# EXTRACTION ARC FOR FLASH2

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*Abstract*

FLASH2 is an extension of the existing Free Electron Laser FLASH at DESY, Hamburg. It uses the same linear accelerator. A separate tunnel and a new experimental hall will be built next to the existing FLASH facilities. FLASH2 will serve electrons up to two SASE or seeding undulator systems and to a proposed plasma wake field accelerator. An extraction system is needed to bend the electrons from the existing straight beam path into the new beamline. The extraction arc design has to fulfill specific requirements such as small emittance and energy spread growth. Furthermore, constrains are given by the existing FLASH buildings. Small betatron functions in the bending magnets mitigate beam quality impairment due to CSR effects. To optimize the extraction arc, simulations for different layouts were carried out using the program ELEGANT.

## INTRODUCTION

The existing single-pass high-gain SASE FEL FLASH (Free-electron LASer in Hamburg) at DESY, Hamburg [1] delivers photons in the wavelength range from 4.1 nm to 44 nm. Electrons are accelerated by seven TESLA type superconducting accelerating modules up to a maximum energy of 1.25 GeV. A third harmonic module for linearization of the longitudinal phase space is also implemented. Six fixed-gap SASE-undulators with a total length of 27 m generate photons which are sent to five experimental stations in the FLASH experimental hall.

In order to increase the beam time for users, an extension for FLASH was planned and is now under construction. Three fast kickers and a septum to be installed behind the last superconducting acceleration module give the possibility to distribute the beam either to the existing beam-line or to the new extraction arc. The multi kicker layout can tolerate a failed kicker because two kickers can also cope with the required deflection to the septum. The beam-lines of FLASH and of the extraction arc have to be separated as fast as possible to preserve space for lattice elements acting separately on each beamline. Thus, a strong DC Lambertson-septum will deflect the beam horizontally by 7 degrees. The advantage of a Lambertson-septum in comparison with a current sheet septum is a smaller sensitivity to damage. The main difference for the optics of the machine using a Lambertson-septum is the additional vertical kick into the deflecting volume of the septum. In the case of the FLASH2 extension, the vertical offset has to be 20 mm. Within the new arc, a pulsed bending magnet allows to direct the beam into two separate beamlines: One hosting undulators for SASE and space for HHG seeding (FLASH2), the other serving a proposed plasma wake field experiment or later on another beamline (FLASH3). The new variable-gap-undulators for SASAE and HHG seeding in FLASH2 make the two beamlines more independent of each other. Parameters for FLASH2 are summarized in Tab. 1.

Table 1: Parameters for FLASH2

| | |
|---|---|
| **Beam parameters** | |
| Beam energy | 0.5-1.25 GeV |
| Normalized emittance (proj.) | <1.4mm mrad |
| Energy spread | 0.5 MeV |
| Peak current | 2.5 kA |
| Bunches per second | < 8000 |
| **Undulator parameters** | |
| Period | 31.4 nm |
| Segments length | 2.5 m |
| Number of segments | ≤ 12 |
| Focusing structure | FODO |
| **Radiation** (at fundamental wave length) | |
| Wavelength range SASE | 4 nm -80 nm |
| Wavelength range HHG | 10 nm -40 nm |

## SPECIFIC REQUIREMENTS TO THE BEAM TRANSPORT

The challenge of the FLASH2 extraction arc is to fulfill many conditions given by the existing building of FLASH and by the sparse space available for extraction magnets in the existing machine. Furthermore, the new tunnel and experimental hall for FLASH2 have to be integrated in the existing building environment. Structural conditions require that the FLASH2 photon beamline has to cross PETRA3, the most brilliant storage-ring-based X-ray radiation source in the world [3], at a dedicated place and this fixes the extraction angle for FLASH2 at 12 degree. The 12 degree deflection for FLASH2 is realized with a 7-1.5-3.5 degree ar-

