

# DESIGN OF A DRIFT TUBE LINAC FOR THE ISAC PROJECT AT TRIUMF

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## Abstract

The ISAC radioactive ion beam facility under construction at TRIUMF combines an isotope-separator-on-line with a post accelerator. Required in the accelerator chain is a drift tube linac capable of accelerating unstable nuclei with a post stripper charge to mass ratio of  $\geq 1/6$  from  $E = 0.15$  MeV/u to a final energy fully variable up to 1.5 MeV/u. Due to the relatively low intensities of some of the ion species continuous ( $cw$ ) operation of the accelerator is required. A five tank interdigital H-type structure, operating at 105 MHz, has been chosen. The beam dynamics conceptual design and the results of various particle simulations are presented. Computer modelling of the rf structure and model measurements have been completed and are reported.

## Introduction

A radioactive ion beam facility is being built at TRIUMF. [1] In brief, the facility includes a proton beam ( $I \leq 100 \mu\text{A}$ ) from the TRIUMF cyclotron impinging on a thick target, an on-line source to ionize the radioactive products, a mass-separator for mass selection, an accelerator complex and experimental areas. The accelerator chain comprises an RFQ [2] to accelerate beams of  $q/A \geq 1/30$  from 2 keV/u to 150 keV/u and a post stripper, variable energy drift tube linac (DTL) to accelerate ions of  $q/A \geq 1/6$  to a final energy between 0.15 MeV/u to 1.5 MeV/u. Both linacs are required to operate  $cw$  to preserve beam intensity.

Both a Wideroe structure and a super-conducting structure have been considered [4] for the post stripper linac in the ISAC project. The former idea was abandoned due to the high power consumption and the latter was abandoned because of the required technological development. Instead, the IH structure has been chosen for its high shunt impedance. The structure has been configured as a *separated function* DTL. Five independently phased IH tanks operating at  $\phi_s = 0^\circ$  provide the main acceleration. Longitudinal focussing is provided by independently phased, double gap, spiral resonator structures positioned before the second, third and fourth IH tanks. Quadrupole triplets placed after each IH tank maintain transverse focussing. A schematic drawing of the DTL is shown in Fig. 1.

When operating at full voltage, the beam dynamics resemble that of a so called ‘Combined  $0^\circ$  Synchronous Particle Structure’[5]. To achieve a reduced final energy, the higher energy IH tanks are turned off sequentially and the voltage and phase in the last operating tank is varied. The spiral resonator cavities are adjusted to maintain longitudinal bunching. In this way, the whole energy range can be covered with minimal longitudinal emittance growth.

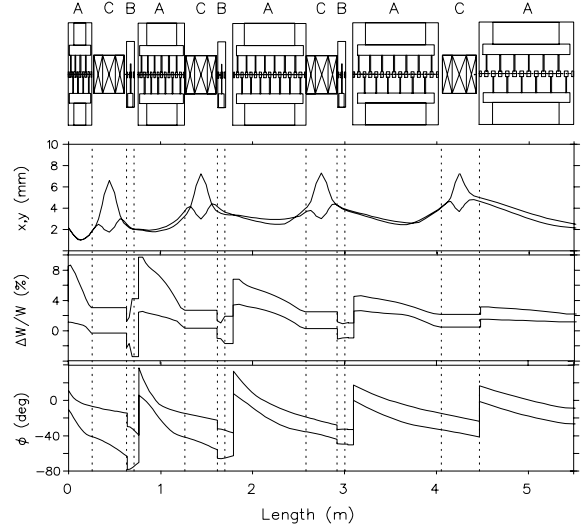


Figure 1: Schematic drawing of the ISAC variable energy 105 MHz DTL (upper figure) and corresponding beam envelopes (lower figures). Five IH tanks (A) provide acceleration at  $0^\circ$  synchronous phase, three double gap spiral resonators (B) provide longitudinal focus ( $\phi_s \sim -50^\circ$ ) and quadrupole triplets (C) provide transverse focus. The beam envelopes define the  $x$  and  $y$  maximum half sizes of the beam and the maximum energy spread and phase spread in the beam as a function of linac length. The calculations are for a beam of  $q/A = 1/6$  with matched elliptical emittances of  $0.25\pi \mu\text{m}$  (normalized) transversely and  $48\pi$  keV-nsec longitudinally.

