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DESIGN STUDY OF AN RF-KICKER MODULE FOR BUNCH CLEANING AT THE ATLAS POSITIVE-ION INJECTOR

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Abstract

Positive-Ion Injector (PII) at ATLAS accelerator facility can accelerate heavy ions and has three key subsystems: an Electron Cyclotron Resonance (ECR) ion source, a 12-MHz multi-stage beam bunching system, and a 12-MV superconducting linac accelerator. The first stage of the bunching system is the multi-harmonic buncher that operates at 12.125 MHz and creates a bunch train with period of 82.5 ns at a 70% bunching efficiency. The remaining un-bunched beam must be removed to avoid the production of undesirable 'satellite' bunches, which can quench the superconducting solenoids downstream during operation. In this paper, We present our progress on the study of a low frequency kicker for the ATLAS Low Energy Beam Transport (LEBT) and intended, ultimately, to improve the transmission efficiency for high-intensity beams through ATLAS.

INTRODUCTION

The Argonne Tandem Linac Accelerator System (ATLAS) at Argonne National Laboratory is a superconducting linear accelerator designed for the acceleration of both stable and neutron-rich heavy-ion beams spanning a broad mass range [1]. It provides high-quality beams for high-precision investigations in nuclear structure, reaction dynamics near the Coulomb barrier, and tests of fundamental symmetries. High-charge heavy ion beams are central to these efforts because their high charge states improve acceleration efficiency, allowing delivery of intense, high-energy beams for diverse applications. These include not only nuclear structure and reaction dynamics studies, but also fusion–evaporation and transfer reactions, strong-field QED experiments, radiation effects in materials, and advanced research in ion beam therapy and radiobiology [2]. However, the use of high-charge beams introduces significant operational challenges in superconducting accelerator environments. Their high ionization power leads to substantial localized energy deposition with minor beam losses and trigger quenches in superconducting cavities and magnets as observed in the Positive ion injector Linac in ATLAS.

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In this work, we present the design study of a normal-conducting RF kicker intended to remove the primary sources of quenching——highly charged satellite bunches— that originate from the temporal tails of the main bunches during acceleration in the Radio-Frequency Quadrupole (RFQ).

NEED FOR A KICKER DEVICE

To understand aforementioned satellite bunch forming mechanism in ATLAS, the Low Energy Beam Transport(LEBT) section of the ATLAS facility (Fig. 1) was simulated in TRACK3d [3].

The LEBT section extracts ion beams from a Electron Cyclotron Resonance (ECR) ion source and conditions them for injection into the Positive-Ion Injector (PII) linac. It includes a multiharmonic buncher [4] that imposes a time-dependent energy modulation to bunch the beam longitudinally, followed by magnetic elements for transverse focusing. The beam is then directed into a RFQ, which provides initial acceleration, transverse focusing, and additional bunching.

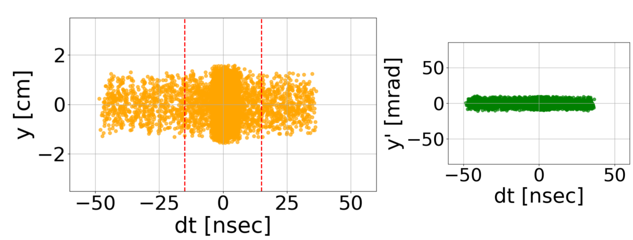

Figure 2: Transverse longitudinal correlations plotted at the entrance of quadrupole triplet magnet.

The transverse and longitudinal correlation of a Xe_{136} bunch (Fig. 2), with charge state of 20^+, was obtained at the entrance of the quadrupole triplet in Fig. 1. It reveals a well-defined temporal core with lower-density tails. Its transverse phase space also exhibits well-defined core, supporting efficient downstream transport and high-quality injection into subsequent accelerating structures.

The longitudinal phase space of the Xe^{20+}_{136} beam (Fig. 3) shows densely populated particles near the temporal center

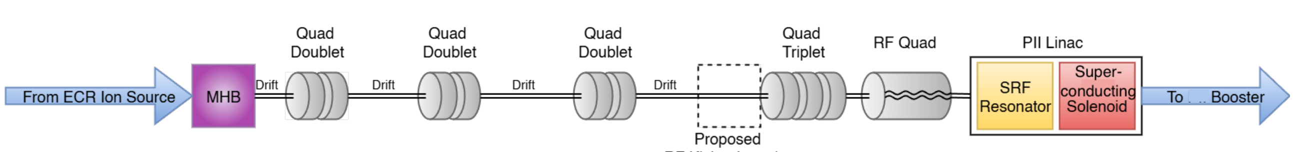

Figure 1: The Low Energy Beam Transport (LEBT) section of the ATLAS facility.

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with elongated tails. About 14% of particles lie in the tail. Such clear distinction allows effective removal of particles in the tail using a fast kicker.

