Alternative Focusing for FLASH

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1 Introduction

In its present configuration, FLASH uses a doublet structure to focus the electron beam along the undulator. This was proposed in 2000 as a modification to the integrated focusing which was used at that time [1]. This compromise solution between integrated focusing and FODO structure was chosen for several reasons based on the experience of TTF1:

- For integrated focusing, there was a quadrupole of fixed strength and position each 0.5 m. Because for each quadrupole, the offset needs to be corrected by means of a corrector coil, the number of knobs needed for alignment was 30 for a 15 m long undulator, which makes the alignment procedure time consuming.
- The undulators were already built and construction of new undulators-supports was too expensive and would require additional resources and time.
- A FODO lattice was not considered since it was assumed that the beam emittance, and therefore the electron beam size, would be larger than it seems to be [2, 3].

The disadvantage of the new focusing structure, the tight tolerance of the alignment of the quadrupoles within a doublet, was considered an acceptable risk. With the present knowledge, we propose a more flexible concept which still makes the doublet focusing possible, but also allows for a FODO structure.

2 Increased flexibility on focusing

The three possible focusing solutions are the present doublet structure, a FOFO structure in which the vertical focusing is due to the natural (weak) focusing of the undulator and the horizontal focusing is determined by the quadrupoles, and finally a FODO structure. The doublet and FOFO focusing can be achieved

with the present structure as shown in Fig. 1. For the FODO focusing, a minor modification shown in Fig. 2 is needed. As it can be seen, the original focusing is still possible, but by changing the polarity of Q5UND2 and switching off Q6UND1, one gets a FODO structure.

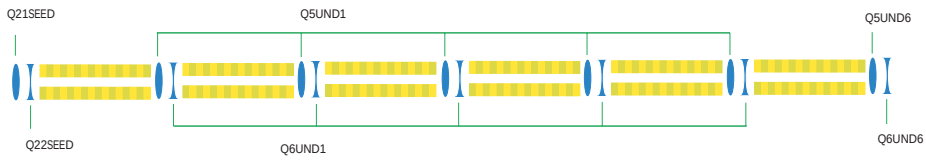

Figure 1: present focusing scheme along the FLASH undulator, consisting of doublets between each undulator segment. The lines and names indicate the connection of the power supplies.

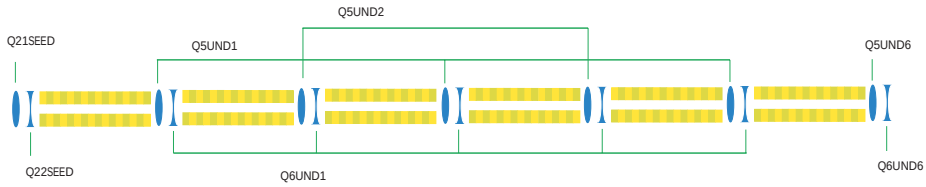

Figure 2: Modified connection of power supplies results in more flexibility. With the current Q5UND1 and Q5UND2 in the same direction and Q6UND1 in opposite direction, one has the standard doublet structure. With Q6UND1 switched off, one has the FOFO structure. With Q6UND1 switched off and the current through Q5UND2 opposite sign, one now has a FODO structure.

The strength of the undulator quadrupoles and the average β-function along the undulator for the different options are indicated in the following table:

Table 1: *Quadrupole strength and average β-function for the different lattices (values correponding to 1 GeV).*

	Doublet	**FODO**	**FOFO**
$\mathbf{k}$ [m^{-2}]	8	2	0.14
$\overline{\beta}$	5	10	17

Using a FODO lattice the focusing would be decreased by a factor of 4 with respect to the doublet structure, resulting in the following advantages:

- The tolerances on quadrupole alignment would be relaxed by a factor of 4. This would make the beam-based alignment in the undulator signifcantly easier.
- The interference patterns for long wavelengths would be reduced.

- The source point of the radiation for users would be closer to the undulator exit for which the optics has been designed. Moreover, by shifting the saturation point to the end of the undulator, multiple sources of radiation due to the emission of coherent radiation would be reduced or even avoided.

