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XFEL ISOCHRONOUS CHICANES: FEASIBILITY STUDY

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Abstract

FEL schemes such as High-Brightness SASE [1] and Mode-Locking [2] require electron beam delays inserted between undulator sections. These schemes have been shown in simulations to perform most effectively when the electron beam delays are very close to isochronous, i.e. the first order longitudinal dispersion is very small. To minimise the disruption to the FEL process in the inter-undulator gaps, these delays must also be as compact as possible. In this paper we study the maximum longitudinal space that a delay chicane could occupy in an XFEL operating at 6 GeV before the peak power drops below a defined threshold, and we present a limit for the maximum longitudinal dispersion of the delay chicanes. We then present the optical designs of two chicanes that satisfy the requirements of length and isochronicity and show how these designs could be realised practically using small-aperture high-field quadrupoles.

ISOCHRONOUS CHICANES

A number of related schemes have been proposed in which electron beam delay chicanes are used to manipulate the electron/radiation interaction within the FEL, for example Mode-Locking [2], the Mode-Locked Afterburner [3] and High-Brightness SASE (HB-SASE) [1]. For all of these schemes, the performance has been shown to be better if the delays are isochronous [4], meaning that the first order dispersion $R_{56} = 0$. For HB-SASE, simulation studies have been done in 1D and 3D codes, and in two different wavelength regimes, to assess the performance as a function of the level of isochronicity. These studies showed that for performance very close to that obtained with purely isochronous chicanes, the normalised chicane dispersion D, defined here as the ratio of the R_{56} to that of a standard 3 dipole chicane imparting the same delay, must satisfy $D \leq 0.01$.

SPACE CONSTRAINTS FOR AN XFEL

In any FEL it is normal practice to make the inter-undulator gaps as compact as possible to minimise the total length of the FEL and to mitigate the degradation to the FEL performance caused by debunching and radiation diffraction. Some initial chicane design work indicated that the minimum length would be several meters. To investigate the impact of a chicane length of this order, two FEL lattices were set up using typical XFEL parameters, with $E = 6$ GeV, $Q = 50$ pC, $\varepsilon_n = 0.5$ mm-mrad, $\sigma_\gamma/\gamma_0 = 10^{-4}$, $I_{pk} = 2$ kA, $\lambda_r = 0.124$ nm and $\lambda_w = 25$ mm. The nominal SASE lattice comprised 4 m undulator modules within a FODO focussing structure with half period 5 m. This meant the gap between undulators was 1m. An alternative lattice was set up in which every other undulator was removed to allow delay chicanes up to several metres long to be inserted. In this lattice the gap between undulator modules is therefore 6 m.

In SASE mode, for the nominal lattice with 1m gaps, the saturation power of 5 GW was reached after 17 undulator modules. For the alternative lattice, with the gap length increased to 6m, the saturation power of 2.2 GW was reached after 18 undulator modules. For the 6m gaps the rms radiation size stabilises at a level about double that of the case with 1m gaps. These results indicate that a 5 m chicane is acceptable in terms of FEL performance, assuming a 50% reduction in output power and 100% increase in floor length are viable.

DELAY CHICANE DESIGNS

The first consideration is the magnitude of the required electron beam delay. For the generic XFEL parameters of a gaussian electron bunch of peak current $I_{pk} = 2$ kA and charge $Q = 50$ pC, the bunch duration is 3 µm. For HB-SASE it is assumed the largest delay ever required would be $\delta = 2.5$ µm. In fact the required delay turns out not to be the limiting factor in making the chicanes as compact as possible. For a three-dipole chicane the beam delay, found from simple geometry, is given by $\delta = (L_m^3/2 + 2L_dL_m^2)(Bc/E[\mathrm{eV}])^2$ where L_m is the dipole length, L_d is the drift length between dipoles and B is the dipole field. For $L_m = L_d$, $\delta = 2.5$ µm, $B = 1$ T and $E = 6$ GeV the mininimum total chicane length of a dipole-only chicane is $L_c \simeq 0.4$ m. However, to obtain an isochronous solution, space must be left for quadrupoles to control dispersion. It is assumed that the aperture is $d = 10$ mm, and the minimum dipole length is $L_m = 3d = 30$ mm. The bend angle is then $\theta = BL_mc/E = 1.5$ mrad and the drift length $L_d = 0.5$ m.

