

ENERGY CALIBRATION OF THE ReA3 ACCELERATOR BY TIME-OF-FLIGHT TECHNIQUE*

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Abstract

We report on a simple method to perform an absolute calibration of the magnetic beam analyser of the reaccelerator ReA3 at the National Superconducting Cyclotron Laboratory. The method is based on the time of flight between two beam stoppers 7.65 m apart. Based on two independent time-of-flight measurements at three different beam energies, the beam analyser magnet is calibrated with an accuracy of 0.12 %, corresponding to a beam energy accuracy of 0.24 %.

INTRODUCTION

The reaccelerator facility ReA3 [1] at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University is a unique, state-of-the-art superconducting linear accelerator for stable and rare isotope beams. Rare isotopes, produced at high energy by the NSCL's Coupled Cyclotron Facility, separated in-flight, and decelerated to low energy using gas stopping technique, can be reaccelerated by ReA3 to energies ranging from 300 keV/u to 6 MeV/u. After acceleration in ReA3 the beam is magnetically analysed before being transported to experimental set-ups connected to three beam lines. In this contribution, we report on an elegant method to perform an absolute calibration of the magnetic beam analyzer of ReA3. This is a simpler variation of the technique described in [2]. The beam, after being analysed is injected into a straight (drift) beam line where it can be stopped at one of two places 7.65 m apart, with the distance between those known with an accuracy of better than 1 mm. Gamma rays from reactions between the beam and the stopper are detected by a single barium fluoride (BaF2) gamma-detector. This detector, with associated cables and electronics, is placed close to the one or the other of the beam stopper positions and its signal is correlated (using a time-to-amplitude converter) with the radiofrequency (RF) electronic signal of the accelerator. With only one detector set-up being used, the time of flight with respect to the RF reference clock of the accelerator is measured at each position. An accuracy of 0.12 % was demonstrated for the time-of-flight determination between both positions. From this, the energy of ReA3 beams can be determined with an accuracy of 0.24%.

METHOD CONCEPT

In ReA3, the beam is bunched at a frequency of the resonators, i.e. 80.5 MHz. Each accelerated particle of the

bunch can produce reactions in the beam stoppers, with subsequent emission of X-rays and/or gamma rays. As those reactions are extremely fast, the radiation is correlated with the beam bunches and will have a distribution revealing the bunch longitudinal elongation only. The beam is stopped alternatively at two locations, placed in a straight line 7.65 m apart. The distance between those two stoppers was measured by laser tracker with an accuracy of 1 mm. In order to have a clear and straight path between the two beam stoppers, all optical elements between the two positions were turned off. The ReA3 beam has a sufficiently small emittance to guarantee that the beam is properly stopped in the 7.6 cm diameter stopper, not in its neighbourhood.

The time of flight between the two positions is measured with respect to a common reference: the linac radiofrequency. In this case, the time-of-flight can be written as:

$$TOF = T1 - T2 + N \cdot T_{RF}, \quad (1)$$

Where TOF is the time of flight between the two beam stop positions, $T1$ and $T2$ are the times between the detected radiation in the upstream and downstream positions with respect to the radiofrequency of the linac, T_{RF} is the radiofrequency period, and N is the number of radiofrequency cycles the beam undergoes between the two beam stop positions. For this technique to work, the beam energy needs to be known sufficiently well in order to avoid ambiguity due to the number N of RF time periods between the two stopper locations. In ReA3, the “approximate energy” is given by the measured magnetic rigidity of the beam in the first dipole magnet after the accelerator using its geometric radius and measured magnetic field. The goal of the time-of-flight technique described here is to achieve a much better accuracy of the magnetic rigidity, providing a correction to the calculated value.

As the BaF2 detector is placed outside the vacuum pipe of the beam line and moved between positions 1 and 2, the whole detection chain is the same in both positions. Therefore, no correction due to cable lengths or electronics is needed and, as a consequence, all associated systematic errors are automatically eliminated.

DETECTION AND ELECTRONICS

The gamma rays produced by reactions of the beam particles and the stoppers were detected by a single BaF2 detector, placed alternatively in front of each stopper. The rise time observed for the gamma signals were of the order of 2 ns. The output of the photomultiplier coupled to the barium fluoride (BaF2) detector was connected to a constant

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fraction discriminator (CFD). Care on the regulation of the monitor of the constant fraction was taken in order to obtain good timing resolution. The fast output signal of the CFD was used as START in a time-to-amplitude module (TAC).

