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DESIGN OF A SUPERCONDUCTING INTERDIGITAL ACCELERATOR STRUCTURE FOR RADIOACTIVE HEAVY IONS

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Abstract

An on-line isotope separator (ISOL) has been installed on one of the beamlines at the TRIUMF cyclotron. Assuming a 60 keV/u, 50 MHz RFQ preaccelerator, a drift-tube linac design based on the superconducting interdigital structure developed at the Argonne National Laboratory, has been studied for acceleration of the ISOL radioactive beams. The linac consists of a first stage with 12 four-gap 50 MHz resonator tanks and 6 inter-tank superconducting solenoid lenses, followed by a second stage operating at 100 MHz, with 21 tanks and 7 inter-tank solenoids. This then can deliver a 1.6 MeV/u beam of ions with $q/A \geq .05$. Including solenoid lens space, the equivalent average acceleratiing gradient for singly charged ions is 1.9 MeV/m, about 60% higher than for a room temperature design reported earlier.[1]

The design was developed using a modified version of the PARMELA code, called PARMION, which dynamically varies the cell lengths to maintain a specified synchronous phase. The optimum synchronous phase was found to be -15°.

Introduction

Motivated primarily by a desire to study nuclear reaction cross sections involving short lived radioactive nuclei that are of astrophysical interest, a conceptual design of a post accelerator for a planned ISOL (isotope separator on line) facility at TRIUMF was developed about five years ago.[1] The accelerator considered at that time was a two stage linac, consisting of an RFQ to capture bunch, and accelerate the very low energy, singly charged ions from the ISOL to 60 keV/u, followed by a stripper to increase the ion charge to mass ratio (q/A) to a least 1/20, before being further accelerated in a Wideroe type drift-tube linac (DTL), to a final energy of 1 MeV/u. Conventional room temperature structures were considered in this case, and would have required more than 1 MW of cw rf power.

In recent years significant progress has been made in superconducting accelerator structure development. At ANL in particular, low beta interdigital structures have been built in which accelerating gradients greater than 6 MeV/m have been achieved[3]. It is possible that similar structures could be used in place of the Wideroe DTL to not only reduce the rf power requirement but perhaps also reduce the overall linac length. The study reported here was undertaken therefore to examine the use of superconducting structures in the ISOL post-accelerator application and in particular to examine the feasibility of providing adequate transverse focusing for the low velocity, low q/A beams. It will be assumed that the first stage of acceleration is a high gradient heavy ion RFQ such as that described by Chidley *et al.*[2]

The Design Approach

The ANL structure is inherently an $n\pi$ mode structure where n is an odd integer. Usually n=1 and the cell lengths (constant within a 4 gap tank, for mechanical simplicity), are equal to $\overline{\beta}\lambda/2$, where $\overline{\beta}$ is the design average ion velocity for the tank, and λ is the resonant rf wavelength for the tank. To accommodate the increasing β as the ion beam is accelerated through the linac, successive tanks should have correspondingly increased cell lengths. Indeed, in the ideal case successive cells within a tank should also increase in length to maintain a constant synchronous phase.

From a practical point of view it is desirable to keep the number of tank designs to a minimum. For this reason the ANL ATLAS injector will use only four tank designs,[3] and an earlier ISOL linac study used five basic tank geometries.[7] The penalty for this simplification is of course reduced accelerating efficiency because of phase slip of the ion bunches relative to the accelerating field for bunches with average velocities that differ from the design value for the tank.

For the current study, a fixed value of the entrance phase at each cell was adopted - as is usually the case in designing drift tube linacs. With a specified value for the field strength in the cell, the cell length is adjusted to equal $\beta\lambda/2$ where β is the average β in the cell.

