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STATUS OF THE ISAC POST-ACCELERATOR DESIGN STUDY

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Preparation of a proposal for the installation of a radioactive beam ISOL facility (ISAC) with a post-accelerator is in progress at TRIUMF. The accelerator specifications call for acceleration of ions with charge to mass ratios greater than 1/60, to energies up to 1.5 MeV/u, in one beamline, and up to 10 MeV/u in a second beamline. The current accelerator concept is a three stage linac with strippers to increase the ion q/A, between stages. The first stage is a RFQ, while the second and third stages are a series of independently driven superconducting quarter-wave resonators, similar to those used for the ATLAS accelerator at ANL, and the post tandem booster at JAERI. Preliminary results of beam dynamics calculations for this accelerator configuration are given.

KEY WORD: Radioactive beams, TRIUMF, ISOL, post-accelerators, RFQ

1 INTRODUCTION

A radioactive beam ISOL facility with a post accelerator was first proposed at TRIUMF in 1985.[1] The specifications dictated primarily by the astrophysics interests, required a maximum energy of only 1 MeV/u for ion beams with A $\leq$ 60. Although the project was not funded at that time, some accelerator studies were continued, in particular to investigate suitability of superconducting accelerator structures for acceleration of the very low charge to mass ratio particles in this application.[2] Now a new proposal is being prepared for submission to our funding agency in early 1994. In support of this new proposal we are in the process of carrying out some post-accelerator design studies, and present here an interim report on the status of our investigations. The results presented are preliminary, and subject to change as the study proceeds. The beam specifications for the present proposal, differing in some respects from those of 1985, and are summarized in Table 1.

The main changes from the earlier proposal is the inclusion of two beamlines and an order of magnitude increase in the maximum output energy specification. To account for a worst case beam emittance (from an ECR source), the input beam emittance specification here is double our 1985 value.

To give some historical perspective, a block diagram of the post-accelerator proposed in 1985, is shown in Figure 1. It consisted of a 9 metre long RFQ to capture, bunch and accelerate the 60 keV singly charged ISOL beam to 60 keV/u. This is followed by a stripper to increase the ion q/A to $\geq$ 1/20, before further acceleration in eight short tanks of an

TABLE 1: ISAC Post — Accelerator Basic Specifications

Input Beam:	
Energy	60 keV
Ion Mass	$A \leq 60$
Ion Charge	1^+, or 1^-
Beam Current	$<1 \mu A$ dc
Beam Emittance (normalized)	1π mm mr
Accelerated Beam:	
Output Energy: (beamline 1)	$.2\ \mathrm{MeV/u} \leq E \leq 1.5\ \mathrm{MeV/u}$
(beamline 2)	$\sim 1.5\ \mathrm{MeV/u} \leq E \leq 10\ \mathrm{MeV/u}$
$\Delta DE/E$	10^{-3}
Duty Factor	100 %

inter-digital drift-tube linac, similar to those used for the RILAC heavy ion linac.[3] but without the variable frequency capability. As a consequence of the low ion velocities and low q/A, a low operating frequency especially for the RFQ is dictated. In this case 23 MHz was chosen as the operating frequency for both the RFQ and DTL. To preserve as many particles as possible of a desired ion species produced in the ISOL, cw rather than pulsed operation was specified. This then leads to a major drawback of this accelerator concept, namely the large cw rf power requirement for the DTL, which for even the modest output energy of 1 MeV/u, was estimated to be about 1 MW. Overall length of the accelerator was 24 metres, with an additional 9 metre drift required for debunching to reduce energy spread.

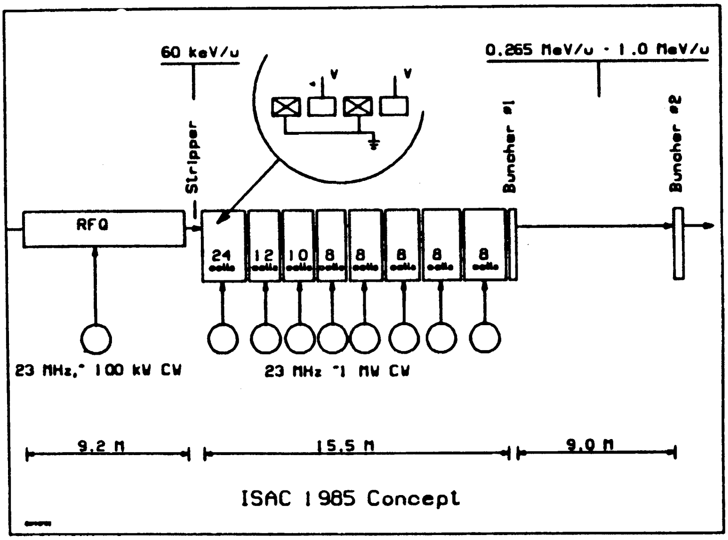

FIGURE 1: The 1985 ISAC post-accelerator concept.

