Laser-plasma wakefield IOTA injector: new tool for modern accelerators

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Introduction

Since its inception, laser-plasma wakefield acceleration (LPWA) activities were mostly focused on the study of the fundamental physics in laser-plasma-beam systems. Here, we propose design, construction and operation of a LPWA-based electron-beam accelerator at the Integrable Optics Test Accelerator; this will be the world's first application of an advanced-accelerator technology as an injector for an operational synchrotron.

This project is on the interface between advanced and traditional accelerators. It will address the scientific and technological challenges required to transition LPWA technology from a bright idea into a readily available accelerator tool. In addition to being used as a primary electron source, the LPWA injector can provide bunches that are ideal test probes for accelerator beamlines and rings operating with hard-to-detect low-intensity or unstable charged-particle beams.

LPWA injector at IOTA

The Integrable Optics Test Accelerator (IOTA, [1,2]) at Femi National Accelerator Laboratory is an optimal place for this project as it is a facility dedicated to research in accelerator and beam physics located at a leading accelerator laboratory. IOTA is a highly configurable synchrotron built for experiments with electrons and protons at momenta between 50 MeV/c and 200 MeV/c. Its scientific program keeps growing and now includes several experiments on nonlinear integrable lattices, space-charge compensation schemes, optical stochastic cooling and quantum physics of multi- and single-electron beams.

The research program with protons in IOTA has a goal of mastering control over high intensity proton beams needed for future neutrino studies, neutron sources and other experiments at the intensity frontier. To increase the power of proton accelerators one needs to control beam induced radiation and to reduce the fractional intensity losses by an order of magnitude from a typical current level of about 5% to better than 0.5%. The latest theoretical breakthroughs in the beam loss suppression using integrable optics lattices will be put to test at IOTA. The most critical requirement of these experiments is the ability to control beam parameters at levels that were so far achieved only in modern synchtrotron light sources and particle colliders.

The first IOTA experiments are being conducted with electrons injected from the superconducting RF linac at the Fermilab Accelerator Science and Technology (FAST) facility (Figure 1). Due to synchrotron radiation in the bending magnets, electrons in circular accelerators quickly form short and narrow bunches. This makes electron beams an ideal probe for beam diagnostic instruments such as capacitive pickup beam position monitors, digital cameras, photomultipliers, etc. Precise information about the beam position and shape allows to use

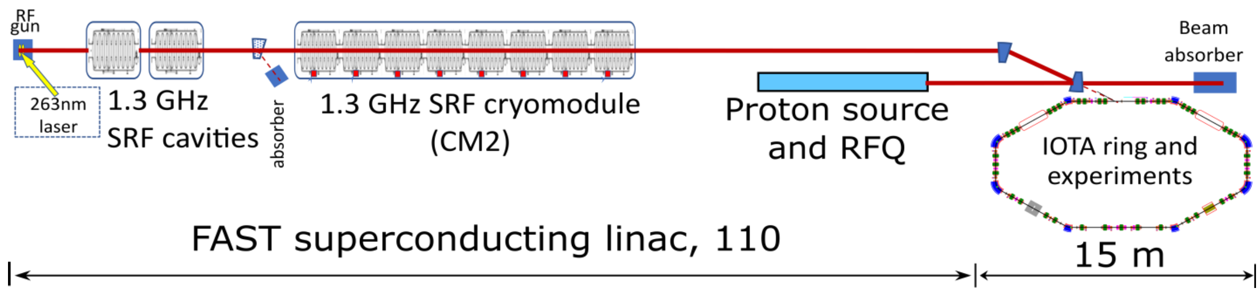

Figure 1. IOTA ring is located near the high energy absorber of the superconducting RF linac.

electron beams for the fine tuning of accelerator optics that is vital for nonlinear integrable optics experiments [3].

The second stage of experiments will be done with 70 MeV/c momentum protons injected into IOTA through the existing electron beam line. Due to the particle charge sign change, this requires reversing the polarity of the ring magnets and hence necessitates the fine tuning of the focusing optics lattice. Unlike electrons, protons practically do not radiate and are hard to detect with electrostatic pickups because of the longer bunch length, therefore, tuning of IOTA with proton beams is expected to be a very challenging task.

A dedicated IOTA electron injector based on the LPWA technology and matched to the ring focusing lattice will offer counter-clockwise circulating electron bunches (Figure 2). In addition to testing the innovative technology of laser-plasma injectors, it will provide unique probe beams suitable for tuning the IOTA proton beam optics to the required high accuracy, it will expand the capabilities for experiments with electron beams, and it will significantly extend the scientific reach of the IOTA facility.

A successful coupling of the LPWA-generated beams with a conventional accelerator will open opportunities to use such cost-efficient high energy electron bunches to improve operational tuning and performance of other machines, such as the storage ring of the Muon g-2 experiment, which operates with secondary low quality beams of muons.

