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Informal Report

Atto-Second Electron Beams Generation and Characterization Experiment at the Accelerator Test Facility

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ABSTRACT

We are proposing an Atto-second electron beam generation and diagnostics experiment at the Brookhaven Accelerator Test facility (ATF) using 1 μm Inverse Free Electron Laser (IFEL). The proposed experiment will be carried out by an BNL/LBNL collaboration, and it will be installed at the ATF beam line II.

The proposed experiment will employ a one-meter long undulator with 1.8 cm period (VISA undulator). The electron beam energy will be 63 MeV with emittance less than 2 mm-mrad and energy spread less than 0.05%. The ATF photocathode injector driving laser will be used for energy modulation by Inverse Free Electron Laser (IFEL). With 10 MW laser peak power, about 2 % total energy modulation is expected. The energy modulated electron beam will be further bunched through either a drift space or a three magnet chicane into atto-second electron bunches. The attosecond electron beam bunches will be analyzed using the coherent transition radiation (CTR).

Introduction

Ultra-fast science is an important new research frontier that is driving the development of novel sources for generation of extremely short x-ray and electron pulses. Recent advances in femtosecond lasers have stimulated development of femtosecond x-ray sources that allow the study of matter at the time scale shorter than period of oscillations of atoms in molecules, ~100 fs. The next breakthrough would be a source of electron pulses comparable with atomic periods ω^{-1} ~100 attosecond (10^{-16}s), where ω is a transition frequency between atomic levels. This will open qualitatively new class of phenomena based on the interaction of atomic electrons in the medium with a *collective electric field* of electron pulses and not with their individual electrons. For example, one can expect phase synchronized excitation of medium followed by its relaxation with a radiation of a single-cycled optical pulse, excitation of entanglement states in the medium of atoms with few valence electrons, and possibly other new phenomena, yet to be identified. The wave function of bound electrons, following an energetic excitation such as ionization or creation of an inner-shell vacancy, tends to evolve on attosecond time scale.

In this report we propose obtaining of a ~ 300 attosecond ($3\text{x}10^{-16}$ s) (FWHM) electron microbunches containing ~10^6 electrons from a picoseconds long electron bunch. It can be either a sequence of ~ 10^3 identical microbunches separated by ~1 micron distance. The collective electric field of the attosecond electron bunch is a truly sub-cycle, unipolar pulse that can be used in the experiments. The attosecond electron bunches can also be used for generation of attosecond pulses of x-rays with several keV photon energy, thus augmenting the extreme-ultraviolet attosecond radiation produced in the process of creation of high-order harmonic of femtosecond laser radiation [1]. The attosecond electron bunches can also be used as injector for high gradient laser accelerators [2].

Analysis of Atto-second Electron bunches Generation

Femto-second electron beam micro-bunches produced by the ten micron Inverse Free Electron Laser (IFEL) have been successfully demonstrated at the ATF [3-5]. In those experiments, the electron beam was first energy modulated in an undulator by the light beam from CO_2 laser. Then, the energy modulation was converted into spatial modulation (bunching) either through magnetic chicane compression or ballistic compression in a drift space.

In this application we propose to further extend this technique and build a one-micron IFEL employing a laser with one-micron wavelength and a high quality electron beam from ATF. This will result in obtaining attosecond electron bunches.

Here are some details of the facility and planed operation. The electron beam is produced in a 4.5 MeV photocathode gun injector with emittance less than 2 mm-mrad. The energy spread of the electron beam is about 25 KeV for a peak current of 100 A, and pulse length of 2.5 ps. The electrons are then accelerated to the energy E_b=63 MeV in a linear accelerator and are injected into a 1 m long VISA undulator with the undulator period λ_u=18 mm. The light pulse from the Nd-YAG laser with the wavelength λ=1.06 micron is also sent into the undulator and co-propagates in the undulator together with the electron bunch. The undulator parameter $K=e\,B\,\lambda_u/2\pi\, mc^2$ =1.26 (where e is the electron charge, B is the undulator peak magnetic field and mc^2 is the electron rest energy), the electron beam energy is chosen to satisfy a condition of IFEL operation:

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right) \qquad (1)$$

where $\gamma=E_b/mc^2$ is the relativistic factor

Interaction of electrons with the light field at this condition leads to the energy modulation of electrons along the electron bunch. The amplitude of this energy modulation can be estimated using the following expression:

$$(\Delta g)^2 = 32p\, M \frac{P}{P_0} x [(J_0(x/2) - J_1(x/2))]^2 \qquad (2)$$

where M is the total number of the undulator periods, P is the laser peak power, $x = (K^2/2)/(1+ K^2/2)$, J_0 and J_1 are Bessel functions of zero and first order, and $P_0 = I_A\, mc^2/e = 8.7x10^9$ W, where $I_A = 17\ kA$ is the Alfen current and e is the electron charge. For a laser power $P=10\,MW$, $K=1.26$ and $M=55$, Eq.2 yields $E= 0.7\,MeV$ what is almost 30 times bigger than the energy spread of electrons.

