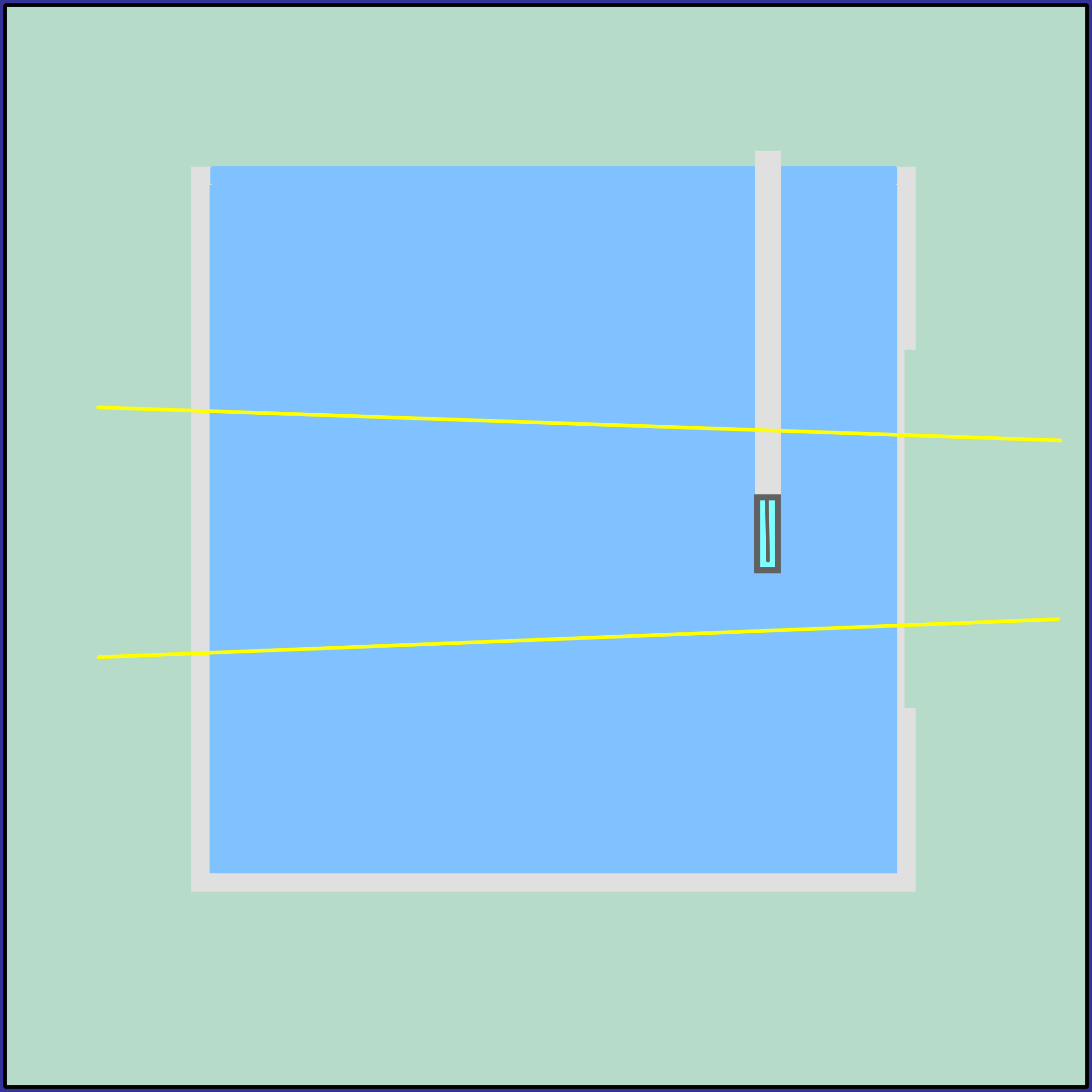


$$D_W = \Delta T * c_p * \Pi k_i$$

u = 0,20 %

Achim Krauss,
Metrologia **43** (2006)
259-272

PTB water calorimeter



$D_W = \Delta T * c_p * \Pi k_i$

$u = 0{,}20\ \%$

$D_W = D_{CAV} * f$

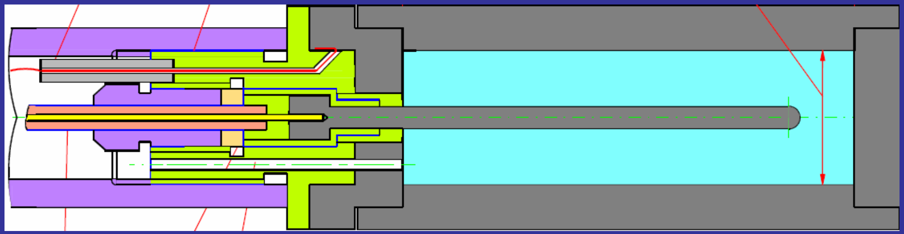
$u = 0{,}30\ \%$

$R = D_{W,ion} / D_{W,cal}$

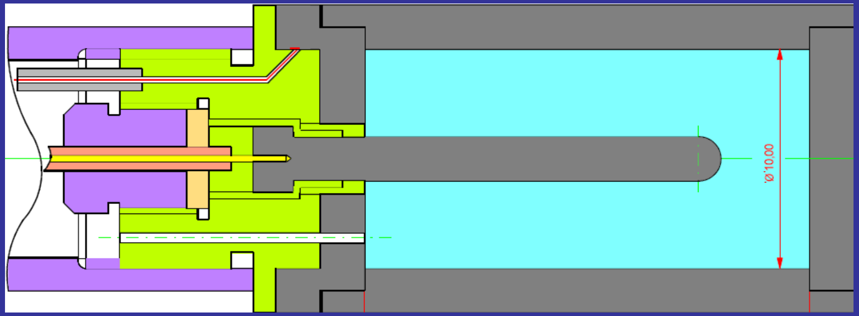
$u = 0{,}36\ \%$

Four cylindrical graphite cavity ionisation chambers with walls of thickness 3 mm.

