Feasibility of MRI Guided Proton Therapy: Magnetic Field Dose Effects

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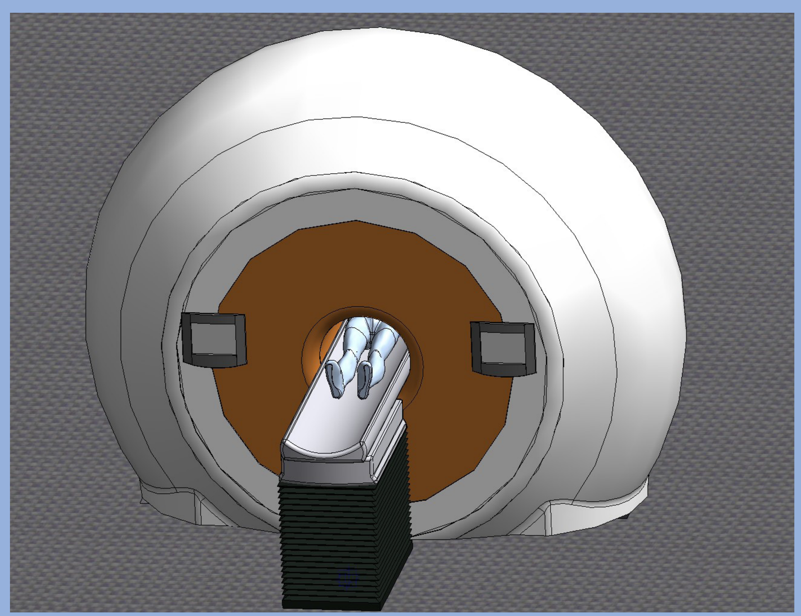
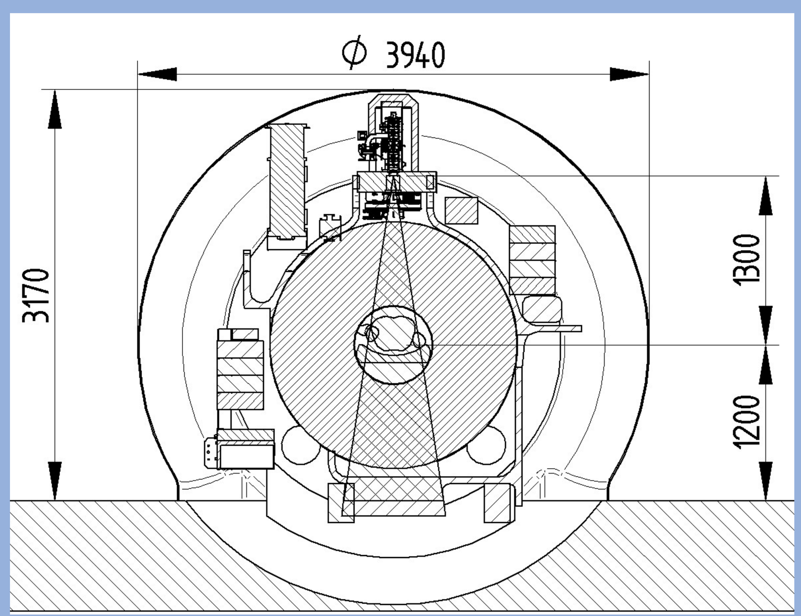
6 MV radiotherapy system with 1.5T MRI functionality for stereo-tactic precision GTV boosting

