Monte Carlo simulations of detector type specific output correction factors in the presence of magnetic field in experimental facilities using EGSnrc

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Small field dosimetry for MRgRT - CCRI webinar

12 September 2023

Outline

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- Background
- Experimental setup
- Beam model validation
- Detector model validation
- Results
- Future work

Background

How do MC simulations contribute to CoPs

- Monte Carlo simulations have become an essential part of reference dosimetry
- Characterisation of physical properties
  - of beams and of radiation detectors
- Validation of MC codes is essential
  - Self consistency (Fano test) at a level of 0.1%
  - Agreement with ion chamber experimental data of the order of 0.3%
- Provides tabulated MC calculated beam quality correction factors

J Wulff *et al* (2008) *Phys. Med. Biol.* **53** 2823

B. R. Muir and D. W. O. Rogers (2010), Med. Phys. 37, 11

J Tikkanen *et al* (2020) Phys. Med. Biol. 65 075003 (15pp)

Mainegra-Hing and Muir (2018): ICRU-90, Med. Phys. 45 (8)

How do experimental facilities support MC simulations

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- Setup configurations that cannot be achieved in MRI-linac facilities
    - i.e. different magnetic field strengths, easily switch the B-field off!
- Detector and radiation field characterisation in the presence of magnetic field needed for the determination and application of output correction factors
- Determination of detector properties such as volume averaging and the effective point of measurement
- Validation of detector models that can be used for the MC calculation of output correction factors in MRI-linac environment

Output correction factor in the presence of magnetic fields

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Definition

$$k_{\vec{B},Q_{clin},Q_{msr}}^{f_{clin},f_{msr}} = \frac{\dfrac{D_{w,\vec{B},Q_{clin}}^{f_{clin}}}{M_{\vec{B},Q_{clin}}^{f_{clin}}}}{\dfrac{D_{w,\vec{B},Q_{msr}}^{f_{msr}}}{M_{\vec{B},Q_{msr}}^{f_{msr}}}}$$

Monte Carlo

$$k_{\vec{B},Q_{clin},Q_{msr}}^{f_{clin},f_{msr}} = \frac{\dfrac{D_{w,\vec{B},Q_{clin}}^{f_{clin}}}{D_{ch,\vec{B},Q_{clin}}^{f_{clin}}}}{\dfrac{D_{w,\vec{B},Q_{msr}}^{f_{msr}}}{D_{ch,\vec{B},Q_{msr}}^{f_{msr}}}}$$

$D_{w,\vec{B},Q_{clin}}^{f_{clin}}$, $D_{w,\vec{B},Q_{msr}}^{f_{msr}}$: Dose to water in clin and msr in B-field [0.25mm thick water disc]

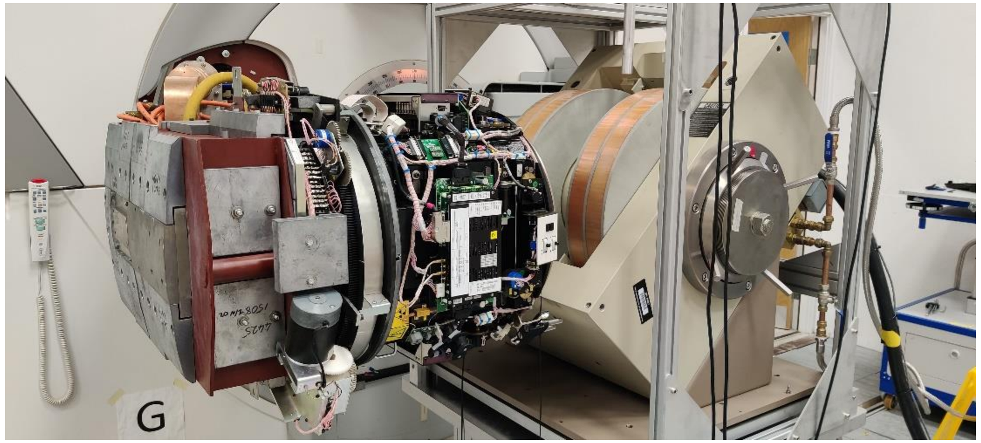
$D_{ch,\vec{B},Q_{clin}}^{f_{clin}}$, $D_{ch,\vec{B},Q_{msr}}^{f_{msr}}$: Dose to air volume in chamber cavity in clin and msr in B-field.

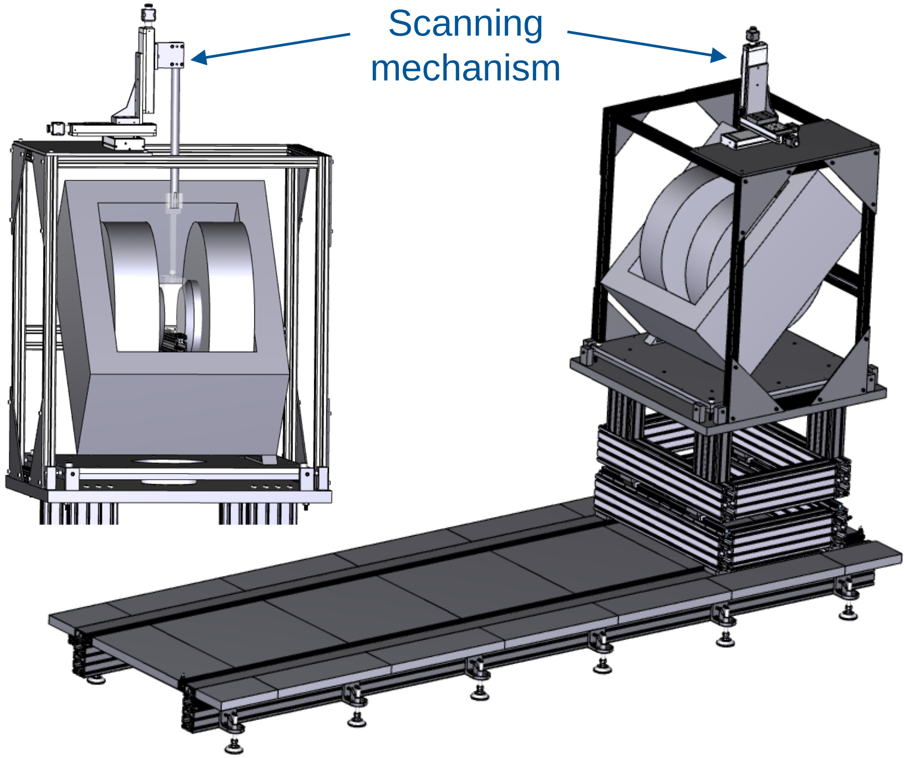
(***Assumption***: *No change* in W/e with magnetic field strength)

