Monte Carlo simulations of output correction factors in the presence of magnetic field in MRI linacs using Penelope

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Extension of TRS-483 formalism for output factors (*OF*) in small fields

$$D_{w,Q_{clin}}(S_{eq}) = M_{Q_{clin}}(S_{eq}) \cdot N_{D,w,Q_0} \cdot k_{Q_{msr},Q_0}^{f_{msr},f_{ref}} \cdot k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}(S_{eq})$$

$$D_{w,Q_{msr}}(S_{eq,msr}) = M_{Q_{msr}} \cdot N_{D,w,Q_0} \cdot k_{Q_{msr},Q_0}^{f_{msr},f_{ref}}$$

:

$$OF(S_{eq}) = \frac{D_{w,Q_{clin}}(S_{eq})}{D_{w,Q_{msr}}(S_{eq,msr})} = ROF(S_{eq}) \cdot k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}(S_{eq})$$

Legend

Readings

Calibration coefficient

k_Q factor

Output correction factor

kB factor

Extension of TRS-483 formalism for output factors (*OF*) in small fields

$$D_{w,Q_{clin}}\left(S_{eq},B\right) = M_{Q_{clin}}(S_{eq},B) \cdot N_{D,w,Q_0} \cdot k_{Q_{msr},Q_0}^{f_{msr},f_{ref}} \cdot k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}(S_{eq}) \cdot k_{\vec{B},Q_{clin}}(S_{eq})$$

$$D_{w,Q_{msr}}\left(S_{eq,msr},B\right) = M_{Q_{msr}}(B) \cdot N_{D,w,Q_0} \cdot k_{Q_{msr},Q_0}^{f_{msr},f_{ref}} \cdot k_{\vec{B},Q_{msr}}$$

:

$$OF\left(S_{eq},B\right) = \frac{D_{w,Q_{clin}}\left(S_{eq},B\right)}{D_{w,Q_{msr}}(S_{eq,msr},B)} = ROF\left(S_{eq},B\right) \cdot k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}(S_{eq}) \cdot \frac{k_{\vec{B},Q_{clin}}(S_{eq})}{k_{\vec{B},Q_{msr}}}$$

Legend

Readings

Calibration coefficient

k_Q factor

Output correction factor

kB factor

Extension of TRS-483 formalism for output factors (*OF*) in small fields

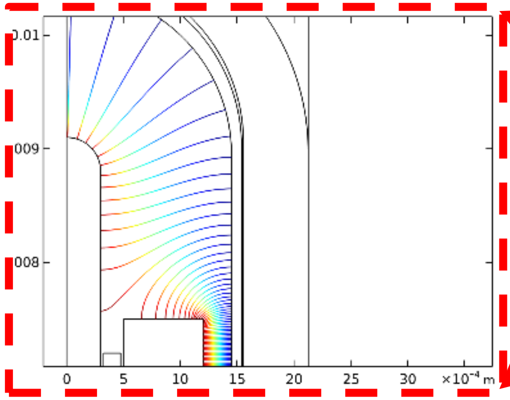
$$k^{f_{clin},f_{msr}}_{Q_{clin},Q_{msr}}\left(S_{eq},B\right) = k^{f_{clin},f_{msr}}_{Q_{clin},Q_{msr}}\left(S_{eq}\right) \cdot \frac{k_{\vec{B},Q_{clin}}\left(S_{eq}\right)}{k_{\vec{B},Q_{msr}}} = \overbrace{k^{f_{clin},f_{msr}}_{Q_{clin},Q_{msr}}\left(S_{eq}\right)}^{\boxed{\text{TRS-483}}} \cdot \overbrace{k_{\vec{B},Q_{clin,norm}}\left(S_{eq}\right)}^{\boxed{\text{This study}}}$$

Purpose

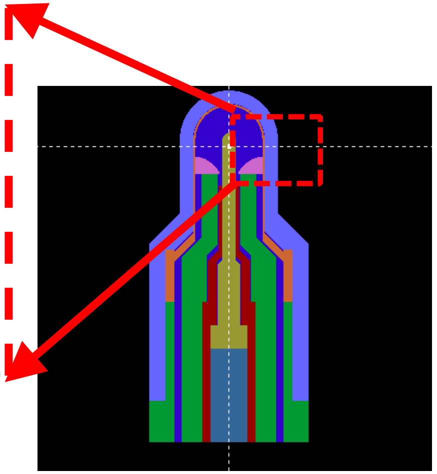
To calculate output correction factors for small field dosimetry in MR-linacs (i.e. with *B* present) using existing output correction factors determined according to TRS-483 (i.e. without *B* present)

Monte Carlo model for $k_{\vec{B},Q_{clin,norm}}(S_{eq})$

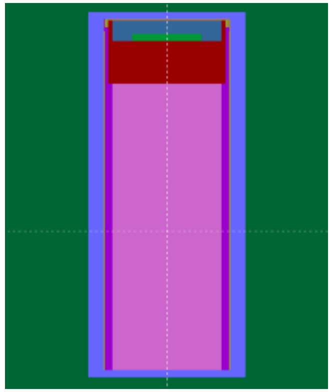
- PENELOPE 2014 with B-field implemented
- Geometry and materials defined based on manufacturer blueprints
  - Ion chamber PTW 31022
  - Diamond detector PTW 60019
- Sensitive volume is cavity volume – <u>dead volume</u>
- Dead volume determined with Finite Element Method (FEM)
- Phase Space files of Elekta Unity™ MRL for: 0.5, 0.7, 1.0, 1.2, 1.5, 2.0 and 10.0 cm field sides



