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TOWARD AN END-TO-END MODEL FOR ISAC-I ACCELERATORS

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Abstract

Diurnal-like transmission variations in the ISAC-I warm accelerator system necessitates periodic retuning by operators. While beam loss points are well known, re-tuning nevertheless results in additional downtime and reduced count rates at experiments. This has motivated the development of an end-to-end simulation of the ISAC-I linear accelerator (linac) system to understand and characterize the nature of transmission instabilities spanning several hours to days.

ISAC LINACS AND TRANSMISSION ISSUES

Facility Overview and Status

The ISAC-I warm accelerator consists of an 8 m, split ring CW radiofrequency quadrupole (RFQ), followed by an IH-cavity drift-tube linac (DTL) that uses the combined zero degree synchronous particle structure (KONUS) [1] [2]. In tandem, the ISAC-I linac system accepts heavy radioisotope beams with $1 \le A/q \le 30$ and produces, thanks to a stripping foil, output beams with $2 \le A/q \le 7$ and energies ranging from 0.153 to 1.50 MeV/u. Output beams are either delivered to nuclear physics experiments in ISAC-I, or may be diverted through an S-bend transfer line to a superconducting linac for delivery to ISAC-II at energies beyond the Coulomb barrier. Variations in ISAC-I linac performance will have effects downstream, potentially limiting experimental yields. Currently, there is no comprehensive end-to-end model of the ISAC-I accelerator.

Transmission Variation

A diurnal-like transmission variation has repeatedly been observed at ISAC-I & II experiments, requiring operator intervention at known beam-loss points, including the 90° MEBT corner, consisting of two 45° dipole magnets. While tuning may restore transmission through the linacs, downstream effects frequently include loss of alignment at the experiment chamber, resulting in extra downtime. Figure 1 shows automated Faraday cup measurements taken at 20 minute intervals along the ISAC-I accelerator chain, over a 44 hour timespan during a beam development period. During this time, operators were instructed not to intervene in any way. Ambient temperatures measured in the ISAC-I hall are overlayed for comparison. Visual inspection shows a correlation between both temperature and transmission trends, particularly for the DTL. Significant transmission losses, over 50% for the DTL, are observed. While no definite conclusion may be drawn as to a causal relation between both trends, this has motivated the development of an integrated end-to-end model, presently inexistant. This would offer insight into beam dynamic effects due to separate RF cavities and ambient conditions, for example time of flight variations due to temperature dependant geometry changes brought on by air and cooling water temperature variability, amongst others. A dual-model approach is favored, with both multiparticle simulations and a fast envelope code, to investigate these effects.

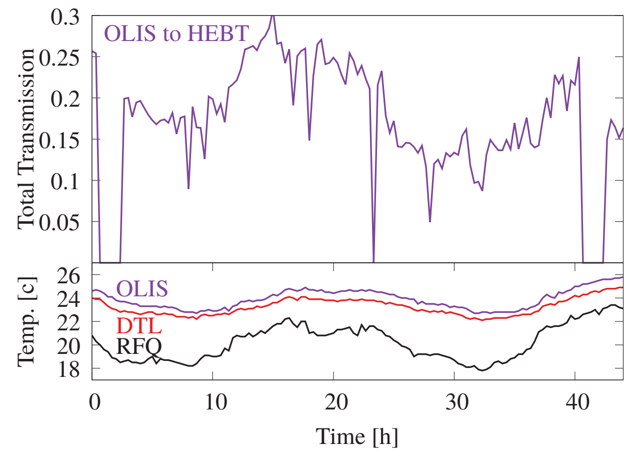

Figure 1: Top: ^{20}Ne transmission readings from the off-line ion source (OLIS), each 20 minutes for 44 hours. Faraday cup readings have been normalized to the cup immediately upstream, showing beam transmission between 0 and 1 for the labeled sections. Gaps in data caused by RF trips. Bottom: ISAC-I experimental hall ambient air temperature, sampled at identical time intervals.

MULTIPARTICLE SIMULATIONS

Up to now, Ray-tracing routines were heavily used to develop ISAC linacs. However, existing models focus on separate, individual elements such as PARMTEQ for the RFQ and LANA for the DTL. Attempting a continuous simulation from one to the other is not straightforward or ideal. Nevertheless, these form the basis for further work.

