Physics of the TG-51 dosimetry protocol

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AAPM's TG-51 protocol for clinical reference dosimetry of high-energy photon and electron beams

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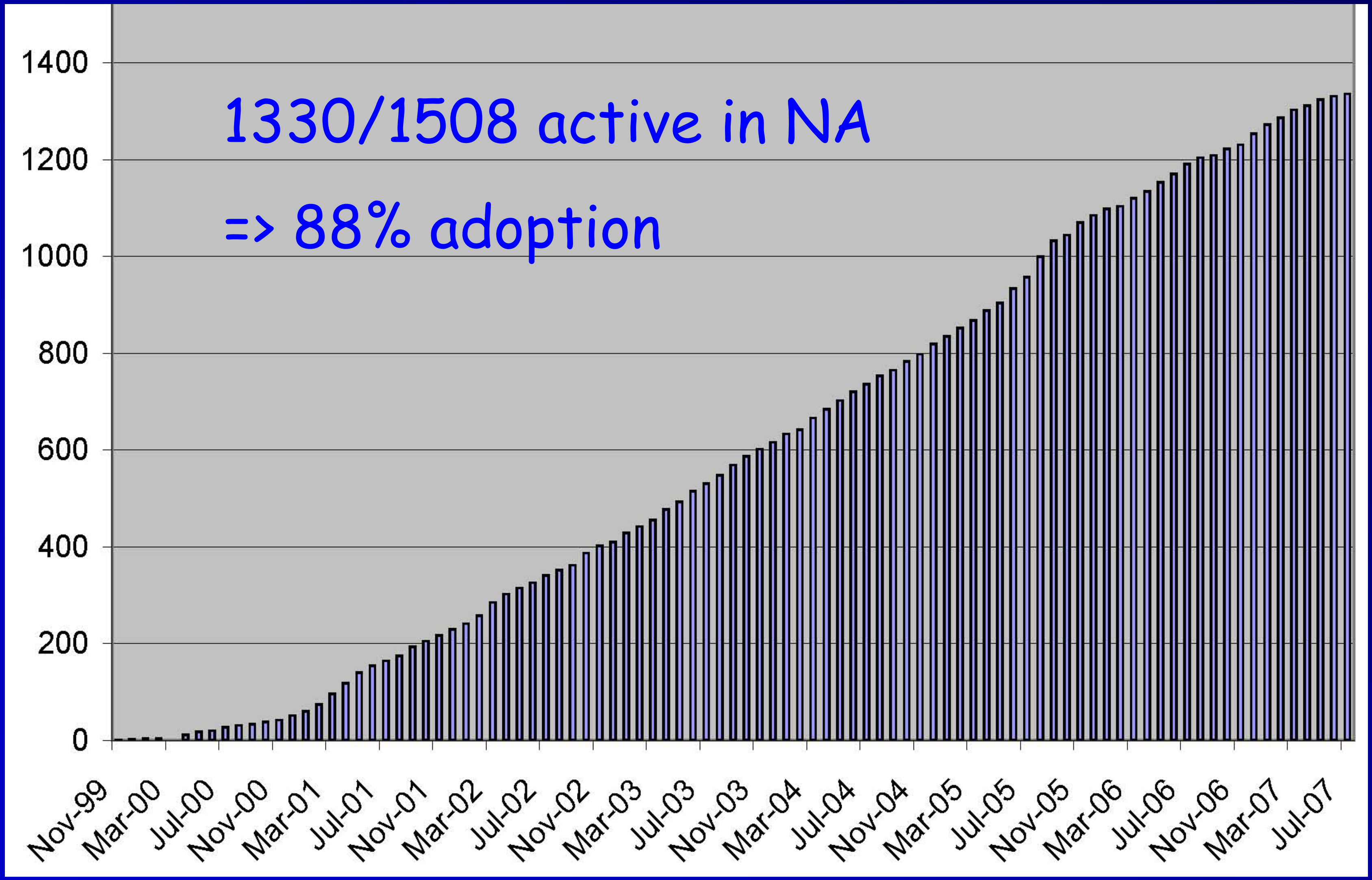
Used by 88% of RPC-monitored clinics

30/30 in Canada



http://rpc.mdanderson.org/RPC with permission from Radiological Physics Center in Houston

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Which statement applies to you?

0%
0%
0%
0%
0%

1. My clinic still uses TG-21 (or equivalent air-kerma based protocol).
2. I have only used TG-51 (or equivalent absorbed-dose based protocol) at the clinic where I currently work, but I have used TG-21 in the past.
3. I have only used TG-51 (or equivalent absorbed-dose based protocol) at the clinic where I currently work, and I have never used TG-21.
4. I made the transition from TG-21 to TG-51 at the clinic where I currently work.
5. I am not at a radiotherapy clinic so the question does not apply.

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Why change from TG-21?

- TG-51 is simpler since it avoids in-air quantities
- TG-51 is much less numerical work
- TG-51 is easier to teach and has fewer errors
- TG-51 has improved accuracy
- Formalism allows measurement of main quantities

  (k_Q, k_{ecal}, k_{R50})
- TG-51 is AAPM and COMP policy and RPC has switched

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General formalism

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

defines: absorbed dose calibration coefficient

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

defines: beam quality conversion factor

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

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

fundamental dose equation of TG-51:
-based on absorbed dose calibration coefficient

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Overview - photons

- get a traceable $N_{D,w}^{60Co}$
- measure photon beam quality, Q
- look up appropriate k_Q factor
- measure ion chamber reading M_{raw} at 10 g/cm^2 and convert to fully corrected charge M
- apply $D_w^Q = M k_Q N_{D,w}^{60Co}$

Question: where does k_Q come from?

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Spencer-Attix cavity theory

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

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

K_h is humidity correction
--needed since air is humid
--but we use dry air values
M is fully corrected charge

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

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

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

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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 for e-, see later

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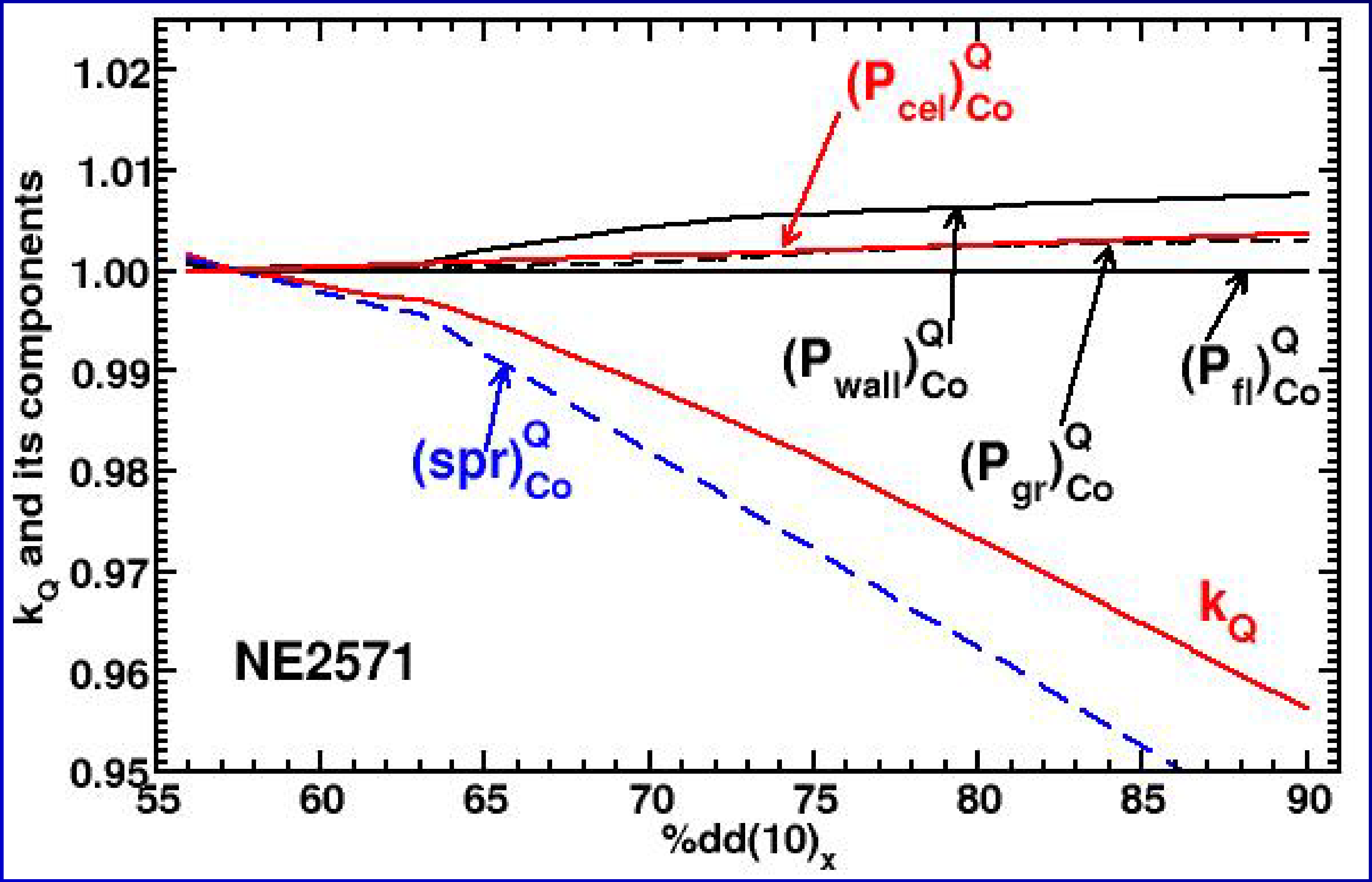
k_Q components



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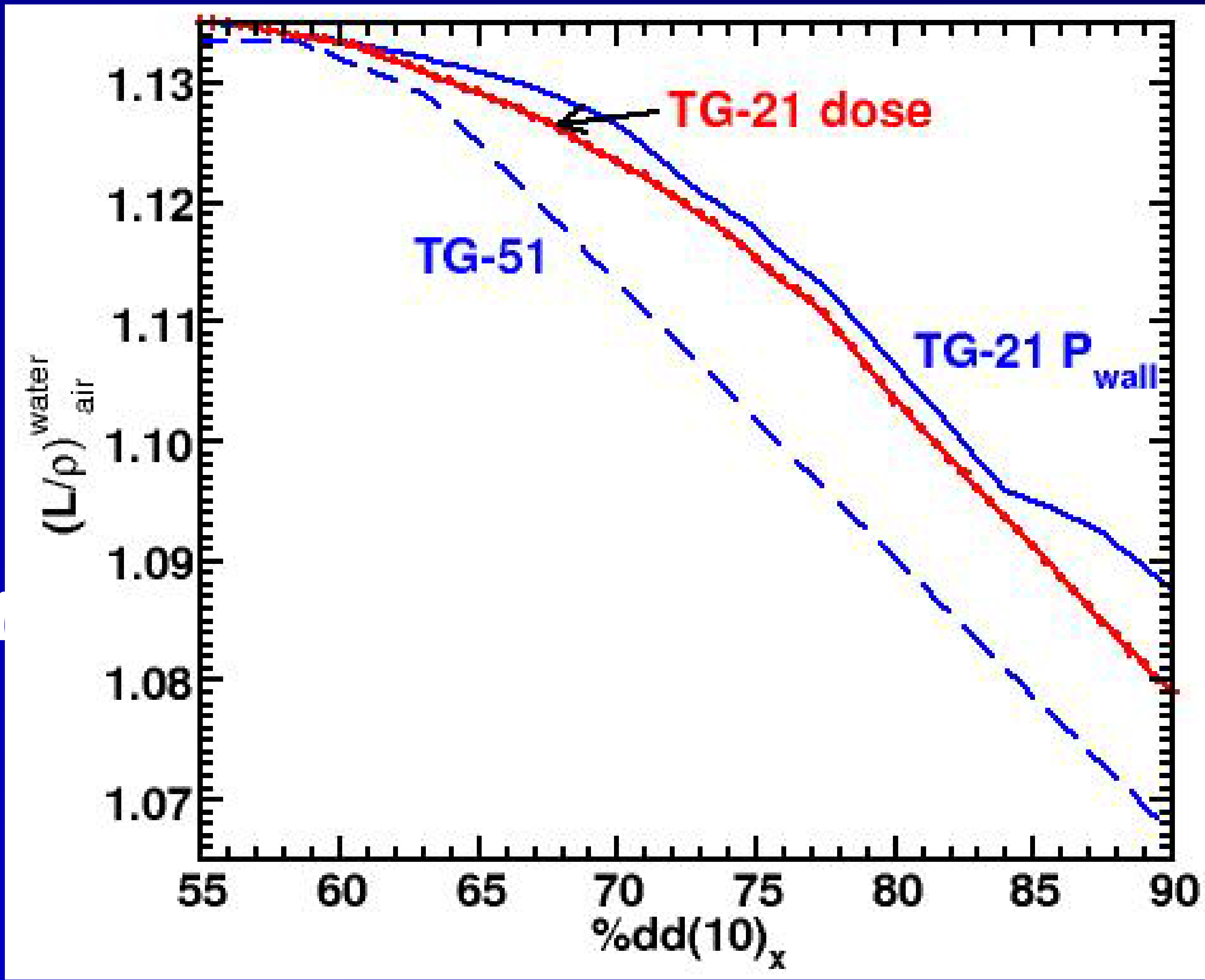
photon stopping power ratios

