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GAS JET PROFILE MONITOR FOR USE IN IOTA PROTON BEAM*

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Abstract

The Integrable Optics Test Accelerator (IOTA) at the Fermilab Accelerator Science and Technology (FAST) Facility will attempt to demonstrate novel techniques for high current accelerators. An electron beam of 150 MeV/c momentum and a proton beam of 70 MeV/c momentum will be used for a number of experiments, including nonlinear focusing integrable optics, space charge compensation, and optical stochastic cooling. The low energy proton beam will provide a space charge dominated regime with which to investigate Hamiltonian diffusion and chaos. A non-invasive beam instrumentation device is needed to study emittance evolution and halo formation without destroying the beam. A supersonic gas jet curtain can be injected perpendicular to the proton beam, which will preserve the integrity of the beam and provide a two-dimensional turn-by-turn profile measurement. Currently, IOTA and the gas jet monitor are being built and commissioned at Fermilab.

INTRODUCTION

The Integrable Optics Test Accelerator (IOTA) is a storage ring designed to test novel high current accelerator techniques. A RFQ based proton source will provide a low energy beam for injection into IOTA. The ring will allow a sufficient number of turns to observe nonlinear effects in a space charge regime. Nonlinear decoherence in nonlinear integrable lattices will suppress halo formation of the beam. To preserve the lifetime of the beam, a non-invasive detector is required [1]. Simulation studies of the beam distribution, with various lattices, turn-by-turn are made using Synergia [2] code running on a server maintained by RadiaSoft [3]. The gas jet parameters, such as the gas density and the detector location, can be optimized for a higher resolution of the beam profile. A gas jet sheet is produced in the interaction chamber of the beam line. The beam ionizes the gas, producing an electron-ion pair. A transverse electric field will direct the electrons toward a micro-channel plate (MCP), which will provide a signal amplification of 10^6. Finally, a phosphor screen and CCD camera will image the signal.

IOTA PROTON BEAM PARAMETERS

The previously existing HINS (High Intensity Neutrino Source) RFQ will be used for injection of protons into the IOTA ring. The source will provide IOTA a beam energy of 2.5 MeV bunched at 325 MHz [4]. Bunches will spread out after a few turns due to the momentum spread and low energy. A dual purpose RF cavity will be used to bunch the beam at 2.18 MHz. The IOTA lattice (Fig. 1) has two integrable lattice sections (upper corners) where the transverse beta functions are matched and dispersion is zero (see Fig. 2). The lower left corner has a RF cavity and the lower right section will contain the electron lens/column. Table 1 provides a summary of HINS and IOTA main parameters.

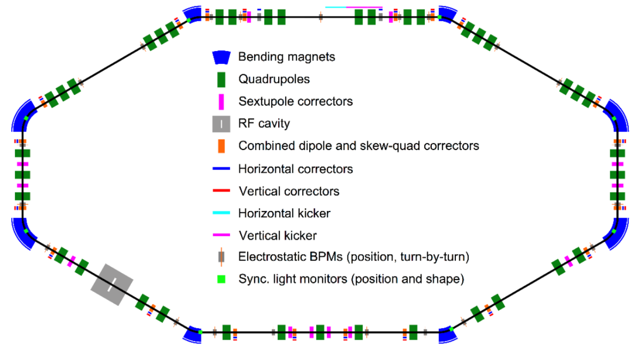

Figure 1: IOTA ring layout

Table 1: Summary of IOTA Proton Beam Parameters

PARAMETER	VALUE
Kinetic Energy	2.5 MeV
dp/p	0.1 %
Circumference, C_0	39.97 m
Revolution period, T_0	1.83 μs
RF bunching	2.18 MHz
Average beam current	8 mA
Vacuum	$6x10^{-10}$ Torr
Beam lifetime	300 s
Pulse rate	<1 Hz
Pulse width	1.77 μs

BEAM SIMULATIONS

The Synergia code has been used to simulate and propagate the beam including space charge effects. A lattice for IOTA with one nonlinear section was used. The nonlinear element in the lattice can be turned on and off. The initial KV beam is randomly distributed and propagated starting at the injection point (middle of the top section in Fig. 1). A virtual detector was placed s = 8.711 m from the right nonlinear section (middle of the lower right section in Fig. 1). The beam was propagated through the lattice for 200 turns with 10240 macro particles. A toolkit in Synergia, 2D

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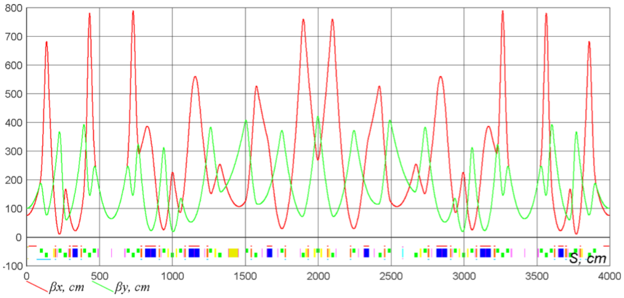

Figure 2: Lattice functions for IOTA with one nonlinear section. The nonlinear inserts are at approximately s = 6 m and 34 m [1].

open boundary condition Hockney space charge solver was used. For the purpose of this study, the dispersion function was set to zero.

