Dosimetry for Flattening Filter Free (FFF) linac beams and small fields (SF)

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Outline

- What is NPL doing to support FFF and SF?
  - Primary and secondary standards
  - Dissemination and codes of practice
  - Audit and training
- Some dosimetry issues
  - FFF (including TomoTherapy):
    - beam profile
    - beam quality and quality index
    - dose rate
  - SF:
    - perturbation effects

What is NPL doing (i)

- New calorimeters:
  - Primary standard for electron/photon beams
  - Non-primary standards for small fields and/or IMRT
- New ion chamber?
  - Do we need a secondary standard for small fields and/or IMRT?
- Beyond the IPSM (1990) Code of Practice
  - What is needed – New reference conditions? Different calibrations?

What is NPL doing (ii)

- Audit

  Development ongoing (IMRT, rotational, SABR, …)

- Training

  Practical Course in Reference Dosimetry (PCRD) is evolving – since 2013, MV module covers small field issues

  New course at NPL (13 May 2014):

  Dosimetry for Advanced Radiotherapy Techniques

  Also on-site delivery of training, e.g. as part of an audit visit;

  And eLearning, e.g. to complement PCRD.

Dosimetry issues: (i) FFF

Simple-minded questions:

- FFF beam isn't flat – uniformity corrections needed?
- FFF beam is less filtered – affects spectrum / quality?
- FFF beam is less attenuated – dose rate issues?

Dosimetry issues: (ii) SF

What makes a small field small, and what are the issues?

