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SINGLE-BUNCH EXTRACTION AT THE 88-INCH CYCLOTRON*

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Abstract

The extraction system of the 88-Inch Cyclotron at Lawrence Berkeley National Laboratory has been modified to enable single-bunch extraction. This is achieved by increasing the voltage of the first deflector to oversteer the beam, halting extraction, and then selectively switching it off using a high-voltage chopper to synchronize the deflector's operational voltage with the transit time of a single bunch, enabling its extraction. A pre-chopper positioned before the cyclotron limits the beam available for acceleration, minimizing activation and sputtering damage from discarded bunches. This cost-effective technique is crucial for time-sensitive experiments and provides precise control over dose delivery, broadening the cyclotron's range of applications. Future efforts will focus on increasing extraction frequency by optimizing the deflector electronics for faster recovery times, and exploring sequential switching of two deflectors to reduce the required oversteering voltage.

INTRODUCTION

Recent developments in pulsed power technology have led to significant enhancements in beam chopping systems for particle accelerators. High-voltage switching units composed of series and parallel arrays of modern semiconductors, such as MOSFETs, IGBTs, and SCRs, can now deliver fast switching performance with low jitter and high efficiency. These systems are capable of managing hundreds of kilovolts and tens of kiloamperes within sub-microsecond timescales, enabling precise temporal control of particle beams for high-resolution applications across various accelerator facilities [1, 2].

Tandem beam chopper systems are typically categorized as either fast and slow choppers or as pre-chopper and main chopper [3, 4]. In the first configuration, fast choppers are used in applications requiring nanosecond-scale resolution, such as precise bunch selection and timing control, while slow choppers serve broader intensity modulation purposes. In the latter configuration, the pre-chopper is generally positioned early in the acceleration stage to shape the beam before it gains significant energy, whereas the downstream main chopper further refines beam delivery by deflecting or transmitting bunches to either the target or the beam dump.

To enhance chopper system performance, researchers have explored advanced hardware and optimization techniques that improve synchronization between beam dynamics and switching events. High-speed electronics and real-time feedback loops enable precise control over bunch timing and beam intensity, capabilities crucial for time-of-flight experiments, neutron cross-section measurements, and laser-driven fusion diagnostics.

For the 88-Inch cyclotron, this precision is especially important for time-of-flight neutron spectroscopy, where accurate timing between pulses prevents overlap from sequential broad-spectrum bunch bursts, particularly in experiments using deuteron beams striking beryllium targets to generate fast neutrons.

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PRE-CHOPPER AND MAIN CHOPPER TANDEM SCHEME

The 88-Inch Cyclotron at Lawrence Berkeley National Laboratory supports research in nuclear science and radiation effects using light and heavy ions produced by three electron cyclotron resonance ion sources: ECR, AECR, and VENUS [5], Fig. 1. These sources can deliver mixed ion species ("cocktails") through an injection line equipped with attenuators for beam intensity control and a pre-chopper that limits beam power into the machine.

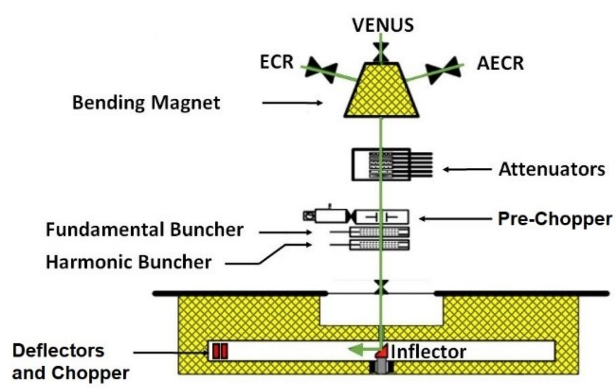

Figure 1: Layout of the extraction lines from the ion sources and the injection line into the cyclotron.

The beam is subsequently bunched by fundamental and harmonic bunchers for acceleration and extraction via three electrostatic deflectors. However, due to energy spread caused by particles arriving at different RF phases, bunches become radially dispersed, resulting in extraction across multiple RF cycles even if a single RF bucket is injected at the cyclotron [6].

