Title

Single radio frequency bucket injection in the 88-Inch Cyclotron using a pulsed high voltage chopper

Journal

Review of Scientific Instruments, 95(1)

ISSN

0034-6748

Authors

Covo, M Kireeff
Bloemhard, P
Benitez, J
et al.

Publication Date

2024

DOI

10.1063/5.0183628

Peer reviewed

Single RF-Bucket Injection in the 88-Inch Cyclotron

M. Kireeff Covo, P. Bloemhard, J. Benitez, M. Johnson, D. Todd, J. Cruz Duran, B. Ninemire, and L. Phair [1, a)]

[1]*Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, California 94720, USA*

A single RF-bucket of the 88-Inch Cyclotron is filled using a fast chopper located in the axial line. The bucket then accelerates until it reaches the deflector, at which point it is extracted as a train of bunches. This phenomenon can be attributed to the characteristic multi-turn extraction of the cyclotron and, by simplifying the complex dynamics of a cyclotron, corresponds to the conceptual transfer function of the cyclotron. Confirmation of the single RF-bucket injection was achieved by operating the cyclotron in the third harmonic mode and observing the absence of intermediate bunches during the multiple-bunch extraction.

I. INTRODUCTION

The 88-Inch Cyclotron located at Lawrence Berkeley National Laboratory uses segmented magnetic fields and electric fields to efficiently focus and accelerate charged particles, maintaining a constant magnetic rigidity of 140. It possesses capabilities for both light and heavy ions, supporting a local research program in nuclear science. Furthermore, it enables the execution of hardware radiation hardening experiments within the Berkeley Accelerator Space Effects Facility [1].

There are three electron cyclotron resonance ion sources (ECR, VENUS, and AECR) in the Cyclotron, Fig. 1. These ECRs possess a unique ability to generate a mixture of ions with nearly identical charge-to-mass ratios, referred to "cocktails" of ions [2]. These produced ions are collectively extracted from the sources and directed toward the axial line using a bending magnet. To reduce the current before reaching a new fast chopper, a set of 6 attenuator meshes can be employed.

The role of the chopper is to confine the beam particles longitudinally prior to their interaction with the fundamental and harmonic bunchers. These bunchers concentrate the ions along their length into buckets, which are adjusted to ensure successful capture and acceleration by the cyclotron's radio frequency (RF). Subsequently, an electrostatic mirror inflector bends the ions toward the Cyclotron's midplane.

Once the ion bunches enter the Cyclotron, the combination of alternating electric fields and a constant perpendicular magnetic field confines and accelerates them until they approach the deflectors for extraction. The Cyclotron functions as a mass spectrometer, capable of selecting various ion species and charge states up to a maximum energy of 55 MeV/u.

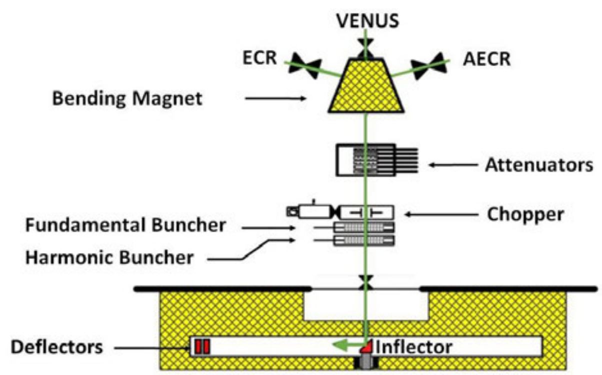


FIG. 1. (Color online). Layout of the axial injection line.

