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TOWARD AUTONOMOUS PHASING OF ISAC HEAVY ION LINACS*

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Abstract

Ongoing development work at TRIUMF aims to implement a model-based tuning approach for accelerators, with the goal of automation of tuning tasks and minimizing tuning times. As a part of this, work is underway toward the development of an analytical model of the linacs using the methodology of Hamiltonian based beam envelope dynamics. The TRIUMF High-Level Applications (HLA) project has been developing software that allows direct interfacing with the control system. The envelope code TRANSOPTR is now being extended to simulate the ISAC-II Superconducting Linac. Within the emerging HLA framework, this will allow for automated phasing and tuning of the linac. The steps of the model development will be presented in this contribution.

INTRODUCTION

ISAC, the Isotope Separator and ACcelerator, is TRIUMF's flagship laboratory for rare-isotope research. The facility postaccelerates beams produced using the isotope separation on-line (ISOL) method, using the TRIUMF 520 MeV cyclotron as a driver for proton induced rare isotope production. High-energy heavy-ion beam delivery at ISAC is subdivided into two areas: ISAC-I and ISAC-II, using three principal accelerators working in sequence. First, an 8 m long, 35 MHz CW radiofrequency quadrupole (RFQ), which features a unique separated pre-bunching function, accepts low energy DC beams and provides initial acceleration to 0.153 MeV/u. RFQ beams are then injected in a separated function, 106 MHz IH-type KONUS [1] drift tube linac (DTL), featuring 5 accelerating tanks and 3 bunchers, enabling a variable output energy range of 0.153 to 1.53 MeV/u for delivery to high energy experiments at ISAC-I. Further acceleration, up to ~15 MeV/u (for A/Q = 2) in ISAC-II, is achieved with the superconducting linac (SCL), consisting of 40 sequential two gap quarter-wave cryogenic niobium resonators.

Considerable overhead is incurred in the operation of the DTL and SCL, both requiring periodic manual re-phasing by operators to accommodate daily changes in energy and isotope species. Adding to this, the operational complexity of the present network of beamlines will triple with the connection of the new ARIEL facility to the existing ISAC-I and -II. This has led to the identification of linear accelerator tuning overhead as an important issue that must be addressed to support the laboratory's future vision. To this end, TRIUMF has established a High-Level Applications project group (HLA), to develop methods and software that will enable these ambitious goals.

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In parallel to this, work has now been underway for several months to build a continuous end-to-end model of the ISAC accelerators, using the envelope code TRANSOPTR [2, 3]. This work, partly motivated by the observation of diurnal-like transmission variations across the ISAC accelerators [4], aims to implement a full modelization of the above discussed accelerators enabling both the study of machine behaviour and a model-based tuning method. In addition, it will allow for the development of automated tuning procedures, via the HLA suite of web-based control room applications [5].

ACCELERATOR PHASING AND HLA

Longitudinal tuning of both the DTL and SCL is performed manually by cavity electric field and phase adjustment, while monitoring beam energy spectrum on a diagnostic device. In the case of the DTL, full beam interception is presently required, with accelerated beam being sent to a beam profile analyzer after deflection through a 90° dipole magnet, itself requiring manual operation. In the case of SCL, a trio of flight time monitors, located on a zero-degree beamline are used to extract beam energy measurements required for tuning. In both cases, an operator undertakes the iterative process of tuning the cavity, which affects the longitudinal beam properties. As this occurs, the transverse tune must periodically be adjusted to accommodate for the adjusted beam energy.

The HLA platform's novel ability to interface with the laboratory's control system now enables communication with and control of all beam transport and accelerator tuneable control variables at ISAC [6]. This way, control system values for the accelerators and beamlines, in addition to readbacks from beam monitoring diagnostic devices may now be fed into a model, such as TRANSOPTR, thereby enabling real-time simulations with feedback implementation, via the HLA framework. As DTL accelerating cavities, each of which have a unique design, contain up to 15 accelerating gaps, while the 40 SCL cavities consist of three separate designs; one for the lower β SCB and two for the higher β SCC designs, each of which consist of two-gap resonators, the SCL is an ideal candidate for initial TRANSOPTR implementation and testing.

The first step of this implementation is the computation of the on-axis, longitudinal electric field component, which is used by TRANSOPTR to integrate the effects of electric field interaction with the beam and the resulting evolution of the second moments defining the overall beam envelope [7, 8]. In the case of the SCL, this first computation was based on the TRIUMF Design Office technical drawings detailing the geometry of the cavities' accelerating gaps, in particular the first SCB cryomodule. Both the computed field and the TRANSOPTR implementation are presented below.

