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DESIGN CONSIDERATIONS FOR A NEW EXTRACTION ARC AT THE EUROPEAN X-RAY FREE ELECTRON LASER

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Abstract

It has been proposed that a new arc, called T20, should be installed for a third fan of undulators at the European X-ray Free Electron Laser (EuXFEL) in the next decade. Due to geometric constraints this arc will need to be at a much larger angle than for the existing arc, called T1. It is expected therefore that coherent synchrotron radiation effects (CSR) in T20 on the bunch emittances will be considerable. To preserve the x-ray beam qualities in any downstream undulators, this effect will need to be understood and ideally mitigated. In this paper the status of the T20 beamline design is discussed, the expected downstream beam properties are shown and possible strategies for improving the beam quality are outlined.

INTRODUCTION

X-ray free electron lasers (XFELs) require ultra-bright electron beams to achieve the desired photon beam characteristics. This means that ultra-short (high peak current) electron bunches with small transverse emittances and energy spread are necessary. However, the impact of coherent synchrotron radiation (CSR), in which radiation from the bunch's tail interacts with its head and subsequently dilutes the bunch's emittance, mandates linear machines. Running counter to this is the desire for multiple undulator beamlines and user experiments. For this reason, XFEL facilities around the world typically branch at relatively small angles (a few degrees with respect to the linac) after acceleration to two or more undulator lines. Still, the effects of CSR on the beam when diverting to these separate lines must be accounted to maintain performance in the downstream undulators.

The EuXFEL [1, 2] splits into three beamlines (T1, T2 and TLD) after the collimation section at the *switchyard*. Directly ahead of the switchyard lies T2, where SASE1 and SASE3 are situated. To the left lies T1 and SASE2, and downwards lies TLD and a beam dump. An additional beamline that branches to the right, called T20, and with it a new set of undulators is planned for the end of the decade. The switchyard and the beam distribution system, including the proposed T20 beamline, were mostly developed during the initial EuXFEL design process [3–5]. The use of CSR mitigation techniques was limited in the T1 arc design due to its small total bending angle (2.3°) rendering them less necessary. Whilst the T20 arc is much larger at 6° to 7°, the T20 design was frozen after considering only the linear optics, without studying collective or non-linear effects. For this reason the impact of CSR on bunches passing through the T20 arc must be investigated, and possible mitigation strategies developed and implemented. In this paper design considerations for transporting ultra-bright bunches in the T20 beamline to new sets of undulators are discussed.

THE T20 BEAMLINE AND COHERENT SYNCHROTRON RADIATION EFFECTS

The T20 arc design mostly developed during the EuXFEL design process outlined in Refs. [3–6] forms a baseline for the performance of subsequent T20 arc designs, as it meets the most fundamental constraints on any such arc—it bends the bunch sufficiently, it matches the upstream optics, and it doesn't overlap with any of the existing magnets, tunnel walls or infrastructure.

To understand the design's performance with regards CSR I tracked 14 GeV, 250 pC Gaussian bunches with initial transverse emittances of 0.6 mm mrad and consisting of two hundred thousand macroparticles with peak currents of 3 kA, 5 kA and 7 kA using OCELOT [7] and its 1D CSR model. I justified the use of the 1D CSR model by evaluating the Derbenev criterion [8] along the entire arc and found that it was satisfied everywhere. The result from this peak current scan is shown in Fig. 1. The local linear dispersion's effect on the emittance at each observation point is accounted for by tracking, without collective effects, each bunch to the end of the arc (where $\eta = \eta' = 0$) before calculating the emittance. The changes in the emittance, $\Delta\varepsilon_x$, are 0.37 mm mrad, 1.3 mm mrad and 3.7 mm mrad at 3 kA, 5 kA and 7 kA, respectively. As expected, this is worse than the simulated impact of CSR on the smaller-angled T1 arc [9], where the simulated projected emittance growth is on order of 1.1 mm mrad in the 7 kA case. The vertical emittances are not discussed here as $\theta_x \gg \theta_y$ for the T20 arc.

The development of the emittance growth can be broadly split into three regions, first the Lambertson kicker-septum scheme up to the 30 m point, the middle six dipoles centred at 50 m and the final three dipoles centred at 70 m (the last two dipoles are vertical). Whilst the emittance growth is clearly dominated by the second two set of dipoles, the impact of the extraction system cannot be neglected, causing the emittance to grow by 0.6 mm mrad to 0.9 mm mrad in the 3 kA to 7 kA range.

