# REQUIREMENTS FOR PARASITIC OPERATION OF THE ORS SECTION

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*Abstract*

The Optical Replica Synthesizer (ORS) section at the Free-electron LASer in Hamburg (FLASH) can be used for a wide variety of experiments involving the co-propagation of an electron bunch and a laser pulse through a sequence of magnetic components: undulator, chicane, undulator, chicane. The difficulties associated with operating this section in a permanent, parasitic capacity constitute the topic of this paper. The primary impediments include: laser safety issues, microbunching instabilities, and dogleg steering. Technical solutions for these problems are described with respect to the needs of individual experiments.

## INTRODUCTION

Based on the theoretical work of Saldin, Schneidmiller and Yurkov [1], the Optical Replica Synthesizer (ORS) section at FLASH was designed to measure the longitudinal profile of the electron beam. It was first constructed in 2007 through a collaboration between DESY and the Universities of Uppsala and Stockholm [2-5]. It was then commissioned in 2008 [6-10]. Today, following a complete rebuild of the section, the ORS setup is only used to diagnose the stability of the synchronization between the electron beam and the sFLASH High Harmonic Gain (HHG) laser system [11]. Besides the original ORS measurement, several other types of experiments will soon be made possible through the installation of a new laser transport line [12]. These experiments include: Echo Enabled Harmonic Generation (EEHG), beam slicing with a few-cycle laser pulse, Electro Optical Sampling (EOS) with Frequency Resolved Optical Gating (FROG), and a new form of optical replica experiment which measures the changes in the spectrum and profile of the laser beam directly after the first undulator.

For these experiments to operate parasitically, without impacting user operation, technical solutions for problems posed by laser safety, microbunching instabilities, and dogleg steering need to be addressed prior to commissioning in January 2012.

- It is recommended that 270 nm be used for initial experiments due to the relatively un-problematic laser safety considerations that it requires.
- It is anticipated that microbunching instabilities will not pose immediate problems for the EEHG and ORS experiments for operation at 270 nm
- It is also anticipated that if practical considerations are regularly taken into account when setting up the orbit in the dogleg, there should be no problem with operating the ORS section in a permanent and parasitic fashion.

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## MICROBUNCHING INSTABILITES

When the beam develops a microbunched structure due to coherent synchrotron radiation or longitudinal space-charge effects prior to the undulator sections, an FEL can still function as long as the beam survives its journey through the undulators with enough peak current and a low enough energy spread an emittance. While LCLS has shown that microbunching instabilities originating prior to the radiator undulators increase the required gain length by as much as a factor of 2 under some circumstances [13], at FLASH, it appears that the FEL operation is always affected by some degree of microbunching instability [14-17] and the problem appears to be worse when the 3rd harmonic cavity is used to linearize the phase space [18]. Despite this, and the lack of a laser heater to reduce the problem, FLASH continues to successfully generate SASE.

The pertinent questions become: how much incoming microbunching can be tolerated in ORS section experiments? Will operation of the ORS section chicanes and undulators make this microbunching significantly worse? Can it make it better?

In the ORS section, microbunched beams can radiate in the ORS undulator magnets and the resulting radiation could be disruptive for SASE or it could send radiation which is dangerous to the eyes into the user area. The ORS chicanes can also exacerbate and bunch energy modulations from upstream of the section. In fact, the ORS section itself has a structure which is not very different from a Longitudinal Space Charge Amplifier (LSCA) [19].

The optimal $R_{56}$ of a chicane for a high LSCA gain is [19],

$$R_{56} \cong \lambda \frac{\gamma}{2\pi\sigma_\gamma}, \qquad (1)$$

where λ is the wavelength of the amplified density modulation. The $R_{56}$s that have been used in the current ORS configuration have been ~100 μm, which, given an electron beam energy spread of 200 keV and an energy of 1 GeV, would enhance wavelengths around 125 nm. For the larger $R_{56}$s (<700 μm) which will be used for future experiments, one might expect amplification of a broad spectrum of microbunching wavelengths centered around 900 nm, a more dangerous range than was used previously.

