

THE ADVANCED SUPERCONDUCTING TEST ACCELERATOR (ASTA) AT FERMILAB*

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Abstract

The Advanced Superconducting Test Accelerator (ASTA) currently in construction at Fermilab will enable a broad range of beam-based experiments to study fundamental limitations to beam intensity and to develop transformative approaches to particle-beam generation, acceleration and manipulation. ASTA incorporates a superconducting radiofrequency (SRF) linac coupled to a photoinjector and small-circumference storage ring capable of storing electrons or protons. This report describes the facility, its capabilities, and provide an overview of enabled research thrusts.

INTRODUCTION

The Advanced Superconducting Test Accelerator (ASTA) currently in construction at Fermilab will establish a unique resource for R&D towards Energy Frontier facilities and a test-bed for superconducting radiofrequency (SRF) accelerators and high-brightness beam applications. The unique features of ASTA include: (1) a high repetition-rate, (2) one of the highest peak and average brightness within the U.S., (3) a GeV-scale beam energy, (4) an extremely stable beam, (5) the availability of SRF and high-quality beams together, and (6) a storage ring capable of supporting a broad range of ring-based advanced beam dynamics experiments. These unique features will foster a broad program in advanced accelerator R&D which cannot be carried out elsewhere.

ACCELERATOR OVERVIEW

The backbone of the ASTA facility is a radio-frequency (RF) photoinjector coupled with 1.3-GHz superconducting accelerating cryomodules (CMs); see Fig. 1 [1]. The electron source consists of a 1-1/2 cell 1.3-GHz cylindrical-symmetric RF gun comprising a Cs₂Te photocathode illuminated by an ultraviolet (UV, λ = 263 nm) laser pulse obtained from frequency quadrupling of an amplified infrared IR pulse. The photocathode drive laser produces a train of bunches repeated at 3 MHz within a 1-ms-duration macropulse.

The ~ 5-MeV electron bunches exiting the RF gun are then accelerated with two SRF TESLA-type cavi-

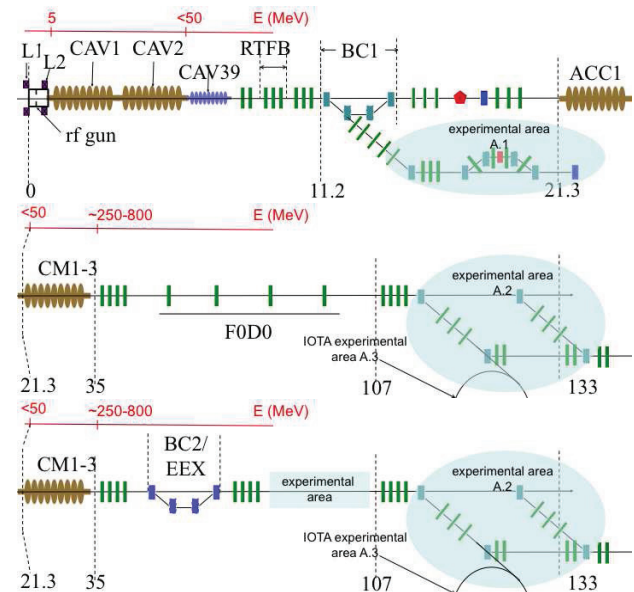


Figure 1: Overview of ASTA photoinjector (top); ASTA nominal high-energy transport beamline (middle) and modified high-energy transport beamline to accommodate a second-stage bunch compressor (bottom); “L1” “L2” stand for solenoids, “CAV1”, “CAV2”, and “CAV39” correspond to accelerating cavities, “CM1-3” to an ILC cryomodule string, “BC1” and “BC2/EEX” to bunch compressors, and “DL” to a dogleg beamline. “PEX” represents a possible reconfiguration of “BC2” to act as a transverse-to-longitudinal phase space exchanger.

ties (CAV1 and CAV2) to approximately 50 MeV. Downstream of this accelerating section the beamline includes quadrupole and steering dipole magnets, along with a four-bend magnetic compression chicane (BC1) [2]. The beamline also incorporates a round-to-flat-beam transformer (RTFB) capable of manipulating the beam to generate a high transverse-emittance ratio. In the early stages of operation, the bunches will be compressed in BC1. In this scenario the longitudinal phase space is strongly distorted and the achievable peak current limited to less than 3 kA. Eventually, a third-harmonic cavity (CAV39) operating at 3.9 GHz will be added enabling the generation of bunches with ~ 10 kA peak currents by linearizing the longitudinal phase space. In addition CAV39 could also be used

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to shape the current profile of the electron bunch [4]. The photoinjector was extensively simulated and optimized [3]. The photoinjector also includes an off-axis experimental beamline branching off at the second dipole of BC1 that will support beam physics experiments and diagnostics R&D.

