BEAM DYNAMICS STUDIES FOR A COMPACT CARBON ION LINAC FOR THERAPY*

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Abstract

Feasibility of an Advanced Compact Carbon Ion Linac (ACCIL) for hadron therapy is being studied at Argonne National Laboratory in collaboration with RadiaBeam Technologies. The 45-meter long linac is designed to deliver 10^9 carbon ions per second with variable energy from 45 MeV/u to 450 MeV/u. S-band structure provides the acceleration in this range. The carbon beam energy can be adjusted from pulse to pulse, making 3D tumor scanning straightforward and fast. Front end accelerating structures such as RFQ, DTL and coupled DTL are designed to operate at lower frequencies. The design of the linac was accompanied with extensive end-to-end beam dynamics studies which are presented in this paper.

INTRODUCTION

There is strong worldwide interest in carbon ion beam therapy [1, 2], but no such facility exists or under construction in the U.S. A variable energy carbon beam with a maximum energy of 450 MeV/u is required for the most advanced treatment. We propose a high-gradient linear accelerator, the Advanced Compact Carbon Ion Linac (ACCIL). It includes the following main sections: a radiofrequency quadrupole (RFQ) accelerator, drift-tube linac (DTL) section and several coupled DTL tanks, operating at a sub-harmonic of the S-band frequency, and followed by an S-band either traveling wave or standing wave accelerating structure for the energy range from 45 MeV/u to 450 MeV/u. ACCIL is designed to accelerate the proton beam as well.

ADVANCED COMPACT CARBON ION LINAC

In order to satisfy the requirements of compactness, reliability and efficiency we examined S-band accelerating structures and structures operating at the sub-harmonics. The following criteria have defined the set of accelerating structures and their operating frequencies: high real-estate average accelerating gradient of 20 MV/m, reasonable heat load (pulsed and average), breakdown rate below 10^{-6} breakdowns per pulse per meter, the repetition rate of 120 Hz and beam pulse width of 0.5 µs.

* This work was supported by the U.S. Department of Energy, Office of High Energy Physics, under Accelerator Stewardship Grant, Proposal No. 0000219678
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Ion Source

The typical radiation dose for hadron therapy is delivered at the rate of (3-10)·10^8 carbon ions/sec and 10^{10} protons/sec [3]. Modern electron cyclotron resonance (ECR) ion sources are capable of providing DC carbon beam with an electric current up to 25 µA at (5+) charge state [4]. Fig. 1 shows the plot for the $^{12}C^{5+}$ pulse beam current required to provide 10^9 ions/sec. One can see that this rate can be achieved at 120 Hz repetition rate, pulse width below 0.5 µs, and an electric current of 13.3 µA. The charge state (5+) is preferred to avoid mixture with other ion species (for example, oxygen) from the ion source plasma into the beam. To get the required particle rate for protons at the same duty cycle, the pulse current should be about 27 µA, which can be easily achieved with an ECR source at DC mode.

The DC beam from the ion source should be chopped into 0.5 µs pulses. For the beam dynamics simulation, we assumed transverse normalized 90%-emittance of 0.35 π·mm·mrad, which is similar to the value from commercially available ECR ion sources [4].

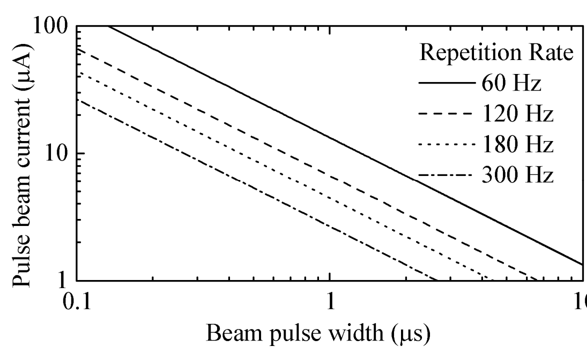

Figure 1: Pulse beam electric current required to provide 10^9 carbon $^{12}C^{5+}$ ions per second.

RFQ

In the front-end, we propose to develop an RFQ based on the brazed technology [5-7] to meet the alignment specifications. The RFQ accelerates the carbon $^{12}C^{5+}$ ion beam to 3 MeV/u on the length L = 4 m. The operating frequency f = 476 MHz provides a reliable accelerating gradient, moderate field sensitivity to local random errors of resonator geometry, which scales as $(f{\cdot}L)^2$ [8], and effective beam acceptance into the sections of higher frequencies. The foil following the RFQ is used to provide fully stripped carbon $^{12}C^{6+}$ ions from $^{12}C^{5+}$.

