FLASH Progress Report

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Abstract

The free electron laser in Hamburg (FLASH) is a user facility providing high brilliant laser light for experiments in the VUV and EUV wavelengths range. It is based on TESLA type superconducting accelerating structures, and therefore a unique facility for testing superconducting accelerator technology for the European XFEL, and for supporting the international linear collider (ILC) R&D effort. This workshop contribution reviews the progress on superconducting RF technology in view of cavity and accelerating module performance and reports about the operational experience gained with FLASH operated as a user facility.

INTRODUCTION

The free electron laser in Hamburg (FLASH) is a user facility providing high brilliant laser light for experiments in the VUV and EUV wavelengths range [1, 2, 3]. Novel time exposures at the fs time scale of biological, chemical and physical processes can be made. FLASH is based on TESLA type superconducting (sc) accelerating structures, and therefore a unique facility for testing superconducting accelerator technology for the European XFEL [4], and for supporting the international linear collider (ILC) research and development effort.

Facilities like FLASH represent a bundle of modern physics applications such as the theory of photon emission, superconductivity and also a bunch of (high) technology like metallurgy and crystallography, welding engineering, (chemical) surface treatments, clean room techniques and process engineering, large scale cryogenics, ultra high vacuum [5], digital electronics for beam diagnostics and controls [6] and so on. Progress achieved by experts in all these fields contribute to the success of the facility. This workshop report can only present some issues.

The report gives a brief overview on the key requirements on the electron beam at FLASH, followed by the progress at the superconducting accelerating structures. At FLASH the focus of activities is currently less on the superconducting technology and more on improving the stability of operation. Beam diagnostics gains importance, as well as rf and beam control. Finally, the report presents the SASE performance and the operational experience gained so far by operating FLASH as a user facility.

FLASH - THE MACHINE

An ultra short bunch of high intensity, travelling along the undulating trajectory resulting from the magnetic field of an undulator, develops micro bunches by interacting with emitted photons. The micro bunches emit themselves photons coherently to the photon field. This self amplified stimulated emission (SASE) of photons requires electron peak currents of 1 kA, e.g. from bunches with 1 nC shorter than 100 fs.

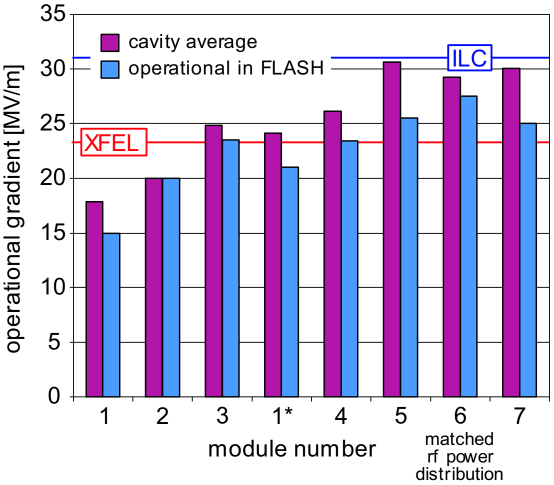

Figure 1: Evolution of accelerating gradients in modules delivering beam at FLASH [9].

The minimum bunch length provided by the photo cathode rf gun to the subsequent accelerator is restricted by collective effects. At FLASH a two stage bunch compression scheme is used for obtaining the electron peak currents required (fig. 2). It is based on accelerating the beam off the rf field crest and passing transverse magnetic chicanes. For satisfactory performance a good rf field stability is mandatory.

SC ACCELERATING STRUCTURES

Superconducting accelerating structures provide a good transfer from rf power into beam power due to the low surface resistance of the resonators [7]. The loaded quality factor are typically two orders of magnitude higher than those of normal conducting structures resulting in an higher rf field stability. High gradients are obtained at lower rf frequencies reducing the demand on the cavity alignment and the beam steering.

