FEL TECHNOLOGIES R&D AND SASE GAIN ENHANCEMENT OBSERVATION AT THE BNL ATF

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Abstract

The research at the Brookhaven Accelerator Test Facility (ATF) covers all major aspects of the future light source (LS) technologies, from high-brightness electron beam source, beam diagnostics to FEL experiments. The ATF itself is the testing ground for photocathode RF gun technologies; it is the only multi-user facility based on the photocathode RF gun injection system. Using vacuum based laser-cleaning technique, 0.5% quantum efficiency (QE) was measured for an Mg cathode. The best emittance (normalized rms) for a 0.5 nC charge with peak current 110 A is measured to be 1.5 mm-mrad. The ATF is the only facility where both laser seeded (HGHG) and SASE FEL experiments are performed, SASE was observed at the ATF from 5.3 μm to visible. A record of 7 orders of magnitude gain was observed at the ATF high-gain harmonic-generation (HGHG) experiment. An order of magnitude SASE gain enhancement by optical klystron was observed at the ATF.

1 INTRODUCTION

The Brookhaven ATF is a laser linac complex user facility dedicated for beam physics and advanced accelerator concept R&D. One of the ATF's main research directions is to develop technologies for future light source (LS). Since the X-ray's discovery more than 100 years ago, accelerator technology is the driving force behind the improvements of X-ray brightness. The future X-ray source should be transverse coherent, and time duration at least an order of magnitude shorter than existing third generation light source. High-brightness electron beam produced by the photocathode RF gun, and linac based single pass FEL are the key technologies for producing sub-picosecond coherent X-ray.

The ATF high-brightness beam R&D covers all aspects of photocathode RF gun injection system. We have developed a complete photocathode RF gun injection system that including RF gun, emittance compensation solenoid magnet and beam diagnostics station (Fig.1). The major challenges in operating a photocathode RF gun injection system are its stability and reliability [1]. The RF gun driving laser and photocathode QE are major sources of those problems. We will first present the techniques we have employed at the ATF to improve the laser system stability, and the new laser-cleaning technique for QE improvement. We will also discuss using laser mask for beam diagnostics, and analyse the advantage of RF kicker cavity for femto-second electron bunch length measurement. Then we will describe the ATF FEL experiments, SASE at 5.3 um and SASE gain enhancement by the optical klystron will be presented.

2 HIGH-BRIGHTNESS ELECTRON BEAM R&D AT THE ATF

2.1 The BNL Photocathode Injector

The photocathode RF gun injection system consists of laser system, photocathode RF gun, emittance compensation solenoid magnet and beam diagnostic station (Fig.1). The latest BNL RF gun (Gun IV) is a 1.6 cell symmetrized RF gun capable of operating at the 50 Hz for a 3 μs RF pulse. The single emittance compensation magnet design simplifies system alignment and operation. The maximum field on the cathode is less than 5 G. The beam diagnostics station is a special device with the functions of a beam profile monitor and a Faraday cup [2]. It can measure the photoelectron beam charge and energy, hence determine the basic parameters of the RF gun operating point, such as RF gun phase and field on the cathode [1]. The most important, and least discussed components of the RF gun injection system is the laser system, which will be the focus of the following section.

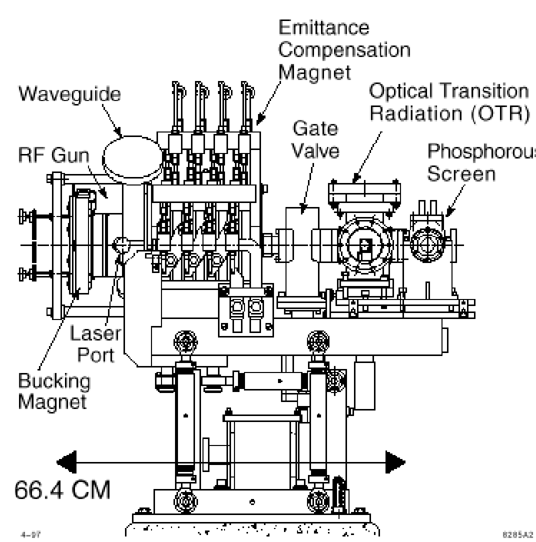


Figure 1: The ATF schematic.

