BEAM QUALITY AND OPERATIONAL EXPERIENCE WITH THE SUPERCONDUCTING LINAC AT THE ISAC II RIB FACILITY

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Abstract

The ISAC II superconducting LINAC is now in the operational phase. The linac was commissioned with stable ion beams from an off-line source. The commissioning not only proved the integrity of the infrastructure but bench marked the beam quality and RF cavity performance. Measurements of the transverse and longitudinal emittance are consistent with little or no emittance growth through the acceleration. Transmission near 100% has been achieved though some solenoid steering is evident due to misalignment. An attempt at correcting the steering effect has been done. The machine is to be easy to tune, reliable in restoring beam and flexible enough to accommodate different tuning strategies. Software routines have been developed in order to facilitate the tuning process. In this paper the operational routine for tuning and beam delivery will be presented as well as the beam characteristics drawn from the commissioning studies.

INTRODUCTION

The new superconducting linac of the ISAC facility (see Fig. 1) is now in operation. The linac can deliver either radioactive or stable ion beams to the ISAC II experiments. Presently the medium beta section of this new linac is installed (the high beta section is foreseen to come online in 2009) composed of five cryomodules each containing four superconducting cavities and a superconducting solenoid.

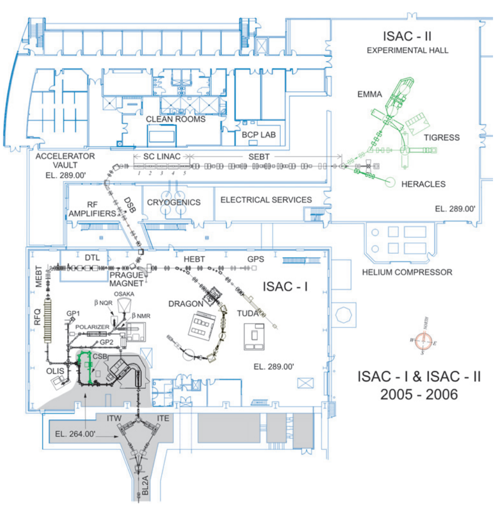

Figure 1: ISAC facility layout

The beam injected in the ISAC II linac is accelerated by the ISAC I accelerator chain. Here a radioactive ion beam, from one of the two radioactive targets (ITW or ITE), or a stable ion beam, from the off line ion source (OLIS), is accelerated first through an RFQ from 2 keV/u to 150 keV/u. A second stage of acceleration is achieved with a DTL capable to boost the beam up to 1.8 MeV/u. Both ISAC I accelerators are normal conducting machines. In order to be injected in the ISAC II linac, the beam is accelerated to 1.5 MeV/u in ISAC I and transported through a high energy transport line (DSB). The beam is bunched in time at the entrance of the superconducting linac by means of a buncher installed in the DSB section. The maximum final energy achieved is 10.8 MeV/u for A/Q=2. The number of cavities turned on sets the total voltage gain. Normally we reach the desired energy tuning the cavities, each one at its maximum voltage, sequentially . The voltage of the last cavity turned on is adjusted in order to reach the required final energy.

ISAC II DIAGNOSTIC

The cryomodule cold mass (four cavities and a solenoid) is suspended below the helium reservoir, attached to three points corresponding to three posts (A, B and C in Fig. 2) on the top of the cryomodule. The posts can be adjusted in order to align the cold mass with respect to the beam port of the cryomodule.

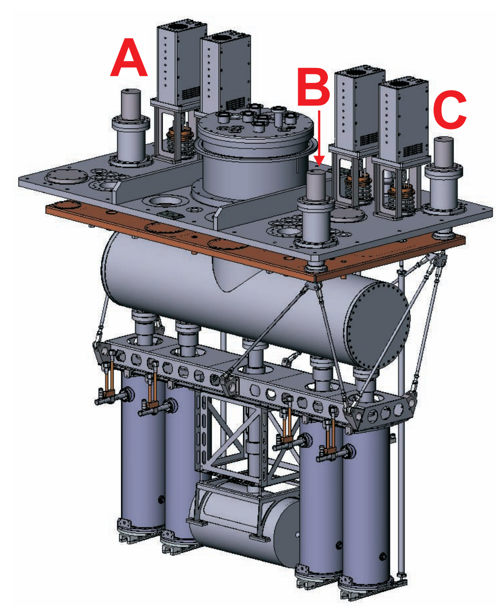

Figure 2: ISAC II cryomodule

Each cryomodule has a thin diagnostic box including a faraday cup (FC) and a linear profile monitor (LPM). The LPM consists of a plate with horizontal and vertical fixed apertures that is scanned across the beam by a stepping motor. The beam transmitted to the downstream intensity diagnostic gives the profile and the centroid of the beam. An LPM can also be driven and stopped in a reference position such as the beam axis. The first cryomodule has also a fast Faraday cup (FFC) that gives information on the time structure of the beam.