The beamline layout, the switchyard, and its position within the tunnel and hall are shown in Fig. 2 and demonstrates the spatial constraints imposed upon the T20 lattice design. The railing at $(z, x) = (2120\,\mathrm{m}, -3.5\,\mathrm{m})$ is 16.3 m from the upstream wall and is angled at 6.6° with respect to the straight ahead (i.e., T2) direction. The angle of this wall

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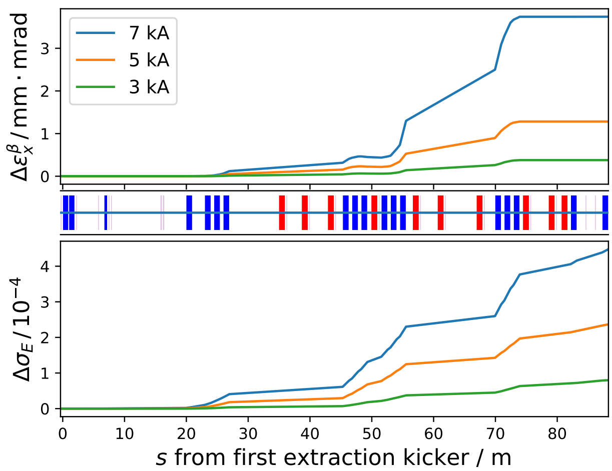

Figure 1: The original T20 design's simulated emittance and energy spread growth along the beamline due to CSR for a range of peak currents. The dispersion-free emittances at the generally dispersive observation points in the beamline were calculated by directly mapping the bunch at each point to the end of the line before calculating the emittance. The Gaussian bunch's initial transverse emittances were 0.6 mm mrad, and the bunch charge used was 250 pC. Dipoles and quadrupoles are shown in blue and red, respectively. Unpowered magnets are shown translucent.sdsa

and the size of the opening into the hall are the immediate fixed constraints on the necessary bending angle. In this design most of the bending is done in the upstream tunnel using relatively weak magnets 0.64 T, meaning much of the space is taken up just by dipoles. For an upgrade of this magnitude, one can reasonably assume new, stronger magnet designs and a maximum field of 1.5 T for a normal-conducting dipole. For the maximum possible future EuXFEL energy of 22 GeV, this corresponds to a minimum bending radius of $\rho = 49$ m, or a maximum curvature of $h = 1.17\,^\circ\,\mathrm{m}^{-1}$.

MITIGATION OF COHERENT SYNCHROTRON RADIATION EFFECTS

There are several approaches to mitigating emittance growth due to CSR. Three possible approaches are outlined in this section, however the list here is not exhaustive and other techniques [10–12] may also need to be considered, although all but the first method following rely on cancelling out a CSR kick in one or more dipoles with one or more additional dipoles further downstream.

Beta Function Waist

The simplest approach involves introducing a waist in the β function in the bending plane of the magnet to minimise the non-linearity of the CSR field and so-called *phase mixing* [13]. Minimising phase mixing preserves slice emittance whereas other methods only prefer its projection. For this reason for any applied CSR mitigation technique, it is generally useful to also have such waists. Additionally, it is useful to consider that when sufficient phase advance is needed between dipoles, a waist in the first dipole will be beneficial as $\delta\varphi \approx \frac{\delta s}{\beta}$, i.e. it will maximise the phase advance going into the downstream section. This approach was applied in the design of the FLASH2 extraction arc [14] as there was insufficient space for other approaches, which tend to require more quadrupoles. To examine the benefits of such a waist, I tracked 250 pC bunches at three different peak currents through a 1 m-long 1.5 T dipole field. The sensitivity to the central β-function is particularly stark at the higher currents, and is shown in Fig. 3.

