PROPOSAL FOR A PRE-BUNCHED LASER WAKEFIELD ACCELERATION EXPERIMENT AT THE BNL DUV-FEL FACILITY*

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Abstract

We propose a pre-bunched Laser Wakefield Acceleration (LWFA) experiment in a plasma channel at the BNL DUV-FEL Facility. BNL DUV-FEL facility is uniquely qualified to carry out the proposed experiment because of the high-brightness electron beam and RF synchronized TW Ti:Sapphire laser system. The DUV-FEL is a 200 MeV linac facility equipped with a photocathode RF gun injector, a 100 fs Ti:Sapphire laser system and a magnetic bunch compressor. The proposed LWFA will inject a 150 MeV, 10 fs electron bunch into a centimeters long plasma channel. Simulation and preliminary experiment showed that, high-brightness 10 fs electron bunch with 20 pC charge could be produced using the technique of longitudinal emittance compensation. The initial experiment will be performed using the existing Ti:Sapphire laser system (50mJ, 100 fs) with 30 μm spot and 4 cm channel, the maximum energy gain will be about 15 MeV. We propose to upgrade the existing SDL laser output to 500 mJ with a shorter pulse length (50 fs). For an electron beam spot size of 20 um, the expected energy gain is about 100 MeV for a 5 TW, 50 fs laser pulse.

INTRODUCTION

The ultra-high acceleration gradient and renewable acceleration structure are the major attractive features of the plasma based accelerators [1-2]. Acceleration gradient over 100 GV/ m has been observed in many labs [3-4]. The challenges now facing the laser plasma accelerator community are to produce and preserve the electron beam quality in the plasma accelerators, and to extend plasma acceleration length.

Plasma channel is being explored to extend the interaction length of the laser plasma accelerators. Though other laser plasma accelerators has demonstrated higher acceleration gradient, standard laser plasma wake field accelerator (LWFA) holds most promise for future applications because of its controllability and quality of the electron beam. Studies showed the optimized LWFA required laser pulse length ranges from 10 fs to 100fs, plasma density $10^{17} – 10^{19}$ cm^{-3} with several centimetres long plasma channel [5-6]. The quality of the electron beam to inject into such LWFA is one of the major challenges to realize GeV plasma accelerator. To reduce the energy spread due LWFA, the injected electron beam bunchlength should be much shorter than the plasma wavelength. The plasma wavelength and channel size also put the stringent requirement on the transverse emittance of the electron beam.

We propose a plasma channel LWFA experiment at the NSLS DUV-FEL facility to demonstrate the feasibility of pre-bunched beam injection and phase lock. The DUV-FEL facility is uniquely qualified for the proposed experiment because of high-brightness electron source and synchronized femto-second TW laser system. In the following sections, we first describe the BNL DUV-FEL facility and possible laser upgrade for the LWFA, followed by ultra-short (10 fs) electron beam generation using the longitudinal emittance compensation technique; then we will describe the proposed LWFA experiment. We will also discuss the phase lock (timing jitter) between the laser and injected electron beam, it is feasible to control the jitter below 10 fs.

THE BNL DUV-FEL

The BNL DUV-FEL facility is a dedicated platform for future light source technology R&D and applications. The main focus at the DUV-FEL is to develop and explore the laser seeded high gain harmonic generation (HGHG) FEL technology.

The major components of the DUV-FEL are high-brightness photocathode RF gun injection system (fig.1), a TW Ti:sapphire laser system, four sections of SLAC type travelling wave linac, a four magnets chicane bunch compressor installed in the middle of the linac, and HGHG free electron laser (fig.2).

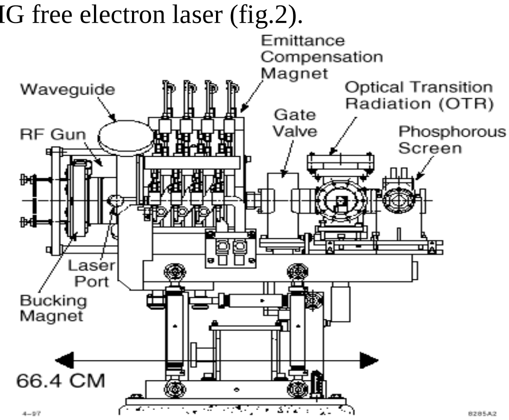

Figure 1: The BNL photoinjector.

