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Beam dynamics analysis of femtosecond microbunches produced by the staged electron laser acceleration experiment

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Preservation of the femtosecond (fs) microbunches, created during laser acceleration, is a crucial step to enable staging of the laser acceleration process. This paper focuses on the optimization of the beam dynamics of fs microbunches transported through the staged electron laser acceleration (STELLA-II) experiment being carried out at the Brookhaven National Laboratory Accelerator Test Facility. STELLA-II consists of an inverse free electron laser (IFEL) untapered undulator, which acts as an electron beam energy modulator; a magnetic chicane, which acts as a buncher; a second IFEL tapered undulator, which acts as an accelerator; and a dipole, which serves as an energy spectrometer. When the energy-modulated macrobunch traverses through the chicane and a short drift space, microbunches of order fs in duration (i.e., ~3 fs FWHM) are formed. The 3-fs microbunches are accelerated by interacting with a high-power CO_2 laser beam in the following tapered undulator. These extremely short microbunches may experience significant space charge and coherent synchrotron radiation effects when traversing the STELLA-II transport line. These effects are analyzed and the safe operating conditions are determined. With less than 0.5-pC microbunch charge, both microbunch debunching and emittance growth are negligible, and the energy-spread increase is less than 5%. These results are also useful for the laser electron acceleration project at SLAC and in possible future programs where the fs microbunches are employed for other purposes.

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I. APPLICATION OF FS MICROBUNCHES IN ELECTRON LASER ACCELERATION

Laser particle acceleration concepts resemble radio-frequency (rf) linear accelerators in that a traveling wave is set up to move synchronously with the particles. Efficient acceleration for both laser and rf acceleration requires that the bunch length be much smaller than the driving wave's wavelength or else that the particles are organized into short-length bunches separated by the driving wavelength. However, laser particle acceleration differs from rf systems in that the wavelength is at laser optical frequencies and is of order microns long rather than centimeters as in rf-based accelerators. Microbunch lengths of order microns is essential for advanced acceleration concepts [1,2] to enable trapping and accelerating the microbunches through multiple laser accelerator stages. Thus, one of the crucial steps is to preserve the femtosecond (fs) microbunch throughout its transport during the laser acceleration process.

Our analysis of fs beam dynamics is based upon the staged electron laser acceleration (STELLA-II) experiment [1,3,4] being carried out at the Brookhaven National Laboratory (BNL) Accelerator Test Facility (ATF). The STELLA-II transport line consists of an inverse free electron laser (IFEL) using an untapered undulator (IFEL1), a magnetic chicane, a second IFEL using a tapered undulator (IFEL2), and an electron beam (*e*-beam) energy spectrometer, as schematically drawn in Fig. 1. IFEL1 modulates the *e*-beam energy using a CO_2 laser beam ($\lambda = 10.6$ μm). The electrons experience uniform CO_2 laser intensity because the 3-ps *e*-beam macropulse is much shorter than the 180-ps CO_2 laser pulse. Since the laser wave oscillates with a period of 30 fs (i.e., 10.6-mm wavelength), the electrons experience varying amplitude and alternating polarity of the sinusoidal laser field, thereby resulting in modulation of the *e*-beam energy. Traveling through the magnetic chicane, the energy-modulated electrons traverse different path lengths depending on their energy. Higher energy electrons group together with the lower energy electrons and form a train of ~85 3-fs microbunches [5] within the 3-ps macropulse envelope. In other words, the microbunch charge is ~0.5 pC corresponding to 0.1 nC of macrobunch charge (note that ~50% of the particles are not trapped in the microbunches). These microbunches enter the tapered IFEL2 undulator and obtain a significant energy gain by interacting with a high-power (> 10 GW) CO_2 laser beam. This energy gain is measured using an energy spectrometer, located downstream of IFEL2, consisting of a dipole where the energy dispersion is in the horizontal direction on a beam profile monitor.