Point-kick Analysis

The point-kick analysis outlined in [15, 16] describes an approach in which the CSR kick can be cancelled completely in the linear regime over a single double bend achromat (DBA). Perfect cancellation for two identical dipoles, on top of the usual achromatic conditions, additionally requires that

$$\frac{\alpha_1 - \alpha_2}{\beta_1} \cong -\frac{12}{L}, \tag{1}$$

where the subscripted Greek letters refer to the Courant-Snyder parameters in the middle of the dipoles, and L is the dipole length. Figure 4 shows the range of optical parameters that satisfy Eq. (1), and specifically show that satisfying this condition is difficult at such large energies due to the relatively weak quadrupole focusing. Large regions of the space have unrealistic optical parameters either in the first or second dipole.

Optical Balance

This involves balancing the Courant-Snyder parameters and phase advances between consecutive dipoles (either $(2n + 1)\pi$ or $2n\pi$) depending on the dipole polarities) so that the CSR kicks cancel each other out in aggregate [17, 18]. This cancellation can occur over several dipoles. This approach is similar to the previous one, in that both schemes rely on a linear proportionality between the magnet length and the CSR-indcued energy spread. For a Gaussian bunch the CSR-induced energy spread is given by

$$\Delta\sigma_E = 0.2459\frac{eQ\mu_0 c^2 L_\mathrm{B}}{4\pi\sigma_z^{4/3}\rho^{2/3}} \tag{2}$$

where the symbols have their usual meanings [8]. More to the point, $\Delta\sigma_E \propto L_\mathrm{B}$.

To ensure that such an approach can be applied, I tracked three different peak currents through various dipole lengths at 1.5 T, shown in Fig. 5. The impact of the nonlinear transient effects is clear for small magnet lengths, but the resulting energy spread is sufficiently small to be neglected. Beyond this there is a linear relationship between the magnet length and the induced energy spread, suggesting the applicability of such cancellation techniques even at such short bunch lengths.

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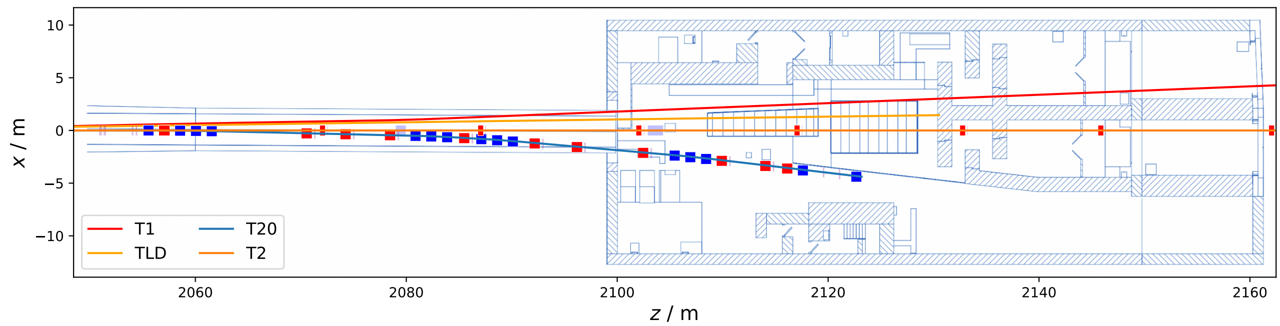

Figure 2: A blueprint for the tunnel and hall in the region of the switchyard at the EuXFEL with the various beamlines superimposed on top. For clarity, only the magnets of the T2 and T20 beamlines are displayed. Dipoles and quadrupoles are shown in blue and red, respectively. Unpowered magnets are shown transparent.

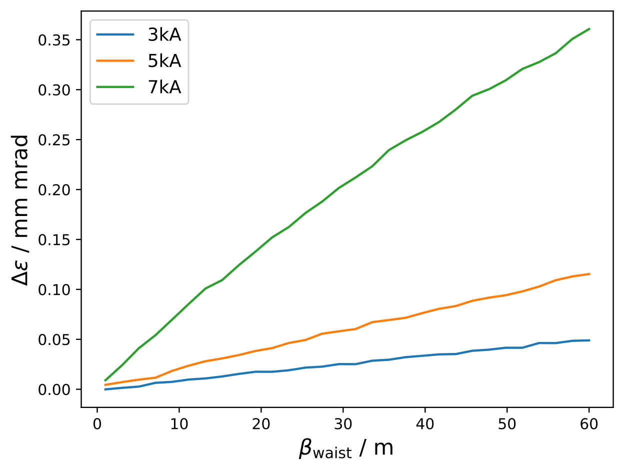

Figure 3: Waist scan at 22GeV for a 250pC bunch for various peak currents, with L_{B} = 1.5 m and θ = 1.7°, which corresponds to a maximum reasonable magnetic field of 1.5 T. The beta waist is in the middle of the dipole and the emittance is sampled 2m past the end of the dipole to account for transient effects.

