MRI Guided Proton Therapy:
Pencil beam scanning in an MRI fringe field

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ICTR-PHE: Geneva, Feb 15-19 2016

Introduction

MRI-guided Proton Therapy (MRPT):

- A proposed modality that uses proton beams to treat cancer patients while being imaged inside an MRI scanner
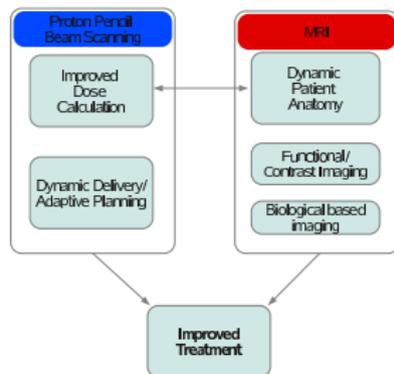
Why consider MRPT?

- Improve the efficacy of proton beam therapy:
  - Superior 4D patient anatomy at **Planning** and **Treatment**:
    - Reduced margins, improved tumor delineation and dose calculations
- Cost effective: $(MRPT) $\sim 1.1 \times$ $(Proton Therapy)

Obvious concerns with MRPT?

- Protons will deflect in the magnetic field!
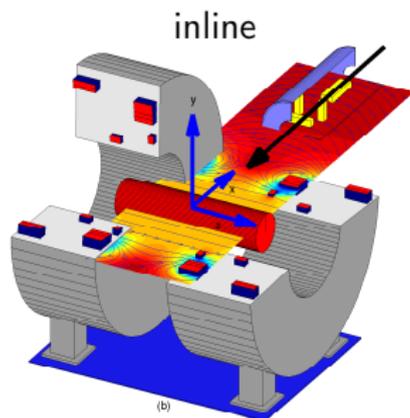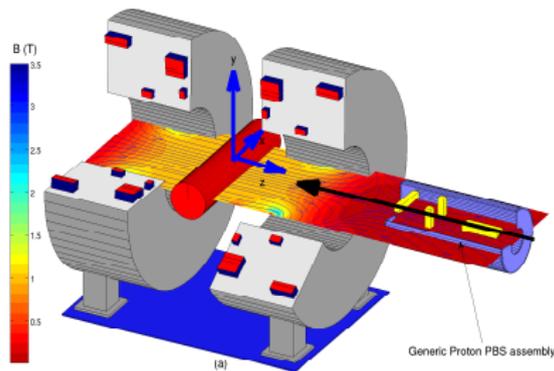- MRI $\iff$ Proton beamline interactions!

Adapted from Bjerre *et al.* Phys Med Biol 2013

MRPT: A prototype based on the Sydney MRI-linac

inline

perp

- Agilent 1 T Split-bore MRI
- Rotating couch = no proton gantry required

MRPT: background

Previous works have looked at proton beam deflection in phantoms and air:

- 90 and 90-200 MeV proton beam deflections[1,2]
- Planning study, 35 cm uniform fringe field[3,4]
- Full fringe field transport, 1 T Agilent MRI design[5]

Conclusions:

1. Moderate but predicatable deflection inside phatom: 28 mm for 200 MeV at 1.5 T
2. Strong but predicatable deflection from fringe field: MRI and orientation specific
3. Pencil Beam Scanning a must: fringe field disperses multiple energy broad beams

