RE-PHASING OF THE ISAC SUPERCONDUCTING LINAC WITH COMPUTED VALUES

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Abstract

The ISAC superconducting linac is a fully operational machine that routinely provides beam to experiments. The linac consists of twenty superconducting independently phased cavities housed in five cryomodules. The initial tune is done manually aided by MATLAB routines to phase the linac and set the correct optics. From the initial tune we calculate the gradient at which each cavity operates based on the energy gain, the transit time factor and the geometry of the cavity itself. Then in the event of a gradient change of one or more cavities we can calculate the RF phase shift of each downstream cavity using the initial gradients, the known geometry of the entire linac and assuming linearity of the RF controls. This possibility has been investigated and we have demonstrated that the calculated phase shift can be implemented automatically thus avoiding a complete retune of the machine. In this paper we will present the calculations and the results of the online tests.

INTRODUCTION

The ISAC facility at TRIUMF (Fig. 1) has at present the most intense driver available for ISOL based radioactive ion beams (RIB) production. The RIBs can be delivered to three experimental areas; one using the beam at source potential (60 kV), the other two using post accelerated beam.

In the ISAC I facility the beam is accelerated through a chain composed of an RFQ injector followed by an IH drift tube linac (DTL). The DTL is design as an energy variable machine [1] being able to deliver all the energies ranging between 150 keV/u and 1.8 MeV/u. The DTL injects also the beam in the ISAC II linac at 1.5 MeV/u.

In the ISAC II facility the beam is accelerated by means of a superconducting (SC) linac operating at 106.08 MHz [3]. The present installation of the SC linac is composed of five cryomodules each housing four superconducting cavities and one superconducting solenoid. The cavity voltages are set to operate each at a fixed power of 7W, for a total of ∼20MV of acceleration. The twenty cavities are independently phased at -25° synchronous phase in sequence starting from the first one. The number of cavities turned on determines the final energy. The tuning time for the SC linac can be as long as four hours although tuning algorithms are being developed to reduce this time. The ISAC II linac is going to be upgraded by the end of 2009 adding twenty more cavities housed in three cryomodules [2]. In this case there is an increased motivation to look for more tuning aids.

In order to maximize the integrated beam at the experiment it is essential to reduce the downtime as much as possible. One possible source of downtime is the retuning of the superconducting linac in case one cavity (or more) experiences a drop of the accelerating gradient. In this paper we call this generic event a cavity failure without specifying the cause. In this case it is possible to recalculate the difference in time of flight and hence the shift of the RF phase for each cavity downstream of the faulty one. In order to calculate the phase shifts we need to know the geometry of the linac, the transit time factor of the cavities and the accelerating gradients. The transit time factor is known from radio frequency simulations of the cavity geometry. The geometry of the linac is also known by design. The operating gradients of each cavity are calculated based on the energy gain measured from the initial tuning of the linac.

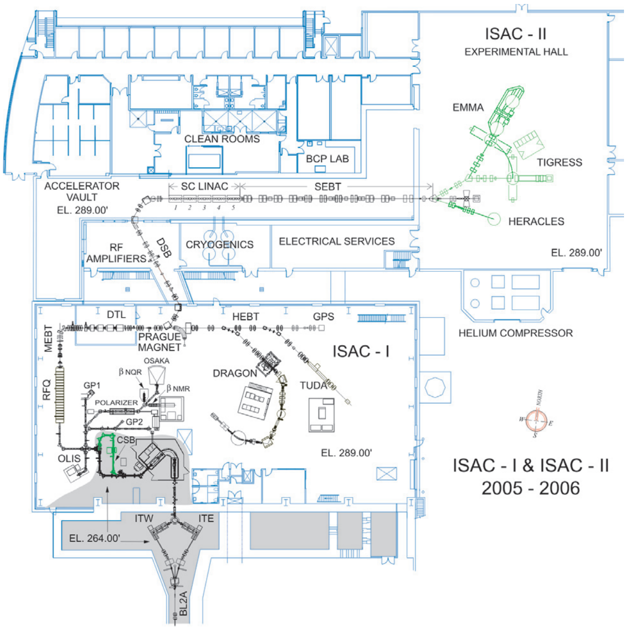

Figure 1: Overview of the ISAC facility at TRIUMF. The ISAC II linac is superconducting while in ISAC I they (RFQ and DTL) are normal conducting.