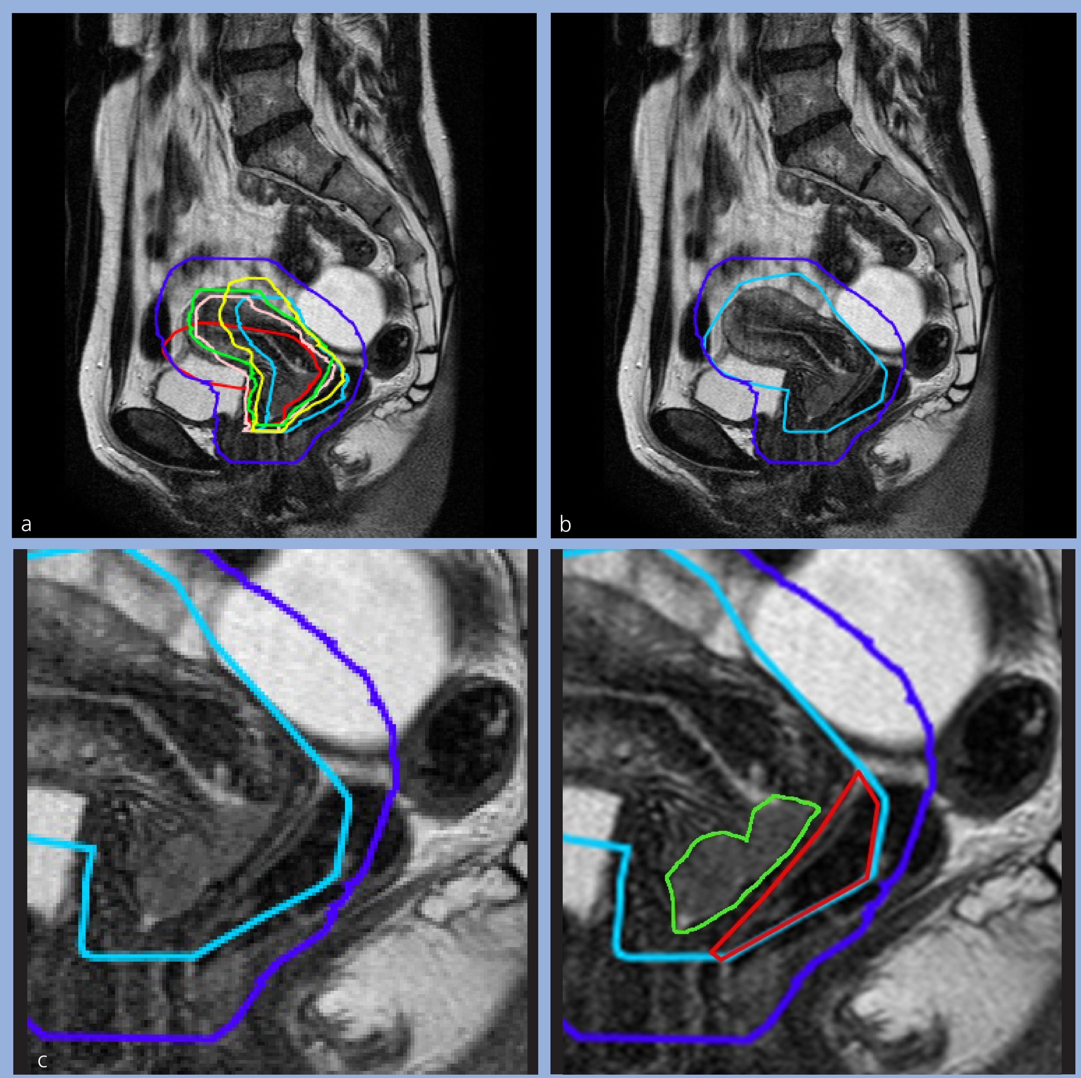
In radiotherapy the healthy tissue involvement still poses serious dose limitations. This results in sub-optimal tumour dose and complications. Daily image guided radiotherapy (IGRT) is the key development in radiation oncology to solve this problem. MRI yields superb soft tissue visualisation and provides several imaging modalities for identification of movements, function and physiology. Integrating MRI functionality with an accelerator can make these capacities available for high precision, real time IGRT. In collaboration with Elekta, Crawley, UK, Philips, Best, The Netherlands, UMC Utrecht is constructing a hybrid 1.5T MRI radiotherapy system, see poster .



Artistic impression of the integrated 6MV accelerator and the 1.5T Philips Achieva MRI system



Cross section through the final system. The ring mounted accelerator is positioned in the mid-transversal plane around the MRI.



