# A COMPARISON BETWEEN ARC-LIKE AND CHICANE-LIKE BUNCH COMPRESSION FOR X-RAY FREE-ELECTRON LASERS*

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## *Abstract*

The spectral brightness of a free-electron laser (FEL) is strongly dependent on the properties of the electron beam used to generate the radiation. Bunches used to drive FELs must have high currents, which are produced through longitudinal bunch compression. However, collective effects (such as coherent synchrotron radiation) degrade the emittance and energy spread during the bunch compression process, which in turn reduces the spectral brightness. A compression scheme for an FEL must be designed to reduce the impact of collective effects on the electron distribution in order to generate high spectral brightness FEL pulses. In this paper we compare commonly used four-dipole chicanes to two alternative bunch compressor configurations that are designed to mitigate coherent synchrotron radiation. We show that compression can be achieved with much reduced emittance degradation compared to four-dipole chicanes in two cases: arc compression of positively chirped bunches, and five-dipole compression of negatively chirped bunches. Each is suited to different FEL schemes.

## INTRODUCTION

Spectral brightness, which describes the photon density of a radiation source, is a key figure of merit for the performance of light sources, such as FELs. To produce high spectral brightness in an FEL, electron bunches in the undulators must have low transverse emittance, small energy spread and high peak current (i.e. high 6D brightness).

Preserving the 6D brightness of an electron bunch as it is accelerated and compressed from the injector to the undulators is essential for the performance of an FEL. Collective effects, such as coherent synchrotron radiation (CSR) and micro-bunching instability (MBI), that occur in magnetic bunch compressors can significantly degrade the emittance and energy spread of an electron beam [1–6].

A range of strategies have been proposed to mitigate CSR and MBI effects in magnetic bunch compressors, including: minimised $\beta$-function in the dipoles of a chicane to reduce CSR-induced emittance growth [7]; asymmetric chicanes that achieve CSR kick cancellation and reduce emittance growth [8–10]; optics balance to achieve CSR kick cancellation between dipoles or achromats [11, 12]; laser heaters to increase the energy spread of electron bunches to limit MBI gain [13]; transverse Landau damping to mitigate MBI gain [14].

In light of these strategies aimed at mitigating CSR and MBI effects in bunch compressors, we compare three bunch compressors for use in a potential future UK X-ray Free Electron Laser (UK-XFEL) facility [15,16]. The comparison aims to understand how the choice of bunch compressors affects the electron bunch properties and the FEL output.

## UK-XFEL

The UK-XFEL is proposed to be a next-generation FEL facility. A conceptual design and options analysis has recently been completed, which outlines a facility based on a high-repetition rate, super-conducting linac to drive multiple beamlines and experiments simultaneously [15]. Each beamline will operate at different photon energies and using different FEL techniques, requiring bunch-by-bunch variations in longitudinal electron beam properties. Additionally, low emittance beams will be required for each beamline, so emittance preservation is essential as these bunches are transported from the injector to each FEL.

## BUNCH COMPRESSOR OPTIONS

The three bunch compressors that are being considered for UK-XFEL are: four-dipole/symmetric C-chicane (SC), five-dipole/asymmetric S-chicane (C5), and arc bunch compressors. Layouts are shown in Fig. 1.

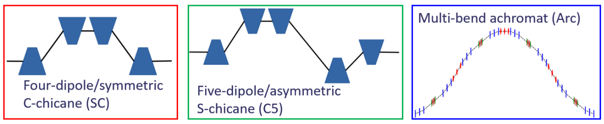

Figure 1: Layout of three types of bunch compressor: four-dipole/symmetric C-chicane, five-dipole chicane, and arc bunch compressors.

Four-dipole chicanes use a C-shaped magnetic layout with four equally powered dipoles of equal length to generate a path-length variation with energy, i.e. longitudinal dispersion $R_{56}$. Harmonic radio-frequency (RF) cavities would be

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used to linearise the longitudinal phase space and compensate for curvature imprinted on the chirp by the fundamental RF cavities [17]. Harmonic linearisation, as well as short-range wakefields, often lead to a chirp that results in folds at the head and tail in the longitudinal phase space. Folds in the longitudinal phase space create spikes in the current profile that radiate strongly over the core of electron bunches and degrade the beam emittance [18].

Emittance growth due to CSR can be partially mitigated by minimising the optical beta function in the bend plane in the final dipoles of the bunch compressor, where the bunch becomes short, reducing the contribution of CSR-induced angular spread to the projected emittance [7, 19]. However, this strategy is progressively less effective at strong compression factors. As a result of this sub-optimal mitigation strategy, it is important to consider bunch compressors that implement other strategies, such as asymmetric chicanes, and arc bunch compressors with optics balance.

Asymmetric chicanes, such as the five-dipole chicane, use a geometry designed to make it possible to achieve more effective cancellation of CSR kicks. The cancellation of CSR kicks in the asymmetric chicanes leads to stronger suppression of CSR-induced emittance growth than simply minimising beta function alone [8–10]. Five-dipole chicanes generate positive longitudinal dispersion $R_{56}$ (path length decreases with increasing energy), so electron bunches with a negative chirp (energy decreases towards the head of the bunch) and harmonic linearisation are required.

