Outline design and cost estimate for the SmartPhantom

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MedAustron is the Austrian centre for proton and carbon-ion radiotherapy and research. Proton beams are routinely delivered for radiotherapy and non-clinical research. Carbon-ion commissioning is underway and it is anticipated that carbon-ion beams will be available for research in the third quarter of calendar 2019. A new, water-based, phantom is being developed for use in the non-clinical research programme. We propose to construct a scintillating-fibre-based dosimeter to measure the dose distribution delivered in real time. The use of 250 μm scintillating fibre will allow dose variation across the beam spot to be measured. The measurements will be used in conjunction with a detailed Geant4-based simulation of the phantom to determine the dose delivered to the biological sample. These calculations will be automated such that the dose delivered to the sample will be provided in real time, shot-by-shot. The dose-measurement system is described. A preliminary cost estimate indicates that the capital investment required to construct the SmartPhantom is £**???**.

1 Introduction

MedAustron is the Austrian centre for proton and carbon-ion radiotherapy and research. The MedAustron facility includes three patient-treatment rooms and a fourth end-station dedicated to non-clinical research. MedAustron acts as a hub for Austrian university groups, such as the Medical University of Vienna (MUW) , to pursue research in various fields including radiobiology. Proton beams are routinely delivered for radiotherapy and non-clinical research. Carbon-ion commissioning is underway and it is anticipated that carbon-ion beams will be available for research in the third quarter of calendar 2019.

A strategic objective for the Centre for the Clinical Application of Particles (CCAP) at Imperial is the development of a programme of radiobiology to elucidate of the micro-biophysical processes that underpin the efficacy of particle-beam therapy. As part of this programme the Centre is contributing to the commissioning of the carbon-ion beam at MedAustron. The execution of the non-clinical radiobiological research programme at MedAustron is led by personnel from the Medical University of Vienna (MUW) in collaboration with personnel from the Technical University of Vienna (TUW) and MedAustron. With this proposal we seek to contribute to the development of the radiobiology programme at MedAustron through the provision of an advanced, high-resolution dosimeter capable of measuring the dose delivered to the biological sample shot-by-shot in real time. This contribution will cement our nascent collaboration with MUW and allow us to take a leading role in the radiobiological exploitation of the MedAustron proton and carbon-ion beams.

2 SmartPhantom concept

2.1 Overview

A new, water-based phantom in which flasks containing the biological sample are suspended in a cubic volume of water is being developed at MedAustron by the MUW and the TUW (see figure 1). The phantom will be