ISAC Pre-Buncher

First, the pre-buncher to RFQ section has been represented using the particle tracking code PARMELA. The single-gap, three harmonic buncher runs 11.8, 23.6 and 35.4 MHz sinusoids generating a pseudo-sawtooth modulation [1], tuned to produce a time-focus 5 m downstream at the start of the RFQ vanes. The PARMELA routine simulates each harmonic as a discrete, zero-length, idealized gap with an instantaneous kick [3]. Bunched beam then drifts 5 m to the ISAC RFQ. Figure 2 shows the transverse and longitudinal phase space profiles for an $A/q = 30$ beam, time-focussed at the RFQ

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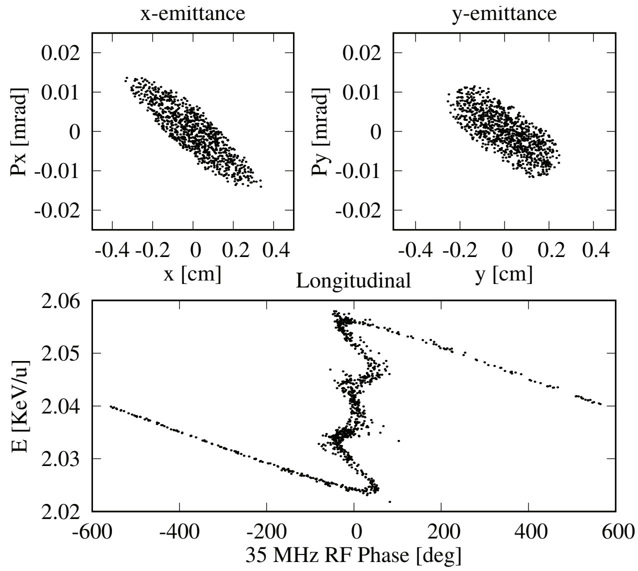

Figure 2: PARMELA simulated A/q = 30 beam using 3000 particles, time focussed at the RFQ entrance, 5 m downstream from the prebuncher.

entrance, corresponding to the upper limit of charge acceptance for the linac. The PARMELA prebuncher & beamline segment to the RFQ allows for investigations of both transverse and longitudinal effects due to mismatches or varying conditions. For example, poorly matched beam, producing a larger than expected transverse envelope, will suffer aberrations during transport, which will potentially affect RFQ transmission and output beam quality. An example mismatched beam is shown in Fig. 3, with the transverse phase space showing aberrations due to a poor tune. In addition to studies on time focus and beam transport effects, PARMELA enables the study of space-charge effects on the RFQ time focus, which is the dominant cause of transmission loss at high injection current [4]. An example is seen in Fig. 4, showing time-focus degradation due to space-charge repulsion, after 5 m drift. PARMELA produces an output file containing the 6-dimensional phase space dimensions for each particle, (x, x', y, y', z, z'), with the last two longitudinal coordinates in 35.4 MHz RF degrees and MeV, respectively. This file may be fed to PAMTEQ for the RFQ simulation.

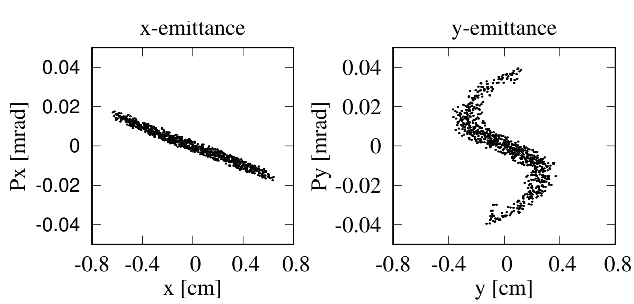

Figure 3: PARMELA simulated A/q = 30 beam using 3000 particles, mismatched at the RFQ entrance and showing effects of aberration, 5 m downstream from the prebuncher.

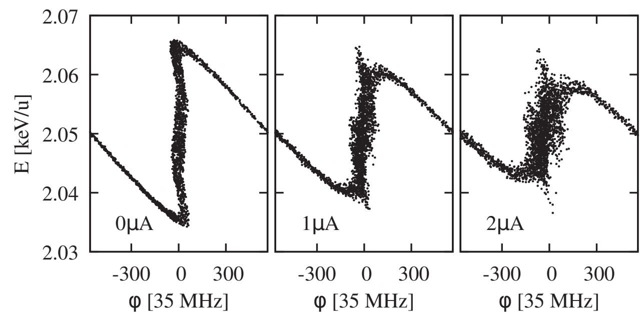

Figure 4: PARMELA simulated A/q = 30 beam using 2000 particles, showing the effects of space charge at the entrance of the RFQ at different averaged beam currents.

ISAC RFQ

Simulations of the RFQ using the code PARMTEQ were used for the ISAC design [5] and have had good agreement with the as-built linac [4]. Much of the original software, coded for DEC machines, has been ported over to unix for this work. The PARMTEQ RFQ is defined in three separate sections. The entrance radial matching section (RMS) and transition cell, in addition to the high-energy cells and exit transition cell are independantly modelled using `relax3D` on a discretized grid, while the main sequence, corresponding to the 193 consecutive accelerating cells are generated by PARMTEQ.