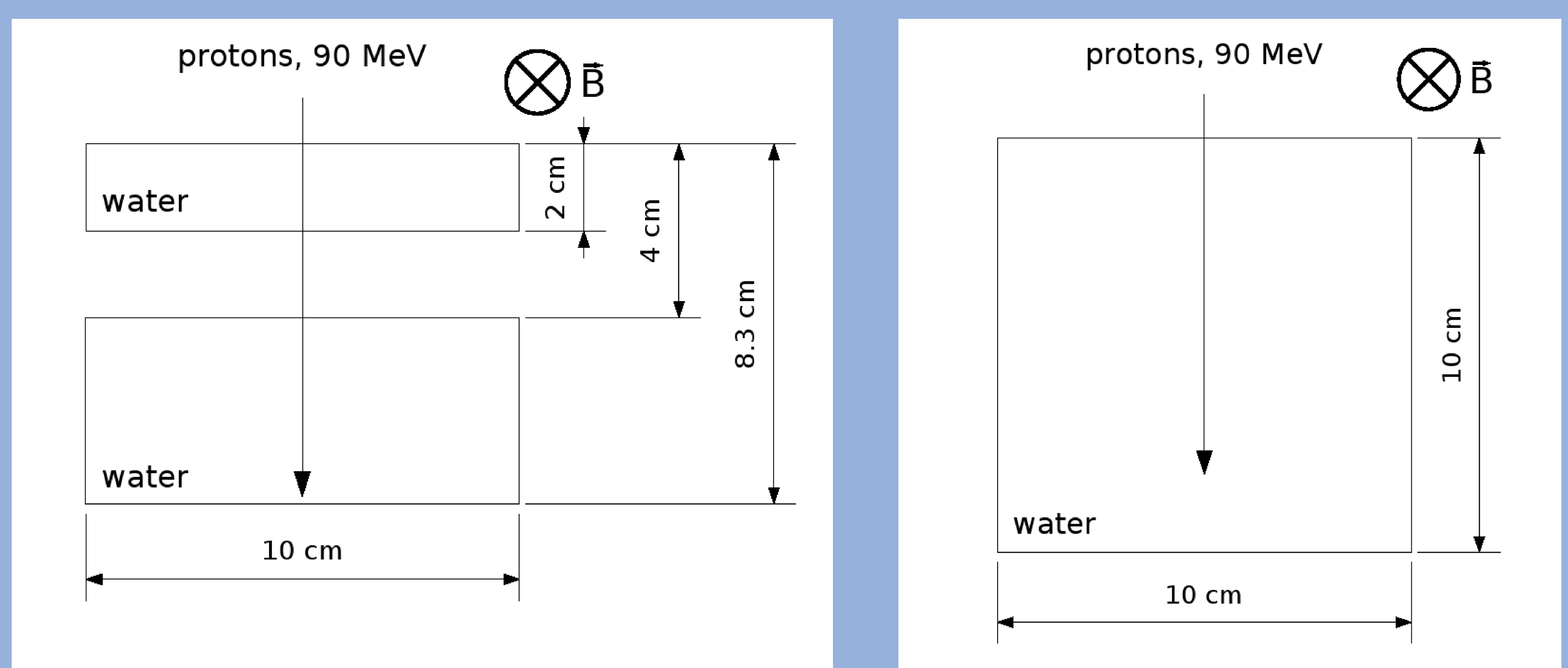
(a) repeated MRI for carcinoma of the cervix at 5 different days with the 5 delineated CTV's and the clinically used PTV (dark blue), (b) these data can be used to define an envelope of the 5 contours for an adaptive PTV (light blue), (c) however, the zoomed MRI still shows overlap of the rectum for both the adaptive and the clinical PTV, (d) Since both the GTV volume (green) and the rectum (red) are still both in the envelope, a boost to only the GTV without overdosing the rectum requires on-line MRI guidance.

MRI guided proton therapy

Proton therapy is favourable for creating highly conformal dose distributions compared to photon therapy, especially small tumours and tumours very close to critical organs can benefit from the sharp dose gradients from protons.
However, it is a waste of effort to create a very conformal dose distribution using protons when the target volume still consists for a large part of healthy tissue. Additionally, due to it sharp gradients proton therapy is quite sensitive for motion. Given this importance of IGRT in general and the sensitivity for anatomy variations for proton therapy, proton therapy can benefit greatly from MRI guidance. Here a first technical feasibility issue of this concept, namely the impact of a 0.5T magnetic field on the dose distribution from a 90 MeV proton beam.