The fs microbunches may experience significant space charge and coherent synchrotron radiation (CSR) effects while traversing the various bends within the STELLA-II transport line caused by magnetic elements such as the chicane and dipole. Understanding how space charge and CSR affect the fs microbunches is important because (i) these effects can directly affect the acceleration

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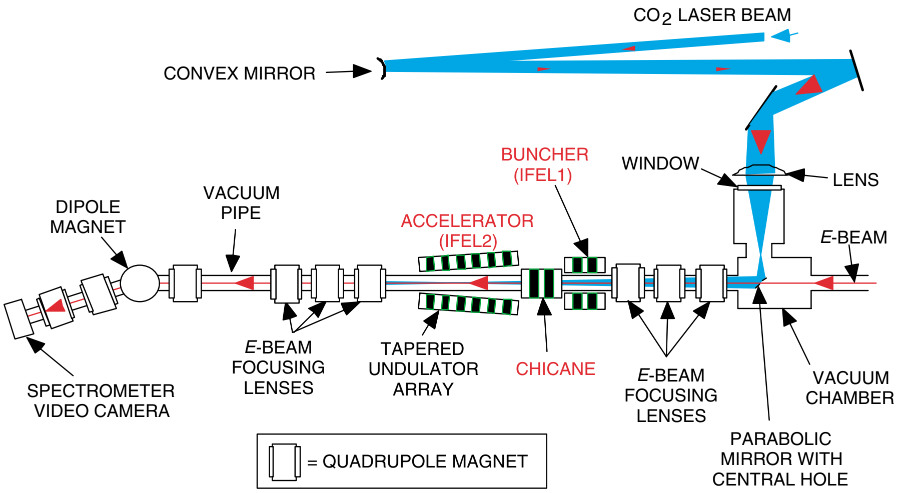

FIG. 1. (Color) Schematic layout of the STELLA-II experiment at the BNL ATF.

efficiency, and (ii) these effects will mix with the net energy gain measured in terms of horizontal beam size thereby possibly altering the energy spectrum.

In this paper, space charge and CSR effects of the fs microbunches traveling through the STELLA-II experiment are studied using analytical calculations and simulations. A safe beam condition is presented that avoids these detrimental effects. These results are also useful for other laser acceleration experiments, e.g., the laser electron acceleration project being carried out at SLAC [2] and possible future experiments in which the fs microbunches are used for other purposes.

II. SPACE CHARGE

Space charge in a beam drives cold plasma oscillations at the plasma frequency, which is determined by the beam density, the relativistic electron inertia, and the elongation of the beam. If the external offsetting forces are significant, space charge forces may be overcome. In the two IFELs of the STELLA-II experiment, space charge effects are negligible because the traveling electromagnetic wave, which modulates the energy of the electrons, tends to overpower the space charge forces on the electrons. If the external offsetting forces are negligible, inertia is the only factor resisting the space charge force. In the short drift space between the chicane exit and IFEL2 undulator, there is no offsetting force and thus the space charge within the fs microbunch may become significant within this region.

An analytical 1D model was developed to judge the space charge effects within this drift [6]. In the 1D limit, longitudinal space charge forces are driven at the plasma frequency and a space charge parameter $\sigma_{\rm sc}$ is used to judge the space charge effect,

$$\begin{aligned}\sigma_{\rm sc} &= \frac{4r_e L}{\gamma^2 l_m \varepsilon_{n,\rm rms}}\frac{Q_m}{e}\\ &= 7.04\times 10^{-5}\frac{L(m)Q_m(nC)}{\gamma^2 l_m(m)\varepsilon_{n,\rm rms}(\mathrm{m\,rad})},\end{aligned} \tag{1}$$

where r_e is the classical electron radius, L is the drift length, Q_m is the bunch charge, γ is the energy Lorentz factor, l_m is the bunch length, and $\varepsilon_{n,\rm rms}$ is the rms normalized emittance. If $\sigma_{\rm sc} \geq O(1)$, space charge effects will be significant. Substituting the STELLA-II experimental parameters into Eq. (1), i.e., $\gamma \sim 91$, drift section length from chicane exit to entrance of IFEL2 ~0.20 m, microbunch length ~3 fs full width at half maximum (FWHM), and 1.5 mm of rms normalized emittance, we find the space charge parameter for a different microbunch charge is calculated as given in Table I. At 0.5 pC the space charge effects start becoming evident and at ≥ 3 pC the effects are significant.

