REAL TIME LONGITUDINAL BEAM MEASUREMENTS IN THE CROCKER NUCLEAR LABORATORY ISOCHRONOUS CYCLOTRON*

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Abstract

The UC Davis Crocker Nuclear Laboratory (CNL) operates a 76-inch isochronous cyclotron dating to the 1960s, with limited internal beam diagnostic instrumentation. Direct measurements of the Cyclotron beam are challenging due to the harsh environment, including high radiation, strong magnetic fields, RF interference, and spatial constraints. A novel beam probe has been developed for transverse bunch structure and longitudinal phase measurements in a 15 mm square transverse profile with 16 independent pixels. The probe consists of a segmented fast plastic scintillator array coupled via fiber optics to external Silicon Photomultipliers (SiPMs), mounted on a radially translating probe. Bunch and phase information are measured and analyzed in real time, with continuously updating visualizations available to operators with sub nano second time resolution. Additionally, offline analysis is performed to support the development of simulations and improve understanding of beam dynamics in the CNL Cyclotron. The Fast Beam Probe opens the door to improved beam stability, more accurate modeling, and future integration with automated control systems at CNL.

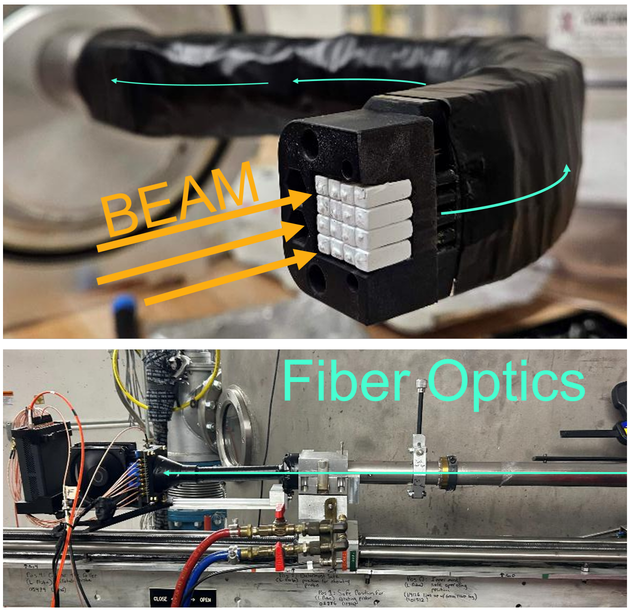

Figure 1: Fast Beam Probe setup showing the in cyclotron detector head (top) and the air side readout with fiber optics and SiPM coupling (bottom).

MOTIVATION

The CNL Cyclotron is currently commissioning a production process for the medical isotope astatine-211 [1]. It was determined that an internal target location within the machine would be used for isotope production. To characterize the beam at this location, a stack of Type HD-V2 Gafchromic film was mounted on a radially translating probe and exposed under the proposed production conditions. A large 12.7 mm square transverse beam spot was observed, indicating significant radial and vertical beam oscillations that were not expected by CNL personnel. As no existing diagnostic hardware is capable of directly resolving these distributions, the Fast Beam Probe has been commissioned to provide direct measurements of beam dynamics inside the Cyclotron.

FAST BEAM PROBE

The Fast Beam Probe is capable of measuring longitudinal phase and several sequential buckets across 16 independent channels arranged in a 4 × 4 grid spanning 15 mm square. The detector consists of a 4 × 4 array of fast plastic scintillators (Eljen EJ-232Q 0.5% benzophenone) coupled to UV-VIS fused silica fibers, seen in Fig. 1, which transmit light to an Onsemi 16-channel SiPM array (Array-J) outside the Cyclotron [2–4]. All SiPM channels and the Cyclotron RF are digitized by a 16+1 channel, 12-bit, 5 GS/s CAEN digitizer (DT5742) [5].