A negative synchronous phase angle is necessary to maintain longitudinal focusing of the beam. This of course leads to a radial rf defocusing force which, in conventional drift-tube linacs, is compensated with quadrupole magnets in some or all of the drift-tubes. Because neither the superconducting surfaces nor the interdigital structure sizes are compatible with an integral magnetic lenses, gaps between tanks must be provided to allow installation of transverse focusing elements, such as superconducting solenoids. It is the maximum achievable transverse focusing that establishes the maximum accelerating field in this case, rather than the intrinsic superconducting surface characteristics.

The solenoid lenses used throughout are assumed to be similar to those described by Jaffey *et al.*[4] They are iron-shielded NbTi wire-wound solenoids operated with not more than 7T magnetic field. The solenoid lengths used varied from 30 cm to 45 cm.

The linac design was carried out using a modified version of the particle tracking code PARMELA.[5] PARMELA incorporates an option to integrate the motion of a group of electrons through the tabulated rf fields of several types of cavities. Relativistic kinematics are used. The modified code, PARMION, handles the kinematics in the same fashion as PARMELA but accepts an arbitrary particle mass (in MeV) with an arbitrary charge state. In addition, a group of four contiguous cells can be designated as a tank with a specified entrance phase that will apply to each of the four cells for the reference particle of the bunch. Each of the four cells in the tank has the same value of the rf field strength. Execution of the code with a small number of particles is sufficient to generate a table of cavity lengths which can be used in later runs without the "tank" card. For cells that are not identical to those for which the rf field is tabulated in two dimensions, the code scales the interpolation intervals radially and longitudinally. In this way a given cell geometry can be used over a wide range of cell length with the understanding that the cell used in the simulation is a scaled replica, both radially and longitudinally, of the original cell for which the rf field was tabulated.

The basic accelerating cell, sketched in Fig. 1. was modelled in the SUPERFISH[6] code in the form of a simple $\lambda/4$ resonator, the right hand side of the figure representing the part connected to the $\lambda/4$ stub. The rf field in the accelerating gap was tabulated in a two-dimensional array for use in PARMION. Typical four-cell tanks are shown in Fig. 1 of Ref.[3]

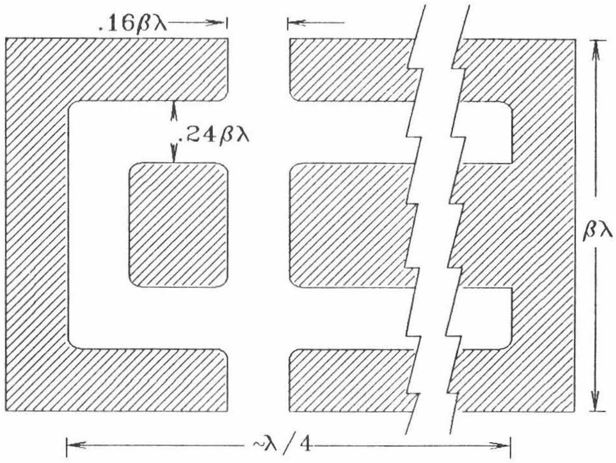

Fig. 1. Sketch of the accelerating cells as modelled in SUPERFISH.[6] In the linac simulation runs, the cell dimensions (with the exception of the stub length) are scaled with β.

The Superconducting Linac

The frequency of the TISOL linac is not tied to the frequency of the TRIUMF cyclotron; the pulsed structure of the primary proton beam is lost in the final production of an ionized beam of secondary heavy ions emerging from the ISOL. For the present study it was assumed that a high gradient, room temperature RFQ would be built to operate at 50 MHz. A beam of singly ionized ions would be accelerated to 60 keV/u with a normalized transverse emittance of $\epsilon_n = 0.035\pi$ mm mrad and in the longitudinal plane $\epsilon = 15 \times 50$ kev degree.[2]

Following the RFQ a stripper raises the charge state from 1^+ to 3^+ for ions of mass number up to 60. The quadrupole symmetry of the beam from the RFQ is transformed in a matching section[7] to deliver a converging beam of circular cross section to the SC linac. The acceptance of the SC linac is illustrated in Fig. 2. The beam delivered from the stripper fits well within the acceptance in all phase space coordinates.