Under normal conditions, injecting several consecutive RF bunches results in extraction on every RF cycle. Figure 2 shows how multiple-turn extraction arises when the chopper narrows the injection window to a single RF bunch. The remaining single bunch, after acquiring energy spread during acceleration, is extracted over multiple turns. Because

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the cyclotron operates in third harmonic mode, extraction occurs every three RF cycles, preserving the original phase relationship from injection, as confirmed by fast current transformer (FCT) measurements.

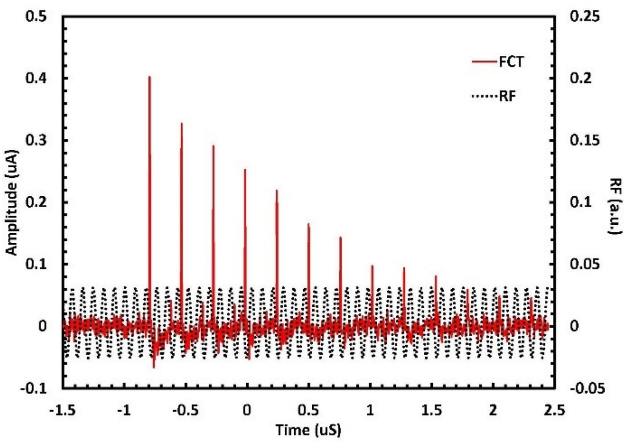

Figure 2: Extraction from a single RF bucket during the injection of a 6 MeV $^2H^+$ beam, with the cyclotron operating at 11.6 MHz in third harmonic mode.

Although single-turn extraction can be realized from a single RF-bucket injection by placing slits near the cyclotron center to restrict phase acceptance, this approach significantly reduces beam intensity.

To achieve single-bunch extraction from the cyclotron's quasi-continuous beam without compromising instantaneous beam intensity, a tandem pre-chopper and chopper configuration was implemented at the 88-Inch Cyclotron. This method repurposes the existing first deflector as a chopper using commercial components, eliminating the need for specialized hardware, concurrent with the use of the pre-chopper to limit the damage and activation from the discarded energetic bunches during extraction into the cyclotron structures.

HARDWARE

The pre-chopper system at the 88-Inch Cyclotron uses commercially available high-voltage MOSFET pulsers (Behlke FSWP 51-02 [7]) to control beam injection. Positioned before the beam enters the cyclotron, it applies up to ±2 kV across electrostatic plates to steer the beam away from the inflector, effectively blocking injection. When the voltage is removed, the beam continues to the inflector and enters the RF acceleration process.

For safe and reliable operation, the pre-chopper is liquid-cooled with Galden HT135 PFPE fluid and includes an interlock that shuts it down if temperatures exceed 75°C. The system also incorporates ceramic capacitors for voltage buffering and series resistors to protect the pulsers from voltage reflections due to impedance mismatches.

The chopper system hardware at the 88-Inch Cyclotron shown in Fig. 3 [8]. It utilizes a fast high-voltage SCR switch (Behlke HTS 800-100-SCR [7]) integrated into the first electrostatic deflector to achieve single-bunch extraction. This switch, capable of handling up to −80 kV, manipulates beam trajectories by oversteering or understeering them during fast voltage transitions. The deflector itself, measuring 0.52 m in length and 5 cm in width, produces about 46 pF of capacitance.

The SCR-based switch is triggered by an isolated driver circuit and sustains conduction until current drops below a threshold. While these switches are reliable and well-suited for high-voltage applications, their frequency limit is a few kilohertz, and they are protected by a thermal interlock if they overheat.

To protect the chopper system from transients and reverse voltages, three high-voltage diode assemblies (Behlke FDA 1000-150 [7]) are employed. These diodes manage flyback voltage spikes, safeguard the power supply, and assist with switching stability. Additional components, such as a 100 nF capacitor and a 200 kΩ discharge resistor, support proper SCR operation by maintaining the necessary holding current. Together, these components enable precise control over beam extraction by biasing the outer electrodes of the first electrostatic deflector, while the inner septum electrodes remain grounded.

EXPERIMENTAL RESULTS

The 88-Inch Cyclotron at LBNL was configured to accelerate 16 MeV deuteron beams using a first harmonic RF at 6.3 MHz. To reduce activation and sputtering from high beam power, the pre-chopper limited the beam duty cycle to 10^{-5}, delivering 10 µs pulses every second.

