Physics of the TG-51 dosimetry protocol

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Ch 9 of book

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General formalism: definitions

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

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

for e- beams

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

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

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General formalism: definitions

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

defines k_{ecal}: chamber specific photon-electron conversion factor

-Q_{ecal} an arbitrary e- energy

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

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

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

-accounts for $N_{D,w}$ variation between Q_{ecal} and R_{50}

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General formalism: dose equations

These 5 definitions lead to two dose equations

photons

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

electrons

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

P_{gr} is part of k_Q for photon beams since the same for all beams of same quality.

For e- beams P_{gr} varies for a give beam quality, R_{50}, - thus must be explicitly found for each beam

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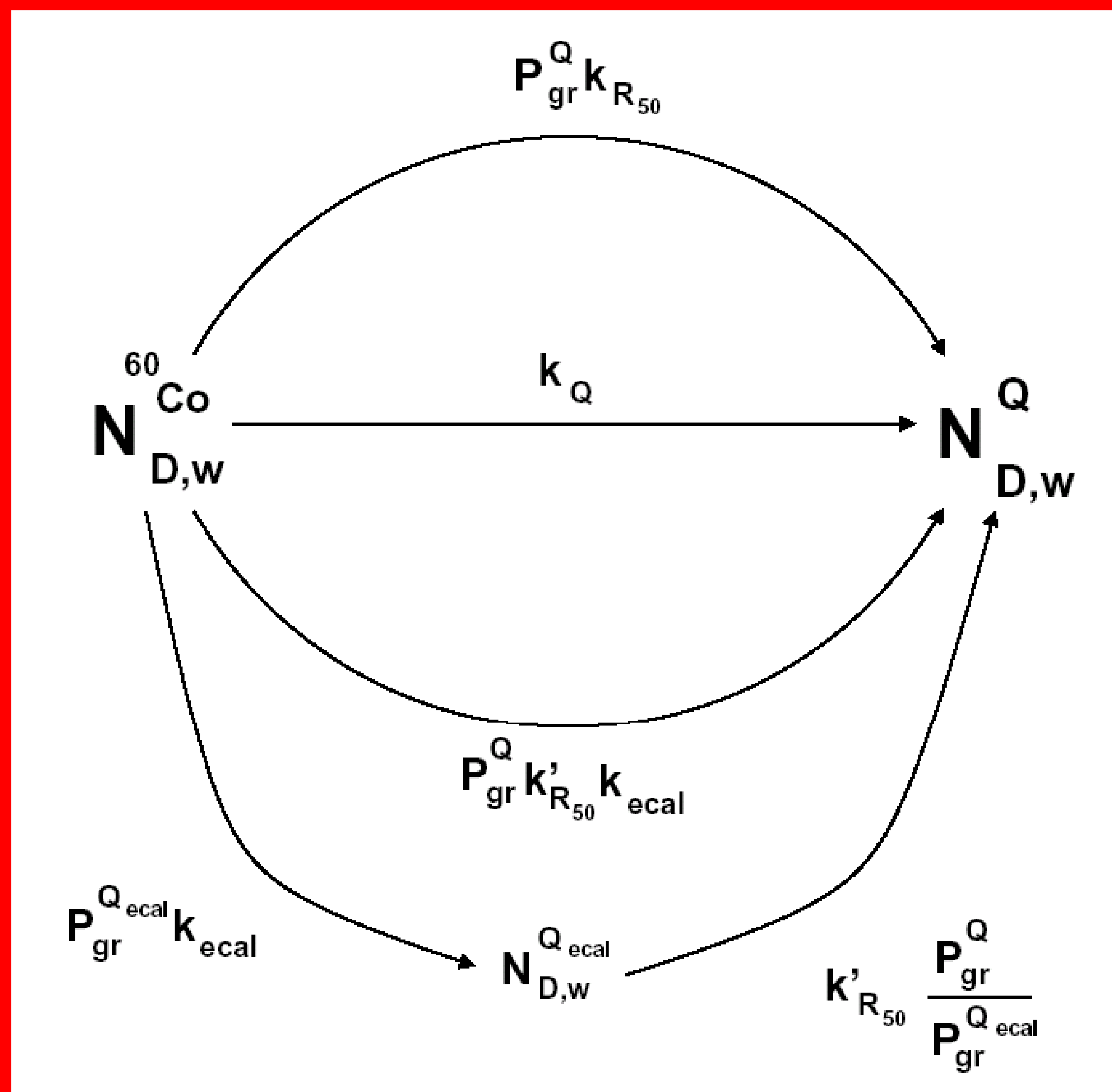
General formalism: $N_{D,w}$ relationships



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Where does k_Q come from?

Basically - same physics as TG-21, ie Spencer-Attix cavity theory but without the complexity of changing from an air kerma calibration coefficient to an absorbed-dose measurement.

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

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

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

K_h accounts for measurements being in humid air but 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 that would be present at point of measurement

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

-usually only thought to apply to cylindrical chambers

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

-handled by:

- effective point of measurement when measuring dose distributions (0.5/0.6 r_{cav} offset for e-/photon beams)

- measuring at d_{max} in e- beams (TG-21)

- P_{gr}, a correction factor: for e- beams $P_{gr} = \frac{M_{raw}(d_{ref} + 0.5 r_{cav})}{M_{raw}(d_{ref})}$

-photon beams dealt with later

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

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

Photon beams

Not required past d_{max} because of
transient charged particle equilibrium
and
Fano theorem tells us spectrum is independent of density and to extent that water is like air, the theorem applies.

Electron beams

Fluence in cavity increases due to lack of out-scatter and hence $P_{fl} < 1$

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Deriving equations for k_Q etc

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

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

-M is fully corrected charge

From defn $N_{\mathrm{D,w}}^{\mathrm{Q}} = \frac{D_{\mathrm{w}}^{\mathrm{Q}}}{M}$

-combining D_{med} & D_{air} eqns gives

$$N_{\mathrm{D,w}}^{\mathrm{Q}} = \frac{K_h}{m_{\mathrm{air}}} \left(\frac{W}{e}\right)_{\mathrm{air}} \left(\frac{\overline{L}}{\rho}\right)_{\mathrm{air}}^{\mathrm{w}} P_{\mathrm{wall}} P_{\mathrm{fl}} P_{\mathrm{gr}} P_{\mathrm{cel}}$$

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Equation for k_Q

- defn of k_Q implies

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

- and from before:

$$N_{\mathrm{D,w}}^{\mathrm{Q}} = \frac{K_h}{m_{\mathrm{air}}} \left(\frac{W}{e}\right)_{\mathrm{air}} \left(\frac{\overline{L}}{\rho}\right)_{\mathrm{air}}^{\mathrm{w}} P_{\mathrm{wall}} P_{\mathrm{fl}} P_{\mathrm{gr}} P_{\mathrm{cel}}$$

- assuming W/e constant gives

$$k_Q = \frac{\left[\left(\frac{\overline{L}}{\rho}\right)_{\mathrm{air}}^{\mathrm{w}} P_{\mathrm{wall}} P_{\mathrm{fl}} P_{\mathrm{gr}} P_{\mathrm{cel}}\right]_{\mathrm{Q}}}{\left[\left(\frac{\overline{L}}{\rho}\right)_{\mathrm{air}}^{\mathrm{w}} P_{\mathrm{wall}} P_{\mathrm{fl}} P_{\mathrm{gr}} P_{\mathrm{cel}}\right]_{^{60}\mathrm{Co}}}$$

- applies to electrons and photons
  - but only used for photons

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Equations for k_{ecal} & $k'_{R_{50}}$

-from defns of k_{ecal} & $k'_{R_{50}}$ & $N_{\mathrm{D,w}}^{\mathrm{Q}} = \frac{K_h}{m_{\mathrm{air}}} \left(\frac{W}{e}\right)_{\mathrm{air}} \left(\frac{\overline{L}}{\rho}\right)^{\mathrm{w}}_{\mathrm{air}} P_{\mathrm{wall}} P_{\mathrm{fl}} P_{\mathrm{gr}} P_{\mathrm{cel}}$

$k_Q = P_{gr}^{Q} k_{R_{50}}$ $\quad k_{\mathrm{ecal}} = k_{R_{50}}^{Q_{\mathrm{ecal}}}$ $\quad k_{R_{50}} = k'_{R_{50}} k_{\mathrm{ecal}}$

$$k_{\mathrm{ecal}} = \frac{\left[\left(\frac{\overline{L}}{\rho}\right)^{\mathrm{w}}_{\mathrm{air}} P_{\mathrm{wall}} P_{\mathrm{fl}} P_{\mathrm{cel}}\right]_{Q_{\mathrm{ecal}}}}{\left[\left(\frac{\overline{L}}{\rho}\right)^{\mathrm{w}}_{\mathrm{air}} P_{\mathrm{wall}} P_{\mathrm{fl}} P_{\mathrm{gr}} P_{\mathrm{cel}}\right]_{^{60}\mathrm{Co}}}$$

a constant for a given chamber

$$k'_{R_{50}} = \frac{\left[\left(\frac{\overline{L}}{\rho}\right)^{\mathrm{w}}_{\mathrm{air}} P_{\mathrm{wall}} P_{\mathrm{fl}} P_{\mathrm{cel}}\right]_{Q}}{\left[\left(\frac{\overline{L}}{\rho}\right)^{\mathrm{w}}_{\mathrm{air}} P_{\mathrm{wall}} P_{\mathrm{fl}} P_{\mathrm{cel}}\right]_{Q_{\mathrm{ecal}}}}$$

=1.00 for $R_{50} = Q_{ecal}$

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Beam quality specification

- need to specify beam quality to select k_Q and k'_{R50}
- goal is to uniquely determine a single k_Q value for a given beam quality
  - this depends mostly on specifying a single stopping-power ratio

Photon beams

$\%dd(10)_X$ is photon component of percentage depth-dose at 10 cm depth in a 10x10 cm^2 field defined on surface of water phantom at 100 cm SSD

TG-51 uses $\%dd(10)_X$ because it makes k_Q values independent of what type of beam they are in.

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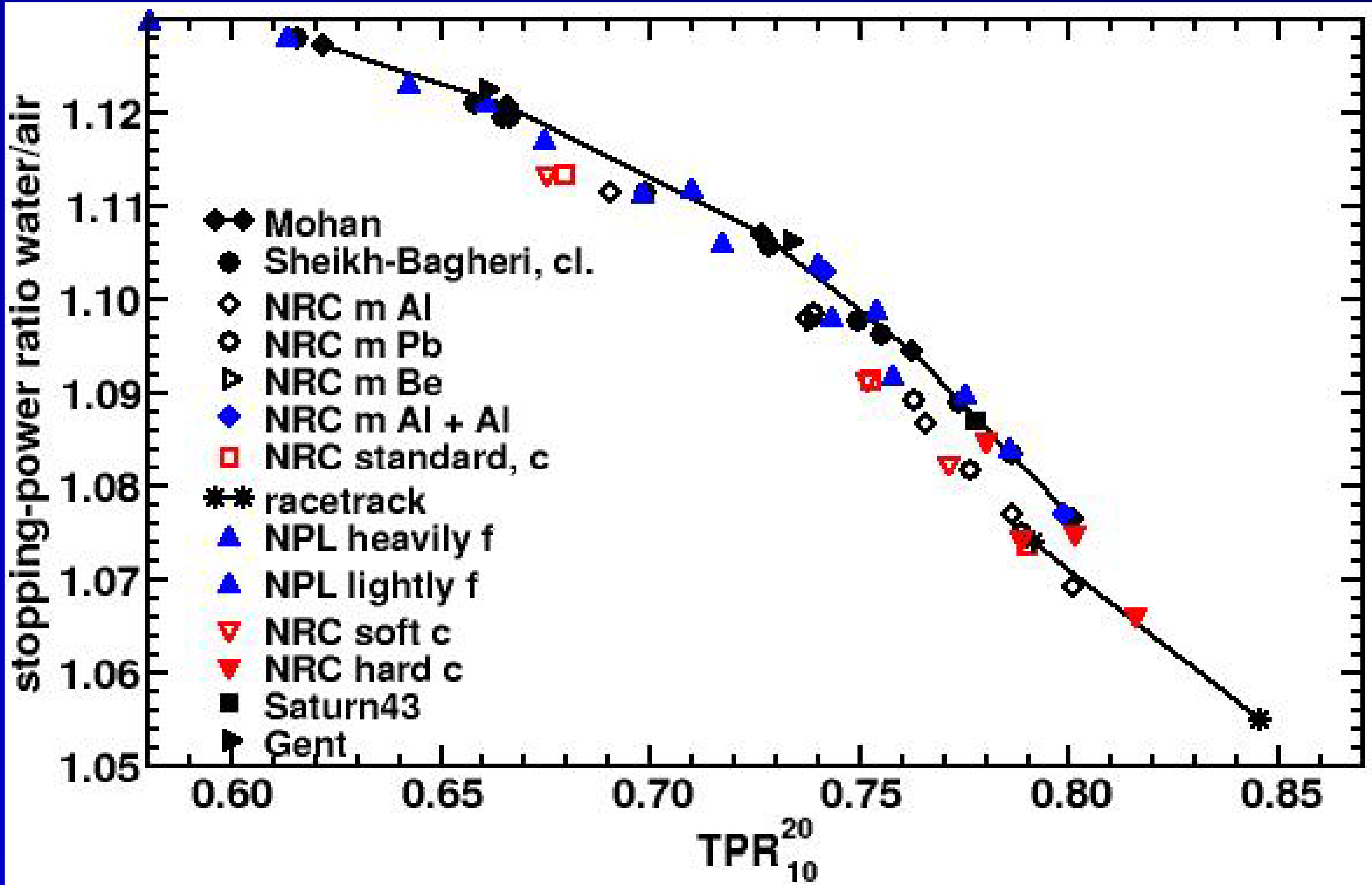
Beam quality specification: Why TPR is not ideal

Heavily filtered "clinical" beams are on upper curve.

