Progress in calculations of k_Q for TG-51

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Acknowledgements

- much of this talk is based on the work of Bryan Muir, a graduate student, who has worked with me over the last few years

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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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The addendum about to be published is exclusively about photon beams.

Work is proceeding on electron beams.

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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Ch 9 is available on my home page
http://www.physics.carleton.ca/~drogers

Status of TG-51 k_Q photon calcs

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

- spr is OK, even in FFF beams
- ratios of P_{wall} values wrong by up to 0.5%
- P_{fl} value of unity assumed OK
- ratios of 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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Not bad except for higher-Z electrode chambers.

They have other problems for reference dosimetry and are not recommended for use.

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

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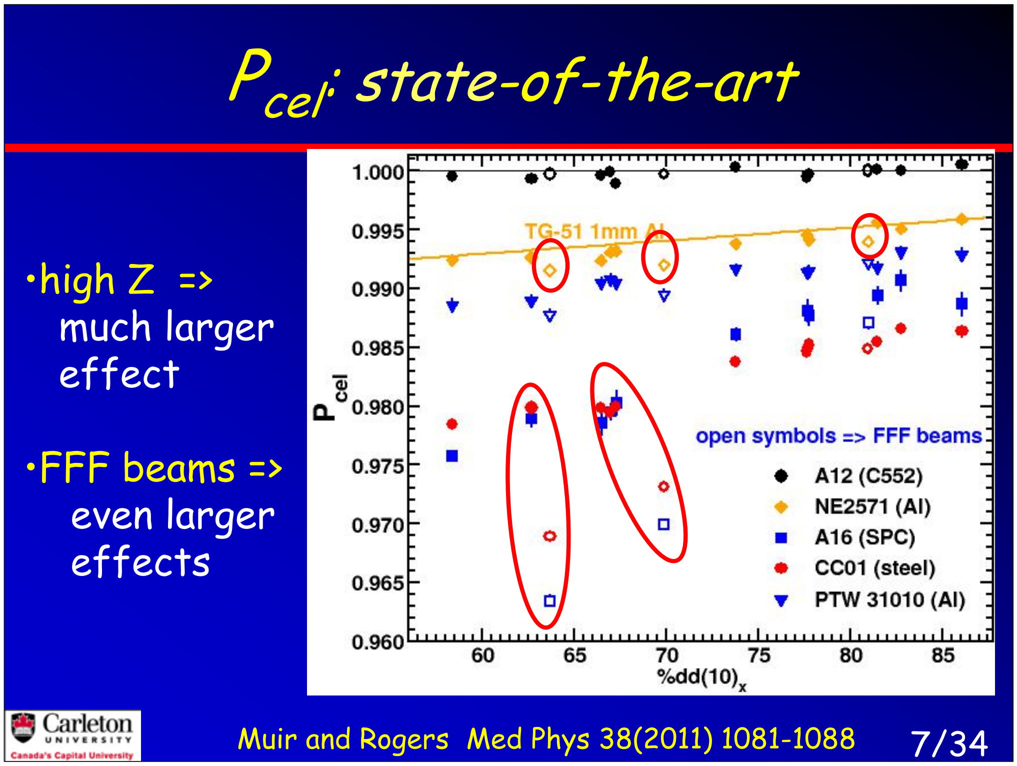
SPC Silver Plated Copper Covered Steel
Exradin A14,T14,A14SL,A16

or just steel PTW 31006, CC01



31010 Al electrode much larger fraction of chamber volume 12% vs 2% for NE2571 => much bigger effect even is same radius roughly.

Note NE2571 small FFF effect is there

The large effects for higher-Z

⇒standard TG-51 kQ calculations do not work unless use these details

These results means high-Z electrodes must be used with care in all FFF beams.

SPC means sliver plated copper covered steel electrodes.

