POST-ACCELERATOR STUDIES FOR THE ISOL FACILITY AT TRIUMF

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ABSTRACT

A conceptual design for an ISOL post-accelerator, based on superconducting linac structures developed at Argonne National Laboratory was described in earlier papers. Periodic focusing provided by 7 T solenoids spaced at 8 cell intervals could maintain adequate transverse focusing only if the accelerating gradients were kept well below the demonstrated 6 MV/m capability of the SC structures. To permit higher accelerating gradients several variations of the solenoid focusing as well as RFQ focusing elements have been investigated. The RFQ elements are $\beta\lambda$ long and act like a quadrupole doublet with time dependent fields that can be much higher than in an electrostatic quadrupole. Using RFQ focusing with 93 kV/cm peak fields in a 1 cm radius bore, spaced at eight cell intervals, it was found that adequate focusing to compensate for the rf defocusing associated with 6 MV/m accelerating gradients could be achieved. The 5.6 m drift-tube linac length in stage 1 of the previous conceptual design could then be reduced to 3.1 m.

1. INTRODUCTION

In an earlier paper we described the conceptual design of a post accelerator (ISAC) for radioactive beams generated in an isotope separator on line (ISOL) at TRIUMF.[1)] As illustrated in Fig. 1, it consisted of a room temperature RFQ to capture, bunch, and accelerate the singly charged ISOL ion beam (with $A \leq 60$) to an energy of 60 keV/u, followed by a stripper to raise the ion charge to mass ratio (q/A) to at least 1/20 before further acceleration to 1.6 MeV/u in two stages of a superconducting interdigital linac. Twelve four gap interdigital tanks of the ANL type,[2)] operating at 50 MHz made up the first stage, while the second stage, operating at 100 MHz consisted of 21 four gap interdigital modules. Superconducting solenoid lenses installed at two tank intervals in the first stage and three tank intervals in the second stage, provided the transverse focusing for the beam. The magnetic induction in the solenoids was chosen to be 7 T, and solenoid lengths varied from .3 m to .45 m.

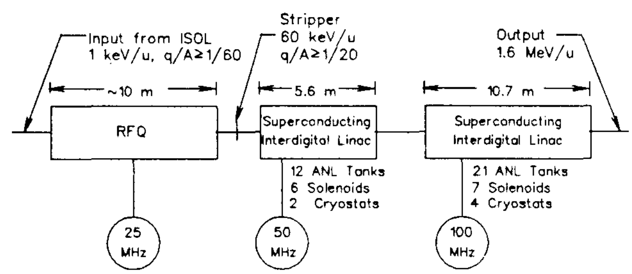

Fig. 1. Conceptual design of ISAC

To limit rf defocusing in the accelerating gaps it was found, in this design, that in addition to choosing a relatively small synchronous phase angle of $-15°$, it was also necessary to choose accelerating gradients in the 50 MHz section well below the demonstrated capabilities of the ANL interdigital structures. Thus the accelerating gradient was limited to 2 MeV/m in the first tank of stage 1, and allowed to ramp up in succeeding tanks, ending at 4.8 MeV/m in the last tank of this stage, still below the 6 MeV/m achieved in such structures.

In the current study two approaches to increase the transverse focusing strength, and hence allow higher accelerating gradients, have been investigated. In one case various options involving solenoid focusing have been reexamined and optimized, while in the other, the possible use of focusing RFQ elements has been investigated. The objective in either case was to attempt to reduce the overall length of the linac, or more particularly, to reduce the required number of superconducting modules.

2. SOLENOID FOCUSING

Several options are possible for increasing the focusing strength using solenoids. These include a) increasing the periodicity from tank-tank-solenoid to tank-solenoid, b) increasing the solenoid lengths (within limits as discussed later), and c) increasing the solenoid strength.

Case No.	Focusing Periodicity	B_s T	Solenoid Length cm	Accel. Field MV/m	Output Emittance cm·mrad	Beam Rmax cm	Linac Length cm	No. Tanks
1	TK-TK-SOL	7	25-35	2-4.8	1.2π	1.0	560	12
2	TK-TK-SOL	8	25	4.8	2.4π	1.0	380	8
3	TK-SOL-TK	7	25	4.8	$.91\pi$	.5	480	8
4	TK-TK-SOL	7	40,50,60	6.0	2.6π	1.0	400	6

Table 1. Summary of solenoid focusing cases studied for the 50 MHz linac section.

