DESIGN OF IONIZATION PROFILE MONITORS AT THE INTEGRABLE OPTICS TEST ACCELERATOR (IOTA) FACILITY AT FERMILAB

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Abstract

The Integrable Optics Test Accelerator (IOTA) at Fermilab is transitioning from an electron-beam facility to a proton-beam facility for studies of nonlinear accelerator optics and space-charge-dominated proton beams. This project involves commissioning and fabricating Ionization Profile Monitors (IPMs) to enable beam-profile measurements at IOTA. In general, IPMs operate on the principle of residual-gas ionization by the beam to generate a beam profile. This work focuses on a mechanical design that leverages a controlled injection of noble gases, primarily Argon, as the ultra-high vacuum of the IOTA ring provides insufficient residual gas for ionization. Efforts to understand vacuum integration to ensure compatibility with the storage ring environment, to integrate real-time data acquisition systems, and to commission the IPMs will be discussed. This project provides a versatile diagnostic tool that supports IOTA's role as a testbed for larger-scale accelerator facilities and contributes to the broader understanding of beam physics in high-intensity, high-space-charge regimes.

INTRODUCTION

The Integrable Optics Test Accelerator (IOTA) is a 40 m storage ring at Fermilab designed as a testbed for advanced beam physics research. IOTA is currently transitioning from electron operation to a proton program. The proton program [1] will use 2.5 MeV protons to study incoherent tune shifts from space charge and coherent instabilities that would lead to uncontrolled beam losses by transverse emittance measurements similar to the Fermilab Booster.

Ionization Profile Monitors (IPMs) are being designed for non-destructive transverse profile measurements at IOTA [2]. Table 1 shows the design parameters of the IPMs to meet these needs. IPMs are widely used in accelerators, and their operating principle is well established. A primary beam, in this case at 2.5 MeV, passes through the IPM chamber and ionizes the residual gas therein. This makes the IOTA IPMs one of the lowest-energy IPM applications to date, comparable to the 4.2 MeV/u measurements performed at LEIR [3,4].

The baseline IOTA residual gas level currently consists of H_2, H_2O, NH_3, CO and CO_2 at 1×10^{-10} Torr. This level is too low to generate sufficient ionization for reliable profile reconstruction. To increase the signal, the vacuum in the IPM region will be locally raised via a controlled injection of

Table 1: IOTA IPMs Design Parameters

Parameter	**Design**	**Range**
Number of IPMs	2	
Total insertion length	0.808 m	
HV gap, D	57 mm	
HV cage length	93 mm	
Strips per IPM	60	
Strip width	0.35 mm	
Pitch, Δ	0.5 mm	
IPM Voltage, V_0	16 kV	4–30
Interg. Time	1 turn	1–100
Vacuum, P_{IPM}	1×10^{-9} Torr	$10^{-9 \ldots -7}$

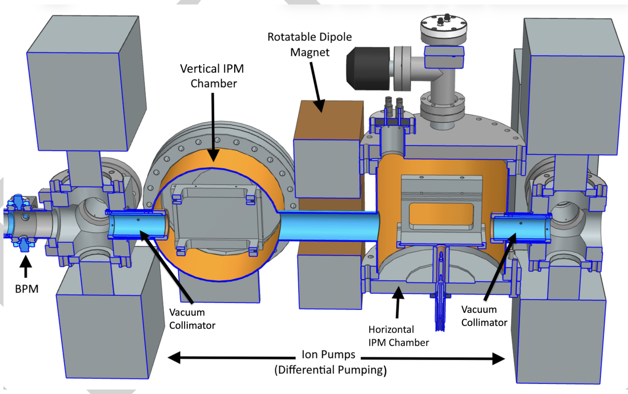

Figure 1: The IOTA IPM region (0.808 m) with a horizontal and a vertical IPM chamber, a rotatable dipole trim in the middle, and four end-mounted ion pumps connected using vacuum collimators.

1×10^{-9} Torr of a noble gas and maintained at that pressure in the IPM chamber. Four ion pumps [5] at both boundaries of the IPM region will confine the elevated pressure to the IPM region as seen in Fig. 1. The IPM chamber, as seen in Fig. 2, is supplied with a 16 kV high voltage that creates an electric field to guide ions generated during the ionization, toward the two stacked micro-channel plates (MCPs). The MCPs amplify the ion signal by liberating electrons each time an ion enters a channel, and this process cascades, releasing additional electrons. The amplified charge is then collected on a strip detector that is aligned parallel to the proton direction. The strips enable the signal to be digitized for profile reconstruction.

Motivation

The objective of this work is to optimize the spatial and temporal resolution of the IPMs for beam intensities between

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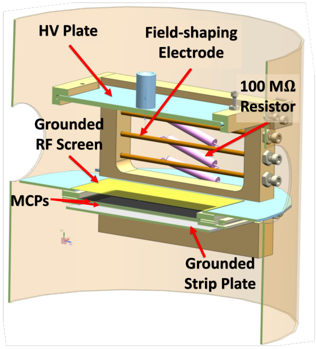

Figure 2: Cross-section view of the IOTA IPMs.

