COMMISSIONING OF TTF2 BUNCH COMPRESSORS FOR GENERATION OF 20 FEMTOSECOND SASE SOURCE

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Abstract

By the help of nonlinearity in the longitudinal phase space, the VUV-FEL at the TESLA Test Facility phase 2 (TTF2) is under operating in the femtosecond (fs) FEL mode which generates coherent and ultra-bright SASE source with photon pulse duration time of around 20 fs (FWHM) and wavelength of around 32 nm. For the fs FEL mode operation, bunch length of electron beams should be compressed by two bunch compressors to have a leading spike in the longitudinal beam density distribution or peak current. The required peak current at the spike is higher than about 1.0 kA, and the spike length is shorter than around 200 fs (FWHM). In this paper, we describe our commissioning experiences to optimize two TTF2 bunch compressors for the fs FEL mode operation.

INTRODUCTION

Originally, Saldin *et al* proposed the fs FEL mode operation for the VUV-FEL due to the delayed installation of the 3rd harmonic cavities and users' request on a shorter pulse [1]. To generate more stable SASE source for a long time, recently, we increased single bunch charge from 0.5 nC to 1.0 nC and changed several other machine parameters from their original scheme [2]. One of our current nominal TTF2 machine layout for the fs FEL mode operation is shown in Fig. 1, where the 3rd harmonic cavities ACC39, the 6th TESLA superconducting accelerator module ACC6, and three seeding undulators SEEDING are not installed yet. Its detail linac parameters are summarized in Table 1. Note that here all parameters are projected ones, and with this machine layout and machine parameters, we could generate SASE source at a wavelength of around 32 nm on April 9th, 2005. Since nonlinearities in the longitudinal phase space can not be compensated without ACC39, two TTF2 bunch compressors (BC2 and BC3) compress bunch length nonlinearly [3]. In this case, a charge concentration or spike in the peak current is generated at the leading head region as shown in Fig. 2 [2], [3]. When the VUV-FEL generated the first lasing at 32 nm, there was no special diagnostic tool such as the LOLA cavity to measure fs range bunch length. However we could optimize two TTF2 bunch compressors (BCs) by comparing measured results with simulation ones and by measuring machine status and beam parameters with basic diagnostic tools such as pyroelectric detector and OTR screens. In this paper, we describe our commissioning experiences to optimize two TTF2 bunch compressors for the fs FEL mode operation.

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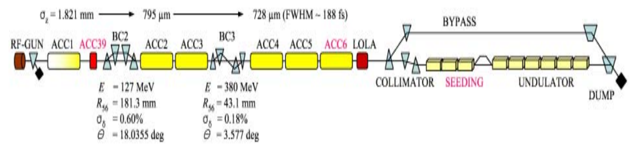

Figure 1: TTF2 layout for the fs FEL mode.

Table 1: TTF2 main linac parameters for the fs FEL mode.

Parameter	Unit	Value
single bunch charge	nC	-1.0
RF frequency of gun and TESLA module	GHz	1.3
gun peak gradient on the cathode	MV/m	40.25
gun phase from zero crossing	deg	38
low / high accelerating gradient in ACC1	MV/m	12.95 / 16.84
ACC1 phase from on crest	deg	$\sim$ -9.0
accelerating gradient in ACC2 / ACC3	MV/m	17.29 / 13.53
ACC2 / ACC3 phase from on crest	deg	$\sim$ 0.0
accelerating gradient in ACC4 / ACC5	MV/m	3.85 / 4.03
ACC4 / ACC5 phase from on crest	deg	0.0
beam energy after ACC5	MeV	445
rms relative energy spread after ACC5	%	0.16
horizontal / vertical emittance after ACC5	μm	3.17 / 2.05
bunch length (FWHM) after ACC5	fs	$\sim$ 188

