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High-Brightness Electron Beam Diagnostics at the ATF*

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Abstract: The Brookhaven Accelerator Test Facility (ATF) is a dedicated user facility for accelerator physicists. Its design is optimized to explore laser acceleration and coherent radiation production. To characterize the low-emittance, picoseconds long electron beam produced by the ATF's photocathode RF gun, we have installed electron beam profile monitors for transverse emittance measurement, and developed a new technique to measure electron beam pulse length by chirping the electron beam energy. We have also developed a new technique to measure the ps slice emittance of a 10 ps long electron beam. Stripline beam position monitors were installed along the beam to monitor the electron beam position and intensity. A stripline beam position monitor was also used to monitor the timing jitter between the RF system and laser pulses. Transition radiation was used to measure electron beam energy, beam profile and electron beam bunch length.

I. INTRODUCTION

The Brookhaven Accelerator Test Facility (ATF) has been in operation for several years as a User's Facility for physics of beams, equipped to study the interaction between high power electromagnetic fields and bright electron beams. Most of the ATF's experiments [1] fall into one of two categories. First type experiments explore new particle acceleration technique using the ATF's powerful CO_2 laser, such as Inverse Cerenkov Acceleration experiments (ICA) and Inverse Free-Electron Laser accelerator (IFEL). The second class of experiments use the ATF's bright electron beam to generate intense electromagnetic radiation, such as Free-Electron Laser (FEL) and Smith-Purcell radiation experiments.

The ATF's experimental program requires electron beam parameters that range widely in charge, pulse length and pulse train length. The single bunch charge can be varied from pC to nC, with a normalized rms emittance from 10 mm-mrad to 0.02 mm-mrad. The electron beam bunch length can be varied (by adjusting the relative phase between the laser and RF gun) from 10 ps to 500 fs. The number of bunched in a macropulse can be varied continuously from one to a few hundred

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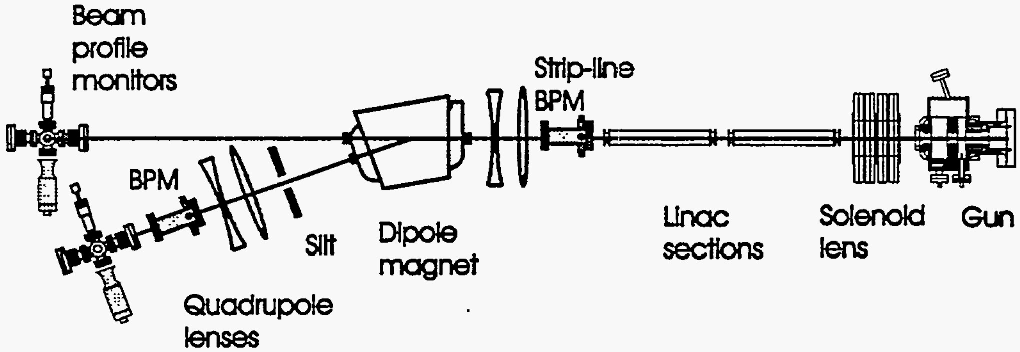

Figure 1. Schematic of the ATF photoinjector and elements relevant to slice measurements.

micropulses. The electron beam diagnostics system at ATF were designed in such a way that both transverse and longitudinal emittance of electron beam can be characterized. The main components of the ATF diagnostics system are beam profile monitors and stripline beam position monitors. Both dipole magnet spectrometer and transition radiation were used to measure the electron beam energy. Transition radiation was also used for electron beam profile and bunch length measurement.

We have developed a new technique of measuring the electron bunch longitudinal charge distribution. The method uses a slit in a dispersive line to pass part of an energy chirped electron beam. The resolution of the measurement is half a ps. A somewhat similar diagnostic (with a quadrupole-scan emittance setup past the slit) was developed to measure the 1 ps slice emittance of 10 ps long electron beam. Using this 'Slice Emittance' diagnostic we have made the first direct demonstration of emittance compensation.

In section II we will introduce the ATF's photoinjector and accelerator, in section III its main electron beam diagnostic elements, in section IV our ps resolved charge distribution and slice emittance diagnostics, and in section V transition radiation measurements and the use of a stripline beam position monitor to measure the timing stability of a single bunch with sub-picosecond resolution.