0.1 mA and 8 mA while minimizing emittance growth and beam loss due to gas-scattering processes.

The spatial resolution of the IPMs is expected to be between 0.1 mm to 1 mm to facilitate space-charge studies, allowing for size variations on the order of ~10%. In the case of multi-turn measurements, a temporal resolution between 1 turns and 100 turns is expected.

The lowest measurable beam size is ultimately constrained by emittance growth resulting from gas scattering, as illustrated in Fig. 15 of [6]. Given that a noble gas will be injected into the IPM to enhance the signal, this may allow for shorter integration times. Thus, there will be a trade-off between signal strength against integration time. This work discusses design considerations for higher-pressure gas injection and its impact on signal generation, and the implications for multi-turn measurements.

DESIGN CONSIDERATIONS FOR SIGNAL GENERATION AND COLLECTION

Following the prescription of [7, 8] for pure Argon gas (Ar, $Z = 18$), the ion production rate for a minimum ionizing particle n_{primary} is 28 ions/cm at 1 atm. In a pressure region of 1×10^{-9} Torr and for an active length of the detector of 8 cm, the expected lower limit of the ionization products is 7.2 ions/turn. This can be scaled by the Bethe-Bloch formula [9] with the $\beta\gamma$ of the IOTA protons. The initial design in [2] calls for a controlled leak of a noble gas at 5×10^{-9} Torr and a beam current of about 2 mA, that is approximately 2.3×10^{10} protons (particles). Then, the expected ion production is 1771 ions/turn.

This calculation is repeated for N_2 and Ar and found both yield ~1.8×10^3 ions/turn. However, noble gases are preferred in the design because of the higher impact ionization cross-section associated with noble gases, and it is expected to minimize profile smearing [10, 11]. Ne is close to them on the order of 1.2×10^3 ions/turn. Kr on the order of 2.8×10^3 ions/turn and Xe on the order of 3.5×10^3 ions/turn. This is as expected for larger values of Z [8]. In this analysis, calculations are carried out to determine the number of ions produced as a function of Ar pressure. Instead of plotting beam lifetime and emittance growth rate against gas pressure, the number of ions is used on the x-axis in Fig. 3.

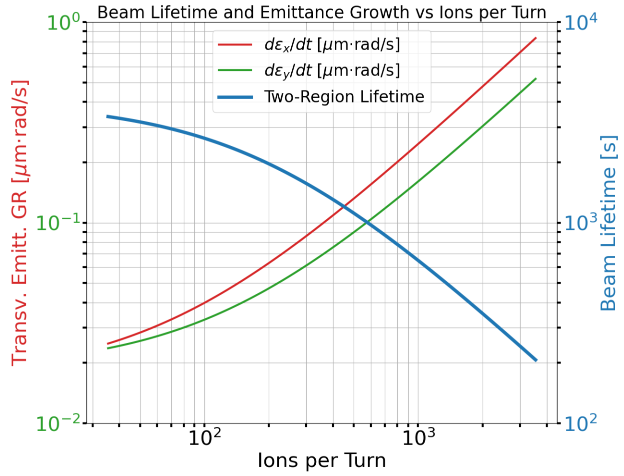

Figure 3: Correlation between the number of ions produced and the emittance growth rate and beam lifetime due to injected Argon gas.

Signal Amplification and Digitization

Once the ions reach the MCPs (32/25/8 D 60:1 NR,MS [12]), they liberate electrons in a cascading manner with the help of a 100 V bias voltage. An increase of this voltage to 500 V has been suggested to prevent smearing of the proton profile as electrons leave the top MCP and enter multiple channels in the bottom MCP. The yield from the bottom MCP is then collected by the anode strips and converted into an electronic signal that is further amplified by pre-amplifier (pre-amp) boards. A pre-amp board will be connected to 20 anode strips, each via a DB25 connector, and mounted on the IPM port. The output of the pre-amp will be 1 V for a 200 nA input and a bandwidth of 2.2 MHz. Once the signal leaves the pre-amp, it goes to a digitizer. The digitizer will have 16 channels per board. It will operate with 80 MS/s at a full scale voltage of ±1 V. Assembly of 3 pre-amp boards and 16 digitizer boards is ongoing.

DESIGN CONSIDERATIONS FOR MEASUREMENT-INDUCED EFFECTS

Two factors are being considered to enhance the ionization signal and improve measurement resolution. First, higher gas pressure levels can increase the signal by collecting more ions. Second, longer integration times can help collect more ions and also facilitate turn-by-turn analysis of beam sizes. This section examines the effects of these considerations to ensure that space-charge effects remain the primary influence on beam lifetimes.

