CSR mitigation in the FCC-ee injector bunch compressor

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Abstract

Coherent Synchrotron Radiation (CSR) encountered in the FCC-ee injector bunch compressor can lead to transverse emittance dilution, undoing some of emittance reduction from the damping ring. The bunch compressor is required to reduce the RMS bunch length from 5 mm to 0.5 mm, prior to injection into the linac. This is achieved through a dogleg comprised of two triple-bend achromats (TBA) tailored to accomplish this compression. Despite the fact that the final bunch length is relatively long (compared to FEL linacs for example, where CSR is a commonly encountered problem), CSR is still capable of increasing the transverse emittance by 30 % if left unchecked. Through careful optics design, the CSR-kick encountered in each dipole can be cancelled and the CSR-induced emittance growth can be significantly reduced.

FCC-ee Injector Layout

Immediately following the second turnaround loop, before the beam is injected back into linac, the bunch is compressed from 5 mm to 0.5 mm. The possibility of using one or both of these turnaround loops for bunch compression was investigated however the impact of CSR-induced emittance growth was unmanageable, without the inclusion of CSR compensation schemes such as those described in References [1-4]. Instead the required bunch compression is performed by dogleg bunch compressor. By delaying the bunch compression, and leaving the bunch length to be longer in the turnaround loops, makes the bunch less susceptible to CSR effects.

- Isochronous and achromatic loops (after damping ring and near 1.54 GeV section of linac)
- Followed by accelerating structure and dogleg compressor

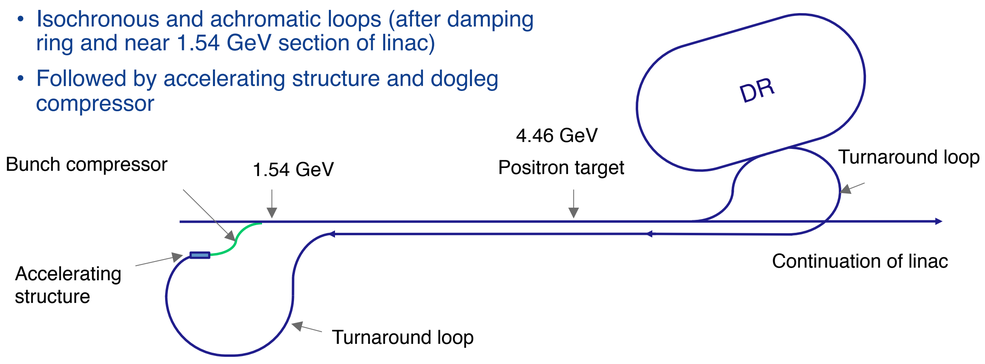


Fig. 1 Section of the injector layout showing the position of the two turnaround loops. After passing through the Damping Ring (DR), the positrons are directed back to the 1.54 GeV section of the linac via the bunch compressor.

Dogleg Bunch Compressor

The relatively long initial bunch length places a limitation on the achievable energy chirp, for a set energy spread. For an initial bunch length of 5 mm, and allowed rms energy spread of 1.1%, the permissible energy chirp is $h_1 = 1/E_0\ dE/ds = -2.19\ m^{-1}$. As the aim is a final bunch length of 0.5 mm, the R_{56} value required is can be estimated using the following first-order approximation,

$$\frac{z_f}{z_i} = 1 + R_{56}h_1$$
$$\sigma_{z,f} = (1 + R_{56}h_1)\sigma_{z,i}, \qquad (1)$$

where $\sigma_{z,i}$ and $\sigma_{z,f}$ are the initial and final rms bunch length respectively. From Eq. (1), the R_{56} required is 0.41 m.

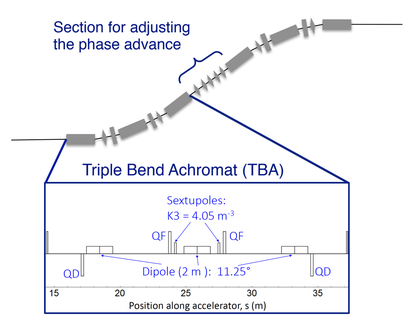


Fig 2. (a) Magnet layout of dogleg bunch compressor. The TBAs are identical except that they bend in opposite directions. (b) detailed layout of one TBA. [5]

This layout has three benefits:
1. It allows for a reasonably large R56 value.

The R_{56} value required of 0.41 m is reasonably large for a dogleg compressor. This can be achieved thanks to the dipole in each TBA, where the dispersion in non-zero.

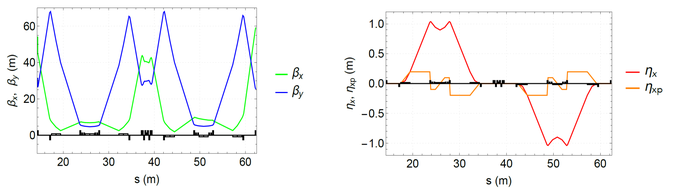
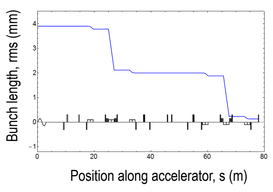


Fig 3. (a) optics through dogleg compressor (b) dispersion through dogleg compressor.