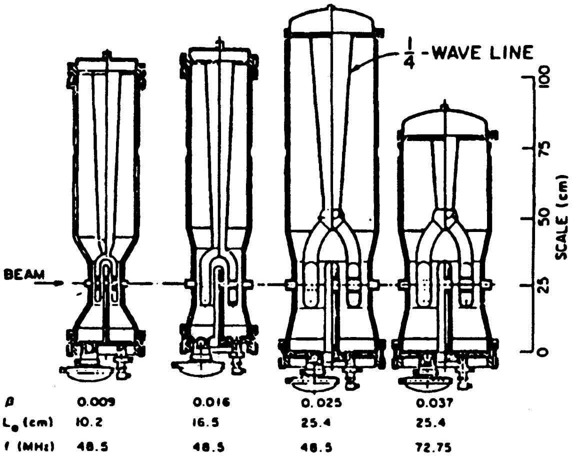

FIGURE 2: Cross sections of the 4 gap superconducting resonators for the ATLAS injector linac.

2 CURRENT CONCEPT

2.1 General Description

In the mid 1980's Shepard *et al.* at ANL reported on development work of low frequency, low β superconducting accelerator structures, for a proposed positive ion injector for the ATLAS accelerator.[4] Subsequent studies at TRIUMF showed that the ATLAS linac concept, which was developed for ion beams with a charge to mass ratios greater than $\sim$.08, could be extended to a linear accelerator capable of accelerating ions with even lower charge to mass ratios, as required for ISAC. In our latest conceptual design therefore we base the first section of post RFQ accelerator on the ATLAS structures illustrated in Figure 2. These are basically quarter wave resonators, capacitvely loaded with a bifurcated drift-tube and counter drift-tube forming four accelerating gaps. The structure, made of niobium and niobium clad copper, is cooled with pool boiling liquid helium in the centre conductor. Three models for mean particle velocities of β = .009, .016, and .025 were developed at ANL for operation at 48.5 MHz. A fourth model, for β = .037, was designed to operate at 72.75 MHz. For the ISAC conceptual design, nominal operating frequencies of 50 MHz and 75 MHz have been chosen for acceleration from 60 keV/u to 1.5 MeV/u, $(0.011 \leq \beta \leq 0.057)$. For acceleration to higher energies we base our conceptual design on the JAERI superconducting post tandem accelerator structure,[5] illustrated in Figure 3.

This is also a capacitively loaded quarter wave resonator, but with only two accelerating gaps. Its operating frequency is 129.8 MHz, and is designed for a particle velocity, β = 0.1. For ISAC the nominal operating frequency would be 125 MHz with a design particle velocity range, $.057 \leq \beta \leq .146$, corresponding to the energy range 1.5 MeV/u to 10 MeV/u.

Figure 4 is a block diagram of the current (October 1993) concept of ISAC post accelerator, incorporating the superconducting structures discussed above. It is a three stage

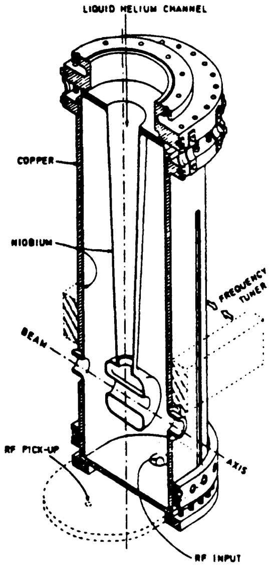

FIGURE 3: Two gap superconducting quarter- wave resonator used for the JAERI post-tandem booster.