- Penumbrae may overlap

  source occlusion

  Lateral disequilibrium effects

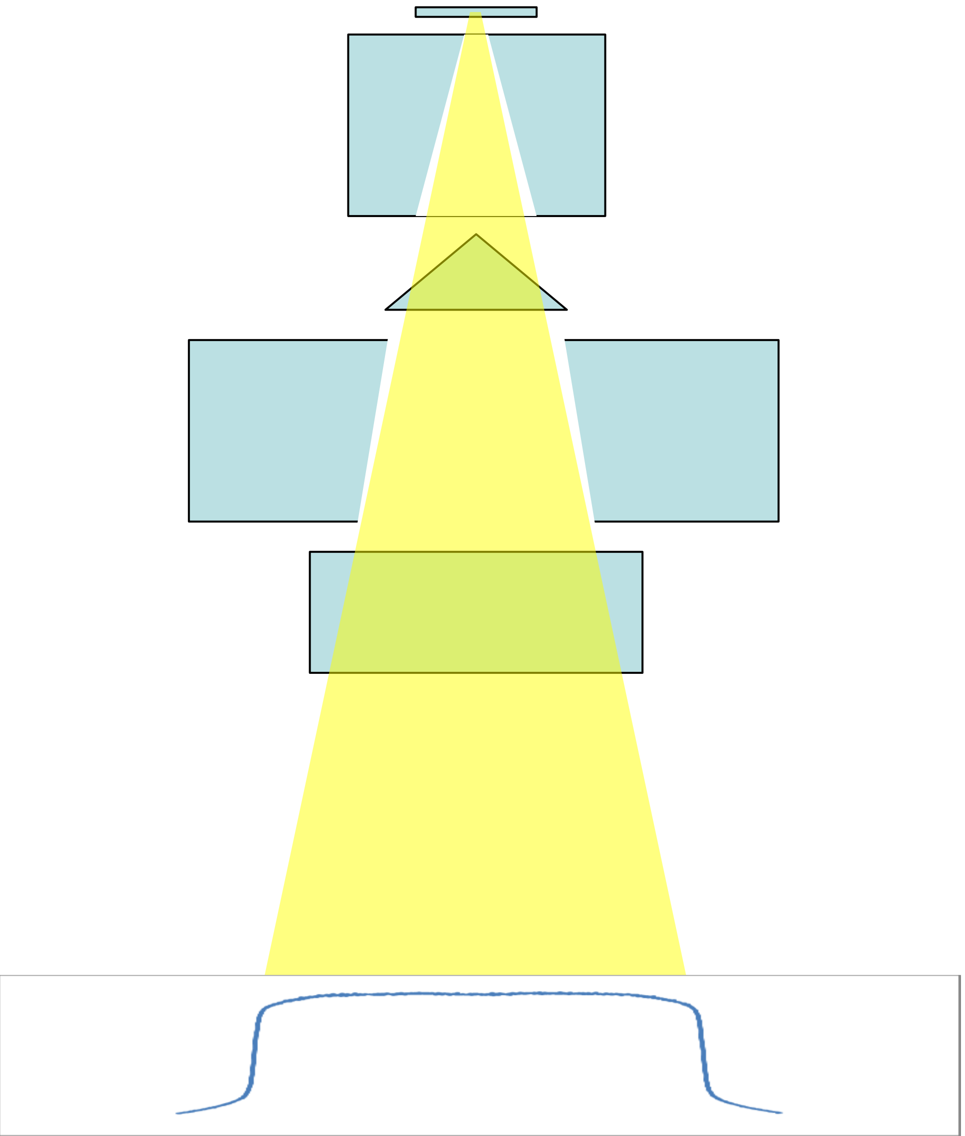
- If penumbrae don't overlap

  Detector may still be too big to fit between them

FFF – a brief reminder

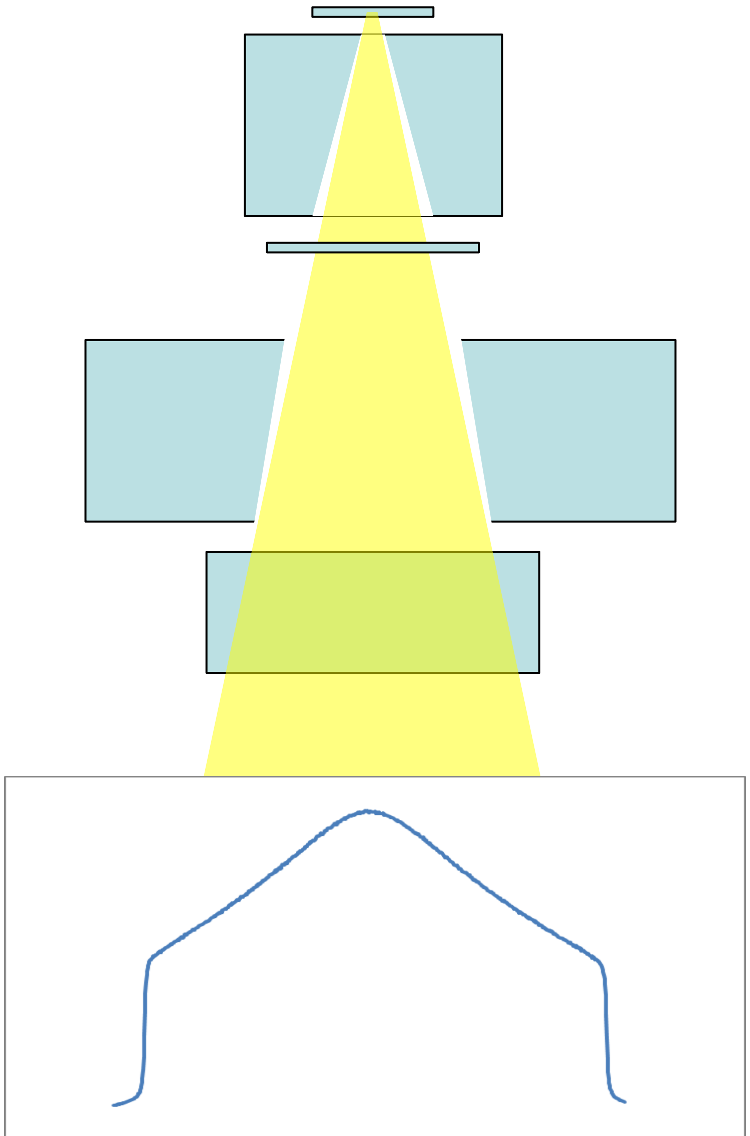
- An FFF beam is not conventionally flattened

Conventionally flattened beams



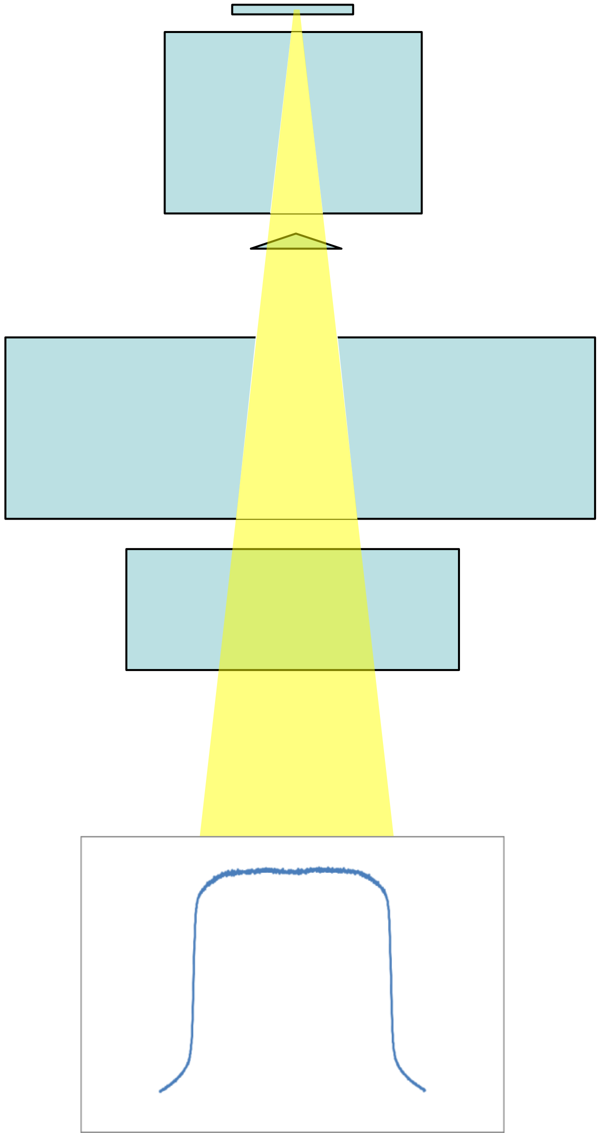
- Target
- Primary collimator
- **Flattening filter**
- MLC (Y1, Y2 leaf banks)
- X1, X2 diaphragms
- **Flat** profile

FFF



- Target
- Primary collimator
- **Flattening Filter Free**
- MLC (Y1, Y2 leaf banks)
- X1, X2 diaphragms
- **Non-flat** profile

Novalis SRS



- Target
- Primary collimator
- **Flattening Filter Lite**
- MLC
- Jaws
- **Flat-topped** profile

What “FFF” means …

- “conventional flattening filter” (cFF)

  filter diameter large enough for 40x40 cm^2 at 100 cm

  implies filter thickness must exceed … (depends on MV)

In this talk – “FFF” means anything else, including

- TomoTherapy, CyberKnife

  even though they do have a beam-hardening filter
- Elekta Versa HD, Varian TrueBeam

  very little extra filtration
- Novalis Tx, etc. high dose rate, flat, SRS beams

  max field only 10x10 cm^2, filter can be (and is) thinner than cFF

But e.g. Elekta Beam Modulator is cFF (maximum field is smaller, but flattening filter is the same as in a standard Elekta linac)

Return of the FFF beams…

Once upon a time, NPL linac beams were a bit like FFF.