DTL

The effective shunt impedance per unit length of an RFQ drops as β^{-2} like any other accelerating structure based on a TE-mode resonator. In order to provide both high efficiency and high accelerating gradient TM-mode is preferred in the sections following the RFQ. The most efficient TM-mode-structure in the 3 – 20 MeV/u energy range is a multi-gap DTL (also known as Alvarez DTL) [8]. Moreover, unlike the TE-mode accelerating structures, stabilization of Alvarez DTLs is well developed for long resonators [9]. The 65-gap 476-MHz DTL is designed to provide acceleration and focusing for both fully stripped carbon $^{12}C^{6+}$ ion and proton beams, however, the focusing FODO lattice is built from compact 140 T/m permanent quadrupole magnets (PMQ) (see Fig. 2). Figure 3 presents the phase advance σ along the fixed gradient lattice calculated with the analytical approach in smooth approximation [8] with equation (1), assuming $\sigma \ll 360°$. The longitudinal phase advance σ_L per focusing period $P = 4\cdot\beta\lambda$ is kept the same for both beams due to the scaling of accelerating field level with particles' charge-to-mass ratio to keep a constant synchronous phase $\varphi_s = -25°$ along the DTL.

The average electric field $E_0 = 8.6$ MV/m, and accelerating gradient $E_0T = 6.58$ MV/m (scaled for carbon beam) remain constant along the whole 6 m DTL section.

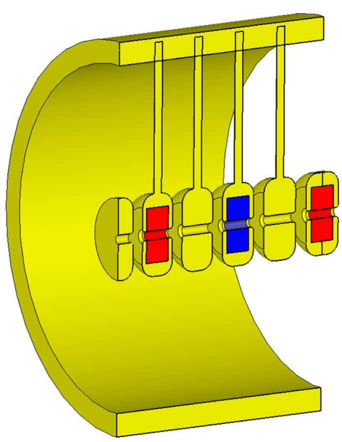

Figure 2: Focusing lattice with compact PMQs.

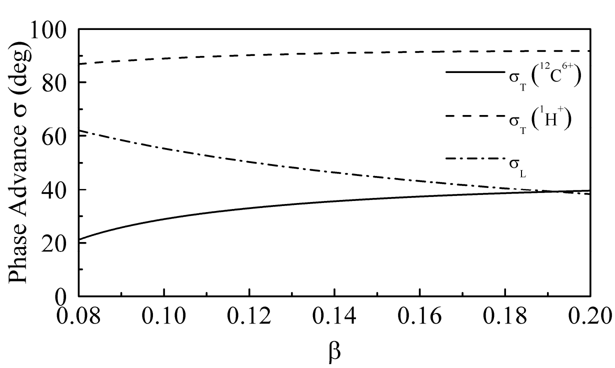

Figure 3: Transverse σ_T and longitudinal σ_L phase advances per focusing period of the synchronous particle in the DTL with PMQs.

Coupled DTL

In order to decrease the construction cost and improve the accelerating gradient (up to 12 MV/m), 10 coupled 6-gap DTLs are used up to the energy of 45 MeV/u at the operating frequency of 952 MHz. The FODO lattice is built from compact 90 T/m electromagnetic quadrupoles (EMQ) located between the tanks.

Each tank has constant cells' lengths or, in other words, synchronous phase $\varphi_s = -90°$ (see Fig. 4) [8]. Thus the RF phase of the beam center (red curve in Fig. 4) slips around the reference phase φ_r, which is defined as an average RF phase of the beam center in a whole tank. In the first tank of the coupled DTLs $\varphi_r = -24°$ and in the last tank $\varphi_r = -17°$. The phase slippage does not exceed 7° in any of the tanks.

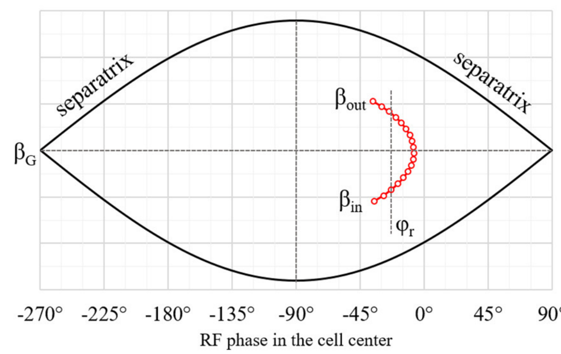

Figure 4: Phase-space (φ-β) trace of the beam in a constant-cell-length structure (the trace corresponds to 18-cell structure).

There are three main factors limiting the tanks' lengths: the phase slippage range, the focusing period length, and the RF defocusing per period. Since the phase slippage inside the coupled DTL tanks is reasonably small, the other two factors matter. They define the stability of the transverse beam motion in a FODO lattice according to the equation for phase advance in smooth approximation [8]:

$$\sigma_T^2 = \left[\frac{qGlP}{2mc\gamma\beta}\right]^2 + \frac{\pi q E_0 T \sin(\varphi) P^2}{mc^2\lambda(\gamma\beta)^3}, \quad (1)$$

here q and m – charge and mass of the beam particle, G – gradient of the magnetic quadrupole, l – length of the quadrupole, P – focusing period, γ – relativistic factor of the beam particle, $\beta = v / c$ – particle velocity, $\lambda = c / f$ – electromagnetic field wavelength. The second term of the equation represents the nonlinear RF defocusing effect. In the case of the high-gradient linac this term can be of the same order of magnitude as the first ("focusing") one. It means, that some particles of the beam can lose their transverse stability, if their σ_T is a pure imaginary number. These particles either form a beam halo or hit the aperture and become lost.

