ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-WEPLH01

LONGITUDINAL BEAM PROFILE MEASUREMENT BY SILICON DETECTOR IN FACILITY FOR RARE ISOTOPE BEAMS AT MICHIGAN STATE UNIVERSITY*

T. Maruta†, P.N. Ostroumov, Q. Zhao, Facility for Rare Isotope Beams, East Lansing, MI, USA

Abstract

The silicon detector (SiD) is widely used to precisely measure the kinetic energy of ion beams. In the Facility for Rare Isotope Beams (FRIB) at Michigan State University, a foil scattered type SiD system was installed after the first three superconducting cryomodules to measure the beam energy, energy spread, and longitudinal bunch length. In this paper, the measurement results with the SiD system is reported.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) being constructed at Michigan State University [1] is based on a continuous wave (CW) superconducting (SC) linear accelerator which is designed to deliver 400 kW heavy ion beam power to the fragmentation target. The installation of the accelerator equipment is approaching completion and multi-stage beam commissioning activities started in the summer 2017 with expected completion in 2021. The direct current (DC) beam extracted from the electron cyclotron resonance ion source (ECRIS) is transported to the Radio Frequency Quadrupole (RFQ) located in the tunnel. Beam is bunched longitudinally by a multi-harmonic buncher (MHB) and then accelerated to 0.5 MeV/u in the RFQ, followed by three SC linac segments (LS1 to LS3) to deliver beams to the fragmentation target.

The second stage of the beam commissioning took place in the summer 2018 and included acceleration of argon and krypton beams in the first three cryomodules, which contain twelve β_{OPT}=0.041 SC cavities and six SC solenoids [2]. ^{40}Ar and ^{86}Kr beams were successfully accelerated up to 2.3 MeV/u while the design energy for both beams is 1.46 MeV/u in this section of the linac. It should be noted that one resonator was disabled most of the time to stay below the energy threshold for neutrons' generation.

For complete characterization of the beam properties a commissioning diagnostics station (D-station), was developed and installed after the third cryomodules, which included AC-coupled Beam Current Monitors (BCMs), a Faraday Cup (FC), Beam Position Monitors (BPMs), Halo Monitor Rings, a Profile Monitor (PM) and a silicon detector (SiD).

SETUP OF SILICON DETECTOR SYSTEM

The SiD system includes three parts: a head part placed on the beam line, a signal processing circuit, and a signal digitization and analysis. The head part of SiD system is comprised from a gold foil and detector itself as shown in Fig. 1. The detector head is parked off the beam line and inserted only to perform beam measurements. The SiD is placed at 67 mm behind and 30° off-axis vertically to the foil to attenuate counting rate. The counting rate should not exceed 10^3 Hz to avoid signal pileups. The intensity of the beams during the linac commissioning was ~10^{13} ions/sec. Therefore, the attenuation by a factor of 10^{10} was provided in two steps: by using the attenuators in the LEBT and a thin gold foil upstream of the detector head.

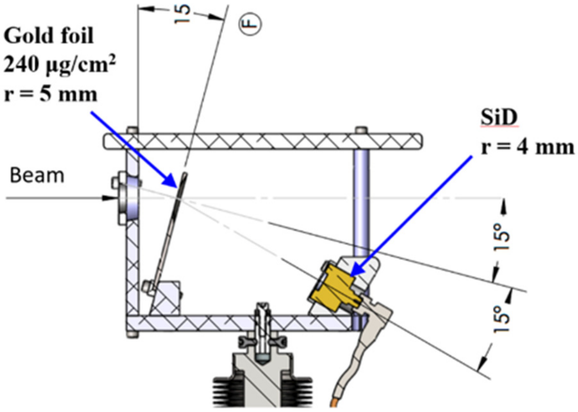

Figure 1: Head part of the silicon detector system.

The 10-mm diameter gold foil of 240 μg/cm^2 thickness is mounted on the aluminium plate that is tilted 15° vertically. The foil thickness was verified by measuring energy loss of alpha particles emitted from ^{241}Am decay.

The silicon detector is a passivated implanted planar silicon detector manufactured by Canberra [3]. Estimated timing resolution by the manufacturer is $<$ 200 psec which corresponds to $<$ 5.8° of the reference RF frequency at 80.5 MHz. The sensitive area's diameter is 8 mm. The sensitive depth is 300 μm that is 10 times more than the penetration depth of 2.3 MeV/u ^{40}Ar ions.