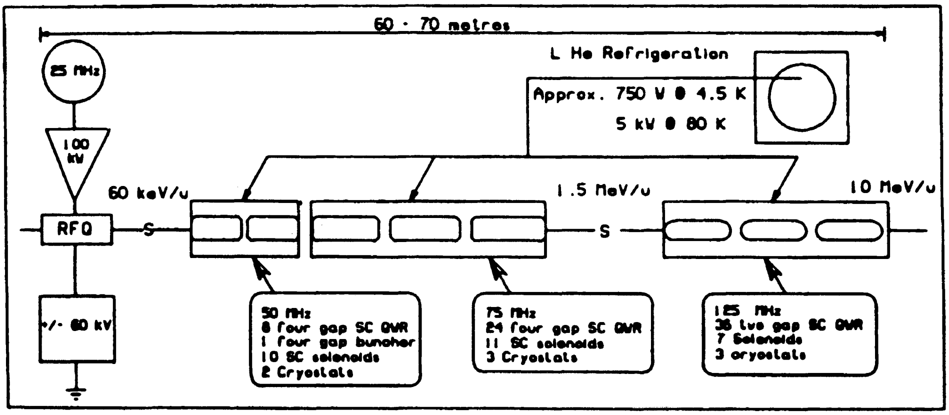

FIGURE 4: The ISAC post accelerator concept, October 1993

accelerator with strippers between stages to increase the ion q/A. The first stage is a RFQ to capture, bunch, and accelerate the singly charged dc beam from the ISOL to 60 keV/u. Because the beam delivered from the ISOL is at a fixed energy of 60 keV irrespective of ion mass, the RFQ is mounted on a high voltage deck and operated with a dc bias so the RFQ input energy is at the design 1 keV/u. The second stage accelerates ions with $q/A \geq 1/20$ to 1.5 MeV/u, where the beam is either deflected to a nuclear astrophysics experimental area, or passed through a second stripper before being accelerated to 10 MeV/u in stage 3.

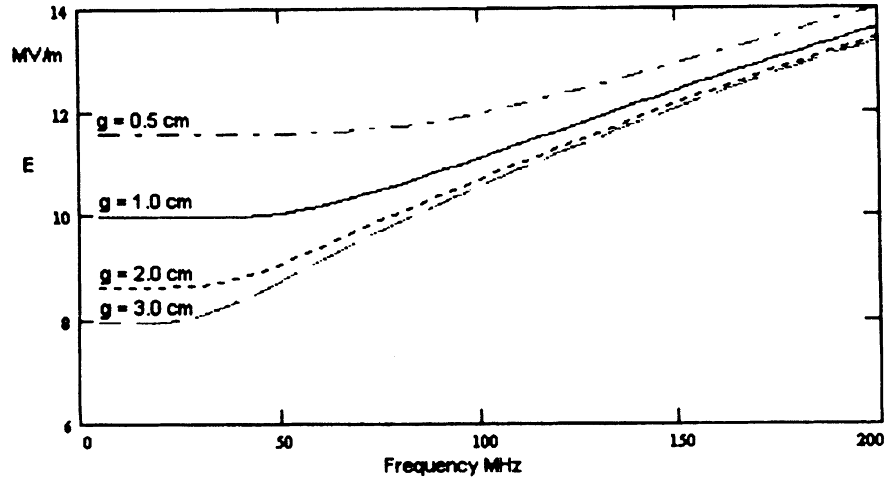

FIGURE 5: Kilpatrick sparking limit for various gap sizes.

Based on experience at the ANL ATLAS accelerator and the JAERI booster, the static heat load at 4.5 K would be about 250 watts for both superconducting stages. With rf drive on, dissipation in each resonator is about 4 watts, adding another 270 watts to the load. Allowing about 230 watts reserve capacity means that a refrigerator providing at least 750 watts of refrigeration at 4.5 K would be required.

2.2 *RFQ*

Design parameters for the RFQ in our current conceptual design were determined with the aid of the Los Alamos codes RFQUIK, and PARMTEQ. A relatively high vane voltage must be used to achieve adequate transverse focusing and an acceptance compatible with the specified input beam emittance. We use a design value for the maximum vane surface field of 18 MV/m, about 1.8 times the Kilpatrick sparking criterion corresponding to a 1 cm gap, as given in the plot in Figure 5.[6] Table 2 summarizes the RFQ parameters.

Phase space plots of the RFQ output beam as calculated with PARMTEQ for an input beam emittance of 0.5 π mm mrad are shown in Figure 6. The calculated transmission is 97%. No attempt was made in this design to minimize the energy spread of the output beam which is in this case about ± 2%.

