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REACHING DESIGN ELECTRON ENERGY AT FLASH AFTER LINAC UPGRADE

V. Ayvazyan*, J. Branlard, C. Christou, K. Honkavaara, V. Katalev, D. Kostin, J. Roensch-Schulenburg, L. Schaper, C. Schmidt, S. Schreiber, M. Wiencek, B. Yildirim
Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

Abstract

The FLASH 2020+ project at DESY includes, among other modernizations, an increase of the electron beam energy. Two accelerator modules were replaced and the RF distribution of other modules was optimized. The limiting factors such as cavity breakdown and field emission were identified and measured through dedicated studies. At a later stage, based on these measurements, adjustments to the high-power distribution were proposed and the optimal operating point was demonstrated to achieve the design electron energy of 1.35 GeV with the nominal RF pulse length at FEL lasing conditions. After proper optimization and tuning of the low-level RF parameters, the linac successfully operated at maximum energy and delivered FEL radiation in the wavelength range below 3.2 nm. The measurement results as well as the achieved cavity gradients with energy gains are presented.

INTRODUCTION

The FLASH [1] linac is based on TESLA superconducting RF technology and is built with accelerating modules (ACC) with eight superconducting RF cavities each. Currently seven ACC's are installed in the linac. In 2022, during the first stage of the FLASH2020+ upgrade project [2], two accelerator modules were replaced and other modules had their RF distribution scheme optimized to increase the beam energy [3, 4]. The modules are powered either by a 5 MW or 10 MW (multi-beam) klystron. The cavities are operating in a pulsed mode. The low-level RF system is used to maintain beam stability. An RF regulation system provides field control for the RF gun and for superconducting modules with the vector-sum group of cavities [5]. RF power is distributed from a high-power klystron to the cavities via a forked set of waveguides. With the vector-sum concept, one klystron powers a set of up to 16 cavities. The synchronism of the incident waves to the cavities is ensured by waveguide tuners in front of each cavity which allows phase adjustment for individual cavities. A frequency tuning mechanism (stepper motor and piezo) is used to operate the cavities on resonance. Each accelerating cavity has one input coupler for RF power and a pickup antenna to measure the cavity field. The probes measure the field directly inside the cavities. The measured fields are digitized and further processed to calculate the vector-sum. After comparison with the set-point, a feedback correction is applied to the klystron drive. Standard operation includes algorithms such as multiple input multiple output-based feedback controller, adaptive feedforward and beam loading compensation.

* valeri.ayvazyan@desy.de

NEW ACCELERATING MODULES IN OPERATION

During the FLASH linac upgrade the two oldest and weakest accelerator modules (ACC2 and ACC3) were replaced by new ones with an adapted waveguide RF power distribution and a new 10 MW klystron to feed 16 cavities. The new modules were installed with a specially tailored waveguide RF power distribution to achieve highest total energy for the new cavity gradient distribution. After installation, both modules were successfully tested with beam at FLASH. The RF station could be operated providing an energy gain up to 465 MeV, with routine operation between 400 and 460 MeV since October 2022. Prior to this replacement, ACC2/3 was operated at a maximum 330 MeV energy gain. Therefore, the two refurbished modules significantly contributed to increasing the maximum FLASH electron beam energy.

Achieved Gradients at ACC2/3

For high energy runs the confirmed operational gradients for ACC2 vary from 26.2 MV/m to 30.8 MV/m. The gradients variation at ACC3 are in a range of 23.3 MV/m to 31.7 MV/m (Fig. 1).

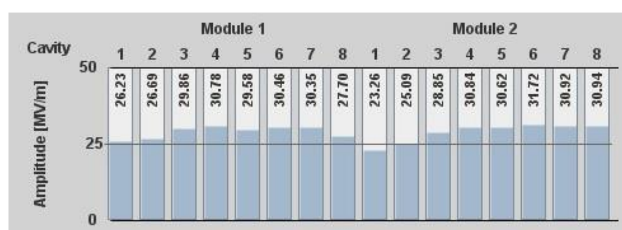

Figure 1: ACC2/3 gradients (peak) at energy 460 MeV. Modules are operated off-crest to allow beam compression.

RF DISTRIBUTION OPTIMIZATION FOR OTHER MODULES

The original RF distribution scheme for ACC4/5 was linear. The klystron output RF power was equally distributed among the cavities. Before the shutdown upgrade, the gradient hard limits (i.e. quench) were measured for each cavity. Figure 2 shows ACC4/5 gradient distribution before shutdown. Based on these measurements, an RF waveguide distribution was tailored and assembled. After start-up of the machine it turned out that the new dominating limiting factor was field emission (gamma radiation) of some cavities in ACC4. The investigations were carried out under nominal RF pulse operation and the maximum operational gradient limit as well as the limiting mechanism of individual cavities were determined. Either

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thermal breakdown (quench) where the maximum operational gradient was set to $E_{acc.oper} = (E_{max}–0.5\ MV/m)$ or field emission where $E_{acc.oper}$ was set so that the neutron and gamma radiation measured at the module ends stays below the threshold of 10^{-2} mGy/min.

