UNDERSTANDING THE ERROR TOLERANCES REQUIRED TO AUTOMATICALLY PHASE THE HIE-ISOLDE LINAC

M.A. Fraser*†, S. Haastrup, J.C. Broere, D. Lanaia, D. Valuch, D. Voulot, CERN, Geneva, Switzerland

Abstract

The broad experimental programme at ISOLDE, CERN means that the same radioactive beam species and energy are rarely studied twice and the cavities of the linac must be scaled or re-phased for each experiment. A software application was developed to automatically re-phase the cavities of the HIE-ISOLDE superconducting linac to the beam from computed settings. The application was developed to expedite both machine set-up in normal operation and in scenarios involving cavity failures. A beam dynamics error study will be presented in order to better understand the challenges facing the automatic phasing routine. The effects of a variety of different errors on the efficacy of the phasing application were studied, leading to a specification of the tolerances required for the calibration of the rf system and the accuracy of the survey system that monitors the positions of the cavities.

INTRODUCTION

The High Intensity and Energy (HIE) linac upgrade will provide post-accelerated radioactive ion beams of better quality at energies over 10 MeV/u to the ISOLDE user community at CERN. The linac is discussed in more detail in other contributions to this conference [1, 2] and further details on the HIE-ISOLDE project can be found in [3, 4].

The tuning of linear accelerators comprised of independently phased cavities is usually carried out with beam-based measurements. The changing beam energy is measured in response to phase shifts of the rf power feeding the cavities as they are turned on sequentially. This procedure can become time-consuming when large numbers of cavities are considered and when the settings must be adjusted for different beam species with different mass-to-charge (A/q) states, as will be the case in the operation of the HIE-ISOLDE linac. The number of cavities will increase from 7 to 35 after the upgrade of the Radioactive ion beam EXperiment (REX) post-accelerator. Therefore, in developing a software tool to calculate and set automatically the cavity phases, we are motivated by reducing the time required to set-up the linac in both normal operational circumstances and in failure scenarios when the performance of a cavity (or several cavities) drops or goes offline. In principle, one could manually set-up the machine with a set of intermediate charge states or 'pilot' beams and scale the linac settings to the mass-to-charge state of each isotope requested by the experimental programme, as must necessarily be done for fixed-velocity linacs and is presently done at REX. However, by tuning the superconducting linac in this way one can neither exploit the maximum accelerating voltage nor react quickly to cavity failures; a single cavity dropping offline would require that all downstream cavities are manually retuned. The re-phasing of the ISAC-II linac at TRIUMF has been successfully carried out using computed values [5]. In these proceedings we investigate the effects of each error source on the beam quality delivered to the experiments. This work builds on tests already carried out at REX where it was identified that further error studies were needed to understand the tolerances required for successfully phasing the extra cavities accompanying the HIE-ISOLDE upgrade [6].

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† mfraser@cern.ch

HIE-ISOLDE LINAC RF SYSTEM

The rf system, shown schematically in Figure 1, has been designed to minimise phase errors between cavities with the automatic cavity phasing concept in mind. An rf reference line distributing the 101.28 MHz master oscillator signal will run alongside the accelerator and for each cavity the reference signal will be extracted by a directional coupler and sent along with the cavity's pick-up signal via a standard cable bundle to the LLRF controller; all phase signals should be subject to similar drift effects [7]. The reference phase signals will be used to normalise the pick-up signals from the cavities. The absolute phase on the reference line is known from calibration with an expected accuracy of a few degrees, but in any case an initial beam-based calibration of the rf system is foreseen to check and correct any phase errors in the system. The beam-based calibration checks will require accurate beam dynamics simulations and diagnostics in order to identify the phase errors.

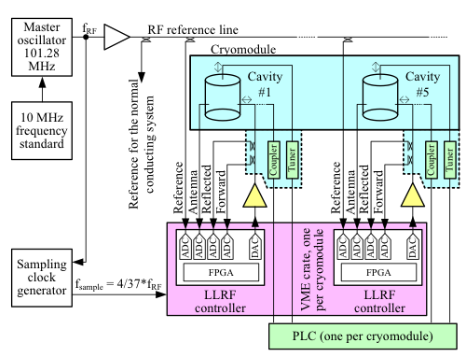


Figure 1: Schematic of HIE-ISOLDE rf system design.

