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DEVELOPMENT OF AN HIGH GRADIENT SIDE COUPLED CAVITY FOR PROBE

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The PROBE project aims to develop a high gradient proton accelerator for protons with energies from 250-350 MeV for proton radiography. Detailed studies have shown that the optimum design is a side-coupled cavity at S-band. With an aperture of 8 mm a gradient of 54 MV/m can be obtained with 13 MW of RF power in a 30 cm structure. A prototype cavity has been machined by VDL and will be diffusion bonded by Bodycote. We present initial measurements of the prototype.

INTRODUCTION

The use of proton therapy is increasing with the expected number of centres offering protons reaching over 50 worldwide [1]. The advantage of protons compared to photons is the precision to which the dose can be delivered, providing lower doses to healthy tissue and organs. However to make full use of this precision we need to ensure that we can target the dose with sufficient accuracy, which requires knowledge of the proton stopping power of the imaged patient. Currently patients are imaged using CT scans and the Hounsfield units are converted to proton stopping power, but this method employs approximations limiting the accuracy of the dose placement. Recent studies have shown that using proton CT (pCT) scans can provide better estimates of proton stopping power. The limitation in pCT is that the protons should not be stopped in the patient but rather in the detector, hence this technique is only useful for children or head imaging using a 250 MeV beam. In order to do full-body scanning of adults higher energy protons are required, up to perhaps 330-350 MeV. The PRoton BOosting Extension (PROBE) project aims to provide a linac that can be retrofitted to an existing proton therapy cyclotron, in order to boost the proton energy for pCT. The linac should fit in a 3 meter space based on available space at the Christie Proton Therapy centre.

BEAM TRANSPORT

While the beam current required for pCT is small (~3 pA) compared to treatment, the linac will have a minimum duty cycle meaning the beam losses may still be a concern. For example, one requires 2% beam transmission for a 50 Hz repetition rate and a 5 µs pulse; however, lower transmission or a shorter RF pulse only results in a longer imaging time so is not a strict limit. As the protons will be delivered from a cyclotron the longitudinal and transverse phase space of the input beam is relatively large hence focussing is required to keep the beam losses to 2%. The project specification was to achieve 100 MV in 3 meters of linac length, however as we require focussing between the cavities this implies a higher gradient than 33.3 MV/m. We believe the minimum feasible drift length between two cavities will be around 135 mm, so having a larger number of shorter cavities will have more drift spaces and hence a higher gradient would be required, while with longer cavities it may be difficult to keep the losses on the aperture within limits. In addition we expect losses both on the aperture and on the energy selection system due to the cyclotron proton bunch being significantly longer than the RF period. Hence we set the energy selection system to collimate particles outside ±1% of the desired beam energy. After the first cavity we can select the synchronous phase of subsequent cavities to either provide more gradient or more capture. In this study we choose a synchronous phase of -20 degrees as this gives only a 6% drop in gradient from the peak while capturing almost 14% of the beam.

A study was performed of the maximum gradient reach of a re-entrant standing wave cavity as a function of beam aperture; in reality the requirement for coupling between cells will reduce this but it is a useful starting point. For a given cavity length we reduce the aperture (using an analytical estimate) until we reach 2% transmission; we increase the aperture by a factor 1.3 as a safety factor. We then in CST optimise a single-cell S-band cavity without side coupling for that cavity length and aperture to see the maximum gradient, and compare this to the required gradient using a 10% safety margin. In this study we limit the peak surface electric field to 200 MV/m, the modified Poynting vector to 2 W/sq-µm [2] and the input power to 100 MW for the 3 meter linac, based on scaling results obtained by other groups [3,4].

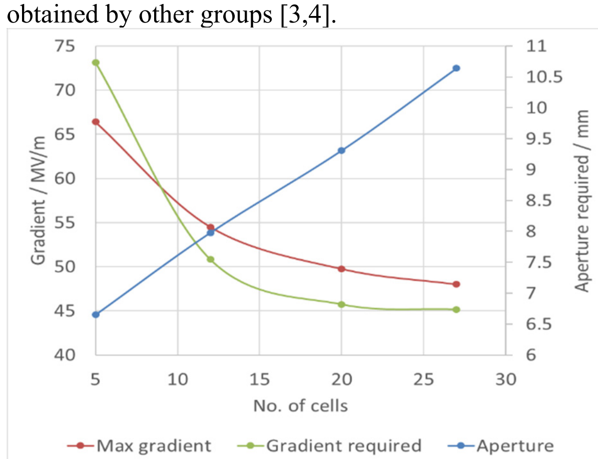

Figure 1: Required and achievable gradients as a function of number of cells per cavity, and the aperture required to meet transmission targets.