The digitizer was operated in continuous trigger mode at an approximate 1700 Hz acquisition rate with a 400 ns acquisition window, capturing 9 RF buckets[1] per event at a sampling rate of 2.5 GS/s. A peak finding algorithm is used to identify the leading edge of each SiPM pulse, establishing beam arrival time relative to RF with a constant but arbitrary phase offset. From this analysis, both the longitudinal beam phase and transverse bunch profile are extracted. Further details regarding the Fast Beam Probe construction and signal analysis can be found in [6, 7]

All digitized events are processed in real time using a parallelized Python framework and C++ modules to perform peak detection and RF timing determination. The system provides live visualization of beam phase evolution to operators, displaying a primary phase plot as a two dimensional histogram of beam phase over time and a secondary plot with mean phase and intensity of all channels. Channels can be dynamically selected as the primary display without loss of historical information. In addition to the live analysis, all raw waveforms are saved for offline analysis.

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[1] For an RF frequency of 22.5 MHz and the largest digitizer window at 2.5 GS/s, 9 buckets are contained within each acquisition.

The Fast Beam Probe uses the same carrier and transport system as the main beam probe and for the probe containing the astatine-211 target, shown in Fig 2. The transport system is fully retractable and contains an airlock to allow for probes to be changed without breaking vacuum to the Cyclotron. The Fast Beam Probe is used for detailed measurements during research and development periods and is not normally in place during general Cyclotron operations.

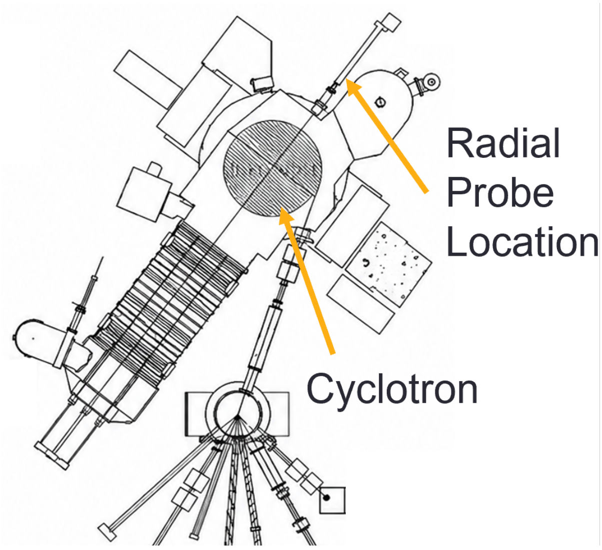

Figure 2: Schematic of the CNL Cyclotron identifying the location of the radially translating beam probe system.

LONGITUDINAL PHASE MEASUREMENTS

Longitudinal phase is measured directly by the difference between the beam arrival time relative to a fixed point on the RF curve. The detector recovery time is longer than the bunch width, thus it is only sensitive to the first particle per bunch per detector channel. Therefore the Cyclotron is operated with a beam current near 15 pA for an RF Frequency of 22.5 MHz to mitigate biasing to the first particle arrival time. The beam phase evolution over time can be visualized using a two dimensional histogram of beam phase vs time seen in Fig. 3.

Magnetic Field Modulation

In a Cyclotron, the magnetic field defines the orbital frequency of the accelerated particles, and stability of the phase therefore highly depends on the field configuration. The CNL Cyclotron contains 11 independently tunable magnetic coils, consisting of a main coil that establishes the primary field and 10 concentric trim coils for fine field corrections. Recent upgrades to the control system enable monitoring of the trim coil settings alongside fully digital coil control. Changes in beam phase are monitored precisely by the probe with examples of phase correlation to trim coil current seen in Fig. 4.