The PI has conducted seed research of the proposed project [4] and has extensive experience in the design, construction and operational tuning of conventional linear and circular accelerators [5]. The relatively moderate requirements for the laser system necessary for the production of 70 MeV/c electrons (Table 1, [4,6,7]) are well aligned with capabilities of the IOTA/FAST team. The team has considerable experience with laser systems, which are used in the operation of the FAST electron photoinjector and previous projects. An additional benefit of performing this project at the IOTA/FAST facility is the simplified allocation of the machine time necessary for the understanding and adjusting parameters of the matching section beam optics, as the IOTA/FAST facility is fully dedicated to research in accelerator and beam physics.

Project Work Plan

At the first stage of the proposed project we will construct the laser system, gas target and perform their commissioning and characterization. All necessary components can be conveniently assembled and tested on site at IOTA/FAST, as the facility was built with a provision for upgrades.

TABLE 1. Parameters of laser-driven injector for IOTA.

Parameter	Value
Particles	Electrons
Injection energy	70 MeV
Energy acceptance	1%
Angular acceptance	20 mrad
Captured bunch charge	10^8 e (16 pC)
Main laser pulse energy	≥ 0.5 J
Main laser pulse duration	≤ 40 fs
Main Laser spot size	≤ 25 um
Main laser wavelength	800 nm
Plasma density	$2\text{x}10^{19}$ e cm^{-3}
Plasma length	2-5 mm

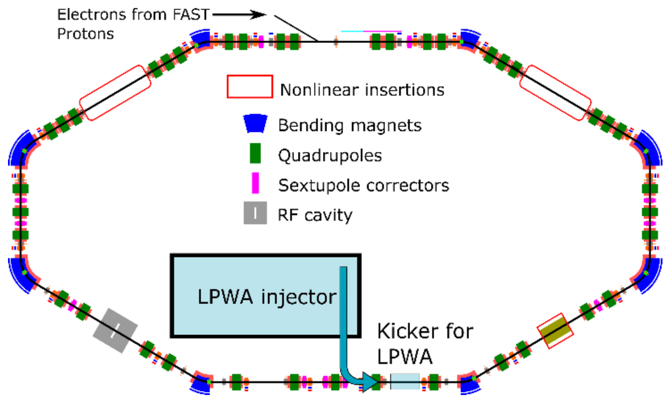

Figure 2. There is enough room inside IOTA ring for the LPWA - based 70 MeV/c electron injector

Next, the equipment will be moved inside the IOTA ring enclosure to start experiments on the laser-plasma acceleration of electrons (Figure 2). At the same time, the design of the injection beam line will be finalized. After that, we will procure and assemble all the components needed for the basic injection line that will transversely match the LPWA-generated beam into IOTA. The longitudinal matching of the electron beam and operational optimization of the LPWA injector will be fulfilled during the final stages.

Injection of particles with a relatively low momentum can be done with just one kicker, without special injection magnets. Momentum acceptance of the ring and the relatively small transverse emittance of the beam are compatible with a small aperture of around 10 mm and a bending radius of the injection line of about 20 cm. A dipole with such parameters and the bending angle of close to 90° can fit between the quadrupole magnets of the central triplet section of the IOTA bottom straight section. The small aperture of the injection dipole combined with a differential pumping scheme will help to prevent degrading the ring beam pipe vacuum and minimize the effect of stray magnetic fields on the circulating IOTA beam.

Conclusion

A successful realization of the electron injector based on laser wakefield acceleration matched to a conventional synchrotron – the IOTA ring – will be the first demonstration of synergy between advanced and conventional accelerators and also a very important and cost-effective research tool. It may become a game changing technology for other existing and future accelerators.

References

1. V. Danilov and S. Nagaitsev, Phys. Rev. ST Accel. Beams **13**, 084002 (2010), arXiv:1003.0644
2. Antipov S. et al 2017 J. Instrum. **12** T03002, IOPscience
3. A. Romanov, G. Kafka, S. Nagaitsev, and A. Valishev, "Lattice Correction Modeling for Fermilab IOTA Ring," in Proc. 5th International Particle Accelerator Conference (IPAC 2014): Dresden, Germany, June 15–20, 2014, p. TUPRO058.
4. A. Romanov, Laser-driven injector of electrons for IOTA. 2017. Published in AIP Conf.Proc. 1812 (2017) no.1, 040012
5. A. Romanov et. al., 2017, FERMILAB-PUB-17-084-AD-APC, arXiv:1703.09757
6. N. A. M. Hafz et al., Nature Photon. **2**, 571–577 (2008).
7. S. P. D. Mangles et al., Nature **431**, 535–538 (2004).

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