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As can be seen in Fig. 1, the largest gradient overhead is obtained for cavities between 11 and 27 cells in length. However, this is not a smooth curve as we can only have an integer number of cavities. As the increased coupling to the side-coupled cells - required for longer structures - will reduce the gradient, we choose the shortest cavity length of 11 cells as the optimum length, thus requiring an 8 mm aperture.

ASTRA was used to further study the beam losses through the PROBE linac as a function of cavity length for an 8 mm aperture [5]. The 2% transmission target is met for an 11-cell cavity requiring a gradient of 55 MV/m, as can be seen in Fig 2. The final beams phase space can be seen in Fig 3.

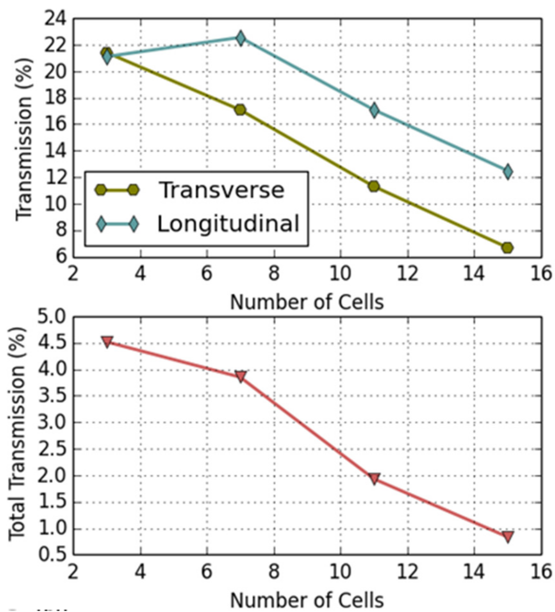

Figure 2: Transmission as a function of number of cells per cavity for an 8-mm aperture structure from ASTRA.

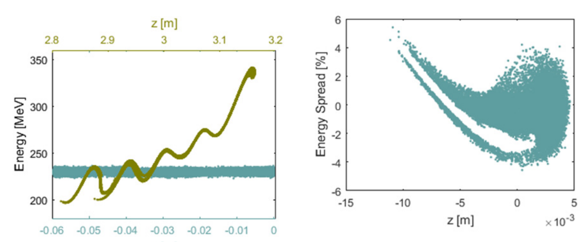

Figure 3: Longitudinal phase space at the linac entrance and exit obtained from ASTRA (left) and the acceptance of the linac (right).

CAVITY DESIGN

We have compared four different structures - backwards travelling wave (bTW) [6] and side-coupled standing wave (SW) cavities, at both S-band and C-band frequencies. In this study we limit the Epk to 200 MV/m, Hpk to 300 kA/m, the modified Poynting vector to 1.75 W/sq-um, and the input power to 12 MW. The structure is required to reach 50 MV/m with a length of 30 cm. As it's difficult to optimise a TWS to exactly match the maximum gradient limited by each parameter, we decided to always be on the side of the higher shunt impedance such that higher gradients could be obtained at higher breakdown rates if the structure performed better than expected. In each case we optimise the nose-cone geometry, and also any coupling slots or cavities in order to maximise the achievable gradient.

The gradient achievable in each structure is roughly similar, as shown in Table I, but the S-band side-coupled structure has a much lower modified Poynting vector. Some studies at CERN suggest structures may operate with higher peak electric field for a given breakdown probability if Sc is low [2], hence this S-band structure was chosen. We slightly modified the number of cells in the final design to 11 cells, which allowed the gradient to increase to 54 MV/m.

Table 1: Comparison of Different Cavity Options

	Parameter	S-band bTW	C-band bTW	C-band SW	S-band SW	Units
f	Frequency	3	5.7	5.7	3	GHz
L	Cell Length	24.8	13.1	15.7	29.8	mm
N	Number of cells	15	22	19	10	a.u
$^{v_g}/_c$ k	Group Velocity k-factor	-0.2 -0.04	-0.5 -0.0	4.2	2.3	%
Z	Shunt Impedance	85.4	65.6	61.2	75.3	$^{M\Omega}/_{m}$
P_{in}	Input Power	10	10	11.4	11.6	MW
E_{acc}	Gradient	48.6	47.5	46.8	51.1	$^{MV}/_{m}$
E_{pk}	Peak Surface E-field	204	200	200	200	a.u.
H_{pk}	Peak Surface H-field	153	256	302	267	$^{kA}/_{m}$
S_c	Peak Modified Poynting Vector	1.6	1.53	1.74	0.8	$^{W}/_{\mu m^2}$

Based on an S-band, 11 cell side-coupled structure we completed a full RF design of the structure. The final design is shown in Fig 4.

