Observation of Longitudinal Phase Space Fragmentation at the TESLA Test Facility Free-Electron Laser

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Abstract

It has been reproducibly observed that the energy distribution of the beam, when fully longitudinally compressed for SASE operation, breaks up into several peaks. In this paper a description of the experimental setup, beam operating conditions, and observations is presented to enable further theoretical studies of this effect.

1. Introduction: Longitudinal beam dynamics at TTF

A schematics of the Tesla Test Facility (TTF) FEL [1] is depicted in Fig. 1. We shall only concentrate on the longitudinal phase space manipulation since the measurements reported hereafter only pertain to this plane: the beam generation line consists of an L-band radio-frequency (RF) photoinjector coupled to a TESLA-type superconducting accelerating cavity that boosts the beam up to 17MeV. The photocathode drive-laser is gaussian-shaped with an rms time duration of 8ps approximately. The electron bunch then enters an accelerating section (Acc. #1)that consists of eight TESLA-type superconducting cavities. The injection phase of the beam in this latter accelerating section is chosen, under nominal operating conditions, to impart the proper time-energy correlation to compress the bunch using the downstream magnetic chicane-based compressor. The beam transport, downstream the bunch compressor, consists of a second accelerating section (Acc. #2, identical to Acc. #1), nominally operated for maximum energy gain,

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followed by the undulator magnets section. Behind the undulator, the beam is separated from the FEL beam by a spectrometer dipole (that bends in the same plane as the compressor). The transfer line up to the dump is instrumented with several diagnostics which especially include a beam profile measurement station.
A detailed description of the magnetic compressor is presented in Reference [2]. During our measurement, the bending angle in the compressor was set to 19deg, which corresponds to a momentum compaction $R_{56}\simeq$-0.18m. This results in an optimum operating phase for the first accelerating section of -10RF-deg off-crest approximately. Because of the rather long bunch length at the injector front-end, typically 2.7mm (rms), the longitudinal phase space is strongly distorted via RF-induced curvature during its acceleration in Acc. #1. This distortion, impinges the compression process by limiting the minimum reachable bunch length to 0.5mm (rms) approximately (as inferred from multiparticle simulations and experimentally verified).

2. Experimental techniques

During our measurements we used the different beam profile monitors mentioned in Fig. 1: energy spread was measured using the optical transition radiation (OTR) viewers OTR1 and OTR/FLU3 (this latter viewer incorporates both an OTR radiator and a fluorescent screen). At the location of these two beam profile stations, the linear dispersion is estimated to R_{16} =0.31m (bunch compressor) and R_{16} =-1.15m (spectrometer) respectively. The nonlinear dispersion, T_{166}, is found, at both locations, to have no significant impact on the beam horizontal profile so that the horizontal coordinate of an electron, x, scales linearly (to first order) with its relative momentum offset, δ, following $x \simeq R_{16}\delta$. This latter scaling implicitly implies that the contribution from the pure betatron term is insignificant, a true assumption since, for all measurements presented in this paper, a set of upstream quadrupoles, located before the bunch compressor or the spectrometer dipole respectively, were tuned to minimize the horizontal beam spot at the observation point thereby asserting the beam spot was essentially dominated by the dispersive contribution. Based on the measurements of energy profiles at OTR/FLU3 for different phases of Acc. #2 a longitudinal tomography technique was implemented [3]. The method to recover the longitudinal phase-space is based on the MENT [4] (Maximum ENTropy) algorithm which computes the best estimate of the phase space density by maximizing its entropy. At the compressor exit the transverse beam density can also be measured using OTR2. At that point the dispersion was found not to be zero, we believe because of spurious dispersion generated by non-zero value of upstream correctors. The diagnostics package also include a bunch length monitor located downstream the second accelerating section. This device provides bunch length measurement by the mean of a sub-millimeter wave polarizing interferometry of coherent transition radiation [5] (CTR). We did not systematically measure the bunch length but rather assess whether the first accelerating section

(Acc. #1) was operated for maximum compression by simply "peaking" the CTR power detected by a pyroelectric detector. All the measurements reported in the following were performed with a charge per bunch of 1nC (within 10%), except when explicitely mentioned. The following observations are proved to be from single RF-bucket by using a streak camera setup.

