12th Int. Beam Instrum. Conf.
ISBN: 978-3-95450-236-3
IBIC2023, Saskatoon, Canada
ISSN: 2673-5350
JACoW Publishing
doi:10.18429/JACoW-IBIC2023-TUP007

USE OF THE ISAC-II FLIGHT TIME MONITORS TOWARD AUTOMATED TUNING

S. Kiy*, P. Jung, T. Planche, O. Shelbaya, V. Verzilov, TRIUMF, Vancouver, BC, Canada

Abstract

A time-of-flight measurement system has been in use at ISAC-II since 2006 for the phasing of cavities and accurate ion beam velocity measurements across the nuclear chart. This system is heavily relied upon as the primary energy-time domain diagnostic downstream of the ISAC-II linac. Ongoing High Level Applications (HLA) development at TRIUMF has enabled the use of methods that are being applied to these measurements - both for processing and automation of data acquisition. An update will be provided on operational experience with the system over the past 10 years including its recent re-calibration and error analysis. A brief summary of the current HLA framework will be given, including a database for beam measurements and the ability to carry out sequential measurement processes. Finally, the way in which these developments enable beam-based calibration of cavity parameters and a shift to model-based tuning methods is discussed.

INTRODUCTION

The present configuration of the ISAC-II linac was installed in two phases, in 2006 [1] and 2010 [2]. Each phase consists of 20 superconducting quarter wave resonators designed to provide a total effective voltage of 40 MV for the full linac. Phase-I houses two cavity types ($\beta = 0.057$ and $\beta = 0.071$) and consists of 5 cryomodules, while phase-II has a single cavity design ($\beta = 0.110$) and consists of 3 cryomodules. Each of the eight cryomodules houses a single superconducting solenoid which provides transverse focusing to the beam. The primary diagnostic devices for measurements of beam velocity and phasing of cavities are three flight time monitors (FTMs) downstream of the ISAC-II linac. The FTMs were originally installed in 2006 [3] and later upgraded in 2011 [4] to have allow their positions to be adjustable with respect to the ion beam.

Shown in Fig. 1, these diagnostics are composed of a 50 µm wire aligned along the axis of a grounded cylinder, with a negative bias of ~2 kV applied to the wire. The full cylinder is actuated at 45 degrees from horizontal into the beam, and the ions induce emission of secondary electrons from the wire. These secondary electrons move away in the electric field and are detected by a micro channel plate (MCP) detector with a time resolution of better than 100 ps.

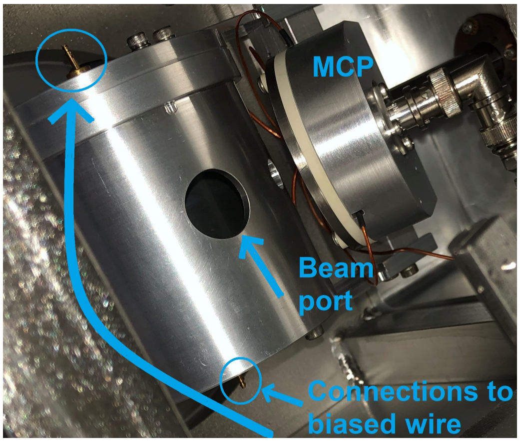

Figure 1: ISAC-II Flight Time Monitor Canister showing beam port and MCP.

OPERATIONAL EXPERIENCE

Maintenance

The FTMs have been regularly used since they were last upgraded in 2011. During this time they have been regularly used both for time of flight (TOF) measurements for calculating the beam velocity, as well as for setting cavity phases during setup to experiments (phase-TOF scans). The latter technique can be a fairly time consuming way to set cavity phases, and with ISAC-II typically serving between 5 and 10 experiments per calendar year, the FTMs can often end up being used for a total of 100 hours or more per year.

These monitors have proven to be very reliable over the past 12 years. The only major repairs required over this time has been the replacement of two of the three MCPs in 2016, and the replacement of the tungsten wires due to increased signs of field emission which can cause damage the MCPs.

Calibration

A calibration laser was installed in 2011 to measure and correct for small discrepancies of delays in cables of the three separate monitors [4]. While it was initially envisioned routinely re-check the calibration, the process was only repeated just recently during the first half of 2023. The same procedure described in Ref. [4] was carried out to measure the arrival time of the laser at each of the three monitors, with the resulting TOF spectrum shown in Fig. 2. Shown below in Table 1, the recent calibration indeed showed small changes in the timing offsets relative to the typical flight times between the monitors.