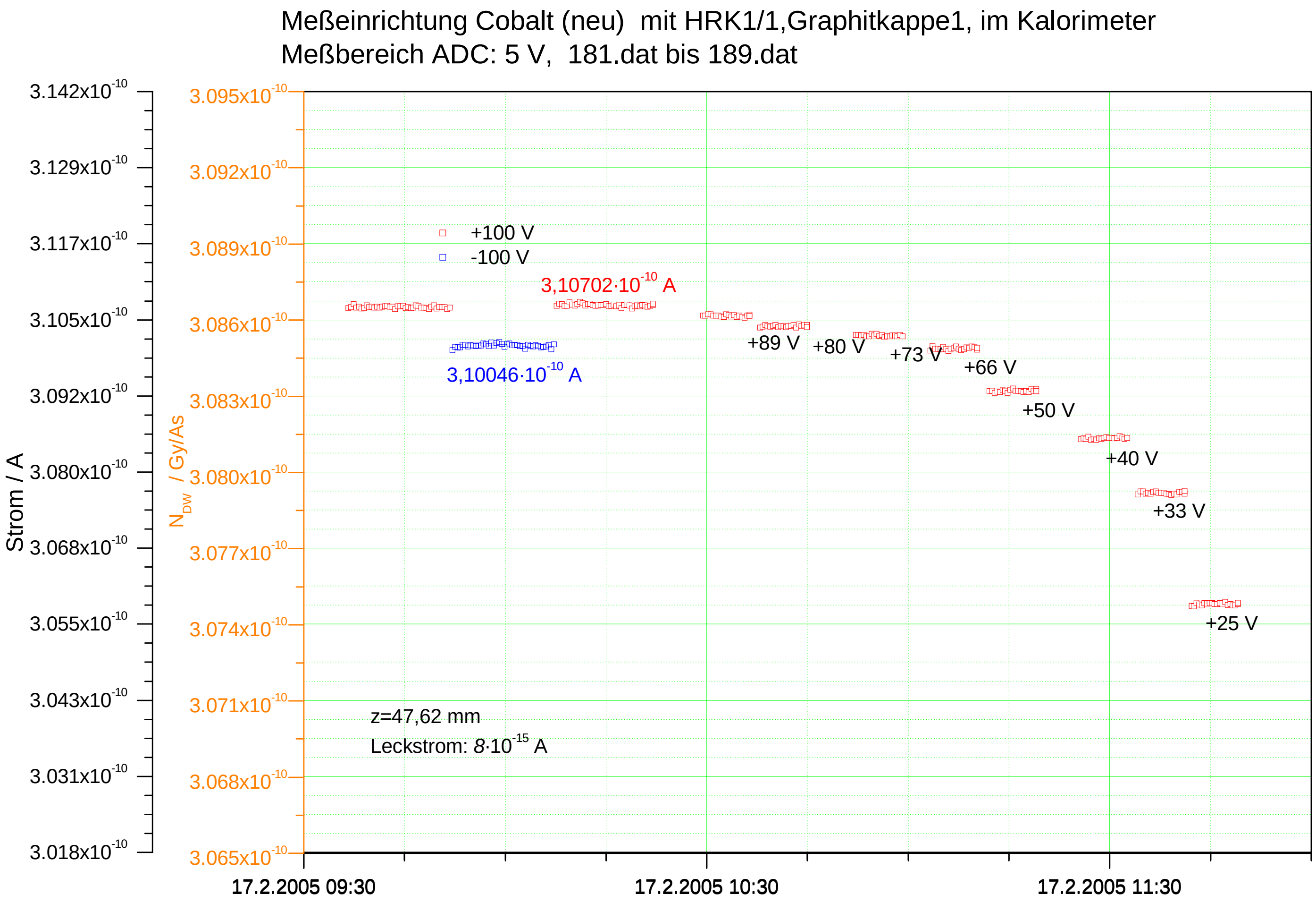
HRK-1: V=0,5539 cm^3
HRK-1C: V=0,5485 cm^3
Cavity height: 20 mm (nominal)
Cavity diameter: 6 mm (nominal)



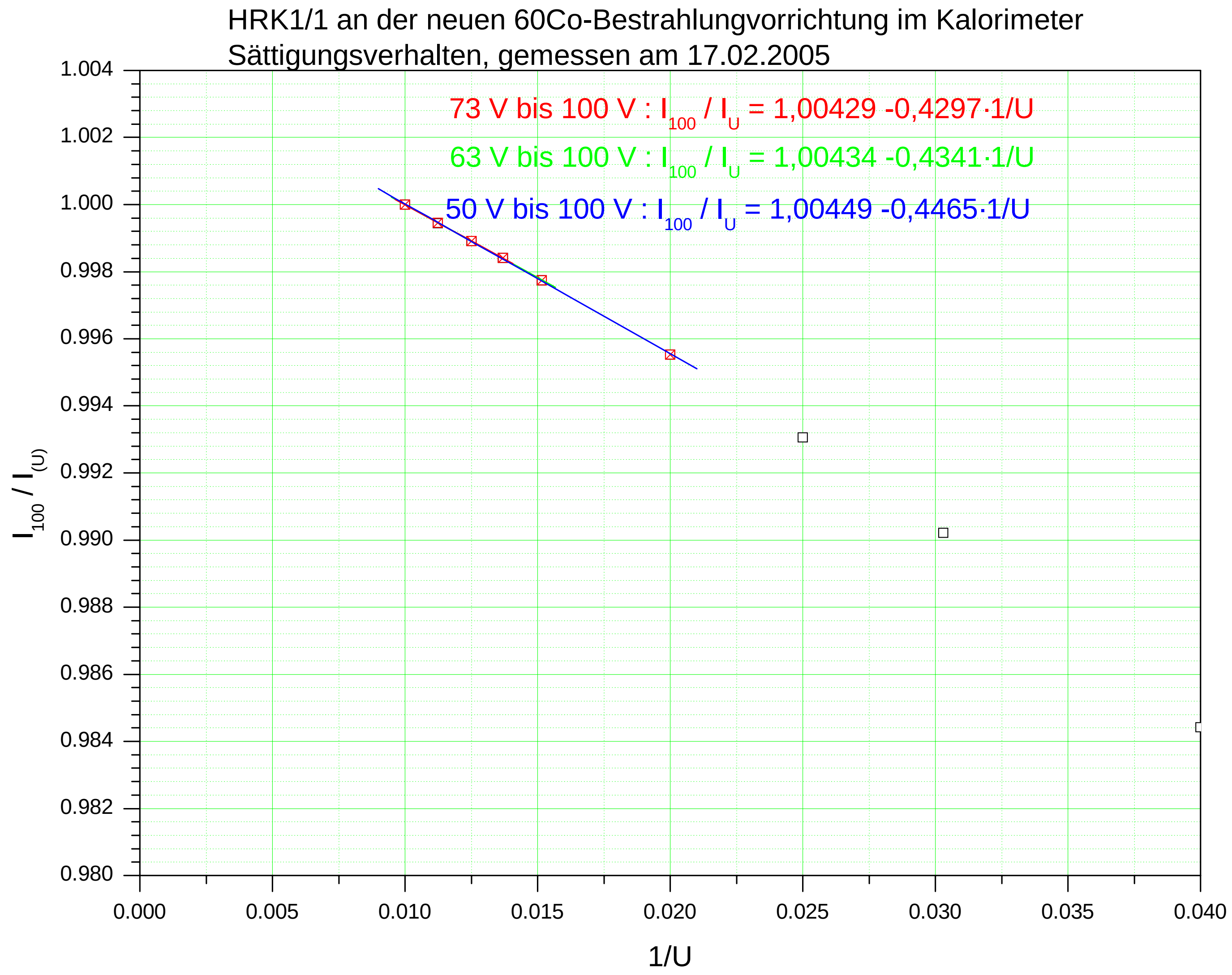
HRK-2: V=1,5190 cm^3
HRK-2C: V=1,5163 cm^3
Cavity height: 20 mm (nominal)
Cavity diameter: 10 mm (nominal)