2.3 *First Stripper and Matching Section*

Following the RFQ the beam is passed through a stripper before further acceleration. At the relatively low RFQ output energy, the required stripper thickness to reach an equilibrium charge state distribution is between 0.1 μg/cm^2 and 0.5 μg/cm^2. This is about an order of magnitude thinner than can be realized with a foil, so a gas stripper is necessary here. The stripper is accommodated in a 1 metre a space provided in the matching section between

TABLE 2: RFQ Parameters

Ion q/A	$\geq 1/60$
Input Energy	1 keV/u
Output Energy	60 keV/u
Operating Frequency	25 MHz
Vane Voltage	96 kV
E_s	18 MV/m ($1.8 \times E_{\mathrm{kil}}$)
RF Power	~100 kW
Beam Aperture (min)	0.5 cm (radius)
Ave. Aperture (r_0)	.75 cm
Focusing Parameter (B)	4.72
Synchronous Phase	– 90° (initial)
	– 30° (final)
No. Cells	289
Length	6.92 m

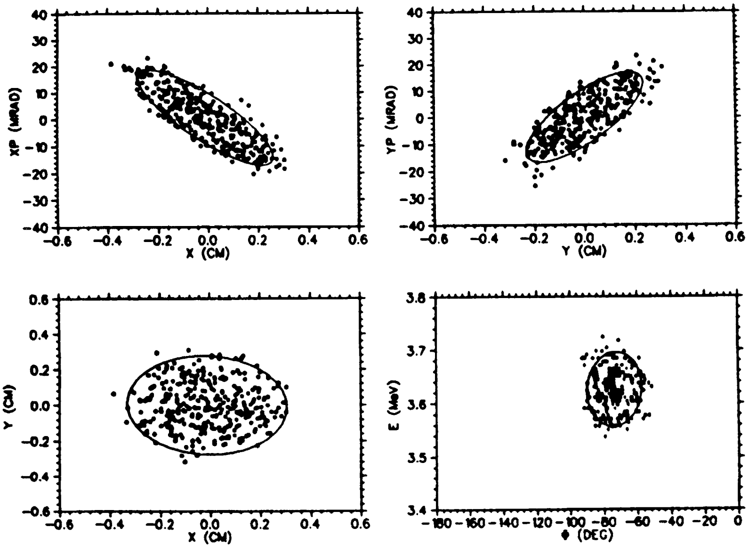

FIGURE 6: Phase space and beam size scatter plots for beam at output of the RFQ

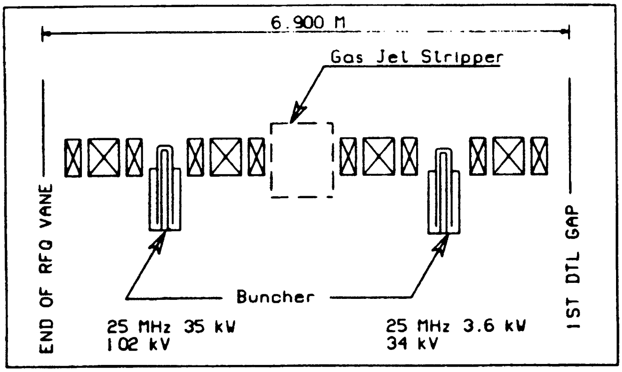

FIGURE 7: ISAC RFQ — DTL beam matching section

the RFQ and DTL as illustrated in Figure 7. Because of the energy spread and low energy of the RFQ beam, debunching distances are short. Therefore, to maintain the bunch structure, provide space for the stripper, and match the beam to the DTL, a rather complex beam transport line including four quadrupole triplets and two rebunchers, is required. Even so this matching section does not meet all of the design objectives, in particular, the 1 π mm mrad transverse acceptance. In this case the matching section will accommodate a beam with half that emittance. Phase space plots of the beam at the stripper and DTL entrance are shown in Figure 8. There are two stripper options, a gas canal or a gas jet. With the assumed beam emittance at the RFQ input the beam transverse dimension at the stripper location would require rather large aperture gas canal and probably impractical differential pumping requirements. For this reason then, a gas jet is envisioned as the first stripper in the present conceptual design.

2.4 *Superconducting Drift Tube Linac*

2.4.1 Elementary Design Considerations The basic configuration of the superconducting drift tube linac is a series of accelerating gaps separated periodically by superconducting solenoids for transverse focusing of the beam. To gain some insight into the required focal strength and focusing periodicity, two simple calculations were carried out assuming, for the longitudinal motion, an impulse approximation for the energy gain in a multigap module with a drift space between modules, and for the transverse motion, a thin lens approximation for rf defocusing in the multigap modules together with a drift space and solenoid focusing.

