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A NEW 2ND BUNCH COMPRESSION CHICANE FOR THE FLASH2020+ PROJECT

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Abstract

The first stage of the FLASH2020+ project is an upgrade of the FLASH injector beamline. Within this framework, the 2nd bunch compression chicane (BCC) will be completely redesigned. The old S-chicane will be replaced with a new C-chicane which is 3.5 m shorter thereby generating space a new section for re-matching the beam from the injector into the linac. The new BCC will be equipped with quad/skew-quad units in both legs of the chicane to compensate correlations of the transverse degrees of freedom with the longitudinal ones. Since quadrupoles tend to have a circular bore, the chicane is designed with movable round vacuum chambers and movable dipoles for maintaining full flexibility in choosing the compression parameters.

This article describes the technical details and introduces a thin-lens model of BCCs which allows analytical estimates on the effects of powering the quad/skew-quad units on optics parameters as well as estimates on the required strengths of these magnets in order to remove correlations of the magnitudes typically observed at FLASH.

INTRODUCTION

FLASH is a Free-electron laser (FEL) with two simultaneously operated FEL beamlines (FLASH1 & FLASH2) for extreme UV and soft X-ray in self amplified spontaneous emission (SASE) mode, driven by a superconducting linac capable of providing bursts of typically a total of 500 bunches at 10 Hz to both beamlines simultaneously [1, 2]. FLASH2020+ is a substantial upgrade project [3] which includes an energy upgrade, machine modifications to ensure improved operability and a complete remodeling of the FLASH1 beamline to enable seeded (HGHG & EEHG) FEL operation in burst mode simultaneous to SASE operation in FLASH2. To establish measuring and correcting the optical mismatch at the 2nd bunch compression chicane (BCC), physical space (and phase advance) for a multi-quadrupole scan has to be generated. Thus the old 6-dipole (S-) chicane will be replaced by a shorter 4-dipole (C-) chicane. Intra-bunch transverse-to-longitudinal correlations from wakefields and coupler kicks are known to be detrimental to the FEL performance, in particular for seeding. It was decided to use quadrupoles in the dispersive legs of the BCC (see below) to correct these unwanted bunch tilts. Moreover, a flexible momentum compaction ($M_{56} \equiv D_\tau$) is needed to balance between the moderately compressed (~ 600 - 800 A) seeding bunches which are extremely sensitive to micro-bunching and residual energy chirp and the stronger compressed (~ 1 - 2 kA), potentially ultra-short SASE bunches.

THE LAYOUT OF FL0CBC2

Combining a flexible M_{56} with the ability to correct transverse-to-longitudinal intra-bunch correlations implies certain constraints on the design of the BCC. The preferred way to correct the correlations requires (at least) an upright and a skew quadrupole in each leg of the chicane (see next section). Due to feasible quadrupoles bores for this purpose, the beam pipe radius is limited to ~ 40 mm. Within this aperture a useful range of the M_{56} can not be achieved inside a fixed vacuum chamber. Therefore the BCC has been designed with the two inner dipoles mounted on a girder which can be moved horizontally on rails, thereby enabling bending angles ranging continuously from 0 to 6° or equivalently an M_{56} from 0 to 100 mm. The momentum compaction in thin lens approximation is

$$M_{56}^{\text{thin}} = 2L \cdot \phi^2 , \qquad (1)$$

where L is the length of a single leg and ϕ the deflecting angle of the dipoles.

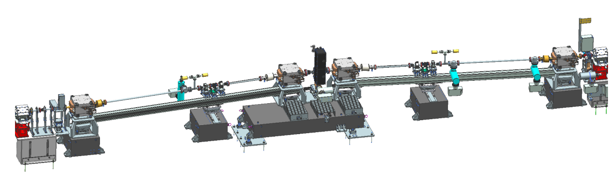

Figure 1: CAD model of the new 2nd BCC for FLASH2020+.