II. THE ATF ACCELERATOR

The ATF's S-band one-and-half cell photocathode RF gun (or photoinjector) [2] is followed by a solenoid magnet. Copper cathode has been chosen as the photoemitter due to its unlimited life time at a reasonable vacuum although its quantum efficiency is low. A second solenoid magnet behind the RF gun bucks the field of the first solenoid magnet. Magnetic measurements were performed to insure that the longitudinal magnetic field on the cathode surface is nearly zero. Following the solenoid magnet is a 45 degree aluminum mirror for monitoring the laser beam

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profile on the cathode and carrying out optical transition radiation (OTR) measurement. A phosphor coated copper block on an actuator is next in line for charge measurements. This copper block can also be used for beam profile and position monitoring. The beam is then injected into the linac. The distance between the cathode and the entrance of the linac is 81 cm, optimal for emittance compensation. The linac consists of two sections of SLAC type traveling wave linac. The RF gun and linac are powered separately by two XK-5 klystrons.

The ATF's photoinjector and two linac section are laid out in a straight line with nine quadrupole lenses, numerous steering magnets and many beam position and profile monitors (Fig.1). The quadrupoles are used for beam matching or emittance measurements, utilizing two beam profile monitors with a five meter separation. A 20° dipole magnet bends the beam into a dispersive section with more magnets and diagnostics, including a momentum analysis slit for energy spread measurement or energy selection. Additional 20° dipoles in this line can bend the beam into three dispersion free beam lines in a shielded experiment hall.

The photocathode is irradiated at a wavelength of 266 nm with FWHM pulse length of 9 ps and energy up to 0.2 mJ. This light is derived from a laser system comprising a diode pumped Nd:YAG oscillator followed by two multiple-pass amplifiers and a pair of frequency doubling crystals. By Fourier relaying an aperture at the beginning of the laser system onto the cathode, position stability of 0.5% has been achieved, and the peak to peak energy stability is 4 %. The laser spot size on the cathode can be changed by varying the focal length and location of one of the imaging lenses. The laser beam incidents at an angle of 72 degree to normal of the cathode. The beam ellipticity caused by this oblique incidence is corrected by a pair of cylindrical lenses as the final imaging optics.

III. THE ATF ELECTRON BEAM DIAGNOSTICS

The main electron beam diagnostic devices at the ATF are Faraday cups, phosphor screen beam profile monitors and stripline beam position monitors. For electron beam energy measurement, several spectrometers consisting of dipole magnets, quadrupole lenses and beam profile monitors are in use. Transition radiation is used extensively at the ATF for beam energy, transverse beam profile and bunch length measurements.

Fig.2 is the schematic of an ATF beam profile monitor [3]. It consists of an imaging system, motorized control system and image analysis. The imaging system comprises a Gd_2O_2S:Tb phosphor deposited on a one mil thick aluminum foil, an aluminum mirror mounted at 45° and a pair of lenses. The phosphor screen is perpendicular to the electron beam, improving the resolution of the BPM. Two lenses image the electron beam image with a magnification of f1/f2. The focal length f2 is short resulting a large light collection angle. The intensity of the image is controlled by a motorized aperture on the f2 lens. Our measurement showed that this BPM has a resolution of 50 µm, and a sensitivity of 5 pC with 0.5 mm diameter spot.

The ATF's BPM can be easily converted into an optical transition radiation beam profile monitor by simply removing the phosphor screen. The CCD cameras currently in use are Pulnix 745E or WAT902A. The later has been used for OTR measurement. A good OTR image is obtained at a beam energy of 40 MeV for a charge of 0.25 nC. The BPM was used for transverse emittance measurement, employing both the quadrupole magnet scan and the multiple screen methods.

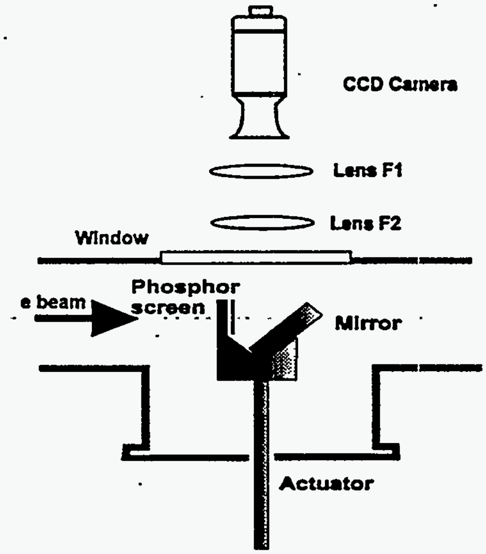

Figure 2. The ATF's Beam Profile Monitor.

