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BEAM-BASED MEASUREMENTS OF THE ISAC-II SUPERCONDUCTING HEAVY ION LINAC

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Abstract

Preparation for experiments, which typically run for one to two weeks in the ISAC-II facility at TRIUMF, requires some amount of overhead, limiting the efficiency of the facility. Efforts are underway to improve the ISAC-II linac model to reduce this overhead while also improving the quality of the delivered ion beam. This can be accomplished with beam-based measurements and corrections of alignment, cavity gradients, focal strengths, and more. A review of the present state of the linac will be given, including measured mis-alignments and other factors that affect the reproducibility of tunes. The outlook on expected improvements will also be summarized, including progress on the automatic phasing of cavities with a focus on integration to the High Level Application platform being developed at TRIUMF. Lastly, a summary will be given on the expected paradigm shift in the tuning approach taken: moving from re-active tuning by operators or beam delivery experts to pro-active measurements and investigations, version-controlled tunes, and continuous feedback from beam physicists.

INTRODUCTION

The superconducting (SC) linac at TRIUMF was designed to accept ion beams with an energy per nucleon of 1.53 MeV/u and add up to an additional 40 MV of acceleration before delivery to various locations in ISAC-II for nuclear physics experiments [1].

Acceleration through the SC linac is provided by forty superconducting two-gap quarter wave niobium cavities, operating at a temperature of 4.2 K. Cavities are distributed over eight cryomodules, each of which contains a liquid helium reservoir and one superconducting solenoid [1]. The first twenty cavities operate at 106.08 MHz while the last twenty operate at 141.44 MHz.

The velocity of an ion beam exiting the SC linac is measured using three flight time monitors (FTMs) spaced along the beamline [2]. Three different velocities can be calculated based on the measured arrival time at each pair of monitors and the known distance between them. A statistically weighted average velocity can then be calculated.

Standard Operation

Setup of the SC linac for an experiment currently begins with determination of operational amplitudes, and checking of cavity stability. Following this a stable pilot beam is tuned through the linac and flight time measured on the FTMs. SC cavities are then phased sequentially, measuring the arrival time at a single FTM for five different cavity phases, fitting this to a cosine (Fig. 1), and then setting the cavity to a predetermined accelerating phase [3]. Once the desired velocity has been exceeded, the amplitude of the last cavity phased is reduced to meet the requirement.

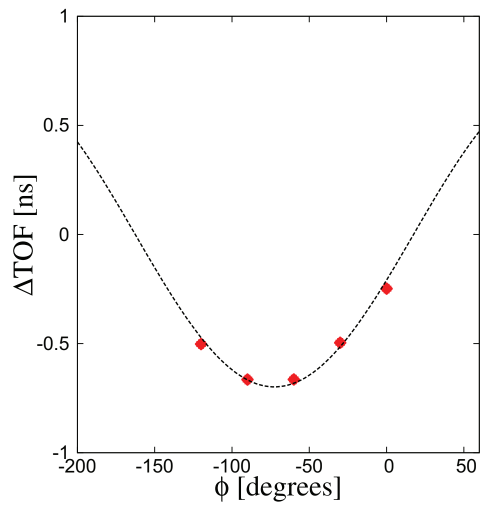

Figure 1: Cosine fit of Cavity TOF vs Phase Data.

The broad velocity acceptance of the two-gap cavities and individual control over each cavity provides a very flexible system. Three cavity types with β_0 values of 5.7%, 7.1%, and 11% have been used allowing efficient acceleration of ions with $2 \leq A/q \leq 6$ with corresponding maximum energies per nucleon of $16\,MeV/u \geq E/nuc. \geq 6.5\,MeV/u$. Non-operational or unreliable cavities can be skipped, and varying amplitudes or accelerating phases can be utilized. The SC linac is often re-tuned when changing experiments, resulting in a certain amount of facility overhead.

Beamline Modeling

Historically, a variety of different codes have been used for beam dynamics simulations at TRUMF. The SC Linac and transfer lines were initially designed using TRACE-3D and COSY-∞ for beam envelope calculations. LANA and TRACK were then used for particle tracking through simulated fields, with the latter being used for studies of linac misalignments [4]. The tunes that are currently used were calculating using a TRACE-3D optimization.