Figure 1 shows the CAD model of the new 2nd BCC. The overall length of the BCC is about 12 m and the leg length is about 5.1 m. The dipoles are 450 mm long rectangular bends with a gap height of 40 mm and a good field region of 60 mm to generate space for the dispersed beam in the inner dipoles with more than 10 σ beam radius. The girder for the inner dipoles is actuated by a stepper motor and controlled by an independent elongation transducer. All movable parts are dragged by this girder and therefore automatically aligned with respect to one another. The vacuum system and the quadrupole packs in each leg are supported on a pivoting joist. The pivoting is realized by a rotation around a point (close to the vertex point) inside the outer dipoles that maximizes the aperture of the vacuum system over the whole angle range. Each joist is connected to the central girder by guiding rails mounted on a bearing to so that the lengthening of the chicane leg during pivoting is

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compensated by slipping along these rails. Each joist has a third support under the quadrupole pack using a cross-table with a bearing unit mounted on rails aligned parallel to the central (inner dipole) rails. The vacuum system consists of custom-shaped chambers in dipoles and round tapered chambers for the legs. Stretch, tilt and shear of the vacuum system are compensated by large membrane bellows. The quadrupole pack unit also hosts a beam position monitor and a vacuum sensor connected to the fast closing valves protecting the cold modules in case of vacuum leaks. In addition the consistency of the horizontal elongation ($\rightarrow$ geometric bend angle) with dipole current and beam energy ($\rightarrow$ beam deflection angle) will be continuously monitored by software.

A THIN-LENS MODEL FOR C-CHICANES WITH QUAD/SKEW-QUAD PAIRS

In order to obtain insight into the structure of the system beyond the (surely more accurate) black-box results from numerical codes, we came up with a (mostly) solvable analytical approximation to estimate the required corrector strengths and the resulting transverse dispersion leakage and the perturbation of the design M_{56} due to the corrections. We start from 6-d phase space (PS) $\vec{z} := (x, a, y, b, \tau, \eta)^{\mathrm{T}}$, where $a =_1 dx/ds$, $b =_1 dy/ds$, $\eta \approx \delta E/E_0$, and with the standard phase space (probability) density (PSD) of the bunch Ψ so that $\int_{\mathbb{R}^6} \Psi(\vec{z}) d^6 z = 1$. Now we separate out the transverse component of $\vec{z}$: $\vec{z}_\perp := (x, a, y, b)^{\mathrm{T}}$, and compute the partial (5-d) averaged centroids of a bunch centered on the design orbit $\vec{z} = \vec{0}$:

$$\langle \vec{z}_\perp \rangle_\perp (\tau) := \int_{\mathbb{R}^5} \vec{z}_\perp \; \Psi(\vec{z}_\perp, \eta, \tau)\, d^4 z_\perp \, d\eta \,, \quad (2)$$

$$\langle \vec{z}_\perp \rangle_\perp (\tau) = \vec{\xi}\, \tau + O(\tau^2) \,. \quad (3)$$

Note that the 5-d averaged η-centroid $\langle \eta \rangle_\perp (\tau) := \int_{\mathbb{R}^5} \eta \Psi(\vec{z}_\perp, \eta, \tau)\, d^4 z_\perp \, d\eta$ and its linear approximation $\langle \eta \rangle_\perp (\tau) = h\,\tau + O(\tau^2)$ are well known from the theory of bunch compression.

The $\langle \vec{z}_\perp \rangle_\perp (\tau)$ represent the intra-bunch transverse-to-longitudinal correlations (also known as transverse bunch-tilts or -chirps), ξ_i, $i = x, a, y, b$. A very clever idea of how to correct these unwanted bunch tilts [4] which was experimentally verified [5] makes use of the dispersion in BCCs. In most FELs bunch compression is realized via transporting a bunch with a, to some extent linear, energy chirp $\langle \eta \rangle_\perp (\tau) = h\,\tau$ through a BCC with a non-zero M_{56}. The dispersion inside the BCC spreads out the trajectories in the bend plane according to their η. Inserting $\tau \approx \langle \eta \rangle_\perp / h$ into (3) shows that transverse beamline elements, e.g. quadrupoles, located inside the BCC can potentially modify the transverse bunch tilts.

Figure 2 shows our thin lens model of a symmetric C-chicane with quadrupole packs. All quadrupoles and dipoles are thin lenses. Each leg ($i = 1, 2$) contains an upright ($\underline{K}_{\mathrm{u},i}$) and a skew ($\underline{K}_{\mathrm{s},i}$) thin lens quadrupole. They are separated by 2δ. As it turns turns out the relevant questions cannot be answered analytically for $\delta \neq 0$. In the limit $\delta = 0$ the two kicks in each leg coalesce into one combined quadrupole kick $\underline{K}_i$. However, some problems can be solved at 1st order

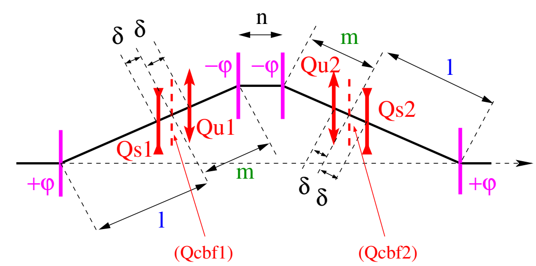

Figure 2: Layout of thin lens BCC model.

