MRI-Guided-PT:
Integrating an MRI in a Proton Therapy System

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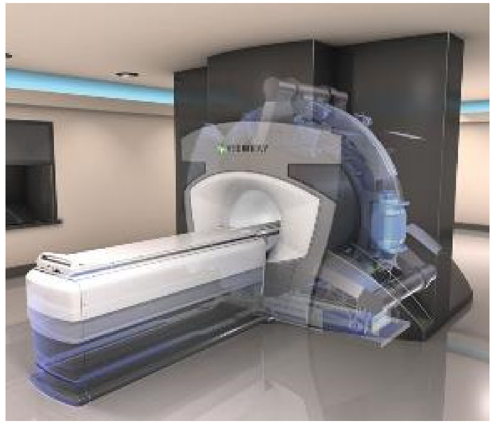
Motivation for MR guided PT

- Better targeting accuracy by exploiting MRI benefits:
  - No radiation dose:
    - Possibility of continuous / real-time imaging
      - Daily treatment plan adaptation (inter-fraction)
      - Motion visualization, e.g. lungs, bowel (intra-fraction)
  - Excellent soft tissue contrast:
    - Could allow margin reduction ➔ reduce toxicity

MR-LINACs:



- See also “*Future of medical physics: real-time MRI-guided proton therapy.*” *Med Phys. 2017;44:e77–e90.*

MRPT challenges

Today:

- Mechanical integration
- Perturbation of MR imaging by PT system

Not today:

- Perturbation of PT by MRI:
  Dosimetry & Treatment planning in B-field to be established
- How to integrate a Faraday cage in the treatment room?
- Receiver coils: in or out of beam path?

How to integrate an MRI on a gantry

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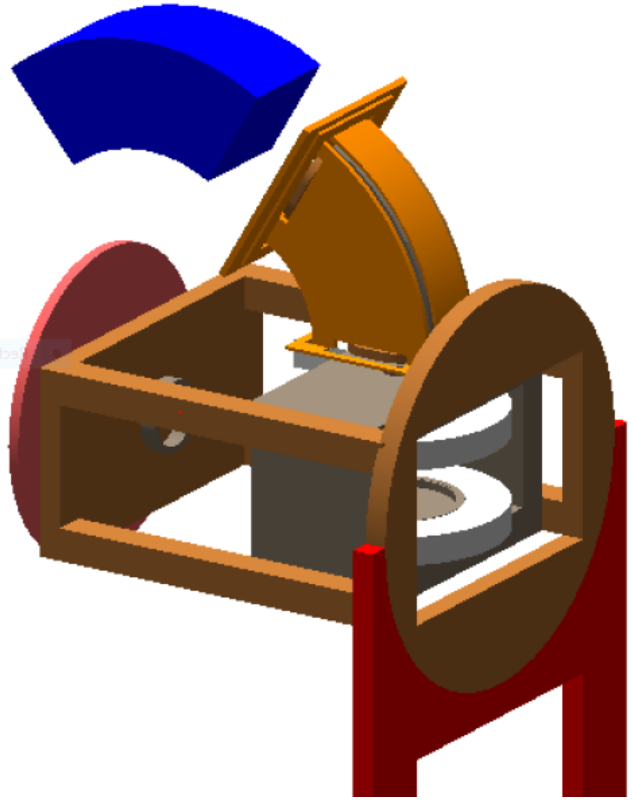
ASG SUPERCONDUCTORS
paramed mri unit