3. Observations

Energy profiles versus incoming time-energy correlation: In this series of measurement the compressor is operated, and the bunch compression is varied by operating Acc. #1 at different phase to act on the incoming longitudinal phase space slope, $d\delta/ds$: at maximum compression it is related to the bunch compressor momentum compaction by relation $d\delta/ds = -1/R_{56}$. We found, using the CTR signal, that the maximum compression was occurring -10deg w.r.t. the maximum energy gain phase. For this operating conditions, the beam energy was about 135MeV at the bunch compressor location and 230MeV downstream Acc. #2. After each change of Acc. #1 phase, the phase of the Acc. #2 accelerating section was reset to maximize the energy at the machine front end. Fig. 2, depicts the evolution of the beam density recorded at the observation point (i.e. OTR/FLU3) for some phase of the Acc. #1. The maximum compression occurs at $\phi \simeq$-8deg[2] whereas the maximum energy gain through the whole linac is obtained for $\phi \simeq$+2deg. From Fig. 2 we conclude that when the time-energy induced correlation by Acc. #1 does not provide compression, i.e $\phi >$+2deg, the energy profile is as expected: it consists of a bright core with a long energy tail due to the RF-induced curvature because of the relative long incoming bunch. As the time-energy induced correlation allows compression, $\phi <$+2deg, the energy profile starts to show multiple fine structure which seems to separate into two main "islands" at maximum compression. Finally, in the over-compression regime, $\phi <$-8deg, these multiple structures start disappearing and are hardly observable at phases below -14deg.

Impact of the bunch compressor: For three cases (i) bunch compressor operated and accelerating section Acc. #1 operated for maximum compression, (ii) bunch compressor operated and Acc. #1 operated on-crest, and (iii) bunch compressor off with Acc. #1 operated approximately -10deg off-crest, we have investigated the evolution of the energy profile in the high energy spectrometer line for various phase of Acc. #2 ultimately to take tomographic data in order to recover the full longitudinal phase space density. The energy profiles for these three cases are presented in Fig. 3 (Acc. #2 was set for maximum energy gain). A structured energy profile, as the one presented previously, is observed only in the case when the linac operated in maximum compression mode. This feature,

[2] The phase value ϕ mentioned hereafter are arbitrary value read from the control system.

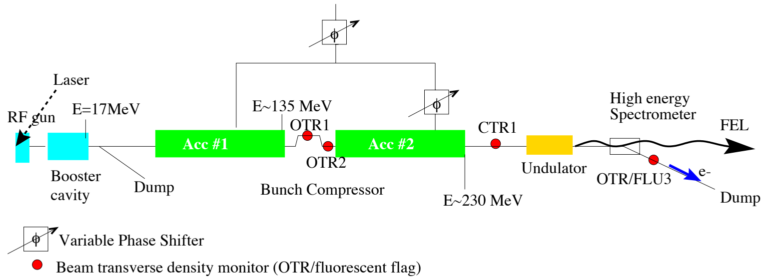

Fig. 1. Overview of the Tesla Test Facility Phase I.

which was also observed for other bunch charge, suggests the induced fragmentation of the energy profile is related to the compression process. At the bunch compressor exit, some structure can already be noticed by observing the beam transverse density at OTR2, but none was observable at OTR1. For the case (ii) the reconstructed longitudinal phase space at the compressor exit is shown in Fig. 4.

Charge-dependence To asses whether the observation could be attributed to collective effects, we also measured the energy distribution for bunch charge ranging from 0.5 to 4nC. The distribution shows no significant dependence on the charge, though the collective effects hypothesis cannot be ruled out: the charge was varied by changing the photocathode drive laser intensity, which impacts the bunch length: from multiparticle simulations we expect that an increase of the charge from 0.5 to 4nC, would double the bunch length (from 2 to 4mm (rms)) principally because of longitudinal space-charge force.

4. Summary

An anomalous "beam break up" of the longitudinal phase space has been observed at TTF-FEL when the linac is operated so that the bunch compression is maximized. A mechanism based on bunch self interaction via coherent synchrotron radiation is discussed in Reference [6].

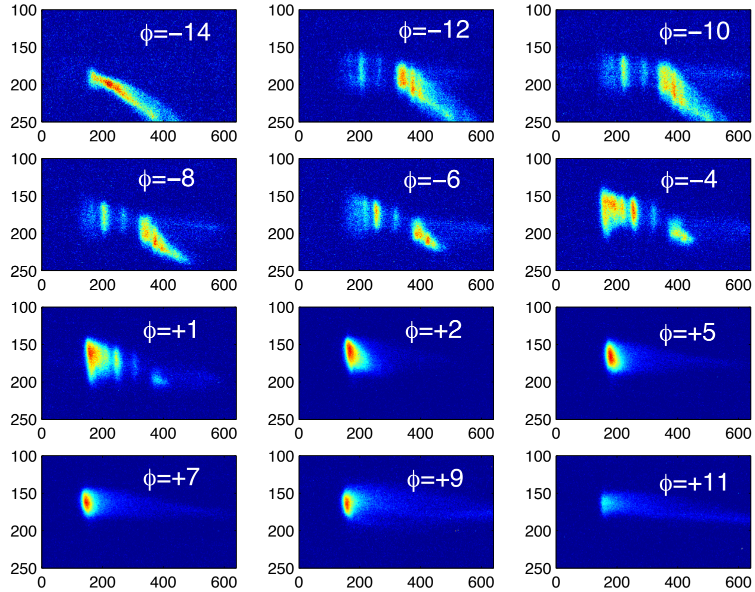

Fig. 2. Single bunch beam transverse density observed at the profile measurement station OTR/FLU3. These measurements were performed using the fluorescent screen.