On the other hand, with the FODO lattice the FEL power is slightly reduced due to the increase of the β-function. Moreover, for short wavelengths it is not clear whether saturation can be reached with the available undulator length. With the FOFO structure the commented advantages and drawbacks are magnified: the tolerances on quadrupole alignments are more relaxed and the FEL performance is more affected since the beam size becomes even bigger. The next section studies the impact of the lattice type on the FEL performance.

3 FEL performance

3.1 Numerical estimations

Using the analytical model developed by M. Xie [4] we have analyzed the impact of all three possible lattices on the FEL performance. We have distinguished between operation without and with the third-harmonic module (ACC39). This accelerator module that will optimize the longitudinal compression will be available for operation in 2010 after the present shutdown. Although with ACC39 the FEL power will be higher and more stable, the shorter pulse obtained without ACC39 makes the so-called *femtosecond* mode also attractive for the users. Therefore, both operational modes may be used in the future.

Table 2: *Beam and undulator parameters.*

Parameter	**Without ACC39**	**With ACC39**
Beam Energy [GeV]	1.0	1.0
Peak Current [kA]	1.3	2.0
Normalized Emittance µm]	1.5	1.5
Energy Spread [MeV]	0.2	0.2
Undulator Period [mm]	27.3	27.3
Undulator Length [m]	27	27
K_{rms}	0.89	0.89

The beam and undulator parameters used in the calculations are shown in table 2. In both cases, the properties correspond to a beam charge between 0.5 and 1 nC and an energy of 1 GeV (equivalent to a radiation wavelength of about 6.7 nm). Without the third-harmonic module the electron beam parameters have been taken from [5]. For the case with ACC39 in operation, the parameters have been taken from [6].

Figure 3 shows the effect of the β-function on the saturation length and on the radiation power at the undulator exit. It clearly shows that without the third-harmonic cavity (left plot) only the doublet and FODO lattices will be able to reach saturation. The saturation length is increased about 5 m when going from doublet to FODO, for which the saturation length is almost as large as the available undulator length (27 m). With the FOFO structure the beam will not saturate and the output power will be negligible. For the case with ACC39 on operation (right plot), both doublet and FODO lattices give enough safe conditions to guarantee saturation. In this mode, even the FOFO structure will be close to reach saturation.

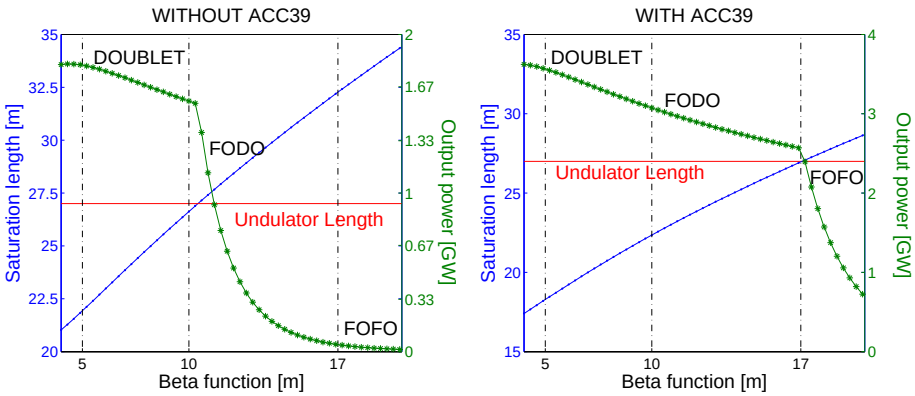

Figure 3: Numerical estimation of saturation length and radiation power at the undulator exit as a function of the average β-function without (left) and including (right) the third-harmonic cavity. The β-functions corresponding to the doublet, FODO and FOFO lattices are indicated.

Figure 4 shows the effect of the electron beam energy and the emittance on the saturation length when ACC39 is in operation for the three different lattices. All other parameters are the ones given in table 2. As it can be seen in the figure, only doublet and FODO lattices will be able provide saturation for all the energy range (i.e. up to 1.2 GeV). The emittance requirements for reaching saturation are quite relaxed for the doublet lattice (≤ 2.8 µm), a bit more restrictive for the FODO option (≤ 2.2 µm) and too close to the expected parameters for the FOFO lattice (≤ 1.5 µm).