Further enhancements at a given wavelength can be generated by tuning the beam size and the resonance frequency of the undulator. The maximally amplified wavelength, $\lambda$, is proportional to the transverse size of the beam $\sigma_{x,y}$ and the longitudinal gamma factor $\gamma_z$ [19],

$$\lambda \cong \frac{2\pi\sigma_{x,y}}{\gamma_z}, \qquad (2)$$

meaning that smaller beam diameters will amplify smaller wavelengths. By changing the beam size in the undulators, we may be able to reduce disruptive LSCA at a particular wavelength.

An additional reduction of LSCA can be produced due to the relations

$$2\pi R_{51}\sigma_{x,y} / \lambda >> 1$$

and

$$2\pi R_{52}\sigma_{\theta} / \lambda >> 1$$

in which the smearing of the microbunches occurs in proportion to the transverse displacement of the beam in the chicane ($R_{52}$) and the bending angle of the chicane ($R_{51}$). Based on single-shot spectrometer measurements done before and after the dogleg, it has been observed that density modulations which are smaller than 600 μm are smeared out in the dogleg [20]. This means that the ORS section would primarily amplify wavelengths which are longer than 600 μm.

Disastrous amplification of an unwanted wavelength would occur if the undulators were tuned to radiate at the wavelengths satisfying the optimal LSCA conditions and the chicanes were tuned to optimally bunch this modulation. This could occur if the undulators were tuned to radiate at 800 nm and the chicane was tuned with an $R_{56}$ of 637 um. Thankfully, this is not required in any experiments planned for 2012. The goal for 2012 will entail that the undulators will be tuned to radiate at 270 nm, a considerably less dangerous regime. This was not and may not always the case.

## MICROBUNCHING IMPACTS

The ORS experiment originally relied on a seed laser operating at 800 nm in a first undulator-chicane segment to produce microbunches which are then used to radiate an optical replica at 800 nm in a second undulator. Because the periods of microbunches created upstream can fall anywhere from the visible to the infrared [14-16], unless the ORS experiment in this configuration can find a way to filter out the radiation from this external radiation source, the experiment will be overwhelmed by a background with a wavelength which will disrupt the longitudinal profile detection scheme. Because the radiation from incoming microbunches will have a much larger opening angle than that which is radiated at 800 nm, a pinhole filter might be used at the exit of the second undulator to isolate the 800 nm radiation. However, given the additional concerns about laser safety and LSCA gain at 800 nm, it would be advisable to avoid this sort of experiment entirely.

An ORS experiment using a 270 nm seed and radiator would have a much better chance of success due to the absence of incoming microbunches below 600 nm, but such an experiment would require a different sort of longitudinal pulse measurement system than the one which was originally purchased for the ORS experiment at 800 nm [2-10]. A single-shot TG-FROG with a ~50 um thick fused silica plate as the non-linear optical element would be a reasonable longitudinal profile measurement option [21,22,23]. This could make ORS into a viable, parasitic diagnostic, but it represents a significant departure from the original strategy.

The EEHG experiment in the ORS section relies on creating energy modulations with a period of 270 nm, over-folding, and bunching the beam with a harmonic of 270 nm. Given incoming bunching and energy modulations, the danger is that these modulations will drown out the modulation produced by the seed laser, rendering the experiment a failure. Because incoming microbunches below 600 nm can be smeared out in the dogleg, there should be no direct impact from incoming microbunches with a period of 270 nm. It is possible that the 3$^{rd}$ harmonic of incoming 800 nm microbunches could radiate in the ORS undulators, but such harmonics should be so weak as to not pose a problem.

Concerning potential difficulties with parasitic operation of the ORS section during SASE, while there are certainly dangerous operation ranges, ranges for which an incoming energy or density modulation would be amplified, operation at 270 nm does not appear to fall within this range.