The ATF beam position monitor consists of a beam pick-up element with four stripline electrodes in a 1.5" diameter stainless steel pipe mounted with 2 3/4" diameter Con-flat flanges, and a local receiver. This device is shown in Fig.2.

The electrodes are shorted at the downstream end, resulting a bipolar output signal with a separation of 550 ps, twice the length of the electrode. The signals of an opposing pair of electrodes are combined in a hybrid to produce sum and difference signals.

The sum is used as a measure of the beam charge (or phase, see below) and the difference over sum provides a normalized beam position. The bipolar sum and difference signals are converted to unipolar video signals in a pair of balanced mixers driven by a reference. Pass band filters are used (not shown in the drawing) to select the desired Fourier component of the bipolar pulses. The current reference frequency is 2856 MHz, which is about the third harmonic in the bipolar signal's spectrum. Currently we are in the process of changing over to a about 1 GHz reference, at which better performing components are available. The video output is amplified and sent to charge sensitive ADCs.

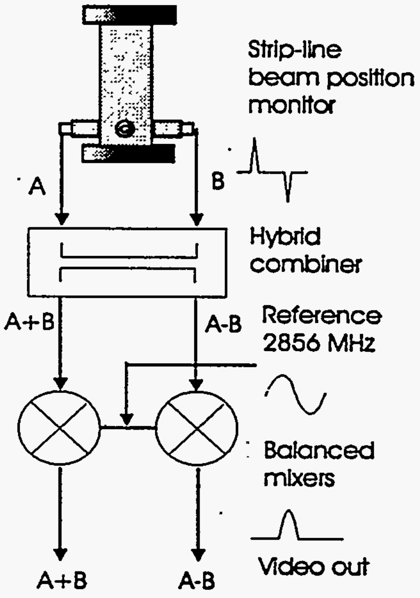

Figure 3. The stripline beam position monitor system.

IV. PICOSECOND RESOLUTION SLICE EMITTANCE AND CHARGE DISTRIBUTION MEASUREMENTS

We have developed a new technique for making sub-picosecond time resolved measurements of local (or 'slice') properties within the bunch. This technique was used to make slice emittance measurements and longitudinal charge distribution measurements. The layout of the slice measurement system is shown in Fig.3.

For a given RF gun phase (referenced to the laser timing), the linac RF power and phase are adjusted to produce a 52 MeV electron beam on crest. Then the second linac section is dephased to 30° off crest. This produces an energy chirp of 0.44% per ps within the electron beam. The electron beam is then transported to the momentum slit. The horizontal beam size observed on the momentum slit is given by,

$$x = \sqrt{\beta\varepsilon} + D\frac{\Delta p}{p} \tag{1}$$

where β is the Courant-Snyder β function, ε is the horizontal emittance, D=5.4 mm/% is the dispersion function at the momentum slit, and Δp/p is the relative energy spread.

To perform the electron beam energy spread measurement and selection, the dispersive term must be larger than the emittance term. This is accomplished by tuning the quadrupole magnets upstream of the dipole magnet to produce a small value of the β function. The opening of the slit is set to 0.5%. At this setting the horizontal beam size is dominated by the energy spread. The dipole magnet is adjusted to a current corresponding to 48.8 MeV, (corresponding to a phase of 30°). The electron beam bunch length and the charge distribution within the bunch are measured by varying the second section linac RF phase and measuring the charge past the momentum slit using the stripline beam position monitor behind the momentum slit for measuring the slice charge. Each degree of RF phase corresponds to about 0.97 ps. The timing jitter between the RF system and linac limits the bunch length measurement accuracy to ± 0.5 ps. The electron beam bunch length was measured for three values of the cathode electric fields: 90, 100, 110 MV/m. The results are shown in Fig.4.

The slice emittance measurement [4] is done in a similar manner to the bunch distribution measurement. The difference is that at each slice (selected as above by the phase of the 2nd linac section) we do a quadrupole scan (on a lens downstream of the slit), measuring the vertical beam size as a function of quadrupole current. The measurement can be done for various settings of the emittance compensation solenoid, yielding significant insight on the process of emittance correction.

We have measured the relative rotation of the beam slices in transverse phase space with the change of the solenoid current. This relative rotation makes it possible to counter the effect of the integrated emittance growth in the RF gun due to space charge and RF effects. The integrated emittance growth is due to the lack of overlap of misaligned slices.

This diagnostic should make it possible to do non-linear emittance corrections, since the beam matrix of arbitrary slices can be measured and corrected individually.

