COMPACT CARBON ION LINAC*

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Abstract

Argonne National Laboratory is developing an Advanced Compact Carbon Ion Linac (ACCIL) in collaboration with RadiaBeam Technologies. The 45-meter long linac is designed to deliver up to 10^9 carbon ions per second with variable energy from 45 MeV/u to 450 MeV/u. To optimize the linac design in this energy range both traveling wave and coupled-cell standing wave S-band structures were analysed. To achieve the required accelerating gradients our design uses accelerating structures excited with short RF pulses (~500 ns flattop). The front-end accelerating structures such as the RFQ, DTL and Coupled DTLs are designed to operate at lower frequencies to maintain high shunt impedance. In parallel with our design effort ANL's RF test facility has been upgraded and used for the testing of an S-band high-gradient structure designed and built by Radiabeam for high pulsed RF power operation. The 5-cell S-band structure demonstrated 52 MV/m acceleration field at 2 μs 30 Hz RF pulses. A detailed physics design, including a comparison of different accelerating structures and end-to-end beam dynamics simulations of the ACCIL is presented.

INTRODUCTION

There is strong worldwide interest in carbon ion beam therapy [1, 2], but no such facility exists or under construction in the USA. 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) which includes the following main sections: a radiofrequency quadrupole (RFQ) accelerator, a drift-tube linac (DTL), 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.

LINAC SECTIONS

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

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]. This rate can be achieved at 120 Hz repetition rate, beam pulse width below 0.5 μs, and a pulsed electric current of 13.3 μA for $^{12}C^{5+}$ and 27 μA for proton beam. Commercially available ECR ion sources [4] can provide the required beam intensity for both C^{5+} and protons. C^{5+} ions are preferable to avoid contamination by residual gas ions. The DC beam extracted from the ECR should be chopped into 0.5 μs pulses. Typically, ECRs can provide carbon and proton beams with a normalized transverse emittance of 0.35 π·mm·mrad containing 90% of ions.

RFQ

To meet the alignment specifications of high frequency RFQ, we will apply high temperature furnace brazing technology [5-7]. Currently, we are considering asymmetric 4-vane structure [8] for the RFQ, which can provide a good separation of non-operational modes [9, 10]. The transverse cross-section of the RFQ is shown in Fig. 1. The RFQ accelerates the carbon $^{12}C^{5+}$ ion beam to 3 MeV/u over the length of $L = 4$ 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 $(f{\cdot}L)^2$ [11], and sufficient beam acceptance. Right after the RFQ, the C^{5+} beam will be converted into C^{6+} by stripping with a thin carbon foil.

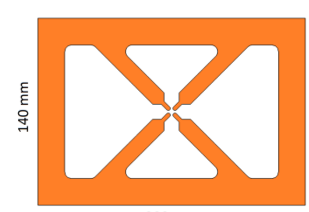

Figure 1: Transverse cross-section of the compact asymmetric 4-vane RFQ.

DTL and Coupled DTL

The effective shunt impedance per unit length of an RFQ drops as β^{-2} like in any other accelerating structure based on a TE-mode resonator. In order to provide both high efficiency and high accelerating gradient, a 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

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DTL) [11,12]. A 65-gap 476-MHz DTL is designed to provide acceleration and focusing for both fully stripped carbon ion and proton beams. A FODO focusing lattice is provided by compact 140 T/m permanent quadrupole magnets (PMQ). The average electric field of $E_0 = 8.6$ MV/m, and the accelerating gradient of $E_0T = 6.58$ MV/m for carbon beam remain constant along the 6-meter DTL section.

In order to reduce the construction cost and keep the accelerating gradient high, up to 12 MV/m, 10 coupled 6-gap DTLs operating at 952 MHz are used up to 45 MeV/u. The FODO lattice is provided by compact 90 T/m electromagnetic quadrupoles (EMQ) located between the tanks. Each tank consists of 6 equal cells and the synchronous phase is $\varphi_s = -90°$ [11]. Thus the RF phase of the beam center slips around the reference phase φ_r, which is defined as an average RF phase of the beam center in a whole tank.

