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Report on system test and performance

Grecki, M (DESY)

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Abstract:

The main goal of the update of LLRF at FLASH was to assure the system suitability to the constantly developing needs in the terms of performance and many abilities (reliability, availability, operability, maintainability, extensibility, flexibility).

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	Name	**Partner**	**Date**
Authored by	M.Grecki	DESY	29/05/2013
Edited by	M Grecki	DESY	25/09/2013
Reviewed by	O. Napoly	CEA	09/06/2013
Approved by	J-P.Koutchouk		23/09/2013

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1. EXECUTIVE SUMMARY

The main goal of the update of LLRF at FLASH was to assure the system suitability to the constantly developing needs in the terms of performance and many *abilities (reliability, availability, operability, maintainability, extensibility, flexibility).

When the EuCARD project was negotiated the existing LLRF control system at FLASH was based on DSP processors and it was expected to satisfy user needs for the next 1-2 years but not to fulfill the long term (3-10 years) requirements.

The main fields requiring upgrade was:

- Field regulation (to improve long and short term stabilities by drift compensation and various calibrations)
- Availability (to reduce or eliminate the downtime through built-in diagnostics)
- Maintenance (to reduce the effort and required expertise to maintain the system)
- Operability (to automatize the operators tasks)

All that goals could not be achieved in the old LLRF system based on DSP processors due to many factors (limited signal acquisition performance, no resources available to implement new algorithms required for automation, not modular and not flexible design).

By development and installation of the new LLRF system at FLASH these goals were fulfilled, however still much software has to be developed (especially in the field of self-diagnostic, exception handling and automation). But the new hardware provides the required resources and performance. That was demonstrated during test runs and is currently being commissioned. The first results show the field stabilization is better than 10^{-4}. The supporting software is being developed.

2. INTRODUCTION

FLASH, the world's first soft X-ray free-electron laser is available to the photon science user community for experiments since 2005.

The accelerator is equipped with seven TESLA-type 1.3 GHz superconducting accelerator modules yielding electron beam energy of up to 1.25 GeV. A special 3.9-GHz module is installed to improve the quality of the accelerated electron bunches. In September 2010, the FLASH accelerator team operated the FEL with an electron energy of 1.25 GeV reaching a wavelength of 4.12 nanometres. Currently (05.2013) FLASH is down to extend it with second photon beam line (FLASH2). This was triggered by constantly increasing requests for the beam time. The second photon beam line will allow performing 2 experiments in parallel. It is also planned to build third and next photon beam line in the future.

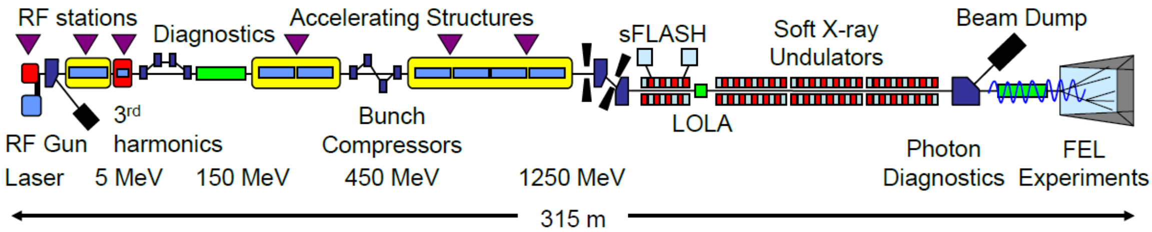

Figure 1 FLASH layout

3. LLRF SYSTEM AT FLASH

FLASH is supplied with RF power by klystrons. There are in total 6 RF stations delivering RF power to the accelerating modules (Figure 1). The LLRF system is responsible for the field regulation (stable amplitude and phase of RF field in cavities in spite of noises and drifts in the system and other disturbances). Some of these disturbances are stable from pulse to pulse (like cavity detuning due to Lorentz force) and can be compensated with feed-forward techniques, some are not correlated to the RF operation (like microphonics, beam fluctuations etc.) and requires feed-back controller. For the purposes of field stabilization and regulation the LLRF system must measure cavity field (both amplitude and phase) and drive a klystron, tune the cavity to RF frequency, distribute reference frequency and realize many LLRF specific applications (e.g. signal conditioning and calibration, exception detection and handling, beam loading compensation, drifts compensation, etc.).

