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 being able to produce radioisotopes such as ^{99m}Tc, the cyclinac can also provide protons at higher energy with beam properties relevant for proton therapy research. 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 could simultaneously provide two proton beams [1]. Fed from a single high-current cyclotron that may generate extracted proton currents in excess of 500 μA to a single beamline, when that current is pulsed it may also feed a linac to obtain much higher energies albeit with lower currents. As such, such a facility could serve both as a regional site for production of medical radioisotopes whilst also being suitable for conducting research with higher-energy proton beams. In particular, we propose to utilise very high gradient X-band cavities to obtain 150 MeV protons suitable for testing methods and equipment to benefit particle radiotherapy. Whilst such research is possible at hospital proton therapy facilities, research time at such facilities is limited and this, a dedicated facility, provides much greater access.

We consider at present a cyclotron, such as the ACSI TR-24 [2], as a high-current cyclotron with multiple extraction ports which can obtain a suitably-high current for isotope production. One notable application is the volume production of ^{99m}Tc for nuclear medicine, in which a single c.1 mA cyclotron can, for example, provision sufficient numbers of technetium doses (around 250,000 per year per cyclotron) for about half of UK clinical demand [3, 4]. The TR-24 - similar to other multi-port cyclotrons - has two ports where we envisage providing up to four stations. Three of these are proposed to be at low energy to provide for radioisotope production; radiobiology research; irradiation experiments. The fourth station will feed the high-energy line that comprises both S- and X-band structures. S-band structures are proposed to accelerate the proton from 24 MeV up to ~100 MeV with an accelerating gradient of ~30 MV/m. High-gradient X-band structures will be used to further accelerate the beam to energies up to 150 MeV, with an accelerating gradient of at least ~50 MV/m.

We have chosen a cyclinac - that uses a cyclotron as its injector - for several reasons. Firstly, for protons energies up to 30 MeV and currents up to c.1 mA the cyclotron is a very mature technology that is compact, readily available commercially, and relatively inexpensive compared to alternative approaches such as linacs. Thus the low-energy stations can be obtained with minimal project risk. Although the extracted cyclotron beam is not naturally matched to the needs of a linac, the cyclinac concept has been explored at several institutions for a number of years and its technical issues have been well explored and addressed (see below). A summary of the extraction beam parameters of the TR-24 cyclotron are given in Table 1 [3, 5].

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

DESIGN CONSIDERATIONS

Transfer Line Optics

The 24 MeV protons extracted from the cyclotron must travel through a beam transfer system (BTS) some distance (~10 m) to the linac entrance. The protons have average relativistic parameters $\gamma_r = 1.026$ and $\beta_r = 0.222$; the velocity spread, σ_v, of the extracted bunches can be expressed in terms of energy spread, σ_E, as

$$\sigma_v = \frac{c\sigma_E}{\gamma_r^3 \beta_r mc^2}. \quad (1)$$

The velocity spread for low-energy bunches can therefore be quite large; which leads to ballistic (velocity) de-bunching that will lengthen the bunches from ~2 ns to ~3 ns. However, the bunches are then divided into sub-bunches in the higher frequency linac so this lengthening has no overall effect; the final pulse structure at the high-energy station will be insensitive to this.

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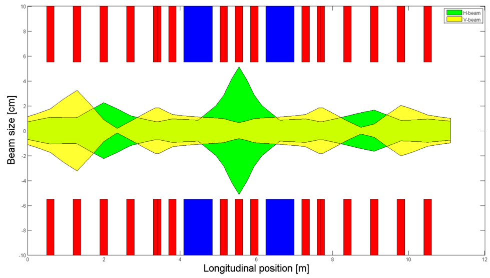

Figure 1: Beam sizes through the cyclotron to linac BTS; the red and blue rectangles represent respectively the quadrupole and dipole magnet effective apertures.

The beam size σ_i in each plane $i = x, y$ is conventionally defined as

$$\sigma_i = \sqrt{\frac{\beta_i \varepsilon_{i,n}}{\beta_r \gamma_r} + \eta_i^2 \frac{\Delta E}{E}}; \quad (2)$$

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, which incorporates a 30-degree achromatic bend, has been designed in MADX; it is shown in Figure 1. The BTS optics design may be realised with fewer quadrupole magnets but this would result in less tuneability of the beam parameters, something which is desired to enable analysis of different coupling into the linac.

Cavity Design

The large geometric emittance (~45-75 mm-mrad) of the proton bunches at low energy implies relatively large beam sizes through the RF structures at lower energies. Larger structure apertures would mitigate against transverse beam losses but will reduce the possible accelerating gradient. As shown in Figure 2, for a given power, S-band structures have higher gradients than X-band for larger apertures, and vice versa for smaller apertures. As the proton energy increases, the cell length of the cavities increases. As the cell length increases, the peak surfaces fields, hence the resistive power losses, of the accelerating structures decrease; resulting in an increase in 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; but, as the proton energy increases it becomes more feasible for X-band structures to achieve the higher gradient.