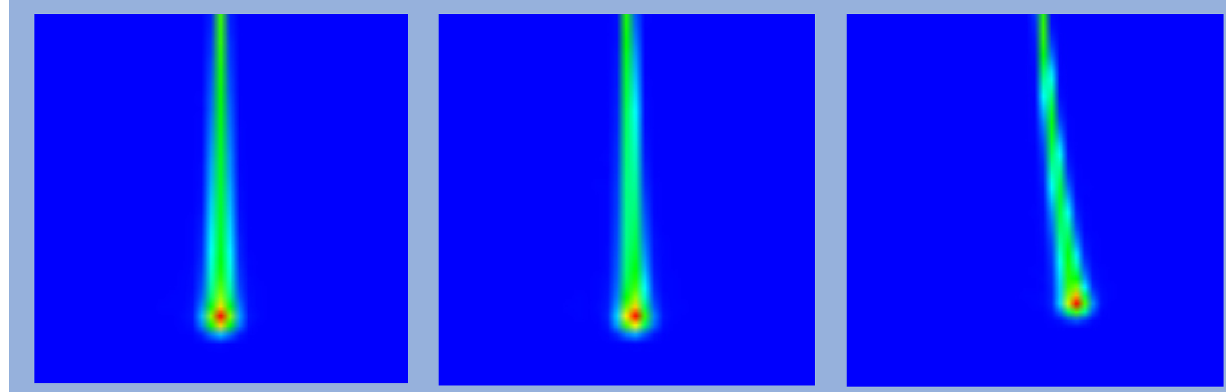
Methods

The dose distribution was simulated using the Monte Carlo toolkit Geant4, version 9.0. The dose distribution for a homogeneous phantom and a phantom with an air-gap was calculated. A 90 MeV proton pencil beam was used, this dose was then convoluted to obtain the dose from a 5x5 cm field.
To pursue more insight in the energy characteristics of the protons and secondary electrons, the energy spectrum of the protons and secondary electrons have been determined as a function of the depth in the homogeneous phantom.
All simulations were done at 0, 0.5 and 3.0 T magnetic field strength.

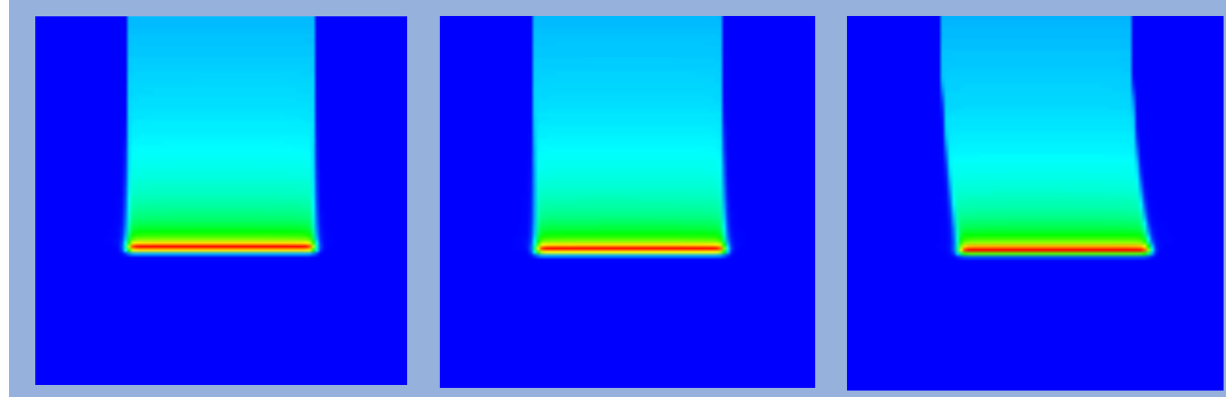


Simulation setup for the calculation of proton dose distribution in the presence of a magnetic field in a homogeneous water phantom (a) and a water phantom with air layer (b). Note that in situation (b) the Bragg peak is located at the distal water-air interface.

