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THE ADVANCED SUPERCONDUCTING TEST ACCELERATOR AT FERMILAB: SCIENCE PROGRAM *

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Abstract

The Advanced Superconducting Test Accelerator (ASTA), currently in commissioning phase at Fermilab is foreseen to support a broad range of beam-based experiments to study fundamental limitations to beam intensity and to develop novel approaches to particle-beam generation, acceleration and manipulation. ASTA incorporates a superconducting radiofrequency (SRF) linac coupled to a flexible high-brightness photoinjector. The facility also includes a small-circumference storage ring capable of storing electrons or protons. This report summarizes the facility capabilities, and provides an overview of the accelerator-science researches to be enabled.

INTRODUCTION

A new facility, the Advanced Superconducting Test Accelerator (ASTA) is currently under construction at Fermilab [1–3]. The facility in its latest evolution consists of a photoinjector [4] coupled to a superconducting radiofrequency (SRF) cryomodule (CM) [5]; see Fig. 1. The RF gun incorporates a high-quantum efficiency CsTe photocathode illuminated by a 3-ps ultraviolet laser pulse. After acceleration in the CM the beam can either be directed to a compact storage ring – the Integrable-Optics Test Accelerator (IOTA) – or to an array of multiple high-energy beam lines that transport the electron beam from the accelerating CM to one of two beam dumps. In addition to testing the accelerator components, the intent of this facility is to also test the support systems required for a future SRF linac. Three experimental areas [A1, A2, and A3 (IOTA) in Tab. 1] will be available to users for installation of experiments. Area A1, situated within the photoinjector, will provide electron bunches, possibly compressed, with energies up to 50 MeV [6]. The high-energy experimental area A2 consists of three parallel beamlines. Two of the beamlines are downstream of doglegs while one is inline with the ASTA linac. Experiments in the three user beamlines and IOTA can be operated in parallel as switching the beam between beamlines would only require minor optical-lattice adjustments. Finally, it is planned to add a 2.5-MeV proton/H- RFQ accelerator which was previously used for High Intensity Neutrino Source (HINS) research at Fermilab [10] to serve as an independent injector for IOTA in support of intensity-frontier R&D.

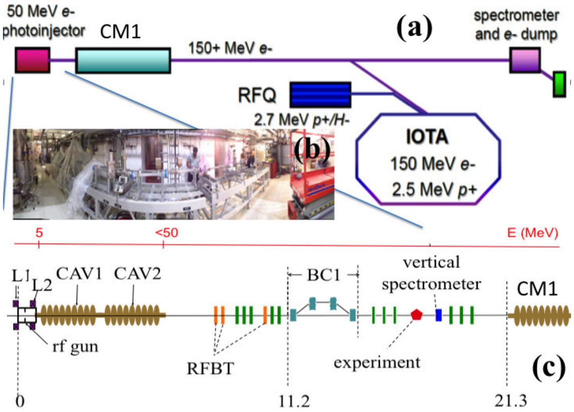

Figure 1: Overview of the ASTA facility (a) with photograph (b) and detailed diagram (c) of the photoinjector section. L1, L2 are solenoid, CAV1 and CAV2 are SRF 1.3-GHz cavities, and BC1 is the magnetic bunch compressor. The green (resp. orange) rectangles represent the normal (resp. skewed) quadrupole magnets.

Table 1: Beam Parameters Expected at the ASTA Facility. The quoted transverse and longitudinal emittance are for the uncompressed case.

parameter	nominal value	range
energy (A1) [MeV]	50	[5,50]
energy (A2) [MeV]	[250-800]	[50,820]
bunch charge Q [nC]	3.2	[0.02,20]
bunch freq. f_b [MHz]	3	$--$
macr. duration [ms] τ	1	≤ 1
macr. freq. f_{mac} [Hz]	5	[0.5, 1, 5]
num. bunch/macro. N_b	3000	$[1,3000]^{(b)}$
trans. emit. [μm]	$2.11Q^{0.69}$	[0.1, 100]
long. emit. [μm]	$30.05Q^{0.84}$	[5, 500]
peak current $\hat{I}$ [kA]	~ 3	≤ 10

In subsequent longer-term upgrade stages, ASTA would incorporate up to two additional CM to boost its final energy to $\sim$ 800 MeV and possibly a 3.9-GHz system to linearize the longitudinal phase space and improve the achievable peak current after compression. In addition, we are also considering the addition of a magnetic chicane downstream of the CM that could operate either as a second-stage bunch compressor or transverse-to-longitudinal phase space exchanger.