## DOGLEG STEERING

To date, whenever the ORS section magnets have been turned on, the steering in the dogleg has needed to be adjusted in order to properly position the beam in the ORS section so that overlap with the laser could be achieved. In principle, this should not be necessary if a reference electron beam orbit is always selected which is compatible with SASE, sFLASH and ORS. Due to the time-consuming nature of manually tuning the overlap between the electron beam and the laser, it is imperative that the machine be routinely set up with a known ORS reference orbit, so that if the ORS laser is steered to a known reference orbit, overlap with the electron beam can be achieved without inserting screens into the electron beamline. When screens are inserted into the electron beam line, it should be done primarily as a cross-check, requiring only very small adjustments of the laser steering to attain overlap. The whole overlap procedure should be automated and should have a minimal impact on the machine operation. At SLAC a Matlab GUI for laser overlap in the laser heater has been developed and the time for automated overlap retrieval is around 10 minutes.

## LASER SAFETY

The parasitic use of 800 nm light poses the largest number of problems for laser safety and 4000 um light will not be immediately available. Consequently, experiments which use 270 nm light will be the only feasible parasitic experiments in 2012. This wavelength should enable parasitic EEHG and ORS experiments. Any longer-term plans to use 800 nm as a seed must be addressed through new infrastructure developed with HASYLAB.

Each individual wavelength requires different laser safety precautions as shown in the graphs of Fig. 1.

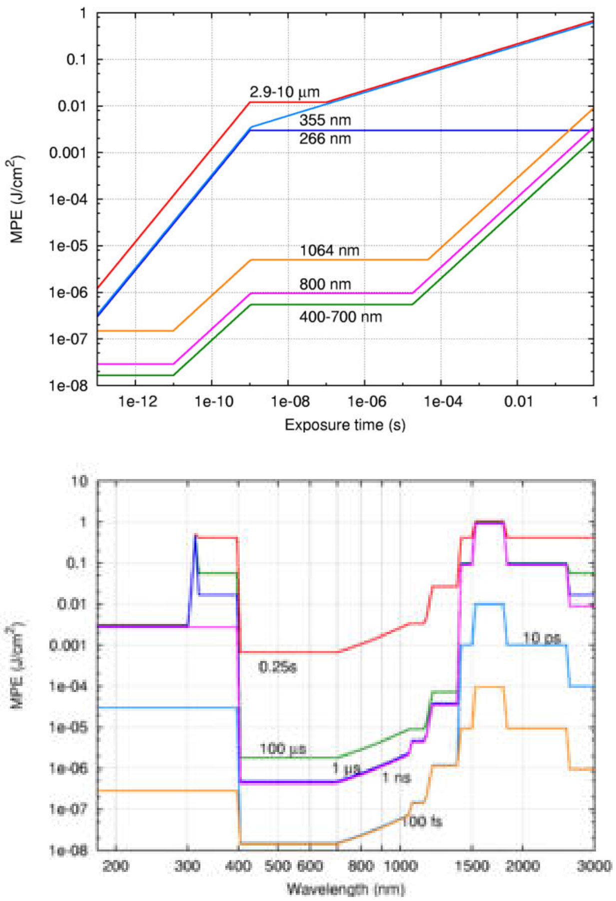


Figure 1: Maximum Permitted Exposure (MPE) plotted versus wavelength and exposure times. These plots were taken from the Wikipedia page on laser safety.

For example, for 100 fs long pulses, $5 \cdot 10^{-8}$ J/cm$^2$ is the limit for 800 nm, $5 \cdot 10^{-7}$ J/cm$^2$ is the limit for 270 nm and $1 \cdot 10^{-6}$ J/cm$^2$ is the limit for 4000 nm. 10 nJ has been specified as the amount of 800 nm allowed in the accelerator beam pipe [25]. For 270 nm, the amount allowed is 300 nJ [25]. Twice that amount would be allowed for 4000 nm light.

The 20-30 mJ of 800 nm which will be used to generate the 270 nm beam is highly dangerous because it travels through the lens of the eye and can be focused on the retinas. It will be filtered out with a series of six mirrors which reflect 270 nm and transmit 800 nm. Each mirror will transmit 95% of the 800 nm light. There will be an additional 10% loss from a window. For a maximum input laser power of 30 mJ, that leaves less than a nano-Joule of 800 nm reflected off of the final mirror and this is less than the 3 nJ cut-off specified by the laser-safety officer [25]. At the injection point, the 800 nm light will be contained in the laser transport line which will only be opened during special night-time, controlled tunnel accesses.

