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PROPOSAL FOR A PROTON-BUNCH COMPRESSION EXPERIMENT AT IOTA IN THE STRONG SPACE-CHARGE REGIME

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Abstract

The longitudinal compression of intense proton bunches with strong space-charge force is an essential component of a proton-based muon source for a muon collider. This paper discusses 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 that can circulate a 2.5-MeV proton beam with varying beam parameters and lattice configurations. The study will aim to demonstrate a bunch-compression factor of at least 2 in the IOTA ring while examining the impact of intense space-charge effects on the compression process.

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. One aspect of R&D related to a MuC complex that can start today, at Fermilab, is a study into the core parameters of the proton driver, shown in Fig. 1, for the production of the muon beams, which is required to deliver extremely intense 1-3 ns bunches. Space-charge is a major performance constraint for

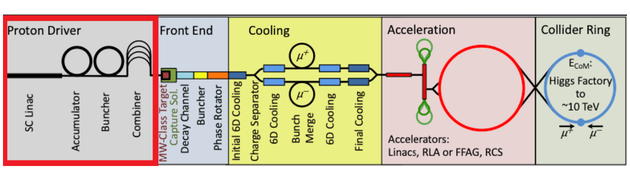

Figure 1: Possible proton driven MuC complex layouts.

a 2-4MW proton driver with 8-GeV protons compressed into nanosecond-scale pulses. Accelerator R&D for these short, intense proton pulses, while critical for realizing a future MuC, has applications in a variety of next-generation High Energy Physics (HEP) experiments including dark sector searches, neutrino physics, and flavor physics [2, 3]. The work discussed here will develop a new experimental proposal for bunch compression at Fermilab's Integrable Optics Test Accelerator (IOTA) [4] 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 various techniques for mitigating coherent instabilities and space-charge effects, such as nonlinear integrable optics (NIO) [5] and electron lenses [6]. With research at IOTA during the proton runs focused on high beam intensity and brightness in proton rings, a natural synergy presents itself in extending that research into compressing that intense proton beam into the short bunches required for next-generation HEP experiments. The IOTA

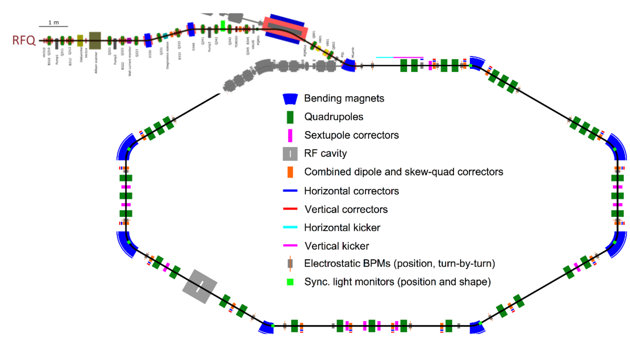

Figure 2: IOTA storage ring and proton injector line layout.

ring itself, shown in Fig. 2 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 8 mA 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 beam physics program to an even more extreme space-charge regime.

THE EXPERIMENT AND PROTONS IN IOTA

The IOTA proton injector (IPI) is currently being commissioned [7] for the upcoming proton runs. As discussed in [8], the RF cavity in the DR section of IOTA contains two RF gaps operating at harmonic numbers $h = 4$ (2.19 MHz) and $h = 56$ (30.6 MHz) which can be used to fully bunch or introduce longitudinal modulation, respectively. The design parameters for proton operations are shown in Table 1 and the various RF parameters for the different systems will be 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. During IOTA's early proton runs, the 1 kV limit for the h=4 RF system will be suf-

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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
γ	1.00266
dp/p	0.001
σ_E (keV)	5.0
Circumference (m)	39.97
Period (ns)	1829.13
f_0 (MHz)	0.5467

ficient for capturing and bunching the protons but is not high enough for substantial longitudinal compression of said bunches. This limit encouraged a search for determining the requirements of possible replacement cavities that would benefit not only this experiment, but the operations of the IOTA ring and its future research program as a whole. In the search for RF cavity parameters, harmonics of $h = 1$ and $h = 4$ RF systems are being analyzed, however, this paper will only discuss the expected compression results using the parameters of an $h = 4$ system.