S-band Accelerating Structure

S-band structures for the main section of the ACCIL can be composed either from standing wave or travelling wave mode structures. For the beam dynamics simulation with the TRACK code [13], we considered only the standing wave option, while the travelling wave module is still under development for TRACK. The current design assumes 19 tanks of coupled cavities (CCL) with electromagnetic focusing quadrupole doublets between them to cover the energy range of 45 – 450 MeV/u. Each tank consists of several identical cells – from 20 to 36 cells per tank, and provides 50 MV/m accelerating gradient. More details on the design of the S-band accelerating structures can be found in ref. [14].

RF POWER EFFICIENCY

The effective shunt impedance per unit length for the DTL (blue bar), Coupled DTLs (green bars) and S-band tanks (orange bars) are presented in Fig. 2. One can see that the efficiency of the most part of S-band sections remains relatively low. This leads to the high heat load of the S-band tanks. Assuming 0.5 µs beam pulses and 40% efficiency of RF power generators, we can obtain both average power losses in the accelerating structures and required wall plug power. Power consumption of the RFQ is less than 1% of the total value, DTL and Coupled DTL sections consume 7% each, the remaining 85% of total power are required for the S-band section of the linac.

NEGATIVE HARMONIC

The performance of the S-band accelerating structures in the velocity range of 0.3c-0.5c (c is the speed of light) can be improved, if a negative spatial harmonic of the travelling wave is used [15,16].We have designed a 5π/6-mode TW structure for $\beta_{-1} = 0.3$ for acceleration by the -1st spatial harmonic (see Fig. 3). This structure has a cell length corresponding to $\beta_0 = 0.42$, therefore it improves the overall efficiency and allows us to apply iris noses (see Fig. 4). The geometry of the -1st traveling wave

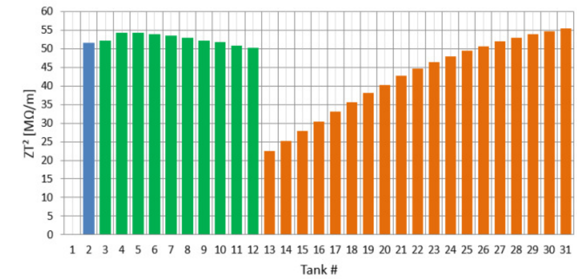

Figure 2: Effective shunt impedance per unit length along the linac.

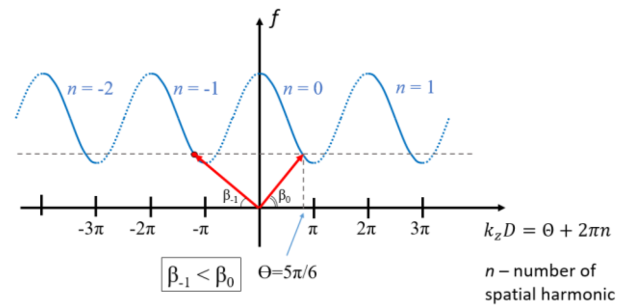

Figure 3: Dispersion diagram for periodic structure with magnetic coupling holes.

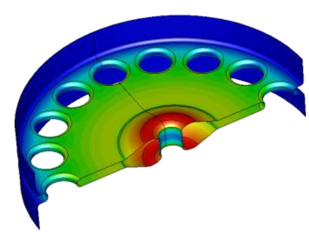

Figure 4: Electric field distribution on the surface of the TW structure cell designed for acceleration by -1st spatial harmonic.

structure has been optimized to achieve both maximum efficiency for β=0.3 ion beam and reduced peak electric and magnetic fields.

Beam dynamics simulations have confirmed the effective acceleration by the -1st spatial harmonic of the travelling wave structure. At the same time, we did not observe any focusing or defocusing effects from the fundamental harmonic of the electromagnetic field.