## Specifications

The physical specifications of the DTL have been determined and the beam dynamics studied using the code LANA[6]. MAFIA has been used to model the rf characteristics of the IH tanks. Due to the relatively small longitudinal and transverse emittances of the beam injected into the DTL ( $\leq 50\pi$  keV·ns and  $\leq 0.16\pi \mu\text{m}$  (normalized)) an rf frequency of 105 MHz was chosen, three times the RFQ frequency. Each IH tank has a diameter of 94 cm with the resonant frequency tuned by optimization of the ridge geometry. The gross specifications of the five IH tanks and the three spiral resonators for the design particle of  $q/A = 1/6$  are given in Table 1. The Q and shunt impedance values of the IH structure are calculated with MAFIA.

The chief design considerations for the DTL are the  $cw$  operation, and the variable energy requirement. To achieve efficient acceleration and to distribute power losses uniformly, a constant gradient IH structure is adopted. The gap length to cell length ratio  $g/\ell$  is tuned to flatten the field distribution[5]. Maximum accelerating gradients are determined by restricting the

Table 1: Summary of parameter specifications for each IH tank and spiral resonator cavity (B1-B3) for the design particle of  $q/A = 1/6$ . All cavities operate at 105 MHz. Here  $L$  is the length,  $a$  is the aperture,  $\bar{\ell}$  is the average cell length,  $\bar{E}_o \cdot \bar{T}$  is the effective field gradient and  $P_\ell$  is the power per unit length. Other parameters have their normal designations. The quoted IH shunt impedance values are from MAFIA. The power/unit length and power calculations for the IH structure assume a shunt impedance 75% of the value quoted. In the case of the buncher cavities, the shunt impedance is quoted from reference [7].

| Tank  | No.   | $L$  | $a$  | $\bar{\ell}$ | $\beta_{out}(\%)$  | $\bar{E}_o \cdot \bar{T}$ | $V_{eff}$ | Q                 | $Z$             | $P_\ell$ | $P$  | $E_{out}$ |
|-------|-------|------|------|--------------|--------------------|---------------------------|-----------|-------------------|-----------------|----------|------|-----------|
| -     | Cells | (cm) | (mm) | (mm)         | $\beta_{in} = 1.8$ | (MV/m)                    | (MV)      | ( $\times 10^3$ ) | (M $\Omega$ /m) | (kW/m)   | (kW) | (MeV/u)   |
| 1     | 9     | 26   | 10   | 28           | 2.2                | 2.1                       | 0.5       | 11                | 374             | 16       | 4    | 0.23      |
| 2     | 13    | 50   | 14   | 38           | 3.1                | 2.4                       | 1.2       | 13                | 410             | 18       | 9    | 0.44      |
| 3     | 15    | 77   | 16   | 51           | 4.1                | 2.5                       | 2.0       | 19                | 471             | 18       | 14   | 0.78      |
| 4     | 14    | 90   | 16   | 65           | 5.0                | 2.4                       | 2.2       | 23                | 421             | 18       | 16   | 1.14      |
| 5     | 13    | 98   | 16   | 76           | 5.6                | 2.3                       | 2.2       | 25                | 376             | 18       | 18   | 1.50      |
| B1    | 2     | 8    | 14   | 33           | 2.2                | 3.2                       | 0.22      |                   | 60              |          | 10   | 0.23      |
| B2    | 2     | 8    | 14   | 33           | 3.1                | 3.2                       | 0.22      |                   | 60              |          | 10   | 0.44      |
| B3    | 2     | 8    | 14   | 33           | 4.1                | 3.2                       | 0.22      |                   | 60              |          | 10   | 0.78      |
| total | 70    | 543  |      |              |                    |                           | 8.1       |                   |                 |          | 91   |           |

total power per unit length to less than 20 kW/m. (For power calculations the quoted MAFIA shunt impedance values are scaled by 75%.) The IH structure is highly efficient with a total effective gradient of 1.5 MV/m and an rf power consumption estimated at only 61 kW.

