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IOTA EXPERIMENT FOR PROTON PULSE COMPRESSION AT EXTREME SPACE-CHARGE

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Abstract

The longitudinal compression of intense proton bunches with strong space-charge force is an essential component of a proton driver for a muon collider. We propose a proton bunch compression experiment at the Integrable Optics Test Accelerator (IOTA) storage ring at Fermilab to explore optimal radio frequency (RF) cavity and lattice configurations. IOTA is a compact fixed-energy storage ring circulating 2.5-MeV protons with extreme space-charge. Using ImpactX and its 3D space-charge solver, simulations indicate that bunch length can be rapidly reduced by a factor of at least two, without appreciable degradation in transverse beam quality, even under strong space-charge conditions. Optimization of bunch compression under such conditions is discussed.

INTRODUCTION

In the wake of the most recent P5 report [1], the vision for the future of HEP programs includes charting a realistic path to a 10 TeV parton center-of-momentum (pCM) collider. A Muon Collider (MuC) is a compelling option for a 10 TeV pCM collider, with Fermilab considered as a potential host facility for MuC R&D projects as well as the collider itself. Fermilab is currently studying the core parameters of the proton driverfor the production of the muon beams, which is required to deliver extremely intense 1-3 ns bunches.

Space-charge is a major constraint for a 2–4-MW proton driver with 8-GeV protons compressed into nanosecond-scale pulses [2, 3]. Accelerator R&D for these short, intense proton pulses, while critical for realizing a future MuC, has applications for many next-generation High Energy Physics (HEP) experiments including dark sector searches, neutrino physics, and flavor physics [4, 5]. This work will develop a new experimental proposal for bunch compression at Fermilab's Integrable Optics Test Accelerator (IOTA) [6] storage ring during its upcoming proton runs.

FAST/IOTA is the only US dedicated facility for intensity frontier accelerator R&D and due to this, its portfolio of R&D interests include techniques for mitigating coherent instabilities and space-charge effects, such as nonlinear integrable optics (NIO) [7] and electron lenses [8]. This includes compressing that intense proton beam into the short bunches required for next-generation HEP experiments.

The IOTA ring itself, shown in Fig. 1 along with the proton injector line, is a compact fixed-energy storage ring that can circulate a 2.5 MeV proton beam with a beam current of up to

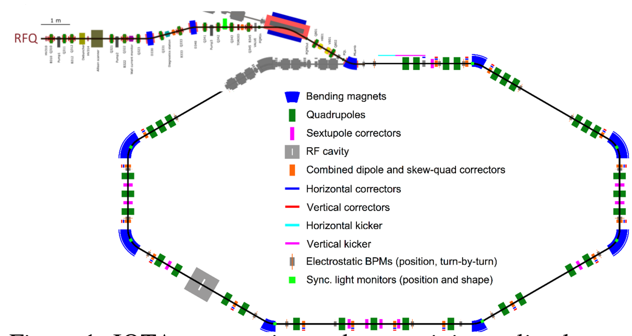

Figure 1: IOTA storage ring and proton injector line layout.

8 mA [6] and a corresponding incoherent space-charge tune shift ($|\Delta Q_{sc}|$) of up to 0.5. The proposed accelerator R&D program will incorporate factor of two bunch compression to extend the space-charge regime.

THE EXPERIMENT

The R&D program, called the FAST/IOTA Bunch Rotation Experiment (FIBRE), would be an upgrade to the existing capabilities of the IOTA ring, allowing the intense proton beams to be compressed into shorter pulses through an RF manipulation called snap bunch rotation. The IOTA proton injector (IPI) is currently being commissioned [9] for the upcoming proton runs slated to start at the end of 2025. As discussed in [10], the RF cavity in the DR section of IOTA contains two RF gaps operating at harmonic numbers $h = 4$ (2.19 MHz) to fully bunch the proton beam, and $h = 56$ (30.6 MHz) to introduce longitudinal modulation for instrumentation. Table 1 shows design parameters, and various RF parameters are discussed in later sections.

The voltage of the 2.19 MHz RF gap is limited to 1 kV based on the maximum power available from the existing high-level RF configuration. This voltage limit encouraged a search for determining the requirements of possible replacement, or additional, RF cavities that would benefit not only this experiment, but the operations of the IOTA ring and its future research program as a whole.

Specifically for this experiment, more voltage is required to successfully perform the snap bunch rotation. Along with more voltage, the new cavity would require a new power supply that could provide enough power for the increase in voltage to be obtained in just a few revolutions. Within the list of currently operational RF cavities at Fermilab, a compatible RF cavity design has been identified and its performance will be discussed in a future paper.