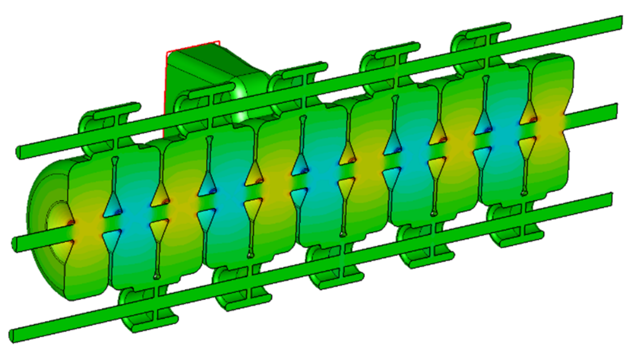

Figure 4: Final PROBE cavity design, with electric field amplitude shown in arbitrary units.

In order to work out the maximum duty cycle for operation, we performed thermal analysis of the cavity assuming water at 32 C inlet temperature. CST was then used to work out the frequency shift due to the deformation of the cavity, allowing us to plot frequency shift versus average power. While we can tune out long-term frequency deviations by altering water temperature, cell-to-cell frequency variations cannot be corrected in this way. The

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cavity's 3dB bandwidth is 230 kHz hence we chose this as a suitable maximum allowable frequency shift. This gives us a maximum average power of 3 kW, (see Fig. 5), but we are likely to only require 2.4 kW based on our RF design. If we allow a water temperature rise of 2 K this will require a chiller with a 16.6 litres per minute capacity.

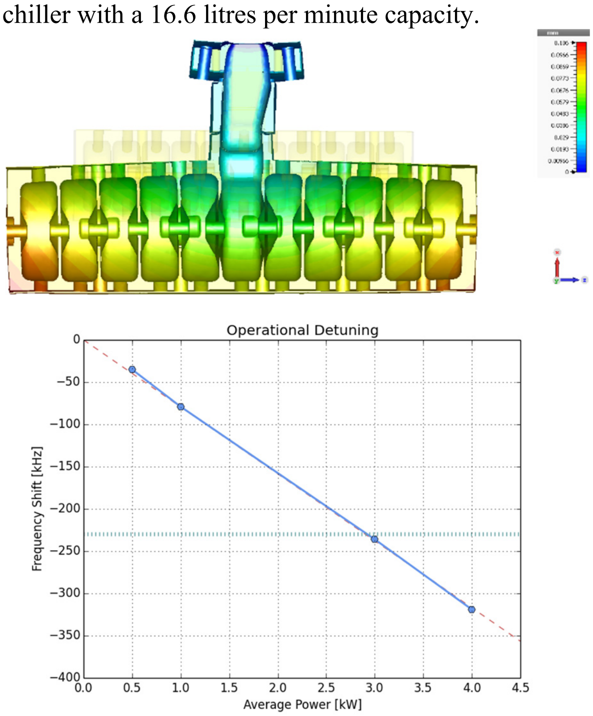

Figure 5: Deformation of the cavity due to RF heating (top) and frequency shift versus average power (bottom).

CAVITY MEASUREMENTS

A prototype cavity is currently being manufactured; the cells have been machined at VDL [7] and have been clamped together to check the cell frequencies. In order to reduce the peak magnetic field on the coupling cell slot we have rounded the edges. However it is difficult to manufacture this part to high precision by stacking disks, when each disk is exactly one cell long. Instead we manufacture each cell in two parts, one including the iris of the accelerating cell and the other containing the nose cones in the coupling cell, such that the slot coupling the accelerating cell and the coupling cell are bisected, as shown in Fig. 6. This provides better access for each slot allowing low peak fields and more accurate machining [8].

