STUDY ON BEAM MODULATION TECHNIQUE USING A MASKED CHICANE AT FAST (FERMILAB ACCELERATOR SCIENCE AND TECHNOLOGY) FACILITY*

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Abstract

Longitudinal density modulations on electron beams can improve machine performance of beam-driven accelerators and FELs with resonance beam-wave coupling. The sub-ps beam modulation has been studied with a masked chicane by the analytic model and simulations with the beam parameters of the Fermilab Accelerator Science and Technology (FAST) facility. 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 generates about 100-µm modulation periodicity with 2.4% correlated energy spread. With the designed slit mask and a 3- ps bunch, particle-in-cell simulations (CST-PS), including nonlinear energy distributions, space charge force, and coherent synchrotron radiation (CSR) effect, also result in ~ 100 µm of longitudinal modulation. 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 extended 3D tracking simulations (Elegant). The modulated bunch generation is tested by a slit-mask installed at the chicane of the ASTA 20-MeV injector beamline and the preliminary test result is presented in the paper.

INTRODUCTION

The masked chicane technique [1–3] has been investigated with the 50 MeV linac in the Fermilab Accelerator Science and Technology (FAST) facility, which is currently being constructed and commissioned in Fermilab [4]. A tungsten slit-mask is currently installed in a magnetic chicane, consisting of four bending dipole magnets, downstream of the 50 MeV photoinjector and the bunch performance and sub-ps micro-bunch generation capability are examined with analytic calculations and PIC simulations.

For the theoretical evaluation on bunching performance, the linear bunching theory is derived to check bunch-to-bunch distance and microbunch length with FAST nominal beam parameters (RMS bunch length $\sigma_{z,i}$ is 3 ps and energy ratio τ is around 0.1) are analyzed by the linear bunching theory, which was tested by beamline simulations using Elegant code and CST-PS. Space charge forces and CSRs are included in the simulations with nonlinear charge distribution over macro-particles. 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.

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ANALYTIC DESIGN

The magnetic chicane is designed with 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). A positive linear energy-phase correlation is imposed by accelerating the beam off the crest of the RF wave in the linear accelerator before the beam is injected into the masked chicane. In this way, 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. The beam is deliberately over-bunched in the second half of the chicane and the beam ellipse is slightly rotated past the vertical. Accompanied with a steeper phase-space slope, the linear energy-phase correlation is preserved by over-bunching. The projection of the beam ellipse on the time axis therefore generates density modulations at a period smaller than the grid spacing.

The microscopic structure of a bunch can be controlled with a masked chicane 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°, 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).

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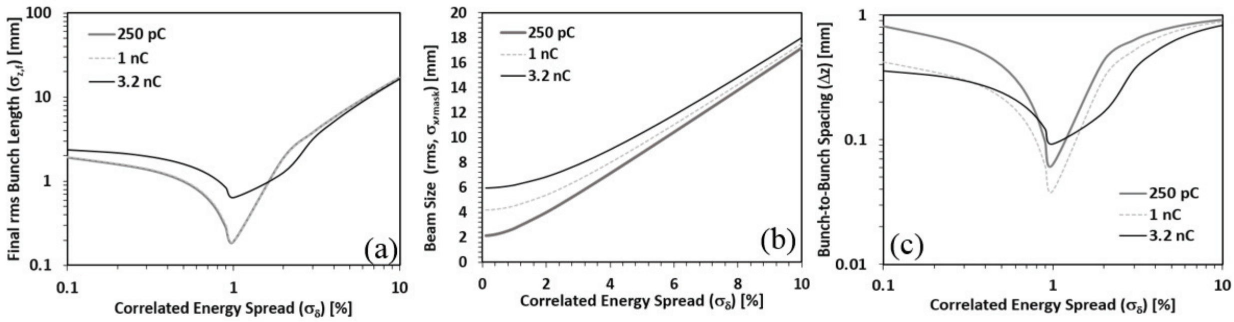

Figure 1: (a) Final bunch length (after BC1), (b) transverse beam size at X115, and (c) bunch-to-bunch distance (Δz) versus correlated energy spread (σ_δ) graphs with bunch charges of 250 pC, 1 nC, and 3.2 nC, calculated by the linear bunch compression theory.

For the 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

$$\sigma_{z,f} = \sqrt{\left(1+h_1 R_{56}\right)^2 \sigma_{z,i}^2 + \tau^2 R_{56}^2 \sigma_{\delta i}^2}, \quad (1)$$

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 FAST photoinjector beamline. Concerning correlated energy spread σ_δ, we have

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

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

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

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 micro-bunches of the compressed beam is determined by the transverse beam size at the mask, $\sigma_{x,mask}$, and the slit period, W, by

$$N_b = \frac{\sigma_{x,mask}}{W} . \quad (4)$$

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

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

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

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

The bunch length of microbunches is defined by $\sigma_{z,m}$ = T·Δz, where T (= a/W) is the mask transparency (~ 33 % here), with the calculated bunch-to-bunch spacing, assuming the time pattern of the beam is similar to the mask pattern [6].

The bunch lengths, compression ratios, and bunch-to-bunch distances with respect to correlated energy spreads, σ_δ, are examined for the beam with FAST nominal parameters [4]. The beam is maximally compressed and the final rms bunch length tends to be minimal, when σ_δ reaches 0.468% corresponding to σ_δ = - $\sigma_{z,i}/R_{56}$ and h_1 = - $1/R_{56}$. Continuously increasing σ_δ renders the beam less compressed and would make the beam rather stretched instead of being compressed. An amount of beam energy-spread determined by a beam injection condition with respect to RF-phase thus dictates the bunch length via the magnetic chicane. As shown in Fig. 1(b), the compress ratio is apparently in inverse proportion as a final bunch length (rms). Therefore, the compression ratio becomes infinite when the beam is maximally compressed. Figure 1(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.

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

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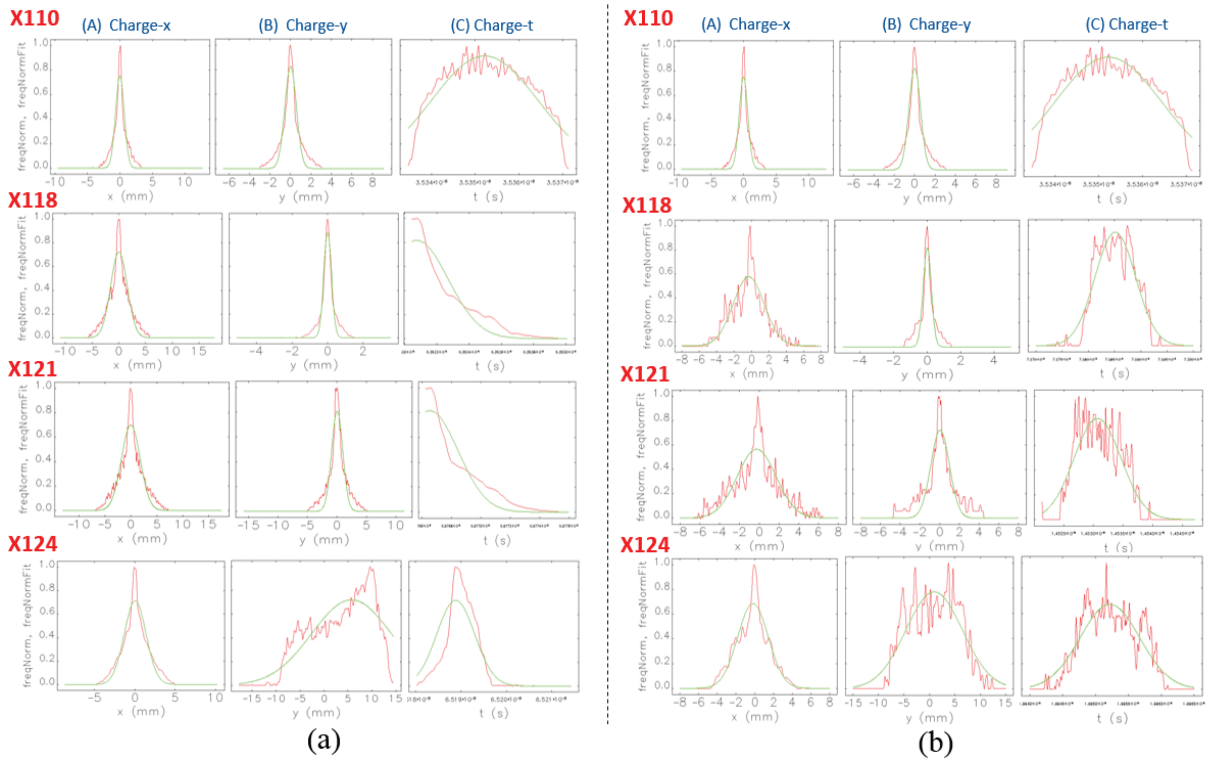

Figure 2: Simulation results with Elegant combined with Shower (Q = 3.2 nC and 50 MeV). Bunch profiles (a) without and (b) with a slit-mask at X115.

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 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.

While 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. In such a condition, the 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, a properly designed masked chicane can produce a micro-modulated bunch with RMS-bunch length around 100 fs under the optimum beam bunching condition.

PRELIMINARY TEST RESULT

A tungsten mask with W = 900 µm and a = 300 µm is placed in the X115 of BC1, as shown in Fig. 3. The bunch modulation is measured by using D122-X124 spectrometer and a skew-quad installed in BC1 with 20 MeV electron beam. 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

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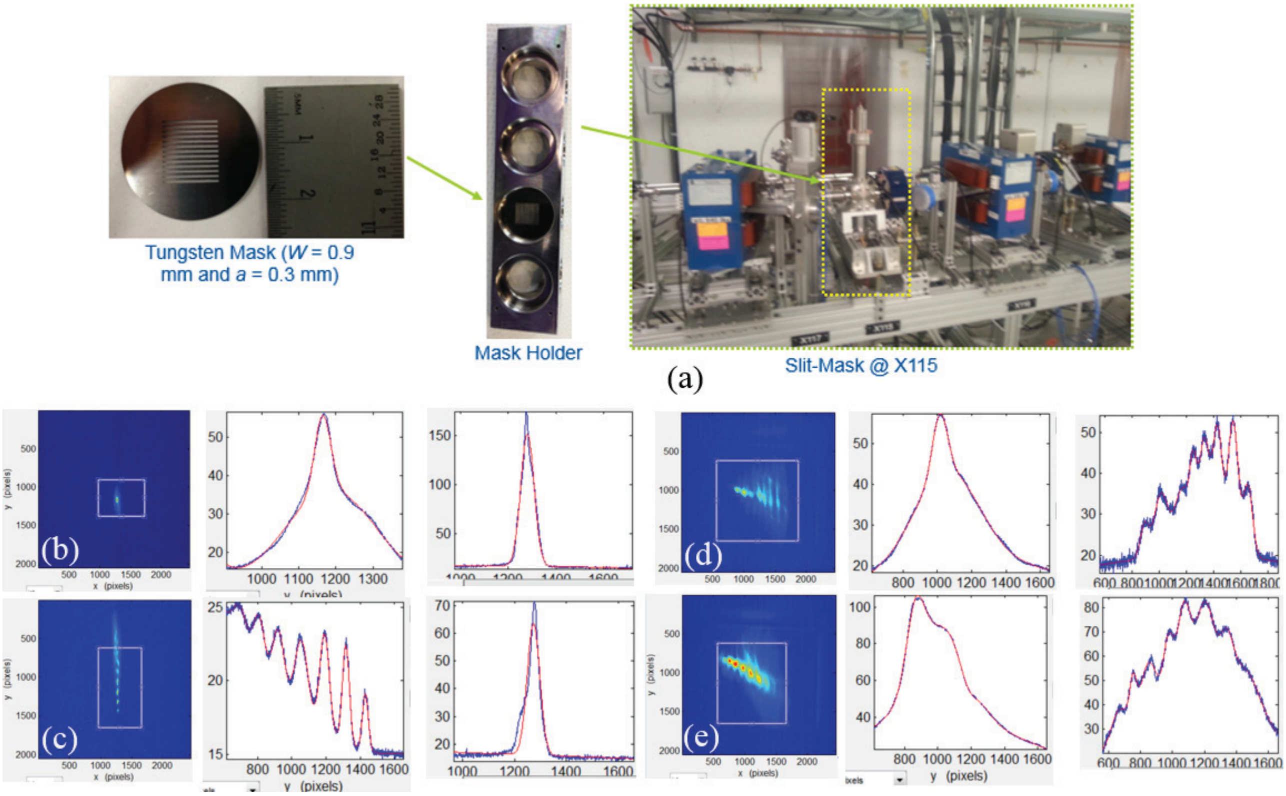

Figure 3: (a) Slit-mask installed in the X115 (BC1). (b) X120-focus with Q115 skew quad (b) OFF and (c) ON at 140 pC per micro-pulse. X124-focus with Q115 skew quad on, (d) 60 pC and (e) optimized.

D122 spectrometer magnet. Secondly, 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. As shown in Fig. 3, a strong modulation appears on the bunch at X121 and X124 without the skew-quad on (Figs . 3(c–d), while it is not shown with the skew-quad off (Fig. 3(b)). The slit-mask will be re-tested for full characterization measurements of the bunch modulation parameters after the FAST beamline is re-commissioned with 50 MeV.

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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