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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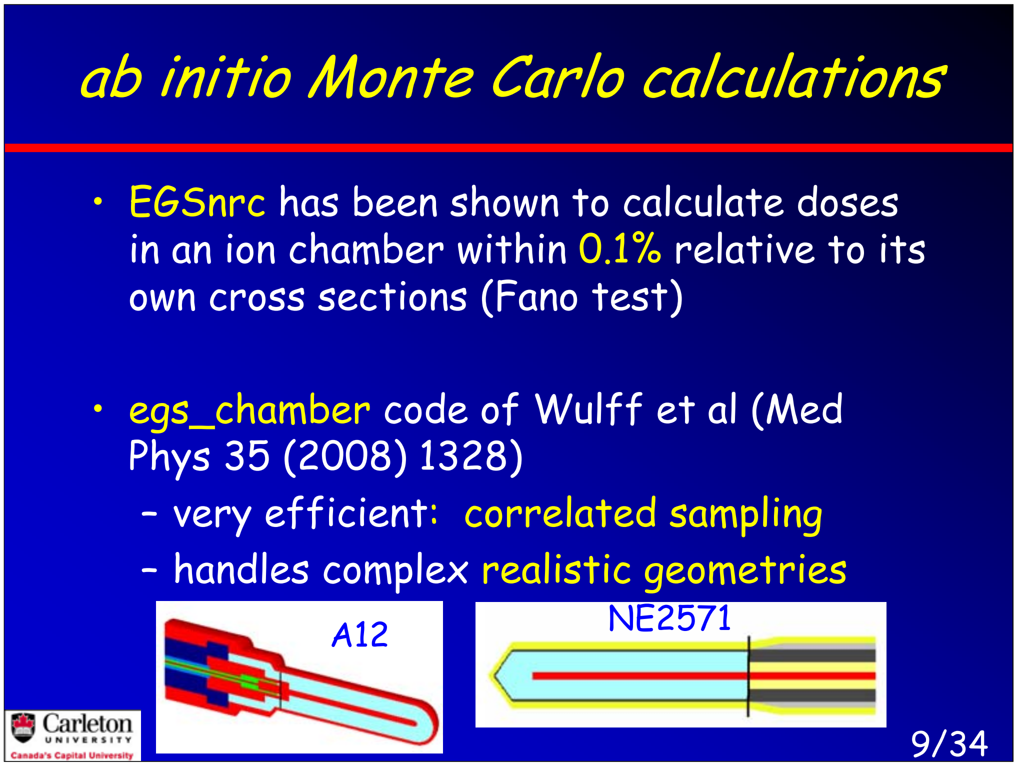
-McEwen covered 27 different chamber models – how do we handle new chambers?

-reworking analytic would be based on multiple MC calc– complex uncertainty analysis



Two significant advances in Monte Carlo since TG-51 written: EGSnrc and egs_chamber (+ much faster computers)

Sheath on NE2571 since not waterproof

Calculating k_Q with Monte Carlo

- definitions:

$$k_Q = \frac{N_{D,w}^{Q}}{N_{D,w}^{Co}} \qquad D_{\text{gas}} = \frac{Q\left(\frac{W}{e}\right)_{\text{air}}}{m_{\text{air}}}$$

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

assume (W/e) is independent of beam quality

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

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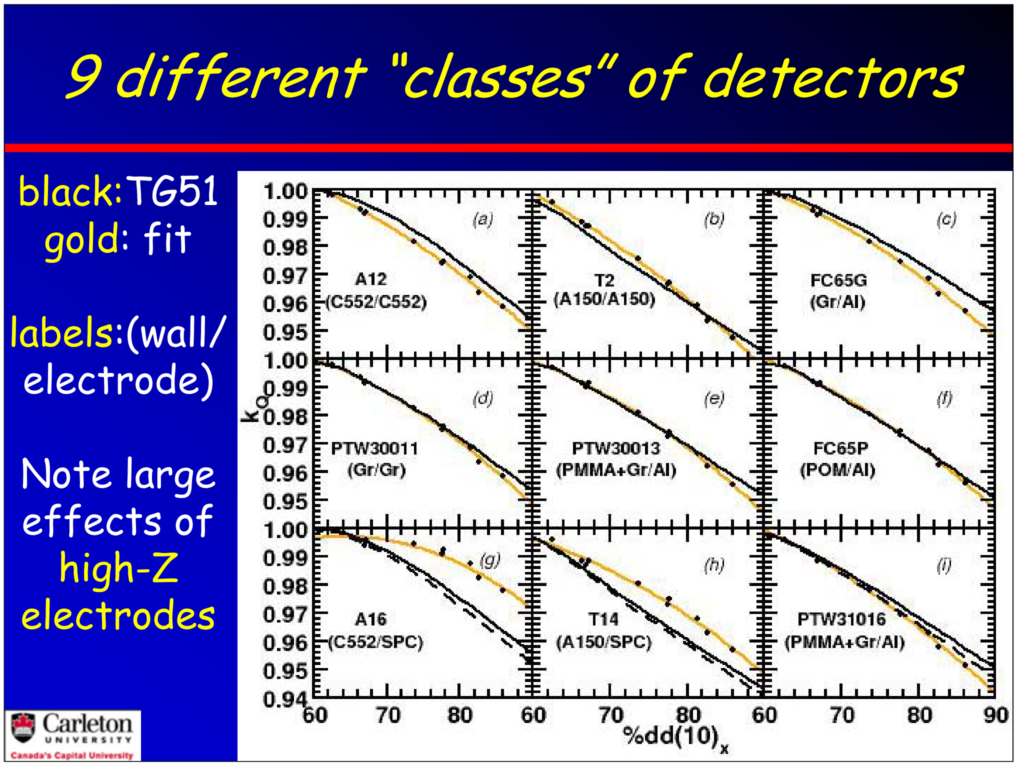
-first done more than 5 yr ago but only with Wulff's egs_chamber did statistical precision get sub -0.1%

The only important eqn on this slide is highlighted in yellow. This is what is used for calculations.