NRC soft beams (used to measure k_Q) and FFF beams are below.



Kalach & Rogers Med Phys 30 (2003) 1546

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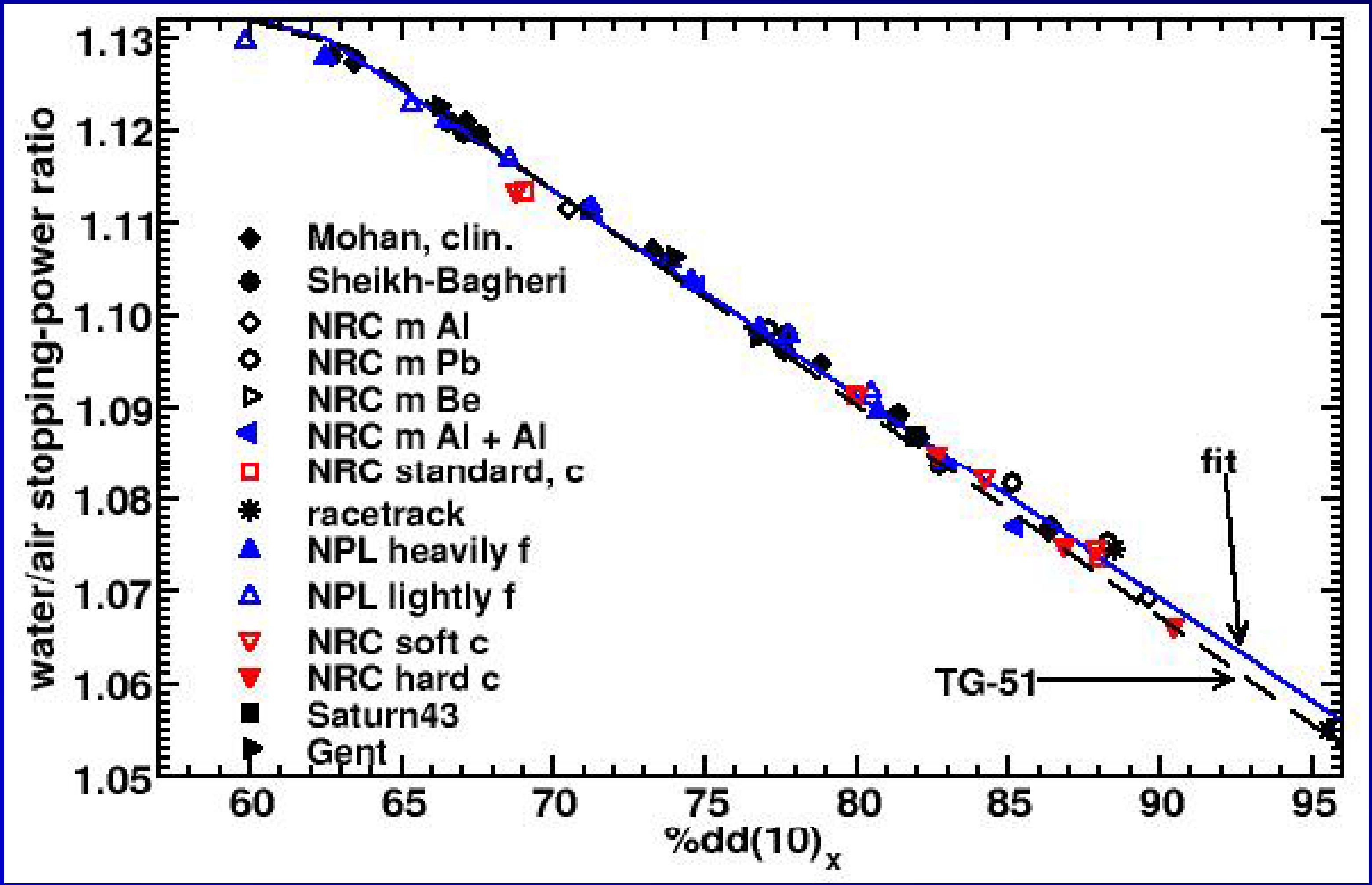
Beam quality specification: Why use $\%dd(10)_x$



Kalach & Rogers Med Phys 30 (2003) 1546

Extracting photon component of %dd(10) removing e- contamination effects

e^- contamination affects D_{max} and hence %dd(10) at or above 10 MV

$\%dd(10)_x = \%dd(10)$ (below 10 MV)

else

$\%dd(10)_x = 1.267\%dd(10) - 20.0$

for $75\% < \%dd(10) < 90\%$ with 50 cm clearance (±2%)

The above is based on very scattered data and only approximate.

Can we do better?

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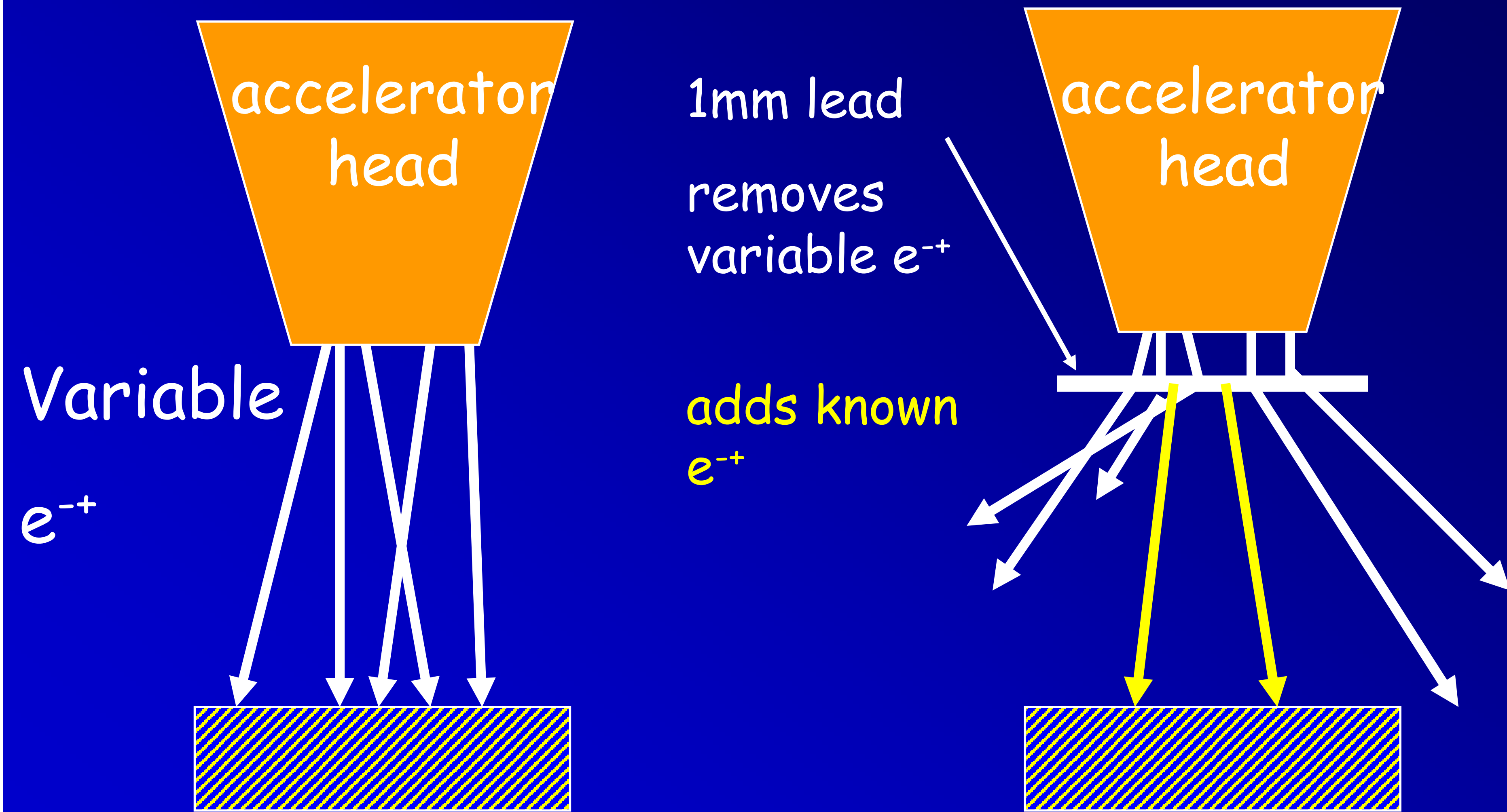
Electron contamination