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Finally, the area A1 would be extended to include an off-axis beamline to accommodate additional user experiments.

EXPERIMENTAL PROGRAM

Accelerator R&D for Particle Physics at the Intensity and Energy Frontiers

The combination of a state-of-the-art superconducting linear accelerator and a flexible storage ring enables a broad research program directed at the particle physics accelerators of the future. The IOTA ring was designed to accommodate 150-MeV electron bunches (or 2.5-MeV proton beams). The research program to be supported by the IOTA ring includes experimental tests of nonlinear integrable optics using with either nonlinear magnets or electron lenses [7–9]. In a first phase, the single-particle dynamics will be characterized by injecting the electron beam generated by the ASTA linac operated at lower accelerating field. The availability of this "pencil" electron beam will be essential to demonstrate stable motion in the nonlinear lattice and explore the dynamical aperture of IOTA. The H^- source will support the investigation of space charge compensation with both nonlinear integrable optics variants (nonlinear magnet and electron lens) but also opens the path to the study other space-charge-compensation schemes, e.g., with electron columns, contemplated for use in high-intensity circular accelerators [11]. The proposed research program to be explored at IOTA has expanded beyond its initial goal to test nonlinear integrable lattices. IOTA will also be used to explore optical-stochastic cooling. The $\sim$ 800-nm radiation produced in a 10-period undulator will be amplified by a single-pass Ti:Sp amplifier and feedback to the beam using a downstream undulator [12]. IOTA is also expected to support fundamental Physics studies such as the measurement of the single-electron wave-function [20].

Other proposed experiments relevant to the energy frontier include the investigation of alternative designs for advanced phase space manipulations. These manipulations scheme provide control over the current shape and offer a way to repartition the beam emittances between the three degrees of freedom [13, 14]. These capabilities have important applications to, e.g., enhance the transformer ratio – the maximum accelerating wakefield over the decelerating field experienced by the driving bunch – in collinear beam-driven acceleration schemes [15]. Additionally the exploration of advanced acceleration concepts fully capitalizing on the available phase space manipulation, e.g., flat-beam-driven dielectric-wakefield acceleration in slab structures [16, 17], is also foreseen. Finally, other advanced acceleration concepts, e.g., based on crystalline structures are also planned [18].

ASTA is also foreseen to support high-power target studies for LBNE and the generation of tagged bremsstrahlung photon beam for detector R&D. The possible availability of a high-flux γ-ray source (see below) could also be beneficial to the measurement of the cross section associated to the $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction which is crucial in nuclear astrophysics. Due to its low cross section, a precise measurement of this reaction using a nucleation process in a bubble chamber remains elusive with photon flux available a current γ-ray source and could be improved if driven by a SRF linac such as ASTA [19].

Accelerator R&D for Future SRF Accelerators

High gradient, high-power SRF systems are critical for many accelerator facilities under planning for the needs of high-energy physics, basic energy sciences and other applications. ASTA offers a unique opportunity to explore most critical issues related to the SRF technology and beam dynamics in SRF cryomodules. The low injection energy ~ 50 MeV combined with achievable low-emittance beams is well suited to explore beam dynamics effects such as, e.g., emittance dilution due to the time-dependent field asymmetries introduced by the input and higher-order mode (HOM) couplers. The pulsed operation of SRF cavities at high-gradient while accelerating mA beam over long period of time has also relevance to the International Linear Collider program. Furthermore, the SRF linac will provide an experimental platform necessary to develop the required low-level RF controls for the Project-X pulsed linac. Additionally, comprehensive beam-based measurements of long-range wakefield in SRF CMs are being planned using an upgraded version of the photocathode laser that would enable the production of charge-modulated bunch trains. Scanning the charge-modulation frequency would enable the characterization of HOMs over a continuous range of frequencies [21]. Finally, a precise characterization of the jitter and beam-based stabilization of the SRF module has been proposed [22].

