TEST AND COMMISSIONING OF THE THIRD HARMONIC RF SYSTEM FOR FLASH

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Abstract

Ultra short bunches with high peak current are required for efficient creation of high brilliance coherent light at the free electron laser FLASH. They are obtained by a two stage transverse magnetic chicane bunch compression scheme based on acceleration of the beam off the rf field crest. The deviation of the rf field's sine shape from a straight line leads to long bunch tails and reduces the peak current. This effect will be eliminated by adding the Fermilab-built third harmonic superconducting accelerating module[1] operating at 3.9 GHz to linearize the rf field. The third harmonic module also allows for the creation of uniform intensity bunches of adjustable length that is needed for seeded operation. This paper summarizes the results from the first complete rf system test at the crymodule test bench at DESY and the first experience gained operating the system with beam in FLASH.

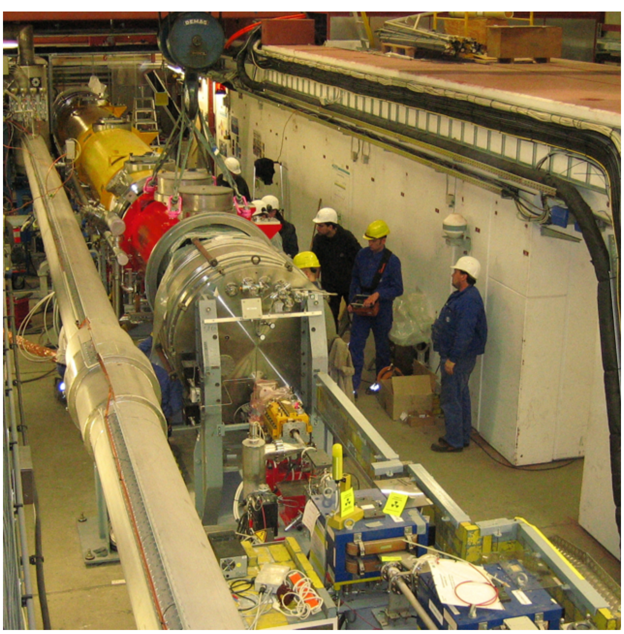

Figure 1: Installation of ACC39 (red) in FLASH after the first accelerating module ACC1 (yellow) before the first magnetic chicane for bunch compression BC2 (blue dipole magnets in the foreground).

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INTRODUCTION

Adding higher harmonic rf systems for phase space linearization improves the bunch compression at recent free electron lasers (FELs). At the DESY free electron laser FLASH the 3rd harmonic rf system is located after the first accelerating module before the first magnetic chicane used for the bunch compression [1]. It consists of the Fermilab built module (ACC39) containing four superconducting 3.9 GHz cavities [2]. DESY provides the power rf consisting of a high voltage power supply and a klystron, the rf control, the coupler vacuum, the cavity tuner motor electronics and the interlock systems for the complete rf system. In autum 2009 the complete system was installed at DESYs cryomodule test bed (CMTB) [3] for the first complete system test before its installation in FLASH (Fig. 1). Table 1 contains a list of design parameters.

Presently the system is being commissioned together with other new components installed in FLASH during the last shutdown [4].

TESTS AT THE CMTB

The tests of ACC39 at the CMTB basically followed the testing procedure which are applied to 1.3 GHz modules. After installation this procedure includes cable continuity checks and calibration, checks of interlocks, wave guides and the power rf, followed by warm coupler con-

Table 1: Cryomodule and Cavity Parameters

number of cavities	4
active length per cavity	0.346 m
design gradient	14 MV/m
phase	$-179°$
$R/Q\,(=U^2/\omega W)$	$750\,\Omega$
$E_{\mathrm{peak}}/E_{\mathrm{acc}}$	2.26
$B_{\mathrm{peak}}\,(E_{\mathrm{acc}}=14\,\mathrm{MV/m})$	68 mT
Q_{L}	1.3×10^6
BBU limit for HOM, Q	$<1\times10^5$
total design energy	19.4 MeV
nominal beam current	9 mA
nominal forward power per cavity	9 kW
maximum power per coupler	45 kW
maximum klystron power	80 kW