2. There is no parasitic compression.



The positive R_{56} BC ensures the bunch length gets progressively shorter, unlike a chicane where the bunch reaches the shortest bunch length before lengthening out again by the end of the BC.

Fig 4. RMS bunch length along dogleg.

3. Self-linearizing achromats.

Sextupoles strengths optimized for chromaticity, rather than for T566. However the resulting T566 is close to optimal anyway. Therefore there is no need for a harmonic cavity.

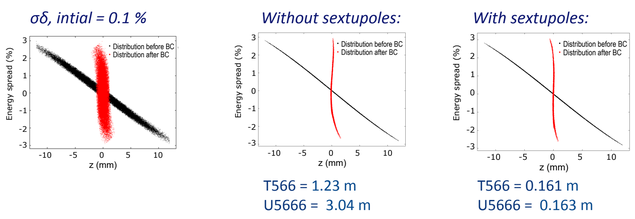
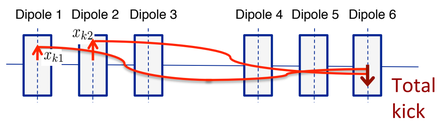


Fig 4. Initial (red) and final (black) longitudinal phase space distributions for (a) without the inclusion of sextupoles and (b) with sextupoles included in bunch compressor.

Influence of CSR

As the bunch passes through dipole, CSR causes a change in energy. The particle starts a betatron oscillation around a new reference trajectory, increasing its Courant-Snyder invariant. The CSR kicks can be calculated using Eq.(2) [6].



The aim is to reduce the total kick at the end of BC.

$$\Delta x_1 = \sqrt{\frac{\beta_6}{\beta_1}}\left[\cos(\phi_{16}) + \alpha_1 \sin(\phi_{16})\right] x_{k1} + \sqrt{\beta_1\beta_6}\sin(\phi_{16})\ x'_{k1}$$
$$\Delta x'_1 = \frac{(\alpha_1-\alpha_6)\cos(\phi_{16}) - (1+\alpha_1\alpha_6)\sin(\phi_{16})}{\sqrt{\beta_1\beta_6}}\ x_{k1} - \alpha_6\sqrt{\frac{\beta_1}{\beta_6}}\ x'_{k1}$$

where

$$x_{k1} = \rho_1^{4/3} k_1 [\theta_1 \cos(\tfrac{\theta_1}{2}) - 2\sin(\tfrac{\theta_1}{2})]$$
$$x'_{k1} = \sin(\tfrac{\theta_1}{2})[2\delta_1 + \rho_1^{1/3}\theta_1 k_1]$$

where

$$k_1 = \frac{W}{E_0} = \frac{dE}{cdt}\frac{\rho_1^{2/3}}{E_0} \qquad \delta_1 = \frac{L_{dip}}{E_0}$$

and

$$\frac{dE}{cdt} = \frac{-2e^2}{4\pi\epsilon_0(3R^2)^{1/3}} \int_{\tilde{z}-z_L}^{\tilde{z}} \frac{d\lambda(z)}{dz}\frac{1}{(z-\tilde{z})^{1/3}}dz$$

Below is the CSR kick Δx and Δx', from dipole 1 propagated to the end of the dipole.

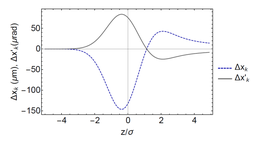
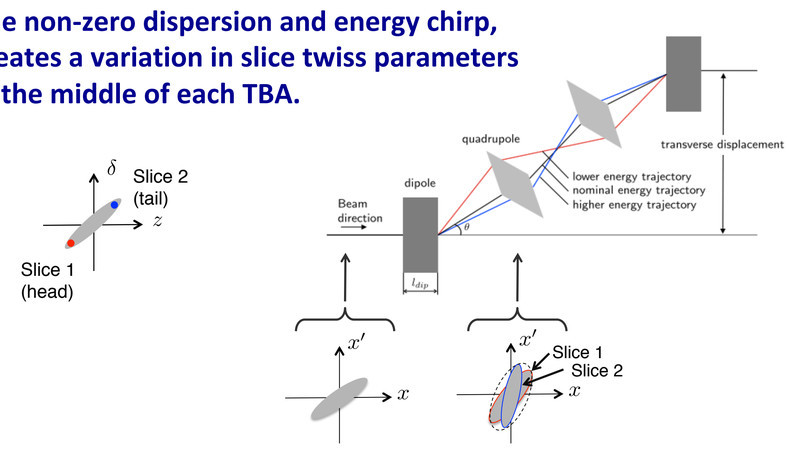
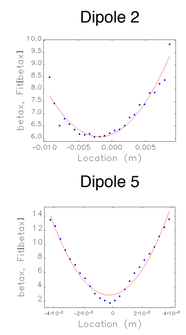


Fig 5. Typical CSR kicks in x and x' encountered in a dipole.