SOFTWARE APPLICATIONS

A software application was written in object-oriented C++11 to simulate the longitudinal beam dynamics in the HIE-ISOLDE linac. In a first step, the cavities were modelled as thin lenses and the energy gain in each cavity computed using a second-order analytical expression, which takes into account small changes in beam velocity during acceleration through the cavity,

$$\Delta W \approx qVT(\beta)\cos\phi + \frac{q^2V^2}{W}\left(T^{(2)}(\beta) + T_s^{(2)}(\beta)\sin 2\phi\right),$$

where all symbols take their usual meaning and two additional transit-time factors are computed from the accelerating fields in the cavities [8]. To accurately compute the arrival time of the beam downstream of a cavity one must also apply a phase correction: $\Delta\phi = -\frac{q}{2}\frac{V}{W}(\sin\phi)\beta\frac{\mathrm{d}}{\mathrm{d}\beta}T(\beta)$. In a second step, the longitudinal equation of motion was solved numerically by integrating the particle motion in the accelerating fields. A benchmarking of the two approaches showed that although the analytical technique has the advantage of being computationally less demanding, it is not sufficiently accurate to calculate and set the cavity phases; phase errors of ~ 10 deg are accrued along the linac.

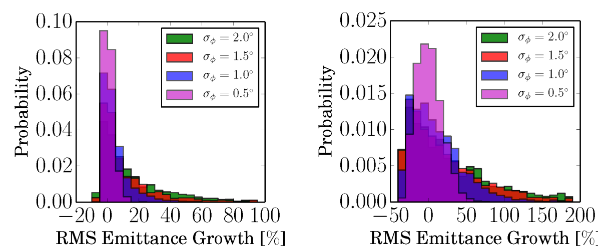
The two software models were adapted (i) for implementation in the accelerator control system and (ii) for error studies. The numerical routine was translated into Java and integrated into the CERN control system with different algorithms for partitioning the available voltage along the linac [9]. The operator can specify the input beam parameters, request the final energy and type of voltage partition and the cavity settings will be generated. The `C++11` software employing the analytical technique was extended to include multi-particle simulations and a range of different sources of error were introduced and studied. For the error studies, this routine was demonstrated to be adequate and was especially useful with multi-particle beams and large numbers of error seeds; it's speed was far superior to the routine incorporating the numerical integration of the equation of motion.

ERROR STUDIES

The linac was first simulated in the nominal case before being perturbed a large number of times from various sources of error, which were distributed with a Normal distribution, parameterised with the rms (σ) and truncated at $\pm 3\sigma$. The relevant sources of error fall into four broad categories: static or dynamic, and random or systematic. In the static case, each error seed represents a possible real-life scenario after the system is calibrated and the beam quality was assessed in terms of the rms longitudinal emittance given by that particular seed. In the dynamic case, each seed represents a snapshot in time and it was the time-averaged rms emittance, including particles from the entire ensemble of error seeds, which was used to parameterise the effective emittance that would be seen at the experiments. The effect of the errors depends on the A/q of the beam and therefore studies were carried out with different beams at the extremes of the A/q acceptance of the machine.[1] The studies were conservative and included all 32 superconducting cavities operating at the design gradient of 6 MV/m, which corresponds to beams delivered to the experiments at energies of 10 MeV/u for $A/q = 4.5$ and 16.6 MeV/u for $A/q = 2.5$. In addition, particles spilt from the bucket were not cut from the rms emittance calculation, enlarging the emittance growth in the seeds where a loss in transmission was registered.

Static, random errors

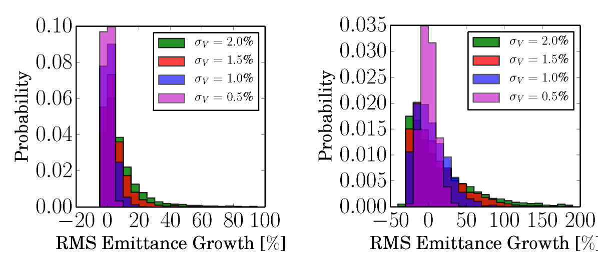
The effect of errors in the phase calibration of the rf system is shown in Figure 2, where the rms emittance growth (compared to the nominal case without error) from 4000 error seeds is plotted for beams with $A/q = 4.5$ and 2.5. Although the effect on 'heavy' beams is quite moderate, a phase calibration error of $\sigma_\phi = \pm 0.5$ deg is required to keep the probability of an emittance growth > 50 % insignificant for 'light' beams. This tolerance is considered challenging. For some error seeds the rms emittance growth is negative, indicating that the original tuning of the linac could be improved by finely adjusting the synchronous phases of each cavity. As an aside, one could consider this type of algorithm to set the optimum working point of the linac.



(a) $A/q = 4.5$ (b) $A/q = 2.5$

Figure 2: The rms longitudinal emittance growth caused by static, uncorrelated phase errors in the rf calibration.

As presented in Figure 3, the voltage of each cavity should be calibrated to within $\sigma_V = \pm 1$ % using the same criterion applied above, which is considered attainable.