It was also pointed out that with adequate changes in the RF system, the ILC-type cryomodule installed at ASTA could in principle be operated in CW mode to perform tests relevant to the proposed next-generation CW light sources [23]. The maximum gradient attainable by the cavities is limited by the cryogenic system and HOM coupler. Cryogenic considerations indicate that the maximum gradient would be limited to $\sim 5-7$ MV/m. Likewise, the ILC-type input coupler design nominally used at ASTA would limit the average beam current to ≤ 1 mA.

Accelerator R&D for Novel Radiation Sources

High-energy, high-peak and high-average brightness electron beams are crucial to the generation of high-brilliance high-flux light sources with photon energies ranging from keVs to MeVs. Head-on collision of the electron bunch with an intense laser pulse produces radiation with upshifted energies: a 1-μm-wavelength laser would provide γ rays with energies ranging from 1 to 20 MeV. If the laser repetition frequency matches the electron bunch frequency, an unprecedented γ-ray brilliance in excess of $\sim 10^{24}$ phot.mm^{-2}.mrad^{-2}.s^{-1}/(0.1%BW) is anticipated [24]. The technical challenge is be to develop a laser system capable of producing Joule-level pulse energy with MHz repetition rate and will rely on a recirculating optical cavity [25, 26].

In the photoinjector area, it is foreseen to test a high-brilliance x-ray source concept by combining the low-emittance beam produced out of the photoinjector with channeling radiation (CR) [27]. The production of CR will occur downstream of the bunch compressor (BC1). Several crystal materials will be tested. Simulations using a $\sim 40\ \mu$m-thick diamond crystal indicate the production of x rays with photon energies in the [10-150] keV range for the electron-beam energies available in the ASTA photoinjector (15 to 50 MeV) [28].

Finally, the combination of flat beams with long bunch train could support the test of micro-undulators [29]. These micro-undulators, made of laser-micromachined bulk rare-earth magnetic materials (SmCo and NdFeB), have magnetic fields with spatial period on the order of a few 100 μm. The associated undulator parameter $K \sim 10^{-2}$ results in a low photon yield. Therefore the test and characterization of the associated undulator radiation would greatly benefit from the available long bunch train.

Accelerator R&D for Stewardship & Applications

With its high energy, high brightness, high repetition rate, and the capability of emittance manipulations built-in to the facility design, ASTA is an ideal platform for exploring novel accelerator techniques of interest for very broad scientific community beyond high energy physics. Some of the experiments include the development and test of subsystem and beam-manipulation scheme to improve the performance and decrease the cost of next-generation accelerator-based light sources. An example include the combination of the aforementioned phase-space manipulations to taylor the emittance partition within the three degrees of freedom to produce ultra-low emittance beams for future hard X-ray free-electron lasers [30].

Several proposals aim at developing techniques to “dechirp" the beam, i.e. to remove the residual correlated energy spread that generally subsists downstream of the final bunch compression stage in FEL drivers. The proposed dechirping methods include (*i*) the use of short-range wakefields impressed on the bunch as it passes in a dielectric [31] or corrugated [32] passive structure, or (*ii*). In addition using these passive structures to further control the longitudinal-phase-space nonlinearities could also be test at ASTA [33]. Demonstrating the compatibility of these techniques with high-repetition rate beam available at ASTA could lead to their inclusions in proposed CW FEL projects.

The flat-beam transformation available at ASTA could also support tests relevant to nuclear-physics accelerator R&D, e.g., to validate some of the concepts under consideration for next electron-ion colliders [34, 35].

Finally, the beam available at ASTA will foster the development and tests of advanced beam diagnostics relevant to, e.g., CW FELs or energy-recovery linacs. Some of these diagnostics especially those capable of measuring single-bunch parameters within the RF macropulse, will be crucial for optimizing the feedback system needed to stably operate the ASTA SRF cryomodule(s).

SUMMARY

ASTA is intended to eventually be operated as a scientific user facility for advanced accelerator research and development. The facility is open to all interested potential users and the facility resources will be determined by merit review of the proposed work. The user program is proposal-driven and peer-reviewed by an external Program Committee (the ASTA Program Advisory Committee) [2]. The ASTA accelerator is currently in its commissioning: the electron source delivered beam within the ILC specifications and the first experiment – the production of X-ray via channeling radiation – is scheduled in the summer 2014 and will be carried in parallel to the 50-MeV beamline commissioning. Further acceleration in one CM is foreseen later in FY15, once the high-energy beamline assembly is completed.

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