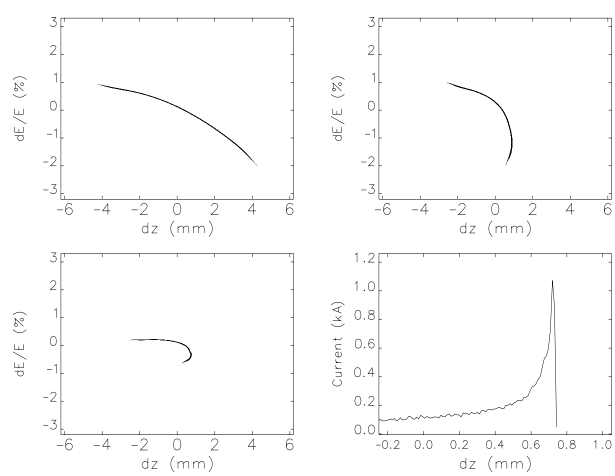

Figure 2: Longitudinal phase space before BC2 (top left), after BC2 (top right), after BC3 (bottom left), and peak current after BC3 (bottom right) for the machine layout in Fig. 1 and linac parameters in Table 1. Here positive dz means the leading head in a bunch.

BC COMMISSIONING EXPERIENCES

Setup of Energy, Energy Spread, and R_{56}

As to two TTF2 BCs, detail design concepts for the nominal FEL mode operation are well described in reference [4]. To get the best BC performance for the fs FEL mode operation, we should properly choose beam energy at BCs, energy spread or RF phases of precompressor linacs (ACC1 for BC2, ACC2 and ACC3 for BC3), and the chicane strength R_{56} or bending angle of dipole magnet [3]. During the fs FEL mode operation, a charge concentration or a spike is generated within a local small area as shown in Fig. 2. Therefore beam energy at BCs should be high enough to avoid any possible beam dilution due to space charge effects in the spike. After considering the maximum available gradient of precompressor linacs, we chose 127 MeV and 380 MeV for the beam energy at BC2 and BC3, respectively. The exact beam energy at the BCs can be set up by positioning the beam image at the center of a screen in the chicane as shown in Fig 3(top row). Here 3BC2 screen is located at a point in BC2 where the horizontal dispersion is its maximum, and its horizontal beam position corresponds to beam energy at the bunch compressor. If beam energy is higher (or lower) than 127 MeV, horizontal beam position is at the left (or right) side of the 3BC2 screen. Although we can adjust bending angle or magnet current of chicane dipole, we fixed the bending angle of the chicane to measure beam energy at BC easily. From beam position on the screen and a calibration factor between chicane dipole current and beam energy, we can measure beam energy at BC easily.

To choose operational phase of precompressor linacs properly, we should consider various things such as projected and slice emittances, bunch length or peak current,

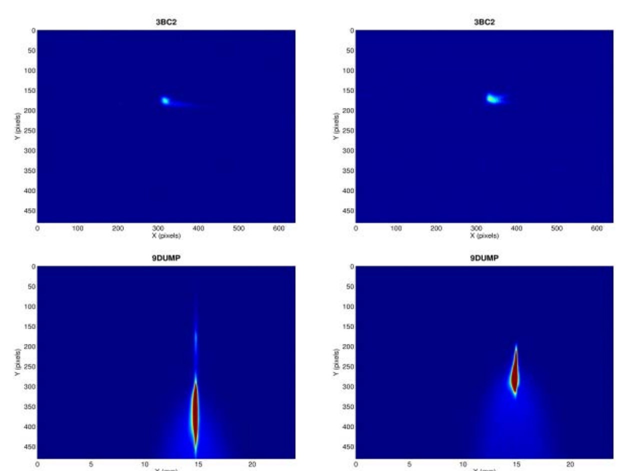

Figure 3: Beam images on 3BC2 and 9DUMP screens when ACC1 phase is on crest (top left), -2.0 degree off crest (top right), around -9.0 degree (bottom left), and around on crest (bottom right).

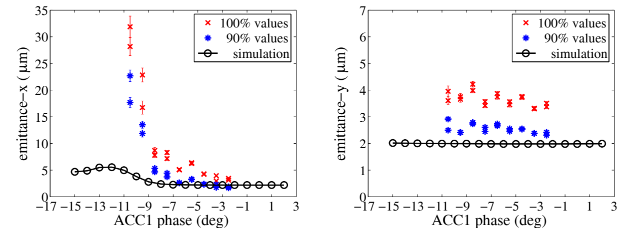

Figure 4: Simulation and measured results of projected emittance after BC2 for different ACC1 phase: (left) projected normalized rms horizontal emittance and (right) projected normalized rms vertical emittance.