In 1992, the TESLA collaboration started the development of superconducting 1.3 GHz nine cell cavities with the aim to reach rf gradients of more than 25 MV/m. Ex-

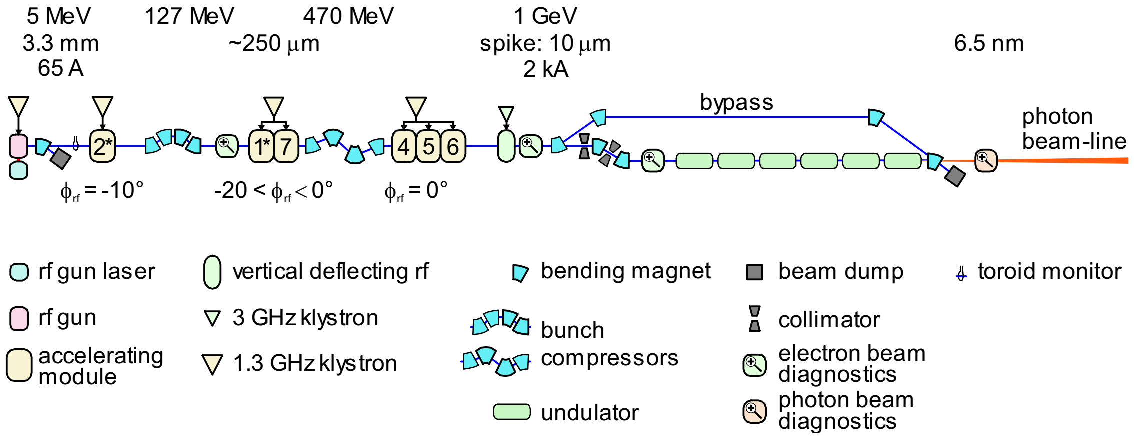

Figure 2: Sketch view of FLASH in autumn 2007 with the main beam parameters.

perience has now been gained form about 130 cavities produced by four companies. Niobium qualification procedures are well established, as well as welding procedures. Different strategies for the surface treatment and the process engineering are still under evaluation [8]. Preseries production exceeded average gradients of 25 MV/m. Recently, a new record has been achieved by measuring a nine cell cavity gradient of 40 MV/m at the horizontal test stand CHECHIA [9].

Cryomodules shield the sc cavities, cooled by liquid helium of 2 K, from room temperature. A typical 1.3 GHz module consists of eight cavities, a quadupole magnet, a beam position monitor and beam steering doublet. After two design iterations, the 'type three' cryostat design is now - with small modifications - the baseline for XFEL and serves as a starting point for an ILC module. Figure 1 shows the evolution of the average accelerating gradient achieved by modules accelerating beam at FLASH. The XFEL specification is met by the newer modules [10].

BEAM DIAGNOSTICS

Providing 100 fs short electron bunches to the undulator requires some tuning of the accelerator for proper bunch compression. Obviously some beam diagnostics (fig. 4) is required supporting the operators at this task. A satisfactory treatment of the electron beam diagnostics at FLASH would require a separate report. In this place, we describe briefly two examples.

By operating a 3 GHz travelling wave structure with an transverse deflecting mode (LOLA), bunches are sheared and observed by a screen and a camera. As a result the longitudinal change distribution can be examined with fs resolution [12].

Beam passing cavities depose rf with the fundamental frequency called beam loading. In addition it excites also higher order modes (HOMs). HOMs are unwanted and damped via HOM dampers. But, the non cylinder symmetric HOMs can be used for the determination of the transverse beam position when measured [13]. Resolutions for the transverse beam position in the order of 2 to 10 μm (r.m.s.) have been obtained for single bunches at FLASH.

BEAM CONTROL AT THE RF GUN

The electron bunches are created via the photo effect by shooting short laser pulses on a photocathode of a 1.3 GHz rf gun powered by a 5 MW klystron. An electrical voltage of 42 MV/m (rf power of 3 MW) at the cathode is build up by the rf field in the $1\frac{1}{2}$ cell copper cavity accelerating the bunches away from the cathode to 5 MeV. This mechanism requires a well adjusted and stable phasing between the laser pulses and the rf called 'emission phase'.

