CARBON ION INJECTOR LINAC FOR A HEAVY ION MEDICAL SYNCHROTRON*

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Abstract

The design of a Carbon Ion Injector Linac for a heavy ion medical synchrotron will be presented. The linac is designed to accelerate quadruply-ionized carbon ions ($^{12}C^{+4}$) with a charge/mass ratio (q/A) of 0.333, and all other ions with the same or higher charge/mass ratios, such as H^{+1}, H_2^{+1}, D^{+1}, T^{+1}, $^3He^{+1}$, $^4He^{+2}$, $^6Li^{+2}$, $^{10}B^{+4}$, and $^{16}O^{+6}$ to an output energy of 7 MeV/u. The 200-MHz linac consists of a Radio Frequency Quadrupole (RFQ) linac to accelerate the ions from an input energy of 0.008 MeV/u to an intermediate energy of 0.800 MeV/u, and an Rf-Focused Interdigital (RFI) linac to accelerate these ions to the output energy. The combined linac structures have a total length of 7.8 meters and a total peak rf power requirement of about 600 kW. The RFQ linac employs a radial-strut, four-bar design that is about twice as efficient as the conventional four-bar RFQ design. The RFI linac, which is basically an interdigital drift tube structure with rf quadrupole focusing incorporated into each drift tube, is about 5 times more efficient than the conventional Drift Tube Linac (DTL) structure. Details of the linac structures and their calculated performance will be presented.

CARBON LINAC (7 MEV/U)

Linac Systems has designed a 7-MeV/u, Carbon+4 Linac to serve as an injector linac for a heavy-ion synchrotron for medical applications. The linac is designed to operate at 200 MHz and consists of a Radio Frequency Quadrupole (RFQ) linac section, an Rf-Focused Interdigital (RFI) linac[1,2] section, an rf power system, a stripper foil assembly, a debuncher cavity, and associated vacuum, temperature control, and linac control systems. The two linac structures, shown in Fig. 1, have a total length of 7.8 meters and a total peak rf power requirement of about 600 kW.

The low rf power requirement is a tribute to the rf efficiencies of the RFQ and RFI linac structures. The RFQ linac structure employs a radial-strut, four-bar design that is about twice as efficient as conventional four-bar designs. The RFI linac structure[1,2], which is basically an interdigital linac structure with rf quadrupole focusing incorporated into each drift tube, is about 5 times more efficient than the conventional Drift Tube Linac (DTL) structure. Two features of the RFI linac structure contribute to its higher efficiency; namely, the interdigital configuration and the rf electric focusing. The efficiency of the interdigital configuration follows from the fact that the rf electric fields are concentrated in the vicinity of the drift tubes, resulting in very low amounts of electric and magnetic stored energies. The rf electric focusing results in smaller diameter beams, which allows smaller diameter drift tubes, which in turn further reduces the capacitive loading of the structure and associated rf power losses.

The linac system is designed to accelerate quadruply-ionized carbon ions ($^{12}C^{+4}$) with their charge/mass ratio (q/A) of 0.333, and all other ions with higher charge/mass ratios. As all of the accelerating and focusing forces are electric, driven by rf power, the only change required to accommodate the different ion species is a change in the rf drive power. By reducing the rf electric fields by a factor of 3, the accelerating and focusing forces in the linac are appropriate for the acceleration of protons at currents as high as 8 mA.

The rf pulse duty factor requirement for this application is very low. The required beam pulse length is less than 50 μs and the required repetition rate is less that 1 per second. However, for operational and rf conditioning reasons, we have designed for an rf pulse length of 100 μs and a repetition rate of 10 Hz, resulting in a duty factor of 0.1%. The average rf power in the RFQ and RFI linac combination is about 600 W.

The resonant frequency of the resonant units will be maintained by a temperature-controlled, recirculating coolant system mannaged by dedicated temperature control units. The rf frequency of the rf power system will be locked to the resonant frequency of the ensemble of resonant units. The setpoints of the temperature control units will be controlled by the linac control system.

The vacuum system is based on turbomolecular vacuum pumps. Two turbo pumps will be mounted on each of the three resonant units to maintain the vacuum level down to about 5×10^{-7} Torr. Several "dry scroll pump" are used to rough down the linac sections and back-up the turbo pumps. The vacuum system will be controlled and monitored by the linac control system.