Even in the case of weak or negligible RF defocusing effect, the focusing period is limited by the relation $\sigma_T < 180°$. For high-intensity beams this relation changes into $\sigma_T < 90°$ to avoid the space-charge-induced envelope resonance [8].

ISBN 978-3-95450-169-4

S-band Accelerating Structure

The S-band structures of the main part of ACCIL can be either standing wave or travelling wave mode structures. For the beam dynamics simulation with the TRACK code [10], we considered only the standing wave option, while the travelling wave module is still under development for TRACK. Current design assumes 19 tanks of coupled cavities (CCL) with focusing quadrupole doublets between them to cover energy range of 45 – 450 MeV/u. Tanks' lengths are calculated in the same way as coupled DTL's one. Transverse phase advance of a particle in a doublet FDO lattice is defined in the smooth approximation as:

$$\sigma_T^2 = \left[\frac{qGl\sqrt{LD}}{mc\gamma\beta}\right]^2 + \frac{\pi q E_0 T \sin(\varphi) P^2}{mc^2\lambda(\gamma\beta)^3}, \qquad (2)$$

here L and D – distances between the centers of adjacent quadrupoles, and $P = L + D$ – focusing period of doublet lattice. FDO lattice allows us to have longer accelerating sections than FODO allows for the same phase advance and RF defocusing strength. However, FDO requires higher integral gradients $G{\cdot}l$ of the quadrupoles than FODO.

Each tank consists of several identical cells – from 20 to 36 cells per tank, and provide the accelerating gradient $E_0T = 50$ MV/m. Since the beam velocity kick in the CCL tanks is relatively high the phase slippage range is about 50-60°. The reference phase $\varphi_r = -20°$ along the whole CCL part of the linac. More details on design of the S-band accelerating structures can be found in [11].

END-TO-END SIMULATION

Maps of electromagnetic fields from CST STUDIO SUITE [12] and POISSON SUPERFISH [13] have been used for end-to-end carbon ion beam dynamics simulation with the TRACK code. The main results of the simulation are shown in Fig. 5. Distortions of the beam on the transverse phase space are mainly caused by strong nonlinear RF defocusing fields in the CCL. Transmission of carbon ion beam is about 92% from the RFQ entrance to the exit of the last CCL section. The simulation does not include any beam dynamics effects from the foil stripping except changing the charge state from (5+) to (6+).

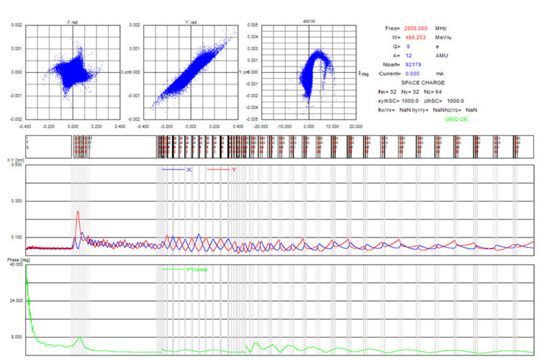

Figure 5: Beam dynamics simulation results: top - phase space plots, center – transverse RMS envelopes, bottom – longitudinal RMS envelope.

CONCLUSION

The ACCIL design has proved the feasibility of the S-band accelerating structures for high-gradient ion linac. The real-estate average accelerating gradient of the 45-meter ACCIL is about 20 MV/m. The opportunity to accelerate both carbon ion and proton beam significantly expand the linac performance. Pulse-to-pulse beam energy variation by switching the CCL tanks at the frequency of 120 Hz makes 3D tumor scanning technique straightforward and fast.

To reduce the fabrication risks and the R&D cost, ACCIL is built from well-known and available components: commercially available ion sources and well-known accelerating structures, in the same time, proving the advanced performance of high-gradient operation. Focusing of both carbon ion and proton beam by PMQs allows building compact high-gradient DTL. Stabilization (via post-coupling or inter-tank coupling) of the DTL tanks will provide the reliable operation in a high heat load regime. Nevertheless, the small apertures require high alignment accuracy of all components of the linac.

One can see, that the CCL section takes about half of the linac length, while consumes about 86% of the "plug" power. The engineering design of the S-band structures has shown a significant increase in their efficiency, by more than 50%, with decreased only 20% reduction in the accelerating gradient. This will save about 50% of the "plug" power for only 5 meter longer linac. This improvement will also provide better beam dynamics, since the RF defocusing effect is the most limiting factor for the linac. Advanced focusing techniques suitable for such high-gradient linacs are under research at present.

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