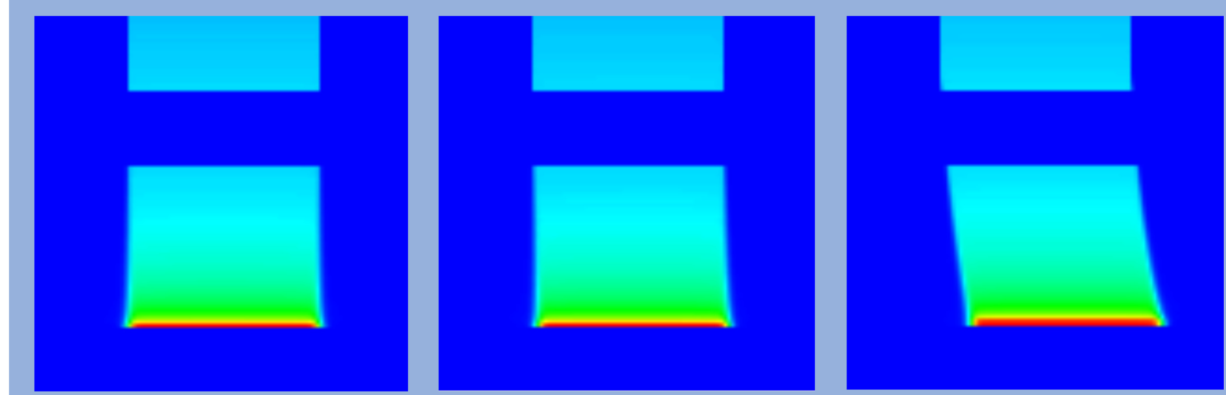
Results



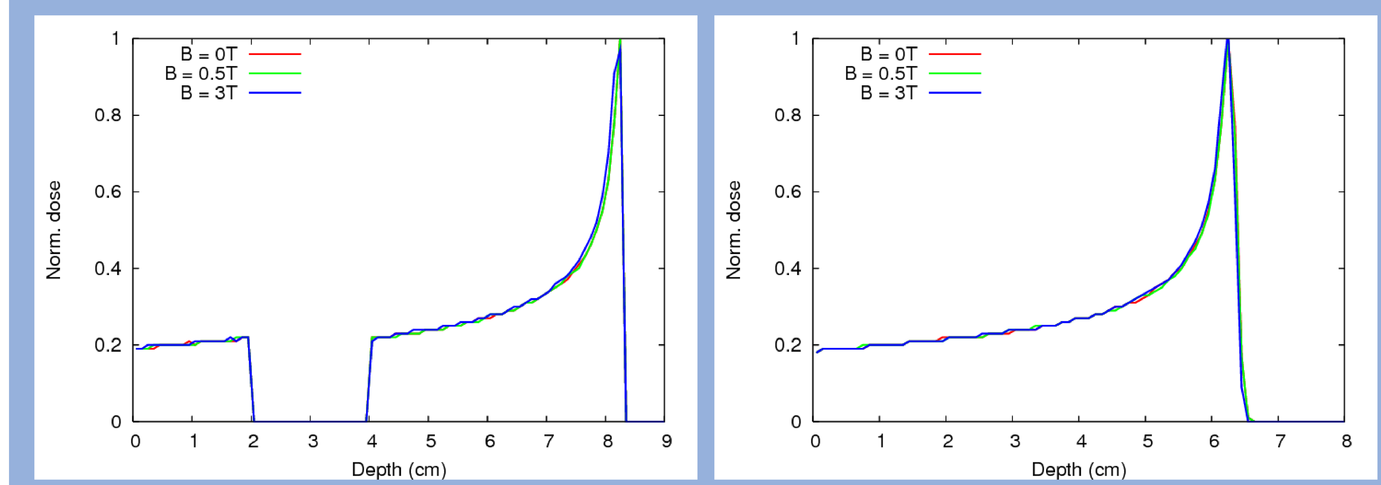
The dose distribution for the pencil beam at 0, 0.5 and 3 T in the homogeneous phantom. The difference between 0 and 0.5 T can hardly be seen. For 3T the curvature of the pencil beam is shown clearly.