FEM for <u>dead volume</u>

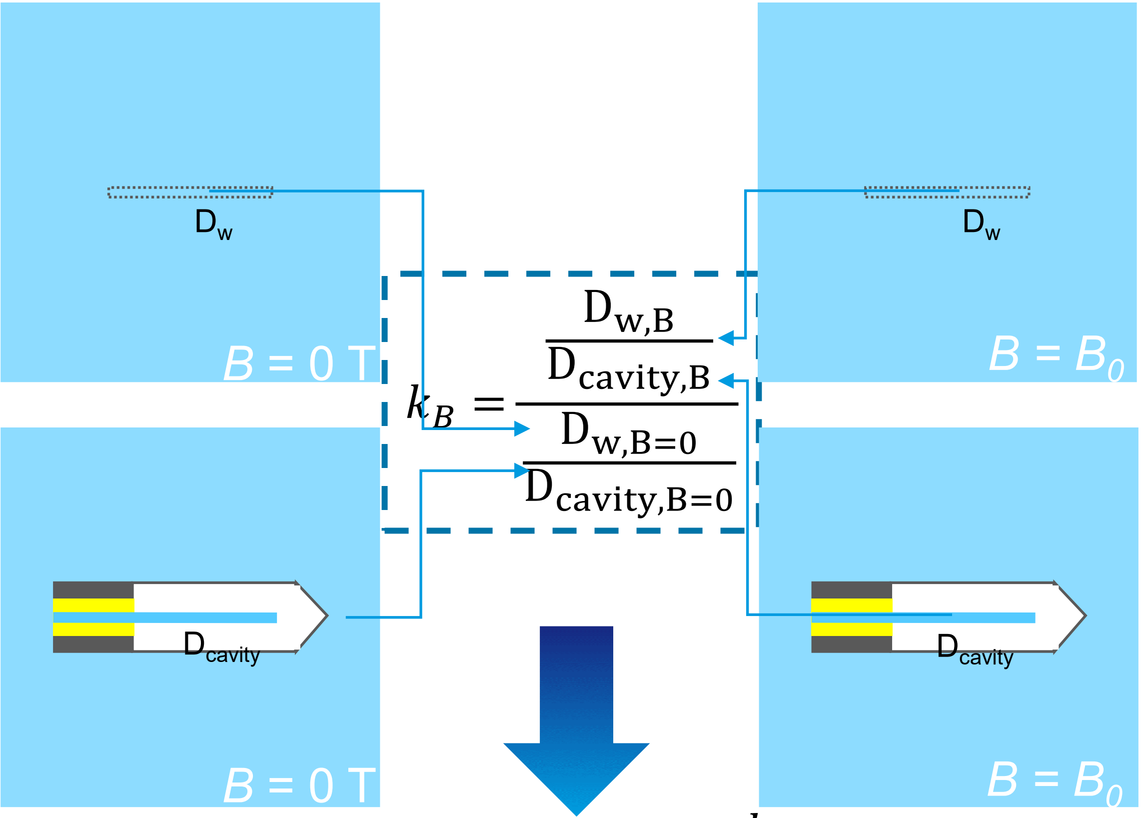


PTW 31022



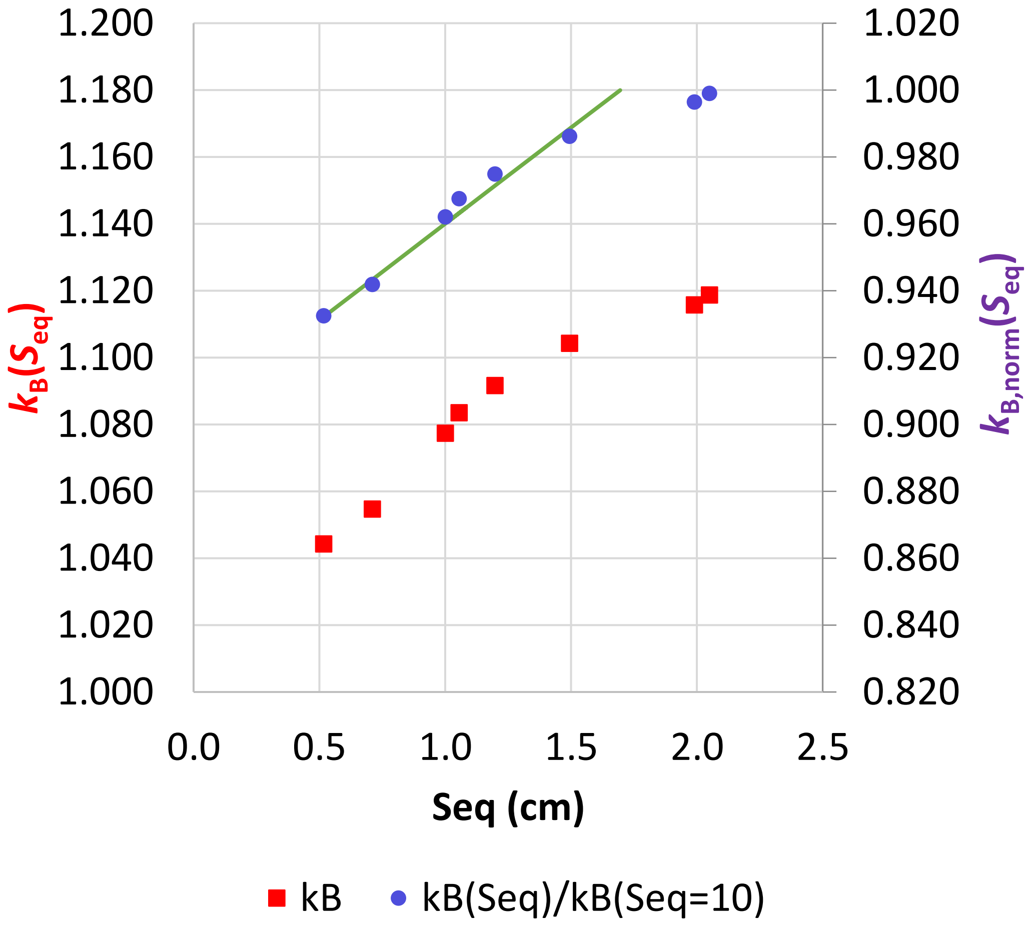
PTW 60019

Simulation and fitting of $k_{\vec{B},Q_{clin,norm}}(S_{eq})$



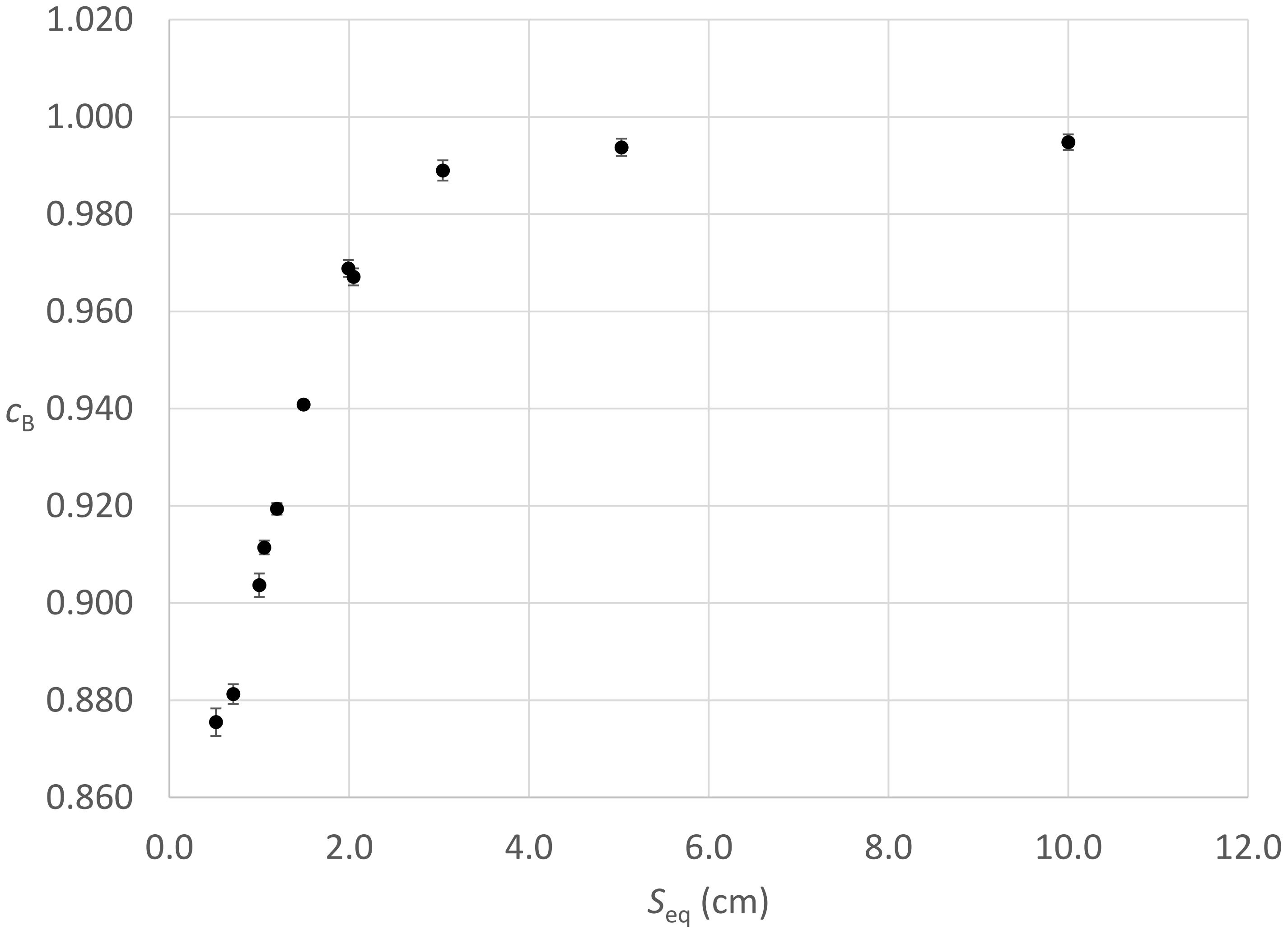
$$k_B = \frac{\dfrac{D_{w,B}}{D_{cavity,B}}}{\dfrac{D_{w,B=0}}{D_{cavity,B=0}}}$$

$$\frac{k_{\vec{B},Q_{clin}}(S_{eq})}{k_{\vec{B},Q_{msr}}} = \underbrace{\frac{k_{\vec{B},M,Q_{clin}}(S_{eq})}{k_{\vec{B},M,Q_{msr}}}}_{\text{Detector dependent}} \underbrace{\frac{c_{\vec{B}}(S_{eq})}{c_{\vec{B}}(msr)}}_{\text{Detector independent}}$$