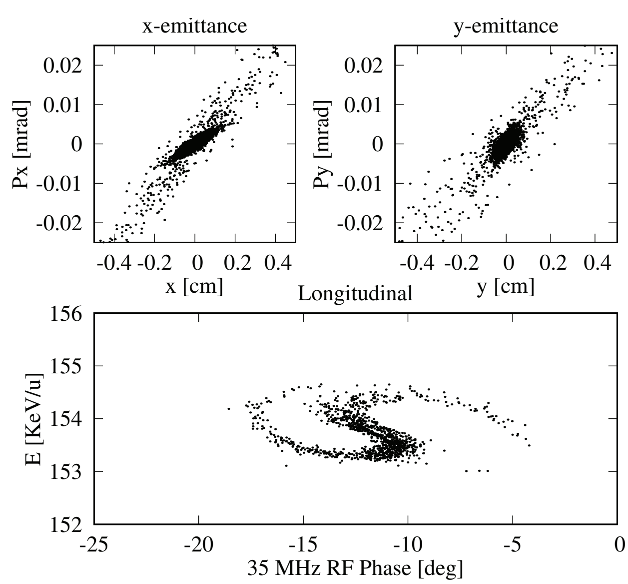

Figure 5: PARMTEQ simulated A/q = 30 beam using 3000 particles, accelerated through ISAC RFQ.

In all, the ISAC RFQ has 198 cells. A/q = 30 beam, injected as shown in Fig. 2, has been accelerated through the linac and the output is shown in Fig. 5, producing good agreement with initial design simulations [6]. PARMTEQ has been modified to extract RMS quantities such as the transverse and longitudinal beam envelopes. The modifications enable cell-by-cell extraction of

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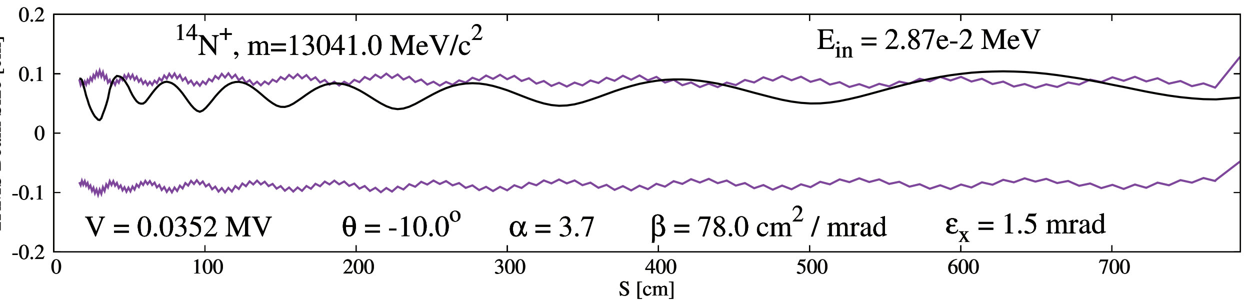

Figure 6: PARMTEQ simulation of an $^{14}N^{+}$ beam, injected at 28.7 keV and accelerated to 2.142 MeV. V denotes the vane voltage, θ the RF injection phase offset in 35.4 MHz degrees, α, β & ε are the input Twiss parameters. The x & y envelope are the upper and lower purple curves, while the longitudinal envelope, divided by 10, is in black.

the full 6-dimensional bunch properties. An example PARMTEQ transverse and longitudinal RMS envelope for a $^{14}N^{+}$ beam accelerated through the RFQ is shown in Fig. 6.

ENVELOPE SIMULATIONS

Tackling online transmission issues requires an efficient model, ideally with subsecond execution time. While the multiparticle simulations effectively simulate bunch dynamics, their execution time is slow, frequently necessitating several minutes per run. Developing an end-to-end simulation for online tuning therefore necessitates a faster approach.

TRANSOPTR Expansion

The second order beam transport code `TRANSOPTR` is heavily used at TRIUMF and has been continually updated [7] since its original implementation by Heighway & Hutcheon at Chalk River National Laboratories. Further, a prescription exists for linear accelerators with axially symmetric fields [8]. The principal challenge of developing an end-to-end simulation for ISAC-I is the RFQ, given the broken symmetry of the quadrupole electric field. Work toward this goal is ongoing, based on the Hamiltonian formalism for charged particle in linear accelerators [9]. The advantage of an envelope code is the running time of simulations, typically below one second for a linac and transport line, versus several minutes, or even hours for PARMELA/PARMTEQ.

HLA Integration

The TRIUMF High-Level Application (HLA) framework is being developed to enable feedback between operations and beam physics, using a web based platform [10]. Another benefit of having a `TRANSOPTR` based model is the ability to pull realtime data from the EPICS control system and produce a live beam simulation. The possibility of an end-to-end model driven by live data further enables the development of an online diagnostic system with corrective feedback, which may be used to mitigate transmission variation effects as shown in Fig. 1.

CONCLUSION

Transmission variation issues at ISAC-I are an ongoing challenge in the endeavour to maximize facility efficiency and output and have motivated the development of an end-to-end model. Multiparticle simulations currently span the pre-buncer to RFQ and will benchmark ongoing work toward the extension of `TRANSOPTR` to the ISAC-I linacs. This implementation has the potential to result in a realtime simulation, using live element values, in addition to aiding in the study of temperature-transmission effects.

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