Figure 1 shows a result of the computer simulation of energy modulation performed with code GINGER [6] for above defined parameters. In this simulation we assume that the laser beam is focused into the center of the undulator with Rayleigh length of 25 cm. In Figure 1 we actually show only a small part of the electron bunch extended over ~ 10 fs. Electron energy modulation occurred all over the entire electron bunch is practically identical to what is shown in Figure 1.

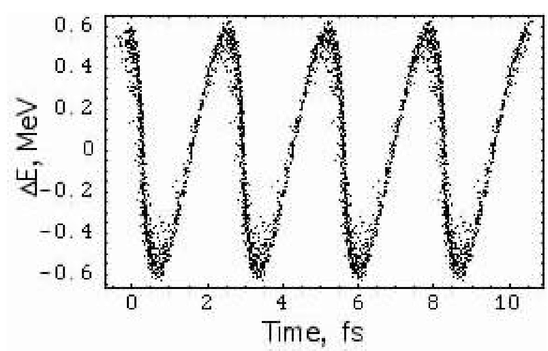

Figure 1. Electron energy modulation at the exit of the undulator. Only a small part of the electron bunch is actually shown.

A correlation between longitudinal positions of electrons (time axes in Figure 1) and their energy clearly dominates the beam energy spread. This can be used for compression (bunching) of electrons using energy-dependent pathlength variations of electron trajectories. Since relative longitudinal displacements of electrons in the process of compression should be less than 1 micron, ballistic compression in a drift space appears to be the most attractive. Compression produces a "train" of electron microbunches separated by one optical wavelength. Figure 2a shows the modulation of the electron peak current after compression that takes place just about 80 cm behind the undulator. As in Figure 1 we see here only a tiny part of the electron bunch. Small adjustments of the magnitude of the compression can be made by adjustment of the laser peak power. Figure 2b shows a single peak taken from Figure 2a.

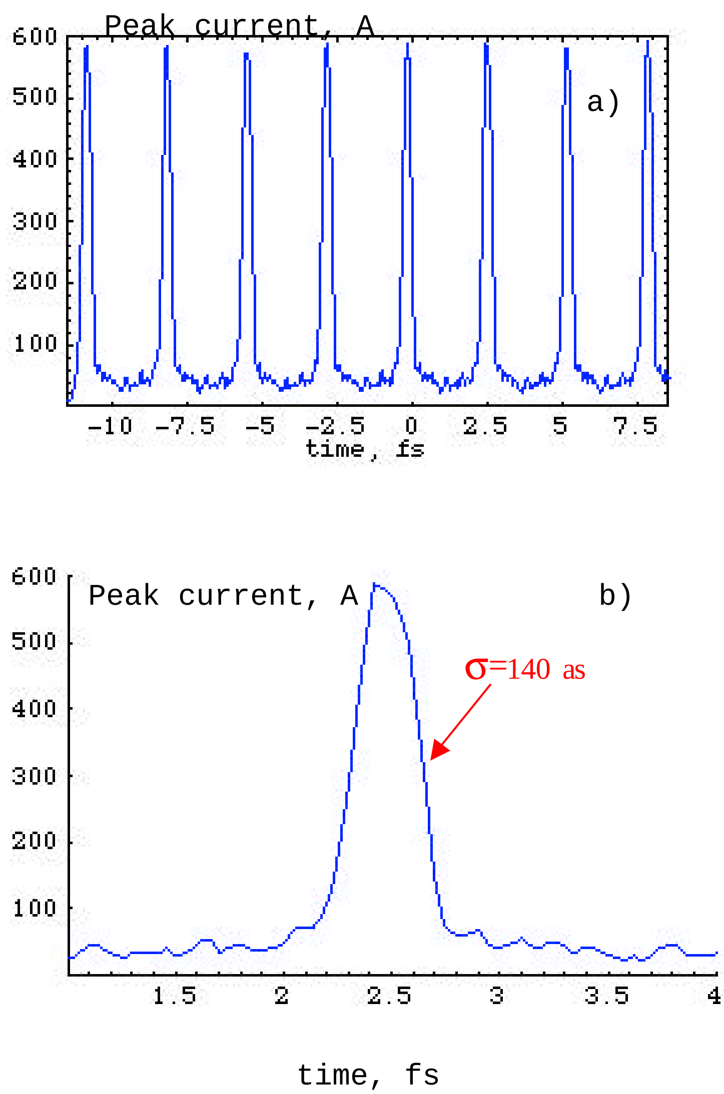

Figure 2. The electron beam current after bunch compression. Only a small part of the electron bunch is actually shown.

