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FIRST COMMISSIONING OF THE CORRECTOR QUADRUPOLES IN THE 2ND BUNCH COMPRESSION CHICANE AT FLASH

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Abstract

FLASH, the superconducting XUV and soft X-ray FEL is undergoing a substantial upgrade (FLASH2020+) with two long shutdowns 2021/22 and 2024/25. In the 1st shutdown, FLASH's 2nd bunch compression chicane (CBC2) has been completely redesigned for the FLASH2020+ upgrade project. The redesign allowed the installation of two quad/skew-quad packs in each of the arms of the 4-dipole (C-type) chicane. With these corrector quadrupoles it should be possible to partially compensate linear correlations between the transverse centroids and the longitudinal position inside the bunch, so called bunch-tilts. During the limited commissioning/development shifts in a year of operation devoted to maximizing user hours we started measuring the impact of the quads on the bunch tilts and the unavoidable effects on dispersion closure and beam optics.

In this contribution we report first results.

INTRODUCTION

The free-electron laser user facility FLASH [1, 2] is in between two shutdowns of a substantial upgrade and refurbishment project (FLASH2020+) [3–5]. In the course of this project the 2nd bunch compression chicane, CBC2 [6], was completely redesigned and rebuild. As is shown in Fig. 1, CBC2 is a C-type 4-dipole chicane with round vacuum chambers and bellows designed, so that the inner two dipoles (including the vacuum chambers) can be moved in- and outwards on rails to accommodate variable longitudinal dispersion M_{56}. The deflection angle ranges from 0° to 6° (nominal 5°) corresponding to an M_{56} from 0 to ~100 mm (nominal ~70 mm). In the following we assume (consistently with [6]) 6-d symplectic (at reference energy E_0 = const) phase space $\mathbb{R}^6$ with coordinates $\vec{z} := (x, a, y, b, \tau, \eta)^{\mathrm{T}}$, where[1] $a := p_x/p_0 =_1 dx/ds$, $b := p_y/p_0 =_1 dy/ds$, $\eta := (E - E_0)/E_0$, $\tau := (t_0-t)E_0/p_0$, and with the standard phase space (probability) density of the bunch Ψ so that $\int_{\mathbb{R}^6} \Psi(\vec{z})d^6z = 1$. Moreover we define the partial averaged (5-d) centroids $\langle x\rangle_\perp(\tau)$, $\langle a\rangle_\perp(\tau)$, $\langle y\rangle_\perp(\tau)$, $\langle b\rangle_\perp(\tau)$, and $\langle \eta\rangle_\perp(\tau)$ by $\langle f\rangle_\perp(\tau) := \int_{\mathbb{R}^5} f\,\Psi(x, a, y, b, \eta, \tau)\,dx\,da\,dy\,da\,d\eta$ for any $f(\vec{z})$. The function $\langle \eta\rangle_\perp(\tau) = h\,\tau + O(\tau^2)$ is called the energy chirp of the bunch, and $\langle x\rangle_\perp(\tau) = \xi_x\,\tau + O(\tau^2)$, $\langle a\rangle_\perp(\tau) = \xi_a\,\tau + O(\tau^2)$, $\langle y\rangle_\perp(\tau) = \xi_y\,\tau + O(\tau^2)$, $\langle b\rangle_\perp(\tau) = \xi_b\,\tau + O(\tau^2)$ are, in general unwanted, transverse-to-longitudinal centroid correlations (bunch tilts).