TG-51 uses stopping powers from ICRU Report 37

This is biggest difference from TG21

Due to underlying stopping powers



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

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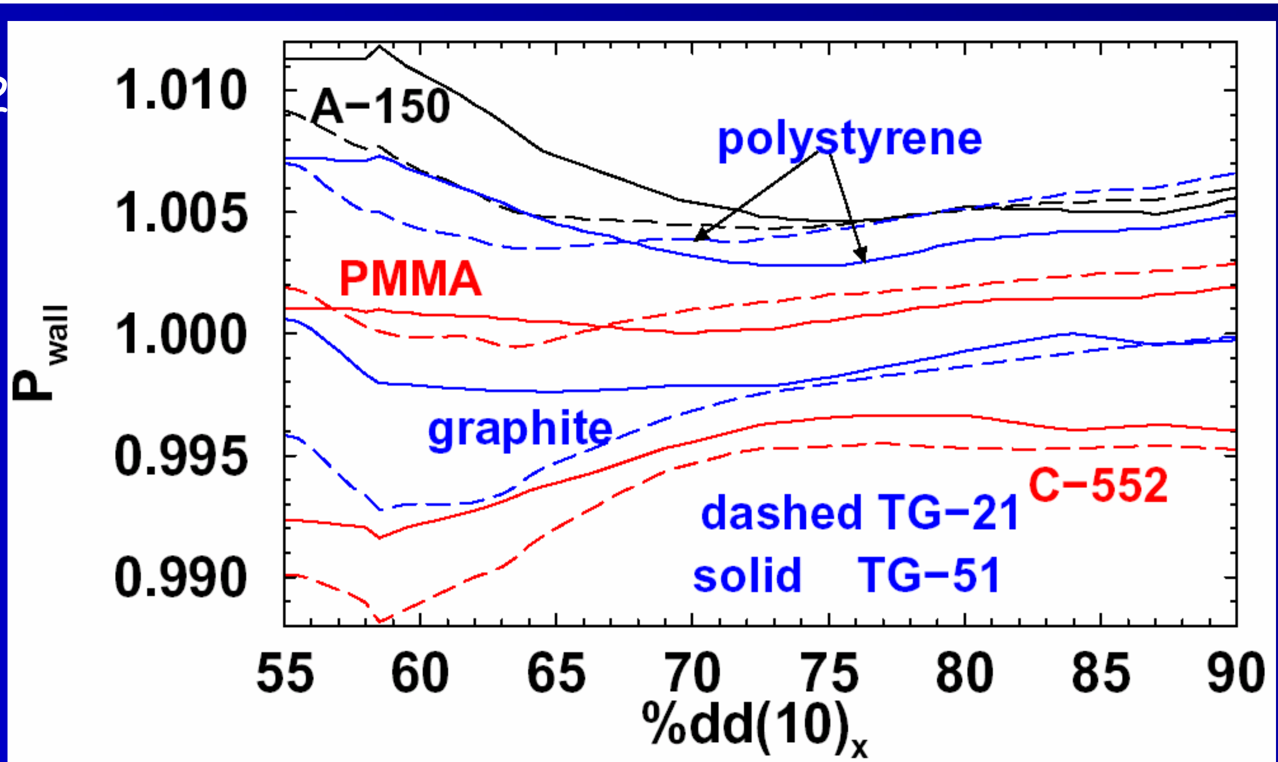
P_{wall}

- accounts for wall not being water
  - » unity for electrons
  - » same as TG-21 for photons

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

For walls 0.05g/cm^2

Changes due to better cross sections



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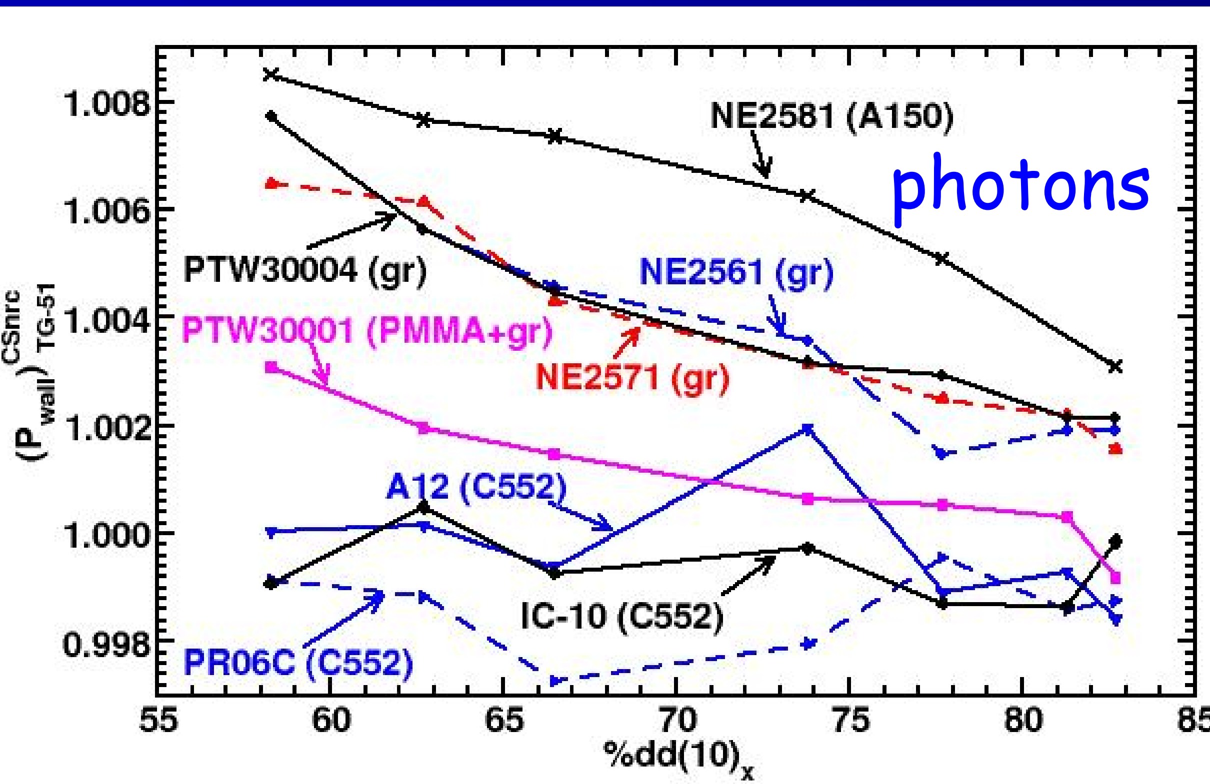
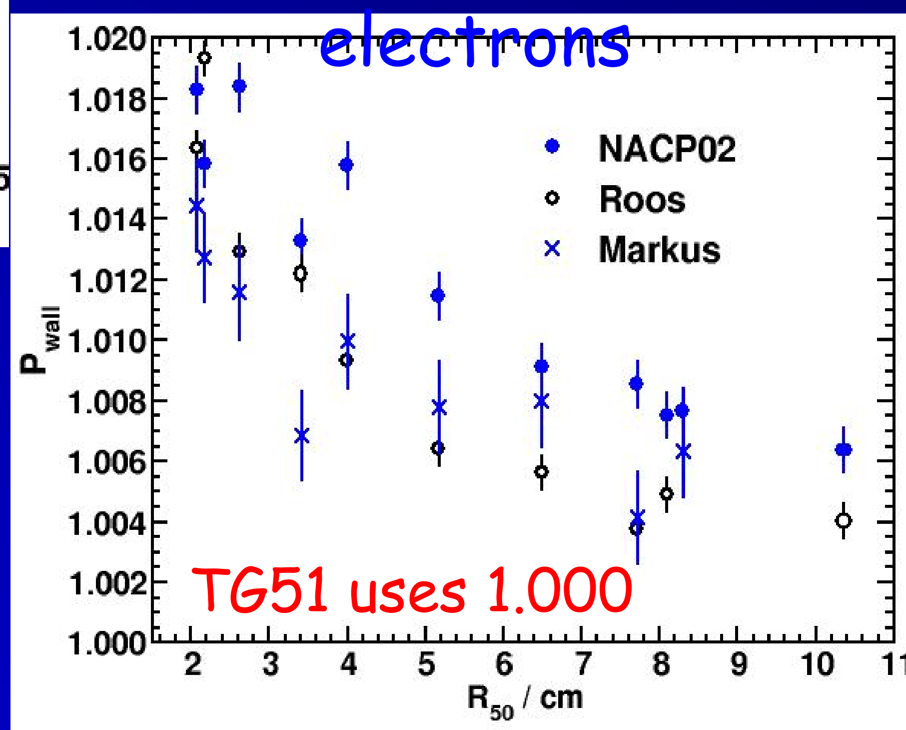
Recent Monte Carlo values of P_{wall}



Buckley et al MP 33(2006) 455

MP 33(2006) 1788



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

P_{repl} replacement correction: accounts for changes caused by the cavity

P_{fl}: fluence correction: changes due to cavity other than gradient effects

P_{gr}: gradient correction

fluence moves upstream because of air's low density

P_{gr} is a function of dose gradient & chamber radius
-taken as 1.00 at d_{max}

Two approaches

-effective point of measurement for depth-dose curves

-P_{gr}: multiplicative correction for absolute dose measurements

Effective point of measurement

Johansson et al (1977)

electrons

0.5 r_{cav} upstream of central axis

photons

0.6r_{cav} (was 0.75r_{cav} previously)

Only used for depth-dose curves with cylindrical chambers

For plane parallel chambers,
effective point of measurement and
point of measurement
are front face of cavity
i.e. P_{gr} = 1.00

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P_{gr}: in dose equations

electron beams

for cylindrical chambers $$P_{\mathrm{gr}} = \frac{M_{\mathrm{raw}}(d_{\mathrm{ref}} + 0.5 r_{\mathrm{cav}})}{M_{\mathrm{raw}}(d_{\mathrm{ref}})}$$

–equivalent to using the effective point of measurement

-but allows rigorous definition of calibration factor

photon beams

–TG-51 uses calculations of Cunningham and Sontag (1980)

(as did TG-21)

-there is considerable variation in data on this correction

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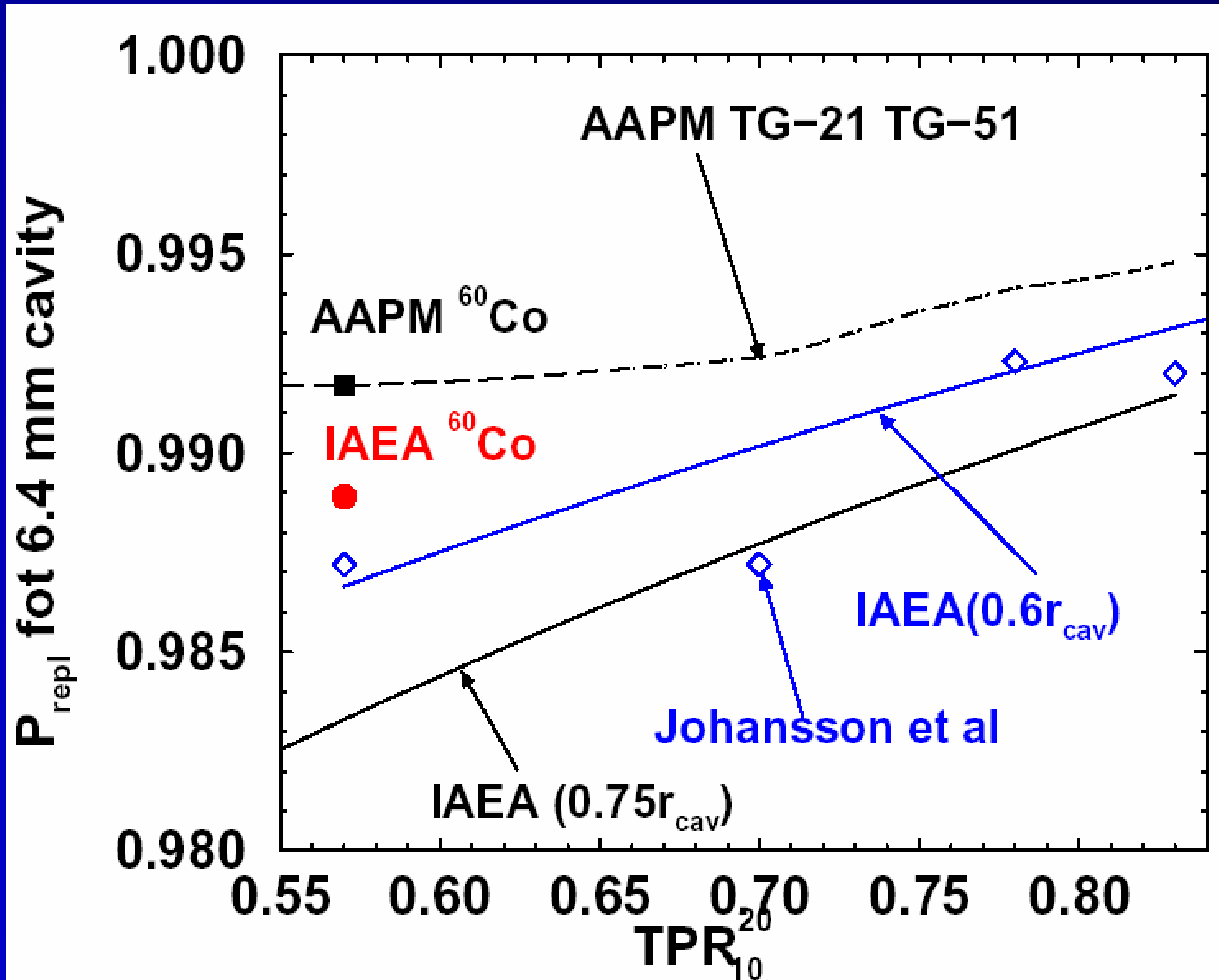
P_{repl}: photon beams (= P_{gr})

