Development of a Silicon Detector Monitor for the HIE-ISOLDE Superconducting Upgrade of the REX-ISOLDE Linac

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Abstract

A silicon detector monitor has been developed and tested at REX-ISOLDE in the framework of the R&D program for the HIE-ISOLDE superconducting (SC) linac upgrade. In the future setup the monitor is intended to be located downstream of the cryogenic SC modules, for beam energy and timing measurements and for the SC cavities phase scanning. In this very first test a passivated ion implanted silicon detector, suited for charge particle spectroscopy, was mounted inside a REX diagnostic box, downstream of the 9-gap resonator. A strongly attenuated stable ion beam with a mass-to-charge state (A/Q) of 4, mainly composed of $^{12}\text{C}^{3+}$, $^{16}\text{O}^{4+}$, and $^{20}\text{Ne}^{5+}$, was used for the tests. The energy measurements carried out allowed for beam spectroscopy and ion identification with an energy resolution of $\sim 3\%$ FWHM. The energy identification of the stable beam was suited for a rapid scan of the cavity; a procedure which could be demonstrated for the third 7-gap cavity. The time structure of the beam, characterized by a 9.87 ns period, could be reconstructed with the time resolution of 200 ps.

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1. Introduction

In the framework of the High Intensity and Energy (HIE)-ISOLDE project [1] for the superconducting upgrade of the REX linac at CERN, an R&D program has been launched including also beam diagnostics developments. A staged construction of a superconducting linac based on sputtered quarter-wave cavities is foreseen downstream of the present normal conducting linac [2]. For beam diagnostics purposes a solid-state detector is in development to be placed downstream of the superconducting modules.

The phase of the Radio Frequency (RF) power fed to the accelerating cavities needs to be accurately set to ensure the beam is efficiently and stably accelerated. The standard procedure of tuning the RF phase relies on relative measurements of the average beam energy downstream of the cavity. The synchronous phase is set relative to the phase at which the average beam energy is maximized by tracking its sinusoidal modulation as a function of phase. At REX the average beam energy is measured using the dispersion developed in the switchyard dipole magnet, which is calibrated by assuming that the average beam energy at output from the Radio Frequency Quadrupole (RFQ) is 300 keV/u. The dipole magnet field needed to keep the beam centered in a Faraday cup on a beam line after the magnet is recorded as a function of the RF phase. To leading order, the change in dipole field is proportional to the change in beam velocity. Such a procedure is robust and reliable but is time consuming and difficult to automate. The number of cavities used to post-accelerate ions at ISOLDE will increase from 5 to 34 with the HIE upgrade, motivating the development of a quick, and eventually automated, solution for tuning the phases of the SC cavities.

In this framework a silicon monitor prototype has been tested in a diagnostic box of the REX linac, downstream of the 9-gap resonator. The purpose of this test was the investigation of the monitor performances in terms of cavity phase scanning and longitudinal beam profile measurements.

2. Silicon Detector Monitor Setup

2.1. PIPS silicon detector

The monitor consists of a 300 μm thick partially-depleted Passivated Implanted Planar Silicon (PIPS) detector manufactured by Canberra (TMPD50-16-300RM), suitable for charged particle spectroscopy, see Fig. 1. It is characterized by an area of 50 mm$^2$, corresponding to an active diameter of ~8 mm, and an entrance window thickness of 100 nm. The detector is supposed to stop the beam particles so that their total energy is measured. SRIM simulations show that heavy ions, from helium to uranium, with energies up to 3 MeV/u, are in fact stopped within a 100 μm thickness. The quoted detector capacitance and leakage current are respectively 29 pF and 4 nA (at 20°C). The recommended bias voltage is 60 V. The quoted value for the electronic noise (pulsar line) at 20°C is 5.8 keV at full width half-maximum FWHM, while the quoted alpha resolution at 20 °C is 14.3 keV FWHM for $^{241}$Am 5486 keV alphas, using standard electronics and 0.5 μs shaping time. The nominal timing resolution is claimed to be 140 ps, as improved by the presence of a 20 nm aluminum layer at little expense to the entrance window thickness and the energy resolution. The custom-made
mechanical support holding the detector and the temporarily modified internal structure of the diagnostic box are shown respectively in Figs. 2 and 3. The silicon support temporarily replaced the aluminum foil normally used for the generation of secondary electrons detected by a Multi-Channel Plate (MCP) for beam profile monitoring [3]. The actuators normally used to move the aluminum foil in the “in” and “out” positions, i.e. intercepting the beam or not, were then exploited for the proper handling of the silicon detector. The Faraday cup is located on the actuator in front of the silicon detector, which can be used to monitor the beam current during setup and to stop the beam to protect the silicon. The detector was connected to a diagnostic box feed-through by means of a radial microdot connector and a 20 cm vacuum-compatible Habia kapton-insulated coaxial cable. The detector housing was grounded by electrical connection to the mechanical support and therefore to the diagnostic box itself. As the feed-through was not ground-isolated, the shielding of the coaxial cable was cut at the feed-through in order to avoid ground loops and related electromagnetic disturbances.