For longitudinal motion studies the impulse approximation was applied to a linac consisting of eight independently phased 4 gap accelerator modules operating at 50 MHz, with an accelerating gradient of 5 MV/m, and a synchronous phase of −30°. Such a linac could accelerate ions with $q/A = 1/20$ from 60 keV/u to 380 keV/u. To determine the longitudinal acceptance of this linac we flood the input with a large longitudinal emittance

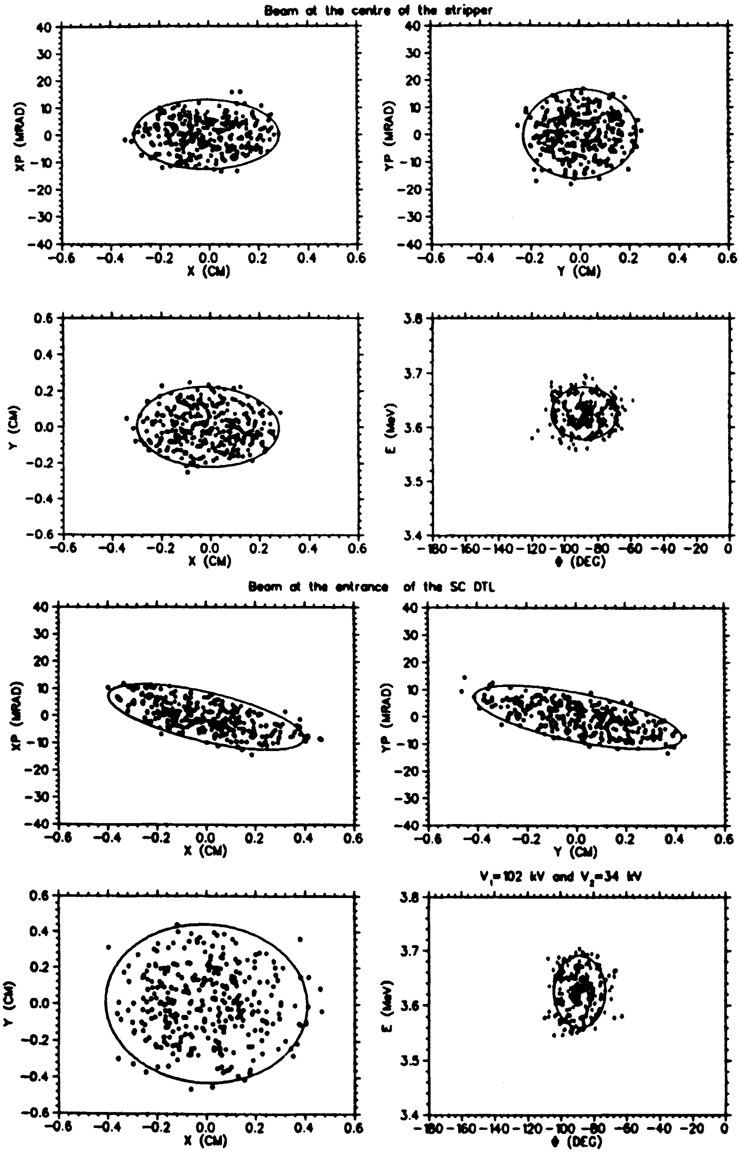

FIGURE 8: Phase space plots and beam size scatter plots for beam at stripper and at DTL entrance.

beam and plot in $E - \phi$ space the coordinates of the particles successfully accelerated. Three plots are shown in Figure 9, for cases in which the inter-module drift distances are 20 cm, 50 cm, and 80 cm. An attempt has been made in each of the cases to fit an ellipse that approximates the RFQ longitudinal emittance into the acceptance region. As can be seen this becomes increasingly difficult as the inter-module distances are increased, and it