-can use correlated sampling at each Q separately or in 4 separate runs (water calcs are common to all chambers)



The calculations are for WFF beams (i.e. with flattening filters)

-FFF big issues for high-Z electrodes

Overall good agreement for B-F chambers with TG-51 except for NE2571 gr/Al

SPC means sliver plated copper covered steel

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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SPC sliver plated copper covered steel

Uncertainties on calculated k_Q

- EGSnrc is accurate to 0.1 % against its own cross sections (Kawrakow, Med Phys 27(2000) 499
- what are effects 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 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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14/34

The final eqn, which is all that matters, holds for absolute or percentage differences.

Derivation is in

Muir and Rogers MP 37(2010) 5939.

First applied this way by

Wulff et al, PMB 55(2010) 4481

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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All correlated means that all photon cross sections are increased by 1%. in which case k_Q does not change.

In related work by Ali and Spencer in my lab, it is shown that the 1% uncertainty on the cross sections is a very conservative estimate.

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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16/34

The uncertainty shown here on W/e is the estimate from TRS-398. Below a better estimate is given as 0.25%, but this table is from a 2010 paper.

For comparisons to experiment discussed in next few slides, we used the correlated, no W/e uncertainty estimate and still get chi-squared values less than 1.

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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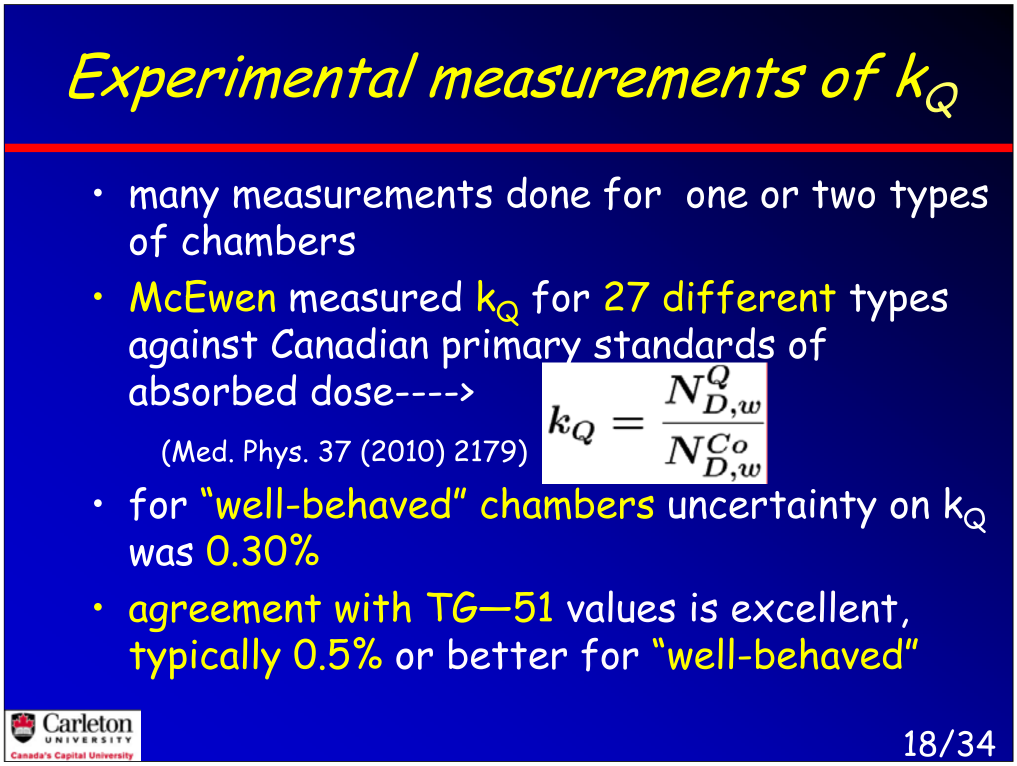
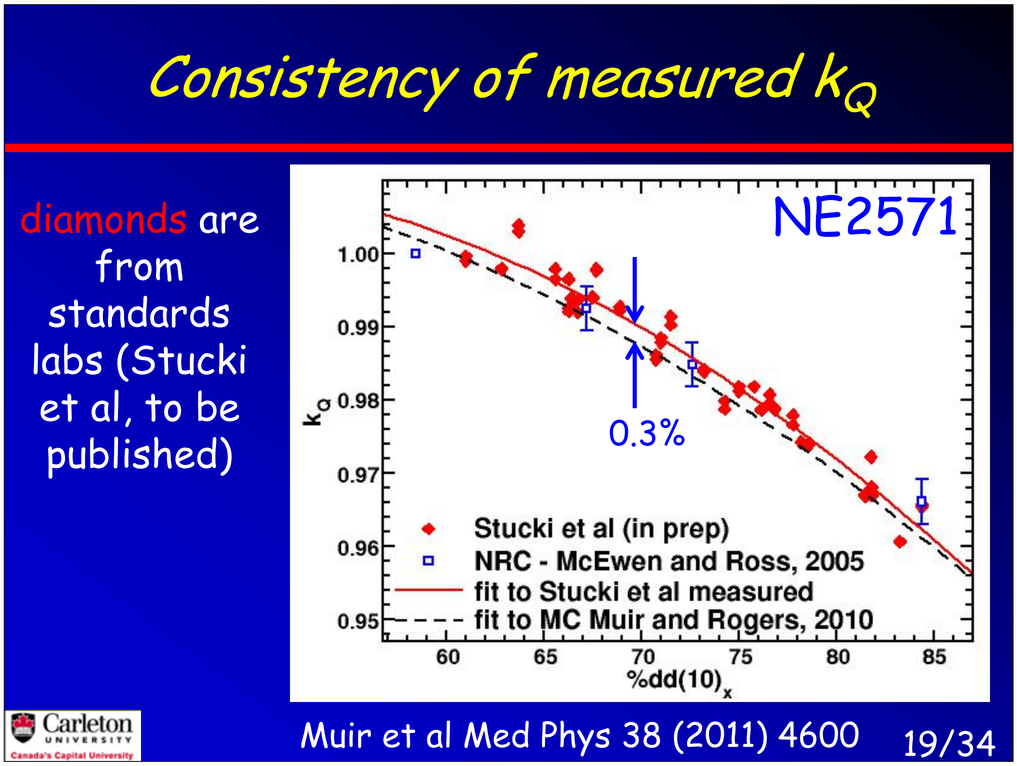
Muir & Rogers Med Phys 37 (2010) 5939