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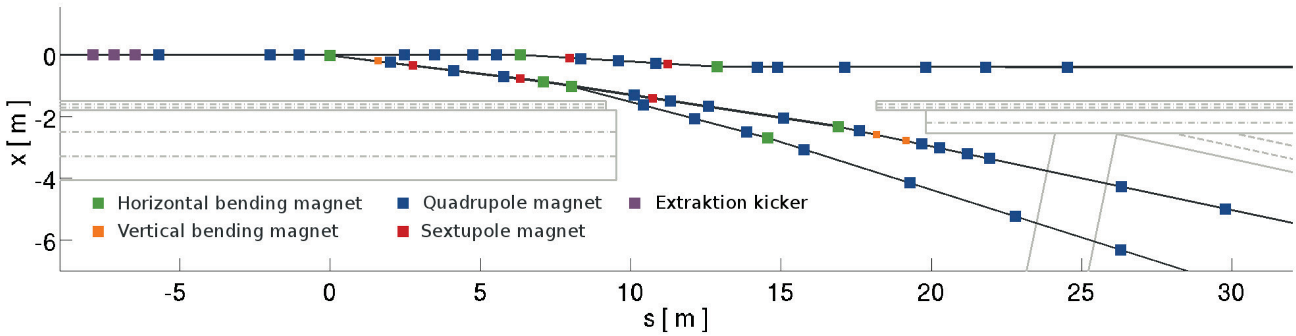


Figure 1: This plot shows a top view of the arc including FLASH on top and of the new beamline of FLASH2 in the middle. The lowest beamline shows a first design of FLASH3. The building walls are sketched in Grey color.

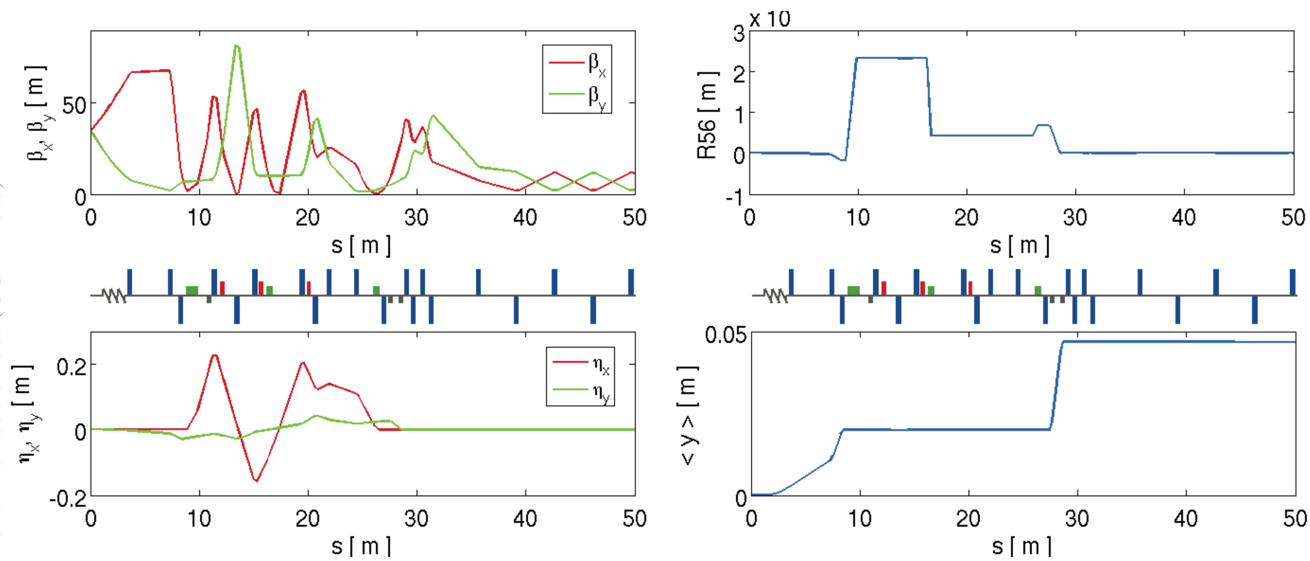


Figure 2: Optic functions for the FLASH2 extraction arc. The upper plots show the betatron functions and the first order momentum compaction (R56) and the lower the dispersion and the vertical beam center position.

rangement of bending magnets where the first magnet is the septum. The additional beamline for FLASH3 starts downstream the second bending magnet were a pulsed bend with 6.5 degree deflection allows distributing the beam either to FLASH2 or to FLASH3. All magnet positions are shown in Fig. 1.

