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Abstract. A microbunch diagnostic system is built at the Accelerator Test Facility (ATF) of Brookhaven National Laboratory for monitoring microbunches (10-fs bunch length) produced by the Inverse Free Electron Laser accelerator in Staged Electron Laser Acceleration experiment. It is similar to one already demonstrated at the ATF. With greatly improved beam optics conditions higher order harmonic coherent transition radiation will be measurable to determine the microbunch length and shape.

1 Introduction

With the success of the Inverse Cherenkov Acceleration (ICA) experiment[1] at the Acceleration Test Facility (ATF) of Brookhaven National Laboratory (BNL), a proposed 100-MeV acceleration demonstration experiment[2] is the next step towards developing the ICA scheme into a practical technique that may eventually lead to a high gradient linear accelerator. Therefore, an important new development in the ICA program is the joining of the ICA experiment with the BNL Inverse Free Electron Laser (IFEL) experiment[3, 4, 5, 6]. Since the IFEL operates in vacuum environment, it is possible to provide a high quality, pre-bunched e^- beam for the next acceleration stage. Using the IFEL as the prebuncher for the ICA in the combined experiment, called Staged Electron Laser Acceleration (STELLA)[4], an

important challenge is characterizing the microbunched e^- beam entering the ICA interaction region.

Over the past year UCLA-BNL group has studied microbunching process using the IFEL accelerator[7] as a microbunch generator at the ATF. In the microbunching experiment the e^- beam passing through the IFEL wiggler and interacting with the CO_2 laser beam in the existence of the magnetic field leaves the interaction region with a distinct velocity distribution pattern which, propagated over a certain distance in a free space, results in self-bunching of the e^- beam. The distance (optimum bunching distance) resulting in a minimum longitudinal bunch length is controllable and characterized by input laser power. The experimental results show that the microbunch length is on a scale of several microns ($\sim 2 \mu\text{m}$)[8].

In the STELLA experiment electron beam optics elements located downstream of the IFEL wiggler have been greatly improved. A tightly focused electron beam with good profile geometry is achievable. A very intense coherent transition radiation (CTR) and its higher order harmonics will be measured to determine the microbunch length and shape.

2 Coherent Transition Radiation of Multiple Bunches

Coherent transition radiation is a collective effect of transition radiation produced by a large ensemble of particles being in phase with each other. The total number of photon radiated is highly enhanced when the observation wavelength is comparable to or greater than the bunch length. The total radiation distribution becomes[9]

$$\frac{d^2U}{d\omega d\Omega} = N [1 + N - 1] F(\omega, \theta) \frac{d^2u}{d\omega d\Omega}, \quad (1)$$

where

$$F(\omega, \theta) = |f(\omega, \theta)|^2 = \left| \int f(r, z) \exp(-i\vec{k} \cdot \vec{r}) d^3x \right|^2 \quad (2)$$

is a bunching factor, containing the electron distribution information. It transfers the electron distribution from a time domain to a frequency domain. The coherent effect scales like N^2 compare to the incoherent part, which scales linearly with the electron number, N . k is the radiation wavenumber.

In multiple bunches the total coherent photon intensity depends on particle distribution in each bunch and number of bunches. In general the coherent effect contributed by transverse distribution of electrons is ignored while the transverse beam size is much smaller than its longitudinal length. However, if the bunch length (in

several micron level) is shorter than or comparable with its transverse dimension, the electron phase difference caused by transverse distribution will reduce the CTR intensity. Furthermore, if a thin foil is inserted into the e^- beam path and is 45° to the e^- beam direction, the individual electrons distributed at the surface of the foil will have an additional phase difference comparing to normal incidence. This additional phase difference will reduce the CTR intensity as well. Thus, these factors should be considered when one deals with microbunch coherent transition radiation.

For a two-foil configuration (Figure 1), the first foil is perpendicular to the electron beam direction, contributing a forward CTR, and the second foil is 45° to the electron beam direction, contributing a backward CTR. The individual electrons distributed at the second foil will have an additional phase difference $\varphi(x, L)$ relative to the electrons at the first foil. The phase difference is given by

$$F(\omega, \theta) = \left| \iiint_{x, y, z} g(r) h(z) \exp(-ik \cdot \vec{r}) [1 + \exp(-i\varphi_1 - i\varphi_2)] d^3x \right|^2$$

$$\varphi_1 = \frac{ikx}{\beta}(1 - \beta \cos \theta) \quad \varphi_2 = \frac{ikL}{\beta}(1 - \beta \cos \theta)$$

Figure 1: Two-foil configuration. First one generates a forward CTR and redirected by the second foil, the second foil generates a backward CTR.