It has been pointed out in [7, 8] that the intrinsic transverse dispersion inside a chicane and the bunch E-chirp which is necessary to cause the chicane to actually compress the bunch (in τ), can be used to partially compensate unwanted bunch tilts in the presence of quadrupoles and skew quadrupoles (and potential higher order upright and skew multipoles) inside the chicane. In [6] we have developed a thin lens model of a C-chicane with added corrector quads/skew-quads and derived corrector strengths to completely compensate incoming beam tilts for given E-chirp. To completely determine $\langle x\rangle_\perp(\tau)$, $\langle a\rangle_\perp(\tau)$, $\langle y\rangle_\perp(\tau)$, and $\langle b\rangle_\perp(\tau)$ one would need a transverse deflecting structure (TDS) with switchable (x/y) streak polarization, and a screen in an, at best dispersion-free, transport channel with phase advances (in both transverse planes) spanning approximately 90°. If at all possible for a given beamline this is a tedious and lengthy procedure not suitable for empirical online tuning. At FLASH we have LOLA [9, 10] in the FLASH1 beamline which has only one streak polarization (vertical, for the time being) and PolariX [11–14] in the FLASH2 beamline which features variable streak polarization but has no dispersion free screen and only limited degrees of freedom for changes of the phase advance. Thus a fully deterministic use of the tilt compensation is at least extremely inconvenient if not impossible during FEL run optimization. However to efficiently tune the FEL performance with the tilt compensators, one needs some kind of "response functions" as guidance for the tuning process. We have stated commissioning the tilt compensators and, as a starting point, have restricted us on the responses of the two upright quadrupoles. The skew quad quadrupoles are more elaborate since they mainly transform centroid offsets between the bend- and the normal plane (e.g. the planes with and without dispersion). Here we only treat 1st order effects, i.p. we treat the linear chirp $\langle \eta\rangle_\perp(\tau) =_1 h\,\tau$, and the linear tilts $\langle z_i\rangle_\perp(\tau) =_1 \xi_i\,\tau$.

THIN LENS MODEL

As in [6] we make the following ansatz for the transport map of the chicane

$$\underline{M}_{\mathrm{cbc}} := \underline{B}^{+}\underline{D}_l\underline{K}_2\underline{D}_m\underline{B}^{-}\underline{D}_n\underline{B}^{-}\underline{D}_m\underline{K}_1\underline{D}_l\underline{B}^{+}\,, \qquad (1)$$

where $\underline{B}^{\pm}$ are thin lens dipoles with deflection angle $\pm\phi$, $\underline{D}_l$, $\underline{D}_m$, $\underline{D}_n$ are the drifts between the outer dipole and the quad/skew-quad pack (length l), the quad/skew-quad pack and the inner dipole (length m)[2] on each side, the central drift between the inner dipoles (length n), and $\underline{K}_{1,2}$ are the thin lens *quad/skew-quad packs* with upright/skew quad strengths κ_1, κ_2, $\tilde{\kappa}_1$, $\tilde{\kappa}_2$ as combined function kicks, i.e. without a separating drift between quad and skew-quad in each pack. We compute the responses of "string bunches"

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[1] $f(u) =_n g(u)$ is shorthand for $f(u) = g(u) + O(u^{n+1})$.

[2] for FLASH's CBC2 the relation $l/m \approx 1.7$ holds.

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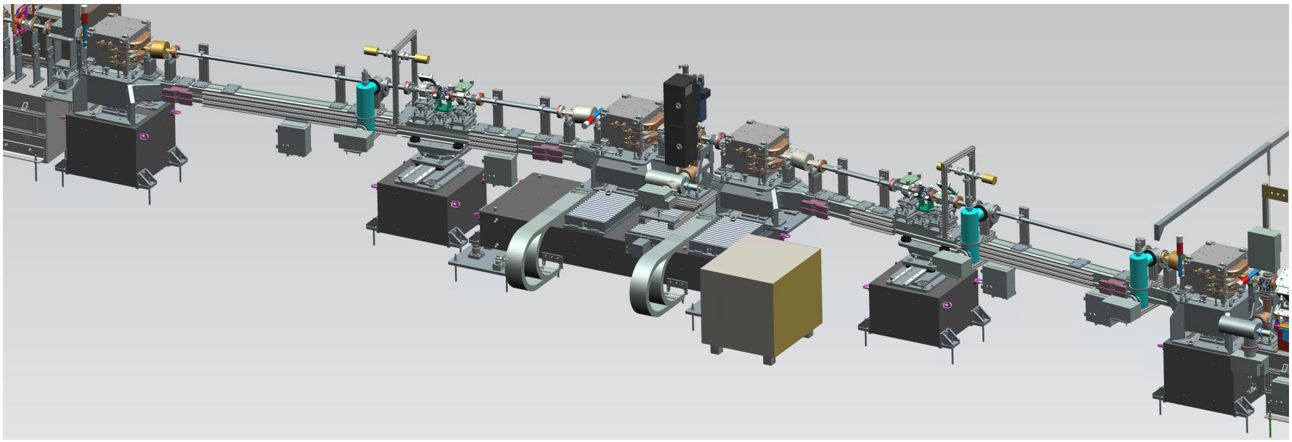