2.2 The ATF system laser Performance

The photocathode RF gun laser system largely determines the stability, reliability and performance of the photocathode RF gun injector. Clean and stable environment is critical for the performance of the laser system. The performance required for the RF gun laser system (pico-second, GW) is much demanding than most manufacture can delivered, especially, long-term stability and reliability. The reliable performance of the RF gun injection requires that timing jitter is less than 0.5 ps (p-p), the energy stability better than 10 % (p-p) at UV, point stability better than 1 % (rms), and a good beam profile. To achieve those performance requirements, large effort was devoted to reduce the mechanical vibration, air turbulence and local heat build-up for the laser system. The laser oscillator timing jitter and UV energy fluctuation routinely measured to be less than 0.25ps and 10 % (p-p), respectively. Fig.2 is the laser and electron beam profiles; e-beam profile is almost rotated by 90 degree relative to the laser by the emittance compensation solenoid magnet. Non-uniformity in laser profile directly leads to the e-beam, which will cause the emittance growth.

The laser profile and QE distribution on the cathode can be measured using laser mask technique. Fig.3 is the electron beam image of a laser mask image on the BPM right after the solenoid magnet. Once electron beam image of the laser on the cathode established, the mask is removed, and e-beam distribution is the convolution of the laser profile and QE distribution on the cathode, this can be further distinguished by movement the laser on the cathode.

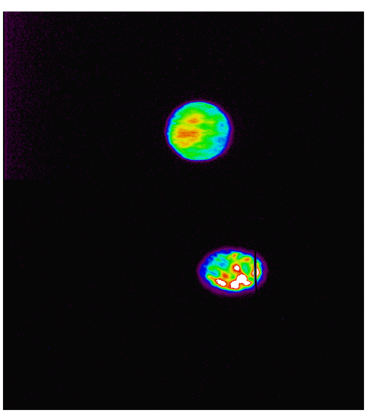
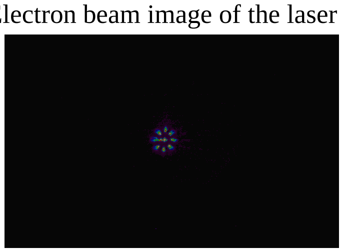


Figure 2: Laser beam (top) and its electron beam image (bottom) for a 100 pC 45 MeV beam.

2.2 QE and the Injector Performance

The QE should be characterized by both its value and uniformity over the cathode. High QE not only reduce the laser output requirements, it also gives you freedom

Figure 3: Electron beam image of the laser mask.



for laser shaping. We have tested Mg cathode with good results many years ago, the main issue is how to reliably to achieve the good QE from Mg cathode. By developing a good Mg mounting technique on the cathode, improving the RF gun vacuum and new laser cleaning technique, we now can reliable produce good QE better than 0.1% for normal operation. The normal operating vacuum of the ATF RF gun is better than $4x10^{-10}$. The laser cleaning now is based on the vacuum observation by adjusting the laser energy; the success rate for such cleaning technique is almost 100%. The best QE after the cleaning is about 0.5% (Fig.4), and QE better than 0.1% usually last more than a month if no continuous RF break down and vacuum deterioration occur.

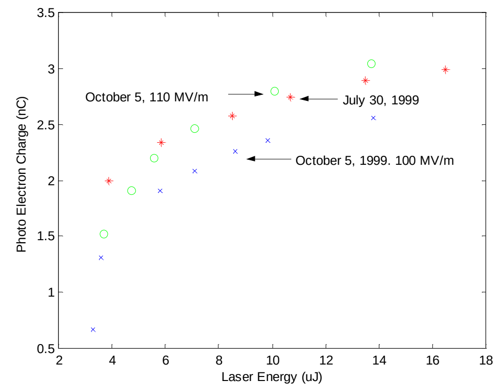


Figure 4: QE measurements.

One of the most important parameter in operating the photocathode RF gun is to determine the RF gun phase; the QE, transverse emittance and electron beam bunch length are all determined by the RF gun phase. By measuring the charge as function of the RF gun phase, the absolute phase of the RF gun can be determined. With QE variation less than 10% and good laser profile, we have be able to optimise the emittance at RF gun phase 25 ° from zero crossing for a charge 0.5 nC (Fig.5), the normalized rms emittance measured to be 1.5 mm-mrad with peak current about110 A.

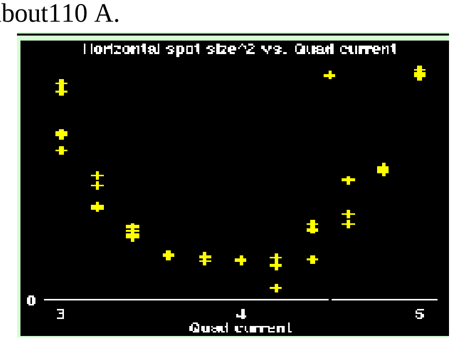


Figure 5: Quad-scan for emittance measure.