The DUV-FEL Ti:sapphire laser system is capable of delivering 100fs 50 mJ output at the 10 Hz. It consists of a Millenium pumped Tsunami oscillator, a single grating

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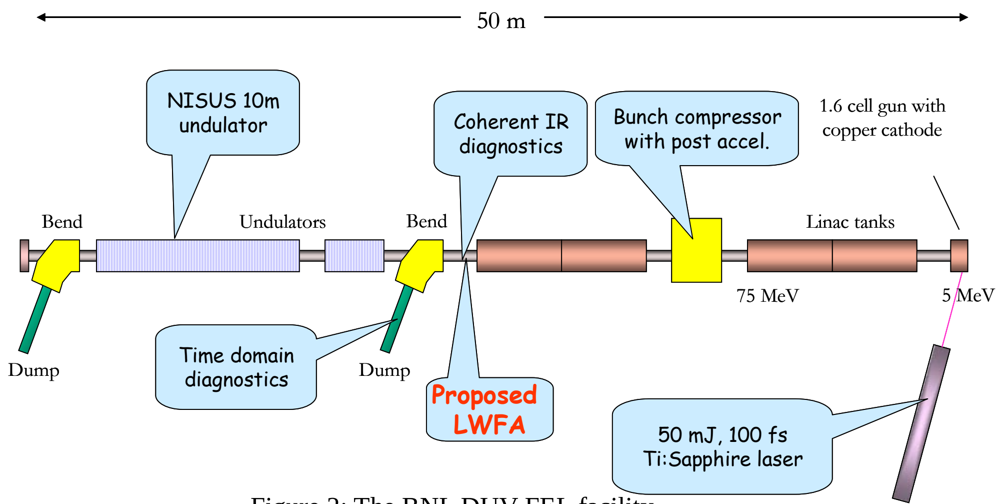

Figure 2: The BNL DUV-FEL facility

stretcher, two grating compressors. Two frequency doubled Nd:YAG pump lasers (GCR150 and GCR170), a regen and two-stages of double-pass amplifier.

The oscillator generate 80~100fs, 8nJ pulse train with 81.6 MHz. The oscillator is synchronized with the RF system of the linac. The laser pulses pass a Faraday isolator before they are sent to stretcher. After the stretcher, the pulse is 200ps, 4nJ. The pulses are then sent to the regen. In the regen, two Pockels cells are used to trap and dump the laser pulse in a repetition rate of 10Hz. The pulse energy is about 2.5 mJ after the regen. The output after the two-stages of double pass amplifier is about 70 mJ. The amplified output is divided into two beams, compressed separately with two independent compressors. One compressor's output is used to drive the photocathode RF gun, and the other is used for high gain harmonic generation (HGHG) FEL, or other laser based experiments, such as proposed LWFA here.

Initially, the proposed LWFA experiment will be performed using the present laser system. We also examine the possible laser upgrade for 100 MeV to 1 GeV LWFA experiment. The proposed upgrade will take place in two steps. First we would like to upgrade the present oscillator with shorter output pulse length, reducing the pulse length from 100 fs down to 50 fs. To minimize the cost, the oscillator pump laser and RF synchronization system will be re-used. The second part of the upgrade will increase the output energy to 500 mJ or more. A vacuum based compressor will also be added.

ULTRA-SHORT ELECTRON BEAM GENERATION

To keep the accelerated electron beam energy spread on the order of a few percent, the electron beam bunch length less than one tenth of the plasma wavelength is required. That means a the injected electron beam should have a few fs long bunch length.

Though optical laser injectors [4] have been explored for LWFA. Large energy spread and relative low energy make it challenging to preserve both transverse and longitudinal emittance before injected into the LWFA. We propose an alternative technique to generate 10 fs electron bunch at 150 MeV for 20 pC charge based on the longitudinal emittance compensation techniques [7].

Our previous study shows that, 10 fs electron bunch can be generated at 40 MeV [8] using the longitudinal emittance compensation. To minimize the space charge effect and generate proper energy chirping, the electron beam is produced using a relative long laser (8ps FWHM) in the photocathode RF gun at the near zero crossing phase (12°). Electron beam first compressed in the RF gun as it is rapidly accelerated. The beam produce by the RF gun will be continually compressed if the first section of the linac after the RF gun is operating at the off-crest (70°). The basic idea of the longitudinal emittance compensation is the bunch compression is accompanied by the acceleration simultaneously. The photoinjector (fig.1) is ideal suit for this purpose, the solenoid magnet for the transverse emittance compensation is now used to control the beam bunch lengthening due to the divergence.

