Integrated MRI-LINAC Radiotherapy Machine

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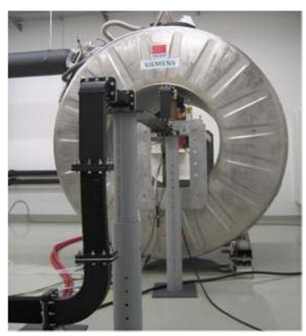
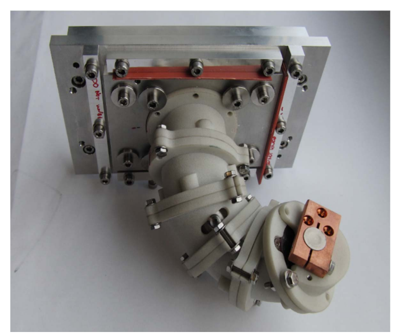
Target audience: Radiation Oncologists. Oncologists. MRI engineers

Purpose
There is a strong desire to directly observe, guide and control X-ray radiation treatments by an imaging method. MRI is an attractive solution due to its soft tissue contrast and its absence of radiation. We propose a combined MRI – LINAC X-ray treatment machine which integrates the LINAC inside the MRI magnetic field and results in a reasonably compact and cost efficient solution [1]

Methods
Linear electron accelerators (LINACS) are notoriously magnetic field sensitive devices. Due to the clinical requirement of a certain distance and orientation of the X-ray source relative to the patient it the LINAC driven X-ray source is confined to spaces where it is very difficult to screen the MRI B_0 main magnetic field. We therefore propose to subject the whole LINAC X-ray source to the magnetic field. This has several consequences: First, the LINAC electron beam has to be precisely aligned with the B_0 field direction over the whole trajectory from electron gun to LINAC accelerator exit. This requires a sufficiently homogeneous and predictable B field at the LINAC. Secondly, the electron beam eventually has to be bent from its axial to an inward pointing radial direction to properly impact on the X-ray producing, forward peaking target. Thirdly, the axially symmetric arrangement enables a CT like gantry within the MRI magnet which allows radial irradiation over full arcs.
Our design places the LINAC in a ring slit between a z-splitted gradient coil and the cylindrical warm bore of a conventional MRI magnet. The B_0 field homogeneity at the LINAC position of order 0.1% is sufficient. Terminal electron beam deflection is accomplished by the B_0 field in conjunction with a dipole – quadrupole – dipole arrangement. Three self-shielding NdFeB Halbach permanent magnet arrays [2] mounted in a 3D printed ABS former (see image) surround a non-magnetic steel bellow vacuum beam tube sealed to the LINAC exit orifice. A welded 75um Titanium foil exit window retains vacuum against a conventional water immersed rotating tungsten disk X-ray target.
A commercial 40cm long 6 MeV LINAC was powered by a 5 MW E2V magnetron microwave tube and a Siemens solid state hard pulser at 5us pulse duration and 1:1000 duty cycle through a rotating joint at the magnet bore end. A Siemens Magnetom Espree magnet with 90cm warm bore and 117cm length served as testbed and would be sufficient for a 40cm clear bore head treatment machine.
We installed the MRI magnet and test arrangement in a X-ray shielded test bunker, which among other things required drilling through 3 m of barite concrete to route the quench pipe.

Results
For our tests we powered the bare, unshimmed MRI magnet to 0.5T. The L3 M592 Pierce electron gun performed surprisingly well within the strong magnetic field. We could achieve 300 mA beam current despite heavily altered electron ballistics within the gun as indicated by particle-in-cell simulation. After geometric alignment the LINAC showed electron transmissivity higher than without B field, at lower stray X-ray production. The bending magnet assembly did not require any adjustments to provide a reasonably useful 2x3mm focal spot size on the X-ray target. The experimental study did not extend to X-ray related equipment like collimators and dosimeters.





Discussion and Conclusion
We report on a proof of concept of a radio-oncology LINAC treatment machine integrated within an MRI magnet. It seems to be possible to operate a conventional 6 MeV LINAC within a relatively conventional superconducting high field MRI magnet. The main system design constraint remains the minimum safe X-ray source to patient distance due to the entry dose effect, which puts a lower limit on the permissible MRI magnet warm bore diameter.

References
[1] O. Heid, et al.: Deutsches Patent DE 10 2008 007 245 A1, US Patent 8487269B2 (2008)
[2] K. Halbach: *Design of permanent multipole magnets with oriented rare earth cobalt material*. In: *Nuclear Instruments and Methods*. 169, Nr. 1, 1980, S. 1-10