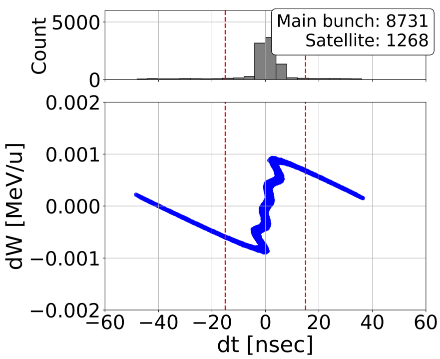

Figure 3: Longitudinal Phase space at the entrance of the Quadrupole triplet.

Figure 4 shows the longitudinal phase space after the RFQ. We can see the satellite bunches, that did not exist, appear after the RFQ. This contains approximately 6% of total particles. We believe these satellite bunches originate from the tail shown in Fig. 3. A RF kicker would be one of the best tools to effectively remove those longitudinal tails in compact manner.

Note that the increase in energy spread after the RFQ is due to the acceleration of the bunch from 30 keV/u to 290 keV/u.

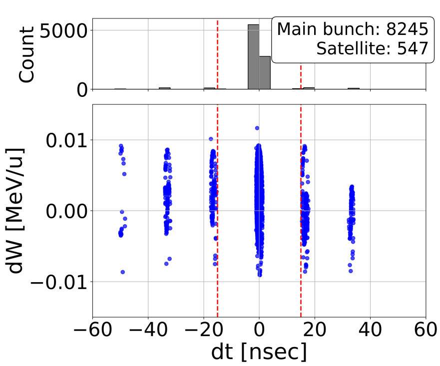

Figure 4: Longitudinal phase space of the bunch after RFQ.

RF KICKER DESIGN

We designed an RF kicker operating at 6 MHz, and it will be placed in front of the RFQ as shown in Fig. 1. A time-synchronized transverse RF kick (see Fig. 5) is applied to the temporal tails of ion bunches, reducing beam losses in the downstream superconducting solenoids and increasing transmission through the PII linac. The kick must be minimal to preserve the quality of the main bunch core, yet sufficient to effectively remove temporally separated satellite particles. The kicker was also designed to fit within the spatial constraints of the ATLAS beamline.

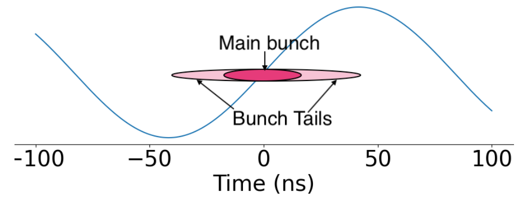

Figure 5: Bunch cleaning with a 6 Mhz E-field.

3D EM Modeling

A quarter-wave helical resonator design [5] was adopted to generate a strong low-frequency RF fields for beam manipulation within a compact quarter-wave resonant cavity as shown in Fig. 6. It has vertically tall shape due to the physical constraints of the facility. A 12.5 m copper coil (150 mm radius, 1 m height) enclosed in a 1.24 m × 200 mm copper can. One end is grounded, the other drives 26 mm deflecting plates. Shielding plates limit stray fields that could introduce undesired deflections. A 40 mm slit at the exit pipe removes kicked tails. Beam pipe is 500 mm long and has 60 mm aperture.

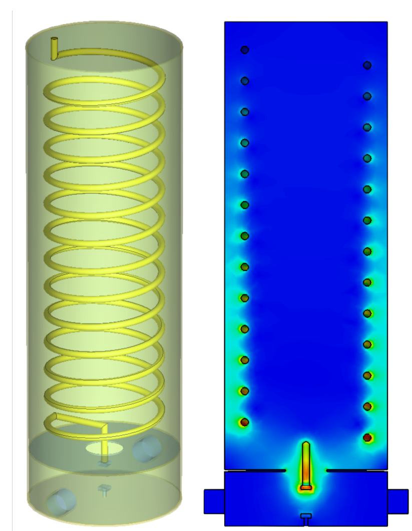

Figure 6: CST model of the RF-kicker. (left) Modeled kicker geometry. (right) Electric field distribution on the cut section.

Inside the kicker, E-field along the beam axis is well-defined and localized as shown in Fig. 7. It can produce vertical deflection in the bunch without introducing coupling in any other planes. Note that stray fields without the shielding plate introduces extra deflection fields near the entrance and exit. It could also introduce extra couplings in other planes.

