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DYNAMICS OF HEAVY ION BEAMS IN AN INTERDIGITAL SUPERCONDUCTING ACCELERATOR STRUCTURE

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ABSTRACT

In 1985, a linac was proposed for the accelerated radioactive beams facility at TRIUMF. The linac comprised a low frequency (23 MHz) radiofrequency quadrupole (RFQ) structure followed by a conventional cw room temperature drift-tube linac. In this paper the use of a superconducting, interdigital structure for the linac is discussed and detailed beam dynamics calculations, using a modified version of the time-dependent PARMELA code are presented. A linac configuration for achieving a final energy of 1 MeV/amu is described.

INTRODUCTION

A post-accelerator was proposed in 1985 for the TRIUMF on-line isotope separator (ISOL).[1,2] Detailed calculations were carried out for a conceptual design of a two stage accelerator consisting of a radiofrequency quadrupole (RFQ), followed by a Wideroe-type drift-tube linac (DTL).[3] In this design the singly charged, low velocity ions (β=0.0015) from the on-line ion source are accelerated to 60 keV/amu (β=.012) in the RFQ and then passed through a foil or gas stripper to increase the most probable charge state to greater than 3+ before being further accelerated in the DTL. Overall length of the linac in this design is 25 metres, made up of 9 metres for the RFQ, and 16 metres for the DTL. Both structures operate cw at 23 MHz, requiring approximately 100 kW of rf power for the RFQ and 1.2 MW for the DTL. The accelerator design accommodated ions with mass numbers in the range $1 \leq A \leq 60$, and a minimum ion charge to mass ratio of 1/20 (no inter-stage stripper would be necessary for ions with $A \leq 20$).

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At the time of these design studies, development at the Argonne National Laboratory of interdigital superconducting structures for heavy ion acceleration was reported.[4,5] These structures with acceleration gradients of 6 MV/m achievable, and very low rf power requirements present an interesting, and possibly less costly alternative to the room temperature DTL.

The interdigital structures developed at ANL are quarter-wave stub resonators incorporating four accelerating gaps in each tank. Figure 1 (reprinted from the Proceedings of the 1987 IEEE Particle Accelerator Conference)[4]

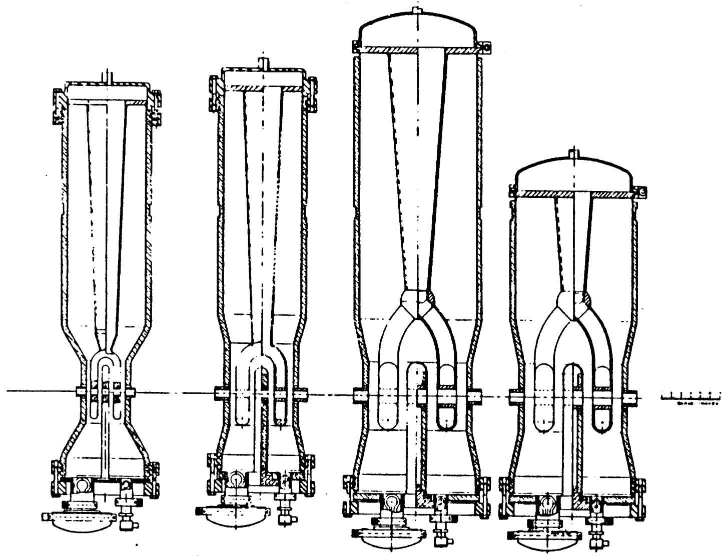

Fig. 1. Four versions of the ANL interdigital superconducting structures for beta increasing from 0.008 on the left to 0.04 on the right

shows four types of low velocity resonator tanks. The cell lengths increase from left to right to match the particle velocity along the linac. For simplicity in mechanical design and fabrication, the cell lengths in each tank are constant. The design velocity for such a tank with a resonant wavelength of λ is defined as the velocity for which $\beta\lambda/2$ is equal to the cell-to-cell spacing. Because β increases as the particles accelerate (from 0.01 to 0.05 for a 1 MeV/amu accelerator), the particle bunches will gradually advance in phase relative to the rf accelerating wave, leading eventually to a loss in effective accelerating gradient. Several tank designs must therefore be used to maintain an acceptable phase slip. In the current study, five tank designs were adopted with the design velocity increasing progressively by a factor of 4/3. The accelerating efficiency, therefore, for each tank type increases to a maximum at the design velocity, then falls. The design velocities for the five tank types are β =0.0131, 0.0175, 0.0232, 0.0310 and 0.0409. The accelerating efficiency variations for these tanks is shown in Figure 2.