Today, NPL determines $N_{D,w,Q}$ for use in beams with a conventional flattening filter

- Reference standard validated using existing primary standard calorimeter in all our flat Elekta beams
- New primary standard calorimeter currently being commissioned – initially in all flat beams, then in FFF beams (various setups)

Dosimetry issues: (i) FFF

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Simple-minded questions:

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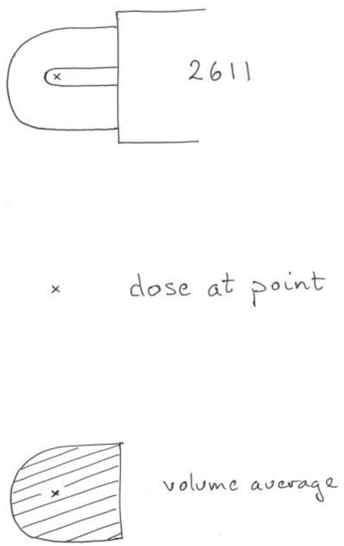
Beam uniformity correction

The 1990 Code of Practice: $D_w = R\ N_{D,w,Q}$

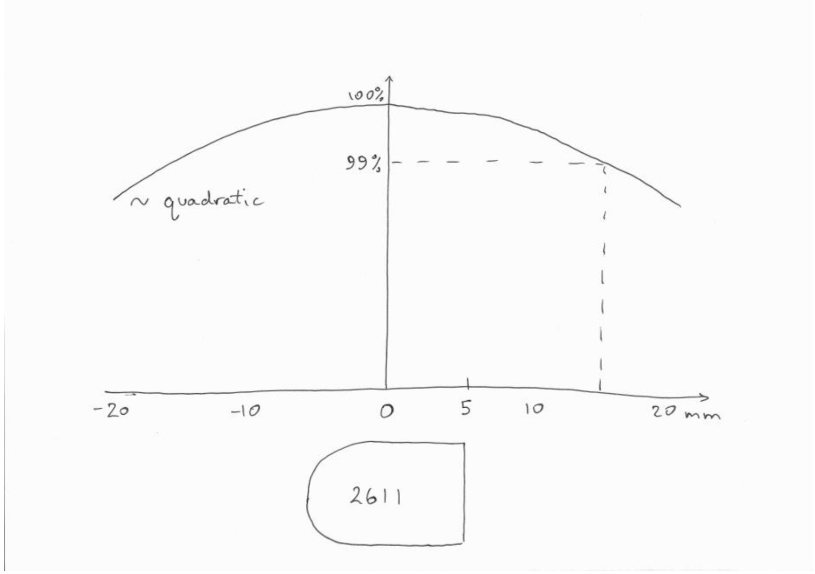


NPL calibration factor gives absorbed dose to water
at the chamber reference point, **in a flat beam**

equivalently:
averaged over the chamber sensitive volume
(but still **in a flat beam**)

Use the second version to analyse the non-flat case…

Uniformity correction estimate



- 6 MV FFF profile is smooth
- 2611 chamber radius ~5 mm.
- Factor ~3 in radius, factor ~3^2 in uniformity effect
- So uniformity correction factor for a 2611 is of the order 1.001
- ~ negligible.

Dosimetry issues: (i) FFF

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Simple-minded questions:

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Beam quality in the 1990 CoP

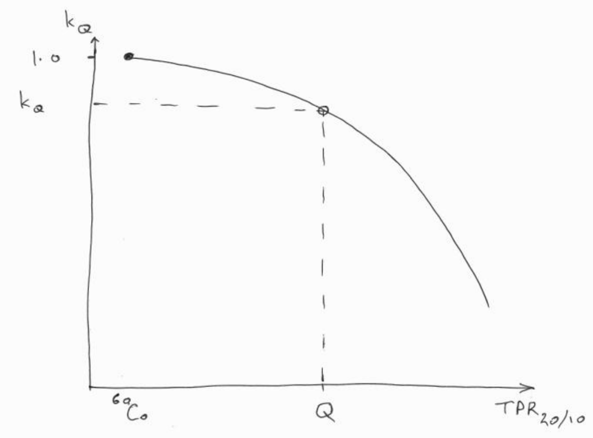
What could be simpler?

$$D_w = R\ N_D$$

Beam quality isn't even explicit in the expression!

