Acceptance and commissioning of MRI-Linacs without 3D scanning water tanks

UMC Utrecht

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University Medical Center Utrecht

Disclosures

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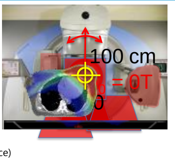
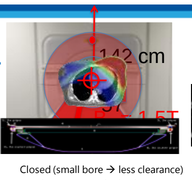
The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

Conv. Linac vs. MRI-Linac



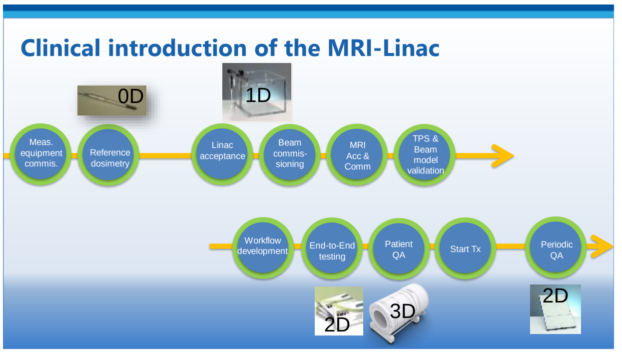


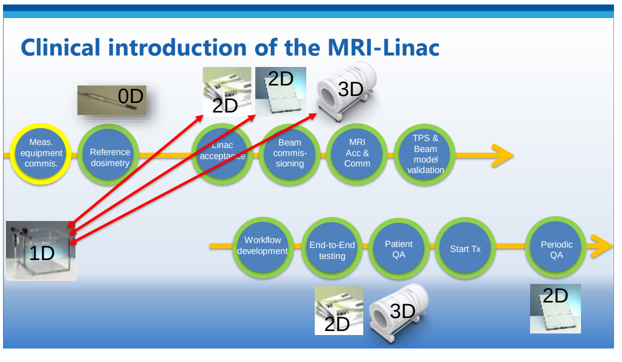
Conv. Linac

- Open (much space)
- Isocenter in the target
- Table movements possible all directions
  - Correct positioning errors using table
- Field size: 40 x 40 cm^2
- Isoc at 100 cm
- Collimator rotations possible
- Cone-beam CT
- Magnetic field: 0.0005 Tesla (Earth magn. field)
- Couch transmission (< 2%)

MRI-Linac

- Closed (small bore → less clearance)
- Fixed isocenter at the body center
- No LR and AP table movements
  - Correct positioning errors using TPS/software solutions
- Field size: 57 x 22 cm^2
- Isoc at 143.5 cm
- No collimator rotations
- MR imaging
- Magnetic field: 1.5 Tesla (= 30000 x Earth magn. Field)
- Couch transmission (< 26%)


Clinical introduction of the MRI-Linac
0D
1D
Meas. equipment commis.
Reference dosimetry
Linac acceptance
Beam commis-sioning
MRI Acc & Comm
TPS & Beam model validation
Workflow development
End-to-End testing
Patient QA
Start Tx
Periodic QA
2D
3D
2D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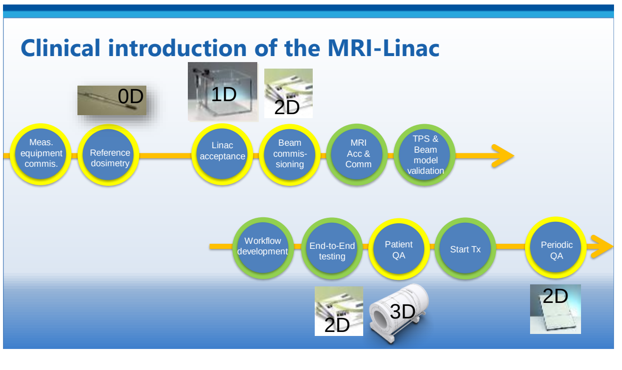
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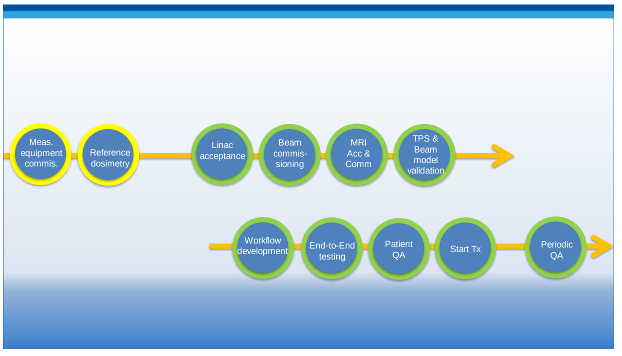
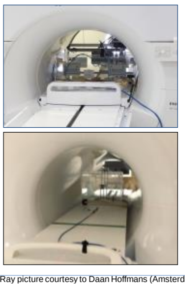