Optics settings are currently available for operator use in a spreadsheet, with field values from the associated TRACE-3D optimization. A visualization of the expected beam envelope along the beamline is not presently available for operator use in the control room.

OPERATIONAL LIMITATIONS

While the SC linac has been operational now for a decade, there remain a number of opportunities for further improvements. Initial investigations into cold mass alignment [3]

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and automatic calculation of cavity settings [5] were never fully realized due to competing priorities and lack of resources. As a result, the time required to setup the linac for an experiment and the procedure involved haven't changed significantly over the years.

Steering Effects of Quarter-Wave Cavities

Quarter wave cavities are widely used to accelerate heavy ions in the low beta range. Due to their design, there are undesired electric and magnetic field components present along the beam axis, which produce a vertical steering effect. To mitigate this the cavities in the SC linac were intentionally installed vertically off of the beam axis, which can offset the steering effect for a certain velocity range [6].

However, due to the nature of the system it is quite difficult and time consuming to align the cavities and solenoids accurately to the beam port of the cryomodule. Alignment of the SC solenoids in the linac was investigated using beam and partially corrected for in the early years of the linac [3], although the steering effects of cavities as installed has yet to be closely studied. In the years since initial installation a number of cryomodules have been removed and serviced, possibly further affecting alignment.

PLANNED IMPROVEMENTS

Alignment

Each cryomodule is designed with a strongback system, from which the cavities and solenoid are suspended. The strongback is suspended from the cryomodule lid via three or four posts, depending on the cryomodule. The intention is to adjust the posts as necessary as with previous investigations [3] to align the solenoids as best as possible to the beam axis with cavities off. The current measured steering effect of the solenoid in the sixth cryomodule can be seen in Fig. 2.

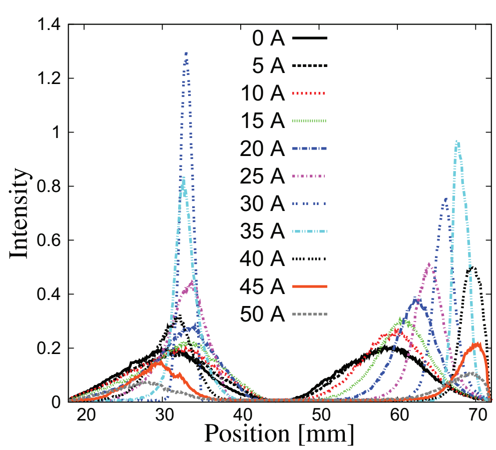

Figure 2: Effect of mis-aligned solenoid at various currents.

The steering effects of cavities can also be investigated. To accomplish this the ion beam will be aligned via up and downstream profile monitors with the cavity off, followed by phasing of the cavity and measurement of its effect on the downstream beam profile. This will help improve the understanding of linac behaviour in models and any significant cavity mis-alignments can be addressed on a case-by-case basis during extended maintenance periods.

Understanding

As with any facility, there will inevitably be some discrepancies between the designed beamline and the beamline as installed. One area that has already been demonstrated as a potential topic is the study of phase-velocity relationship between cavities. The beam velocity is measured on the FTMs, and two cavities are phased one at a time with the other cavity off. The difference between the two accelerating phases can be plotted against velocity as in Fig. 3. For a simple model the resulting fit should be related to the design distance between the cavity centres:

$$\frac{T_{RF}}{360}[\phi_2 - \phi_1 + K] = \frac{d_{12}}{\beta_{out} \cdot c}$$

$$\Delta\phi = \left[\frac{360}{T_{RF}}\frac{d_{12}}{c}\right]\frac{1}{\beta_{in}} - K,$$

where $\Delta\phi$ is the difference between the two cavity phases, d_{12} is the distance from one cavity centre to the next, T_{RF} is the RF period, c the speed of light, β_{in} the velocity measured with both cavities off, and K the phase offset between the two cavities.

This approach is basically reverse-engineering from the end-goal of automatically calculating cavity phases based on known distances, cavity gradients, etc. Any model used to calculate phases must then recreate the observed behaviour. If it doesn't, sources of error need to be investigated - this could be the model itself, phase measurements, velocity measurements, or intercavity distances.

