Progress in calculations of k_Q for TG-51

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Acknowledgements

- most of this talk is based on the work of several graduate students who have worked with me over the last few years:
- Lesley Buckley (P_{wall}),
- Lilie Wang (P_{repl})
- Byan Muir (Monte Carlo calculations of k_Q) critical to central part of this talk

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TG-51 for photon beams

$$D_w^Q = M N_{D,w}^Q$$

defines: chamber's absorbed dose calibration coefficient

$$N_{D,w}^Q = k_Q N_{D,w}^{^{60}Co}$$

defines k_Q: chamber specific beam quality conversion factor

-accounts for $N_{D,w}$ variation with Q

$$D_w^Q = M k_Q N_{D,w}^{^{60}Co}$$

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Where does k_Q come from?

Basically - same physics as TG-21,
ie Spencer-Attix cavity theory

$$D_{\text{med}} = D_{\text{air}} \left(\frac{\overline{L}}{\rho} \right)_{\text{air}}^{\text{med}} P_{\text{wall}} P_{fl} P_{gr} P_{\text{cel}} K_h$$

P_{wall} corrects for the wall not being same as med

P_{cel} corrects for central electrode not being wall material

K_h accounts for measurements being in humid air - all factors refer to dry air (K_h = 0.997)

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$P_{repl} = P_{gr} \, P_{fl}$

P_{repl} accounts for effects of cavity on electron spectrum at point of measurement

P_{gr}: that part of P_{repl} which accounts for less attenuation in cavity than in phantom.

-usually only applied to cylindrical chambers

-depends on local gradient => no effect at d_{max}

-handled by: -effective point of measurement when measuring depth-dose (0.6 r_{cav} offset)

- multiplicative results used in k_Q calculations

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$P_{repl} = P_{gr} P_{fl}$ (cont)

P_{fl}: that part of P_{repl} which accounts for other changes in spectrum in cavity.

Photon beams

P_{fl} not required past d_{max} because of transient charged particle equilibrium.

Fano theorem tells us electron spectrum is independent of density for cpe and to extent that water is like air, theorem applies.

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Equation used by TG-51 for k_Q

$$k_Q = \frac{\left[\left(\frac{\overline{L}}{\rho}\right)^{\mathrm{w}}_{\mathrm{air}} P_{\mathrm{wall}} P_{\mathrm{fl}} P_{\mathrm{gr}} P_{\mathrm{cel}}\right]}{\left[\left(\frac{\overline{L}}{\rho}\right)^{\mathrm{w}}_{\mathrm{air}} P_{\mathrm{wall}} P_{\mathrm{fl}} P_{\mathrm{gr}} P_{\mathrm{cel}}\right]}$$

This eqn assumes $(W/e)_{air}$ (relating charge measured to dose to the air in cavity) is independent of beam quality

For a detailed derivation, see Ch 9 in 2009 AAPM Summer School book

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Physical data sets in TG-51

Much of data comes directly from TG-21 and/or IAEA's TRS-277 (1987 Code of Practice).

TG-51 consistently uses ICRU Report 37 stopping powers (TG-21 used 35 and 37 values).

For photon beams,TG-51 stopping-power ratios are based on Monte Carlo calc'ns for 25 beam qualities

$$\left(\frac{\overline{L}}{\rho}\right)_{\mathrm{air}}^{\mathrm{water}} = 1.275 - 0.00231(\%dd(10)_x) \qquad \%dd(10)_x \geq 63.35\%$$

Values from Rogers and Yang Med Phys 26 (1999) 536

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stopping-power ratios: state-of-the-art

Uncertainties are uncertainties in stopping powers
-recent I-value measurement => 6% change
for H_2O => 0.1 % to 0.4 % change in k_Q.

Using full photon beam phase-space (with horns and varying energy across beam) rather than realistic spectra from uniform point sources shows no significant changes.

Similarly, sprs as a function of %dd(10) do not change when flattening filter is removed

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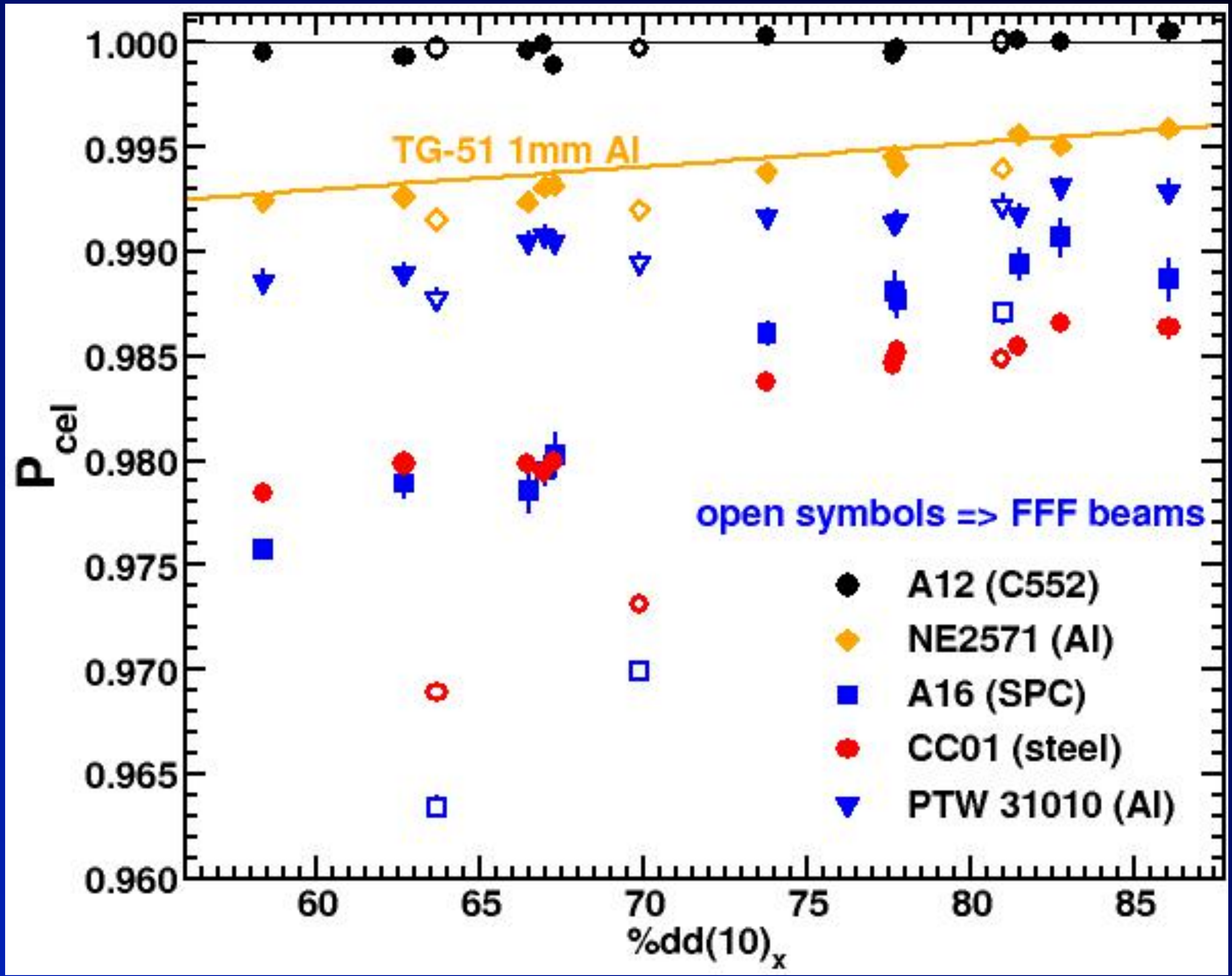
P_{cel}: *electrode correction*

