First experimental research of the bunch compressor at CAEP

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Abstract Magnetic bunch compressor is one of the key technologies on the path to next generation accelerator driven facilities. In this paper we report the design principles and the first experimental research of the bunch compressor developed at Chinese Academy of Engineering Physics (CAEP). The length of the bunch after compressor is found to be about 0.7 ps (rms) and the peak current exceeds 500 A when operated in the optimized condition. The sensitivity of the bunch length on the phase of the acceleration field and magnetic field of the bunch compressor was also measured and analyzed.

Key words free electron laser, RF gun, bunch compressor, bunch length measurement

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1 Introduction

There is growing interest in developing high brightness electron beam source, as required by the free electron laser (FEL), energy recovery linac (ERL), international linear collider (ILC) and other accelerator driven facilities. At present the typical way to provide high brightness beam source is first using a photocathode RF gun to a generate high charge low emittance beam, and then using a magnetic bunch compressor to compress the beam longitudinally to obtain a high peak current beam.

In order to provide a high peak current beam for the FEL at Chinese Academy of Engineering Physics (CAEP) [1], a 4-dipole magnetic bunch compressor (BC) has been developed. In this paper we report the design principles and the first experimental research of the BC, with special attention paid to the sensitivity of the bunch length on the phase of the photocathode RF gun and magnetic field of the BC. The bunch length after the BC was determined by measuring the spectrum of coherent transition radiation (CTR) and coherent diffraction radiation (CDR) with a Martin-Puplett interferometer [2]. The rms bunch length is found to be about 0.7 ps and the peak current exceeds 500 A when operated in the optimized condition. The possibility of using CDR as input signal for the feedback system that adjusts the photocathode RF gun phase and magnetic field of the BC accordingly to provide a stable bunch length is also estimated.

2 Design principles of the bunch compressor

The upgraded beamline of the FEL at CAEP consists of a 4.5 cell L-band photocathode RF gun, a BC, a booster linac, an undulator and other auxiliary components. The BC which has standard symmetric 4-dipole configuration is located at the gun exit where the beam energy is about 8 MeV. The sketch of the BC is shown in Fig. 1. The physical length of the dipole is $L_b = 20$ cm, the drift distance between the first and second dipole is $L = 50$ cm and that between the second dipole and the third dipole is $L_c = 20$ cm. The nominal bending angle is $\theta = 17.3°$. When the beam passes through the BC, the electron with relative energy deviation δ will have a path difference Δz with respect to the reference particle as

$$\Delta z = R_{56}\delta + T_{566}\delta^2 + \cdots . \quad (1)$$

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For the symmetric 4-dipole BC, the linear dispersion term can be calculated as,

$$R_{56} \approx -2\theta^2 (2L_b/3+L). \quad (2)$$

From Eq. (2) we see that the linear dispersion term for the symmetric 4-dipole BC is always negative and the bunch compression can only be achieved when the beam has a negative energy chirp for which the beam energy at the head of the bunch should be lower than that at the tail of the bunch.

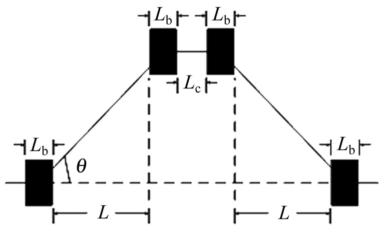

Fig. 1. Sketch of the bunch compressor.

The nominal beam energy for the BC is 8 MeV and the beam charge is 1 nC. The FEL at CAEP could be operated either at 100 μm when the beam energy is about 8 MeV or 3–8 μm when the beam energy is about 35 MeV. The BC has been designed to have large energy and deflection angle acceptance, in order to provide flexible operation. Specifically, when the FEL operates at 100 μm, the BC is tuned to provide only moderate compression as a compromise between the peak current and energy spread, due to the fact both the peak current and energy spread affect the FEL gain and that there is no further linac to compensate the energy spread after compression. Instead, when the FEL operates at 3–8 μm, the BC can be tuned to provide maximum compression and the related large energy spread which can be compensated by the booster downstream. Simulation shows that maximum bunch compression could be achieved at laser launching phase (hereafter called RF gun phase) 35° and magnetic field of the BC 48.8 mT. With these parameters, the longitudinal phase space of the beam before and after the BC from PARMELA [3] simulation is shown in Fig. 2.

