ProTec - A NORMAL-CONDUCTING CYCLINAC FOR PROTON THERAPY RESEARCH AND RADIOISOTOPE PRODUCTION

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Abstract

The ProTec cyclinac proposes the use of a 24 MeV high-current cyclotron to inject protons into a normal-conducting linac pulsed at up to 1 kHz to give energies up to 150 MeV. As well as producing radioisotopes such as ^{99m}Tc, the cyclinac also provides proton beams at higher energy with clinically-relevant beam properties. In this paper we present a comparison of linac designs in which S-band structures are used at lower energies prior to injection into a high-gradient X-band structure; issues such as beam capture and transmission are evaluated.

INTRODUCTION

The ProTec cyclotron-linac, or cyclinac, is proposed as a multi-purpose facility which will provide proton beams for medical research, radioisotope production and proton radiotherapy. A cyclotron such as the ACSI TR-24 [1], is intended to provide the high-current proton beam. The ACSI TR-24 has two extraction ports. It is intended to use each of these extraction ports to provide beam to a total of 4 stations; 1 for radioisotope production, 2 user stations for medical research and 1 for proton therapy. Each cyclotron extraction line will provide beam to one of two stations, selected by a switching magnet (Figure 1). A cyclotron has been chosen as the proton source because they are compact, commercially available, relatively inexpensive and based on a mature technology. A summary of beam parameters at extraction from the TR-24 cyclotron are given in Table 1 [2].

Table 1: TR-24 extracted beam parameters

Parameter	Value
ε_x (90%, normalised)	10μm.rad
ε_y (90%, normalised)	17μm.rad
Beam energy	24 MeV
Energy spread (FWHM)	0.41 MeV
RF frequency	84.75 MHz
Bunch spacing	11.8 ns
Bunch length	2 ns

Due to global shortages of radioisotopes such as ^{99m}Tc and ^{99}Mo [3], there are strong incentives for domestic production of radioisotopes in the UK. In addition to the importance of radioisotope production, the narrow Bragg peak at the end of the proton range makes it an efficient means of delivering radiation to cancer cells while minimising the dose to nearby healthy cells [4,5]. The two other stations would be allocated for users and would help contribute to the running costs of the facility.

The linac will consist of S-band structures to accelerate the proton from 24 MeV up to ~100 MeV with an accelerating gradient of ~30 MV/m. After this, high-gradient X-band structures will be used to accelerate the beam to energies up to 150 MeV, with an accelerating gradient of ~50 MV/m.

DESIGN CONSIDERATIONS

Transfer Line Optics

The 24 MeV protons extracted from the cyclotron have relativistic parameters $\gamma_r = 1.026$ and $\beta_r = 0.222$; thus they can be considered as non-relativistic particles. β_r and γ_r can be expressed in terms of a particle's energy and mass (Eqs. 1 and 2).

$$\beta_r = \sqrt{1 - \frac{1}{\left(1 + \frac{E}{mc^2}\right)^2}} \tag{1}$$

$$\gamma_r = 1 + \frac{E}{mc^2} \tag{2}$$

The velocity spread of a bunch can be expressed in terms of energy spread as shown in Eq. 3.

$$\sigma_v = \frac{c\sigma_E}{\gamma_r^3 \beta_r mc^2} \tag{3}$$

Thus for low energy particles, the velocity spread is strongly dependent on energy spread; which will lead to ballistic (or velocity) de-bunching of the longitudinal beam. However, this is not foreseen as a significant problem for ProTec because there is no need for short bunches.

The beam size, σ_i, through a beam line can be defined in terms of the value of the beta function, β_i, dispersion function, η_i, and energy spread, ΔE (Eq. 4).

$$\sigma_i = \sqrt{\frac{\beta_i \varepsilon_{i,n}}{\beta_r \gamma_r} + \eta_i^2 \frac{\Delta E}{E}} \tag{4}$$

Therefore the low beam energy implies a relatively large beam size through the beam line and first RF accelerating structures. The optics for the transfer line between the cyclotron and the S-band linac has been designed in MADX and is shown in Figure 2; the red and blue rectangles represent the quadrupole and dipole magnets respectively.