V. TIMING JITTER AND TRANSITION RADIATION MEASUREMENTS

Maintaining the timing stability between the RF system of the photocathode RF gun and its driving laser system is crucial for the performance of the RF gun. Since the pulse length of the laser is on the order of a few picoseconds, the timing jitter is required to be on the order of sub-picosecond. We have developed a new

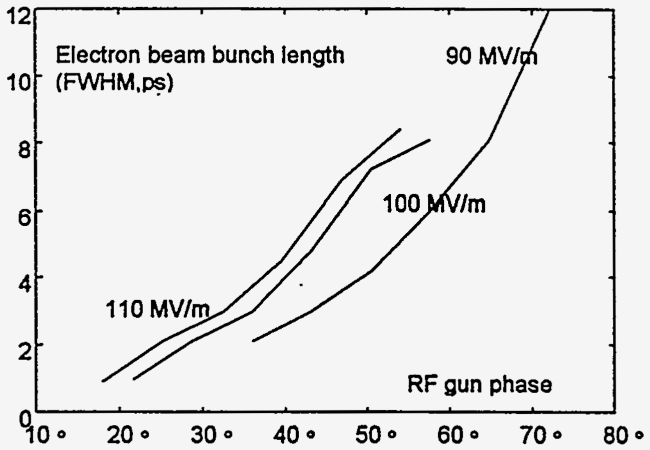

Figure 4. Measured electron beam bunch length as a function of the RF gun phase for three values of the gun cathode fields.

technique [5] of measuring the sub-ps timing jitter between the RF and laser using stripline beam position monitor (BPM). As we discussed earlier, one of the resonant frequency of the BPM is ATF RF system frequency 2856 MHz. Using the ATF low level RF signal as local oscillator, the output from the mixer with stripline sum signal contained both intensity and relative phase information of the photoelectron beam. The output of mixer is plotted in Fig.5 as a function of local oscillator phase, near the zero crossing, the output is almost linearly proportional to the relative phase between the RF system and electron beam. The sensitivity of our system was measured to be 6.5 mV/ps. Using this technique, we have measured the rms timing jitter between the laser and RF system is 0.5±0.25 ps.

Transition radiation is extensively used at ATF for electron beam diagnostics. The coherent transition radiation was observed using pyroelectric detector [6], the observed square dependency of radiation power on the electron beam intensity (BPM sum signal) confirmed ATF electron beam bunch length is short. Transition radiation was used to measure the energy of electron beam from RF gun. Since the space between the RF gun and linac is very limited, transition radiation provided easy solution. A aluminum mirror was installed inside a 4 inch six-way cross to produce transition radiation. A mirror on the rotational stage outside the vacuum window reflected the radiation to a photomultplier. Fig.5 shows the angular distribution of the transition radiation for two different input RF powers into the RF gun, 6 MeV electron beam corresponds to a peak acceleration field of 130 MV/m on the RF gun cathode.

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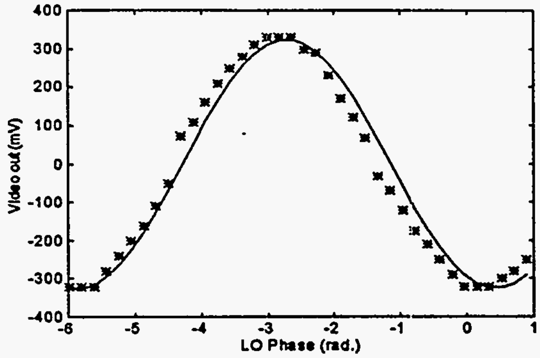

Figure 5. Stripline BPM sum video out vs. Local oscillator phase.

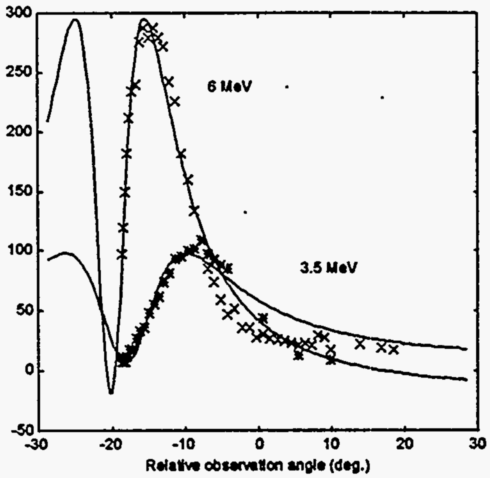

Figure 6. OTR angular distributions and their best fit

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