DEVELOPMENT OF A SILICON DETECTOR MONITOR FOR THE SUPERCONDUCTING UPGRADE OF THE REX-ISOLDE HEAVY-ION LINAC AT CERN

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Abstract

A silicon detector monitor has been developed and tested in the frame of the beam diagnostics development program for the HIE-ISOLDE superconducting upgrade of the REX-ISOLDE heavy-ion linac at CERN. The monitor is intended for beam energy and timing measurements as well as for phase scanning of the superconducting cavities. Tests have been performed with a stable ion beam, composed of carbon, oxygen and neon ions accelerated to energies from 300 keV/u to 2.85 MeV/u. The energy measurements performed allowed for beam spectroscopy and ion identification with a resolution of 1.3 % rms. The achieved resolution is suited for cavity phase scanning, which was demonstrated with the REX 7-gap resonator. The time structure of the beam, characterized by a bunch period of 9.87 ns, was measured with a resolution better than 200 ps. This paper describes the results from all these tests as well as providing details of the detector setup.

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]. 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. At REX the average beam energy is measured using the dispersion developed in the switchyard dipole magnet. 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.

MONITOR STRUCTURE

The prototype monitor consisted of a 50 mm^2 300 µm-thick partially-depleted Passivated Implanted Planar Silicon (PIPS) detector manufactured by Canberra. An actuator could place the detector on the beam line to directly stop the beam, so that the total energy of the particles was measured. In Fig. 1 the monitor scheme and the data acquisition setup are shown. A FET-input low-noise charge-sensitive preamplifier was connected to a feed-through outside the diagnostic box, providing energy and timing output signals. The energy signal was processed by a quasi-Gaussian shaping amplifier (Ortec Mod. 572) and a Multi-Channel Analyzer (MCA) integrated on a PCI card and providing the beam energy spectrum. The timing output signal was referenced to the RF master-clock that controls the phase of the accelerating cavities. The Caen Multi-Hit TDC (Time-to-Digital Converter) V1290N, characterized by a resolution of 25 ps (LSB), was adopted to measure the time interval between the particle signal and a reference signal synchronized with the RF. As the maximum frequency of the reference signal accepted by the TDC was 10 MHz, the 101.28 MHz RF master-clock had to be frequency-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. A fast discriminator converted both the reference signal and the particle signal into standard NIM, as requested by the TDC input. A system electronic noise of 10.6 keV was measured. It was evaluated as the full width at half maximum (FWHM) of the pulser line acquired while injecting a test pulse at the preamplifier input node

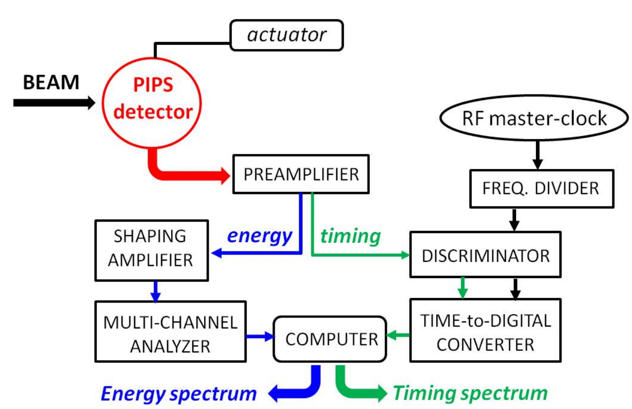

Figure 1: Monitor structure and data acquisition setup.

through the provided test capacitance. The monitor energy resolution was tested with an alpha source temporarily placed inside the monitor diagnostic box. The resolution obtained with ^{241}Am 5.486 MeV alphas was 21.2 keV (0.38 %) FWHM.