The 2 mJ of 270 nm light which will be used for EEHG is much less dangerous for the eyes since it is blocked by the lens and is not focused on the retina. In the short-term, it can cause photokeratisis, a type of inflammation of the cornea which is equivalent to sunburn. For standard ORS operation, the 270 nm beam will be extracted by a mirror in the second ORS chicane which extends down to the middle of the 35 mm diameter beam pipe, but because this is a passive laser safety measure, the possibility that the beam could travel unimpeded past this mirror must be considered. In this case, there are four apertures which block the beam. Following the 35 mm diameter ORS section beam pipe, there is the 7x15mm sFLASH undulator pipe. Then, at the sFLASH extraction point there is a mirror which blocks more than half of the beam pipe, extending from the bottom of the beam pipe. If the sFLASH extraction mirror and the ORS OS2 mirror are both included in the laser interlock, one could be assured that straight-ahead beams would be completely blocked. Only a portion of light which could diffract or reflect around the mirror could pass both apertures. After the sFLASH extraction mirror, there is another aperture provided by the 9 mm SASE undulator pipe diameter and lastly, there is the window in the user section which could transmit light reflected from the inside pipe at a sufficiently steep angle. The dimensions of the electron beam pipe apertures are depicted in Fig. 2.

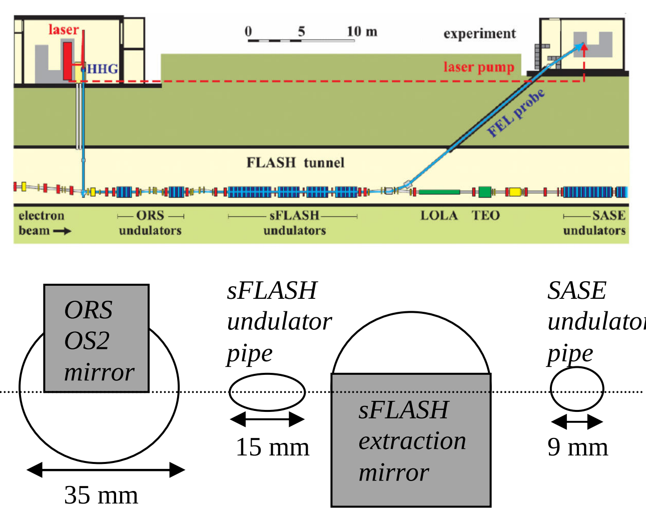


Figure 2: Aperture dimensions in the sFLASH area. There is no possible straight ahead path for the beam. Multiple reflections would be required in order to pass through all four apertures.

The only light which could possibly make it past these three apertures would be highly divergent and it would have to reflect off of the inside surface of the beam pipe several times. Each reflection of 270 nm from a polished Aluminum surface produces losses of more than 20%. An unpolished Aluminum surface produces at least 50% more losses than a polished Aluminum surface [26]. Assuming a very generous 30% transmission of the highly divergent beam through each of the three apertures, only 6 reflections would be required to reduce the intensity of the 2 mJ 270 nm beam to below the 300 nJ safety threshold. It is safe to assume that the beam could not possibly make it out of the window in the user area with less than 6 reflections.

The 1 mJ of 4000 nm light which is of interest for beam slicing experiments is dangerous to the corneas and can cause harmful thermal damage. But it is important to note the highly divergent nature of infrared light. On this basis, it is believed that extra laser safety considerations are not required in the user area for 1 mJ of 4000 nm light entering the ORS section.

Using 10-30 mJ of 800 nm in the ORS section is much more difficult than using 270 nm or 4000 nm. It is possible, remotely possible, but still possible, that a collimated portion of a >3 nJ 800 nm beam could make it all of the way from the ORS section to the windows in the user areas. To protect the user areas, this would require a foil absorber with an active interlock to be installed prior to the beamlines. Installation of such an interlock requires acceptance from the users and will not be attempted this year. The possible locations of future absorbers are indicated by red arrows in Fig. 2.