The beam line optics can be achieved with fewer quadrupole magnets but this would result in less control over the beam parameters. Further studies could be undertaken

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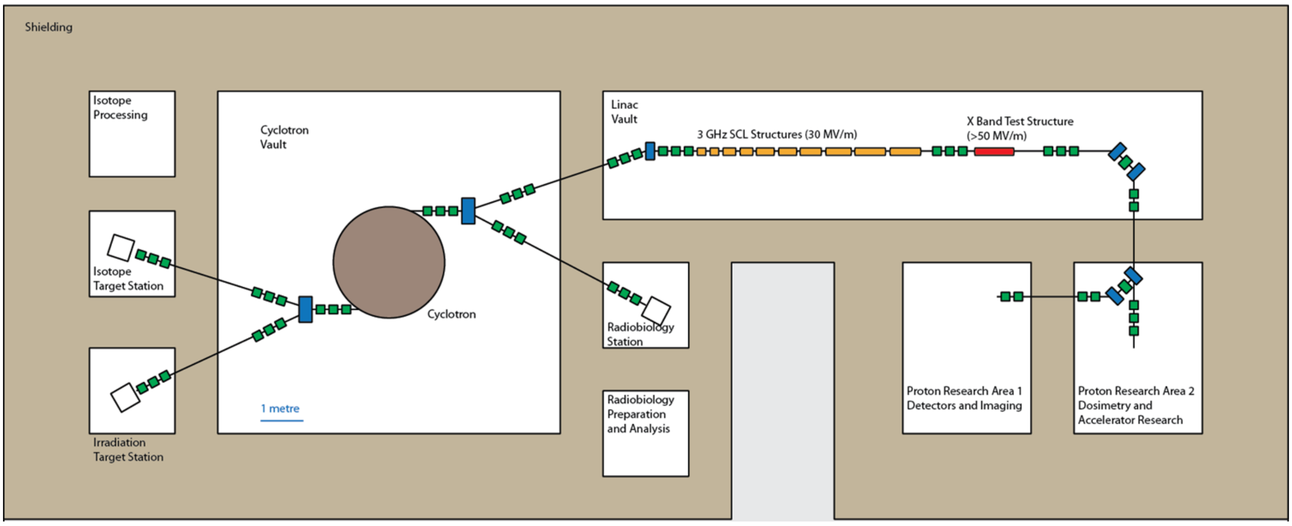

Figure 1: Schematic layout of the ProTec facility, showing the four proposed stations.

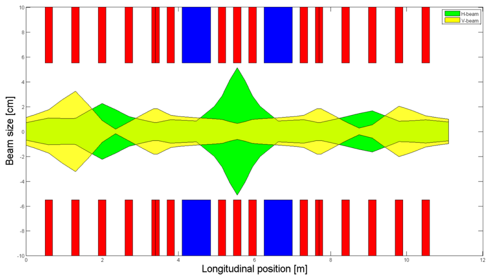

Figure 2: Plot of the transverse beam sizes along the cyclotron to S-band transfer line.

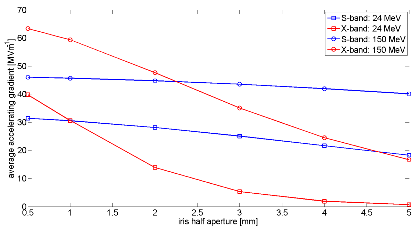

Figure 3: Plot of the accelerating gradient vs. iris aperture for 3 GHz (S-band) and 12 GHz (X-band) accelerating structures for 24 MeV and 230 MeV.

to minimise the number of quadrupoles required without severe detriment to the tuneability of the beam line optics.

Cavity Design

The large geometric emittance of the proton bunches at low energy implies relatively large beam sizes through the RF structures at lower energies. Larger apertures through the RF structures would mitigate against transverse beam losses through the structures, but will reduce the accelerating gradient of the structure. As shown in Figure 3, S-band structures have higher gradients than X-band for larger apertures and vice versa. As the proton energy increases, the transit time factor, T, increases as shown in Eq. 5.

$$T = \frac{\int_{-L/2}^{L/2} E(0,z)\cos(\omega t(z))\,dz}{\int_{-L/2}^{L/2} E(0,z)\,dz} \quad (5)$$

As the transit time factor increases, so does the average accelerating gradient. Consequently, the critical aperture where S-band and X-band cavities provide equal accelerating gradients also increases with energy. Hence for lower energy protons, S-band cavities provide higher accelerating gradients and allow for large iris apertures to minimise beam losses. As the proton energy increases, X-band structures become more feasible to achieve higher gradients.

S-band Cavity Design The TULIP project [5] uses S-band cavities to accelerate 24 MeV protons from a cyclotron to 230 MeV. Due to the similarity between ProTec and TULIP, we have opted to use the same design for the standing wave cavity design; as shown in Figure 4. A re-entrant side-coupled cavity design is employed to maximise the shunt impedance and therefore maximise the accelerating gradient.