Figure 4 illustrates the effectiveness of the chopped deflector system used for beam selection at the 88-Inch Cyclotron. The x-axis represents time in microseconds. The left y-axis displays current from a FCT diagnostic, Bergoz Instrumentation model FCT-082-05:1-H [9], located after the deflectors. The right y-axis shows the chopper voltage signal.

The top trace in blue shows the pre-chopped beam, which consists of a continuous train of bunches selected by the pre-chopper without activating the chopper. The red trace beneath it represents the extracted beam after the chopper is turned on: several bunches are allowed through initially, and once the deflector is switched off, subsequent bunches are suppressed. The green dash-dotted line shows the chopper voltage for timing purposes. Before applying the trigger, the first deflector voltage is at its operational level, approximately −44.6 kV in the experiment, allowing bunches to be extracted. After the trigger arrives, the chopper shuts off the deflector field, preventing further bunches from being steered out of the cyclotron. The RF signal, shown as a continuous sinusoidal waveform at the bottom in light blue, matches the cyclotron's operating frequency.

Figure 5 demonstrates the effect of varying deflector voltages on beam suppression and single-bunch extraction at the 88-Inch Cyclotron. The x-axis shows time in nanoseconds. The left y-axis represents the beam current in arbitrary units as measured by the FCT mentioned before, and the right

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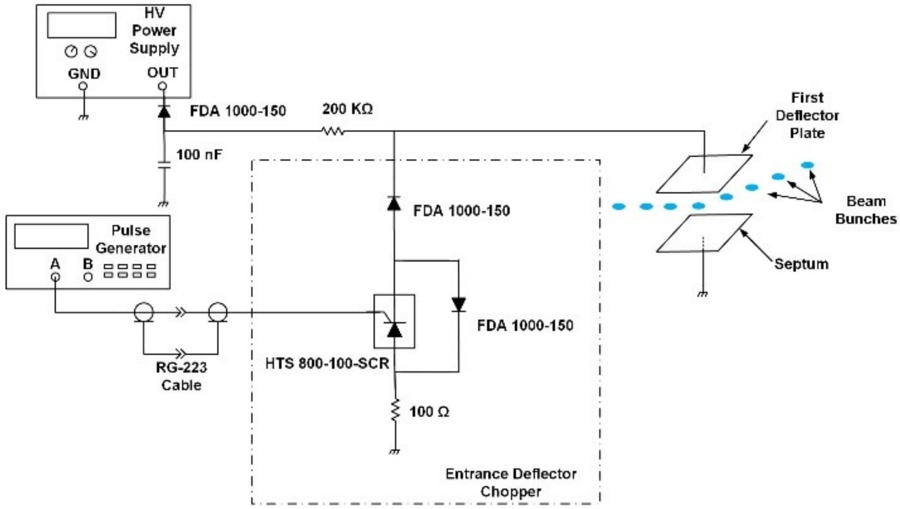

Figure 3: Deflector beam chopper. One HTS 800-100-SCR unit can switch up to −80 kV to the first deflector plates, enabling single bunch extraction from the cyclotron.

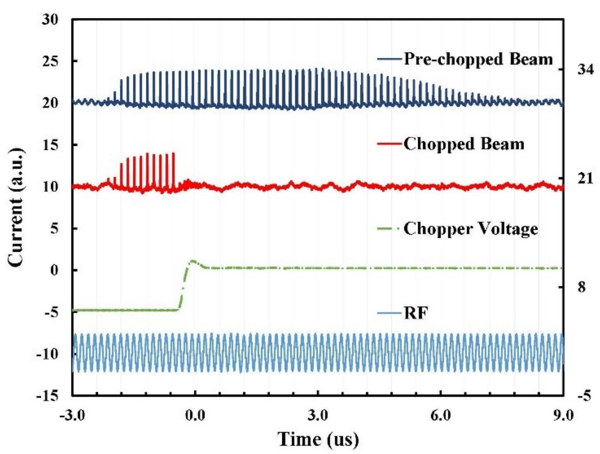

Figure 4: A deflector beam chopper suppresses 16 MeV deuterium beam bunches. The figure shows the microstructure of a 10 µs macro pulse defined by the pre-chopper, both before and after being chopped. The head and tail of the extracted beam macro pulse have different amplitudes due to the energy spread during the acceleration process.