Figure 1: 3-d CAD drawing of the new movable 2nd bunch compression chicane CBC2. Beam goes from right to left.

parameterized by the longitudinal spatial coordinate:
$\vec{z}_0(\tau) := (0,0,0,0,\tau,h\tau)^{\mathrm{T}}$ (E-chirp only),
$\vec{z}_x(\tau){:=}(\xi_x\tau,0,0,0,\tau,h\tau)^{\mathrm{T}}$, $\vec{z}_a(\tau){:=}(0,\xi_a\tau,0,0,\tau,h\tau)^{\mathrm{T}}$,
$\vec{z}_y(\tau){:=}(0,0,\xi_y\tau,0,\tau,h\tau)^{\mathrm{T}}$, $\vec{z}_b(\tau){:=}(0,0,0,\xi_b\tau,\tau,h\tau)^{\mathrm{T}}$,
where the latter 4 are with chirp *and* tilt in one transverse coordinate.

Single Quad Tilt Responses

While in [6] we studied analytic solutions $\underline{M}_{\mathrm{cbc}}\vec{z}_i = (0,0,0,0,\tau/\tilde{C},h\tau)^3$ in the 4 corrector quad strengths, here we will study the responses $\vec{z}_i^{\,j,u} := \underline{M}_{j,u}\vec{z}_i$ of the chicane with one single non-vanishing corrector strength:
$\underline{M}_{0,0} := \underline{M}_{\mathrm{cbc}} : \underline{K}_2 = \underline{1}\ ,\ \underline{K}_1 = \underline{1}$ (plain chicane)
$\underline{M}_{1,u} := \underline{M}_{\mathrm{cbc}} : \underline{K}_2 = \underline{1}\ ,\ \underline{K}_1 = \underline{U}_1$ (only 1st upright q.)
$\underline{M}_{2,u} := \underline{M}_{\mathrm{cbc}} : \underline{K}_2 = \underline{U}_2\ ,\ \underline{K}_1 = \underline{1}$, (only 2nd upright q.)
where $\underline{1}$ designates a completely *inactive* corrector pack, and $\underline{U}_i(\kappa_i)$ designates a corrector pack with a single active *upright* quad.

As an example we find

$$\vec{z}_0^{\,1,u}/\tau = (\phi l(l+2m+n)h\kappa_1, \phi l h\kappa_l, 0, 0, 1/\tilde{C}_0^{1,u}, h)^{\mathrm{T}} \quad (2)$$
$$\vec{z}_0^{\,2,u}/\tau = (\phi l^2 h\kappa_2, \phi l h\kappa_2, 0, 0, 1/\tilde{C}_0^{2,u}, h))^{\mathrm{T}} \quad (3)$$
$$\tilde{C}_0^{i,u} := 1/(1+\phi^2(2(l+m)-l^2\kappa_i)h)$$
$$\vec{z}_x^{\,1,u}/\tau = ((\phi l h+\xi_x)(l+2m+n)\kappa_1+\xi_x, (\phi l h+\xi_x)\kappa_1, 0, 0, 1/\tilde{C}_x^{1,u}, h)^{\mathrm{T}} \quad (4)$$
$$\vec{z}_x^{\,2,u}/\tau = ((\phi l^2 h+l\xi_x)\kappa_2+\xi_x, (\phi l h+\xi_x)\kappa_2, 0, 0, 1/\tilde{C}_x^{2,u}, h)^{\mathrm{T}} \quad (5)$$
$$\tilde{C}_x^{i,u} := 1/(1+\phi^2(2(l+m)-l^2\kappa_i)h-\phi l\kappa_i\xi_x)$$
$$\vec{z}_y^{\,1,u}/\tau = (\phi l(l+2m+n)h\kappa_1, \phi l h\kappa_1, \xi_y(1-(l+2m+n)\kappa_1), -\xi_y\kappa_1, 1/\tilde{C}_x^{1,u}, h)^{\mathrm{T}} \quad (6)$$
$$\vec{z}_y^{\,2,u}/\tau = (\phi l^2 h\kappa_2, \phi l h\kappa_2, \xi_i(1-l\kappa_2), -\xi_y\kappa_2, 1/\tilde{C}_x^{2,u}, h)^{\mathrm{T}} \quad (7)$$