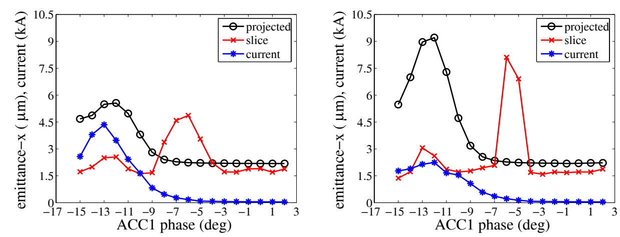

Figure 5: Simulation results of projected and slice normalized rms horizontal emittances and peak current after BC2 (left) and after BC3 (right).

projected and slice energy spread, beam loss in the collimator, and the longitudinal space charge force. After considering simulation and measured results of projected emittance after BC2 as shown in Fig. 4, we chose phases between -10 degree to -9 degree as the best operational phase of ACC1. In this case, slice emittance is around its minimum, and peak current is high enough as shown in Fig. 5(left), where slice emittance is the averaged slice emittance within the FWHM of the leading spike. Although we can choose more off crest phase to get a higher peak current after BC2, horizontal projected and slice emittance become worse due to stronger coherent synchrotron radiation (CSR) effects at BC2 as shown in Figs. 4(left) and 5(left). Since CSR attacks only in the bending horizontal plane, vertical projected emittance is almost constant though peak current is about a few kA as shown in Figs. 4(right) and 5(left). That constant vertical emittance also indicates that space charge effects at BC2 is weak enough though peak current is high. To reduce beam loss at the collimator and to reduce the projected and slice energy spread at the entrance of undulator, we chose on crest phase from ACC2 to ACC5 modules. In this case, ACC1 module and BC2 supply $dz - dE/E$ chirping at BC3, and BC3 can continuously compress bunch length to get more higher peak current of around 1 kA as shown in Figs. 2 and 5. To compress the bunch length more strongly at BC3, we can choose somewhat off crest phase in ACC2 and ACC3 modules.

Note that there are two special things in Fig. 5: First, slice emittance is significantly increased if ACC1 phase is between -8 degree and -4 degree off crest. This is related with the longitudinal position in a single bunch where compression is generated. For those off crest phases, the compression is generated around the head region where slice emittance is generally high [5]. But phases between -10 degree and -9 degree, compression position is shifted to the bunch core where slice emittance is low. Second, peak current after BC3 is not increased further if ACC1 phase is lower than -11 degree. This is related with the nonlinearity in the longitudinal phase space and the maximum compression at BC2. Since the maximum compression at BC2 is happened at around -13 degree off crest as shown in Fig. 5(left), and there is strong nonlinearity in the longitudinal phase space for ACC1 phase ≤ -11 degree, bunch length can not be compressed further by BC3. In this case, two or three spikes in peak current are generated by BC3, and the maximum peak current among spikes is always lower than that after BC2 as shown in Fig. 5.

Since bunch length or peak current after BC3 is significantly changed according to the ACC1 phase, it is important for us to know how to set up off crest phase of ACC1 exactly. Since a signal from the pyroelectric detector is proportional to the intensity of CSR, we can use the detector signal to find a phase which gives the maximum bunch length compression. At the TTF2, we find that there is always a constant phase difference between on crest phase and the maximum compression phase. At the BC2 (BC3), the maximum compression is always happened when ACC1 (ACC2 and ACC3) phase is about -13 degree (-42 degree) off crest as shown in Fig. 6. Therefore on crest phase can be exactly determined just by adding +13 degree (+42 degree) to the maximum compression phase of ACC1 (ACC2 and ACC3). There is the second method which can be used to find on crest phase of ACC1. Whenever ACC1 phase is around -2.0 degree off crest, we can find two symmetric branches at the tail region or lower energy region in the beam image on 3BC2 screen as shown in Fig. 3(top right). Here, we can clearly see those branches in the figure by zooming in with the Acrobat Reader. This is related with symmetric shape of longitudinal phase space when ACC1 phase is -2.0 degree. We can find its related longitudinal phase space from Y. Kim's presentation in reference [2]. By adding +2.0 degree to the phase which gives the symmetric two branches at the tail region on 3BC2 screen, we can find on crest phase of ACC1 module exactly.