Atto-second Electron beam diagnostics using Coherent transition radiation

We propose to measure attosecond electron pulses using the transition radiation of electrons passing through the foil. Remarkably electron will radiate coherently at wavelength down to approximately 0.1 um because of the extremely short electron microbunches. Therefore all measurements can be performed in the visible part of spectra where lots of instruments are easily available.

The theory of CTR and its use for longitudinal microbunching measurements of electron beams has been extensively studied [7-8]. The most common model of this process describes transition radiation (TR) — radiation emitted when an electron propagates from one medium to another, and in our case from vacuum into a perfect conductor — approximately as an annihilation (or creation) of an electron with its image charge at the foil/vacuum interface.

Assuming the charge distribution of an electron beam after the IFEL and bunch compressor is described by,

$$r(x, y, z) = \frac{eN \exp\left(-\frac{x^2}{2s_x^2} - \frac{y^2}{2s_y^2} - \frac{z^2}{2s_z^2}\right)}{(2p)^{3/2} s_x s_y s_z}\left[1 + \sum_{n=1}^{\infty} b_n \cos(nk_r z)\right]. \tag{3}$$

where N is the number of electrons in the bunch, $s_{x,y,z}$ are the transverse (x,y) and longitudinal (z) beams sizes, respectively, k_r is the input laser wavenumber from Eq. 1, e is the charge of an electron, n is the harmonic number, and b_n is the microbunching amplitude at the harmonic n of the input laser wavelength.

Assuming the periodicity of the bunching in the beam's rest frame is small compared to the transverse beam size, $k_r s_{x,y}/g >> 1$, the CTR energy emitted at a given harmonic may be expressed as:

$$U_n = \frac{N^2 e^2 b_n^2}{8\sqrt{\pi}\sigma_x \sigma_y \sigma_z}\left(\frac{\gamma}{nk_r}\right)^4\left(\frac{1}{\sigma_x^2}+\frac{1}{\sigma_y^2}\right). \qquad (4)$$

The bunching factor b_n can be estimated using above formula once the CTR energy at the each harmonic and the electron beam size measured.

Atto-second electron beam production and diagnostics set up

The proposed atto-second experiment will take advantage of the existing facility and equipments at the ATF. We are proposing the experiment to be installed at the ATF experimental beam line II, which should be compatible with existing experiments.

The ATF Nd:YAG laser system for photocathode RF gun application will be also used for the IFEL modulation. This laser system is capable of producing two pulses with separation of multiple of 12.5ns. The laser energy available is about 5mJ with pulse length 15 ps (FWHM), which is much more the experiment required. At present time, laser transport and delay lines to the ATF experiment hall are all available. New optical transport and matching to the proposed experiment need to be designed and constructed.

Fig.3 One meter long VISA undulator section.

The undulator we are planning to use is one of the extras sections for the VISA experiment built by SSRL for NSLS [9]. We have the permission from the NSLS management to use this undulator (Fig.3). Table 1 summarize the major parameters of the undulator.

Table 1: Undulator paramenters.

Period length	18 mm
Number of periods	55 segment
Magnetic gap g	6.0 mm
Maximum B field B max	0.75 T
B field error D B _ max	0.4%
Undulator parameter K	1.26

The chicane magnet from the ATF HGHG experiment (Fig.4) will also be available for the attoseocnd experiment. The chicane will give us another handle to optimize the bunch length for a fixed energy modulation.

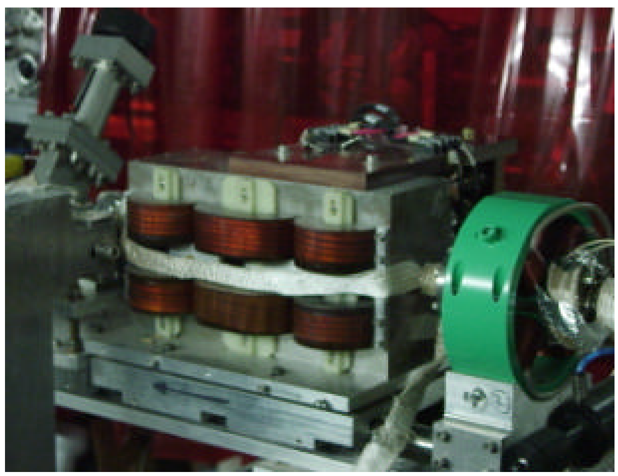

Fig. 4 Chicane magnet at the ATF.