To more extensively investigate the space charge effects in the STELLA-II drift region, the PARMELA tracking code [7] was used. The fs microbunches in reality are gradually formed throughout the drift and maximum bunching occurs ideally at the entrance to the IFEL2 undulator. Thus, for a worst-case estimate we simplify the beam conditions and assume that the fs microbunches are formed at the exit of the chicane and must travel through a 0.20-m drift space to the undulator. The main

TABLE I. Space charge parameter versus microbunch charge.

Charge (pC)	$\sigma_{\rm sc}$
0.1	0.113
0.5	0.565
3	3.39

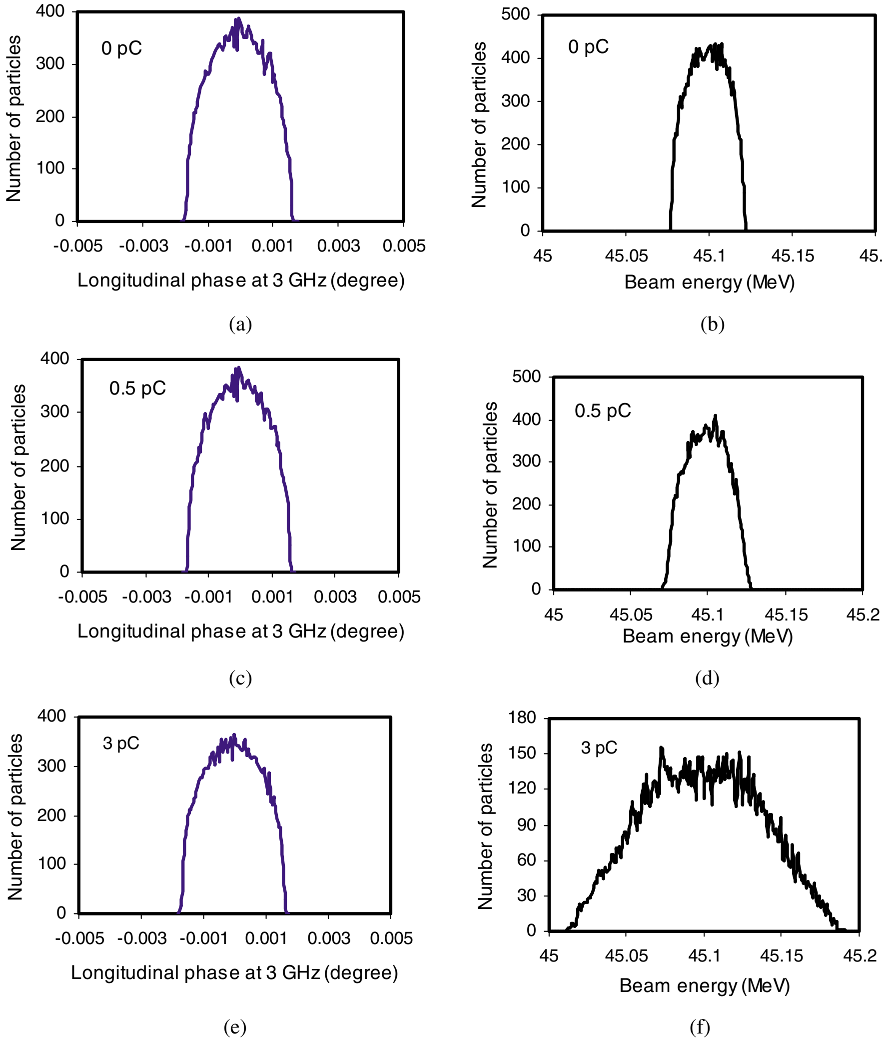

FIG. 2. (Color) Longitudinal phase spectrum (a),(c), and (e), and energy spectrum (b),(d), and (f) at the entrance to IFEL2.

beam parameters for the PARMELA simulations are as follows: the microbunch length is ~3 fs FWHM, 45.1 MeV beam energy, 0.1% intrinsic energy spread, and 1.5 mm normalized rms transverse emittance.