- TG-51 corrects for chambers with Al central electrodes
- more recent, more precise calculations agree with values TG-51 used for Al electrodes in filtered beams
- even more recent calculations for higher-Z electrodes show major effects
  - P_{cel} effects much larger
  - P_{cel} in FFF (flattening filter free) beams even larger effects

P_{cel}: state-of-the-art

- high Z => much larger effect
- FFF beams => even larger effects



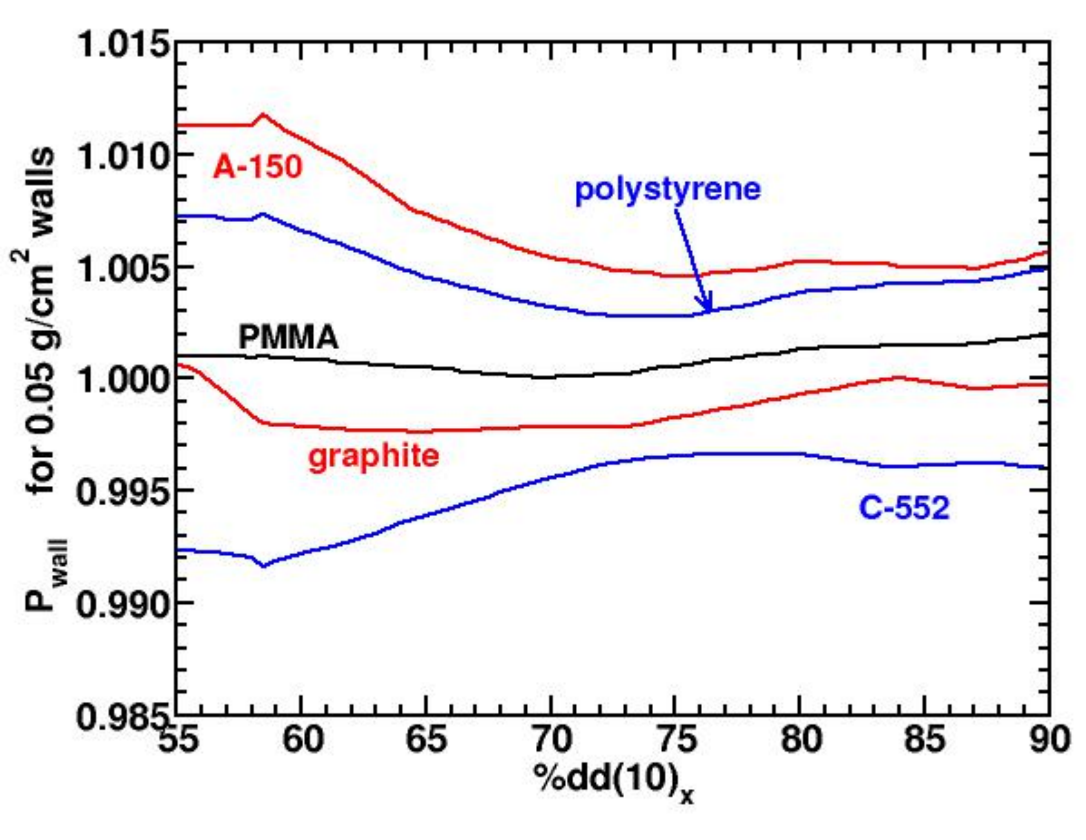
Muir and Rogers Med Phys 38(2011) 1081-1088

P_{wall} in TG-51

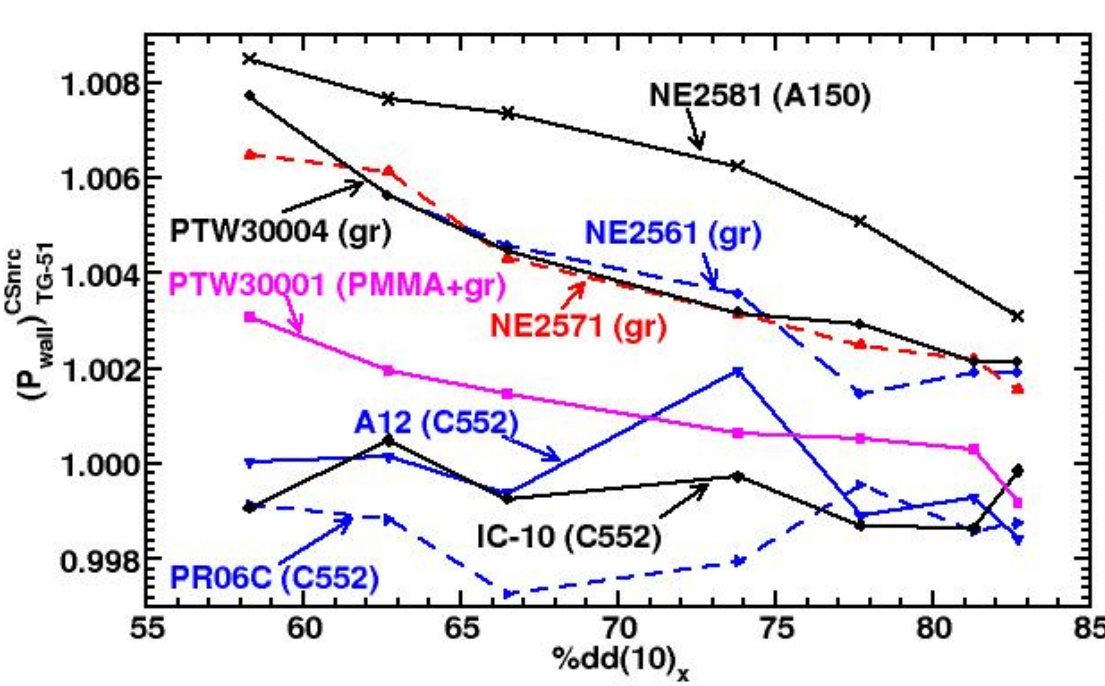
$$P_{\mathrm{wall}} = \frac{\alpha \left(\frac{\overline{L}}{\rho}\right)^{\mathrm{wall}}_{\mathrm{air}} \left(\frac{\overline{\mu_{\mathrm{en}}}}{\rho}\right)^{\mathrm{med}}_{\mathrm{wall}} + \tau \left(\frac{\overline{L}}{\rho}\right)^{\mathrm{sheath}}_{\mathrm{air}} \left(\frac{\overline{\mu_{\mathrm{en}}}}{\rho}\right)^{\mathrm{med}}_{\mathrm{sheath}} + (1-\alpha-\tau)\left(\frac{\overline{L}}{\rho}\right)^{\mathrm{med}}_{\mathrm{air}}}{\left(\frac{\overline{L}}{\rho}\right)^{\mathrm{med}}_{\mathrm{air}}}$$

