Measurement of Transverse Emittance in ASTA at Fermilab

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1 Abstract

Transverse emittance is an important diagnostic for charged particle beams. The Advanced Superconducting Test Accelerator (ASTA) at Fermilab incorporates imaging targets and camera stations throughout the beam line, allowing real-time data acquisition at various energy levels and positions. Emittance Calculator, a new Java application to be run through the Accelerator Controls Network (ACNET), performs analysis on these images, providing values for the size and divergence of the beam and its size in position-momentum phase space and calculating its emittance. This program is intended to be an interface with the camera stations and provide beam diagnostics to aid in the design and maintenance of ASTA.

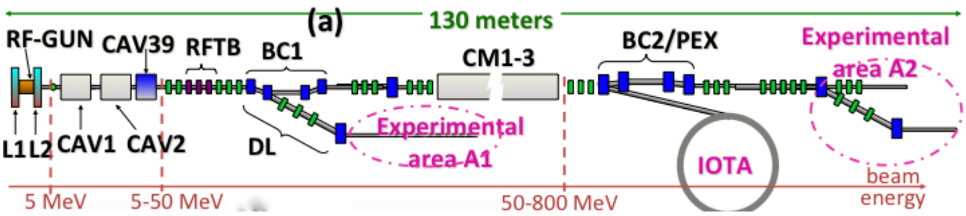

Figure 1: Schematic of ASTA beamline.

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2 ASTA

The Advanced Superconducting Test Accelerator at Fermilab is a high-repetition, high energy superconducting linear accelerator designed to support Advanced Accelerator Research and Development, especially relating to the International Linear Collider (ILC).

A radiofrequency photoinjector, comprised of a UV ($\lambda = 263nm$) pulse on a Cs_2Te photocathode, gives ASTA a remarkably high repetition rate: 3 MHz over a 1 ms duration macropulse. Two 1.3 GHz superconducting RF cavities accelerate to approximately 50 MeV, followed by three cryomodules; this section of the linac is an ILC RF unit. [7]

ASTA's high repetition and high energy are well suited for experiments on the intensity and energy frontiers. Designed for development of SRF cryomodules, the inclusion of the ILC RF unit makes it an important stage for ILC component testing. An Integrable Optics Test Accelerator (IOTA) and an oscillator-based free electron laser are planned additions to expand the experimental scope and take advantage of ASTA's high repetition and beam quality.

As of August 2013, ASTA is under construction, with only one of the three cryomodules installed. When complete, ASTA will be capable of producing a 750MeV-1GeV electron beam with ILC parameters. [2]

3 Emittance

The behavior of charged particle beams can be predicted with knowledge of the components of the accelerator. The motion of individual particles through the accelerating structures and bending and focusing elements acts as a harmonic oscillator described by

$$x + K(s)x'' = 0 \tag{1}$$

The general solution to this equation is of the form

$$x = Aw(s)\cos[\psi(s) + \delta] \tag{2}$$

where A and δ are constants of integration whose value is based on the particle's initial conditions. The amplitude function $w(s)$ is determined by the accelerator design. The Courant-Snyder parameters α, β, and γ, descriptors of the particles' path, are defined as [3]

$$\beta(s) = \frac{w^2(s)}{k} \tag{3}$$

$$\alpha(s) = -\frac{1}{2}\frac{d}{ds}\frac{w^2(s)}{k} \tag{4}$$

$$\gamma = \frac{1+\alpha^2}{\beta} \tag{5}$$

Each particle moves along the ellipse through phase space determined by the equation of motion and its initial conditions. This causes irregularly shaped beams to gradually conform to a characteristic shape. In the ideal accelerator this is an ellipse; however, field nonlinearities tend to cause a distorted shape in phase space. The area of this phase space ellipse is described by

$$\epsilon = \gamma x^2 + 2\alpha x x' + \beta (x')^2 \qquad (6)$$

The distribution of particles in the ASTA beam is roughly gaussian. Although the center of the distribution contains the most particles, some will be found throughout the pipe. Emittance is considered when designing components to prevent beam loss from collisions with walls or other components. Some particles will naturally be lost to the walls of the beam pipe; we define the RMS emittance as the size of the phase space ellipse of those particles within one σ in both transverse directions. This relevant subset of the particles is tracked and considered in component design.