EFFECTS OF THE RF KICKER DEVICE ON THE BUNCH

The kicker was integrated into the TRACK3D simulation for the LEBT section. The simulated beam after the kicker is

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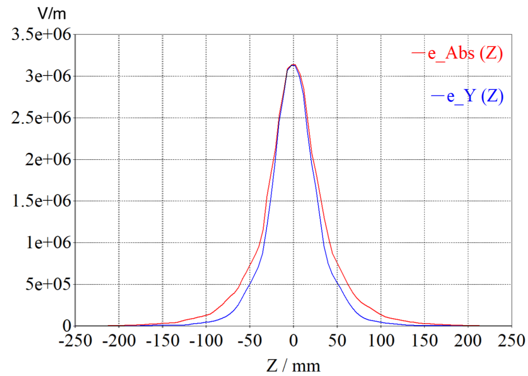

Figure 7: E-field profile on the beam axis.

provided in Fig. 8 and Fig. 9. The time-dependent kick from the kicker introduces a tilt in $t-y$ and $t-y'$ phase spaces as seen in Fig. 8. It is worth noting that the kicker also slightly altered the particle energies as shown in Fig. 9. We scanned the kicker field level to find the optimal strength. The results showed that an E-field of 315 kV/m provides sufficient kick to effectively remove tails without significant loss of the bunch core. The 40 mm aperture slit at the end of the RFQ filters out about 4% of the satellite particles, corresponding to roughly 0.7% of the total beam.

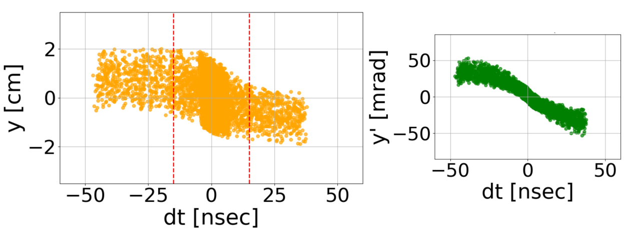

Figure 8: Transverse longitudinal correlation after the kicker.

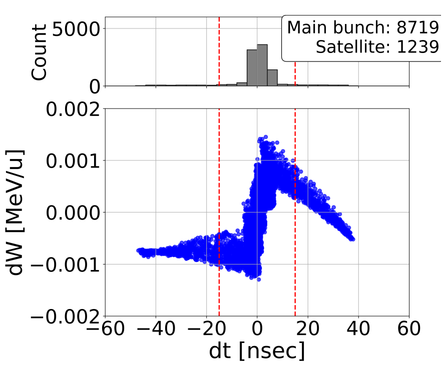

Figure 9: Longitudinal phase space of the bunch before the Quadrupole triplet entrance with the kicker.

The beam phase space after the RFQ is shown in Fig. 10. The results show complete removal of the satellite bunches with 9.7% loss in the main bunch compared to the simulation without the kicker.

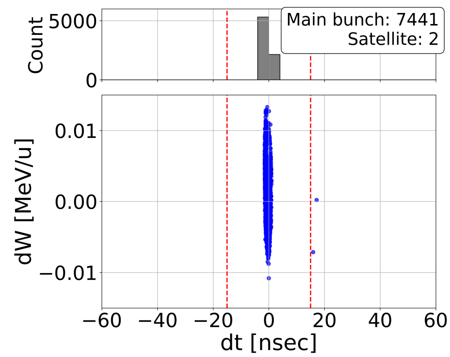

Figure 10: Longitudinal phase space of the bunch downstream of the RFQ with the kicker.

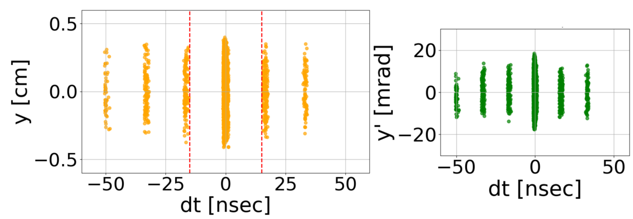

Figure 11: Transverse longitudinal correlation downstream of the RFQ without the kicker.

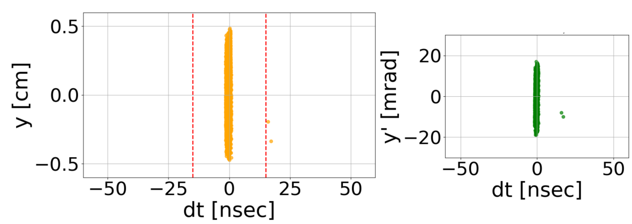

Figure 12: Transverse-longitudinal correlation downstream of the RFQ with the kicker.

As can be seen from Fig. 11 and Fig. 12 the vertical beam size of the bunch has increased slightly. However, the y'-distribution remained consistent indicating minimal impact on the core and its stable propagation downstream. Additionally, the plots demonstrate that the majority of satellite particle losses occur within the RFQ, as its vertical aperture is smaller than the kicked bunch tails.

CONCLUSION

An RF kicker has been designed to remove satellite bunches that damaging superconducting solenoids at the ATLAS facility. The TRACK3D simulations, combined with CST-based EM model, showed that the designed kicker, operating at 6 MHz, effectively removes satellite bunches while making minimal impact on the main bunch core.

One current concern is that the slit at the kicker exit did not effectively remove satellite particles due to insufficient deflection. Intercepting these tail particles at this location would reduce losses within the RFQ, thereby minimizing potential damage to it. Further R&D is required on the de-

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flection voltage and on downstream beam dynamics related to particle losses in both the core and the tail.

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