DESIGN OPTIMIZATION OF THE PROPOSED ISAC-2 PROJECT AT TRIUMF

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Abstract

A radioactive ion beam facility, ISAC, is presently under construction at TRIUMF. The post-accelerator takes ions of $A/q \leq 30$ from 2 keV/u to energies up to 1.5 MeV/u. For the next five year plan, it is intended to increase the final energy above the Coulomb barrier (roughly 6.5 MeV/u) and broaden the mass range up to roughly A=150. The ISAC-2 proposal utilizes the existing RFQ, and a new IH drift tube linac to reach a new stripping energy of 0.4 MeV/u. A post-stripper superconducting linac will accelerate ions with $3 \leq A/q \leq 7$ to 6.5 MeV/u for the heaviest ions and to more than twice this value for the lightest ions. This paper documents the optimization of the ISAC-2 linac design.

1 INTRODUCTION

The ISAC facility now under construction at TRIUMF[1] will provide exotic ions of mass $A \leq 30$ up to energies of 1.5 MeV/u. The post-accelerator (dashed area in Fig. 2) consists of a 35 MHz RFQ to increase the energy of ions with $A/q \leq 30$ from 2 keV/u to the 150 keV/u stripping energy and a post-stripper 105 MHz drift-tube linac (DTL) to accelerate ions with $3 \leq A/q \leq 6$ to a final energy fully variable between 0.15 and 1.5 MeV/u. All linac components operate cw to maintain the intensity of the ions.

For the next five year funding segment beginning April 2000 it is proposed to upgrade the present ISAC facility. The proposed expansion, ISAC-2, would extend the accepted mass range up to 150 and the final energy to above the Coulomb barrier ($E \geq 6.5$ MeV/u) making TRIUMF a unique world class center for exotic beam investigations.

2 OVERVIEW OF SCHEME

The ISAC-2 proposal utilizes the existing ISAC-1 RFQ for low energy acceleration and therefore requires that the ion charge from the source obeys $A/q \leq 30$. Recent advances in charge state booster (CSB) development[3] make this choice feasible. A CSB will be added after the mass-separator to increase the charge state of ions with $A > 30$.

Assuming a single stripping stage the total voltage required to reach 6.5 MeV/u from 2 keV/u is given by

$$V_{tot} = \frac{A}{q_i}(E_s - 0.002) + \frac{A}{q_s}(6.5 - E_s)$$

where q_i is the initial charge injected into the RFQ, q_s is the charge state after stripping and E_s is the stripping energy. The total voltage required for accelerating several different ions to 6.5 MeV/u as a function of stripping energy is given in Fig. 1. The optimum energy for stripping is ~400 keV/u with stripping efficiencies varying from 50% for the lightest ions to 15% for $A = 150$.

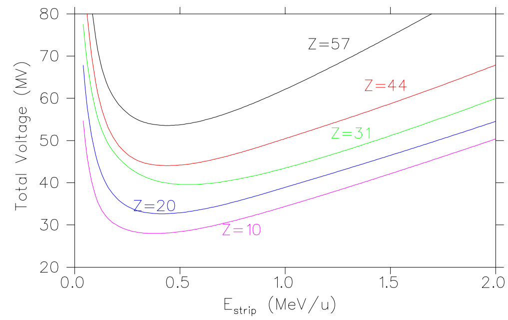

Figure 1: The total voltage required to accelerate various ions from 0.15 to 6.5 MeV/u as a function of stripping energy.

A room-temperature DTL operating in cw mode will be used to accelerate ions of $A/q \leq 30$ from the RFQ from $0.15 - 0.4$ MeV/u. The beam then is stripped and the ion charge selected in a new MEBT-2 that bends the beam through 90° to a line parallel to the ISAC-1 DTL line. Ions of mass to charge ratio $3 \leq A/q \leq 7$ are matched into a superconducting DTL on this line and accelerated to at least 6.5 MeV/u and then transported to the experimental stations. A summary of the linac specifications is shown in Table 1. A schematic of the proposed ISAC-2 linear accelerator complex is shown in Fig. 2.