These are uncertainties on calculated k_Q



Well-behaved means the chambers met the specifications for use with TG-51 as given in the addendum. These are related to Pion, Ppol, reproducibility and stability criteria. Basically, it excludes all very small volume chambers which are the ones with high-Z electrodes.



note good agreement between calns and fit to meas

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,

- $\chi^2/df < 0.65$ for all chambers at 1 energy
- $\chi^2/df < 1$ for all chambers vs energy except 1

Suggests, if anything, uncertainties are too large

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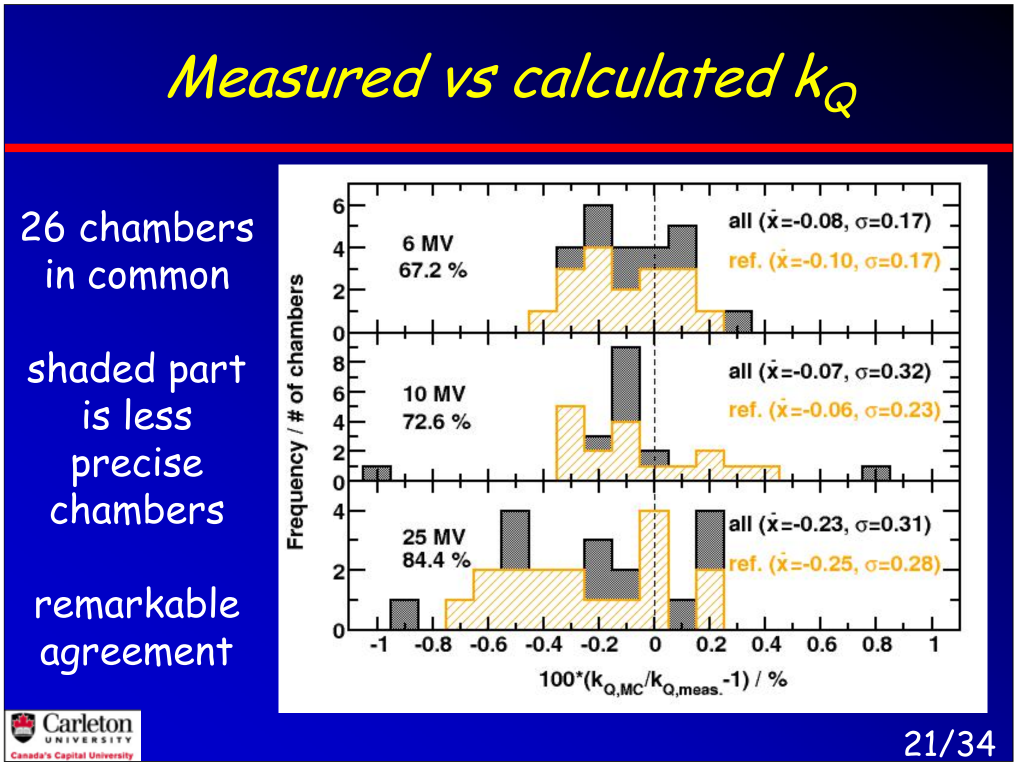
http://www.physics.carleton.ca/clrp/kQ

-df is number of degrees of freedom

-s^2_c is for correlated, no W/e uncertainty

http link has a report with plots of comparisons for each individual chamber



-ve ➔ calc are smaller than measured

What does this tell us?