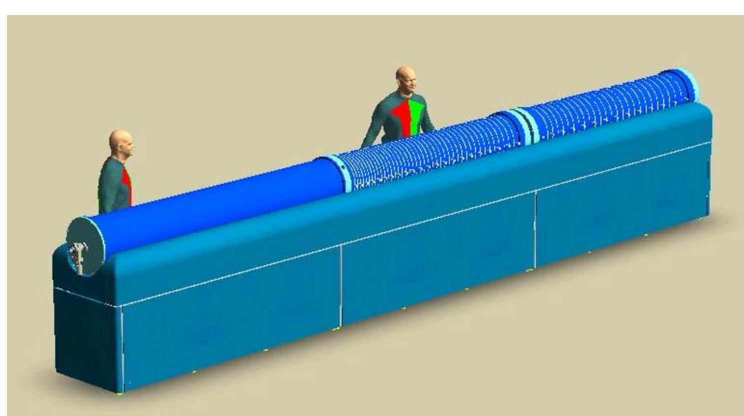

Figure 1: 7-MeV/u, Carbon+4 Injector Linac.

A distributed, Ethernet-based linac control system with fiber-optic links to the main synchrotron control system is proposed. There is little, however, to control. The acceleration and focusing actions of the linac structures depend solely on the distribution of the rf electric fields within the three resonant units, namely the RFQ linac section and the two RFI linac tanks. The distribution of the fields within each resonant unit is determined by the geometry of the unit. The three resonant units are resonantly coupled together, which locks their relative amplitudes and phases.

A variety of data will be monitored by the linac control system for diagnostic and maintenance purposes. The beam current into and out of the linac will be monitored. The forward and reflected powers from the rf power system will be monitored. The amplitude of the rf fields will be monitored in at least two locations in each resonant unit. The outlet temperature of the coolant from the many parallel coolant circuits will be monitored. As there are no steering magnets or focusing magnets, there are no magnet power supplies to be controlled or monitored. Diagnostic procedures will be in place to test the "health" of the rf power, vacuum, and temperature control systems.

Preparation for "Operation" requires simply that the vacuum pumps and temperature control systems are on and working properly. The rf power system is then brought up to "stand-by" condition. The next step is to excite the linac structures with rf power to the desired level, depending on the ion species to be accelerated. After checking that the rf field levels at the monitor loops are at their expected values, and opening a couple of beamline vacuum valves, the linac is ready to go. All of these operations will be automated through the control system.

RFQ LINAC

The RFQ linac for this system will be of the four-bar type. It will capture the 8 keV/u ion beams from the low energy beam transport system, and accelerate them to a suitable energy for acceptance by the RFI linac. Because of the exceptional low-energy capabilities of the RFI linac structure, the RFQ will only need to accelerate the ion beams to an energy of 0.80 MeV/u.

The bore radius is 3.6 mm and the length is 2.73 m. The rf cavity inner diameter of 288 mm and a strut spacing of 228 mm results in a resonant frequency of 200 MHz. The rf dipole mode for this configuration is several MHz above the quadrupole mode and does not present a problem with rf field stability. The peak rf power requirement is 105 kW, which for the 0.1% duty factor, results in an average rf power of only 105 W.

The main structural element of the RFQ is the heavy-wall aluminum rf cavity. The bars are extruded aluminum, with a longitudinal hole for cooling purposes. Each bar is supported by ten struts. The four-bar/strut assemblies are cooled by four separate cooling circuits. A counterflow arrangement will be employed so that the average temperature at all locations along the structure will be the same. The RFQ linac structure will be mounted inside a vacuum tank that provides the high-vacuum conditions required by the beam, the rf power, and the linac structure. The RFQ vacuum tank will be pumped by two 400 l/s turbomolecular vacuum pump and will typically operate in the 5×10^{-7} Torr range.

RFI LINAC

The RFI linac structure represents an effective combination of the Wideröe (or interdigital) linac structure, used for many low frequency, heavy ion applications, and the rf electric quadrupole focusing used in the RFQ linac structure and the Rf-Focused Drift tube (RFD) linac structure. The rf focusing is introduced into the RFI linac structure by configuring the drift tubes as two independent pieces operating at different electrical potentials as determined by the rf fields of the linac structure. Each piece (or electrode) of the RFI drift tube supports two fingers pointed inwards towards the opposite end of the drift tube forming a four-finger geometry that produces an rf quadrupole field along the axis of the linac for focusing the beam.

We have adopted what we call the "Stacked Cell" approach, where the basic unit of the structure is a single cell, complete with a two-piece drift tube, supported by major and minor stems in a short section of the outer wall. The linac structure is assembled by stacking up a sequence of these cells, each with the proper dimensions. The stack is held together by tie-bolts running along the structure or by welding the cells together into a single unit.

The RFI linac section will be configured as two tanks. The first tank accelerates the beam from 0.8 MEV/u to 3.88 MeV/u. The second tank accelerates the beam to the final energy of 7.0 MeV/u. The bore radius for both tanks is 6 mm and the total length of the two tanks is 4.47 m. The peak rf power requirement for the two tanks is 500 kW, which for the 0.1% duty factor, results in an average rf power of only 500 W.