In contemporary times, pulsed power technology has advanced significantly. High-voltage and power semiconductor switching units, which utilize combinations of MOSFETs, IGBTs, and SCRs in both series and parallel configurations, are readily available off-the-shelf [3,4]. These units demonstrate high reliability and the ability to switch swiftly, handling hundreds of kilovolts and tens of kiloamperes within nanoseconds, all while exhibiting minimal jitter [5,6]. Notably, the chopper, located in the axial line, has been upgraded using commercially available switches, specifically the FSWP 51-02 model [7]. This enhancement facilitates the filling of a single RF bucket within the cyclotron.

a) Electronic mail: mkireeffcovo@lbl gov

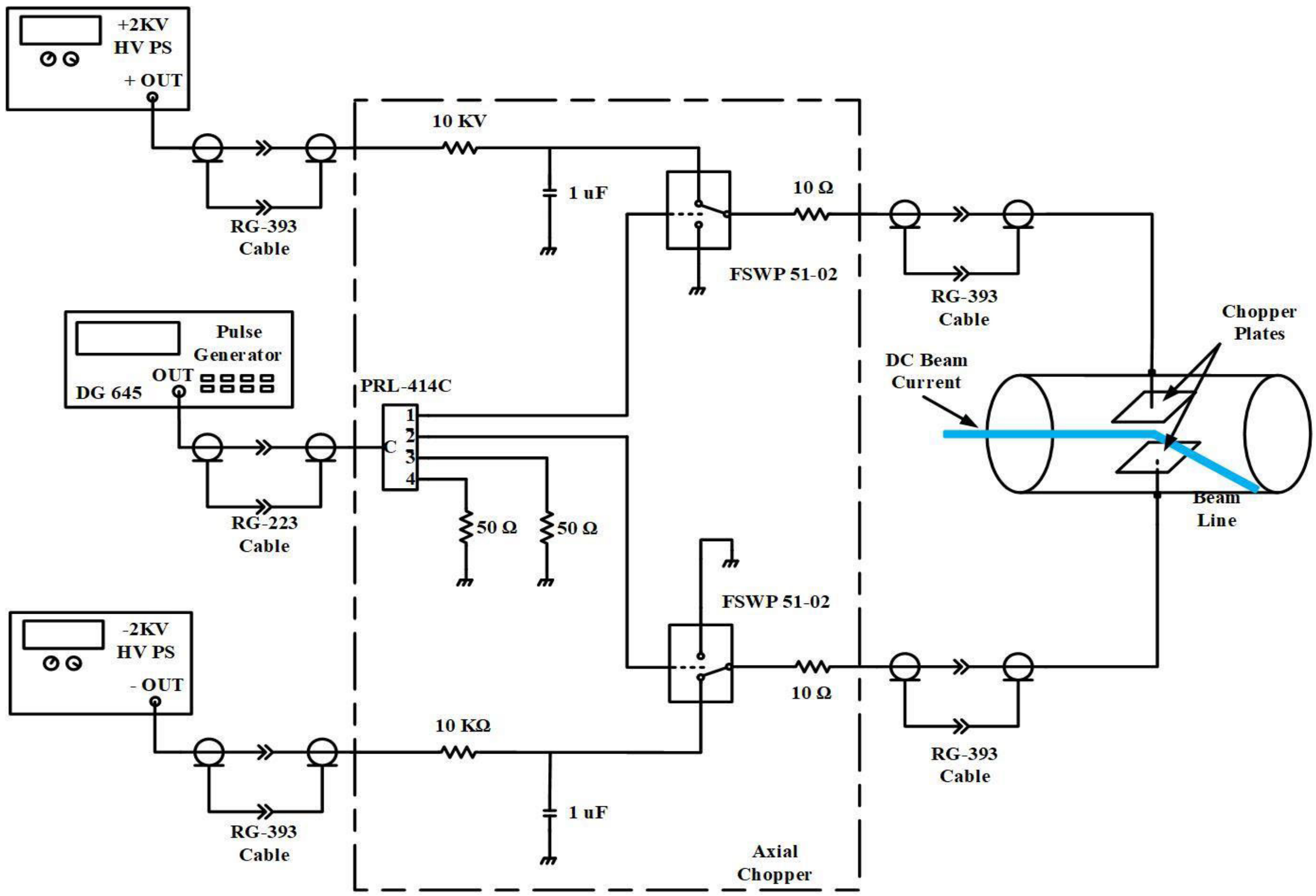


FIG. 2. (Color online). Axial Chopper. Two FSWP high-voltage pulsers may apply up to + 2 KV to the chopper plates and deflect the beam to the beam line walls, before reaching the inflector.