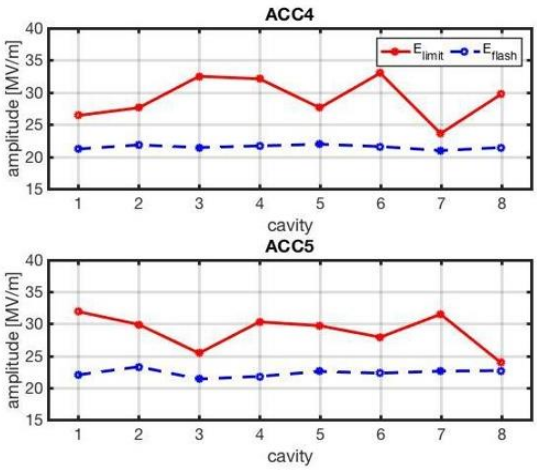

Figure 2: ACC4/5 gradients distribution before upgrade. Blue: operating gradients at max. energy. Red: quench limits.

Radiation Investigation

In order to monitor the gamma radiation coming from ACC4/5 during the field emission investigations, three radiation sensors of type UNIDOS (1 liter / 5 kV chamber) were installed at the beginning, between and at the end of the two cryomodules, as illustrated with red dots in Fig. 3. This was in addition to the permanently installed radiation detector (Pandora F005) located close to the ACC4 module.

Figure 3: An overview of ACC4 and ACC5 cryomodules RF distribution. Red dots are X-ray sensors 1,2,3. The circle shows the position of the inserted attenuator for cavity 5 of ACC4.

The investigation consisted of the following:

- Detune all cavities and ramp up one at a time, observing the radiation level on the UNIDOS.
- Measure the radiation onset level for all field emitting cavities.
- Measure the operational gradient (corresponding to 10^{-2} mGy/min) for all field emitting cavities.
- Measure the radiation level for ACC4 only, and ACC5 only.
- Partially detune the strongest field emitters to assess the maximum gradient achievable within the radiation budget.

The measurement results are shown in Fig. 4.

To optimize the input power distribution of the cavities, a 5.1 dB attenuator was installed between the most problematic cavity (cavity 5 of ACC4) and the isolator. In Fig. 3 the position of the installed attenuator is marked with a red circle. The reduction of power to this limiting cavity allowed increasing the power to the other cavities and thus increasing the total power to the modules. This improvement resulted in a total beam energy gain of about 40 MeV.

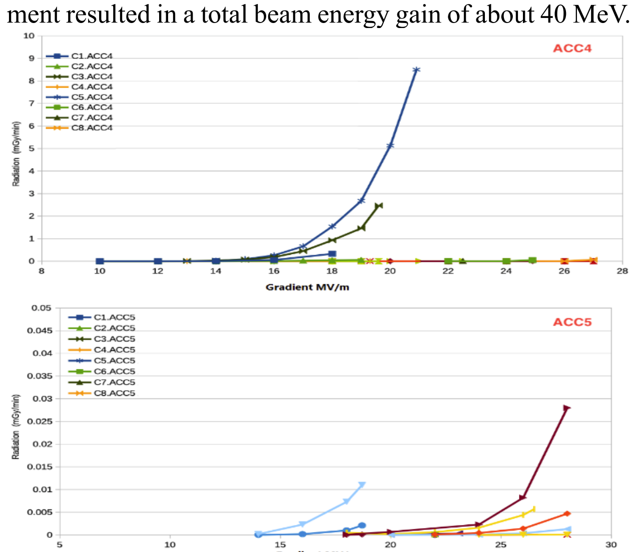

Figure 4: ACC4/5 radiation investigation at high gradient.

The upgrade for ACC6 and ACC7 modules includes the klystron waveguide distribution system and the phase tuning for RF station [4]. The distributions of both modules have already been adjusted in advance in 2019. Figure 5 shows ACC6/7 gradients distribution and quench limits. The RF power for cavity 8 at ACC7 was attenuated (3 dB) due to field emission.

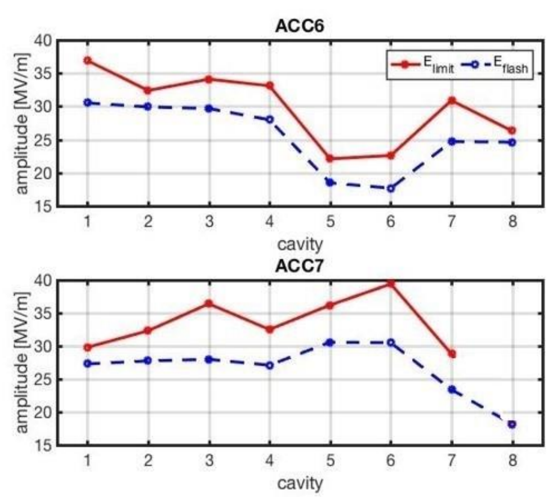

Figure 5: ACC6/7 gradients distribution. Blue: operating gradients at high energy before upgrade, red: quench limits. (RF power for cavity 8 at ACC7 is attenuated).

