ProBE - PROTON BOOSTING EXTENSION FOR IMAGING AND THERAPY

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Abstract

Conventional proton cyclotrons are practically limited by relativistic effects to energies around 250 MeV, sufficient to conduct proton therapy of adults but not for full-body proton tomography. We present an adaptation of the cyclinac scheme for proton imaging, in which a c.250 MeV cyclotron used for treatment feeds a linac that delivers a lower imaging current at up to 350 MeV. Our ProBE cavity design envisages a gradient sufficient to obtain 100 MeV acceleration in 3 metres after focusing is included, suitable for inclusion in the layouts of existing proton therapy centres such as the UK centre under construction at Christie Hospital. In this paper, we present the results of design studies on the linac optics and RF cavity parameters. We detail particle transmission studies and tracking simulation studies.

INTRODUCTION

Proton radiotherapy of adult patients is typically specified to require incident kinetic energies of protons up to around 250 MeV, but the treatment advantages made possible by the inherent Bragg peak require improved range determination of those protons [1, 2]. One favoured imaging technique is to conduct proton computed tomography (pCT) in which incident protons with energy sufficiently large to pass through the patient have their resulting energy loss used to construct an accurate density map of the patient better than that possible from other imaging techniques such as X-ray CT [3–5]. The UK is investing £250M in two nationally-funded proton therapy centres each with 3 gantries [6], and there is much interest both in the UK and elsewhere in developing pCT as a clinical technique [7, 8]. However, no suitable source of protons with sufficient energy is yet available as upgrade, although design studies have proposed the use of FFAGs as a source [9, 10]. Cyclotrons deliver protons essentially with a fixed energy, and other energies below that must be obtained using a suitable degrader.

Here we propose the use of a linac to boost the energy of a medical cyclotron to imaging energies, an extension of the well-known cyclinac method for therapeutic energies [11–14]. At treatment energies up to 250 MeV, proton currents of around 0.1 to 10 nA are required to obtain average dose rates of 1 Gy/min, readily achieved from cyclotrons even when accounting for degrader losses. Losses in cyclinacs are typically over 90% due to the frequency mismatch between cyclotron (10s of MHz) and linac (typically S-band), but for proton imaging the required currents are much lower, ~ pA rather than ~ nA; the large losses are not really a problem, although they should be minimised. The combination of higher initial energy (250 MeV) and less restriction on losses allows different design choices for the RF structures, offering the opportunity to obtain a larger accelerating gradient and thus a smaller overall footpring. This is the idea behind the ProBE study, which aims to produce 100 MeV of energy gain in a space of around 3 metres. This size allows such a linac to be used potentially as a retrofit to existing proton therapy cyclotrons in the BTS between source and gantry.

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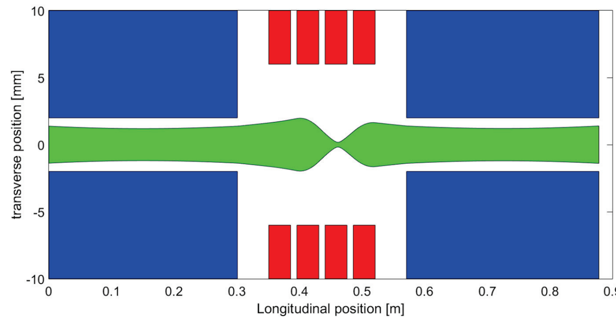

Figure 1: Horizontal 1σ beam size through two 30 cm RF cavities and a 4-quadrupole matching cell.

BOOSTER OPTICS DESIGN

We have considered two different optical setups for the linac in order to achieve 100 MeV in 3 m. Firstly, we consider a ‘minimum aperture’ scheme whereby quadrupole matching sections are used to create a small transverse beam size through each cavity; this scheme allows for a smaller iris aperture through the cavities and therefore a higher potential accelerating gradient through the linac. The second scheme is a conventional ‘FODO’ lattice using a single quadrupole between each cavity. This scheme requires the least amount of space for optics and therefore the maximum amount of space for cavities; thus minimises the required accelerating gradient from the cavity to obtain 100 MeV over the full system length.

Minimum Aperture Scheme

To determine whether the minimum aperture scheme is viable for the ProBE linac, we assume a cavity accelerating gradient no more than 65 MV/m [15]; assuming a synchronous phase of 20° this is 61 MV/m over a cavity of approximately 30 cm length. The scheme therefore uses 5 cavities and 4 matching cells, so the matching cell can be up to 35 cm long. Figures 1 and 2 show the horizontal and vertical 1σ beam sizes through the first two cavities in the linac.