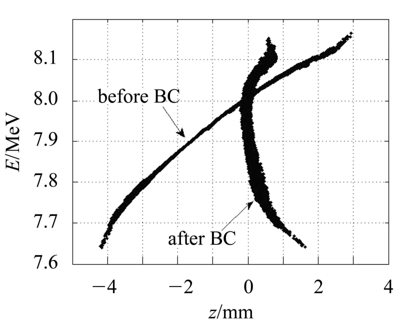

Fig. 2. Longitudinal phase space before and after BC.

In the simulation the laser pulse length is assumed to be 10 ps (FWHM) and has a Gaussian distribution in longitudinal direction. The rms bunch length before and after the BC is about 5.8 ps and 0.8 ps, respectively.

In addition to the bunch length compression, attention was also paid to the emittance degradation during compression. Among the many detrimental factors that could potentially cause emittance growth during compression, coherent synchrotron radiation (CSR) may be the most serious one. The CSR generated by the electrons in the tail of the bunch could catch up with the electrons in the head of the bunch and the interaction results in an energy redistribution which causes emittance growth because it occurred in a dispersive region.

Since the emittance growth caused by CSR is very sensitive to the phase space of the beam at the entrance of the compressor [4, 5], in our design a triplet quadrupoles is put upstream of the BC to provide both matching phase space and optics that reduce the emittance growth to an acceptable level.

3 Performance of the bunch compressor

The bunch length after electron beam passes through the BC is measured with CTR and CDR using a Martin-Puplett interferometer. CTR is generated when electron beam bombards a metal foil and CDR is generated when electron beam passes through a metal aperture. The detailed measurement principles, set-up and data analysis technique can be found elsewhere [2]. Here we just present the results. The CTR and CDR is measured with a Golay cell detector. We first optimized the accelerator to maximize the detector signal. This is achieved at bunch charge about 0.5 nC, RF gun phase of 48° and magnetic field of 34.5 mT for the BC. The longitudinal bunch form factor measured with CTR is shown in Fig. 3. Solid circles are experimental data; solid line and doted-dashed line represent the theoreticalcurve for a Gaussian beam with rms bunch length of 0.6 ps and 1 ps respectively.

The bunch form factor is the square of the modulus of the Fourier transform of the normalized longitudinal distribution. For Gaussian beam with rms bunch length σ ,the bunch form factor is $F(f) = \exp(-4\pi^2\sigma^2 f^2/c^2)$, where f is the frequency and c is the speed of light. Due to diffraction loss and limited frequency response of the detector, the data for very low frequency components (<0.1 THz) are absent. The estimation of the rms bunch length could be achieved by assuming a Gaussian bunch shape and fitting the measured data to the theoretical curve. From Fig. 3, we can see that the lower limit and upper limit of the rms bunch length should be 0.6 ps and 1.0 ps respectively. However, it is also clear that a simple Gaussian assumption can not provide a good fit.

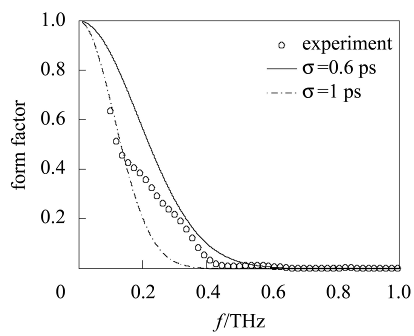

Fig. 3. Longitudinal bunch form factor.

In order to quantitatively determine the peak current, we need to know the detailed longitudinal profile of the beam. With the Kramers-Kronig relation [6], we are allowed to recover the detailed longitudinal bunch shape, as shown in Fig. 4.