The longitudinal phase spectrum for a different microbunch charge from 0 to 3 pC is simulated as shown in Figs. 2(a), 2(c), and 2(e). (Note that 1 fs ≡ 0.00108° for the 3-GHz rf frequency in these figures). It shows that debunching does not happen for charges smaller than 3 pC.

The energy spread at the end of the drift region is also simulated as shown in Figs. 2(b), 2(d), and 2(f). The charge in Figs. 2(b), 2(d), and 2(f) is 0, 0.5, and 3 pC, respectively. It shows that the energy spread tends to increase ~5% when the microbunch charge is 0.5 pC. The FWHM energy spread increases by a factor of 2 at 3 pC from the 0-pC case, which agrees well with the 1D model estimates as given in Table I. The transverse emittance is constant below 5 pC of microbunch charge.

To resist the space charge force in the drift space, the elapsed time through the drift space should be a fraction of a plasma oscillation period. With the 3 fs and 0.5 pC of microbunch, the plasma oscillation period is ~0.5 m using the formula developed in Ref. [6]. The space charge effect dependence on drift space length is also simulated, as given in Table II. The simulations are also performed

TABLE II. Longitudinal energy spread versus drift length for 3-fs and 0.5-pC microbunches (FW is full width).

Drift length (cm)	Energy spread FWHM/FW (keV)	Debunching
0	45/60	⋯
20	46/63	No
40	60/89	No
60	80/123	Slightly
80	98/156	Slightly

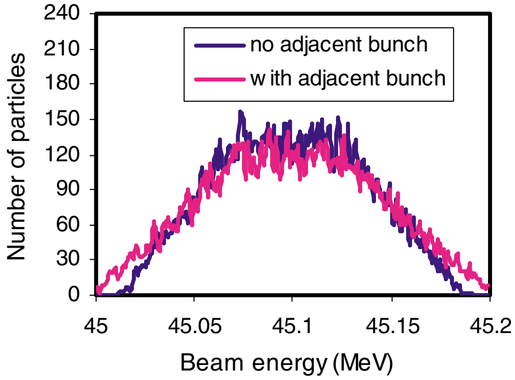

FIG. 3. (Color) Energy spread comparison with and without adjacent microbunches in the simulations.

for a 3-fs FWHM microbunch length and 0.5 pC of microbunch charge. It shows that space charge effects are negligible at 0.2 m of drift space and become evident with drift spaces longer than 0.4 m, which agrees well with the above simple judgment. Simulations also indicate that the space charge induced energy spread is much more sensitive to debunching of the microbunch and emittance growth.

The preceding discussion focused on single microbunch effects. As mentioned in the first section, the macrobunch consists of a train of microbunches separated by 10.6 mm. Thus, the adjacent microbunches may affect the beam dynamics of the bunch of the interest. Figure 3 shows the energy spectrum comparison with and without adjacent microbunches in the simulations. The calculations are performed at 3 pC and 3 fs of microbunch. It shows that the adjacent microbunches have negligible effects on the energy spread. This is because the microbunch separation (10.6 mm) is much longer than the microbunch duration (3 fs $\equiv$ 0.9 μm).

III. COHERENT SYNCHROTRON RADIATION EFFECTS

In addition to the space charge effects, significant CSR can be created when the fs microbunches traverse through the STELLA-II transport line. In contrast to beam-chamber interaction induced wakefields, where the head particles act on the tail particles, the CSR effects discussed here refer to the field produced by the particles in the tail that can catch up with the head particles. This can occur because the electrons' trajectory is curved in the bending magnets, whereas the photon trajectory is straight. As a direct consequence, the longitudinal energy spread can be affected. Since the electron bunch is in the dispersive region, the chromatic transfer function will couple with this longitudinal energy distribution into transverse betatron motion. Hence, the transverse emittance may also increase.