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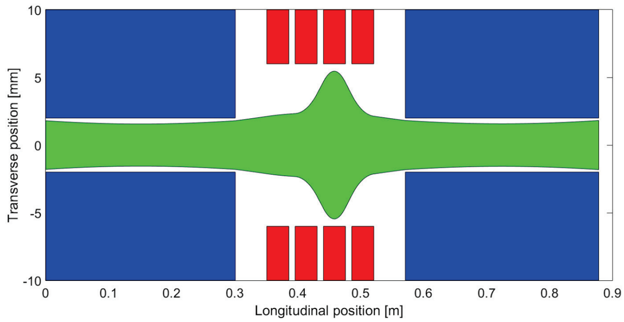

Figure 2: Vertical 1σ beam size through two 30 cm RF cavities and a 4-quadrupole matching cell.

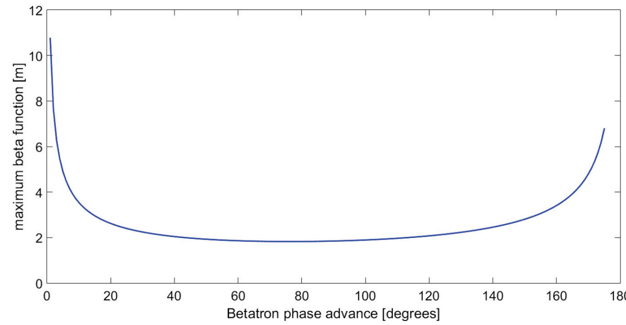

Figure 3: Maximum beta function vs. betatron phase advance.

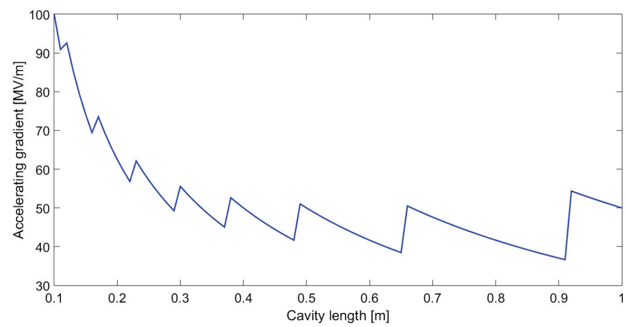

Figure 4: Required acclerating gradient vs. cavity length for a FODO lattice.

We assume the use of permanent magnet quadrupoles (PMQs) for the matching, likely to be neodymium rare-earth magnets with a pole-tip field of ~1.4 T. Assuming a maximum 1σ beam size through the PMQs of ~6 mm (Figure 1 and 2), we may obtained a maximum field gradient of ~230 T/m. Using the conventional scaling of gradient to k of

$$k = \frac{e}{pc}\frac{\partial B}{\partial r} = \frac{ec}{\beta E}\frac{\partial B}{\partial r} \tag{1}$$

this gradient corresponds to a maximum k-strength of the PMQs of 100 m^{-2} at 230 MeV to 82 m^{-2} at 330 MeV. However, we have determined that for good optics matching we require k-strengths of ~1000 m^{-2} for a 4-PMQ matching cell which is less than 35 cm in length. We also investigated matching cells consisting of 2 or 3 PMQs, but the required cell length for these designs were 2-3 m. Therefore this minimum aperture scheme is not practical for our linac design as it is not possible to design a short enough matching cell which uses practically-achievable quadrupole strengths.

Conventional FODO Scheme

A FODO scheme was considered as this minimises the lengths of the sections between cavities and therefore reduces the required accelerating gradient. To determine the optimal lattice parameters, we consider a thin-lens approximation for the FODO quadrupoles. The maximum and minimum beta functions can be expressed are

$$\beta_{max} = \frac{L}{\sin\left(\frac{\mu}{2}\right)}\sqrt{\frac{1+\sin\left(\frac{\mu}{2}\right)}{1-\sin\left(\frac{\mu}{2}\right)}} \tag{2}$$

$$\beta_{min} = \frac{L}{\sin\left(\frac{\mu}{2}\right)}\sqrt{\frac{1-\sin\left(\frac{\mu}{2}\right)}{1+\sin\left(\frac{\mu}{2}\right)}} \tag{3}$$

where the k-strength may be expressed as $kl_q = \frac{2\sin(\frac{\mu}{2})}{L}$.