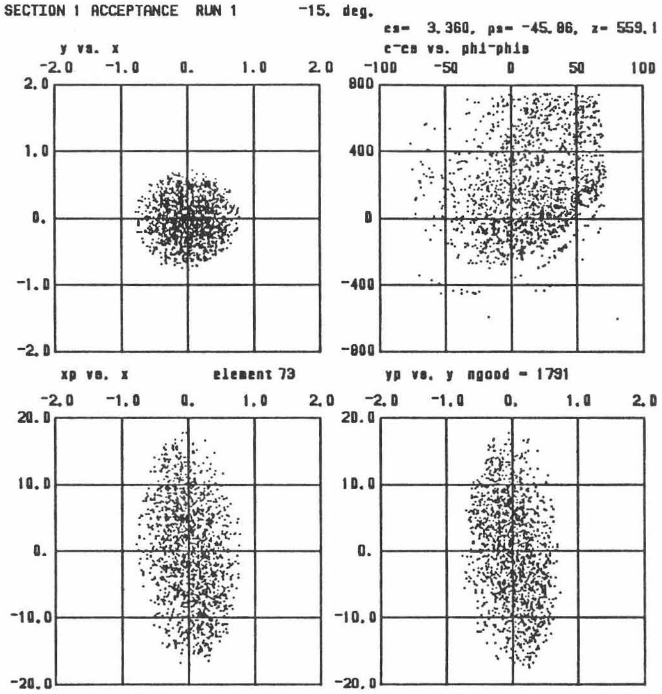

Fig. 2. Scatter plot of the linac acceptance. The plots show the initial phase space coordinates of particles surviving at the end of the 50 MHz section out of an initial population of 10,000.

Computations were made for synchronous phases in the range -40° to -10° for the initial few tanks of the 50 MHz section of the linac. At the -40° extreme the bunching force is large as is the radial defocusing force. Moreover, the average acceleration is relatively low. At the other extreme, the acceleration is higher and the bunching and defocusing forces are smaller. The bunching force is adequate over the whole range; the best balance between acceleration and defocusing was found at -15 degrees. For radial focusing, a solenoid is placed after every second tank.

Not surprisingly, it was found that emittance growth was held to a minimum when the focusing was strong enough to hold the beam radius below 1 cm. Under these conditions the transmission was 100 percent and the emittance growth was of the order of 20%.

The initial cell length for a beam of $\beta = .01$ is about 3.4 cm. At a beam energy of 0.5 MeV/u, the cell length is about 9.2 cm, sufficiently long to permit a frequency doubling to 100 MHz. In the 100 MHz section of the linac, solenoids were placed after every third tank. This density of solenoids was found to be necessary to contain the beam for low emittance growth, not to prevent beam loss on the walls.

The complete SC DTL then consists of twelve 50 MHz tanks with six inter-tank solenoids, contained in two cryostats each about two metres long, followed by twenty-one 100 MHz tanks with seven solenoids in four 2 metre cryostats. The overall length of the DTL is 16.3 m and has an output energy of 1.6 MeV/u. This can be compared to the room temperature DTL of the earlier study[1] which had a similar length but an output energy of only 1 MeV/u.

The scatter plots of Fig. 3 show that at the exit from the linac, the longitudinal phase space is sufficiently correlated to allow a substantial reduction of the energy spread by rotating the phase space diagram in an energy compressor.

