ProBE: PROTON BOOTING EXTENSION FOR IMAGING AND THERAPY*

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Abstract

Proton beam therapy is an alternative to traditional x-ray radiotherapy utilised especially for paediatric malignancies and radio-resistant tumours; it allows a precise tumour irradiation, but is currently limited by knowledge of the patient density and thus the particle range [1]. Typically X-ray computed tomography (CT) is used for treatment planning but CT scans require conversion from Hounsfield units to estimate the proton stopping power (PSP), which has limited accuracy . Proton CT measures PSP directly and can improve imaging and treatment accuracy. The Christie Hospital will use a 250 MeV cyclotron for proton therapy, in this paper a pulsed linac upgrade is proposed, to provide 350 MeV protons for proton CT within the facility. Space constraints require a compact, high gradient (HG) solution that is reliable and affordable.

INTRODUCTION

The precise dose delivery achievable with proton therapy requires accurate treatment planning to obtain the greatest benefit. Presently, margins defined around treatment volumes are greater in treatment planning than they might be, to account for uncertainties in CT scans. Proton CT (pCT) can reduce this margin of error by directly measuring the PSP of the tissue between the beam and the patient treatment volume (PTV). While head-and-neck and paediatric pCT is within the energy reach of current 230-250 MeV proton therapy machines, full adult pCT would require around 330-350 MeV to ensure the Bragg peak is outside of the patient.

The Christie Hospital (Manchester, UK) will soon have a 250 MeV cyclotron providing gantries with protons for treatment. A pulsed linac upgrade in 3 metres of space within the planned facility is proposed, to provide 350 MeV protons for pCT. This 3 m space must contain all aspects of this booster accelerator including radio-frequency (RF) cavities and beam focusing; such a system will require an RF linac with an accelerating gradient higher than any currently-existing structure at that particle velocity. The ProBE project was initiated to study the feasibility of such a linac.

RF DESIGN

Studies of high-beta cavities have shown that moving to higher frequencies (such as X band) can increase the gradient via the increased shunt impedance (R_s) per unit length, provided the aperture is small enough [2]. It was not clear if this trend would continue at lower beta, hence we initially investigate a disk-loaded cavity with a medium beta (β=0.6) using CST Microwave Studio; S-band, C-band and X-band frequencies were all considered. Single-cell pillbox cavities were simulated with their septum thicknesses scaled inversely proportional to frequency from 1-4 mm. Due to the limited space and high gradient requirement, we chose to use one 50 MW klystron was per 1 m of linac. This and R_s per unit length were used to calculate the maximum gradient of each single cell.

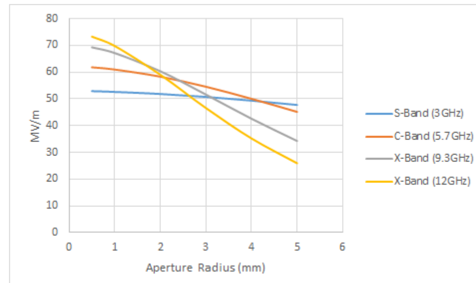

Figure 1: Aperture vs accelerating gradient based on shunt impedance and power per unit length.

The maximum gradient is strongly reliant on the aperture radius as can be seen in Figure 1, especially for X-band structures. However, nose cones can be added to increase the R_s of a structure at the expense of peak fields. The next step would be to add nose cones and decrease the gap to increase R_s until the peak fields at maximum gradient fall within reasonable limits. Based on results from the TERA collaboration on re-entrant cavities [3] it was decided to focus on the modified Poynting vector (S_c) as the key measure of peak fields [4], and a maximum value of 4 W/m^2 was chosen for the optimisation. It is also not entirely clear what the minimum septum thickness can be and how it scales with frequency, hence this parameter was varied during the optimisation. Proton imaging requires relatively low beam current (pA) so initially small apertures of 3.5 mm were utilised to maximise gradient, which we revisited later.

The results seen in Figure 2 show that these maximum gradients have very high peak surface electric fields (E_{peak}) which are thought to contribute to RF breakdown. HG tests performed on S-band and C-band cavities elsewhere have suggested that higher E_{peak} than the traditional Kilpatrick limit [5] can be reached within the S_c constraint; however the E_{peak} values seen in Figure 2 are still much higher than that [6,7]. To set a conservative limit, the breakdown rate (BDR)

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was scaled to a rate of 10^{-6} at a 5 µs pulse length at S-band using the scaling constants found by Alberto Degiovanni [3], giving a maximum E_{peak} of 200 MV/m. The structures were then re-optimised using this limit.

