EXPERIMENTAL CHARACTERIZATIONS OF 4-D TRANSVERSE PHASE-SPACE OF A COMPRESSED BEAM*

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Abstract

Coherent synchrotron radiation (CSR) may severely deteriorate electron beam qualities, such as distortion of energy spectrum and transverse phase-space in the bending plane when the beam transports through a magnetic bunch compressor. Recently some laboratories conducted some investigations on CSR effects but mostly focused on the measurements of emittance growth and energy spread and or/ energy loss. However, these parameters may not completely represent a fully compressed beam because its phase spaces may be severely distorted and thus some information may be lost if only these basic parameters are used. It is preferred to reconstruct six-dimensional phase spaces of a compressed beam using tomographic techniques in order to fully understand a beam affected by CSR effects. This report will focus on the four-dimensional transverse phase-space tomographic measurements for a fully compressed beam at 60-MeV energy. Its experimental characterizations at different beam parameters are preliminarily examined.

INTRODUCTION

Short electron bunches traversing a dipole can emit coherent synchrotron radiation (CSR) at wavelengths longer than the bunch length. The enhanced radiation power is proportional to the square of the bunch charge, which results in significant energy loss and increase of energy spread. Since it takes place in a dispersion region, the effect is coupled to transverse plane through optical-chromatic transfer function R_{16} and R_{26} resulting in emittance growth: $\langle \Delta x^2 \rangle = \left(\int R_{16}(s) \frac{d\sigma_\delta}{ds} ds \right)^2$ and $\langle \Delta x'^2 \rangle = \left(\int R_{26}(s) \frac{d\sigma_\delta}{ds} ds \right)^2$, σ_δ is the relative energy spread. Experimental investigations on emittance degradation and the increase of energy spread and or/ energy loss caused by the CSR effects are already performed at some laboratories [1-3]. However, by discussing beam ellipses or by making a-priority assumptions concerning the distribution of the beam in phase space in order to fit quadruples-scan data or other measurement techniques to some beam parameters such as emittance some information may be lost particularly when the beam is distorted in phase-space through a magnetic bunch compressor. It is strongly recommended to apply the tomographic techniques to reconstruct phase spaces of a compressed beam. UCLA group used multi-slit system to reconstruct the transverse phase space of a compressed beam at 12-MeV energy, and firstly discovered the phase-space bifurcation [4]. However, most bunch compressors for x-ray FELs and linear colliders operate at least several tens of MeV to overcome strong space charge effects. As for that, we will investigate the transverse phase space of a compressed beam at a high energy of 60-MeV at Brookhaven Accelerator Test Facility (ATF) using quadruples-scan-based tomographic technique [5].

TOMOGRAPHIC TECHNIQUE

Figure 1 shows a schematic of the ATF H-line including a photoinjector, two s-band linac sections, a magnetic bunch compressor (or call it as chicane), beam profile monitors (BPMs) and other focusing elements. The electrons are produced at the ATF by a photo-injector, whose photocathode is illuminated by a frequency-quadrupled Nd:YAG laser. Two S-band (2856 MHz) linac sections are used to accelerate electrons. There are three triplets and a 4-bend magnetic bunch compressor, with which the electron bunch length can be compressed down to sub-ps. The beam images were monitored using six YAG-screen-based BPMs at different locations. The tomographic measurements are performed at the ATF H-line.

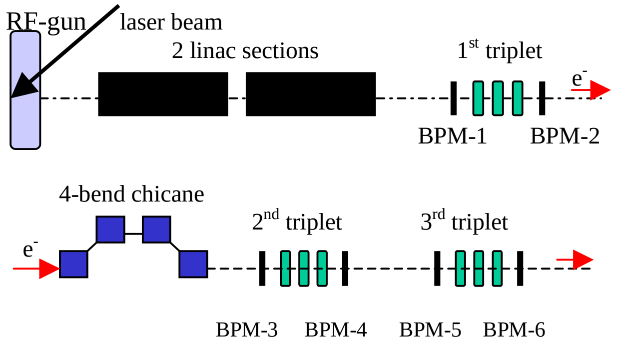

Figure 1: Schematic of the ATF H-line

The tomographic technique developed at the ATF [5] uses a number of quadruples in the beam transport in order to rotate the phase-space distribution. In principle, projections of the electron beam taken at various phase-

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advance angles can be used to derive the phase-space density distribution. The phase-space reconstruction technique uses the “filtered back-projection”. The desired density in x and x′ phase-space μ(x, x′) can be obtained from the measured data $\lambda_\phi(x)$ by the transform below. $\lambda_\phi(x)$ is obtained from the BPM data by projecting the x-y distribution onto the x-axis for a given phase advance ϕ. Total phase rotation angle is 180-deg. The phase-space density distribution μ(x, x′) is obtained by the following integral of the “filtered projection”:

$$\mu(x,x') = \int_0^{\pi} \lambda_\phi^{+}(\xi)\,d\phi\Big|_{\xi = x\cos\phi + x'\sin\phi} \qquad (3)$$

where $\lambda_\phi^{+}(\xi)$ is called as the “filtered projection”, which can be obtained from the projection data $\lambda_\phi(x)$ by the following equation:

$$\lambda_\phi^{+}(ms) = \frac{1}{4s}\lambda_\phi(ms) - \frac{1}{\pi^2 s}\sum_{\substack{n \\ (m-n)odd}} \frac{\lambda_\phi(ms)}{(m-n)^2} \qquad (4)$$

where m is an integer, s is the pixel size and x = ms. The resolution of the reconstructed transverse phase space is extensively studied, which shows totally 32 projections in the phase rotations are needed to provide high resolution.