RF Capture 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 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. The minimum voltage required to capture the protons into a bunch is [9]

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

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, the capture voltage will be abiabatically ramped to some maximum value. For modeling the adiabatic capture process, we used an optimized adiabatic capture curve between an initial voltage,V_0, and a final voltage, V_1, given by [10],

$$V(t) = \begin{cases} \dfrac{V_0}{\left[1-\left(1-\sqrt{\frac{V_0}{V_1}}\right)\frac{t}{t_1}\right]^2} & ;t < t_1 \\ V_1 & ;t \geq t_1 \end{cases} \quad (2)$$

where

$$t_1 = \left(1 - \sqrt{\frac{V_0}{V_1}}\right)\frac{n_{ad}}{2\pi\nu_{s,0}} \quad (3)$$

with t_1 providing the time required for the capture ramp in terms of number of turns. For all analysis, the adiabatic capture begins with an initial cavity voltage $V_0 = 10$ V, so $\nu_{s,0}$ is the synchrotron tune at $V = 10$V and the adiabaticity number, n_{ad}, was set to 10.

Table 2: Summary of Adiabatic Capture

	Value		
Parameter	**h=56**	**h=4**	**h=1**
I_{ave} (mA)	1.0	1.0	1.0
ϵ_x, ϵ_y (μm)	4.3, 3.0	4.3, 3.0	4.3, 3.0
f_{RF} (MHz)	30.6	2.187	0.5467
N_{bunch} (protons)	2.04×10^8	2.85×10^9	1.14×10^{10}
$V_{cap}, 3\sigma_E$ (V)	9045	645	165
$\nu_s(@3\sigma_E V_{cap})$	0.122	0.0087	0.0022
$\sigma_{t,cap}$ (ns)	5	68	270
$\lvert\Delta Q_{sc}\rvert$ (x,y)	0.16,0.23	0.16,0.23	0.16,0.23

Table 2 provides a comparison between the considered RF systems and some of their notable bunch characteristics after adiabatic capture. From Table 2, at a moderate beam current of 1.0 mA, the incoherent tune shift due to space-charge effects is already approaching 0.3 in the vertical plane. Focusing on the $h = 4$ RF system, with some RF manipulations, we can longitudinally compress the bunches by a factor of 2, pushing the achievable space-charge tune shift beyond 0.3, in which case, the particles in the core of the bunch cross the integer resonance.

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

$$r_c = \sqrt{\frac{V_{rot}}{V_{cap}}} \quad (4)$$

For a capture voltage $V_{cap} = 645$ V and a desired compression factor of at least 2, we find that the required snap voltage is about $V_{rot} = 2.6$ 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

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(IPM) [11] in IOTA, allowing a measurement of the beam's transverse profiles.

A 1-D MODEL ANALYSIS

The preliminary studies have been carried out with a simple python-based 1-D longitudinal dynamics model of IOTA where I tracked 100,000 macro-particles for several thousand turns. I start with a distribution that's gaussian in time and all σ's reported are RMS values. The longitudinal phase