Starting with a beam from the RFQ, with an energy of 60 keV/u, an emittance of 4.2π cm-mrad, and q/A=1/20, the time dependent code PARMION was used to generate linac geometries for the 50 MHz section and trace particles through them for various solenoid focusing schemes. In all cases a tank is considered to be a four gap ANL type interdigital structure.[2] Drift space allowances between tanks, and between a tank and solenoid are 10 cm and 5 cm respectively.

Table 1 contains a summary of the solenoid focusing cases studied for the 50 MHz linac section. The first case in this list is the conceptual design described previously.[1] Cases 2 and 3 with relatively short solenoids similar to that used in the previous study, show that by either increasing the solenoid induction to 8 Tesla or by increasing the focusing periodicity to Tank - Solenoid - Tank with 7 Tesla solenoids, a constant accelerating gradient of 4.8 MV/m could be accommodated. For the last case listed the solenoid lengths were chosen to maximize their focusing strength. To determine the appropriate lengths, a simple analytical treatment to describe solenoid focusing in linacs was used.

If B_s is the solenoid magnetic induction, l is the length of the solenoid, and $B\rho$ is the magnetic rigidity of the ion, and we define $\theta = B_s l/(B\rho)$, $C = \cos(\theta/2)$, and $S = \sin(\theta/2)$, $\alpha = \theta/(2l)$, then, provided we rotate the exit coordinates by an an angle $\theta/2$, one finds that the the transfer matrix for a solenoid[3] is equivalent to a thin lens with focal strength $-\alpha S$ included between two drift spaces of length $(1-C)/(\alpha S)$. For a given ion energy and magnetic induction, the maximum equivalent thin lens focal strength is achieved when the solenoid length L_{max} is equal to $\pi/(2\alpha)$.

The defocusing action of an acceleration gap may be approximated by a thin lens of focal strength Δ, given by,

$$\Delta = \frac{-qET}{m_o c^2 \beta^2} \sin(\phi)(1-\beta^2) \qquad (1)$$

where, E is the peak accelerating field in the gap, T is the transit time factor(slightly less than 1 for our case), ϕ is the gap crossing phase measured relative to the peak of the r.f. voltage, and β is the usual relativistic factor.[4]

Assuming now that the defocusing effects of the N accelerating gaps preceding a solenoid lens can be approximated with the defocussing effect of a a single thin lens having a focal strength $G = N\Delta$, and using the standard solenoid transfer matrices, we derive an expression for the maximum value of the Twiss parameter β describing the transverse motion within a matched periodic (thin lens)-(drift space)-(solenoid)-(drift space) structure and obtain;

$$\beta_{max} = \frac{|\frac{S}{\alpha}(DG+1) + \frac{1-C}{2\alpha^2}G + \frac{C+1}{2}D(2+DG)|}{\sqrt{1-(\frac{SG}{2\alpha} + C[DG+1] - \frac{\alpha DS}{2}[2+DG])^2}} \qquad (2)$$

where D is the drift space between the solenoid and the defocusing thin lens, and C, S and α are the solenoid

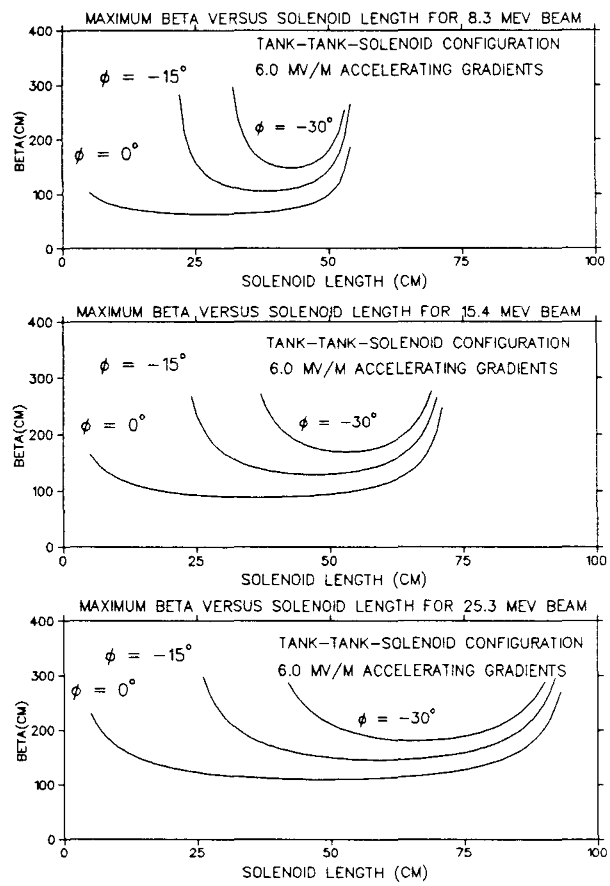

Fig. 2. Maximum values of β versus solenoid length for various beam energies.

transfer matrix parameters defined earlier*. In Fig. 2 β_{max} is plotted as a function of solenoid length for three beam energies that correspond roughly to the energies after 8, 16, and 24 accelerating gap crossings with $E_{acc} =$ 6 MV/m. From this we see a rather broad minimum for β_{max} over the range of gap crossing phases of -30° to 0° with optimum solenoid lengths of approximately 40, 50, and 60 cm for beam energies of 8.3, 15.4, and 25.4 MeV respectively. Using these values in the PARMION[1)] calculations results in the linac that is summarized as case 4 in Table 1.