Table 2: Beam Size with and without the Nonlinear (NL) Element

	no NL element	NL element	Units
$\epsilon_{x,y,I}$	5.00, 4.99	5.00, 5.00	mm-mrad
$\epsilon_{x,y,F}$	8.64, 9.94	6.46, 5.72	mm-mrad
$RMS_{x,y,I}$	2.37, 3.98	2.58, 3.27	mm
$RMS_{x,y,F}$	3.21, 5.68	2.87, 3.95	mm
X,Y^{I}_{max}	4.74, 8.01	5.21, 6.49	mm
X,Y^{F}_{max}	11.99, 21.30	9.82, 14.0	mm

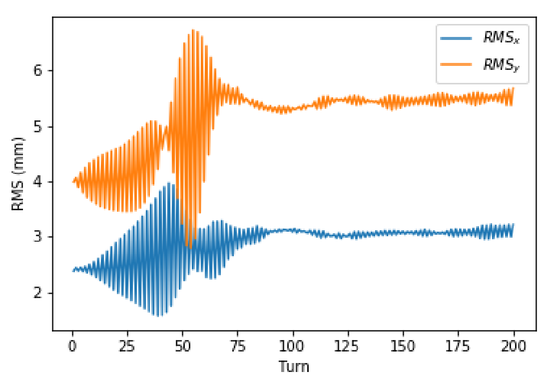

Figure 3: Beam Evolution without non-linear element.

Table 2 has the first and final turn beam emittance, x and y RMS, and max value in the transverse plane for with and without the nonlinear element. A measurement at each turn can determine the beam evolution and studies of the halo can be made.

Figure 3 shows the RMS beam size as it evolves through 200 turns without the nonlinear element. After approximately 100 turns the beam envelope stabilizes. The beam distribution is shown in Fig. 4 for both the nonlinear insert on and off. Without the nonlinear element, the transverse emittance significantly grew by 72% and 99% in x and y,

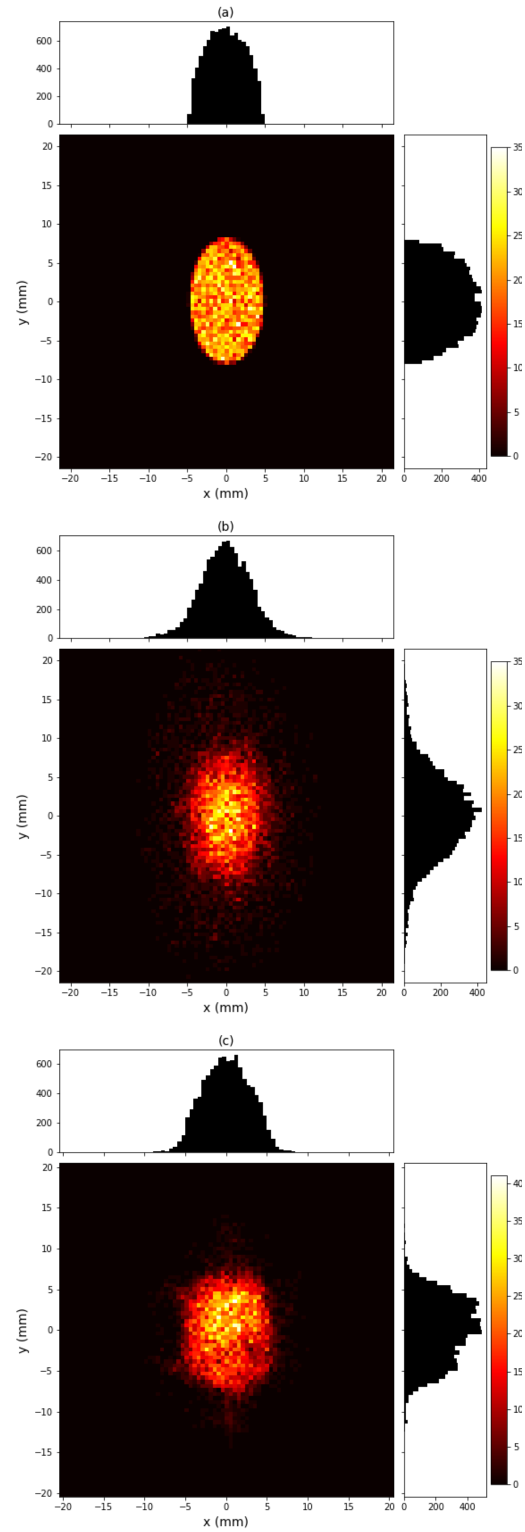

Figure 4: First turn particle distribution (a). Final particle distribution with non-linear element off (b) and non-linear element on (c).

respectively. The x and y RMS grew by 35% and 42%. With the nonlinear element the emittance grew marginally by 29% and 14% in x and y, while the RMS grew by 11% and 20%.