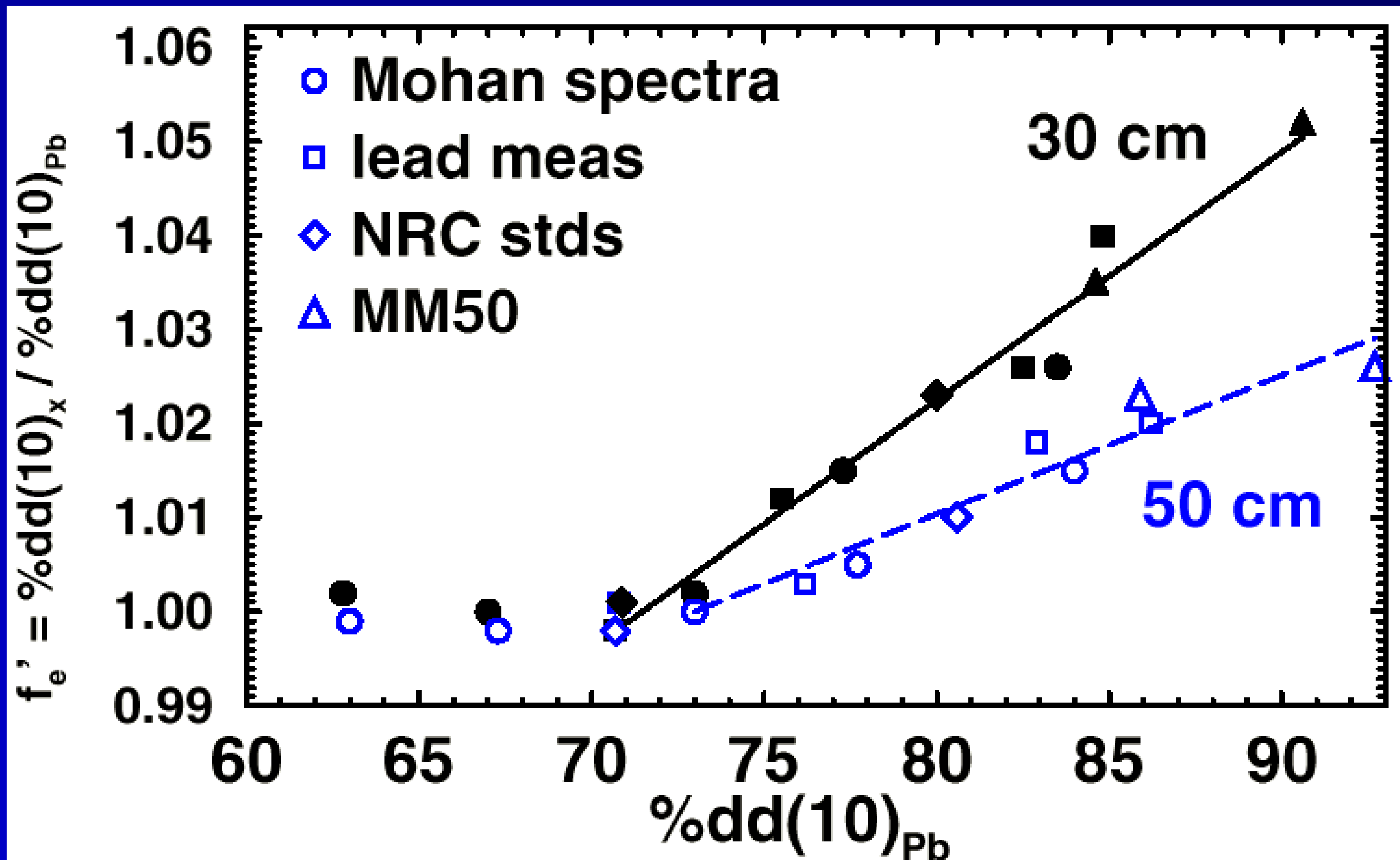
Correction for e^- contamination

$$f_e' = \frac{\%dd(10)_{\mathrm{x}}}{\%dd(10)_{\mathrm{Pb}}}$$

BEAM code + ``tricks" used to calculate with high precision

The PDD measurements with the lead foil in place are used to extract the PDD for the photon only component of the beam.

Correction vs %dd(10)$_{Pb}$



Med Phys 26 (1999) 533

$$\%dd(10)_x = [0.8116 + 0.00264\%dd(10)_{Pb}]\,\%dd(10)_{Pb}$$

$$[\text{foil at 30 cm}, \%dd(10)_{Pb} \geq 71\%]$$

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How important is correction?

Say f_e' wrong by 1% (ie. a 50% error) near $\%dd(10)_x$=80%.

=> $\%dd(10)_x$ is 80.8%, not 80.0%

=> error in k_Q is 0.17%

Ignore correction => 0.35% error in k_Q

TG-51 is not sensitive to accounting accurately for e- contamination .

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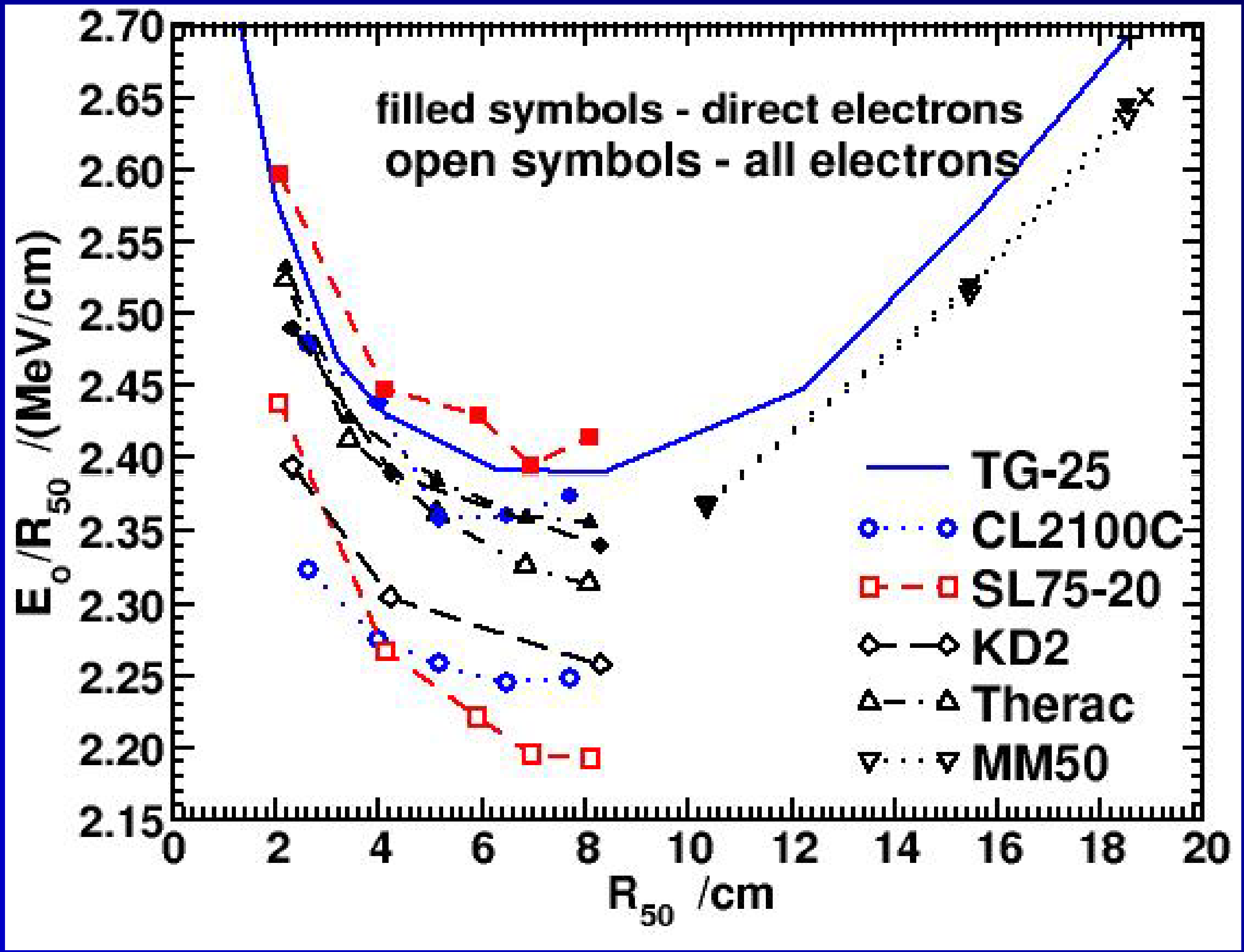
Beam quality specification in e- beams: What's wrong with E_o=2.33R_{50}?

It doesn't work

-parallel beams

-mono-energetic

Realistic beams at SSD=100 show variation



Ding et al Med Phys 23 (1996) 361

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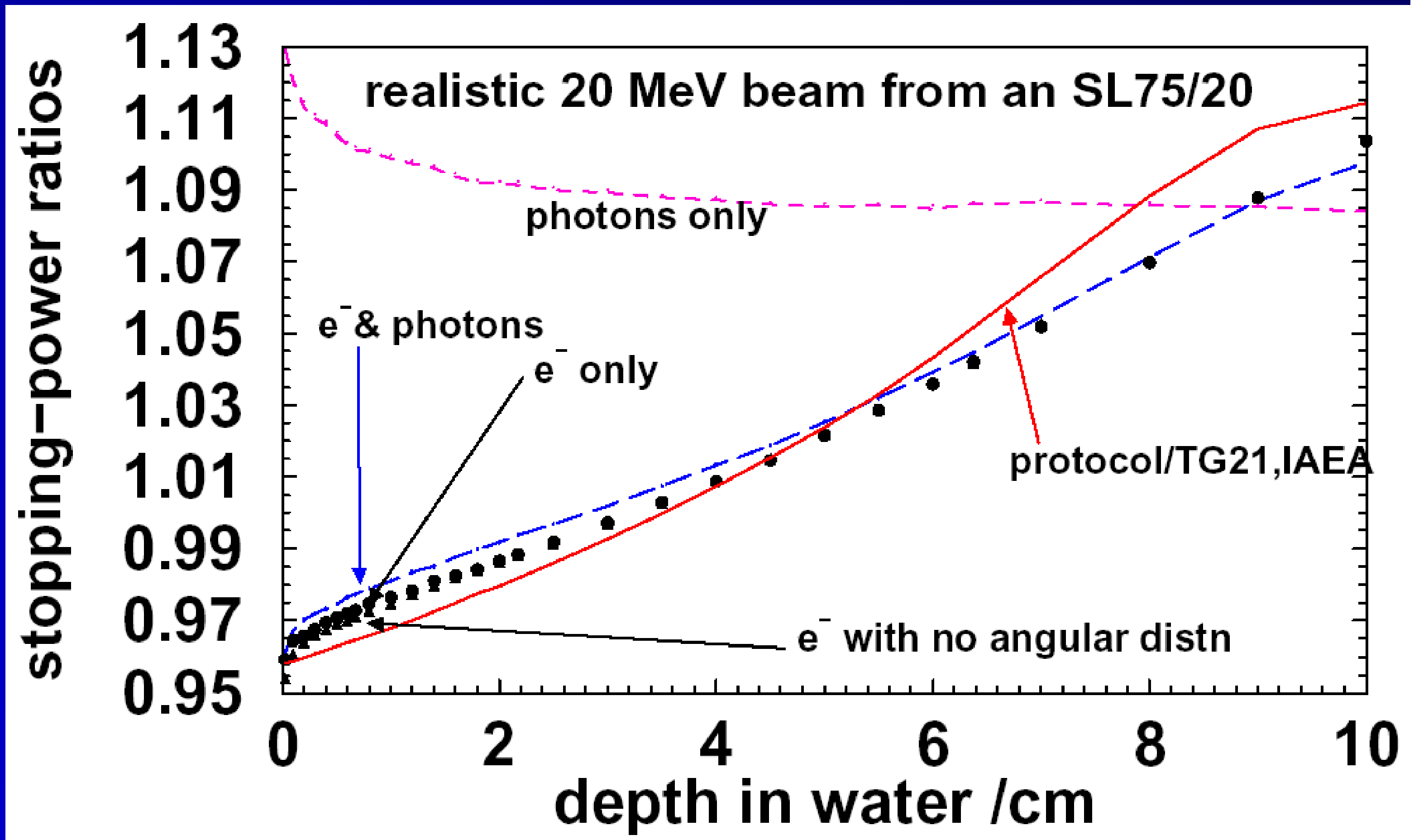
Beam quality specification in e- beams: realistic electron beam sprs