Experimental setup

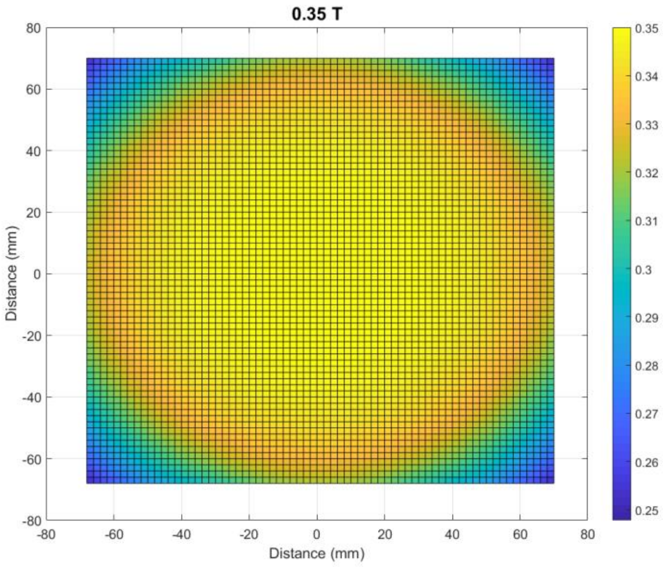
NPL electromagnet (EM) setup

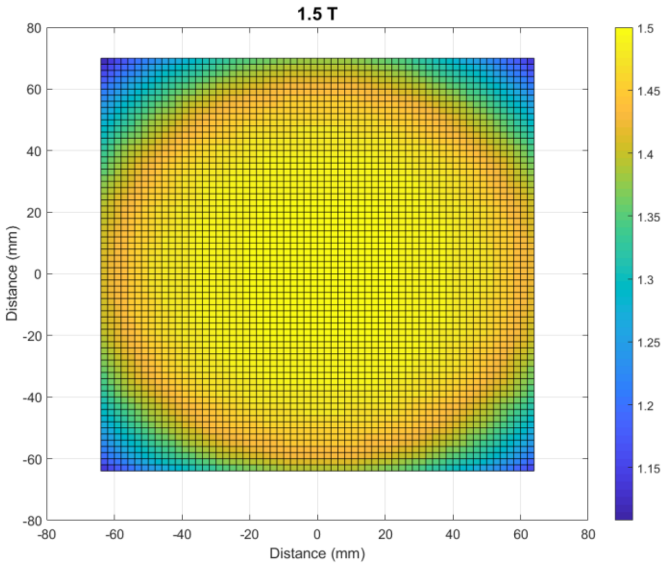
- Elekta Synergy clinical linac - 6 MV energy beam (flatten)
- Fixed height with the centre of the poles at the iso centre
- Lateral movement: ±15 cm for off axis fields
- Pole gaps: 7.3 cm
- Maximum magnetic field strength: ~ 1.55T





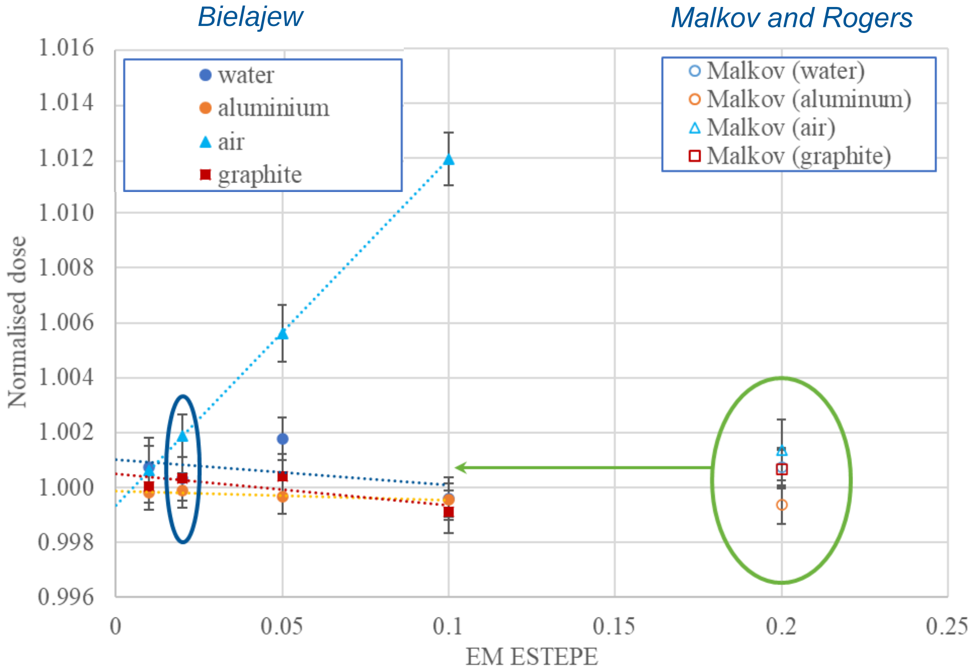
Magnetic field uniformity





Beam model validation

EGSnrc self consistency check

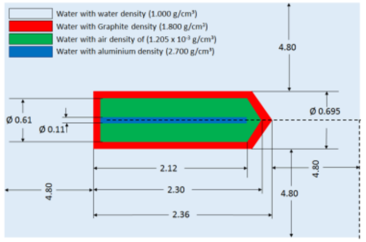


Original default EM field macro by Bielajew[1]
With EM ESTEPE = 0.01 => within 0.1% of analytic value (all cavity densities)
~440 hours to obtain ~0.1% uncertainty in cavity dose

Enhanced EM field macro by Malkov and Rogers[2]
With EM ESTEPE = 0.2 => within 0.1% of analytic value (all cavity densities)
~230 hours to obtain ~0.1% uncertainty in cavity dose

MC code: EGSnrc

Farmer-type chamber

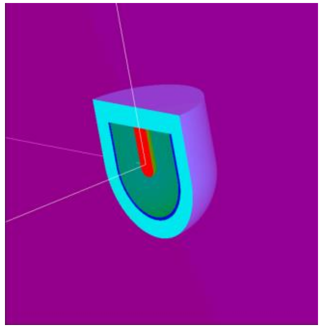


8MV ESTEPE=0.25, EM ESTEPE=0.2 (Malkov)

Cavity density	0T		0.35T		1.5T	
	Norm dose	SDOM	Norm dose	SDOM	Norm dose	SDOM
air	1.0005	0.0011	0.9995	0.0010	1.0014	0.0011
water	1.0011	0.0007	0.9997	0.0008	1.0007	0.0007
graphite	0.9994	0.0006	0.9993	0.0006	1.0007	0.0006
aluminium	0.9998	0.0006	0.9989	0.0006	0.9994	0.0006

Self consistency achieved within ~0.1% (or *k=1*) of expected (analytical) value for both detectors

Pinpoint 3D PTW/31022



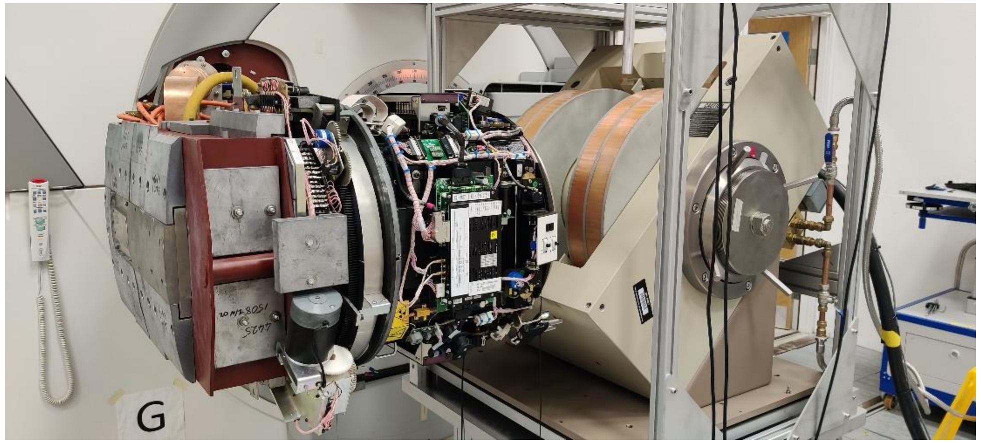
8MV ESTEPE=0.25, EM ESTEPE=0.2 (Malkov)