in $\delta > 0$. l is the length of the drift $\underline{D}$ from the outer dipole to the center of the quadrupole-pack, while m is distance from the quadrupole-pack to the inner dipole ($L = l + m$) and n is the distance between the inner dipoles. In this article we neglect the geometric body focusing as well as the edge focusing of the dipoles but note that for "chicane R-bends" (see appendix) analytical solutions to most relevant problem can still be found. The deflection angle of the dipoles $\underline{B}^{\pm}$ is $\pm\phi$ and κ, ρ are the $:= \int kdl$ of the *upright* quadrupoles, while θ, ψ are the $:= \int kdl$ of the *skew* quadrupoles, so that $\underline{K}_1 = \underline{K}(\rho, \psi)$ and $\underline{K}_2 = \underline{K}(\kappa, \theta)$.

The transfer matrix of the full BCC for $\delta = 0$ is

$$\underline{M}^{(\delta=0)} := \underline{B}^{+} \underline{D}_l \underline{K}_2 \underline{D}_m \underline{B}^{-} \underline{D}_n \underline{B}^{-} \underline{D}_m \underline{K}_1 \underline{D}_l \underline{B}^{+} \,. \quad (4)$$

And its M_{56} for vanishing κ, ρ, θ, and ψ is given by (1).

Now we remark that to linear approximation the centroids ($\langle \vec{z}_\perp \rangle_\perp$) evolve according to the same equations of motion as single trajectories ($\vec{z}_\perp$). Hence we can represent the linear motion of the transversely linearly tilted bunch by a single trajectory starting at the entrance of the BCC where all components are linearly parameterized by τ:

$$\vec{z}_i := (\vec{\xi}^{\mathrm{T}} \tau, \tau, h\tau)^{\mathrm{T}} \,. \quad (5)$$

At the exit of the BCC we require the transverse tilts to be removed

$$\vec{z}_f := \underline{M}^{(\delta=0)} \vec{z}_i \stackrel{!}{=} (0, 0, 0, 0, \widetilde{M}_{56}\tau, h\tau)^{\mathrm{T}} \,, \quad (6)$$

and solve for κ, ρ, θ, and ψ.

Examples

In the case of only horizontal positional and angle tilts ($\xi_y \equiv \xi_a \equiv 0$) we find that no skew quads are needed ($\theta \equiv \psi \equiv 0$) and the upright quadrupole strength for removing the correlations are

$$\kappa = \frac{l \xi_a + \xi_x}{l\,(2m + n)\, h\, \phi} \quad (7)$$

$$\rho = -\frac{\xi_a\,(l + 2m + n) + \xi_x}{hl\phi\,(2m + n) + \xi_a l\,(2m + n) + 2\xi_x\,(2m + n)} \quad (8)$$

The horizontal dispersion (not shown) is no longer closed and $\widetilde{M}_{56} = M_{56} + l\phi\xi_a/h$.

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Correcting only $\xi_y \neq 0$ requires two skew and one upright quadrupole.

The most general case with all $\xi_i \neq 0$ is shown in Figs. 3, 4, and 5 which were created by evaluating the analytical formulae (not shown) for κ, ρ, θ, and ψ and the dispersions numerically. The BCC geometry, the chirp and the transverse tilts at the chicane entrance are typical values compatible with the FLASH2020+ design. Figures 3 and 5 show that the required quadrupole strengths are rather moderate and enable the installation of comfortably small quadrupoles, and that required strengths have a broad minimum as a function of the actual location of the quadrupole pack.

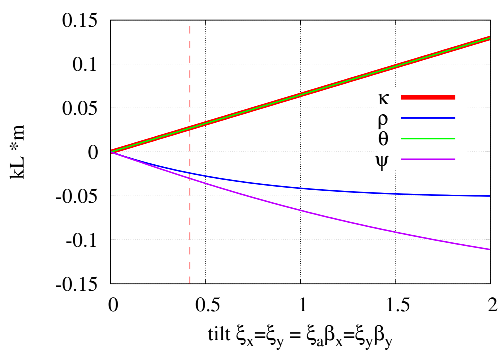

Figure 3: Correcting integrated quadrupole strengths κ, ρ, θ, and ψ for the case with all $\xi_i \neq 0$ and typical FLASH2020+ parameters. The vertical red broken line is the expected tilt for FLASH2020+.