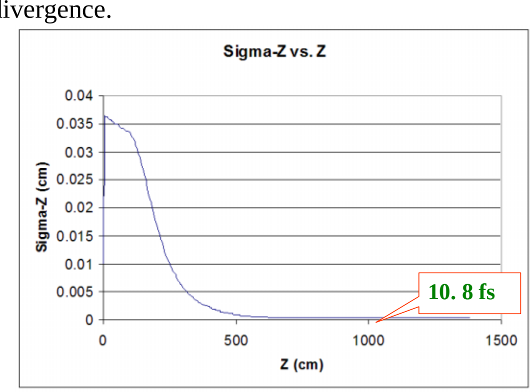

Figure 3: Electron beam bunch length as the function of the distance along the linac.

Fig.3 shows the electron beam bunch length evolution along the linac. The last three sections of the linac are used to accelerate the electron beam and minimize the energy spread. The energy spread at the 150 MeV is about 0.1%.

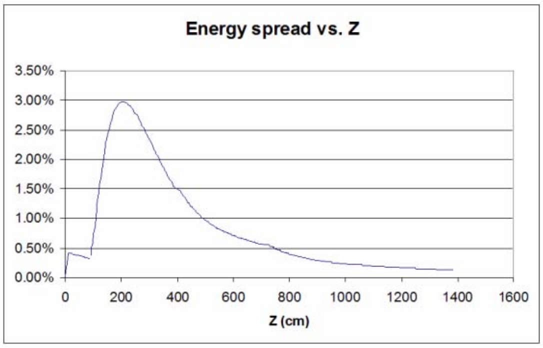

Figure 4: Electron beam energy spread as the function of the distance along the linac.

Using longitudinal emittance compensation technique will also allows us to minimize the transverse emittance because of the coupling between the transverse and longitudinal emittance. Fig.5 shows the emittance as the function of the distance along the linac, the oscillation of the emittance inside the linac is due to the lack of focusing. The final emittance ε_n <0.5 mm-mrad.

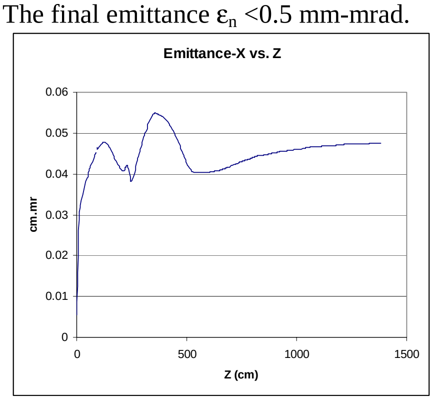

Figure 5: Transverse emittance as the function of the distance along the linac.

PRE-BUNCHED LWFA

The combination of femtosecond TW laser and ultra-short electron beam at the BNL DUV-FEL facility will make it extreme attractive to perform the pre-bunched LWFA experiment.

The proposed LWFA will use the pre-formed plasma channel developed at the NRL [9]. Table I summarize the laser and plasma channel parameter for the experiment. For 4 cm long interaction and 0.5 TW laser power, 15 MeV energy gain is expected (fig.6).

Many fundamental issue of GeV LWFA can be studied in our initial experiment, such as emittance growth, plasma stability and phase locking between the laser and electron beam.

We have recently investigated the phase locking (jitter) between the laser and electron beam [10]. Since the electron is generated by the same laser, the jitter is mainly caused by the electron beam energy fluctuation. Presently technologies existing to reduce this jitter below 10 fs.

Table 1: Summary of the parameters of LWFA.

Laser power (TW)	0.5
laser spot size radius (μm)	30
Laser pulse length (FWHM, fs)	50-100
Input electron beam Energy (MeV)	150
Electron Beam Bunch length (rms,fs)	10
Channel radius (μm)	60
Plasma density on axis (1/cm^3)	8x10^{17}
Rayleigh length (cm)	0.35
Interaction length (cm)	4
Maximum Energy gain (MeV)	15

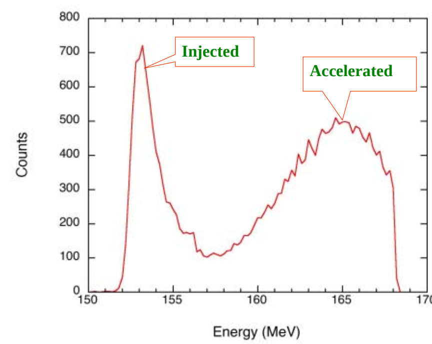

Figure 6: Electron beam energy spectrum before and after the LWFA.

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