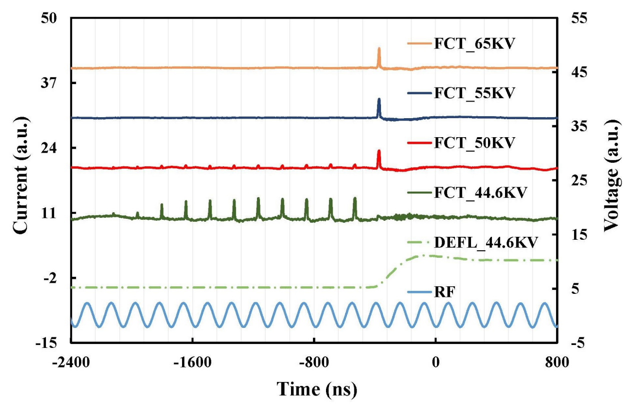

Figure 5: Single-bunch extraction with the chopped deflector technique.

y-axis corresponds to the voltage across the deflector, also in arbitrary units.

Four current traces labeled FCT_44.6KV, FCT_50KV, FCT_55KV, and FCT_65KV are shown, each corresponding to a different fixed voltage applied to the first deflector. The green FCT_44.6KV trace, which uses the −44.6 kV nominal deflection voltage for beam extraction, shows multiple bunches being extracted over time. As the voltage is increased to −50 kV (red), −55 kV (blue), and −65 kV (orange), beam extraction becomes increasingly suppressed. At −65 kV, only a single bunch is observed, confirming effective single-bunch extraction.

The green dash-dotted line labeled DEFL_44.6KV represents the switching of the deflector voltage from its −44.6 kV nominal value to zero, occurring just before time zero. The bottom waveform in light blue shows the RF signal from the cyclotron, providing a phase reference synchronized with the beam bunches.

Together, these traces highlight the tuning process for achieving single-bunch extraction by adjusting the deflector's over-steering voltage. As the voltage deviates from the nominal value, only a narrow time window remains in which the beam receives the precise steering force needed for extraction, enabling the selection of a single bunch while blocking the rest. The switching occurs during bunch transit, and the optimal phase ensures consistent single-bunch delivery. This confirms precise synchronization between the RF system and deflector switching, enabling controlled extraction.

The extracted bunches showed a Gaussian profile with a 5.5 ns standard deviation, and the deflector's switching off time was about 350 ns. Subsequent phase shifts demonstrated the setup's precise timing control and reproducibility.

In the current configuration, the 100 nF buffer capacitor charges to the high-voltage level in approximately 50 ms

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through the power supply's 100 kΩ output impedance. Once the SCR is triggered, the capacitor begins to discharge through the 200 kΩ resistor. This partial discharge continues for about 60 ms until the current falls below the SCR's 100 mA holding current threshold, at which point the SCR turns off. This ensures reliable SCR turn-off and allows the system to reset for the next switching cycle in approximately 110 ms, limiting the maximum achievable pulse repetition rate.

As part of future improvements, replacing the 200 kΩ resistor with a 2 MΩ resistor causes the current through the SCR to drop below its holding threshold much sooner, turning it off before the buffer capacitor is significantly discharged. In this configuration, only the first deflector plate, estimated to have a capacitance of 46 pF, is discharged with a time constant of 92 ns. The discharge is essentially complete within about 460 ns. This modification protects the power supply and enables significantly higher repetition rates.

CONCLUSION

This study introduces a cost-effective chopped deflector method for achieving a single-bunch extraction at the 88-Inch Cyclotron. The technique combines a pre-chopper to reduce power deposition from discarded beam bunches with a modified first deflector, equipped with a fast high-voltage SCR switch, to select and extract a single bunch. The method proved repeatable and is adaptable for various ion species by initially oversteering the beam with the first deflector and then switching it off to coincide with the transit time of a single bunch. Future improvements will permit higher repetition rates by maintaining the buffer capacitor's mostly charged.

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