

# THE FREE-ELECTRON LASER FLASH AT DESY

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## Abstract

The free-electron laser FLASH at DESY routinely produces up to several thousand photon pulses per second with wavelengths ranging from 44 nm down to 4.2 nm and with pulse energies of up to 500 micro Joule. After a significant technical upgrade in 2010, emphasis was put on consolidation and automation of operational procedures and better control of the electron/photon beam properties. Some highlights are: on-line measurements of the electron bunch length in the regime of several 10 fs to 100 fs, extending the wavelengths accessible to users into the water window, increased photon pulse energies, and the improved machine reproducibility. Construction work is ongoing for a 2<sup>nd</sup> beam-line (FLASH2) for which commissioning will start in early 2014.

## INTRODUCTION

FLASH is a SASE FEL in the XUV and soft X-ray regime, driven by a superconducting linac with an RF photo cathode gun and a two stage bunch compression system.

From January 1<sup>st</sup> 2012 to the beginning of the 2013 shutdown (February 18-th 2013), 2715 h of SASE were delivered to the FEL users. That is about 92% of the original schedule. In the same time 2934 h of FEL and machine studies have been performed. By now, the photon experiments carried out at FLASH have resulted in about 180 publications, many of them in highly ranked journals [1].

We summarize here the present status of FLASH, highlight the key achievements of the present run period and briefly touch the upgrade to 2 beam lines (FLASH1/FLASH2). Part of the material presented here has been already discussed in proceedings of previous conferences [2, 3, 4].

## THE FLASH LINAC

FLASH consists of a superconducting L-band (1.3 GHz) electron linac followed by a photon transport line equipped with photon diagnostics and 5 experimental beam lines for users. The total length including the experiments is about 315 m. A schematic layout is shown in Fig. 1.

Because of the high duty cycle of 1.3% that the superconducting RF can provide, FLASH delivers up to 8000 bunches per second in 10 trains (one per RF pulse) of up to 800 bunches/train (800  $\mu$ s flat top & maximum bunch repetition frequency of 1 MHz). The bunches are generated usually with charges of 0.08 nC to 1.0 nC in a warm photo cathode RF gun. Then they are accelerated and compressed in two stages: 1 superconducting L-band module followed

by a chicane at 150 MeV and two more modules followed by a chicane at 450 MeV. FLASH has a superconducting 3<sup>rd</sup> harmonic RF system to linearize the bunch compression. The main linac behind the last bunch compressor consists of 4 more cold modules, allowing for beam energies up to 1250 MeV, i.e. SASE wavelengths down to 4.2 nm. A slightly more detailed description of the FLASH facility and a table containing some of its key electron/photon parameters valid for most of the 2011–2013 operation can be found e.g. in [4].

## MACHINE DEVELOPMENT

During the 2009/10 upgrade, the vertically deflecting traveling wave RF structure was moved to its present location upstream of the SASE undulators. It is followed by a switchable dispersive arm (horizontal dipole) equipped with a screen to image the streaked bunch. This configuration maps the longitudinal phase space into the  $x$ - $y$  plane of the screen [5], but unfortunately the dispersive DC dipole excludes its use during SASE production. Another constraint is that the “mini dump” at the end of the dispersive arm can only withstand 2 bunches every 100 ms. In 2012 we have commissioned a “straight” version of this diagnostics. It employs a fast kicker magnet that allows to deflect an arbitrary bunch out of the train into an off-axis screen in the main vacuum chamber. This variant destroys at most *one* bunch per train and can thus be used as an on-line bunch length monitor during FEL operation. This on-line monitor constitutes a major operational tool for setting up SASE parameters, and is particularly useful for short pulse tuning.

We have now integrated several beam based slow longitudinal stand alone feed back clients, which monitor the bunch charge, and the peak current and bunch arrival time after both chicanes into a single server which offers the possibility to treat inter channel correlations.

An energy BPM in the first magnetic chicane was commissioned to augment our knowledge of the  $E$ -profile along the linac. After measuring the orbit response matrix over the linac and carefully analyzing the deviations from the theoretical response we have identified [6] a couple of perturbations which will be removed during this year’s shutdown. The server based slow orbit feed back will clearly benefit from these fixes, however already now we have established orbit feedback configurations for certain sections of the linac using measured response matrices. Some FEL experiments require reduced pulse-to-pulse arrival time jitter. The FLASH standard LLRF without any extra timing control delivers bunch trains with an rms arrival time jitter as small as 50 fs to 70 fs. If this is not