3. RFQ FOCUSING

Use of electric focusing is often advantageous in beam transport systems for low velocity ion beams such as those found in the first stage of the ISAC interdigital linac. Here we consider a special type of electric focusing element, namely an RFQ with no vane modulation and of length $\beta\lambda$ producing, in the quasi-static approximation, a time varying potential of the form

$$V(x,y,z,t) = K(x^2 - y^2)\sin(\omega t + \psi) \qquad (3)$$

where x and y are the transverse coordinates, $K = V_p/a^2$ is the RFQ strength constant evaluated in terms of the peak voltage V_p on one of the electrodes and the electrode aperture a, ω is the r.f. frequency, and ψ is an r.f. phase angle. Such a device will only have transverse electric fields(provided we ignore fringe field effects near the entrance and exit), and will act as an electric quadrupole doublet. The rf fields with higher sparking limits than in the electrostatic case can provide relatively strong focusing in the two orthogonal transverse phase space planes.

To investigate the application of this type of focusing to the ISAC linac, the PARMION[1)] code was modified to include an RFQ element for which the particle equations of motion are solved using the fourth order Runge-Kutta method. With the modified PARMION, the phase dependent focal properties of RFQ lenses could be calculated. Fig. 3 shows the focusing strength versus the angle $\omega t + \psi$ of the RF voltage when the ion enters the RFQ. The focussing is strongest for the 0° phase ions and decreases as the phase is increased or decreased. It is anticipated that the phase acceptance of the first interdigital stage of ISAC will be approximately 30°, and we see from the figure that the phase dependence of the focusing will be small over such an interval provided the interval is centered near 0°.

In order to do a preliminary assessment of the feasibility of using RFQs as focusing elements in the 50 MHz section of ISAC, a series of analytic calculations similar to those described in the previous section were carried out. The acceleration tank configuration was assumed

*Since the beam envelope is equal to $\sqrt{\beta\epsilon}$ where ϵ is the beam's emittance, for a fixed emittance, minimizing β will minimize the beam envelope.