In order to phase the cavities we use a timing diagnostic consisting of a gold foil that scatters the particles toward a silicon detector (SID). The SID gives the energy and the time spectrum of the beam. The time resolution of the SID is 49 ps/channel. The spectra are fitted with a gaussian curve generated by a MATLAB application. The fit gives the peak and the σ of the distributions.

The energy of the beam is measured with a time of flight (FTM) system consisting of three monitors (during commissioning only the actual last two monitors were available). The distances between the monitors are respectively 2.1927 m and 9.0711 m apart. The data acquired by the monitors are compared with the 11.78 MHz RF signal (bunching frequency) corresponding to a bunch period of 85 ns . The time distribution coming from the three monitors are fitted with a gaussian (as for the SID) and then used to calculate the three time of flights (TOF) between the monitors.

The final energy is calculated weighting the three energies with the inverse square of the absolute energy error ϵ (see Eq. 1). Each ϵ is calculated using the time spread δ relative to one standard deviation (1 σ) of the gaussian fit (see Eq. 2) The three ϵ are also used to attribute the error $\epsilon_{\overline{E}}$ to the final energy (see Eq. 3).

$$\overline{E} = \frac{E_{12}/\epsilon_{12}^2 + E_{23}/\epsilon_{23}^2 + E_{13}/\epsilon_{13}^2}{1/\epsilon_{12}^2 + 1/\epsilon_{23}^2 + 1/\epsilon_{13}^2} \quad (1)$$

$$\epsilon_{12}^2 = \frac{\delta_1^2 + \delta_2^2}{\mathrm{TOF}_{12}^2} \cdot E_{12}^2 \quad (2)$$

$$\epsilon_{\overline{E}}^2 = \frac{1}{1/\epsilon_{12}^2 + 1/\epsilon_{23}^2 + 1/\epsilon_{13}^2} \quad (3)$$

Downstream the superconducting linac there is an emittance rig (designed by DANFISYK) used to measure the transverse emittance. The rig is composed by an slit and a harp 1.615 m apart. They move synchronously by means of stepping motors and they are capable of both horizontal and vertical plane measurements. The harp consist of fifteen 0.005 inches diameter wires spaced 0.8 mm apart.

LINAC TUNING PROCEDURE

The ISAC I linac [1] acts as injector for the ISAC II linac, accelerating the beam to 1.5MeV/u with an energy spread of ∼0.4% and a time spread of <1 ns. The tuning procedure for the ISAC I linac is not part of this paper.

The SID is the diagnostic we use to tune the ISAC II linac. Usually we consider the energy spectrum provide by the SID, but the time spectra have been used in some cases.

First we set up the DSB buncher. The RF phase is chosen for no acceleration meaning a synchronous phase of -90°. The amplitudes is chosen in order to minimize the time spread (typically <1 ns) at the linac entrance.

The cavities are then tune sequentially. The voltage of each cavity is normally set to the maximum allowed for stable operation. The phase is set using the SID. We follow a routine to find the phase that consist in collecting five energy gains correlate to five RF phase. These values are plotted on a energy gain versus phase graph and fitted with a cosine curve to give 0° synchronous phase and hence the operating phase of -25°. This phasing routine is going to be implemented in a semi automatic software developed with MATLAB. The tuning of twenty cavities requires ∼4 hours.

The downstream high energy transport line (SEBT) is tuned using calculated values for the quadrupoles. A MATLAB routine is already in place to upload the calculated values based on the accelerated ion. The transmission through the linac and the SEBT line is ∼100%.

It is possible to tune the linac missing one or more cavities. This is important in case of deficiency of one of these. When the number of cavities turned on are less than twelve, we can use a downstream cavity to bunch the beam (in energy or time) at the experiment (a proper buncher downstream of the linac is foreseen). When we change ion, and therefore A/Q ratio, we can rescale the voltage of each cavity without retuning the linac.