II. EXPERIMENTAL SETUP

As the energy of the beam in the injection line is less than 25 KeV/u, the beam possesses a relatively low momentum. Consequently, electric fields are employed to deflect the beam towards the beam line walls using a chopper, akin to other slow wave deflectors [8], without any dosimetric consequences.

A block diagram of the fast chopper is presented in Fig. 2. Positioned 4.1 m from the cyclotron midplane, this chopper is frequently utilized to confine the beam particles longitudinally, thereby controlling either the integrated flux or the time of arrival at the target. The fast chopper has the ability to apply bias to two parallel electrostatic chopper plates, each measuring 15.25 cm in width and 8.25 cm in length, with a separation of 8.25 cm between them. The ions traverse through the center of these plates. If the plates are unbiased, the ions can reach the inflector. Conversely, if bias is applied to the plates, the ions are directed towards the beam line wall.

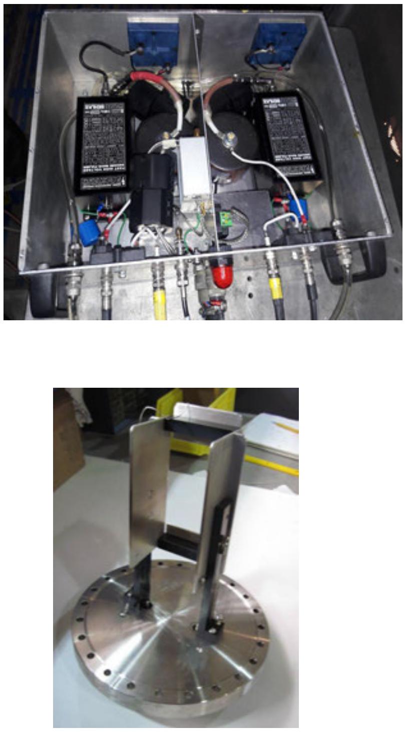
A. Axial Line Fast Beam Chopper Electronics

The fast chopper is triggered by a TTL input pulse from an SRS DG645 digital delay generator with a rubidium timebase, synchronized to the RF reference signal of the cyclotron. It processes the TTL pulse generator into two complementary signals by using the PRL-414C. Each signal will drive two fast square wave pulsers (Behlke, model FSWP 51-02), as shown in Fig. 2, enabling it to provide + 2 KV to the chopper plates.

The FSWP-51-02 pulsers consist of a series of Metal-Oxide-Semiconductor Field-Effect Transistors triggered by an isolated circuit, and the unit can be configured to deliver efficient, high-power, and low-distortion positive or negative high-voltage pulses.

The pulsers are directly cooled with a dielectric liquid, Galden HT-135, which is known for its excellent specific heat capacity and insulation properties, enabling continuous switching in just tens of nanoseconds. A thermal interlock provides protection against overheating due to rapid frequency switching by disabling the control circuit when the temperature exceeds 75 °C.

Low inductance capacitors of 1 μF, rated up to 5KV from Condenser products, are installed before the FSWPs to buffer the external HV power supplies. 10 KΩ resistors located before the capacitors decrease the reflections and safeguard the HV power supplies. Additionally, 10 Ω ceramic resistors are installed after the FSWPs to minimize reflections from the chopper plates during switching.



(a)

(b)

FIG. 3. (Color online). Axial Line Fast Beam Chopper. (a) Electronic chassis. (b) Parallel electrostatic plates.

In Fig. 3, an image of the electronic chassis and the electrostatic plates is presented. The electrodes are deliberately unmatched to reduce power consumption at expense of increasing reflections. Ferrite toroids made of material 43 encircle the cables as common-mode chokes, minimizing reflections and preventing retriggering of the FSWPs when the pulse width is decreased to ~100 ηs.