To obtain an isochronous chicane the R_{56} of the chicane transfer matrix must be set to zero. The R_{56} is defined as the integral of the dispersion over the bend radius, i.e. $R_{56} = \int \eta(s)/\rho(s)\mathrm{d}s$ so can be minimised by balancing positive and negative dispersion within the dipoles using quadrupoles. Two chicane options are considered. Option 1 is a three-dipole chicane with four quads which are inserted 1/4 and 3/4 of the way along the drifts between the dipoles. Option 2 is a four dipole chicane with three quads inserted midway between the dipoles. Both options are shown in Fig. 1 with properties summarised in Table 1.

Option 1

Option 1 is shown in Fig. 1 (top). The quadrupoles set the dispersion to zero at the midpoints between the dipoles and at the dipoles themselves. This means the effect of the quadrupole is to invert the sign of the dispersion gradient

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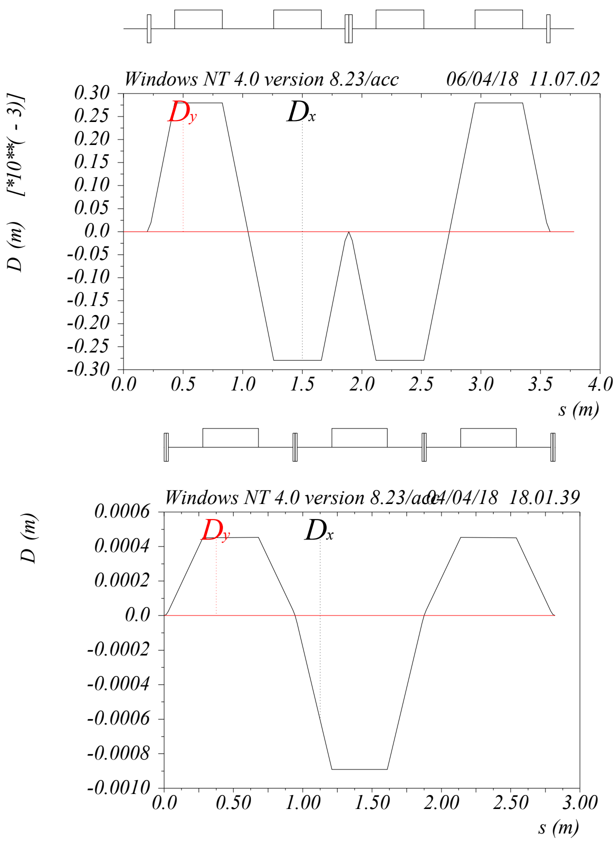

Figure 1: Top: Chicane Option 1, a three-dipole chicane with four quads. Bottom: Option 2, a four dipole chicane with three quads.

η_{px} [5]. This condition is achieved if the quadrupole focal length is $f = \eta_x/(2\eta_{px})$ where η_x and η_{px} depend on the dipole bend angle θ, bend radius ρ and drift length from dipole to quad L_d as $\eta_x = \rho(1 - \cos\theta) + L_d \sin\theta \simeq L_d\theta$ and $\eta_{px} = \sin\theta \simeq \theta$ where the approximations are valid for small θ. Using $k = 1/fL_q$ the required quadrupole k to invert the sign of the dispersion gradient is $k = 2/(L_d L_q)$ then also using $k = 300G[\mathrm{T/m}]/E[\mathrm{MeV}]$ the required integrated quadrupole gradient is $GL_q[\mathrm{T}] = 2E[\mathrm{MeV}]/300L_d$. This shows that for small angles the quadrupole integrated gradient only depends on the drift length and the beam energy, and is independent of the electron beam delay. It also shows that the quadrupole gradient needs to be high. For example, for drift length and quadrupole length 0.5 m and beam energy 6 GeV the required gradient is $G = 160$ T/m.