From Fig. 4, we see that the bunch contains a main bunch and a satellite bunch. The rms length of the main bunch is found to be about 0.65 ps and the peak current is about 250 A. In a later experiment, when the beam charge is increased to 0.8 nC and other parameters optimized to maximize the detector signal, a peak current of 500 A has been achieved [2]. The presence of the satellite bunch is most likely to be caused by the laser system. When changed the RF gun phase and the magnetic field of the BC, the measured bunch shape also changed, but the satellite bunch always exists.

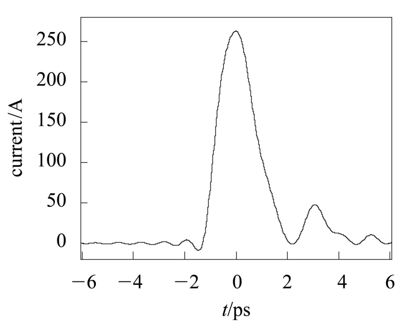

Fig. 4. Reconstructed longitudinal profile.

The successful operation of a FEL requires the BC to provide a stable bunch length. However, due to phase jitter and energy jitter, the beam energy and energy chirp at the entrance of the BC changes from shot to shot. To find the tolerances of the phase jitter, we measured the detector signal for various RF gun phases. The results are shown in Fig. 5 at beam charge 1 nC and the magnetic field of the BC 34.5 mT.

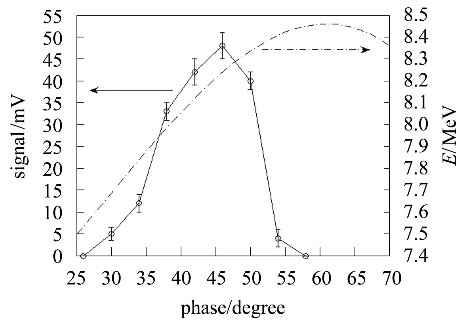

Fig. 5. Detector signal (solid circle) and beam energy (dashed line) vs. photocathode RF gun phase.

The detector signal can be calculated as

$$V(\sigma) \propto \int P(\omega)F(\omega)R(\omega)\mathrm{d}\omega, \tag{3}$$

where $P(\omega)$ is the spectrum of the radiation, $F(\omega)$ is the longitudinal bunch form factor and $R(\omega)$ is the detector response. Qualitatively, the shorter the bunch length, the larger the detector signal.

From Fig. 5, we see that the signal increases as the RF gun phase increases and reaches its maximum when the RF gun phase is about 46°. When the phase is larger than 46°, the signal dramatically decreases to zero. To see how this happens, the beam energy for various RF gun phases is simulated with PARMELA and also shown in Fig. 5. Qualitatively, if the RF gun phase is smaller than 60°, the beam has negative energy chirp and can be compressed. On the contrary, if the RF gun phase is larger than 60°, the beam has positive energy chirp and can not be compressed with the BC. For this case the bunch length remains quite long and thus the signal dramatically decreases.

It is worth pointing out that from the simulation, the shortest bunch length is achieved when the RF gun phase is 35° and the magnetic field of the BC is 48.8 mT. However, in our experiment the shortest bunch length is obtained at RF gun phase 46° and the magnetic field of the BC 34.5 mT. The deviation may be due to the relatively serious beam loading effect which makes the beam energy to be a bit smaller than the designed value. The uncertainty in the RF gun phase measurement is also a possible cause of the deviation. The absolute RF gun phase is measured by performing Schotty scan [7] method in which the beam charge is measured as a function of drive laser launching phase. The maximum charge is achieved when the laser sees the highest acceleration field. The uncertainty of the RF gun phase measured in this way is generally comparable to the laser pulse length which is about 10°.