Considerations for measuring in an MRI-linac

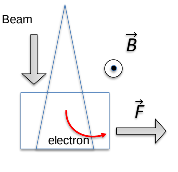


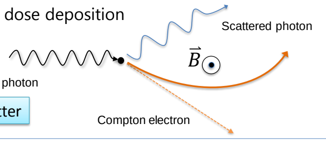
- Less clearance
  - Equipment should be set up on the couch
  - 130 (length) x 70 (diameter) cm
- Divergent from conventional field size :
  - MRIdian: 25.7 x 25.7 cm^2, Unity: 57 x 22 cm^2
  - Maximum field size does not fit in standard detectors or Water tanks
- Different source to isocenter distance
  - MRIdian: 90 cm, Unity: 143.5 cm
- No collimator rotations
  - Conventional beam alignment procedures cannot be used
  - Gantry 0 / 180 measurements are limited due to high couch transmission
- MR imaging / MV imaging
  - No light field or (officially) lasers
  - Setup of measurement equipment requires new methods
  - RF safety
- Strong magnetic field:
  - MRIdian: 0.35T (= 7000 x Earth magn. Field)
  - Unity: 1.5 Tesla (= 30000 x Earth magn. Field)
  - Detectors behave differently in strong magnetic fields

ViewRay picture courtesy to Daan Hoffmans (Amsterdam UMC)

Dose delivery a magnetic field

- Photons are *not* affected by the magnetic field
- Electron trajectory is changed by the Lorentz force
- Therefore the local dose deposition will change

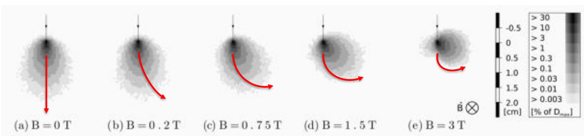




Compton scatter

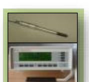
Dose delivery a magnetic field

Point spread kernels in water from 6 MV beam
Orientation: B-field perpendicular to the beam

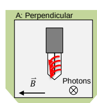


Raaijmakers *et al*., Phys. Med. Biol. **53** (2008) 909–923

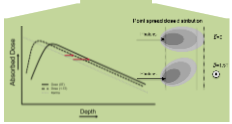
Reference dosimetry



$Co^{60} \rightarrow 7\ MV\ FFF$

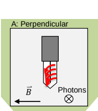


$$D^{\vec{B}}_{w,Q} = M^{\vec{B}}_{Q} \times N_{D,w,Q_0} \times k_{Q,Q_0} \times c_{\vec{B}} \times k_{\vec{B},M,Q}$$

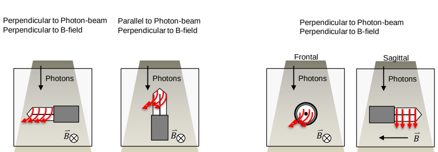


Van Asselen et al 2018 PMB **63** (12) O'Brien et al 2016 MedPhys **43** (8)