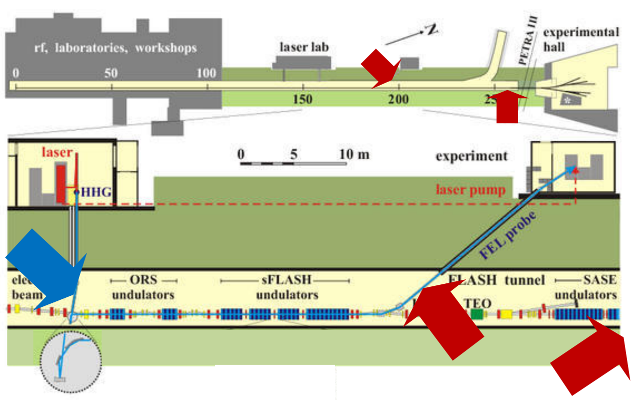


Figure 2: Potential locations 800 nm interlocks are indicated by red arrows. An existing 800 nm foil interlock is indicated by a blue arrow.

A foil absorber could possibly break and so there must be an interlock to verify that the foil is in and functioning. This interlock would consist of an LED which shines on the front side of the foil and two photodetectors which detect the reflected and transmitted light. If the light is fully reflected and none is transmitted, then the interlock is closed. If any is transmitted, then it is broken. The design shown in Fig. 3 was taken from an existing sFLASH laser interlock which is installed in the location indicated by the blue arrow in Fig. 2.

This interlock was designed and built by J. Boedewadt. While the hardware for such an interlock was built last fall for the HHG beam, the effect of a foil on the transmission of the extraction line and FEL beamline x-rays must still be studied. There are presently 8 foils installed in vacuum, many of which are in the FEL beamlines. Two of these foils broke while the vacuum was being pumped down, but all others have survived for 2 years [27].

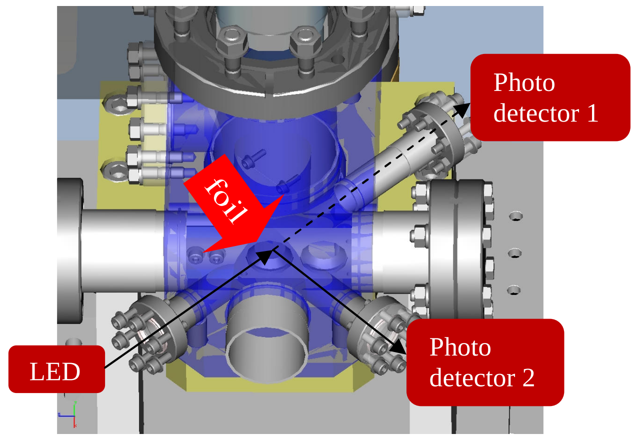


Figure 2: Foil with active interlock. If the light is detected by photodetector 2 and not by photodetector 1, the foil is intact. If the light is detected by photodetector 1 and not by photodetector 2, then the foil is broken and so is the interlock. This drawing is taken from an sFLASH design from J. Boedewadt.

Based on these considerations, it should be possible to commission EEHG, ORS and slicing parasitically with 270 nm and 4000 nm, but any experiments with 800 nm cannot be conducted parasitically without the required interlocked foils. Non-parasitic operation of 800 nm requires a daily renewed agreement between 800 nm operators and users in the experimental stations. Regarding laser alignment work in the tunnel, it is planned to only do this during night-time controlled tunnel accesses.

## CONCLUSION

For ORS experiments to operate parasitically, without impacting SASE user operation in 2012, it is recommended that 270 nm be used for initial experiments, due to the relatively un-problematic laser safety considerations that it requires and due to the benefits of operating in a regime without incoming density modulations. It is anticipated that density modulations at 270 nm will be completely smeared out in the dogleg. If practical considerations are regularly taken into account when setting up the orbit in the section, there should be no problem with operating the ORS section in a permanent and parasitic fashion.

## ACKNOWLEDGEMENTS

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