In case of ACC4 and ACC5 modules, we can approximately find on crest phase by scanning phase while monitoring beam image on the 9DUMP screen or 5ECOL screen in the dog-leg. If vertical beam size on 9DUMP screen is close to its smallest one, and beam image on 9DUMP screen is located at the lowest vertical position, beam energy is highest, and the phase is close to on crest.

Since we fixed bending angles in BCs to measure beam energy easily, R_{56}s of two BCs are always constant as shown in Fig. 1. Instead of adjusting R_{56}, we change phases of precompressor linacs to adjust compression strength at BCs.

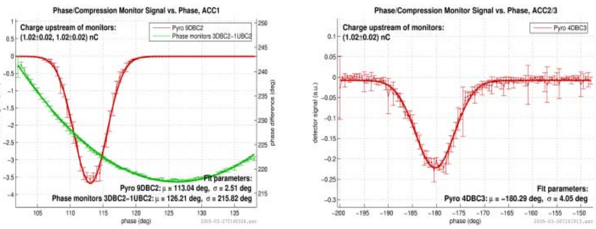

Figure 6: Measured signals of pyroelectric detector and phase monitor: (left) at 9DBC2 while ACC1 phase is scanned and (right) at 4DBC3 while ACC2 and ACC3 phases are simultaneously scanned for on crest ACC1 phase. Here 9DBC2 and 4DBC3 pyroelectric detectors are located at the downstream of BC2 and BC3, respectively.

Fine Tuning for fs FEL Mode

Whenever we get the lasing, beam image at 9DUMP screen has a sharp leading beamlet at the top region as shown in Fig. 3(bottom left), which corresponds to the spike at the leading head in the peak current. When we do not compress bunch length or we lose SASE, beam image at 9DUMP screen is such as shown in Fig 3(bottom right). Therefore, for the fs FEL mode operation, we can finely tune phases and gradients of GUN and precompressor linacs by monitoring beam image at 9DUMP screen and the MCP gain of SASE source. With a similar machine layout as shown in Fig. 1 and similar machine parameters as summarized in Table 1, we could generate about 155 fs (FWHM) long electron spike in the leading head region, which was recently measured with the LOLA cavity for ACC1 phase $\simeq -10$ degree off crest as shown in Fig. 7. This measured bunch length is well agreed with our simulation results; about 160 fs (FWHM) for -10 degree and about 188 fs (FWHM) for -9 degree off crest. With around 155 fs (FWHM) long electron spike, recently, we could generate coherent SASE source with peak photon energy of about several μJ and photon pulse length of around 20 fs at 32 nm [6], [7].

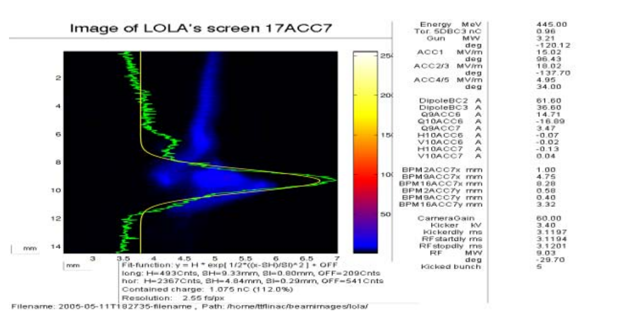

Figure 7: Electron beam image on LOLA screen 17ACC7 when ACC1 phase is about -10 degree and other parameters are such as summarized in Table 1. Here measured bunch length is about 155 fs (FWHM).

Stability of Bunch Length

Even though we could generate 20 fs long SASE source during TTF2 commissioning period, we lost SASE source from time to time. This loss is generated mainly by the unstable RF low level system. Since unstable ACC1 RF phase induces drift in energy spread at BC2, bunch length and peak current after BC2 is continuously changed.