1. Raaymakers *et al.*, Phys. Med. Biol. 53(20), 5615-5622 (2008).
2. Wolf and Bortfeld, Phys. Med. Biol. 57(17), N329-N337 (2012).
3. Moteabbed *et al.*, Med. Phys. 41(11), 111713 (11pp.) (2014).
4. Hartman *et al.*, Phys. Med. Biol. 60, 5955–5969 (2015).
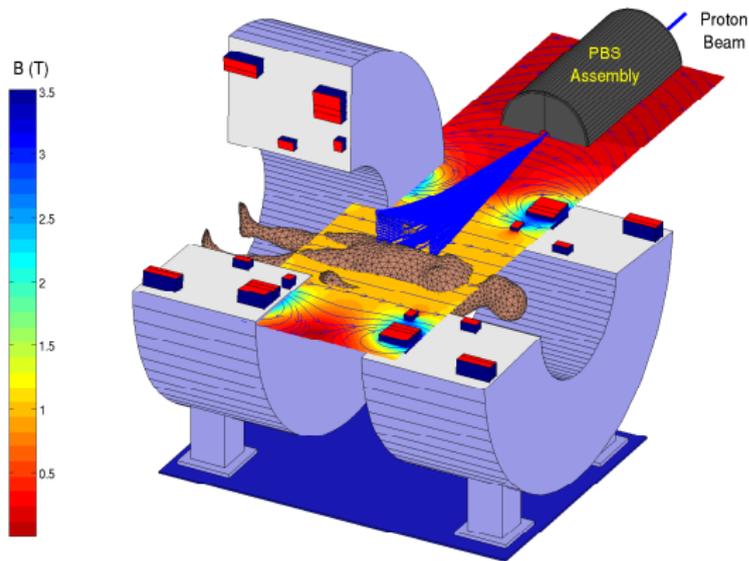5. Oborn *et al.*, Medical Physics, 42, 2113 (2015).
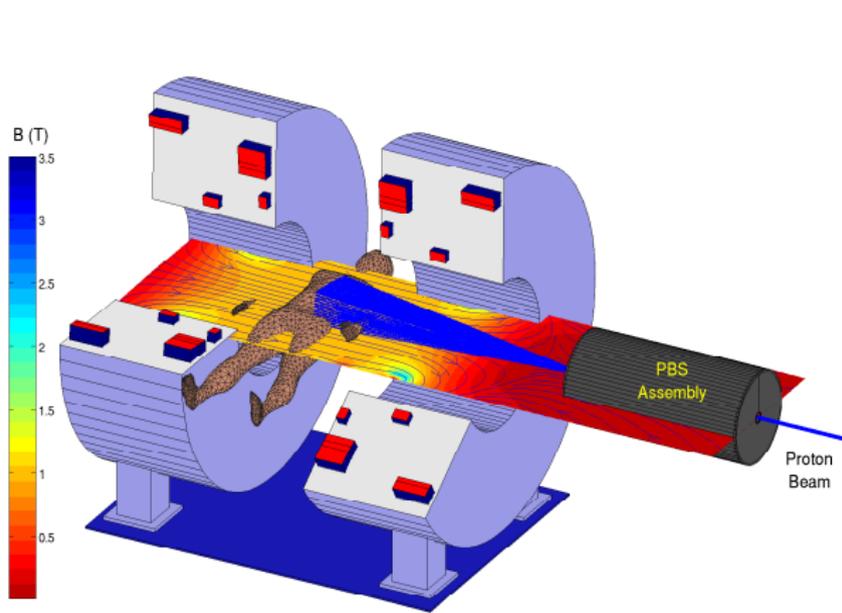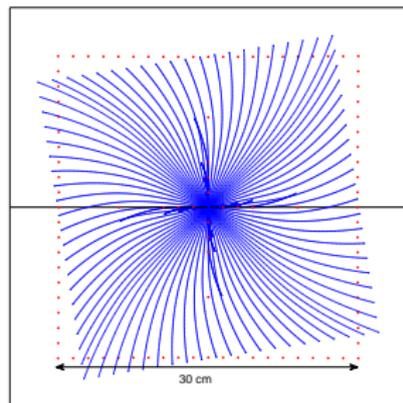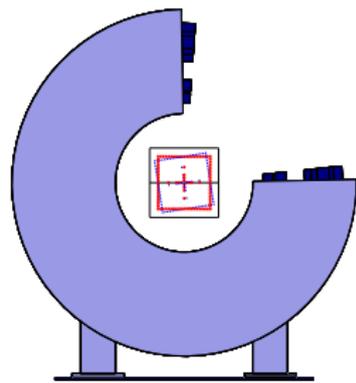
300 MeV diverging pencil beam phase space source (emulates beam scanning)

