ProBE: PROTON BOOSTING EXTENSION FOR IMAGING AND THERAPY*

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Abstract

The ProBE linac aims at accelerating protons from a particle therapy cyclotron to the c. 330 MeV required for proton tomography. To obtain the c. 54 MV/m gradients required to achieve 100 MeV gain in a suitably short distance, we propose the use of a high-gradient S-band side-coupled standing-wave structure. In this paper we discuss the progress toward the testing of the prototype at the S-box facility at CERN.

INTRODUCTION

The precise dose delivery achievable with proton-based radiotherapy requires accurate treatment planning to obtain the greatest benefit. Presently, margins defined around treatment plan volumes are greater than they might be; these margins account for uncertainties in translating densities from CT scans. Proton CT (pCT) may reduce this error by directly measuring proton stopping via the loss of energy as protons pass completely through an imaged structure; margins could be reduced from as much as 10 mm to as little as 2 mm using this technique, and several proton-counting detector technologies may be employed. Whilst head-and-neck and paediatric pCT is within the energy reach of current 230-250 MeV proton therapy machines such as cyclotrons, full adult pCT will require up to 350 MeV protons to maintain the Bragg peak beyond the imaged patient. The Cockcroft Institute is developing solutions to obtain 330 MeV protons using either FFAG or cyclinac approaches. In this paper we discuss the ProBE (Proton Booster Extension) cyclinac which we have proposed as a convenient and compact method to augment the c.250 MeV energies - readily obtainable from modern proton therapy cyclotrons - to the 330 MeV (or higher) required for pCT. 330 MeV is judged enough to allow imaging of adults with good density resolution, and our ProBE 3 GHz design will accomplish a 100 MeV increase in energy up to 350 MeV using six 54 MV/m structures in around 3 m when associated beam transport is included.

A summary of the ProBE booster parameters is given in Table 1. A fuller description of the beam dynamics through the cyclinac system, and a description of the superconducting gantry delivery concept, are given in separate papers presented at this conference. In this paper we describe the evolution of the cavity design toward manufacturing.

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Table 1: Summary of ProBE S-band SC-SWS Booster Linac Parameters

Frequency	3	GHz
Gradient	54	MV/m
Entrance Energy	250	MeV
Exit Energy	350	MeV
Phase Advance	90	deg
Cell Length	29.8	mm
Coupling Factor	2	%
R_S/L	76	MΩ/m
$\sqrt{S_c}/E_{acc}$	2.4×10^{-2}	$\sqrt{W}$/MV
H_{pk}	254	kA/m
E_{pk}	200	MV/m

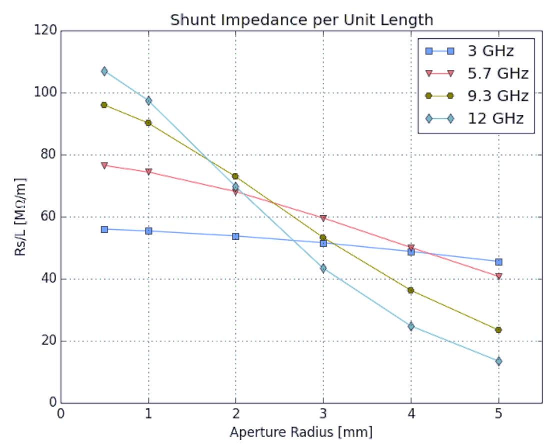

Figure 1: How obtainable cavity gradient is dependent on iris aperture for different single-cell cavity designs at $\beta = 0.6$.