$$\begin{aligned} \varphi(x, L) &= \varphi_1(x) + \varphi_2(L) \\ &= \frac{kx}{\beta}(1 - \beta \cos \theta) + \frac{kL}{\beta}(1 - \beta \cos \theta), \end{aligned} \quad (3)$$

where L is the separated distance between the two foils. Following the same treatment for a single foil [10, 11], the two-foil CTR photon angular distribution is expressed as follow:

$$\begin{aligned} \frac{dN_{ph}}{d\theta} &\approx \frac{\alpha\beta^2}{8\sqrt{\pi^3}} \left(\frac{k_r\sigma_z}{\pi} \right) \left(\pi \frac{Nb_n}{k_r\sigma_z} \right)^2 \left(\frac{1}{n} \right) \frac{\sin^3 \theta}{(1 - \beta \cos \theta)^2} \times \\ &\quad \left\{ \exp \left[- \left(\frac{nk_r\sigma_r}{\beta} \right)^2 (\beta \sin \theta - \beta \cos \theta + 1)^2 \right] + \right. \\ &\quad \exp \left[- (nk_r\sigma_r \sin \theta)^2 \right] + \\ &\quad \left. 2 \exp \left[- \frac{1}{2} \left(\frac{nk_r\sigma_r}{\beta} \right)^2 (\beta \sin \theta - \beta \cos \theta + 1)^2 \right] \right\} \times \end{aligned}$$

$$\begin{aligned}
& \exp \left[-\frac{1}{2} (nk_r \sigma_r \sin \theta)^2 \right] \times \\
& \exp \left[-\left(\frac{L}{2\beta\sigma_z} \right)^2 (\beta \cos \theta - 1)^2 \right] \times \\
& \cos \left[\left(\frac{nk_r L}{\beta} \right) (\beta \cos \theta - 1) \right] \Bigg\}. \tag{4}
\end{aligned}$$

From the above equation we know that the total CTR intensity is produced by two individual CTR sources plus their interference at far region. The contribution of interference depends on the separation distance (L) of two foils.

The physical meaning of Eq.(4) is quite clear. In the first row of the equation the second term represents the length ($2\sigma_z$) of the macrobunch in unit of the modulation wavelength λ_r . The third term is the square of the total number of electrons which contribute the n th harmonic wavelength CTR within a single microbunch (the laser modulation 'chops' the macrobunch into a number of microbunches). The fifth term describes the contribution of single-electron transition radiation and n is a harmonic number. The second row represents the contribution from the transverse electron distribution of the 45° foil, the third row represents from the 90° foil, the rest part is contributed by the CTR interference of two foils. The CTR intensity of higher harmonic wavelengths will be significantly weaker than that of the fundamental wavelength. By Fourier analysis of the CTR spectrum, the coefficient b_n will be found. If the microbunch length is very short, the contribution from the higher harmonic components can be detectable.

3 Improved Beam Optics Conditions

In the microbunching experiment[8] there were no electron beam optics elements between the exit of the wiggler and the vacuum chamber which contains CTR target. The electron beam position and profile at the target surface were very difficult to optimize. These resulted in a relative small signal/noise (background) ratio. In the STELLA beamline has been refurbished and number of new beam optics elements have been added. A plan view drawing of the beamline is shown in Figure 2. The electron and CO_2 laser beams pass through the IFEL wiggler from right and travel towards the ICA cell. In the ICA cell the energy modulated electron beam will form microbunches and meet with the second CO_2 beam for high gradient acceleration. The ICA cell (center) is separated from the wiggler exit by 220cm. The CTR chamber attaches to the ICA cell entrance. The distance between target in the chamber to the wiggler exit is about 190cm. In between there is a quadrupole triplet (triplet #4)

Figure 2: Plan view drawing of the beamline for the STELLA experiment at the ATF.

to refocus the microbunched beam and two steering magnets in front and behind the triplet to adjust the beam position shift. The expected transverse beam diameter at the target surface is between $50\text{-}100\mu\text{m}$. In the previous microbunching experiment the minimum beam size was larger than 1mm . This tremendous improvement of the beam size and geometry will result in a great increase of CTR intensity. Thus, we expect that higher order harmonic wavelength CTR can be measured using our exist liquid Nitrogen cooled Indium Antimonide (InSb) detector.

4 System Layout

The diagnostic system consists of a transition radiation generator (CTR target), an optical transport line, a CCD camera and an INFRARED (IR) detector. The components are assembled on a breadboard above the beamline. A strip-line detector is placed the upstream of the chamber to provide the e^- beam charge information. A schematic diagram drawing is shown in Figure 3. The basic features are similar to the previous one[8], except that the whole system including the target chamber is fixed. Because it is experimentally known that the optimum bunching distance is controllable and characterized by input laser power[8].