- accounts for wall not being water

For walls 0.05g/cm^2

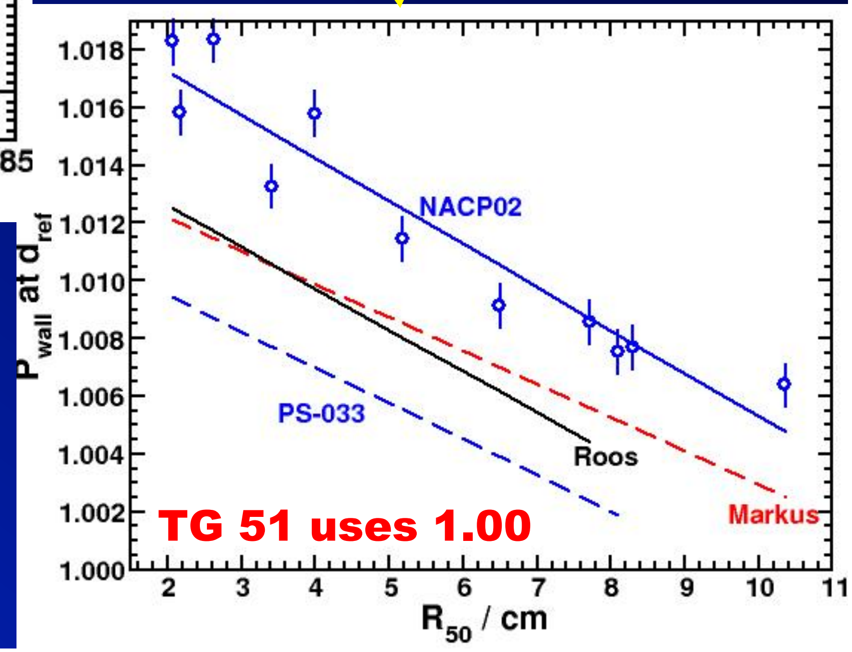


Monte Carlo values of P_{wall}



photon beams

electron beams



Buckley et al MP 33(2006) 455

MP 33(2006) 1788

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P_{gr} for cylindrical chambers

TG-51 (& TG-21) use P_{gr} values from Cunningham & Sontag(1980)
-values buried in k_Q values

IAEA uses values from Johansson et al (1977).
Same paper led to the 0.75 r_{cav} and 0.6 r_{cav} offsets used in the effective point of measurement approach

$$P_{gr}^{\mathrm{offset}} = 1 + \left(\frac{1}{10} \ln \frac{D_{20}}{D_{10}} \right) \Delta z$$

Relates multiplicative factor to offset

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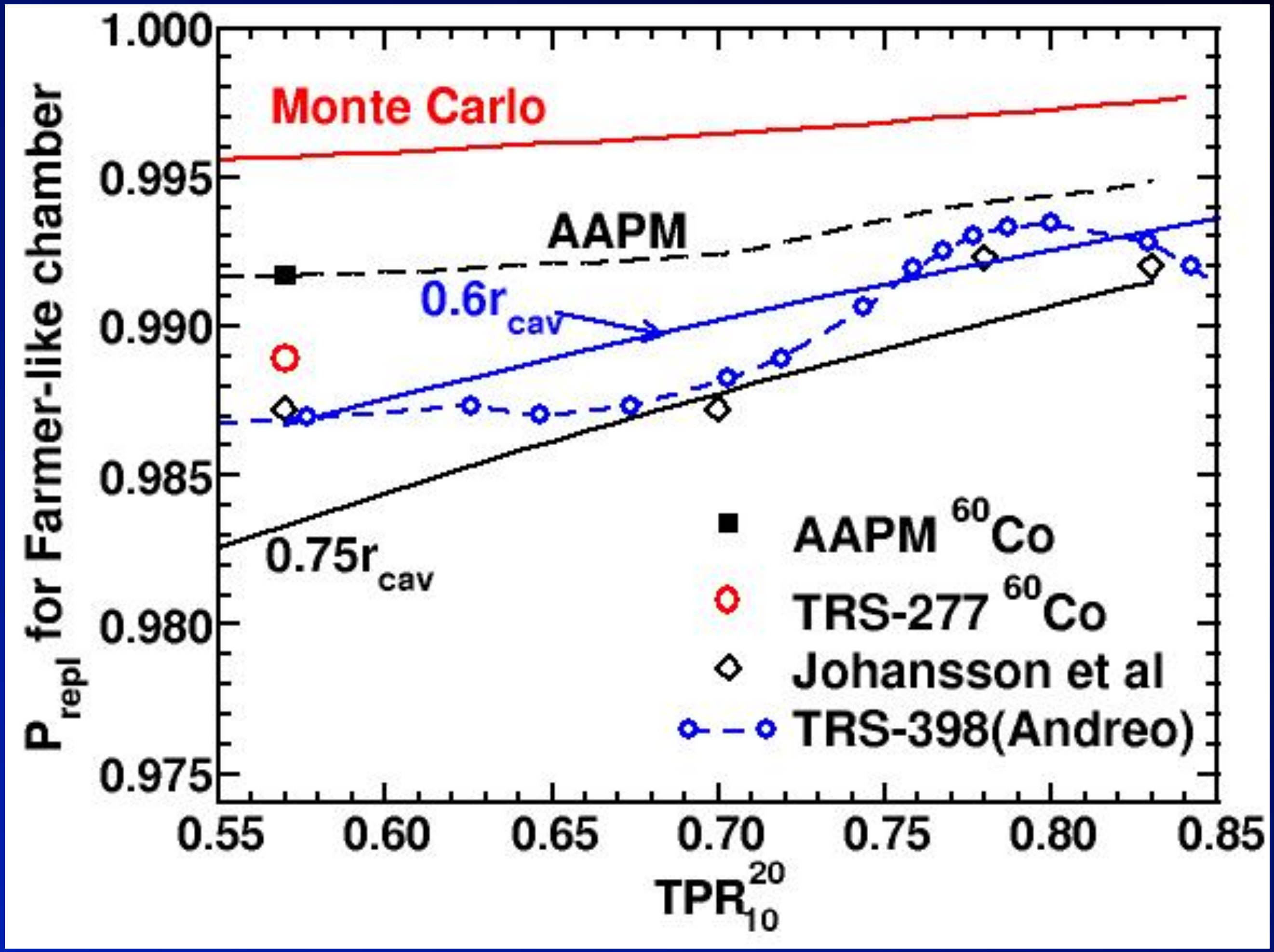
P_{gr} for cylindrical chambers

P_{gr} is largest TG51-TRS398 difference

Wang's MC calns disagree with both: while explaining previous measurements
PMB 54(2009)1609



TG-51's P_{gr} ratio hardly changes since lines parallel

Status of TG-51 k_Q photon calc'ns

$$k_Q = \frac{\left[\left(\frac{\overline{L}}{\rho}\right)^{\mathrm{w}}_{\mathrm{air}} P_{\mathrm{wall}} P_{\mathrm{fl}} P_{\mathrm{gr}} P_{\mathrm{cel}}\right]}{\left[\left(\frac{\overline{L}}{\rho}\right)^{\mathrm{w}}_{\mathrm{air}} P_{\mathrm{wall}} P_{\mathrm{fl}} P_{\mathrm{gr}} P_{\mathrm{cel}}\right]}$$

- spr is OK, even in FFF beams
- P_{wall} values wrong by up to 0.5%
- P_{fl} value of unity assumed OK
- P_{gr} values wrong by up to 0.2%
- P_{cel} values wrong by up to 3% for high-Z electrodes

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Which path forward?