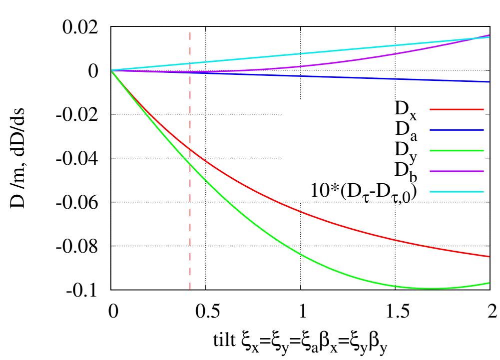

Figure 4: Leaking dispersions D_x, D_a, D_y, D_b, and the change of momentum compaction $D_\tau - D_{\tau 0}$ at the chicane exit for the case with all $\xi_i \neq 0$ and typical FLASH2020+ parameters. The vertical red broken line is the expected tilt for FLASH2020+.

CONCLUSION AND OUTLOOK

The FLASH2020+ upgrade foresees a 2nd BCC with variable M_{56} and upright/skew quadrupole packs for correcting unwanted transverse-to-longitudinal correlations within the bunch. As a consequence the chicane must have movable

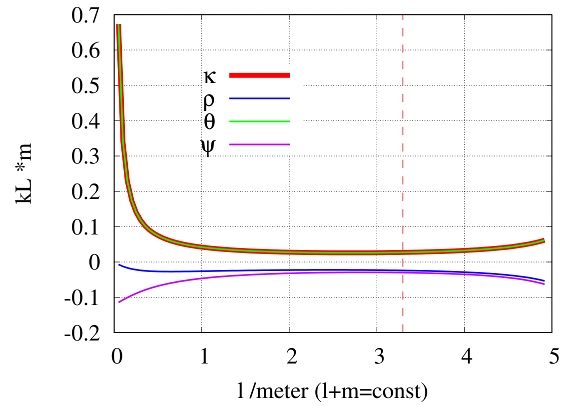

Figure 5: The dependence of the correcting quadrupole strengths κ, ρ, θ, and ψ on the location of the quadrupole pack inside the chicane leg (vary l with $l + m$ =const.). The vertical red broken line is the l of the FLASH2020+ design.

inner dipoles and round vacuum chambers. We have developed a thin lens model of C-chicanes with inner quadrupoles packs that allows explicitly determining the quad-strengths needed for removing given correlations. This model shows that reasonably small integrated quad-strengths and thus reasonably small/light quadrupole hardware are sufficient for correcting the expected correlations. The design is finished. A chicane of this type will be installed as 2nd BCC at FLASH during the 2021/2022 shutdown. We are looking forward to the commissioning in autumn 2022.

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APPENDIX

For δ = the matrix for the chicane *with* dipole focusing reads

$$\begin{aligned}\underline{M}^{(\delta>0)} \quad := \quad & \underline{B}^{+}\underline{D}_{l-\delta}\underline{K}_{\mathrm{s},2}\underline{D}_{2\delta}\underline{K}_{\mathrm{u},2}\underline{D}_{m-\delta}\underline{B}^{-} \\ & \underline{D}_{n} \\ & \underline{B}^{-}\underline{D}_{m-\delta}\underline{K}_{\mathrm{u},1}\underline{D}_{2\delta}\underline{K}_{\mathrm{s},1}\underline{D}_{l-\delta}\underline{B}^{+}\,. \end{aligned} \tag{9}$$

For $\delta > 0$ the matrix for the chicane *without* dipole focusing reads

$$\begin{aligned}\underline{M}^{(\delta=0)}_{\text{dip.foc.}} \quad := \quad & \underline{S}_{r,+\phi}\underline{E}_{r,+\phi}\underline{D}_{l}\underline{K}_{2}\underline{D}_{m}\underline{E}_{r,-\phi}\underline{S}_{r,-\phi} \\ & \underline{D}_{n} \\ & \underline{S}_{r,-\phi}\underline{E}_{r,-\phi}\underline{D}_{m}\underline{K}_{1}\underline{D}_{l}\underline{E}_{r,+\phi}\underline{S}_{r,+\phi}\,, \end{aligned} \tag{10}$$

where $\underline{S}_{r,\phi}$ is the thin lens map for a sector-bend including the geometric (body) focusing, and $\underline{E}_{r,\phi}$ is the corresponding focusing kick from an edge plane tilted by ϕ.

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