The change in calibrations in Table 1 is attributable to 2016 maintenance of the system, during which monitors were removed and MCPs replaced. Plotting the relative

---

* spencerkiy@triumf.ca

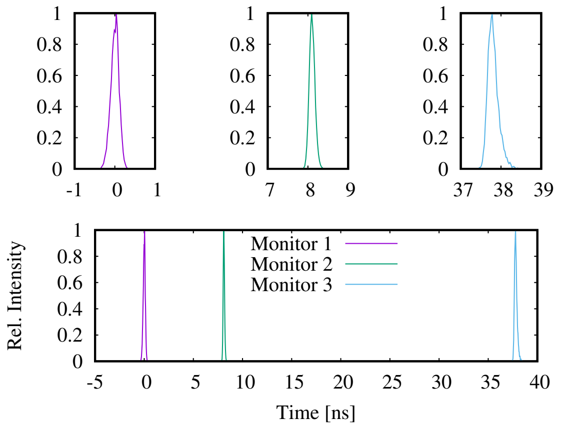

Figure 2: Time-of-flight measurement of the calibration laser.

Table 1: Summary of changes in FTM offsets, measured with respect to the first monitor.

FTM	Change [ns]
2	-0.7
3	+0.04

difference of velocities calculated between different pairs of monitors (V_{12}, V_{23}, V_{13}) supports this, as it shows a step function in the difference at the same date the work was done.

Low Intensity Measurements

Since 2020, the FTMs are now in regular use to measure low intensity radioactive beams prior to delivery to experiments. An example of the TOF measurement for a ^{20}Mg beam in 2023 is shown in Fig. 3.

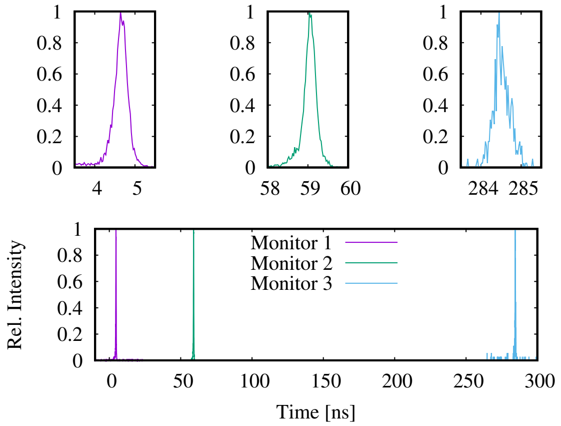

Figure 3: Time-of-flight measurement of a beam of ^{20}Mg^{6+} at an intensity of 9×10^3 /s.

These monitors have in principle been capable of measuring intensities down to as low as 10^4 ions/s since their initial installation in 2006. However in practice this was not done regularly until 2020. The new method for low intensity TOF measurements is:

1. Establish a tune with a stable beam at the desired energy.
2. Carefully document the necessary positions of the FTMs for the established tune.
3. Scale the tune and switch to the radioactive beam.
4. Set MCP bias to its maximum allowable voltage and restore FTM positions to their established values.
5. Collect for extended periods of time (up to 30 minutes).

Using this method, the energy of radioactive beams of ^{11}Li at 8×10^3 /s, ^{59}Cu at 5×10^3 /s, and ^{20}Mg at 9×10^3 /s have been successfully measured so far.

UNCERTAINTIES AFFECTING FTM MEASUREMENTS

During the recent 2023 laser calibration, data was also collected to further investigate the uncertainties involved in the FTM measurements. Previous data collected in 2022 [5] for repeat measurements of a beam of ^{20}Ne^{4+} showed non-negligible deviations in calculated beam centroids at the three monitors. This deviation increased when the transverse positions of the monitors were moved and there was a clear correlation observed between FTM position and beam centroid for all three monitors as shown in Fig. 4.