- rework TG-51 analytic calculations accounting for all the new data?
- base k_Q values on measured values
  - McEwen published an extensive set of values in 2010 (Med Phys 37(2010) 2179)
- do ab initio Monte Carlo calculations of k_Q

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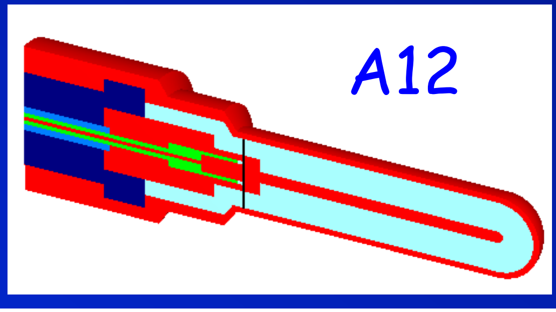
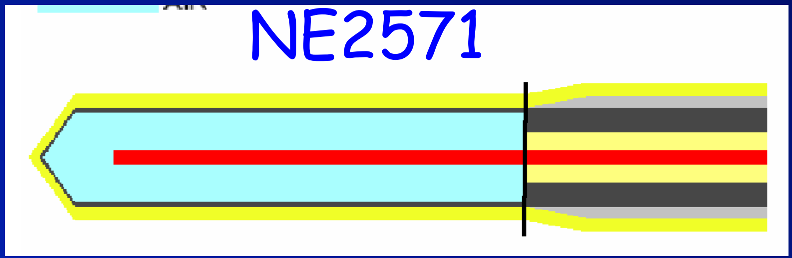
ab initio Monte Carlo calculations

- EGSnrc has been shown to calculate doses in an ion chamber within 0.1% relative to its own cross sections (Fano test)
- egs_chamber code of Wulff et al (Med Phys 35 (2008) 1328)
  - very efficient: correlated sampling
  - handles complex realistic geometries





Calculating k_Q

- definitions:

$$k_Q = \frac{N_{D,w}^{Q}}{N_{D,w}^{Co}}$$

$$D_{\mathrm{gas}} = \frac{Q\left(\frac{W}{e}\right)_{\mathrm{air}}}{m_{\mathrm{air}}}$$

$$N_{D,w} = \frac{D_{\mathrm{w}}}{Q} = \frac{D_w}{D_{\mathrm{gas}}\frac{m_{\mathrm{air}}}{\left(\frac{W}{e}\right)_{\mathrm{air}}}}$$

assume (W/e) is independent of beam quality

$$k_Q = \frac{N_{D,w}^{Q}}{N_{D,w}^{Co}} = \frac{\frac{D_w^Q}{D_{\mathrm{gas}}^Q}}{\frac{D_w^{Co}}{D_{\mathrm{gas}}^{Co}}} = \left(\frac{D_w}{D_{\mathrm{gas}}}\right)_{Co}^{Q}$$

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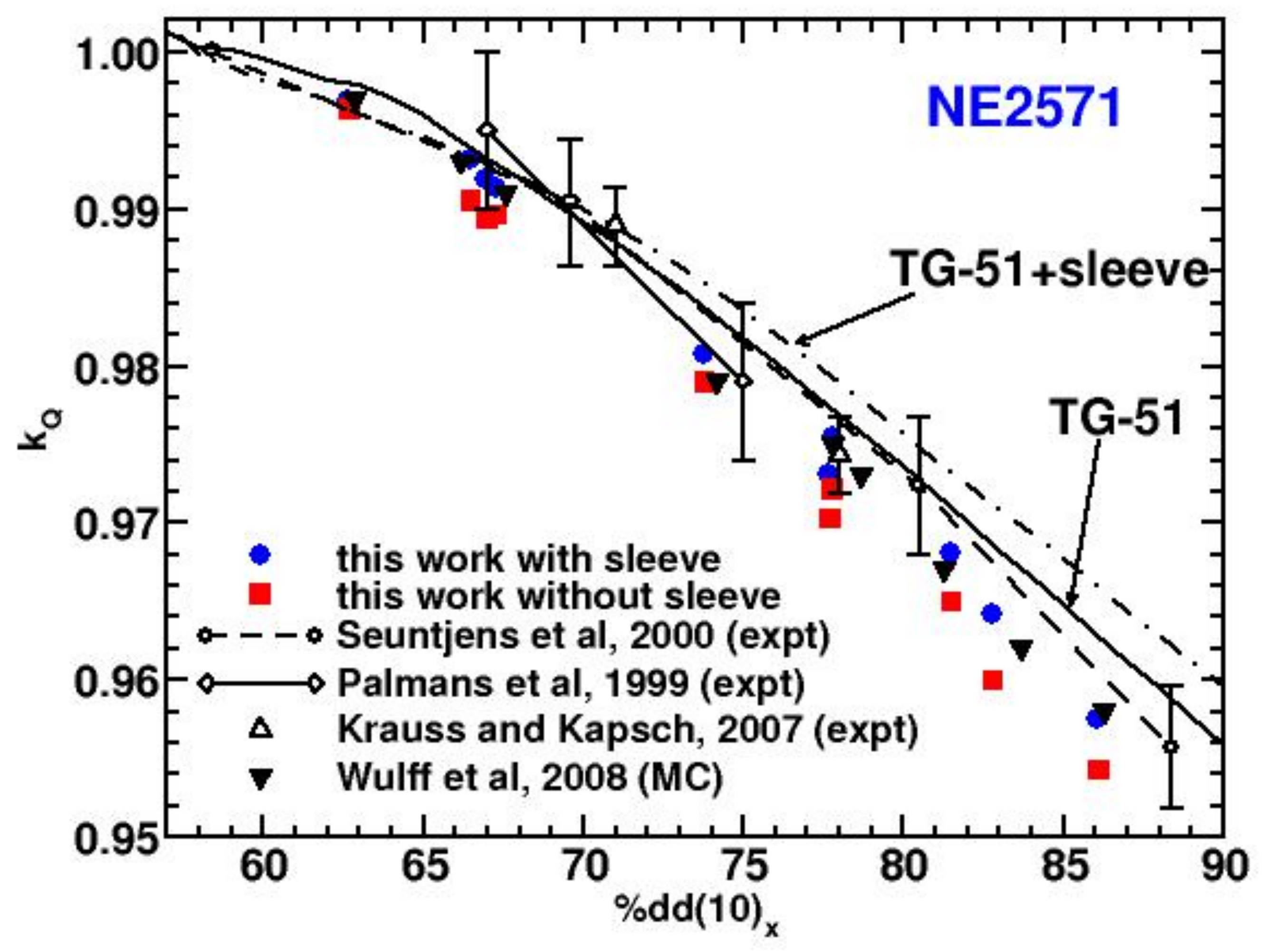
Some k_Q results: NE2571