Two signal-processing circuits to measure absolute energy and timing w.r.t RF reference signal were integrated by Nuclear Instrument Modules (NIMs). Both energy and timing information are converted to pulse height and input to a multi-channel analyser (MCA), Lynx [4]. Different electronic circuits are used to process the SiD signal for beam energy or timing measurements. The circuit details are discussed in another paper at this conference [5].

The signal height manipulated by the circuit is digitized by Lynx for these measurements. The pulse height is digitized by a 15-bit (32768 channels) analog-to-digital converter (ADC) and then recorded as corresponding channel number. The Lynx was installed in the same rack of the NIM circuits to mitigate noise contamination. Data-taking

---

* Work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661, the State of Michigan and Michigan State University.

† maruta@frib.msu.edu

is controlled from the control room through Ethernet communication. The acquired data is plotted by ROOT [6] toolkit.

SILICON DETECTOR MEASUREMENTS

Calibrations

Since the SiD signals are recorded as a channel number of 15-bit ADC, we need to convert them to absolute energy or timing. In this section, we describe how to obtain the conversion coefficients.

Energy Measurements The coefficient for the channel-to-energy conversion was calibrated by measuring the energy of the alpha particles emitted by ^{228}Th decay. A ^{228}Th source is positioned such a way that the alpha particles are directly injected to the SiD when the SiD head is in the parked position. The calibration data was taken after finishing beam studies during the day. ^{228}Th decay emits several monochromatic energies of alpha particles [7]. Six isolated and well identified energies, 5.340, 5.423, 5.685, 6.288, 6.778 and 8.785 MeV, of alpha particles are picked up as shown in the top left of Fig. 2. The channels of each peak were obtained by fitting them to Gaussian function. The top right of Fig. 2 shows energies as a function of peak channel. We obtained 0.00287 MeV/ch, so the maximum channel number corresponds to 2.35 MeV/u ^{40}Ar beam.

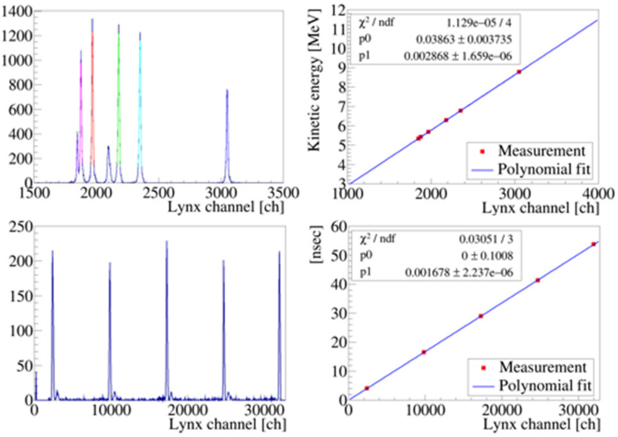

Figure 2: SiD calibration for absolute energy and timing measurements. Kinetic energy spectrum of ^{228}Th taken by Lynx (top left) and correlation of peak channels and corresponding kinetic energy (top right). Timing measurement of 80.5 MHz beam (bottom left) and correlation of Lynx channel to time.

Timing measurements The channel-to-time coefficient was estimated by measuring an ion arrival time w.r.t the RF reference signal. Since the fundamental RF frequency is 80.5 MHz, beam bunch comes every 12.4 nsec. The timing spectrum of 1.46 MeV/u ^{40}Ar is measured as shown in the bottom left of Fig. 2. Five sharp peaks are observed and channel-to-time coefficient is obtained to be 1.68 psec/ch, which is corresponding to whole time window to be 55 nsec. The linearity is good for the entire region.

Absolute Beam Energy Measurements

An absolute energy of ^{40}Ar beam was measured after completion of the phase and amplitude setting in each resonator. Each resonator was set to synchronous phase of −30° and design accelerating gradient of 5.1 MV/m.

As mentioned above, the SiD is located behind of the gold foil and only ions scattered by 30° reach the SiD. Since the scattering process reduces the ion energy, obtained energies need to be compensated for this reduction effect to derive correct beam energies. The energy loss in the gold foil was simulated with the SRIM code [8]. In the simulation, ^{40}Ar ions with five monochromatic energies from 0.5 to 1.5 MeV/u are axially injected to the gold foil. The gold foil thickness is set to be 3.5% thicker than the actual thickness to reproduce 15° tilted placement with respect to the beam axis. The kinetics of each ion after the foil is picked up to select the ions that hit the SiD. The left side of Fig. 3 shows the average beam energy after the foil as a function of the injection energy. The extraction energy changes linearly with the injection energy in this energy region, so correction function is obtained by fitting the correlation with a first order polynomial function. The energy spectrum is obtained after applying the corrections, as shown in Fig. 4. In this figure, the beam energy spectrum after each resonator are superimposed. The data obtained with SiD system confirmed that the beam was successfully accelerated to the design energy of 1.5 MeV/u utilizing 11 SC resonators.