Detector response in a high magnetic field



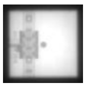
$k_{\vec{B},M,Q}$

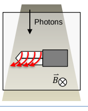


Detector response depends on orientation of beam and B0 (0 – 5%)

Affects Reference dosimetry & Water tank measurements

Relative dosimetry using a water tank





- Setup using projection images from on-board MV imager
- Alignment cannot rely on field edges
- Large field size. Use of two detectors
- Less clearance means shorter PDDs

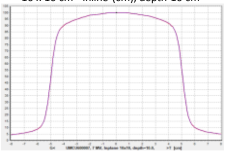
- Detector response changes
- EPOM changes in B0 field and photon beam directions
- Angular variation increases: large fields and off axis fields
- The water tank, motors etc influences the magnetic field
- Continuous moving detectors induces Eddy currents
- Location of reference chamber: Mobile structures affects the scattered electrons above the tank

Relative dosimetry using a water tank

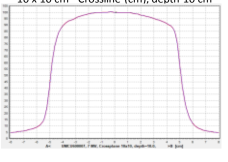
- Issues are known and can be corrected / prevented
- Perfect reference other detector arrays / film

- Crossline symmetry is perturbed by Lorentz force

10 x 10 cm² inline (cm), depth 10 cm

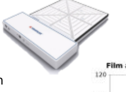


10 x 10 cm² Crossline (cm), depth 10 cm



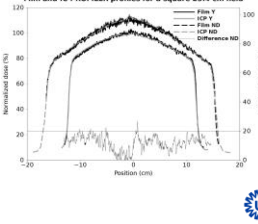
BistroMath software, Freeware by Theo van Soest

Detector arrays
Sun Nuclear IC profiler



- Minimal changes to the design
  - Power supply on extension
- Comparisons with/wo B-field

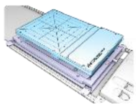
- Detector properties
  - Short term reproducibility
  - Dose response linearity
  - Saturation and recombination
  - Warm-up effects
  - Chamber orientations
  - Influence of ionization chamber shape

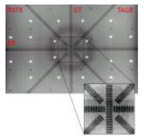


- ICProfiler versus Gafchromic EBT2

Smit, K. et al. PMB **59** (2014)

Detector arrays
PTW StarCheck maxi MR

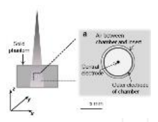


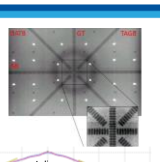


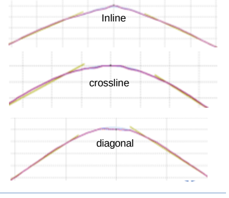
- Minimal changes to the design
  - Power supply
  - Network connection
- Detector properties
  - Short term reproducibility (no difference)
  - Dose response linearity (no difference)
  - Warm-up effects (no difference)
  - Chamber orientations
    - Rotational dependence
    - Difference between AB and GT profiles (2.1% with B0, 0.4% wo B0)
  - Saturation and recombination (no difference)

Perik, T.J. et al. PMB **63** (2018)

Detector arrays
Issues to consider





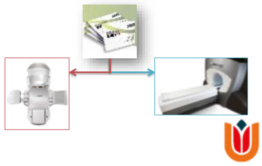


- Air-gaps around detectors
  - Response differs between detectors
  - Higher angular sensitivity
  - Partially solvable by calibration
  - MR-compatible versions has been improved
- Full scatter condition cannot always be achieved
- Detector geometry and alignment affects reading
  - AB, GT and diagonal response differs
  - Partially solvable by calibration
  - Calibration difficult due to size of detector array
- Alignment difficult due to lack of collimator rotation
  - Used by the on-board EPID and MV beam

Hackett S.L. et al. MedPhys **43** (2016) Perik, T.J. et al. PMB **63** (2018)