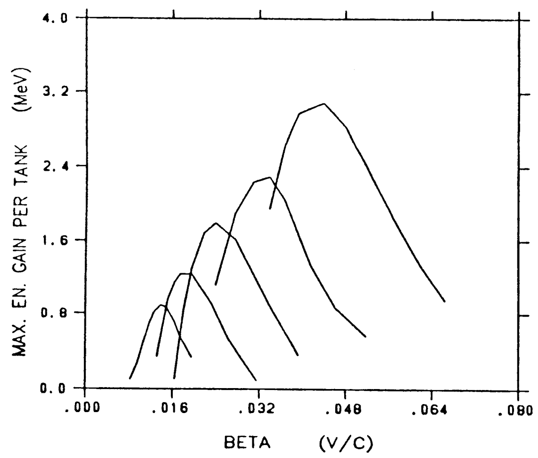

Fig. 2. Maximum acceleration (input phase 0°) vs beta for five tanks used in the present study.

ACCELERATOR DESIGN

The conventional drift tube linac is a combined function structure in the sense that acceleration and transverse focusing, necessary to overcome the rf defocusing at each acceleration gap, is provided in the same structure. This is accomplished by incorporating quadrupole magnets in all or some of the drift-tubes.

In the Wideroe DTL previously proposed, the quadrupoles were located as a matter of convenience in every second drift tube because they were at ground potential. Since the quadrupole magnets cannot be accommodated in the drift-tubes of the superconducting (SC) interdigital structure, inter-tank superconducting solenoids were developed at ANL[6] for use in this case. If we are to take advantage of the high accelerating field possible in the SC structures, the radial focusing provided by the solenoids must compensate for the correspondingly stronger rf defocusing forces. Moreover, with four drift-tube gaps in each tank contributing to the defocusing, the focusing strength required is increased even further.

With the use of solenoidal focusing, a beam of circular cross section is most easily matched to the SC linac acceptance. Since the initial acceleration after the

ion source is in an RFQ, the beam naturally acquires a quadrupole symmetry. A matching section is therefore required between the RFQ and the SC linac.

The emittance matching section is of the type described by K.L. Brown[7] as $\pi/2$-phase shift quadrupole doublet flanked on each side by a tuning quadrupole. The phase space parameters of a 3.36 Mev ^{56}Fe beam exiting the RFQ are taken as:

$$\epsilon = 40.0\pi\text{mm} - \text{mrad}$$
$$\alpha_x = 1.5, \alpha_y = -1.5$$
$$\beta_x = \beta_y = 0.060$$

giving $x_{max} = 0.5$ cm, $x'_{max} = 15$ mrad. On the other hand, an acceptable match to the SC linac is one in which $\alpha_x = \alpha_y = 0$, and $\beta_x = \beta_y \leq .25$, for a beam with radius of less than 1.0 cm. A solution is arrived at, first by adjusting the quadrupole doublet strengths and the three spacings to produce a 90° phase shift in both the x-x' and y-y' phase space planes. Second, with the spacings held constant, all four quadrupoles are varied to produce a double waist ($\alpha_x = \alpha_y = 0$) at the exit of the fourth quadrupole. A strong solenoid (B_z = 5T) placed after a short drift space downstream from the fourth quadrupole then yields the desired result of a circular, convergent beam delivered to the SC linac.

A gas stripper would give a small increase in emittance[2] but the increase has been ignored in the present calculation.

Since the on-line isotope ion source retains none of the rf structure of the TRIUMF cyclotron (23 MHz), the choice of rf frequency for the ISOL SC linac is open. We have chosen 50 MHz, close to the ANL design frequency of 48.5 MHz and within the feasible range for a cw RFQ.[2]

Figure 3 shows a block diagram of the linac used for the present beam dynamics calculations. Far from being an optimized design, it should be viewed as the framework for an initial design study.

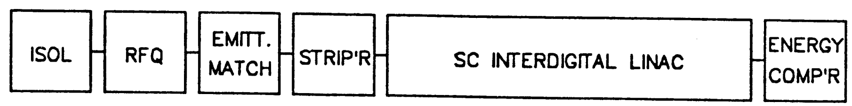

Fig. 3. Block diagram of a proposed ISOL accelerator including an SC linac.

The SC linac is assumed to be contained in a single cryostat in which the spacing between elements (resonant tanks and solenoids) is dictated principally by mechanical considerations. As a result, each tank is independently powered and phased. The structure adopted in the calculation comprises 40 tanks and 33 solenoids. The operational complexity of this design dictates the use of a large number of beam diagnostic devices for measuring beam size and energy or velocity.