-agreement remarkable

-even single chambers representative

-no massive change in W/e: MC assumes none, meas make no assumptions

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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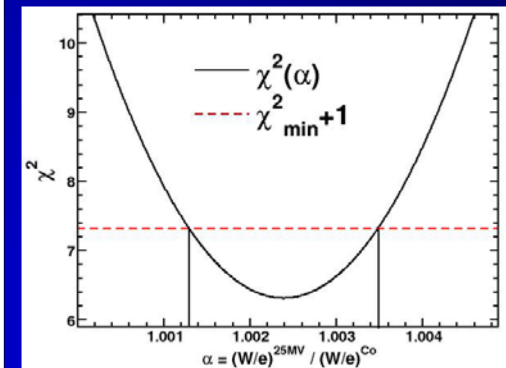
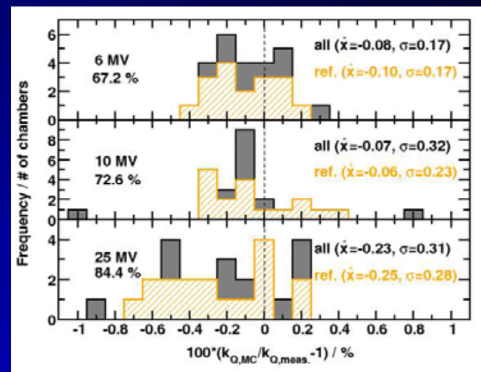
What is the value of α ?





α = 1.0024±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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$chisq_{min}$/df = 6.3/17 =0.38 for the reference chambers

What about parallel-plate chambers?

- not allowed in TG-51 for photon beams because of a lack of P_{wall} data
- Muir et al (Med Phys 39(2012)1618) provides a complete set of calculated and measured k_Q values (which agree with rms deviation <0.36%)
  - unfortunately, unacceptable variations in $N_{D,w}$ were observed although k_Q was unchanging
  - => still not recommended (although with a cross calibration technique, a protocol could be devised)

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$N_{D,w}$ varied by up to 1.5%

What about electron beams?

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

$$k_Q = P_{gr}^{Q} k_{R_{50}}$$

defines k_{R50}: component of k_Q which is independent of P_{gr}, the gradient at point of measurement.

$$k_{\rm ecal} = k_{R_{50}}^{Q_{\rm ecal}}$$

defines k_{ecal}: chamber specific photon-electron conversion factor
-Q_{ecal} an arbitrary e- energy

$$k_{R_{50}} = k'_{R_{50}} k_{\rm ecal}$$

defines k'_{R50}: chamber specific electron quality conversion factor

$$D_{\rm w}^{Q} = M P_{gr}^{Q}\, k'_{R_{50}}\, k_{\rm ecal} N_{\rm D,w}^{^{60}Co}$$

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k_{ecal} accounts for $N_{D,w}$ variation between ^{60}Co and Q_{ecal}

k'_{R50} accounts for $N_{D,w}$ variation between Q_{ecal} and R_{50}

For e- beams P_{gr} varies for a given beam quality, R_{50},

=> must be explicitly found for each beam

What about electron beams?