Film dosimetry
EBT3 suitability in magnetic field

- Very versatile
- High spatial resolution, large dose range
- Conversion of Monomers → polymers (having a dipole moment)
- Magnetic field might influence
  - Polymerization process
  - Orientation of polymers



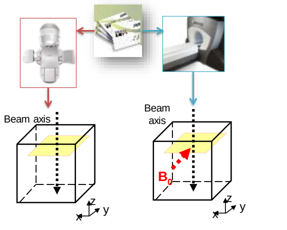
Evaluating EBT3 properties in 0.35T field
- EBT3 dose response curves
- B0-field orientation influence
- Real-time imaging influence

Courtesy to Daan Hoffmans (Amsterdam UMC)

Barten *et al* (2017), Estro 2017 OC-0231

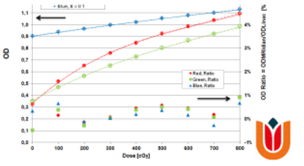
EBT3 suitability in magnetic field

Dose response curves



Optical density (OD) as function of dose

- Measurements performed in water
- N = 4
- Dose range 100 – 800 cGy
- Red, green and blue color channels assessed

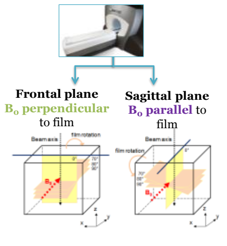


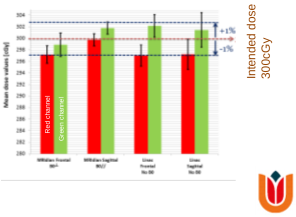
Courtesy to Daan Hoffmans (Amsterdam UMC)

Barten *et al* (2017), Estro 2017 OC-0231

EBT3 suitability in magnetic field

B0-field orientation influence





Courtesy to Daan Hoffmans (Amsterdam UMC)

Barten *et al* (2017), Estro 2017 OC-0231

GafChromic film – magnetic field effects

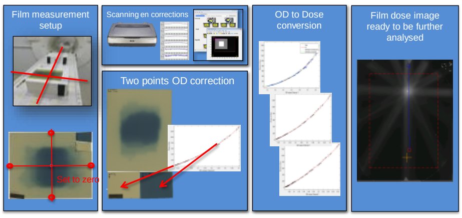
	B (T)	D (Gy)	Device	Change
Raaijmakers *et al.* (2007)	0.6/1.3	4	Linac	1-4%
Reyhan *et al.* (2015)	1.5	0-8	Linac*	4%
Wen *et al.* (2016)	1.5	1.18-4.74	Unity	No effect (2% accuracy)
Reynoso *et al.* (2016)	0.35	2-17.6	MRIdian	Up to 15%
Roed *et al.* (2017)	1.5	2-8	Co-60	<2%
Barten *et al.* (2017)	0.35	0-8	MRIdian	No effect
UMC U	0-1.5	0-3	Linac	No effect

*not irradiated in presence of a magnetic field

Raaijmakers *et al.* 2007 (PMB, Vol. 52)
Reyhan et al. 2015 (JACMP, Vol. 16)
Wen et al. 2016 (MP, Vol. 43)
Reynoso *et al.* 2016 (MP, Vol. 43)
Roed et al (2017), Estro 2017 PO-0763
Barten *et al* (2017), Estro 2017 OC-0231

Slide courtesy to Bram van Asselen

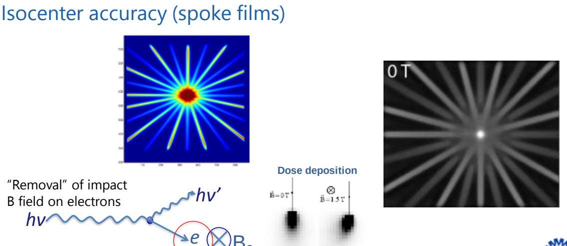
Film processing (always convert to dose)



Andre Micke *et al.* MedPhys 2011

Linac QA measurements

Isocenter accuracy (spoke films)



van Zijp *et al.* PMB (2016)