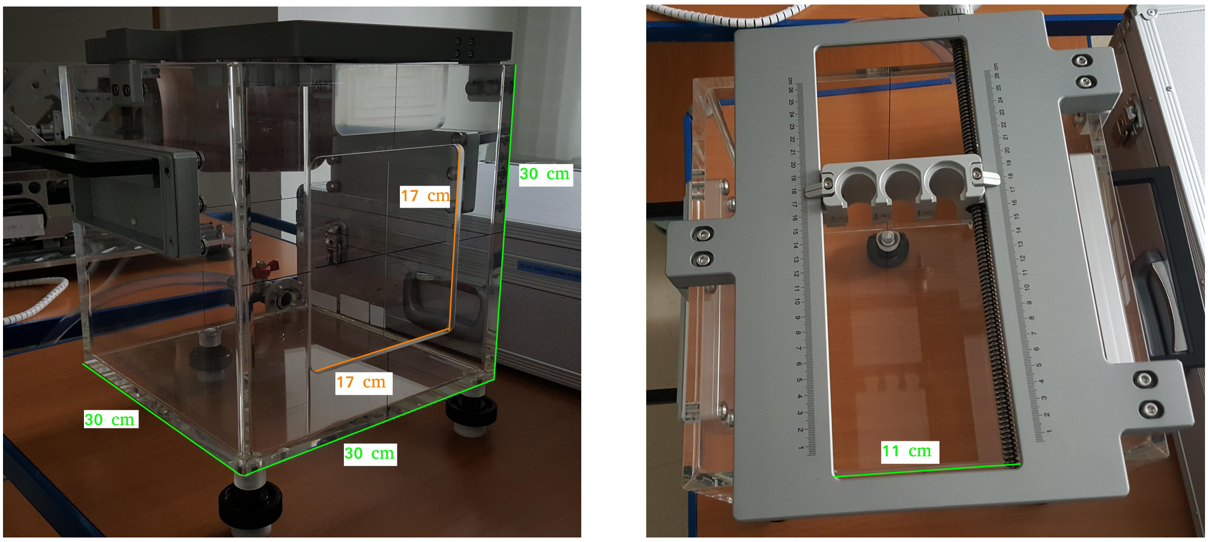


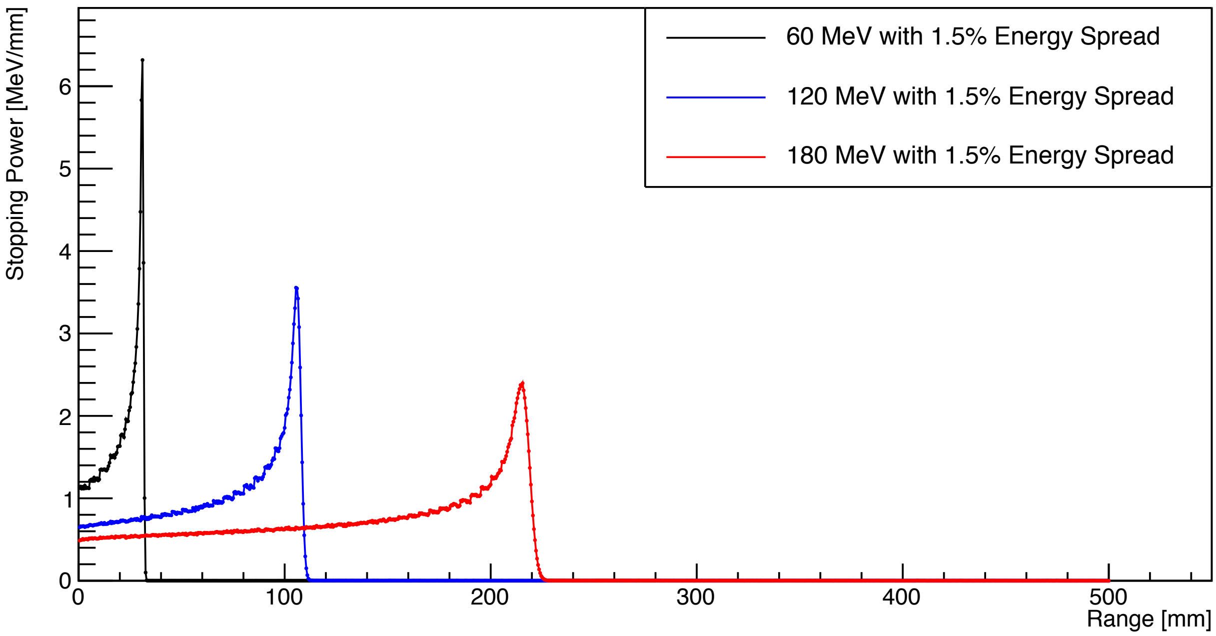
Figure 1: Photographs of the vessel that will contain the water in which the sample flasks will be immersed. Left panel: isometric view showing the dimensions of the vessel and of the beam entrance window. Right panel: view of the mechanical support secured on top of the phantom by which ionisation chambers and biological-sample flasks will be supported and accurately positioned.