Following a rigorous cylinder symmetric design the gun provides no mechanical tuner and no rf probe to prevent sparking effects at the high rf voltage [14]. As a consequence the rf field has to be calculated by the digital controller form the forward and reflected power supplying a sensor signal to the subsequent control algorithms [15]. Proportional control with a recursive 20 kHz low pass filter for stabilising the loop at gain values of 5 reduces non repetitive rf field errors within rf pulses. This loop is sup-

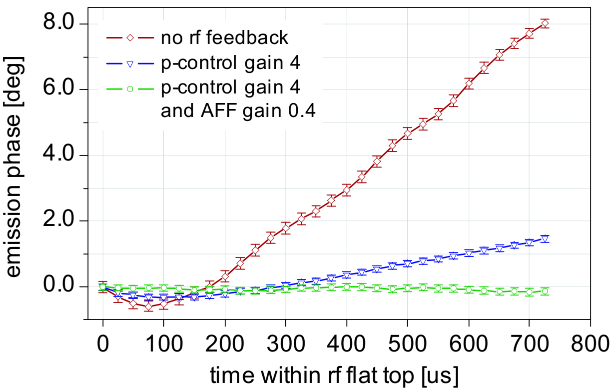

Figure 3: FLASH rf gun emission phase along the rf pulse measured with the beam.

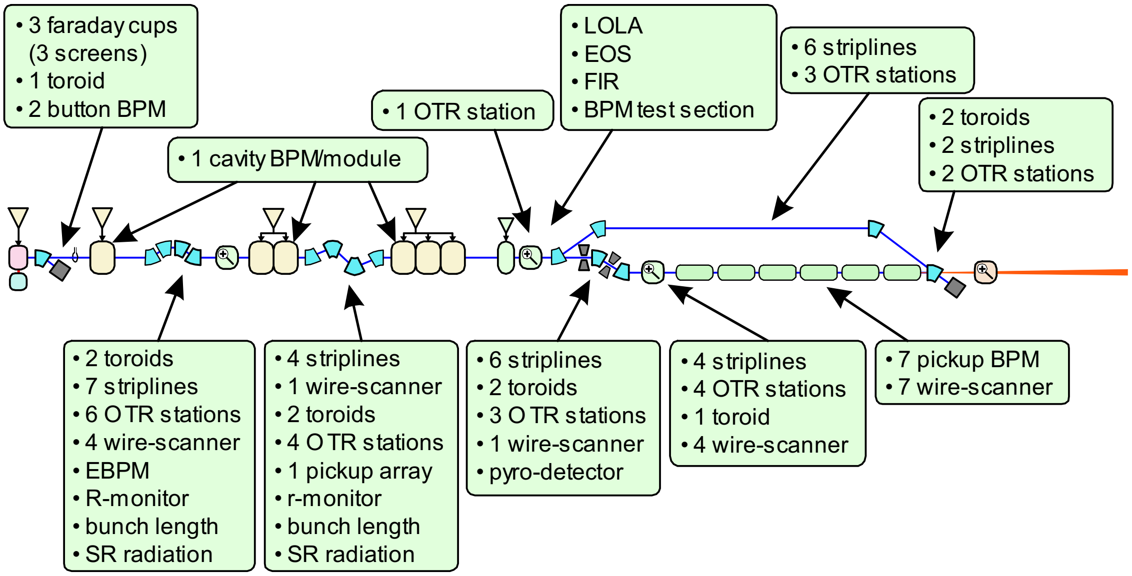

Figure 4: Overview on the electron beam diagnostics at FLASH in autumn 2007 [11].

ported by an adaptive feed forward (AFF) algorithm acting from rf pulse to pulse and correcting repetitive rf field errors mainly caused by resonant frequency changes due to the rf heating within the pulse. Beam based rf phase measurement (resolution ±0.01° fs) [16] showed, this approach is well suited for stabilizing the rf over the flat top of 800 μs (fig. 3). The intra pulse phase stability amounts 0.14° and the long term stability 0.4° (peak-to-peak). Both are below the empiric FLASH requirement of 0.5° at the rf gun.