BEAM STRUCTURE AND INTENSITY

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 prepare the A/Q state for acceptance into the REX linac [3]. The beam macro-pulse observed after the REX linac is determined by the synchronisation of the RF pulse of the linac with the beam pulse extracted from the EBIS. During the measurements documented in this paper the RF pulse length was 450 µs. With an applied repetition rate of 33 Hz, the machine duty cycle was then 1.5 %. 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 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. In the presented test measurements a beam with A/Q=4 was used, which was composed mainly of $^{12}C^{3+}$, $^{16}O^{4+}$ and $^{20}Ne^{5+}$. The beam intensity had to be strongly attenuated to reach the kHz level inside the 450 µs RF pulse window, such that single-particle events could be discriminated. A data rate of approximately 2 kHz inside the RF window was achieved by manipulating the trapping electrode voltages inside the EBIS and by using collimators along the linac. This corresponds to a count rate of 0.75 particles per EBIS pulse and, at a repetition rate of 33 Hz, an average beam particle count rate of 25 Hz.

MEASUREMENT RESULTS

Energy profile measurements were performed at 300 keV/u, at the output energy of the RFQ (Radio-Frequency Quadrupole). The acquired beam spectrum is shown in Fig. 2, where helium, carbon, oxygen and neon peaks are well identified. The energy spread of 190 keV (3.2 %) FWHM was measured through a Gaussian fitting on the neon line at 6 MeV. Assuming the beam energy spread from the RFQ as 1.9 % FWHM, quoted in [4], the system resolution can be estimated as 2.6 % FWHM or ± 1.1 % rms (1σ). The energy spread of the beam at 300 keV/u was also measured by changing the effective voltage of the rebuncher cavity, located 1.0 m after the exit of the RFQ. The measurement results are compared in Fig. 3 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 or ± 1.3 % rms (1σ) is subtracted in quadrature. This value can be reasonably assumed as the system energy resolution.

The energy resolution achieved with the neon beam at 6 MeV is substantially worse than the resolution obtained

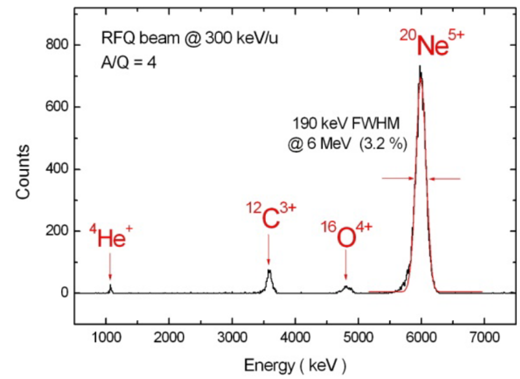

Figure 2: Beam energy spectrum acquired at 300 keV/u.

with alpha particles from a source at close energy (5.486 MeV). This is partially due to the interaction of the beam ions with the silicon detector entrance window and it may also be due to an affected intrinsic energy spread of the beam when critical techniques are applied to reduce its intensity. Some further investigation is needed in this direction. However, although absolute measurements of the energy spread are challenging with the achieved system resolution, the monitor performance fully meets the main requirement of a fast and accurate phase tuning procedure of the cavities. The principle was demonstrated with REX 7-gap resonator, as shown in Fig. 4, at the energy of 1.92 MeV/u. As the 7G3 cavity phase was rotated, the peak channel number of the $^{16}O^{4+}$ energy signal measured by the MCA was recorded and then plotted in terms of energy gain by means of a prior calibration. A second-order analytic expression was used to fit the data points in Fig. 3, as they deviate from the sinusoidal modulation, owing to the large number of accelerating gaps and the large change in velocity during acceleration in the structure. The maximum change in the average energy was ± 15 % @ 1.92 MeV/u, and the monitor resolution of ± 1.3 % rms allowed for accurate peak energy measurement while varying the cavity phase. 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

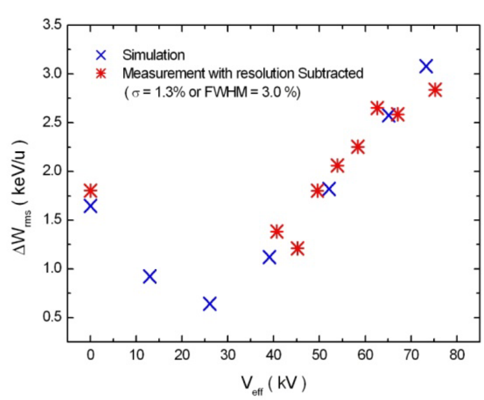

Figure 3: Simulated and measured energy spread as a function of the rebuncher voltage.