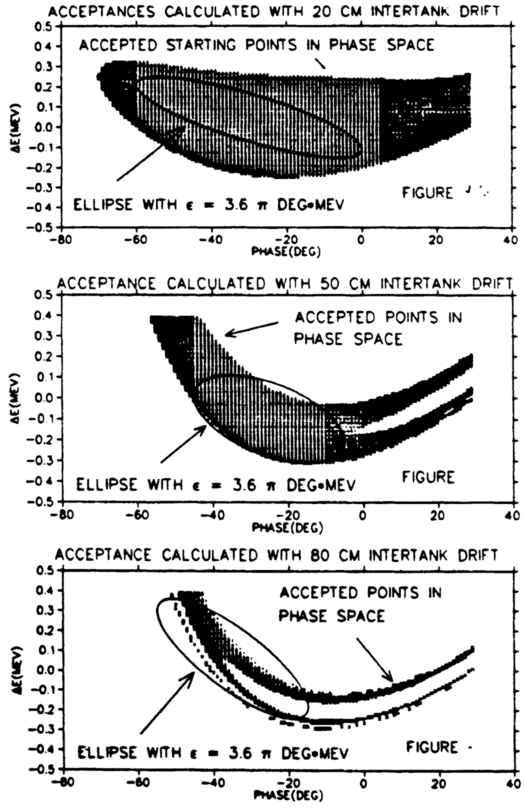

FIGURE 9: Longitudinal acceptances in 50 MHz DTL for three inter-module spacings.

appears that we should avoid drift distances greater than about 50 cm. Since we require a space of about 10 cm between the accelerator module and solenoid, this means that the maximum solenoid length at this energy should be no greater than 30 cm.

For the transverse motion investigation we assume a magnetic induction of 6.5 T in the solenoid, and calculate, as a function of solenoid length, the maximum beta function (the beam envelope is given by $\sqrt{(\beta \cdot \varepsilon)}$) for a periodic structure in which one cell consists of an accelerator module, a drift space, and a solenoid. The high transverse acceptance objective, along with the limitation on solenoid length noted above, places a constraint on the choice of accelerating gradient. In general, as the accelerating gradient is decreased, the transverse acceptance increases, and the length of solenoid required to produce adequate focusing decreases. Beta function calculations were done for two cases, one assuming an accelerating gradient of 5 MV/m in a 4 gap accelerator module, and the second assuming a gradient of 2 MV/m in a 2 gap module. The results for three gap crossing phases, are plotted in Figure 10 as a function of solenoid length, (assuming a drift distance of 11 cm between accelerator module and the solenoid). It is apparent from these plots that for 5 MV/m accelerating gradient, 40 cm solenoids, or inter-module drift spaces of 62 cm,

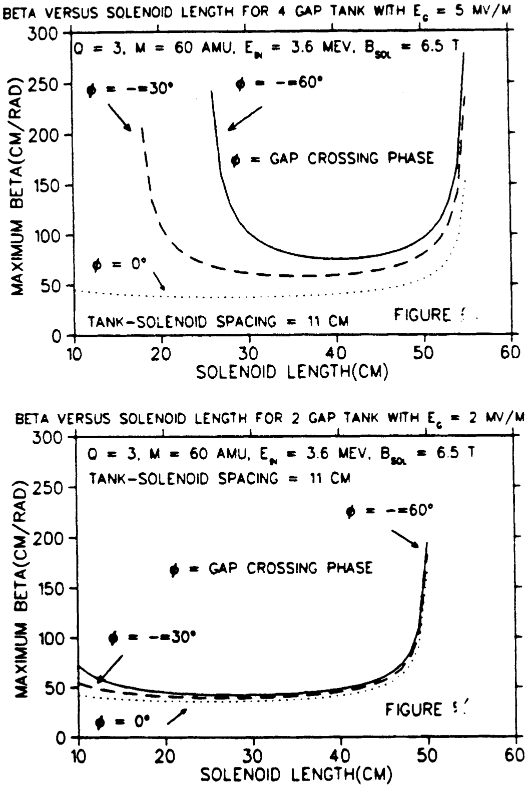

FIGURE 10: β-max as a function of solenoid length for a 4 gap, 5 MV/m, and a 2 gap, 2 MV/m, DTL configuration.

$(40 + 2 \cdot 11)$ would be necessary to minimize beta. With a 2 MV/m accelerating gradient, on the other hand, a 20 cm solenoid (42 cm drift space) is adequate. The beta functions in the low gradient case are smaller, and have much less phase dependence.

Although these results have been obtained for the 50 MHz section of the ISAC accelerator, the conclusions are generally true for the higher energy sections as well. At all stages we must be careful not to use too high an accelerating gradient, if large transverse and longitudinal acceptances are to be realized.