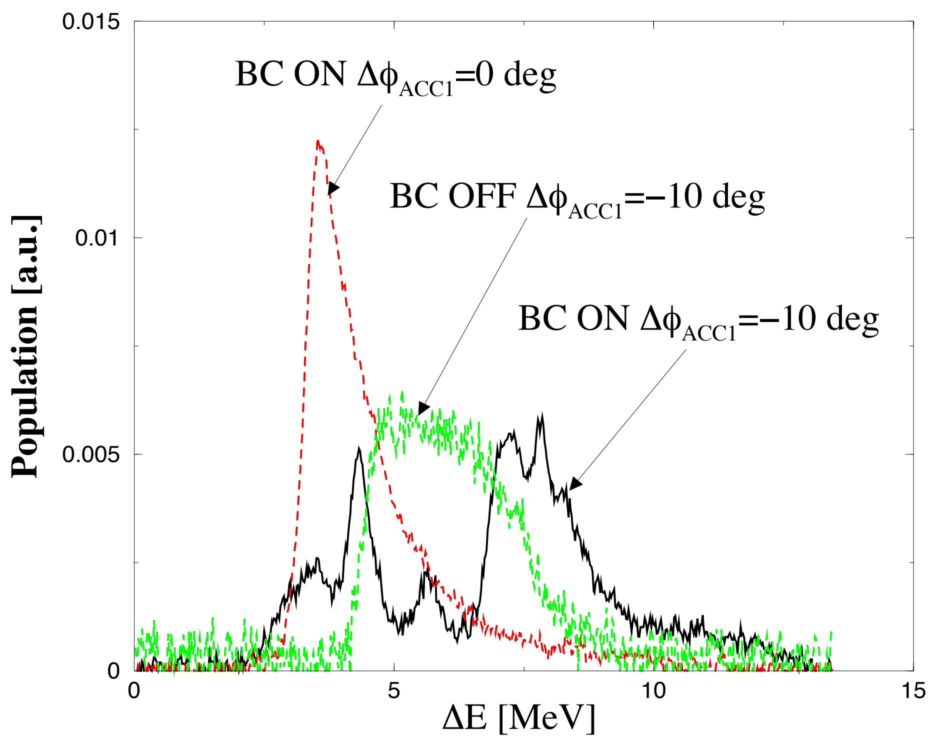

Fig. 3. Energy profile obtained for three different senarii of operation: bunch compressor ON with Acc. #1 on-crest ($\Delta\phi = 0$deg), and setup for minimum bunch length ($\Delta\phi = -10$deg), and bunch compressor OFF with $\Delta\phi = -10$deg.

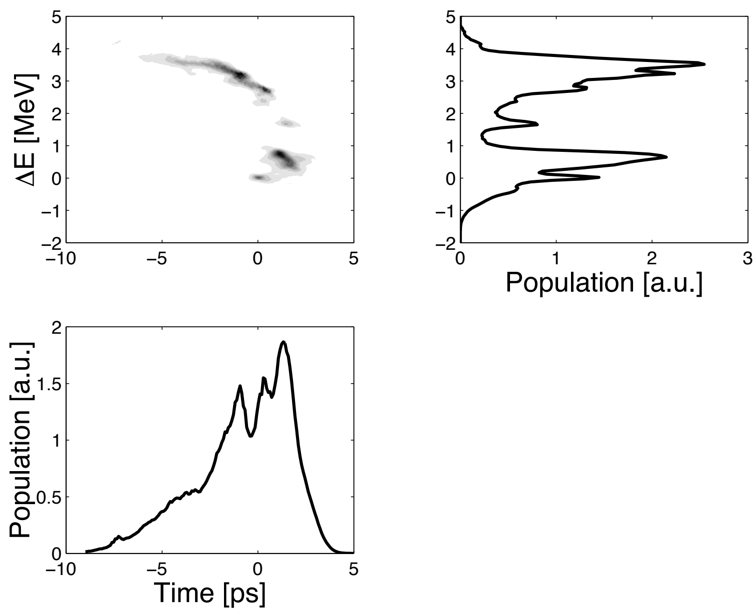

Fig. 4. Reconstructed longitudinal phase space downstream the bunch compressor **(top left)** and energy **(top right)** and time **(bottom)** charge density. (Time>0 correspond to the bunch head)

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