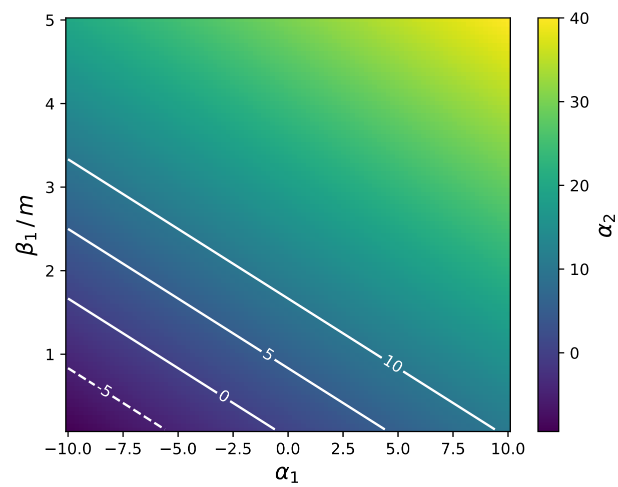

Figure 4: The required Courant-Snyder parameters in a double bend achromat with 1.5 m dipoles to achieve perfect cancellation in the linear regime given the condition in Eq. (1).

CONCLUSION

I described the proposed T20 arc discussed its challenges. The main challenge is the strong CSR effect on bunches in the arc due to the large bending angle, which leads to unacceptable emittance growth at large peak currents. There are several solutions, but they all require strong focussing. This is difficult for two reasons, firstly space is at a premium in the tunnel, and secondly quadrupoles will be effectively quite weak due to the very high beam energy. For these reasons cancelling the CSR kick over two or three achromats may be necessary. Additionally, the EuXFEL is designed for bunch energies up to 1 nC, and the performance of any arc design will need to consider this much higher bunch charge. Finally, a full analysis of chromatic effects will be needed to achieve the required ±1.5 % energy acceptance.

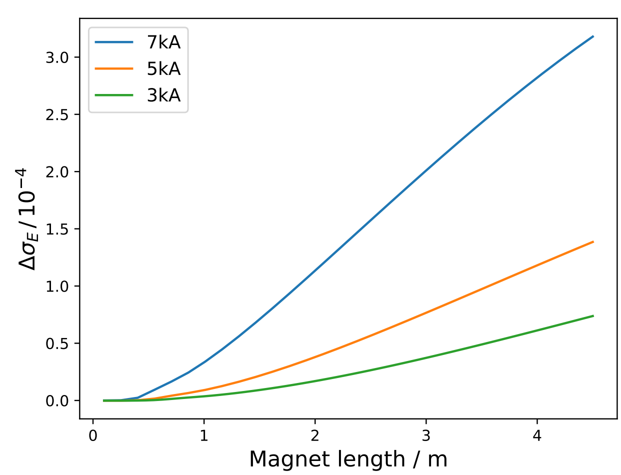

Figure 5: The CSR-induced energy spread in a 250 pC Gaussian bunch for magnets with a range of lengths and ρ = 48 m, the minimum plausible bending radius at 22 GeV and using normal-conducting magnets.

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REFERENCES

[1] M. Altarelli *et al.*, "XFEL: The European X-Ray Free-Electron Laser technical design report", DESY, Hamburg, Germany, Rep. DESY-06-097, Jul. 2007. doi:10.3204/DESY_06-097

[2] W. Decking *et al.*, "A MHz-repetition-rate hard X-ray free-electron laser driven by a superconducting linear accelerator", *Nat. Photonics*, vol. 14, pp. 391–397, 2020. doi:10.1038/s41566-020-0607-z

[3] W. Decking and F. Obier, "Layout of the beam switchyard at the European XFEL" in *Proc. 11th Eur. Particle Accelerator Conf. (EPAC'08)*, Genoa, Italy, Jun. 2008, paper WEPC073, pp. 2163–2165.

