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GENERATION OF MODULATED BUNCH USING A MASKED CHICANE FOR BEAM-DRIVEN ACCELERATION EXPERIMENTS AT ASTA

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Abstract

Density modulations on electron beams can improve machine performance of beam-driven accelerators and FELs with resonance beam-wave coupling. The beam modulation is studied with a masked chicane by the analytic model and simulations with the beam parameters of the Advanced Superconducting Test Accelerator (ASTA) in Fermilab. With the chicane design parameters (bending angle of 18°, bending radius of 0.95 m and R_{56} ~ - 0.19 m) and a nominal beam of 3 ps bunch length, the analytic model showed that a slit-mask with slit period 900 μm and aperture width 300 μm induces a modulation of bunch-to-bunch spacing ~100 μm to the bunch with 2.4% correlated energy spread. With the designed slit mask and a 3 ps bunch, particle-in-cell (PIC) simulations, including nonlinear energy distributions, space charge force, and coherent synchrotron radiation (CSR) effect, also result in beam modulation with bunch-to-bunch distance around 100 μm and a corresponding modulation frequency of 3 THz. The beam modulation has been extensively examined with three different beam conditions, 2.25 ps (0.25 nC), 3.25 ps (1 nC), and 4.75 ps (3.2 nC), by tracking code Elegant. The simulation analysis indicates that the sliced beam by the slit-mask with 3 ~ 6% correlated energy spread has modulation lengths about 187 μm (0.25 nC), 270 μm (1 nC) and 325 μm (3.2 nC). The theoretical and numerical data proved the capability of the designed masked chicane in producing modulated bunch train with micro-bunch length around 100 fs.

INTRODUCTION

We have been investigating the masked chicane technique [1 – 3] with the available beam parameters such as the 50 MeV photoinjector of the Advanced Superconducting Test Accelerator (ASTA), which is currently being constructed and commissioned in Fermilab [4]. Downstream of the ASTA 50 MeV photoinjector beamline, a magnetic bunch compressor, consisting of four rectangular dipoles, is adopted and a slit-mask is designed and inserted in the middle. Based on this slit-masked chicane, the bunching performance and the ability of sub-ps microbunch generation are studied.

In order to evaluate bunching performance with nominal beam parameters, the masked chicane has been analyzed by the linear bunching theory in terms of bunch-to-bunch distance and microbunch length. Elegant code is employed to examine the theoretical model with the ASTA nominal beam parameters (RMS bunch length $\sigma_{z,i}$ is 3 ps and energy ratio τ is around 0.1). The Particle-In-Cell (PIC) simulation (CST-PS) includes space charge and CSR effect and nonlinear energy distribution over macro-particle data. For Elegant simulations, bunch charge distribution and the beam spectra are mainly investigated with three different bunch charges, 0.25 nC, 1 nC, and 3.2 nC, under two RF-chirp conditions of minimum and maximum energy spreads. The corresponding bunch length for the maximally chirped beam is 2.25, 3.25, and 4.75 ps and the correlated energy spread is 3.1, 4.5, and 6.2 % respectively for bunch charge of 0.25 nC, 1 nC, and 3.2 nC

ANALYTIC DESIGN

The designed chicane consists of four dipoles and a slit mask with slit spacing, *W*, and aperture width, *a*, is inserted in the middle of the bunch compressor (dispersion region). Before the beam is injected into the masked chicane, a positive linear energy-phase correlation is imposed by accelerating the beam off the crest of the RF wave in the linear accelerator. The chicane disperses and re-aligns the particles with respect to their energies in phase space. The input beam is then compressed and the phase space ellipse is effectively rotated toward the vertical. In the middle of the chicane, the beam is partially blocked by the transmission mask and holes are introduced in the energy-phase ellipse. In the second half of the chicane, the beam is deliberately over-bunched and the beam ellipse is slightly rotated past the vertical. In this step, the linear energy-phase correlation is preserved by over-bunching, accompanied with a steeper phase-space slope. Consequently, the projection of the beam ellipse on the time axis generates

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density modulations at a period smaller than the grid spacing.

With a masked chicane, one can control the microscopic structure of a bunch under compression by adjusting the grid period and/or by varying the chicane magnetic field. In principle, if a grid period (or slit-spacing) is smaller than a hundred microns, a modulation wavelength of the bunched beam is possibly cut down to a few tens of microns. The beamline for the mask is originally designed with the four dipoles having bending angle of 18^{o}, bending radius R = 0.95 m, and dipole separation D = 0.68 m. The 125 μm thick tungsten mask with a slit-array is designed with period of W = 900 μm and aperture width of a = 300 μm (~ 33 % transparency).

For the ASTA 50 MeV chicane, R_{56} (longitudinal dispersion) = - 0.192 m and η_x (maximum transverse dispersion) = - 0.34 m. The bunch-to-bunch spacing (or modulation wavelength), Δz, is defined by the final bunch length divided by the number of micro-bunches in a compressed beam [2]. The final bunch length is

$$\sigma_{z,f} = \sqrt{\left(1+h_1R_{56}\right)^2 \sigma_{z,i}^2 + \tau^2 R_{56}^2 \sigma_{\delta i}^2} \tag{1}$$

, where h_1 is the first order chirp, $\sigma_{z,i}$ is the initial bunch length, $\sigma_{\delta i}$ is the initial un-correlated RMS energy spread, and τ is the energy ratio. The energy ratio is normally ~ 0.1 at ASTA photoinjector beamline. Concerning correlated energy spread σ_δ, we have

$$\sigma_\delta^2 = \tau^2\sigma_{\delta i}^2 + h_1^2.\sigma_{z,i}^2 \tag{2}$$

The correlated energy spread, σ_δ, and transverse emittance, ε_x, normally determine a transverse beam size at the mask by

$$\sigma_{x,mask} = \sqrt{\varepsilon_x \beta_{x,mask} + \left(\eta_{x,mask}\sigma_\delta\right)^2} \tag{3}$$

, where $\beta_{x,mask}$ is the beta function and $\eta_{x,mask}$ is the transverse dispersion at the mask [5, 6]. After passing through a slit-masked chicane, the number of microbunches of the compressed beam is determined by the transverse beam size at the mask, $\sigma_{x,mask}$, and the slit period, W, by

$$N_b = \frac{\sigma_{x,mask}}{W} \tag{4}$$

The correlated energy spread, σ_δ, and transverse emittance, ε_x, normally determine a transverse beam size at the mask by

$$\sigma_{x,mask} = \sqrt{\varepsilon_x \beta_{x,mask} + \left(\eta_{x,mask}\sigma_\delta\right)^2} \tag{5}$$

The bunch-to-bunch spacing of modulated beam, Δz, can thus be derived to be

$$\Delta z = W\frac{\sqrt{\left(1+h_1R_{56}\right)^2\sigma_{z,i}^2 + \tau^2R_{56}^2\sigma_{\delta i}^2}}{\eta_{x,mask}h_1.\sigma_{z,i}} = W\frac{\sqrt{\left(\sigma_{z,i}+R_{56}\sigma_\delta\right)^2 + \tau^2R_{56}^2\sigma_{\delta i}^2}}{\eta_{x,mask}\sigma_\delta} \tag{6}$$

With the calculated bunch-to-bunch spacing, the bunch length of microbunches can be evaluated by $\sigma_{z,m} = T\cdot\Delta z$, where T (= a/W) is the mask transparency (~ 33 % here), assuming the time pattern of the beam is similar to the mask pattern[6].

We examine bunch lengths, compression ratios, and bunch-to-bunch distances with respect to correlated energy spreads, σ_δ, for the beam with ASTA nominal parameters [4]. When σ_δ reaches 0.468%, which corresponds to $\sigma_\delta = -\sigma_{z,i}/R_{56}$ and $h_1 = -1/R_{56}$, the beam is maximally compressed and the final rms bunch length tends to be minimal. One can see that continuously increasing σ_δ renders the beam less compressed and would make the beam rather stretched instead of being compressed. The bunch length via the magnetic chicane is thus mainly governed by an amount of beam energy-spread determined by a beam injection condition with respect to RF-phase. As shown in Fig. 2(b), the compress ratio is apparently in inverse proportion as a final bunch length (rms), which therefore becomes infinite when the beam is maximally compressed. Figure 2(c) shows bunch-to-bunch distance (bunch modulation length) with correlated energy spread, σ_δ. The analytic calculation points out that the distance becomes ~ 100 μm with correlated energy spread of ~ 2.4%. With a 33.3% mask transparency, it is predicted that the ~ 100 μm spaced bunch produces a microbunch length of ~ 33 μm, corresponding to 100 fs in time.

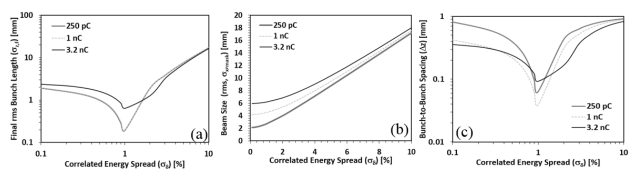

Figure 1: (a) Final bunch length (after BC1), (b) transverse beam size at X115, and (c) bunch-to-bunch distance (Δz) versus correlated energy spread (σ_δ) graphs with bunch charges of 250 pC, 1 nC, and 3.2 nC, calculated by the linear bunch compression theory.

SIMULATION ANALYSIS

In order to verify the analytic model, the masked chicane is simulated by Elegant with macro-particle data imported. For Elegant simulations, macro-particles are imported from a space-charge tracking code, ASTRA [7], which is combined with an extended analysis program called "Shower [8]" to include particle transition effect through a mask material. In order to analyse characteristics of the bunched beam, bunch profiles (charge distributions) at x-/y-planes and time axis are monitored at the image station positions, X110, 118, 121, and 124, along the injector beamline, as shown in Fig. 2. The designed slit-mask with W = 900 μm and a = 300 μm is modelled with bunch charges of 250 pC, 1.0 nC and 3.2 nC. As theoretically analysed, the beam is strongly modulated with W = 900 μm and ~ 100 μm of modulation length (Δz), which is consistent with the peak (~ 3 THz) appearing in the beam spectrum. Two different bunching conditions with minimum and maximum energy spreads (on-crest and off-crest with maximum chirp) are examined with Elegant. Also, the simulation analysis includes three different bunch charges (0.25 nC, 1.0 nC and 3.2 nC). For the chirped beam with bunch charge of

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0.25 nC, 1.0 nC and 3.2 nC, the rms bunch length is 2.25 ps, 3.25 ps, 4.75 ps and correlated energy spread 3.1%, 4.5% and 6.2% respectively. The normalized charge distributions of the injected beam with charge 3.2 nC are plotted in Fig. 2. Apparently, the beam charge profile follows approximately Gaussian distribution and the minimum energy chirp leads to about 1 % spread, which is far less than that of the chirped beam with linear energy distribution and 6.2% correlated energy.

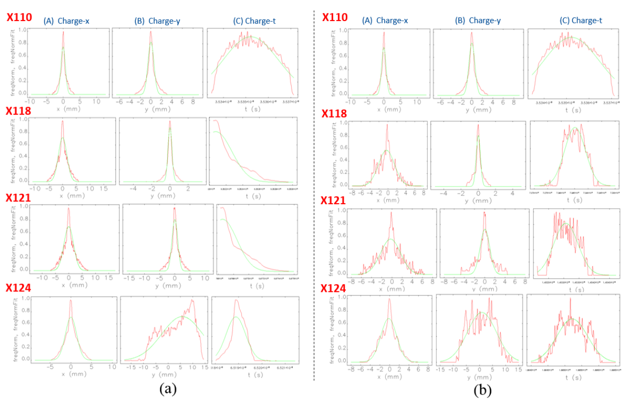

Figure 2: Simulation results with Elegant combined with Shower (Q = 3.2 nC and 50 MeV). Bunch profiles (a) without and (b) with a slit-mask at X115.

After passing through the masked chicane, the initial linear energy-time distribution is reversed from positive to negative. This conforms to the principle of slit-masked chicane in micro bunch train generation. The beam with minimum energy chirp (red) appears not to carry a modulation pattern in the particle distribution. Under this condition, presence of the slit-mask negligibly influences on the beam profile and the chicane behaves as a normal bunch compressor without modulating the beam. On the contrary, the beam modulation under the condition with maximum energy chirp (green) appears much stronger than that with minimum energy spread. It is found that modulation wavelengths of 0.25 nC, 1.0 nC and 3.2 nC are about 187 μm, 270 μm and 325 μm, corresponding to bunch lengths of 16 μm, 23 μm and 27 μm, respectively. Note that the linear model predicts 36 μm of bunch length under the same condition. Although there are some differences due to approximation in analytic model and some perspectives disregarded in Elegant simulations, those results show the feasibility of ~ 100 fs microbunch generation from the designed chicane. We also notice that the corresponding frequency of the bunch-to-bunch spacing is around 1.6 THz, 1.4 THz, and 1.2 THz, respectively. Taking into account all the theoretical and numerical analyses, one sees that a properly designed masked chicane can produce a micro-modulated bunch with RMS-bunch length around 100 fs under the optimum beam bunching condition.

EXPERIMENTAL PLAN

Currently, it is planned to test a bunch modulation of the masked chicane method with the designed slit-mask. A tungsten mask with W = 900 μm and a = 300 μm is already installed in the X115 of BC1, as shown in Fig. 3, which is ready for the test. We consider two different ways to detect bunch modulation: using D122-X124 spectrometer and a skew-quad installed in BC1. Our simulation results indicate that a bunch modulation prominently appears with maximum energy chirp, so the X124 screen will most likely have a sliced beam image in y-axis (energy axis) in the case the bunch is modulated since the beam will be deflected with about 5 – 6 % correlated energy spread by D122 spectrometer magnet. Another way is to use a skew-quad installed in BC1. At the skew quadrupole, the particle gets a y-kick proportional to its x-position. This kick is converted to a y-position change at the screen (X121) downstream of the bunch compressor. This technique will allows us to measure a beam modulation wavelength more accurately.

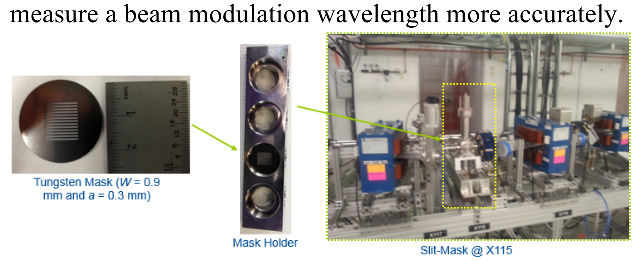

Figure 3: Designed slit-mask installed in BC1.

CONCLUSION

Since bunch modulation of high brightness beams can significantly improve performance of accelerator-based coherent light sources and high energy linacs, we have investigated a simple way for micro-bunch train generation with a masked chicane, in particular with the bunch compressor at the 50 MeV. The linear model is derived to estimate performance of the designed masked chicane, indicating that the designed slit-mask produces σ_{ms} = 33μm long micro-bunches spaced with ~ 100 μm out of σ_t = 3 ps bunch with about 2.4 % correlated energy spread.

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