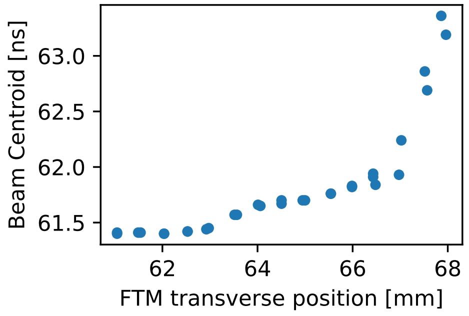

Figure 4: Correlation between transverse position of FTM with measured beam centroid for a ^{20}Ne^{4+} beam.

As it can be difficult to assess whether the changes in centroid were due to drifts and correlations in the beam, some repeat measurements were carried out with the calibration laser for comparison to ^{20}Ne^{4+} data from 2022. The resulting deviations in beam centroids at the three different monitors are shown in Tables 2 (for ^{20}Ne^{4+}) and 3 (for calibration laser).

Table 2 shows a significant increase in deviation when the FTM positions are varied vs fixed. This is apparent for both cases of the ISAC-II linac off, and ISAC-II linac on (bunching cavity and 37 SC quarter-wave cavities on). In contrast to this, the measurements with the laser show a much smaller

ISBN: 978-3-95450-236-3 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2023-TUP007

Table 2: Standard deviation of repeat measurements of the time centroid of the ^{20}Ne^{4+} beam at each of the three FTMs under various conditions in 2022 (reproduced from Ref. [5]).

Measurement	σ_1 **[ps]**	σ_2 **[ps]**	σ_3 **[ps]**
Linac off, static FTMs	300	300	400
Linac off, moving FTMs	700	700	800
Linac on, static FTMs	20	30	70
Linac on, moving FTMs	70	170	90

Table 3: Standard deviation of repeat measurements of the time centroid of the calibration laser at each of the three FTMs under various conditions in 2023. The conditions of the laser are identical in each of the three cases.

Measurement	σ_1 **[ps]**	σ_2 **[ps]**	σ_3 **[ps]**
Static, over 2.5 hrs	6	0	5
Static, over 8.3 hrs	27	5	17
Moving, over 1.7 hrs	16	4	9

deviation. Although there does appear to be an increase in deviation if the monitor positions are varied, the effect is much smaller than for the beam-based measurements.

Based on this, the conclusion is that, due to the small amount of beam that the 50 µm wire of the FTMs intersects, it is likely measuring a real difference in the arrival time of different slices of beam as it is moved. There is a known chromatic bend in the upstream ISAC-I section that contributes to (x, E) coupling [6], which later due to the solenoids in ISAC-II is mixed with the y dimension. Further to this, the quarter-wave resonators in use at ISAC-II are known to have a phase dependent vertical steering effect [7], that while minimized may also be contributing to couplings between the transverse and longitudinal coordinates.

AUTOMATIC DATA COLLECTION

Automation

A High Level Application (HLA) task force was implemented at TRIUMF [8] in 2017 to try and automate various tasks where possible and to utilize real-time physics simulations to expedite machine configuration changes as well as improve reliability. This has led to the development of sequential measurements [9], which consist of a series of commands that are managed by the HLA server and sent to EPICS [10]. This allows for automated measurements that previously required highly repetitive manual changes and saving of data either by operators or beam physicists. One example of a task that this expedites are standard phase-energy scans of the ISAC-II quarter wave resonators either for calibration of cavity amplitudes, or for identifying the correct accelerating phase during setup to an experiment.

Beam Database

Also described in Ref. [9], a beam database (beamDB) has been developed which allows for a more structured and searchable way to catalog measurements of an ion beam at TRIUMF. Historically, built-in tools from EPICS and EDM (Extensible Display Manager) have been used to dump data from an EDM screen to a user-defined filename on a fileshare server. Intensity measurements were saved solely as HTML tables within an electronic logbook. This approach made it difficult for others to find past measurements, to identify which optics settings were in use for a measurement, or even to know the beam in use for a given measurement. In contrast to this, the implemented beamDB pairs the sequential measurement process with a way to save data, collecting multiple related diagnostic measurements together in a fixed format together with the entire machine state for each measurement. In reference to operation of the ISAC-II linac, this beamDB allows for saving of TOF profiles continuously throughout a phase-energy scan.