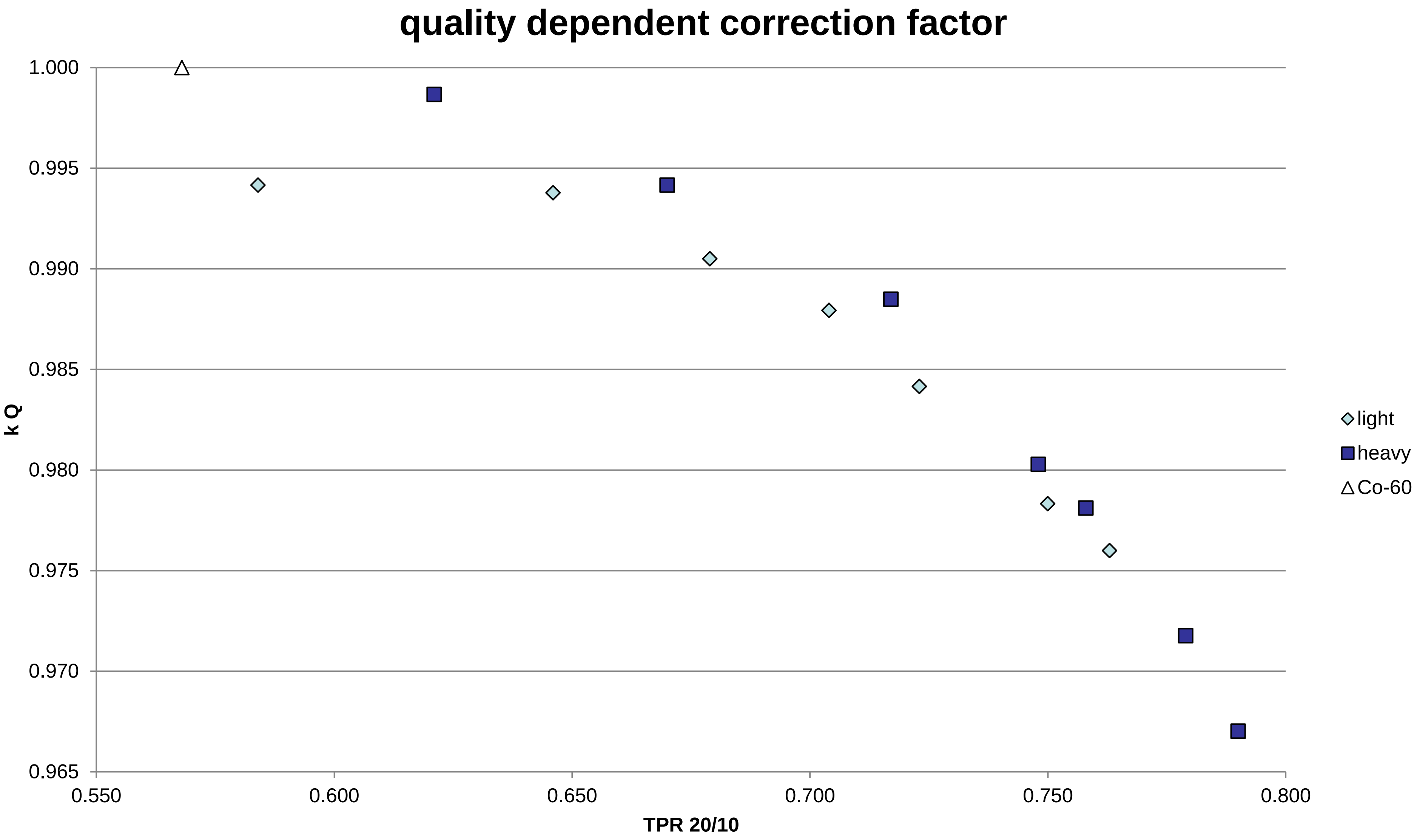
Measure your quality index Q and use it to read off a calibration from the NPL curve:

$$N_D = N_{D,w,Q}$$



but it's not so simple…

Research linac data (1987-1995)



NPL D_w service – what happened

Ancient history:

- Service launched 1988:

  beams from research linac

  FF only 3 mm – 5 mm thick

  max field only ~10x10 cm^2

- Calibration curve "looked odd"

  ^{60}Co and 4 MV ~0.6% different

- Beam hardening added, 5 cm – 14 cm aluminium

  1989: 12 MV – 19 MV and

  1992: 4 MV – 10 MV:

- Calibration curve "looked ok"

Remarks

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- As long as all clinical beams are similar (flat), NPL calibration beams can match them (all):

  Life is simple for secondary standard users, but…

  The D_w calibration is only valid for flat beams.

- But FFF beams will become increasingly common. What can we do?

  Extend our calibration beams to include FFF and
  extend the scope of our primary standard.
  Quantify the correction for filtration.

Beam "quality" vs "quality index"

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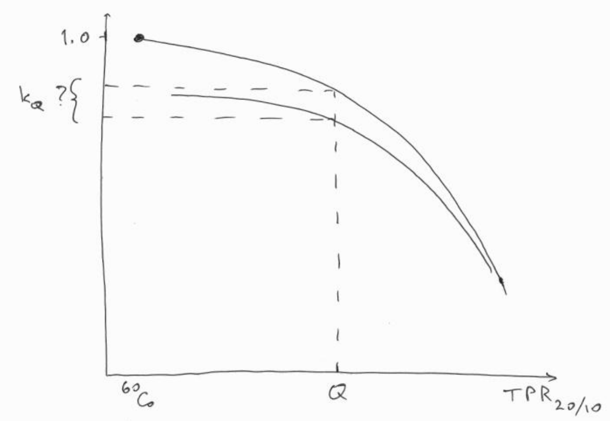
- The physics of ion chamber response involves stopping power ratios, fluence perturbations, etc – the calibration factor depends on the electron spectrum at the point of measurement

- A single beam quality parameter such as $TPR_{20/10}$, or $\%dd(10)_X$, is unlikely to have the same spectral dependence as ion chamber response

- The calibration function is not a (single valued) function of quality index

  The research linac data exemplify this



Dosimetry issues: (i) FFF

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FFF dose rate

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- Elekta nominal 2400 MU/min (10MV, 400Hz) is 0.1MU per pulse.

  Ion recombination ~2.4% for a 2611 at -200V, compared to ~0.9% in a flat beam (400 MU/min for 10MV, 200Hz)

  This correction must be determined carefully for good uncertainty. The two voltage method works, as does the formula in terms of dose per pulse.

Dosimetry for FFF - summary

- Beam profile effects

  Small. Of the order 0.1% in 6 MV FFF.
- Beam quality effects

  Important in principle, but unlikely to exceed 0.5%
- Dose rate effects

  Ion recombination must be corrected – otherwise the error could be up to 2.4%.

What is NPL doing (i)

- New calorimeters:

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- New ion chamber?

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- Beyond the IPSM (1990) Code of Practice

  What is needed – New reference conditions? Different calibrations?

New calorimeters

- Primary standard for electron / photon beams
  - More robust (an ~identical calorimeter now travels to proton and ion beam facilities a few times a year)
  - Lots more sensors, heaters
  - Still being characterised in flat beams (FFF beams will follow)
- Small field / IMRT calorimeter (prototypes)
  - Simpler devices; calibrated in water; details of use in small fields still being explored…

A new reference chamber?