The extraction arc is optimized to mitigate emittance growth due to coherent synchrotron radiation (CSR). For this reason, the optics elements have to be chosen such that small horizontal beam waists can be ensured in all horizontal bending magnets [2] [4]. Therefore it is necessary to place focusing quadrupole magnets upstream and downstream close to the bends. An extraction design using a -I transport matrix between the bending magnets [5] could not be implemented due to restrictions caused by the surrounding buildings. Downstream the septum and the pulsed bend positions of the lattice elements have to be chosen carefully in order not to have overlapping elements in the two beamlines.

The vertical and horizontal dispersions have to be closed at the end of the arc and also the first order momentum compaction (R56) has to be zero. Since all bends in the extraction arc deflect the beam in the same direction, the dispersion has to be negative in the second bend to achieve zero momentum compaction. This leads to additional constrains on the betatron functions within the extraction arc. The functions for horizontal and vertical betatron function as well as for dispersion and momentum compaction are shown in Fig. 2

The necessary beam waist in the septum requires at least one focusing quadrupole between the kickers and the septum. This quadrupole will amplify the vertical kick and can be used to decrease the kicker strength. For the arc layout, the decision was made to implement three quadrupoles enabling the beam waist in the septum and amplifying the kick as requested. The third quadrupole is vertically focusing and deflects the beam back to straight trajectory. The function of the vertical beam center is displayed at the bot-



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tom right plot in Fig. 2. In order to close the vertical dispersion two more vertical bends are needful. The position of this bends is chosen downstream the last horizontal bending magnet. This will also be the place for the HHG laser in-coupling. Three sextupole magnets in the extraction arc suppress horizontal second order dispersion.

It is proposed to increase the maximum energy of the linac from 1.25 GeV to 1.6 GeV, thus, all elements of the new beamlines have to be designed to cope with the higher particle energy.

## SIMULATIONS

All simulations presented in this paper were carried out with the tracking program ELEGANT, version 23.1.2 [6]. All simulations were executed with 1 nC charge and a particle energy of 1 GeV.

An intuitive approach to investigate the effects of the optics on the beam is to track 3-$\sigma$-ellipses for different energies through the arc. Evaluating these ellipses in a normalized phase space helps to detect chromatic aberrations or dispersive effects. This simulation was performed for the FLASH2 extraction beamline with the design energy of 1 GeV and with two additional ellipses with an energy deviation of $\pm$ 0.5 %. The results are presented in Fig. 3.

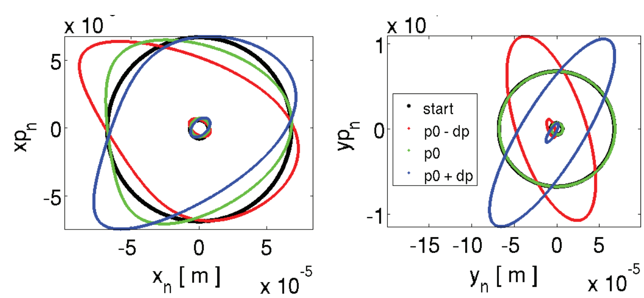


Figure 3: 3-$\sigma$-ellipses with $\pm$ 0.5 % energy deviation in normalized horizontal and normalized vertical phase space.

In the ideal case, all three ellipses are centered and shown as perfect circles. In the horizontal phase space, the drawings are centered but chromatic aberrations appear. In vertical plane, stronger aberrations are visible and in addition the ellipses are not centered. The latter points out that the higher order dispersion in vertical plane is not zero and the stronger aberrations suggest a stronger beta beating.

