Small Field Dosimetry and FFF-Beam Technology

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Contents

Small Field Dosimetry

Dosimetry Protocols

- Dosimetry is based on reference field sizes typically (10x10)cm² and air vented ionization chambers in international protocols such as

IAEA 398, AAPM TG-51 or DIN 6800-2

- National and international committees are working on dedicated dosimetry protocols for small field dosimetry

Small Field Dosimetry

Considerations

- The field is smaller than approximately (4 x 4)cm^2
- The focus is partially hidden by the collimators
- Lateral electron equilibrium is not given in the center of the field

Small Field Dosimetry

Influence of Detector Size

- Gold standard for dose measurements are vented ionization chambers as specified in [IEC60731]*

Advantages: good response in direction, dose rate and energy
Disadvantage: size of the active volume

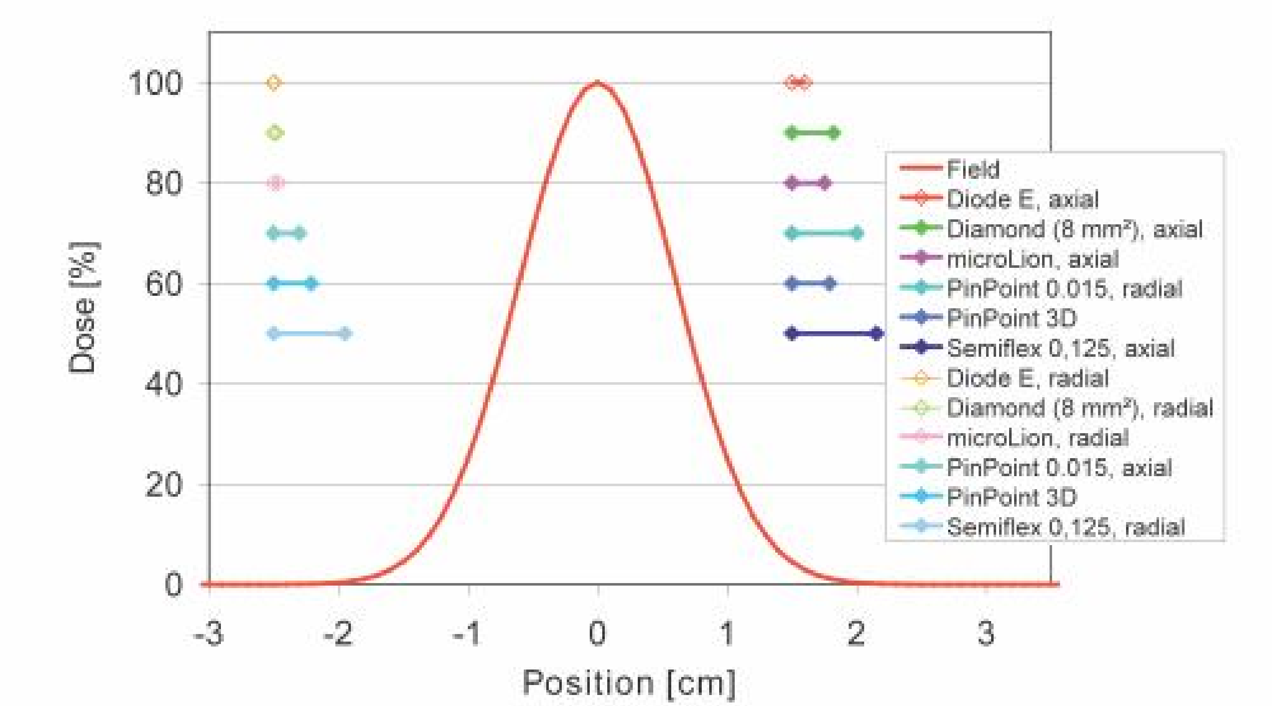
- The volume effect has two disadvantages:
  a) Large detectors tend to underestimate the central axis dose
  b) Broadening of measured steep dose gradient in penumbra region

* Medical electrical equipment – Dosimeters with ionization chambers as used in radiotherapy