The variable energy requirement sets restrictions on the tank and quadrupole lengths, and on the specifications of the bunching cavities. Any tank and triplet combination is required to be short enough to limit the phase spread entering the next section to  $\Delta\phi \leq 90^\circ$  so that the beam can be bunched without longitudinal emittance growth. This requirement forces a short first tank of 9 cells and 27 cm with corresponding reduction in shunt impedance. The quadrupole triplets are designed to be very compact. Each triplet unit has an effective length of 32 cm, with a bore aperture of 28 mm and a maximum gradient of 63 T/m. They will occupy a 40 cm space between tanks.

The two gap spiral resonator structure is chosen for its large velocity acceptance and large multipactor-free voltage range. The three bunchers must operate over  $\beta$  regimes given by 1.8%  $\rightarrow$  2.2%, 1.8%  $\rightarrow$  3.1%, 1.8%  $\rightarrow$  4.1% respectively and over voltage ranges varying by a factor of ten or more. For ease of manufacture, three resonators with a constant  $\beta = 2.3\%$  have been specified yielding a gap crossing time constant of at least 75% over the whole velocity range. The properties of the device have been studied extensively elsewhere [7] and the quoted shunt impedance value is taken from the literature. We are presently modelling the device with MAFIA.

### Beam Dynamics

Beam dynamics calculations have been done using the code LANA with  $^{30}\text{Na}^{+5}$  as the reference particle. All transverse emittances quoted below are normalized values. The calculated envelopes for the full energy case are shown in Fig.1 for matched elliptical emittances of  $0.25\pi \mu\text{m}$  and  $48\pi \text{keV}\cdot\text{nsec}$ . The longitudinal optics is typical for a  $0^\circ$  structure. The beam is injected into each accelerating structure with an energy higher than that of the synchronous particle. The longitudinal phase space position rotates  $\sim \pi/2$  in each tank and remains primarily in the second quadrant providing a stable transport. The strong

periodic longitudinal and transverse focussing yield small beam sizes and increased acceptance. The true useable region of the longitudinal acceptance corresponds to  $144\pi \text{keV}\cdot\text{nsec}$  and the transverse acceptance is  $1.3\pi \mu\text{m}$ .

An 11.7 MHz time structure is imposed on the beam from the separator ( $\epsilon_{x,y} \leq 0.1\pi \mu\text{m}$ ) by a pre-buncher upstream of the RFQ (35MHz)[3]. Particle simulations through the RFQ, stripping foil and pre-DTL matching section produce *realistic* particles that are subsequently run through the DTL. A summary of before and after emittances for two MEBT conditions (Case A and Case B) are given in Table 2. Case A includes a bunch rotator before the stripping foil while Case B has none. The transmission is 100% in both cases for an ensemble of 4000 particles.

Table 2: Beam quality before and after DTL for two MEBT set-ups.

| % enclosed |     | $\epsilon_{x,y} (\pi \mu\text{m})$ |      | $\epsilon_z (\pi \text{keV}\cdot\text{nsec})$ |     |
|------------|-----|------------------------------------|------|---|-----|
|            |     | 90%                                | 98%  | 90%   | 98% |
| Case A     | in  | 0.11                               | 0.17 | 10  | 20  |
|            | out | 0.12                               | 0.21 | 12  | 22  |
| Case B     | in  | 0.11                               | 0.17 | 27  | 54  |
|            | out | 0.13                               | 0.24 | 29  | 58  |

### Variable energy operation

A plot of the tank voltage and phase required for a given final energy are shown in Fig. 2. For a reduced voltage the particle bunch is phased negatively with respect to the synchronous phase so that as the particles lose step with the synchronous particle and drift to more positive phases they gain the maximum possible energy. This phase setting also coincides with the minimum phase spread at the exit of the following triplet section. The buncher following this tank is then used to capture the diverging beam. The following bunchers provide longitudinal transport. Simulations show that in this way the longitudinal emittance growth for typical beams can be kept below 15% for the whole energy range.

The final phase spread of the beam exiting the DTL for either none, one, two, or three bunching cavities is shown in Fig. 3. The

aim is to achieve a phase spread no larger than can be bunched with a 35 MHz buncher in the HEBT. The plot shows that the first and second bunchers are essential and that the third would improve the beam quality in the energy range from 0.5–0.7 MeV/u.