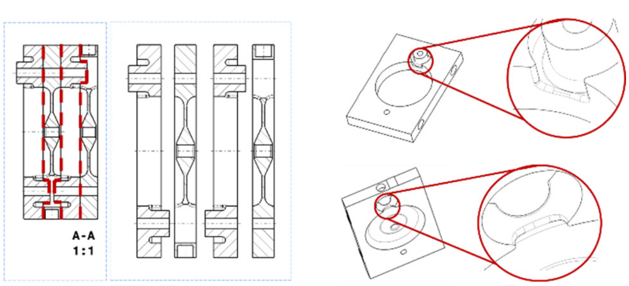

Figure 6: Drawing of the cavity cells to allow improved manufacturing tolerances.

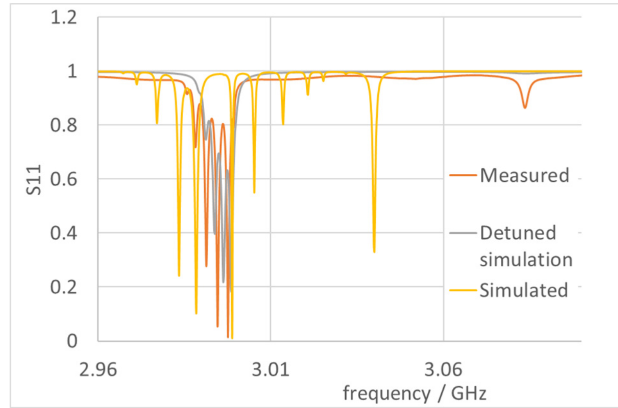

Figure 7: Measure reflections from the clamped structure and simulated results.

The final structure has been manufactured (Fig. 8) and has been clamp-tested as shown in Fig. 7. Unfortunately, the clamped measurements do not correspond well to the simulated cavity; however the $\pi/2$ mode has the correct frequency and coupling plus we see an additional mode 80 MHz away from the centre frequency. This suggests that the side-coupled cells are off tune by 80 MHz. A CST simulation was performed with detuned side-coupled cells and agrees well with the measured results. This is likely due to the large capacitance in those cells making them very sensitive to the gap.

After bonding the cavity will be transported to CERN for high gradient testing at CLEAR to validate the high gradient performance of side-coupled linacs.

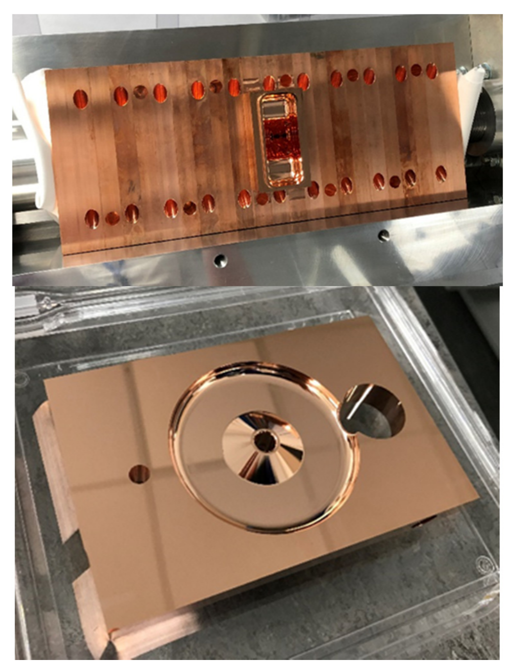

Figure 8: Manufactured cavity cell from VDL.

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REFERENCES

[1] Particle Therapy Co-Operative Group (PTCOG), www.ptcog.ch

[2] A. Grudiev, S. Calatroni and W.Wuensch, "A New Local Field Quantity Describing the High Gradient Limit of Accelerating Structures", *Phys. Rev. ST Accel. Beams* 12/10 (2009) 102001.

[3] A. Degiovanni *et al.*, *Nucl. Instr. and Meth.* A (2011). doi:10.1016/j.nima.2011.05.014.

[4] S. Verdú-Andrés *et al.*, “High Gradient Test of a 3GHz Single Cell Cavity”, *Proc. LINAC’10*, Tsukuba, Japan, Sep. 2010, paper THP037, pp. 839-841.

[5] R. Apsimon *et al.*, “Coupled Longitudinal and Transverse Beam Dynamics Studies for Hadron Therapy Linacs,” in *Proc. IPAC’17*, Copenhagen, Denmark, May 2017, pp. 4772-4775. doi:10.18429/JACoW-IPAC2017-THPVA134.

[6] S. Benedetti, PhD thesis (2018).

[7] VDL, http://www.vtl-group.com/

[8] S. Pitman *et al.*, International Patent Application No. PCT/GB2018/051343.