TG-51 uses the ratio

$P_{repl}^{Q}/P_{repl}^{Co}$

=> reduced uncertainty



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P_{fl}: fluence correction

photon beams

-fluence corrections not needed -due to transient CPE

electron beams

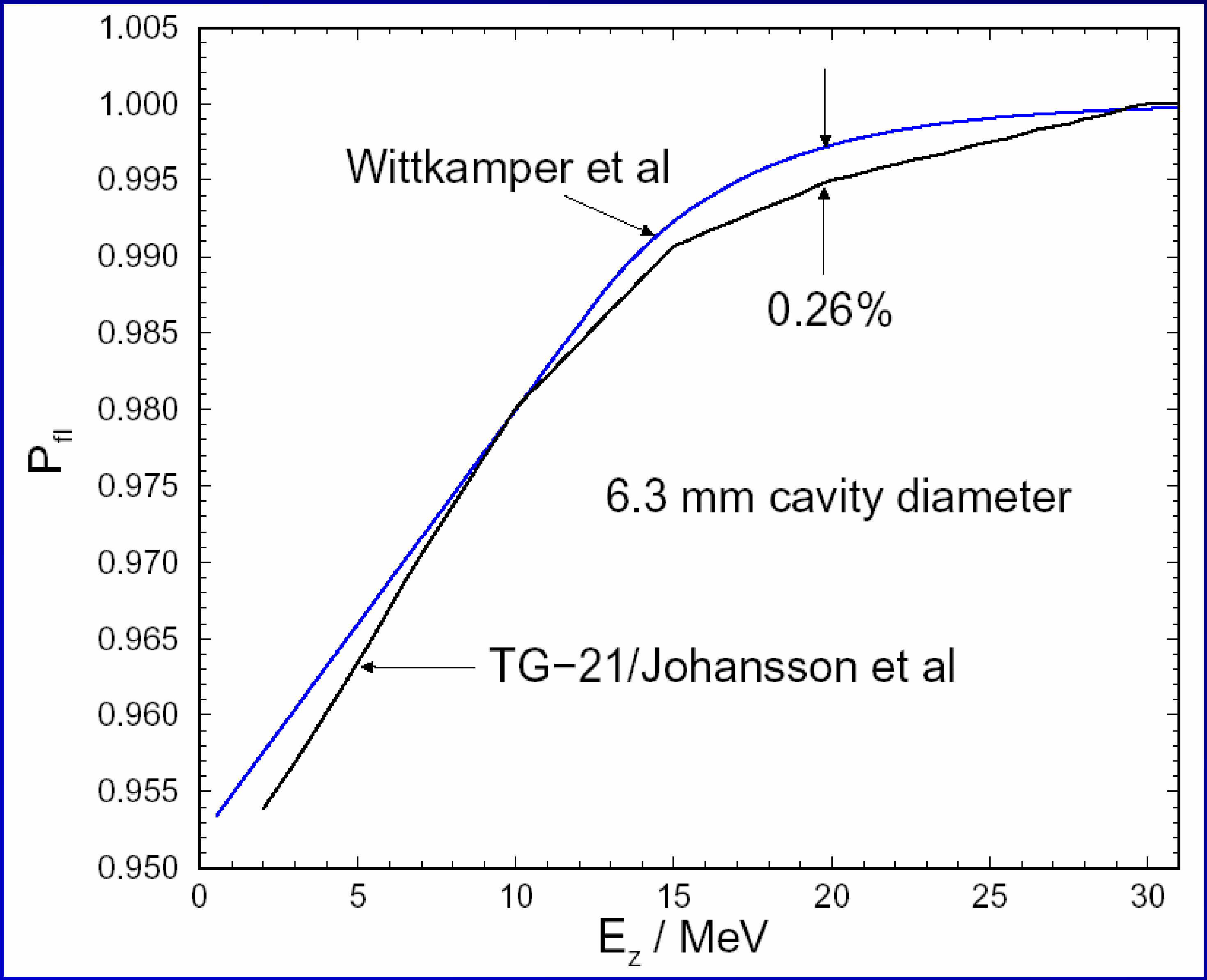
TG-51 uses same factors as TG-21 for cylindrical chambers

and same factors as TG-39 for plane-parallel

P_{fl}: cylindrical (e-)

Newer data **agrees well** with that used in TG-51

Need value as a **function** of R_{50} at d_{ref}



Wittkamper et al PMB 38 (1991)1639

P_{fl}: plane-parallel

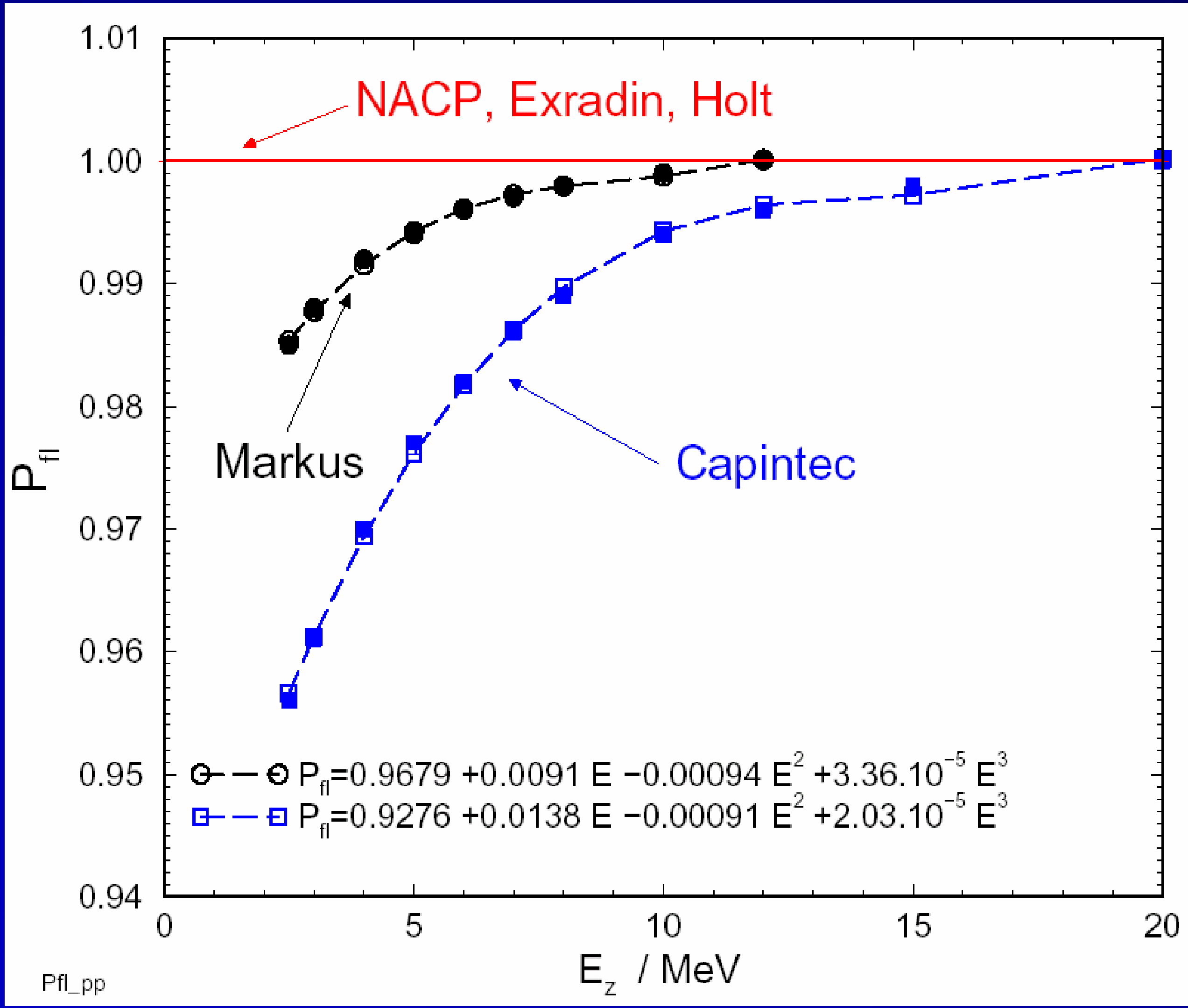
TG-51 uses TG-39 data with a new fit

TG-39 MP 21(1994)1251

Need E_z as a function of R_{50}

Start with Harder eqn: $$E_z = E_0\left(1 - \frac{z}{R_p}\right)$$

$$R_p = 1.271 R_{50} - 0.23$$



$$E_z = 2.33 R_{50}\left(1 - \frac{z}{1.271 R_{50} - 0.23}\right)$$

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P_{cel}: Al electrode correction

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

Ma and Nahum(93) showed aluminum electrodes have an effect

-larger in photon beams

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

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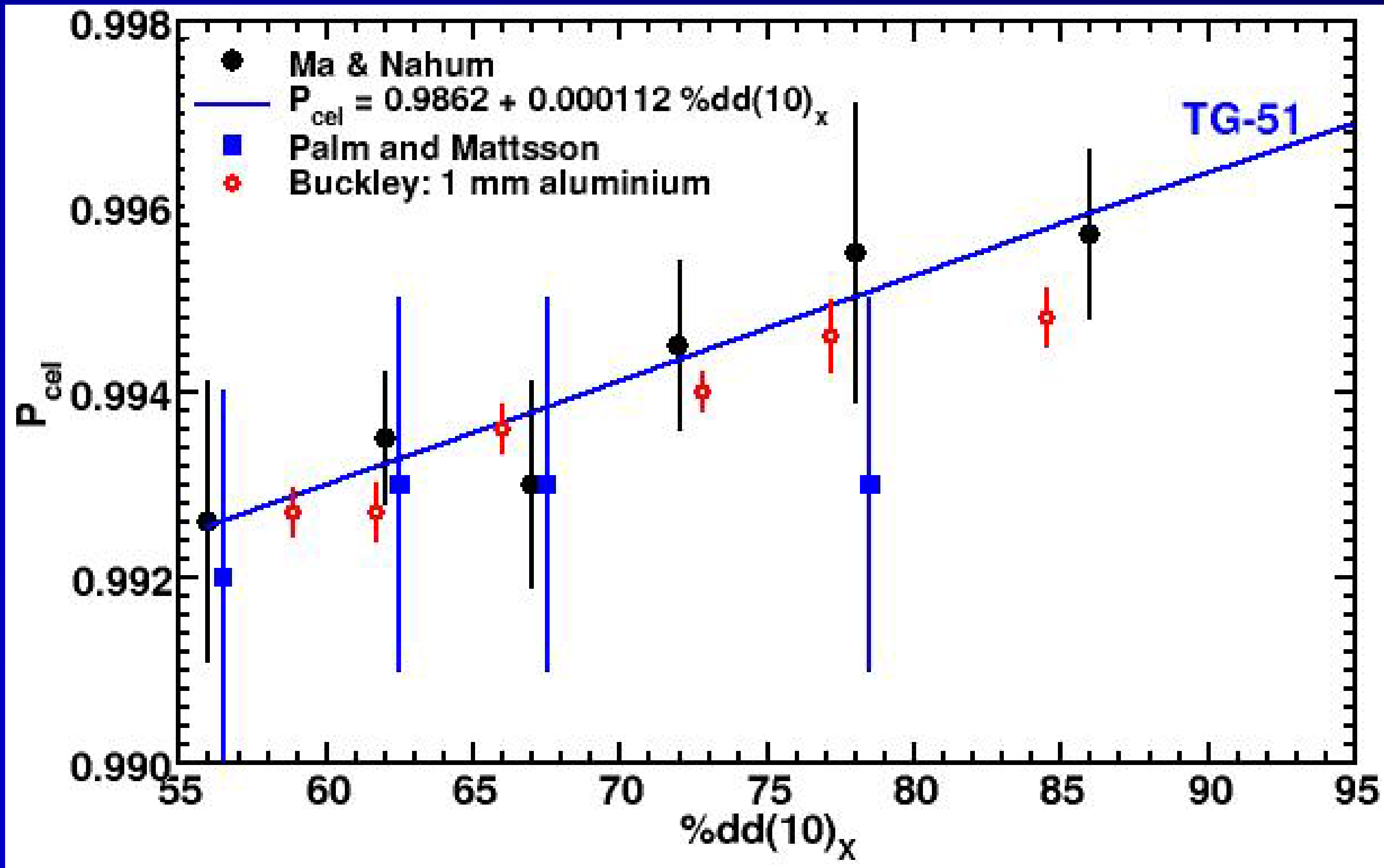
Ma & Nahum PMB 38 (1993) 267

P_{cel}: Al electrode correction

-expts confirm calns

but not as precise

more accurate recent calculations are in good agreement



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

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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 the photon component of the percentage depth-dose at 10 cm depth in a 10×10 cm^2 field defined on the surface of a water phantom at 100 cm SSD