The FOFO option is ruled out since it can not provide saturation in the *femtosecond* mode of operation. Moreover, when ACC39 is in operation the beam can not reach saturation for all possible beam energies, and the requirements for the beam emittance to reach saturation for 1 GeV are too stringent. Both FODO and doublet options are suitable since they allow to reach FEL saturation for the considered cases with reasonable values of electron emittance. In the next subsection detailed FEL simulations for the doublet and FODO cases will be presented.

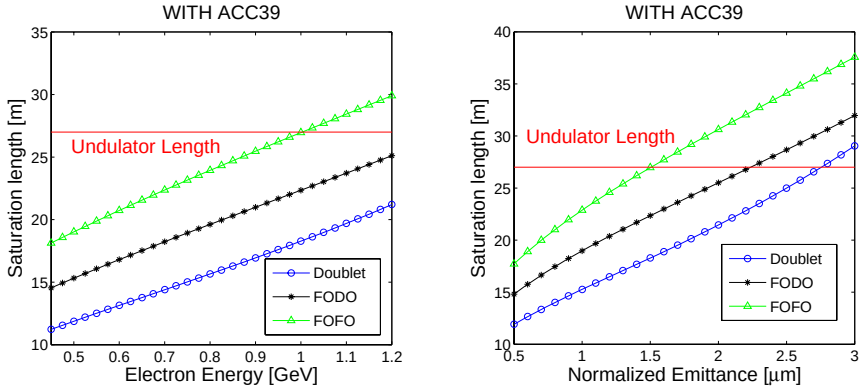

Figure 4: Numerical estimation of saturation length as a function of beam energy (left) and normalized emittance (right) for doublet, FODO and FODO lattices.

3.2 SASE simulations

Simulations have been done with Genesis [7] in order to compare the effect of doublet and FODO lattices on the FEL performance. A file with the properties shown in Figure 5 has been used for the simulations. This file has been adapted to 1.2 GeV from start-to-end simulations done for FLASH at 1.0 GeV and 1 nC, and with the third-harmonic cavity in operation [8]. As compared to the estimates given in the figures 3 and 4, where only the average β-function is taken into account, the simulations consider the actual focusing structure.

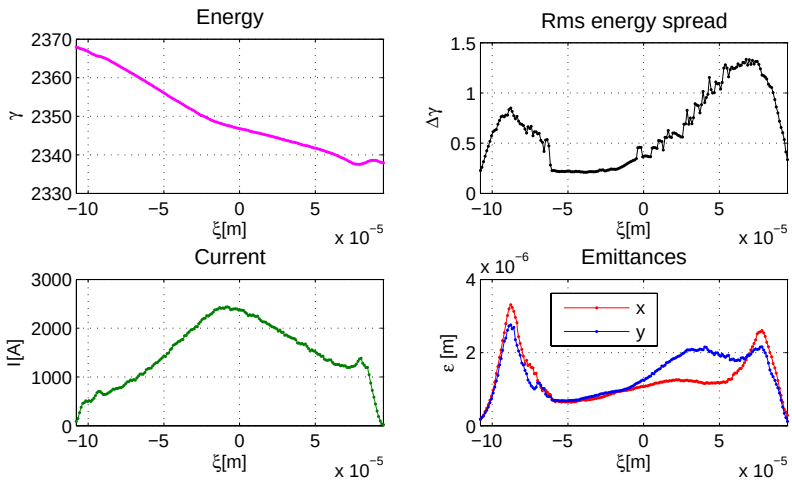

Figure 5: Electron beam properties at the undulator entrance obtained from start-to-end simulations.

Figure 6 shows the radiation energy along the undulator for the doublet and FODO lattices. The simulated results are averaged over 10 shots. In both cases the beam reaches saturation with the available undulator length, although the saturation length is 5 m larger with the FODO lattice (i.e. it increases from about 20 to 25 m). The output radiation power is similar for both cases.