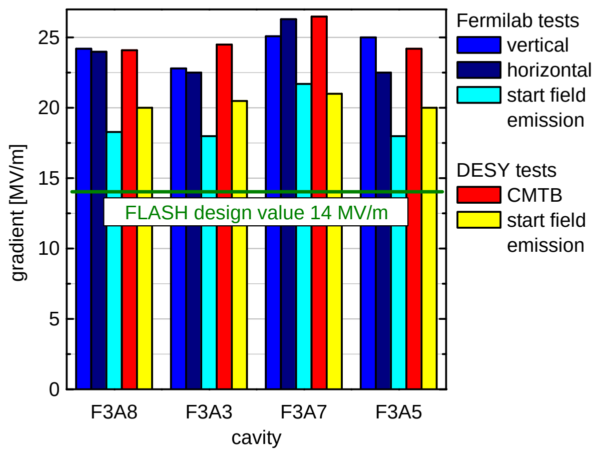

Figure 2: Quench limits and gradients where field emission starts in the cavities in ACC39 measured at the Fermilab test stands and the DESY CMTB.

ditioning. Conditioning entails directing the klystron output to each coupler individually in a sequenced increase of both pulse length and power to finally more than 50 kW rf power and 1.3 millisecond pulse length. Thereafter ACC39 was cooled down and the cavity spectrum measured [5] at both 4 K and 2 K. Since the cavity length and frequency change during cool down the accelerating mode (π-mode) frequency needs to be adjusted to match the master oscillator frequency. This is accomplished by moving the cavity tuners from their warm position to the cold position by observing the cavity spectrum. Conditioning each coupler by itself in the cold is the next step followed by the measurement of the individual cavity quench limits, loaded quality factors (Q_{L}) and the gradients at which field emission starts. Figure 2 shows the results of these tests in comparison with the vertical and horizontal tests performed at Fermilab. Table 2 contains the numerical values of the results, the cavity serial names and the HOM formteil type – whether double leg (dl) of the original design or single post (sp) [6].

Due to the comparatively large beam pipe diameter some rf cross talk was measured between the cavities as described by a coupling matrix $E_{\mathrm{acc},j} = M_{jk}\, E_{\mathrm{acc},k}$

$$M_{jk} = \begin{pmatrix} 1 & 0.051 & 0.005 & 0.002 \\ 0.055 & 1 & 0.016 & 0.022 \\ 0.008 & 0.035 & 1 & 0.123 \\ 0.003 & 0.002 & 0.107 & 1 \end{pmatrix}$$

The coupling is strongest where the rf power couplers are next to one another [7, Fig. 4]. Apart from complicating the adjustment of cavity resonance frequencies and Q_{L} no further issues are envisaged due to this cross talk.

For the subsequent testing steps, the rf power was equally distributed to all four cavities thus demonstrating the functionality of the complete system. The adjustability

Table 2: ACC39 Cavity Properties Measured at CMTB

ACC39 position	1	2	3	4
cavity serial name	F3A8	F3A3	F3A7	F3A5
HOM type	sp	dl	sp	dl
$Q_{\mathrm{L}}/10^6$	1.32	1.48	1.93	1.32
X_{start}/MV/m	20	20.5	21	20
E_{quench}/MV/m	24.1	24.5	26.5	24.2
$\mathrm{HOM}_{\mathrm{quench}}$/MV/m	-	-	-	20

of Q_{L} was checked by moving the 3-stub tuners and examined rf control stability when applying rf control. The inloop vector sum amplitude and phase stability achieved $\Delta A/A = 2\times10^{-5}$ and $\Delta\phi = 0.003°$ surpassed the requirements of $\Delta A/A = 1\times10^{-4}$ and $\Delta\phi = 0.03°$ [8].

THE MODULE IN FLASH

For phase space linearization the 3rd harmonic system decelerates the beam. Consequently, beam loading increases the rf voltage in the cavities and may cause quenches if not compensated. Hence, hard-wired gradient restricting interlocks were installed switching the rf power and the beam off in the case a cavity gradient exceeds an adjustable limit. Similarly, the HOM cans and HOM antennas are equipped with temperature sensors which trigger interlocks if pre-determined limits are exceeded. These also switch the rf and beam off.