The chassis was connected to the chopper electrodes, and the power supplies were adjusted to $\pm$ 2KV bias. Fig. 4

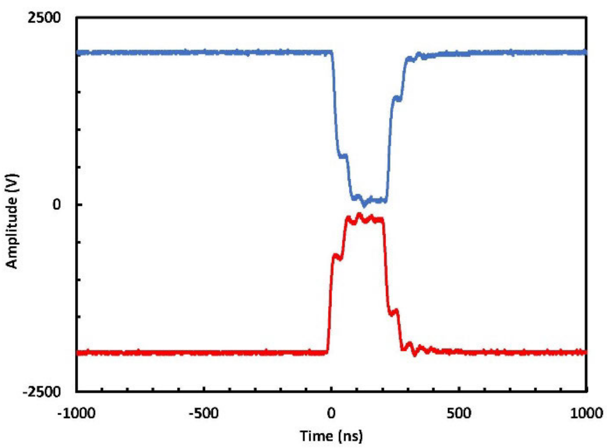
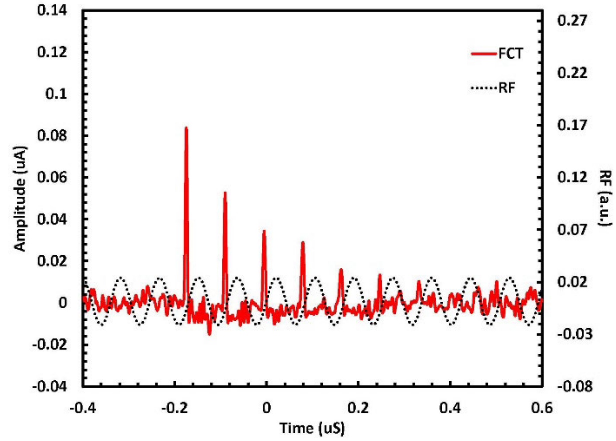
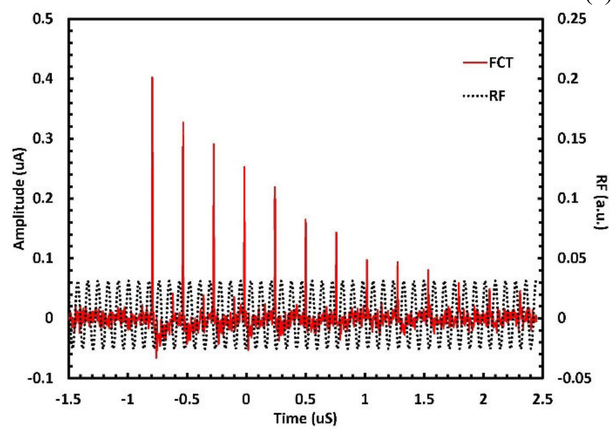


FIG. 4. (Color online). $\pm$ 2 KV pulse measurement from the chopper electrodes when a 200 ns pulse is applied to the Axial Line Fast Beam Chopper electronics with frequency of 1Hz. The +2 KV electrode (blue line) and -2 KV electrode (red line) go to zero at the same time, allowing the ion beam to reach the inflector. The small distortions are caused by reflections from mismatches.



(a)



(b)

FIG. 5. (Color online). Multiple-turn extraction structure obtained from a single RF-bucket injection. (a) 29.6 MeV H+1 by running the cyclotron at 11.8MHz in the first harmonic mode. (b) 6 MeV 2H+1 by running the cyclotron at 11.6 MHz in the third harmonic mode.

illustrates a measurement using a HV probe connected to the electrodes, applying a 200 ns pulse at a frequency of 1 Hz. Slight pulse distortions arise from reflections due to mismatches.

III. COMISSIONING

The cyclotron is tuned to produce a 29.6 MeV H^{+1} beam by operating the cyclotron at 11.8 MHz in the first harmonic of the acceleration frequency, and a 6 MeV $^2H^{+1}$ beam by operating the cyclotron at 11.6 MHz in the third harmonic. The chopper is configured to allow the beam to pass during a single period of the RF signal, and the phase is adjusted to maximize the current, corresponding to a single-bucket injection that fills one RF bucket.