The emittance varies inversely with beam energy; as the beam is accelerated the transverse momentum decreases with respect to the longitudinal momentum and the emittance seems to shrink. Because emittance will be measured at points along the accelerator, between 5 MeV at the photoinjector and up to 1 GeV after the final cryomodule, we concern ourselves with the normalized emittance $\epsilon_n = \beta\gamma\epsilon$, which we will use as the value of emittance throughout this paper. This formula uses the relativistic β and γ:

$$\beta = \frac{v}{c} \quad , \quad \gamma = \frac{1}{\sqrt{1-\beta^2}} \qquad (7)$$

In the idealized case, neglecting non-linear field effects, En is conserved through acceleration.

The Courant Snyder parameters in terms of RMS normalized emittance are

$$\alpha = -\frac{< xx' >}{\epsilon_{rms}} \qquad (8)$$

$$\beta = \frac{< x^2 >}{\epsilon_{rms}} \qquad (9)$$

$$\gamma = \frac{< x'^2 >}{\epsilon_{rms}} \qquad (10)$$

By measuring ϵ_{rms}, the position x and momentum x', the Courant Snyder parameters can be determined and position-momentum phase space constructed.

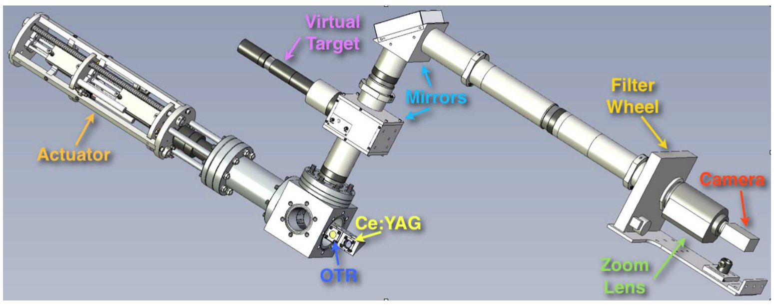

Figure 2: Hardware used in ASTA beam imaging.

4 Hardware

Each camera station uses identical image station hardware, shown in Figure 2. A stepping actuator contains an array of targets, a beam cage, and a slit collimator. The image produced by the targets is transported through a tube of optics to a digital camera connected to the Accelerator Controls Network (ACNET).

The beam cage is the default setting for the actuator. Image stations are designed to interfere with the beam only when in use. Wakefield effects, varying electric fields created when a charged particle beam experiences a change in aperture, can lead to unpredictable beam behavior. Thus, a beam cage with the same diameter as the beam pipe is placed in the beam path to minimize change in aperture that can affect the beam.

ASTA uses two varieties of targets: YAG:Ce crystal scintillators and aluminum foil that produces Optical Transition Radiation (OTR).

4.1 Slit Collimation

To measure emittance, we must know the divergence of the beam. A stack of tungsten blocks with 50 μm spacing collimates the beam. The difference between the collimator slit size and the size of the bands of imaged beam after a known drift length is the value of the divergence of the beam.

4.2 Scintillation

Scintillation occurs when a charged particle interacts with the molecules of the crystal, exciting some electrons to higher energy states. The excited electrons then return to the lower-energy ground state through emission of photons. This method yields bright images because much of the energy of the incident particle acts to excite the target crystal. Some energy is lost to heat as electrons drop into lower vibrational energy states but much of it is passed into emitted photons.

Because the excitation of the crystal is not tightly localized, spatial resolution from scintillation is poor. The decay time of the energy levels is on the order of 70 nanoseconds so temporal resolution is also relatively poor. [1]

4.3 Optical Transition Radiation

Optical transition radiation occurs when a charged particle passes between materials with different dielectric constants. In ASTA imaging stations, this transition occurs between vacuum and aluminum. The electric fields differ between the two materials; the particle can shed some energy by the emission of a photon to reorganize the fields. The peak of this radiation occurs at an angle of $\frac{1}{\gamma_{rel}}$ around the angle of specular reflection.

ASTA imaging stations use a foil at 45° to the beam to create a cone with a spread of $\frac{1}{\gamma}$ at 90° to the beam. By directing the emitted photons at an angle normal to the beam, collection through the optics is simplified. This radiation occurs on the order of femtoseconds, yielding time-resolved measurements limited by the hardware capabilities. [4] Elsewhere along the beam line, the speed of OTR is utilized in measuring the pulse profile with streak cameras. [5]

4.4 Optics

It is important to know the dimensions of the optics precisely to ensure faithful image production in the cameras. The angular acceptance was determined to be on the order of 100 mrad; this is sufficient to prevent clipping by the sides of the optic tubes.

The field of view of the camera, when focused on the imaging target, was determined to be 14 mm. Accurate measurements rely on well-calibrated field of view; the size of the image is calculated by measuring its size in pixels and converting to relevant units (here, μm) by multiplying by (field of view/image pixels).