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

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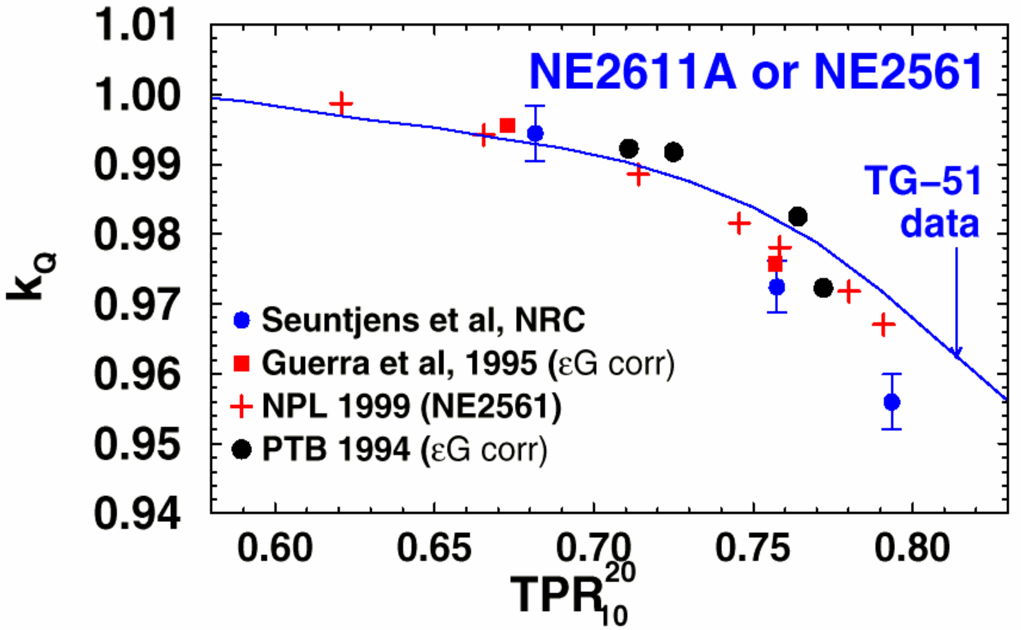
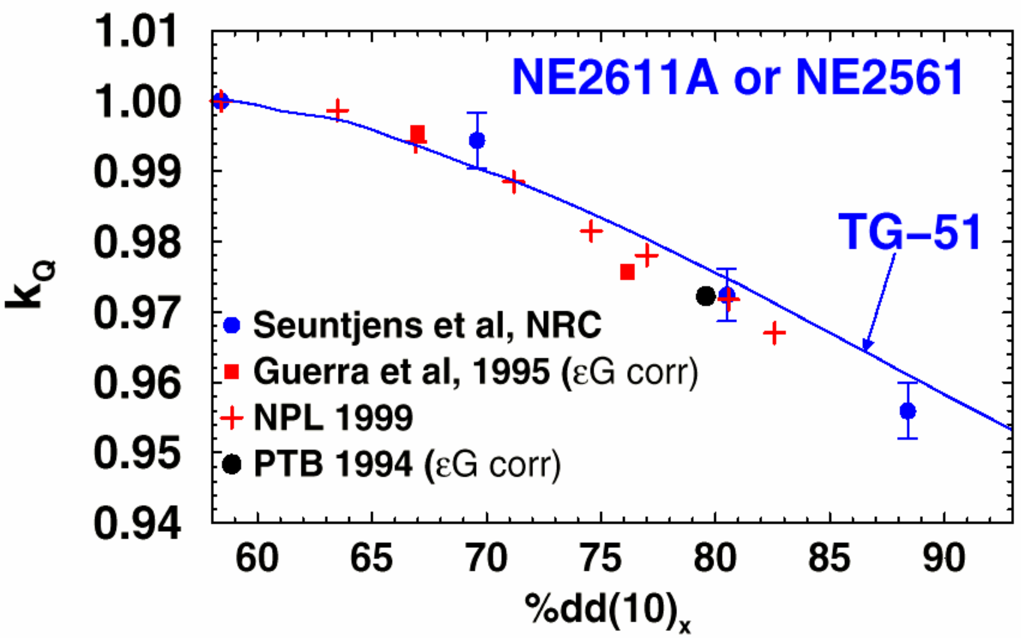
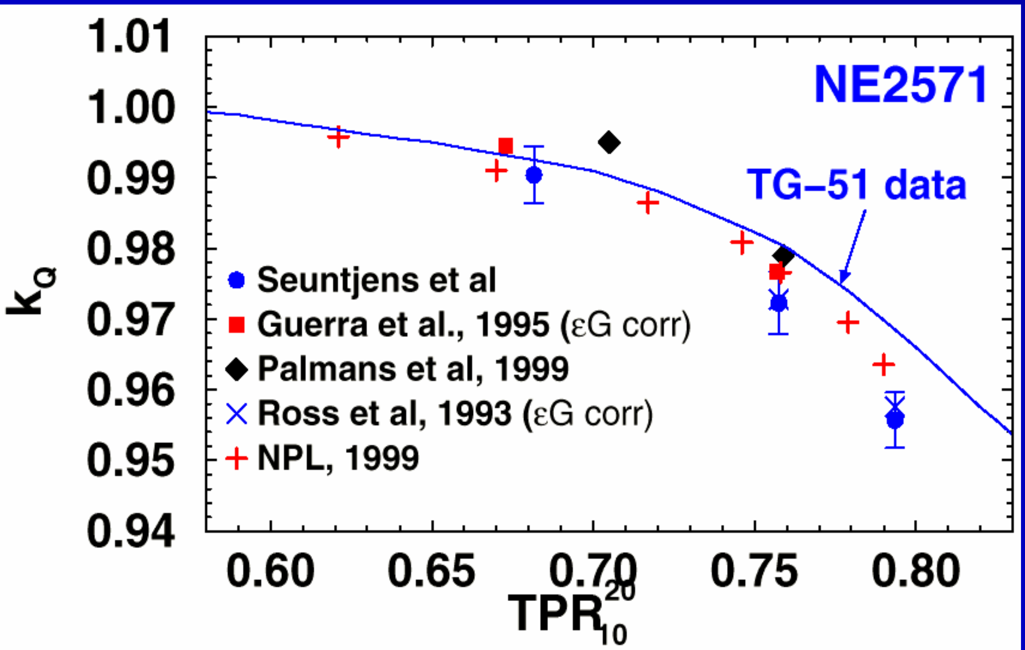
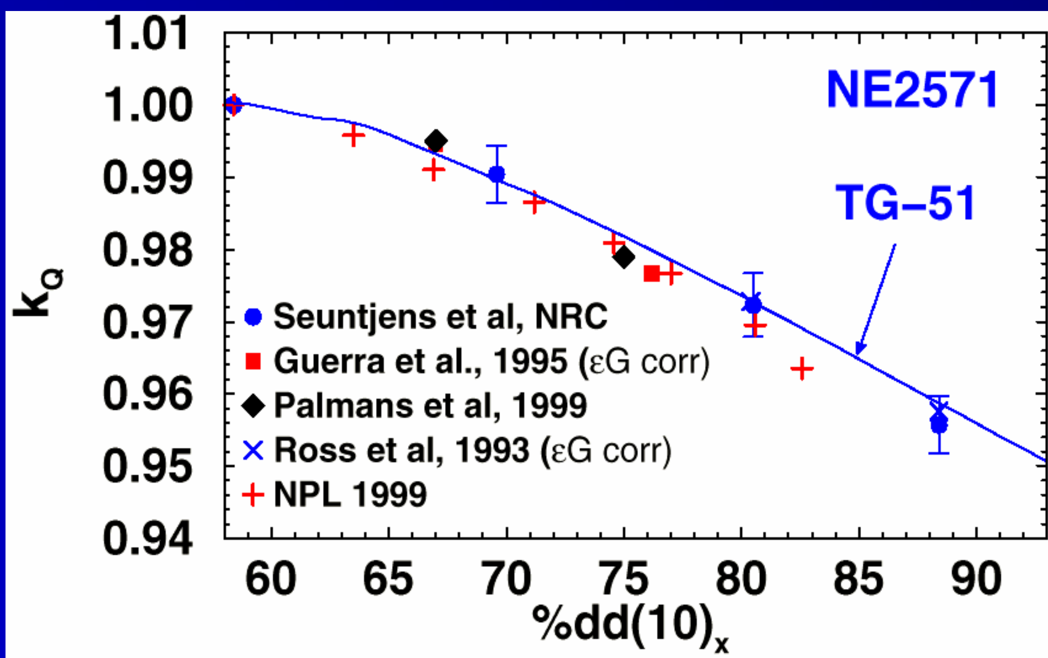
Measured k_Q vs TPR or $\%dd(10)_x$









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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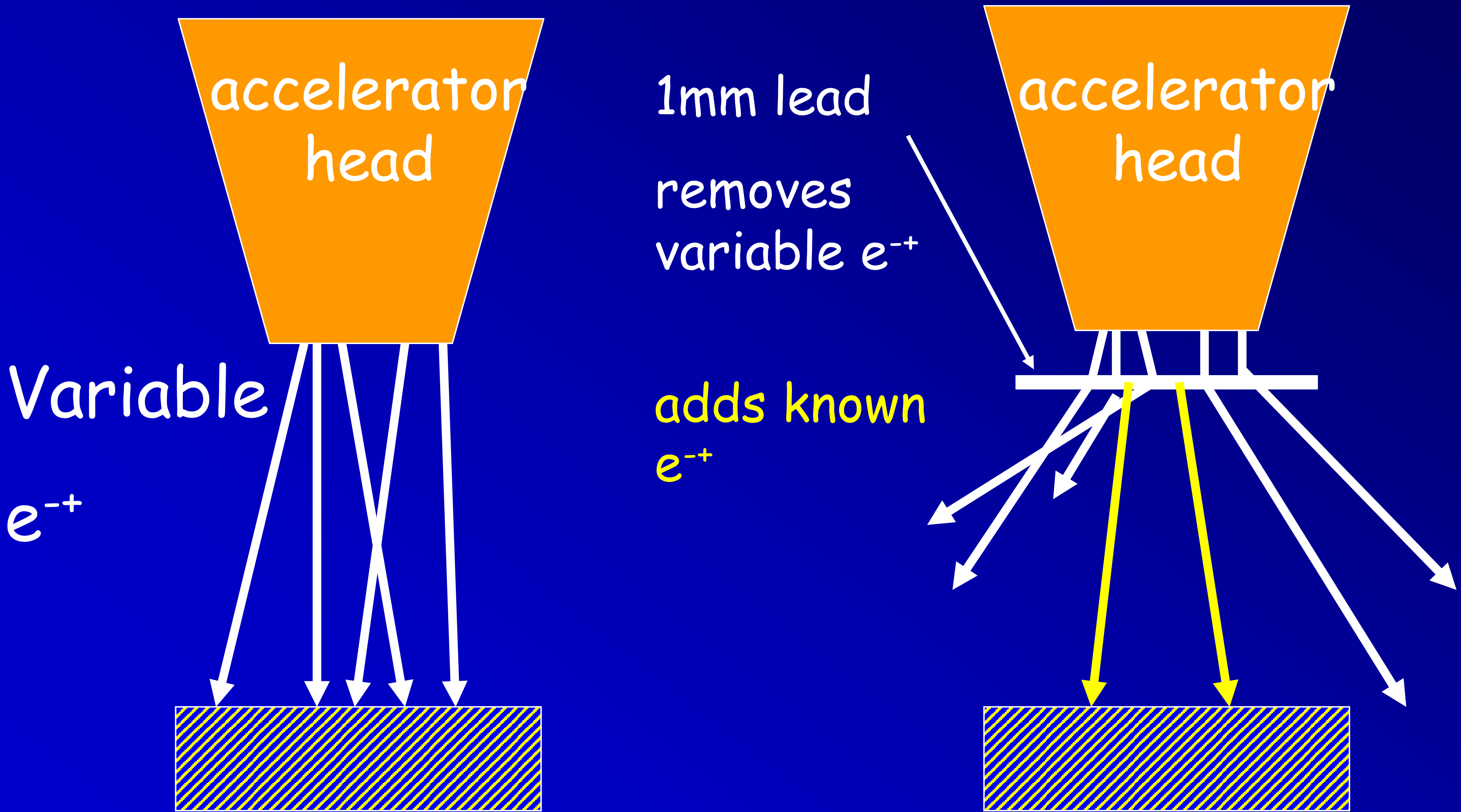
Electron contamination



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Correction for e⁻ contamination

$$f'_e = \frac{\%dd(10)_{\mathsf{x}}}{\%dd(10)_{\mathsf{Pb}}}$$

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.

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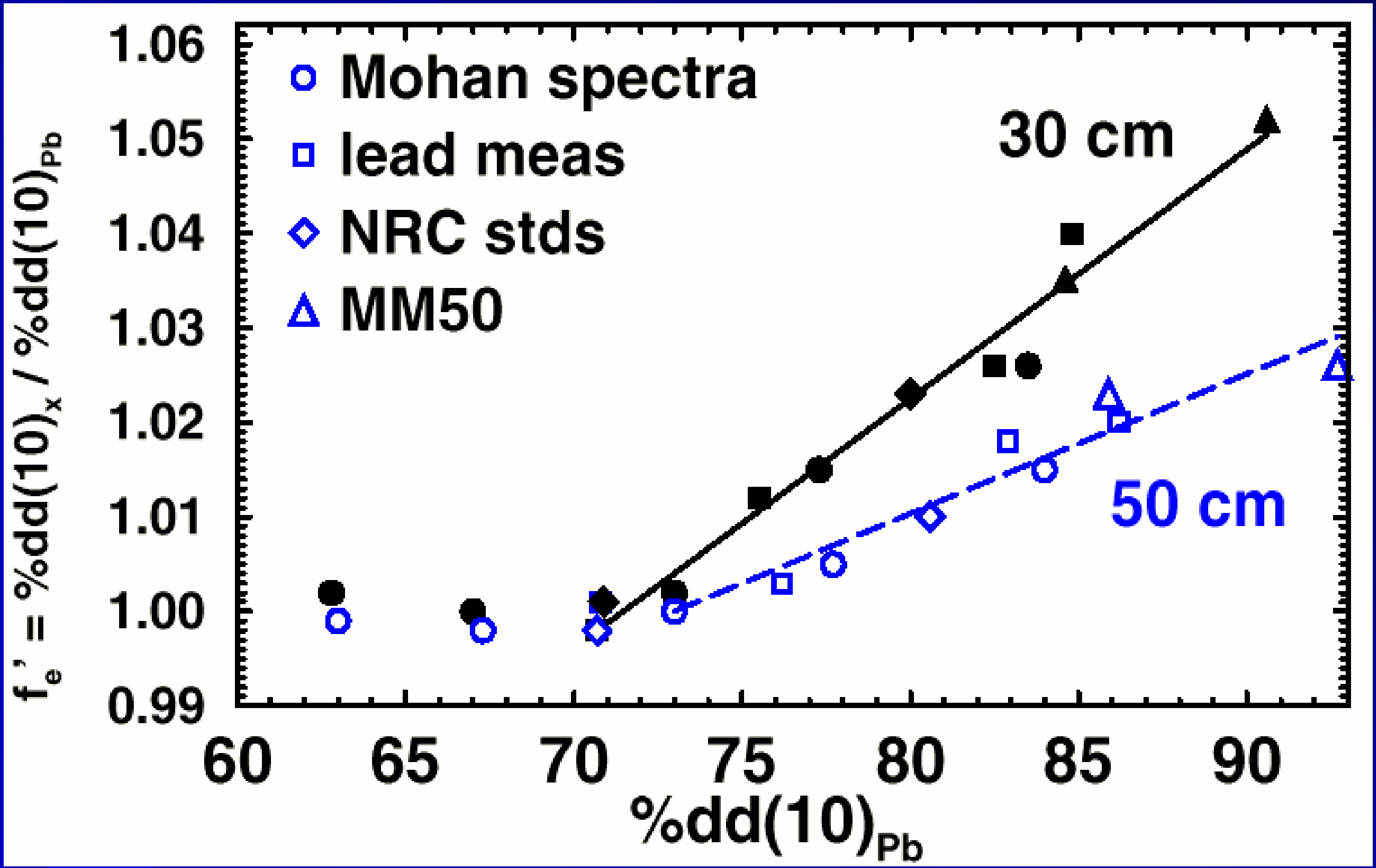
Correction vs $\%dd(10)_{Pb}$



MP 26 (1999) 533

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

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

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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 measuring e- contamination accurately.