Future Work

The central part of the HLA framework is an internal web API for accessing EPICS. This web API handles multiple functions including: authentication, writing to EPICS, maintaining process variable (PV) monitors with EPICS, long-running sequential measurements, and read/write access to the beam database. An upgrade to the web API is underway that will modularize the code, separating many of the functions into different services that can be maintained and re-deployed independently. Along with this will be the addition of a new service to allow for optimization of EPICS PVs, that can then be run within a sequential measurement. This will be a significant improvement to the use of the ISAC-II FTMs, as it will allow the count rates on the FTMs to be maximized via optimization of their positions before each set of profiles is saved (Fig. 5).

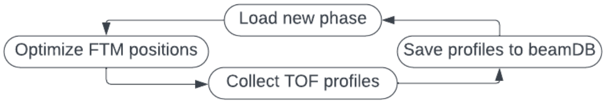

Figure 5: Sequential measurement process for collecting calibration data for ISAC-II cavities.

MODEL BASED PHASING OF ISAC-II LINAC

A recently completed MSc thesis [5] has utilized the FTMs and other work summarized in this paper to begin implementing model based phasing of the ISAC-II linac. This involved two main parts - the first was to collect phase-energy calibration data for each of the 40 cavities in the ISAC-II linac. From this, the scaling between the control system amplitude and the physical field of a cavity could be calculated, as well as the phase offsets of all cavities. These

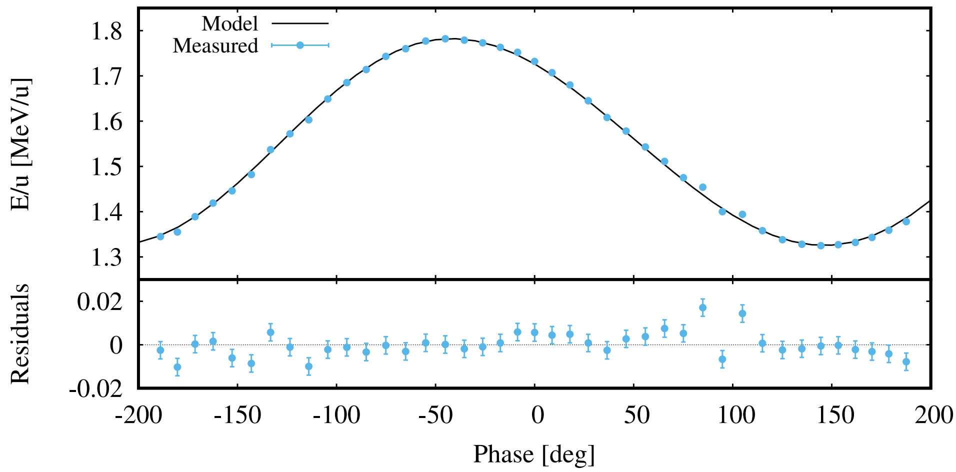

Figure 6: Energy-phase scan and resulting model fit for first linac cavity.

are then input into a model of the machine in an envelope code, `TRANSOPTR` [11]. This model was then used for the second part of this project, verification of the new approach - using the model to predict the necessary phases for given beam properties (mass, charge, input energy, and requested output energy).

The phase-energy calibration data during this work (and historically in general) has been difficult to collect due to the relative positioning of the FTMs with respect to the 40 linac cavities. The 40 cavities are spaced over approximately 18.6 metres, with the three FTMs at distances of 2.74, 4.93, and 13.99 metres downstream of the last cavity. There are no longitudinal diagnostics within the linac, and as a result the beam must be transported by up to 32.6 metres (in the case of the first cavity) between the cavity being adjusted and the last FTM. Further to this, the relative energy gain is quite significant at the start of the linac, with the first cavity increasing the beam energy by between 10 and 30%. For the first half of the linac, especially the first few cavities, this means that as the phase is changed, the necessary settings for the solenoids for transport are changing significantly due to energy alone, on top of which the RF focusing effect is changing by a non-negligible amount. The Facility for Rare Isotope Beams (FRIB), has implemented automated calibration of the linac model and instant phase setting [12] that has a number of similarities to the approach used at ISAC-II. However by contrast, FRIB has a BPM after each cryomodule, and a diagnostics-per-cavity number that is much higher than ISAC-II.