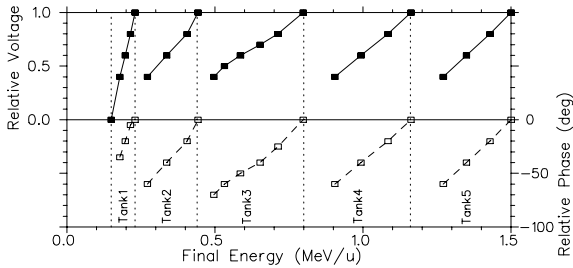


Figure 2: Tank voltage and phase required for a certain final energy. Full energy case corresponds to tank voltages of 1.0 and phases of  $0^\circ$ .

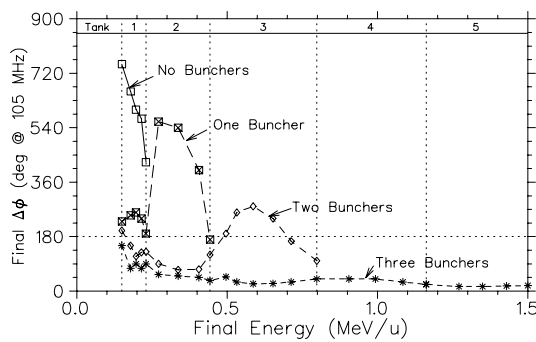


Figure 3: Results of LANA studies showing the final phase width of the beam exiting the last tank for either none, one, two or three bunchers. Superimposed on the figure are the tank energy regimes (vertical lines) and the phase width corresponding to  $60^\circ$  of width in a 35 MHz buncher (horizontal line).

### MAFIA Studies

All IH tanks were simulated with MAFIA. The results of the shunt impedance and  $Q$  calculations have been reported in Table 1. The calculations give power density information which will then be used to determine the cooling requirements. MAFIA was also used to predict the appropriate  $g/\ell$  dependence to flatten the field distribution in an 11 gap full scale model (see below) and to predict the performance of various tuners.

### Model Studies

A full scale model of an 11 gap tank was built to test the tuning of the field distribution and the characteristics of various mechanical tuners. The tank is built from a rolled copper sheet 6 mm thick. The end plates are made from aluminum on which a thin foil of copper is glued. The ridge and the drift tube are made from brass to ease the fabrication. All pieces are bolted together to facilitate changes of the cavity geometry. The coupling loop and the tuner are installed in the median plane, one on each side of the tank. The field distribution from a bead pull measurement is given in Fig.4(b). The associated  $g/\ell$  values predicted from MAFIA simulations are shown in Fig.4(a).

The drift tubes will be cooled by a water circuit coming up through the ridge and into a drilled out portion of the stem. A

NC machined copper model of a stem and tube was made to test the mechanical rigidity of the structure under various heat and water loads. The tests show that a water flow of 3  $\ell$ /min is sufficient to cool the drift tube. The water flow does not produce any measurable mechanical vibrations.

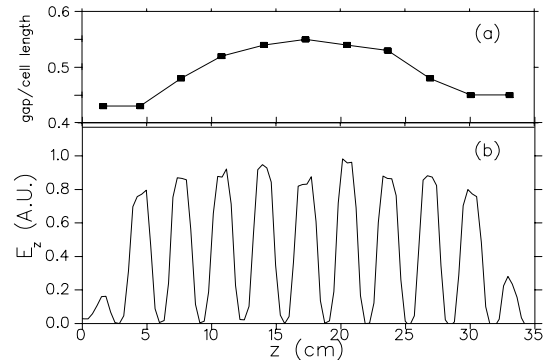


Figure 4: Field distribution measured on an 11 gap model (b) and associated  $g/\ell$  values for each gap (a).

### Conclusions

The *separated function* DTL concept provides a low power solution to achieve variable energy heavy ion acceleration in the low  $\beta$  regime without significant increase in the longitudinal emittance. A mechanical concept for the DTL is being discussed. The first module consisting of Tank 1, a quadrupole triplet and a double-gap buncher is scheduled to be completed by the end of 1997. The DTL is scheduled to be fully installed by the middle of 1999.

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