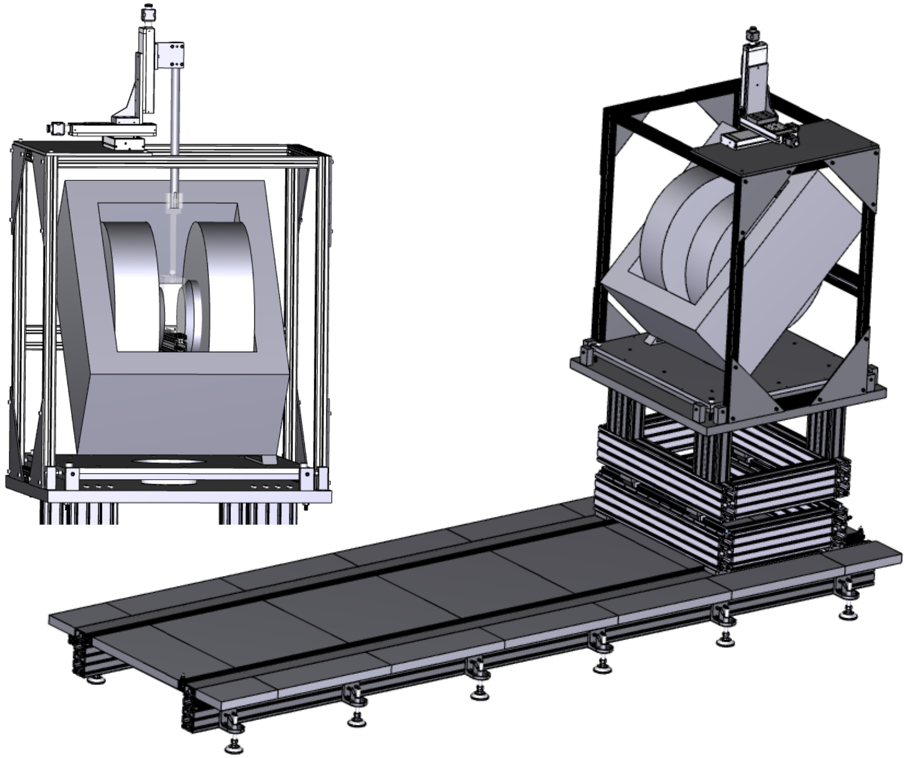
Cavity density	0T		1.5T	
	Norm dose	SDOM	Norm dose	SDOM
air	1.0008	0.0022	0.9984	0.0019
water	1.0007	0.0011	1.0014	0.0008
graphite	1.0012	0.0010	0.9998	0.0010
aluminium	1.0009	0.0009	0.9994	0.0010

[1]Bielajew A F 1989 Electron transport in E and B fields Monte Carlo Transport of Electrons and Photons Jenkins T M et al (New York: Plenum) pp 421–34
[2]Malkov V.N. and Rogers D. W. O. (Med. Phys. 43 (7), July 2016)

Validation of beam models

- NPL Elekta Synergy clinical linac - 6MV x-rays
- Source-to-centre of poles; 100cm (isocentre)
- Field sizes:
  - **square**: 1x1, 2x2, 3x3, 4x4, 5x5, 7x7 cm
  - **rectangular**: 1x4, 4x1, 10x1, 10x4 cm
  - **offset**: square +/- 5 cm & +/-10 cm
- PDD and XY profile measurements in PTW plotting tank at 5 cm depth in water
- *DOSXYZnrc / BEAMnrc (EGSnrc)*: optimize spot configuration, beam energy & MLC/jaw parameters by comparing Profile simulations in water phantom with measurement (voxels sizes ~ detector size)



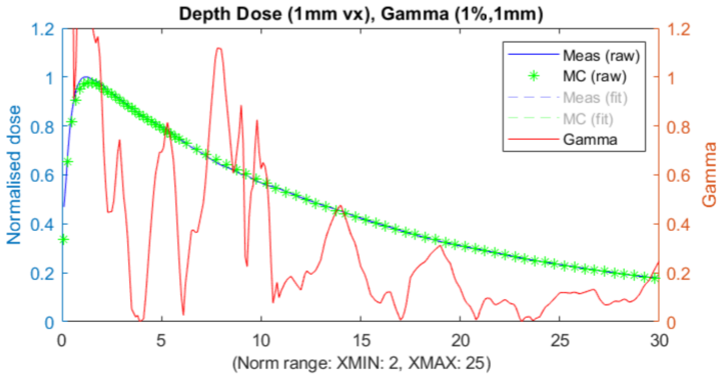


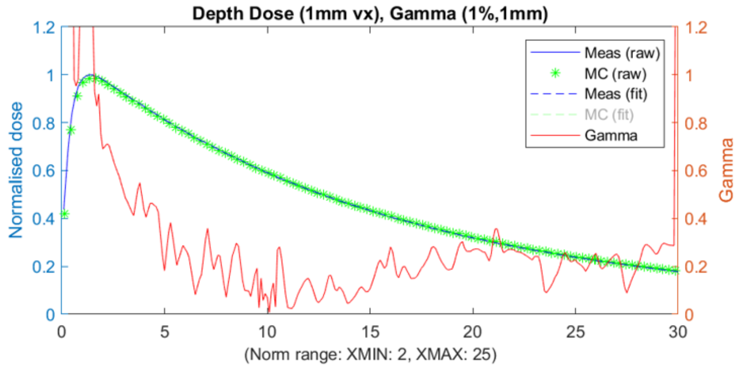
Validation of source models at 0 T (NPL EM setup)

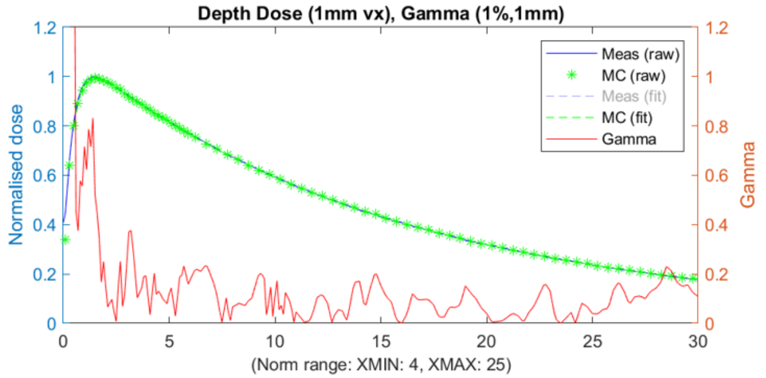
Square: 1 cm x 1 cm

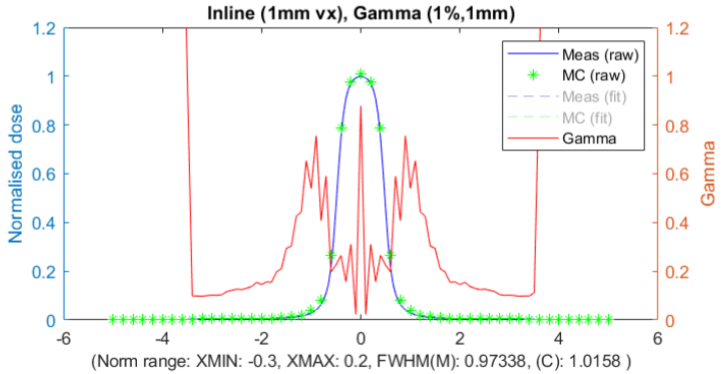
Rectangular: 1 cm x 4 cm

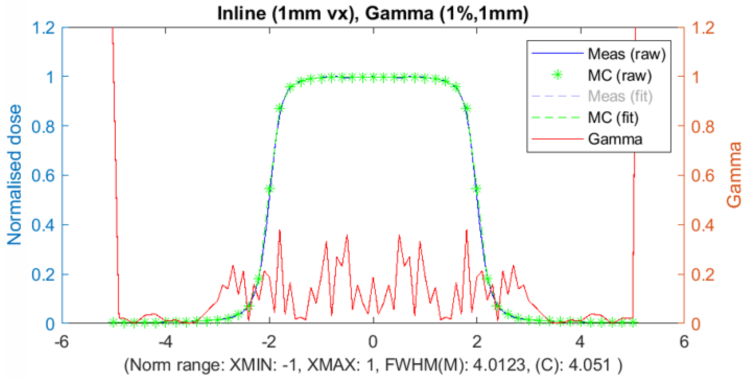
Offset: 2 cm x 2 cm (+5 cm inline)