The non-zero dispersion and energy chirp, creates a variation in slice twiss parameters in the middle of each TBA.



Slice variation twiss parameters in dipole 2 and 5:



This variation in the slice Twiss parameters creates a different mean kick in x, as shown in Fig. 5. In addition, the slice variation in the beta function can create atypical CSR kicks.

$$\Delta x_5 = \sqrt{\frac{\beta_6}{<\beta_5>}}[\cos(\phi_{56}) + \alpha_6\sin(\phi_{56})]x_{k5} + \sqrt{<\beta_5>\beta_6}\sin(\phi_{56})\ x'_{k5}$$
$$\Delta x_5 = \sqrt{\frac{\beta_6}{\beta_5(z)}}[\cos(\phi_{56}) + \alpha_6\sin(\phi_{56})]x_{k5} + \sqrt{\beta_5(z)\beta_6}\sin(\phi_{56})\ x'_{k5}$$

CSR kicks in x propagated to the end of the dogleg.

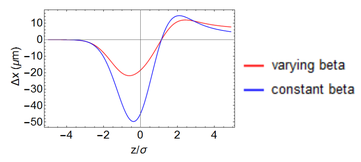


Fig 6. CSR kick in x, for a constant beta_x value (red) and a varying beta_x value (blue).

Atypical CSR kicks encountered in dipole 2 and 5 due to slice variation in β_x.

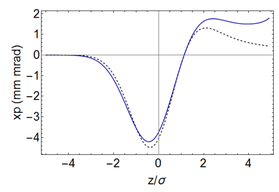


Fig 7. Atypical CSR kicks in x' due to non-uniform β_x in dipoles 2 and 5.

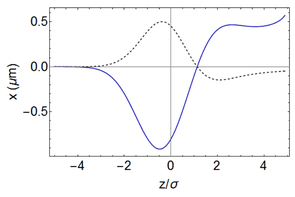
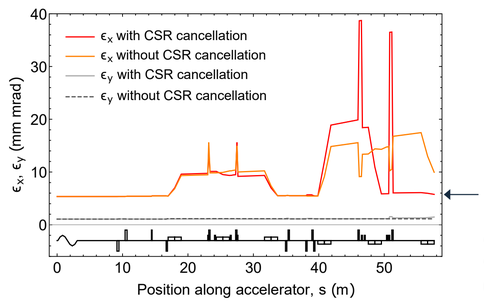


Fig 8. Atypical CSR kicks in x and x' due to non-uniform β_x in dipoles 2 and 5.

- 10 % of x' kick after passing through the centre of dipole 1.
- x' kick from dipole 1, propagated to at the end of the dogleg.
- x kick after passing through the centre of dipole 1.
- x kick from dipole 1, propagated to at the end of the dogleg.

CSR Mitigation

After passing through all of the dipoles, the off-momentum particles (in each slice) return to the initial trajectory. Therefore, minimizing the emittance growth.



Initial emittance growth	Emittance growth after CSR cancellation technique applied
85.8 %	6.8 %

Final $\varepsilon_{x,N}$ = 5.72 mm mrad

Fig 8. Emittance along the bunch compressor, before CSR cancellation technique applies (orange) and after (red).

Conclusion

- A bunch compressor was presented for the FCC-ee injector. Notably, the bunch compressor is a dogleg compressor comprised of two TBAs, for a positive R_{56}, and favourable T_{566}.
- CSR kicks encountered in each dipole can be cancelled to large extent, reducing the CSR-induced emittance growth from 85.8 % to 6.8 %.

References:

[1] D. Douglas, "Suppression and Enhancement of CSR-Driven Emittance Degradation in the IR-FEL Driver," Technical Report JLAB-TN-98-012, 1998. [2] S. Di Mitri, M. Cornacchia, and S. Spampinati, "Cancellation of coherent synchrotron radiation kicks with optics balance," Phys. Rev. Lett., **110**, 014801, 2013. [3] S. Di Mitri and M. Cornacchia, "Electron beam brightness in linac drivers for free-electron-lasers," Phys. Rep., **539**, 2014. [4] R. Hajima, "A first-order matrix approach to the analysis of electron beam emittance growth caused by coherent synchrotron radiation," Japanese Journal of Applied Physics, Part 2: Letters, **42**, pp. 974–976, 2003. [5] T. K. Charles et al. "Bunch Compression and Turnaround Loops Design in the FCC-ee Injector Complex" IPAC18 proceeding [1] T. K. Charles et al. "Bunch Compression and Turnaround Loops Design in the FCC-ee Injector Complex" IPAC18 proceeding [2] S. Ogur et al. "Layout and Performance of the FCC-ee Pre-Injector Chain Location of Presentation" IPAC18 [6] Y. Jiao et. al (2014) Phys. Rev. ST AB **17** 060701