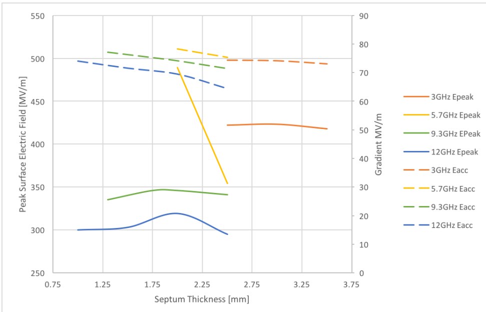

Figure 2: Maximum accelerating gradient of re-entrant cavities limited by shunt impedance and modified poynting vector.

Figure 3 shows the maximum achievable gradient of single-cell RF re-entrant cavities at 3.5 mm aperture diameter using both limits of peak fields separately. The black markers show the maximum gradient that can be achieved using S_c as a gradient limit; the orange markers show the reduction in gradient when E_{peak} is also limited. It can be seen that there is an advantage in going to higher frequencies if E_{peak} is neglected, and only S_c is used to limit the breakdown rate (BDR), especially if thinner septa could be used at higher frequencies. However, if E_{peak} is limited to 200 MV/m then S band is likely the optimum frequency, with C band being better if the septum be thinner. If the beam dynamics were to require a larger aperture to achieve the required transmission then S band clearly be optimal. To study this a number of structures were simulated with a larger aperture of 6.5 mm; in this case magnetic coupling was included in the study, as well as including transmission losses in the available power to find the realistic maximum achievable gradient.

A side-coupled standing wave structure (SCSWS) at C band was simulated with a 2 mm septum thickness, which produced an expected gradient of 53 MV/m. An S-band SCSWS with a septum thickness of 2 mm was then investigated which achieved a gradient of 54 MV/m limited by E_{peak} and R_s. An S-band backwards travelling wave structure (bTWS) was also investigated, utilising magnetic coupling between each cell; however the coupling slot size and hence the group velocity through the structure was limited by a 273 kA/m limit placed on it to keep pulsed magnetic heating below 40 K. This meant a constant gradient could not be achieved which resulted in the gradient being limited to <52 MV/m.

Beam Dynamics

Since the space available is limited, longer focussing sections decrease the the space available for cavities; however, smaller apertures allow higher gradients. Studies of transmission using ASTRA - including both longitudinal and transverse losses and assuming a 2% energy acceptance - indicated that the optimum cavity length for the transmission required (<3%) is 30 cm per structure, with 13.5 cm FODO matching sections between them containing 1 x 120 T/m quadrupole magnets (plus a few additional centimetres for bellows and flanges).

To achieve adequate transmission, the aperture would have to increase to 8 mm diameter, significantly larger than the original investigated apertures. However this focussing scheme allows for 6 x 30 cm structures in 3 m requiring an accelerating gradient of 55 MV/m to achieve the 100 MeV acceleration required, far lower than the 70–80 MV/m seen in the small-aperture single cell simulations of the previous section. Using a triplet in between each cavity result in a substantially longer system, and couldn't decrease the beam size with practical field strengths to a small enough value to obtain sufficient gradient to overcome the loss in accelerating length. More detail on this work can be found in the IPAC16 conference proceedings [8].

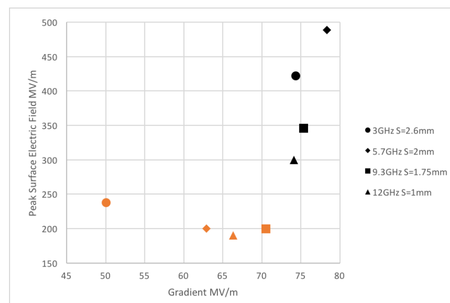

Figure 3: Peak surface electric field vs accelerating gradient. Black - Sc limited, Orange - E_{peak} limited.

Chosen Structure

The study in the previous section showed that at an aperture of 6.5 mm, S band is the optimum frequency; hence at 8 mm S band is still likely to be best. We therefore chose a SCSWS operating in the $\frac{\pi}{2}$ mode. A coupling factor of 2% was chosen to ensure adequate coupling throughout the structure up to 1.5 MHz manufacturing errors. The SCSWS structure was chosen as it reached closest to the required gradient of 55 MV/m, and also because S-band klystrons at 50 MW are affordable for medical facilities and are widely commercially available in sufficiently long pulse durations and duty cycles. In addition, a study by TERA on brazing creep suggested that a 2 mm septum thickness was achievable in S band [3, 9]. At this thickness the structure was found to theoretically achieve a gradient of 54 MV/m which is within 2% of the required gradient, allowing a 3 m system to basically achieve 100 MV energy increase.

Table 1 shows all relevant parameters.

MECHANICAL DESIGN

Once the RF design had been completed it was necessary to consider the mechanical engineering of a prototype structure. An aperture was introduced to the side-coupled cells to allow for any field to be detected via bead-pull experiments.