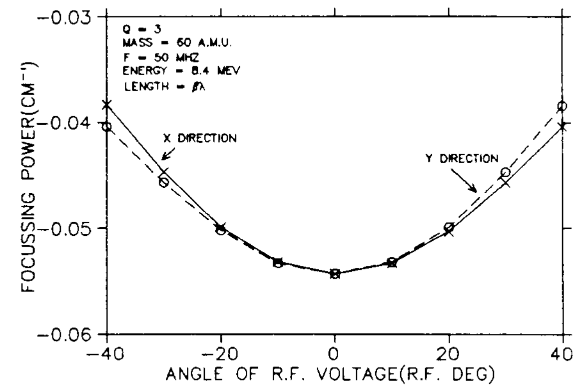

Fig. 3. RFQ focussing power versus angle of r.f. voltage

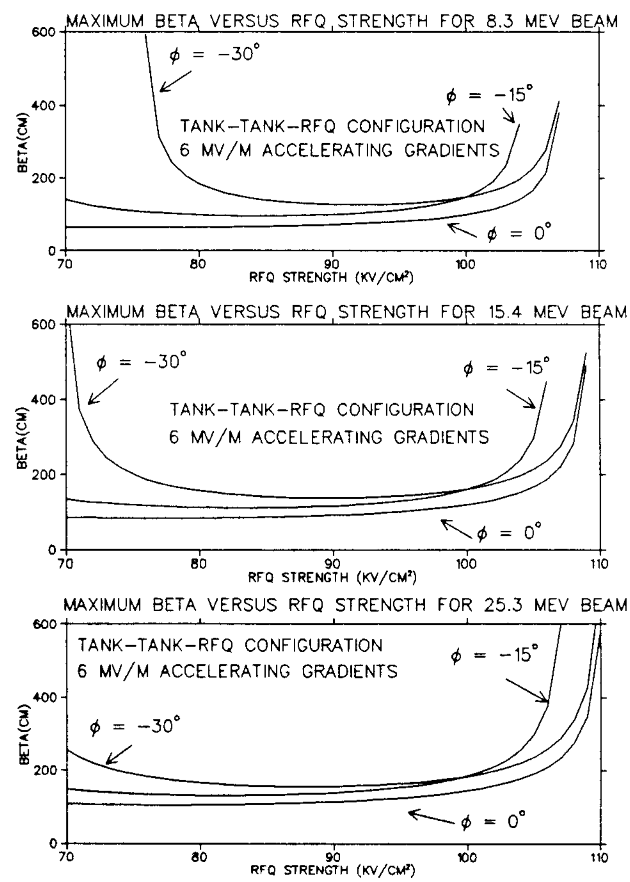

Fig. 4. Maximum values of β versus RFQ strength for various beam energies.

Focussing Periodicity	RFQ Strength Const. kV/cm^2	Accelerating Field MV/m	Output Emittance cm·mrad	Beam Rmax cm	Linac Length cm	No. Tanks
TK-TK-RFQ	93.8	6.0	2.4π	1	310	6

Table 2 Summary of RFQ focussing case studied for the 50 MHZ linac section

to be the same as in case 4 of the solenoid focusing study described earlier. Using the same thin lens approximations for the defocusing at the acceleration gaps and the same periodic transport system assumptions but with an RFQ replacing the solenoid, β_{max} was calculated and is shown in Fig. 4 as a function of the RFQ strength constant K. Plots in Fig. 4 for particle phases of $-30°$, $-15°$, and $0°$ relative to the rf in the accelerating structure show that within this phase band β_{max} has a very broad minimum centered approximately about $K = 90$ kV/cm^2.

Calculations with the RFQ modified version of PARMION were carried out to verify that it would be possible to build a 50 MHz linac section using RFQ focusing elements with $K \approx 90$ kV/cm^2 as predicted above. Table 2 summarizes the results of these computations. The beam envelopes and the emittances obtained are similar to those obtained with the optimized solenoid example shown as case 4 in Table 1.

In order to determine the feasibility of constructing an RFQ lens with $K \approx 90$ kV/cm^2 and $a \approx 1$cm, we must estimate the surface electric fields on the electrodes. Assuming hyperbolic electrodes, the profiles of the cross-sections will satisfy equations of the form $a^2 = x^2 - y^2$. Using this result along with the electric field intensity derived from equation 2, we find that the peak surface field E_s is given by

$$E_s = 2K\sqrt{2x_{max}^2 - a^2} \tag{4}$$

where x_{max} is the maximum extent of the electrodes in the x direction. Assuming $x_{max} \approx 2a$ gives $E_s \approx 480$ kV/cm for the case under consideration †. This is well below the peak fields of over 1000 kV/cm achieved at ANL in a 64 MHz test RFQ structure.[5)]

4. DISCUSSION

Taking focusing power per unit length as a figure of merit, a plot of this against energy, in the energy range covered by 50 MHz linac section, is shown in Fig. 5. This illustrates the potential advantage of RFQ focusing over solenoid focusing at the lower energies. At higher energies the two focusing approaches are roughly equivalent.

†A second estimate of the surface fields may be obtained by considering the peak surface electric field on the surface of two circular cylinders of radius a with sufficient spacing to approximate the geometry of the RFQ vanes. Using this approximation, a calculation by one of the authors indicates that $E_s \approx 2.7V_p/a$ which is about 240 kV/cm in our case.

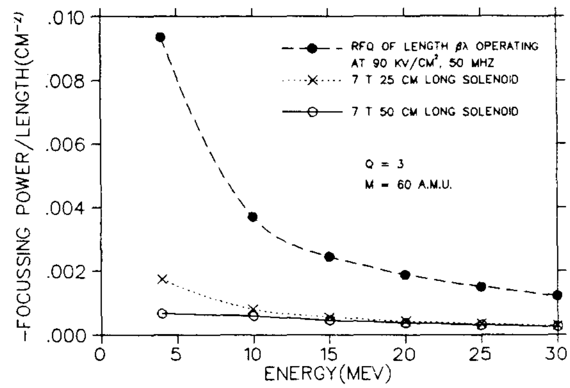

Fig. 5. Comparison of figures of merit for RFQ and solenoid

Using either solenoids with optimized lengths, or RFQ elements for focusing, would permit accelerating gradients of up to 6 MV/m in the 50 MHz section of the present conceptual design for ISAC. This reduces the number of tanks in this section to 6 from 12 in the previous design, and reduces the overall length of the section by up to 2.5 m. The penalty paid for this improvement is an approximate doubling of the output beam emittance.

5. REFERENCES

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