Small Field Dosimetry

Volume effect of large ionization chambers

- Small field detectors against a Gaussian shaped field of FWHM* (2 x 2)cm²

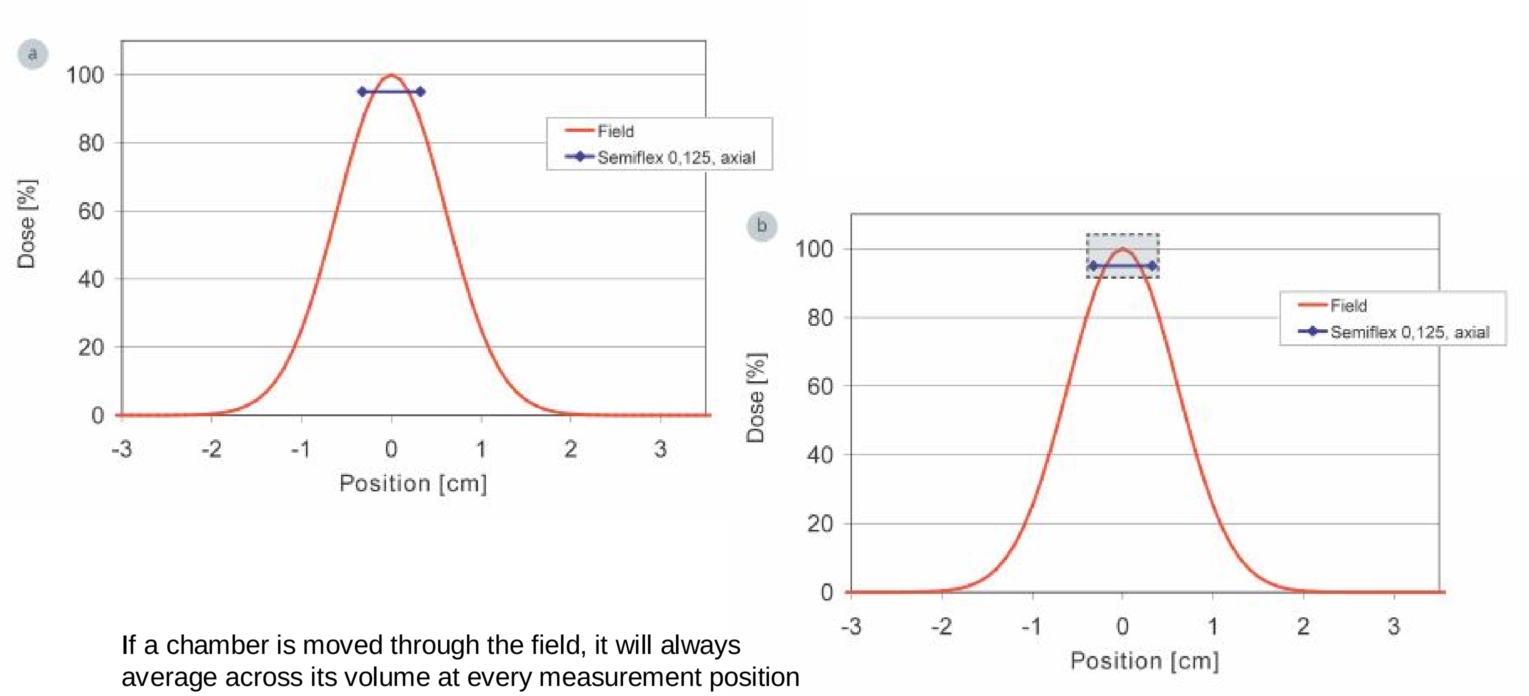


* Full width at half maximum which is the same as the width of the 50% isodose

Small Field Dosimetry

Volume effect of large ionization chambers

- Each (!) detector will average the dose across its sensitive volume

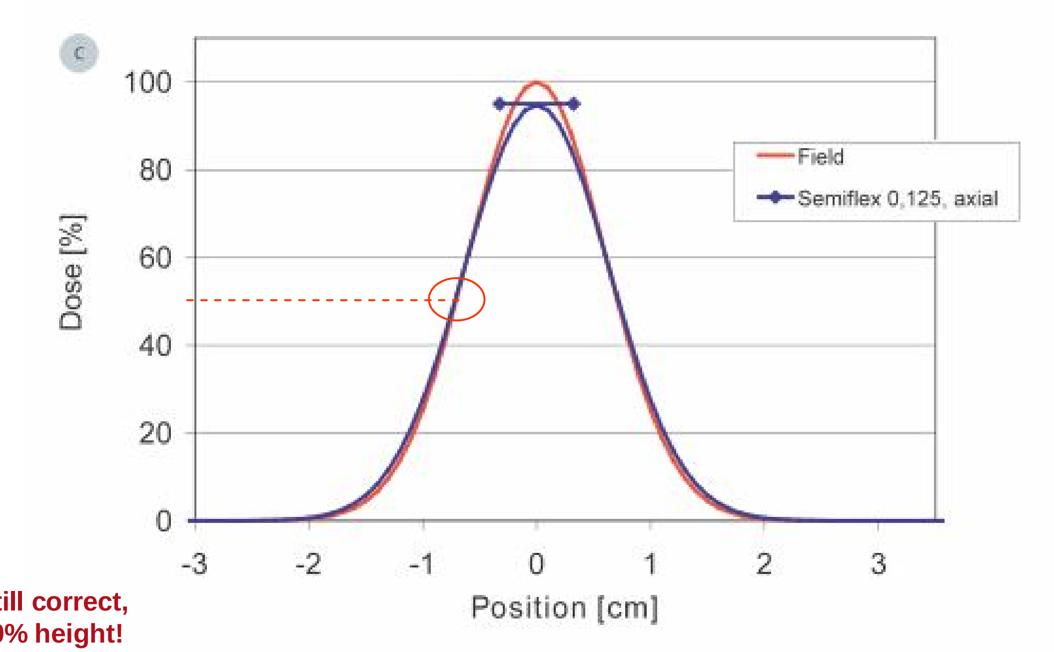


If a chamber is moved through the field, it will always average across its volume at every measurement position

Small Field Dosimetry

Volume effect of large ionization chambers

- Signal after averaging: The CAX value of the dose is underestimated and the penumbra is broadened

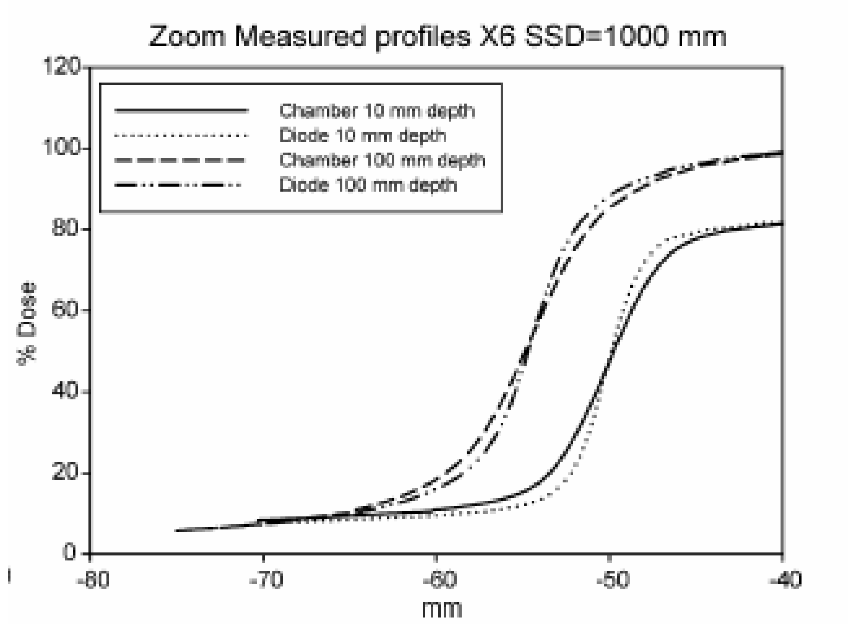


Note that the FWHM field size is still correct, the blue and red curve meets at 50% height!

Small Field Dosimetry

Volume effect of large ionization chambers

- Broadening of measured penumbra



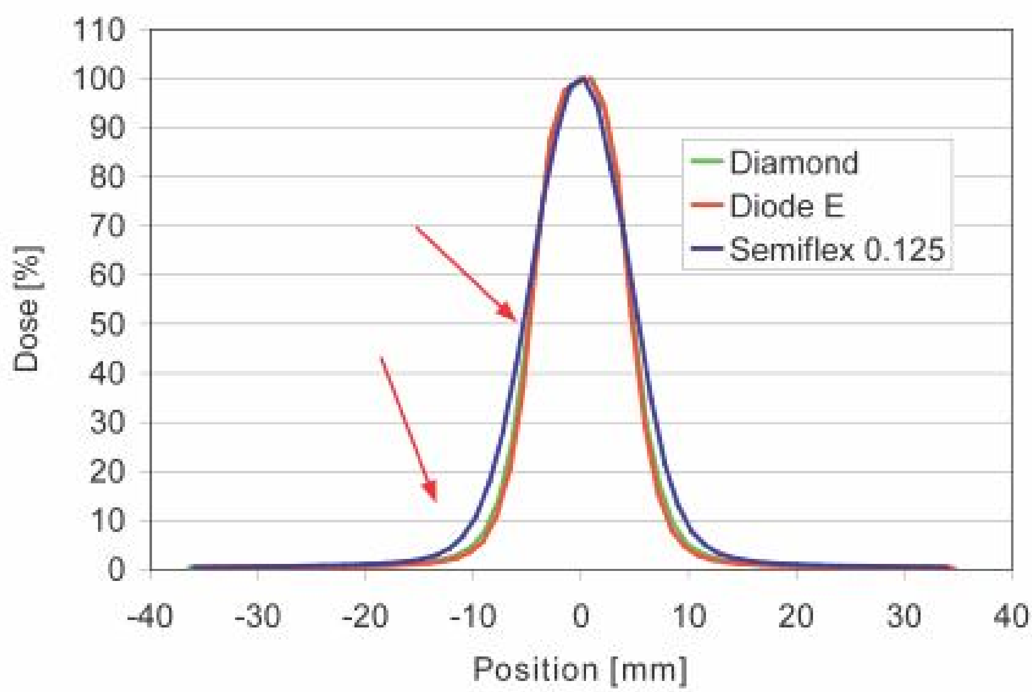
Broadening of the measured penumbra region at two different depths, depending upon detector type (0.125cm³ ion chamber and silicon diode).

Phys. Med. Biol. 54 (2009) 485-495: Manolopoulous et al.

Small Field Dosimetry

Additional effects due to CAX normalization

- The out-of-field dose and the penumbra dose will be overestimated



Small Field Dosimetry

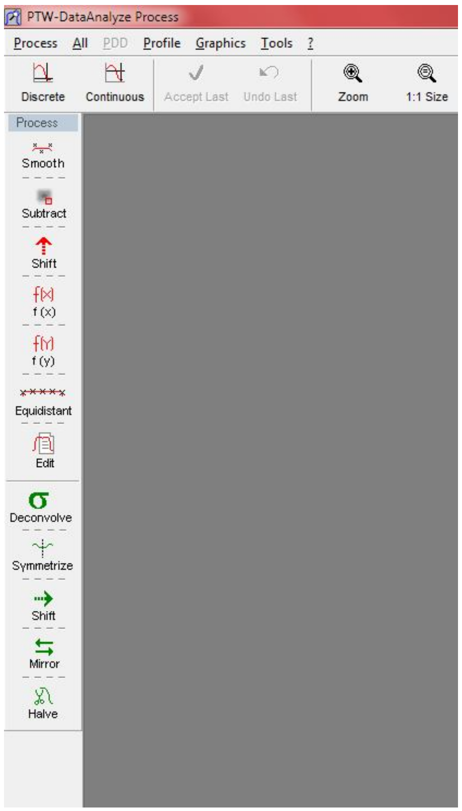
Other effects

- Alignment of beam and detector
- Irradiation is often composed of many small fields. To add these up the penumbras of fields must be determined very precisely
- Field size must not equal set of collimator value due to partial occlusion of focus by collimators and penumbra overlap
- Lateral electron equilibrium is often not given which can influence k_Q factors
- FFF-beams* and their spectrum is softer compared to conventional beams. This can influence k_Q factors

* Flattening Filter Free

MEPHYSTO 3.0

Deconvolution algorithm

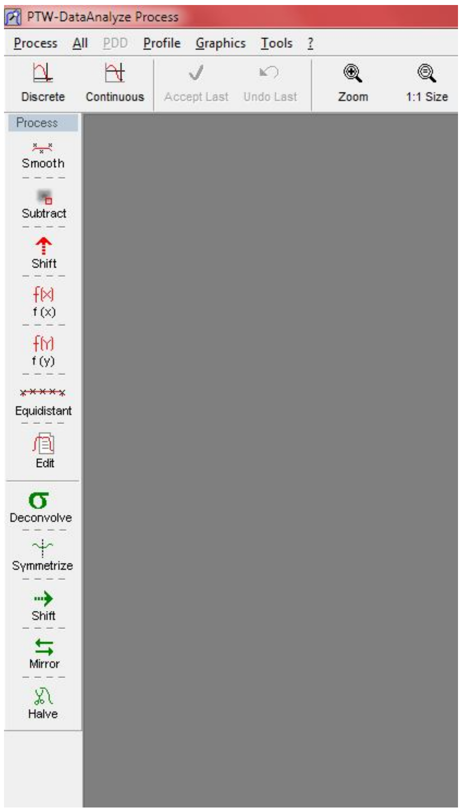


What do we need…

- The best guess approximating the true profile (called "*best guess*" in the following slides)
- The *Kernel* of the detector
- The measured profile
- A computer program
- In theory, the Kernel is the response of the detector to an extremely thin field (only the size of a point)
- In practice, the Kernel is provided by Looe et al.

MEPHYSTO 3.0

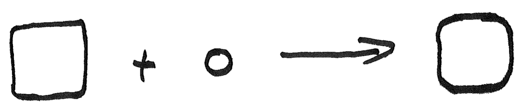
Deconvolution algorithm



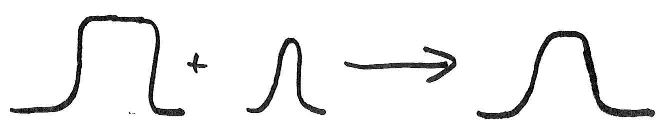
Assuming a perfect system…

- If our best guess is perfect, it is equal to the true profile
- Measuring the true profile with our detector is mathematically equivalent to calculation the convolution of the true profile with the Kernel of the detector
- Hence, after calculation the convolution, we get exactly the measured curve

50 % isodose:



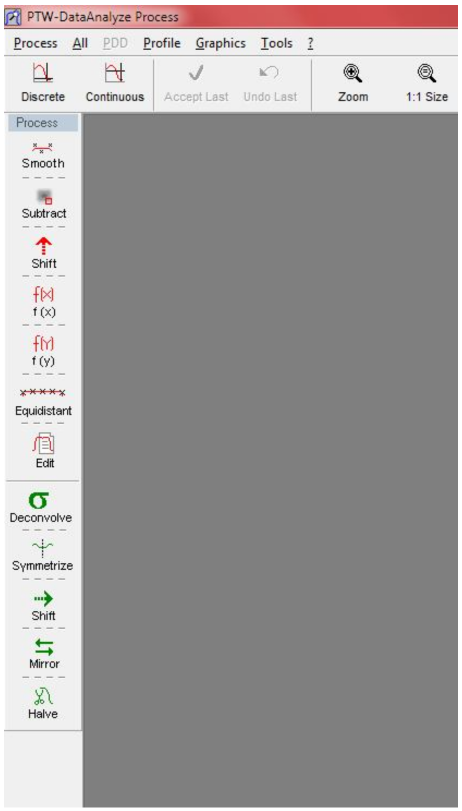
Profile:



true detector measured

MEPHYSTO 3.0

Deconvolution algorithm

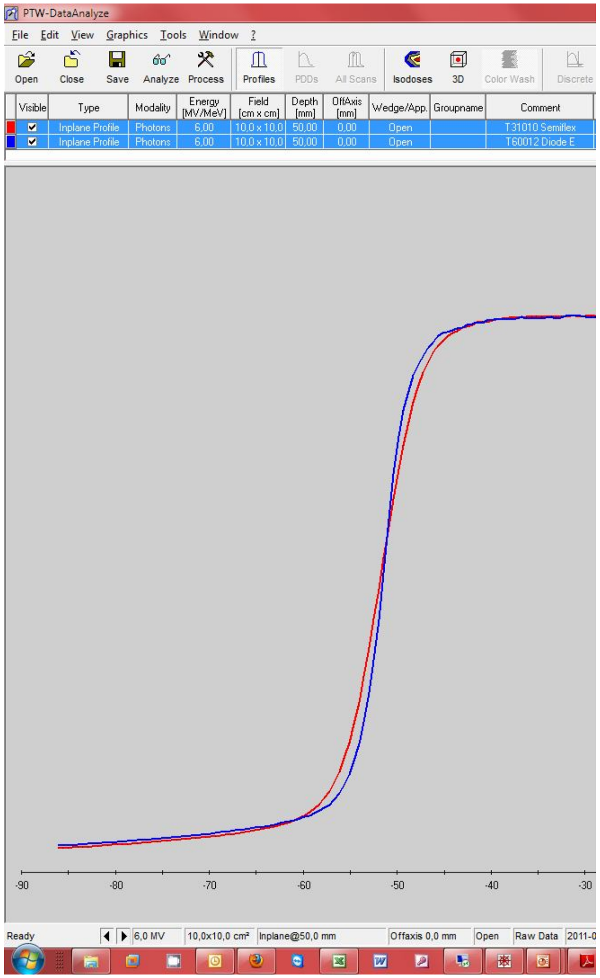


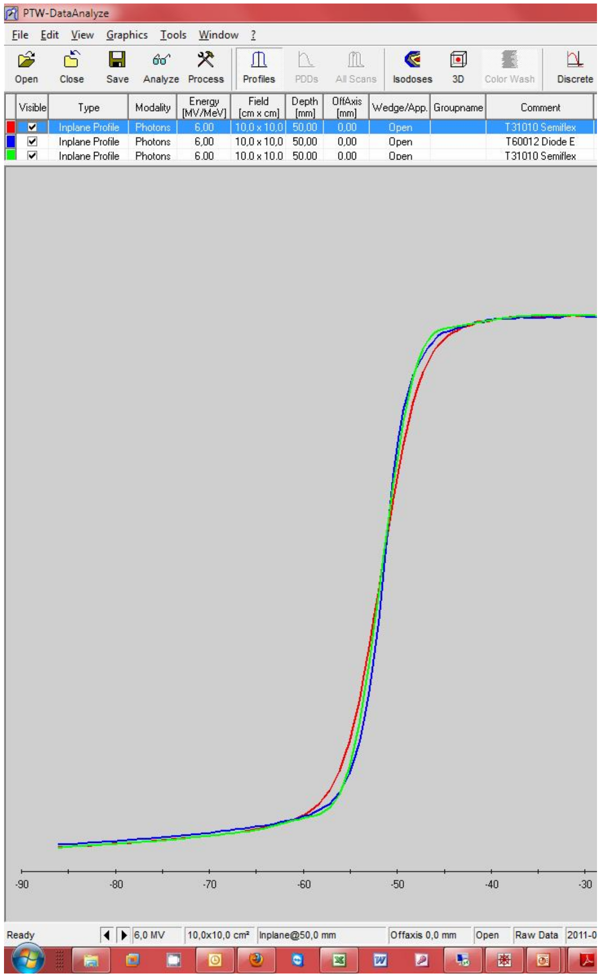
The real world…

- The best guess will not be equal to the true profile but differ a little
- Let's assume a data point that deviates 2% from the true profile and perform the convolution
- If we now compare the convolved signal with the measured one, the data point will probably deviate roughly 2% from the measured profile
- …in other words: *the error between the best guess and the true profile is roughly the same error as between convolved and measured profile*

MEPHYSTO 3.0

Deconvolution approach implemented in MEPHYSTO





Sigma 6MV lateral	Sigma 15MV lateral	Sigma 6MV longitudinal	Sigma 15MV longitudinal	Imag
				farmer_chamber.
				farmer_chamber.
				farmer_chamber.
				farmer_chamber.
				farmer_waterproof.
				farmer_waterproof.
				rigid1.
				rigid1.
				rigid2.
				rigid2.
2,18	2,28	2,26	2,48	semiflex1.
2,18	2,28	2,26	2,48	semiflex1.
2,39	2,42	4,86	5,04	semiflex2.
2,39	2,42	4,86	5,04	semiflex2.
0,94	0,94	1,96	2,00	Pinpoint1.
1,37	1,46	2,21	2,28	Pinpoint2.
1,35	1,35	1,75	1,88	Pinpoint3D.
2,35	2,43			markus.

Conclusion, Small Field Dosimetry

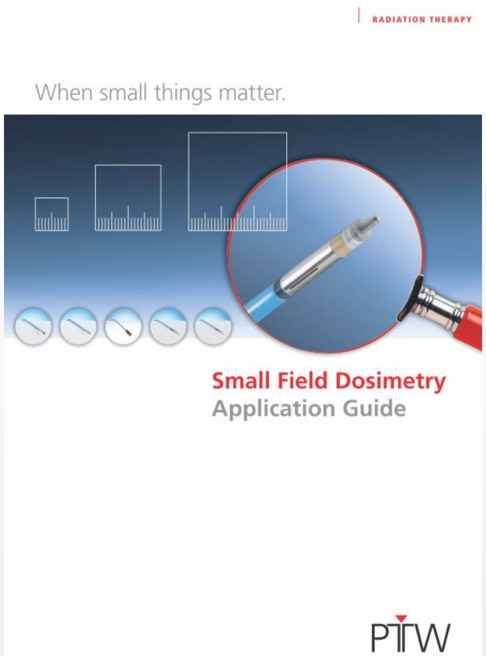
- If the detector dimension in the scanning direction is larger than roughly 1/4 of the field diameter, watch out for the volume effect

- Low-energy scattered radiation does not play a large role in small fields. Unshielded diodes can be used. In fields below roughly 7cm x 7cm, they are the best choice together with diamond detector and PinPoint chambers. Keep an eye on the field size limits

- If the volume effect is present:
  - The dose in the field center will be underestimated
  - The signal at the field edge will be overestimated

- CAX normalization combined with the volume effect in a small field leads to:
  - The dose in the out-of-field region and the field edge will be overestimated
  - PDDs at large depths will be overestimated
  - The field (50% isodose) will appear slightly larger than it is

Application Guide



Detector Selection Tree

Minimum field size required 1 cm x 1 cm

MAXIMUM field size (cm) required:	10 x 10		20 x 20	
Type of measurement:	Absolute dose & output factors	Profiles & PDDs	Absolute dose & output factors	Profiles & PDDs
Suitable detectors:	Diode E Diode SRS Diode P Diamond microLion	Diode E Diode SRS Diode P Diamond microLion	Diode P Diamond microLion	Diode P Diamond microLion
Recommended detectors:	Diode SRS (6 MV or less) Diode E (more than 6 MV)	Diode SRS (6 MV or less) Diode E (more than 6 MV)	microLion	microLion
Remarks	As the keV energy response is of lesser relevance, the smallest detector, the unshielded diode, can be used.		The microLion chamber is an excellent compromise betwen small size and good water equivalence for precise dose determination in larger fields. This also applies to the Diamond detector. As a natural resource, this detector is, however, more difficult to provide.	

Overview: Key Selection Criteria

Key Selection Criteria								Suitable Detector
Field Size		Absolute Dose Measurements				Profile Measurements		PTW Detector
min. cm x cm down to…	max. cm x cm up to…	< 2 cm x 2 cm	2 cm x 2 cm … 3 cm × 3 cm	3 cm x 3 cm … 4 cm × 4 cm	≥ 4 cm × 4 cm	≤ 10 cm	> 10 cm	
1 x 1	10 x 10	✔	✔	✔	✔	✔	–	Diode E, unshielded
1 x 1	10 x 10	✔	✔	✔	✔	✔	–	Diode SRS, unshielded
1 x 1	40 x 40	✔	✔	✔	✔	✔	✔	Diode P, shielded
1 x 1	20 x 20	✔	✔	✔	✔	✔	✔	DIAMOND Detector
1 x 1	20 x 20	✔	✔	✔	✔	✔	✔	microLion Chamber
2 x 2	30 x 30	–	✔	✔	✔	✔	✔	PinPoint Chamber, 0.015 cm³
2 x 2	30 x 30	–	✔	✔	✔	✔	✔	PinPoint Chamber, 0.03 cm³
2 x 2	30 x 30	–	✔	✔	✔	✔	✔	PinPoint Chamber 3D, 0.016 cm³
3 x 3	40 x 40	–	–	✔	✔	–	✔	Semiflex Chamber, 0.125 cm³

✔ Detector requires cross-calibration against Semiflex 0.125 cm³ chamber for absolute dose measurements.
– Not recommended or suitable

Overview: Additional Selection Criteria

Detectors	Penumbra Precision	Out-Of-Field Dose Precision	Dose Stability	Dose Rate Independence	Energy Response (MeV)	Energy Response (keV)
Diode E, unshielded	++++	++ [1]	++	+++	+++	–
Diode SRS, unshielded	++++	++ [1]	++ [2]	++++	+++	–
Diode P, shielded	++++	++	++	+++	++	++
Diamond Detector	+++	+++	++++	++	+++	+++
microLion Chamber	+++	+++	++++	++++ [3]	++++	+++
PinPoint Chamber, 0.015 cm³	++	++++	++++	++++ [4]	++++ [5]	++++
PinPoint Chamber, 0.03 cm³	++	++++	++++	++++ [4]	++++ [6]	++++
PinPoint Chamber 3D, 0.016 cm³	++	++++	++++	++++ [4]	++++ [7]	++++
Semiflex Chamber, 0.125 cm³	+	++++	++++	++++ [5]	++++ [5]	++++

++++ excellent +++ very good ++ good + OK

[1] for fields ≤ 10 cm x 10 cm
[2] only ≤ 6MV
[3] this depends on the repetition frequency of the linac: below 180 Hz basically no dose rate dependence, above 180 Hz correction after [Toelli2010]
[4] can be corrected
[5] can be corrected, k_Q available in [DIN 6800-2] and [IAEA 398]
[6] can be corrected, k_Q available in [Muir2010]
[7] can be corrected, k_Q available in [DETECTORS]

FFF Beam Technology

History

- A standard LINAC delivers a flat field profile using a cone-shaped flattening filter (FF Beam)
- Radiation at central axis is harder as on the field edge
- Dose exposure in healthy tissue because of scattered radiation from the flattening filter
- Modern TPS can handle the dose calculation in flattened and flattening filter free beams (FFF Beam)
- A flattening filter absorbs a lot of radiation. Dose rate in FFF Beams is about 2-times higher than in FF Beams

FFF Beam Technology

Consideration of a FF LINAC

- Flattening filter: YES
- Dose rate: 6 Gy/min at 6 MV
- Dose per pulse: 0.2 mGy/pluse up to 0.6 mGy/pulse (field)
- Profile shape: flat
- Definition of field sizes: 50% Isodose
- Beam quality: 6 MV electrons generate a spectrum of 6 MeV in the target which is hardened by the flattening filter
- Profile shape will be changed in deeper water depth and the radiation in the field depends on the cone-shaped flattening filter

FFF Beam Technology

Consideration of a FFF LINAC

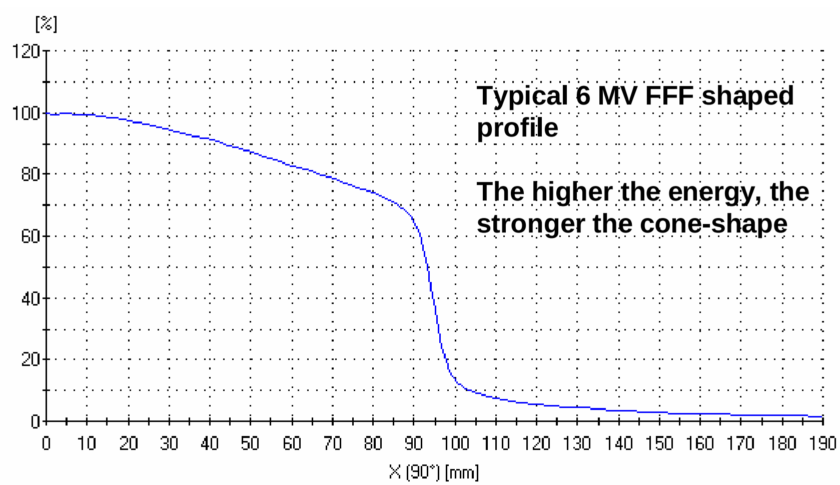
- Flattening filter: NO
- Dose rate: *Elekta Agility 14 Gy/min at 6MV FFF and 10MV FFF
  *Elekta Agility 24 Gy/min at 10MV FFF
  Varian TrueBeam up to 24 Gy/min at 10 MV FFF
- Dose per pulse: *Elekta Agility 1 mGy/pluse at 10MV FFF
  Varian TrueBeam 1.3 mGy/pulse at 10MV FFF
- Profile shape: cone-shaped from field size 7cm x 7cm (@ 6MV)
- Definition of field sizes: no international definition available
- Beam quality: no common convention. Some LINAC vendors increase electron energy to get “similar” radiation hardness
- Profile shape is expanded in deeper water depth and the radiation in the field is equally hardened

* Temporarily information

FFF Beam Technology

Type of LINAC

- Elekta Agility / VersaHD: FF Beams and FFF Beams
- Elekta Axesse: FF Beams and FFF Beams
- Varian TrueBeam: FF Beams and FFF Beams
- Siemens Artiste: FF Beams and FFF Beams
- Cyberknife: FFF Beams
- TomoTherapy: FFF Beams



Suitable Detectors

Specific and designated characteristics

- Absolute dose measurements: Correction of **saturation effect** and no **volume effect** in the centre of the field sizes: Semiflex type 31010 and PinPoint type 31015
- Profile measurements: saturation effect does not play a role: Small field size detectors
- PDD curve measurements: saturation effect does not play a role: Small field size detectors
- Output factor measurements: saturation effect does not play a role: Small field size detectors
- Small field size detectors: Dosimetry diodes, Diamond detector, Pinpoint chamber and eventually Semiflex 0.125ccm chamber

Suitable Detectors

Saturation effect for profiles and PDD curves

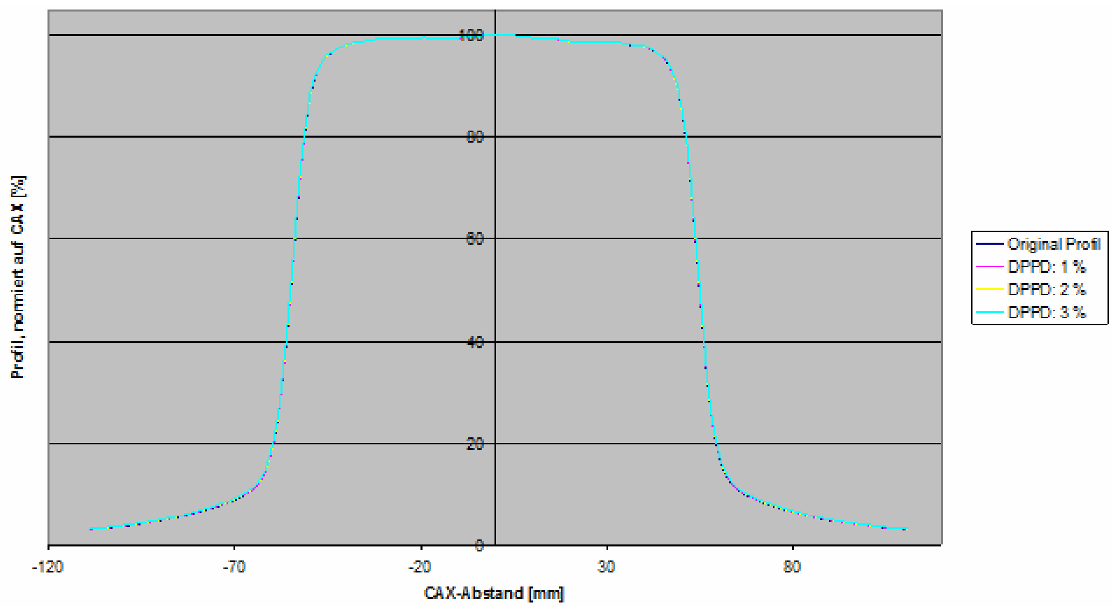
General issues…

- Saturation effect near the 100% dose (in the field) is negligible because of CAX normalization
- Saturation effect near the 0% dose (at the field edge) is negligible, since no ***Dose Per Pulse Dependency (DPPD)*** exists
- Maximum discrepancy of 50% dose is defined as follows: maximum DPPD / 4

Suitable Detectors

FF profile and a detector with DPPD

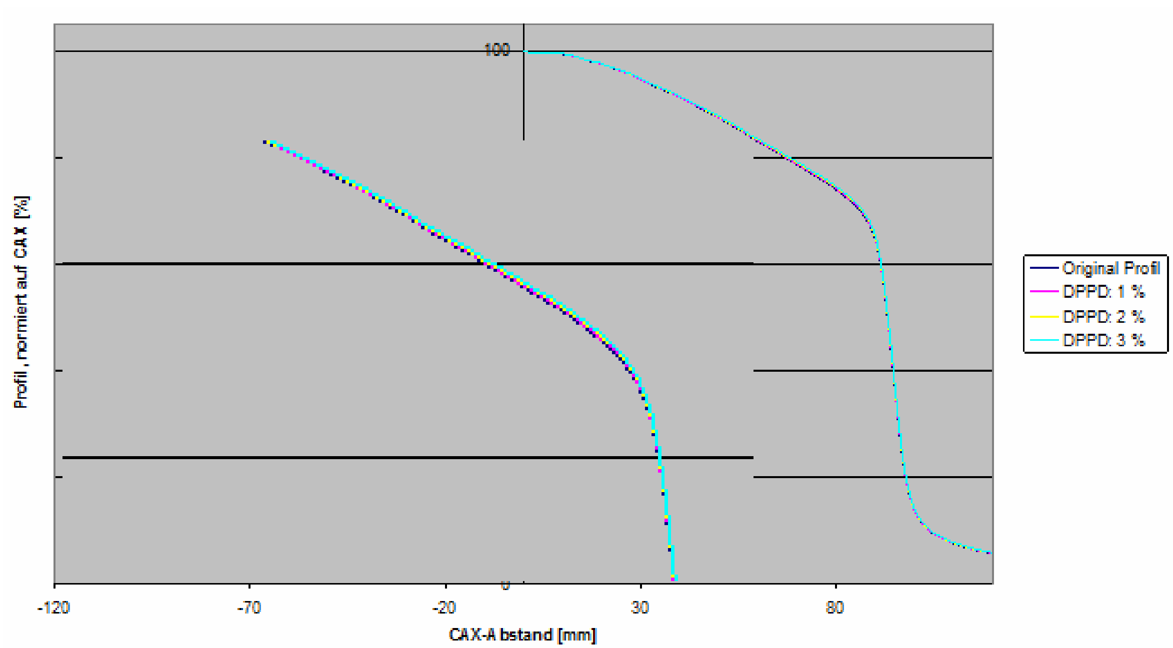
- As you see you see nothing (nearly no discrepancy for 1%, 2% and 3% dose rate dependency)
- Maximum discrepancy of 50% dose with a maximum DPPD of 2% results in a 0.5% dose deviation