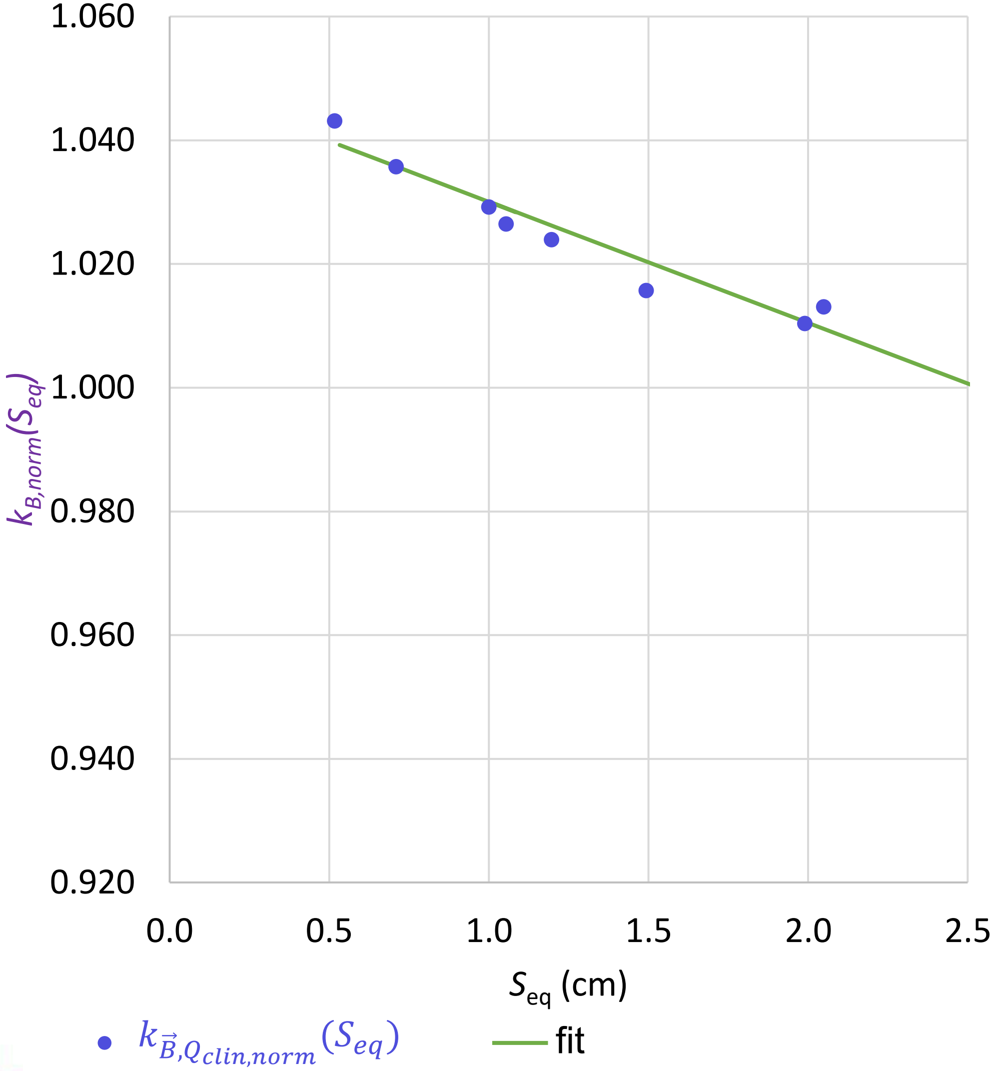


$k_{\vec{B},Q_{clin,norm}}(S_{eq})$: linear fit below threshold $S_{eq,0}$

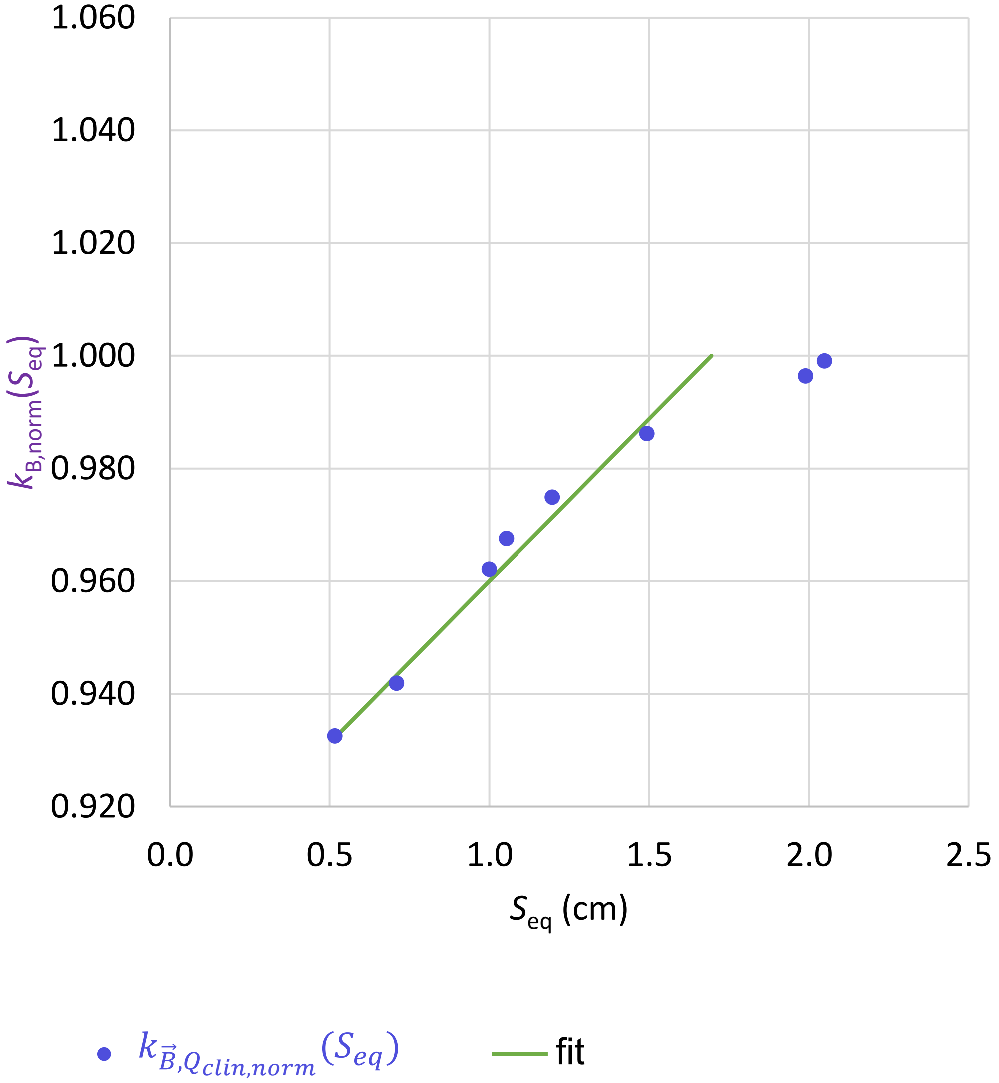
$c_{\vec{B}}$ as a function of field size