All chambers were used with graphite wall thickness of 3 mm. In the water phantom, a cylindrical PMMA cover of thickness 1 mm was used to make them waterproof.



Meßeinrichtung Cobalt (neu) mit HRK1/1,Graphitkappe1, im Kalorimeter
Meßbereich ADC: 5 V, 181.dat bis 189.dat
Strom / A
N_DW / Gy/As
3.142x10^-10
3.129x10^-10
3.117x10^-10
3.105x10^-10
3.092x10^-10
3.080x10^-10
3.068x10^-10
3.055x10^-10
3.043x10^-10
3.031x10^-10
3.018x10^-10
3.095x10^-10
3.092x10^-10
3.089x10^-10
3.086x10^-10
3.083x10^-10
3.080x10^-10
3.077x10^-10
3.074x10^-10
3.071x10^-10
3.068x10^-10
3.065x10^-10
+100 V
-100 V
3,10702·10^-10 A
3,10046·10^-10 A
+89 V
+80 V
+73 V
+66 V
+50 V
+40 V
+33 V
+25 V
z=47,62 mm
Leckstrom: 8·10^-15 A
17.2.2005 09:30
17.2.2005 10:30
17.2.2005 11:30



HRK1/1 an der neuen 60Co-Bestrahlungvorrichtung im Kalorimeter
Sättigungsverhalten, gemessen am 17.02.2005
73 V bis 100 V : I100 / IU = 1,00429 -0,4297·1/U
63 V bis 100 V : I100 / IU = 1,00434 -0,4341·1/U
50 V bis 100 V : I100 / IU = 1,00449 -0,4465·1/U
I100 / I(U)
1/U
1.004
1.002
1.000
0.998
0.996
0.994
0.992
0.990
0.988
0.986
0.984
0.982
0.980
0.000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040

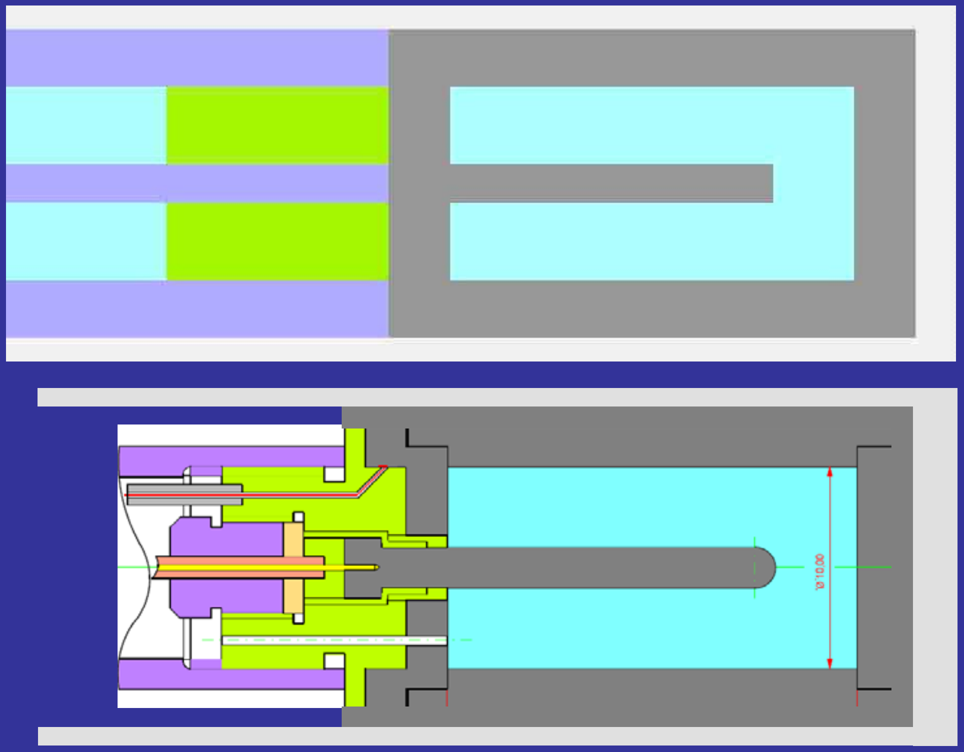
Monte Carlo simulation

The EGSnrc code system was used to calculate the conversion factor *f*. This code is known to be capable of calculating the air cavity absorbed dose accurately within 0,1%.