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ELECTRIC AND MAGNETIC FIELD MAPS

The electromagnetic simulation software Opera2D [9] was used in conjunction with mechanical drawings to produce static electric field mappings for the quarter wavelength SCB cryogenic RF resonator in a simple way and as a good approximation. A reference design drawing is shown in Fig. 1. The cryomodule itself is simulated in TRANSOPTR by calling the subroutine linac [7, 8], which expects a normalized on-axis electric field profile, which is then linearly scaled to produce the correct accelerating field amplitude.

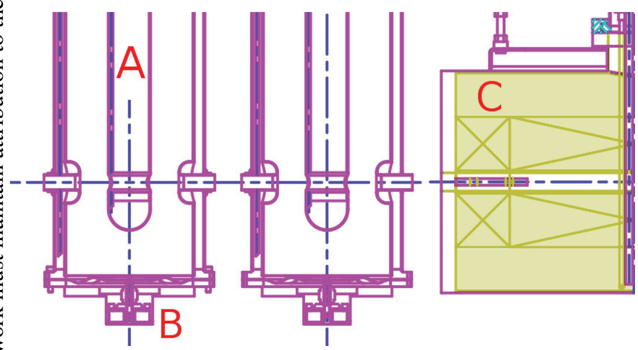

Figure 1: Reference drawing, showing half of a 4 resonator SCB-type module and half the central focusing solenoid. The cryomodule is mirror symmetric about the right edge of the drawing. Labels denote: (A) central resonator, (B) grounded outer resonator surface and (C) solenoid. Beam runs from left to right.

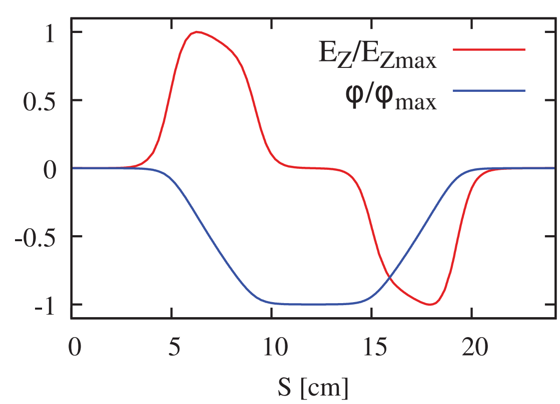

Figure 2: Opera-2D computed potential (ϕ, blue) and on-axis electric field (red) for an SCB cryomodule.

The Opera2D field map is produced by setting a control voltage on the central resonator within one cavity and normalizing the resulting on-axis electric field mapping to the maximum value in the set, as shown in Fig. 2.

The resulting mapping and the computed TRANSOPTR electric field gradient suggests a cavity effective voltage gradient of 16 MV/m applied to the electric field of Fig. 2. Considering the gap width of 4 cm, this implies a voltage of 640 kV, which is in agreement with standard quoted operating voltages for the resonator [10].

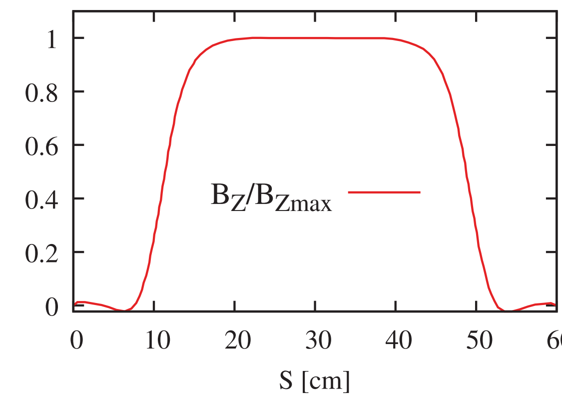

Figure 3: Mapping of the SCB cryomodule magnetic field z-component, as supplied to TRANSOPTR.

Analogously to the on-axis electric field, the on-axis magnetic field through the solenoid, obtained in [11] and shown in Fig. 3, must also be supplied to TRANSOPTR. The normalized field map is scaled with beam energy to produce the appropriate focusing effect to maintain a transverse match.

BENCHMARKING - SCL TIME OF FLIGHT

The ISAC beamlines downstream of the RFQ were all designed successfully using Trace-3D [12]. This code calculates envelopes using hard-coded transfer matrices. For online modeling and tuning, however, TRANSOPTR is more appropriate because it can integrate envelopes through time- and space-varying electric and magnetic fields, and thus can seamlessly simulate through all of the accelerator cavities and focusing elements. For example, Trace-3D models the cavity as an instantaneous kick in energy at the centre of the cavity instead of continuously integrating on axis fields. The Trace-3D drift-kick SCL model was used in initial investigations into possible automatic phasing. This model was successfully used for some preliminary SCL rephasing tests [13], however discrepancies were found between observed and calculated behaviors. As a result it was proposed to improve the model driving the calculations as well as to devote further work to benchmark the re-phasing behaviour.