exposed to proton beams with kinetic energy between 60 MeV and 250 MeV and C^{6+}-ions beams with kinetic energy between 120 MeV and 400 MeV. The transverse dimensions of the proton beam that impinges on the phantom varies from $20 \times 20\,\mathrm{mm}^2$ at 60 MeV to $7 \times 7\,\mathrm{mm}^2$ at 250 MeV. For C^{6+} beams, the beam-spot size varies from $10 \times 10\,\mathrm{mm}^2$ at 120 MeV/u to $6 \times 6\,\mathrm{mm}^2$ at 400 MeV/u. The typical spill length is ~ 5 s for protons and ~ 4 s for C^{6+}. There are approximately $\sim 1.8 \times 10^{10}$ protons ($\sim 4.5^8$ C^{6+} ions) in a typical spill. The length of a full cycle ranges from 9 s to 14 s.

Figure 2 shows the 'stopping power' (or specific ionisation, dE/dx) of proton and C^{6+} beams as a function of distance travelled in the phantom (range). The peak in the energy deposited just before the particle comes to rest, the Bragg peak, is clearly visible. To determine precisely the dose delivered to the biological sample requires that the energy lost by the beam be measured as a function of depth. We propose to construct a series of planar scintillating-fibre detectors by which to:

- Measure the energy loss as a function of range and transverse position before the Bragg peak;
- Observe the rapid increase in the rate of energy deposition and the beam profile just before the Bragg peak;
- Measure the energy-loss distribution and transverse beam profile within the Bragg peak (in the absence of a biological sample); and
- Characterise the rapidly-falling distal edge of the Bragg peak.

We propose to construct the detectors using fibres with a diameter of $250\,\mu$m. The thin fibre reduces the channel occupancy and therefore enhances the ability of the detector to resolve the timestructure of the beam within a spill. Each detector will be composed of a pair of fibre layers, the fibres in the first layer will be orthogonal to those of the second layer. The density of the detectors will be similar to that of water since the core of the fibre is polystyrene. $250\,\mu$m diameter fibre has been chosen to ensure that the transverse profile of the beam is sampled at many locations when the phantom is exposed to beams with the smallest spot size.