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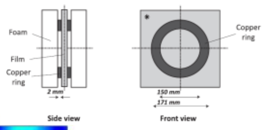
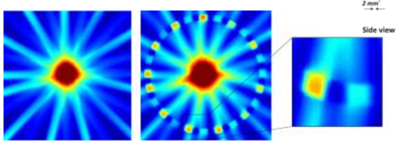
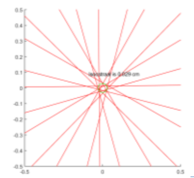






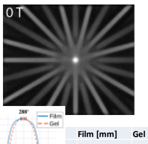
Isocenter radius = 0.3 mm

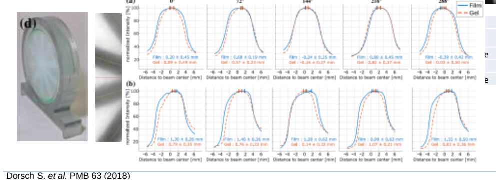
(std. linac = 0.5 – 1.0 mm)

van Zijp *et al.* PMB (2016)

Machine QA using polymer gel

- Isocenter accuracy alignment
  - Feasibility of polymer gel-based measurements of radiation isocenter accuracy in magnetic fields
  - Take into account the shift of the magnetic field





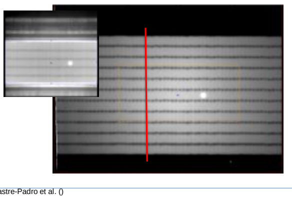
	Film [mm]	Gel [mm]
	0.39 ± 0.01	0.44 ± 0.02
e	0.82 ± 0.02	0.52 ± 0.03
	1.37 ± 0.01	0.97 ± 0.02
e	0.12 ± 0.02	0.35 ± 0.07

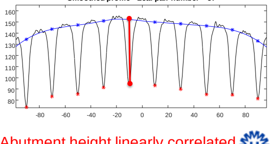
Dorsch S. *et al.* PMB 63 (2018)

Linac QA measurements

MLC-bank alignment and leaf position accuracy

- 11 adjacent stripes of known distance
- Film sandwiched in Cu
- Use simultaneously acquired EPID images to align film





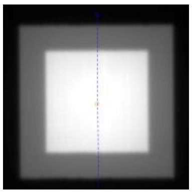
Abutment height linearly correlated to dosimetric leaf gap at isoc

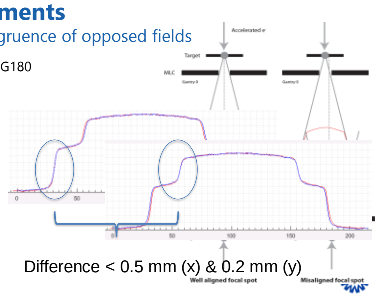
Sastre-Padro et al. ()

Linac QA measurements

Beam alignment using congruence of opposed fields

- 5x5 @ G0 and 10x10 @ G180
- Film sandwiched in Cu



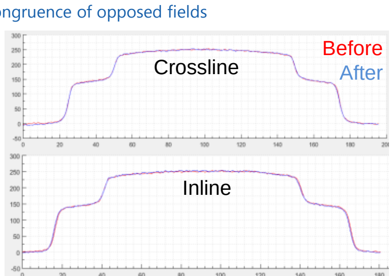


Linac QA measurements

Beam alignment using congruence of opposed fields

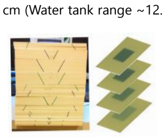
Magnetron replacement

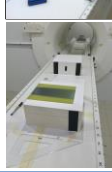
- Output
- Energy
- Beam alignment (SiSo)



Beam commissioning data acquisition using film

- No flood possible in the MRI
- Easy to handle, quick setup
- 2D data instead of 2 x 1D profile
- High resolution in film plane (penumbra)
- Complete data set per field size in a single shot (300 MU)
- PDD = 25 cm (Water tank range ~12.5 cm)