The re-entrant structures, also known as nosecones, effectively increases the axial voltage, V_0, and reduces power dissipated, P_d, by concentrating the RF power into the accelerating region of the cavity; thus the shunt impedance, R_{shunt}, is increased (Eq. 6). Re-entrant cavities are used to maximise the accelerating gradient of RF cavities where RF power is limited.

$$R_{shunt} = \frac{V_0^2}{P_d} \quad (6)$$

An alternative cavity design is also being investigated; which is known as an annular-coupled cavity (Figure 5). The annular-coupled cavity couples RF power through 4 ports per cell rather than one port as in the side-coupled

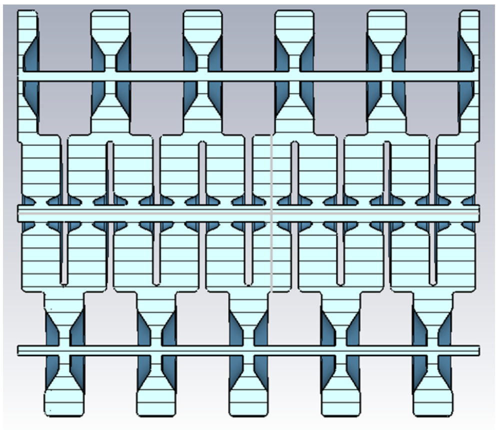

Figure 4: Cross-sectional diagram of the S-band side-coupled cavity structure.

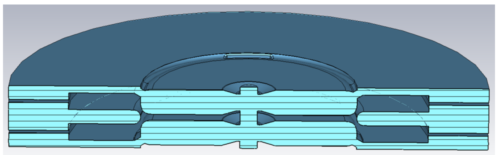

Figure 5: Cross-sectional diagram of the S-band annular-coupled structure for 2 accelerating cells.

design; thus peak fields in this region should be significantly reduced and allow for additional coupling. The coupling ports from one cell to the next are offset by 45° from one another to prevent RF power coupling into the coupling cells rather than the accelerating cells.

Further simulations are still required to determine which S-band standing wave structure provides the higher accelerating gradient.

X-band Cavity Design A side-coupled X-band standing wave cavity is currently being optimised, based on the TULIP LIBO structure (Figure 6) [5]. At present, simulation results suggest that the X-band standing wave cavity is capable of achieving an average accelerating gradient of 91 MVm^{-1}, although with further optimisation it is expected to reach an accelerating gradient of approximately 95 MVm^{-1}.

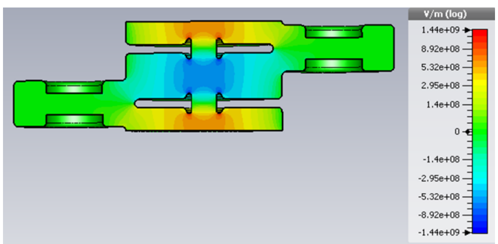

Figure 6: Cross-sectional diagram of the X-band side-coupled cavity structure.

Table 2: Summary of S-band and X-band side-coupled standing wave parameters

Parameter	**S-band**	**X-band**
Accelerating gradient [MVm^{-1}]	30	>90
Frequency [GHz]	3	12
Energy range [MeV]	24-100	100-150
Iris half aperture [mm]	3.5	2

Beam transmission

Studies are currently underway to determine the optimal beam optics and synchronous phase of the RF in order to maximise beam transmission through the S-band and X-band linacs. In order to maximise the transverse transmission through the structure, it is required that the beam size, σ_i, and angular spread, σ_i', are equal at either end of the cavity as this minimise the beam envelope through the structure. We assume that there is no dispersion in the cavity region, the initial Twiss parameters, $\beta_{i,1}$ and $\gamma_{i,1}$, can be expressed in terms of the final Twiss parameters and the initial and final relativistic parameters (Eq. 7).

$$\begin{aligned} \beta_{i,1} &= \frac{\beta_{r,1}\gamma_{r,1}}{\beta_{r,2}\gamma_{r,2}}\beta_{i,2} \\ \gamma_{i,1} &= \frac{\beta_{r,1}\gamma_{r,1}}{\beta_{r,2}\gamma_{r,2}}\gamma_{i,2} \end{aligned} \tag{7}$$

The longitudinal transmission is determined by the synchronous phase, ϕ_s, and is approximately $3\phi_s/2\pi$. However as the synchronous phase changes, so do the transverse forces experienced by the beam through the cavity. Thus further tracking simulations are required to determine the optimal synchronous phase for different cavity designs.

CONCLUSION

In this paper we outline the design of a high gradient cyclotron-linac or cyclinac as a viable facility for proton therapy. A first design of the transfer line optics is presented as well as different designs of S-band and X-band cavities for the linac sections. An investigation into the maximisation of beam transmission through the linacs is currently being undertaken.

Further studies are required to complete the full design of the ProTec facility, including more detailed studies of the beam dynamics and cavity designs. The future work will include studies on traveling wave cavities as they should be able to achieve higher accelerating gradients than standing wave structures.

REFERENCES

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[2] ACSI, private communication.

[3] H. Owen et al., "Options for UK Technetium-99m Production using Accelerators," IPAC'14, Dresden, May 2014, THOAB02 (2014).

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