R_{50}=8.1 cm

d_{ref}=4.8 cm



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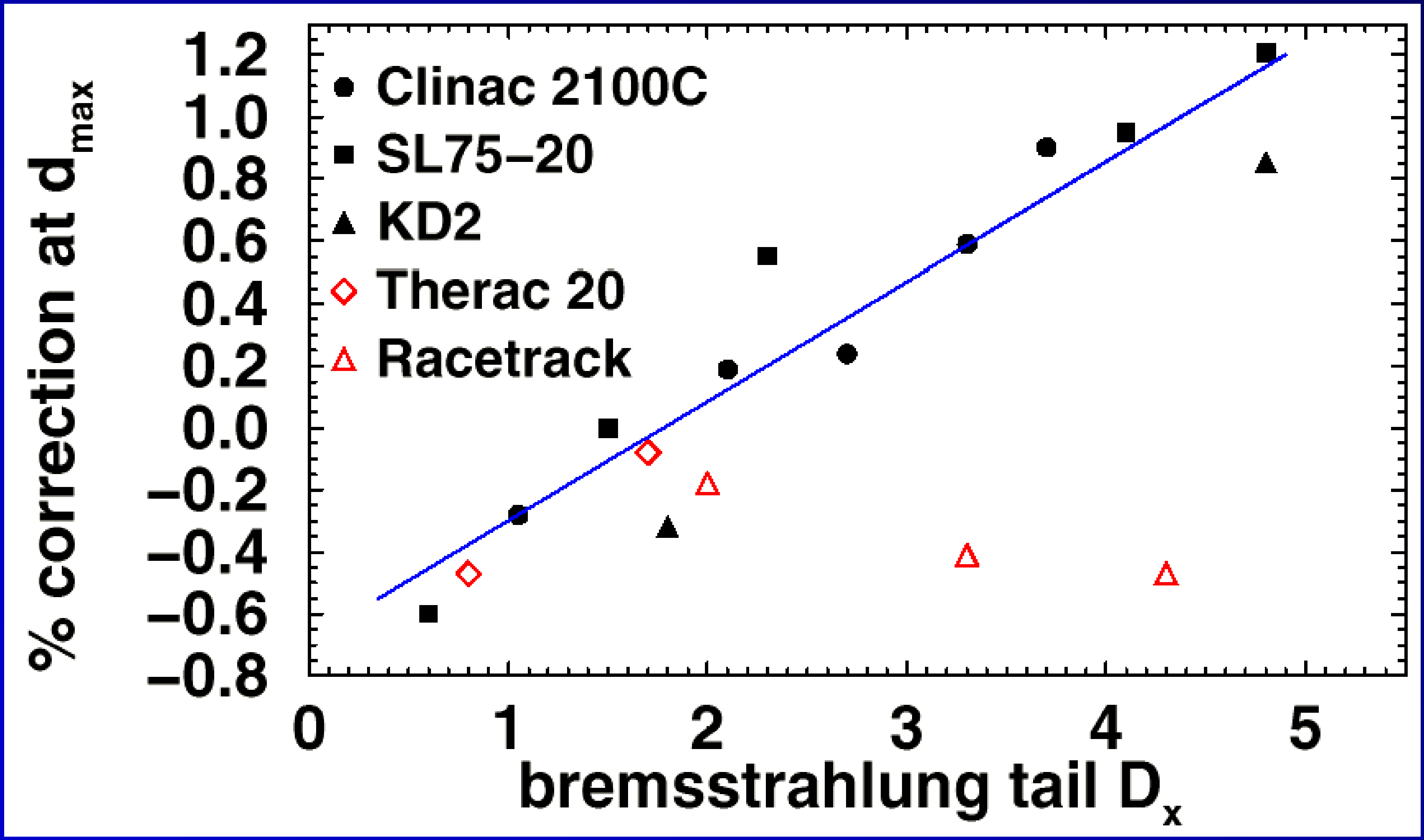
Ding et al Med Phys 22 (1995)489

Effects of realistic sprs



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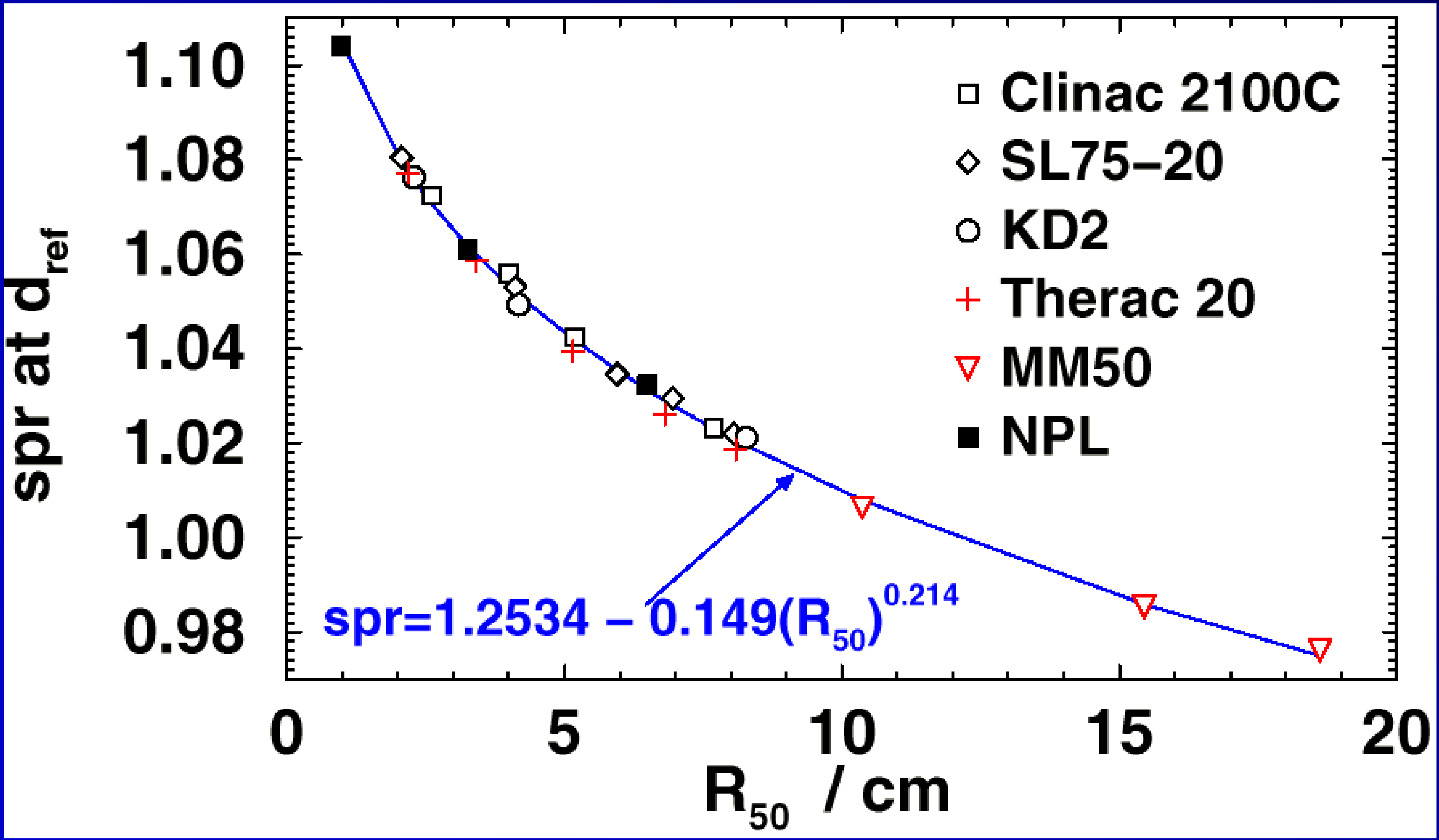
Ding et al Med Phys 22 (1995) 489

Solution re realistic sprs-change dref: $d_{ref}=0.6R_{50} - 0.1$



Burns et al Med Phys 23 (1996) 383

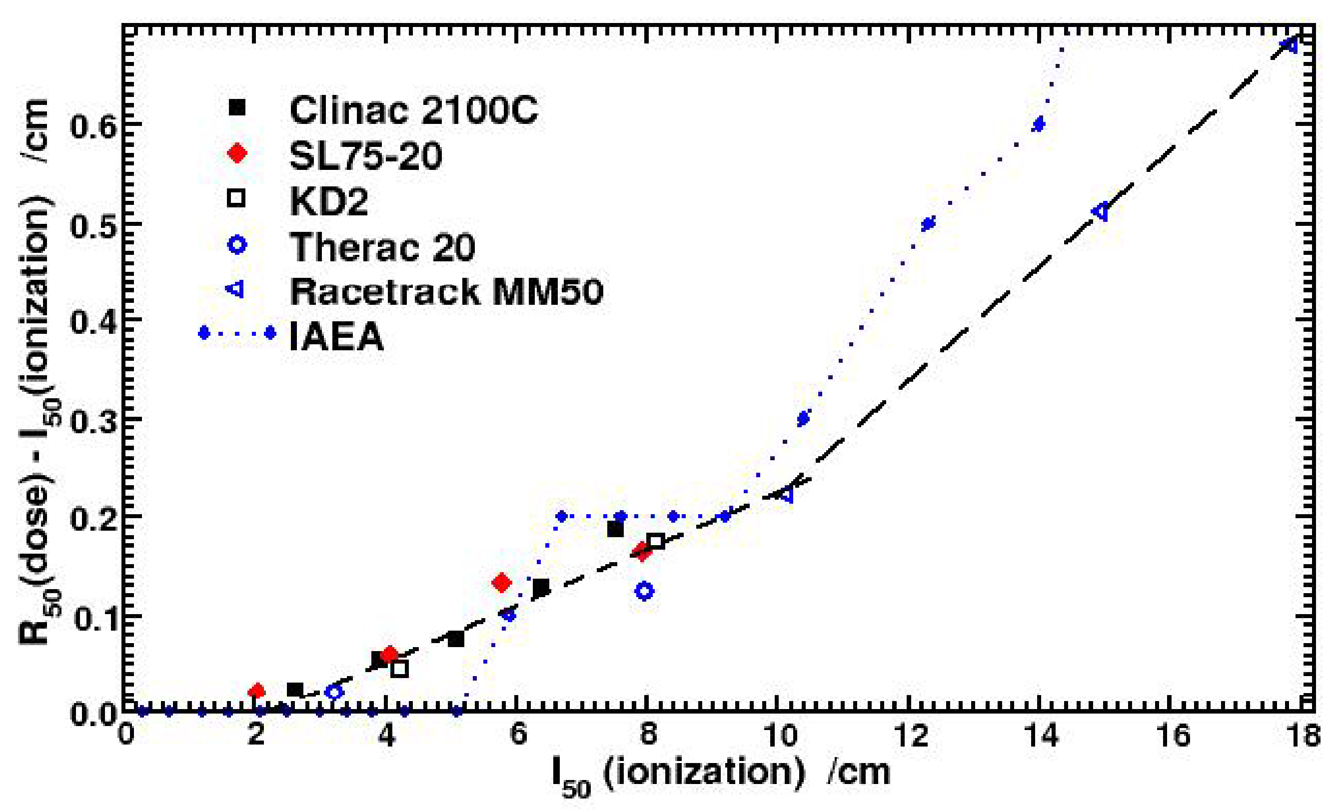
Measuring R_{50} via I_{50}

We measure I_{50} but need R_{50}

$$R_{50} = 1.029 I_{50} - 0.063 \qquad (I_{50} \leq 10\ cm)$$

$$R_{50} = 1.059 I_{50} - 0.37 \qquad (I_{50} > 10\ cm)$$

Calculations ignore all corrections except spr going from dose to ionization



Ding et al Med Phys 22 (1995) 489

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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-21 used different stopping power data for e- and photon beams (ICRU Reports 37 and 35 respectively).

TG-51 consistently uses ICRU Report 35 stopping powers. For photon beams, based on Monte Carlo calculations for 25 different beams:

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

Burns et al eqn for e- beams is also based on ICRU Report 37 stopping powers

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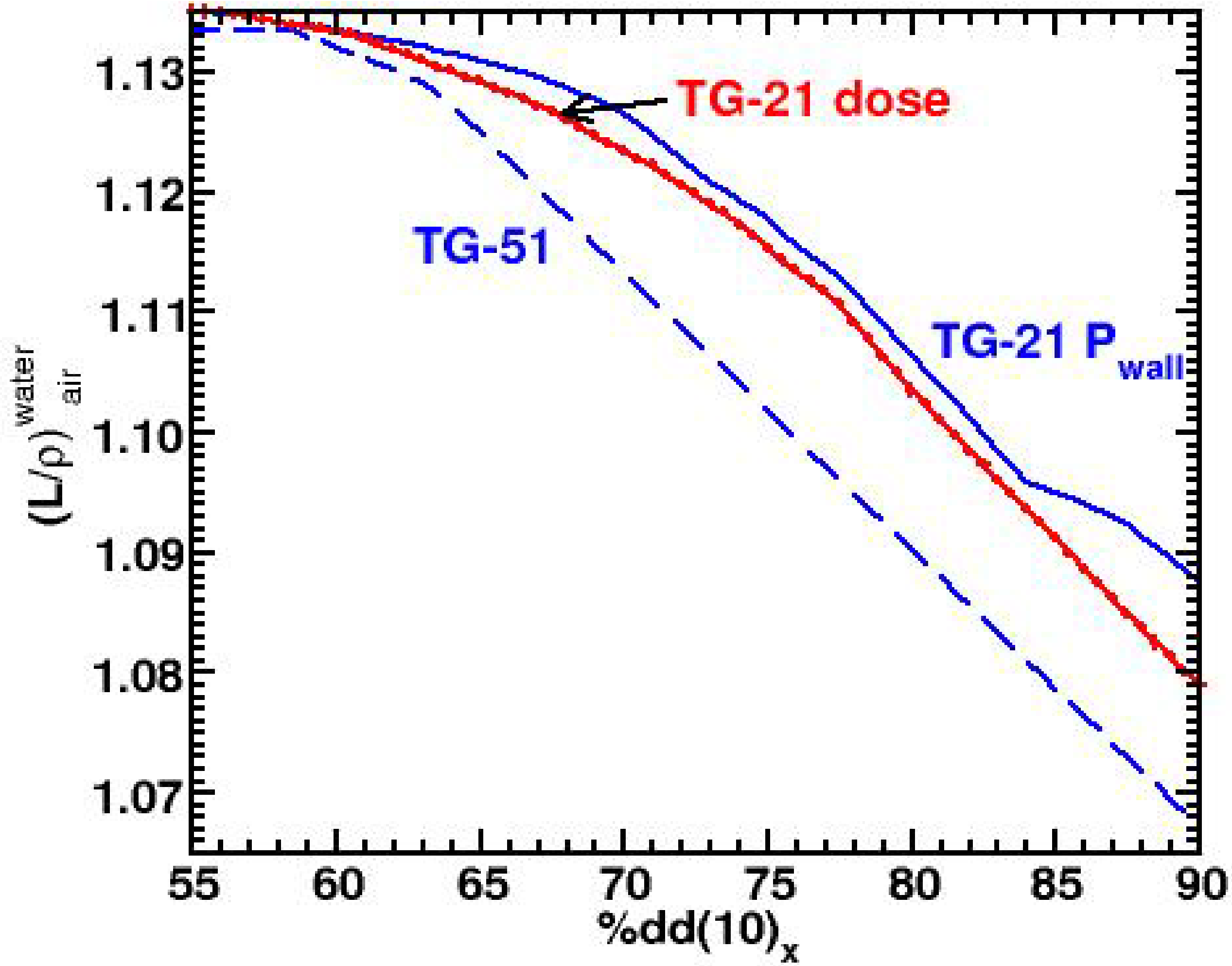
photon stopping power ratios

TG-51 uses stopping powers from ICRU Report 37

This is biggest difference from TG21.

Due to underlying stopping powers



-TG-51 values from Rogers and Yang Med Phys 26 (1999) 536

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stopping power ratios: state of the ar

Uncertainties are related to uncertainties in underlying stopping powers

-I-values: most recent water I-value measurement is 6% different from that used
=> 0.1 to 0.4% change in k_Q.

Calculations with full photon beam phase-space (with horns and varying energy cross beam) rather than calc with realistic spectra but uniform point sources show no significant changes.

Similarly, the sprs as a function of $\%dd(10)_x$ do not change when flattening filter is removed (they change as a function of TPR)

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Calculation of TG-51 factors

To calculate k_Q, k_{ecal}, etc we need:

-sprs, P_{wall}, P_{cel}, P_{fl}, P_{gr}

- plus a method to convert $TPR_{20,10}$ to $\%dd(10)_x$

since much of original data is in terms of $TPR_{20,10}$

Ch 9 gives details for each of these.

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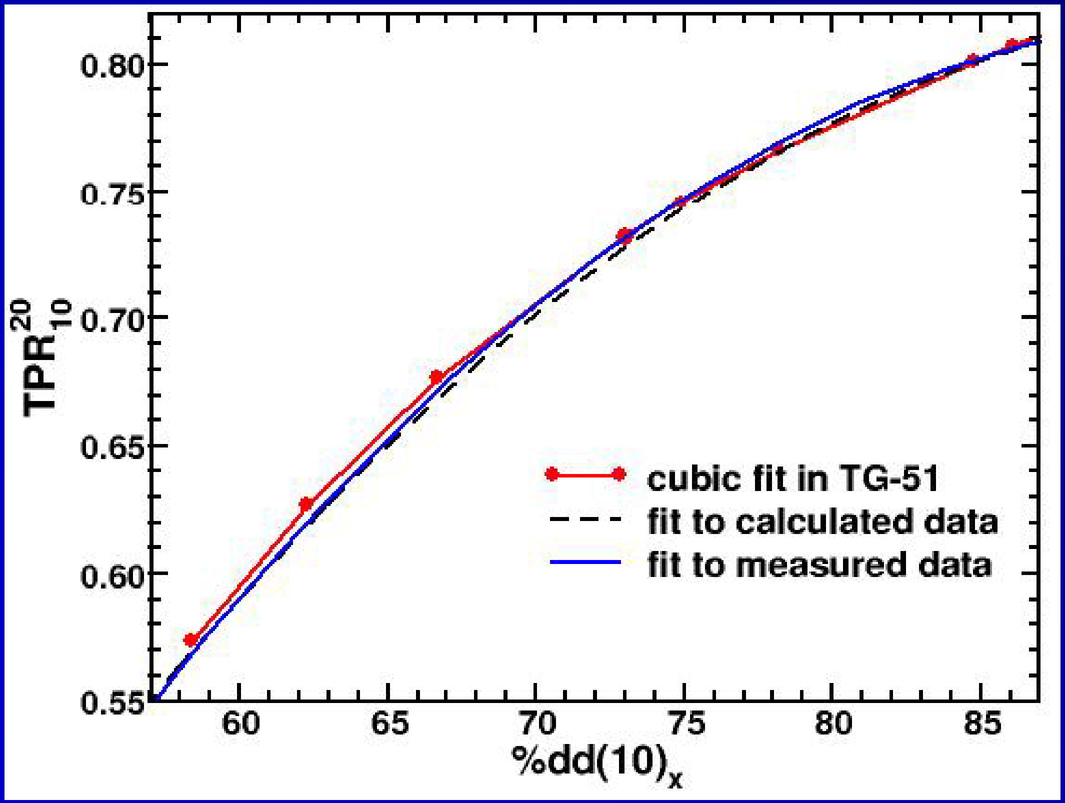
$TPR_{20,10}$ <--> $\%dd(10)_x$

This applies to heavily filtered beams only.

$$TPR^{20}_{10} = -0.8228 + 0.0342\,(\%dd(10)_X) - 0.0001776\,(\%dd(10)_X)^2$$

$$\%dd(10)_x = -430.62 + 2181.9\left(TPR^{20}_{10}\right) - 3318.3\left(TPR^{20}_{10}\right)^2 + 1746.5\left(TPR^{20}_{10}\right)^3$$



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P_{cel}: Al electrode correction

-for electrode same as wall material, any effect is in P_{fl}

-Ma & Nahum showed aluminum electrodes have an effect

-larger in photon beams

-but biggest effect in TG-51 is in electron beams because it cancels in photons

-was not included in TG-21

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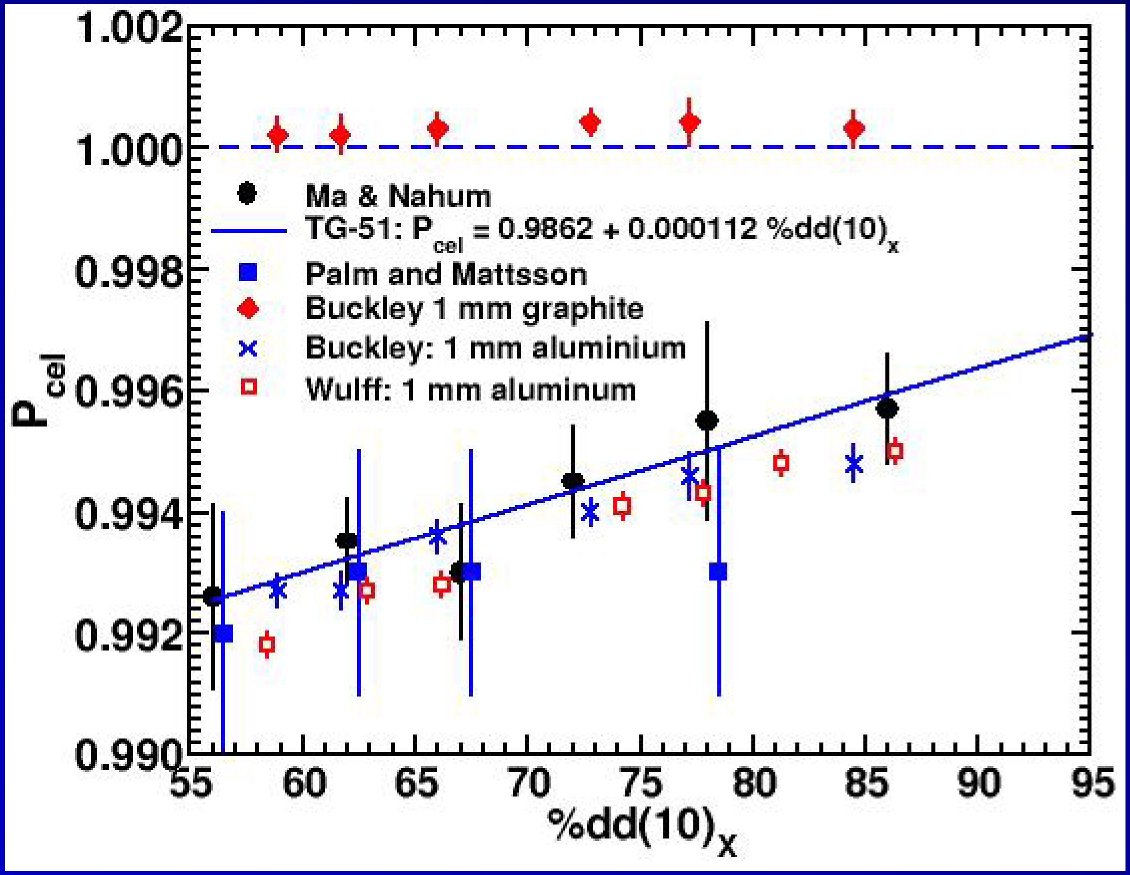
Ma & Nahum PMB 38 (1993) 267

P_{cel}: Al electrode correction

-expts confirm calns

-more accurate recent calculations are in good agreement

-effect much smaller in e-beams (<0.2%)



expt: Palm & Mattsson PMB 44 (1999) 1299
caln: Buckley et al MP 31 (2004) 3425
Wulff et al, PMB 53 (2008) 2823
orig caln: Ma & Nahum PMB 38 (1993) 267

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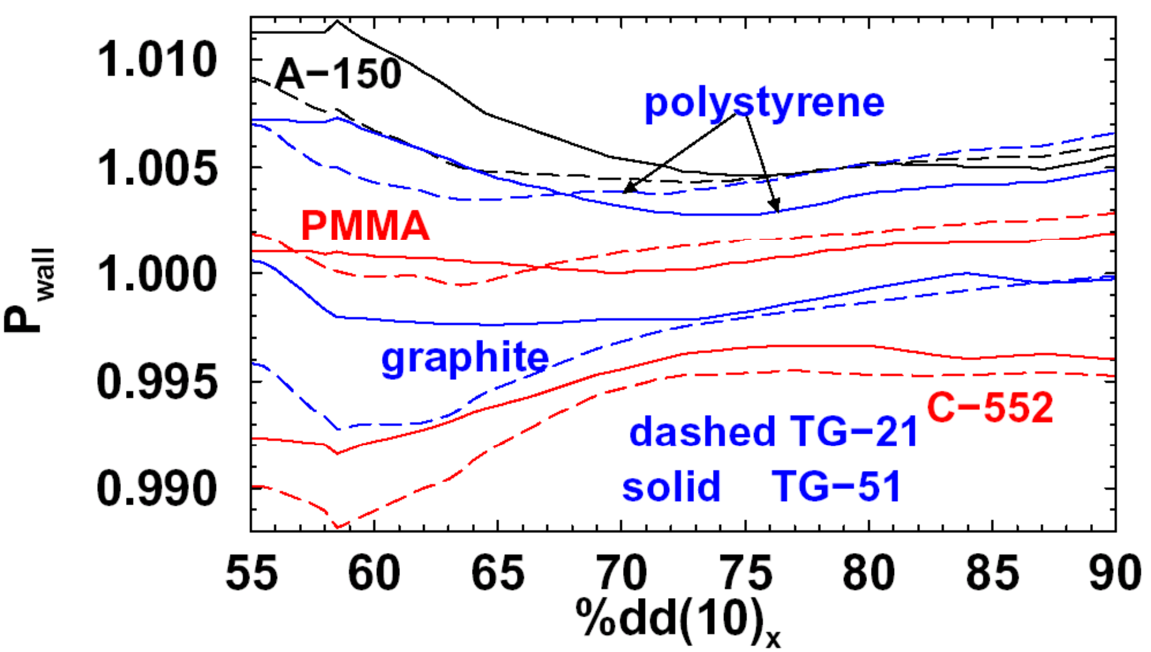
P_{wall}