ISAC II LINAC PERFORMANCES

The medium beta ISAC II cavities are designed to perform at 6 MV/m at 7W of cryogenic power (ISAC specification). Pre installation tests done on each single cavity show performances equal or above specification, reaching an average gradient of 7.6 MV/m at 7W [2]. When installed online the cavities maintain good performance with an average gradient of 7.2 MeV/u. After one year from the installation we have accumulated many results from commissioning and gained operative experience.

Commissioning Result

In the second half of 2006 we completed the commissioning. Beam quality measurements of transversal and longitudinal emittance are carried out besides acceleration test. Final energies reached are in line with the previous results [2].

The transverse emittances for $^{20}\mathrm{Ne}^{5+}$ is measured. These are consistent with the values measured for $^{4}\mathrm{He}^{1+}$ in the first part of commissioning [4]. The results for both measurements are listed in Table 1.

We estimate the longitudinal emittance as well. We use three timing monitors: the SID, the second and the third time of flight monitor. After acceleration the bunch drifts in the SEBT line through the three monitor in absence of any accelerating field. Using the time spread measured at each

Table 1: Transverse normalized emittances for $^{4}He^{1+}$ and $^{20}He^{5+}$

$^{4+}$He^{1+}			$^{20+}$Ne^{5+}		
Energy (MeV/u)	ε**x** (π·**mm**·**mrad**)	ε**y**	**Energy (MeV/u)**	ε**x** (π·**mm**·**mrad**)	ε**y**
n/a	n/a	n/a	1.509	0.07	0.08
2.674	0.18	0.17	2.612	0.06	0.13
3.761	0.12	0.18	3.622	0.09	0.12
4.748	0.11	0.17	4.613	0.10	0.16
5.841	0.11	0.18	5.516	0.07	0.20
6.778	0.10	0.18	6.475	0.11	0.19

monitor we calculate the Twiss parameters of the longitudinal phase space. The first estimation of the longitudinal emittance gives a value ∼1 keV/u·ns.

Operational Experience

In January 2007 the ISAC II accelerator delivered the first radioactive beam ($^{11}Li^{2+}$) to an experiment (MAYA). The experiment was scheduled in January and in May after the winter shutdown [3]. In the first running period we accelerated to 3.6 MeV/u using eleven of the twenty cavities at an average gradient of 7 MV/m.

In May, after the shutdown, the cavities performance were consistent with the previous period. We accelerated 3.6 MeV/u with thirteen cavities at an average gradient of 6 MV/m. This level guarantied more stability for a long run (five weeks) experiments. In this second phase the experiment requested also to run at 5MeV/u (maximum allowed by license). In order to reach this energy we tuned all twenty cavities at 6.2 MV/m average gradient.

During the run we experience an instability problem with cavity number nine. This cavity was turned off and the downstream ones retuned to a higher gradient. The average gradient of these cavities went from 6.5 MV/m to 7 MV/m. The overall average remained the same. This demonstrate a great flexibility in the tuning strategy of the machine.

The same experiment requested also a different ion, $^{9}Li^{2+}$, at the same energy of 5 MeV/u. We reduced the gradient of all nineteen cavities according to the A/Q ratio, meaning a reduction of ∼20%. The scaling worked successfully requiring no further tuning.

The first experiment demonstrates that the linac is stable over a long run (five weeks).

SOLENOID MISALIGNMENT INVESTIGATION

Each cryomodule solenoid is aligned, in a clean room assembly area, with respect to the cryomodule beam ports. The cryomodule is then aligned in the vault with respect to the laboratory frame.

Beam measurements show that ramping the solenoid moves the beam profile shown by the LPM. To investigate and try to improve the alignment we decided to use the beam as a diagnostic tool.

The beam axis is defined by the LPM center positions for the horizontal and vertical planes. Starting from cryomodule 1 we stop the LPM upstream and downstream in the horizontal position first, in the vertical later, and align the beam with the solenoid current at zero. The current is then ramped in 10 A step up to 60 A and the profile of the beam is recorded. The cold mass can be moved with respect to the cryomodule by means of the support posts (see Fig. 2). We characterize different post movements in order then to make the right choice trying to reduce the steering effect. In particular for the first cryomodule, and relative solenoid, we needed four different post settings in order to characterize them and three more settings to reach a reasonable reduction of the steering effect. The same procedure have been applied up to now to the first four cryomodules.

The procedure is still being developed.

FINAL COMMENTS

Many developments are underway to improve the quality of the delivered beam. Software routines are being implemented using MATLAB.

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