CAVITY DESIGN CHOICES

Frequency Choice

Cyclinac approaches all resemble each other in that there is an inherent frequency mismatch between the natural frequency of the proton bunches extracted from a cyclotron source and the frequency of the linear accelerator cavities that capture those bunches and accelerate them. Hence one expects a significant beam loss in this scheme of around 90% of the initial particles; this is acceptable since the required currents at the cyclinac end are no more than 10 nA from a cyclotron that can readily deliver several hundred nanoamperes. In particular, the proton current required to obtain a pCT image in one minute is 3.2 pA [1], so the over-riding requirement in retro-fitting a booster to a c.250 MeV cy-

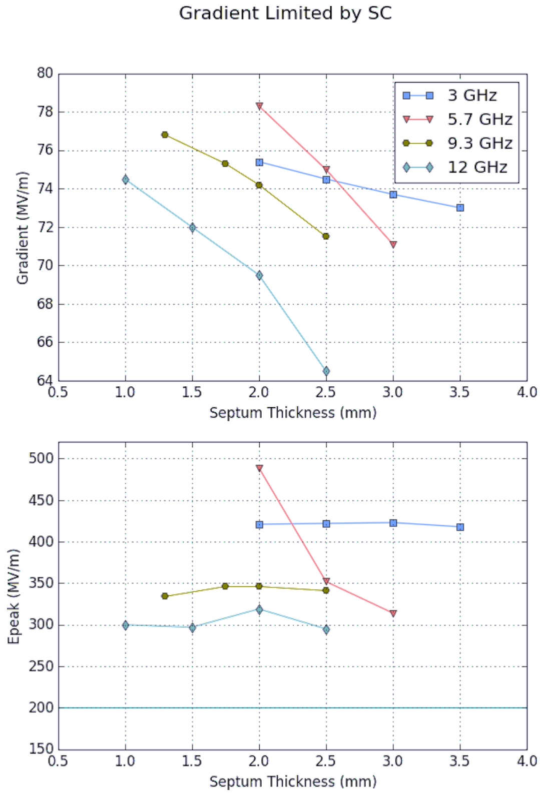

Figure 2: Maximum accelerating gradient of small aperture re-entrant cavity designs limited by shunt impedance and Modified Poynting vector.

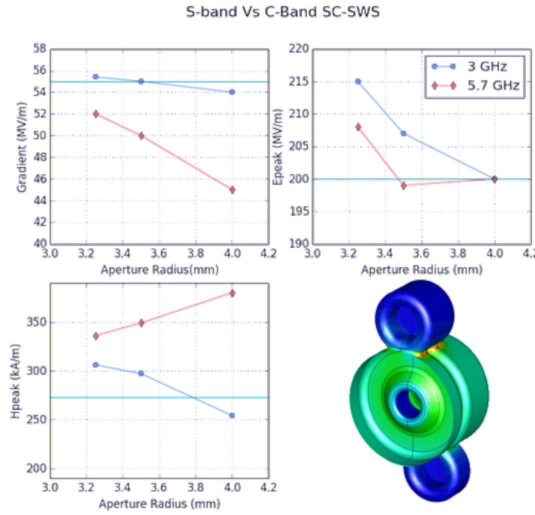

Figure 3: Comparison of S- and C-band side-coupled standing wave structures. Gradient limited by R_s and input power. (Bottom Right) Peak magnetic field on C-band quadruplet.

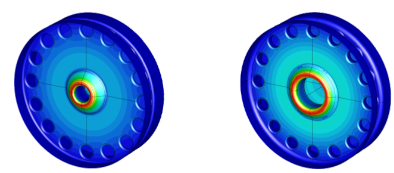

Figure 4: Electric field distribution in the single cell backwards travelling wave structures investigated (Left) S-band (Right) C-band.

clotron treatment scheme is to maximise the cavity gradient to minimise the real estate usage in a facility.