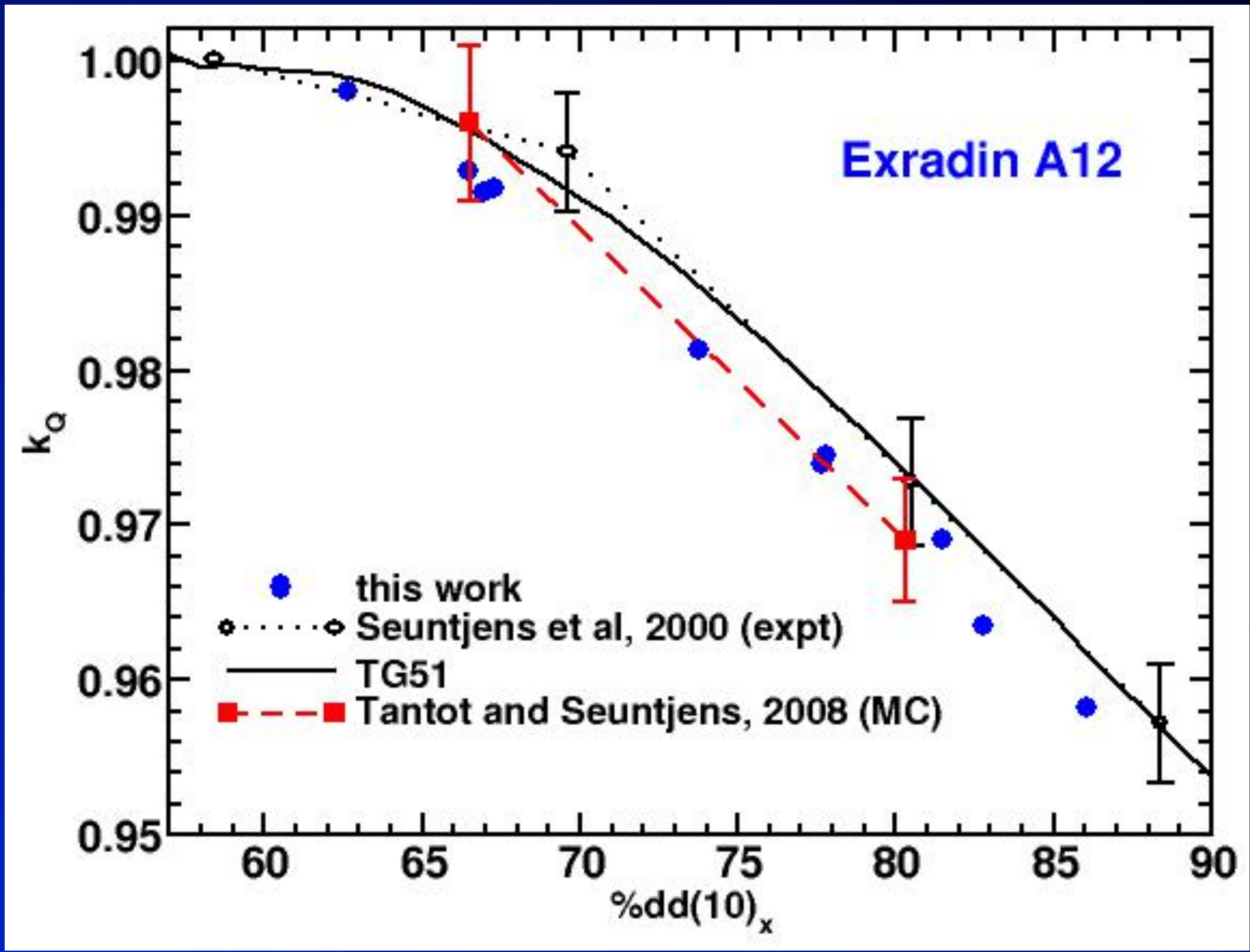
Comparison to McEwen's data comes later

NE2571 one of furthest from TG-51



Muir & Rogers Med Phys 37(2010) 5939

more k_Q results: A12



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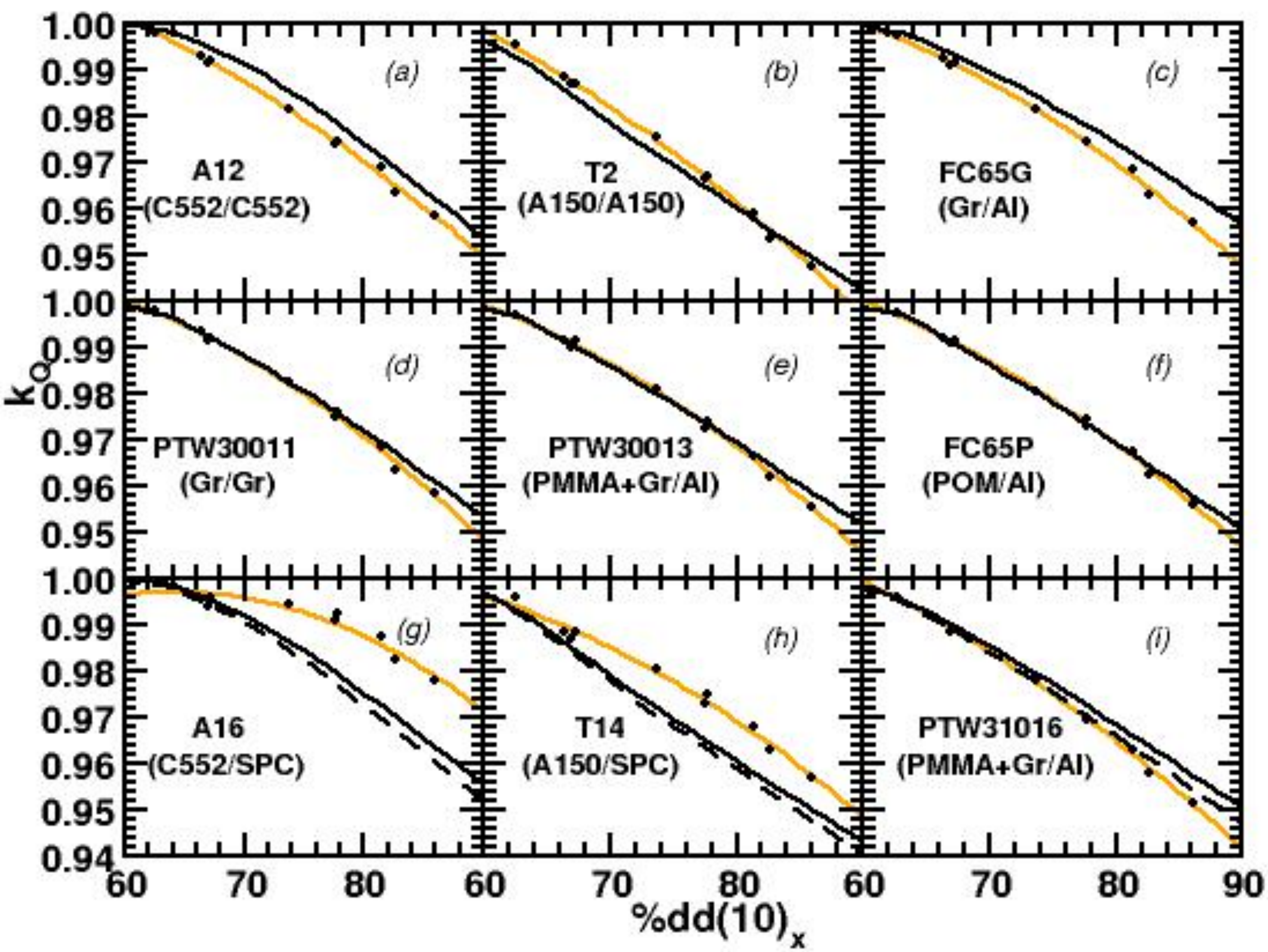
9 different "classes" of detectors