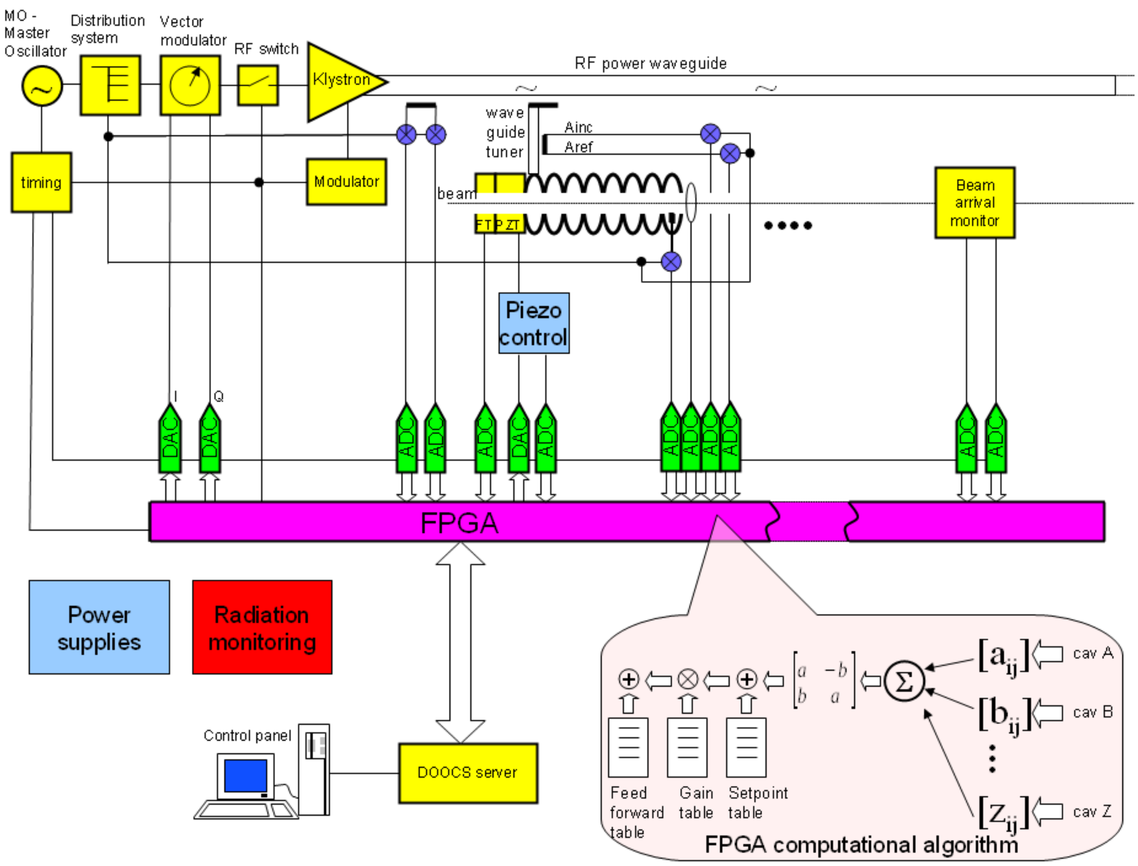

Figure 2 Block diagram of LLRF system and its relation to the accelerator components (simplified picture of single RF station)