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BEAM-GAS INTERACTIONS

The lifetime of the beam in the IOTA ring will be limited by interactions with residual gas. At energies above a few hundred keV, ionization is dominant over excitation for protons in nitrogen gas [5]. The cross section for ionization of nitrogen by 2.5 MeV protons is $7.19\times10^{-17}\mathrm{cm}^2$ [6]. For the circumference of the IOTA ring given in Table 1 and assuming a gas sheet thickness of 0.2 cm, the path length through the residual gas is 2×10^4 greater than that through the gas sheet. To produce no more than a 1% effect on the lifetime of the beam, for the vacuum pressure given in Table 1, the pressure of the gas jet would have to be 1.2×10^{-7} torr.

At room temperature, the gas jet would have a density of 3.9×10^9 cm^{-3}. The number of electron-ion pairs produced per second by the beam can be found by:

$$\dot{N} = \sigma \frac{I_b}{q} n_g \, l \tag{1}$$

where σ is the ionization cross section, I_b is the beam current, q is the proton charge, n_g is the gas number density, and l is the gas sheet thickness. The total number of electron-ion pairs produced per turn (i.e. 8.85×10^{10} incident protons) is 5.03×10^3.

A more accurate estimation would take into account excitation, secondary ionization, etc., and is derived from measurements of the average energy required to ionize a gas molecule [7–9]. In this case, the number of electron-ion pairs produced per second is:

$$\dot{N} = \frac{dE}{dx} \frac{I_b}{q} \frac{\rho_g \, l}{W_i} \tag{2}$$

where dE/dx is the stopping power of protons in nitrogen, ρ_g is the mass density of the gas, and W_i is the average energy required to ionize a gas molecule. Using 118 MeV cm^2/g for dE/dx and 36 eV for W_i, the total number of electron-ion pairs produced per turn is 1.14×10^4.

HARDWARE

Groups at the Cockcroft Institute and KEK [10, 11] have previously developed gas jet monitors. The device to be used in IOTA will be based on these designs, with modifications to fit the experiment constraints. Various skimmers and capillary configurations will be tested for optimal gas jet thickness, orientation, and velocity. Vacuum requirements will be maintained to ensure minimal residual gas along the beam pipe. Other hardware such as the MCP and CCD array will be configured to the beam revolution period to have an integrated measurement at each turn.

OUTLOOK

Further simulation of the beam gas interaction to be done includes propagating the beam for a larger number of turns and implementing an electric extraction field where the gas jet is to be placed to determine if perturbation of the beam preserves integrability. Currently a gas-jet monitor test bench is being installed in FAST at Fermilab. It is planned to test various parameters of the gas jet for optimal performance. A proton beam in the IOTA lattice is expected in 2019.

REFERENCES

[1] S. Antipov, *et al.,* “IOTA (Integrable Optics Test Accelerator): facility and experimental beam physics program”, *JINST*, vol. 12, no. 03, p. T03002, Mar. 2017

[2] J. Amundson, P. Spentzouris, J. Qiang, R. Ryne, "Synergia: An accelerator modeling tool with 3-D space charge", *Journal of Computational Physics*, **211**, 1, (2006).

[3] RadiaSoft, LLC `http://radiasoft.net`

[4] E. Prebys, S. A. Antipov, K. Carlson, H. Piekarz, and A. Valishev, “Proton Injection into the Fermilab Integrable Optics Test Accelerator (IOTA)”, in *Proc. IPAC2016*, pp. 1638–1640,

[5] B.C. Edgar, W.T. Miles, and A.E.S. Green, “Energy Deposition of Protons in Molecular Nitrogen and Applications to Proton Auroral Phenomena”, *J. Geophys. Res.* **78**, 28 (1973).

[6] M.E. Rudd, R.D. DuBois, L.H. Toburen, C.A. Ratcliffe, and T.V. Goffe, “Cross Sections for Ionization of Gases by 5-4000-keV Protons and for Electron Capture by 5-150-keV Protons”, *Phys. Rev. A* **28**, 6 (1983).

[7] R.A. Lowry and G.H. Miller, “Ionization Yield of Protons in Nitrogen and Argon”, *Phys. Rev.* **109**, 3 (1958).

[8] C.J. Bakker and E. Segrè, “Stopping Power and Energy Loss for Ion Pair Production for 340-Mev Protons”, *Phys. Rev.* **81**, 4 (1951).

[9] H.V. Larson, “Energy Loss Per Ion Pair for Protons in Various Gases”, *Phys. Rev.* **112**, 6 (1958).

[10] V.Tzoganis, A. Jeff, C.P. Welsch, "Gas dynamics considerations in a non-invasive profile monitor for charged particle beams", *Vacuum*, **109**, pp. 417-424, (2014).

[11] Y. Hashimoto *et al.*, "Development of a Beam Profile Monitor Using a Nitrogen-Molecular Jet for the J-PARC MR", in *Proc. IBIC2013*, pp. 848-851