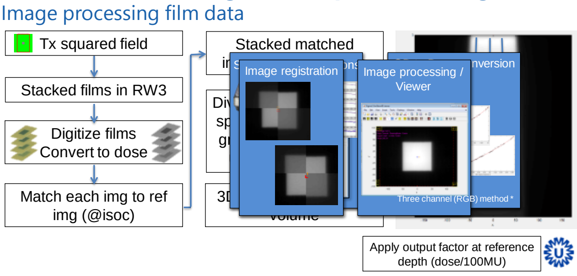


Beam commissioning data acquisition using film

- PTW RW3 slab phantom
  - 30 x 30 x 30 cm³ / 40 x 40 x 10 cm³
- EBT3 radiochromic film (20 x 25 cm²)
- SAD setup (SSD = SAD + 10 cm)
- Field size
  - 1x1, 2x2, 5x5, 10x10 and 20x20 cm²
- Depths
  - 1.0, 2.0, 5.0, 10.0 and 20.0 cm
- Axial film for High-res PDD, 3mm off-center
- Output measurements with IC in RW3 at reference depth (SAD = SSD – 10 cm)

Beam commissioning data acquisition using film

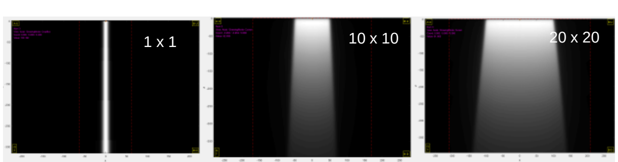
Image processing film data



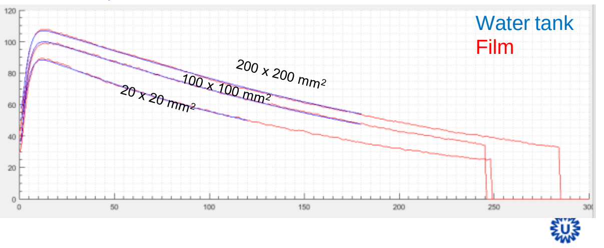
* Andre Micke *et al.* MedPhys 2011

Beam commissioning data acquisition using film

Results 3D processed film data



Beam commissioning data acquisition using film
Results 3D processed film data (Film vs. Water tank)



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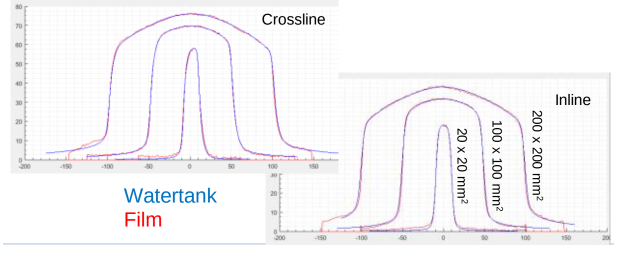
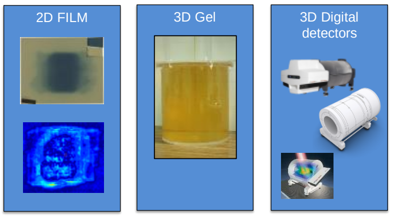


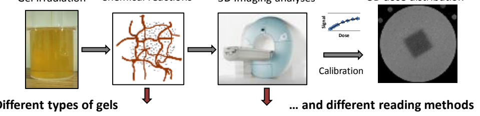
Film dosimetry

- No significant magnetic field effects on film dosimetry
  - Film OD2Dose calibration curves within B0 field are advised
- Use water (droplets!) to avoid any possible airgaps
- Use Cu plates to capture the secondary electrons
- On a Elekta Unity system isocenter coordinate can be transferred via the on-board EPID