The 50-MeV beam is injected into the SRF linac, which will eventually consist of three, 12-m long, TESLA/ILC-type CMs. Each CM includes eight 1.3-GHz nine-cell cavities. The first two cryomodules (CM1 and CM2) are a TESLA Type-III+ design, whereas the third (CM3), will be an ILC-Type IV design [5]. Together, these three CM constitute a complete ILC RF Unit. The SRF linac will be capable of generating a beam energy gain of ~ 750 MeV. The installation of the cryomodules will be staged pending the completion of their construction. The first CM has already been installed in the ASTA Facility [6].

Downstream of the linac is the test beam line section, which consists of an array of multiple high-energy beam lines that transport the electron beam from the accelerating cryomodules 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. The facility anticipated beam parameters appear in Table 1.

Table 1: Beam Parameters Expected at the ASTA Facility

parameter	nominal value	range
wenergy (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	see ^(a)
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 ^(b) [μm]	$2.11Q^{0.69}$	[0.1, 100]
long. emit ^(b) [μm]	$30.05Q^{0.84}$	[5, 500]
peak current \hat{I} ^(c)	~ 3	≤ 10

^(a) f_b and N_b are quoted for the nominal photocathode laser. Optical pulse stacking methods or field-emission sources could lead to smaller bunch separation within the rf macropulse.

^(b) normalized rms values for an uncompressed beam. The scaling laws are obtained from Ref. [3] and correspond to an uncompressed case. Bunch compression results in larger horizontal emittances; see Ref. [2].

^(c) the nominal value corresponds to a 3.2-nC compressed bunch without operation of CAV39. Higher values of \hat{I} are possible with CAV39. For the uncompressed case, we have $\hat{I}[\text{A}] \simeq 54.95Q[\text{nC}]^{-0.87}$.

During the first high energy beam operation and commissioning, only one CM will be installed allowing for the production of bunches with energies up to ~ 300 MeV. Eventually, the second and third cryomodules will be installed in Stage II. Together, the three cryomodules plus

the RF power systems will make up one complete ILC RF unit. During Stage II operation the beam energy will reach approximately 800 MeV. Beyond that stage several options are under consideration, including the installation of a 4th cryomodule downstream of a phase-space-manipulation beamline (either a simple magnetic bunch compressor or a phase space exchanger) [7, 8].

ASTA was designed with the provision for incorporating a small storage ring to enable a ring-based AARD program in advanced beam dynamics of relevance to both Intensity and Energy Frontier accelerators. The Integrable Optics Test Accelerator (IOTA) ring is 39 meters in circumference capable of storing 50 to 100-MeV electrons to explore, e.g. optical stochastic cooling methods [10] and integrable optics [11].

It is planned to expand capabilities for AARD in ASTA by the installation of the 2.5-MeV proton/H- RFQ accelerator which was previously used for High Intensity Neutrino Source (HINS) research at Fermilab [12]. That accelerator starts with a 50-keV, 40-mA proton (or H- ion) source followed by a 2-solenoid low-energy beam-transport line. The protons/ions are then accelerated by the pulsed 325-MHz RFQ to 2.5 MeV (with 1 ms pulse duration) prior to injection into IOTA.

USER OPPORTUNITIES

ASTA is intended to be operated as a scientific user facility for advanced accelerator research and development [13]. All the characteristics of a national user facility will be in evidence in the operation of ASTA and its user program. 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 will be proposal-driven and peer-reviewed in order to ensure that the facility focuses on the highest quality research. Proposals will be evaluated by an external Program Committee (the ASTA Program Advisory Committee), consisting of internationally recognized scientists. Proposal evaluation will be carried out according to established merit review guidelines. We expect the first batch of proposal submitted as part of our proposal to DOE [14] will be reviewed during the fiscal year (FY) 2014.