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Achieved Gradients after Optimization

At high energy runs the confirmed operational gradients for ACC4 vary from 11.7 MV/m to 24.9 MV/m. The gradients variation at ACC5 are in a range of 17.7 MV/m to 26.4 MV/m (Fig. 6, top).

The gradients for ACC6 vary from 19.4 MV/m to 35.0 MV/m. The gradients variation at ACC7 are in a range of 13.0 MV/m to 28.1 MV/m (Fig. 6, bottom).

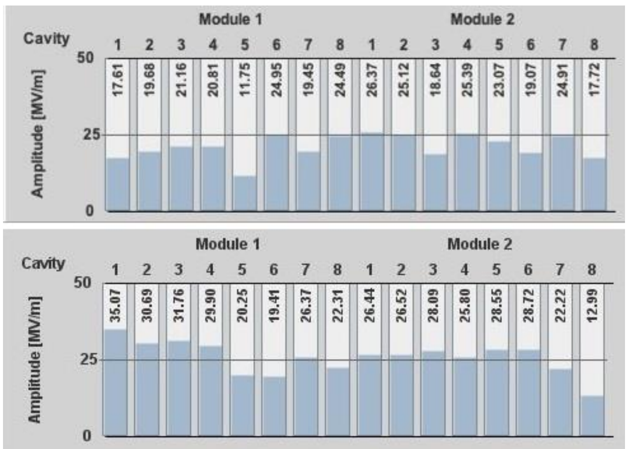

Figure 6: ACC4/5 (top, at energy gain 349.5 MeV) and ACC6/7 (bottom, at energy gain 430 MeV) gradients (peak) after RF distribution optimization.

RF OPERATION PERFORMANCE

The requirements for the in-loop amplitude and phase stability over the flattop is 0.01% and 0.01 deg., respectively [1]. The stability of the accelerating field depends critically on the precision of the calibration of the vector-sum which is based on transient beam loading [6]. Figure 7 shows the amplitude and phase stability reached at the 1.3 GHz RF stations during high energy run. The achieved performance in amplitude and phase is up to a factor of two more stable than required. The presented data was taken during nominal operation with beam (400 bunches, 0.4 nC, 1 MHz spacing). The required RF amplitude and phase stability is continuously and reliably met since the commissioning after the upgrade.

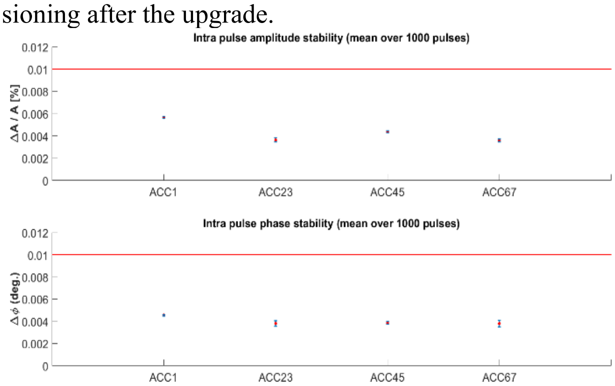

Figure 7: In-loop intra-pulse amplitude (top) and phase (bottom) stability of 1.3 GHz superconducting RF stations averaged over 1000 pulses as of 16th of May 2024. The red line indicates the required stability level.

SUMMARY

Two new installed modules (ACC2/3) were tuned and routinely operated at 460 MeV energy at FLASH. After RF distribution optimization two old modules (ACC4/5) reached at energy gain 350 MeV, with routine operation at ~340 MeV during the last user run. The last two modules (ACC6/7) were tuned to a 430 MeV stable operation point. Further tuning of the low-level RF system parameters and operational procedures optimization like cavity resonance filling, etc. allowed establishing stable FLASH linac operation at the design electron energy with nominal RF pulse length. FLASH reached above 1360 MeV operation (Fig. 8), demonstrating stable operation on both beam lines with 400 bunches at FEL radiation condition. The user operation has improved markedly during the last run in May 2024. The electron beam energy gain was confirmed by measurement at self-amplified spontaneous emission radiation with a high precision photon spectrometer.

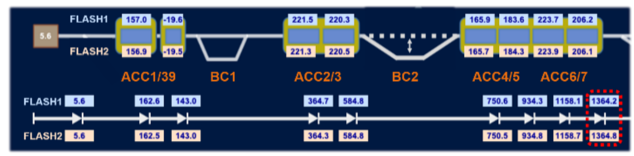

Figure 8: Energy profile along the accelerator calculated from monitoring system. (All values shown are in MeV).

ACKNOWLEDGEMENTS

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