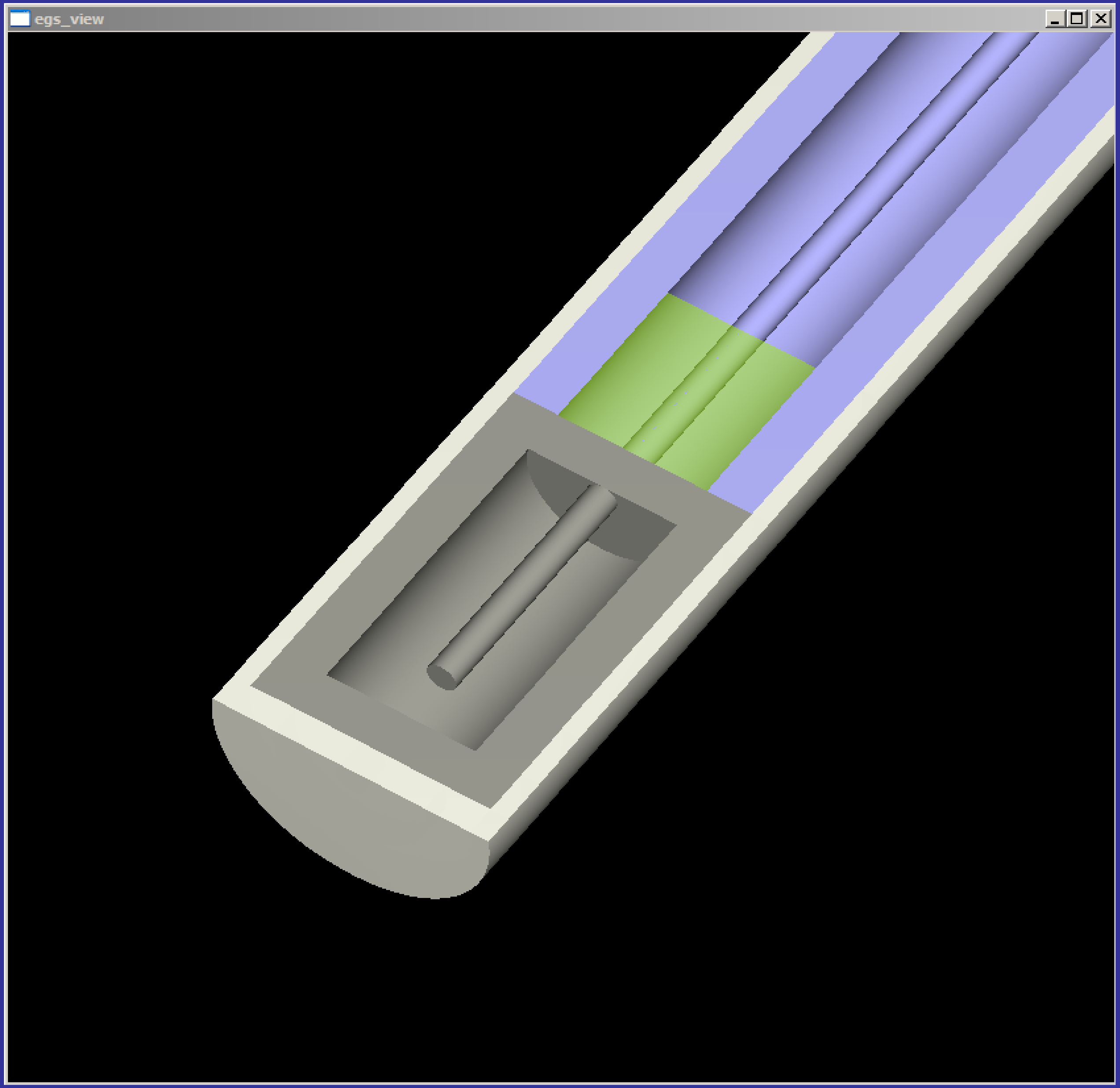
The EGSnrc C++ class library (egspp) was used because it allows more flexible definition of geometry and source.

Main transport parameters used in the simulation:
AE=521 keV, AP=10 keV
ECUT=521 keV, PCUT= 10 keV
Photon transport: New features switched on
Electron transport: New algorithms used (e.g. exact BCA)

HRK2 cavity chamber model used in MC simulation compared with the technical drawing of the original chamber