The described setup was installed at first in diagnostic box DB6, downstream of the REX switchyard magnet on the 20° beam line. In order to get rid of some mechanical misalignment problems and the effects of dispersion, the monitor was moved into diagnostic box DB5, located before the dipole magnet downstream of the 9-gap resonator [4]. Unless otherwise stated, all the measurements described in this paper were acquired in this final position.

Fig.1. Canberra PIPS silicon detector. Fig.2. Silicon detector in its mechanical holding.

Fig.3. Internal structure of REX diagnostic box as modified by the presence of the silicon detector.
2.2. Charge-sensitive preamplifier

A charge-sensitive preamplifier was connected to the feed-through outside the diagnostic box. It is a Canberra Model 2003BT charge sensitive FET-input preamplifier, see Fig. 4, providing at the same time an energy output signal, proportional to the input charge released by the silicon detector, and a timing output signal, derived from the main energy signal through a pulse shaping network, see Fig. 5. As shown in Fig. 6, the characteristic energy output response is a positive exponential pulse with fast rise time (<12 ns at $C_{det}=0$pF) and an exponential decay time constant of about 250 $\mu$s. The energy-to-voltage conversion factor (preamplifier sensitivity) is 20 mV/MeV with an input energy dynamic range of 500 MeV. The preamplifier electronic noise contribution is quoted to be < 2 keV FWHM at $C_{det}=0$pF with a slope of 10 eV/pF. The timing output is a negative rectangular pulse of constant amplitude (about 150 mV) with a very fast trailing edge (< 3 ns) and a width proportional to the rise time of the corresponding energy output. A test-bench characterization of the preamplifier has been performed, which confirms the quoted specifications, with a measured minimum noise level of 2.2 keV FWHM at $C_{det}=0$pF and 3 $\mu$s shaping time.

![Charge-sensitive preamplifier](image1)

![Preamplifier circuit scheme](image2)

![Preamplifier energy and timing output](image3)
3. Energy measurements

3.1. Signal processing and DAQ setup

The monitor electronics and data acquisition setup is shown in the block diagram of Fig. 7. The different elements are described in this section and in section 4.1. The preamplifier energy output signal is processed by an NIM Ortec shaping amplifier Mod. 572. The exponential shape of the preamplifier signal is converted into a semi-Gaussian shape for signal-to-noise ratio optimization. The time constant for the pulse-shaping filtering (the so-called shaping time) can be selected from 0.5, 1, 2, 3, 6, and 10 μs, as presented in Fig. 8. The shaping time value that minimizes the noise level is finally selected. A screwdriver adjustable potentiometer allows setting the pole-zero cancellation to compensate for the input decay time of 250 μs. A standard rear-panel connector (Amphenol 17-10090) provides the power supply to the preamplifier through a 3 m cable. An automatic internal control has been chosen to properly set the threshold of the internal baseline restorer (BLR) circuit, which establishes the baseline reference for the Multi-Channel Analyzer (MCA). The shaping amplifier output signal is in fact processed by an MCA for pulse-height analysis and acquisition of the energy spectra. An ICS (Integrated Computer Spectrometer)-PCI card by Spectrum Techniques Inc. providing a 1024-channel MCA has been adopted in this case, see Fig. 9. Associated ICS Windows-based software has been used to acquire the energy spectra. The setup is completed.
by two test pulse generators, the Tektronix AFG3252 arbitrary function generator and the Ortec 419 precision pulse generator, and a 500 MHz 2 Gs/s LeCroy 454 digital scope.

### 3.2. Electronic noise

The electronic noise of the detector setup quoted by Canberra is 5.8 keV FWHM, evaluated as the pulser line width grown with standard Canberra electronics. In order to evaluate the noise performance of the system, a test pulse was injected at the preamplifier input node through the provided test capacitance and the Ortec 419 precision pulse generator. The FWHM of the grown pulser line is determined by the total electronic noise of the system, to which the detector capacitance gives a substantial contribution. In Fig. 10 the electronic noise is plotted as a function of the shaping time with the silicon detector mounted first in DB6 (downstream of the dipole magnet) and then in DB5 (final position). The minimum electronic noise is achieved at the shaping time of 0.5 μs, and it is found to be 6.9 keV FWHM in DB6 and 10.6 keV FWHM in DB5. In Fig. 11 the corresponding acquired 800 keV pulser lines are shown. The increase of the electronic noise in DB5 is likely due to an increased level of low-frequency pick-up disturbances because the position of DB5 is in a noisier area as far as mechanical vibrations and pumping are concerned. However, as already discussed in Section 2.1, this monitor position is found to be a more reliable one as far as the beam measurements are concerned.