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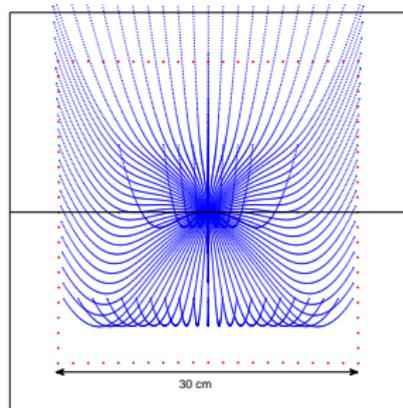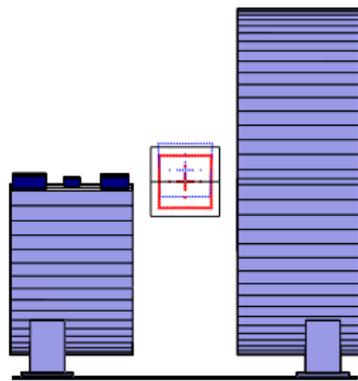
# Aim + Methods

Aims:

- To model pencil beam scanning in MRPT and assess:
    - MRI image distortion
    - Scanning magnet operation
    - MRI and Scanning Magnet cross-talk
    - Magnetic forces

Methods:

- COMSOL Finite element model: Agilent 1 T MRI + IBA Nozzle Scanning magnets in clinical position
    - Produce field maps for Monte Carlo model
    - Calculate image distortion
    - Calculate forces on scanning magnets
- Geant4 Monte Carlo model:
    - Pencil beam deflection process through combined system
   - Pencil beam dose to water phantom in magnetic field

Methods: The core finite element model

- MRI coils, pencil beam scanning magnet coils, and steel yokes
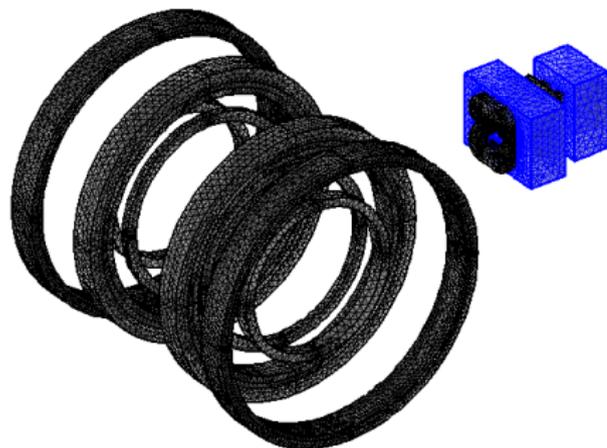
Methods: Pencil beam scanning = changing current density in scanning magnets
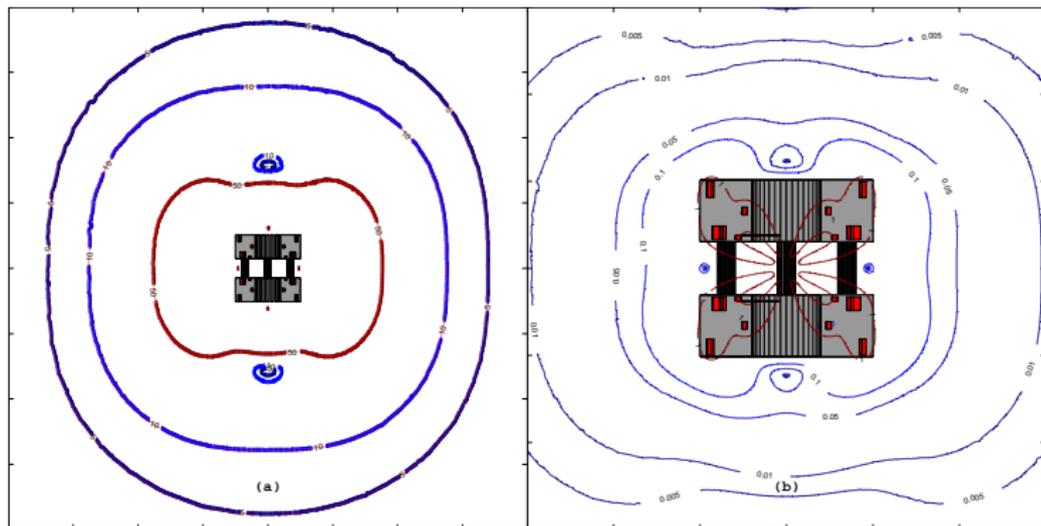
- Model a scanning calibration pattern:
  - 230 MeV proton beam, 81 points over a 30×30 cm field
- Model MRI off and on
- Each scan point simulation: 8 cores, 20 hours, 60 GB RAM
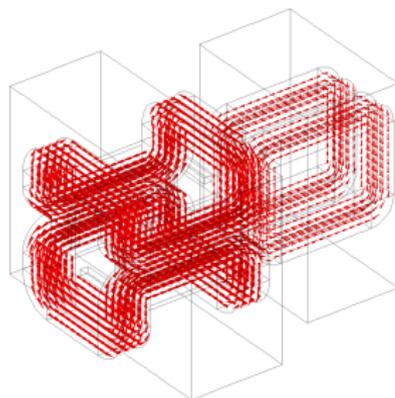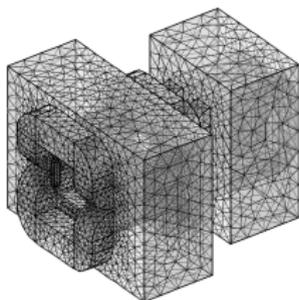
Results: MRI model