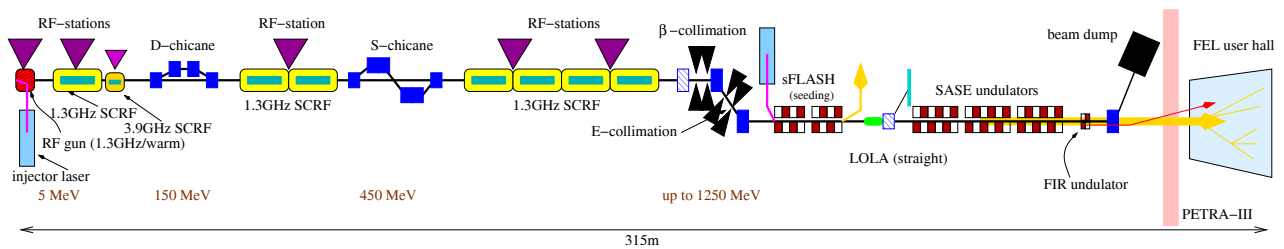


Figure 1: Overview of FLASH from the RF photo cathode gun (left) to the experimental hall (right).

enough an intra train arrival time feedback can be used to reduce the rms jitter down to as low as 20 fs for bunches with more than 0.3 nC charge ( $\approx 30$  fs for 0.2 nC). Last but not least the new  $\mu$ TCA based RF controls were tested. It will become operational when FLASH1 will be recommissioned in August 2013.

## THE RF-GUN

After a failure of the coupler window just 10 days before the run end in 2011, the gun was recommissioned with a new window in only about 2 weeks in the beginning of 2012. On May 22<sup>nd</sup> (during IPAC 2012) a drastic interlock event (vacuum and light in the cavity/vacuum side of coupler) occurred. Thereafter decent operation with the gun was no longer possible. It was diagnosed that the connection between the cathode carrier and the back plane of the cavity was irreversibly damaged by a spark. The gun was exchanged by a freshly conditioned one from DESY-Zeuthen and equipped with an older, well tested and extremely reliable coupler window. After a short time of reconditioning, the user run was restarted with almost no interlocks at a 500  $\mu$ s gun flat top with a typical  $P_{\text{fwd}}$  of 4 MW. In September 2012 the trip rate started to increase and in November a continuous pedestal of light over the RF pulse appeared which quickly increased beyond the standard interlock level. However, it was possible to operate the gun with slightly reduced flat top of 400  $\mu$ s and with increased (light) interlock level. With these settings, accepting sporadic trips, and a high and slowly oscillating light pedestal, user operation was resumed until the scheduled run end in mid February 2013. In the shutdown the gun was opened and again a damaged back plane was found. The gun was replaced again. In the mean time a new design for connecting the cathode carrier was finished and is in the process of testing.

## USER OPERATION

The FLASH (future: FLASH1) experimental hall has 5 separate photon beam lines of which one at a time can be served with FEL radiation, while others can be modified/equipped for/with new user experiments. The user's requests for photon parameters are manifold, including wavelength, bunch pattern, intensity, pointing, photon pulse length, bandwidth, stability, additional THz radi-

Table 1: Requested FLASH Operation Modes 2012

Pulse Pattern	requested by	
Single Bunch	47%	
Multi Bunch	53 %	35% > 200 b.
<b>Spacing:</b> 1 MHz	30 %	
	200 kHz	43 %
	other	27 %
		40 – 500 kHz
<b>FEL pulse duration (FWHM)</b>		
< 50 fs	42%	56% multi bu.
50 - 100 fs	33%	64% single bu.
not critical	26%	83% max $E_\gamma$

tion, reduced/monitored arrival time jitter, etc. Table 1 contains some statistics on the requested bunch patterns in the last year.

In August and December 2012 FLASH provided for two user experiments photons of wavelength in the water window. The photon pulse energies were 100  $\mu$ J and 250  $\mu$ J respectively.

Operation with short bunches of low charge, i.e. short photon pulses below 50 fs FWHM has become more and more standard. This is partly because of the improved diagnostics (see above) and because of the increasing operational experience with the short pulse mode. The photon pulse length diagnostics still poses a problem. Dedicated short pulse FEL studies involving prototype diagnostics supplied by the FEL users suggested that there is at best a mid term solution to measuring the photon pulse length.

With the improved diagnostics and operational procedures the SASE level and uniformity in multi bunch operation increased. As an example pulses 300 bunches/train were provided with fairly uniform 200  $\mu$ J/pulse, leading to a new record on average power of 600 mW.

An increasing number of users requested use of the THz-undulator (downstream the SASE undulator) to use the fully synchronized combination of FEL and THz radiation. FLASH is a unique THz source worldwide:  $\approx 100 \mu$ J/pulse has been achieved for 600 pulses/s at 160  $\mu$ m. Tuning for maximum THz intensity is not yet established as a standard procedure. The THz diagnostics needs upgrading and systematic studies will be scheduled in the future.