2.4.2 Design Description As illustrated in Figure 4, the superconducting DTL following the RFQ is divided into three sections with operating frequencies of 50 MHz, 75 MHz, and 125 MHz respectively. In view of the discussion above, the first section begins with short 2 gap quarter wave resonators (QWR) with a relatively low accelerating gradient of 2 MV/m initially, but rising to 5 MV/m at the sixth 2 gap QWR. A second part of the 50 MHz section employs seven 4 gap QWRs and accelerating gradients ranging from 3 to 5 MV/m, to accelerate the beam to 405 keV/u. At this point a structure frequency change is

TABLE 3: ISAC Post Accelerator

2 DTL Sections 1 & 2: Ion $q/A \geq 3/60$	Section 1 A	Section 1 B	Section 2
Structure	2 gap QWR	4 gap QWR	4 gap QWR
Frequency MHz	50	50	75
Number of Resonators	6	7	24
E_{acc} MV/m	2–5	3–5	3–5
ϕ_s	-30°	-30°	-30°
E_{out} MeV/u	0.118	0.405	1.50
β_{out}	0.0156	0.0292	0.0565
Focusing	Superconducting Solenoid		
Solenoid Length	17.5 cm – 55 cm		45 cm – 105 cm
B_{sol}	6.5 T		6.5 T
Focusing Periodicity	Res–Sol–Res		

made and the beam is then accelerated in the second DTL section, to 1.5 MeV/u in twenty four 4 gap QWRs Solenoid focusing is used between each QWR. The main parameters of the first and second DTL sections are summarized in Table 3.

On reaching 1.5 MeV/u the beam is either sent to the astrophysics experimental area, or passed through a foil stripper to raise the ion $q/A \geq 18/60$, before being accelerated to 10 MeV/u in the thirty six quarter wave resonators of the 125 MHz DTL section. The main parameters of this section are summarized in Table 4.

TABLE 4: ISAC Post Accelerator

DTL Section 3: Ion q/A $\geq$ 18/60	
Structure	2 gap QWR
Frequency MHz	125
E_{acc} MV/m	3–5
ϕ_s	-30°
β_{out}	0.145
E_{out} MeV/u	10
Focusing	Superconducting Solenoid
Solenoid Length	13 cm – 23 cm
B_{sol}	6.5 T
Periodicity	6 Res – Sol – 6 Res

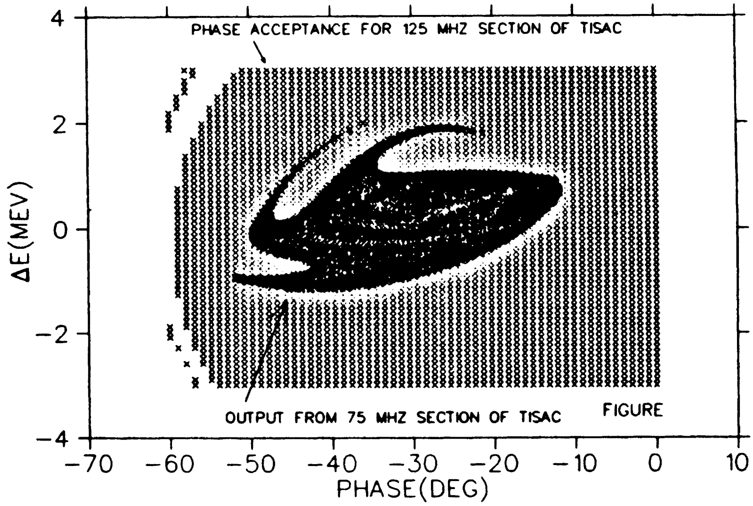

FIGURE 11: Acceptance in longitudinal phase space of the 125 MHz linac section.

Only preliminary beam dynamics calculations have so far been done. Because design of the matching section between the second and third DTL sections has not yet been done, calculations for the third section assume an input beam transverse emittance of 1 π mm mrad, and a longitudinal emittance as calculated at the output of the second DTL section, and shown in Figure 11. The calculated phase space plots at the output of the linac are shown in Figure 12.

Both the longitudinal and transverse emittances of the accelerated beam are large. The longitudinal emittance in this case is approximately 530 keV-ns, or about an order of magnitude larger than the that currently specified for ISL. In part this large longitudinal emittance arises from the energy spread introduced in the RFQ as a consequence of designing it to accommodate the large transverse emittance of the input beam.

3 RFQ PROTOTYPE

Design experience for low frequency RFQs is much more limited than for the higher frequency versions appropriate for acceleration of protons or fully stripped light ions. Even for these, few have been designed for cw operation. To gain engineering design and fabrication experience therefore, construction of a prototype RFQ is planned. To keep the project a reasonable size, and match the rf power requirement to an available rf power source, the RFQ will be limited to about two metres in length. Most of the design parameters for the prototype will be the same as for the full size ISAC RFQ. The main difference is in the ion q/A specification, which for the prototype RFQ will be $\geq 1/20$. Tentative parameters for the RFQ are summarized in Table 5.