### 3.3. Alpha resolution

In order to check the energy resolution of the system, an alpha source was temporarily placed inside the diagnostic box (under vacuum) and mechanically supported by the collimator wheel. The alpha resolution quoted by Canberra as obtained with $^{241}$Am 5.486 MeV alphas is 14.3 keV (0.26 %) (FWHM). The available alpha source used to test the setup consisted of a mixed-radioactive source containing three isotopes: plutonium ($^{239}$Pu), americium, ($^{241}$Am) and curium ($^{244}$Cm), producing three pairs of alpha peaks, respectively at energies of 5.157 MeV and 5.144 MeV, 5.486 MeV and 5.443 MeV, 5.805 MeV and 5.762 MeV [5]. The acquired spectrum is shown in Fig. 12. The close peaks are not fully resolved from each other.

![Fig.10. Electronic noise vs. shaping time](image1.png)  ![Fig.11. Pulser lines grown at 0.5 μs shaping time](image2.png)
due to the system resolution and so a double Gaussian fitting was performed to disentangle the line width. The Gaussian fitting on the $^{241}$Am peaks is shown in Fig. 13. The resolution obtained for the three main peaks at 5.157, 5.486 and 5.805 MeV are respectively 21.9 keV (0.42 %), 21.2 keV (0.38 %) and 22 keV (0.38 %) FWHM. The larger spread in the alpha peaks, as compared to the one quoted by Canberra, is mainly due to the higher electronic noise contribution measured in the system. In addition, the quality of the alpha source and its relative position to the detector may also influence the final resolution, as related to the energy losses of the alpha particles in the source itself and to angular effects in the detector entrance window.

3.4. Beam structure and composition

The REX beam has a pulsed time structure determined by the charge breeding system, consisting of a Penning Trap and Electron Beam Ion Source (EBIS) operating in series, which prepares the A/Q state for acceptance into the REX linac. [4]. The beam macro-pulse observed after the REX linac is determined by the superposition of the pulse extracted from the EBIS and the RF pulse of the linac, which we term the “RF window”. During the measurements documented in this report the RF pulse length was 450 $\mu$s. The macro-pulse from the EBIS is terminated by an electrostatic kicker integrated into its extraction system and is controlled to activate at the end of the EBIS timing signal. The REX accelerating cavities are excited by RF power at 101.28 MHz, which gives further temporal structure to the beam and divides the pulse from the charge breeding system, into micro-bunches separated by 9.87 ns. The test beam was composed of ionized residual gas from inside the EBIS, which is a typical pilot beam used to tune the linac. For most of the test measurements presented a beam with A/Q = 4 was used, which was composed mainly of a mix of $^{12}$C$^{3+}$, $^{16}$O$^{4+}$ and $^{20}$Ne$^{5+}$. In some instances it was useful to use a pure beam of $^{12}$C$^{4+}$ with A/Q = 3.

3.5. Control of beam intensity

An important functionality of the diagnostic system is to be able to rapidly and reproducibly attenuate the beam intensity to levels that facilitate the use of the silicon detector (a few kHz

![Fig.12. Acquired spectrum of the alpha source.](image1)

![Fig.13. Fitting of the $^{241}$Am alpha peak.](image2)
during the RF window). The beam intensity had to be strongly attenuated in order to perform a pulse-height energy spectroscopy of the beam particles, as the monitor is intended for single-particle detection. Pile-up effects and baseline fluctuations can easily spoil the energy resolution. This effect can be seen in Fig. 14, where the preamplifier output signal (yellow scope trace) and the corresponding shaper output signal (pink scope trace) are shown. The baseline recovery after each pulse is strongly reduced by means of the Gaussian shaping. A minimum time interval of 5 to 10 μs is however needed for the single-particle processing. The pulse peak is detected and sampled by the internal ADC of the MCA. Therefore, signal pile-up effects and fluctuations of the baseline due to the intrinsic error of the shaper baseline recovery system easily introduce a fluctuation in the detected peak value and spoil the energy resolution. In the worst cases spurious peaks even appeared in the acquired spectrum. Count rates below a few kHz are typically required in spectroscopic measurements to reduce these effects and preserve a satisfactory energy resolution.

![Energy signal as acquired at the preamplifier output (yellow trace) and at the Gaussian shaper output (pink trace).](image)

Another motivation for reducing the beam intensity is to limit the radiation damage from integrated beam exposure in order to maximize the lifetime of the silicon detector. A common strategy used to reduce the beam intensity is to scatter the beam off a tilted gold foil into the detector located away from the beam axis, see [6], [7], [8]. Such systems are typically used where the average beam current is high (usually when the beam has a continuous time structure) and the integrated radiation dose gives serious cause for concern for the longevity of the silicon detector. However, such systems suffer from poor energy resolution caused by the scattering process [7]. Often attenuators and collimators still have to be used in addition to the gold foil to satisfactorily reduce the beam intensity [9]. For the tests of the prototype detector it was decided to directly intercept the beam with the silicon detector to simplify the system and to enable better measurements of the system’s energy resolution. Radiation damage issues are not such a pressing concern at REX because of the low average beam currents arising from the duty cycle of the charge breeding injection system. However, regardless of whether the beam is directly or indirectly sampled, or whether the beam is...
continuous or pulsed, the peak beam intensity has to be attenuated to the kHz level such that single-particle events can be discriminated. Two methods of attenuation were tested with the prototype setup at REX:

a. Perforated copper foils.

b. Manipulation of the EBIS parameters and linac synchronization.