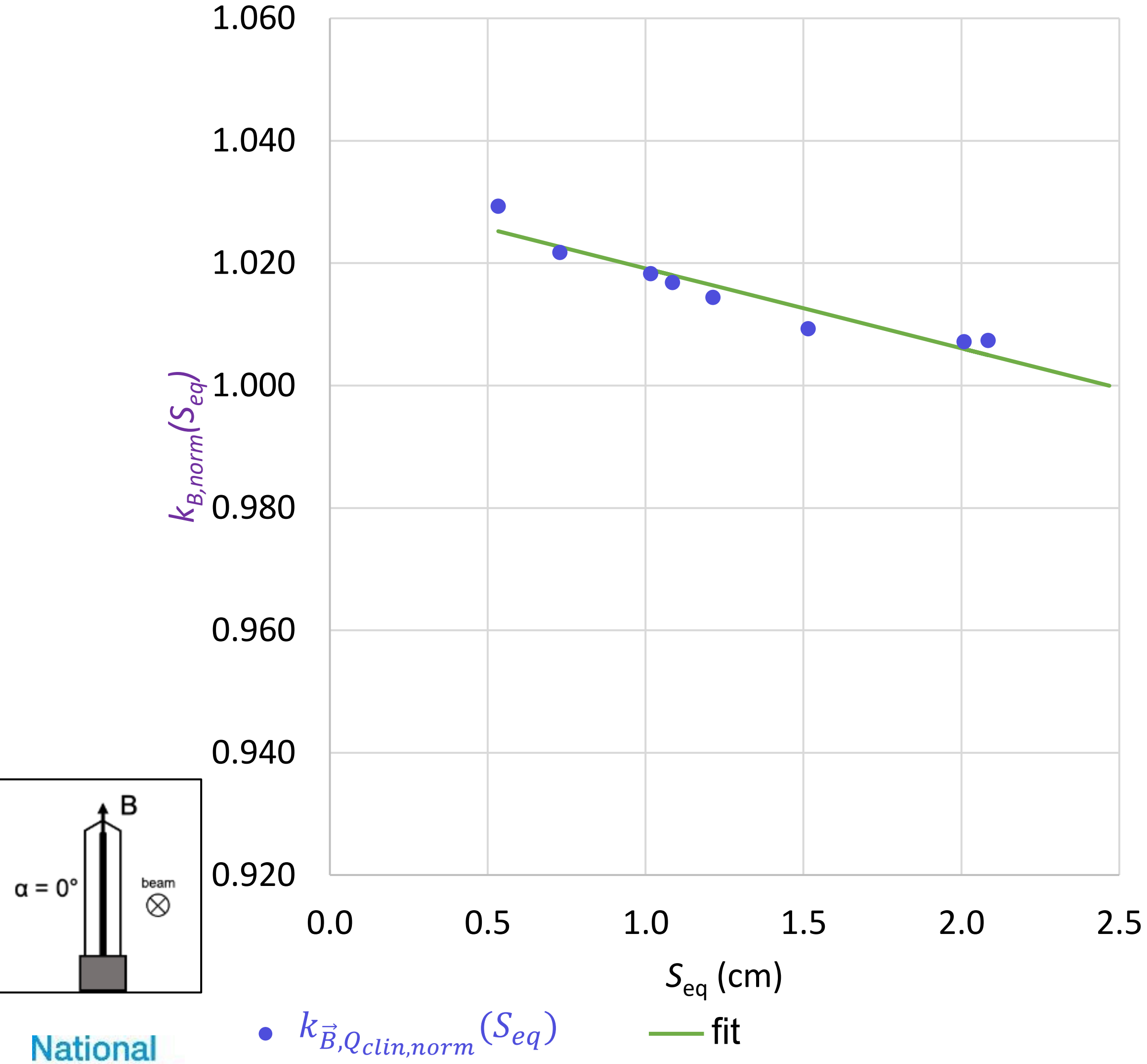
PTW 31022 axial



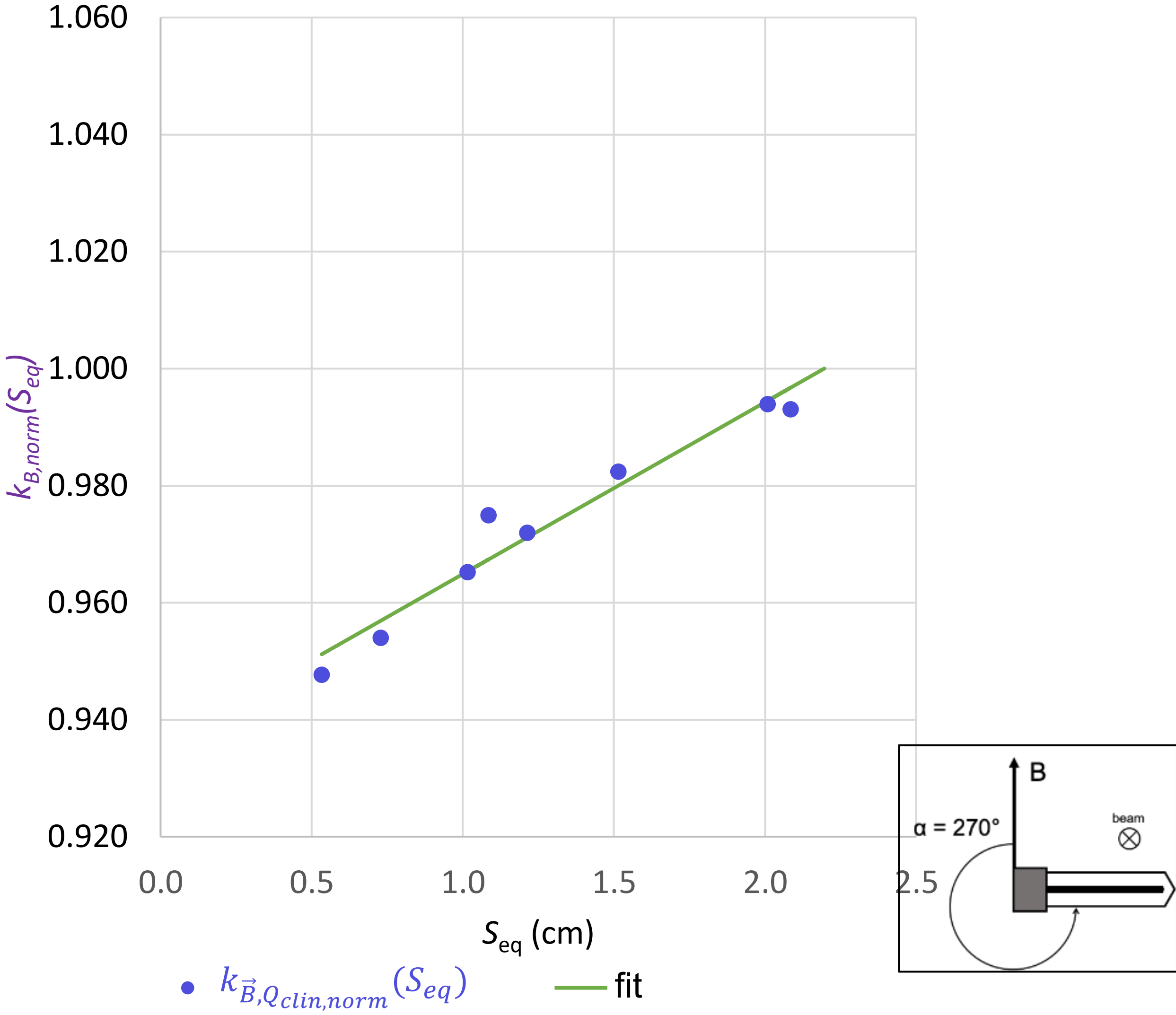
PTW 60019 axial



PTW 31022 parallel



PTW 31022 perpendicular



Measurements of output factors (*OF*) and uncertainty evaluation

- $ROF\left(S_{eq}, B\right)$'s measured for MRL Unity:
  - PTW 60019 (axial),
  - PTW 31022 (axial, perpendicular, parallel)

- Nominal square field sizes: 0.5, 0.7, 1.0, 1.2, 1.5, 2.0, 3.0, 4.0, 5.0 and 10.0 cm^2 => $ROF\left(S_{eq}\right)$

- 3d dose profiles measured with PTW 60019 =>
  - S_{eq} (50% level B =1.5 T profile)
  - $k_{\vec{B},Q_{clin,norm}}\left(S_{eq}\right)$ from fit