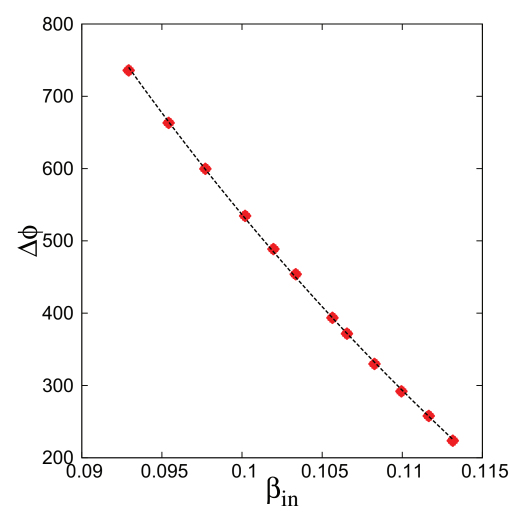

Figure 3: $\Delta\phi$ *vs* β_{in} relationship for cavities 30 & 34.

Gradients used for automation are also calculated using beam-based investigations, by measuring the energy per nucleon gained from that cavity:

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$$G = \frac{A}{Q}\frac{\Delta E_{pernucleon}}{L \cdot TTF \cdot cos\phi},$$

where G is the cavity gradient, ΔE the energy per nucleon gained through the cavity, A the relative isotopic mass, Q the charge state, L the cavity length, TTF the transit time factor calculated at the input velocity, and Φ the accelerating phase.

Currently a simple drift-kick-drift model is used for calculated cavity phases. Using this model to automatically calculate the phase shift between cavities 30 & 34 at an energy per nucleon of 6.0 MeV/u would result in an error in the cavity 34 phase of 22 degrees when comparing to the observed behaviour shown in Fig. 3.

Beam-based measurements will improve calculation of cavity phases and be useful for improving models, as TRIUMF moves towards TRANSOPTR as a standard beam envelope code [7].

Automation

The end goal of improved alignment and understanding of the linac is to develop a high level application which will allow for automatic calculation of cavity phases and amplitudes, as well as optics settings.

Recent tests have established the viability of improved automation. A linac tune with 36 operational cavities was documented with measured gradients, phases, and optics settings. The amplitude of the fifth cavity was reduced to 50% of its initial setting, and the necessary changes to downstream cavities were automatically calculated. After minor optimization of the fifth cavity the expected output energy on the FTMs was achieved while maintaining 100% transmission through the linac.

INTEGRATION INTO HLA FRAMEWORK

A High Level Application (HLA) taskforce [8] has been established at TRIUMF to improve the tools available to operators and beam delivery experts as the radioactive ion beam (RIB) facility prepares to increase delivered hours of RIBs by a factor of three.

Information about beamlines and tunes are stored on a web server in xml files. This structure provides the perfect base for studying and improving the tune through the SC linac. Findings can be fed back into the xml files describing the beamline and tunes, which will then provide more accurate information for calculating tunes and running simulations.

This is an essential transition in the beam delivery philosophy at the RIB facilities at TRIUMF - moving from re-active tuning, often based on the original design tune, towards a pro-active approach dedicating more time to development, establishing re-producible methods, and fault-correction while reducing standard tuning times.

TuneX

TuneX is a web-based application that when fully implemented will consolidate information from over four different sources and functionality from over five different utilities into one centralized tool for operators to interact with a tune.

TuneX pulls data from the xml files and EPICS to accomplish one of three main functions: Load, Display, or Scale. While these three functions are very similar and require many of the same routines, they have historically been scattered among different applications and locations in the control room. They now share a standard scaling routine for calculating different values based on beam parameters, point to the same tunes and beamline information (xml files), and very importantly share a common, consistent, user interface.

CONCLUSION

The ISAC-II SC linac at TRIUMF provides a wide variety of stable and radioactive ion beams at velocities varying from 5-17% the speed of light. However it is observed from experience and methods used at other laboratories that there is room for improvements to the ways the ISAC-II SC linac is utilized. Improved alignment, understanding, and automation are keys to minimizing overhead and increasing reproducibility. The TuneX HLA and HLA platform in general at TRIUMF provide an ideal platform for the implementation of these improvements.

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