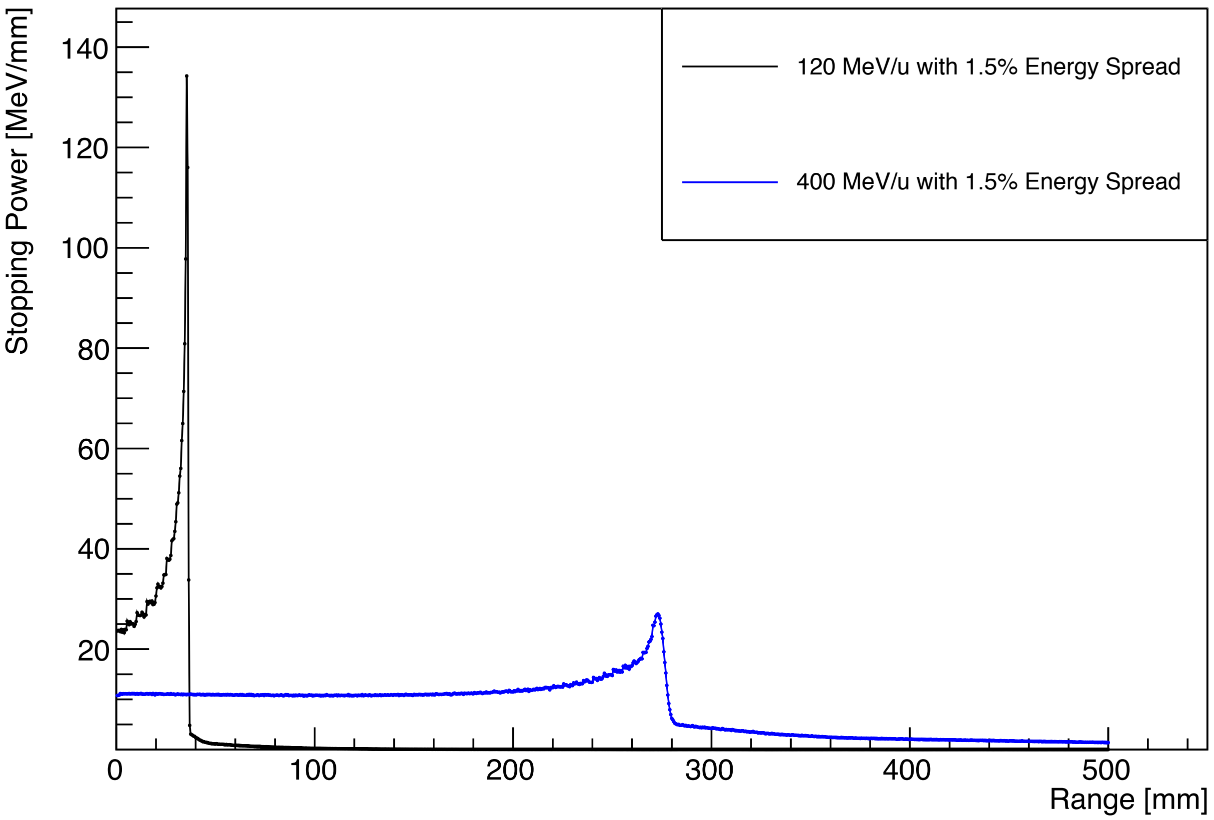


Figure 2: Stopping power (or specific ionisation, dE/dx) of proton (top panel) and C^{6+} (bottom panel) beams as a function of distance travelled in the water phantom (range). The stopping power is plotted for proton kinetic energies of 60 MeV (top panel, black solid line), 120 MeV (top panel, blue solid line), and 180 MeV (top panel, red solid line). For carbon-ion beams, the stopping power is plotted for beams with kinetic energies of 120 MeV (top panel, black solid line), 400 MeV (top panel, blue solid line). The kinetic-energy spread of the beams at MedAustron is 1.5%.