Table 1: Summary of ISAC-2 linac specifications.

Device	E_{in} (MeV/u)	E_{out} (MeV/u)	A/q	ΔV_{max} (MV)
CSB	–	0.002	≤ 30	0.06
RFQ1	0.002	0.15	≤ 30	4.44
IH-DTL2	0.150	0.40	≤ 30	7.50
strip				
SC-DTL	0.40	6.5	$3 \rightarrow 7$	42.7

3 CHARGE STATE BOOSTER

The CSB would take the singly charged radioactive beam from the mass-separator and boost the charge state to be compatible with $A/q \leq 30$ for the RFQ. Both ECR and EBIS sources are being considered. An attractive option is to develop a charge state booster which would give $A/q \leq 7$. This would obviate the need for any stripping and the inherent loss of intensity. Recent results suggest that efficiencies of 2% are possible in this latter mode and from 10-20% in the low-q mode[3]. A budget amount of **2 M$** has been allocated for this project.

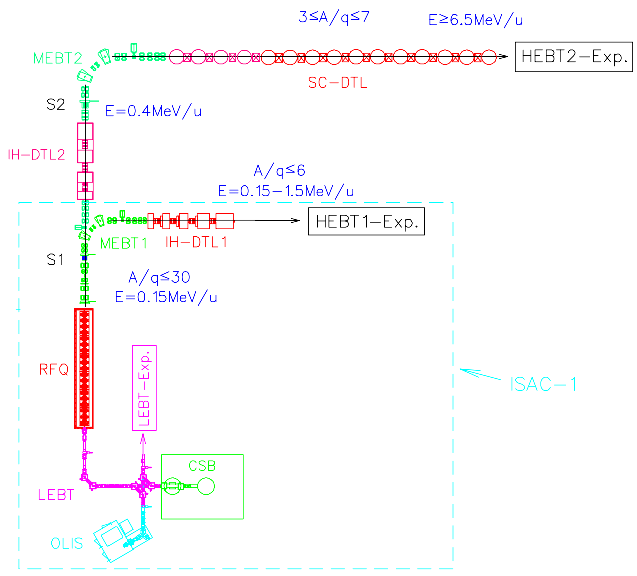

Figure 2: The ISAC-2 linear accelerator complex.

4 PRE-STRIPPER LINAC

The IH linac structure operates at very high shunt impedance values making cw operation at room temperature possible. In ISAC-2 the application is for a fixed final velocity, so long tanks each containing many drift tubes are used to achieve the highest acceleration efficiency. Magnetic quadrupoles are installed both in tanks and between tanks to provide periodic transverse focusing. The small longitudinal and transverse emittances from the RFQ ($\epsilon_z = 0.3\pi$ keV/u ns and $\beta\epsilon_{x,y} = 0.1\pi$mm mrad) allow a frequency of 70 MHz, double that of the RFQ frequency, reducing the size of the DTL tanks and improving the shunt impedance. The shunt impedance for the structure is estimated to be ~ 300 MΩ/m. In a cw DTL the dissipated power is a more limiting factor than the peak surface field in establishing the operating gradient. A power dissipation of 20 kW/m can be safely cooled. The relation $P_l = (\overline{E_oT})^2/Z$, where P_l is the power per unit length and Z is the effective shunt impedance then gives an average effective gradient $\overline{E_oT}$ of 2.4 MV/m.