As expected, x-, and a-component of the upright-quad responses to the non-tilted string bunch $\vec{z}_0^{\,i,u}$, $i=1,2$ are proportional to κ_i (they are the D and D' leakage at the exit of the chicane due to the correctors) and $\tilde{C}_0^{i,u} \rightarrow C := 1/(1+\phi^2 2(l+m)h)$ for $\kappa_i \rightarrow 0$, the well known thin lens result for an ordinary C-chicane. The x-components of $\vec{z}_x^{\,i,u}$ have unique (non-vanishing) zeros in κ_i, the a-components are proportional to κ_i. The $\vec{z}_a^{\,i,u}$ have a similar structure but with more lengthy terms that go beyond the scope of this paper. The y-components of $\vec{z}_y^{\,i,u}$ have unique (non-vanishing) zeros in κ_i, while the b-, x-, and a-components are proportional to κ_i. Much alike the $\vec{z}_a^{\,i,u}$, the $\vec{z}_b^{\,i,u}$ have similar properties that the $\vec{z}_y^{\,i,u}$ but turn out too long for this paper.

[3] $\tilde{C}$ is the compression modified by the action of the corrector quads.

TDS Images

At FLASH1/2 the TDS screens are about 130 m/170 m apart from the center of CBC2. Thus the actual phase advances are difficult to assess during run preparation and tuning. But without making any assumptions on the exact phase evolution one can measure the change of the observed tilt at the TDS due to changes of the upright quads in the chicane. Both FLASH TDSs can streak in the vertical direction and have no vertical design dispersion on the measurement screens. Thus we assume a TDS with vertical streak polarization and a screen with potentially (finite or vanishing) horizontal dispersion. The most simple model of the system is a thin lens vertical streaking TDS followed by a drift map with additional horizontal dispersion.

$$\underline{M}^{+} := \underline{D}_{L,\Delta}\,\underline{T}_{+\zeta}\ \ ,\ \ \underline{M}^{-} := \underline{D}_{L,\Delta}\,\underline{T}_{-\zeta}\ , \quad (8)$$

where $\underline{D}_{L,\Delta}$ is a drift of length L with additional $D_{16} = D_{52} =: \Delta$ and $\underline{T}_{\pm\zeta}$ is a thin lens TDS with streak ζ on the + and − zero-crossing. The image on the screen is the projection of the incoming 6-d phase space on the x-y-plane $\vec{XY} : \vec{z} \mapsto (z_1,z_3)^{\mathrm{T}}$. Because of linearity we can study the x-y-image of string bunches after application of $\underline{M}^{\pm}$ on both zero-crossings of the field in the TDS: $\vec{z}_i^{\,\pm} := \underline{M}^{\pm}\vec{z}_i$ and $\vec{w}_i^{\,\pm} := \vec{XY}(\vec{z}_i^{\,\pm})$. Most naturally a TDS is used to image the longitudinal phase space, and with the chosen orientation one has $\tau \mapsto y$ and $\eta \mapsto x$, so one generally interprets a y-x-image (x-y-image rotated by 90°) as τ-η-image convoluted with the y-x transverse distributions. In the linear model

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we can solve $y_i^{\pm}(\tau)$ (on the screen) for τ and eliminate τ in $x_i^{\pm}(\tau)$ to obtain $x_i^{\pm}(y) =_1 (\mathrm{d}x/\mathrm{d}y)_i^{\pm} y$ for both zero-crossings and obtain σ_i and θ_i, from every string bunch $\vec{z}_i$

$$2\sigma_i = \left(\frac{\mathrm{d}x}{\mathrm{d}y}\right)_i^+ - \left(\frac{\mathrm{d}x}{\mathrm{d}y}\right)_i^+ \tag{9}$$

$$2\theta_i = \left(\frac{\mathrm{d}x}{\mathrm{d}y}\right)_i^+ + \left(\frac{\mathrm{d}x}{\mathrm{d}y}\right)_i^+ ,. \tag{10}$$

We illustrate this with three examples.