The STOP signal for the TAC was correlated with the 80.5 MHz radiofrequency of the linac. The signal from the reference clock of the linac was connected to a discriminator. The output was scaled by 1/4 to allow 4 time bunches to be observable in a time-of-flight spectrum. It also allows to take multiple data points in a single measurement. The output of the TAC was sent to a multi-channel analyzer.

TUNE OF THE BEAM LINE

The ReA3 layout and performances are described in reference [1]. Just after the last cryomodule of the accelerator, the beam is analysed by a 45-degree magnetic dipole with approximately 1-m bending radius [3]. The alignment of the beam through this magnet is critical for having a reliable reference for the magnetic rigidity calibration. Just after the cryomodule (see Fig. 1) two 5-mm apertures are spaced about 1.2 m apart. They are used to align the beam out of the linac to the entrance face of the dipole. With the dipole turned off, the acceptance criteria is that more than 80% of the beam current must pass through both apertures. Steerers and solenoids in the cryomodules are used to align the beam and achieve a near-parallel envelope in this region. This procedure defines the incident direction of the beam with an uncertainty of about 2 mrad.

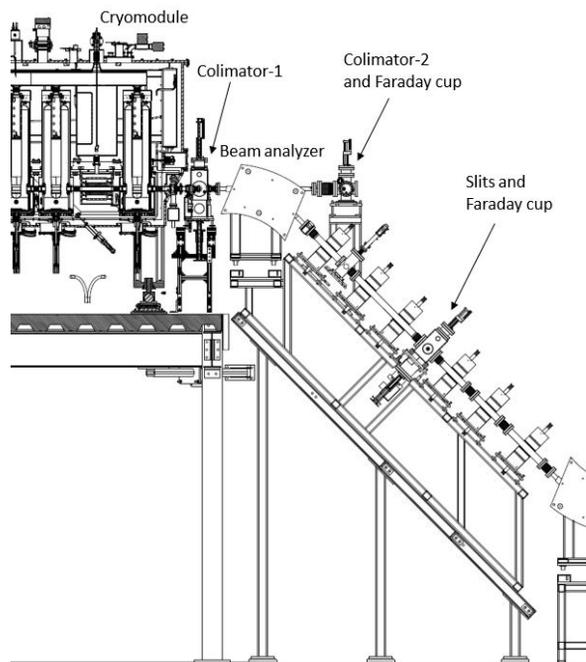


Figure 1: ReA3 vertical beamline just after the LINAC. Beam direction is left to right. Positions of collimators, slits and faraday cups, as indicated in the text, are shown.

After the beam is aligned horizontally, the dipole analyser is switched on and the beam is bended 45-degree to

the vertical beam line. The quadrupole magnets of the vertical beam line are switched off in order to avoid any steering. The beam passes through a 2-mm-wide slits located in the middle of the vertical section and hits a Faraday cup just behind. When the beam is centred, the magnetic field in the beam analyser is recorded from its Hall probe reading.

After such a magnetic field measurement, the whole beam line was powered and the beam was sent to the horizontal straight beam line where the time-of-flight measurement was performed (see Fig. 2).

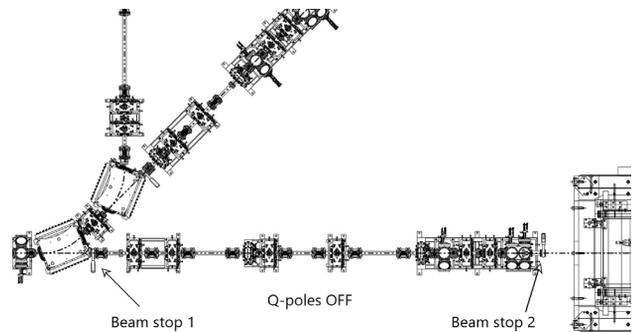


Figure 2: Horizontal beam line where time-of-flight measurement was performed. Beam direction is left to right.

During the time-of-flight measurement none of the quadrupoles in the straight beam line between the two beam stoppers were powered, in order to guarantee a straight path between the two positions for all particles of the beam.

DATA ANALYSIS

In this contribution, we present results of the calibration performed with a ^{12}C beam at three energies of 4.0 MeV/u, 4.5 MeV/u and 4.95 MeV/u. In order to have redundant measurements, two different BaF2 detection set-ups were used alternatively at the two beam stopper positions, giving two independent measurements per beam energy.

The typical TOF spectra obtained during the experiment for two positions with one of the BaF2 detectors is shown in Fig. 3.

The channels were calibrated against a time calibrator. For each run and taking both spectra (each with 4 peaks), 16 experimental data points (T1-T2) can be determined, corresponding to differences between contiguous or not contiguous peaks, each difference correlated to a different N cycle.