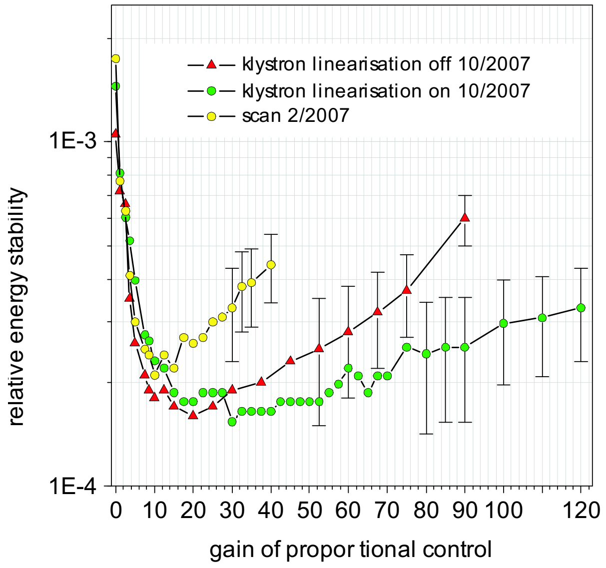

Figure 5: Relative single bunch energy stability and ACC1 rf amplitude stability measured for different gain values of the proportional rf control.

BEAM CONTROL AT ACC1

Satisfactory bunch compression requires a stable rf phase and amplitude for the off crest acceleration. At the accelerating module in front of the first bunch compressor (ACC1) high gain proportional control in combination with beam based beam loading compensation is applied [17]. The effect of this approach can be observed using the first bunch compressor as spectrometer. Recording a synchrotron light spot within the bunch compressor the beam energy stability can be examined [18] with a resolution of $\Delta E/E = 10^{-4}$ [17].

Single bunches do not suffer from beam loading. Recording the beam stability of single bunches while changing the gain value of the proportional control, the gain value resulting in the most stable beam can be determined. A relative single bunch energy stability and a relative ACC1 rf voltage stability of 1.6×10^{-4} have recently been measured for gain values between 30 and 40 (fig. 5).

Operating with many bunches a proper compensation of the beam loading becomes essential. The beam based beam loading compensation applied at ACC1 is not yet ideal. Nevertheless, it already stabilises the rf field sufficiently so that long bunch trains of 800 bunches have been accelerated and compressed. A better calibration of the beam loading compensation should improve the multi bunch stability.

Further rf control developments are the klystron linearisation, optimal control [19], different adaptive feed forward algorithms, new sampling schemes [20] and so on. In addition, beam position monitors at the first bunch compressor for examining rf amplitude and phase in real time are under development [21]. They may serve as the sensor part for an rf and beam feedback system.

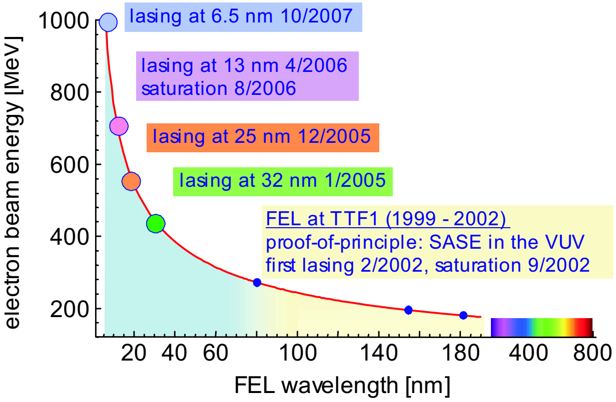

Figure 6: Evolution of the FLASH beam energy and the SASE wavelength.