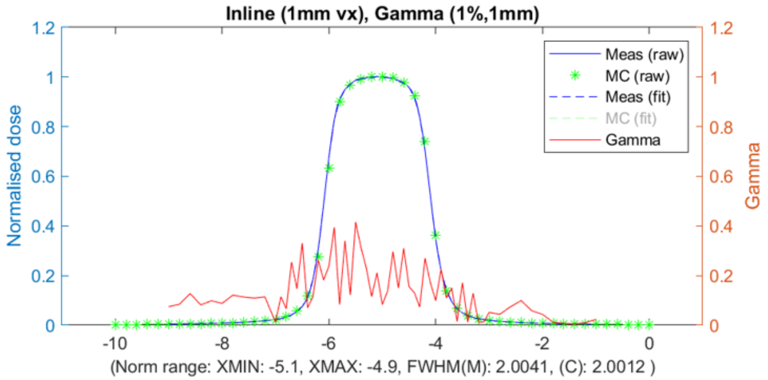


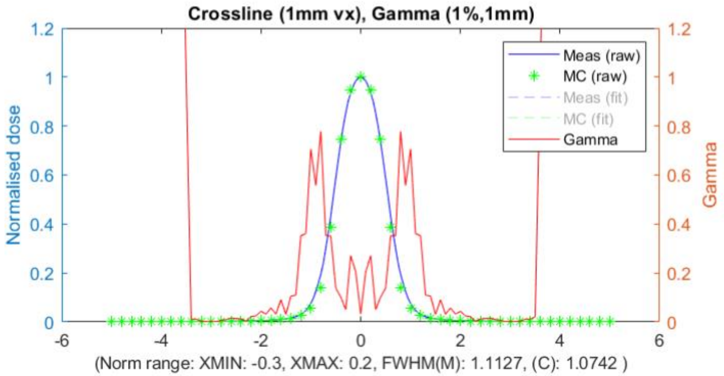


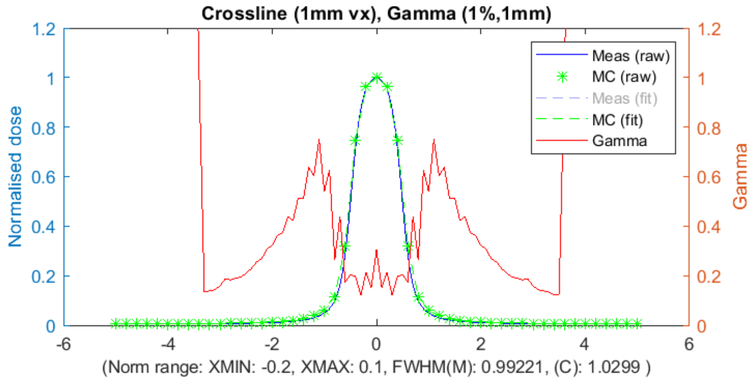


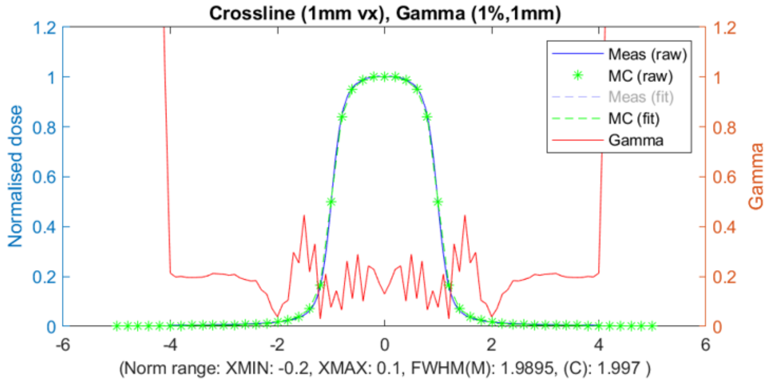












Detector model validation

Detector response simulations (NPL EM Setup)

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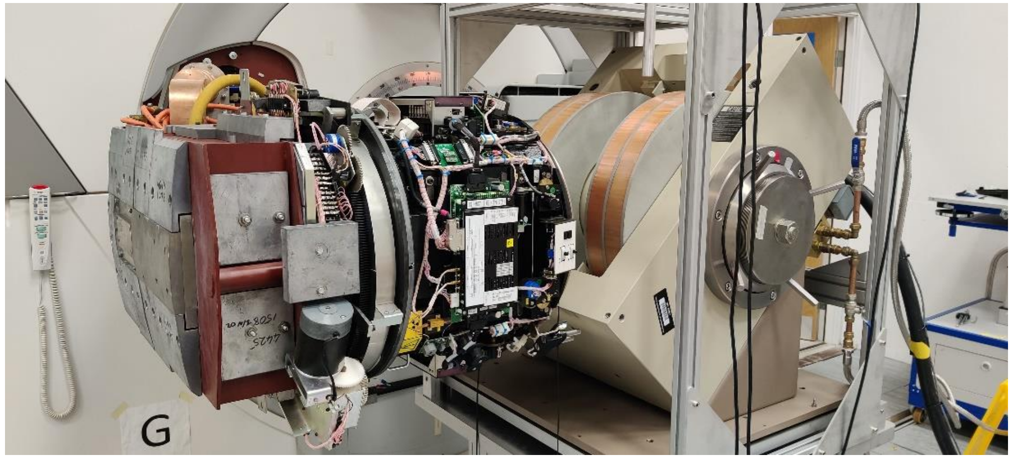
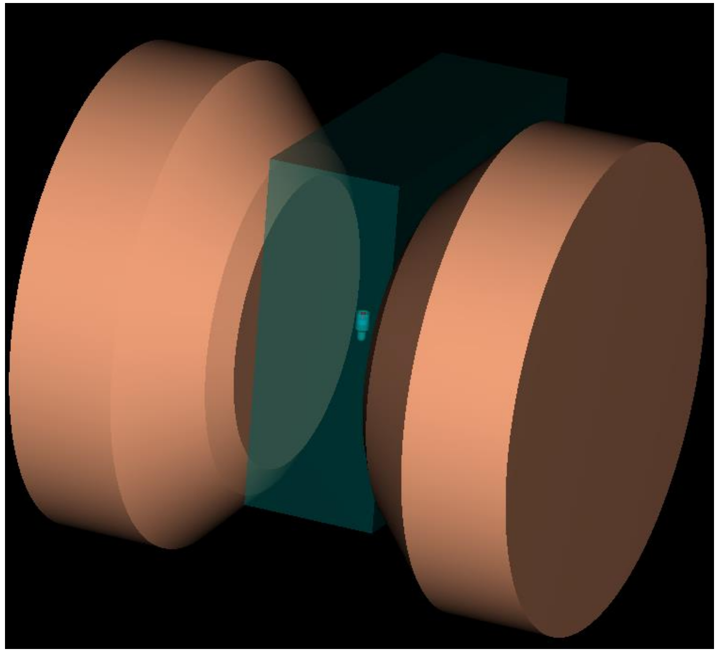
- Detectors:
  - PTW 60019 microdiamond: || orientation only w.r.t x-ray beam axis (always ⊥ to B-field)
  - PTW 31022 Pinpoint 3D chamber: ⊥ & || orientation w.r.t x-ray beam axis (always ⊥ to B-field)
- Detectors placed with reference point at:
  - at 5cm depth in water at isocentre (centre-of-poles) [CAX]
  - at 5cm depth offset up/down to position of max response [MAX]
    - 0.35T (‘reverse’ current): -0.75mm down
    - 1.5T (‘reverse’ current): -1.75mm down
    - (same offsets up for ‘forward’ current)
- Field sizes (6MV x-rays):
  - square: 1x1, 2x2, 3x3, 4x4, 5x5, 7x7 cm
  - rectangular: 1x4, 4x1, 10x1, 10x4 cm
    - offset: as square +/- 5 cm & +/-10 cm (to be done)

- B-fields : 0, 0.35 & 1.5T (‘reverse’ & ‘forward’ current)



‘Reverse’ current B field

‘Forward’ current B field



Detector response simulations (NPL EM Setup)