Another alternative to the four-dipole chicane is an arc bunch compressor with optics balance. In an arc bunch compressors, emittance growth due to CSR is suppressed through optics balance, where the phase advance between CSR sources is optimised for cancellation of CSR kicks. Arc bunch compressors are distinct from chicanes as they have opposite sign first-order longitudinal dispersion $R_{56}$ (i.e. 'arc-like' $R_{56}$), and therefore electron bunches must be accelerated on the falling side of the RF waveform in order to be compressed. The result is an electron bunch with the opposite sign chirp to that from a chicane-like compression scheme. Additionally, harmonic RF is generally not required, as the second-order longitudinal dispersion has the correct sign to correct the curvature in the longitudinal phase space imprinted by the fundamental RF cavities.

## APPLICATION TO UK-XFEL

UK-XFEL proposes a 1.3 GHz super-conducting linac to accelerate electron bunches to 8 GeV. The necessary peak currents will be achieved using a two-stage compression scheme, with bunch compression occurring at 270 MeV and 2.1 GeV.

Simulations are used to compare the proposed UK-XFEL linac equipped with four-dipole/symmetric C-chicanes to the linac with five-dipole chicanes and four-achromat arc bunch compressors. In particular, the bunch compression schemes are evaluated through particle tracking in `ELEGANT` [20], in which two bunch charges are studied: 75 pC and 300 pC

The emittance growth due to CSR is investigated for each bunch compression scheme at different bunch lengths by performing a scan of the compression factor. The RF phase and voltage in the linac between the two bunch compressors are varied to control the chirp of the bunch (and hence the compression factor in the second bunch compressor) while maintaining the same beam energy at the end of the linac. Figure 2 shows the peak current and the emittance of the peak current slice as functions of bunch length for each case.

The emittance of the peak current slice is well preserved over most of the bunch lengths for the five-dipole chicane and arc compression schemes, and only begins increasing at short bunch lengths, whereas the symmetric C-chicane compression schemes suffer from emittance growth at longer bunch lengths.

Two specific compression cases are chosen for further study: 75 pC compressed to 40 fs and 300 pC compressed to 100 fs. The slice bunch properties (current, emittance and energy spread) for each compression scheme and bunch charge are shown in Fig. 3.

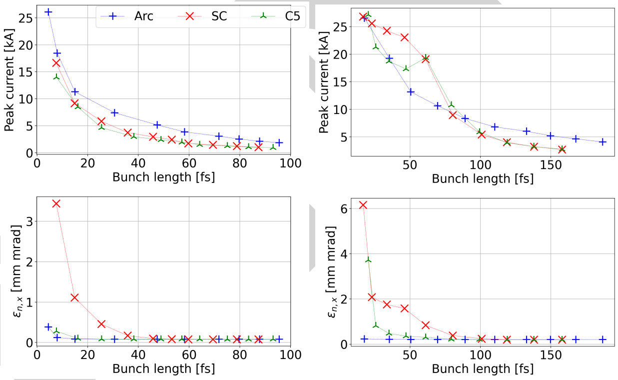

Figure 2: Peak current (top) and horizontal emittance of peak current slice (bottom) as a function of bunch length from compression scans of each compression scheme using bunch charges of 75 pC (left) and 300 pC (right). The bunch length is scanned by varying RF phase in linac 2 to control the compression factor in the second bunch compressor.

The current profiles (top row of Fig. 3) indicate significant differences between chicane-like and arc-like bunch compression schemes: arc-like bunch compression schemes have a single current spike at the core of the electron bunch that results from magnetic linearisation and a strong chirp generated by short-range wakefields and CSR; chicane-like bunch compression schemes produce uniform current profiles at the core, and current spikes at the head and tail. In addition to the difference in current profile, the peak current is also larger for arc-like compression schemes for given bunch lengths (full width at 10 % max bunch length, FWTM).

The projected energy spread of electron bunches from the arc compression is larger than that from chicane compression schemes due to the short-range wakefields that act on the bunch in linac 3 (after the last/second bunch compressor). Additionally, the slice energy spread shown on the middle row of Fig. 3 is larger at the core for electron bunches from