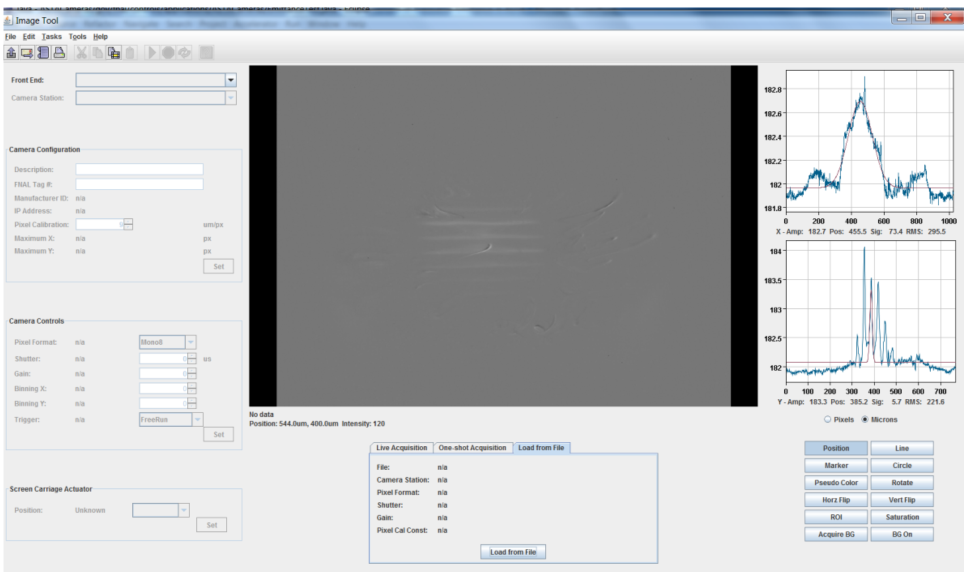

Figure 3: ImageTool graphical user interface with beam image from A0PI.

5 ACNET and ImageTool

Fermilab's Accelerator Controls Network (ACNET) is a three-tiered system composed of front-end interfaces with hardware, a central database, and an application environment. Operators can control the accelerator and acquire and analyze data through ACNET applications. ACNET runs Java applications on the user layer, which works with the front end and allows remote data collection and accelerator control.

The application described in this paper is an extension of ImageTool, an ACNET application for live imaging of the ASTA beam. ImageTool, shown in Figure 3, provides the framework to interact with the front end to acquire data from the camera stations, as well as a graphical user interface (GUI) to control the analysis. The front end background selection tool is used to eliminate dark current from the image data.

ImageTool produces projections of the image intensity on the two transverse axes; GUI controls allow user selection of regions of interest and Gaussian fits to the data. From the fitted curves, the position and intensity of the beam at chosen points may be determined. [6]

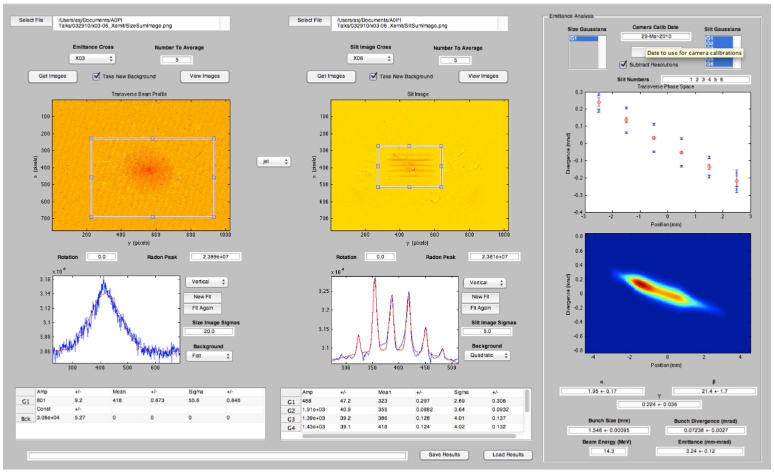

Figure 4: A0PI graphical user interface.

6 A0PI Emittance Calculator

The A0 Photoinjector used a Matlab program (shown in Figure 4) to calculate the position-momentum phase space ellipse and the beam emittance. Up to 8 Gaussian fits may be performed on the image projections. The program provides support for two images and an interpolated plot of beam intensity in phase space. [8]

7 EmittanceCalculator

EmittanceCalculator is designed to extend the functionality of ImageTool by incorporating features of the A0PI program. Images are acquired through the existing ACNET front-end controls and processed in the GUI framework of ImageTool.