Using all data extracted for each energy, the average value of the time-of-flight was determined and the corresponding magnetic beam rigidity (B-rho) was calculated. Figure 4 shows the results obtained for each energy plotted as a function of the magnetic field (B) measured by the Hall probe of the beam analyser. The Hall probe used has a fixed position and is temperature corrected.

The line in Fig. 4 corresponds to the linear least squares fit ($\chi^2 = 0.9$) of the three measured energies with respect to the Hall probe readings (B) using the equation: $B\text{-rho} = B \cdot R$, where R is a calibration constant related to

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the magnetic radius, with respect to the Hall probe readings.

The result of the fit for the constant with its standard deviations is $R = 0.9763(12)$ m.

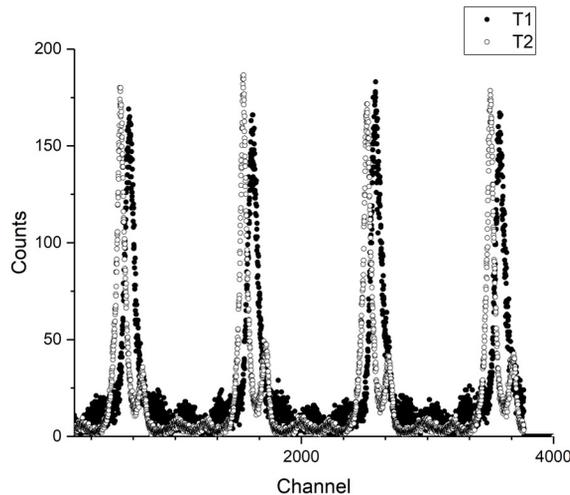


Figure 3: BaF2 timing spectrum with peaks related to times T1 (closed dots) and T2 (open dots) of equation (1). Note that the second smaller peak in T2 is spurious, corresponding to a small amount of the beam hitting an obstacle in the beam line prior to the beam stopper.

It's important to note that the calibration may present a very small dependence on the applied magnetic field – or may not remain constant – outside the measured region, i.e. outside 0.7 T and 0.8 T.

The final standard deviation of 0.12% corresponds to the accuracy of this calibration. This corresponds to an accuracy of 0.24% in the ReA3 beam energy.

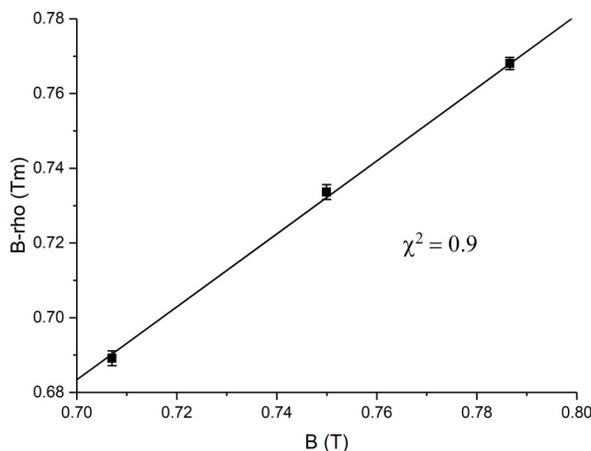


Figure 4: Magnetic rigidity ($B\rho$) deduced from time-of-flight measurements as a function of the measured field in the magnet (B). The line corresponds to the best fit.

LIMITATION OF THE METHOD

This method is limited to the possibility to detect X-rays or gamma rays from reactions between the beam and a beam stopper. Due to the thickness of the beam pipe around the beam stopper, only relatively high energy gamma rays produced by nuclear reactions could be observed in our case. This can be overcome by thin windows in the beam line. The yield of gamma rays is dependent on the nature of the beam, its energy as well as the nature of the stopper. Beam energies below or close the Coulomb barrier (i.e. below 4 MeV/u in our ^{12}C case) didn't provide enough radiation intensity to use this approach. Other reactions, including the use of protons and changing the nature of the beam stopper (stainless steel in this case) is under study in order to expand the calibration region.

SUMMARY AND CONCLUSION

We report on a method to perform an absolute calibration of the beam analyzer of the reaccelerator ReA3 at the National Superconducting Cyclotron Laboratory. The method is based on the time of flight between two beam stoppers 7.65 m apart. The method was applied at three beam energies. From the measured time of flight, the magnetic rigidity of the beam was deduced and used to obtain the calibration constant of the beam analyser dipole with respect to its fixed Hall probe. Based on the three beam energy measurements and corresponding Hall probe readings, the calibration constant of the beam analyser dipole was determined as $R = 0.9763$ m within an accuracy of 0.12%. This corresponds to an accuracy of 0.24% in the beam energy.

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