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

B. D. Simons ∗, Northern Illinois University, DeKalb, IL, USA
N. Banerjee, J. Eldred, Fermi National Accelerator Laboratory, Batavia, IL, USA
P. Piot, Argonne National Laboratory, Lemont, IL, USA
V. Shiltsev, Northern Illinois University, DeKalb, IL, USA

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 a 2-4 MW 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 intense proton beam into the short bunches required for next-generation HEP experiments. The IOTA 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-

---

* bsimons1@niu.edu
where \( n \) will only discuss the expected compression results using the
This bunch train is injected into IOTA in a single turn and
mum value. For modeling the adiabatic capture process, we
capture voltage will be abiabatically ramped to some maxi-
tudinal phase-space and undesirable emittance growth, the
ceptance (\( \eta \)) required to capture the protons into a bunch is [9]
the low energy and the relatively large momentum spread of
\( dp/p = 0.001 \), the beam debunches within a few turns. Most
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 syn-
chrotron 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 charac-
terize 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 volt-
age for snap bunch-rotation of the core of the beam through
the relation
\[
r_c = \frac{V_{rot}}{V_{cap}}
\]
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

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]
\[
V_0 = \left( \frac{1}{e} \right) \frac{(n\sigma_E)^2\pi^3h|\eta|}{8\beta^2E_s}
\]
where \( n \) is the number of standard deviations of energy ac-
ceptance (\( n\sigma_E \)) we want for the injected beam, \( \eta \) is the phase
slip-factor of the lattice, \( \beta \) is the relativistic \( \beta \) 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 longitudi-
unal phase-space and undesirable emittance growth, the
capture voltage will be adiabatically ramped to some maxi-
mum 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],
\[
V(t) = \begin{cases} 
V_0 & ; t < t_1 \\
V_1 & ; t \geq t_1 
\end{cases}
\]
where
\[
t_1 = \left(1 - \frac{V_0}{V_1} \right) \frac{n_{ad}}{2\pi\nu_{s,0}}
\]
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 provides a comparison between the considered
RF systems and some of their notable bunch characteris-
tics 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 verti-
cal 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.

\[
\Delta Q_{sc}(x,y) = 0.16 \begin{cases} 
1.0 & ; h = 56 \\
0.23 & ; h = 4 \\
0.23 & ; h = 1 
\end{cases}
\]

Table 1: Relevant IOTA Ring Parameters for Protons

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>KE (MeV)</td>
<td>2.5</td>
</tr>
<tr>
<td>Momentum (MeV/c)</td>
<td>65.5</td>
</tr>
<tr>
<td>Beta</td>
<td>0.0723</td>
</tr>
<tr>
<td>Gamma</td>
<td>1.00266</td>
</tr>
<tr>
<td>dp/p</td>
<td>0.001</td>
</tr>
<tr>
<td>( \sigma_E ) (keV)</td>
<td>5.0</td>
</tr>
<tr>
<td>Circumference (m)</td>
<td>39.97</td>
</tr>
<tr>
<td>Period (ns)</td>
<td>1829.13</td>
</tr>
<tr>
<td>( f_0 ) (MHz)</td>
<td>0.5467</td>
</tr>
</tbody>
</table>

Table 2: Summary of Adiabatic Capture

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I_{ave} ) (mA)</td>
<td>1.0</td>
</tr>
<tr>
<td>( \epsilon_x, \epsilon_y ) (( \mu m ))</td>
<td>4.3, 3.0</td>
</tr>
<tr>
<td>( f_{RF} ) (MHz)</td>
<td>30.6</td>
</tr>
<tr>
<td>( N_{bunch} ) (protons)</td>
<td>2.04\times10^8</td>
</tr>
<tr>
<td>( V_{cap,3}\sigma_E ) (V)</td>
<td>9045</td>
</tr>
<tr>
<td>( \nu_s @3\sigma_E V_{cap} )</td>
<td>0.122</td>
</tr>
<tr>
<td>( \sigma_{l,cap} ) (ns)</td>
<td>5</td>
</tr>
<tr>
<td>(</td>
<td>\Delta Q_{sc}</td>
</tr>
</tbody>
</table>

MOP57
MOPS: Monday Poster Session: MOPS
MCS.D09 Emittance manipulation, Bunch Compression and Cooling

ISBN: 978-3-95450-247-9
ISSN: 2673-5490
do: 10.18429/JACoW-IPAC2024-MOPS57
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 $\sigma$’s reported are RMS values. The longitudinal phase 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 $\sigma$’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.

ACKNOWLEDGEMENT

I would like to sincerely thank all of my advisors who have guided me with my work so intently, it is truly a privilege to get to learn from such an incredible group of people. This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.
REFERENCES


[6] G. Stancari et al., Beam physics research with the IOTA electron lens, JINST 16, no.05, P05002 (2021). doi:10.1088/1748-0221/16/05/P05002