  - $k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}\left(S_{eq}\right)$ from data of Casar *et al*. Med. Phys (2019, 2020)

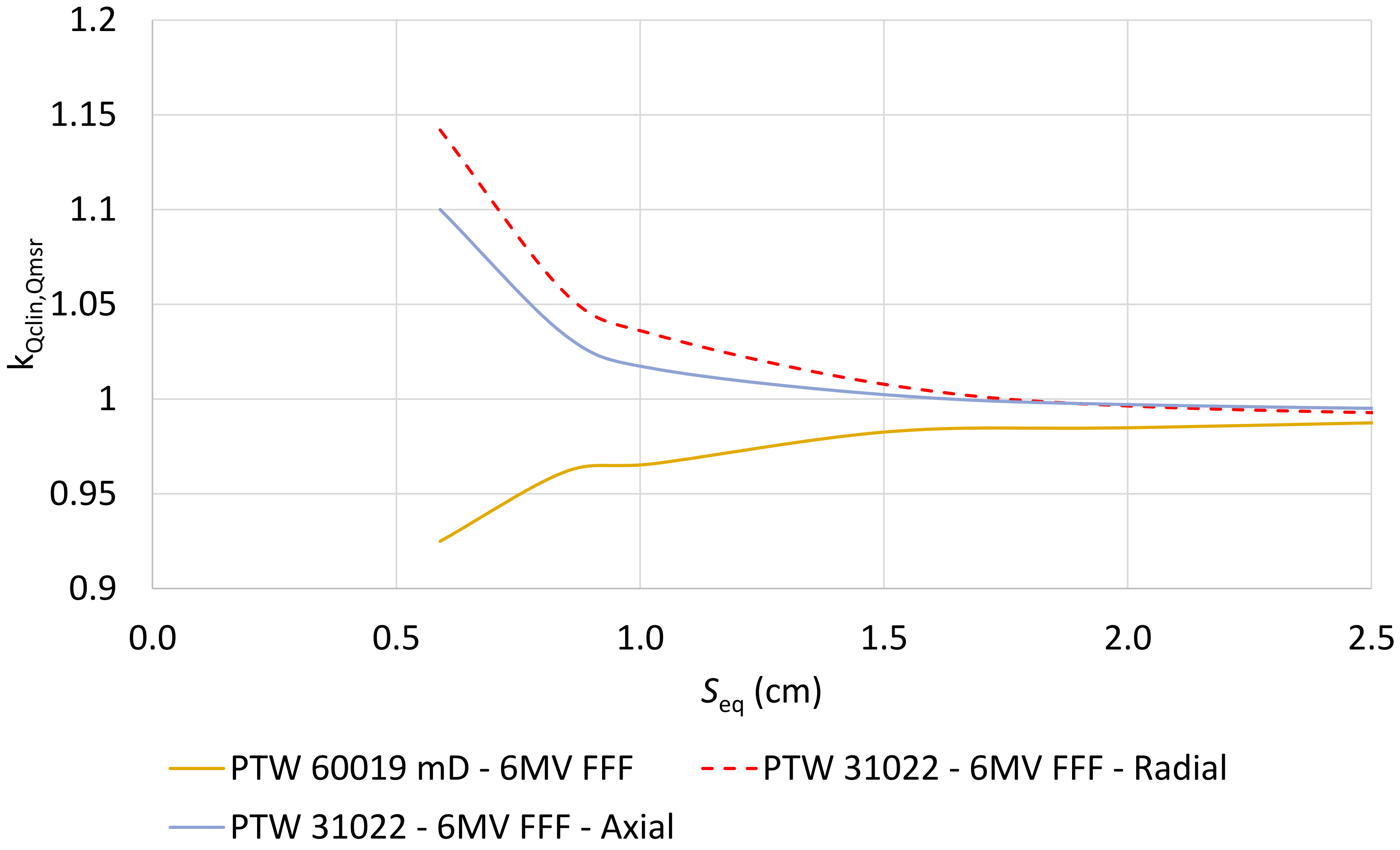
- $OF\left(S_{eq}\right) = ROF\left(S_{eq}\right) \cdot k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}\left(S_{eq}\right) \cdot k_{\vec{B},Q_{clin,norm}}\left(S_{eq}\right)$

	u_A (%)	u_B (%)
$ROF\left(S_{eq}, B\right)$	0.14	0.0 – 1.0
Recombination correction: k_s		0.08
Output correction factor $k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}\left(S_{eq}\right)$ (i.e. B = 0.0 T)		0.8 – 1.8
$k_{\vec{B},Q_{clin,norm}}\left(S_{eq}\right)$		0.7 – 0.8
		1.1 – 2.2