These simulations indicate that, in addition to the expected CSR induced emittance growth, also the optics of this extraction arc will worsen the beam quality. To investigate the impact of the two effects, further simulation were carried out using two different Gaussian distributed bunches both with small energy spread, maximum current of 2.5 kA, 1 $\mu$m rad projected and normalized emittance in both planes and 1 nC bunch charge. Earlier simulations showed that 200 000 particles are sufficient to avoid numerical effects especially for the CSR calculations, thus, the number of particles per bunch used for these simulations

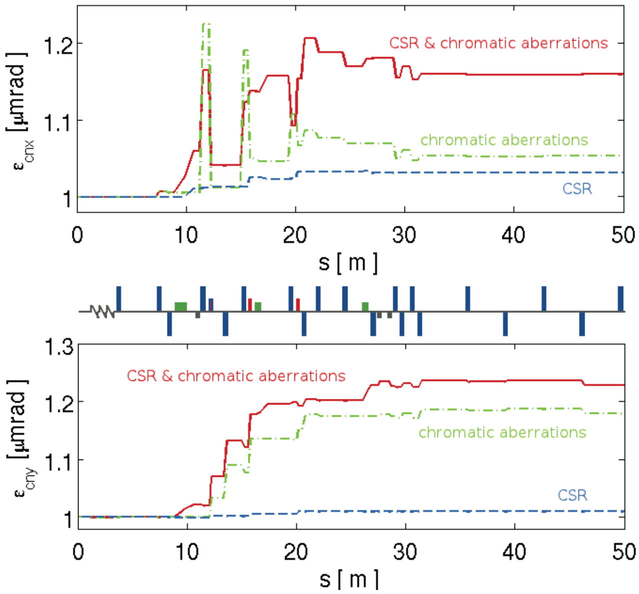


Figure 4: Plots of the results to compare the impact of CSR and chromatic aberration on the projected emittance.

was set to 200 000. What distinguishes the two bunches is that one has an energy chirp of $\pm$ 1.5 %. With this bunches, three different simulations were performed:

- First simulation with the chirped bunch and including CSR effects in order to observe the impact of both effects together.
- For the second run, the chirped bunch was used but without CSR effects. The results show only the impact from the chromatic aberrations.
- Finally, the unchirped bunch was tracked through the arc including CSR to get only theses effects.

All plots from these simulations are presented in Fig. 4.

The simulation results show that the impact from chromatic aberration is higher than the impact from CSR effects especially for the vertical plane. This results are consistent with the 3-$\sigma$-ellipses simulations.

In order to get meaningful results for the complete FLASH2 extraction, two start-to-end simulations were carried out using two typical particle distribution from FLASH with charges of 100 pC and 1 nC. The results of this simulations are shown in Fig. 5. Surprisingly, the emittance growth is less than initially expected. This is due to the advantageous interaction between arc beam optics and bunch shape and can not be generalized for arbitrary bunches.

## CONCLUSIONS

The arc presented meets all the conditions which were imposed on the extraction lattice. Both, the horizontal and vertical first order dispersions are closed at the end of the extraction arc and also the first order momentum compaction R56 is set to zero as required. The three sextupole magnets in the FLASH2 extraction arc enable also to close

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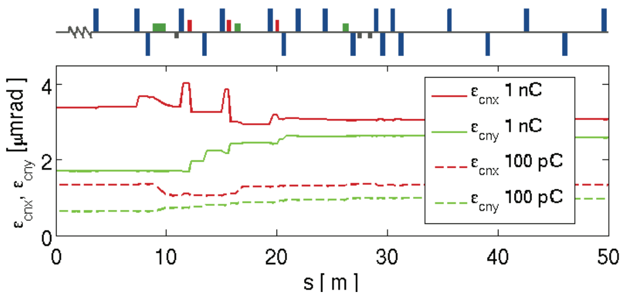


Figure 5: S2E simulations with two typical particle distributions with 100 pC and 1 nC charge.

the horizontal second order dispersion. Horizontal beam waists in the bending magnets mitigate emittance growth due to coherent synchrotron radiation such that theses effects are smaller than the emittance growth due to chromatic aberrations. The extraction arc has the required angle of 12 degree and points to the intended position in the new FLASH2 tunnel. Also the turnoff for the beamline serving electrons to the proposed plasma wake field accelerator and later on to FLASH3, the pulsed bending magnet, is considered. Downstream the last vertical bending magnet, there is enough space left to match the beam into a FODO structure for the following undulator section. The design of the arc leads to the circumstance that the vertical and horizontal plane can't be tuned independently from each other but one quadrupole between the last horizontal and first vertical bend reduces the coupling.

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