Recently, semi-automated phase-energy scans have been successfully tested, using the model to calculate necessary changes to optics as the phase is scanned, and automatically saving data before moving to the next phase. The only manual adjustments still in use were occasional optimization of the FTM positions and steering through the linac. This allows for much more detailed scans, such as that shown in Fig. 6, which in turn improve the accuracy of the model. The data shown in Fig. 6 took approximately one hour to collect compared to a manual scan for the same cavity a year early which took over four hours. The two calibrations taken one year apart using different ion beams and amplitude setpoints agreed to within 2%.

CONCLUSION

The flight time monitors in ISAC-II have been reliable diagnostics over the past 17 years for both measurement of the beam velocity as well as phasing of cavities. Recent calibrations have been done to ensure their continued accuracy, and various other improvements summarized here have contributed to their use in automated tuning tools. The ISAC-II flight time monitors are now being used to collect detailed phase-energy scans which are automated and saved to a beam database. The resulting calibrations from these detailed scans are expected to continue increasing the accuracy of the ISAC-II model and hence the model-based tuning techniques which rely on it.

REFERENCES

[1] R.E. Laxdal, “Commissioning and Early Experiments with ISAC II”, in *Proc. PAC’07*, Albuquerque, NM, USA, Jun. 2007, paper THXAB01, pp. 2593–2597. `https://jacow.org/p07/papers/THXAB01.pdf`

[2] M. Marchetto, “Commissioning of the 20MV Superconducting Linac Upgrade at TRIUMF”, in *Proc. PAC’11*, New York, NY, USA, Mar.-Apr. 2011, paper FROBN4, pp. 2570–2574. `https://jacow.org/PAC2011/papers/FROBN4.pdf`

[3] V.A. Verzilov, R.E. Laxdal, M. Marchetto, and W.R. Rawnsley, “Time Domain Diagnostics for the ISAC-II Superconducting Heavy Ion Linac”, in *Proc. DIPAC’07*, Venice, Italy, May 2007, paper WEPB07, pp. 247–249. `https://jacow.org/d07/papers/WEPB07.pdf`

[4] V.A. Verzilov, J. Lassen, R.E. Laxdal, and M. Marchetto, “Upgrade of the ISAC Time-of-flight System”, in *Proc. IPAC’11*, San Sebastian, Spain, Sep. 2011, paper TUPC065, pp. 1147–1149. `https://jacow.org/IPAC2011/papers/TUPC065.pdf`

[5] S. Kiy, "Automated Optimization of the ISAC-II Heavy Ion Linac," TRIUMF, University of Victoria, Tech. Rep. TRI-BN-23-15, 2023, `https://dspace.library.uvic.ca/bitstream/handle/1828/14955/Kiy_Spencer_MSc_2023.pdf`.

[6] O. Shelbaya, "Model Coupled Accelerator Tuning (PhD thesis)," TRIUMF, UVic Dept. of Physics & Astronomy, Tech. Rep. TRI-BN-23-04, 2023, `https://dspace.library.uvic.ca/handle/1828/14804`.

[7] A. Facco and V. Zvyagintsev, "Beam steering in superconducting quarter-wave resonators: An analytical approach," *Phys. Rev. ST Accel. Beams*, vol. 14, p. 070101, Jul 2011. `doi:10.1103/PhysRevSTAB.14.070101`

[8] C. B. Barquest *et al.*, "Web-Based Control Room Applications at TRIUMF", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 4832–4835. `doi:10.18429/JACoW-IPAC2018-THPML078`

[9] S. Kiy *et al.*, "Beam Tuning Automation Activities at TRIUMF," in *Proc. HIAT'22*, Darmstadt, Germany, Jun.-Jul. 2022, pp. 52–56. `doi:10.18429/JACoW-HIAT2022-TU2C4`

[10] L. R. Dalesio, A. Kozubal, and M. Kraimer, "Epics architecture," Los Alamos National Lab., NM (United States), Tech. Rep., 1991.

[11] R. A. Baartman, "Fast Envelope Tracking for Space Charge Dominated Injectors", in *Proc. LINAC'16*, East Lansing, MI, USA, Sep. 2016, pp. 1017–1021. `doi:10.18429/JACoW-LINAC2016-FR1A01`

[12] A. S. Plastun and P. N. Ostroumov, "Instant Phase Setting in a Large Superconducting Linac," in *Proc. NAPAC'22*, Albuquerque, NM, USA, Aug. 2022, paper THZD1, pp. 885–890. `doi:10.18429/JACoW-NAPAC2022-THZD1`