- Poles, coils and cryostats: from Paramed MR-Open
- Yoke is different

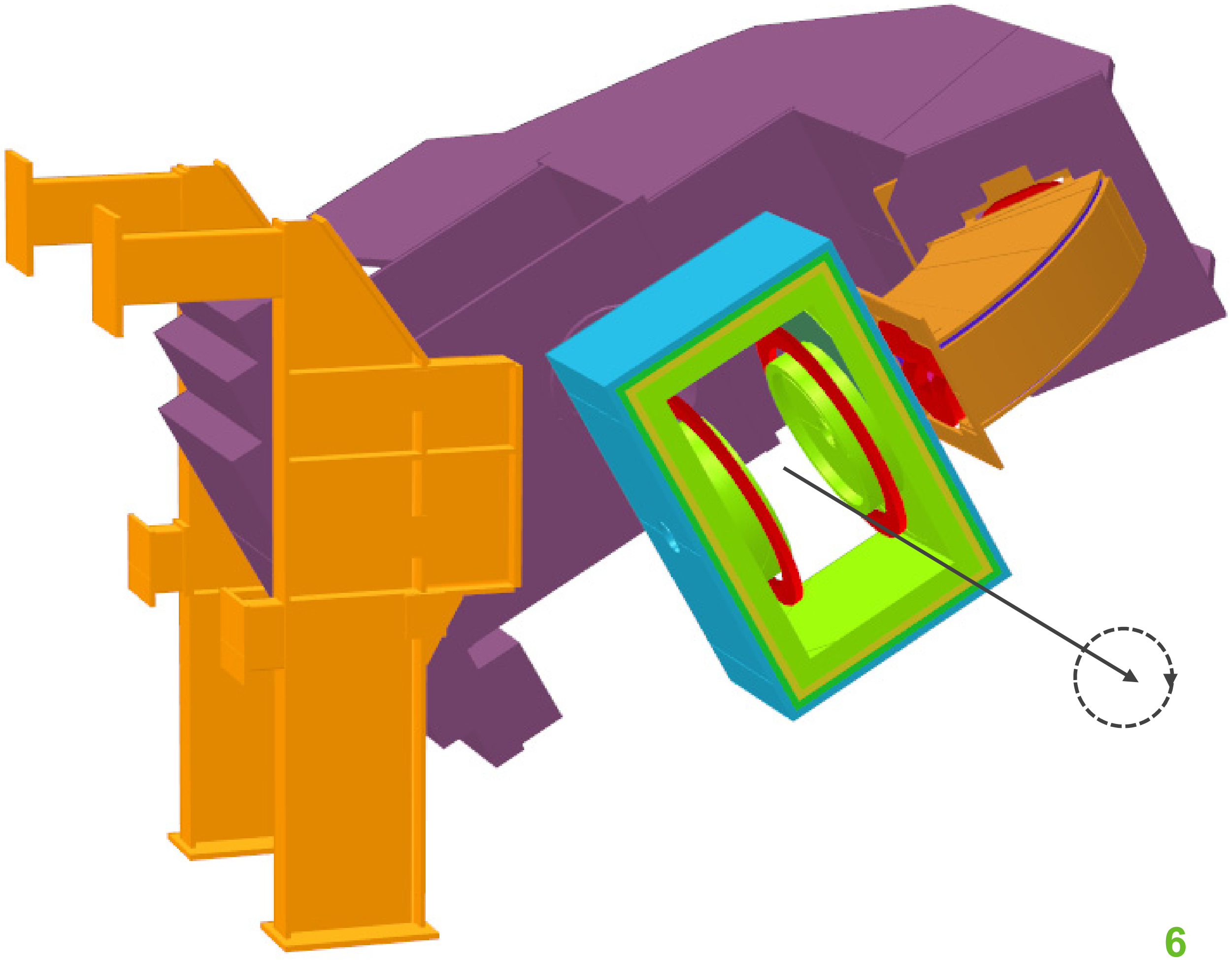
➢ Experience on prototypes → feasible.

OPERA 3D simulations - MRI at isocentre

- Nine models meshed:
  - Rotation of gantry + MRI wrt **chair** at -30°, 0°,…, 210°.
- Chair/gantry simulated as iron & air

HOMOGENEITY:

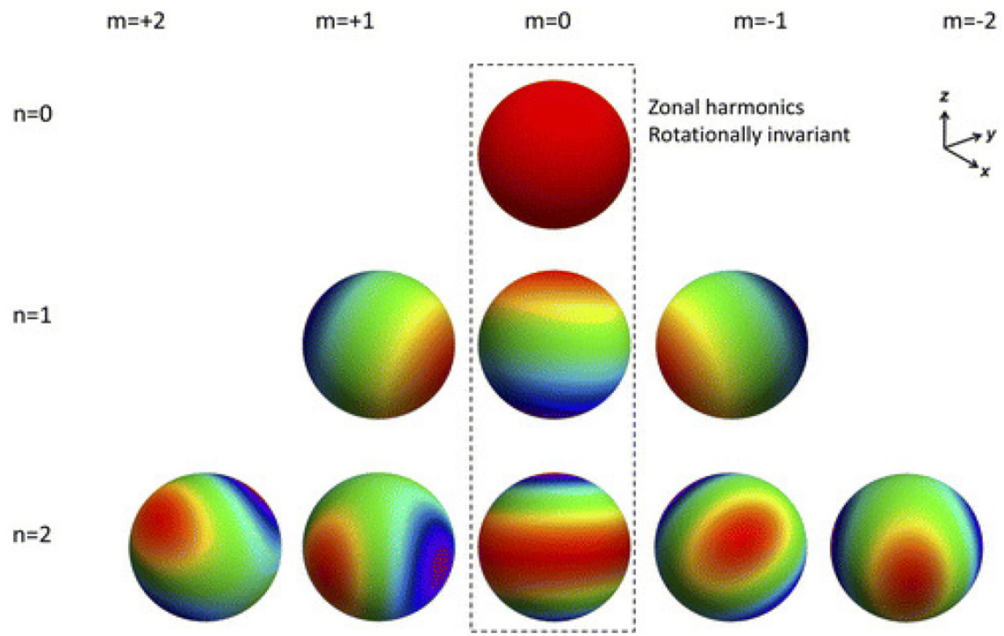
- Studied magnetic perturbation in MRI due to:
  - Rotation
  - Magnetization of PT bend
- Calculated dependence on yoke thickness



Magnetic field – Spherical harmonics decomposition

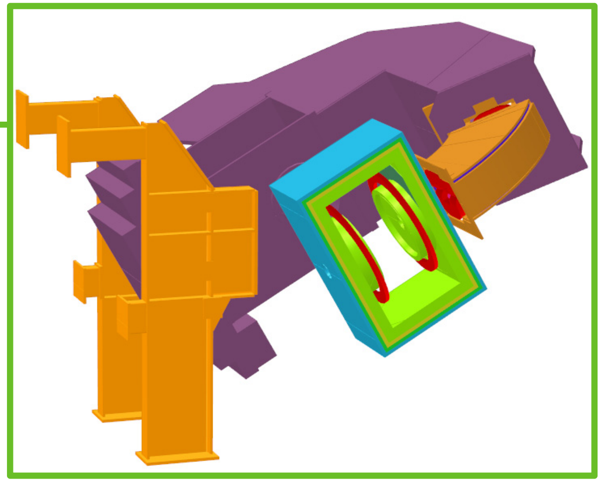
$$\frac{(B_z - B_0)}{B_0} \,.\, 10^6 = \sum_{n=0}^{N} \sum_{m=0}^{n} P_{nm}(\cos(\theta))[\alpha_{nm} \cos(m\varphi) + \beta_{nm} \sin(m\varphi)]$$

- B_0 is B-field at isocenter, with gantry+chair set to AIR.
- Legendre polynomial is fitted:
  - At radius 200 mm
  - For first 15 orders
- Resulting in parameters α_{nm} and β_{nm}
  - By symmetry, most β_{nm} are zero.



From Andrew Webb, **The Principles of Magnetic Resonance, and Associated Hardware**