TG-51 uses %dd(10)$_x$ as a beam quality specifier because:

0%
0%
0%
0%
0%

1. it uniquely determines the stopping-power ratio to be used in that beam
2. it uniquely determines the k_Q value to be used
3. it is independent of electron contamination effects
4. the $TPR_{20,10}$ specifier does not work well for some standards labs accelerators which have beams that are not like those in the clinic, whereas %dd(10)$_x$ does.
5. all of the above
6. only (2) and (4)

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Answer is 5: all of the above

- 1) *it uniquely determines the stopping-power ratio* is correct since the major component of the k_Q values is the stopping-power ratio and hence it must be specified uniquely.
- 2) *it uniquely determines the k_Q value to be used* is correct since k_Q is the only quantity which needs to be determined based on the beam quality for photon beams, so clearly it must be uniquely determined. If we use $TPR_{20,10}$ as a beam quality specifier, then for a given value of $TPR_{20,10}$ there could be a range of k_Q values, especially when using beams that are not clinical in primary standards laboratories

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Answer is 5: all of the above

- 3) *it is independent of electron contamination effects* is correct since by definition %dd(10)$_x$ does not include electron contamination. TG51 provides methods for taking into account electron contamination
- 4) *$TPR_{20,10}$ specifier does not work for some accelerators* is correct. During the talk, and in the Kosunen paper (see ref list) data were presented which showed an example of beams at the NPL and NRC which both had a TPR of 0.79 but their measured k_Q values in those beams differed by over 1%. However, using %dd(10)$_x$ these beams had very different beam qualities and the overall k_Q vs %dd(10)$_x$ curves in both labs were close to identical.

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Hence answer 5 (all of the above) is correct.

Overview - electrons

- get a traceable $N_{D,w}^{60Co}$
- measure I_{50} to give R_{50}

$$R_{50} = 1.029 I_{50} - 0.06 \qquad I_{50} \leq 10 \text{ cm}$$
$$R_{50} = 1.059 I_{50} - 0.37 \qquad I_{50} > 10 \text{ cm}$$

- deduce $d_{ref} = 0.6\, R_{50} - 0.1$ cm
- measure ion chamber reading, M_{raw}, at d_{ref}
- convert to fully corrected charge ($M = P_{ion} P_{TP} P_{elec} P_{pol} M_{raw}$)
- lookup k_{ecal} for your chamber
- determine $k'_{R_{50}}$ (fig, formula)
- establish P_{gr}^{Q} (M_{raw} 2 depths)
- apply $D_{\mathrm{w}}^{Q} = M P_{gr}^{Q}\, k'_{R_{50}}\, k_{\mathrm{ecal}} N_{\mathrm{D,w}}^{60Co}$

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e- beams: calibration coefficients

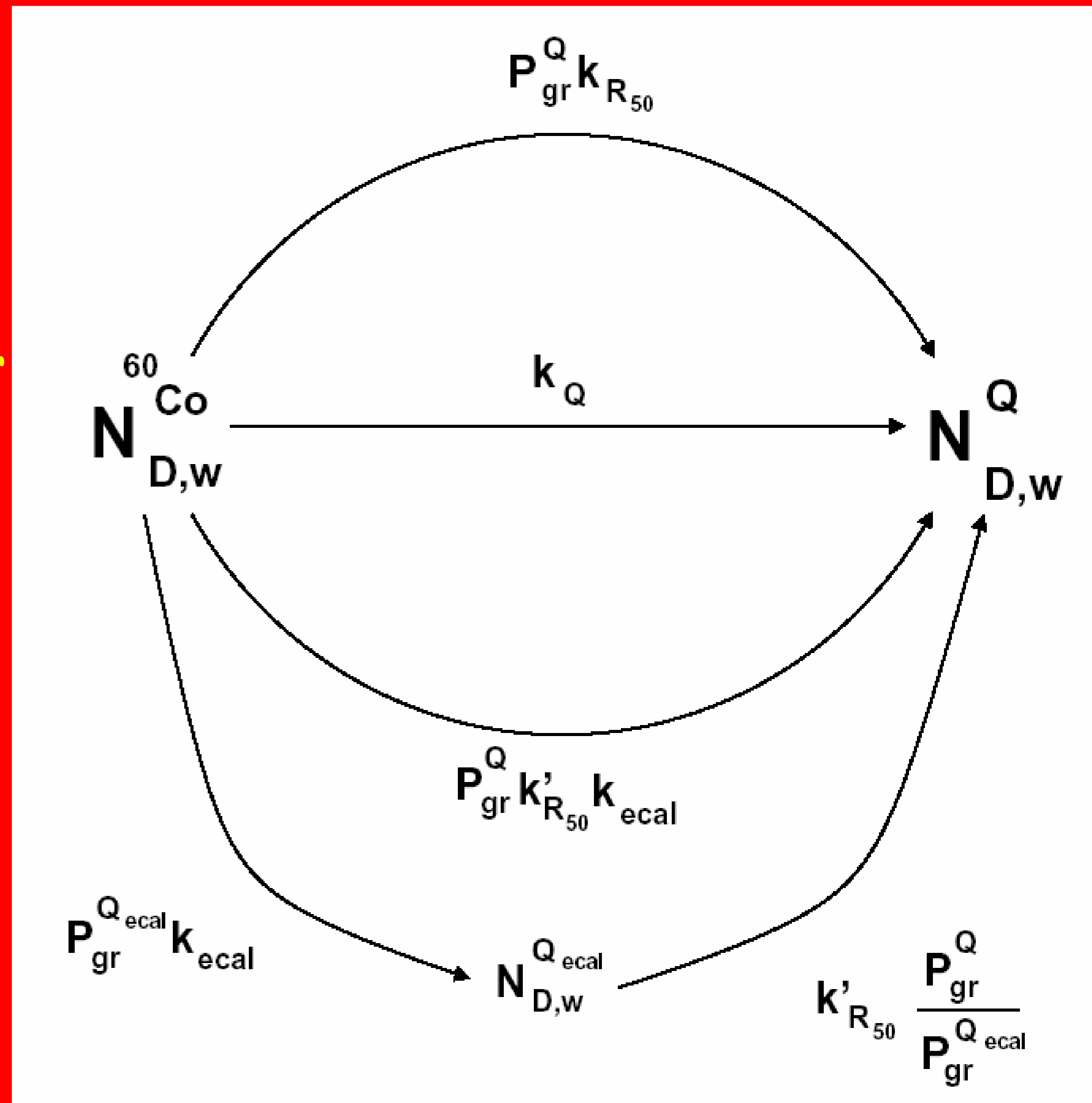
$$k_Q = P_{gr}^{Q} k_{R_{50}}$$

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

photon-electron conversion factor

electron quality conversion factor

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



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

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

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

a constant for a given chamber

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

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

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Why is it done this way for e-?

- parallel to photon formalism as much as possible
- k_{ecal} and k'_{R50} can be measured directly
- k_{ecal} useful in cross-calibration for plane-parallel chambers

- R_{50} used as a beam quality specifier since
  - E_o has significant problems
  - realistic stopping power ratios at d_{ref} are well specified by R_{50}

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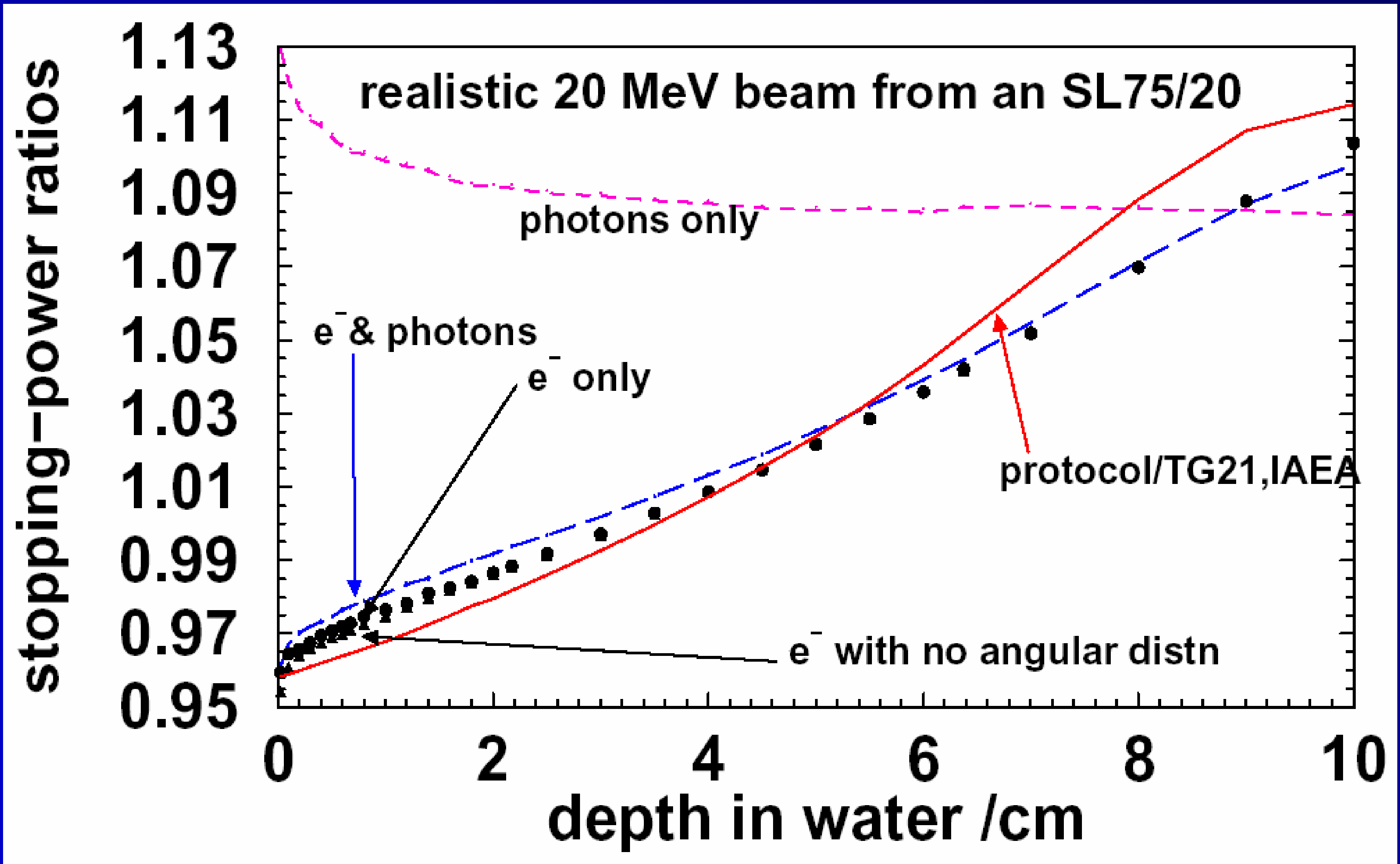
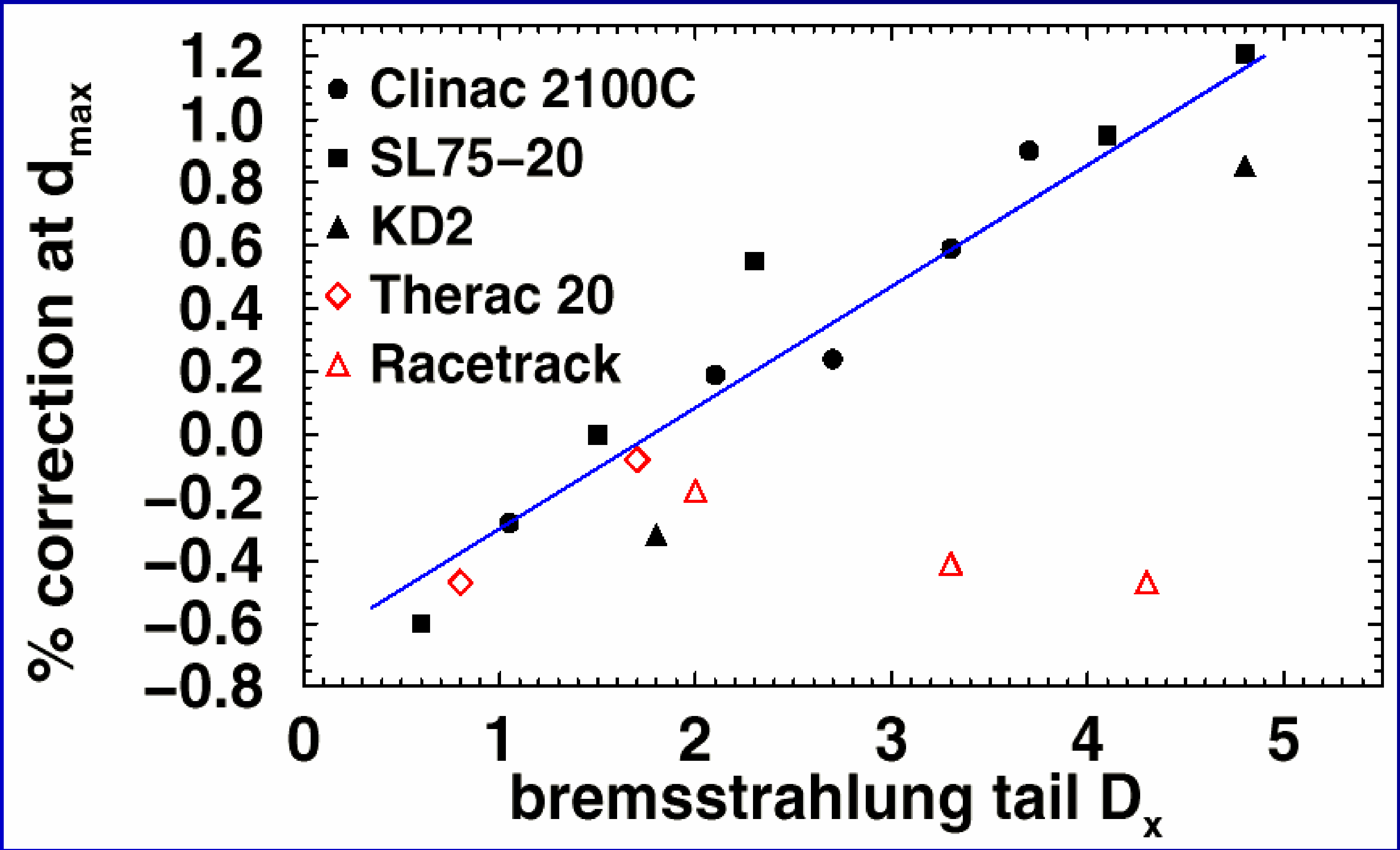
Realistic electron beam sprs