RF POWER SYSTEM

The rf power system[3] consists of a low level rf system, a solid state amplifier, two one-tube intermediate power amplifiers, a final power amplifier (FPA), and an output directional coupler. It is designed to provide 800 kW of 200-MHz power at 0.1% duty factor. The rf power amplifier utilizes six GB-35B planar triodes in parallel in an axial array around the output coax. Each tube is capable of 140 kW of peak power output up to 1 GHz. Each tube has its own cathode bias and heater power circuit. The cathode bias circuit adjusts the bias on each tube to maintain a programmed level of cathode current. In order to make a compact amplifier, the anodes will be liquid cooled.

The directional coupler provides rf samples proportional to the forward and reflected wave amplitudes in the output coax. The forward amplitude signal is used in the frequency control circuit to lock the rf system to the accelerator resonant frequency. A pickup loop in the cavity provides a signal that is used in the frequency control loop and in the amplitude control feedback circuit. The reflected amplitude signal is used for fault protection due to high VSWR.

RFI BEAM DYNAMICS

The beam dynamics of the RFI linac structure was investigated with the aid of TRACE-3D, a well-known, linear beam dynamics computer program, and PARMIR, a PARMILA-like beam dynamics code that simulates multi-particle beam dynamics in drift tube and interdigital linacs that employ rf focusing inside the drift tubes. TRACE-3D calculations for the Carbon+4 linac, configured in the + + - - focusing sequence, were made for cell lengths of 30, 45, 60, 75, and 90 cm, corresponding to the carbon ion energies of 0.75, 1.68, 3.00, 4.70, and 6.78 MeV/u. The phase advance of the transverse oscillation ranges from 36 degrees for the shortest cell to 47 degrees for the longest cell. The Twiss beta parameter varies from 0.26 cm/mrad for the shortest cell to 0.62 cm/mrad for the longest cell. The beam radius is 2 mm or less throughout the linac.

Due to the similarity in the transverse focusing forces in the RFQ and RFI linac structures (rf electric quadrupole focusing in both cases), very little is required to match the beam from the RFQ structure into the RFI structure. There is very little space between the two structures – the RFQ rods end only millimeters from the first half cell of the RFI structure. The RFQ structure ends in a "transition cell", which reduces the angular content of the output beam from the RFQ in both transverse planes. The RFI structure begins at a point of symmetry in the + + - - focusing sequence, which reduces the angular content of the input beam for the RFI in both transverse planes. Only minor changes to the lens strengths in the first four cells of the RFI structure are required to match the beam from the RFQ into the RFI. Figure 2 shows the TRACE-3D simulation of the matched beam in the last 10 cells of the RFQ, through the very short drift between the two structures, through the slightly modified first four cells of the RFI, and then through the rest of the RFI structure. This simulation also demonstrates that a constant-aperture, constant-voltage RFI lens, with a length that is a constant fraction of the cell length (1/3), results in a constant diameter beam.

The RFI linac structure offers a "one knob" accommodation for ions of other charges and masses. As all of the acceleration and focusing forces are electric and proportional to the rf field strength, a change in the magnitude of the rf field strength is all that is needed to accommodate other ion species. For example, to change from Carbon+4 to proton acceleration, the only change required is to reduce the rf electric field strength by a factor of 3. In the beam dynamics simulations, changing the charge/nucleon from 0.3333 (for Carbon+4) to unity (for protons) and reducing the acceleration and focusing field strengths by a factor of 3, the resulting beam profiles and phase spaces are indistinguishable from the carbon results.

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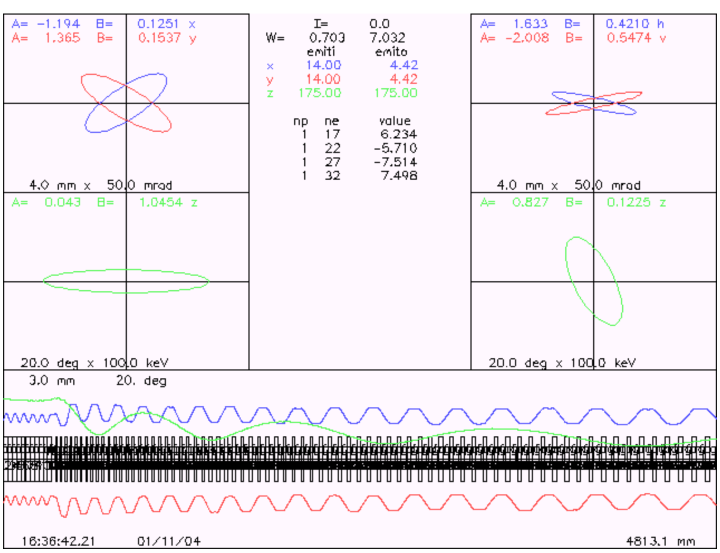

Figure 2: Trace Display showing beam in last ten cells of the RFQ and all of the RFI for Carbon +4.

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