- Depends how reference dosimetry develops in UK:
  - If we go beyond IPSM 1990 (small fields, IMRT), we may need a new reference chamber.
  - For TomoTherapy dosimetry, the 2611 is ok, and a new addendum will recommend this.
- A new project, starting in Jan '14, will look at what is would be required to provide support for a likely successor to the 1990 Code of Practice

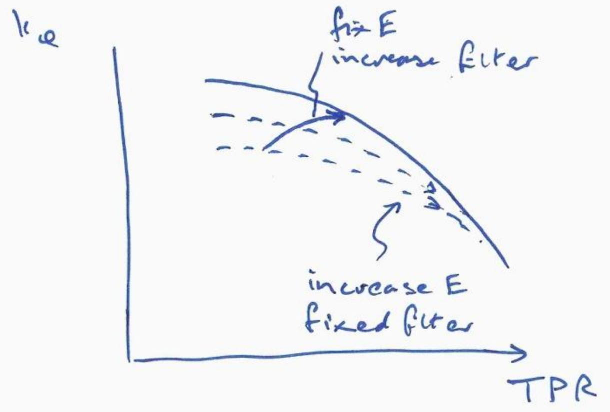
FFF beams – planned work

- 2013-2014:

  Calibrate our 2611 reference chambers in a selection of FFF beams (various setups).

- 2014:

  If time permits, determine the quality dependent correction for a range of (flat) filters, interpolating between 6MV FFF and flat 6MV.



So get clinical linac data analogous to research linac data

What is NPL doing (ii)

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- Audit

  Development ongoing (IMRT, rotational, SABR, …)

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A training day at NPL

Dosimetry for Advanced Radiotherapy Techniques

- Absolute and reference dosimetry for small fields
- Composite field dosimetry
- Relative dosimetry and issues in the clinic
- Choice of detectors
- FFF beams
- Future issues: protons, hadrons, MR linacs

Lecture-based – Tuesday 13 May 2014

What is NPL doing (ii)

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  Development ongoing (IMRT, rotational, SABR, …)

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  Also on-site delivery of training, e.g. as part of an audit visit;

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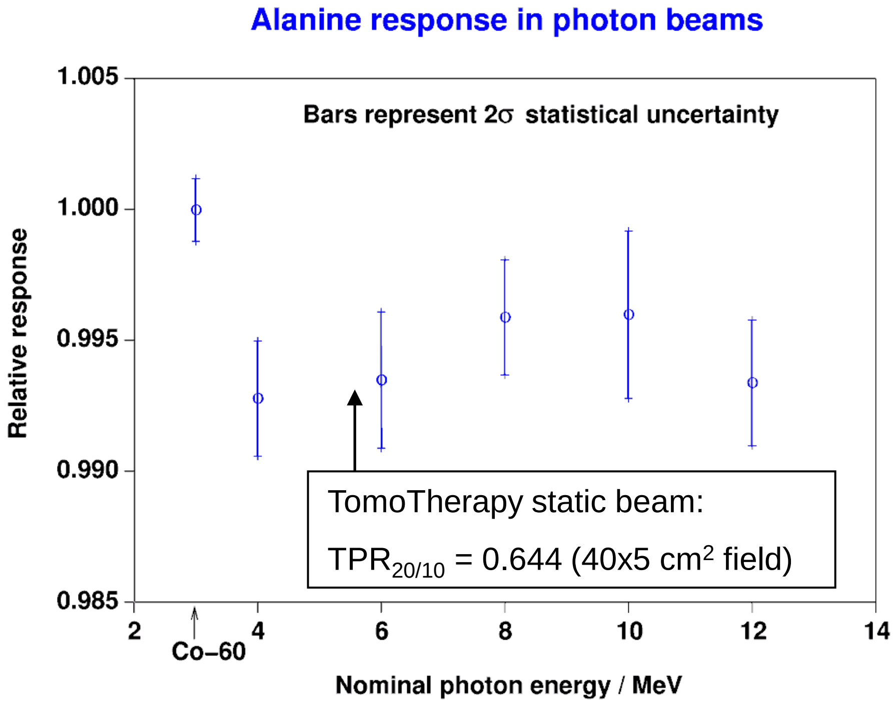
In the meantime…

- Until we have primary and secondary standards valid for FFF and SF, we transfer dose using alanine/EPR
- alanine/EPR is ~water equivalent and energy-independent:



An example of FFF: dosimetry for TomoTherapy

- Rely on quality-independence of alanine/EPR
  - Calibrate 2611 and A1SL chambers on-site
- There is no code of practice
  - We made something up:
    - Measure relevant fields (helical treatments)
    - Assume nothing about machine performance
      - "Black box" integrates treatment plan and delivery
- FFF-specific issues
  - It's a learning experience. What did/do we expect?

Issues expected

- Beam profile

  The beam isn't flat

  but the open field profile is rather smooth – effect is small

- Beam quality

  No flattening filter means altered spectrum. Tomo has a beam hardener. Expect the effect to lie between old NPL "light" and "heavy" beams

- Dose rate

  Is high: measure recombination. Chamber 2611 is well-behaved: dose per pulse formula works.

Outcome

- A Tomo beam quality index equivalent to $TPR_{20/10}$ can be derived from measurements in 5x10 cm^2

  Cannot use the raw TPR value of the small field to evaluate $N_{D,w,Q}$ from NPL calibration

- Beam quality is not a significant issue

  The correction for any additional change in 2611 response associated with the change in beam filtration can be taken as 1.000

TomoTherapy and the 1990 CoP

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IPEM RTSIG WP has prepared, with NPL input

- An addendum to the 1990 Code of Practice for MV photon dosimetry.
  - restricted scope - tomotherapy only
  - adopts IAEA formalism (Alfonso et al.)
  - NE2611 remains the recommended chamber
  - deals with non-standard reference conditions

Arguably, we need a more substantial revision to / replacement for the 1990 code.

Is the 1990 CoP *too* simple?

- Perhaps users can’t be protected from the change in beam quality between calibration and measurement.
- Where known, the effect of the change has so far turned out to be small. In general?
- Aside from $TPR_{20/10}$ and $\%dd(10)_X$, what could a user determine to find out if a chamber calibration is valid for the planned measurement?

Dosimetry issues: (ii) SF

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What makes a small field small, and what are the issues?

- Penumbrae may overlap

  source occlusion (source has a finite size)

  Lateral disequilibrium effects (electron transport)

- If penumbrae don't overlap

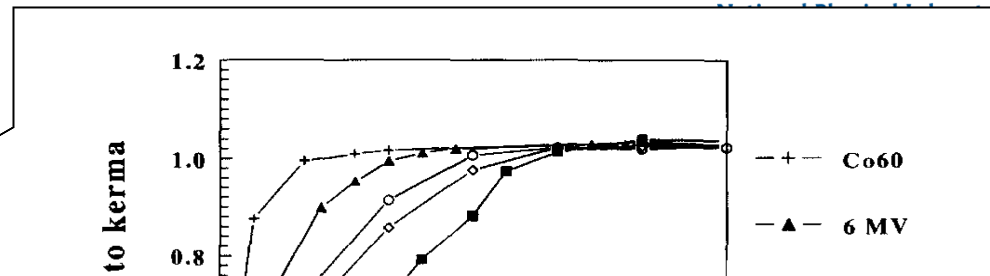
  Detector may still be too large to fit between them

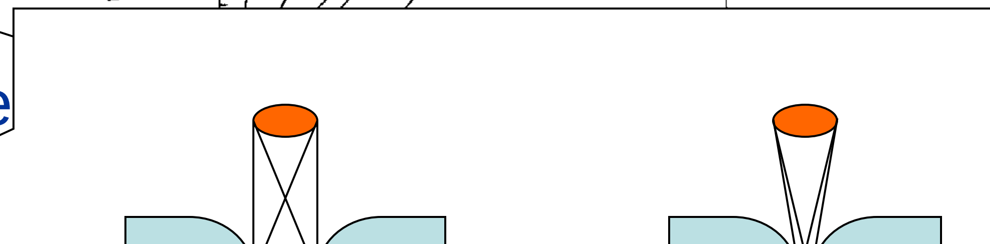
Problem: what is a small field?