Ding et al Med Phys 22 (1995)489

Effects of realistic sprs



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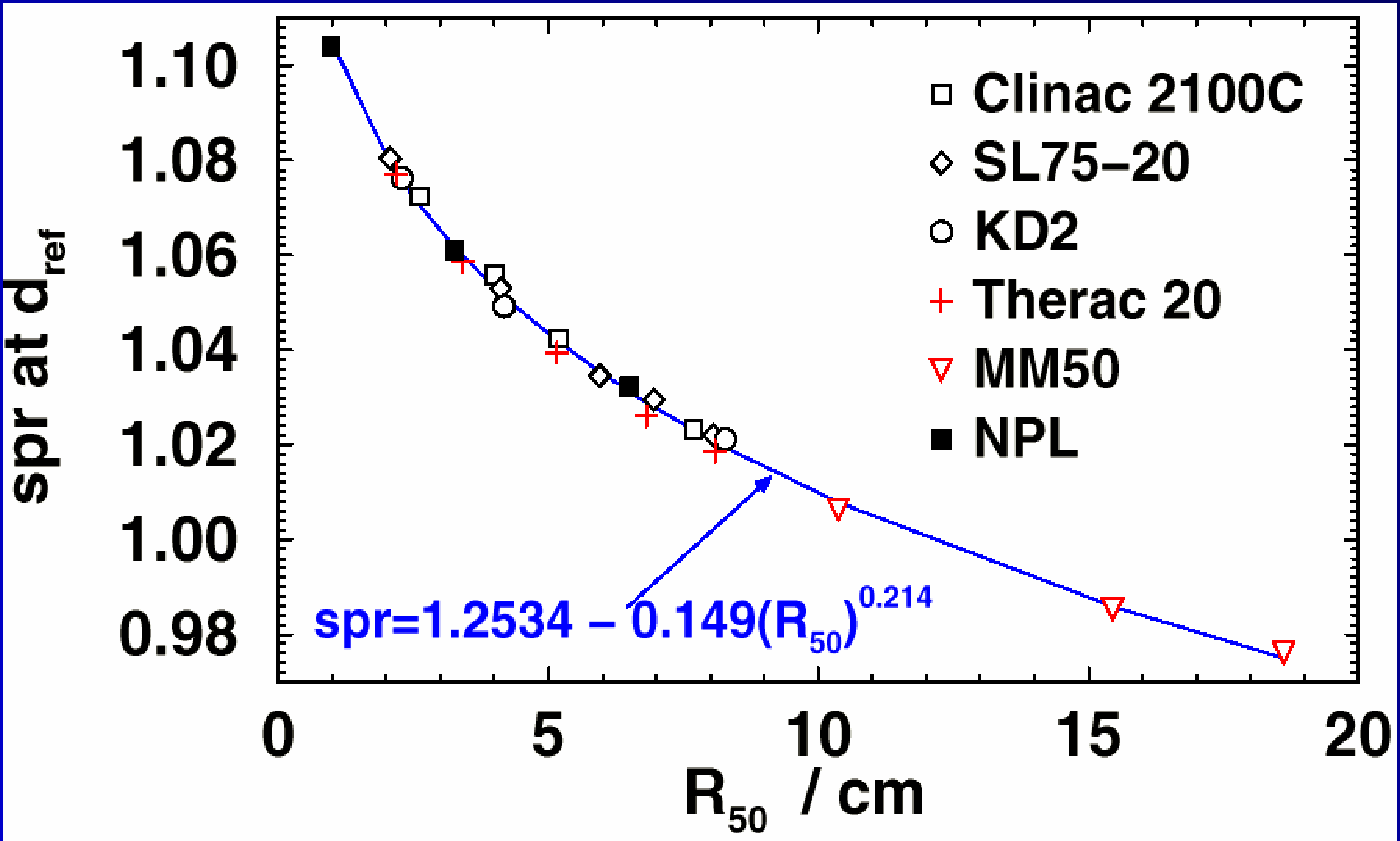
Ding et al MP 22(1995)489

Realistic sprs: $d_{ref}=0.6R_{50} - 0.1$



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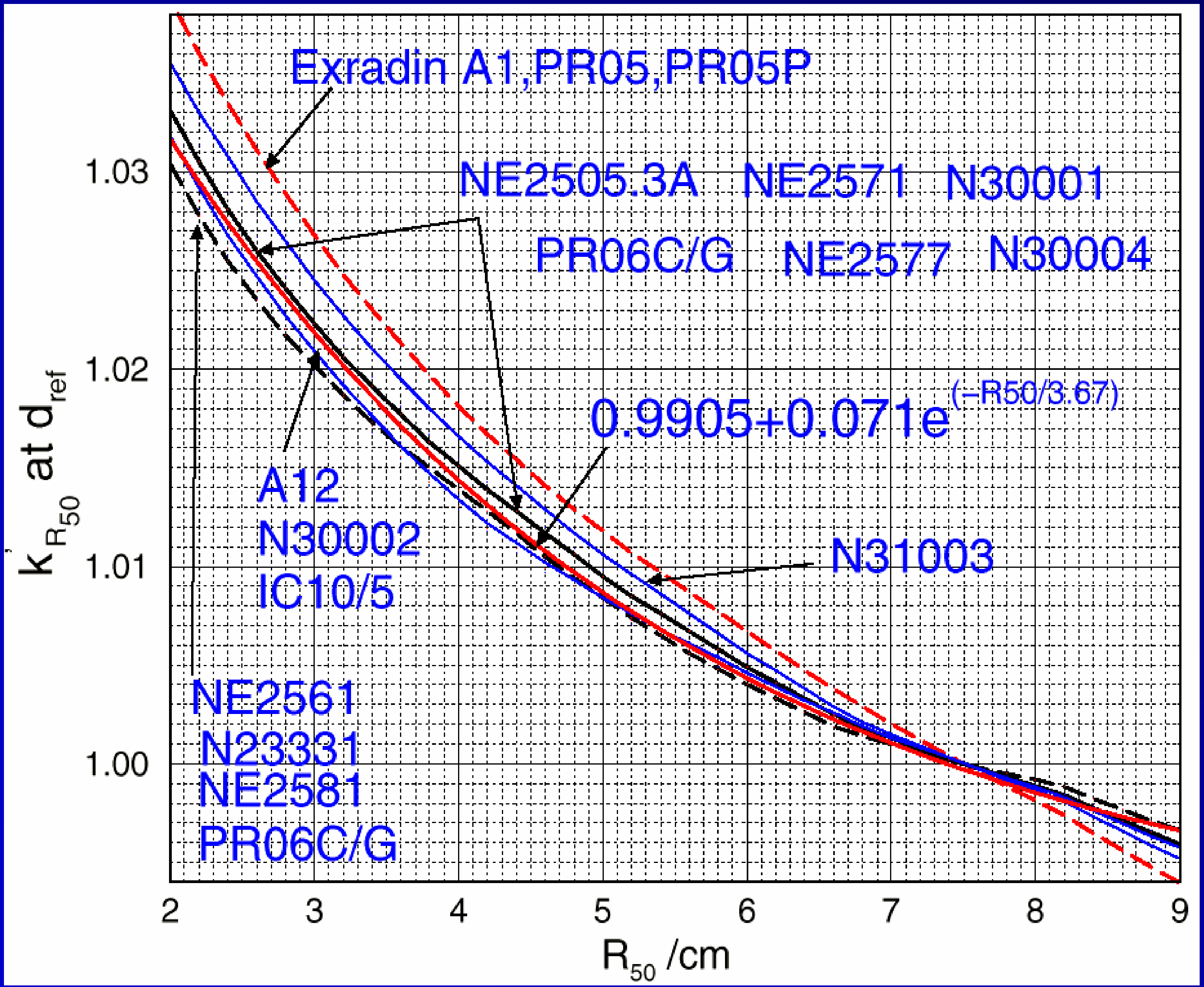
Burns et al MP 23(1996)383

$k'_{R_{50}}$ for cylindrical chambers



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TG-51 equations e- beams are more complex than those for photon beams because:

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0%
0%
0%

1. stopping-power ratios in electron beams change with depth, unlike those in photon beams which are nearly constant.
2. gradient correction factors must be measured in each user's beam and thus P_{gr} cannot be included in the protocol's k_Q values as done for photon beams
3. electron beams have a finite range in the patient
4. there is an intrinsic complexity added because the calibration coefficient is for a photon beams and we need the dose in an electron beam
5. (2) and (4)

all of the above

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Ans is 5: (2) & (4) make e- formalism more complex

1. *stopping-power ratios in electron beams change with depth, unlike those in photon beams .*

   Although a true statement, this does not affect the complexity of the protocol since at d_{ref}, there is a simple relationship between beam quality specifier and stopping-power ratio, just as for photon beams.

2. gradient correction factors must be measured in each user's beam and thus P_{gr} cannot be included in the protocol's k_Q values as done for photon beams.

   Is correct since the measured gradient correction requires the introduction of k_{R50} and hence complicates the formalism.

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Ans is 5: (2) & (4) make e- formalism more complex

3. electron beams have a finite range in the patient

   Although true, this has no effect on the formalism

4. intrinsic complexity because calibration coefficient is for a photon beam and we need dose in an e- beam

   Is correct since switch from beam type to another is handled by introducing k_{ecal}. This proves very useful for the cross-calibration technique for parallel-plate ion chambers, but also adds complexity.

5. (2) and (4)
   is correct because 1 and 3, although true, do not affect the complexity.

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6. all of the above is incorrect

Summary so far

- Have reviewed
  - the formalism
  - the equations
  - how each factor is obtained
  - the effects of different data bases
- How good is it?

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Measurement of photon 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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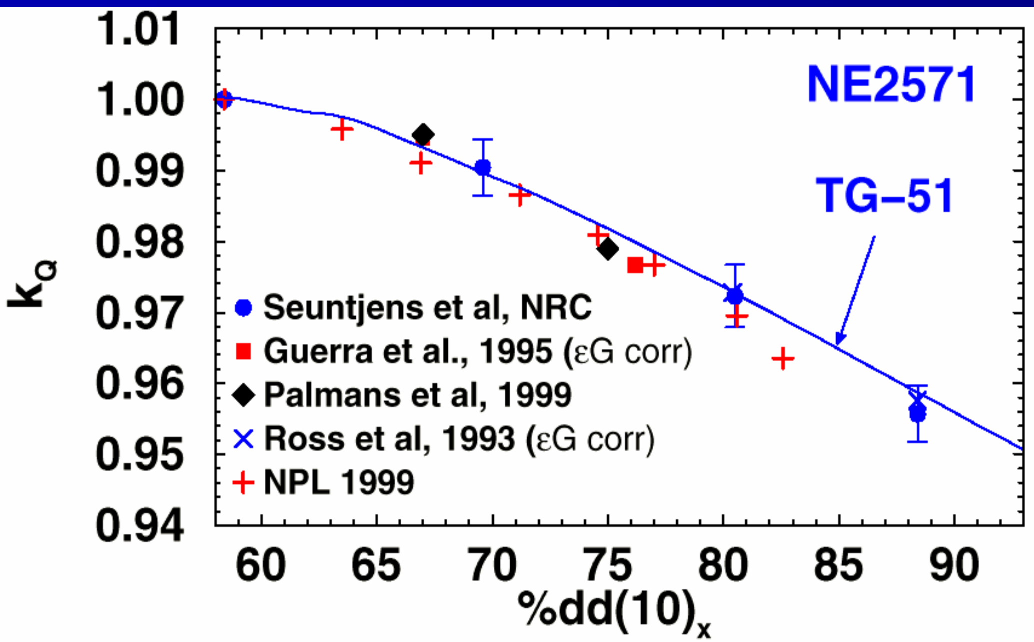
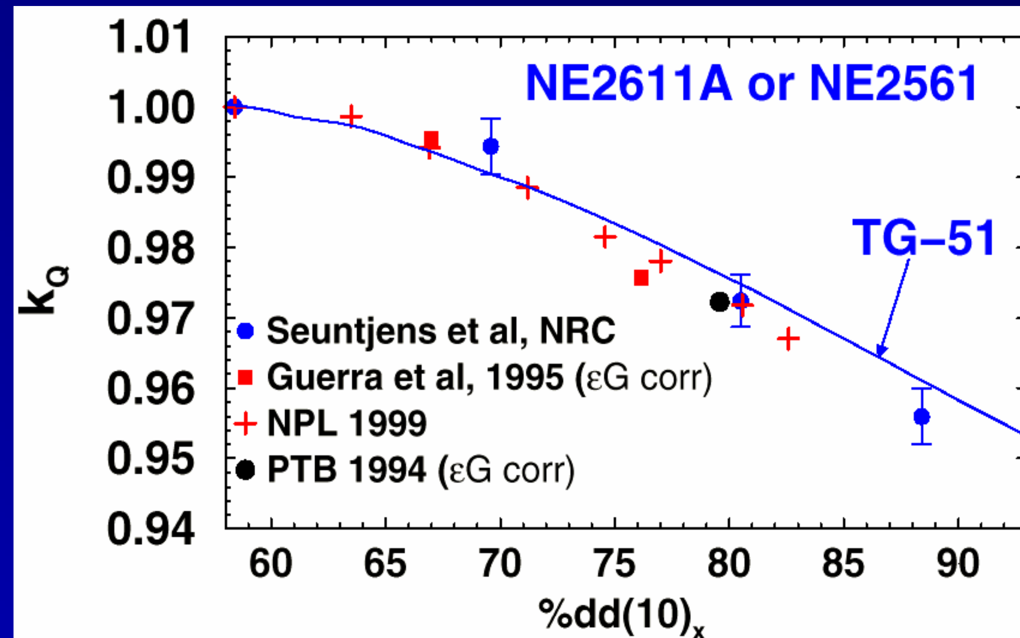
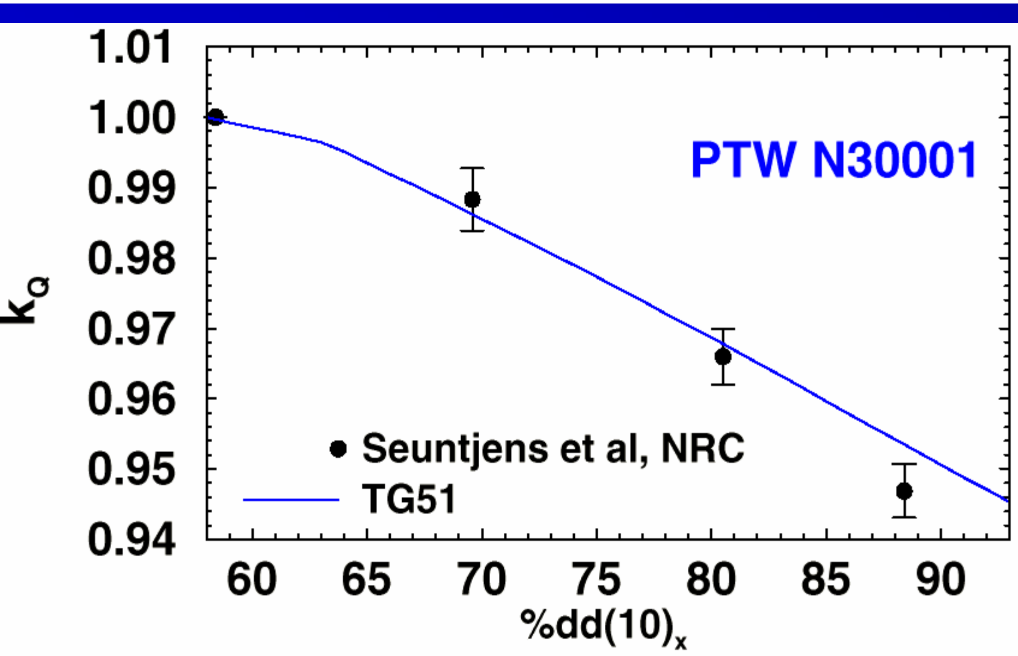
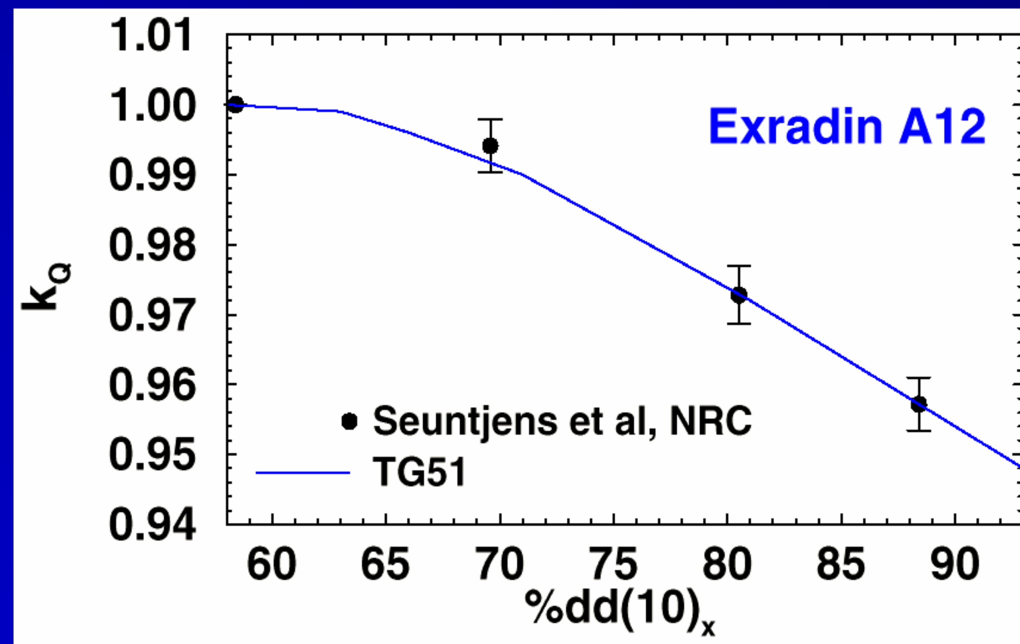
Measured k_Q vs TG-51