Studies of high-β cavities have shown that moving to higher frequencies (such as X-band) can increase the available gradient via the increased shunt impedance per unit length (R_s/L), provided the aperture is small enough. It was not initially clear to us if this behaviour was also true at a lower β, so we investigated S-band, C-band and X-band disk-loaded cavities at a moderate $\beta = 0.6$ (using CST Microwave Studio) corresponding roughly to the typical proton energy from a therapy cyclotron (230 MeV); single-cell pillbox cavities were examined with septa thickness scaled inversely with frequency from 1 to 4 mm, and assuming 1×50 MW klystron per meter of linac. We found that the obtainable gradient is strongly dependent on the iris aperture as shown in Figure 1, and increased (R_s/L) for X-band structures with a small aperture.

Based on CLIC procedure we focused on the Modified Poynting Vector (S_C) as the important gradient limit [2], assuming a maximum value of 4 W/µm^2; we also studied the effect of septum thickness. The results (Figure 2) showed very high peak surface fields (E_{peak}) so we introduced a limit of 200 MV/m using scaling results from the TERA collaboration [3] [4] [5]. We decided to optimise multicell S- and C-band cavities with 2 mm septum thickness as they demonstrate the highest achievable gradient, and this thin septum has been successfully demonstrated at S-band in the TERA backwards travelling wave (bTW) design [6]. It is true that similar gradients can be achieved at X-band with lower peak fields, however studies showed the high coupling required between cells offsets this. Furthermore, beam dynamics studies indicated an aperture radius of 4 mm was necessary, and Figure 2 was produced with a 1.75 mm aperture radius. Increasing the aperture inherently lowers the peak fields and Figure 1 confirms S- and C-band to have the highest (R_s/L) at the chosen aperture.

Effect of Beam Focusing Scheme

Whilst a significant beam loss of around 90% of particles is inherent in all cyclinac schemes, a small transverse aperture can contribute more loss considering the relatively large emittances c.10 mm-mrad obtained from therapy cyclotrons. Mitigating this loss in a small-aperture structure necessitates use of shorter cavities and a larger number of (PMQ) focusing magnets, cancelling any advantage of the higher frequency. Hence we conclude that a large-aperture (8 mm) S-band structure offers the most compact scheme for a cyclotron booster.

Structure Design

Side-coupled standing wave (SCSW) and bTW multicell structures were optimised at the chosen frequencies. The C-band SCSW was not suitable due to peak magnetic fields on the coupling slot shown in Figure 3. Neither the S- nor

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C-band bTW structures shown in Figure 4 outperformed the S-band SCSW structure, as they were limited by peak electric field at gradients of 52 MV/m and 43 MV/m respectively.

Based on our studies we have chosen an S-band SCSWS with 8 mm aperture operating in the $\pi/2$ mode with a coupling factor of 2%. Summary parameters are given in Table 1. A further advantage of S-band is that 50 MW klystrons are widely available with long pulse duration and duty cycle, and are affordable. A complete 6-cavity system plus associated focusing can deliver around 100 MeV energy gain over 3 m of beam transport. The small gap in the side coupled cells (shown in Figure 5) raised concerns about multipacting; however, the high gradient means the lowest field in that gap is safely above the threshold for multipacting.

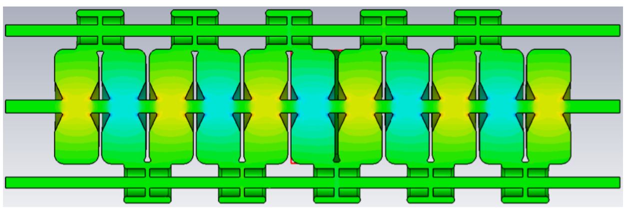

Figure 5: Cutaway view of the ProBE 11-cell prototype cavity presently being manufactured. This is a 3 GHz, 54 MV/m side-coupled standing-wave structure to demonstrate acceleration from 250 MeV upwards.