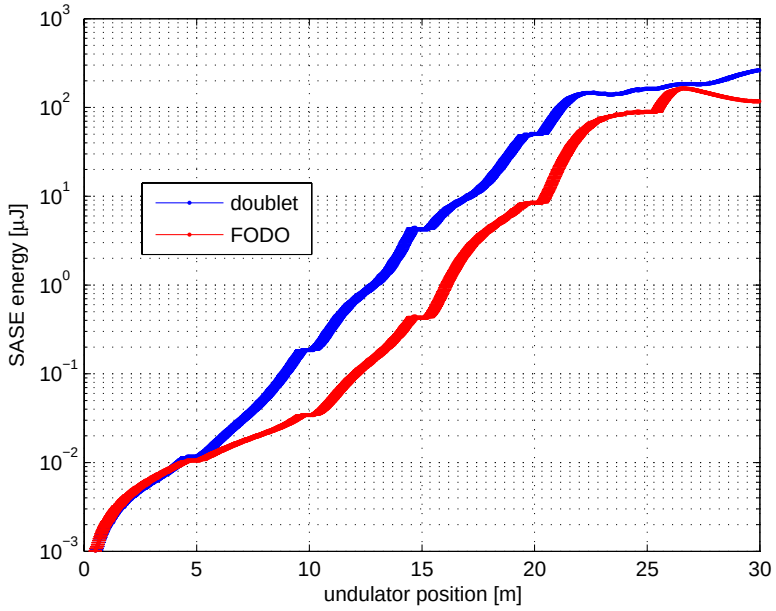

Figure 6: FEL energy along FLASH undulator for doublet and fodo lattices.

4 Optics matching

Six quadrupoles upstream of the undulator in the so-called SMATCH section will be used to match the beam at the undulator entrance. Figure 7 shows the β-function along the undulator and the required k-value for the matching quadrupoles corresponding to both doublet and FODO lattices. As it can be seen from the figure, the change in quadrupole strength from one configuration to the other is small for all the magnets (i.e. smaller than 0.5 m^{-2}).

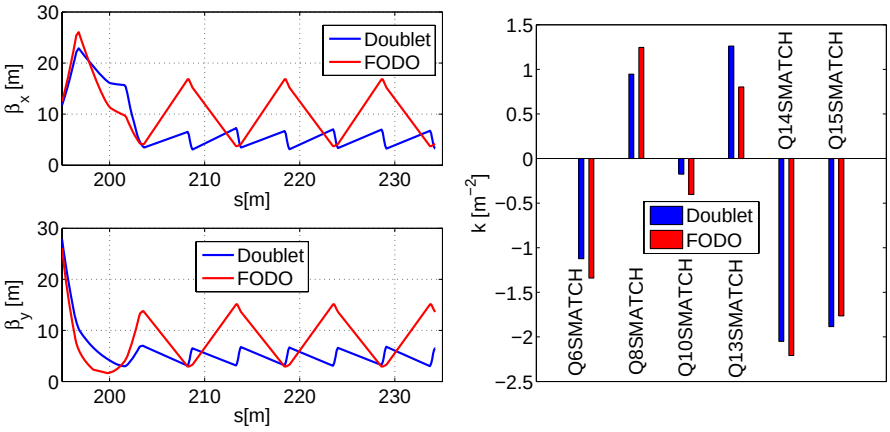

Figure 7: β-function along the undulator (left) and strengths for the matching quadrupoles (right) corresponding to the doublet and FODO lattices.

5 Summary

For a FODO lattice, the modification needed is quite moderate: an additional power supply and a few cables. With the modified setup proposed here, the old setup is still available in case the focusing should be stronger. The main advantage is that the tolerances on quadrupole alignment are relaxed by a factor of 4 due to the reduced current. Especially the increased beam size for longer wavelengths may have as advantage that the saturation point is moved to the undulator exit, for which the optics has been designed, and the source will be enlarged, resulting in smaller diffraction and therefore fewer problems with apertures in the beam line towards the users. As it has been shown, the reduction of the FEL power and the increase of the saturation length with respect to the doublet structure are acceptable. An open issue is the transverse coherence. However, the diffraction parameter is moderate (up to 40 for the shortest wavelength as compared to 18 now) and not believed to be a mayor issue. Furthermore, the change in initial electron beam size is small and not considered to be a problem.

6 Acknowledgments

We thank Martin Dohlus for useful discussions about the start to end simulations at FLASH.

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