This bucket is subsequently accelerated and extracted from the cyclotron. The measurement of the extracted beam was conducted using a low-inductance current transformer, model FCT-082-05:1-H, from Bergoz Instrumentation. Positioned after the deflectors, this transformer boasts a rapid response of 5V/A and a bandwidth of 700 MHz.

The extracted beam structures are displayed in Fig. 5. The primary ordinate displays the current with a solid red line, while the secondary ordinate showcases the RF signal with a dashed black line. The abscissa represents time. The top plot depicts the 29.6 MeV H^{+1} beam extracted, performed during operation in the first harmonic, while the bottom plot portrays the 6 MeV $^{2}H^{+1}$ beam extraction, conducted in the third harmonic. Notably, the extracted beams exhibit a “tail” content as a consequence of the cyclotron’s multiple turn extraction process [9].

IV. DISCUSSIONS

Chopping the beam at injection, where the DC beam from the sources possesses energy lower than 25 keV/u, requires lower electric fields for deflection, and the dumped beam results in negligible dosimetric consequences. The chopper is routinely employed to limit the power delivered to the targets and to mitigate beam-induced activation.

Single RF-bucket injection is achieved by chopping the beam along the axial line until it is short enough to occupy only one RF bucket during the cyclotron's RF phase acceptance. Although this method inherently leads to multiple-bunch extraction, obscuring the success of the injection, verification of this process can be accomplished by operating the cyclotron in the third harmonic. In this mode, each bucket synchronizes with the RF every three cycles. As the chopper narrows the bunch during injection to fit into a single RF-bucket, intermediate bunches observed during extraction begin to diminish and ultimately disappear, leaving only a main bunch with a tail being extracted every three cycles of RF, a pattern consistent with the cyclotron’s characteristic multi-turn extraction, indicating the successful attainment of a single bucket injection.

Clearly, a cyclotron is not purely linear. Multiple nonlinearities, such as space charge effects or beam-beam interactions, might affect the bunches as they circulate. Nonetheless, this can be a valuable initial approach to predicting the extracted beam.

In a classical cyclotron, multiple-turn extraction occurs because particles in the RF bucket gradually drift in phase and diverge in energy. Fig. 6 presents a sketch of the bucket distribution near extraction during the final turn N, represented by the solid blue line. The ordinate plots kinetic energy, while the abscissa depicts phase distribution [10]. E1 and E2, marked by two parallel solid red lines, denote the energy level boundaries set by the septum and entrance deflector, respectively. The figure illustrates that a segment of the single RF bucket will be extracted when its energy increases and it reaches the deflector within the phase confined between φ1 and φ2. The remaining particles execute another turn, accumulating enough energy to enter the septum-deflector gap, where they are successively sliced and extracted. This dynamic process persists until all particles have been either extracted or lost in the process. Consequently, a single RF bucket is extracted as a train of bunches. By simplifying the complex dynamics of a cyclotron, where particle acceleration involves nonlinearities, resonances, and multiple interacting variables, such as space charge effects or beam-beam interactions, the multiple-turn extraction process can be viewed as the machine's conceptual transfer function, serving as a valuable initial approach to predicting the extracted beam.

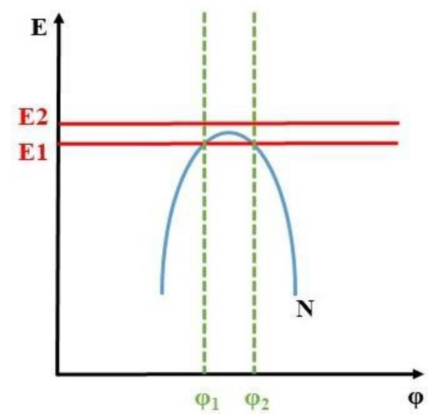


FIG. 6. (Color online). Particle kinetic energy at the extraction as a function of RF phase for the last turn N, solid blue line. Kinetic energy, E, is represented in the ordinate and phase distribution, φ, is depicted in the abscissa. The bunch will be extracted when the particles reach the energy level boundaries set by the septum and entrance deflector, E1 and E2, with phase between φ1 and φ2.