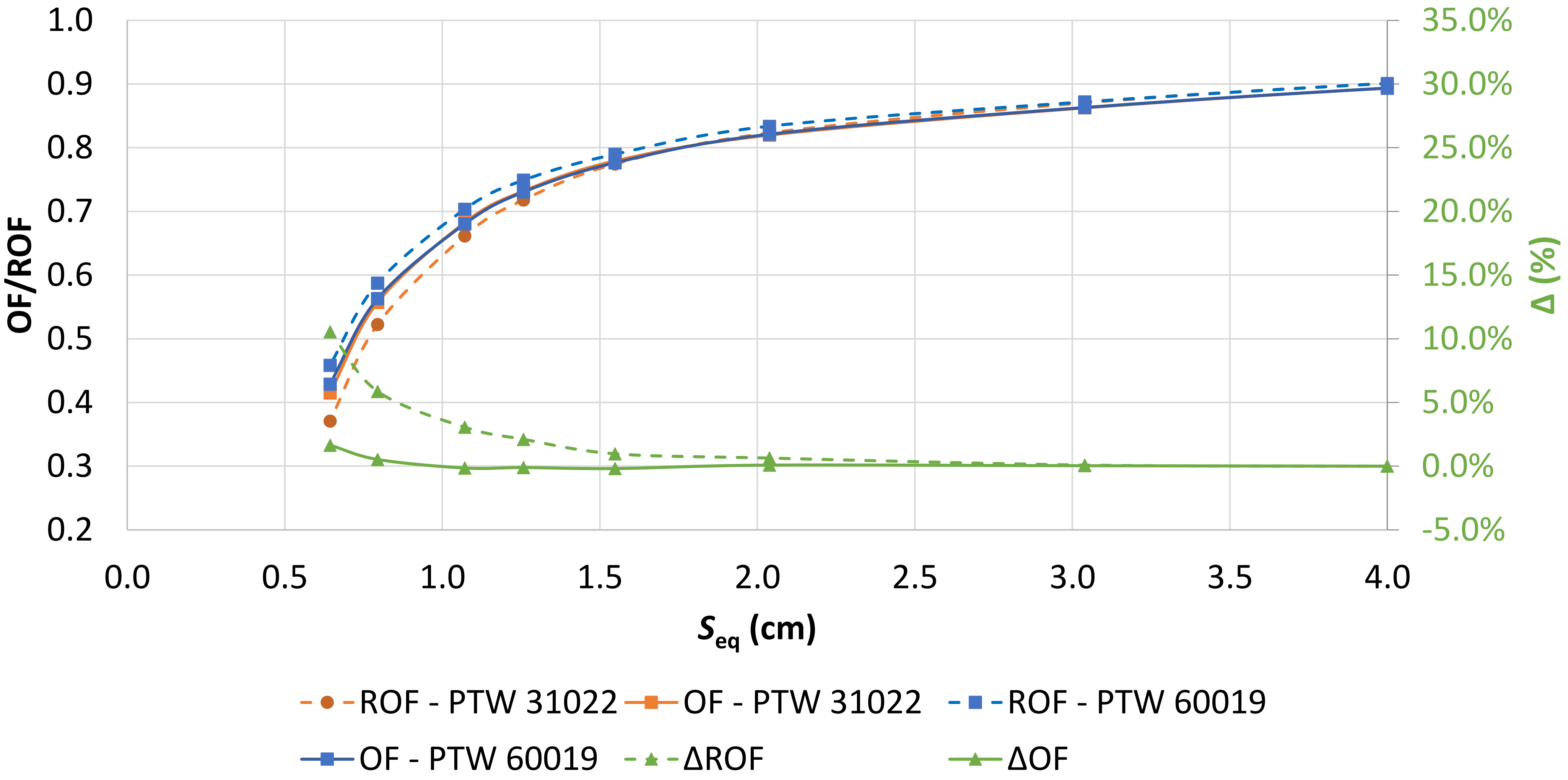
Uncertainty budget

- Uncertainty *ROF* from positioning and variation in reading
- Uncertainty output correction factor Casar *et al*. Med. Phys (2019, 2020)
- Uncertainty $k_{\vec{B},Q_{clin,norm}}\left(S_{eq}\right)$ from fit

$k_{Q_{clin},Q_{msr}}^{f_{clin},f_{msr}}(S_{eq})$: PTW 31022 and 60019 (Casar *et al.*)

