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SIMULATION ANALYSIS ON MICRO-BUNCHED DENSITY MODULATION FROM A SLIT-MASKED CHICANE

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Abstract

Pre-bunching a beam at a resonance condition with an accelerating structure vastly improves performance of beam-driven accelerators and undulators since it enhances a beam-wave coupling. For instance, injecting a driver beam with multiple micro-bunches in multi-mode accelerating media such as plasma channels improves field gradient, transformer ratio, and energy efficiency of wakefield acceleration with a single mode excitation. The slit-mask technique is the simplest method to create multiple micro-bunches. We plan to test a slit-mask micro-buncher at the chicane of Fermilab-ASTA 50 MeV beamline in the effort of advanced accelerator research. With the chicane design parameters (bending angle (α) of 18°, R_{56} ~ - 0.18 m, and bending radius of ~ 0.78 m), analytic model showed that a slit-mask with W (period) = 900 μm and a (aperture width) = 300 μm (30 % transparency) generates 100 μm spaced micro-bunches with 5 ~ 6 % correlated energy spread. Two kinds of combined beamline simulation, CST-PS+Impact-Z and Elegant+Shower, including space charge and CSR effects, showed that a 900 μm spaced, 300 μm wide slits placed in the middle of chicane splits 20 pC – 1 nC bunches into ~ 100 μm spaced micro-bunches. It is possible that a further optimization of mask design creates sub-100 fs micro-bunches, which is currently under development.

INTRODUCTION

Many front-end applications of electron linear accelerators, such as free-electron lasers, electron microscopes, and linacs, depend on the generation and acceleration of electron bunches to relativistic level with the short bunches in a desired scale [1 – 9]. There are generally two ways of shortening the bunch length. One is the widely used magnetic bunch compressor, such as chicane, S-chicane, and Dogleg [1, 7]. Another is the combined acceleration and compression using velocity bunching [8, 9]. The masked chicane method was first suggested by D. C. Nguyen and B. Carlsten (Los Alamos National Laboratory) in 1996 to reduce the required undulator length [4, 5] of FELs. Employing the mask technique with wire-grid, the Brookhaven National Laboratory (BNL) demonstrated the generation of a stable train of micro-bunches with a controllable sub-picosecond delay. The slit-mask technique was attempted as the simplest way to generate micro-bunches on the sub-ps time scale.

Based on the 50MeV photoinjector of the Advanced Superconducting Test Accelerator (ASTA) currently under construction at Fermilab [6], we designed a masked bunch compressor to generate micro-bunches with longitudinal bunch length around 100μm. Two combined simulation codes, Elegant+Shower [10, 11] and CST-PS [12], are used to study the beam modulation and validate the slit mask design. The beam with minimum energy spread and with maximum energy chirp are used for the simulation analysis. For the simulations, beam energy distribution, bunch charge distribution and the Fourier-transformed spectra are mainly investigated with three different bunch charges, 250 pC, 1 nC, and 3.2 nC.

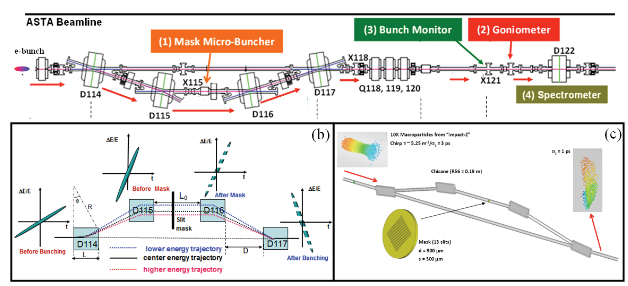

Figure 1: (a) Fermilab-ASTA beam line (low energy) configuration for the slit-mask micro-bunching experiment (b) conceptual performance diagram of the slit-mask micro-buncher with the phase-space plots in time sequence (c) CST-PS+Impact-Z simulation model.

ANALYTIC DESIGN OF A SLIT-MASK

In the ASTA beam line, the slit-mask technique is used to generate the desired longitudinal beam modulation. The chicane is constructed by four rectangular dipoles (D114-D115-D116-D117) and a slit mask with slit period W and aperture width, a, which is inserted in the middle of the Bunch Compressor. The principle of such a masked chicane can be shown with the phase-space plots in Fig. 1(b). 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. For the chicane delays different beam energies by different amounts along the phase axis, the input beam is compressed and the phase space ellipse is effectively rotated toward the vertical. In the middle of

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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. Over-bunching preserves the linear energy-phase correlation with a steep slope. Consequently, the projection of the beam ellipse on the phase axis exhibits density modulations at a period smaller than the grid spacing.

Using a masked chicane, it is feasible to control the bunch microscopic structure by adjusting the grid period or by varying the chicane magnetic field. And it could be expected to superimpose on the electron bunch density modulations as short as a few tens of microns with a grid period on the order of a hundred microns.