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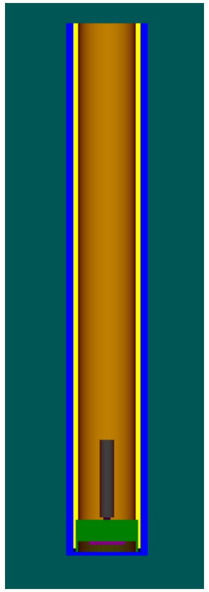
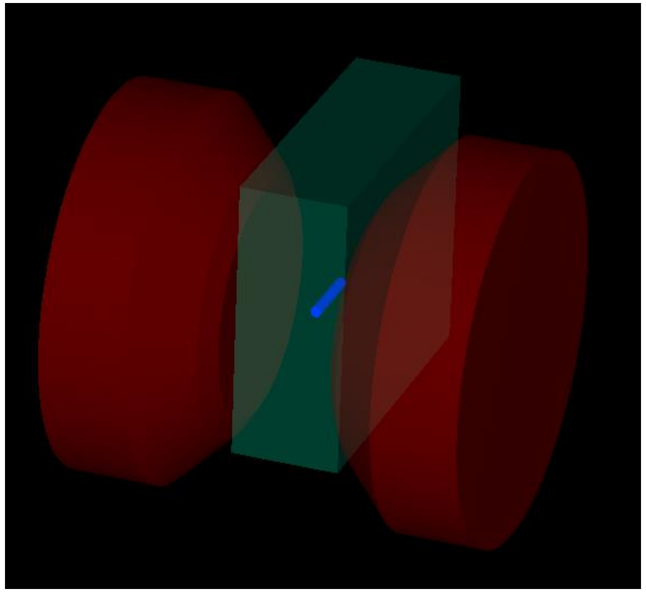
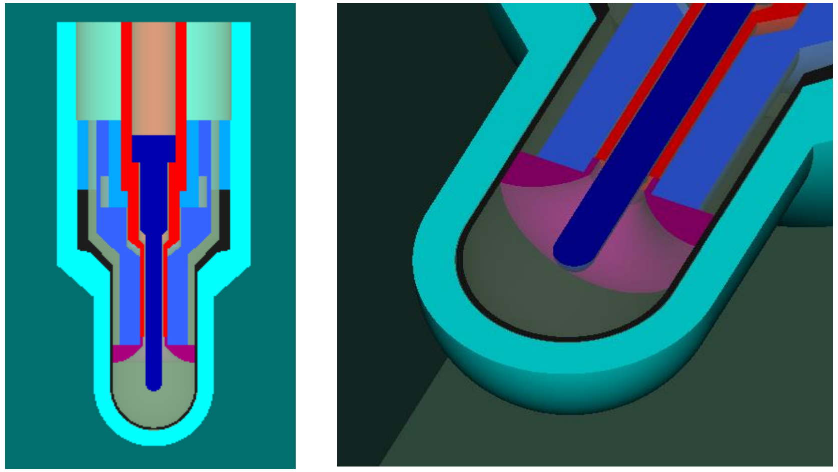
- egs_chamber (with Malkov EEMF macros) (EGSnrc 2020)
- Validated source model for each field size (6MV x-rays): used to generate multiple phase space data.
- Detailed detector models constructed:
  - *PTW 60019 microdiamond:*
    - from PTW drawings (including brass contact pins etc)
    - dose to sensitive region: 2.2 (diam) x 0.001 (th) mm
  - *PTW 31022 pinpoint 3D:*
    - dead volume excluded from the scoring region (COMSOL)
    - dose to chamber cavity (excluding dead volume region)
- Dose–to-water in thin disc (2mm diam) scored at detector position in all cases.
- Variance Reduction (VR) techniques used:
  - *Photon cross-section enhancement (XSCE), Intermediate Phase-Space Scoring (IPSS), Range based Russian Roulette (RR)*
- Type A uncertainties typically < 0.1% (k=1)
- NPL HPC (minerva) utilised



microdiamond



Electromagnet setup



Pinpoint 3D

Detector model validation

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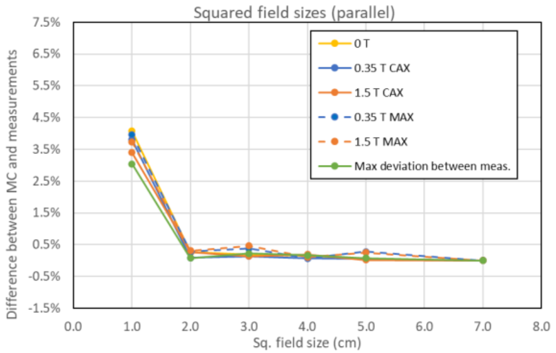
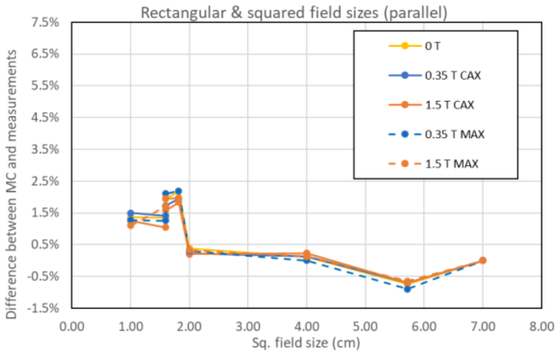
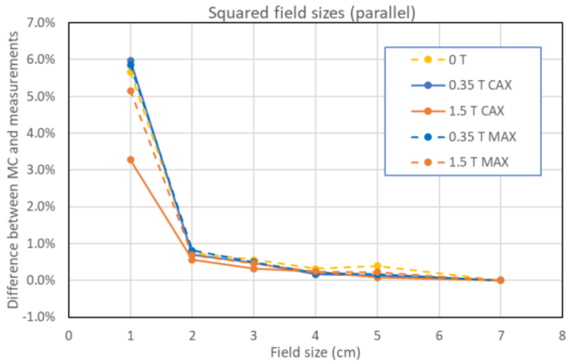
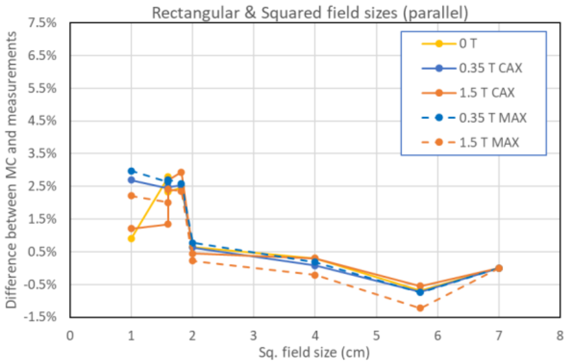
PTW 60019 microdiamond