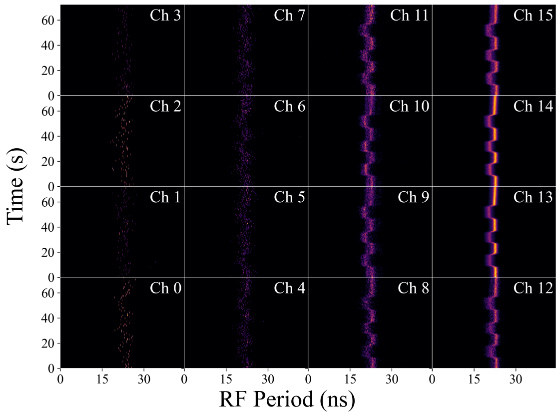

Figure 3: Grid of two dimensional histograms binned in beam phase and time, arranged according to physical channel location demonstrating beam phase changes over time. The channels are oriented such that the beam impinges on the scintillator faces, with the rightmost column (channels 15, 14, 13, and 12) corresponding to the smallest radius and thus the innermost detector positions.

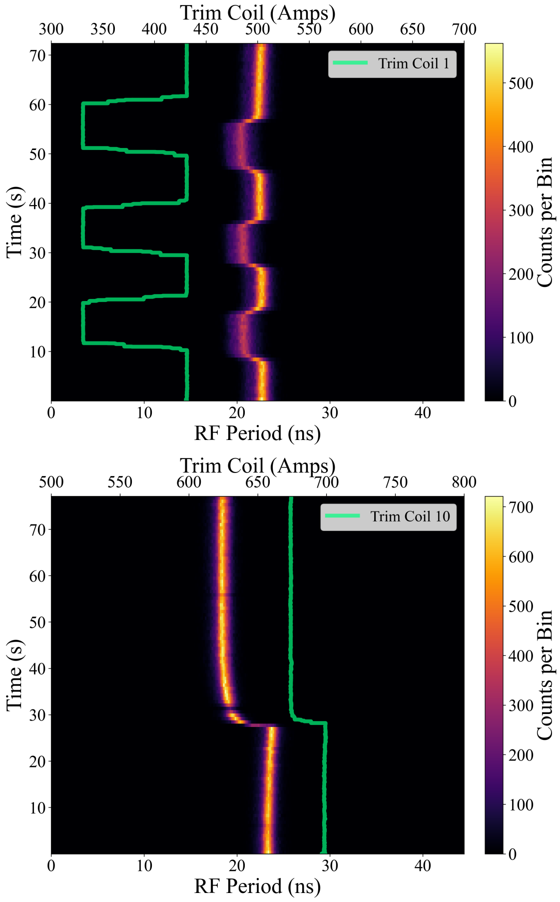

Figure 4: Example illustrating the relationship between beam phase and trim coil currents for channel 14. The top panel shows digital modulation of Trim Coil 1 with a 100 A step change, while the bottom panel shows an analog variation of Trim Coil 10 with a 25 A adjustment.

Radial Scans

The Fast Beam Probe is capable of making measurements over a radial range from 355 mm to 558 mm. A radial phase scan is performed by initially positioning the probe at 558 mm and then driving it inward through the machine until it reaches 355 mm. The resulting scan, shown in Fig. 5, reveals three distinct beam dynamics regimes. In the phase lagging region from 355 mm to 390 mm, the particle cyclic frequency is lower than the RF frequency, which corresponds to a positive slope in the measured phase vs radius. In the isochronous region 390 mm to 425 mm, the particle cyclic frequency matches the RF frequency, corresponding to a zero slope. Finally, in the phase advancing region from 425 mm to 558 mm, the particle cyclic frequency exceeds the RF frequency, resulting in a negative slope.