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Table 1: Relevant IOTA Ring Parameters for Protons

Parameter	Value
KE (MeV)	2.5
Momentum (MeV/c)	65.5
β	0.0723
η	-0.9256
dp/p	0.001
σ_E (keV)	5.0
f_0 (MHz)	0.5467
Circumference (m)	39.97
RF bucket length (h=4) (ns)	475
Bare lattice tunes (Qx,Qy)	5.3, 5.3

RF Considerations

The 350 MHz radio frequency quadrupole (RFQ) in the IPI accelerates low energy protons to 2.5 MeV resulting in a bunch train with 0.3 ns bunches spaced apart by 2.86 ns. This bunch train is injected into IOTA in a single turn and the beam fills the entire circumference of the ring. Due to the low energy and the relatively large nominal momentum spread of $dp/p = 0.001$, the beam debunches within a few turns. Most of the proton experiments planned for IOTA, including this proposal, require bunched beam, meaning we need to capture and then bunch the coasting DC beam.

Neglecting space charge, the minimum voltage required to capture the protons into a bunch is [13]

$$V_0 = \left(\frac{1}{e}\right) \frac{(n\sigma_E)^2 \pi^3 h|\eta|}{8\beta^2 E_s} , \tag{1}$$

where n is the number of standard deviations of energy acceptance ($n\sigma_E$) we want for the injected beam, η is the phase slip-factor of the lattice, β is the relativistic β from Table 1, and E_s is the energy of the synchronous particle, given as $E_s = mc^2 + KE$. In order to avoid filamentation in longitudinal phase-space and undesirable emittance growth, adiabatic capture is performed according to [10, 11]. For all analysis, the adiabatic capture begins with an initial cavity voltage $V_0 = 10$ V and the adiabaticity number was set to 10.

Snap Bunch-Rotation

Snap bunch-rotation involves instantaneously increasing the RF voltage in the cavity, which expands the bucket height and reduces the synchrotron period, and then allowing the bunch to rotate in longitudinal phase space for 1/4 of a synchrotron period before extracting the compressed bunch. It should be noted that within the experiment being proposed, the bunches won't be extracted, they will be used to characterize the beam quality in the ring.

The ratio between the initial (in our case after adiabatic capture) bunch length, and the compressed bunch length is called the compression factor, r_c. We find the required voltage for snap bunch-rotation of the core of the beam through the relation

$$r_c = \sqrt{\frac{V_{rot}}{V_{cap}}} . \tag{2}$$

For capture and bunching of 3σ of the beam, a voltage of $V_{cap} = 645$ V is required. With a desired compression factor of at least two, we find that the required snap voltage is $V_{rot} = 2.58$ kV.

Diagnostics in IOTA

The initial diagnostics available include a DC current transformer (DCCT) which provides total beam current, along with beam position monitors (BPMs) which provide a measurement of the beam's transverse position. There are also plans in motion to install an Ionization Profile Monitor (IPM) [15] in IOTA, allowing a measurement of the beam's transverse profiles.

SIMULATION ANALYSIS

The experiment is being simulated in ImpactX, which is an s-based beam dynamics code with space charge. The space-charge solver is fully 3D and uses an integrated greens function space charge solver (”FFT solver”) with a [64,64,256] grid, 100k macroparticles, and 999 space charge kicks. The incoherent space charge tuneshift parameter, $|\Delta Q_{sc}|$ is given by

$$|\Delta Q_{sc}| = \frac{N_p r_p L_{RF}}{4\pi \epsilon_N \beta \gamma^2 \sigma_z} , \tag{3}$$

where N_p is the total number of protons in the ring, r_p the classical radius of the proton, L_{RF} the length of the RF bucket, ϵ_N the normalized rms beam emittance, β, γ the relativistic Lorentz factors and σ_z is the rms bunch length, in meters, of the proton bunch in the RF bucket. From Eq. 3 shows that as the bunch is compressed, the incoherent tuneshift will grow larger, pushing particles in the core of the bunch closer to and even crossing the integer resonance.

Results

Simulations were ran for injected currents of 1 µA, 0.5 mA, 1 mA, 2 mA, 4 mA, and 8 mA. The lowest current (1 µA) serves as the reference case with very little space charge, and the highest current (8 mA) is the quoted maximum current the injector can provide. Figure 2 shows the longitudinal distributions for immediately after adiabatic capture (left) and immediately after rotation (right) at selected beam currents.

At 4 mA, there is a clear distortion to the RF bucket shape as a result of the defocusing effect of the longitudinal space charge force. The voltage (V_{SC}) from this defocusing force can be found as

$$V_{SC} = E_{s,SC} C_0 , \tag{4}$$

where $E_{s,SC}$ is the electric field created by the space charge potential, acting in the direction of motion of the bunches, and C_0 is the circumference of the ring. $E_{s,SC}$ is given as [12]

$$E_{s,SC} = -\frac{e}{2\pi\beta c} \left|\frac{Z_0}{n}\right|_{SC} \frac{\partial \rho(\tau)}{\partial \tau} , \tag{5}$$

with $|Z_0/n|_{SC}$ being the longitudinal space charge impedance and for simplicity, we are assuming the longitudinal particle density, $\rho(\tau)$, to be a Gaussian distribution.