The LLRF system at the FLASH (Figure 2) is designed as a closed loop digital control. The state of RF power filling the accelerating cavities is measured by sensors determining electric field, forward power and reflected power signals (RF probe, Ainc, Aref in Figure 2). All of them are RF signals and their digital processing requires downconversion to intermediate frequency signals, preserving information about the amplitude and phase of RF field. The IF (Intermediate Frequency) signals are sampled by ADCs (Analogue to Digital Converters). The signals for each cavity require calibration due to the different cable length, probe and downconverter characteristics. The probe signals from all cavities driven by the same RF power station (klystron) are aggregated creating the vector sum. The current value of vector sum is compared to the setpoint and the error signal is driving a regulator that can be a simple PI controller or much more complex filter. The signal processing is provided by FPGA (Field Programmable Gate Array) realizing control algorithm. Regulator outputs drive the vector modulator through DACs (Digital to Analogue Converter) providing the required input signal to the klystron supplying the accelerating cavities with RF field. The cavities are tuned to the RF frequency (1.3GHz) using slow step-motor tuners. Fast piezo tuners compensate detuning due to Lorentz Force and microphonics measured with piezo sensors through ADCs. The beam loading compensation uses beam signals measured by toroid. The beam-based feedback allows regulating directly beam parameters. This is done through beam arrival time monitoring and feedback loop inside signal processing unit (FPGA). The environment radiation level is measured by radiation monitoring subsystem. Everything is managed through control system (DOOCS – Distributed Object Oriented Control System).

3.1. HISTORY OF DEVELOPMENT

The LLRF control at FLASH was evolving along the time. Initially (until 2009) the LLRF control was realized using DSP technology. Together with arising expectation in term of performance of field regulation, reliability, flexibility, maintainability and operability, it has occurred that conversion to FPGA technology is required. With support of the EuCARD predecessor (CARE project) the SimConDSP boards for VME crates were developed (2006) and later tested in the RF Gun and ACC1. Finally SimConDSP boards were installed at the whole FLASH at 2010. However it was clear that the system would not satisfy user requirements for longer perspective, especially in the terms of reliability, flexibility and performance.

The experience gained with SimConDSP boards has allowed developing a new version of LLRF control using commercial technology coming from telecommunication industry (xTCA) with satisfying performance and reliability.

The demand for high availability (HA), modularity, standardization and long time support favours the choice of the ATCA and uTCA standards with carrier boards and AMC modules. This technology came from telecommunication industry and therefore lacks instrumentation needed for High-Energy Physics experiments.

3.2. DESIGN OF A NEW LLRF SYSTEM

Initially it has been planned to use ATCA crates but later the decision was made to switch to uTCA. The arguments were better suitability of uTCA to small and medium size systems and establishing of MTCA.4 standard especially developed for physics instrumentation.

First version of the system consisted of ATCA crate equipped with CPU, carrier boards, AMC (Advanced Mezzanine Card) modules with timing receiver, ADCs, vector modulator (Figure 3). At back side of the crate the RTM modules with downconverters were installed.