Following the linac, an energy compressor is used to reduce the energy spread acquired by the beam. The energy compressor is simply a drift space with two or more solenoids followed by one or two accelerator gaps to rotate the longitudinal phase space.

BEAM DYNAMICS

In the early stages of acceleration, the rf field is maintained at a moderate level (2 MV/m) to keep the radial defocusing in the drift-tube gaps within the manageable range of the solenoids. The peak field in the solenoids was kept below 9 T, a level achievable readily with Nb_3Sn but at the limit of feasibility with NbTi. Along the linac, the rf field is ramped up in steps to the final value of 4.0 MV/m.

Because of the constant cell length within a tank and the limited number of tank designs used, there will be, in general, a phase slip of the beam bunches relative to the rf as the particles pass through the tank. To maintain adequate phase focusing, and small energy spread, tank phasing is chosen so the average bunch phase relative to the rf at the entrances of the middle two cells of a tank is -45°.

As the beam progresses through the linac the difference between the beam velocity and the tank design velocity will grow. When the resulting bunch phase slip across a tank, relative to the rf reaches 90°, the effective accelerating gradient begins to fall rapidly. At this point then, a change is made in the tank design to the one with the next higher design velocity.

Calculations are carried out using a modified version of the code PARMELA[8] called PARMION. The PARMELA code (Phase And Radial Motion in an Electron Linear Accelerator) was written to accommodate only electrons and a unit charge. The principal modifications in PARMION are provisions for an arbitrary mass (in MeV) and an arbitrary charge state of the particle.

The code is limited to a total of 100 beam line elements. Therefore, the complete linac has to be calculated in three sections. At the end of sections 1 and 2, the transverse and longitudinal phase spaces are fitted and the shape parameters used as input to the following section. Figure 4 shows three beam parameters

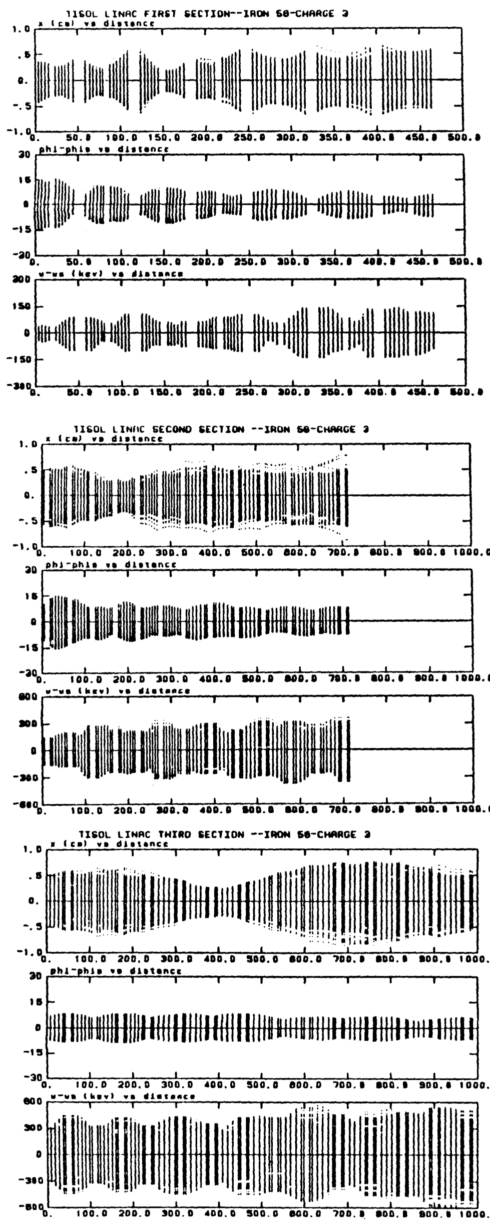

Fig. 4. Beam size, phase spread and energy spread along the length of the SC linac.

(beam size, the energy spread and the phase spread) for three sections of the linac. The large gaps in the diagram at $z = 55$, 115 etc. cm represent the drift spaces in which a solenoid is located (25 cm). The beam entering the SC linac is triply-charged ^{56}Fe, a mass-to-charge ratio of 18 2/3. The emittance is 40.0π mm-mrad, of circular cross section with a radius of 5 mm and converging. The total phase spread is initially 20° and the total energy spread is 40 keV.

Table 1 lists some linac data and beam properties at the end of each tank type.

Table 1 Tabulation of some of the calculated beam properties at the beginning of the SC linac and at the end of each of the five tank types.