SASE PERFORMANCE

All the effort mentioned above pays off, especially when increasing the beam energy and lasing with long bunch trains. Figure 6 shows the devolvement of the FLASH beam energy and the SASE wave length. After the installation of the 6th module in the summer shutdown, FLASH reached quickly the energy (1 GeV) and wavelength (6.5 nm) planned [3].

Different experiments using the SASE light require different wavelengths. Sometimes FLASH has to change the wavelength within one shift. Meanwhile lasing at more than 15 wavelengths has been achieved. Each new beam energy requires a separate tuning of the operation parameters. By saving the settings lasing at this wavelength can be re-established quite fast by reloading the settings form the control system. Hitting the wavelength requested within 0.1 nm is sometimes lengthy.

FLASH accelerates bunch trains of up to 800 bunches and SASE has been measured for more than 450 bunches of such long trains at levels up to 70 to 80 μJ in average. The photon beam diagnostics was at the time of the measurement restricted to 450 laser flashes. Most likely all bunches of such long bunch trains are lasing.

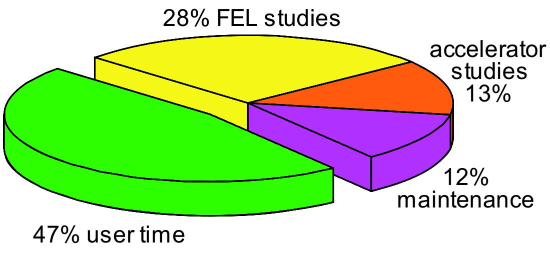

Figure 7: Typical FLASH beam time distribution. The values given are for the user run 2 lasting from May 2006 until March 2007.

STATISTICS AND RUN TIME DISTRIBUTION

The user operation since 2005 was spitted in two periods, called run 1 and run 2. Run 1 took place in 2005 and 2006 lasting 119 days and run 2 from 2006 to 2007 with 160 days. The next user period will start at the end of this year and last about 200 days.

Besides to user runs, dedicated periods for general accelerator studies concerning the XFEL or the ILC, FEL related studies and a period for the preparation of the user run are scheduled. Figure 7 shows the typical time distribution [22].

More than 70% of the scheduled time for user is actually beam delivery to the experiments by FLASH [23]. The residual time is divided into time for the tuning, scheduled off time and downtime due to technical problems. From user run 1 to user run 2 the SASE delivery improved by reducing technical malfunctions. A few big events contribute significantly to the downtime statistics and a lot of small problems add up.

NEXT MILESTONES

End of November 2007, the second period of user experiments will start at FLASH. At the shutdown scheduled beginning of 2009 the installation of the 3rd harmonic module to flatten the longitudinal phase space and improving the bunch compression is planned [24]. There is also the possibility to install a seventh module to increase the beam energy to 1.2 GeV or perhaps to 1.3 GeV to obtain lasing at 4.4 or 3.7 nm.

SUMMARY

The superconducting TESLA technology arrived at typical average cavity gradients well above 25 MV/m in preseries production. Recently a cavity has been tested with 40 MV/m in the horizontal test stand CHECHIA. The newest cryomodules assembled accelerate beam with average gradients of 27 MV/m resulting in a FLASH beam energy of 1 GeV.

At FLASH, the focus is more and more shifted towards improving the stability of the operation. Beam diagnostics plays an essential role for setting up and tuning the accelerator and SASE. Rf and beam control operate quite well and a relative energy and rf stability of 1.6×10^{-4} has been measured at the first bunch compressor.

The effort invested in diagnostics, better understanding of the beam dynamics and rf and beam control pays off. Short after accelerating the first beam to 1 GeV lasing with 6.5 nm has been reached. More than 70% of the scheduled beam time for user experiments is provided to the users, the rest is mostly required for tuning and consumed by downtime.

At the end of 2007 the next period of user operation will start and at the shutdown beginning of 2009 the installation of the 3rd harmonic is planned.

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