Effect on Emittance Growth and Beam Lifetime

An analytical model of the emittance growth rate (EGR) following [6] is developed for a controlled increase in Ar pressure in the IPM region and for Ar that leaks to the rest of the ring, on top of the residual gas. The calculation is scaled by the distance that the proton beam travels for each region, and the results are shown in Fig. 3. The model indicates that the EGR is 0.40 μm · rad/s in

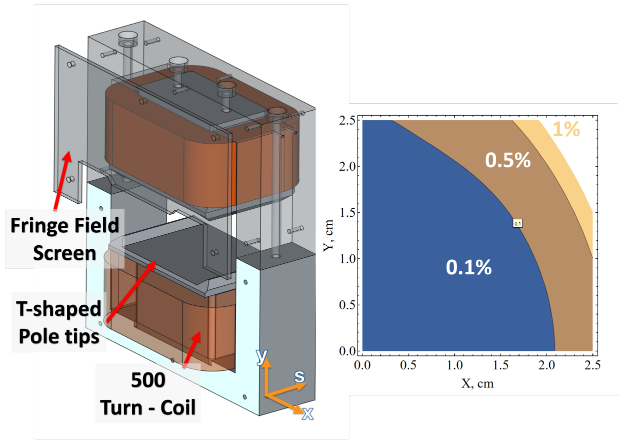

Figure 4: IOTA trim design and the field map.

the horizontal and 0.20 µm · rad/s in the vertical while the beam lifetime is ~350 s, for a 2 mA proton beam to yield 1.8×10^3 ions/turn in an Ar pressure of 5×10^{-9} Torr. If the Ar pressure is reduced to 1×10^{-9} Torr, the yield is about 3.5×10^2 ions/turn and the EGR is 0.10 µm · rad/s in the horizontal and 0.07 µm · rad/s in the vertical while the beam lifetime is ~1500 s.

The IOTA facility is currently commissioning the proton beam and has not yet made emittance measurements. The measured beam lifetime of 12.9 s at an initial current of 0.6 mA is an order of magnitude shorter than the expected value obtained from residual gas scattering. While this discrepancy indicates the presence of intra-beam scattering or space-charge effects, optimization of the beam orbit, and linear optics correction via the LOCO method are anticipated to reduce losses. However, multi-turn measurements using the IPM may also limit the lifetime due to orbit distortion caused by the guiding field used in to move the ions towards the MCPs. The design considerations to mitigate this issue will be discussed in the following section.

IPM Guiding Field Effect on Orbit

The IPMs were originally designed for single-turn measurements to test various noble gases to determine optimal ionization conditions [2]. However, IPMs main use will now be for multi-turn measurements in the IOTA Proton Program. The IPM's 12×10^{-4} T · m guiding field is expected to induce a kick angle of 5.2 mrad to the proton beam whose beam rigidity is 0.23 T · m. This results in a horizontal deflection of 14.5 mm and a vertical deflection of 3.7 mm. To counteract the distortion, a dipole trim is being designed. The design, illustrated in Fig. 4, includes two coils, each with 500 turns wound around a T-shaped pole, to improve the uniformity of the magnetic field at the center. The expected integrated field strength is approximately 35×10^{-4} T · m, with a peak strength of 0.04 T. The dipole will be capable of rotating from 0 to 90° around the beam pipe and will initially be set at a 45° angle, then optimized later. Additionally, two other trims existing in the IOTA will be utilized to create a three-bump and mitigate orbit distortion.

SUMMARY AND FUTURE WORK

The design of the IOTA IPMs has transformed, incorporating a dipole in response to the expanding application demands. A summary of the effects on proton beam lifetime and emittance growth rate was calculated for one-turn measurements in this work and presented in Table 2. It demonstrates that increasing the pressure of the injected Ar results in more ions produced per turn, a shorter beam lifetime, and higher emittance growth rates in both the horizontal and vertical planes. Calculations will be repeated to evaluate the effects of Ar injection for multi-turn measurements. A simulation of Ar localization in the IPM region will also be conducted. Additionally, the design of a noble gas cylinder stand and CF flanges, which will accommodate both high-voltage and low-voltage feedthroughs, readout connectors, pressure gauges, and the gas injection manifold, is being finalized. Once the components are procured, assembly will be conducted on a test stand to calibrate and confirm the measurements will reflect the true beam size prior to installation and commissioning. After the IPM commissioning phase, both emittance and beam lifetime will be evaluated and optimized to ensure accurate beam profiles.

Table 2: Calculated Effects on the proton beam lifetime and emittance growth rate due to Ar injection in the IPM region and potentially leaking to the rest of the ring per turn

IPM pressure	**1×10^{-9} Torr**	**5×10^{-9} Torr**
No. ions/turn	3.5×10^2	1.8×10^3
Beam Lifetime	1.5×10^3 s	3.5×10^2 s
$d\varepsilon_x/dt$	0.10 µm · rad/s	0.40 µm · rad/s
$d\varepsilon_y/dt$	0.07 µm · rad/s	0.20 µm · rad/s

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