The obtainable gradient from a Halbach quadrupole is given by $G = 2B_r K(1/r_i - 1/r_e)$ with B_r the permanent magnet remanent field, K a geometric factor which depends on the number of radial elements, and r_i and r_e internal and external radii [6]. Using $B_r = 1.35$ T, $K = 0.94$ (which assumes 16 radial elements), $r_i = 5$ mm and $r_e = 30$ mm, the maximum achievable gradient is 430 T/m and hence the maximum achievable k for a 6 GeV beam is $k = 21.5\mathrm{m}^{-2}$. For a electromagnetic quadrupole the maximum gradient is limited by the pole-tip field B_0. Assuming $B_0 = 1$ T and

Table 1: Summary of Option 1 and Option 2 Parameters

	Option 1	Option 2
Length (m) (Halbach quads)	3.75	2.8
Length (m) (EM quads)	5.35	4.0
Delay (µm)	2.7	2.5
R_{56}	33 nm	3.0 nm
T_{566}	-7.3 µm	-18.0 µm
Scaled dispersion D	0.006	0.0006

$r = 5$ mm then the maximum gradient is 200 T/m and the maximum achievable k for a 6 GeV beam is $k = 10\ \mathrm{m}^{-2}$.

An optimisation was therefore done to achieve the required quadrupole k in the minimum total chicane length. This was done for the design shown in Fig. 1, incorporating Halbach quadrupoles and then EM quadrupoles. The results are shown in Fig. 2. The left plot is the required quadrupole k for reversing the gradient of the dispersion, *vs* the quadrupole and drift space lengths. The bold contours indicate the maximum achievable k for Halbach and electromagentic quadrupoles. The right plot shows the total chicane length $L(\mathrm{chicane}) = 4L_m + 8L_d + 4L_q$ *vs* L_q and L_d. It is clear that a high quadrupole k enables a more compact chicane. The red dot indicates combination of L_q and L_d that gives the *minimum* chicane length that provides sufficient quadrupole k, assuming Halbach quads. The blue dot indicates the same but assuming EM quadrupoles. The minimum chicane length if using Halbach quadrupoles is therefore 3.75 m, and if using EM quads it is 5.35 m.

Figure 1 (top) , calculated in MAD, corresponds to the parameters of this minimum length chicane. In fact in MAD the quadrupole k value turns out to be $k = 17.5\,\mathrm{m}^{-2}$. It is seen that the dispersion is close to zero at each dipole allowing a small R_{56}. For a 6 GeV beam the delay given by the chicane is $\delta = 2.7$ µm and the R_{56}, after subtraction of the drift R_{56} over the chicane length is $R_{56} = 33$ nm. For the equivalent chicane without quadrupoles, a standard four-dipole chicane, then $R_{56} = 5.57$ µm. This means that the scaled chicane dispersion is $D = 0.006$, within the required value of $D \lesssim 0.01$. The second order dispersion term is found to be $T_{566} = -7.3$ µm, compared to $T_{566} = -9.8$ µm for a dipole-only chicane.

Option 2

Option 2 is a more simple, and slightly more compact design, as shown in Fig. 1 (bottom). The same optimisation and analysis was done as for Option 1. The minimum chicane length if using Halbach quadrupoles is 2.8 m, and if using EM quads it is 4 m. For a 6 GeV beam the delay given by the chicane is $\delta = 2.5$ µm and $D = 0.0006$, a factor of ten lower than for Option 1 and again within the required value of $D \lesssim 0.01$. The second order dispersion term is $T_{566} = -18.0$ µm, compared to $T_{566} = -8.6$ µm for a dipole-only chicane. This is three times larger than for Option 1.