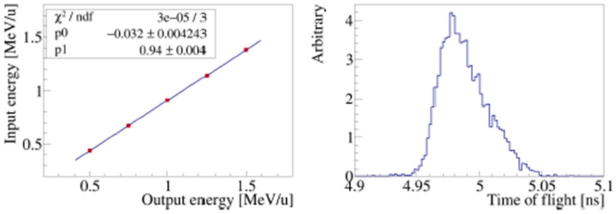

Figure 3: Simulation results by SRIM. (left) Extraction energy from a gold foil as a function of the injection energy of ^{40}Ar ion for energy loss compensation. (right) time-of-flight from the foil to the SiD. Injection ions are 1.03 MeV/u ^{40}Ar.

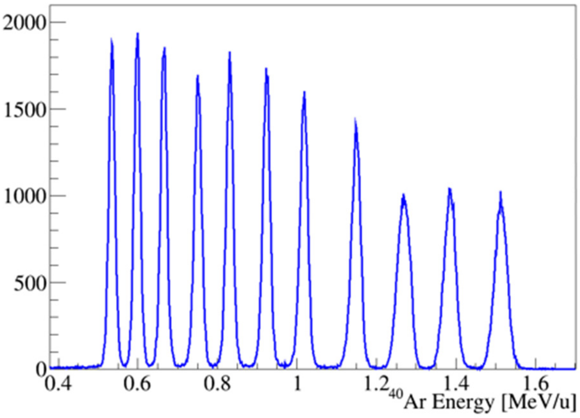

Figure 4: Absolute energy after each resonator. All measurement are superimposed.

ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-WEPLH01

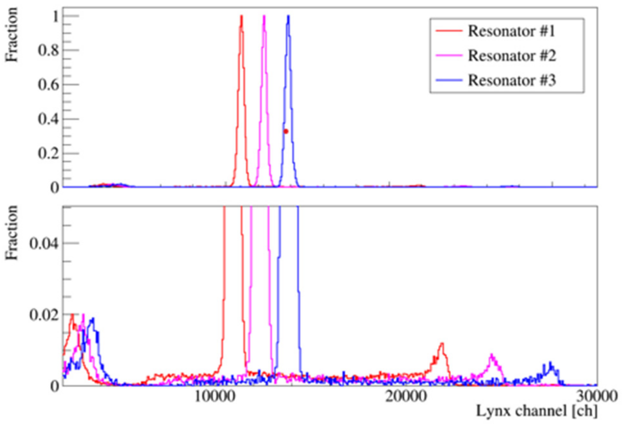

Figure 5: Energy spectra after the first three resonators. In each spectrum, peak height is normalized to 1.

The energy spread ($\Delta W/W$) after the last resonator is estimated to be 0.58%. The measured spread includes the energy resolution of SiD system and energy struggling in the foil. They were estimated by peak widths of the ^{228}Th measurements and SRIM simulations, respectively, and then subtracted.

Beam Contaminants

During the absolute energy measurements, we noticed that beam was contaminated with other ion species. Figure 5 shows the energy spectra after the first three resonators. The total beam energy spectrum contains two subpeaks corresponding to the lighter and heavier than argon ions. The lower energy peak is about 20% of the beam energy and the higher one is about twice higher than ^{40}Ar. These ion species were accelerated with the same setting of resonators which means that the contaminant ion species have very close *q/A* ratio to that of argon ions. The fraction of contaminants was less than 2%. From the ratio of the absolute energy to the ^{40}Ar beam, we deduced that the light and heavy contaminants are ^{9}Be and ^{80}Se or ^{86}Kr respectively.

Longitudinal Beam Emittance Measurements

The longitudinal beam emittance is measured by scanning RF amplitude of one SC resonator at bunching phase ($\varphi_s = -90°$) to vary the bunch length at the SiD.