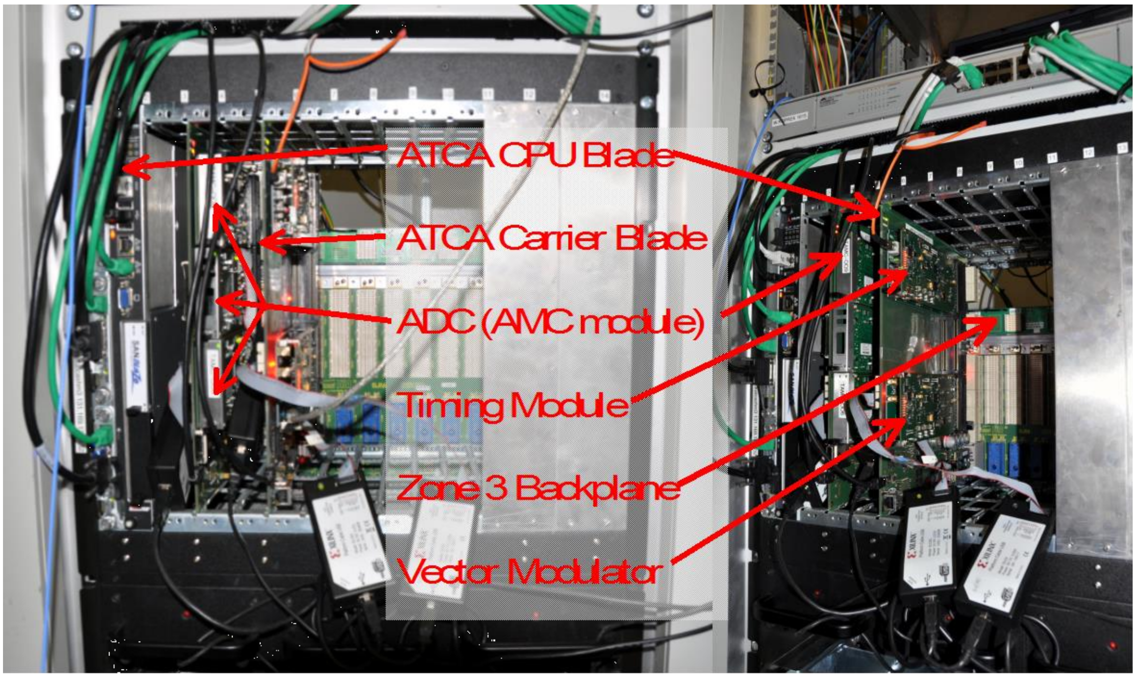

Figure 3 Experimental ATCA based LLRF system.

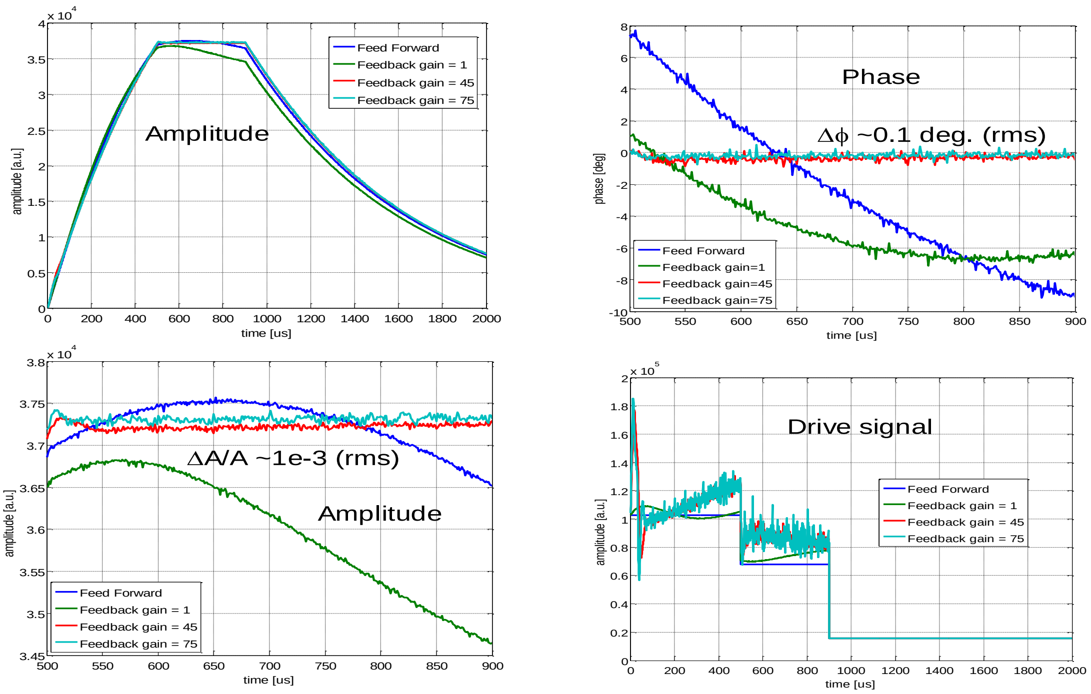

Figure 4 Field stability achieved with ATCA based LLRF system prototype

The results of the field stability achieved with ATCA based system is presented in Figure 4. This was result of very rough tests without system optimization. Anyway it has proved the xTCA based compact system can provide sufficient performance to be implemented at FLASH.

Later the system was converted into uTCA hardware platform. The 12 slots uTCA crate was filled in with electronic boards. The crate layout is presented in Figure 5.