As yet, the designs do not include transverse focussing. Option 1 would allow insertion of 2 matching quadrupoles

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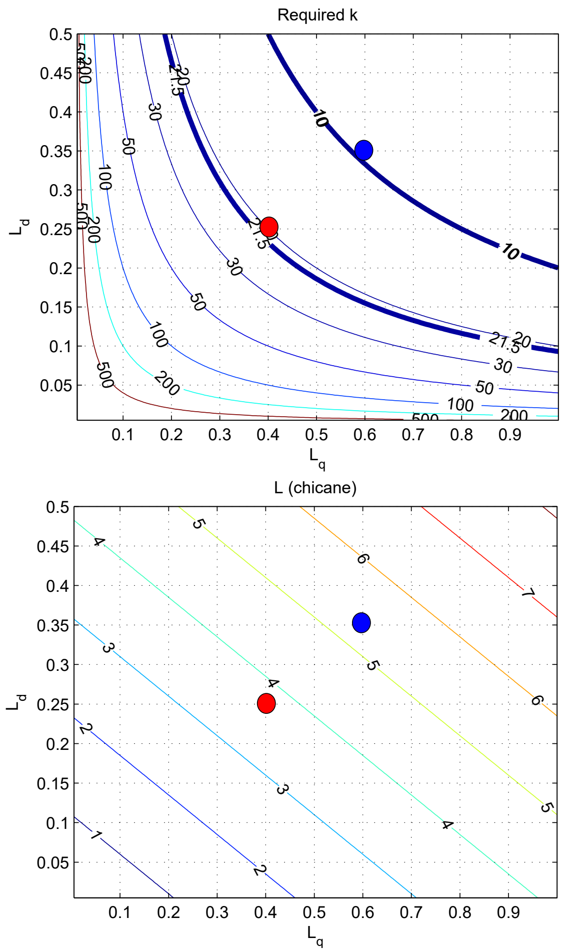

Figure 2: Chicane Option 1 optimisation. Top: Required quadrupole k vs L_d and L_q, with bold contours indicating the maximum achievable k for Halbach and EM quadrupoles. Bottom: total chicane length *vs* L_q and L_d. The red and blue dots indicate the combinations of L_q and L_d giving the minimum chicane length that provides sufficient k for Halbach and EM quadrupoles respectively.

at the midpoints between the dipoles and the central dipole could be split to add a third matching quad. These positions all have zero dispersion so the quadrupoles for dispersion control would change little and the design would allow the transverse matching and dispersion cancellation to be approximately independent. The extra length would then be a minimum of $3L_q$, approximately 1.2 m taking the total length (using Halbach quadrupoles) to approximately 5 m, i.e. just within the space assumed to be feasible in terms of FEL performance. For Option 2 there are no obvious locations to add matching quadrupoles. One possibility would be for dipoles 2 and 3 to be replaced by offset quadrupoles, then an extra quadrupole either side of the chicane. The total length increase would then be $2L_q + 2L_d$, approximately 1.3 m, taking the total length to about 4.1 m (if using Halbach quadrupoles). Further considerations should be the tolerances to errors in magnet position, beam trajectory, beam energy and magnet field quality.

CONCLUSION

For High-Brightness SASE the performance is close to ideal if the chicane scaled dispersion factor $D \lesssim 0.01$. With generic XFEL parameters, the acceptable delay chicane length could be as long as 5 m which would allow the saturation power to be nearly 50% of that of normal SASE with a saturation length, in terms of the number of undulator periods, only increased by 6% (although the total floor length is more than doubled). Two candidate designs for chicanes have been investigated and shown to have a level of isochronicity satisfying $D \lesssim 0.01$. The length of the chicanes is determined by the available integrated gradient of the quadrupoles used for dispersion control and does not depend on the required delay. The quadrupole field does not need to be changed depending on the delay. The designs shown here are not suitable for the Mode-Locked Afterburner schemes because the fact that these schemes require much smaller delays does not mean that the chicanes can be more compact. The fact that the quadrupole field does not need to vary with delay but only with beam energy implies that only a small range of tuning is required for a fixed beam energy (in fact a prototype of a tunable hybrid quadrupole with inscribed radius 4.125 mm, peak gradient 500 T/m and tuning range of 20% has previously been demonstrated [7]) . The candidate designs do not yet include transverse focussing but it is anticipated that the inclusion of extra quadrupoles to achieve this can be done while keeping the overall chicane length within 5 m—this has yet to be confirmed. The effect of higher order dispersion on the FEL performance has not been studied but the value of the T_{566} term has been determined and is of the same order as that for a dipole only chicane with the same delay.

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