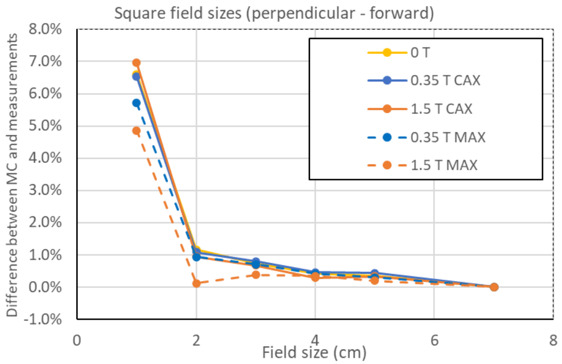


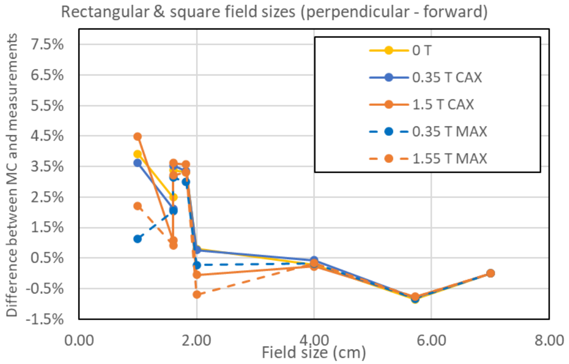


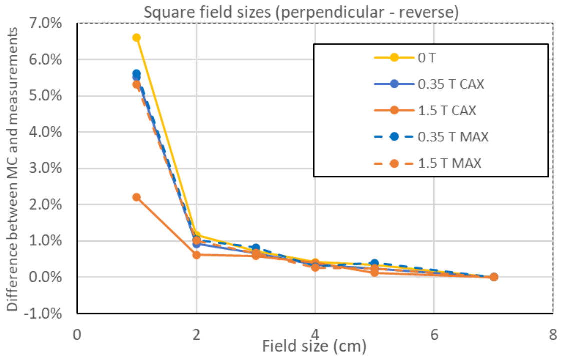
PTW 31022 pinpoint 3D

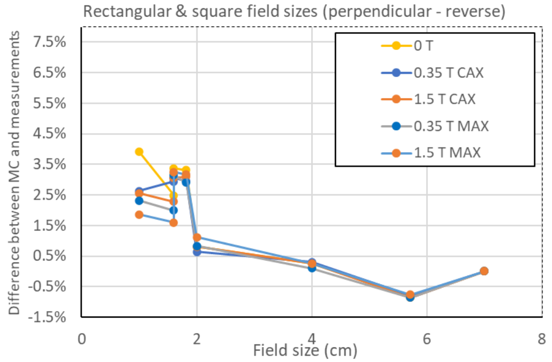












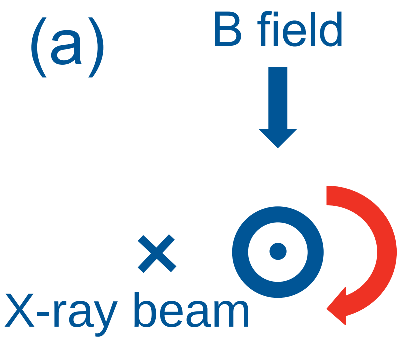
In general

- For field sizes ≥ 2 x 2 cm^2 the agreement is good, within ±1%
- For field sizes < 2 x 2 cm^2 the discrepancies are large, i.e. for 1 x 1 cm^2 from 4% to 7%

Detector intra-type response variation

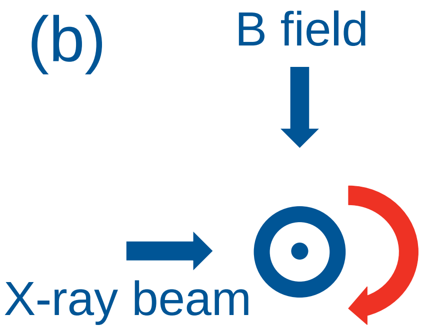
- Two detectors
  PTW 31022 Pinpoint 3D chamber x 3
  PTW 60019 microdiamond x 6
- All measurements at CAX
- Field sizes: 1x1, 1.5x1.5, 2x2, 3x3, 5x5 cm^2
- Two setups:
  PTW 60019 microdiamond: || orientation only w.r.t x-ray beam axis (always ⊥ to B-field)
  PTW 31022 Pinpoint 3D chamber: ⊥ & || orientation w.r.t x-ray beam axis (always ⊥ to B-field)
- Rotational chamber response dependence
  - 0º, 90º, 180º, 270º and 360º

(a)



Detector orientation w.r.t
to beam and B field

(b)



Detector orientation w.r.t
to beam and B field

Detector intra-type response variation

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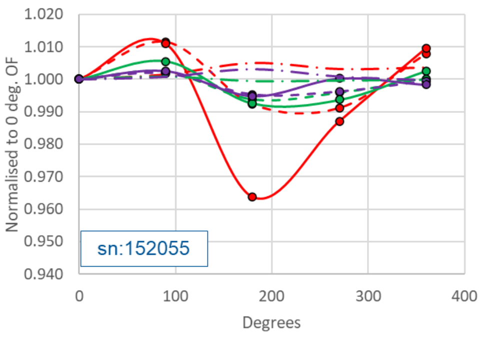
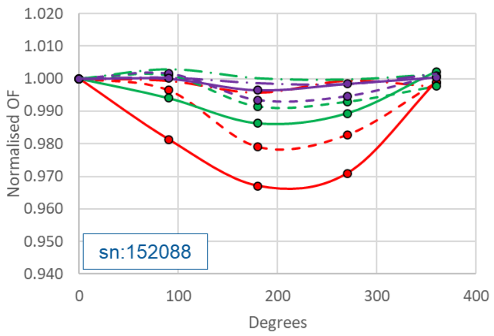
Maximum deviation between the OFs at different angles

PTW 31022 Pinpoint 3D

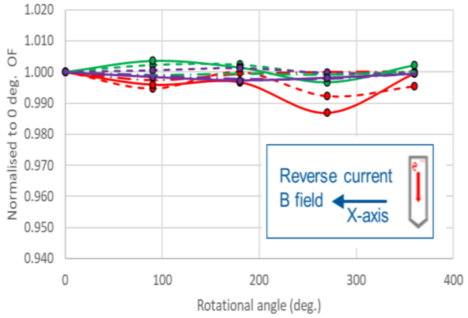
- parallel to the beam: can be as much as 4%
- perpendicular to the beam: approximately 1.5% and below

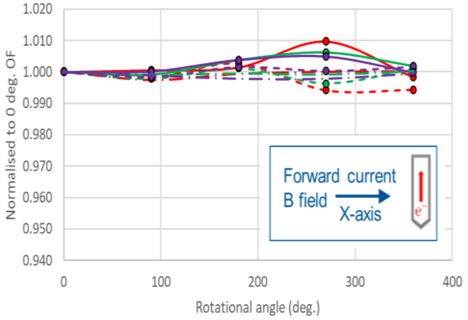
Chamber orientated parallel to the beam





Chamber orientated perpendicular to the beam





Red: 1x1
Green: 1.5x1.5
Purple: 2x2
Solid lines: 1.5 T
Dashed lines: 0.35 T
Black line: 0 T

Maximum deviation between the OFs at different angles

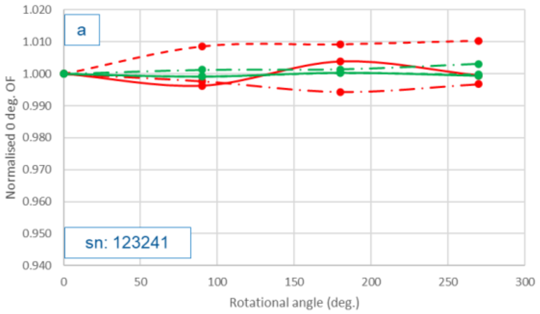
PTW 60019 microdiamond

- Parallel to the beam only: within 1%

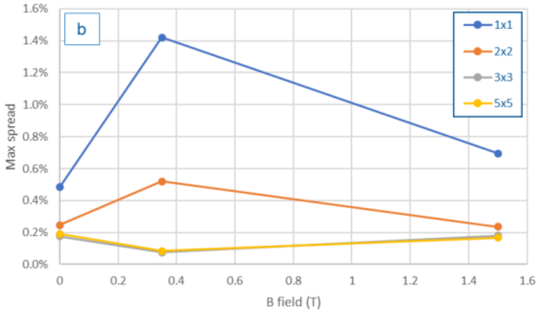
Maximum spread between six same type microdiamond detectors is 1.4% at 0.35 T.