- accounts for wall not being water
  - unity for electrons
  - same as TG-21 for photons (Almond-Svensson eqn)

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

For walls 0.05g/cm^2

Changes vs TG-21 due to better cross sections



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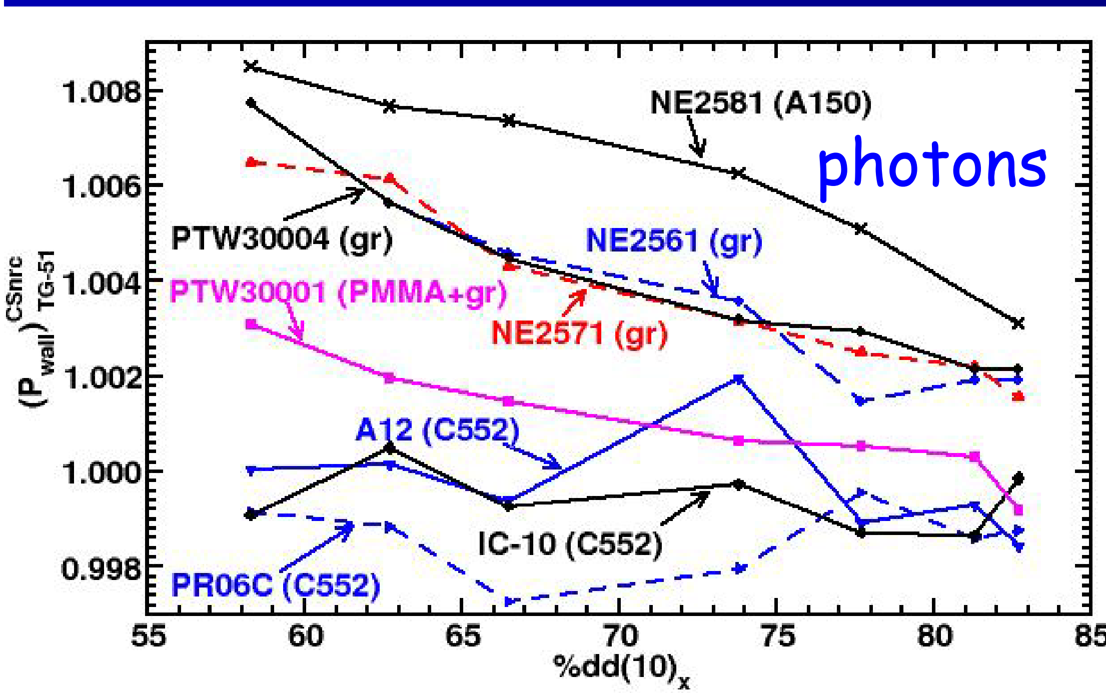
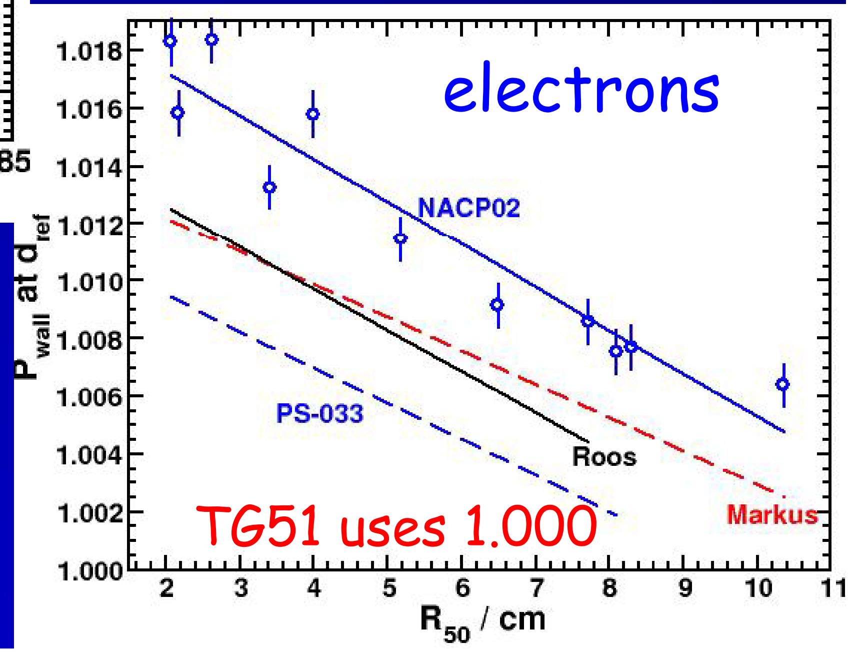
Recent Monte Carlo values of P_{wall}



Buckley et al MP 33(2006) 455

MP 33(2006) 1788



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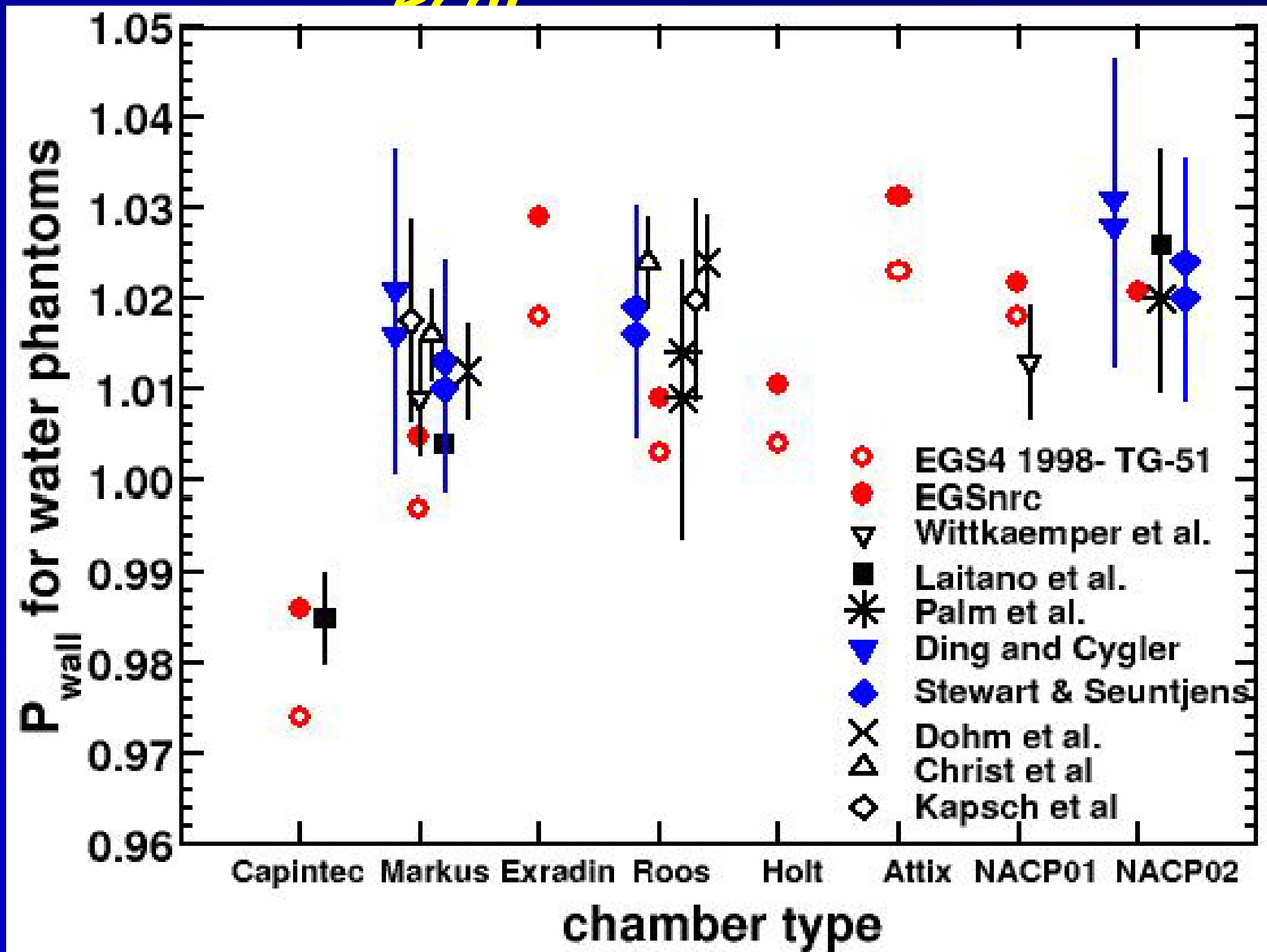
P_{wall} for parallel-plate chambers in ^{60}Co -k_{ecal}

EGSnrc results supersede EGS4 results used in TG-51

k_{ecal} values will decrease since

$$k^{pp}_{\rm ecal} = \frac{0.9038}{P^{60Co}_{\rm wall}}$$

(note Ch9 misleading)



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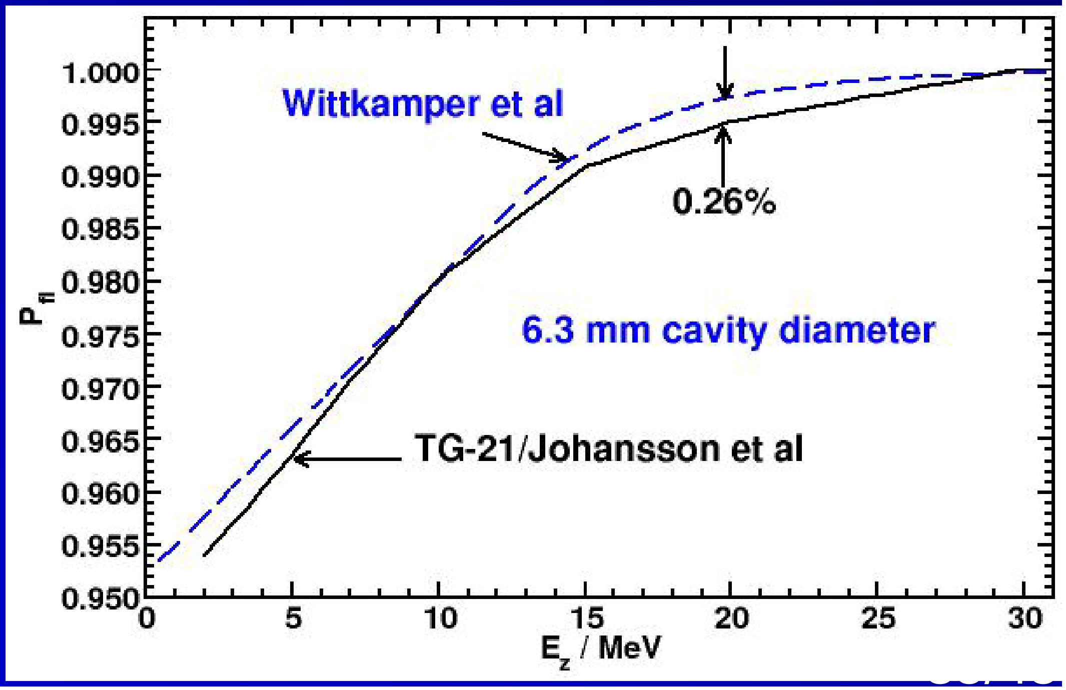
P_{fl} for cylindrical chambers

P_{fl} = 1.000 in photon beams at 10 cm depth because of transient charged particle equilibrium

For cylindrical chambers in e- beams, TG-51 uses values as a function of E_z and r_{cav}. These are from TG-21 based on measurements by Johansson et al (1977) at d_{max} .

More recent but less extensive measurements by Wittkamper and others confirmed the original measurements.



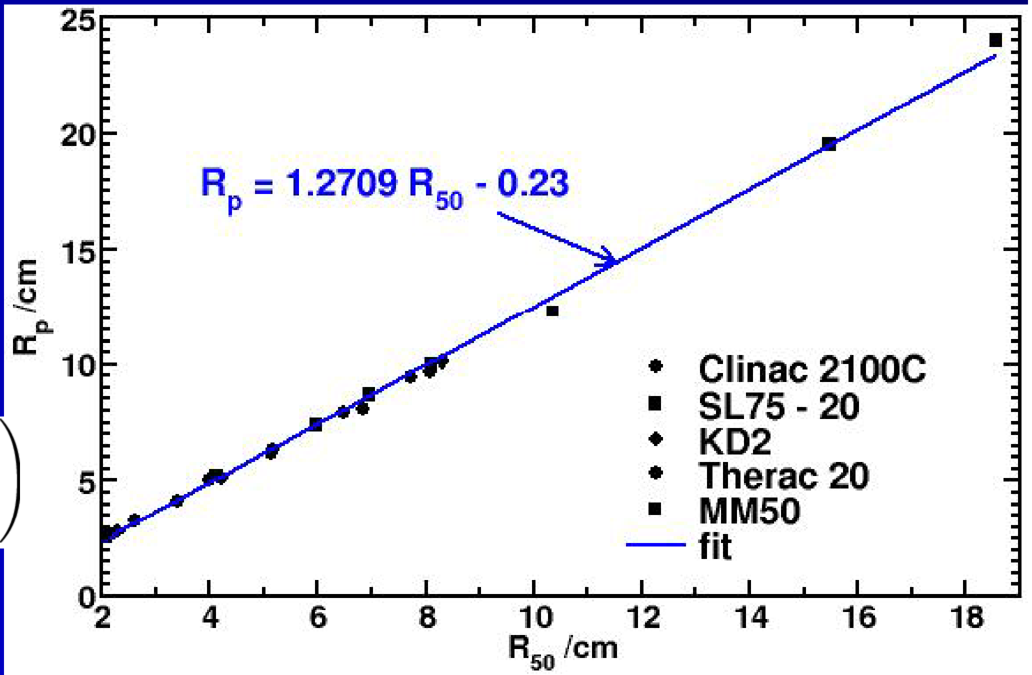
P_{fl} for cylindrical chambers

Tabulated vs E_z at d_{max}, but we need values at d_{ref}.
Calculate E_z at d_{ref} and use tabulated values for d_{max}.

How do we get E_z at d_{ref} given R_{50}?

Harder relationship: $$\overline{E}_z = \overline{E}_0 \left(1 - z/R_p\right)$$

Figure shows linear relationship between R_{50} & R_p for many calculated depth-dose curves



$$\overline{E}_z = 2.33 R_{50} \left(1 - \frac{z}{1.2709 R_{50} - 0.23}\right)$$

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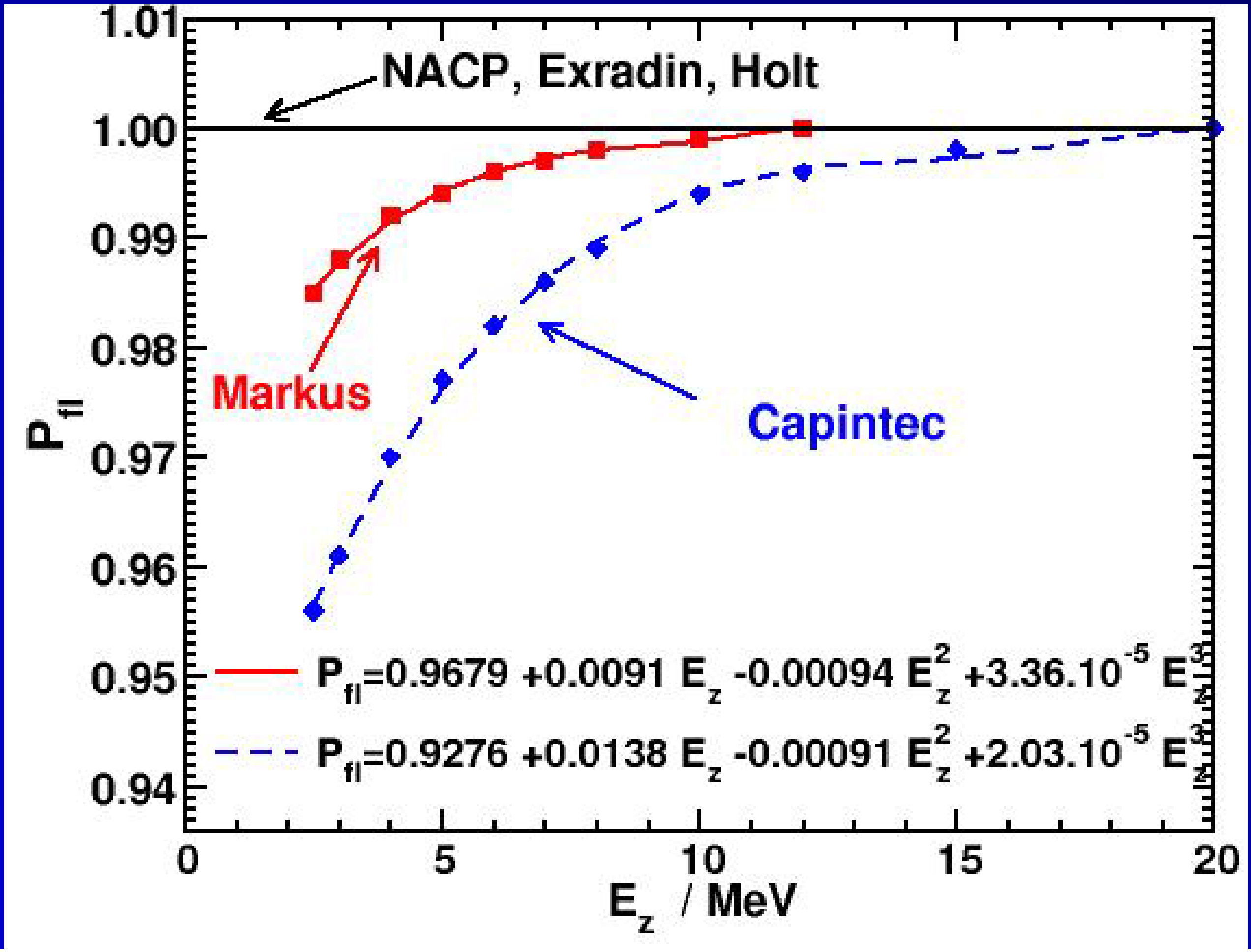
P_{fl} for plane-parallel chambers

Based on values in TG-39: Unity for "well-guarded" chambers and less than 1.0 for others

Markus & Capintec values based on many measurements with large uncertainties.



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P_{gr} for cylindrical chambers

As discussed previously, e- beams use a simple measurement to obtain P_{gr}.

Photon beams

TG-51 & TG-21 use values of Cunningham & Sontag(1980) -values buried in k_Q values

IAEA uses values from Johansson et al (1977) which also led to the 0.75 r_{cav} and 0.6 r_{cav} offsets used for the effective point of measurement approach

Offset values can lead to equivalent correction factors

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

$$\frac{D_{20}}{D_{10}} = 0.05607 + 0.77639\ TPR_{10}^{20}$$

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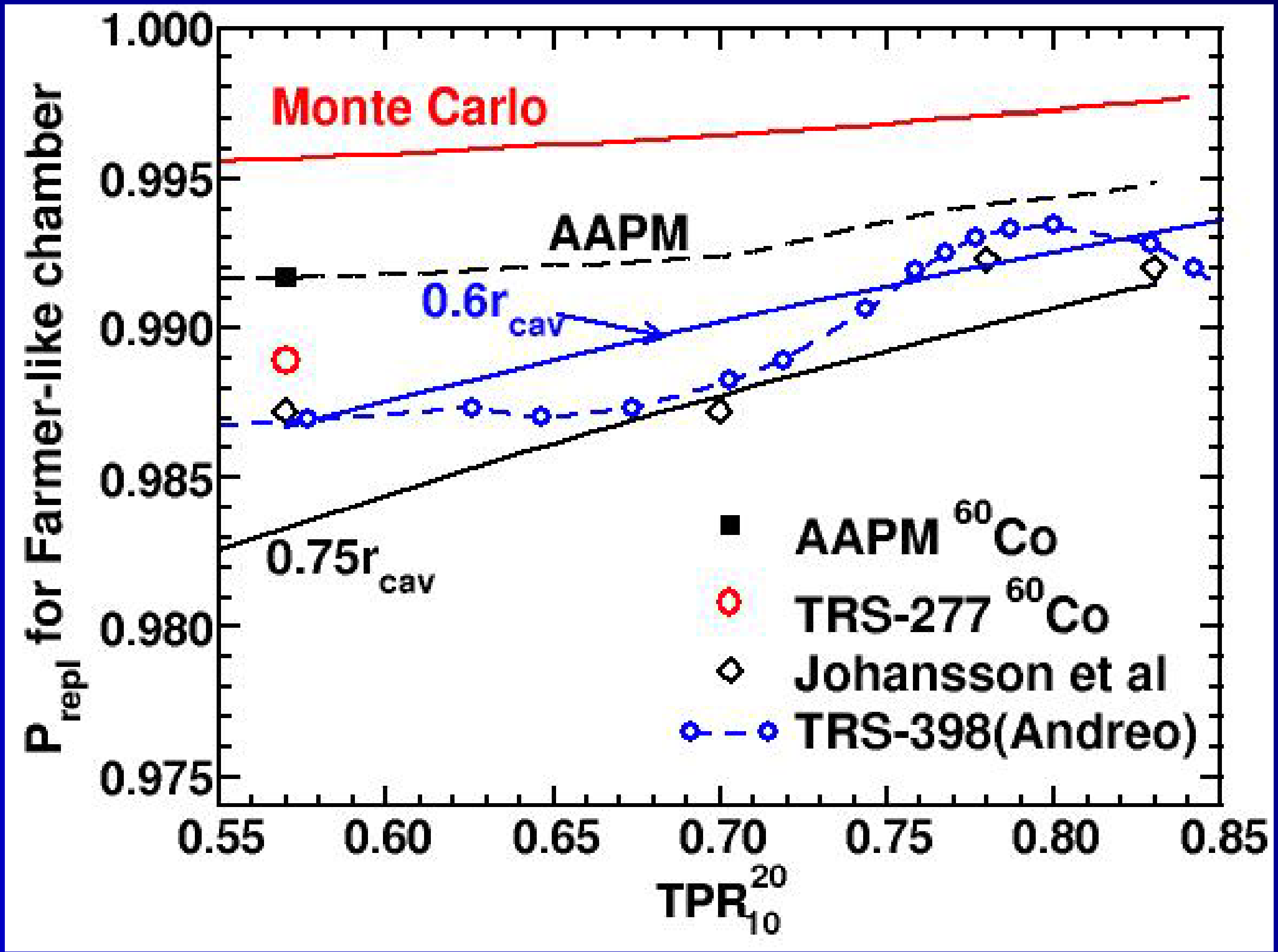
P_{gr} for cylindrical chambers

P_{gr} is largest difference between TG-51 and TRS-398

Wang's MC calns disagree with both: and can explain previous measurements



P_{gr} ratio used in TG-51 hardly changes since lines parallel

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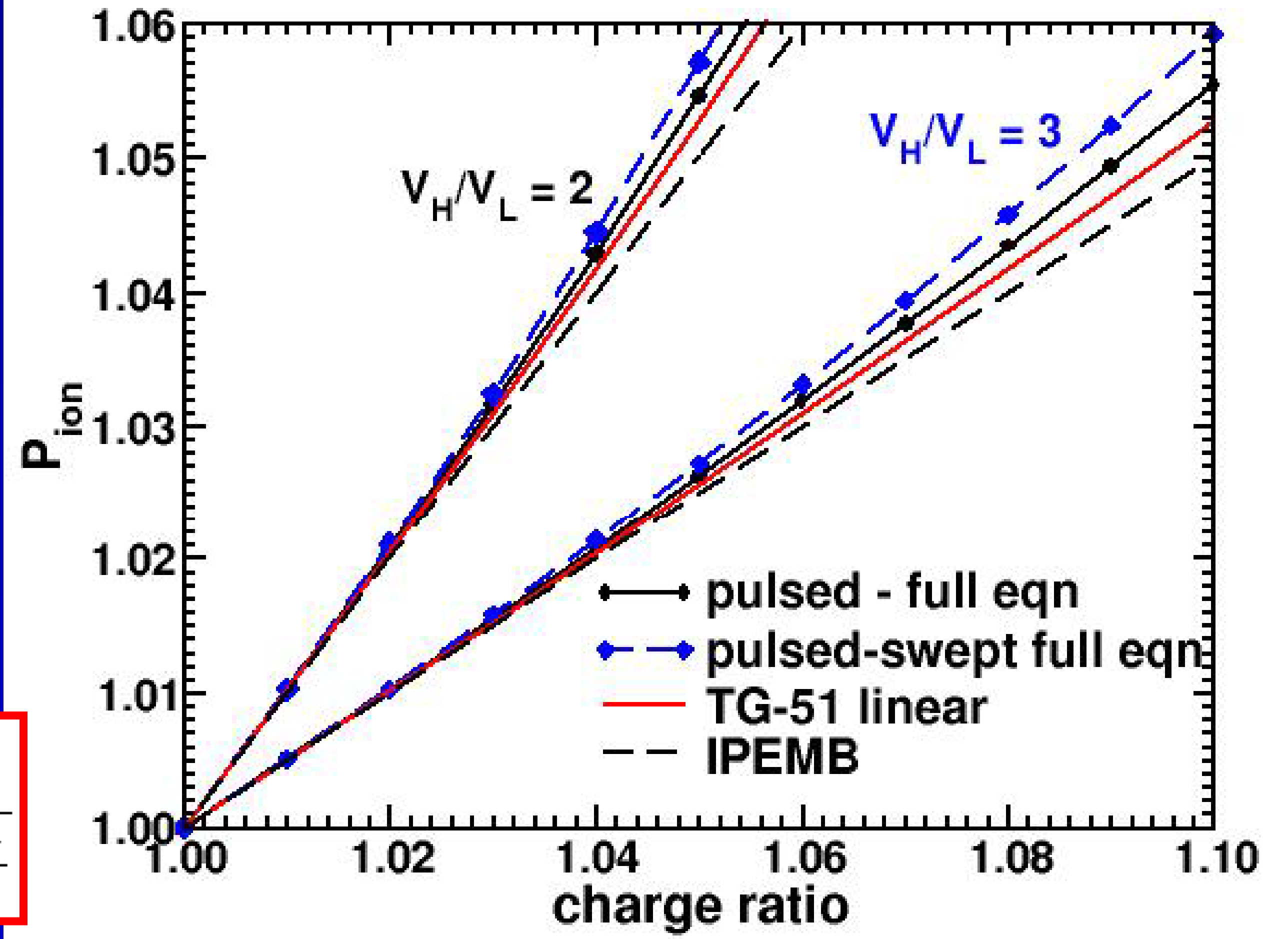
ion recombination: P_{ion}

Corrects reading to 100% collection efficiency.

For pulsed beams a then "new" linearized form of the TG-21 eqn is used.

$$P_{\text{ion}}\left(V_H\right) = \frac{1. - \frac{V_H}{V_L}}{\frac{M^H_{\text{raw}}}{M^L_{\text{raw}}} - \frac{V_H}{V_L}}$$



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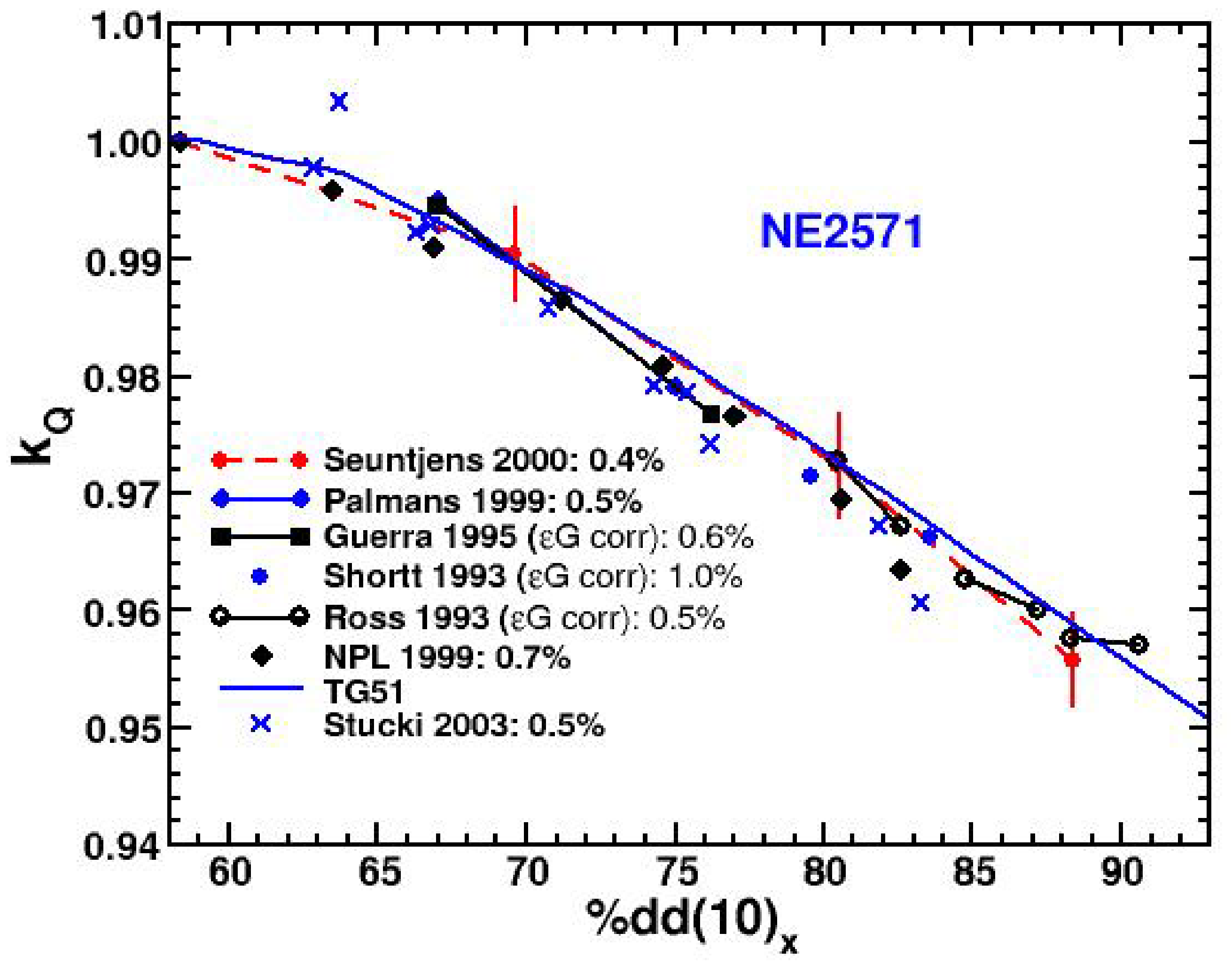
Must be measured at dose-rate to be used at

experimental verification of k_Q

Expts agree with TG-51 values within experimental uncertainties.



Seuntjens et al (Med Phys 27 (2000) 2763)

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experimental verification of k_Q

Seuntjens et al at NRC measured k_Q for >=3 of each of 6 chamber types

Measured against primary standards

Measurement accuracy ±0.5%

k_Q consistent for each type

RMS deviation TG-51 vs expt for 60 data points is 0.4%

Based on this agreement with measurements
-a reasonable uncertainty on
TG-51 photon beam k_Q values is 0.5%

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What is uncertainty on dose?

$$D_{\mathrm{w}}^{Q} = M k_Q N_{\mathrm{D,w}}^{^{60}Co}$$

- Uncertainties (photons)
  - on $N_{D,w}$ is 0.5-0.6%
  - on k_Q is 0.5%
  - on M (%dd(10)$_x$, monitor etc) 0.7%
- total uncertainty 1.0%

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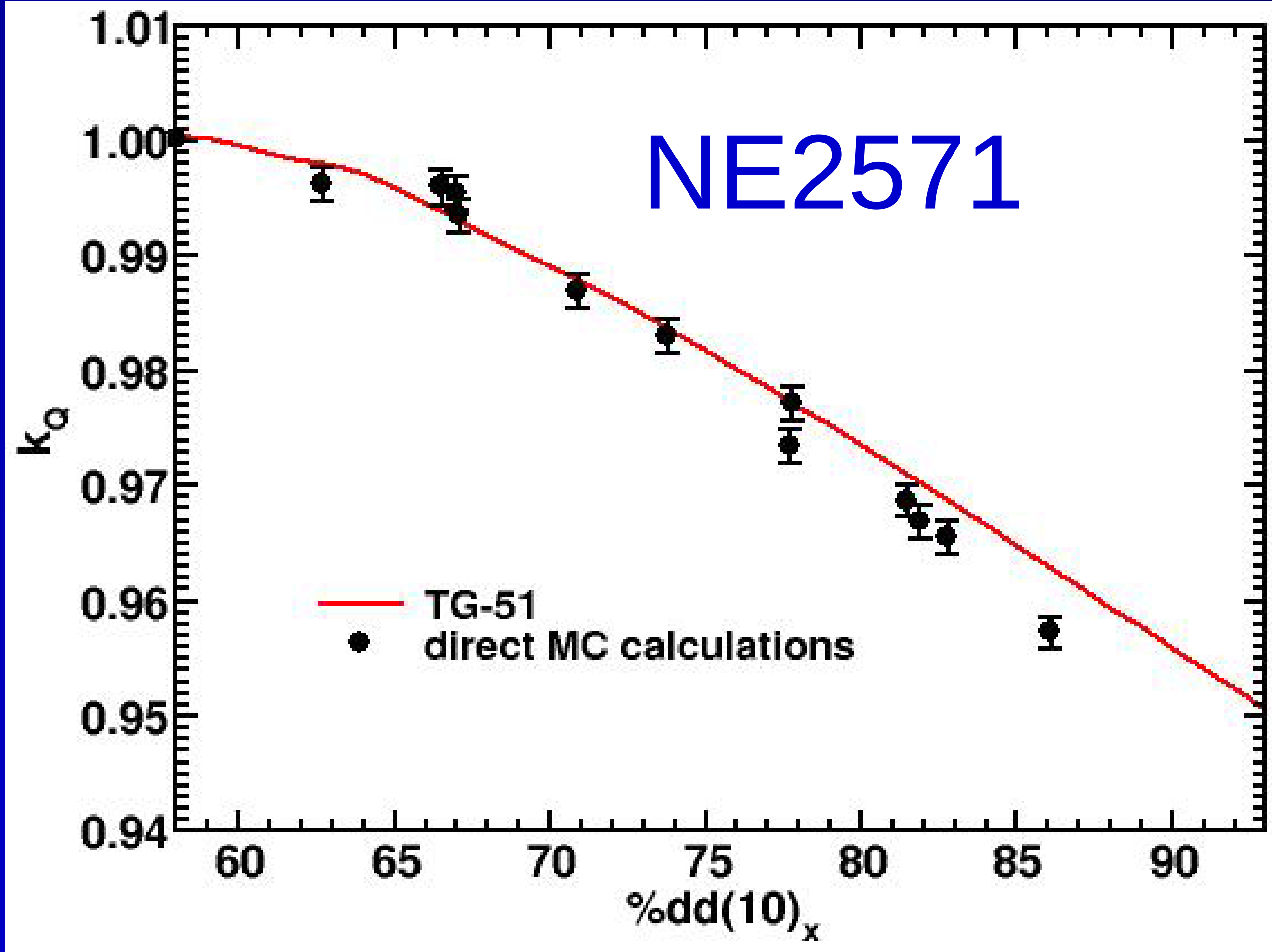
k_Q: state-of-the-art

The photon beam P_{wall} and P_{repl} values in TG-51 have been shown to be wrong.

What is overall effect on k_Q ?



Conclusion

Despite various improvements in our understanding of the details of corrections used in TG-51, the overall accuracy is still thought to be of the order of 1% or better, at least for photon beams.
We still need some more experimental confirmations in electron beams.

Acknowledgements

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