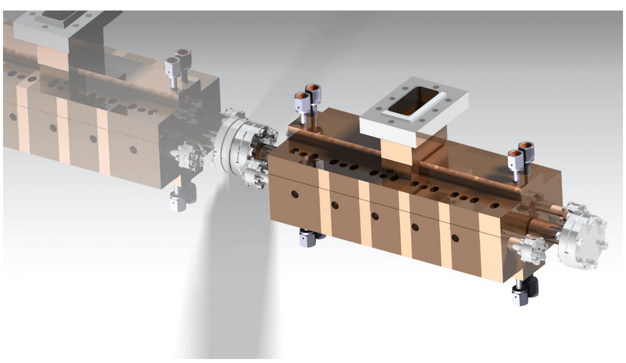

Figure 6: Visualisation of the ProBE 11-cell cavity prototype, showing RF coupler (above), additional access apertures for bead-pull tests (ends) and four tuning pins per cell that provide 4 MHz adjustment (corresponding to 10 µm tolerance).

MECHANICAL DESIGN

In addition to ordinary construction techniques for such cavities, our prototype structure (Figure 6) includes an aperture introduced to the side-coupled cells to allow bead-pull experiments and to assist with machining (Figure 7). To assist with achieving tolerances we assemble asymmetric disks using diffusion bonding with an entire septum thickness in each disk, as shown in Figure 7. Cooling is obtained via separate (brazed on) cooling blocks to limit the risk of leaking, a 10 mm wall thickness being a compromise between ability to braze and cooling efficiency.

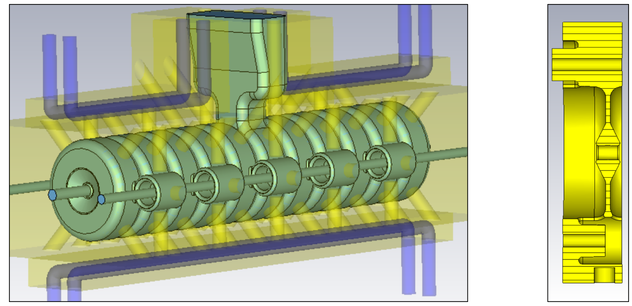

Figure 7: Internal 3D model of the 11-cell prototype indicating coupler, coooling (blue) and (right) method of disk cutting for construction.

Thermal Performance

We envisage 2×50 MW klystrons to power 6 structures, i.e. 14 MW per structure with c.15% losses. If coupled to the Christie Varian cyclotron we may pulse the cyclotron ion source at a rate up to 200 Hz; however, at this rate cooling is insufficient so we instead assume pulsing at around 30 Hz to limit the average power to 2 kW and detuning to <1 MHz. A 30 Hz repetition rate is still suitable for proton imaging, with a current of around 4 pA. The resulting temperature profile is shown in Figure 8.

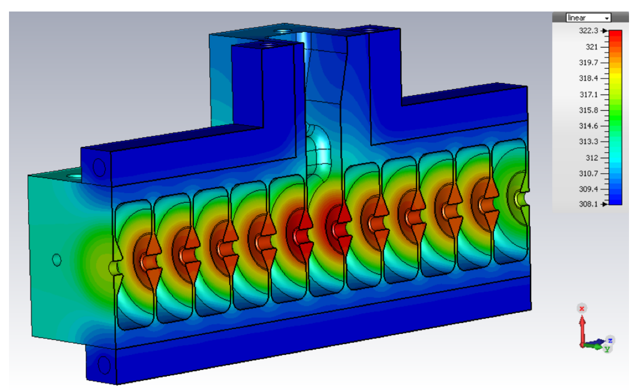

Figure 8: Temperature gradients in typical structure when operated at 30 Hz repetition rate, obtained using CST Multi-Physics Studio; the maximum temperature rise is 14 K.

Manufacturing Progress

The cavity disks are currently being manufactured by the VDL group, and are expected at the end of June this year. The bonding/brazing rig is currently being designed for use immediately after the disks are delivered. Once the structure is complete it is foreseen that it will be tested at the S-Box test facility at CERN, where they can provide a 5 µs 14 MW pulse (max. 43 MW) at a 25 Hz repetition rate.

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