Three experimental areas [A1, A2, and A3 (IOTA) in Fig. 1] will be available to users for installation of experiments. Area A1, situated in an off-axis beamline within the photoinjector, will provide electron bunches, possibly compressed, with energies up to 50 MeV. The current layout of the off-axis beamline includes a chicane-like transverse-to-longitudinal phase space exchanger, and provision for the installation of a short undulator for beam-laser interaction (e.g., to enable microbunching studies). 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 could be ran simultaneously (switching the beam from one beamline to the other would only require minor optical-lattice adjustment). Fi-

nally, the eventual availability of a H^- source would allow IOTA to be operated independently of the ASTA electron-beam users. In addition, in order to accommodate additional experiments during the stage I, we are considering the installation of a chicane that could operate as a second-stage bunch compressor or transverse-to-longitudinal phase space exchanger (BC2/EEX in Fig. 1).

ANTICIPATED RESEARCH THRUSTS

In this Section we highlight expression of interests to perform experiments along the five main research thrusts enabled at ASTA.

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 proposed research program includes at IOTA has expanded well beyond its initial goal to test non-linear, integrable, accelerator lattices, which have the potential to shift the paradigm of future circular accelerator design [15, 16, 17]. IOTA will also be used to explore optical-stochastic cooling [10]. The addition of an H^- source will also enable the investigation of integrable optics in presence of significant space charge effects. The H^- beam will also open the path to the study of space-charge compensation schemes in high-intensity circular accelerators [18]. IOTA will also support some fundamental Physics studies such as the measurement of the wave-function associated to a single electron using a method similar to an experiment previously attempted [19].

The availability of advanced phase space manipulations will also support the development and test of beam-driven acceleration methods, which would greatly benefit from shaped current profiles [21, 22, 23] to significantly increase the transformer ratio – the energy gain of the accelerated bunch over the energy loss of the driving bunch. When combined with the aforementioned round-to-flat beam transformation, this shaping technique could produce flat beams with tailored current profiles suitable for test of beam-driven acceleration methods based on, e.g., slab dielectric-loaded waveguide (DLW) [24, 23]. Other advanced acceleration techniques to be explored at ASTA include the acceleration and cooling of muon beams based on carbon-based crystal structures [25].

Finally, the high-power beam produced by the SRF linac will provide opportunities for high-energy Physics detector R&D. These include the high-power tests of target required for the Long-Baseline Neutrino Experiment (LBNE) and the generation of tagged-photon beams necessary to test components associated to the Project-X detectors.

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 and especially beam degradation 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 currents 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 [26]. 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 and recording the HOM-induced beam displacements downstream of the cryomodule(s) under test would enable the characterization of HOMs over a continuous range of frequencies [27]. Finally, a precise characterization of the jitter and beam-based stabilization of the SRF module has been proposed. It relies on the measurement of the bunch relative time of flight downstream of a bunch compressor, bunch energy and on the detection of coherent synchrotron radiation. These measurements are fed to an algorithm and used to control the phase and amplitude of the SRF cryomodule(s) [28].

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 [30]. 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 [29].

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 photo energies ranging from keVs to MeVs. The high average power and brightness of the ASTA electron beam has unmatched potential for development of several novel radiation-source concepts. Head-on collision of the electron bunch with an intense laser produces radiation with maximum up-shifted frequency $\omega \simeq 4\gamma_l^2\omega_L$ where γ_l is the bunch's Lorentz factor and ω_L the laser frequency. At ASTA, colliding the bunch with a 800-nm laser would provide γ rays with energies ranging from 1 to 20 MeV; see typical spectrum in Fig. 2 (left). If the laser repetition frequency matches the electron bunch frequency, an unprecedented γ -ray brilliance in excess of 10^{24}

phot.mm⁻².mrad⁻².s⁻¹/(0.1%BW) could be attained [31]. The main technical challenge will be to develop a laser capable of producing Joule-level pulse energy with MHz repetition rate and will rely on a recirculating optical cavity [32, 33]. Such high-flux γ -ray source is foreseen to be extremely beneficial to the measurement of the cross section associated to the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction which is crucial in nuclear astrophysics as it enters in the synthesis of many elements. Due to its low cross section, a precise measurement of this reaction using a nucleation process in a bubble chamber remains elusive with presently available γ -ray sources (as only a handful of events per year are expected). The potential availability of a high-flux γ -ray source at ASTA could result in significantly higher statistics (up to 200,000 events per year).