Patient specific QA



Gel dosimetry



Different types of gels

- Fricke gels
- Polymer gels
- Plastic, radiochromic gels

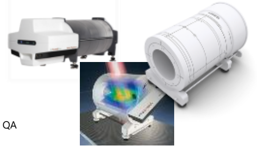
… and different reading methods

- MRI (various sequences)
- Optical reading
- X-ray imaging

- **Read-out just after irradiation**
- **Can be used for complex shapes**
- **Irradiation + readings with MRgRT**

Slide courtesy to Christel Stien

3D Detector arrays

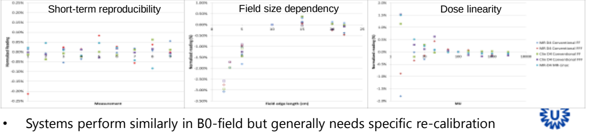


- Current MR compatible systems on the marker
  - Sun Nuclear Arc Check
  - Scandidos Delta4
  - PTW Octavius 3D (rotates with the gantry angle)
    - Perpendicular alignment to beam, potential use for linac QA
- Remove as many ferrous components as possible
- B-field effect on electrons can cause strange behaviour, especially at interfaces between materials of different densities (e.g. air cavities of ion chambers).

- Default positioning at isocenter using frame
  - no light field or lasers
  - RF can be damaging to electronics. No MR image of device position.
- Off-axis positioning (accuracy less)

3D Detector arrays

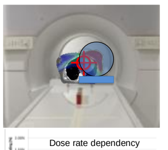
- Systems have been tested on
  - Short term reproducibility
  - Field size dependency
  - Dose-linearity
  - Dose-rate dependency
  - Angular dependency



- Systems perform similarly in B0-field but generally needs specific re-calibration

Houweling A C *et al.* PMB 61 (2016) Ellefson S.T. *et al.* JACMP (2017) Li H. *et al.* IJROBP (2015) Vries J.H.W. de *et al.* PMB 63 (2018)

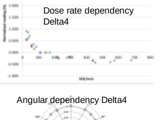
3D Detector arrays

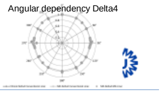


- Most devices are developed for axial treatments
  - The center of the device at isocenter
  - Generally the high dose region

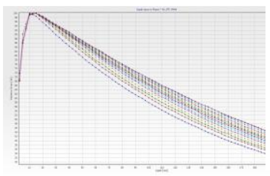
- MRI-Linac treatments does not necessarily have target in the machine isocenter
  - Many "low dose contributions" to diodes
  - Diodes have a individual angular sensitivity related to their individual orientation from the manufacturing process
- Two main aspects to consider
  - Behavior at low dose rates
  - Behavior at various gantry angles

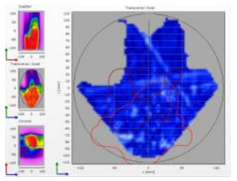
- If device rotates with the gantry angle (PTW) then Eddy currents exists due to rotation of electronics in B-field





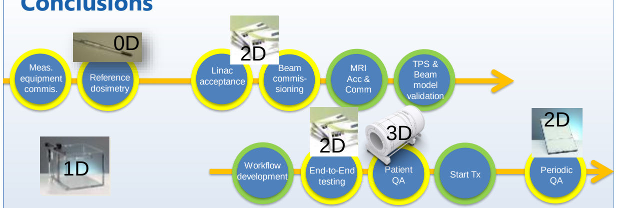
Patient QA using Delta4





- Two establish a 3D reconstruction from Orthogonal 2D planes PPD info is required
- Due to magnetic field, there is no continuous dose drop over the phantom geometry
  → Electron Return Effect should be taken into account

Conclusions



- Completed the loop from commissioning to patient specific QA using film in a 1.5T MRI-Linac
- All QA can be performed using 2D detectors (film or arrays)
- B0-field affects all ion chambers and 2D and 3D detector arrays
- All detectors rely on "full scatter water conditions", still best maintained in a water tank

Thank you for your attention!