black:TG51
gold: fit

labels:
(wall/
electrode)

Note large effects of high-Z electrodes



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fits to k_Q

$$k_Q = a + b(\%dd(10)_x) + c(\%dd(10)_x)^2$$
$$\%dd(10)_x \geq 62.7\%$$

- rms deviation: less than 0.1 % for 10 WFF beams, except for 1 chamber (A14, 0.2%, very small volume, SPC electrode).
- a,b,c tabulated in paper and report (also as a function of TPR)

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Uncertainties on calculated k_Q

- EGSnrc is accurate to 0.1 % against its own cross sections (Kawrakow, Med Phys 27(2000) 499

- what is effect of cross section uncertainties?

- what is uncertainty on $(W/e)_{air}$ being constant?
  - TRS-398 says 0.5% but evidence for any value is very thin

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Cross section uncertainties on k_Q

standard error propagation, assuming uncorrelated

$$u_{k_Q} = \left[\sum_{i=1}^{n} \left(\frac{\partial k_Q}{\partial x_i} \right)^2 u^2(x_i) \right]^{\frac{1}{2}}$$

where $u(x_i)$ is the uncertainty on cross section x_i

Approximate $$\left(\frac{\partial k_Q}{\partial x_i} \right) = \frac{\Delta k_Q}{\Delta x_i}$$

where Δk_Q is change in k_Q when cross section i is changed by Δx_i . Calculate Δk_Q for a Δx_i corresponding to $u(x_i)$.

$$u_{kQ} = \left[\sum_{i=1}^{n} (\Delta k_Q)_i^2 \right]^{\frac{1}{2}}$$

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Cross section uncertainties on k_Q(cont)

- Calculating Δk_Q as a % change

$$\Delta k_Q = \left| \frac{R_{ch}(Co)}{R_{ch}(Q)} - 1 \right| \times 100\%$$

where R_{ch} is the ratio dose to gas calculated with a cross section changed by its stated uncertainty over that calculated with standard cross section.

Can use correlated sampling.

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Cross section uncertainties on k_Q(cont)

Material	Mean Excitation Energy ΔI (%)	Δk_Q (%)	Photon Cross-sec Δk_Q (%)
Water (NE2571)	1.5	0.03	0.55
C552 (Exradin A12)	5	0.30	0.53
Graphite Wall (NE2571)	4.5	0.19	0.29
PMMA (PTW 30013)	2	0.09	0.16
Air (NE2571)	2.5	0.03	0.02
Aluminum (NE2571)	0.5	0.00	0.01
POM/Delrin (IBA FC65P)	5	0.23	0.21
A150 (Exradin T2)	5	0.33	0.53
Steel Wire (IBA CC01)	5	0.01	0.05
SPC Electrode (Exradin A16)	5	0.03	0.02

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NE2571 k_Q uncertainty components

Variable, x_i	$u(x_i)$ (%)	$\Delta(k_Q)_i$ (%)
Mean Excitation Energy, I		
Water	1.5	0.03
Air	2.5	0.03
Graphite Wall	4.5	0.19
Aluminum Electrode	0.5	0.00
Photon Cross-sections		
Water	1.0	0.55
Air	1.0	0.03
Graphite Wall	1.0	0.29
Aluminum Electrode	1.0	0.01
All (Correlated)	1.0	0.0

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NE2571 k_Q uncertainties (cont)

Other Sources	$u(x_i)$ (%)	$\Delta(k_Q)_i$ (%)
Statistical Uncertainty	-	0.1
EGSnrc[30]	-	0.1
Wall Thickness	5.0	0.1
Cavity Dimensions	5.0	0.00
Source model	-	0.1
$\frac{W}{e}$	-	0.5
	u_{k_Q}	
corr, no W/e	-	0.28
uncorr, no W/e	-	0.68
corr, with W/e	-	0.57
uncorr, with W/e	-	0.85

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Uncertainties on k_Q for all chambers

Group (Wall/Electrode)	u_{k_Q}			
	corr no W/e	uncorr no W/e	corr with W/e	uncorr with W/e
a (C552/C552)	0.36	0.85	0.62	0.98
b (A150/A150)	0.39	0.86	0.63	0.99
c (Graphite/Al)	0.28	0.68	0.57	0.85
d (Graphite/Graphite)	0.28	0.68	0.57	0.85
e/i (PMMA+Graphite/Al)	0.31	0.71	0.58	0.86
f (POM/Al)	0.32	0.66	0.59	0.83
g (C552/SPC)	0.36	0.85	0.62	0.98
h (A150/SPC)	0.39	0.86	0.63	0.99

worst case: 0.39% 0.86% 0.63% 0.99%

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Muir & Rogers Med Phys 37 (2010) 5939

Experimental measurements of k_Q

- many measurements done, but most papers measure one or two types of chambers
- McEwen measured k_Q for 27 different types against the Canadian primary standards of absorbed dose---->

  (Med. Phys. 37 (2010) 2179)

$$k_Q = \frac{N_{D,w}^{Q}}{N_{D,w}^{Co}}$$

- for "well-behaved" chambers

  measurement uncertainty on k_Q was 0.30%
- agreement with TG—51 values is excellent, typically 0.5% or better for "well-behaved"