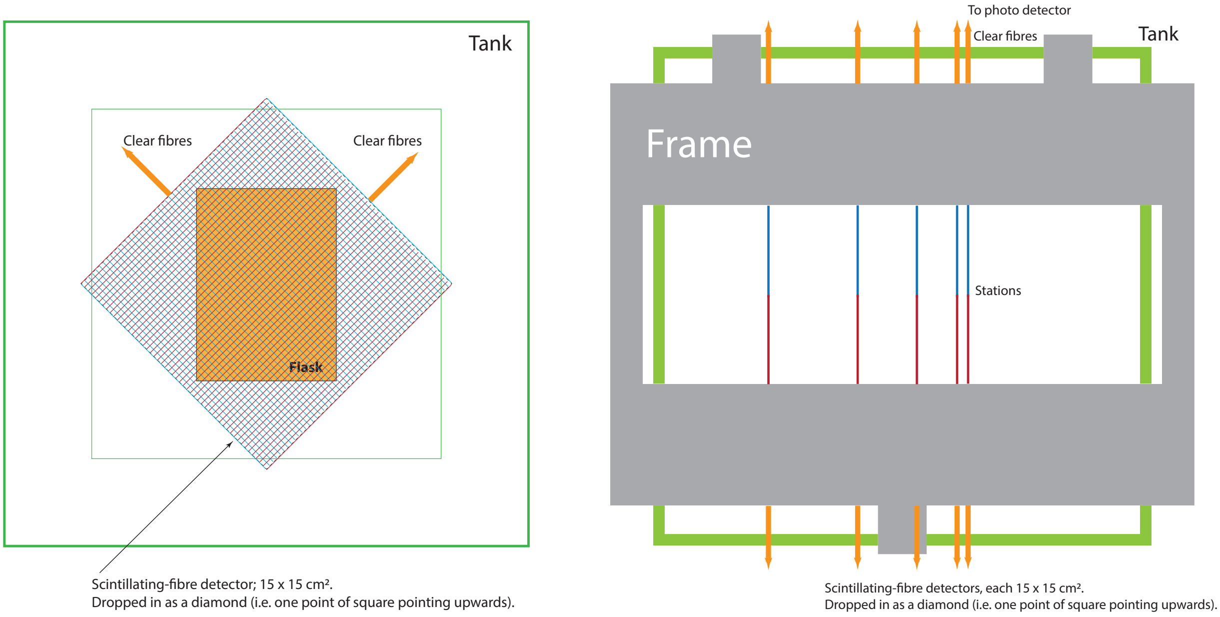


Figure 3: Schematic diagrams of the SmartPhantom. Left panel: beam's-eye view of the SmartPhantom. The water tank is indicated by the outer solid-green square and the beam window is indicated by the smaller green square. The active area of the scintillating-fibre stations is shown by the shaded rectangle. The direction in which the light-guides transport the scintillation light to the photo-sensors is indicated. The orange rectangle indicates the transverse projection of the largest sample flask that will be used with the water phantom. Right panel: top view of the SmartPhantom. The beam is incident from the left. The water tank is indicated by the green rectangle and the precision support frame located on the water tank is shown in grey. The positions of the five stations are indicated along with the exit routes for the light-guides.

2.2 Outline mechanical design

The layout of the SmartPhantom is shown in figure 3. The five stations are held in position using a carbon-fibre space-frame. The distance between neighbouring stations is such that each nearest-neighbour spacing is unique. The station spacing, together with other key parameters of the SmartPhantom, are presented in table 1.

Each station consists of two 'doublet layers' of 250 μm scintillating fibres glued on a carbon-fibre station body. The doublet layers are arranged such that the fibres in one layer run at an angle of 90° to the fibres in the other layer. The arrangement of the fibres within a doublet layer is shown in figure 4. This packing arrangement ensures that there are no inactive regions between adjacent fibres.

2.3 Light-guides and optical connectors

Clear-fibre light guides will transport the scintillation light to the photo-sensors. Optical connectors will be manufactured that couple the clear-fibre to the scintillating-fibre planes. A one-to-one mapping of sintillating to clear fibre is envisaged. The length of the light-guides will be minimised, but being long enough to allow the photo-sensors, digitiser boards and readout to be located behind the phantom out of the way of the services required by the biological samples. A length of 750 mm has been assumed for the costing.

Table 1: Key parameters of the SmartPhantom. The first section of the table presents the parameters of the SmartPhantom itself. The second section reports the baseline specification for the optical readout and digitisation of each channel.

Heading	**Item**	**Value**	**Unit**
Scintillating fibre	Diameter	0.25	mm
Clear fibre	Diameter	0.25	mm
Plane	Structure	doublet	
	Pitch	0.305	mm
	Size [x,y]	[150.0, 150.0]	[mm, mm]
	Number of channels	982	
Light guide	Length	500.0	
Station	No. of planes	2	
	Orientation	[0.0, 90.0]	degrees
Smart Phantom	Number of stations	5	
	Separation	[15.0, 12.0, 6.0, 3.0]	mm
Photo-diode	Diode Corp ODD-B1		
Low-noise amplifier	LMP7712		
Digitiser	AD7779		