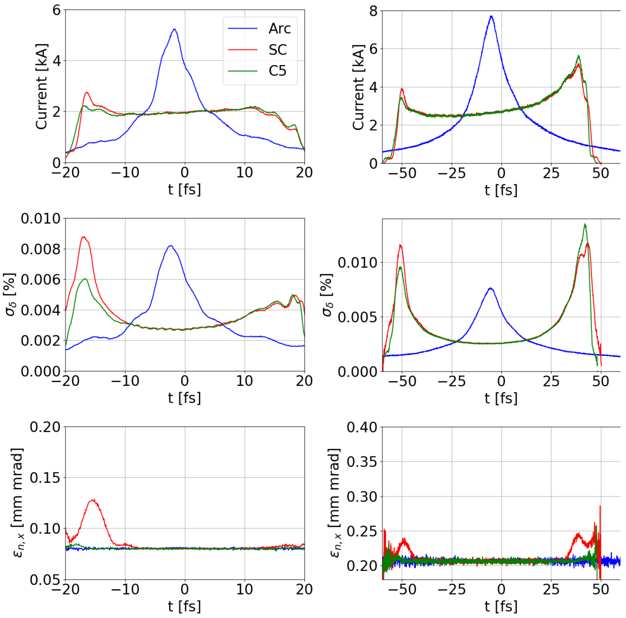

Figure 3: Current (top), slice energy spread (middle) and horizontal slice emittance (bottom) of electron bunches at entrance of the FEL from arc (blue), symmetric C-chicane (red), and five-dipole chicane (green) compression schemes for bunch charges 75 pC (left) and 300 pC (right).

the arc compression schemes than for bunches from the chicane compression schemes.

The slice emittance (shown in the bottom row of Fig. 3) is preserved along the length of the electron bunches from the five-dipole and arc compression schemes, while it is increased in bunches from symmetric C-chicane compression schemes. The same trend is also true for the projected emittance, in which the symmetric C-chicanes lead to more significant emittance growth than either five-dipole chicane or arc bunch compressors. The projected horizontal emittances for each case are shown in Table 1.

Table 1: Emittances of electron bunches at the FEL from each compression scheme. An additional arc compression case (arc-2), in which the peak current is matched to that from the chicane compression schemes, has been included in the comparison.

| | SC | C5 | Arc | Arc-2 |
|---|---|---|---|---|
| $\varepsilon_x$ at 75 pC [mm mrad] | 0.18 | 0.09 | 0.15 | 0.09 |
| $\varepsilon_x$ at 300 pC [mm mrad] | 0.46 | 0.25 | 0.30 | 0.025 |

The FEL performance for each case is evaluated using `GENESIS` simulations. Parameters are chosen to produce radiation with a wavelength of $\lambda_r = 62$ pm (critical photon energy $E_{ph} = 20$ keV) with an electron beam energy of 8 GeV. The (helical) undulator has a period $\lambda_w = 1.6$ cm and on-axis magnetic field $B_0 = 0.63$ T. The FEL lattice consists of 40 undulator modules with an active length of 4 m each (160 m total), separated by drift spaces with a quadrupole at the centre to provide transverse focusing.

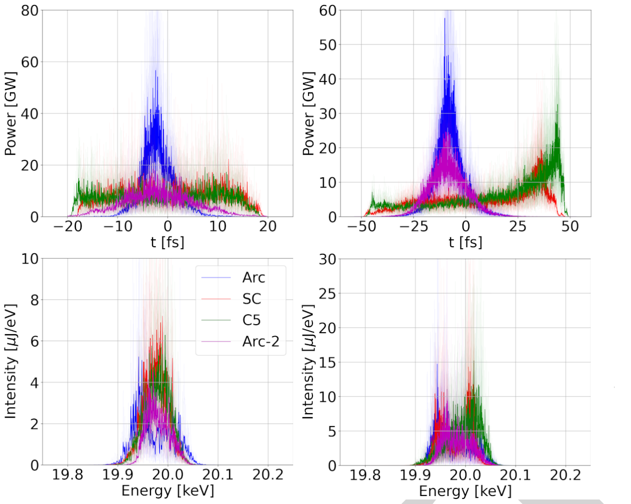

Figure 4: The longitudinal power profiles (top) and energy spectra (bottom) of FEL pulses at peak spectral brightness. Results from simulations using the 75 pC (left) and 300 pC (right) electron bunches from the arc (blue), symmetric C-chicane (red), five-dipole chicane (green), and arc-2 (magenta) compression schemes.

The longitudinal power profiles (shown in the top row of Fig. 4) closely follow the current profiles of the electron bunches used to generate the radiation. The arc bunch compression schemes produce a Gaussian-like profile with a large peak power, while chicane compression schemes produce pulses with more uniform profile along the pulse. The Gaussian-like profile from the arc compression scheme would be suitable for short pulse or attosecond science given appropriate adjustments to the bunch length and bunch charge of the electron beam used to drive the FEL [21].

The energy spectra of the FEL pulses (shown in the bottom row of Fig. 4) do not show any significant differences except a marginally larger relative bandwidth from the arc compression scheme, which results from the electron bunches from the arc compression scheme having larger projected energy spread.

## CONCLUSION

Four-dipole/symmetric C-chicanes are not optimal for emittance preservation, compared to the other schemes studied here. The two alternatives, five-dipole chicane and arc compression schemes, better preserve the transverse emittance, and also lead to FEL pulses with larger peak spectral brightness and peak power. In addition, arc-like and chicane-like compression schemes produce different current profiles, and therefore different FEL power profiles, which make them suitable for different FEL schemes. The single current spike from arc-like compression schemes would be suitable for short pulses and attosecond schemes, while the uniform current profiles and smaller energy spread bunches from chicane-like compression schemes would be more suitable for self-seeding or high brightness self-amplified spontaneous emission (HB-SASE).

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