Fitting multiple regions of data is important when calculating emittance. The Levenberg-Marquardt damped least-squares method is used to produce a Gaussian fit to the data.

Like all iterative methods, this requires fairly accurate initial conditions. Users of EmittanceCalculator select peaks of the data set with the mouse; there is no programmed limit to the number of Gaussians the program can fit.

Simulations of the ASTA beam follow a Gaussian distribution. ASTA is currently under construction. If the beam is found to conform less closely to a Gaussian distribution after more components are added to the beam line, EmittanceCalculator may be expanded to produce non-Gaussian or multiple Gaussian fits as the beam requires.

Slit width, drift length, and other accelerator parameters such as beam energy can be changed by the user. Because there are image stations at various points along the beam, it is important to provide correct values for these parameters at the given position to obtain accurate calculations.

Currently this is done manually; when EmittanceCalculator is integrated into ACNET it will automatically use the appropriate values corresponding to a camera station's signature. The system knows the position of each image station and therefore the distance between them (drift length) and the beam energy at each.

Individual fits to peaks in the data provide points for the plot of position and divergence from which the phase space ellipse is interpolated.

8 Results

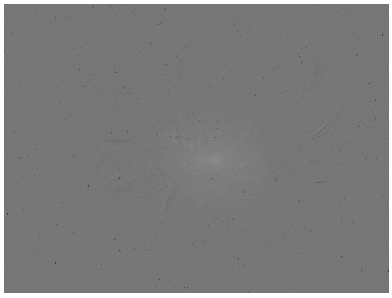

Figure 5: Beam spot image (A0PI).

Figure 5 shows an image of the A0 photoinjector beam captured by camera stations similar to those used at ASTA. These beam images were used to test the functionality of EmittanceCalculator because ASTA has only recently (June 2013) produced an electron beam. Shown is a low-intensity image of an electron distribution that is very closely Gaussian in the transverse plane.

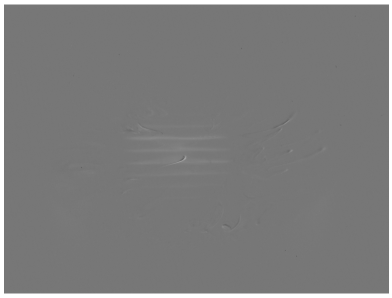

Figure 6: Beam slit image (A0PI).

Figure 6 is an image of the beam downstream of the tungsten collimator. Here, the slits are oriented horizontally; some imaging stations have vertical slits while others have horizontal. Because emittance is conserved, we can use values from horizontally and vertically measured values interchangeably.

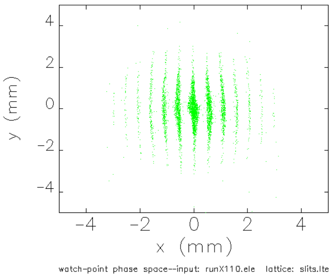

Figure 7: Simulated ASTA beam image.

Figure 7 shows a simulated image of the collimated beam for ASTA. In coming months, EmittanceCalculator will be used to determine how closely the ASTA beam corresponds to theoretical expectations.

Divergence and position (the location of the slit on the axis of the transverse plane in which divergence is measured) are plotted; this is position-momentum phase space. Points between the values from the image are interpolated. Intensity is plotted on this phase space ellipse, creating a visualization of the beam in phase space.

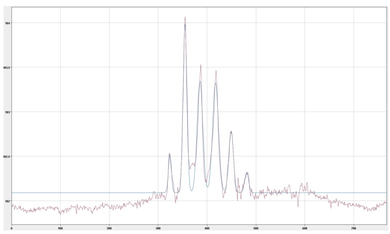

Figure 8: Emittance Calculator fits

The fits from Emittance Calculator, shown in Figure 8, are composed of the sum of a single Gaussian fit to each slit image. If beam quality changes as ASTA construction proceeds, the fit mechanism may be updated to provide more accurate fits. Currently, the simulated ASTA beam follows a Gaussian distribution so the assumption is considered valid.

9 Conclusions

ASTA is a state of the art linac designed for development of SRF cavities. The inclusion of cryomodules identical to the ILC design makes ASTA a leading test accelerator. As such, it is important to implement diagnostics throughout the beam line with a simple user interface.

Emittance Calculator is a robust Java program that employs thoroughly tested and widely-used ACNET processes to network camera stations throughout the accelerator. Because it is under construction, ASTA has not run much beam; further testing will compare values from EmittanceCalculator to theoretical values to test the software and hardware performance.

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