1. $\vec{z}_0$ (E-chirp only):
   First we find $\vec{w}_0^{\pm}(\tau) = (Dh\tau, \pm L\zeta\tau)^{\mathrm{T}}$, so that $\theta_0 = 0$ and $\sigma_0 = \frac{Dh}{L\zeta}$. The bunch has no tilt but a chirp h which can be computed from the measured image by $h = \frac{L\zeta\sigma_0}{D}$.

2. $\vec{z}_x|_{h=0}$ (no E-chirp but x-tilt):
   We find $\vec{w}^{\pm}_{x,h=0}(\tau) = (\xi_x\tau, \pm L\zeta\tau)^{\mathrm{T}}$ and again $\theta_{x,h=0} = 0$ but $\sigma_{x,h=0} = \frac{\xi_x}{L\zeta}$. The bunch has no chirp but an x-tilt $\xi_x = L\zeta\sigma_{x,h=0}$

3. $\vec{z}_x$ (E-chirp & x-tilt):
   The y-x-image gives $\vec{w}_x^{\pm} = ((Dh + \xi_x)\tau, \pm L\zeta\tau)^{\mathrm{T}}$, so that again $\theta_x = 0$ and $\sigma_x = \frac{Dh+\xi_x}{L\zeta}$. Now let the horizontal dispersion $D = 0$ as is the case for the non-invasive LOLA measurement (kicker and off-axis screen). Then one finds for the x-tilt $\xi_x = L\zeta\sigma_x$ similar to case 2.

Vertical tilts are more difficult to assess with this method since vertical offset is transformed into E-gain in a vertically streaking TDS. In particular is in general $\theta \neq 0$ for the vertically tilted string bunches.

EXPERIMENTAL RESULTS

We have set up compression with an approximately linear E-chirp in LOLA, i.e. slightly compressed to minimize the effect of the cosinusoidal accelerating voltage in the main linac cavities, but still long enough for a good relative resolution (bunch length over $\delta_\tau \gg 1$ & bunch fits screen) in LOLA. We checked that the $x(y)$ slopes for the two zero-crossings can well be distinguished for inactive corrector quads. We checked that the corrector quads have a visible influence on the slopes. We established scan ranges for the upright corrector quads, so that the transmission is not affected by the optics mismatch nor the leakage of the chicane dispersion. Then we ran a 2d-scan of κ_1 and κ_2 and measured the slopes for both zero-crossings. The evaluattion of the horizontal beam tilt is shown in Fig.2. Equations (4) and (5) show that the single quad responses of κ_1 and κ_2 are similar (basically only differing by the characteristic lengths). Thus a result of the form $\xi_x^{\mathrm{final}} \approx \xi_x^{\mathrm{initial}} + \omega_1\kappa_1 + \omega_2\kappa_2$ with constants ω_i, $i = 1, 2$, so that $\xi_x^{\mathrm{final}} \approx 0$ for $\kappa_2 = -\frac{\xi_x^{\mathrm{initial}} + \omega_1\kappa_1}{\omega_2}$ is at least plausible.

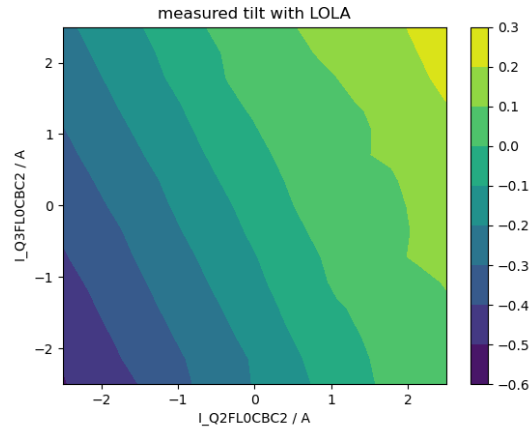

Figure 2: A scan of the resulting x-τ correlation at LOLA non-dispersive screen vs. the quad currents of the two upright quads.

CONCLUSION

Our first measurements where quite successful, but we have to elaborate also on the effect of the skews and assess the effect of the correctors on optics mismatch and on the leakage of chicane dispersion in the framework of a FEL set up.

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