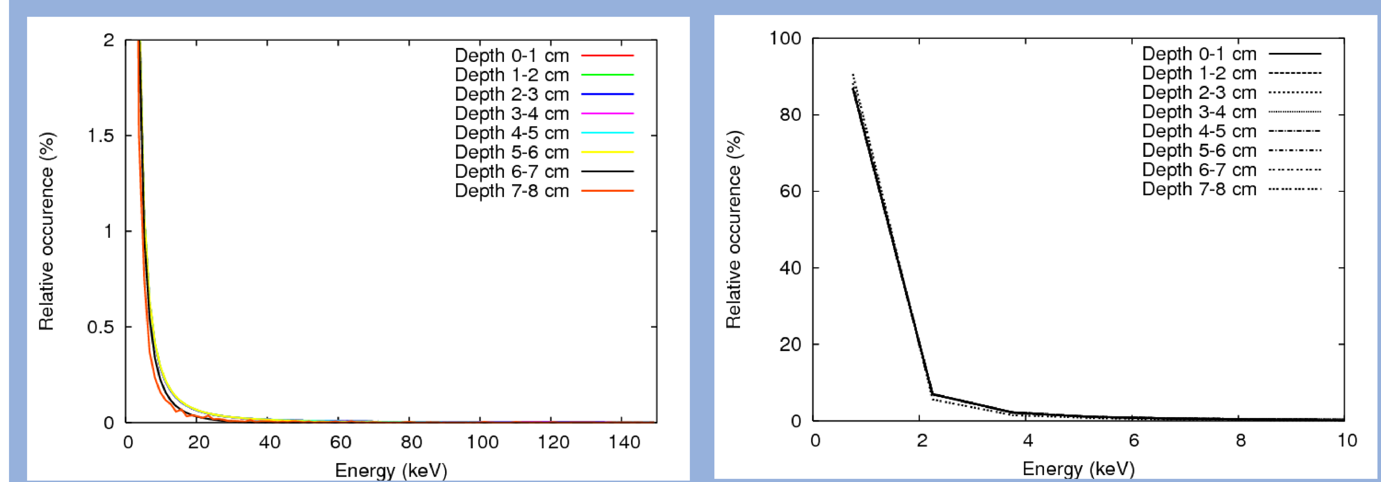
The dose distribution for the 5x5 cm beam at 0, 0.5 and 3 T in the homogeneous phantom. The difference between 0 and 0.5 T can hardly be seen. For 3T the curvature of the beam is shown clearly.



The dose distribution for the 5x5 cm beam at 0, 0.5 and 3 T in the phantom with the air-gap. The difference between 0 and 0.5 T can hardly be seen. For 3T the curvature of the beam is shown clearly.



The central depth dose profiles for the 3 magnetic field strengths for the 5x5 cm beam in the homogeneous phantom (a) and the phantom with the air gap (b). Note that the lines are nearly perfect overlapping.



The energy histograms for secondary electrons at various depths for 0T. Note the scale on the Y-axis in (a). Figure (b) is a zoom in on the low energy part of (a). The lines for various depths are overlapping.

Discussion

Strikingly different from photon irradiation in the presence of a magnetic field is the absence of the ERE (see poster). This is due to the very low energies of the secondary electrons (average electron energy1.5 keV) which makes that there are simply too few electrons leaving tissue to cause an ERE.

Clearly, the integration of a proton therapy facility with on-line MRI functionality faces several technical hurdles. Basically, these are similar to the ones addressed for the technical feasibility work on integrating a 1.5 T MRI with a photon therapy system (see poster): magnetic and RF interference, beam transmission through the MRI and the dose deposition in a magnetic field.

The advent of compact proton accelerators such as presented by the Tomotherapy company (see news release NR-07-06-06 from Lawrence Livermore National Laboratory) and an open 0.5 T MRI similar to the hybrid interventional MR/X-ray system by Fahrig and co-workers in Stanford initiate the thoughts on a hybrid MRI proton therapy system. Also from an economical point of view this seems justified: the additional investment for MRI guidance is small compared to the total investment for a proton therapy facility.

Conclusion

In contrast to photon therapy, for MR-guided proton therapy the impact of the magnetic field on the dose distribution is very small. The main impact is due to the curvature of the proton beam itself by the magnetic field. This causes a lateral shift of the Bragg peak and the curvature should be accounted for when determining the entry point for that beam.

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