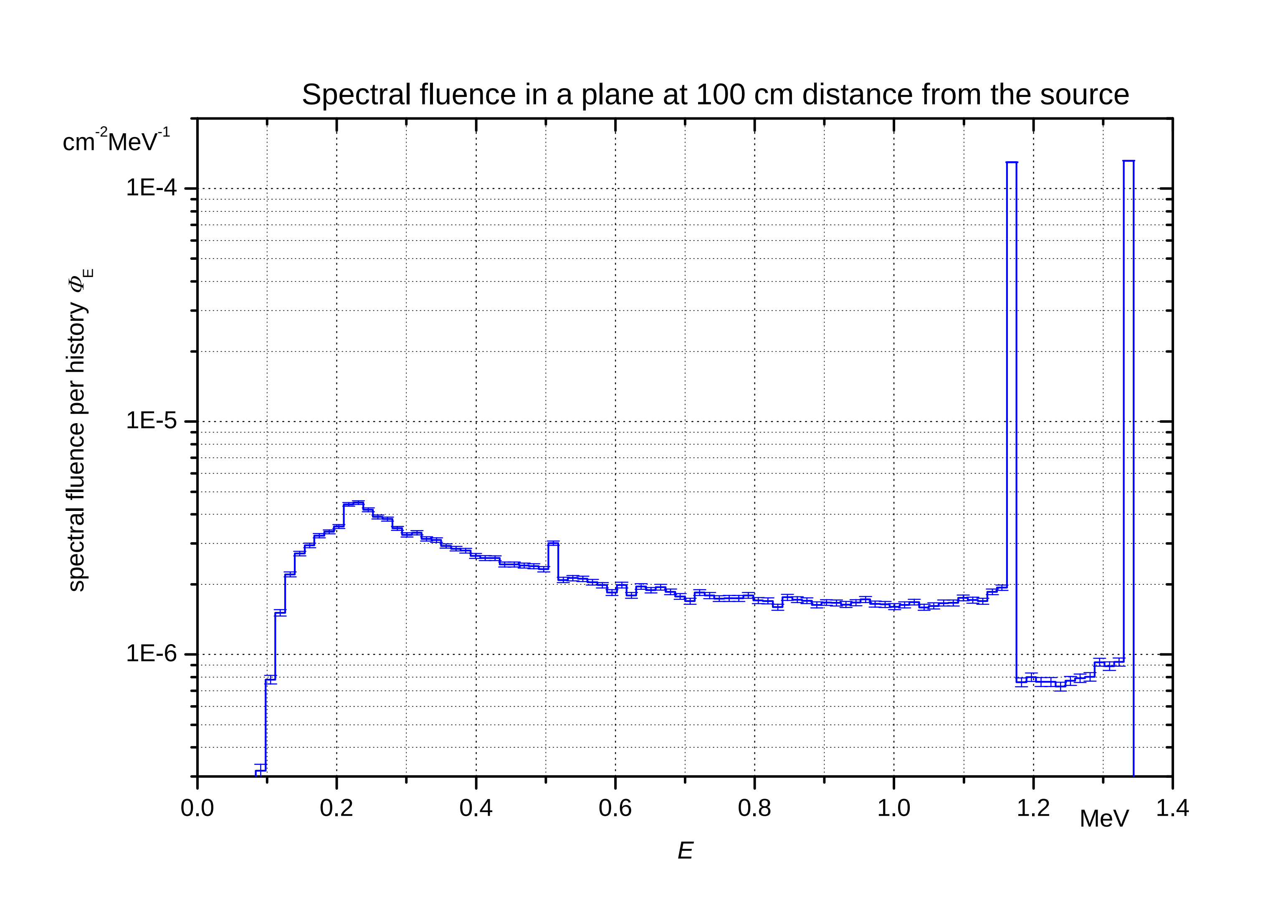


- Air
- Graphite
- Makrolon
- Aluminum
- PMMA



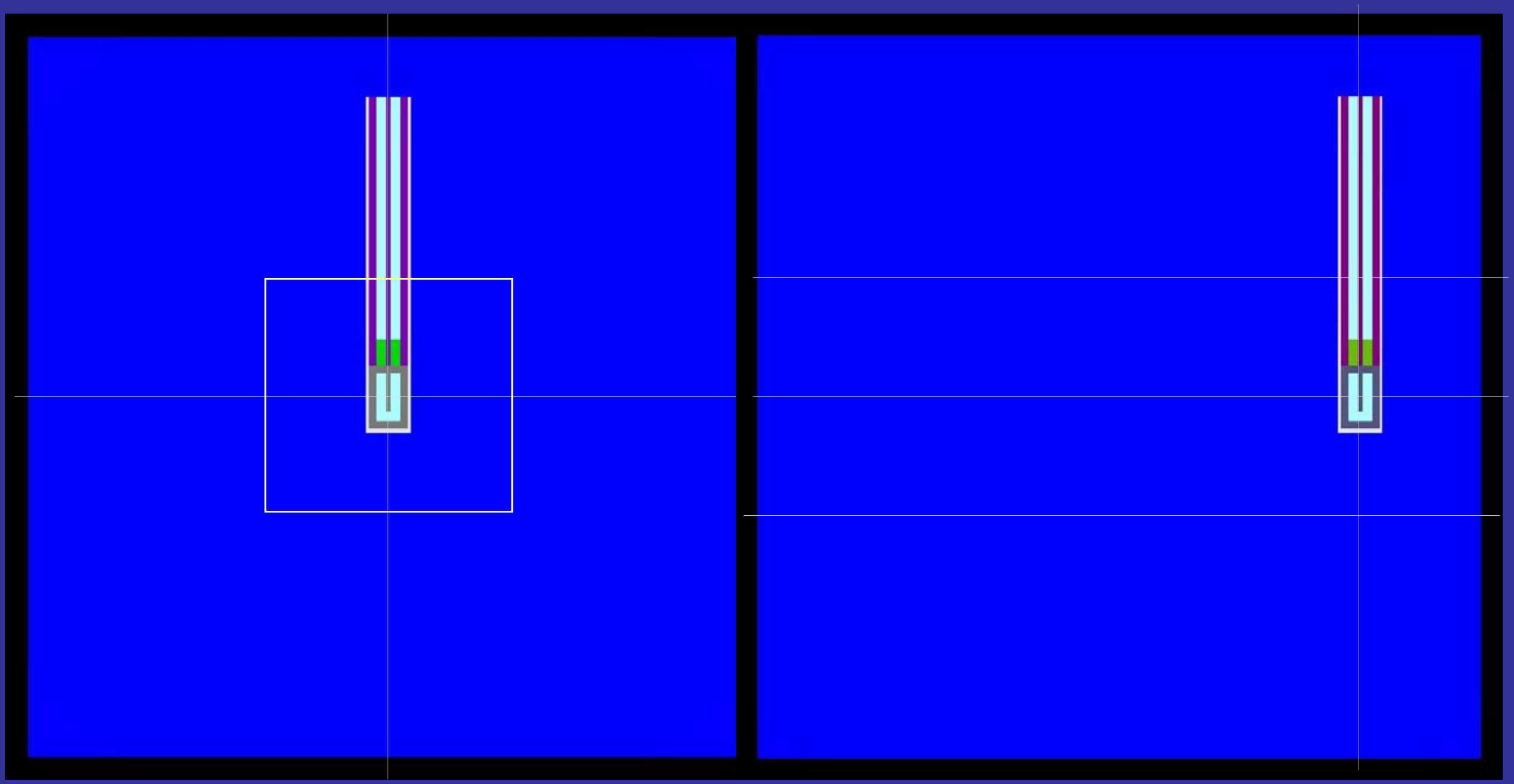
(picture generated with the egspp geometry viewer egs_view)

Spectrum of PTB Co-60 therapy source
(calculated by Ralf-Peter Kapsch, using the BEAMnrc code)

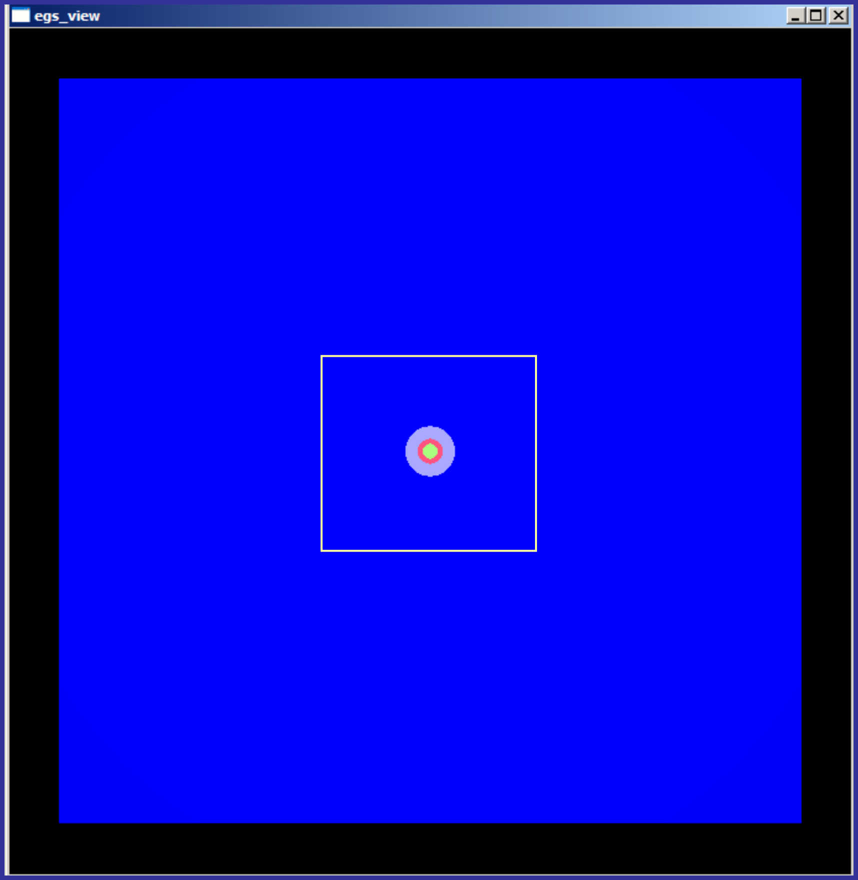


HRK2 cavity chamber with PMMA cover positioned at the reference point in the water phantom