Excellent match to Agilent specs:
- 6.8 parts per million (ppm) magnetic field non-uniformity in the 30 cm diameter spherical volume (DSV)
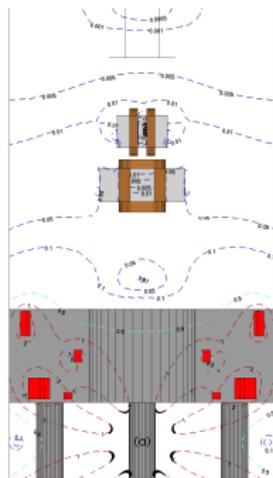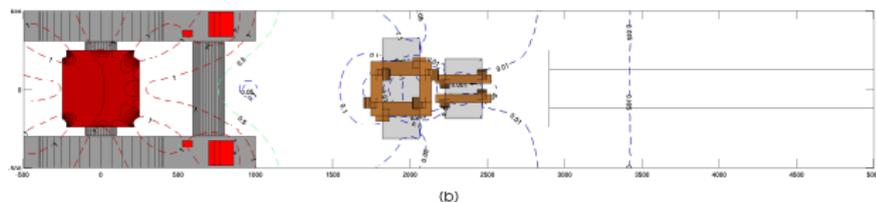- contour match at all values

Far Fringe   Near Fringe

Results: MRI + Scanning magnets model (passive)