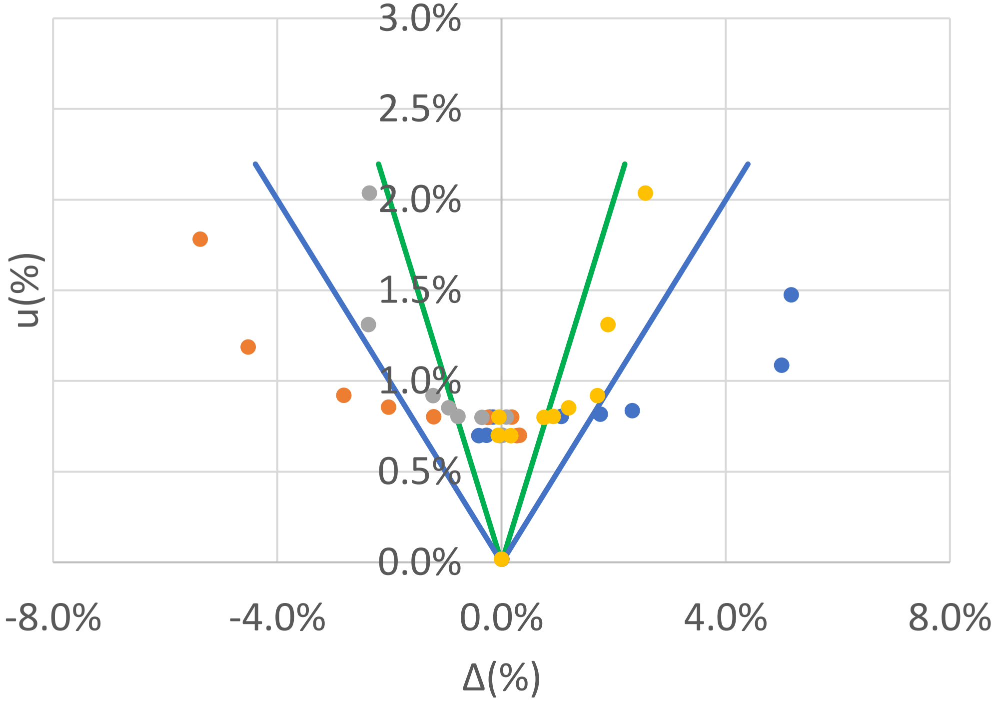


OF data B=0.0 T

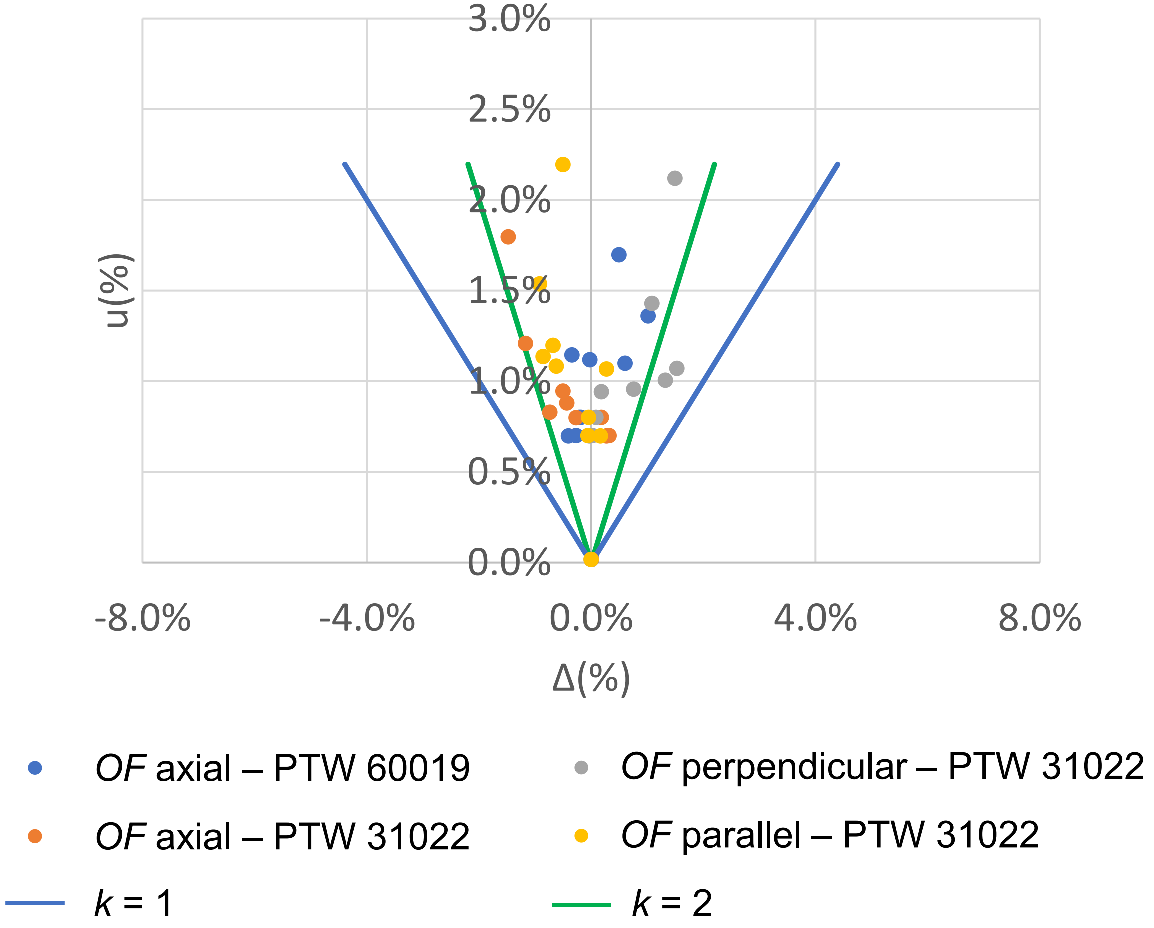

OF/ROF
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
S_{eq} (cm)
35.0%
30.0%
25.0%
20.0%
15.0%
10.0%
5.0%
0.0%
-5.0%
Δ (%)
ROF - PTW 31022
OF - PTW 31022
ROF - PTW 60019
OF - PTW 60019
ΔROF
ΔOF

OF data B=1.5 T

$$OF\left(S_{eq},B\right) = ROF\left(S_{eq},B\right) \cdot k^{f_{clin},f_{msr}}_{Q_{clin},Q_{msr}}\left(S_{eq}\right) \cdot \cancel{k_{\vec{B},Q_{clin,norm}}\left(S_{eq}\right)}$$



$$OF\left(S_{eq},B\right) = ROF\left(S_{eq},B\right) \cdot k^{f_{clin},f_{msr}}_{Q_{clin},Q_{msr}}\left(S_{eq}\right) \cdot k_{\vec{B},Q_{clin,norm}}\left(S_{eq}\right)$$



Δ: difference between *OF* and mean *OF* (per field size)
u: uncertainty on Δ

Conclusion

- A method to calculate output correction factors for MR-linacs was developed
- The method is based on existing data for output correction factors for conventional linacs and an additional correction $k_{\vec{B},Q_{clin,norm}}(S_{eq})$
- $k_{\vec{B},Q_{clin,norm}}(S_{eq})$ and therefore the output correction factor in magnetic fields strongly depends on detector type and detector orientation
- The validity of the method was demonstrated by the consistency of measured OF data using the simulated $k_{\vec{B},Q_{clin,norm}}(S_{eq})$ data in combination with the data of Casar *et al. Med. Phys.* (2019, 2020)
- Uncertainty of measured *OFs* using the calculated correction factors is smaller than 2.2 % for field sides 0.5 – 2.0 cm.

Acknowledgement

- This project has received funding from the EMPIR programme, grant 19NRM01 ‘Traceable dosimetry for small fields in MR-guided radiotherapy’, co-financed by the Participating States and from the European Union’s Horizon 2020 research and innovation programme.