Detector orientated parallel to the beam

Angular rotation

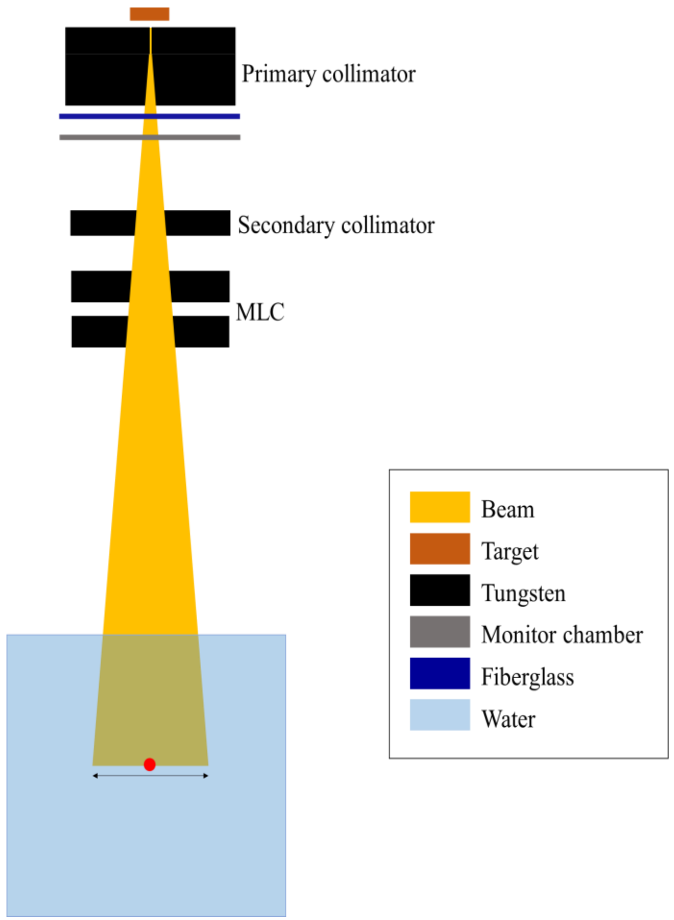


Maximum deviation between 6 same type PTW 60019 microdiamond



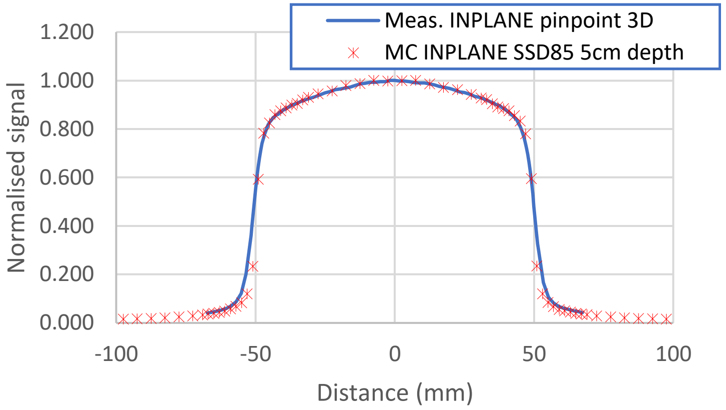
Results

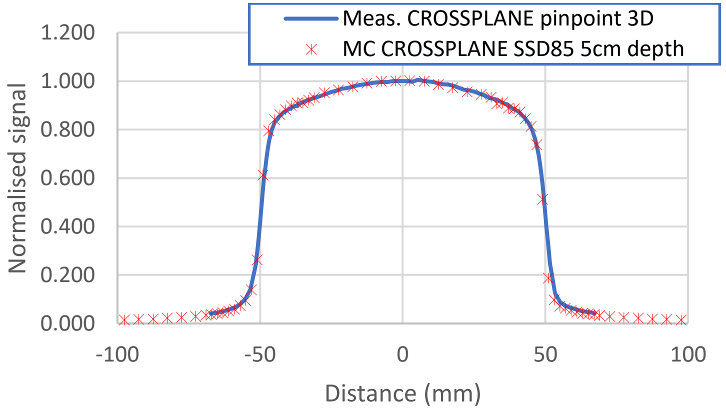
ViewRay MRIdian
Accelerator head model

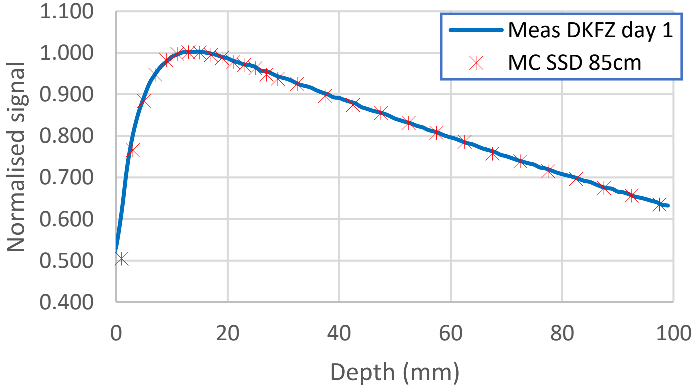


Accelerator head model of the ViewRay MRIdian™ MRI-linac system build at NPL using EGSnrc. Sufficient for kQBQ calculations in reference beam, but for small field, more detailed model is needed and the validation requires small field profiles.

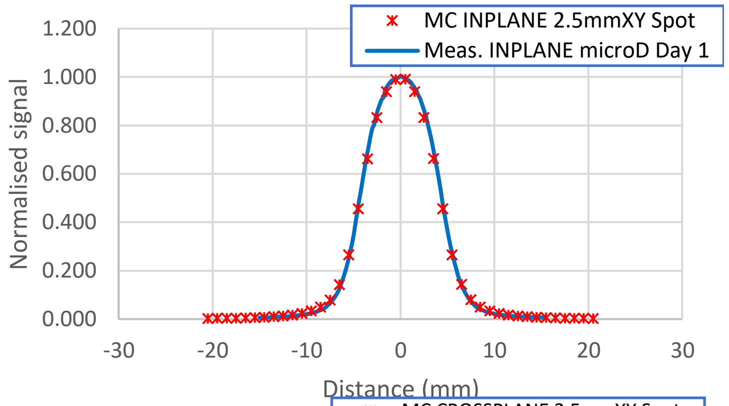
9.96 cm x 9.96cm

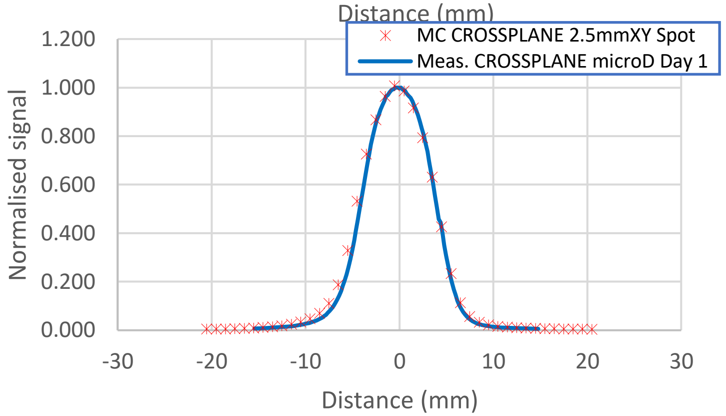


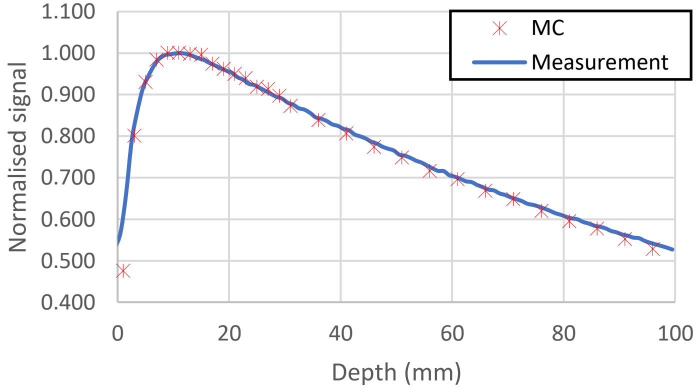




0.82x0.82







MRIdian output correction factors

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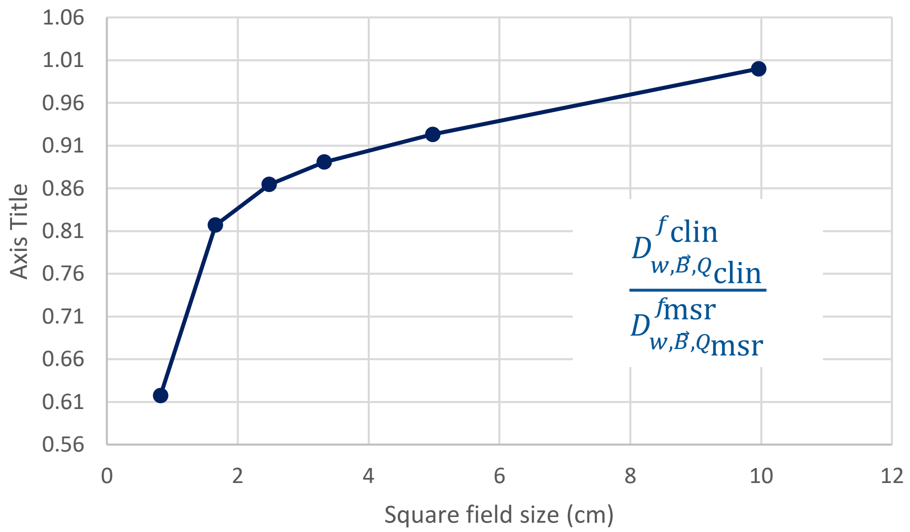