The CSR effect can be characterized by an overtaking length $L_0 = 2(3R^2\sigma_s)^{1/3}$ [8], which corresponds to the length required for the photons to catch up with the head electrons. When it is less than the magnet length L_d, enhanced coherent effects should take place. Studies of the energy loss gradient for a bunch with a Gaussian linear charge density distribution indicate that the head particles gain energy while the tail and center particles lose energy, and the CSR effect becomes stronger when the bunch gets shorter and denser [8]. The resulting transverse forces can cause the particles at the head of the bunch to defocus due to the overtaking radiation fields while other particles are focused, i.e., emittance growth. These investigations show that the mechanisms to induce the emittance growth are due to (i) the coupling between the longitudinal energy redistribution and the transverse phase space by the chromatic transfer function as described earlier; (ii) centrifugal forces, which are generally negligible since the effect of this force on the bunch is canceled by the effect of the particle energy's deviation under the influence of the transverse electric field; and (iii) the centripetal field, which is negligible compared to the magnetic field in the chicane. Thus, the first mechanism is dominant and it is justified to use the ELEGANT simulation code [9] to estimate this effect. This code has already been benchmarked with experiments [10,11].

A. CSR effects at the chicane and dipole spectrometer

A magnetic chicane is typically used to compress the bunch down to subpicosecond lengths for, say, x-ray free electron lasers and linear colliders, by properly employing an amount of correlated energy spread. The magnetic chicane in STELLA-II is used to form 3-fs microbunches from the macrobunch whose energy is modulated by passing through IFEL1. Unlike the chicanes to compress bunches using energy-phase correlation, the chicane at STELLA-II is to form microbunches by using the velocity-bunching principle, i.e., no energy-phase correlation is employed in this chicane. The chicane is a hybrid permanent magnet/electromagnet with built-in steering trim coils. (The electromagnet is used for phase adjustment between the microbunches and the laser light and is not related to the topic of this paper.) The permanent magnet has three poles, where the middle pole has a 6.2 kG magnetic field and a 2.5 cm effective length, and each side pole has a 2.2 kG magnetic field and a 3 cm effective length. Approximately 1.0% energy modulation by the IFEL1 undulator is needed to cause maximum microbunching at the entrance to IFEL2. Model simulations show that the microbunches are gradually formed throughout the chicane e-beam trajectory.

It is a nontrivial task to estimate CSR effects in such a complicated geometry. However, we can consider a pessimistic case in order to simplify the microbunching process. We assume that the microbunches (~ 3 fs) have already formed halfway through the chicane and then estimate the CSR effects.

Downstream of the IFEL2 undulator there are two types of dipoles, 4° and 90°, which are used as energy spectrometers. The spectrometer with a 90° dipole is used to observe the fine structures in the energy spectrum, but it is limited to narrow energy acceptance. The spectrometer with a 4° dipole has a larger energy acceptance, but the energy resolution is lower compared with the 90° dipole. Which dipole is used depends on the needs of the experiments.

When the fs microbunch traverses through the chicane and a dipole, it will emit coherent radiated power since the microbunch length is much shorter than its radiated wavelength. The resulting enhancement of the coherent radiated power with respect to classical synchrotron radiation can be expressed as [12,13]

$$P_{\rm co} \approx 0.028 N^2 \frac{ce^2}{\varepsilon_0 \rho^{2/3} \sigma_z^{4/3}}, \qquad (2)$$

where N is the number of electrons, c is the speed of light, ρ is the bending radius, and σ_z is the bunch length. The enhanced coherent radiated power in the chicane and dipoles is less than 50 W for a 0.5-pC and 3-fs microbunch. The power loss becomes significant when the microbunch charge is larger than 1 pC. Since the duty cycle at the ATF is small (only one bunch at 1.5 Hz), the temperature rise in the wall would be negligible even with this high-power loss. At high duty cycles, the temperature rise may become more evident.