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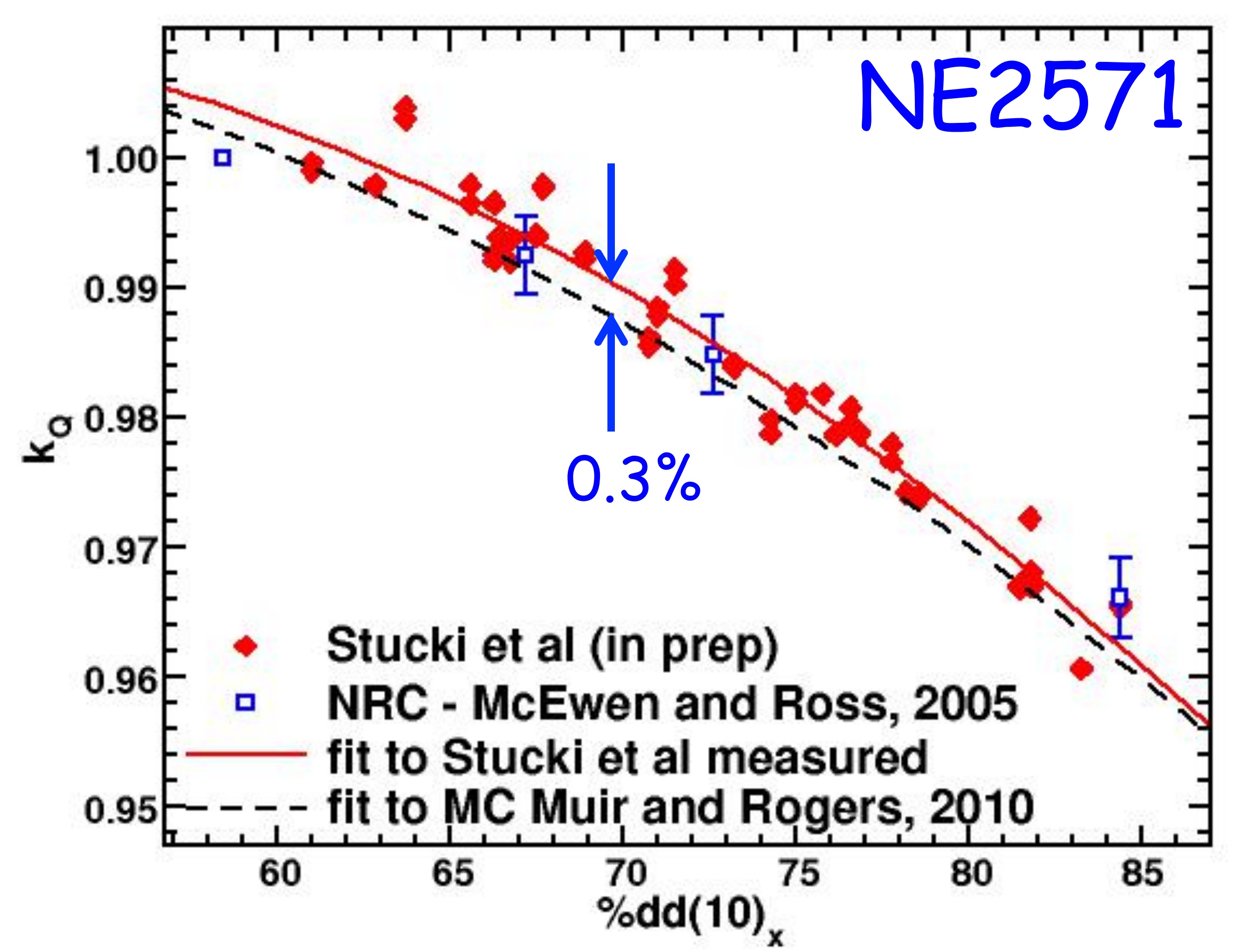
Consistency of measured k_Q

diamonds are from standards labs (Stucki et al, to be published)



Muir et al Med Phys 38 (2011) 4600

How well do calculations and measurements agree?

$$\Delta_i = \frac{k_{Q,i}(calculated) - k_{Q,i}(measured)}{k_{Q,i}(measured)} \times 100\%$$

$$\chi^2/df = \frac{1}{f}\sum_{i=1}^{f}\frac{\Delta_i^2}{s_m^2 + s_c^2}$$

For 26 chambers in common,

- χ^2 /df < 0.65 for all chambers at 1 energy
- χ^2 /df < 1 for all chambers vs energy except 1

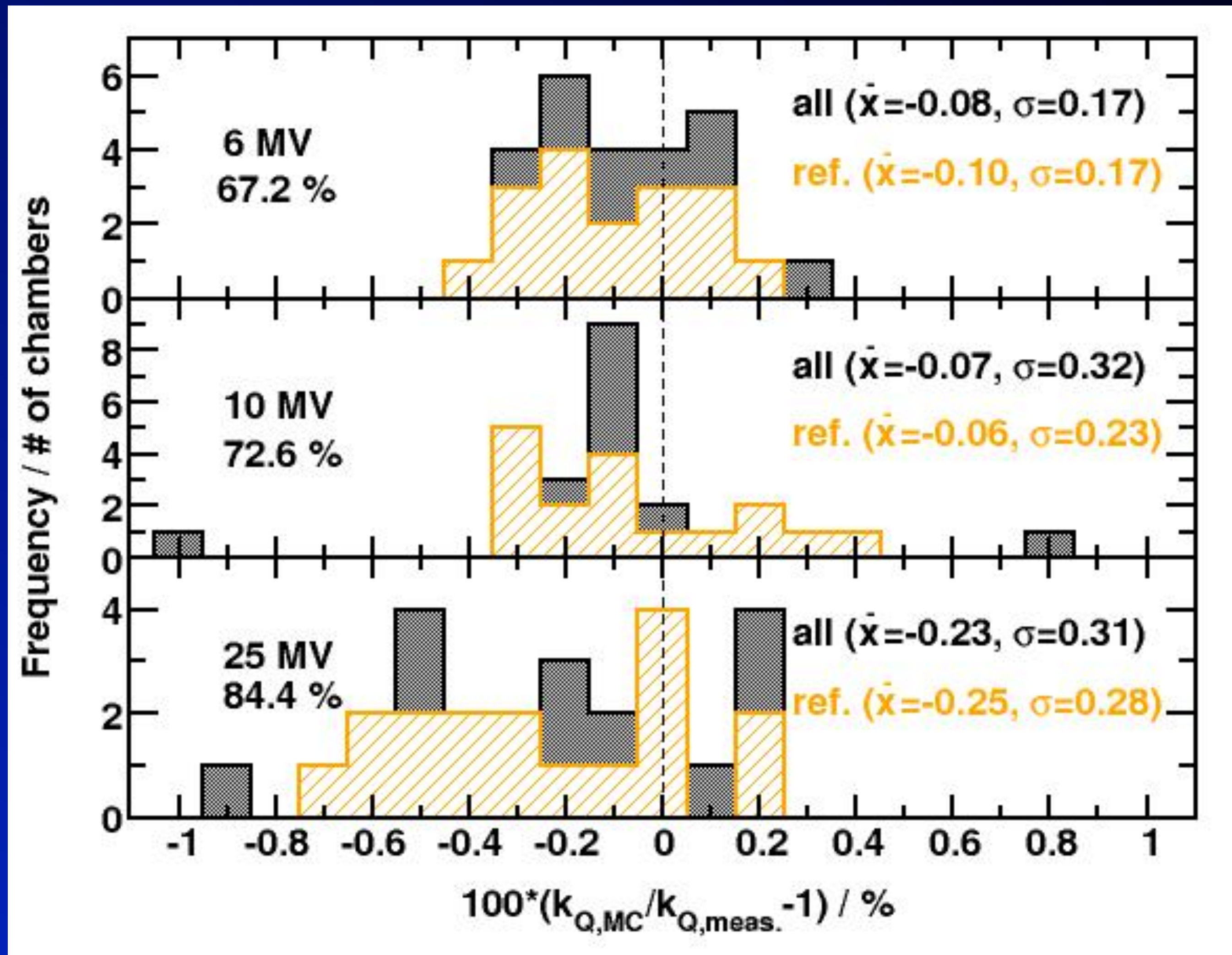
Suggests, if anything, uncertainties are too large