In the measurement, ^{40}Ar beam was accelerated to 1.03 MeV/u by the first seven resonators. The 8th resonator was off. The 9th resonator was set at the bunching phase and its amplitude was varied while bunch length was measured with the SiD. The voltage of the 9th resonator was varied for the bunch root mean square (rms) length measurements with two different MHB settings [2]. The first setting of the MHB was tuned for the “maximum transmission” through the RFQ. The other setting was tuned for the “minimum longitudinal emittance”. In this case, the amplitude of each frequency of the MHB was adjusted to form a smaller longitudinal emittance at the entrance of the RFQ. Figure 6 shows the rms longitudinal beam sizes as a function of amplitude of the 9th resonator for the two MHB settings. The 9th resonator field amplitude was scanned from 0.6 to 1.9 MV/m. Bunch size is varied from 0.15 to 0.35 nsec and becomes minimum at fields around 1.2 to 1.3 MV/m in both settings. The measured beam size includes an additional component due to the time-of-flight from the gold foil to the SiD which was estimated by SRIM. In the simulation, 1.03 MeV/u ^{40}Ar ions enter the centre of the foil and then the arrival time of each ions are picked up as shown in the right plot in Fig. 3. The time-of-flight is deviated from 4.95 to 5.05 nsec and rms (z_{SRIM}) is 22.8 psec. This variation was subtracted from the measured size (z_{meas}) by the following expression

$$z = \sqrt{z_{meas}^2 - z_{SRIM}^2}. \qquad (1)$$

The obtained longitudinal rms emittance and Twiss parameters are listed in Table 1. As can been seen, the emittance in the maximum transmission setting is about 40% larger than in the case of minimum longitudinal emittance setting.

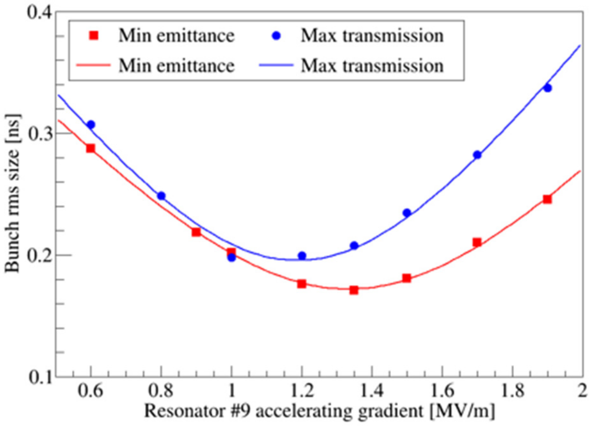

Figure 6: Longitudinal rms beam size as a function of accelerating gradient of the 9th resonator. Solid line shows fitting curves.

Table 1: Measured Longitudinal Parameters and RFQ Transmission with Two MHB Settings. Twiss parameters are given just upstream of the 9th resonator.

	Min. Emit	**Max. Trans**
ε [π ns keV/u]	0.159	0.227
α	1.55	1.47
β [π ns /(keV/u)]	0.093	0.105
RFQ transmission [%]	76	84

SUMMARY

The SiD system played an important role to characterize beam properties in the longitudinal phase space. Argon beam energy and energy spread were measured after each resonator. The longitudinal emittance was measured by measuring longitudinal beam size while the RF amplitude of one of resonators operating in bunching mode was varied. The measured data fully confirms the design specification of the longitudinal beam parameters in the FRIB linac. Also, the energy measurements revealed two sub-peaks apparently coming from the contaminant ion beams.

ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-WEPLH01

REFERENCES

[1] J. Wei *et al.*, *International Journal of Modern Physics E*, vol. 28, p. 1930003, 2019.

[2] P.N. Ostroumov *et al.*, “Heavy ion beam acceleration in the first three cryomodules at the Facility for Rare Isotope Beams at Michigan State University”, *Phys. Rev. ST Accel. Beams* vol. 22, p. 040101, 2019.

[3] `https://www.mirion.com/products/passivated-implanted-planar-silicon-detectors`

[4] `https:www.mirion.com/products/lynx-digital-signal-analyzer`

[5] Q. Zhao, “Silicon Detector for Heavy Ion Linac Tuning at NSCL/FRIB”, presented at the North American Particle Accelerator Conf. (NAPAC'19), Lansing, MI, USA, Sep. 2019, paper TUPLE10.

[6] ROOT – An object oriented data analysis framework-`https://root.cern.ch/`

[7] National Nuclear Data Center, `https://nndc.bnl.gov`

[8] The Stopping and Range of Ions in Matter, `http://www.srim.org`