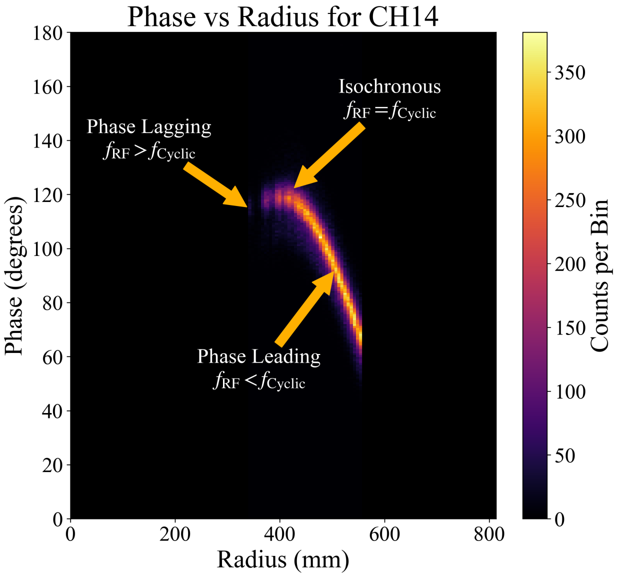

Figure 5: A two dimensional histogram of beam phase vs detector radius. Three regions are measured and indicated on the plot, phase lagging, isochronous, and phase leading from innermost to outermost radii.

TRANSVERSE BUNCH ANALYSIS

The Fast Beam Probe provides transverse individual bunch profiles over the segmented 15 mm square profile for 9 sequential bunches. The number of sequential bunch measurements is only limited by the readout electronics and in principle there is no upper limit to the physical detector system.

Transverse bunch profiles can be used to identify the presence of horizontal or vertical beam oscillations. For each RF bucket, the detector response from all channels is accumulated into a spatial distribution, from which the centroid position is calculated using the mean of the positional distribution for each bunch. The resulting centroids are binned on a two dimensional histogram cut by the number of particles detected. Fig. 6 shows the results from 70 seconds of acquired data. Bunches with at least four particles detected most clearly shows that the beam is well centered vertically and with little radial extent. The transverse distributions of the centroids do not show any indications of oscillations.

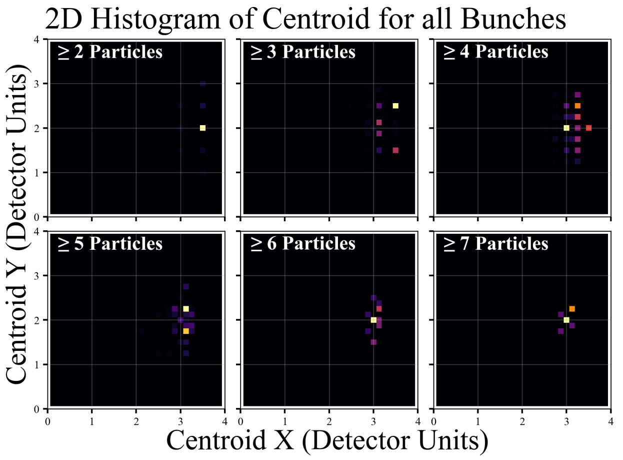

Figure 6: Two dimensional histograms of transverse centroid positions grouped by the minimum number of particles detected per bunch. Individual histograms are shown for bunches containing at least 2, 3, 4, 5, 6, and 7 detected particles. The centroid distributions remain centered and concentrated toward the innermost region for higher particle amounts, indicating no observable transverse beam oscillations during the measurement period.

CONCLUSION

The Fast Beam Probe successfully completed its first internal beam measurements inside the CNL Cyclotron. These measurements demonstrated the detector's capability to measure transverse bunches and longitudinal beam phase across a range of magnetic fields and radial positions. Analysis of the bunch resolved transverse centroid distributions showed no evidence of horizontal or vertical beam oscillations in the 67.5 MeV proton beam tune. This contrasts with previous Gafchromic film measurements of the 35 MeV alpha beam tune, which suggested the presence of significant transverse oscillatory behavior. Future measurements of the alpha beam tune are planned in order to investigate and characterize these previously observed distributions. Additionally, specialized readout electronics are being considered for future upgrades to increase the number of sequential bunches that can be resolved.

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