The perforated copper foils were placed in the only available position at the time of testing: on the collimator wheel directly in front of the silicon detector. The attenuation factor of the foils had been previously calibrated during the test of diamond detectors at ~5-8 per foil by using a Faraday cup [10]. The attenuators were observed to strongly scatter ions directly into the detector so that the resolution of the measurement was strongly affected. The energy spectra acquired for one, two and three foils are shown in Fig 15.

Although an attenuation factor of ~1000 was possible using four overlapped foils, the beam-foil interaction induced a background spectrum that appeared continuous and masked the characteristic beam spectrum. In this situation no further measurements could be taken. In future tests, it is planned to place the attenuators at low energy and to test the RF cleaning of the scattered particles by the accelerating cavities of the linac.

The time structure of a typical pulse extracted from the EBIS is short (~50 μs) and intense with a tail that decays exponentially as presented in Fig. 5 of [11]. In normal operation the RF pulse is synchronized to maximize the beam intensity captured and accelerated by the REX.
linac by triggering the RF just before the EBIS pulse is extracted. The EBIS timing signal was extended and the linac RF trigger delayed so that only ions populating the tail of the EBIS pulse were accelerated and the beam intensity was reduced. This procedure of attenuation will be called the first EBIS operating mode or “Mode 1.” In a second mode of operation, “Mode 2,” the same level of attenuation was achieved by manipulating the trapping electrode voltages inside the EBIS. The potentials of all the trapping electrodes were flattened to 700V and made static during the EBIS cycle of injection, breeding, extraction and cleaning to remove the time structure of the extracted pulse, as shown in Fig. 16. The 700V potential is important to ensure that the extracted pulse is injected into the REX linac within its velocity acceptance. In both EBIS operating modes the fourth trapping electrode closest to the injection/extraction side was set to zero, which changes the temporal structure of the ejected pulse resulting in an addition reduction of beam intensity by a factor of ~1.3.

The time structure of the pulses in each operating mode was investigated by measuring the count rate on the silicon detector as a function of the delay of the linac RF trigger with respect to the start of the EBIS cycle, as shown in Fig. 17. The intensity decays exponentially as a
function of delay time in the first operating mode and is static in the second; the EBIS pulse is very quickly extracted after the start of the EBIS cycle (< 100 μs). The drift tubes voltages in “Mode 2” are constant during the EBIS cycle and as a result the ejected beam has no time structure and is continuously ejected throughout the cycle. The reduction in the peak current correlates to a reduction in the beam intensity captured and accelerated by REX during the RF pulse giving attenuation factors of ~60. The count rate is proportional to the beam intensity accepted and accelerated inside the RF window. The lowest attainable intensity for both operating modes is limited by the rate of ionization of the residual gas by the electron beam, which depends on the residual gas pressure inside the EBIS and the electron beam current. An additional attenuation factor of ~10 could be gained by turning off the lens electrode controlling the transverse beam size on extraction from the EBIS. In principle, the longitudinal beam properties are left unaffected after the above changes to the EBIS setup and synchronization. It was assumed that most particles extracted from the EBIS see the nominal RF amplitude inside the cavities of the REX linac because the sharp rise/fall time of the RF pulse is short with respect to its length, see Fig. 18.

![Fig. 18. The EBIS Timing Signal (in blue) and RF Pulse (in yellow).](image)

Although both of the EBIS operating modes mentioned above could be used to provide sufficiently attenuated pilot beams with which to tune the cavities, Mode 2 was preferred because it leaves the linac timing unadjusted. All the following results presented used the EBIS operating in Mode 2 with a few collimators placed along the linac. A measured data rate of approximately 2 kHz inside the 450 μs RF window was considered a safe acquisition rate. This corresponds to a count rate of 0.75 particles per EBIS pulse and, at a repetition rate of 33 Hz, an average particle count rate of 25 Hz.

### 3.6. Beam energy profile

In Fig. 19 the beam energy spectrum is shown as acquired after the 9-gap resonator at the energy of 2.8 MeV/u and A/Q = 4. The average particle count rate is 25 Hz, corresponding to a count rate of 1.7 kHz in the RF pulse window (EBIS repetition rate of 33 Hz). Carbon,
The oxygen and neon peaks are identified, with an energy spread of 1.7 MeV (3.8 %) FWHM for the oxygen peak at 44.6 MeV (Fig. 20). The measured energy spread is at least a factor of two larger than previously quoted measurements of 1.2-1.9 % FWHM, which were made using a spectrometer magnet [12]. The above values of FWHM were calculated assuming the quoted values were equivalent to two standard deviations with a Gaussian distribution. Assuming the beam energy spread was 1.2 % FWHM, the de-convoluted contribution of the system would be 3.6 %.