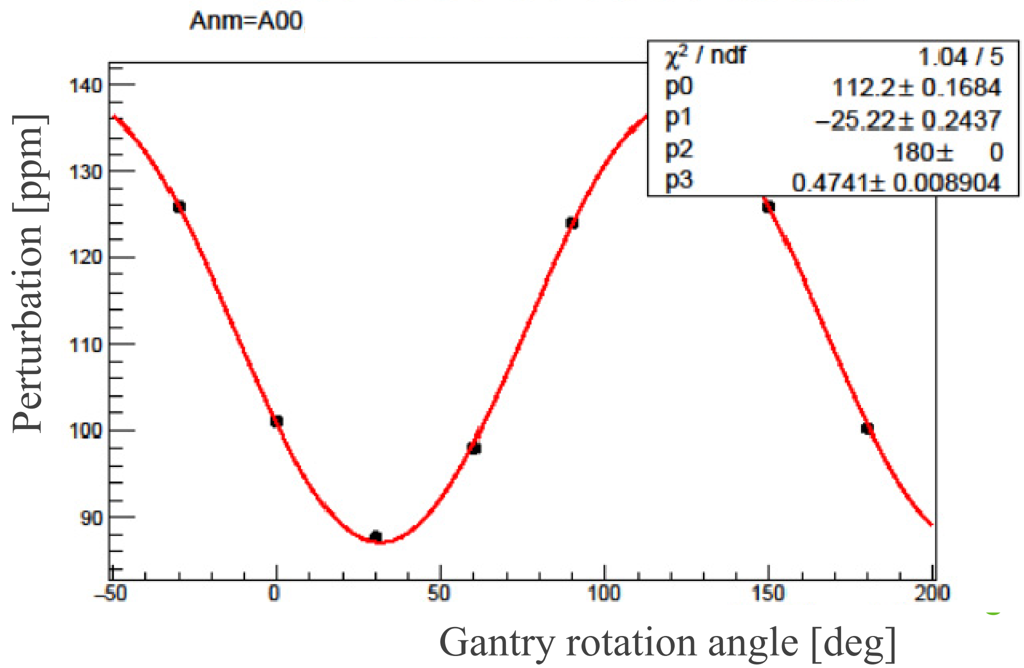
Results for α_{00} – the average



At each angle, polynomial fit parameters are subtracted:

- $\alpha_{nm}^{diff} = \alpha_{nm}^{\textbf{chair} = \text{iron}} - \alpha_{nm}^{\textbf{chair} = \text{air}}$

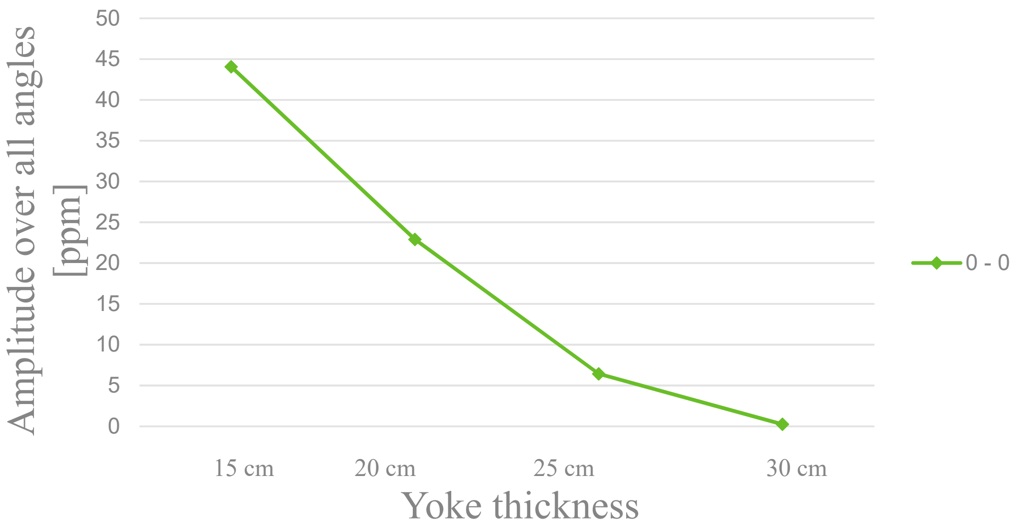
- α_{00}^{diff} :
  perturbation effect of the gantry chair on average of MRI B-field →



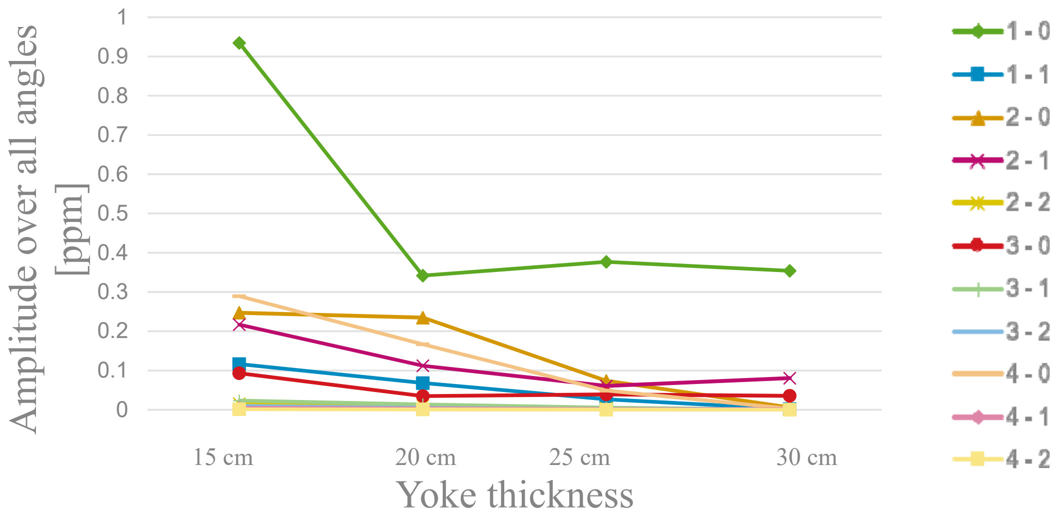
Results for α_{nm} – as function of yoke thickness

- Average: requires passive compensation, i.e. one-time shimming
- Amplitude: requires active compensation.

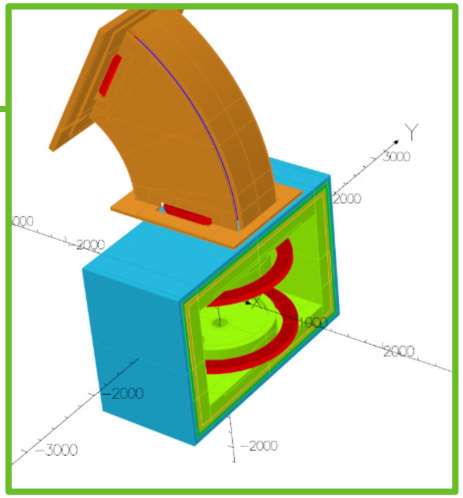
- For α_{00}, adjust RF pickup coil frequency (i.e. nuclear resonance freq.)



- For α_{1i} use gradient coils.
- For higher orders would need dedicated coils.
- Perturbations are acceptable (<1ppm)



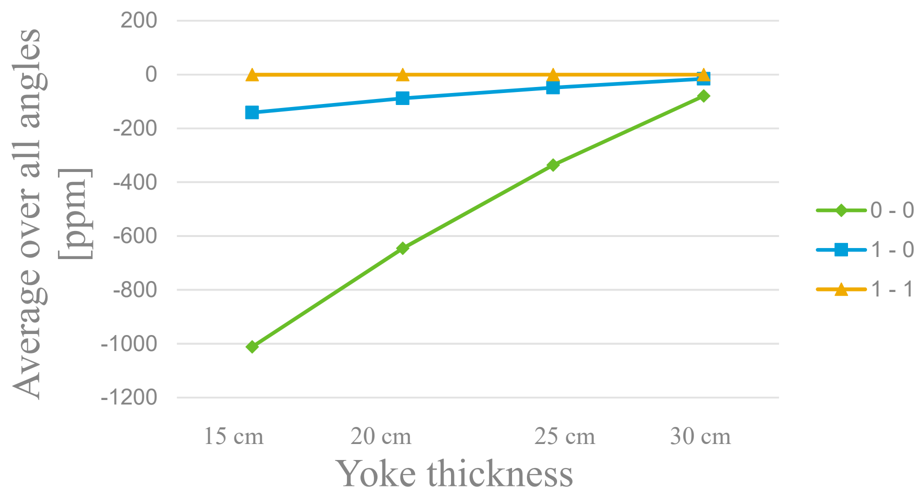
Perturbation by bending magnet fringe field



At each angle, polynomial fit parameters are subtracted:

- $\alpha_{nm}^{diff} = \alpha_{nm}^{I=100\%} - \alpha_{nm}^{I=0\%}$

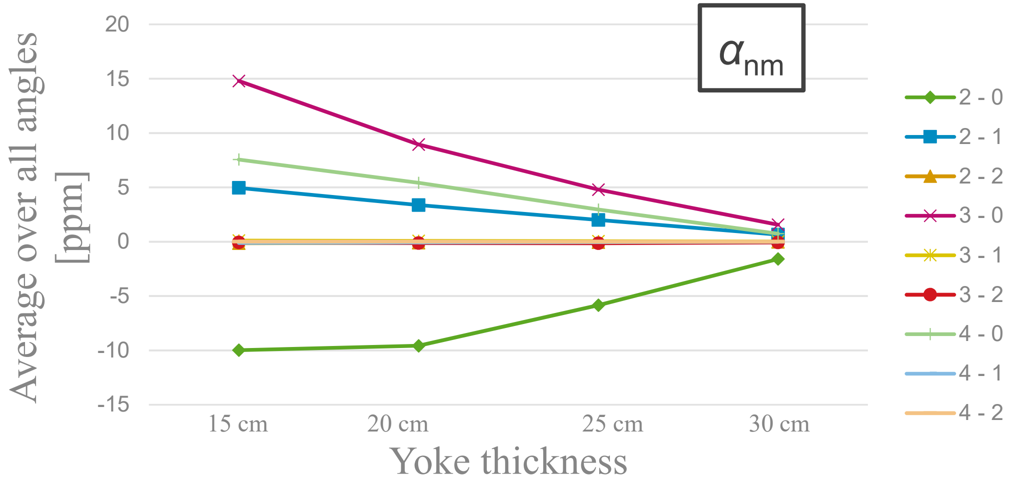
- Fluctuation over gantry angles negligible, only average perturbation is relevant.
- Shown here are α_{00}, α_{10} and α_{11}
  - Components n=1 can be compensated for, up to 100-170 ppm.

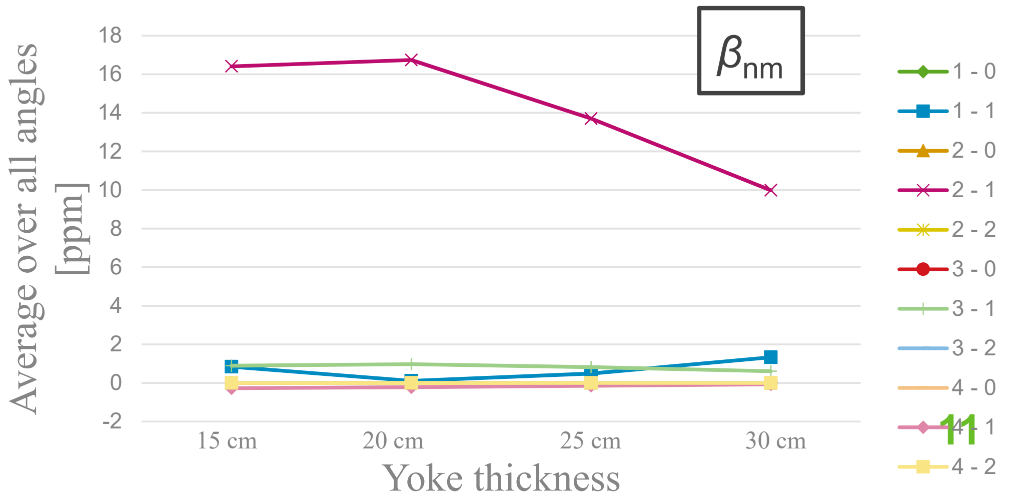


Higher order Perturbation by bending magnet

- Components α_{20}, α_{21}, β_{21}, α_{30} and α_{40} are non-negligible

➢ Imaging and changing magnet setpoints should be done successively, or extra compensation coils are required.

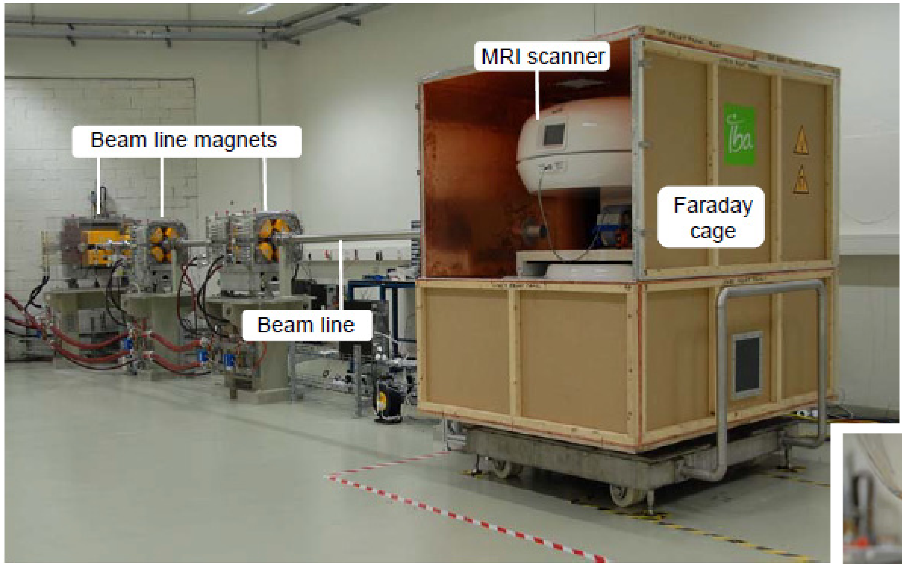


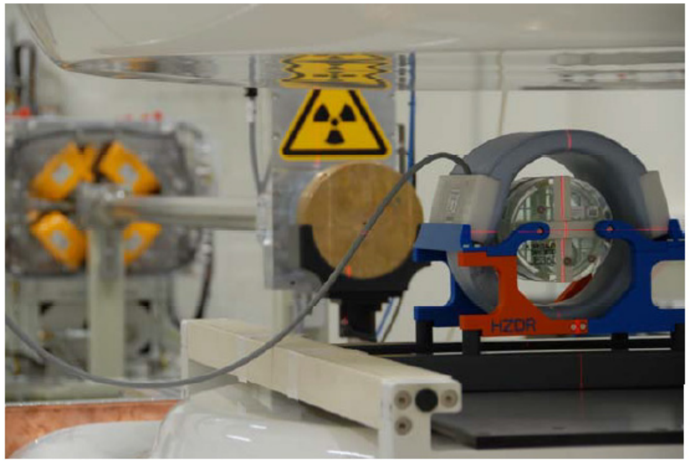


Experimental tests in Dresden Research Area

Schellhammer et al., Phys Med Biol 63(23), 2018

Paramed MRJ – 0.22T
(J = joints)





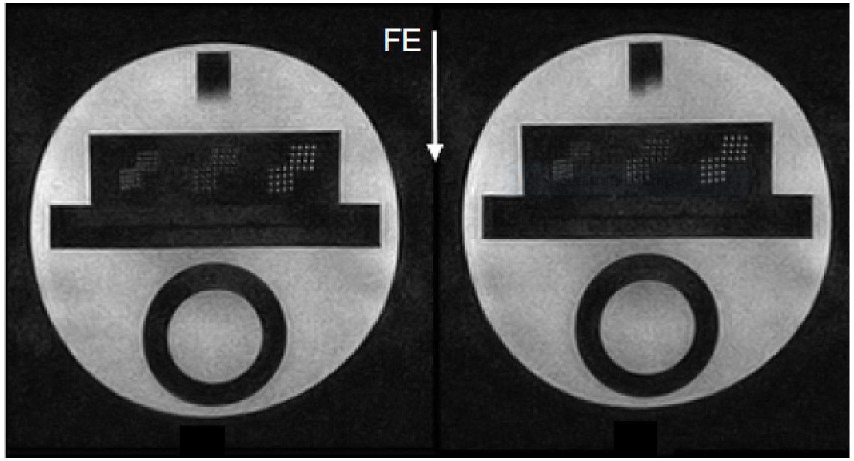
- Beam aligned for energies 125-220 MeV
- ACR knee phantom positioned in centre of FOV in the Paramed knee coil

Image perturbation due to magnetic fields

Schellhammer et al., Phys Med Biol 63(23), 2018

- Irradiation with continuous beam of E=125 MeV, I = 5 nA

T2* GE images



*Beam **OFF*** *Beam **ON***

Results:

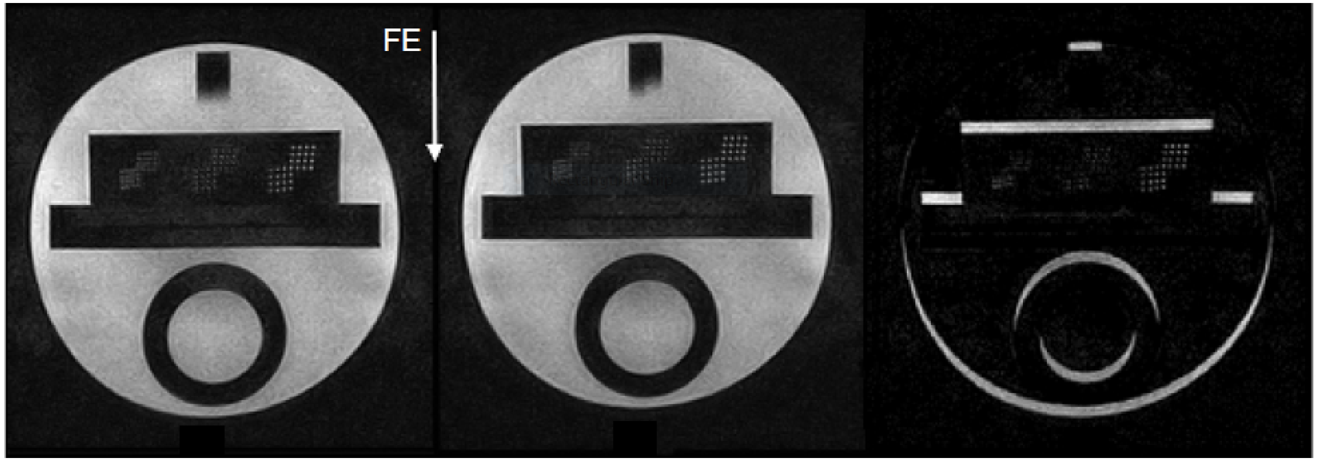
- No apparent image degradation
- No significant change in ACR image quality parameters
- Small uniform shift (< 3 mm) in frequency encoding direction

Image perturbation due to magnetic fields

Schellhammer et al., Phys Med Biol 63(23), 2018

- Irradiation with continuous beam of E=125 MeV, I = 5 nA

T2* GE images

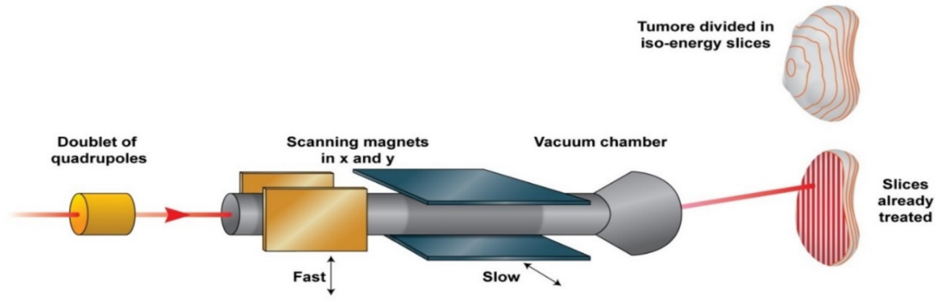


*Beam **OFF*** *Beam **ON*** *Difference*

- Shift (<3 mm):
  - occurs only in frequency encoding direction
  - is due to fringe field of beam line magnets
  - is predictable and correctable

Future tests

Positioned MR-J in front of new fixed beam line with PBS nozzle



Study:

- Effect of scanning magnets on MR image quality
- Effect of fringe field on beam steering and control system

Summary

- Shown how an MR could be integrated on an IBA ProteusOne
- Non-linear perturbations on the MRI field homogeneity by the PT bending magnet are to be taken into account.
  - Imaging and changing magnet setpoints should be done successively, or extra compensation coils are required.
- Experimental tests on fixed beam line:
  - MR image degradation due to magnetic fringe fields negligible
  - MR image shift is non-negligible and to be compensated for