For a masked chicane, the bunch spacing and the micro bunch length of the beam passing through it can be easily evaluated. The final bunch length $\sigma_{z,f}$ of the beam after going through a bend system is

$$\sigma_{z,f} = \sqrt{\left(1+\kappa R_{56}\right)^2 \sigma_{z,in}^2 + \left(R_{56}\left|\Delta E / E_0\right|\right)^2} \quad (1)$$

where $\sigma_{z,in}$ is the initial bunch length of the input beam. $\Delta E/E_0$ is the initial energy spread. R_{56} is the longitudinal dispersion of the bend system, and κ is the beam linear chirp.

Once introducing the slit mask, the final bunch length $\sigma_{z,f}$ is divided by the number of micro-bunch, N_b, in the full bunch train. The number of micro-bunch, N_b, is calculated by

$$N_b = \frac{\sigma_{x,mask}}{W} \quad (2)$$

where W is the period of the slit mask, $\sigma_{x,mask}$ is defined as

$$\sigma_{x,mask} = \sqrt{\sigma_{x,in}^2 + \left(\eta_{mask}\left|\Delta E / E_0\right|\right)^2} \quad (3)$$

Here, η_{mask} is the dispersion at the mask position. And the slit mask is expected to generate a bunch-to-bunch spacing $\Delta z = \sigma_{z,f}/N_b$. Meantime, the micro-bunch length $\sigma_{z,out}$ can be estimated by

$$\sigma_{z,out} = \sqrt{\left(1+\kappa R_{56}\right)^2 \sigma_{z,slit}^2 + \left(R_{56}\left|\Delta E / E_0\right|\right)^2} \quad (4)$$

where $\sigma_{z,out} = \sigma_{x,slit} = a$. With an appropriate beam emittance, the bunch spacing is larger than the micro-bunch length and a desired micro bunch generation and beam charge modulation can be obtained.

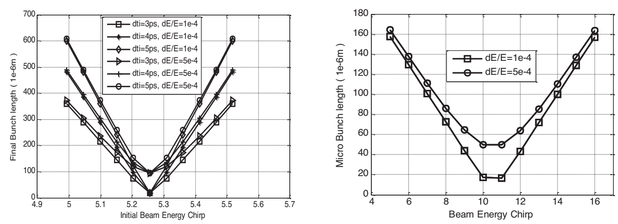
The chicane is designed four rectangular dipoles with bending angle of (+, - , - , +) 18°, bend radius (R) = 90 cm and dipole separation (D) = 68.25cm. The tungsten mask with multi-slit array is designed with W = 900μm and a = 300μm (33.33% transparency). The mask thickness is 125μm. According to

$$D_{//} = R_{56} = \gamma \frac{dz}{d\gamma} = -4L\sec\theta + 4R\theta - 2D\sec\theta\tan^2\theta \quad (5)$$

$$D_{\perp} = \gamma \frac{dx}{d\gamma} = -2L\tan\theta + 2R\left(1-\cos\theta\right) - D\tan\theta\left(1+\tan^2\theta\right) \quad (6)$$

We get the longitudinal dispersion of this chicane R_{56} ~ - 0.19m and the maximum horizontal dispersion inside the chicane $D_{\perp}$ ~ - 0.34 m.

For the analysis on the bunch compressor performance, we take κ_0 = - $1/R_{56} \approx 5.26$ and sweep κ from $0.95\kappa_0$ to $1.05\kappa_0$. Using a 3ps ultra-violet laser illuminating the cathode, the bunch length of the electron beam is generally around 3ps to 5ps, whose corresponding longitudinal bunch length is 0.9mm to 1.5mm. The intrinsic energy spread is between 0.01% and 0.05%. Here we calculate the final longitudinal bunch length of the beam with initial longitudinal bunch length 0.9mm, 1.2mm and 1.5mm respectively, with energy spread 0.01% and 0.05%. Using Eq. (1), the final bunch length of the beam going through this chicane without slit mask is plotted in Fig. 2(a). With $\sigma_{z,out} = \sigma_{x,slit} = a$ = 300 μm, the micro bunch length is obtained using Eq. (4) and plotted in Figure 2(b). From Figure 2(b), it is easy to see that with the designed slit mask a micro bunch length around 100μm can be expected. According to Eq. (3), with $\sigma_{x,slit}$ = 0.5 mm and $\Delta E/E_0$ = 0.05 %, four micro-bunches are generated and the bunch-to-bunch separation, Δz, appears to range from 4.75μm to 150μm.



(a) (b)

Figure 2: (a) Beam bunch length of the bunch compressor without slit mask; (b) Micro bunch length estimation of the masked chicane.

MODELING ANALYSIS

To verify our masked bunch compressor, the beam performance of masked chicane was simulated by two combined simulation codes, CST-PS+Impact-Z and Elegant+Shower. The beam dynamics before the masked chicane were obtained from ASTRA simulation and are used as a starting point for transport and compression through the chicane. Using CST-PS, we examined two different slit-mask designs: with W = 900μm and a = 300μm and with W = 600μm and a = 200μm. For Elegant/Shower simulations, two kinds of beam are employed: with minimum energy spread and the beam with maximum energy chirp. Two bunch charges are considered for the simulations: 250pc and 3.2nc. The beam phase space at the entrance of the masked chicane are plotted in Fig. 3, in which the x-y, z-t, normalized particle number distribution of the beam with beam charge 3.2nc are presented. At the same time, the energy phase space corresponding to minimum energy spread and maximum energy chirp are provided. The longitudinal bunch length is about 4.75 ps. The chirped beam has a nearly linear energy distribution. From the CST-PS+Impact-Z simulation, one can see that the beam modulation strongly appears with W = 900μm, and yet its amplitude is significantly weaker with W = 600 μm. The

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slit-mask design for Elegant+Shower simulation is thus selected with W = 900 μm for benchmarking in the case of the maximum and minimum energy spreads.

With the Elegant+Shower simulation, note that the beam with minimum energy spread has almost no modulation, while the beam charge profile is changed and the particles are compressed to a region of ~ 4ps, ~ 2ps, ~ 1ps respectively corresponding to bunch charge 3.2nc, and 250pc. Attributed to the correlated energy spread (Fig. 3), the on-crest particles with the highest energy will catch up with the off-crest particles. For the chirped beam, comparing the energy phase space in Fig. 3, it should be noted that the linear energy phase space is compressed and reversed from positive to negative after passing through the masked chicane. CST-PS+Impact_Z and Elegant/Shower simulation results all indicated that the beam longitudinal charge at the end of the bunch compressor exhibits strong modulations at a period of ~ 1ps, which indicates a longitudinal micro-bunch length ~ ~ 100μm, which is close to the analytic calculations.

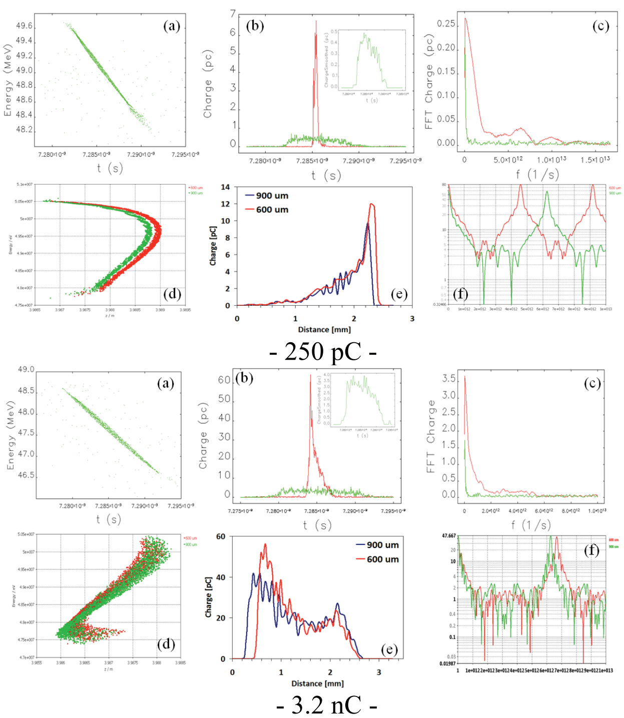

Figure 3: Simulation results from Elegant+Shower, (a – c), and CST-PS+Impact-Z, (d – f), of a slit-masked chicane with 250 pC (top) and 3.2 nC (bottom), including energy distribution ((a) and (d)), charge distribution ((b) and (e)) in time (or longitudinal distance), and their FFTed spectra ((c) and (f)) with minimum energy spread (red) and maximum energy chirp (green) in (a – c) and W 900 μm (blue) and W = 600 μm (red) in (d – f), respectively.

SUMMARY/CONCLUSION

Based on the 50MeV photoinjector of the Advanced Superconducting Test Accelerator (ASTA) at Fermilab, a masked bunch compressor is introduced to generate micro-bunches within sub-picosecond scale, in which the tungsten slit-mask is designed by Elegant/Shower and CST-PS+Impact-Z. The phase space and the modulated charge distribution with minimum energy spread and maximum energy chirp are mainly analyzed with analytic calculations. When travelling through the masked chicane, the beam with minimum energy spread appears not to be modulated, while the beam charge of the chirped beam is strongly modulated. The results also show that the designed slit-mask with 900μm period and 300μm width can modulate a maximally compressed bunch to about 100μm and meet the design requirement.

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