Seuntjens et al, MP 27(2000)2763









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%

TG-51 is more accurate than TG-21 because:

0%	1.	TG-51 properly accounts for an aluminum central electrode
0%	2.	TG-51 uses a more up-to-date and consistent set of stopping powers
0%	3.	TG-51 takes into account realistic stopping-power ratios in electron beams
0%	4.	TG-51 avoids the conversion from air-kerma-based quantities to absorbed-dose-based quantities
0%	5.	all of the above
	6.	only (1) and (3)

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Ans is 5:

TG-51 is more accurate than TG-21 because:

1. *TG-51 accounts for an aluminum central electrode*
   is correct since TG-21 ignored the central electrode effect which is an 0.8% effect in Co-60 beams and somewhat less at higher energies and much less in electron beams.

2. *TG-51 uses a more up-to-date and consistent set of stopping powers*
   is correct since TG-21 used ICRU Report 35 stopping powers for photon beams and those from Report 37 for electron beams. The Reports' values differed by up to 1%. ICRU Report 37 is now considered the gold standard for stopping powers and TG-51 uses these stopping powers consistently.

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Ans is 5: TG-51 is more accurate than TG-21 because:

3. *TG-51 takes into account realistic stopping-power ratios in electron beams* is correct because the switch to d_{ref} and use of the spr data from Burns et al means that the values used correspond to realistic electron beams rather than to mono-energetic electron beams as used in TG-21.
4. *TG-51 avoids conversion from air-kerma- to absorbed-dose-based quantities* is correct because the use of absorbed dose to water calibration coefficients means that there is no need to convert from the air kerma calibration coefficients to an absorbed dose quantity. This avoids the use of the extensive theory needed to make this conversion.
5. Hence the correct answer is (5), all of the above

Odds and ends

- P_{ion}
  - new equations
  - problems with the theory

- stopping power ratios for depth-dose curves
  - need sprs for realistic beams

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P_{ion} equations

P_{ion} continuous beams (as TG-21)

$$P_{\rm ion}(V_H) = \frac{1. - \left(\frac{V_H}{V_L}\right)^2}{\frac{M_{\rm raw}^H}{M_{\rm raw}^L} - \left(\frac{V_H}{V_L}\right)^2}$$

P_{ion} pulsed or pulsed swept ($P_{ion} < 1.05$)

$$P_{\rm ion}(V_H) = \frac{1. - \frac{V_H}{V_L}}{\frac{M_{\rm raw}^H}{M_{\rm raw}^L} - \frac{V_H}{V_L}}$$

Do not increase voltage to get $P_{ion} < 1.05$

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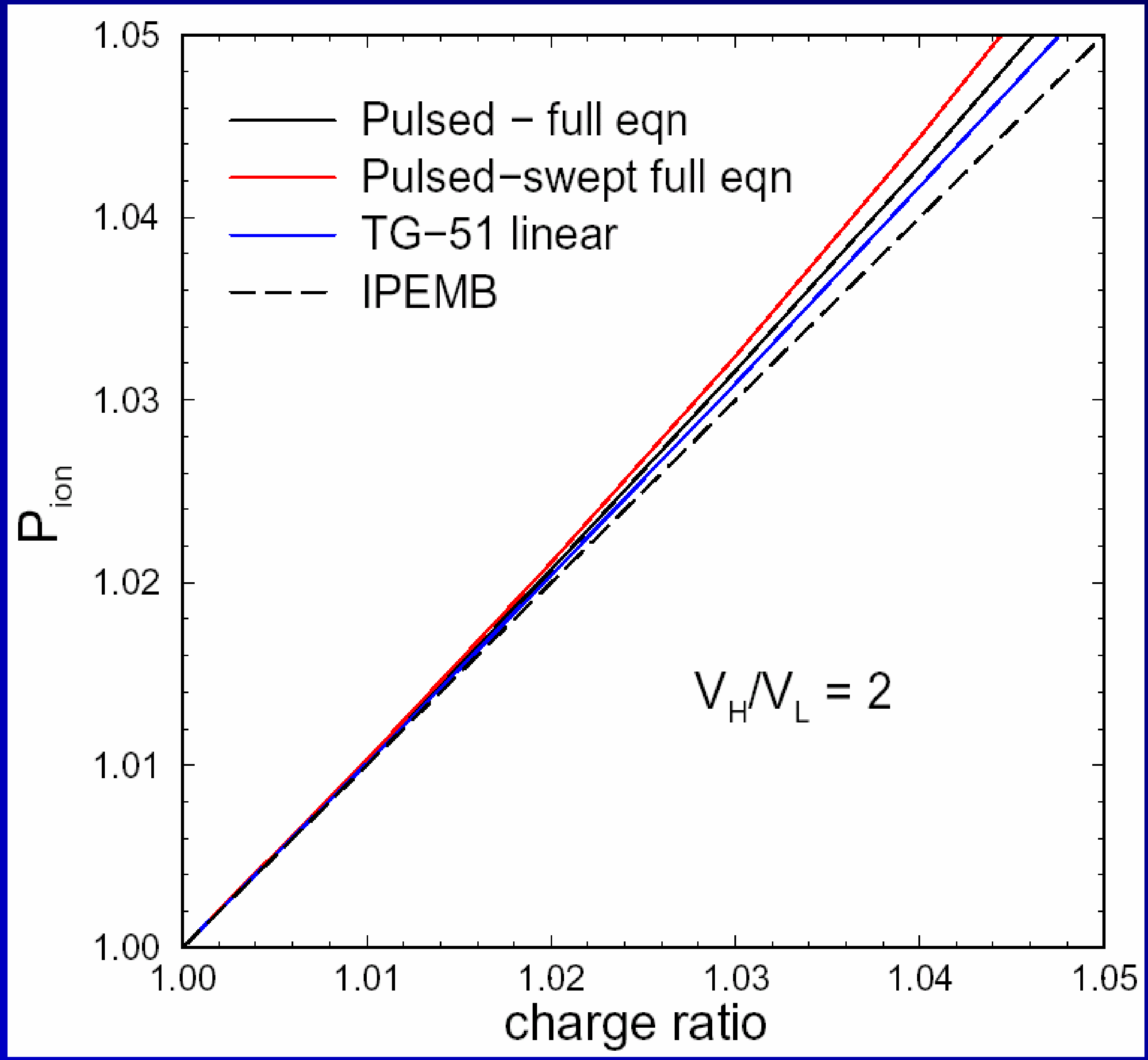
P_{ion} equations

For P_{ion} < 1.05

TG-51 eqn is good to 0.2% for pulsed beams

or

to 0.4% for pulsed-swept beams



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sprs for depth-dose curves

TG-51 gives the dose at d_{ref}

To get the dose at d_{max} requires a high-quality depth-dose curve

Need to correct for spr and P_{fl} (cylindrical chambers)

Need realistic spr vs depth to be consistent with spr at d_{ref}

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$L/\rho(R_{50},z)$

Burns et al gave a fit to the Monte Carlo realistic spr values

$$\left(\frac{\overline{L}}{\rho}\right)^{\text{water}}_{\text{air}}(\mathrm{R}_{50}, z) = \frac{a + b(ln\mathrm{R}_{50}) + c(ln\mathrm{R}_{50})^2 + d(\mathrm{z}/\mathrm{R}_{50})}{1 + e(ln\mathrm{R}_{50}) + f(ln\mathrm{R}_{50})^2 + g(ln\mathrm{R}_{50})^3 + h(\mathrm{z}/\mathrm{R}_{50})}$$

a= 1.0752	b= -0.50867	c= 0.088670	d= -0.08402
e= -0.42806	f= 0.064627	g= 0.003085	h= -0.12460

Tabulated vs R_{50} and z/R_{50} at

http://www.physics.carleton.ca/~drogers/pubs/papers

NOTE: Formula is good over a limited range ($0.02 < z/R_{50} < 1.2$) and has limited accuracy away from d_{ref} (about 1%). See Med. Phys. 31 (2004) 2961

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Conclusion

There is too much in TG-51 to cover in 1 lecture

Thank you for your attention

Resources/References

- TG-51 protocol MP 26 (1999) 1847 -- 1870

- Kosunen et al, Beam Quality Specification for Photon Beam Dosimetry MP 20 (1993) 1181
- Li et al, Reducing Electron Contamination for Photon-Beam-Quality Specification, MP 21 (1994) 791
- Burns et al, R_{50} as a beam quality specifier for selecting stopping-power ratios and reference depths for electron dosimetry MP 23 (1996) 383
- Rogers, A new approach to electron beam reference dosimetry, MP 25 (1998) 310

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Resources/References

- Rogers, Fundamentals of Dosimetry Based on Absorbed-Dose Standards in 1996 AAPM Summer School book (http://www.physics.carleton.ca/~drogers/pubs/papers)
- http://rpc.mdanderson.org/RPC and click on TG-51 on left
- Rogers, Fundamentals of high energy x-ray and electron dosimetry protocols in 1990 AAPM Summer School book (http://www.physics.carleton.ca/~drogers/pubs/papers)