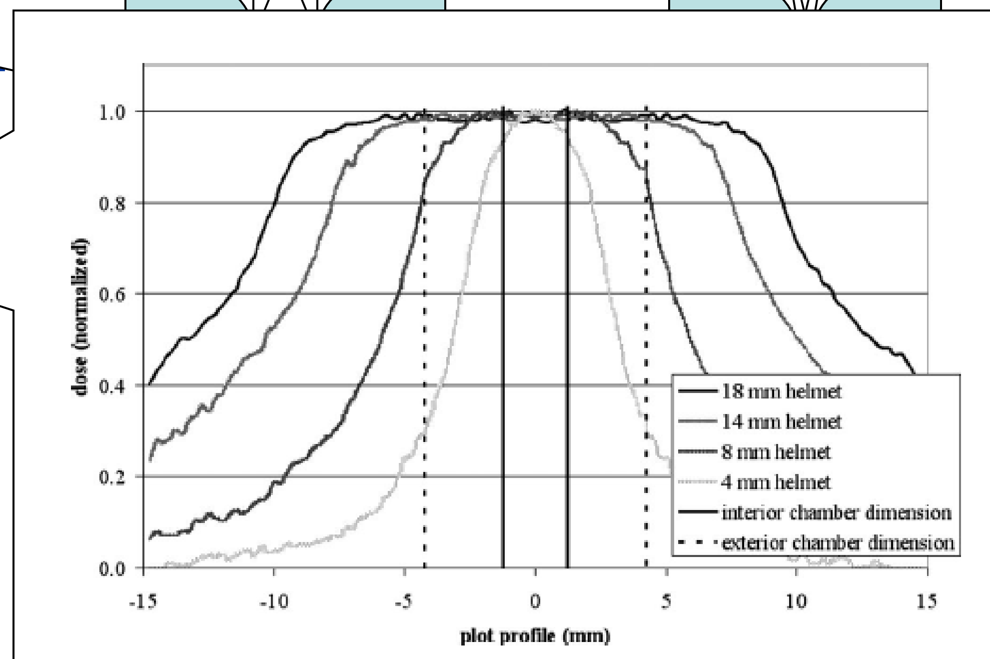
- Loss of lateral charge

  Partial occlusion of th

- Detector size to

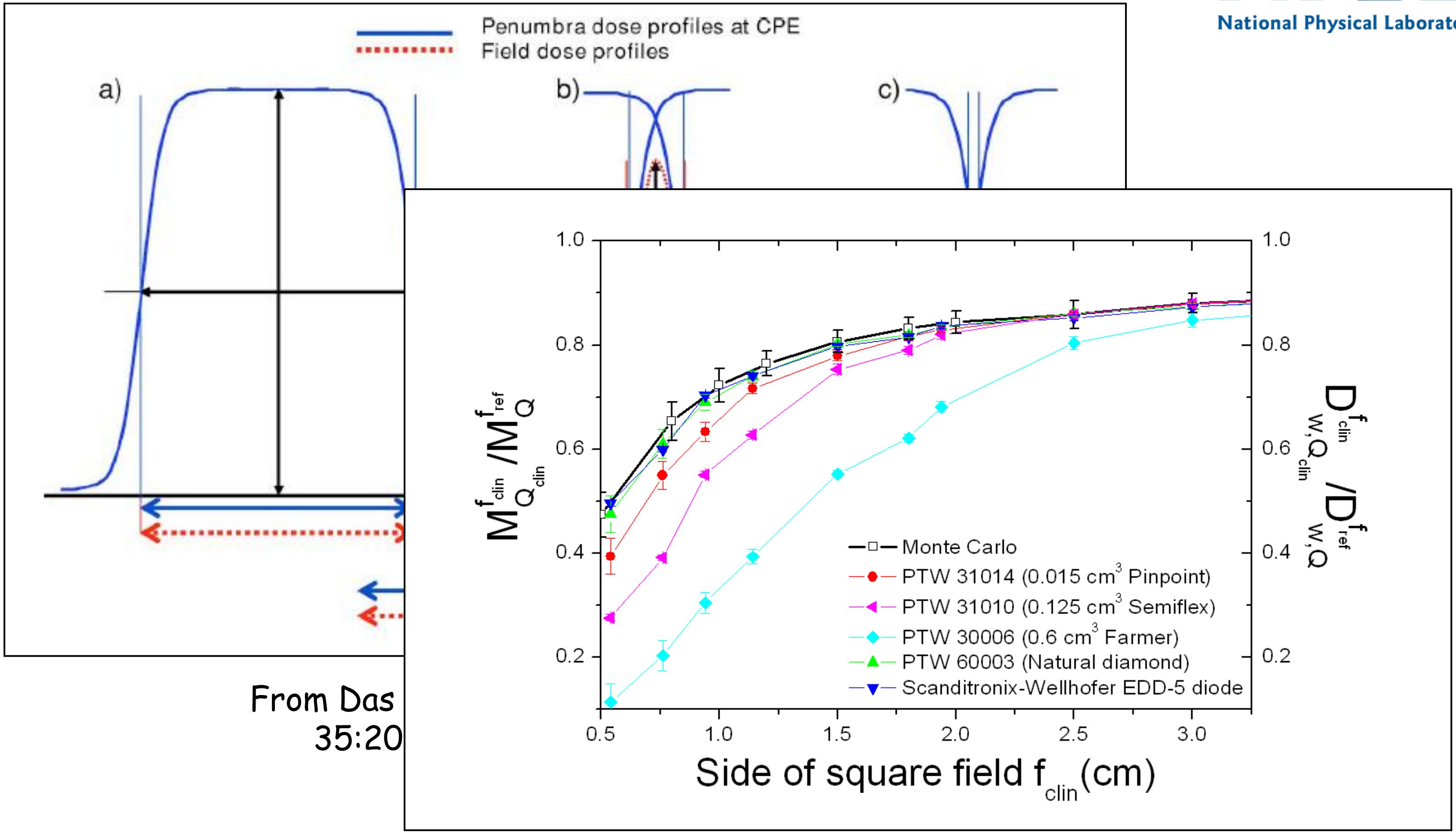






From Meltsner et al. 2009 Med Phys 36:339-50

Problem: small field size /apparent field widening



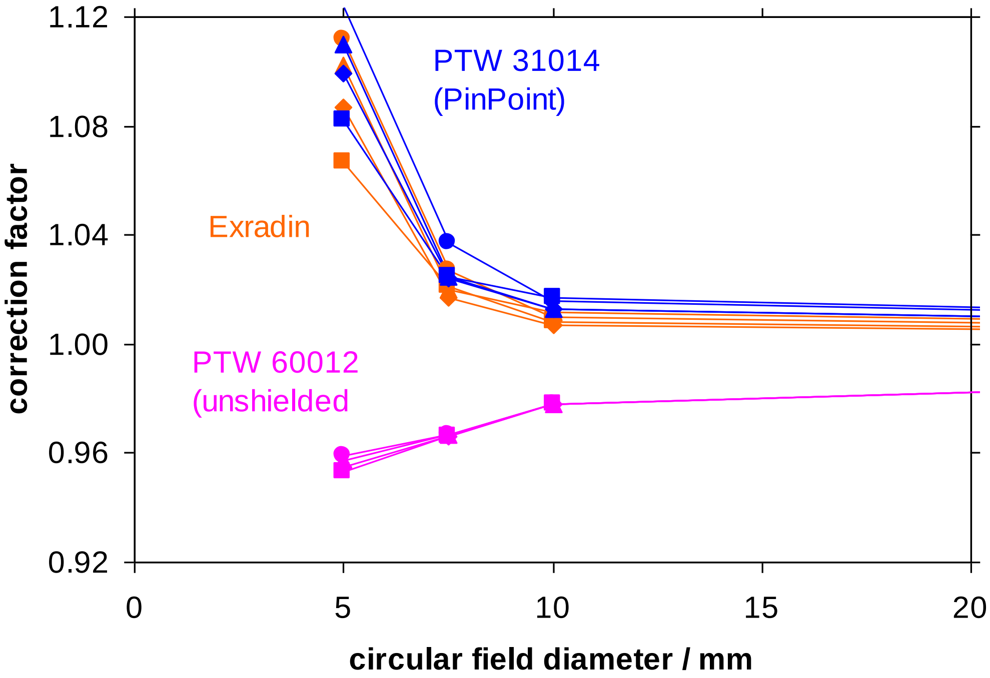
From Das
35:20

From Doblado et al. 2007 Phys Med 23:58-66

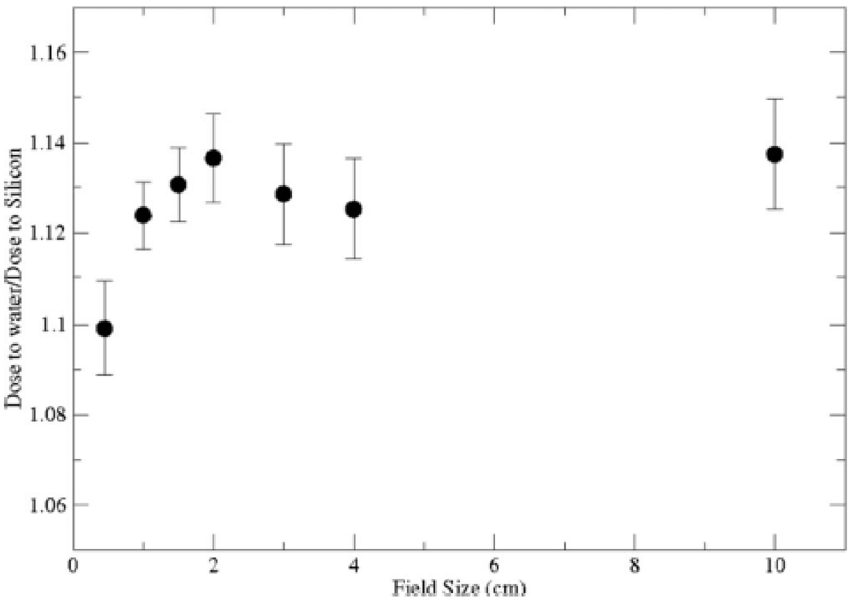
Solution: report both collimator setting and FWHM