TOMOGRAPHIC MEASUREMENTS

Twiss Parameters Measurements at the 4-bend Magnetic Bunch Compressor

The ATF magnetic bunch compressor was designed, manufactured and installed by the UCLA group [6]. It has four bends with a 20-deg of nominal vertical bending angle. The Twiss parameters of the four-bend chicane are characterized in order to understand: strong edge focusing in the four bends; beam spot sizes inside the chicane probably affecting phase spaces; and Twiss parameters at the chicane exit used for tomographic measurements.

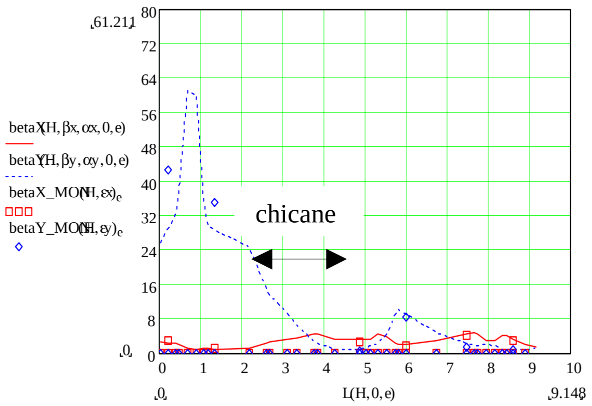


Figure 2: β_x and β_y (m) at ATF H-line with chicane-on

There exist the rotation angles of entrance and or/ exit pole faces in the bending magnets resulting in strong edge focusing in both x and y planes. A MathCAD program is developed to measure beam spot sizes at six BPMs at the ATF H-line and then obtain the Twiss parameters at each position. Figure 2 shows the typical results β_x and β_y, which show the measurement data β_x (red square) and β_y (blue diamond) agree well with the theoretical prediction β_x (red line) and β_y (blue dash-line). It shows beam spot sizes σ_y at 3rd and 4th dipole is smaller than 200-μm rms. Note no any amount of correlated energy spread is applied in the measurement. With the same manner the Twiss parameters at the compressor exit for a compressed beam can be obtained, which are used for optics matching for the tomographic measurements.

Evidences of Full Bunch Compression: Energy Spectrum Distortion and Emittance Growth

R_{56} of the four-bend chicane is ~5.2 cm at a 20-deg of bending angle. Elegant code suggests that the initial 1.7-ps rms bunch length can be compressed down to 110-fs rms by employing suitable amount of correlated energy spread in the chicane (theoretically -11° RF off-crest from two s-band linac sections). Although measuring the compressed bunch length is a straightforward solution to judge whether the bunch is fully compressed, at the ATF there is no so-called convenient advanced diagnostic to directly measure the sub-ps bunch length to date. However, there are some evidences of full bunch compression and thus how many degrees of RF off-crest from both linac sections to induce suitable correlated energy spread can be deduced. The CSR effects created in a bunch compressor can significantly distort the longitudinal energy spectrum and increase the transverse emittance when the bunch is fully compressed. We may make use of these observations to determine the degree of RF off-crest for the compression. The measured energy spectrum shows that it is severely distorted at -11° RF off-crest. The transverse emittance is measured through monitoring beam spot sizes at four BPMs in the downstream of the compressor. Figure 3 shows the emittance vs the RF off-crest, which shows the emittance is increased significantly at -11° RF off-crest. Results from both measurements are consistent.