- Inline Orientation: 6.8 ppm $\mapsto$ 56.5 ppm
- Perpendicular Orientation: 6.8 ppm $\mapsto$ 120.5 ppm
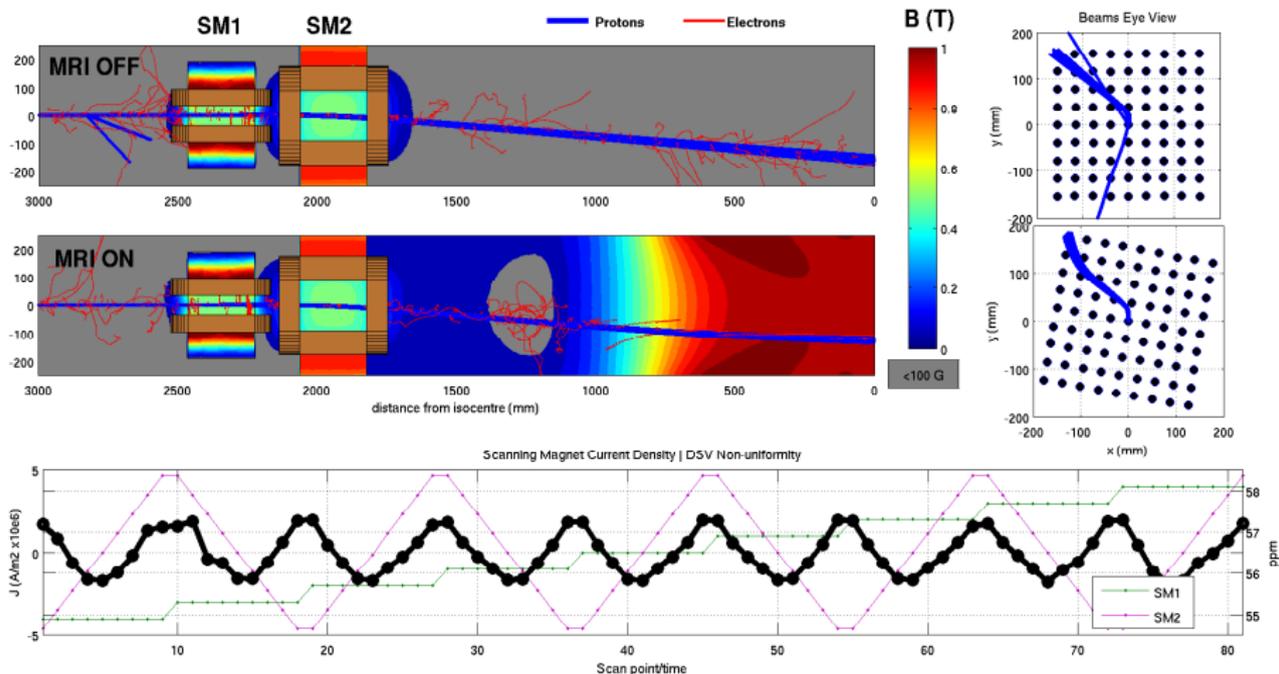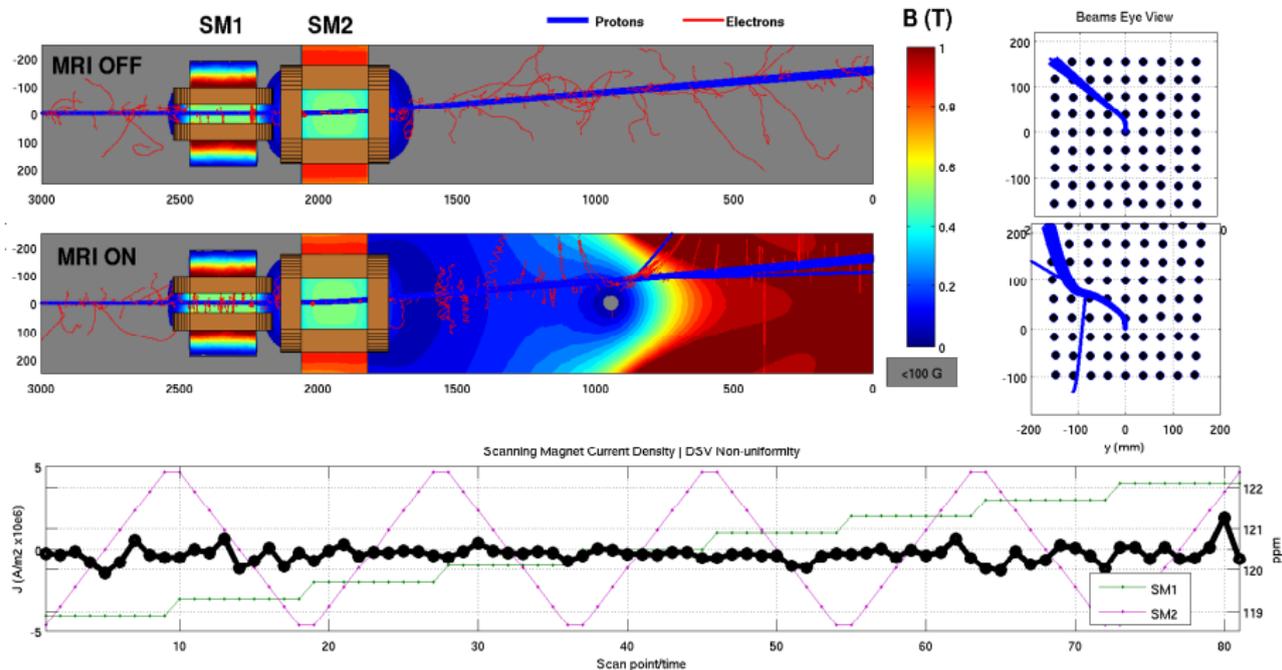- Both of these are < 300 ppm preshim threshold (correctable)