Correction factors for unshielded diodes

Francescon et al 2008, Med Phys 35:504



Scott et al 2008, Med Phys 35:4671



Water equivalence in small fields

- Charged particle equilibrium in a detector requires that out-scattering matches in-scattering: this depends on electron range and matched medium densities is the key.
- Silicon diodes have a higher density than water and over-respond on the central axis of very small fields.
- Air filled ion chambers under-respond.

Optimising SF detector response

- Pay attention to medium densities and the arrangement of of high and low-density regions.
- Try to make disequilibrium effects tend to cancel.

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The IAEA code, TRS-398 (2000)

- Quality dependence made explicit:

$$D_{w,Q} = M_Q \, N_{D,w,Q0} \, k_{Q,Q0}$$

where

Q – quality index of beam being measured

$N_{D,w,Q0}$ – calibration factor in reference quality Q_0

$k_{Q,Q0}$ – quality dependent correction factor

IAEA: "If available, directly measured values of $k_{Q,Q0}$ for an individual chamber are the preferred option."

- This is what the UK already did:

$$N_{D,w,Q} = N_{D,w,Q0} \, k_{Q,Q0}$$

Alfonso et al. Med Phys 35, 5179.

IAEA / AAPM group, chaired by Hugo Palmans.

- Not a protocol, but a formalism for writing a protocol:

$$D_{w,Q_{user}}^{f_{user}} = M_{Q_{user}}^{f_{user}} \cdot N_{D,w,Q_0} \cdot k_{Q,Q_0} \cdot k_{Q_{user}Q}^{f_{user}f_{ref}}$$

where

D – is dose to water in the field f_{user} and quality Q_{user}

M – is the measurement in f_{user} and Q_{user}

N – is the calibration factor in a reference quality Q_0

k – are quality dependent correction factors

Quality dependent corrections

- In general

$$N_{D,w,Q_2} = N_{D,w,Q_1} \cdot k_{Q_2,Q_1}$$

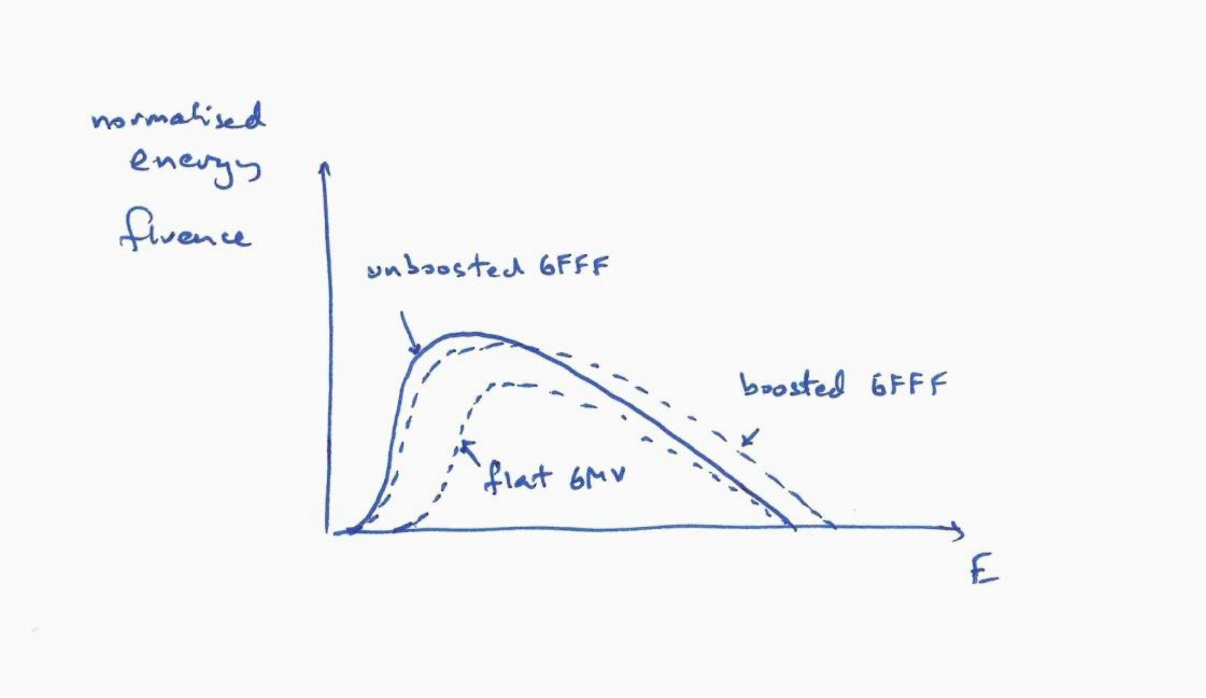
$$k_{Q_2,Q_1} \stackrel{\text{def}}{=} N_{D,w,Q_2} / N_{D,w,Q_1}$$

and this correction is needed whenever the beam qualities of calibration and use are different

- NB beam quality (not quality index)
- Two beams can have the same quality index but different beam quality:

Flattening filters and MV affect beam quality in different ways: their effects on quality index can cancel, but not their effects on beam quality

Changing MV and filtration



- Less filtration means more low energy photons get through.

  Spectrum gets wider, mean energy is reduced.

- Raising MV (in an FFF beam) increases the upper limit of the spectrum. This adds more high energy photons.

  Spectrum gets wider and mean energy is increased.