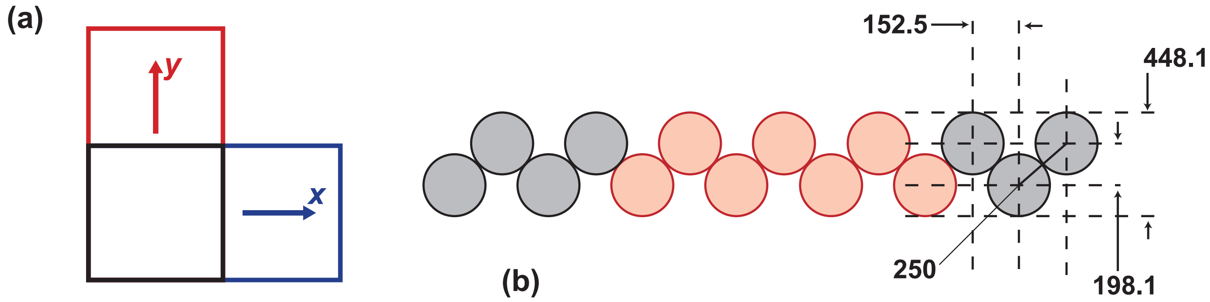


Figure 4: (a) Arrangement of the doublet layers in the scintillating-fibre stations. The square bounded by the solid black line shows the limit of the active area. The regions bounded by the solid blue and green lines indicate the direction that the individual 250 μm fibres run (moving outward from the centre) in the x and y directions respectively. (b) Detail of the arrangement of the scintillating fibres in a doublet layer. The fibre spacing and the fibre pitch are indicated on the right-hand end of the figure in mm.

2.4 Photon-detection system and readout

During a spill, particles are delivered to the phantom at a rate of several between 5 MHz and 10 MHz. The following scheme has therefore been adopted to estimate the cost-per-channel of the digitisation and readout systems:

- Photodiode with reasonable response at short wavelength: Opto Diode Corp ODD-B1;
- Low-noise amplifier: LMP7712);
- Digitiser, AD7779, which has a dynamic range of 10^5–10^6 depending on speed and is capable of a sampling rate of up to 16kHz;
- Readout backend mounted on a PCB.

3 Initial estimate of capital cost

An initial estimate of the capital cost of constructing the SmartPhantom has been made on the assumption that the scintillating and clear fibre will be sourced from Saint Gobain. Saint Gobain have given an indicative cost rather than a firm quote. The estimate for readout chain, from photo-detector to PC, has been made based on the costs for the various items recorded in recent catalogues.

Table 2: Summary of the capital cost of constructing the SmartPhantom described in section 2 with the parameters listed in table 1. The basis of estimate of the each row in the table is explained in the text.

Cost	Scintillating fibre	23.93	£k
	Clear fibre	92.11	£k
	Mechanical structure	20.00	£k
	Photo-detectors	16.69	£k
	Readout	43.20	£k
	Labour	60.00	£k
	Total	**239.25**	**£k**

The basis of estimation for the capital costs presented in table 2 is:

Scintillating fibre:
Saint Gobain, 250 μm diameter round scintillating fibre, BCF-10, multiclad: \$1.25 per metre, minimum order \$1.25k;

Clear fibre:
Saint Gobain, 250 μm diameter round fibre: \$1.25 per metre, minimum order \$1.25k;

Mechanical structure:
The mechanical design of the SmartPhantom needs to be developed. The cost presented in table 2 is based on our experience with the scintillating-fibre tracker for the MICE experiment at RAL. The total is to be taken to include: the precision jigs, stages and microscope required to assembled the doublet layers; the carbon-fibre structure required to support the doublet layers in the station; the precision support frame; and the precision stages required to accurately position the stations within the phantom;

Photo-detectors:
The photo-detector proposed for the SmartPhantom, Opto Diode Corp ODD-B1, is estimated to cost £1.70 per channel;

Readout:

The cost of the low-noise amplifier, digitiser, readout back-end, and computer has been roiled into a cost per channel of £4.4; and

Labour:

The assembly of the doublet layers and stations of the MICE scintillating-fibre tracker was a labour-intensive process. The MICE double-layers were constructed using 350 μm diameter fibre and had a circular active area of diameter 300 mm. The work involved in constructing the instrumentation for the SmartPhantom has been estimated based on our experience in the construction of the trackers for MICE.

An exchange rate of 1.27 US dollars to the pound has been used.