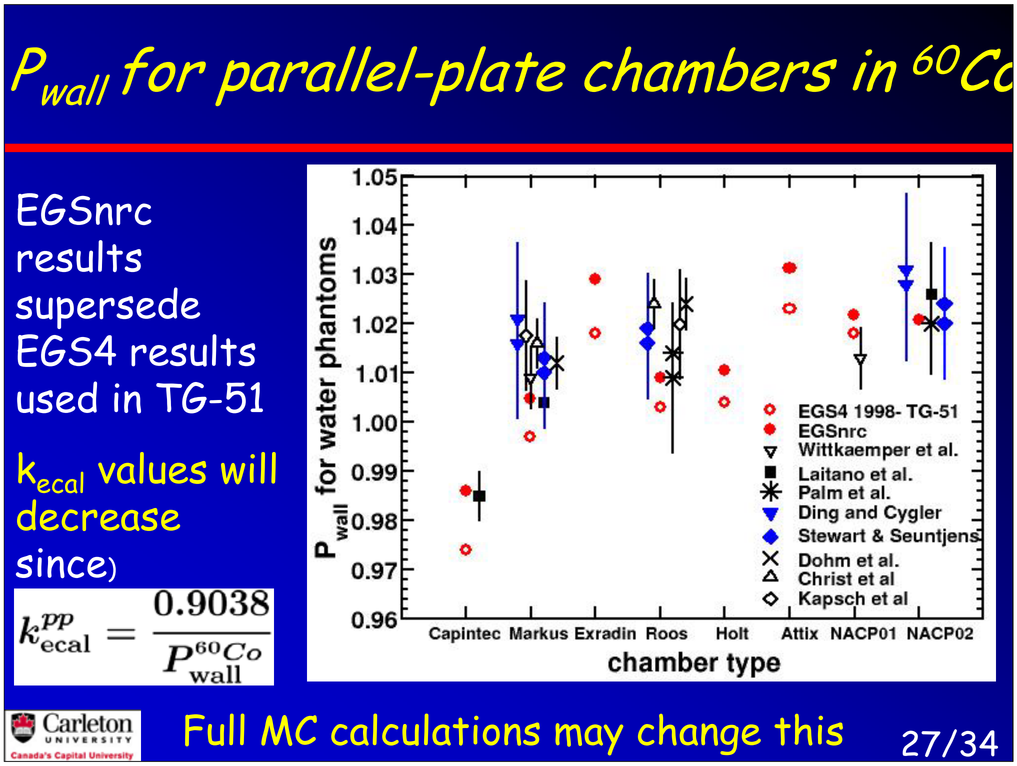
$$D_{\mathrm{w}}^{Q} = M P_{gr}^{Q} \, k'_{R_{50}} \, k_{\mathrm{ecal}} N_{\mathrm{D,w}}^{^{60}Co}$$

Much more complicated

Paper TU-A-BRB-11 (Muir et al) discussed an extensive set of calculations and measurements for these electron beam factors.

Once primary standards in e- beams are in place, more direct measurements are possible.

In the meantime, we already know k_{ecal} factors need to change.

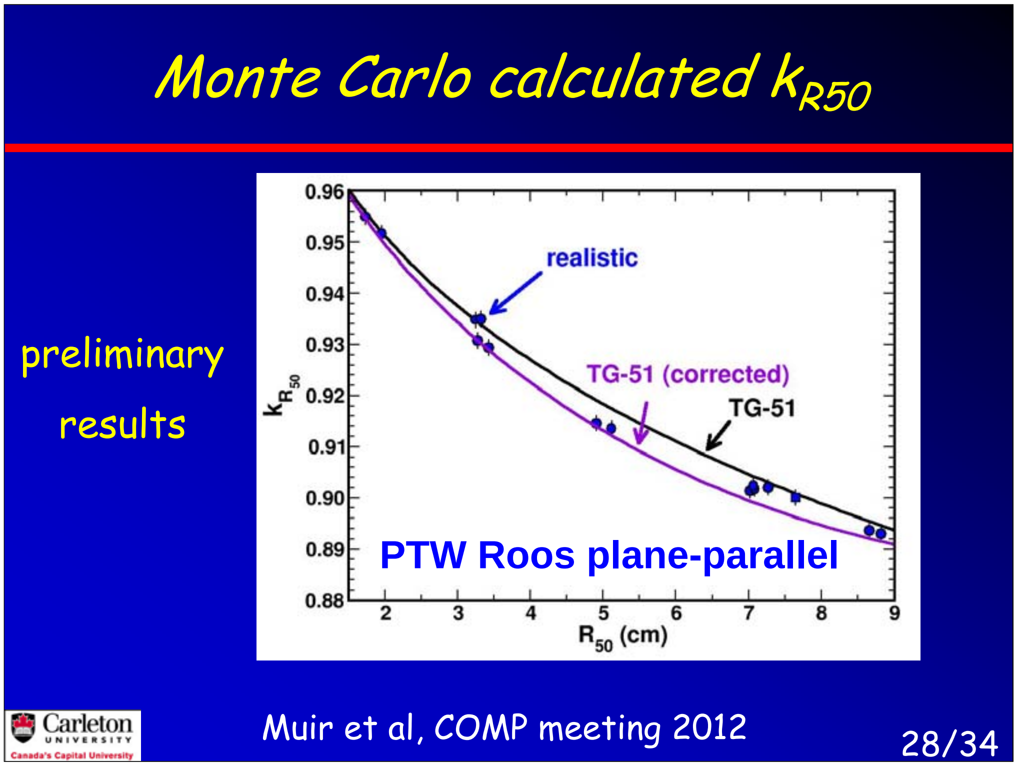


Note the EGSnrc P_{wall} values are systematically up to 1% larger than the EGS4 values used in TG-51.