Viewed from ACC1, ACC39 represents a significant contraction from the 70 mm 1.3 GHz cavity iris down to the 30 mm iris of 3.9 GHz cavities. Beam passing through ACC1 off center can easily get lost in ACC39. Dark current created by the photo injector gun is accelerated by ACC1 and partly dumped in ACC39 increasing the temperature sensor reading in the closest helium vessel to more than 2.4 K. This can be prevented by placing a so-called dark current collimator, a copper piece with an opening of 8 mm diameter and about 1 cm depth, in front of ACC1. The HOM temperature sensors also show impressive increases to values up to 100 K in the case of strong off axes beam steering even with single bunch operation. Dark current is also visible at these sensors.

At FLASH, the 3rd harmonic rf control converts 3.9 GHz rf signals down to 54 MHz which is then used for digital I and Q sampling rather than applying the two-step approach used at the CMTB. The direct down conversion improves the signal to noise ratio.

Applying beam based vector sum calibration and measuring the beam energy in the first bunch compressor yields the rf monitoring and control calibration values. Adjusting the cavity to cavity phasing requires manual adjustment of the wave guide length followed by a fine tuning via the three stub tuners which are also used for Q_{L} adjustment. Q_{L} adjustment requires usually some π-mode frequency correction. During commissioning this required several iterations. Verdigris in a three stub tuner, presumably built up by sparking effects, caused stochastic variations of Q_L and the π-mode frequency of the connected cavity until the problem was localized.

By delaying the complete timing of the third harmonic section by 2 ms allows the 3.9 GHz rf pulse to come shortly after the 1.3 GHz rf pulse end. This enables 3.9 GHz rf operation and testing in parallel to FLASH commissioning when not relying on 3.9 GHz operation. This has proved to be quite useful for parasitic commissioning.

First studies on the 3.9 GHz rf control stability applying Multi Input Multi Output (MIMO) control surpassed the results from the CMTB [8]. Future beam stability measurements at BC2 will reveal the rf stability of the combined action of ACC1 and ACC39.

Anticipating that the 3.9 GHz cavities have three times stronger transverse wakes than 1.3 GHz ones, great effort was put to the string and module alignment. First measurements in BC2 resulting in emittances of 1.8 μm in both planes confirm that this effort paid off. HOM studies are under way [5].

PHASE SPACE LINEARIZATION

Figure 3 shows the first phase space linearization performed with the FLASH 3rd harmonic system recorded with the electron beam phase space diagnostics using a transverse deflecting structure (TDS) [9]. Applying a 3.9 GHz voltage of 16 MV removes the bending by the 1.3 GHz rf fields. The phase space pictures shown were taken after adjusting rf amplitude and phase parameters and some magnet settings for about one hour.

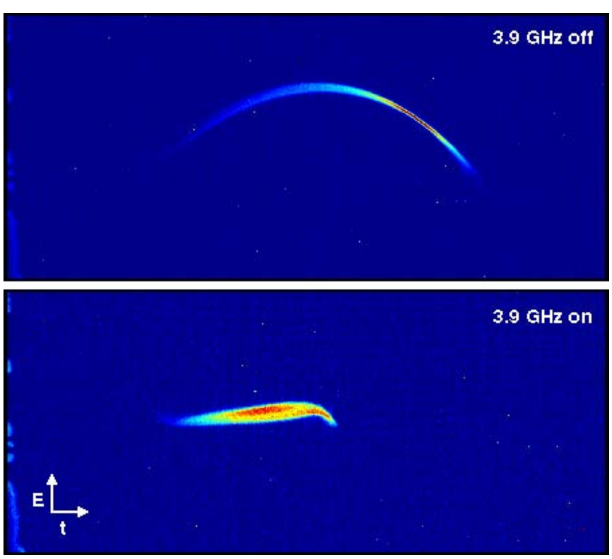

Figure 3: The first linearization of the longitudinal phase space measured with a TDS. Without and with applying 16 MV 3.9 GHz voltage and a BC2 energy near 150 MeV.

SUMMARY AND OUTLOOK

The third harmonic rf system of FLASH has successfully been tested and put into operation. A major milestone has been achieved – demonstration of the first phase space linearization applied to beam. Nevertheless, some work remains to be done getting the whole system more easy to use and improving individual components. The integration of the third harmonic system into the FLASH operation is just in a beginning stage. Experience to date and continued progress will prove useful for future projects as this system serves as a prototype for a similar one planned for the European XFEL [7].

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