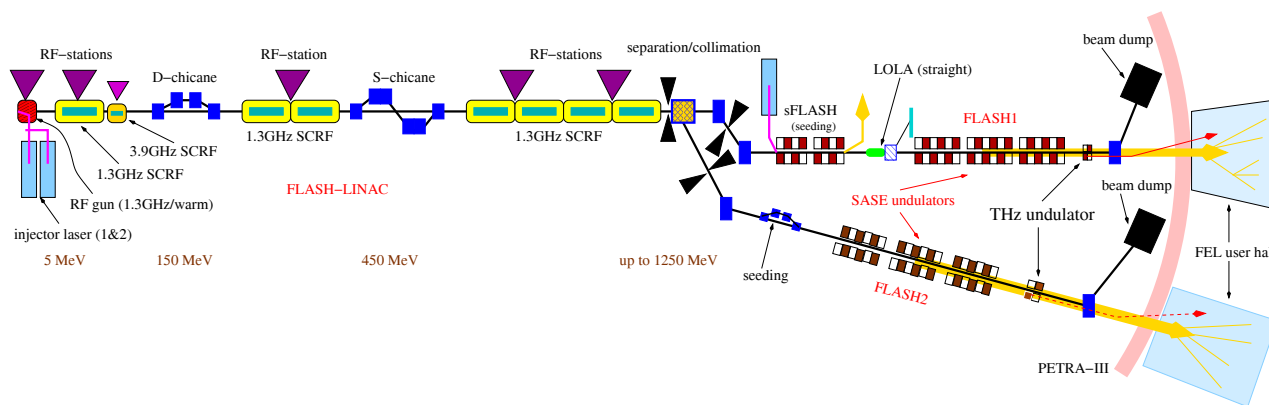


Figure 2: Overview of the FLASH linac, the existing FLASH1 beam line and the new FLASH2 beam line to be commissioned early 2014.

## MACHINE STUDIES

In February and September 2012 studies on long bunch trains and high beam loading were performed with an international group designing the RF for the ILC [7]. Up to 5 mA (charge / flat top) were transported in up to 2400 bunches (at a bunch frequency of 3 MHz).

In collaboration with the University of Hamburg a new short pulse ( $\approx 1$  ps) injector laser was installed [8]. The aim is to provide single spike, bandwidth limited, longitudinally fully coherent SASE pulses. The standard injector lasers at FLASH are bandwidth limited at 6–7 ps rms. One could in principle attenuate the long laser pulse to very low charge and then compress the bunches more strongly to achieve the necessary peak current. However, the extremely high compression factor needed would make the system too sensitive to RF phase jitter. The new short pulse laser was commissioned in 2012 and first SASE was achieved in January 2013 [9].

### TOWARDS A 2<sup>nd</sup> BEAM LINE : FLASH2

In autumn 2011 civil construction started for upgrading the FLASH facility with a 2<sup>nd</sup> beam line (FLASH2) [10]. The layout of the FLASH linac, the (existing) FLASH1 beam line, the extraction, and the new FLASH2 beam line is sketched in Fig. 2. There will be two injector lasers capable of filling every RF flat top (at 10 Hz) with 2 independent bunch patterns, separated by a  $50 \mu\text{s}$  gap. The FLASH RF stations are capable of providing slightly different amplitude and phase in two parts of the flat top, with a transient time of  $< 50 \mu\text{s}$ . The (DC) magnets in the FLASH linac, however are common to both beams, therefore constraining the maximum attainable differences in the  $E$ -profile. Between the last module and the FLASH1 dog leg three vertical flat top kickers with a rise/fall time of  $< 50 \mu\text{s}$  will kick the part of the train allocated for FLASH2 in the upper (deflecting) channel of a horizontally Lambertson septum which leads into the extraction/collimation channel of FLASH2. The users at FLASH1 and FLASH2 can thus have different bunch spacings and bunch charges. Take as an arbitrary example: 10 bunches at 100 kHz

with 0.15 nC each, compressed for short pulses sent to FLASH1 and 650 bunches at 1MHz with 0.5 nC each, compressed for maximum SASE power sent to FLASH2. The FLASH2 undulators are variable gap undulators so that the SASE wavelength of FLASH2 can be tuned (within certain bounds) at energies chosen to provide the right wavelength at FLASH1 which has fixed gap undulators. In FEL studies in 2011/2012 the flat top kickers, the multi plateau capabilities of the RF and the synchronization and control of the two injector lasers have been successfully tested. A highlight was SASE with two sub trains in FLASH1 with different charge and independently optimized compression.

## SUMMARY

Despite problems with the RF gun cavity, FLASH had a very successful run for FEL and machine users. Several upgrades towards a consolidated machine operation were successfully implemented. After the assembly of the FLASH2 extraction in August 2013 FLASH/FLASH1 will be recommissioned for FEL operation, and first beam in the FLASH2 beam line is expected early 2014.

## ACKNOWLEDGMENTS

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