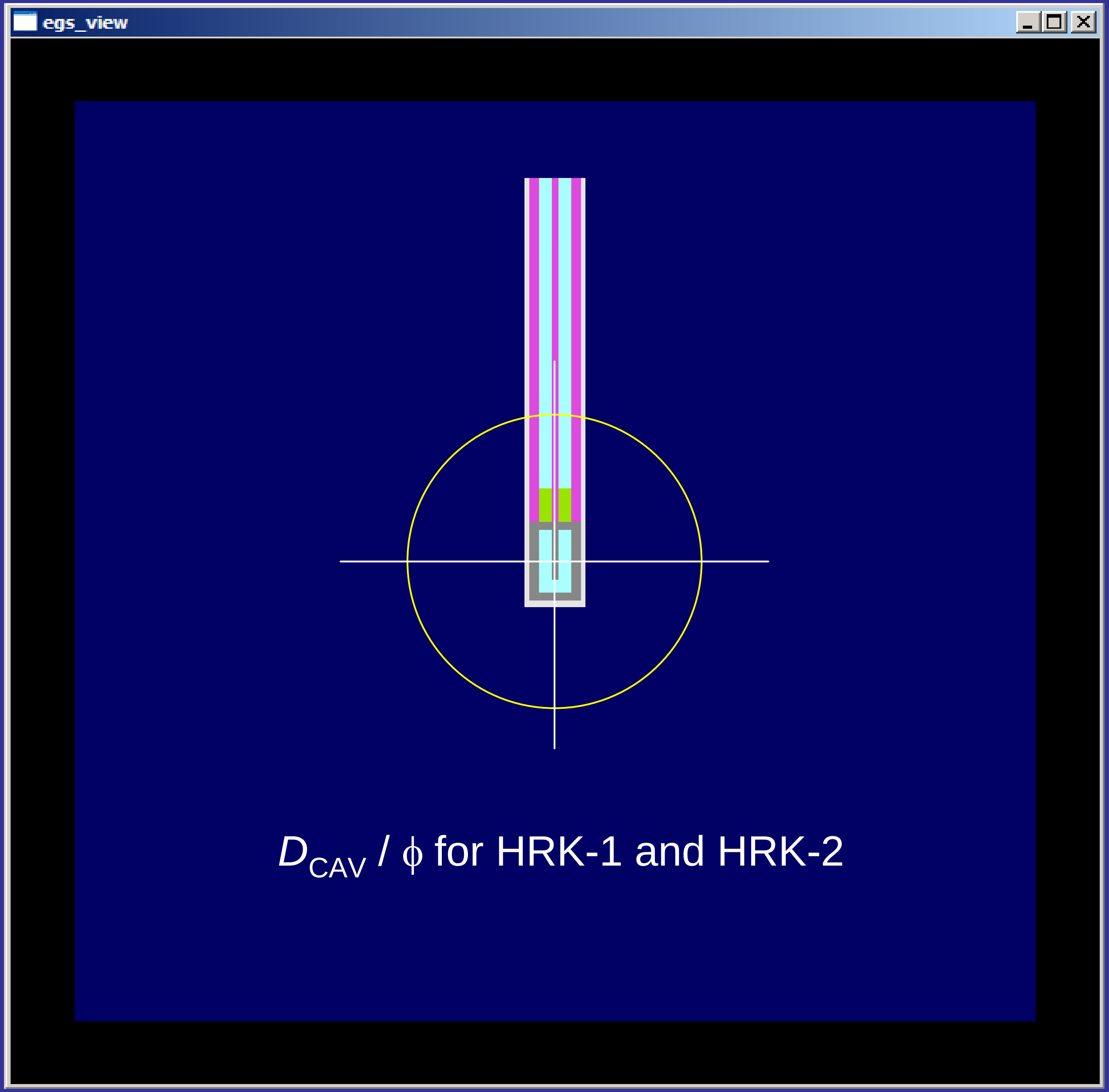
(pictures were generated with the egspp geometry viewer egs_view)



D_W/ϕ was calculated using spherical dose counting regions with decreasing radii until no more significant change was observed

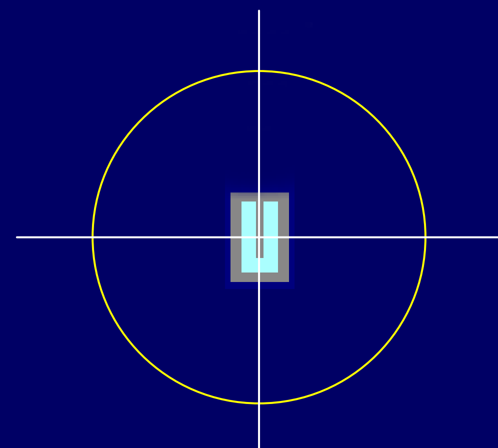


Spherical Detector	D_W/ϕ $*10^{-12}$	U %
R = 0,3 cm	4,2615	0,13
R = 0,5 cm	4,2684	0,10
R = 1 cm	4,2716	0,11