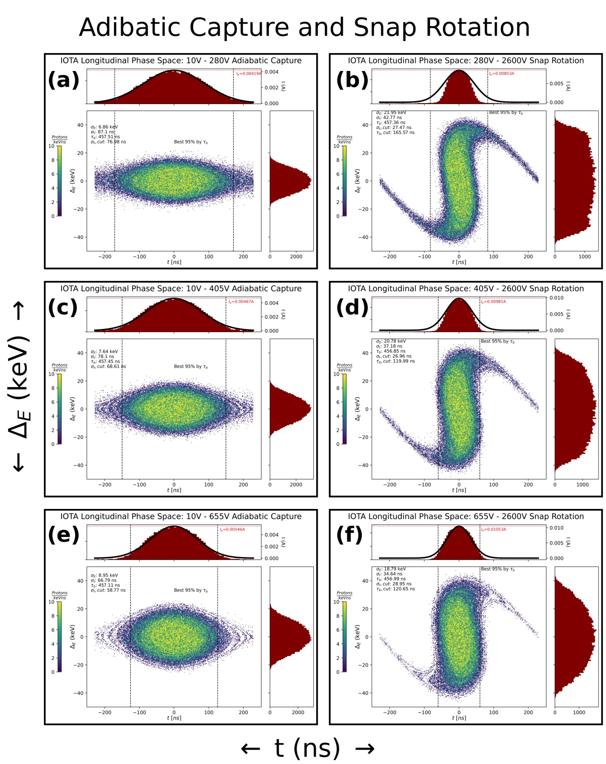

Figure 3: Longitudinal phase spaces for three capture voltages: (a)-(b) adiabatic capture at 280V - snap rotation of captured beam, (c)-(d) adiabatic capture at 405V - snap rotation of captured beam, (e)-(f) adiabatic capture at 655V - snap rotation of captured beam.

space of the captured bunches and rotated bunches can be seen in Fig. 3 for three different capture voltages. The snap voltage was kept constant at 2.6kV for each value of capture voltage to allow for a scan through multiple values of the compression factor. The vertical dotted lines in each plot from Fig. 3 highlight the "best 95%" of the beam, which also provides an accurate representation of what could reliably be measured during the experiment. Table 3 provides a summary of what can be seen in Figs. 4 and 5. The σ's for the best 95% are the RMS values of only that 95% of the beam.

OUTLOOK

Proton operations within this strong space-charge regime is one of the core capabilities of IOTA and understanding the effects of strong space-charge is increasingly important for not only experiments at IOTA but for the accelerator community at large. Regarding the proposed experiment, the next step is to take the analysis from the 1-D model to a more robust, particle-in-cell (PIC) simulation where we can include 3-D space charge effects. There is already a model of the IOTA lattice made for ImpactX, an s-based beam dynamics code with space charge, so we will start there. We are also working on a more detailed analysis of the RF and diagnostics requirements to run the experiment.

Table 3: Summary of Capture and Rotation for $h = 4$

Parameter	280V	645V
$\sigma_{t,cap}$ (ns)	87	67.2
$\sigma_{t,cap(best95\%)}$ (ns)	76.8	59.2
$\sigma_{t,rot}$ (ns)	34	28.9
$\sigma_{t,rot(best95\%)}$ (ns)	27.5	28.7
$\lvert\Delta Q_{sc}\rvert$ (x,y) no rotation	0.12,0.18	0.16,0.23
$\lvert\Delta Q_{sc}\rvert$ (x,y) w/rotation	0.26,0.37	0.32,0.46

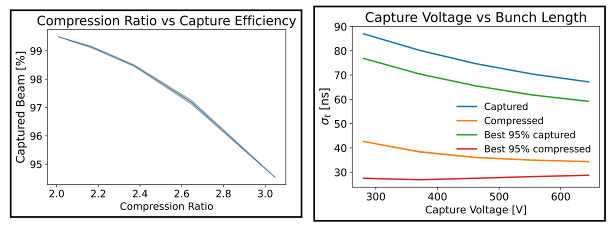

Figure 4: The left plot shows compression ratio versus capture efficiency as percentage of total beam captured. The right shows the capture voltages and the corresponding bunch lengths.

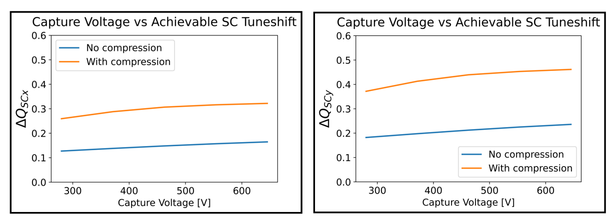

Figure 5: Both plots show the achievable space-charge tune shifts at various capture voltages, horizontal on the left and vertical on the right.

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