The CTR light is transported from the chamber through a ZnSe window and an IR lens, collected by a gold coated parabolic mirror and focused onto the IR detector. The IR lens helps reduce the CTR divergent angle, especially, for a relative large beam spot size. The parabolic mirror is remote-controlled and is able to rotate in

Figure 3: Schematic of the CTR diagnostic setup for the STELLA experiment.

two axes (α , β) to bring the CTR to the IR detector. Different wavelength bandwidth pass filters or short wavelength pass filters can be placed in front of the detector to help measure either different single harmonic wavelength CTRs or total CTR up to the cut-off wavelength.

The detector active area is about 1.00 mm in diameter and its sensitive wavelength region is in 1.1 to 5.5 μm . Its quantum efficiency at 4.52 μm is 74.74%. Also, the sensitivity has been measured at the ATF using different wavelength diode lasers. The measured sensitivities are 5.7×10^4 photon and 4.8×10^4 photon at wavelength 1.55 μm and 1.33 μm , respectively. The detector surface is located in the parabolic mirror focal plane and well shielded by lead bricks to reduce x-ray noise level. A HeNe laser is used to align the optics and to monitor parabolic mirror rotation trace.

5 CTR Target Chamber

The CTR target is mounted in a 6-way cross which serves as a small vacuum chamber. The chamber consists of two actuators placed in horizontal: one holds the CTR target, other holds a phosphor screen for electron and laser beam alignment. The target and phosphor screen can be inserted and retracted by remote-controlled actuators. But only one is allowed to present in the beam path at the same time or none of them presents in the beam path if not in use. Both CTR and phosphor emissions are reflected out vertically through the same ZnSe window. Figure 4 shows the CTR

target configuration only. The target is made up of a thin copper foil (2.5mil) and a gold-coated copper mirror in 45° behind it, both mounted on the same actuator. A metal cone is placed inside beam pipe to interface with the foil frame through an

Figure 4: A CTR chamber. (a) A foil and a mirror, mounted on the same holder. (b) A cone, used inside of beam pipe to interface with (a). (c) A side view of CTR chamber with positioned target. e^- beam enters from right. (d) Bottom view of positioned target in the chamber. (e) the size of a thin copper foil.

O-ring which isolates the chamber from the beam pipe when the target is inserted.

This particular target design is based on the following facts. Both the residual CO₂ laser light (usually very strong) and the e^- beam will reach the target at the same time after they interact in the wiggler. In addition, while the CO₂ laser passes through the wiggler (Sapphire waveguide) it loses about 50% of its power in the wiggler and results in a very strong and broad bandwidth radiation. Such a broad bandwidth radiation will overwhelm the CTR if it leaves the chamber entering the detector. Thus, the foil before the mirror prevents this extraneous radiation from entering the CTR detector. It seals against the cone to ensure that no radiation makes it around the foil.

The 45° mirror is used to direct the forward transition radiation away from the e^- beam and out of the chamber through the ZnSe window to the detector. However, the passed e^- beam hits the 45° mirror and generates a backward CTR. The backward CTR is directed by the same mirror and following the same path through the ZnSe window to the outside of the chamber. The two CTRs will interfere in far region and enhance the detected CTR intensity. The foil, besides to use in measuring the CTR, has another use in measuring the e^- beam profile by focusing a CCD camera on the foil surface to observe optical transition radiation (OTR). Since the foil diameter is 1mm, the e^- beam spot size generated by OTR is easy to calculated according to the calibration of foil image.

6 Goals

The improved beamline optics configuration will provide a great help with optimizing the microbunched electron beam profile at the CTR target surface. As a use of microbunch monitor in the STELLA experiment and a continuation of the microbunch study, there are a number of goals could be achieved. The previous experimental results will be confirmed and a short wavelength (less than 2.5 μm) CTR intensity quadratic dependency curve on electron beam charge (eN) will be given. An inverse Fourier analysis of the harmonic components yields information about the microbunch characteristics. Obtaining this type of information requires sensing the magnitude of as many higher harmonics as possible.

The signal strength tends to decrease with harmonic number. Hence, detecting higher harmonics implies the need for a strong CTR signal. This signal strength is dependent on many factors, such as the degree of microbunching, the e^- -beam current, and the diameter of the e^- -beam on the CTR target. This latter factor is an important one since the photon yield inverses to the square of rms beam radius exponentially. We have utilized the TRANSPORT code to systematically calculate

the electron beam size (transverse) for the use of the microbunching study with the aid of new beam optics between the IFEL wiggler and the ICA cell. Based on the simulation results it is possible to expect the beam size (σ) less than 50 μm at the ICA cell entrance (CTR chamber location). This could lead to the CTR intensity increase of 3-4 magnitudes comparing to previous experimental conditions. Higher harmonic wavelength CTR should be measurable using the exist InSb detector. The microbunch length and shape will be studied experimentally.

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