Suitable Detectors

FFF profile and a detector with DPPD

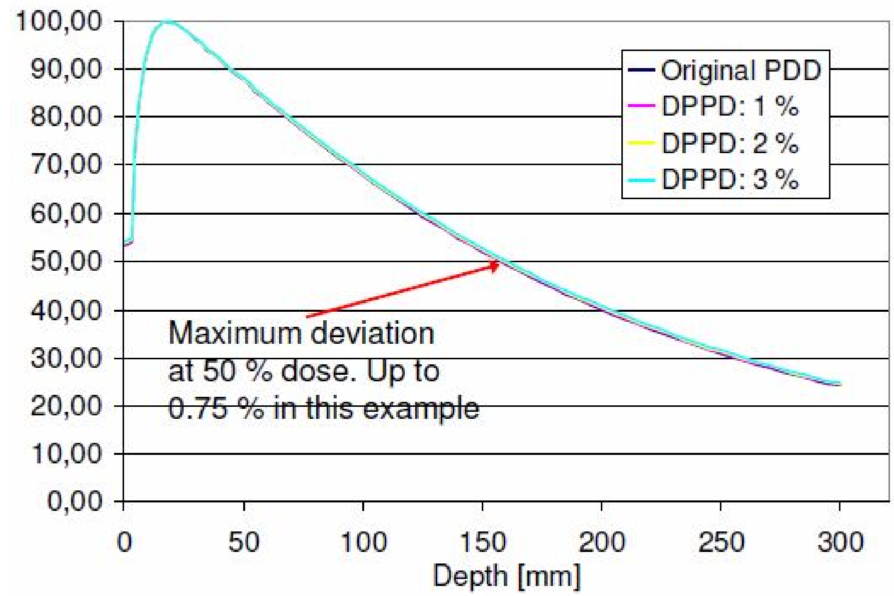
- If you look precisely to the region 60%..80% of CAX-value a slightly discrepancy is given because of less steep dose gradient
- Maximum discrepancy of 50% dose with a maximum DPPD of 1%, 2%, 3%



Suitable Detectors

FFF PDD and a detector with DPPD

- The deviation is still small but better visible in a PDD because the PDD is less steep at 50% dose
- Maximum deviation at 50% dose with a maximum DPPD of 1%, 2%, 3%



Suitable 2D Arrays

OCTAVIUS Detector 729

- Air vented ion chamber technology
- Specified range of up to 48 Gy/min
- 99% saturation at 0.73 mGy/pluse can end up leading to a 2% saturation deficiency at 10MV FFF

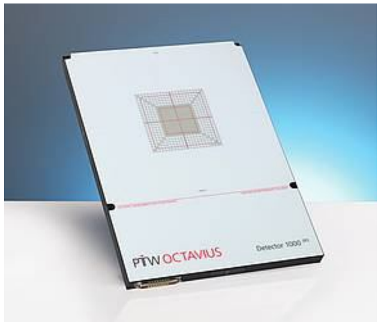
Suitable 2D Arrays

OCTAVIUS Detector 1000 SRS

- Liquid filled µLion technology
- Specified range of up to 12 Gy/min and usable up to 36 Gy/min
- 99% saturation with a DPPD of 1%:

  Repetition frequency of 60 Hz and DPPD of 0.546 mGy/pulse
  Repetition frequency of 180 Hz and DPPD of 0.414 mGy/pulse
  Repetition frequency of 360 Hz and DPPD of 0.264 mGy/pulse

- Saturation effect for liquid filled ion chambers can be assumed as a first estimate as linear with dose per pulse



Suitable 2D Arrays

STARCHECK and STARCHECK *maxi*

- Air vented ion chamber technology
- Usable up to 80 Gy/min (start-up behavior) and up to 50 Gy/min with continuous radiation
- 99% saturation at 1.22 mGy/pluse can end up leading to a 1% saturation deficiency at 10MV FFF

QUICKCHECK *webline*

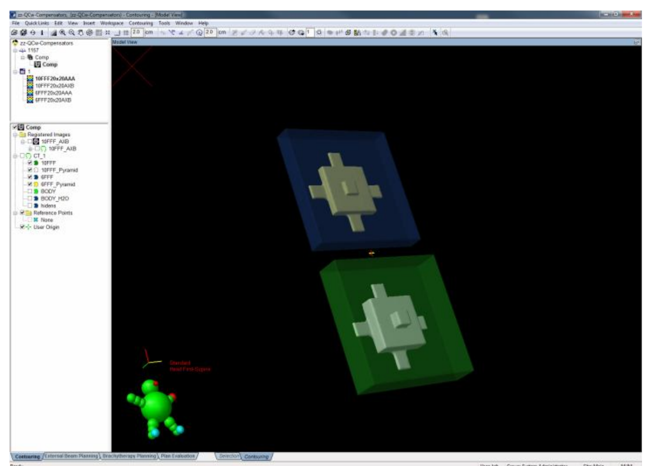
FF Beam Technology

- Air vented ion chamber technology
- Automatic air density correction
- Docking station available
- Specified range of up to 10 Gy/min and up to 25 MV
- Measures Central Axis Dose (CAX), flatness of the field, wedge angle, symmetry, radiation quality and radiation time
- Gantry mount holder available
- Physicist’s software tool WorklistGenerator and evaluation software QUICKCHECK

QUICKCHECK *webline*

FFF Beam Technology

- QUICKCHECK FFF Compensator X6
- QUICKCHECK FFF Compensator X10
- Air vented ion chambers
- Specified range of up to 25 Gy/min with the use of compensators
- Compensation in dependence on the position of the ion chamber in order to evaluate the “traditional” flatness of field



Summary

FFF Beam Technology

- FFF Beam: Twice the dose rate and dose per pulse (DPPD) or even more
- FFF Beam: Flatness, Field size etc. are not clearly defined
- PTW chambers and 2D-Arrays are well suited for FFF Beam technology
- Dose rate dependence in relative measurements is a lot less severe than one might think at first sight. Maximum deviation is only 1/4th of max dose rate dependence
- The same is true for cross calibrated measurements and output factor measurements. Deviations are even less
- There is a quick and easy way to estimate the saturation loss for ionization chambers and diamond detectors
- For absolute dose measurements use detector with known k_s or measure k_s

Thank you for your attention.

Any Questions?