The first SCL cryomodule has now been modeled using TRANSOPTR, using the aforementioned field maps of the cavities and solenoid. A comparison of the Trace-3D and TRANSOPTR models of an SCL cryomodule is shown in Fig. 4. The effective energy gain of the cavities used in the initial Trace-3D model were assumed to be identical (10.8 MeV), which includes the effects of the time-varying fields. To optimize the TRANSOPTR model for comparison, the cavities were phased −25° off-peak, with the electric field map then scaled to match the output energy of the cavity to the corresponding Trace-3D energy. As the energy into each cavity is different and the cavities are of the same

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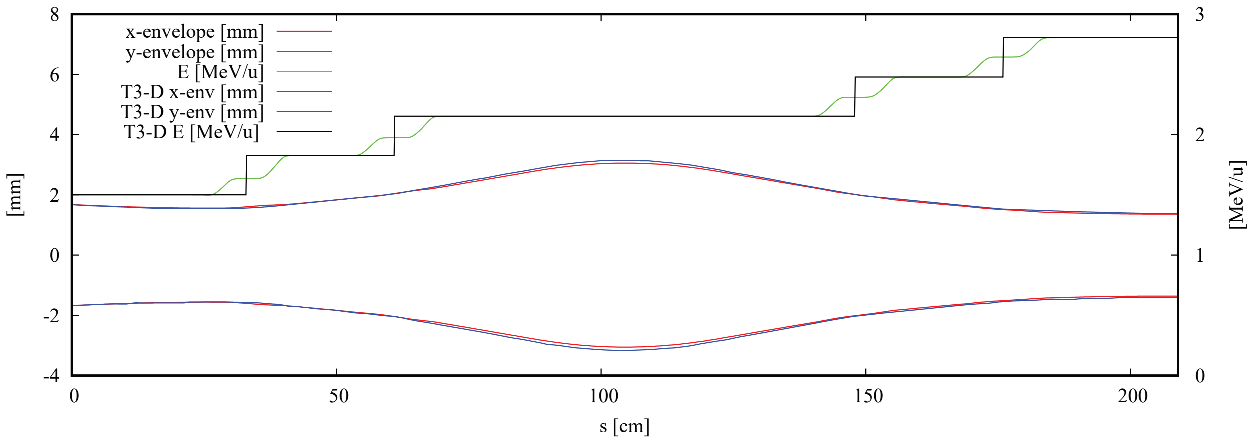

Figure 4: Transverse beam envelope and energy/nucleon for a beam 30 amu, charge state 10, and input velocity $\beta = 0.057$ calculated using both the Trace-3D and TRANSOPTR models. The transverse envelopes defining the 2RMS contours of the beam distribution (left y-axis), in addition to the energy (right y-axis) are presented for a generic SCB cryomodule.

design velocity, each has a different transit time factor. The peak electric fields found using TRANSOPTR are 15.8, 14.7, 14.4, and 14.2 MV/m for the four cavities. The two models agreed well with a minor 1% change to the solenoid field. The most notable differences are the larger envelope within the solenoid in the Trace-3D simulation, and inside the cavities where Trace-3D models the transverse RF defocusing instantaneously at the centre of the cavity.

NEXT STEPS

With one cryomodule modeled using TRANSOPTR, the next steps for improved operation of the SCL are to expand the model to the other coaxial resonator types, allowing simulations including all 40 cavities. Benchmarking of the model will then be carried out first using flight time monitor measurements to calibrate the amplitude of the cavity fields, and then studying the phasing behaviour as input parameters are adjusted. Peak cavity fields can be calculated by running a TRANSOPTR simulation to match the measured output energy of each cavity in turn, as was done to match to the Trace-3D model. Under the assumption that the RF control system scales the cavity fields linearly, the model can then be run by an HLA during experiment setup to calculate the change in energy due to a failing cavity that has a reduced or zero operating electric field amplitude. The model can also be used to determine the flight time to the next downstream cavity and the necessary phase adjustment. With modeling and benchmarking complete, the final steps towards automation of the ISAC-II linac will be integration into the HLA framework to provide a simplified interface for operators.

The TRANSOPTR-Trace-3D comparison of Fig. 4 represents an important step forward toward the goal of an end-to-end model for the ISAC linear accelerators. The methodology around the Opera-2D SCB simulation and the resulting envelope simulations, consistent with the existing Trace-3D envelopes, in addition to the predicted gap voltages are but a first step toward a more in-depth model, complete with online feedback. The Opera-2D calculations will be benchmarked with CST Microwave Studio simulations for each of the ISAC-II resonator types. A full SCL TRANSOPTR implementation, in addition to further beam-based benchmarking will allow for the extension of the HLA suite of control room applications.

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