The simple formula for k_{ecal} makes use of the fitted eqn for stopping-power-ratios whereas a full Monte Carlo caln (similar to the k_Q calns) would include this.

Full MC calns are needed for cylindrical chambers as well.

The P_{gr} correction makes the analysis more complex.

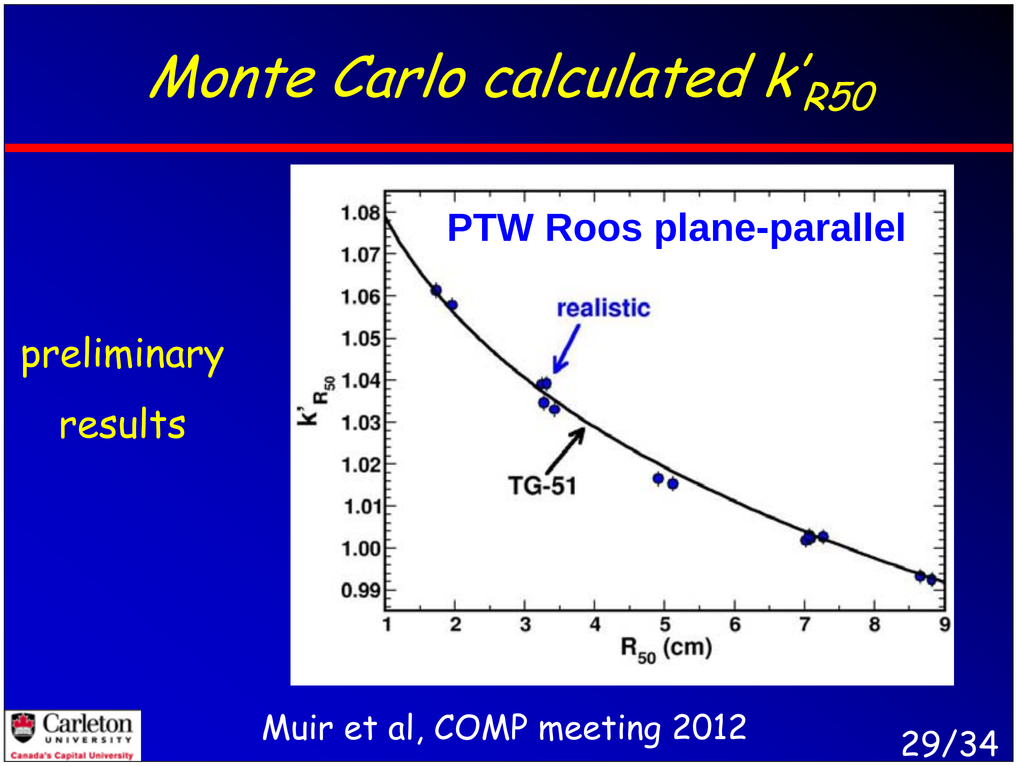


The 'realistic' calculations use a full BEAMnrc simulation as the beam source.

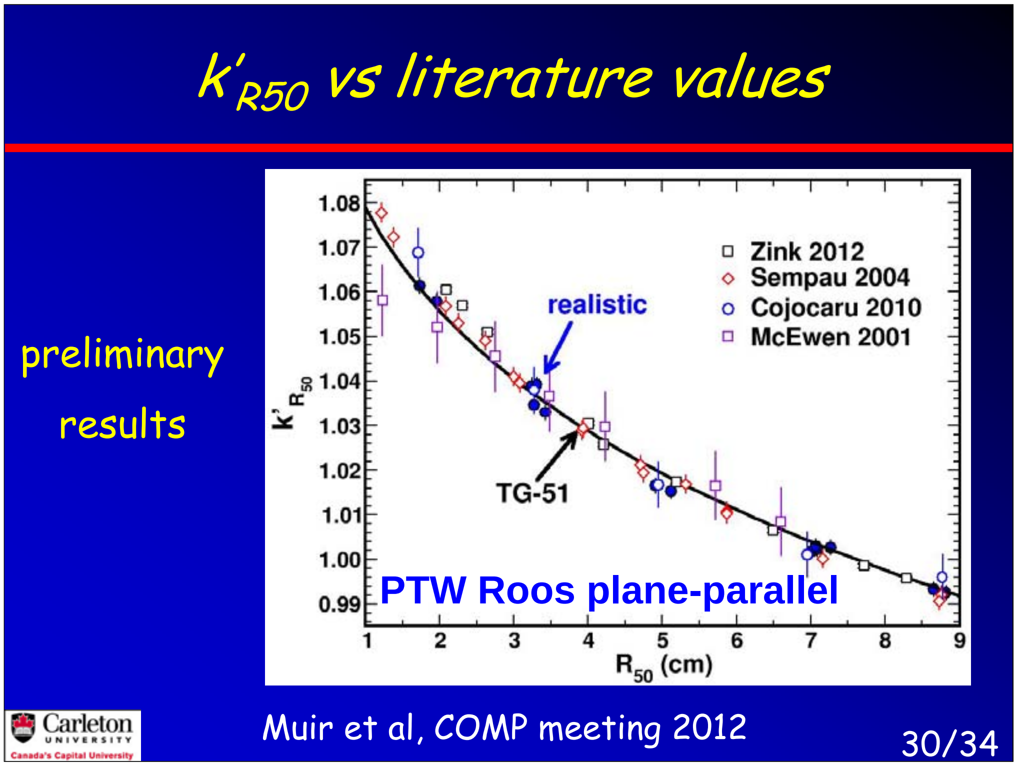
The agreement with TG-51 for this simple chamber is quite good.