[4] V. Balandin, W. Decking, and N. Golubeva, "Tilted sextupoles for correction of chromatic aberrations in beam lines with horizontal and vertical dispersions" in *Proc. 1st Int. Particle Accelerator Conf. (IPAC'10)*, Kyoto, Japan, May 2010, paper THPE062, pp. 4656–4658.

[5] V. Balandin, W. Decking, and N. Golubeva, "Optics for the beam switchyard at the European XFEL" in *Proc. 2nd Int. Particle Accelerator Conf. (IPAC'11)*, San Sebastián, Spain, Sep. 2011, paper WEPC008, pp. 2016–2018.

[6] S. D. Walker and N. Golubeva, "An overview of the T20 beamline for the LUXE Experiment at the European XFEL" in *Proc. 13th Int. Particle Accelerator Conf. (IPAC'22)*, Bangkok, Thailand, Jun. 2022, paper TUPOPT008, pp. 1014–1017. https://accelconf.web.cern.ch/IPAC2022/papers/tupopt008.pdf

[7] I. Agapov, G. Geloni, S. Tomin, and I. Zagorodnov, "OCELOT: A software framework for synchrotron light source and FEL studies", *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 768, pp. 151–156, Dec. 2014. doi:10.1016/j.nima.2014.09.057

[8] Y. Derbenev, J. Rossbach, E. Saldin, and V. Shiltsev, "Microbunch Radiative Tail-Head Interaction", DESY, Hamburg, Germany, Rep. TESLA-FEL-95-05, Sep. 1995.

[9] I. Zagorodnov, "Beam Dynamics in SASE2 Arc", https://www.desy.de/fel-beam/s2e/talks/2020_09_29/MAC2019_Zagorodnov.pdf (retrieved 13 Aug. 2022).

[10] M. Venturini, "Design of a triple-bend isochronous achromat with minimum coherent-synchrotron-radiation-induced emittance growth", *Phys. Rev. Accel. Beams*, vol. 19, no. 6, p. 064401, Jun. 2016. doi:10.1103/PhysRevAccelBeams.19.064401

[11] C. Zhang, Y. Jiao, C.-Y. Tsai, "Quasi-isochronous triple-bend achromat with periodic stable optics and negligible coherent-synchrotron-radiation effects", *Phys. Rev. Accel. Beams*, vol. 24, no. 6, p. 060701, Jun. 2021. doi:10.1103/PhysRevAccelBeams.24.060701

[12] R. Hajima, "Emittance compensation in a return arc of an energy-recovery linac", *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 528, pp. 335–339, Aug. 2004. doi:10.1016/j.nima.2004.04.063

[13] Dohlus, Martin; Kabel, Andreas; Limberg, Torsten, "Optimal Beam Optics in the TTF-FEL Bunch Compression Sections: Minimizing the Emittance Growth", in *Proc. PAC'99*, New York, NY, USA, Mar. 1999, paper TUP74, pp. 1650–1652. doi:10.1109/PAC.1999.794210

[14] M. Scholz, "Design of the Extraction Arc for the 2nd Beam Line of the Free Electron Laser FLASH", Ph.D. thesis, Phys. Dept., Univ. Hamburg, Hamburg, Germany, 2013.

[15] Y. Jiao, X. Cui, X.Huang, and G. Xu, "Generic conditions for suppressing the coherent synchrotron radiation induced emittance growth in a two-dipole achromat", *Phys. Rev. Accel. Beams*, vol. 17, no. 6, p. 060701, Jun. 2014. doi:10.1103/PhysRevSTAB.17.060701

[16] M. Venturini, "CSR-induced emittance growth in achromats: linear formalism revisited", *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 794, pp. 109-112, Sep. 2015. doi:10.1103/PhysRevAccelBeams.19.064401

[17] D. Douglas, "Suggestion and enhancement of CSR-driven emittance degradation in the IR-FEL driver", JLab, Newport News, VA, USA, Rep. JLAB-TN-98-012, Mar. 1998.

[18] S. Di Mitri, M. Cornacchia, and S. Spampinati, "Cancellation of Coherent Synchrotron Radiation Kicks with Optics Balance", *Phys. Rev. Lett.*, vol. 110, no. 1, p. 014801, Jan. 2013. doi:10.1103/PhysRevLett.110.014801