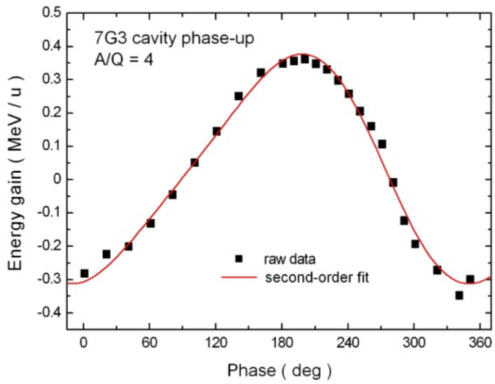

Figure 4: Demonstration of cavity phasing with the REX 7-gap resonator.

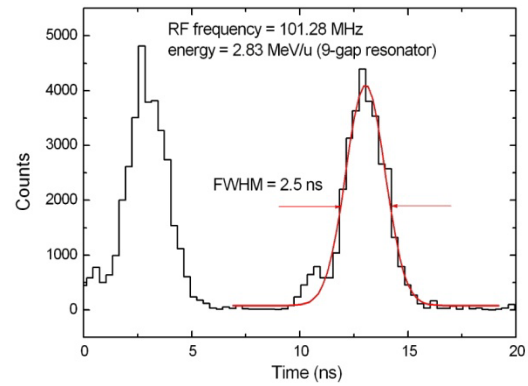

Figure 5: Beam timing profile and bunch length.

with an expected peak shift (energy change) ranging from ± 15 % to ± 3.5 %, depending on the considered cavity. This requirement is hence fully 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. In this case the phase scanning may be critical, also because of the large expected beam energy spread of ± 1.5 % rms.

The beam time profile was acquired at 2.85 MeV/u, which is the output energy of the 9-gap resonator. A time structure of 14 bunches was acquired, with the expected period of 9.87 ns, because the adopted reference signal was the RF master-clock divided by a factor 14. The acquired timing profile is shown in Fig. 5 in a two-bunch window. The measured bunch length was 2.5 ns FWHM, compatible with the time spread expected at the output of the 9-gap resonator [5] and after a drift of approximately 9 m to the silicon detector.

A phase-up scanning was tested for the 7-gap resonator by using in this case a Time-of-Flight (ToF) procedure, as shown in Fig. 6. 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-ISOLDE upgrade and the bunch spacing increased. In Fig. 6 the raw data are 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.

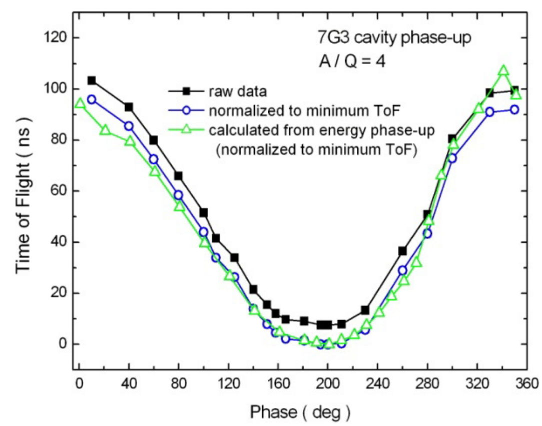

Figure 6: Phase scanning of the 7G3 cavity through ToF measurements.

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