A schematic diagram of the linac is shown in Fig. 3. In order to reduce the demands on the rf amplifier the DTL is divided into two tanks each with one quadrupole triplet inside roughly midway down the tank and one quadrupole triplet between tanks. Each triplet is ~ 65 cm long with gradients up to 60 T/m. A diagnostic box will also be added to the intertank region. The total length of the linac is 5.8 m. The beam dynamics utilizes the method developed at GSI[2] where a short $-60°$ section is used after each magnet system for rebunching followed by an accelerating section at a synchronous phase of $0°$. A summary of the tank specifications is given in Table 2. The acceptance of the linac is $\epsilon_z = 3.6\pi$ keV/u ns and $\beta\epsilon_{x,y} = 0.8\pi$mm mrad. With the expected beams from the RFQ the emittance increase during acceleration is calculated to be less than 5%.

Table 2: Specifications for the pre-stripper IH-DTL.

Parameter	Tank 1	Tank 2
Energy Range	150-250 keV/u	250-400 keV/u
A/q	30	30
$V_{\rm eff}$	3.0 MV	4.5 MV
No. of cells	13, 21	21, 20
E_g (MV/m)	2.7	2.7
Length (m)	2.2	3.0
Power (kW)	30	45

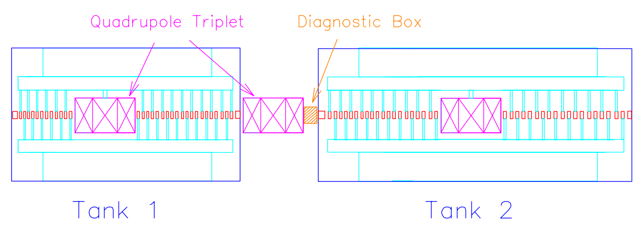

Figure 3: The pre-stripper IH-linac for ISAC-2.

5 POST-STRIPPER LINAC

Recent improvements in accelerating gradient and simplification of fabrication procedures[4] plus flexible operation and high beam quality make a superconducting linac a favourable choice for the ISAC-2 post-stripper accelerator. Superconducting heavy ion linacs are composed of several independently fed cavities arranged in a common cryostat with focusing magnets at periodic intervals down the length. In the ISAC-2 linac we choose a geometry having four resonators in a cylindrical vertically mounted cryostat with room-temperature quadrupoles between cryostats. A two-gap quarter wave structure was chosen for its high velocity acceptance and inherent mechanical stability. The former is useful to efficiently accelerate the wide range of ions with a minimum of cavity types and the latter is essential to produce high accelerating gradients.

For optimization the acceleration efficiency is calculated for both two- and three-gap cavities each using two or three different β regimes. Efficiencies over the whole A/q range are calculated assuming a fixed acceleration gradient. The conclusion is that linac performance even with a two-β, two-gap solution is remarkably good, with an integrated time constant of better than 82% over the whole mass range compared to a theoretical maximum time constant of 90%. The acceleration efficiency for $A/q = 7$ and $A/q = 3$ for two-gap cavities with two β sections (SC-DTL1 and SC-DTL2) corresponding to β_o values of 4.8% and 9.6% and a voltage gain ratio in respective sections of 1:3 are shown in Fig. 4. To reach $V_{\rm eff} = 42.7$ MV with an integrated time constant of 82% and an average synchronous phase of $-25°$ requires a voltage of 57.5 MV with roughly 14.4 MV and 43.1 MV from the low- and high-β sections respectively.

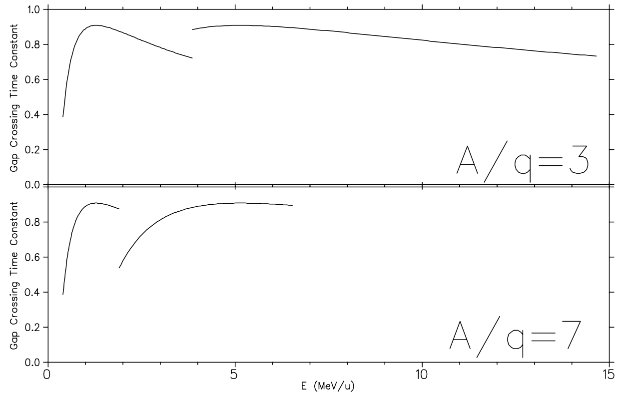

Figure 4: The acceleration efficiency for $A/q = 7$ and $A/q = 3$ for two-gap cavities with low- and high-β sections corresponding to β_o values of 4.8% and 9.6%.