(a) $A/q = 4.5$ (b) $A/q = 2.5$

Figure 3: The rms longitudinal emittance growth caused by static, uncorrelated voltage errors in the rf calibration.

In the same manner, the longitudinal position of the cavities should be known to an accuracy of better than $\sigma_z = \pm 0.5$ mm, as shown in Figure 4. This will also be challenging for the HBCAM [10] online alignment monitoring system, which was designed and optimised for the measurement of the transverse position of the active linac

[1] As the voltage of the superconducting cavities is held fixed and not scaled, the lower A/q beams are more sensitive to errors in the field level.

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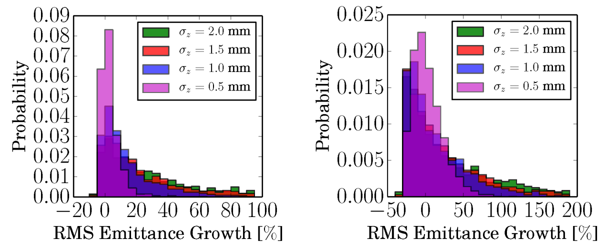
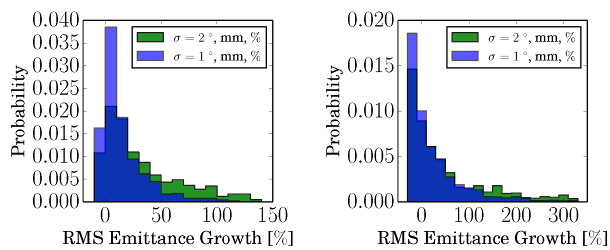
components. The system is expected to give a resolution in the longitudinal position of $\sigma_z \approx \pm 1 - 2$ mm, without further improvements.



(a) $A/q = 4.5$ (b) $A/q = 2.5$

Figure 4: The rms longitudinal emittance growth caused by static, uncorrelated errors in the position of each cavity.

The combined effect of static, random errors is presented in Figure 5. In all the cases presented, the average beam energy after the linac varied from the nominal energy by no more than $\sim \pm 2$ %, which can be compensated manually by adjusting the voltage of the last cavity. In principle, any longitudinal optics can be set up from simulation and applied using the software application, e.g. if a time focus is required or if de-bunching with low energy spread is requested by the experiments.



(a) $A/q = 4.5$ (b) $A/q = 2.5$

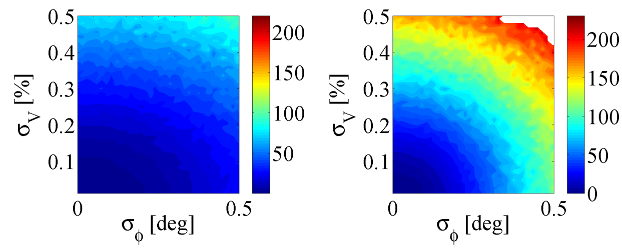
Figure 5: The rms longitudinal emittance growth caused by combined static voltage, phase and position errors.

Static, systematic errors

For static, systematic errors each cavity in a given error seed was designated the same error. The effect of systematic errors in the voltage and phase calibration of the rf system is generally smaller than for random errors and depends on the details of the longitudinal optics in each case. The calibration of the rf system can be probed using the beam by deliberately introducing systematic phase and voltage shifts and measuring the response of the beam [11].

Dynamic errors

Dynamic errors were considered in the rf system. In this case, we considered a fast-jitter of the master oscillator of $\sim$ Hz, which is comparable to the bandwidth of the cavity but far slower than the time it takes the beam to traverse the linac; the error on each cavity was therefore correlated. The effective (time-averaged) rms longitudinal emittance growth is shown in Figure 6. The rf system should remain stable to better than $\sigma_V = \pm 0.2$ % and $\sigma_\phi = \pm 0.2$ deg to control the effective rms emittance growth.



(a) $A/q = 4.5$ (b) $A/q = 2.5$

Figure 6: Effective rms longitudinal emittance growth [%] caused by dynamic, correlated rf jitter.

CONCLUSION

A software routine was written to automatically set the phases and voltages of the cavities in the HIE-ISOLDE linac from computed settings. Beam dynamics error studies were carried out in order to better understand the challenges facing the automatic routine. A worst-case scenario with all cavities operating at nominal gradient accelerating a beam of $A/q = 2.5$ produces a challenging specification, particularly on the required position and phase accuracy of the system. It is likely that most beams can be delivered automatically with only a moderate degradation in emittance, given that most post-accelerated beams at ISOLDE are heavy: ~ 80 % of beams delivered to date had $A/q > 3.5$ [12, 13].

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