To understand both the longitudinal and transverse phase spaces, the ELEGANT code is used to simulate the STELLA-II transport. Figure 4 shows the energy-spread increase versus microbunch charge at different microbunch lengths, 1, 3, and 4 fs (FWHM), after traveling through the half-chicane, focusing quads (see Fig. 1), and the 90° dipole. It demonstrates that below 1 pC microbunch charge, the energy-spread increase is less than 5% for a 3-fs microbunch. Further studies show that almost all of the energy-spread contribution comes from the chicane, i.e., the contributions from the 90° or 4° dipole is negligible.

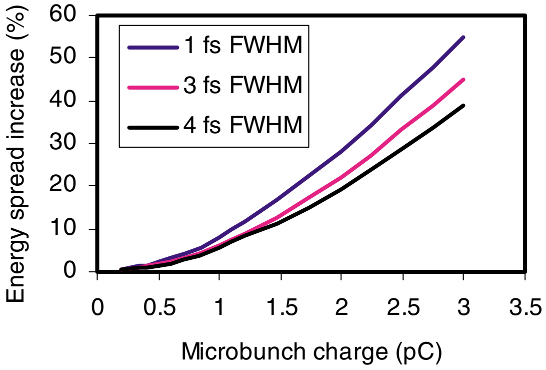

FIG. 4. (Color) Energy spread increase versus microbunch charge at different microbunch lengths.

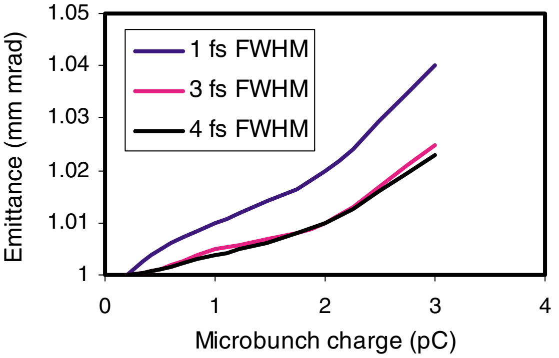

FIG. 5. (Color) Transverse emittance versus microbunch charge at different microbunch lengths.

The emittance growth is negligible when the charge is below 3 pC, as shown in Fig. 5. It indicates that the coupling between transverse and longitudinal phase spaces is very weak in these small-dispersion regions.

B. CSR effect within IFEL2

IFEL2 uses a permanent-magnet gap-tapered (~ 8%) undulator with ten periods. The emittance dilution due to the synchrotron radiation loss in an undulator is $\Delta\gamma\varepsilon_x \propto 2 \times 10^{-7} E^6 \times \theta^5(\mathrm{m\,rad})$ [14], where E is the beam energy in GeV, and θ is the bending angle. At energies in the GeV range, this effect can be significant. Since the operating e-beam energy in STELLA-II is ≈ 45 MeV, the induced emittance growth due to synchrotron radiation is negligible.

IV. CONCLUSION

Preserving fs microbunches can be a challenge in applications such as the staging of laser accelerators. In this paper, the space charge and CSR effects of the fs microbunches created during the STELLA-II experiment are analyzed and the maximum operating limits are determined. Microbunch charge thresholds for the space charge and CSR-induced debunching, energy-spread increase, and emittance growth are listed in Table III. It indicates that the energy-spread increase is much more sensitive to the debunching and emittance growth, and the resulting energy-spread increase becomes significant when the charge is larger than 0.5 pC. The microbunch charge needs to be below 0.5 pC, in which case the

TABLE III. Microbunch charge threshold for STELLA-II.

	Bunch debunching	Energy spread	Emittance
Space charge	3 pC	0.5 pC	5 pC
CSR	⋯	1 pC	3 pC

energy-spread increase is less than 5% and both the debunching and emittance blowup are negligible. The space charge effect versus the drift space length was also analyzed. At less than 20 cm of drift space length, the space charge effect is not significant; however, the energy spread will increase by a factor of 2 when the drift space length increases from 20 to 60 cm.

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