The `corrected' TG-51 curve uses the know problems with Pwall, Prepl and spr from literature values to correct the original TG-51 curve.

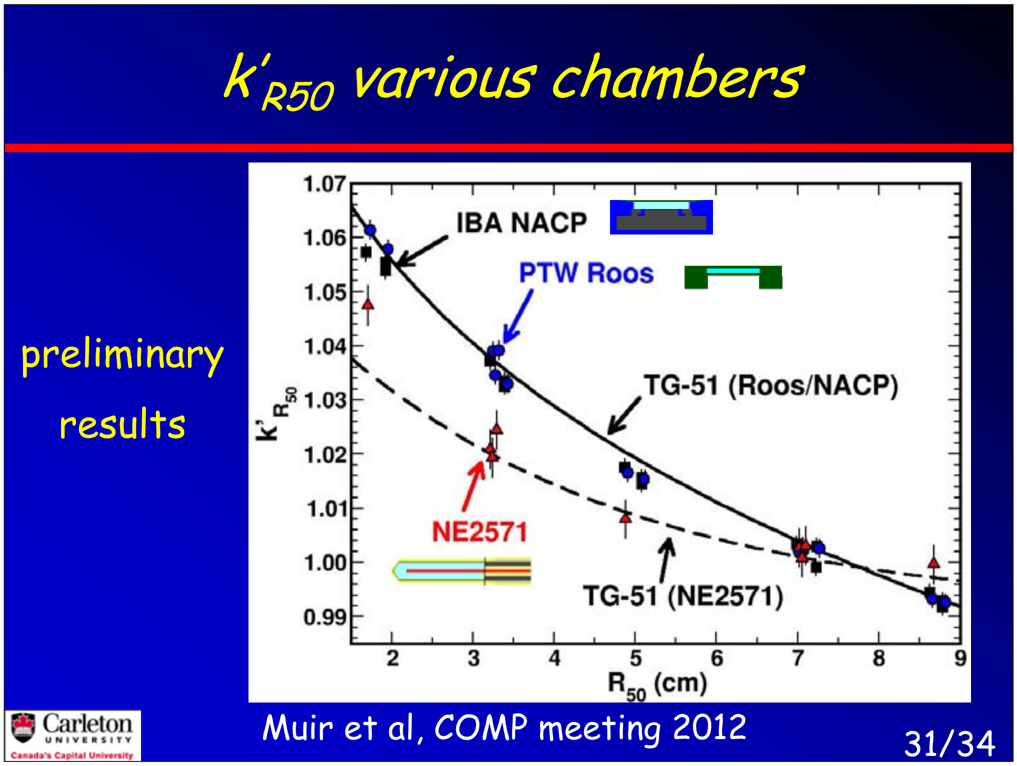
The next few figures come from a paper presented by Bryan Muir in the Young Investigators Symposium at the COMP meeting in Halifax in July, 2012.



This basically takes out the value of kecal



The Zink and Sempau results are other Monte Carlo calculations. The Cojocaru and McEwen results are measured values.



These are preliminary results but the good news is that TG-51 values look fairly good.

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 calculated k_Q values is between 0.40 and 0.49 % depending on wall material
- uncertainty on variation of $(W/e)_{air}$ from Co to 25 MV is 0.25 % (68 % limit)

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32/34

Note the limit on W/e includes the data from Muir et al, Med Phys 39(2012)1618 which did a similar analysis as presented above, but including the calculations and measurements for the parallel-plate chambers.

Conclusions (cont)

- 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)
- work on electron beams is on-going
- it is more complex because of effective point of measurement issues
- changes are mostly expected to be small

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final uncertainty assume correlated uncertainties in photon cross sections

FFF=>Flattening Filter Free

WFF=> with flattening filter

Acknowledgements

-as mentioned before, much of the work was done by Bryan Muir and the experiments in conjunction with Malcolm McEwen

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