S-band Cavity Design The TULIP project [6] proposes S-band cavities to accelerate 24 MeV protons from a cyclotron to 230 MeV; such structures have been demonstrated. Due to the similarity between the ProTec and TULIP low-energy beam requirements, we have opted to use the same standing-wave cavity design; this is shown in Figure 3. A re-entrant side-coupled cavity design is employed to maximise

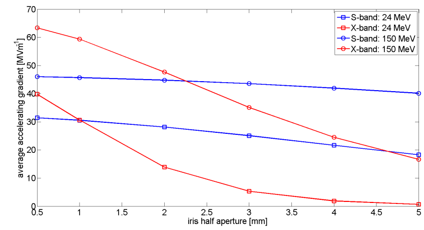

Figure 2: Plot of the accelerating gradient vs. iris aperture for 3 GHz (S-band) and 12 GHz (X-band) accelerating structures for 24 MeV and 150 MeV.

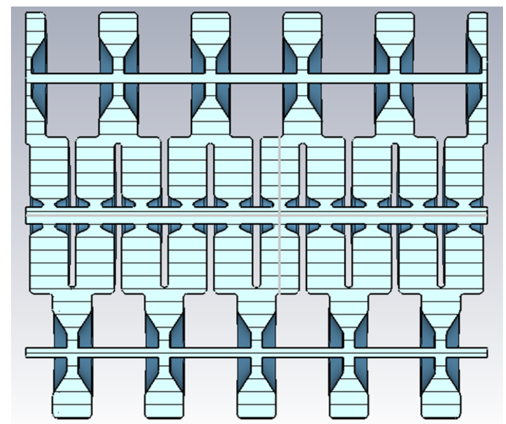

Figure 3: Cross-sectional diagram of the S-band side-coupled cavity structure.

the effective shunt impedance, $R'_{shunt} = (V_0 T)^2 / P_d$, and therefore to maximise the accelerating gradient; re-entrant cavities are used to maximise the accelerating gradient when RF power is limited. The re-entrant structures increase the effective shunt impedance by reducing the gap across the cell with nosecones; therefore increasing the transit time factor, T. Other approaches to high gradient are also being explored elsewhere [7].

$$T = \frac{\int_{-L/2}^{L/2} E(0,z) \cos(\omega t(z))\, dz}{\int_{-L/2}^{L/2} E(0,z)\, dz}. \quad (3)$$

An alternative cavity design known as an annular-coupled cavity is also being investigated (see Figure 4). The annular-coupled cavity couples RF power through 4 ports per cell rather than one port as in the side-coupled design; thus peak fields in the ports should be significantly reduced and should thereby allow for additional power. 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 into the accelerating cells. Further simulations are 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, similar to the TULIP LIBO structure [6]; its design is shown in Figure 5.

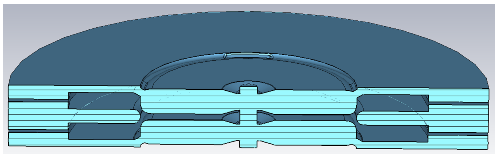

Figure 4: Cross-sectional diagram of proposed S-band annular-coupled structure; two accelerating cells are shown.

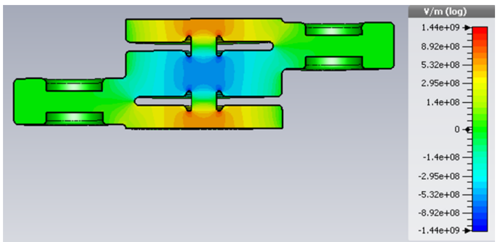

Figure 5: Cross-sectional diagram of the high-gradient X-band side-coupled cavity structure, under design.

At present, simulation results suggest that the X-band standing wave cavity is capable of achieving an average accelerating gradient of 54 $\mathrm{MVm^{-1}}$, although with further optimisation it may reach an accelerating gradient of approximately 60 $\mathrm{MVm^{-1}}$.

Table 2: Summary of S-band and X-band Side-coupled Standing Wave Parameters

Parameter	**S-band**	**X-band**
Accelerating gradient [$\mathrm{MVm^{-1}}$]	30	>50
Frequency [GHz]	3	12
Energy range [MeV]	24-100	100-150
Iris half aperture [mm]	3.5	2

Beam Transmission

Studies are being performed to determine the optimal beam optics and synchronous RF to maximise beam transmission through the S-band and X-band linacs. 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 minimises the average beam envelope. We have assumed that there is no residual dispersion from the BTS and that 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 as

$$\begin{aligned} \beta_{i,1} &= \frac{\beta_{r,1}\gamma_{r,1}}{\beta_{r,2}\gamma_{r,2}}\beta_{i,2} \\ \gamma_{i,1} &= \frac{\beta_{r,1}\gamma_{r,1}}{\beta_{r,2}\gamma_{r,2}}\gamma_{i,2} \end{aligned} . \quad (4)$$

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. At present the beam transmission is likely to be somewhat less than 10%, in line with other cyclinac designs; whilst this is a large fractional loss it is tolerable due to the low final beam current requirements (several nA) and that it enables a very simple injector technology (a pulsed cyclotron) to be used.

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 BTS 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.

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