Measurements were also acquired at 300 keV/u, at the output energy of the RFQ. In this scenario all other RF cavities after the rebuncher were turned off. The beam energy spectrum with the rebuncher turned off, i.e. $V_{\text{eff}} = 0$ kV, is shown in Fig. 21. In this case the dominant peak was the neon, and the helium peak could also be identified. The average particle count rate was 100 Hz, corresponding to a count rate of 6.7 kHz in the RF window pulse. The energy spread was 190 keV (3.2 %) FWHM for the neon line at 6 MeV, see Fig. 22. Taking the beam energy spread from the RFQ as 1.9 % FWHM, quoted in [13], the system resolution can be estimated as 2.6 % FWHM (156 keV). The system resolution remains a limiting factor.
for measurements of the beam energy profile. 

The longitudinal emittance of the RFQ was measured by changing the effective voltage of the rebuncher cavity, located 1.0 m after the exit of the RFQ, and measuring the variation of the energy spread of the beam with the silicon detector at 300 keV/u. In addition to the measurement of emittance this exercise provided an opportunity to study the resolution of the solid-state diagnostic system. The measurement results are compared in Fig. 23 to a simulation of the measurement assuming nominal beam parameters at output from the RFQ. Good agreement is attained between measurement and simulation if a resolution of 3.0 % FWHM is subtracted in quadrature, which is consistent with the other estimations made above. Although absolute measurements of the energy spread are challenging with the achieved system resolution, sufficient variation was observed for the system to remain useful as a diagnostic for tuning the linac. For example, one could determine if the synchronous phase of a cavity was stable or unstable from a comparison of the energy spread.

In order to analyze the contributions involved in the measurement of the energy spread, a comparison was made with the acquired peaks from the alpha source (Figs. 12-13), which are very close in energy to the neon peak. It is known that the energy resolution in charged particle spectroscopy is determined by: (i) the electronic noise of the system, (ii) the statistics of the created charge carriers (Fano factor), (iii) variations in the energy loss in the detector entrance window/dead layer, (iv) fluctuations in the energy loss due to nuclear interactions where a small portion of energy is transferred to recoil nuclei rather than to electrons, (v) and effects of incomplete charge collection (defects, trapping, recombination, low field effect) [14]. Contributions (iii), (iv) and (v) are responsible for the significant tailing towards low energy that are clearly visible both for the alpha and neon peaks. In general, these contributions are enhanced for heavy ions with respect to alpha particles, because the fractional energy loss in the dead layer (iii) is much more significant for heavy ions owing to the higher stopping power at the start of their range, the probability of nuclear interactions (iv) is more significant as the ion velocity decreases and the recombination of electrons-hole pairs

Fig.23. Energy spread as a function of rebuncher voltage as simulated and as measured with a resolution correction of 3.0 % FWHM).
(v) is highly enhanced by the high density of charge carriers (plasma effect) that are created along the heavy ion track. If we consider a mono-energetic 6 MeV neon beam, we would expect a worsening in the energy resolution compared to the alpha resolution because of contributions (iii)-(v). In fact, contribution (i) is a constant of the system, while contribution (ii) is unlikely to differ strongly between the alpha calibration and beam measurement because the ion energies were similar in both cases. SRIM simulations show that the energy straggling of a mono-energetic 6 MeV neon beam crossing the detector entrance window composed of a 200 Å aluminum and 800 Å silicon dead layers is about 44 keV. Nevertheless, according to reference data [15], [16] and [17], such a strong deterioration in the measured resolution (from 22 keV with alpha source to 156 keV with neon beam) cannot be justified by the above discussion. A substantial contribution must then be due to the beam measurement setup, and in particular to the relatively high count rate and the presence of collimators in front of the silicon detector. In the alpha source test measurement a very low count rate of 0.5 Hz was measured and no collimators were present in front of the detector. In the measurement with beam the count rate (6.7 kHz in the RF window) was much higher so that an imperfect baseline restoration could have introduced a substantial worsening in resolution. Collimators were also put along the linac and scattering effects from beam-collimator interactions could introduce energy straggling and hence worsen the resolution. Unfortunately, the use of collimators was mandatory in order to keep an acceptable count rate and to avoid being dominated by severe pile-up effects. As discussed above, the use of attenuators at low energy will be investigated to avoid the use of collimators close to the detector. Tests of a silicon detector with a thinner entrance window are also foreseen. Nonetheless, the system energy resolution is satisfactory for accurate peak energy identification and therefore suited for a quick cavity phase-up procedure.

3.7. Cavity phase-up by means of energy measurements

The change in the average energy of a bunched beam passing through an RF cavity can be expressed as,

$$\Delta W_0 = qV_{\text{eff}}(\beta)\cos \phi,$$

where $q$ is the ion charge, $V_{\text{eff}}(\beta)$ is the maximum accelerating voltage seen by the beam in crossing the cavity as a function of the reduced velocity $\beta$ and $\phi$ is the phase.