In order to maximise the achievable accelerating gradient in the cavity, it is preferable to minimise the iris aperture. Figure 3 shows the maximum beta function vs. betatron phase advance (μ); the minimum occurs when $\mu \sim 70°$.

We define the required accelerating gradient as $G_{req} = \frac{1.1G_{beam}}{\cos\phi_{synch}}$, which includes a 10% overhead the gradient obtained from the RF structure. G_{beam} is the accelerating gradient seen at the synchronous phase ϕ_{synch}. Figure 4 shows the required accelerating gradient versus cavity length. Given the required 100 MeV energy gain over 3 m, we have defined the length of the PMQs as 3.5 cm and assumed a 5 cm gap between a cavity and a quadrupole to allow for flanges and the cavity cutoff; hence the total space between cavities is 13.5 cm.

Local minima occur in Figure 4 when $nL_{cav} + 0.135\,(n-1) = 3$ where n in an integer. While the minimum required accelerating gradient occurs when we use longer structures, this requires a larger iris aperture because the beam size scales as $\sqrt{L}$ where the space between quadrupoles $L = L_{cav} + 0.1$. In addition, longer cavities require more powerful klystrons to achieve the same gradient compared to a shorter structure, and their gradient tends to be limited by pulse heating due to magnetic fields near the coupling ports. At present we are considering 30 cm-long cavities. Figure 5 shows the transverse, longitudinal and total particle transmission through a 3 m FODO scheme using 30 cm accelerating structures. The transmissions were compared between tracking simulations in ASTRA [16] and a theoretical model.

As the cavity length changes with energy and the longitudinal dynamics are not constant, the real lattice is not a perfect FODO, thus the beam parameters in ASTRA will

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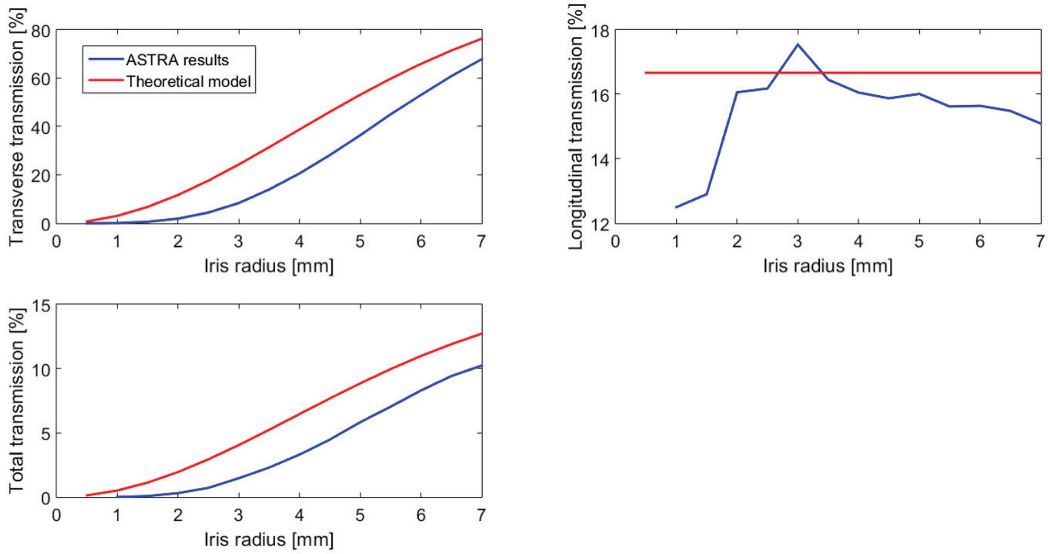

Figure 5: Transverse, longitudinal and total particle transmission vs. iris half aperture.

be slightly mismatched and ASTRA will give slightly larger transverse losses than the theoretical model. Due to relatively low particle statistics the longitudinal transmission in ASTRA is only able to show the approximate transmission, but it can be seen that the results are consistent with the theoretical value.

CONCLUSION

In this paper we have considered two optical designs for the ProBE 3 m long linac. We consider that the minimum aperture scheme is not feasible because the required quadrupole strengths and matching cell lengths are too high to be practical; the conventional FODO scheme is chosen as this minimises the space between cavities, and thereby the required gradient to achieve 100 MeV of energy gain in 3 m.

We derive values for the main optical parameters in order to achieve 100 MeV energy in 3 m and use tracking simulations in ASTRA to determine particle transmission as a function of iris aperture. This will be used for future work in order to design a cavity with an appropriate iris aperture to allow sufficient beam current to exit the linac.

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