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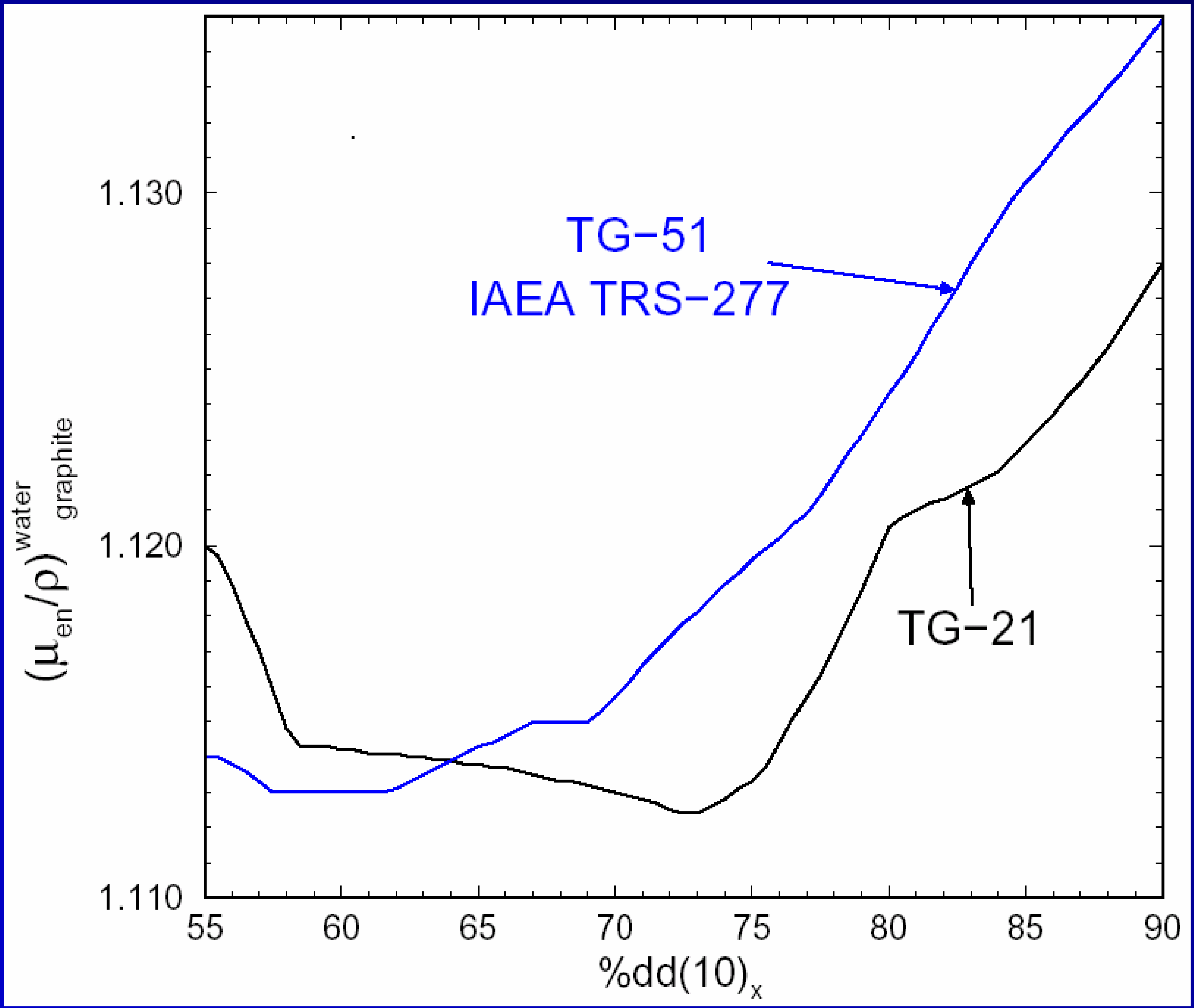
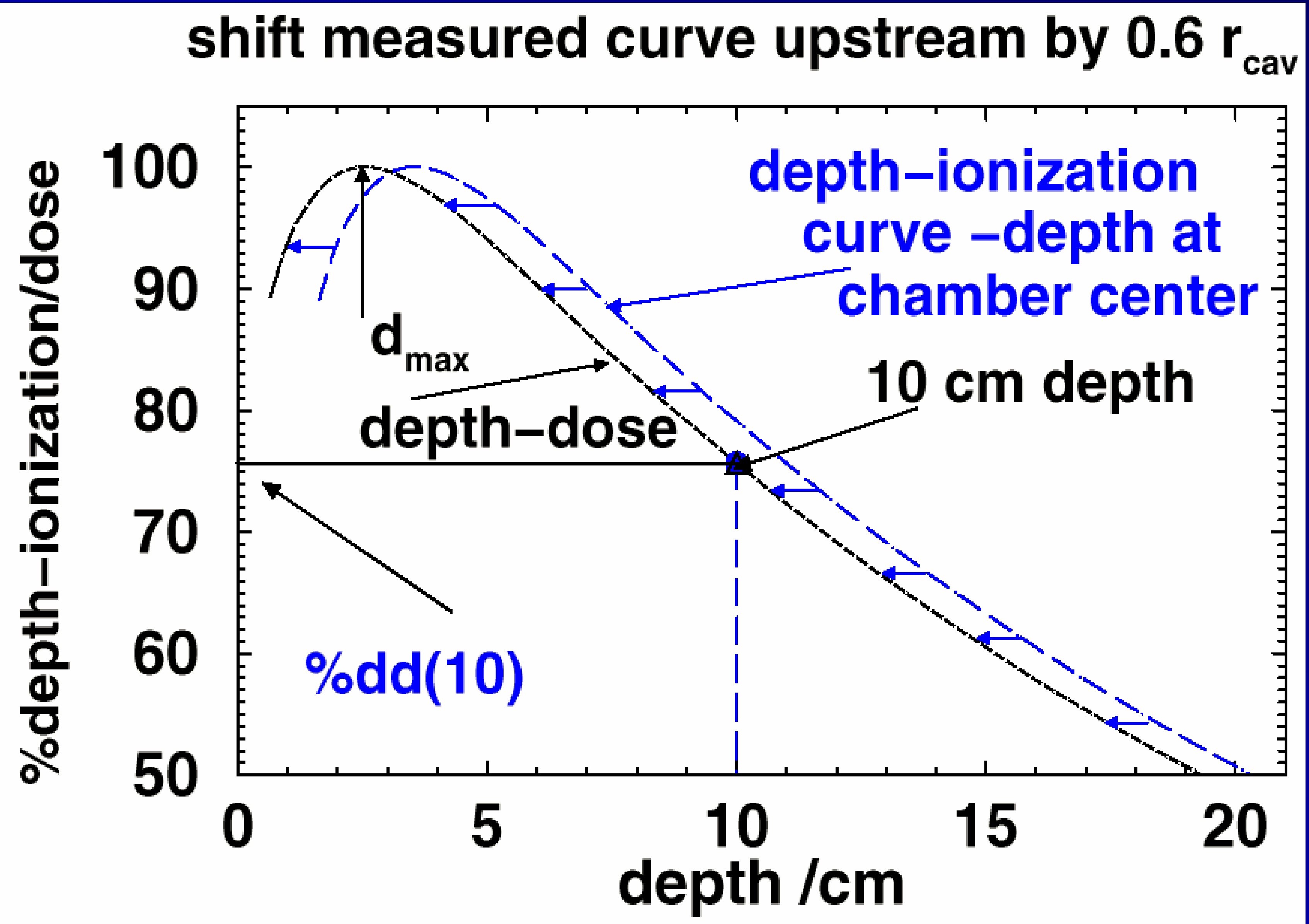
EXTRAS

Mass energy absorption coefficients

TG-51 data is based on Hubbell's 1982 data set and Cunningham's MC calns



Measuring depth-dose curves



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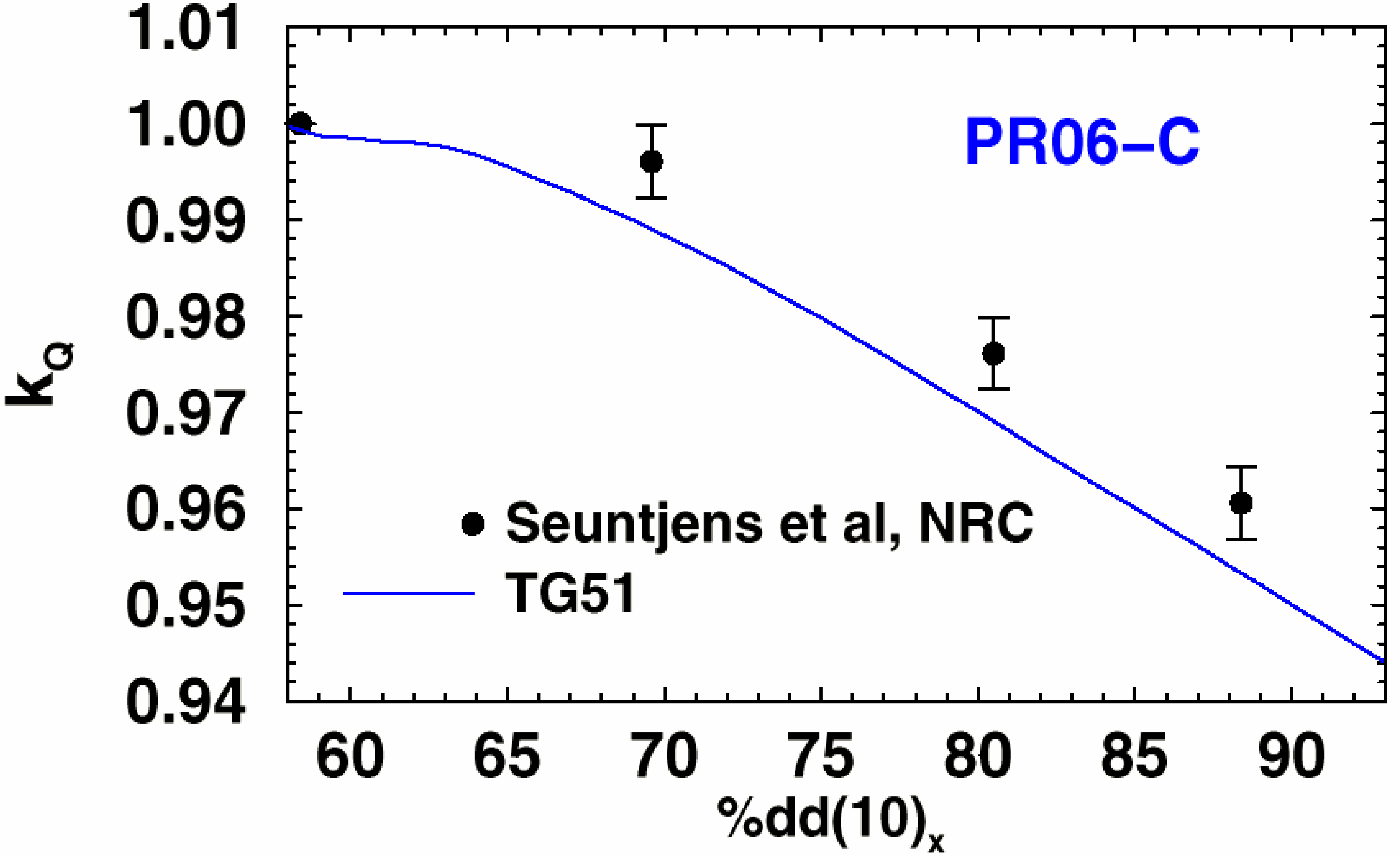
Measured k_Q vs TG-51



Seuntjens et al, MP 27(2000)2763

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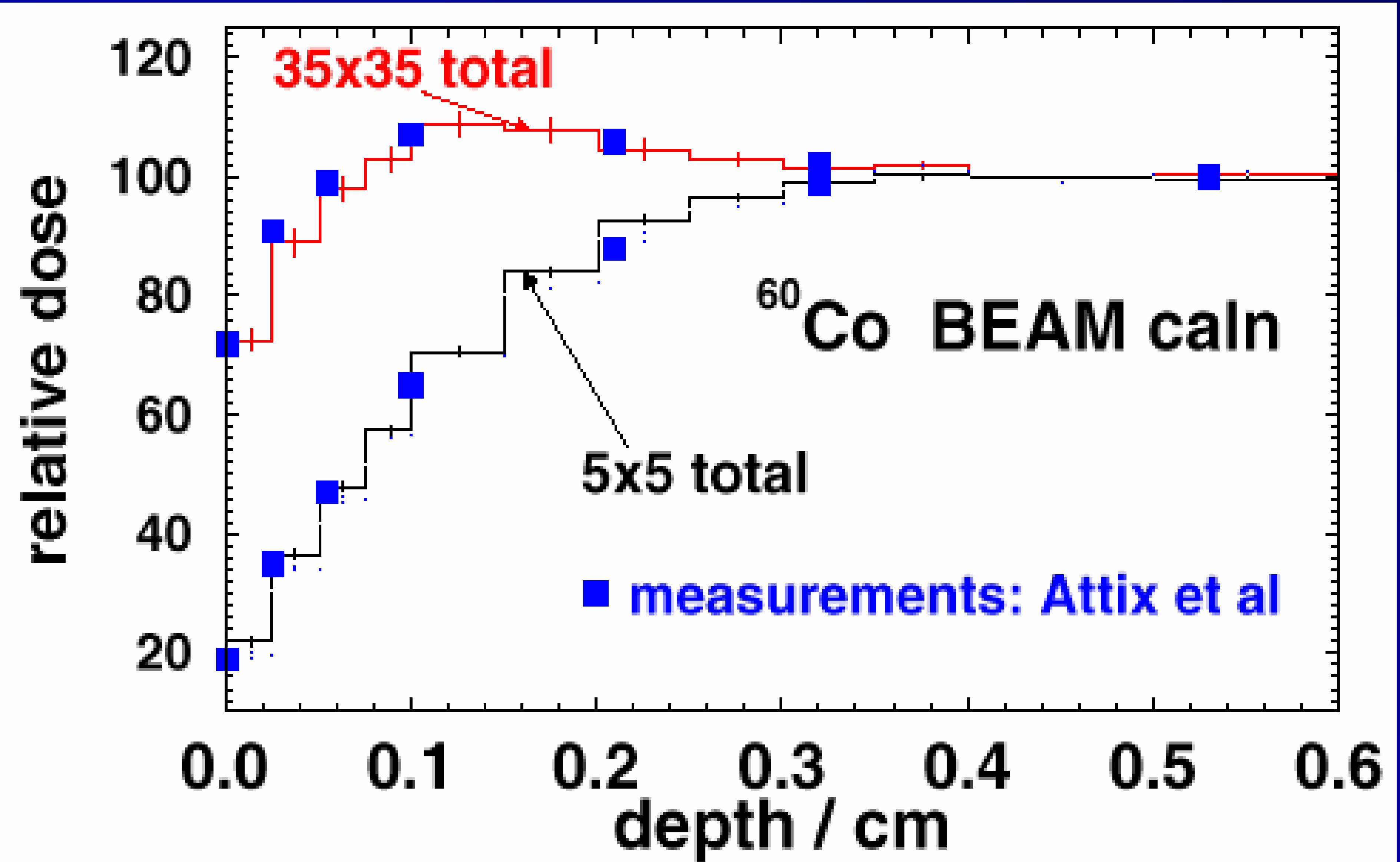
e⁻ contamination can be calculated



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Mora et al, MP 26(1999)2494

e- beams: absorbed-dose calibration factors

$$N_{\mathrm{D,w}}^{Q_{\mathrm{ecal}}} = P_{gr}^{\mathrm{Qecal}} k_{\mathrm{ecal}} N_{\mathrm{D,w}}^{^{60}Co}$$

$$N_{\mathrm{D,w}}^{\mathrm{Q}} = \frac{P_{gr}^{Q}}{P_{gr}^{\mathrm{Q_{ecal}}}} k'^{Q}_{R_{50}} N_{\mathrm{D,w}}^{Q_{\mathrm{ecal}}}$$

These can be used to measure k_{ecal} and $k'_{R_{50}}$

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