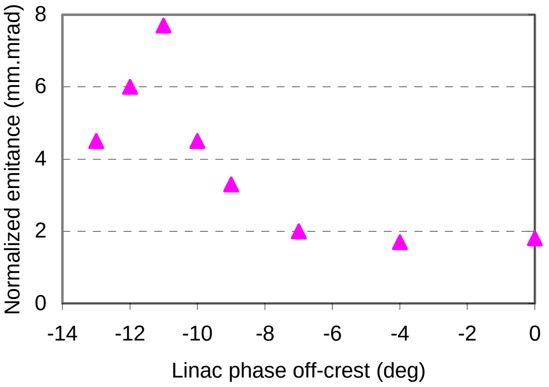


Figure 3: Measured emittance vs linac RF off-crest

Real Transverse Phase Spaces of Uncompressed and Compressed Beams

Analysis shows that the space charge effects may cause the transverse phase-space bifurcation of a compressed beam at 12-MeV energy [4]. However, most bunch compressors operate at higher energy to avoid the space charge effects resulting in beam performance deterioration. Thus, it is essential to characterize the phase-space of a compressed beam at higher energy, particularly whether the phase-space is bifurcated or not. Our phase-space tomographic measurements focus on a compressed beam with 60-MeV energy. In the measurements a lower gun phase is chosen to operate so that the bunch length at gun exit is shorter [7-9], which allows to produce the shortest final bunch after compressor resulting in strong CSR and also apply small correlated energy spread for the compression resulting in small chromatic effects in the downstream of the compressor. Procedure to reconstruct the transverse phase spaces of the compressed or uncompressed beams consists of four steps: to measure the Twiss parameters at the compressor exit for the uncompressed and fully-compressed beams; to match beam optics using both the second and third triplets for different phase rotations based on the measured Twiss parameters at the compressor exit; to record beam images at the BPM-6 for different phase rotations; and to reconstruct the transverse phase spaces using the "filtered projection" as described in Eq. 3 and 4. We did the scan of the phase-space measurements with linac RF phase. Figure 4 shows the reconstructed transverse phase space of an uncompressed beam with RF on-crest. Figure 5 shows the typical reconstructed 4-D transverse phase space of beams with under-, full- and over-compression operating at -5°, -11° and -13° RF off-crest respectively. Note the calibrations in Figs. 4 and 5 are same. It shows the phase spaces in x-plane are similar for these beams. The phase space in y-plane expands and is bifurcated notably but not pronouncedly as observed in the lower energy beam at full bunch compression (i.e., -11° RF off-crest). In both under- and over-compressions, the phase-space shrinks compared with the one at full-compression. The beam spot size at 3rd and 4th bend is smaller than 200-µm rms based on Twiss parameter measurements. The bunch charge for these measurements is constant, 200-pC.

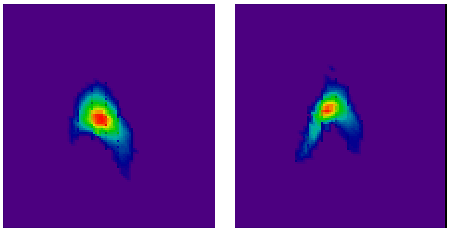
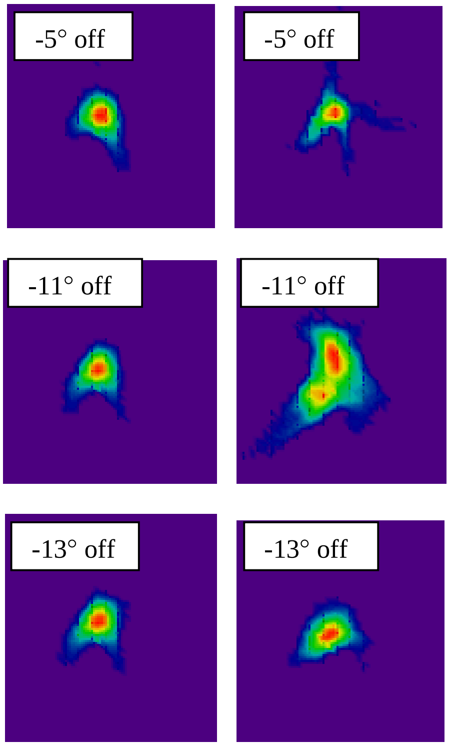

x-x′ y-y′

Figure 4: reconstructed transverse phase space of an uncompressed beam; ordinate axis is x′ (y′), and the abscissa axis is x (y).



x-x′ y-y′

Figure 5: Reconstructed 4-D transverse phase spaces of beams with under-, full- and over-compression operating at -5°, -11° and -13° linac RF off-crest respectively; left plots are x-x′, and right plots are y-y′; note that bending plane is in y-direction; the ordinate axis is x′ (y′), and the abscissa axis is x (y).

SUMMARY

Transverse phase-space bifurcation of a compressed beam is firstly discovered at UCLA/Neptune at 12-MeV beam energy, where the space charge plays dominant role. We characterized the phase-space of a compressed beam at a higher energy where most compressors operate using the quadruple-based tomogrphic technique. The data shows the reconstructed transverse phase space in x-plane is constant. The phase space of a fully compressed beam in the y plane (i.e., bending plane) at 60-MeV energy expands and is bifurcated notably but not pronouncedly as observed in lower energy. We may conclude that the space charge resulting in the novel phase-space bifurcation is alleviated at energy higher than 60-MeV.

REFERENCES

[1] H. Braun, *et al.*, PRST –AB, Vol. 3, 124402 (2000).
[2] M. Borland, *et al.*, PAC2001, Chicago, 2001.
[3] W. Graves, *et al.*, PAC 2001, Chicago, 2001.
[4] S. Anderson, *et al.*, PRL, 074803 (2003)
[5] V.Yakimenko, *et al.*, PRST-AB, 122801 (2003).
[6] J. Rosenzweig, ATF Users meeting, Jan. 2004.
[7] X. Wang, *et al.*, PRE 54, 3121 (1996).
[8] F. Zhou, *et al.*, PRST-AB, 094203 (2002).
[9] F. Zhou, *et al.*, PRL, 174801 (2002).