D_{CAV} / ϕ for HRK-1 and HRK-2

egs_view

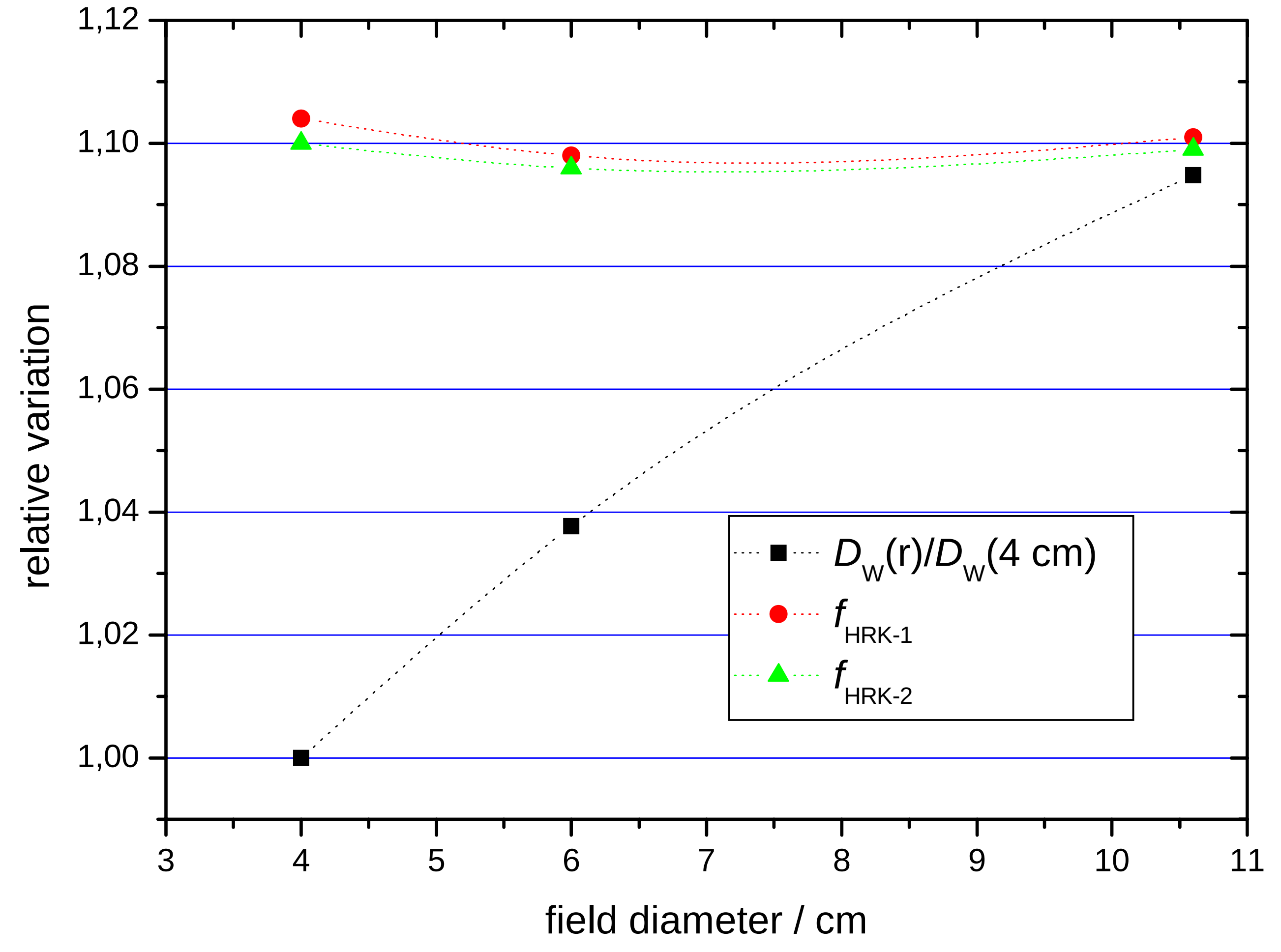


D_{CAV} / ϕ for HRK-1 and HRK-2

Ratio HRK-1: 0,9987(20)

Ratio HRK-2: 0,9977(20)

Variation of *f* with circular field size 4 cm, 6 cm and 10,6 cm



Uncertainty budget of the measurement with HRK-1:

$$\dot{D}_{\mathrm{W}} = \dot{D}_{\mathrm{CAV}} f = I_{\mathrm{CAV}} \cdot k_{\rho} \cdot k_{\mathrm{h}} \cdot k_{\mathrm{s}} \cdot k_{\mathrm{rn}} \cdot (d / d_0)^2 / (\rho_0 \cdot V_{CAV}) \cdot W / e \cdot f$$

Quantity		Value		Relative standard uncertainty	
ρ_0	(dry air density at NTP)	1,2048	kg/m^3	0,05	%
W/e	(W-value of air)	33,97	J/C	**0,15**	%
V_{CAV}	(volume of the cavity)	0,5539	cm^3	0,05	%
I_{CAV}	(ionization current)	333,56	pA	0,05	%
k_{ρ}	(air density)	1,0000		0,013	%
k_{h}	(air humidity)	0,9970		0,03	%
k_{s}	(recombination loss)	1,0043		0,05	%
k_{rn}	(radial non-uniformity)	1,0000		0,01	%
d_0	(nominal distance)	1050	mm	0,04	%
d	(real distance)	1050	mm		
f	(conversion factor)	1,0965		**0,24**	%
D_{W}/t	**(water absorbed dose rate)**	**18,642**	**mGy/s**	**0,30**	**%**

Results

PTB Calorimeter: D_W / t = 18,628 mGy/s, 2004-08-01

2004-08-01 00:00 UTC	HRK-1	HRK-1/2	HRK-2	HRK2/2
I_{corr}	333,98 pA	330,59 pA	914,65 pA	912,24 pA
D_{CAV} / t	17,001 mGy/s	16,994 mGy/s	16,978 mGy/s	16,963 mGy/s
f	1,1111	1,1111	1,1131	1,1131
D_W / t	18,889 mGy/s	18,882 mGy/s	18,898 mGy/s	18,882 mGy/s
Ratio Ion. / Calor.	**1,0140(36)**	**1,0136(36)**	**1,0145(36)**	**1,0136(36)**

Dose rate obtained from ionometry is about 1,4 % higher then those measured with the water calorimeter! The relative standard uncertainty of the ratio is 0,36 %. What's wrong?

$$\dot{D}_{\mathrm{W}} = \dot{D}_{\mathrm{CAV}}\, f$$

$$\dot{D}_{\mathrm{CAV}} = \left(\frac{I}{m}\right)_{\mathrm{CAV}} \frac{W}{e}$$

Assumption:

W/e = (33,97 +- 0,05) J/C

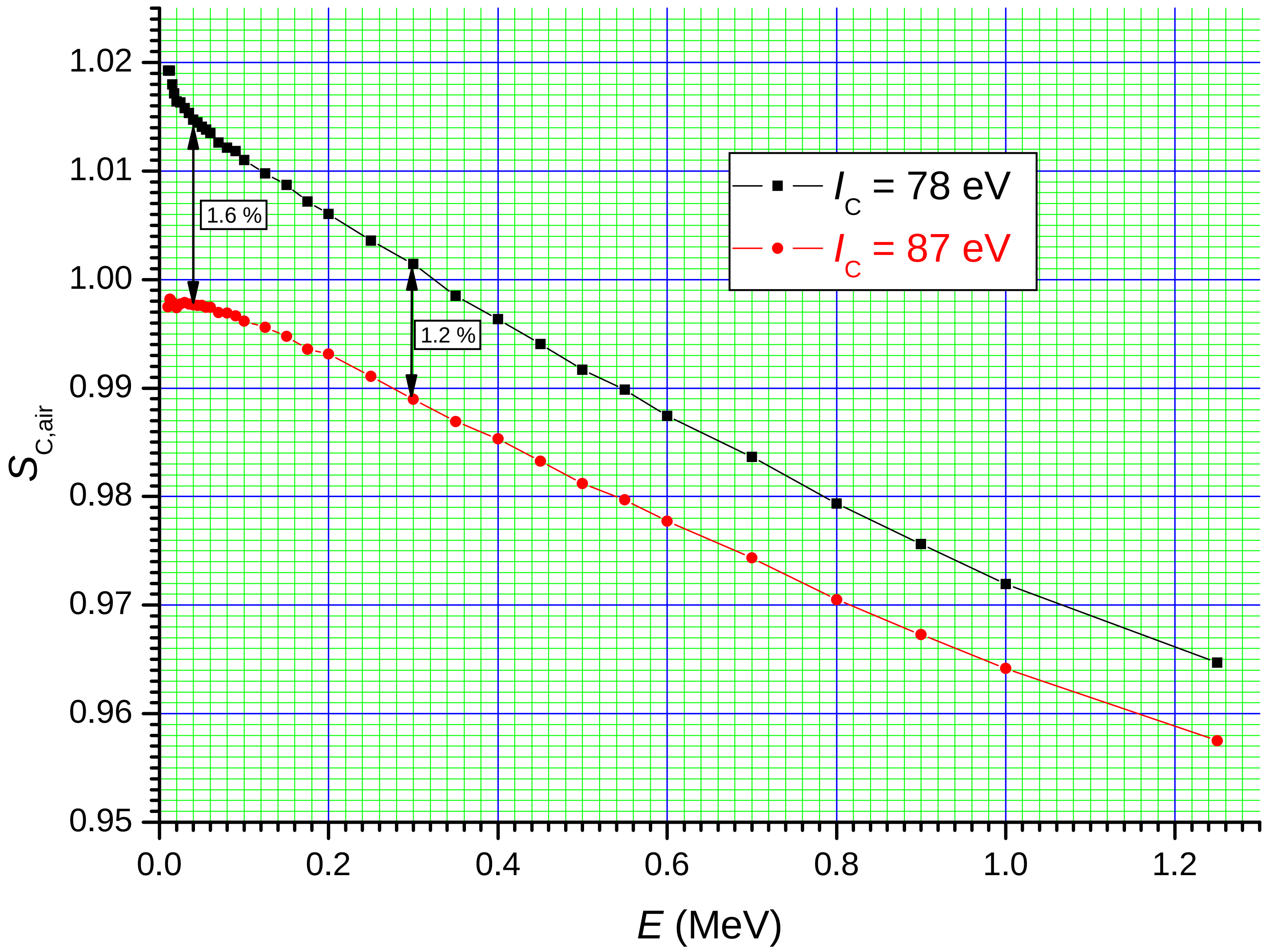
$$f = \left(\frac{D_{\mathrm{W}}}{D_{\mathrm{CAV}}}\right)_{\mathrm{MC}} = \bar{s}_{\mathrm{c,a}} \left(\frac{\bar{\mu}_{\mathrm{en}}}{\rho}\right)_{\mathrm{w,c}} \prod k_i$$

f was derived from a MC simulation which reflects not only statistical uncertainties but also uncertainties due to the underlying interaction coefficients. We assume that the ratio of water to graphite of the mean mass-energy-absorption coefficients reflects an uncertainty less than 0,15%. Further we assume that the product of correction factors is calculated correctly within the statistical uncertainties of the MC simulation.
Recently, there have been some discussion about the graphite stopping power values based on I_C=78 eV, as published in ICRU 37.

EGSnrc uses ICRU 37 stopping power values. An important parameter for the calculation of collision stopping power values is the mean excitation energy of the absorber, called *I*-value.

In ICRU 37, I_C=78 eV was chosen for graphite. This value has an uncertainty of ΔI=7 eV. However, Bichsel *et al* (1992) published a value of I_C=86,9 eV with a much lower uncertainty of ΔI = 1,2 eV.

Using Berger‘s ESTAR program, stopping power values of graphite were calculated using I_C= 87 eV and the conversion factor *f* was re-calculated with EGSnrc (egspp).



1.02
1.01
1.00
0.99
0.98
0.97
0.96
0.95
$S_{C,air}$
0.0
0.2
0.4
0.6
0.8
1.0
1.2
E (MeV)
I_C = 78 eV
I_C = 87 eV
1.6 %
1.2 %

Results, if s_C based on I_C=87 eV is assumed

PTB Calorimeter: D_W / t = 18,628 mGy/s, 2004-08-01

2004-08-01 00:00 UTC	HRK-1	HRK-1/2	HRK-2	HRK2/2
I_{corr}	333,98 pA	330,59 pA	914,65 pA	912,24 pA
D_{CAV} / t	17,001 mGy/s	16,994 mGy/s	16,978 mGy/s	16,963 mGy/s
$f\ (I_C = 87\ eV)$	1,0965	1,0965	1,0974	1,0974
D_W / t	18,642 mGy/s	18,635 mGy/s	18,631 mGy/s	18,615 mGy/s
Ratio Ion. / Calor.	**1,0008(36)**	**1,0004(36)**	**1,0002(36)**	**0,9993(36)**

Re-calculation of *f* with egspp using graphite stopping power values generated with Berger‘s ESTAR program and I_C=87 eV instead of I_C=78 eV solves the discrepancy and yields an almost perfect agreement!

Summary and conclusion

- The absorbed dose rate to water in a Co-60 reference field at the reference point in a water phantom was measured with graphite cavity ionization chambers and compared with the result obtained by the PTB water calorimeter.

- The dose rate obtained by ionometry was about 1,4 % higher than those obtained by calorimetry if *W/e*=33,97 J/C is assumed and the ICRU 37 graphite stopping power values are used for the calculated factor *f* which converts the cavity absorbed dose rate into the water absorbed dose rate. In ICRU 37 I_C=78 eV is chosen for the calculation of the graphite stopping power values.

- An almost perfect agreement was achieved, if *f* was calculated based on I_C= 87 eV, a value obtained from measurements published by Bichsel et al (1992).

⇒ Results strongly support graphite stopping power values calculated according to the methods described in ICRU 37 but with the mean excitation energy I_C= 87 eV instead 78 eV.