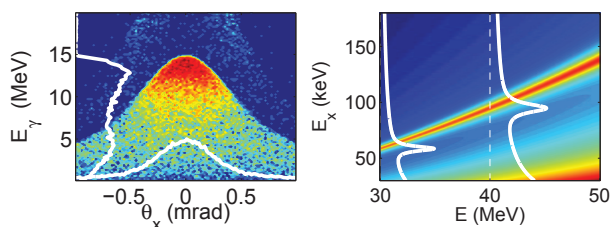


Figure 2: left: Spectral-angular distribution of γ rays produced by a 800-nm laser pulse backscattered on the ASTA 800-MeV beam (the density is plotted using a logarithmic color scale). right: X rays spectral yield as function of electron beam energy and photon energy for the $1 \rightarrow 0$ transition in (110) plane of diamond. Both CR and bremsstrahlung are considered in these calculations. The white traces are expected photon-energy spectrum for 30 and 40-MeV electrons

In the photoinjector area, it is foreseen to test a concept enabling the production of high-brilliance x rays by combining the low-emittance beam produced out of the photoinjector with channeling radiation (CR) [34]. The production of CR will occur downstream of the bunch compressor (BC1). Several crystal materials will be tested. Simulations using a $\sim 40 \mu\text{m}$ -thick diamond crystal indicate the production of x rays energy in the [10-150] keV range for the electron-beam energies available in the ASTA photoinjector (15 to 50 MeV); see Fig. 2 (right).

Additionally, it was suggested that the available long stable bunch train could serve for a proof-of-principle experiment of an extreme-ultraviolet (EUV) FEL oscillator at 13.4 nm wavelength. Preliminary simulations indicate that saturation of the FEL process occurs after 300-350 passes [35]. Initial experiments could be conducted at low energy (250-300 MeV) and provide 120-nm FEL radiation.

Finally, the combination flat beams with long bunch train could support the test of micro-undulators [36]. 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 is on the order

of $K \sim 10^{-2}$ which results in a low photon yield $\sim \alpha K^2$ (where α is the fine-structure constant). Therefore the test and characterization of the associated undulator radiation would greatly benefit from the long bunch train available at ASTA.

Accelerator R&D for Stewardship and 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 tailor the emittance partition within the three degrees of freedom to produce ultra-low emittance beams for future hard X-ray free-electron lasers [37].

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 [38, 39] or corrugated [40] passive structure, or (ii) the judicious arrangement of three transverse-deflecting cavities to produce a transfer matrix with a non-vanishing R_{56} . In addition using these passive structures to further control the longitudinal-phase-space nonlinearities could also be test at ASTA [41]. 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 the concept of a fast beam-beam kicker [42] for the Medium-energy Electron-Ion Collider (MEIC) [43] being under design at Jefferson Laboratory.

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).

STATUS

The ASTA accelerator is currently under construction [44]: the electron source and associated subsystems were installed and are being commissioned; see Fig. 3. First electrons were produce in June 2013 from a temporary molybdenum cathode resulting in a 8-pC electron bunch. Typical operating parameters during the commis-



Figure 3: Photographs of the RF gun assembly used to produce first electrons (left) and of the cryomodule CM1 installation (right).

sioning phase are 80 μ s-long RF macropulse, 31.5 MV/m peak electric field on the cathode surface and $f_b = 1$ Hz repetition frequency. The measured beam's kinetic energy at the gun exit is $E_k = 3.24 \pm 0.1$ MeV.

In parallel the 50-MeV injector line is being assembled and we anticipate that 50-MeV electron bunches will be produced early in CY2014. Further acceleration in one CM is foreseen late in FY14, once the high-energy beamline assembly is completed.

A program advisory committee (PAC) was formed and the first ASTA users' and PAC meeting was held at Fermilab on July 23-24, 2013. The meeting had ~ 80 attendees (about 2/3 were external to Fermilab) and led to 24 expressions of interest. Further details on this users' meeting can be found in Ref. [45].

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