Z (m)	Tank Type	Energy (MeV)	Normalized Emittance (π -mm.mrad)	Δ E (MeV)	$\Delta\phi$ (deg)
0.	–	3.4	0.317	±-0.02	±15
2.6	1	6.8	0.325	±0.15	±12
4.6	2	11.6	0.323	±18	±11
8.0	3	19.2	0.284	±0.28	±9
14.1	4	35.2	0.320	±0.35	±7
21.6	5	59.1	0.368	±0.60	±4

The final energy of 59.1 MeV (1.1 MeV/amu) meets the initial goal of the TRIUMF ISOL programme. The normalized rms beam emittance for 90% of the current of 0.37π mm-mrad is only 16 percent higher than the normalized emittance of the input beam. The relatively high accelerating field gives an energy half-width of 0.6 MeV but the half phase spread is small at 4°. The transmission through the linac is 100 percent.

Figure 5 shows four scatter plots for a beam of 400 pseudoparticles at the end of the linac.

The beam is nearly parallel at the exit and the E-ϕ diagram of longitudinal phase space is highly correlated. Therefore, energy compression (at the expense of phase debunching) is simply achieved by using a drift space of 2 m followed by a two-gap tank acting as a debuncher. The result (see lower part of Fig. 5) is an energy half-width of 0.1 MeV (0.2%). This should be more than adequate for cross-section measurements and would not impose unreasonable limits on nuclear

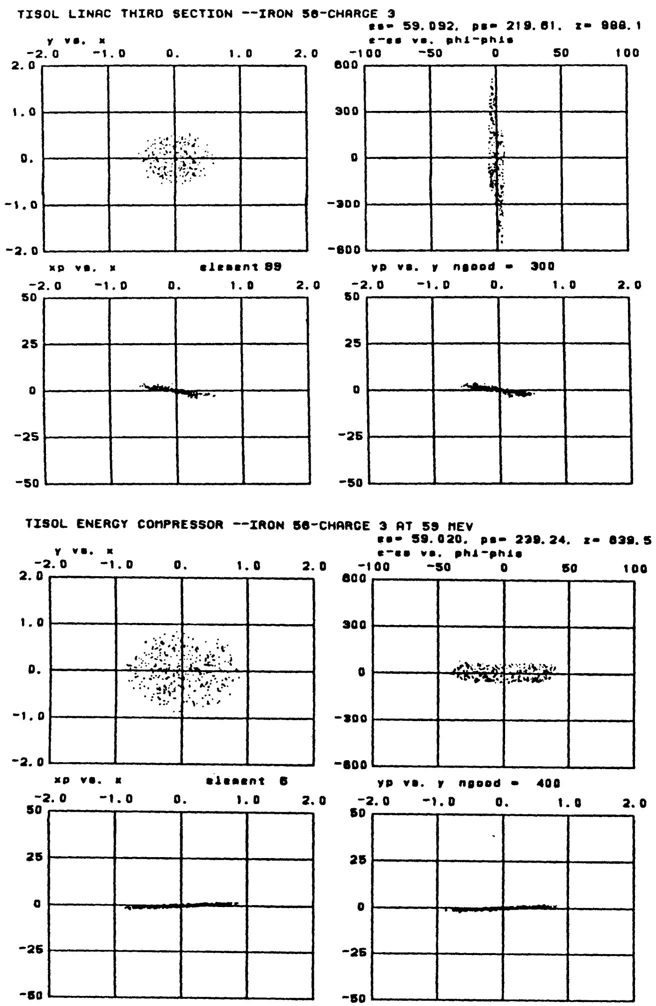

Fig. 5. Scatter plots of the beam size and phase spaces of the beam at the SC linac exit (top) and after energy compression

spectroscopy experiments.

DISCUSSION

These results show that inter-tank solenoid focusing is capable of coping with the strong rf defocusing forces through most of an ISOL post-accelerator linac composed of the high gradient superconducting structures. At the low energy end of this linac however the critical field limitations of solenoids wound with the usual NbTi superconductor would restrict design accelerating gradients to values considerably less than the structures would otherwise permit. Use of the higher critical field Nb_3Sn superconductor could ease this constraint somewhat, but at the expense of more difficult solenoid fabrication.

In spite of the much higher accelerating gradients possible in the SC linac its overall length is longer than the comparable room temperature linac studied earlier.[1)] The reason for this is of course the necessity to insert a solenoid between every five cells, on the average. This aspect of the SC linac obviously increases the capital cost because of the larger space requirement and to a small extent, also because of the increased cost of refrigeration to cover the heat losses in a longer cryostat.

Further studies to optimize the design should be directed towards the following objectives:

- A smooth velocity profile obtained by continuously increasing the cell lengths to keep in step with the beam. In this manner, the cell entrance phase could remain constant at, say, -45°.
- Minimize the number of solenoids.
- Use only solenoids made with NbTi.

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