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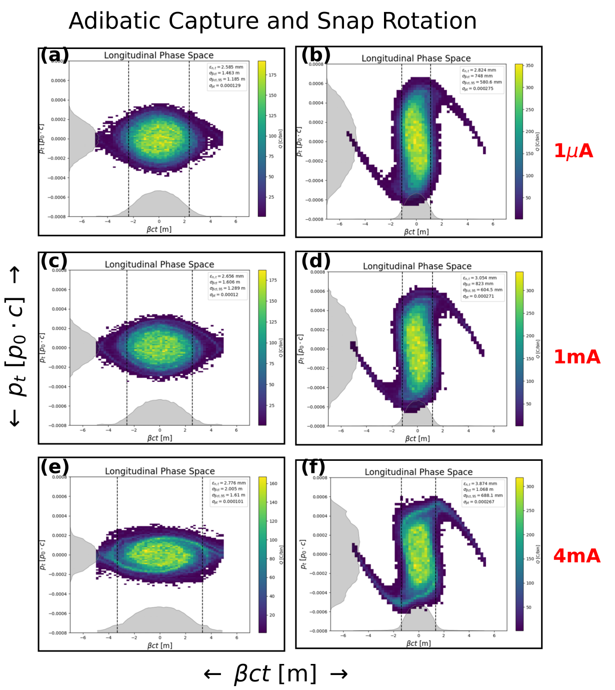

Figure 2: Longitudinal phase spaces after capture and after rotation for three beam currents: 1 µA (a-b), 1 mA (c)-(d), and 4 mA (e-f).

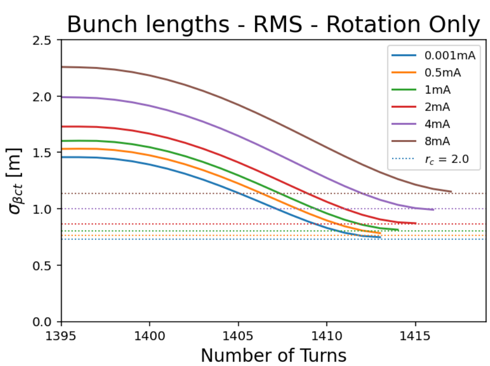

Figure 3: Bunch lengths through the snap rotation.

Plugging everything back into Eq. 4, we can approximate the longitudinal space charge potential as

$$V_{SC} = \left(\frac{1}{h\omega_0^2}\right)\left(\frac{Z_0 g_0}{2\beta\gamma^2}\right)\left(\frac{eN_b}{\sqrt{2\pi}\sigma_\tau^3}\right), \tag{6}$$

where $Z_0 \approx 377\ \Omega$ is the free-space impedance and g_0 is a geometrical factor, which for our purposes is set to 1.

An example illustrates the defocusing effect's impact. Using Eq. 6, we can estimate the space charge potential for the 4 mA beam: $N_b = 1.1418e10$, so $V_{SC} = 131$ V for capture and $V_{SC} = 1050$ V for rotation. The defocusing effects of the longitudinal space charge forces lead to a lengthening of the bunch and a smearing of the core of the beam. Figure 3 shows the bunch lengths through the rotation process where you can clearly see as the intensity increases, the captured bunches are longer.

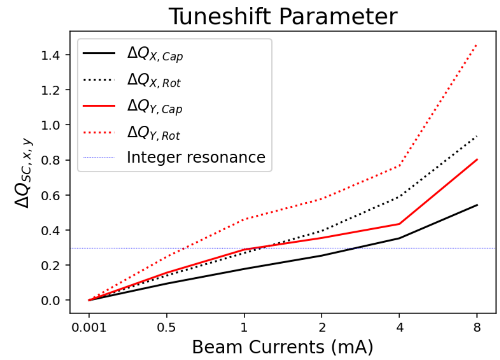

Figure 4: Calculated space charge tuneshift parameters for captured beam and rotated beam in both transverse planes. Solid lines are for the captured beam and the dotted lines of the same color are for the rotated beam. The blue horizontal line indicates a possible encounter with the integer resonance.

Figure 4 gives the calculated incoherent tuneshift parameters using the beam sigmas from the simulations and plugging them into Eq. 3.

The final space charge tuneshift does get very high, as shown in Fig. 4, but the beam doesn't completely blowup during the snap rotation because the rotation happens very fast, requiring only 17 turns (~31µs) for full compression. Without any mitigation, however, as the intensity increases, the bunch requires more time to fully compress, as can be seen in Fig. 3.

CONCLUSION

Based on the MuC proton driver parameters detailed in [2, 3], proton pulse compression at extreme space charge will be paramount in the success of delivering the proton beam necessary for the production of the muon beams. With FIBRE, charge-dominated proton beams would undergo fast-slipping bunch compression with world-leading space charge performance. The IOTA ring provides an avenue to perform detailed studies on the interactions of a lattice's phase-slip factor with the compression process in a heavily charge-dominated proton beam. The next step for this work is to continue the simulation effort in ImpactX, including an analysis of the possible upgraded RF capabilities. We also plan to analyze the feasibility of compensating longitudinal space-charge effects in IOTA by introducing inductive inserts, as proposed in [16] and experimentally studied at the LANL Proton Storage Ring [17].

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