Measured vs calculated k_Q

26 chambers in common

shaded part is less precise chambers

remarkable agreement



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Can we use this agreement to set a limit on the variation of $(W/e)_{air}$?

- assume some variation of $(W/e)_{air}$

$$\alpha = \left(\frac{W}{e}\right)_{Co}^{Q}$$

- in this case:

$$k_Q = \alpha \left(\frac{D_w}{D_{ch}}\right)_{Co}^{Q}$$

- now we have

$$\Delta_i = \frac{\alpha \times k_{Q,i}(calculated) - k_{Q,i}(measured)}{k_{Q,i}(measured)}$$

- calculate χ^2 as before as function of α

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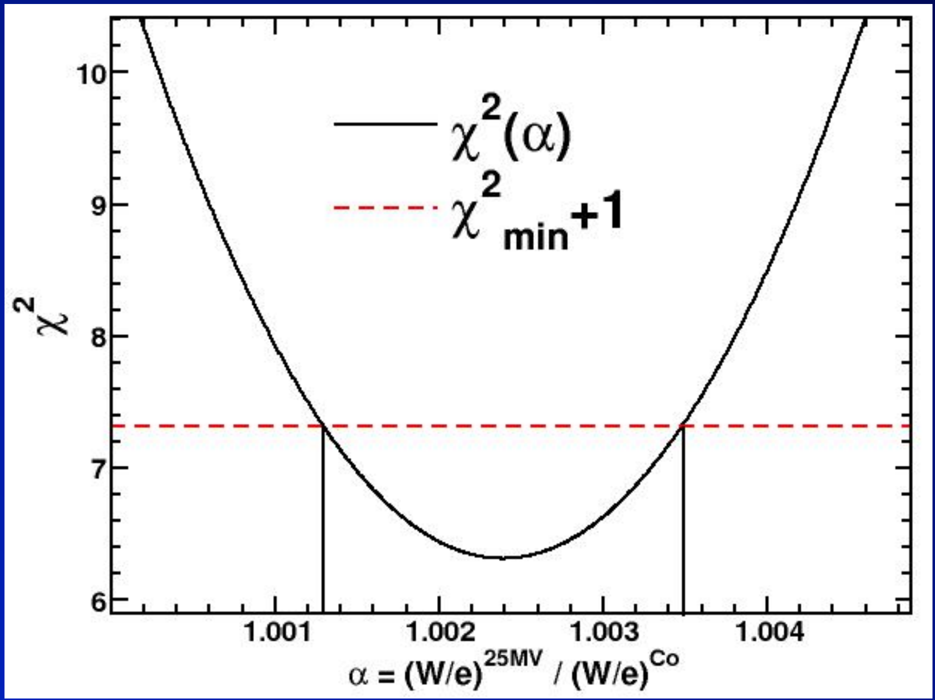
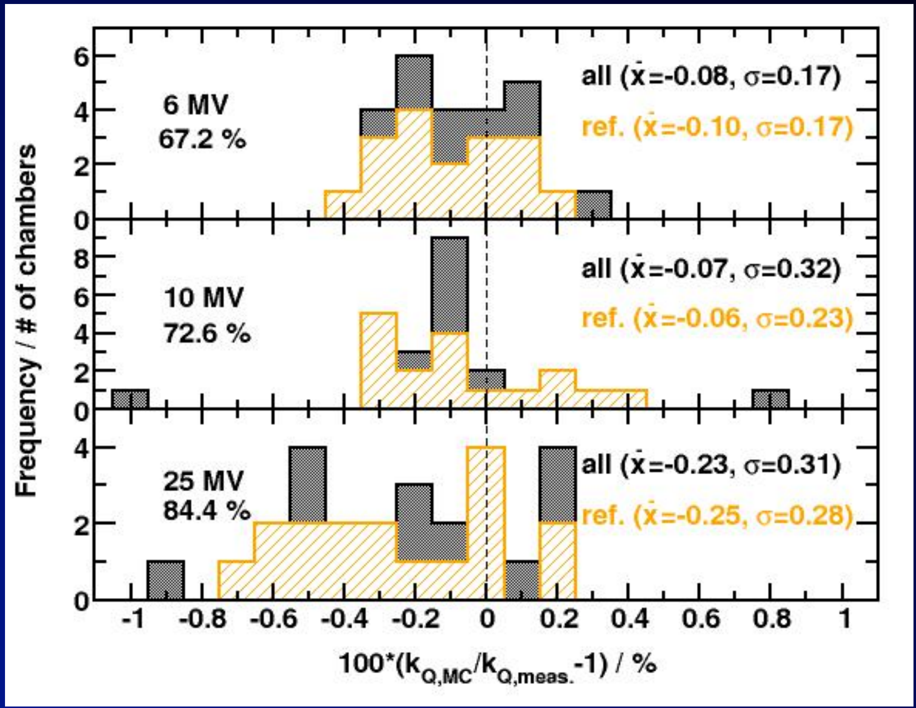
What is the value of α ?





$\alpha = 1.0024 \pm 0.0011$

$$\alpha = \left(\frac{W}{e}\right)^{Q}_{Co}$$

Conservatively one can say

W/e is constant within 0.29% (0.42%) with 68% (95%) confidence

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Conclusions

- Monte Carlo calculations of k_Q are feasible

- experimental agreement is exceptional
  - 0.13 % mean difference for 26 chambers
  - 0.31 % RMS deviation for 26 chambers

- uncertainty on variation of $(W/e)_{air}$ from Co to 25 MV is 0.29 % (68 % limit)

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Conclusions (cont)

- uncertainty on calculated k_Q values is between 0.40 and 0.49 % depending on wall material
- individual chambers appear representative else agreement could not be so good
- results apply only to filtered beams
  - with low-Z electrodes, results still apply
  - with Z > 13 electrodes, values will not hold in FFF beams (OK in WFF beams if reference quality)

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Thanks for your attention

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