Assuming that the bunch has a Gaussian distribution and the detector response is constant in the range from 0.1 THz to 1 THz which used as the integration boundary in Eq. (3), we calculated the detector signal for various bunch lengths. The results are shown in Fig. 6.

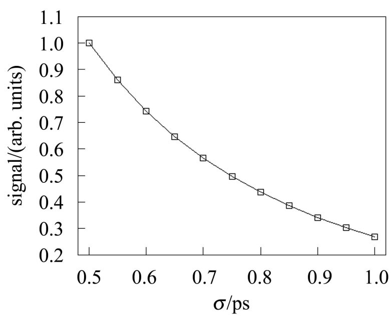

Fig. 6. Detector signal vs. bunch length.

A comparison between Fig. 5 and Fig. 6 indicates that in order to control the peak current fluctuation within 5%, the phase jitter should be controlled within 4°.

We also measured the sensitivity of electron bunch length on the magnetic field of BC. Fig. 7 is the detector signals for various magnetic fields at the RF gun phase 46°. From Fig. 7 we can see the bunch length is also very sensitive to magnetic field of the BC. The minimum bunch length is achieved when the magnetic field of the BC is 34.5 mT for which the BC has the most suitable R_{56}.

It's worth pointing out that in addition to the phase jitter, there are actually many other terms that could affect the bunch length. For example, due to the beam loading effect, the beam energy and energy chirp also fluctuates when the laser energy changes. To provide a stable bunch length, it's best to adjust the phase of the acceleration field to provide a suitable energy chirp and the magnetic field of the BC to provide the suitable R_{56}, based on early information of the bunch length after the BC. The CDR could be monitored by the detector at the exit of the BC and the detector signal could be used as input for the feedback system [8] that adjusts the phase of the acceleration field and magnetic field of the BC, which finally provides a stable bunch length. The key advantage of using CDR as the input signal for the feedback system is that CDR is an non-interceptive method which allows real-time monitoring the bunch length.

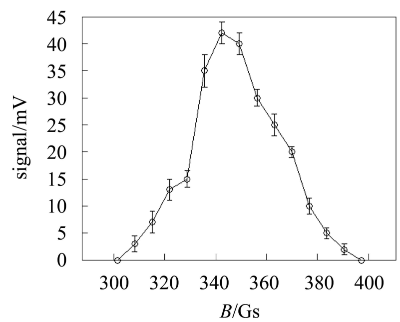

Fig. 7. Detector signal vs. magnetic field of the BC.

4 Conclusion

To provide the high peak current beam for the FEL at CAEP, we have developed a 4-dipole magnetic BC. The bunch length after the BC is found to be about 0.7 ps and the peak current of the bunch exceeds 500 A when operated in the optimized condition, which is a strong confirmation for the successful commissioning of the BC. The tolerance of the phase jitter was determined by measuring the sensitivity of the bunch length on the phase of the acceleration field. The possibility of using the CDR as the input signal for a feedback system is also preliminarily estimated.

References

1 JIN X, LI M, XU Z et al. HEP & NP, 2006, **30**: 96–98 (in Chinese)
2 XIANG D, YANG X F, HUANG W H et al. Chin. Phys. Lett., 2008, **25**(7): 2440
3 YOUNG L M, Billen J. The Particle Tracking Code PARMELA. http://epaper.kek.jp/JACow/proceedingsnew.htm
4 XIANG D, HUANG W H, HE X Z. HEP & NP, 2004, **28**: 555–559 (in Chinese)
5 Stulle F, Adelmann A, Pedrozzi M. Phys. Rev. ST Accel. Beams, 2007, **10**: 031001
6 Lai R, Sievers A J. Phys. Rev. E, 1994, **50**: 3342–3344
7 DU Y C, YAN L X, DU Q et al. Chinese Phys. Lett., 2007, **24**: 1876–1878
8 Loos H, Borden T, Emma P et al. Measurements of Compression and Emittarce Growth after the First LCLS Bunch Compressor Chicane. http://epaper.kek. jp/JACow/ proceedingsnew.htm