ONLINE MEASUREMENT

In order to validate the calculated values of the rephasing routine the first cavity is turned off and online RF phases are manually reset for the nineteen cavities downstream. Four separate runs are completed using different ion beams, meaning also that the energy gain after each cavity is different from one run to another due to different A/Q. These four series together with their original phase setting give the online phase shift for cavity one off. Fig. 2 represents the calculated time of flights (TOF) before and after cavity one failure for a $^{22}\mathrm{Ne}^{4+}$ beam. In the same figure the calculated phase shift, relative to the TOFs, are plotted as well as the measured (online) phase shift for the same type of ion. The comparison of the calculated versus the online values shows a discrepancy in some cases of more than ten degrees.

These discrepancies between the online (measured) and the calculated values are the phase errors of the calculated values themselves. The discrepancy data of the four runs are binned and the distribution of the binned phase errors is represented in Fig. 3; it has σ=6.5 deg.

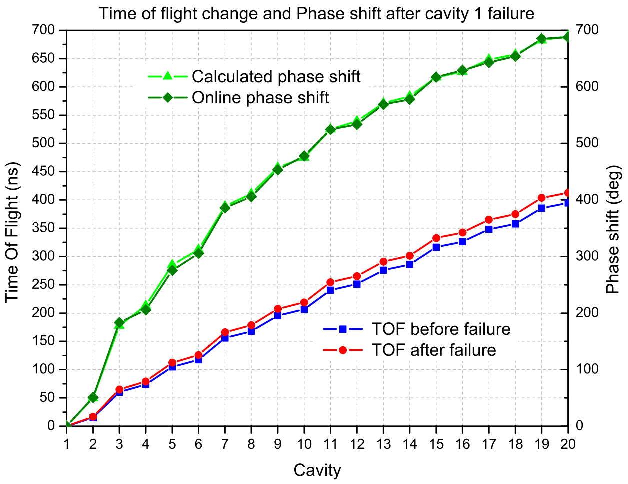

Figure 2: The plot represents the time of flights (TOF) before and after the failure for a $^{22}\mathrm{Ne}^{4+}$ beam. The relative phase shifts are also plotted together with the online measured phase shifts.

We can identify three possible sources of error for the discrepancy. First of all the distances between cavities have some systematic error. Second, the gradient of the cavities is calculated through the energy gain, and the measurement of the energy is affected by a random error. These two errors contribute to the error of the calculated values. In addition the rephasing routine assumes the cavity has no dimension meaning the acceleration happens instantly at the center of the cavity. Third, the phasing method we use [4], by cosine fitting the energy gain versus the RF phase curve, has also a random error estimated to be ±3°. This last error affects the phases set manually. Both series of phases (manual set and calculated) contain some uncertainties meaning none of them are the absolute RF phases. Nevertheless the online measurements can be considered as the actual values for the phasing the linac.

BEAM SIMULATION

In order to analyse the effect of the random phase error we simulate the longitudinal emittance growth for different cases. The phase errors distribution produced by the calculated values (see Fig. 3) is then associated to an emittance growth. The emittance growth is also compared with the acceptance of the linac. Both the emittance growth and the acceptance are estimated via simulation done with the LANA code [5].

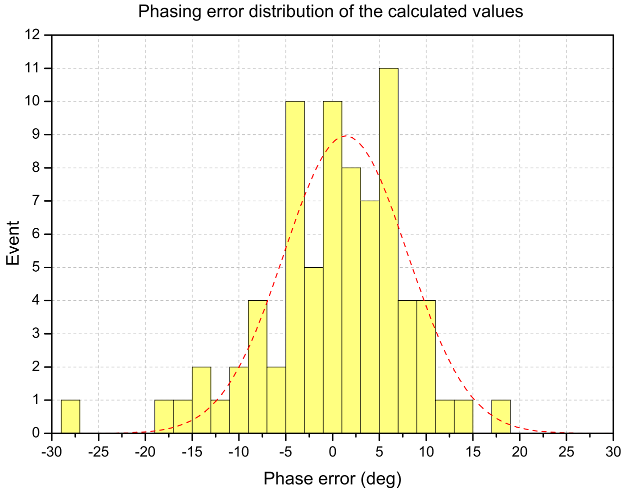

Figure 3: The plot shows the distribution of the phase error we commit when we use the rephasing calculated values. The distribution σ=6.5 deg.

The beam dynamics of the ISAC linacs are simulated using the LANA code. The LANA models of our linacs well match the online measurements at the machines. We therefore use this code model to characterized the SC linac in terms of emittance growth and acceptance of the linac. The ion we simulate has A=3, Q=1 and E_{in}=1.5 MeV/u.

Longitudinal Emittance Growth

The longitudinal emittance of the injected beam we use for the simulation is 1.5 π keV/u·ns (this emittance is the design one, the measured emittance of the real beam is around 1 π keV/u·ns).