2.3 RF Kicker cavity

We have developed beam diagnostic tools at the ATF enable us to characterize beam properties in 6-D. One of the most challenge issues of the X-ray FEL is to measure the femto-seconds electron beam required. Single-pass FEL process involve electron beam micro bunching on

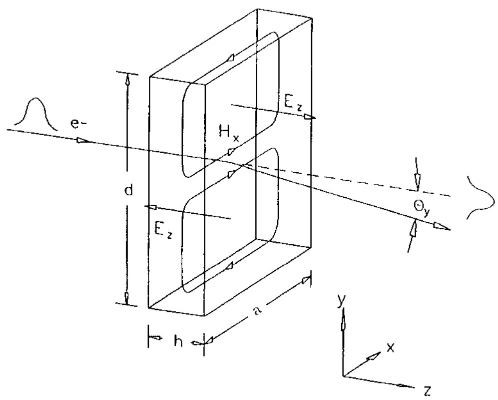


Figure 6: RF Kicker cavity.

the radiation wavelength scale, and electrons radiate coherently on the scale so called coherent length, which is on the order of thousand radiation wavelength. To fully understand single-pass FEL, the detailed information of electron beam distribution within the femto-seconds bunch is required. RF kicker cavity is the only technique could provide such knowledge for a GeV femto-seocnd electron beam (Fig.6) [3].

The principle of RF kicker cavity for bunch length measurement is exactly similar to that streak camera, which converts the time information to special information. One of the common misunderstanding about RF kicker cavity is its applicability to high energy beam, the scaling for the kicker effect is not linearly inverse proportional to the beam energy, it is inverse proportional to the square root of the beam energy because of the emittance reduces with the increase of the beam energy. One of the fundamental limitations of the streak camera, space charge effect, is absent for RF kicker cavity. Further more, RF kicker is synchronized with electron beam and self-calibration. It can be used to measure the slice emittance and longitudinal phase space. Using a 2-meter long S-band travelling RF kicker structure, 10 to 20 femto-second resolution can be achieved.

2 FEL EXPERIMENTS AND OPTICAL KLYSTRON EFFECT

The ATF is the only facility has both laser seeded and SASE FEL experiments. SASE was observed at the ATF from visible to IR using a MIT 60 cm long micro-undulator [4]. A BNL-LANL-LLNL-SLAC-UCLA collaboration is now commissioning a visible SASE FEL (VISA) at the ATF. VISA has a 4-meter long strong focusing undulator with distributed diagnostics for both electron and photon beams. By taking advantage of sensitive diagnostics tool available at the visible spectrum, VISA will be able to study the SASE physics in detail. VISA itself is also a tool for electron beam quality optimisation since it operating at relative low energy, and slight variation in either beam emittance or peak current will lead to large variation in SASE gain.

The BNL/APS HGHG experiment employed three undulators. The first one is a 10 periods 0.8-meter long modulator (modulator), the second one is a three-magnet chicane (dispersion), while the last one is the 2-meter long undulator with 3.3 cm period (radiator). HGHG experiment set up is very much similar to the optical klystron except that, radiator is operating at the harmonic of the modulator, and the length of the modulator is rather short. SASE was measured from 3 to 5.3 μm (Fig.10) in the radiator. The highest gain for single pass FEL, more than seven orders of magnitude, was measured with out power 35 MW [5].

Without seed laser, we measured SASE out at 5.3 μm as the dispersion was varied (Fig.7). A gain enhancement of a factor of ten was observed. We intend to continuous this study in the near future by varying the beam energy, or directly observe the electron beam micro bunching.

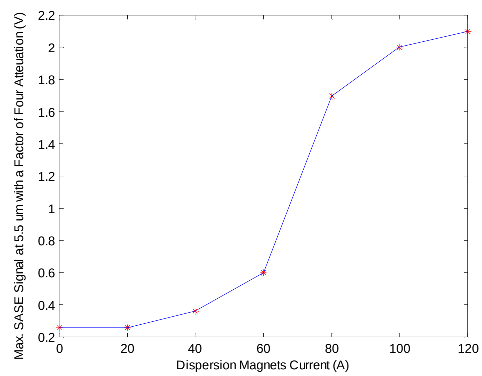


Figure 6: SASE output as function of dispersion magnet.

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