Cavity Dimensions Once the design β_o is established the cavity dimensions are set by the rf frequency choice. The beam is bunched at 11.7 MHz and therefore many harmonics are available. A lower frequency increases the cavity length, hence reduces the required number of cavities but requires a longer inner conductor where mechanical oscillations may be problematic. For the present example we choose frequencies of 70 MHz and 140 MHz, the 6^{th} and 12^{th} harmonics of the bunch frequency, for the low- and high-β linac sections respectively. (The beam emittance is small enough and the inherent acceptance of the SC-linac large enough that higher frequencies are possible if required.) This gives a fixed cavity diameter of 20.5 cm, hence a common cryostat diameter for both sections of about 1 m, and cavity heights of 107 cm and 53.5 cm.

Linac Structure Recent developments at Legnaro[4] have shown that cavities of bulk Niobium or with Niobium films sputtered on a copper substrate can deliver gradients consistently above 5 MV/m and in some cases as high as 8 MV/m with cooling loads of 7 W at $4°$K. We have decided to set the number of cavities based on a gradient of 5 MV/m with a lattice that is compatible with gradients up to 10 MV/m. Each cavity is then capable of an accelerating voltage of 1 MV. We opt for 16 low-β cavities (4 cryostats) and 44 high-β cavities (11 cryostats) for 60 MV. (Note that this is somewhat different than the optimum values quoted above since cavities are installed in units of four.) Due to the strength of the accelerating fields and hence the rf defocusing, it is proposed to use quadrupole triplets between cryostats to refocus the beam into the next cryostat. Even in this case accelerating gradients are limited to 5 MV/m and 7.5 MV/m in the first two cryo-stats while 10 MV/m can be tolerated in the remainder of the linac. It is also possible to provide a four-quadrupole transition cell after the low energy section and change the lattice to a triplet every second cryostat at the expense of a larger average beam size. The transverse focusing sections are 50 cm long for the low-β section and 60 cm long in the high-β section with maximum gradients of 70 T/m. A short diagnostic box will be included in each inter-cryostat region. A summary of the specifications for the post-stripper linac is given in Table 3.

Table 3: Specifications for each section of the post-stripper superconducting DTL.

Parameter	SC-DTL1	SC-DTL2
E $(A/q = 7)$	0.4-2 MeV/u	2-7 MeV/u
E $(A/q = 3)$	0.4-4.2 MeV/u	4.2-15 MeV/u
A/q	$3-7$	$3-7$
β_o	4.8	9.6
f (MHz)	70	140
N_{cav}	16	44
N_{cryo}	4	11
E_g (MV/m)	5	5
V_o,V_{eff} (MV)	16, 11.5	44, 33.1
Length (m)	6.0	18.5

Beam Simulations Beams of initial emittance $\beta\epsilon_{x,y} = 0.2\,\pi$mm-mrad and $1.6\,\pi$keV/u-ns and for $A/q = 3$ and $A/q = 7$ were simulated in the linac code LANA[5] using a triplet every cryostat and a gradient of 5 MV/m. Final beam energies were 14.9 MeV/u and 6.9 MeV/u respectively. Growth in the transverse and longitudinal emittance was less than 5%. The longitudinal acceptance in both cases was 50π keV-ns; 30 times larger than the design input beam.

6 COSTS AND SCHEDULE

The estimated cost of the upgrade, not including internal manpower or building expansion, is 18 M$ (Can). The proposal is now before the funding agency. A decision on the project is expected by Feb. 2000. Assuming the requested funds are obtained, first beams at 5 MV/m and at a limited mass range would be available as early as 2003 with the complete facility operational in April 2005.

7 REFERENCES

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