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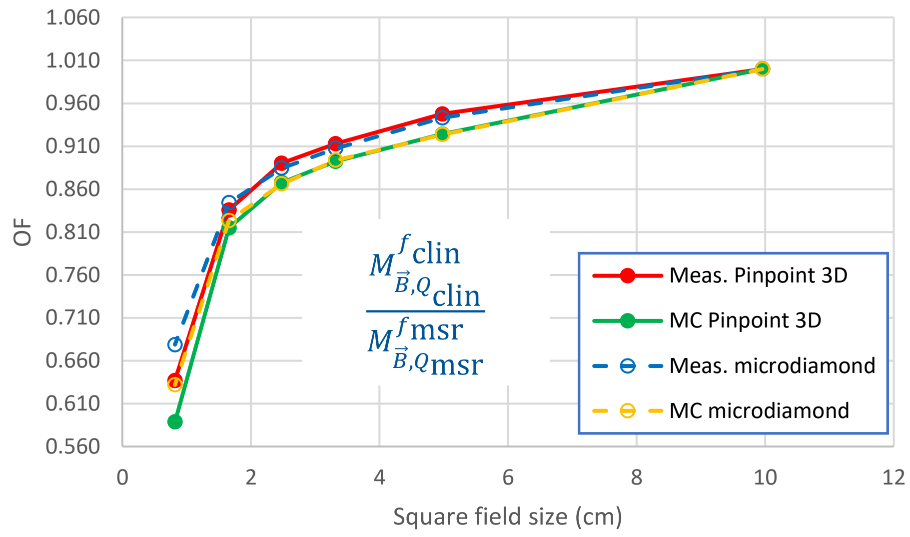
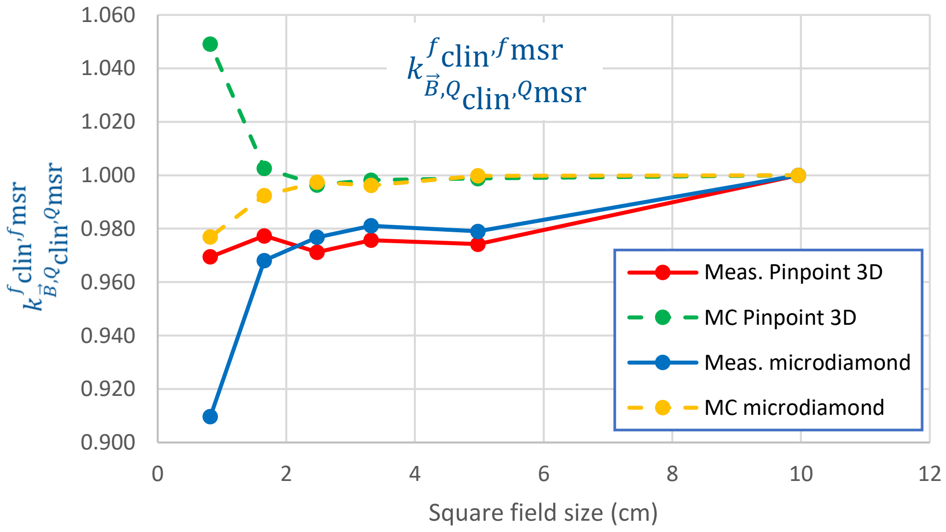
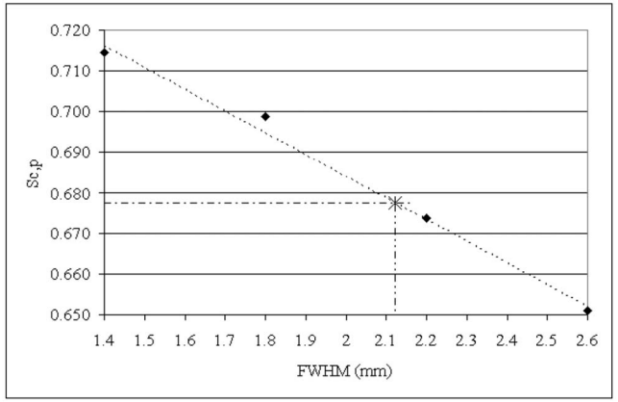




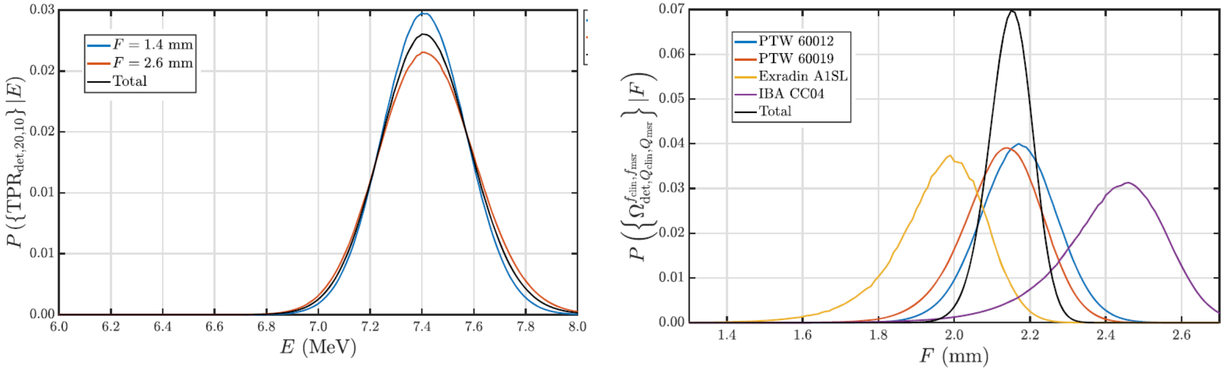
Future work

- Method proposed by Sheikh-Bagheri and Rogers (Med. Phys 29(3), March 2002) Sheikh-
  - Compare simulated against measured PDD: tune the beam energy, and lateral profiles: tune the radial intensity distribution of the electron beam (FWHM)
  - However, this method is good for standard fields and does not consider the detector dose response
- Method proposed by Francescon et al (Med. Phys. 35 (2), February 2008)
  - Applied in the context of small fields
  - Fine tune the beam energy based on the agreement of the simulated with the measured tissue-phantom ratios (TPR) and output factors (OF) using different detectors.



Francescon et al (Med. Phys. 35 (2), February 2008)

- Method proposed by Duchaine et al (Phys. Med. Biol. 67 (2022) 045007) extend the Francescon et al methodology
  - introduce a new maximum likelihood estimation method to determine the energy and radial intensity distribution of the electron beam.



Duchaine et al (Phys. Med. Biol. 67 (2022) 045007)

Thank you for your attention

National Physical Laboratory

Acknowledgment

- Michael Homer (NPL)

Department for Business, Energy & Industrial Strategy

FUNDED BY BEIS

The National Physical Laboratory is operated by NPL Management Ltd, a wholly-owned company of the Department for Business, Energy and Industrial Strategy (BEIS).

MRgRT Metrology

This project 19NRM01 MRgRT-DOS has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme.