BEAM TEST OF MASKED-CHICANE MICRO-BUNCHER*

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Abstract

Masking a dispersive beamline segment such as a dogleg or a chicane is a simple way to shape a beam in the longitudinal and transverse space. This technique is often employed to generate arbitrary bunch profiles for beam/laser-driven accelerators and FEL undulators or even to reduce background noise from dark currents in electron linacs. We have been investigating a beam-modulation of a slit-masked chicane at the electron injector beamline 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 $R_{56} \sim -0.19$ m) and a nominal beam of 3 ps bunch length, Elegant simulations showed that a slit-mask with slit period 900 μm and aperture width 300 μm induces a modulation with bunch-to-bunch space of about 187 μm (0.25 nC), 270 μm (1 nC) and 325 μm (3.2 nC) with 3 ~ 6% correlated energy spread: An initial energy modulation pattern has been observed in the electron spectrometer downstream of the masked chicane using a micro-pulse charge of 270 pC and 40 micro-pulses. The first Optical Transition Radiation (OTR) signals of the longitudinally modulated beam were measured with a Martin-Puplett interferometer and a synchro-scan streak camera at a station between the chicane and spectrometer.

INTRODUCTION

One of the easiest ways to achieve the beam-modulation is to mask the beam in a chicane with a slit-mask or a wire-grid. The basic concept was first suggested by D. C. Nguyen and B. Carlsten in 1996 in the effort to reduce the length of FEL undulators [1]. Also, Brookhaven National Laboratory (BNL) demonstrated the generation of a stable train of micro-bunches with a controllable sub-ps delay with the mask technique using a wire-grid. The main advantage of the masking technique is to facilitate control of micro-structured density profiles, including the energies and phases. We have implemented the masked chicane method in the 50-MeV electron injector at the Fermilab Accelerator Science and Technology (FAST) facility [2,3]. Downstream of the FAST 50-MeV photoinjector beamline, a magnetic bunch compressor consisting of four rectangular dipoles was installed with a slit-mask inserted into the middle section (see Fig. 1). Based on this slit-masked chicane, the bunching performance and sub-ps microbunch generation were studied. In order to evaluate bunching performance with nominal beam parameters [4], the masked chicane has been analyzed against linear bunching theory in terms of both bunch-to-bunch distance and microbunch length and verified through Elegant [5]. For Elegant simulations, bunch charge distribution and the beam spectra were investigated principally 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. We took initial data from masked-chicane micro-buncher at the FAST 50-MeV beamline with the plan to demonstrate beam-shaping control, in particular temporal modulation, of FAST linac and to check micro-bunching effects on angle-dependent energy-shifts of channeling beam via crystalline targets.

THEORETICAL ANALYSIS

The bunch-compressing chicane consists of four dipoles and a slit mask. The mask with slit spacing, W, and aperture width, a, is inserted in the middle of the bunch compressor (dispersion region). The configuration of such a masked chicane is shown with the phase-space plots in Fig. 1. 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 to lower the bunch length while increasing the momentum spread. 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 second half of the chicane refocuses the beam in the longitudinal direction 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.

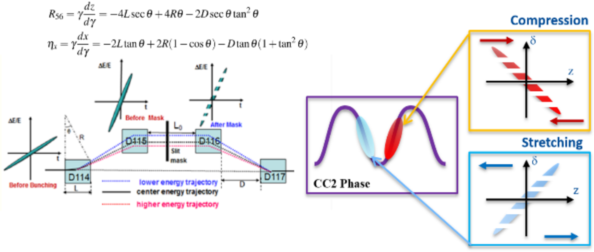

Figure 1: Time-tagged beam ellipse diagram (L) of bunch modulation process through the masked chicane with respect to RF-phase conditions (R).

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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 [6]. The final bunch length can be written as

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

where h_1 is the first order chirp, R_{56} is the longitudinal dispersion, $\sigma_{z,i}$ is the initial bunch length, $\sigma_{\delta\mathrm{i}}$ 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. The bunch-to-bunch spacing of modulated beam, Δz, can thus be derived to be

$$\Delta z = \frac{\sqrt{\left(\sigma_{z,i}+R_{56}\sqrt{\sigma_\delta^2-\tau^2\sigma_{\delta i}^2}\right)^2+\tau^2 R_{56}^2\sigma_{\delta i}^2}}{\eta_{x,mask}\sqrt{\sigma_\delta^2-\tau^2\sigma_{\delta i}^2}} \qquad (2)$$

where η_x is the transverse dispersion.

With the calculated bunch-to-bunch spacing, the micro-bunch length can be evaluated as $\sigma_{z,m} = T \cdot \Delta z$, where T ($= a/W$) is the mask transparency (~33 % here), assuming the time structure of the beam is similar to the mask pattern [5].

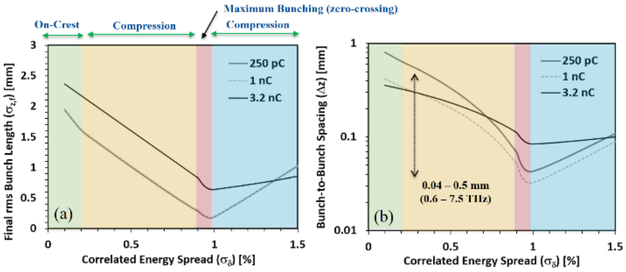

Figure 2: (a) Final rms bunch length ($\sigma_{z,f}$) and (b) bunch-to-bunch spacing (Δz) versus correlated energy spread.

We examined final bunch lengths ($\sigma_{z,f}$) and bunch-to-bunch spacings (Δz) with respect to correlated energy spreads, σ_δ, for the beam with nominal FAST electron beam parameters [2, 4] and three discrete bunch charges: 250 pC, 1 nC, and 3.2 nC. The modulated bunch profiles are calculated with the following conditions based on the FAST chicane design parameters: $\sigma_{\delta,i} = 0.1$ %, $\tau = 1$, $R_{56} = -0.192$ m, and $\eta_x = -0.34$ m. For a beam with small correlated energy spread ($\sigma_\delta \sim 0.1$ %), the bunch is barely compressed and the final bunch length ($\sigma_{z,f}$) is nearly same as initial bunch length $\sigma_{z,i}$ (= 1.93 mm for 250 pC, 1.95 mm for 1 nC, and 2.56 mm for 3.2 nC), as shown in Fig. 2. One can see that the compression becomes quickly effective and the bunch length is steeply shortened as σ_δ increases until it reaches 1 %. When σ_δ reaches about 1 – 2 % with $h_1 = -1/R_{56}$, the beam is maximally compressed and the final rms bunch length ($\sigma_{z,f}$) tends to approach $\tau \cdot R_{56} \cdot \sigma_{\delta i}$.

Note that further increase of σ_δ results in stretching of the beam again from the minimum compression bunch length. The bunch length through 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. Figure 2(b) 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 ~ 1 %. 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, Shower [8], to include particle transition effects through a mask material. In order to analyse characteristics of the bunched beam, charge distribution, beam energy distribution, and the beam spectrum are monitored at the exit of the chicane. As shown in Fig. 3, a slit-mask with W = 900 μm and a = 300 μm was modeled with bunch charges of 250 pC, 1.0 nC, and 3.2 nC. As theoretically assessed, 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. However, the amplitude of beam modulation is noticeably reduced if the slit is replaced with the one with the period of W = 600 μm. The slit-mask design with W = 900 μm and a = 300 μm was selected for further investigation with Elegant.

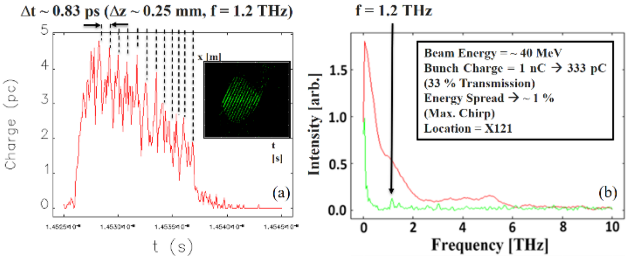

Figure 3: Elegant simulation result (a) temporal bunch profile (inset: x-t distribution) (b) FFT beam spectrum with maximum (green) and minimum (red) energy spreads.

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 [1]. The charge distribution for the beam with minimum and maximum energy chirps are shown in Fig. 3. The beam with minimum energy chirp (red) appears not to carry a modulation pattern in the particle distribution. One can see that under this condition, the presence of the slit-mask negligibly influences 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 chirp (green) appears much stronger than that with minimum energy spread, as plotted in the normalized charge distribution of Fig. 3(a). Although there are some differences due to approximations in the analytic model and some perspectives disregarded in Elegant simulations, those results show the feasibility of ~ 100 fs micro-bunch generation from the designed chicane. We also notice that the corresponding frequency of the bunch-to-bunch spacing is around 1.2 THz, which is just around the first peak of the frequency spectrum of the modulated beam as shown in Fig. 3(b).

PRELIMINARY MPI-MEASUREMENT

The slit-mask was tested with the BC1 masked chicane and we took preliminary data from the modulated beam with respect to RF phases of the 2nd capture cavity (CC2). For the experiment, a tungsten slit-mask was inserted at instrumentation cross X115 of BC1, as shown in Fig. 4. OTR signals from the beam sliced by the mask were measured at X121. The beam signals were sent to the Martin-Puplett Interferometer (MPI) and streak camera. Both supply temporal distributions of a longitudinally modulated bunch. The longitudinal profiles were first measured by the MPI/streak camera without the slit-mask and re-tested with the mask with three times higher bunch charge to compensate for the mask transparency (33 %). The total number of electrons arriving at the X121 screen was normalized for the two tests: with and without the mask inserted in the chicane. CC2 RF-phases were scanned from on-crest (minimum energy spread) to maximum chirp (maximum energy spread) for the MPI-measurement.

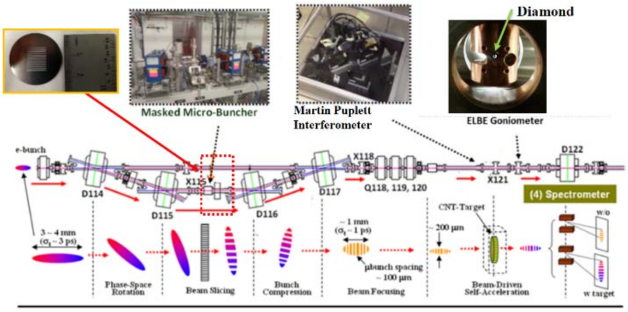

Figure 4: FAST 50 MeV injector beamline with masked-chicane micro-buncher test setup.

The initial data were measured for 90 pC (no slit) and 270 pC (slit-in) with ~ 43 MeV beam energy, ~ 14 MV/m CC2 gradient, and 50 bunches/macro-pulse. The CC2 RF phase was scanned from 103 degrees (on-crest) down to 73 degrees, slightly past the maximum-chirp RF-phase of 78 degrees. Figure 5 shows the signal-to-noise ratio (SNR) versus CC2 RF-phase graph with summarized phase-scan data, including autocorrelations and beam spectra. Here, the SNR is defined as

$$SNR = \frac{<|I(slit_{in}) - I(slit_{out})|>}{\sqrt{\delta^2_{slit_{in}} + \delta^2_{slit_{out}}}} \qquad (3)$$

where $I(slit_{in})$ and $I(slit_{out})$ are the signals from the modulated beam with the slit in and the unmodulated beam with the slit out respectively, and $\delta_{slit\text{-}in}$ and $\delta_{slit\text{-}out}$ are similarly the noise-errors with the slit-in and the slit-out. Note that the signal is more dominant than the noise if the SNR is larger than unity. Of the tested phases, only the SNR for a CC2 RF-phase of φ_{CC2} = 84 degrees appeared to be greater than 1 (SNR = 1.2, see Fig. 5), which indicates that there could be a sign of beam modulation at that phase.

The signals of other phases were not strong enough and it is not clear if the beam was modulated in those phase conditions. In particular, the transverse beam size becomes too small at the X115 mask-position for $\varphi_{CC2} >$ 91 degrees, so no modulation is possible. In this case the bunch length is too large so no meaningful autocorrelation signal is detected in the MPI. The energy-spread dependent modulations will be further investigated.

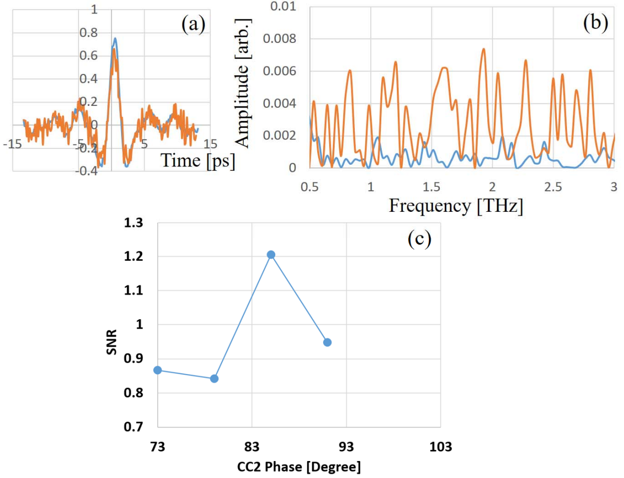

Figure 5: (a) Autocorrelation and (b) beam spectral plots at φ_{CC2} = 84 degrees (c) signal-to-noise (SNR) versus CC2 RF-phase graph.

CONCLUSION AND FUTURE PLAN

The chicane micro-buncher was designed with a periodic multi-slit for the FAST 50 MeV injector beamline parameters. Temporal structure and signal spectra of the modulated beam was analyzed through linear theory and tracking simulation software (ASTRA, Shower, & Elegant) with respect to various bunch charges and correlated energy spreads. The slit-masked chicane was tested with a MPI and streak camera. The preliminary experimental data indicate that the beam might be modulated with some degree of bunch compression, although SNRs of this first study are mostly too low to identify a clear modulation pattern. We are planning to re-test it with higher bunch charges to increase the SNR for a next FAST run in parallel with beam-driven crystal channeling acceleration test.

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