The principle of tuning the phase of an accelerating cavity using the silicon detector was demonstrated with the 7G3, as shown in Fig. 24, at the energy of 2.26 MeV/u. During the measurement the dominant ion species present in the beam was $^{16}\text{O}^{4+}$. As the cavity phase was rotated, the peak channel number of the $^{16}\text{O}^{4+}$ energy signal measured by the MCA was recorded and then plotted in terms of energy gain by means of a prior calibration. The maximum change in the average energy is $\pm 15$ % @ 2.26 MeV/u. The silicon detector monitor resolution, as already discussed in Section 3.6, was 3.0 % FWHM (or $\pm 1.3$ % rms). The achieved energy resolution therefore allowed for accurate peak energy measurement while varying the cavity phase. Only close to the minimum of the curve the transmission through the 7G3 was low and the beam energy spread large such that the final energy resolution was poor. This issue is dynamical and not caused by the monitor. The result is consistent with measurements made with the switchyard magnet.
Owing to the large number of accelerating gaps and the large change in velocity during acceleration in the structure, Eq. (1) is somewhat of an approximation compared to the behavior observed. Nonetheless, second-order analytic expressions exist [18] that can be used to fit the data points as shown in Fig. 24 and have the form,

$$\Delta W_0 = a(\beta)\cos\phi + b(\beta)\sin2\phi + c(\beta),$$

(2)

where $a$, $b$ and $c$ are constants for a given velocity. The HIE-REX SC cavities in nominal operation would not deviate so far from the sinusoidal modulation as observed for 7G3 but second-order fitting techniques will be used to minimize the size of the data sample required to tune the cavity.

Each data point requires the acquisition of a beam energy spectrum with sufficient statistics to give a reliable measurement for the centre of the $^{16}\text{O}^{4+}$ peak. With respect to other systems measuring continuous beams, described in refs [6], [7] and [8], the acquisition time at REX is longer by the duty factor of the linac, $\eta_{RF}$. Nonetheless, the time required to grow the spectrum can be kept reasonable. If one assumes that the beam intensity $I$ extracted from the EBIS during the RF window is constant, as it is in Mode 2, the average data rate $R$ acquired at the detector can be expressed simply as,

$$R = \frac{\tau_{RF}}{\tau_{EBIS}} I = \eta_{RF} I,$$

(3)

where $\tau_{RF}$ is the length of the linac RF pulse and $\tau_{EBIS}$ is the repetition period of the charge-breeding system. As the linac RF is synchronized to the EBIS, the ratio of $\tau_{RF}$ to $\tau_{EBIS}$ is the linac duty cycle. As discussed above the beam intensity should be controlled to the level of a few kHz to avoid pile-up effects. At conservative beam intensities and EBIS repetition rates of 2 kHz and 25 Hz respectively, i.e. $\eta_{RF} \approx 1\%$, one could acquire at a rate of 20 Hz and collect reasonable statistics in under a minute. As presented above, during the measurements
of the RFQ emittance, reliable data could be acquired at a rate five times faster with an EBIS repetition rate of 39 Hz and beam intensity of over 6 kHz during the RF window.

Some further considerations are mandatory about the energy resolution of the silicon detector monitor needed in the phasing of the HIE-REX superconducting cavities. Simulations were run to evaluate the change in average energy $\Delta W_0$ as a function of the phase $\phi$ for each of the foreseen 32 SC cavities. The results are shown in Fig. 25, 26 and 27. In Figure 25 and 26 the plots for the 12 low-energy cavities and the 20 high-energy cavities are shown respectively, when operating in the standard accelerating mode. In Figure 27 the plots for the 12 low-energy cavities are shown when operating in decelerating mode. The purpose of this simulation was evaluating the expected change in $\Delta W_0$ in order to estimate the needed energy resolution in the phase-up procedure. The simulations were done with heavy beams ($A/q = 4.5$), which give the smallest change in energy per each cavity. The plots of Figs. 24 and 25 show that in normal accelerating mode the change in energy ranges from $\pm 15\%$ to $\pm 3.5\%$, with the smallest occurring in the last ($20^{th}$) high-beta cavity at 10 MeV/u. In this cavity the simulated beam energy spread is $< \pm 0.5\%$ rms, so that the silicon detector energy resolution of $\pm 1.3\%$ rms will dominate the final line width. The achieved rms resolution can be considered suitable for a phase up procedure of all the SC accelerating cavities, being lower than the smallest expected peak shift by almost a factor 3.

A different consideration should instead be made for the low-energy cavities when operated in decelerating mode. The change in energy ranges from $\pm 18\%$ to $\pm 2.3\%$, the smallest one occurring in the last ($12^{th}$) low-beta cavity at 0.45 MeV/u. In this cavity the simulated beam energy spread is large, $< \pm 1.5\%$ rms, which will contribute significantly to the final line width. If we square sum the detector resolution of $\pm 1.3\%$ rms, we get an expected final line width of $\pm 1.98\%$ rms to be compared to an expected peak shift of $\pm 2.3\%$. The phase up of

![Fig.25. Simulated plots of the average energy gain vs. phase for the HIE-REX low-energy SC cavities operated in accelerating mode.](image-url)
cavities 11 and 12 in decelerating mode may hence be critical. The monitor resolution should be improved as much as possible to get a line width which is at the end mostly dominated by the large beam spread only.