Inline

Perp

Results: Inline Orientation Scanning Pattern

230 MeV pencil beam scanning, scanning magnets in clinical position: (gif)

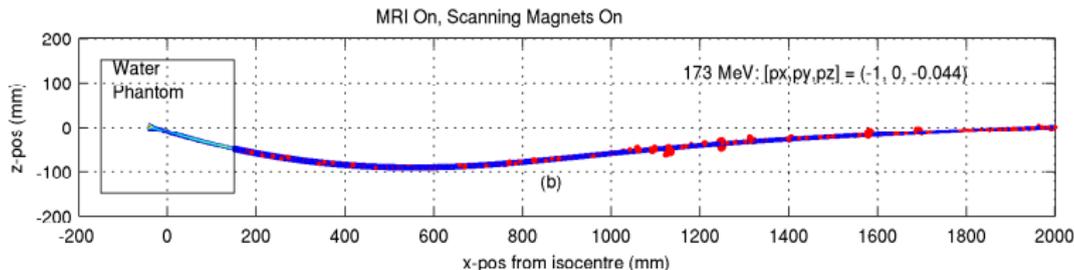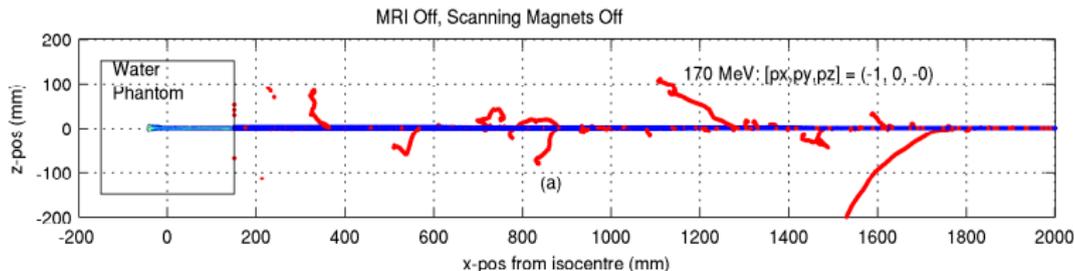230 MeV pencil beam scanning, scanning magnets in clinical position: (gif)

Results: Example full beam transport to a water phantom

- To get a Bragg-peak at 190 mm depth (Perpendicular Orientation)....

- Its clear that a full trajectory model is required for planning purposes

Results: Summary

- MR image distortion (extreme case):
  - Inline Orientation: 56.5 ±0.75 ppm
  - Perpendicular Orientation: 120.5 ± 0.4 ppm
  - Shimable, expect no image distortion

- Pencil Beam Scanning Process:
  - Scanning magnets work as intended...
  - Minimal cross-talk expected (1.5 ppm change in extreme case)
  - Forces < 1000 N
  - Fringe field corrections required for downstream deflections

Discussion and Conclusions...

- The performance of a proton pencil beam scanning assembly has been modelled in the presence of and MRI fringe field:
  - Some MRI imaging correction required, will need active/passive shimming
  - Scanning process appears normal, downstream fringe correction (software/planning) required
- Next steps including modeling detector systems

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- The performance of a proton pencil beam scanning assembly has been modelled in the presence of and MRI fringe field:
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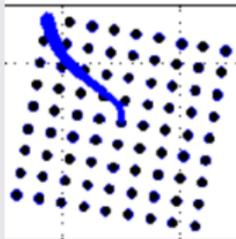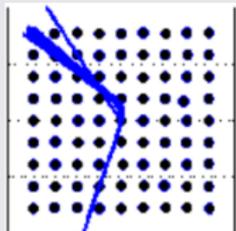
I hope that was a real *spin!*
Are you now *distorted*
towards MRI-guided
Proton Therapy?