Based on the experience of the earlier ATF CTR experiment [3], a three-positions CTR detector was built and tested in the VISA micro-bunching experiment (Fig.5). The first position is a aperture so electron beam and alignment laser can pass three. The second position consist a 45 degree Copper mirror, it is mainly used for alignment purpose. The third position will be used for the CTR experiment. It consist a 12.5 um foil followed by a 45 degree mirror, this mirror is adjust so it parallel with the second position mirror. The foil is perpendicular to the electron beam and will block the input laser completely. Both jole-meter and photo diode can be used for the CTR detection from 1 µm to UV.

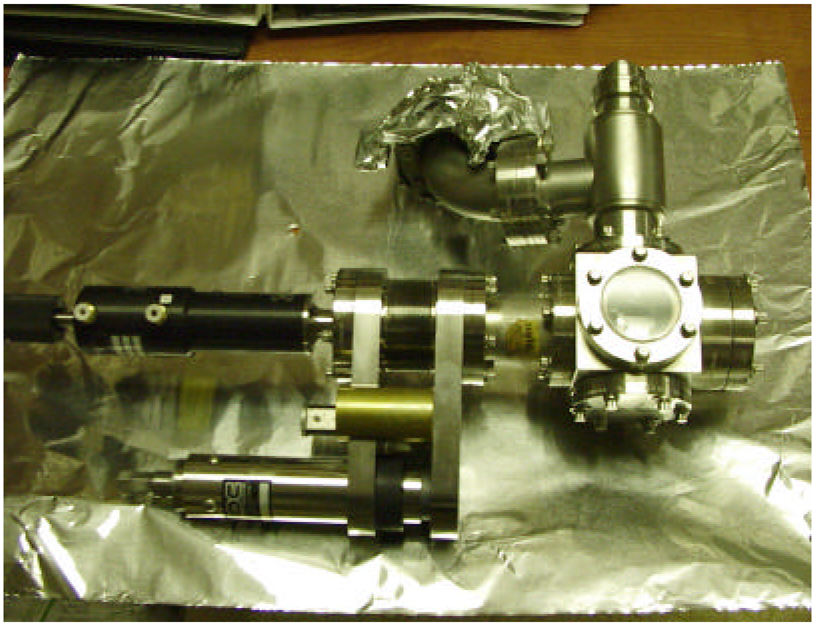

Fig.7 Three-position CTR detector.

Other Potential Applications

In the last section of this proposal, we will briefly outline other potential experiments and physics we can carry out using the experiment set-up described here.

1. **Beam diagnostics for micro-bunches beam:** on e of the main advantage of using 1 μm IFEL to produce microbunched beam is the stability comparing to SASE or other scheme. The stability of the ATF 1μ YAG laser system has a energy stability better than 1% (rms), and timing jitter less than 250 fs(rms). Those number is at least one order of magnitude better than CO_2 laser and SASE FEL. This will provide unique opportunity for developing beam diagnostics for micro-bunch beam. Presently, only coherent transition radiation (CTR) .is used for micro-bunch beam diagnostics [3,7-8], but CTR signal from harmonic is strongly suppressed In order to have complete longitudinal information of the electron beam, harmonic information is critical. We are investigating possibility of either using a second stage of IFEL, or fluctuation interferometer techniques for atto-seconds micro-bunch diagnostics.
2. **Harmonic IFEL:** One of the most important applications for IFEL is electron beam micro-bunching, this has been demonstrated in both HGHG [4] and Stella [5] experiments. We know from RF linac, a good buncher should contain fundamental and third harmonic. For a planar undulator, both fundamental and third harmonic will strongly couple to electron beam if undulator parameters K is larger than one. Harmonic IFEL will make electron beam micro-bunching much more efficient [10]. For the proposed 1μm IFEL experiment with VISA

undulator (K=1.26), it will make it possible for the first time to experimentally demonstrate harmonic IFEL. Further more, we can also carry out study on second harmonic IFEL to investigate new interaction mechanism proposed by Ming Xie [11].

3. **Ultra-high Harmonic Generation:** If micro-bunched beam contains rich harmonic content, and it could be used to produce copious UV and X-ray radiation. The highest harmonic can produce is determined by the ratio of the energy modulation to electron beam's inherent energy spread. Since ATF electron beam has a energy about 0.1%, and energy modulation can be reached as high as 5%, we expected 50^{th} harmonic should observable.

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