The error we commit in the RF phase setting of the twenty cavities is assumed to be random with normal distribution centered around the synchronous phase we want to set, for us being -25°. In the simulations we consider four different distributions with σ values of 2.5°,5°,10° and 15° centered around -25°. For each distribution we run 300 seeds (each seed corresponding to a LANA simulation run) of twenty RF phase. For each seed we record the final emittance and the final energy. For each distribution we then collect the final longitudinal emittance distribution and the final energy distribution.

The energy distribution can be fitted with a gaussian curve and therefore characterize the spread of the final energy in terms of σ .

The longitudinal emittance distribution is instead asymmetric with a minimum value represented by the initial longitudinal emittance. In this case we calculate the rms value to characterize each error distribution.

The final results are plotted in Fig. 4. The longitudinal emittance growth is normalized to the initial emittance. In the graph it can be noticed that at 0° spread, meaning no error in the set up of the RF phase, the emittance slightly grows to a value of 1.04.

For σ=6.5 deg the emittance growth factor is ∼1.4.

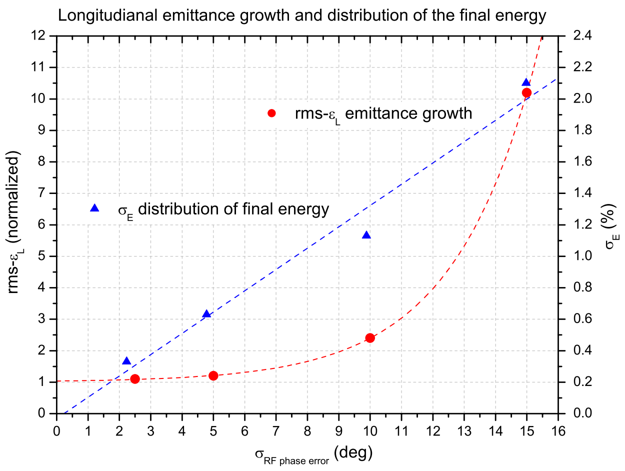

Figure 4: A plot of the longitudinal emittance growth and the spread of the final energy as a function of the RF phase error spread. The longitudinal emittance growth is normalized to the initial emittance.

Acceptance of the ISAC SC Linac

An estimate of the acceptance of the linac can be simulated by injecting a beam with a large longitudinal emittance and noting those particles that are transmitted to the end. The surviving particles are then mapped back to the original distribution.

The initial beam distribution for the simulation runs is uniformly distributed over 360 degree with a ±15% energy spread. The cavity accelerating gradient is set to 6MV/m.

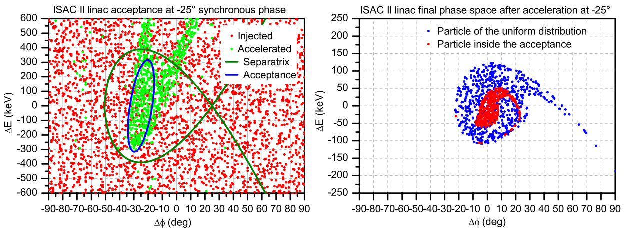

Figure 5: (Right) The red and green dots represent the injected and the accelerated particle of the initial phase space. The drawn ellipse is the acceptance. (Left) The phase space after acceleration at -25° synchronous phase. The final energy is 20.31 MeV. The red dots represent the accelerated particles inside the acceptance.

The acceptance is the maximum emittance that can be accelerated through the linac without loss. The acceptance is estimated fitting an ellipse to the initial reconstructed phase space. The acceptance and final phase space for -25° synchronous phase are represented respectively in Fig. 5.

The estimated acceptance at -25° synchronous phase is 22 π keV/u·ns. For comparison we recall that the measured longitudinal emittance of the injected beam is ∼1 π keV/u·ns. At -10° the estimated acceptance is 6 π keV/u·ns.

CONCLUSION

Based on the estimated emittance growth (see Fig. 4) we expect to have less than 50% emittance growth when using the calculated phase shift of the rephasing routine. This means that if ∼1 π keV/u·ns emittance is injected, a ∼1.5 π keV/u·ns emittance is expected at the exit of the linac. This longitudinal emittance is more than one order of magnitude lower with respect to the acceptance of the linac at -25°. The analysis shows that even though the rephasing values are affected by an error it is acceptable to rephase the linac in case of cavity failures. The first beam test using $^{22}\mathrm{Ne}^{4+}$ successfully demonstrated the utility of the rephasing routine.

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