Table 1: Parameter Table

Parameter	Units	S-Band SCSWS
Phase adv.	[deg]	90
Cell Length	[mm]	29.8
Coupling Factor	[%]	2.16
Rs/L	[MΩ/m]	76
$\sqrt{Sc}$/Eacc	[$\sqrt{W}$/MV]	2.4e-2
Eacc	[MV/m]	54
Hpk	[kA/m]	254
Epk	[MV/m]	200

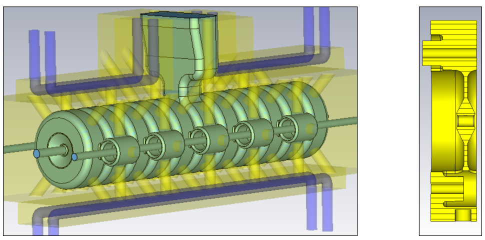

Figure 4: Left - 3D model of the final 11 cell prototype structure in CST Microwave studio including coupler, cooling blocks, and holes for tuning pins. Right - Off centre disk cut.

Additionally, these points that go through each disk in the cavity make good points of location for machining.

As previously mentioned, the septum was designed to be as thin as possible to maximise the shunt impedance of the structure. Typically the septum is halved during manufacture as the structure is machined in separate rectangular disks. However, in our structure we will cut off-centre to preserve the full septum thickness, since 1 mm thick copper would deform during bonding. The capacitative region in the side-coupled cell extends beyond the edge of the disk to enable the structure to be cut in the way shown in Figure 4.

Separate cooling blocks - brazed on to the structure after it has been constructed - were chosen over pipes integrated into the structure disks themselves. Integrated cooling would be more effective at dissipating the heat as it would be physically closer to the iris, however it is desirable to limit risk of leaking for the prototype structure. Diffusion bonding was chosen as the method to assemble the disks over brazing, as it has been shown to have better high-gradient operation [10] and also negates the risk of braze running into the cavity.

A 10 mm wall thickness was chosen to allow enough contact area for bonding, and also to minimise the distance between the cavity and the cooling blocks for adequate heat dissipation. A lip has been added to two sides of the cavity perpendicular to one another and to a similar groove on the other face of the disk. This is to create an interlocking system used for both linear and rotational alignment. Furthermore, four tuning pins have been added per cell to enable any frequency errors resulting from manufacturing to be tuned for. This will allow us to tune each cell by 4 MHz which is within our 10 µm tolerances [9].

THERMAL GRADIENT

2 x 50 MW klystrons will power 6 structures of the linac, i.e. around 14 MW per structure, where we assume ~15% transmission losses. The cyclotron ion source may be pulsed at a maximum repetition rate of 200 Hz, thus initially the klystron power was going to be pulsed at 200 Hz with a 5 µs pulse resulting in an average power of 20 kW. This resulted in a temperature gradient of 112 K assuming the entire cavity volume expands by 112 K, and linearly scaling frequency for worst case detuning the cavity would detune by -5.6 MHz. Whilst the water temperature could be varied during turn-on to compensate for this, there is also likely to be an accompanying change in field flatness as the temperature of each iris is not constant. The repetition rate was therefore limited to 34 Hz - providing an average power of 2 kW- to reduce operational detuning to <1 MHz.

The resulting temperature gradient can be seen in Figure 5 (performed using CST MultiPhysics Studio). The predicted temperature difference has been reduced to 14 K; simulations to confirm the estimated frequency shift are in progress. The consequence of reducing the duty cycle in this way is a reduction in the achievable current; the output beam current is predicted to be ~2.5 pA, sufficient for proton imaging in a clinically-acceptable timescale.

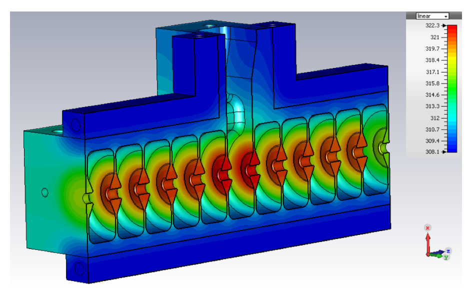

Figure 5: Temperature Gradient between cooling and iris resulting in an operational frequency shift of 2 MHz.

CONCLUSION

The optimisation and mechanical engineering considerations of a 3 GHz high-gradient SCSWS are presented in this paper, where we conclude that S band is the optimal frequency. Our design predicts an accelerating gradient of 54 MV/m with a E_{peak} of 200 MV/m. An 11-cell prototype cavity is currently being manufactured and will be tested at CERN. This test will also represent the first systematic study of high-field breakdown limits in a magnetically-coupled SWS, the results of which may have a significant impact in the design methodology of future side-coupled structures at high gradient.

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