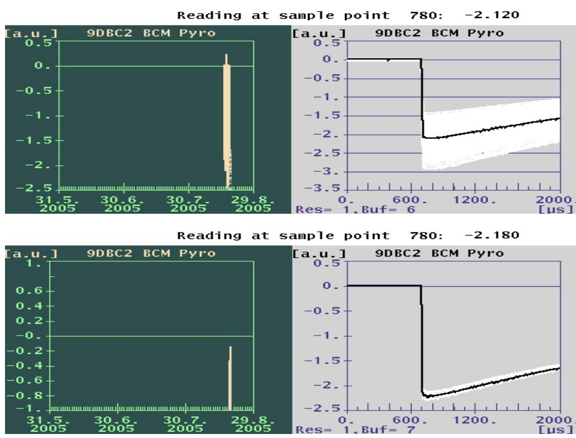

Figure 8: 9DBC2 pyroelectric detector signal: (top) when no slow feedback is applied to ACC1 RF phase and (bottom) when a slow feedback is applied to ACC1 RF phase to keep energy spread at BC2 constant and to generate stable bunch length at the downstream of BC2.

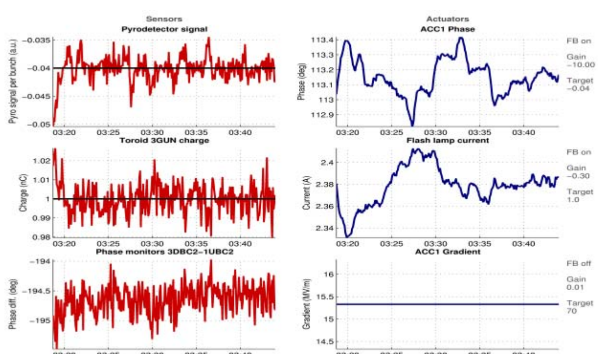

Figure 9: Three slow feedback systems to improve BC performance: (top left) 9DBC2 pyroelectric detector signal per bunch, (top right) a slow feedback system is applied to ACC1 RF phase to keep constant pyroelectric detector signal or bunch compression status at BC2, (middle left) 3GUN toroid signal at the downstream of RF gun, (middle right) a slow feedback system is applied to laser flash lamp current to keep constant single bunch charge at the 3GUN toroid, (bottom left) difference in signals of two phase monitors, which are located at the upstream and downstream of BC2, (bottom right) a slow feedback system can be applied to ACC1 gradient to keep beam energy at BC2 constant. Here last slow feedback system is turned off.

This drifting bunch length is detected by the 9DBC2 pyroelectric detector as shown in Fig. 8(top), where white lines show history of drifting 9DBC2 pyroelectric detector signal or drifting bunch length. To solve drift in bunch length and peak current, we apply a slow feedback system in ACC1 RF phase as shown in Fig. 9(top). By applying the slow feedback in ACC1 RF phase in every few ten seconds, we can effectively reduce drift in energy spread at BC2 and drift in 9DBC2 pyroelectric detector signal as shown in Fig. 8(bottom). Therefore we could generate stable bunch length and peak current after BC2, and we can keep stable SASE source for a longer time. To improve BC performance further, we apply three slow feedback systems to laser flash lamp current, ACC1 RF phase, and ACC1 RF gradient as shown in Fig. 9.

SUMMARY

By using nonlinearities in the longitudinal phase space and by choosing proper RF phases in precompressor linacs, we could generate about 155 fs (FWHM) long spike at the leading head region of electron bunch. Even though we used several basic diagnostic tools, estimated bunch length with simulation was well agreed with measured one with the LOLA cavity. That means that our bunch compressors were optimized properly as we desired. Since estimated peak current and slice emittance at the leading spike are around 1 kA and 2 μm, respectively, we can generate about 20 fs long SASE source from the spike. By applying slow feedbacks to the RF phase and amplitude of the precompressor linac and to laser flash lamp current, we can keep bunch length and peak current constant, which is helpful to generate stable SASE source for a longer time. We will optimize bunch compressors further by measuring bunch length and slice beam parameters with the LOLA cavity and by measuring projected emittance with OTR screens.

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