Single-turn extraction can be achieved from a single RF-bucket injection by positioning slits close to the cyclotron’s center, which serve to limit the bucket's phase width and confine the phase between φ1 and φ2 [11]. Reducing the phase width further narrows the energy spread, albeit at the cost of diminished beam intensity. An alternative method for attaining single-turn extraction entails the use of a chopper during injection to curtail the quantity of accelerated particles — effectively limiting beam power — followed by the selection of a single RF-bucket through a sinusoidal voltage chopper situated in the beam transport line post-extraction [9].

V. CONCLUSIONS

Advancements in pulsed power technology have led to the availability of off-the-shelf high-voltage and power semiconductor switching units, capable of switching hundreds of kilovolts and tens of kiloamperes in nanoseconds with low jitter. By leveraging such technology, a fast chopper has been designed using commercially available switches from Behlke, specifically the model FSWP 51-02. Installed at the injection line, this chopper requires lower voltage for its electrodes to steer ions with reduced momentum, thereby minimizing beam activation.

During the commissioning phase, a single RF-bucket fill at the injection is achieved by longitudinally constraining the DC beam from the ECR sources, compressing the beam with bunchers, and adjusting its phase before it is deflected into the cyclotron. The RF-bucket progressively phases out, resulting in multi-turn extraction. This phenomenon arises because particles, having varying energies and phases, complete a different number of revolutions before reaching the septum-deflector energy gap and exiting the cyclotron.

The successful confirmation of a single RF-bucket injection is demonstrated by operating the cyclotron in third-harmonic mode and observing the suppression of intermediate bunches.

ACKNOWLEDGEMENTS

The authors want to thank Taimoor Hassan, Patrick Coleman, Kenneth Lambert, Brendan P. Ford, Nathaniel Bohm, Patrick Colleman, Erik Line, and Collin Anderson for the electronics group support; Alexander Donoghue, Scott M. Small, Nicholas M. Brickner, Nishi Intwala, and Devin T. Thatcher for the operations support; Nathan Seidman, Roman Nieto, John P. Garcia, Donald Bell, and Sixuan Zhong for the mechanical group support of the LBNL 88-Inch Cyclotron. This work was supported by the Nuclear Physics, Nuclear Physics Division of the U.S. Department of Energy under Contract DE-AC02-05CH11231.

[1] M. B. Johnson, M. A. McMahan, T. L. Gimpel, and W. S. Tiffany, in *IEEE Radiation Effects Data Workshop*, Ponte Vedra, FL (2006), pp. 183.

[2] D. Leitner, M. A. McMahan, D. Argento, T. Gimpel, A. Guy, J. Morel, C. Siero, R. Thatcher, and C. M. Lyneis, in *15th International Workshop on ECR Ion Sources*, ECRIS '02, Jyvaskyla, FI (2002), pp. 183.

[3] T. Fowler, T. Stadlbauer, F. Mueller, M. Barnes, and T. Kramer, Conf. Proc. C 1205201, 3689 (2012).

[4] W. Merz and M. Grimes, in *2012 IEEE International Power Modulator and High Voltage Conference* (IPMHVC), pp. 308.

[5] A. V. Ponomarev, Y. I. Mamontov, A. I. Gusev, and M. S. Pedos, Journal of Physics: Conference Series 830, 012006 (2017).

[6] A. Caruso *et al.*, Journal of Physics: Conference Series 1067, 042015 (2018).

[7] https://www.behlke.com/pdf/fswp_91-01_rs.pdf.

[8] F. Caspers, in *22nd International Linear Accelerator Conference*, Lubeck, Germany (2004), p. 578.

[9] S. Kurashima, N. Miyawaki, H. Kashiwagi, S. Okumura, M. Taguchi, and M. Fukuda, Review of Scientific Instruments 86, 073311 (2015).

[10] H. Hagedoorn, N. Hazewindus, and J. Van Nieuwland, in *Proc. 5 Int. Conf. on Cycl.*, Butterworths, London (1969), pp. 274.

[11] J. Botman and H. Hagedoorn, in *Proceeding of CERN Accelerator School* (1996), pp. 169.