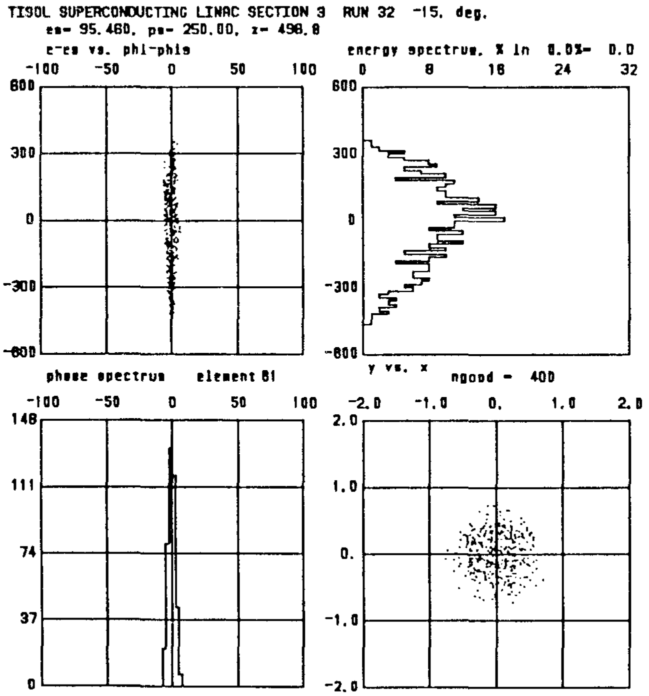

Fig. 3. Scatter plots and profiles of the beam delivered at the linac output.

Discussion of the Design

The continuously varying cell length used in this design has resulted in a large overall accelerating gradient (about 1.9 MeV/m for a $^{20}Ne^{+}$ ion). Variation in the beam energy up to ±7% can be obtained by varying the rf phase in the last tank. Larger beam energy variations will require changes in the operating conditions for more than one tank.

In general, the tuning of the linac for a given output energy and ion q/A requires the adjustment of the phase and amplitude of the rf drive to every tank.

In the later stages of both the 50 MHz and the 100 MHz sections, the length of the four cells in the tank becomes a significant fraction of the $\lambda/4$ stub. For four cells the total length of structure in the beam direction on the end of the $\lambda/4$ stub is approximately $5\beta\lambda/2$ or a fraction 1.25 β of the stub length. At the linac output this amounts to 6.25% of the stub length. In the design and construction of the tanks, tuning and field flattening devices will therfore be required in the high-field regions to achieve a uniform field.

In the construction of such a linac, the continuous variation of the cell length may have to be compromised. For example, the cell lengths in a given tank could be made equal to the average cell length as given by the PARMION code. This would reduce the multiplicity of cell designs by a factor of four although the tank lengths would still all be different, viz. 2 $\beta\lambda$.

References

1. H.R. Schneider, G.E. McMichael, B.G. Chidley, and R.M. Hutcheon, "A conceptual design study of a linear accelerator for radioactive ions at TRIUMF", Proc. of Accel. Rad. Beams Workshop, TRIUMF Report TRI-85-1, p. 189 (1985)
2. B.G. Chidley, R.M. Hutcheon, and G.E. McMichael, "A heavy ion RFQ with high accelerating gradient", Proc. 1986 Linac Conf., SLAC-303, p.361, (1986)
3. K.W. Shepard, "Development of a very low velocity superconducting linac" Proc. 1987 Part. Accel. Conf. p.1812, (1987)
4. A.H. Jaffey, R. Benaroya, and T.K. Khoe, "A hybrid superconducting solenoid as a focusing element in a superconducting heavy ion accelerator", Proc. 1976 Linac Conf., AECL-5677, p.102, (1976)
5. PARMELA, a time dependent, electron dynamics code for linear accelerators, Los Alamos National Laboratory, circa 1979.
6. K. Halbach, R.F. Holsinger, W.E. Jule, and D.A. Swensen, " Properties of the cylindrical RF cavity evaluation code SUPERFISH" Proc. 1976 Linac Conf., AECL-5677, p.122, (1976)
7. J.S. Fraser, J. D'Auria, L. Buchmann, and H.R. Schneider, "Dynamics of heavy ion beams in an interdigital superconducting accelerator structure", Proc. First Int'l Conf. on Radioactive Beams, p.553, (1989)