Fig.26. Simulated plots of the average energy gain vs. phase for the HIE-REX high-energy SC cavities operated in accelerating mode.

Fig.27. Simulated plots of the average energy gain vs. phase for the HIE-REX low-energy SC cavities operated in decelerating mode.
4. Timing measurements

4.1. Signal processing and DAQ setup

In order to measure the beam timing distribution, the measured particle timing signals must be precisely referenced to the RF master-clock that controls the phase of the accelerating cavities. The block diagram of the data acquisition setup is shown in Fig. 7. The Caen Multi-Hit TDC (Time-to-Digital Converter) V1290N has been adopted, which is not based on the standard concept of Start and Stop signals, but on the time “stamping” of multiple hits. This VME module houses two high-performance TDCs, providing a resolution of 25 ps (LSB) with a full scale range of 52 μs. Each of the 16 NIM input channels can be enabled for the detection of multiple hits rising/falling edges, while the time origin of the measurement is given by the latest reset of the internal counter. In order to get the time distribution of the beam, two channels are enabled for time measurement, one fed with the particle timing signals and one with the RF reference signal. The hit time stamps for both channels are acquired so that the needed time interval between the particle arrival and the RF reference is calculated through custom-made software. Although the double-hit resolution can be as high as 5 ns, the maximum rate of a periodic signal that can be accepted by one channel without losing hits has been estimated around 7 MHz. Consequently the 101.28 MHz frequency of the RF signal had to be divided. Actually, a factor of 14 was set for a frequency divider characterized by a 114 MHz maximum accepted rate, thus providing a 7.23 MHz reference signal synchronized with the RF. Both the reference signal and the particle signal must be converted into standard NIM, as requested by the TDC input. A LeCroy discriminator mod. 4608C was adopted, as characterized by an adjustable amplitude threshold of -5mV to -1V, an adjustable output width from 4.5 ns to > 100 ns, rise times and fall times better than 2 ns, and a maximum rate of 150 MHz.

Finally the proper acquisition mode was set on the TDC V1290N. The data acquisition can be programmed in Continuous Storage Mode or in Trigger Matching Mode. In the first mode, the data loaded by the first level buffer are directly forwarded into the readout FIFO of the TDC and then loaded by the FPGA master into the output buffer of the module. In the second mode, the data acquisition is instead organized in “events” according to an arbitrary external trigger signal. A time acquisition window can be defined with respect to the trigger, so that only the hits that are matching this acquisition window are forwarded to the readout FIFO and are then loaded in the output buffer, where they are organized in “events” and marked with headers and trailers. The Trigger Matching Mode is found to be particularly useful in this context because of the pulsed structure of the REX beam and the very low average count rate of beam particles on the silicon detector. The pulsed structure is characterized by the duty cycle of the linac, i.e. the ratio of the RF pulse duration to the EBIS repetition period, and is typically of the order of a few percent or less. Therefore, a continuous acquisition mode would dominantly acquire the RF reference signal with respect to the measured particle signals. Instead, an acquisition window triggered on the EBIS pulse would be much more efficient. However, the maximum width of the TDC acquisition window per event is only 100 μs. As the average particle count rate is about one particle per pulse, the 100 μs acquisition window may not be enough to catch a particle hitting inside the entire 450 μs RF window. Therefore, the most efficient acquisition mode consists of triggering on the particle
signal itself, so that a relatively short acquisition window can be set around the particle hit to detect at the same time the divided RF reference signal. Actually, as shown in Fig. 28, an acquisition window 500 ns in width was set and centered on the particle signal trigger. The final timing measurement consists of the evaluation by software of the time interval between the trailing edges of the particle signal and the closest RF timing signal detected before it. The Caen V1290N TDC is operated in a stand-alone VME crate and programmed through the Caen VME-USB Bridge V1718. Two custom-made LabView Virtual Instruments have been realized to communicate to the TDC: one for programming all the needed settings and parameters (trigger matching mode, trailing edge detection, acquisition window width and offset), and one for programming the data acquisition from the TDC output buffer and saving the binary data on files to be later analyzed offline through a custom Matlab program.

4.2. Time resolution estimate

The timing resolution of the system has been evaluated to be of the order of 200 ps. As already mentioned, the detector nominal timing resolution quoted by Canberra is 140 ps, thanks to the addition of a 200 Å aluminum layer. The reference signal resolution has been
evaluated while measuring the RF-divided period through a single-channel TDC acquisition. A standard deviation of 42 ps (98 ps FWHM) has been obtained, as shown in Fig. 29. This resolution also accounts for the intrinsic 25 ps TDC resolution (LSB) and the jitter eventually introduced by the NIM discriminator.