BEAM DYNAMICS SIMULATION

Maps of electromagnetic fields from CST STUDIO SUITE [17] and POISSON SUPERFISH [18] have been used for the 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 in the transverse phase space are mainly caused by strong nonlinear RF defocusing fields in the CCL. The transmission of carbon ion beam is about 92% from the RFQ entrance to the exit of the last CCL section. The stripping effect on beam quality is negligible and ignored in the simulations (except for changing the charge state from 5+ to 6+). More details on beam dynamics studies in ACCIL can be found in ref. [19].

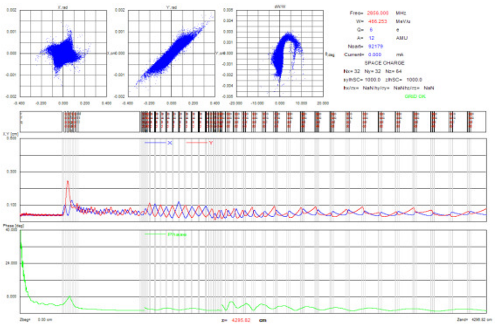

Figure 5: Beam dynamics simulation results: top - phase space plots, center – transverse RMS envelopes, bottom – longitudinal RMS envelope.

RF POWER TESTS

Recently, a compact ultra-high gradient S-Band β = 1 accelerating structure (see Fig. 6), operating in the π-mode at 2856 MHz, has been developed at RadiaBeam [20]. In February 2016, the structure was delivered to Argonne to perform high power tests. Cavity conditioning was conducted with a 30 Hz pulse repetition rate while varying the RF pulse width and power. A 40 MV/m accelerating field level was achieved at 10 MW RF power and 2 µs pulse length. However, severe outgassing prevented further progress. After three days of baking, the static vacuum levels improved by one order of magnitude and a stable field of about 44 MV/m was achieved. After another bake and about two weeks of RF conditioning, an accelerating field level of 52 MV/m was achieved at 16.7 MW and 2 µs pulse width. The cavity was held at this level for 24 hours. The accelerating field level may have been slightly lower since no measurements of dark currents were performed. The vacuum gauge reading during the whole conditioning process as a function of the accelerating field is shown in Fig. 7.

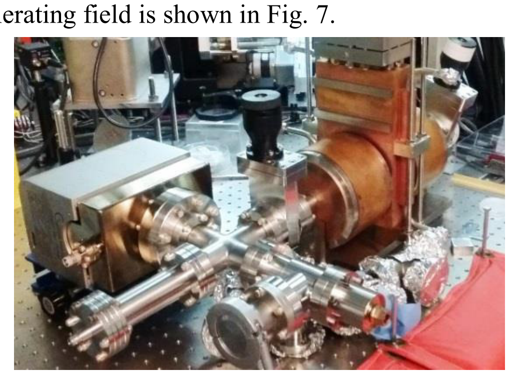

Figure 6: S-band high-gradient structure at the Argonne RF Test Facility.

CONCLUSION

Compact S-band accelerating structures for high-gradient ion linacs are entirely feasible. The real-estate average accelerating gradient of the proposed 45-meter ACCIL is 20 MV/m. The possibility to accelerate both carbon ion and proton beams significantly expands the linac performance. Pulse-to-pulse beam energy adjustment by turning off the CCL tanks makes 3D tumor scanning technique straightforward and fast. Small apertures of accelerating and focusing structures require high alignment accuracy of all components. The S-band section takes about half of the linac length, while consumes about 85% of the wall plug power. Our next step in the linac design optimization is to increase the effective shunt impedance of the S-band accelerating structures and to reduce slightly the real-estate accelerating gradient. Per our estimation these two factors will reduce the power consumption by a half.

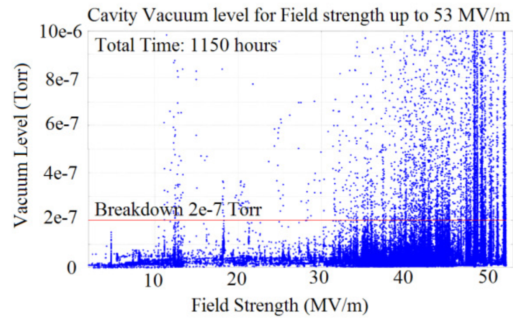

Figure 7: High-power test results.

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