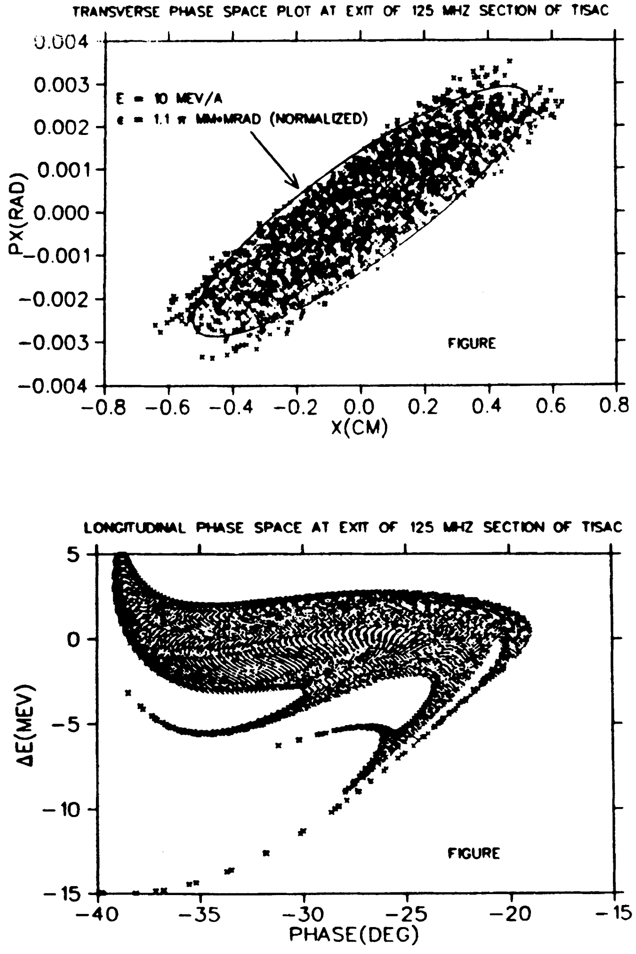

FIGURE 12: Transverse and longitudinal phase space plots for beam at exit of the 125 MHz section.

By using the conventional RFQ design approach, with adiabatic bunching in a gentle buncher section, one gets a RFQ design that is slightly more than 3 metres long. More than half of this length is accounted for by the gentle buncher. To keep within a 2 metre maximum length objective, and still achieve the 60 keV/u output energy, we propose to replace the gentle buncher by a simple double drift buncher incorporated into the vane modulation. Because space charge forces are unimportant, beam capture of over 80% should be achievable in this case. An overall reduction in RFQ design length of about 1 metre is possible with this change. A similar design was employed by Schempp *et al.* in the Cryring injector.[7]

TABLE 5: RFQ Prototype Parameters

Ion q/A	1/20
Input Energy	2 keV/u
Output Energy	60 keV/u
Operating Frequency	25 MHz
Vane Voltage	81 kV
RF Power	< 30 kW
Modulation Factor (m)	1.95
Focusing Factor (B)	11.07
Beam Aperture (min)	0.5 cm
Ave. Aperture (r0)	0.75 cm
Bunching	Double Drift Buncher
No. Cells	59
Length	2.05 cm

In addition to testing of the RFQ at full rf power, we also intend to test it with radioactive beams from the existing TISOL facility at TRIUMF.[8] This will require operation of the RFQ with a dc bias adjustable between ± 20 kV.

4 DISCUSSION

The objective in this study has been to develop a credible, self consistent post-accelerator concept for the ISAC proposal. Although the calculations are still incomplete, it is clear that the RFQ — superconducting DTL concept can probably satisfy the ISAC specifications. Details concerning energy variability, and reduction of energy spread by debunching remain to be investigated. Some problems have however been revealed by this study. The major one is related to the large transverse emittance specification for the input beam. As noted above, because of beam dynamic limitations in the RFQ — DTL matching section, it has not been possible to accommodate the large emittance through the whole accelerator. Moreover the large emittance is at least in part the cause of the large energy spread in the RFQ output. This in turn then leads to undesirable design choices and compromises in the first part of the drift tube linac. In the next design iteration a reduction in both the input beam emittance specification and the linac acceptance should be tried. In addition the RFQ design needs reexamination to see if the output energy spread can be reduced.

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