4.3. Beam timing profile

The beam time structure could be reconstructed with relatively high resolution. In Fig. 30 a beam time profile is shown, as acquired after the 9-gap resonator at the energy of 2.8 MeV/u and A/Q=4. The corresponding energy spectrum is the one shown in Fig. 19. The time profile shows 14 bunches, with the expected period of 9.87 ns, because the adopted reference signal was the RF signal divided by a factor of 14. The obtained bunch profiles can be overlapped in

![Fig.30. Beam timing profile as acquired in DB5 at the output of the 9-gap resonator.](image)

![Fig.31. Bunch length estimate in DB5 at the output of the 9-gap resonator.](image)
a two-period window to increase the statistics of the timing distribution, as shown in Fig. 31. The measured time spread of the bunch was 2.5 ns FWHM, as obtained from the Gaussian fit shown. It is compatible with the time spread expected at the output of the 9-gap resonator [12] and after a drift of approximately 9 m to the silicon detector in diagnostic box DB5.

**4.4. Cavity phase up by means of Time-of-Flight measurements**

A phase-up was tested for the 7G3 cavity to demonstrate a Time-of-Flight (ToF) procedure, as shown in Fig. 32. The beam energy as a function of phase was measured by recording the arrival time of a bunch relative to the reference signal. The modulation of the energy as a function of phase was enough to vary the arrival time of a bunch by up to 90 ns over the 10.6 m drift distance between cavity and monitor. At 101.28 MHz the bunch spacing is only 9.87 ns, making it challenging to differentiate between bunches arriving at the monitor. A measurement was possible by slowly varying the phase such that the bunch being tracked never moved more than 9.87 ns in arrival time and could always be identified. Such a measurement was time-consuming and made far easier with the prior knowledge gained by phasing in the energy domain. Nonetheless, the ToF principle was validated and remains a viable option for phasing the cavities should a chopper be incorporated into the HIE upgrade. The independent measurements made in the time and energy domains were used to validate each other. From the measurements of the change in energy as a function of phase it was possible to calculate the change in arrival time as a function of phase with knowledge of the drift distance. In Fig. 32 the raw data is compared to the calculation using the energy domain measurements by normalizing the curve to zero at the minimum of the ToF. The agreement is good and only breaks down where the energy resolution was poor.

Fig.32. Phase scanning of the 7G3 cavity through ToF measurement.
5. Conclusion

A silicon detector monitor is under development and has been tested in the frame of the beam diagnostics development program for the HIE-ISOLDE superconducting upgrade of the REX-ISOLDE linac. The monitor is intended for beam energy and timing measurements as well as for phase scanning of the superconducting cavities.

The test was performed with a stable ion beam composed of carbon, oxygen and neon ions accelerated at energies from 300 keV/u to 2.85 MeV/u. The silicon detector was placed directly in the beam line and tested with a beam that was strongly attenuated to simulate the single particle detection regime for which the monitor is intended to finally function. Attenuation mechanisms were investigated and beam intensities as low as a few pps could be reached, by means of manipulation of the EBIS parameters and use of collimators along the beam path.

The main purpose of the test was investigating the possibility of using the silicon monitor for a quick phase-up of the future HIE-REX superconducting cavities, both through energy and timing measurements. The monitor performance in terms of energy and timing resolution was hence investigated as a first step. The monitor energy resolution was estimated to be of about 3.0 % FWHM (or ±1.3 % rms). Such a resolution is not adequate for the measurement of the beam energy profile, as it dominates over the beam intrinsic energy spread, which is evaluated to be < 2 % FWHM in REX linac. Nevertheless it is fully adequate for accurate peak energy measurement as required by a phase-up procedure. This was demonstrated with a complete phase scanning performed for the 7G3 cavity. Simulations were run to evaluate the expected change in average energy as a function of the phase for each of the HIE-REX SC cavities. In case of a standard accelerating mode the monitor energy resolution should be compatible with an expected peak shift (energy change) ranging from ± 15 % to ± 3.5 %, depending on the considered cavity. This requirement is met by the monitor resolution of ± 1.3 % rms. In case of decelerating operation mode of the low-energy cavities, the expected peak shift ranges from ± 18 % to a very low value of ± 2.3 % for the last couple of decelerating cavities. This last condition may be critical because of the large intrinsic beam energy spread of ± 1.5 % rms.

As far as timing measurements are concerned, the monitor timing resolution is estimated to be < 200 ps. The beam time profile, characterized by a bunch period of 9.87 ns, was measured. A bunch length of 2.5 ns FWHM was measured at the energy of 2.83 MeV/u and is considered compatible with the expected one. The cavity phase-up principle was demonstrated also in the time domain through a ToF procedure. This measurement was time-consuming and not suitable for a quick and automated procedure. Nonetheless, it is considered a viable option for phasing the cavities should the bunch spacing be increased through the incorporation of a chopper into the HIE-ISOLDE upgrade.

As far as future developments are concerned, tests of beam attenuators are foreseen in order to decouple the EBIS from the measurement setup, which will include placing perforated copper foils at low energy before the main RF of the linac. We also plan to investigate the energy resolution of the setup in order to further improve the resolution, if possible, and to test a second type of silicon detector. Development of the electronic acquisition system is also envisaged as well as a monitoring of the detector performance with radiation damage.
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