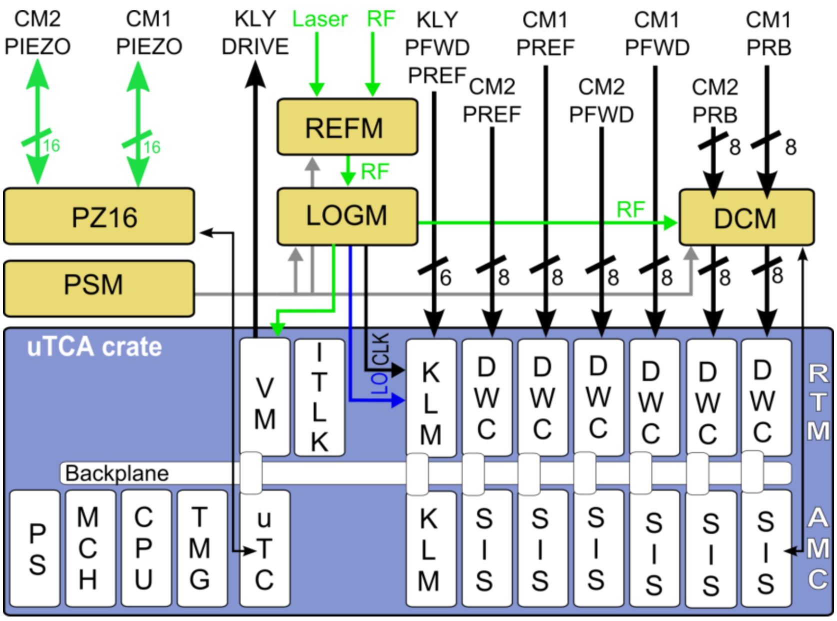

Figure 5 LLRF system - layout of uTCA crate

The boards are placed both at the front (AMC) and back side (RTM - Rear Transition Modules) of the crate. The communication between the boards is provided through backplane. There are 2 kinds of backplanes: one for digital signals and the other to carry RF reference signals, high precision clocks and timing signals. The system consists not only of the uTCA crate but also a few external modules. Due to their properties it was not possible to integrate together with the main part of the system.

The system components are as follows:

- PS – Power Supply (for uTCA crate)
- MCH – MicroTCA Carrier Hub (management unit for uTCA crate)
- CPU – microprocessor board
- TMG – timing AMC module
- uTC – Controller (signal processing unit)
- VM – Vector Modulator
- ITLK – Interlock interface (RTM module)
- KLM – Klystron Management Unit (front and RTM modules)
- SIS – SIS8300 digitizer board (10 channels, 16 bits resolution, 125MHz ADCs board from Struck)
- DWC – downconverters RTM board (10 channels)

The assembled uTCA crate with LLRF system (not all components are placed in) is presented in Figure 6. Not all system components mentioned in Figure 5 were plugged in. The system was used to control ACC1 with single accelerating module so only 3 downconverter/digitizer pairs were needed.

a) *b)*

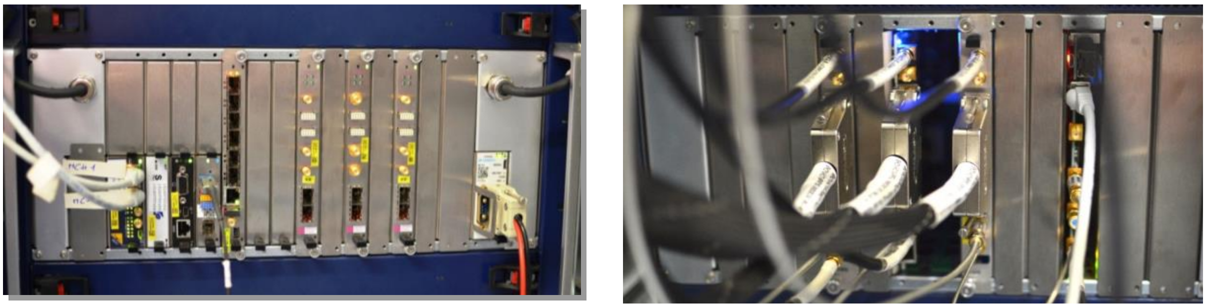

Figure 6 uTCA crate with LLRF system assembled
a) front side b) back side

Figure 7LLRF system installed at FLASH ACC23

The full version of the system was installed at ACC23 RF station inside the FLASH accelerator tunnel (Figure 7 and Figure 8).

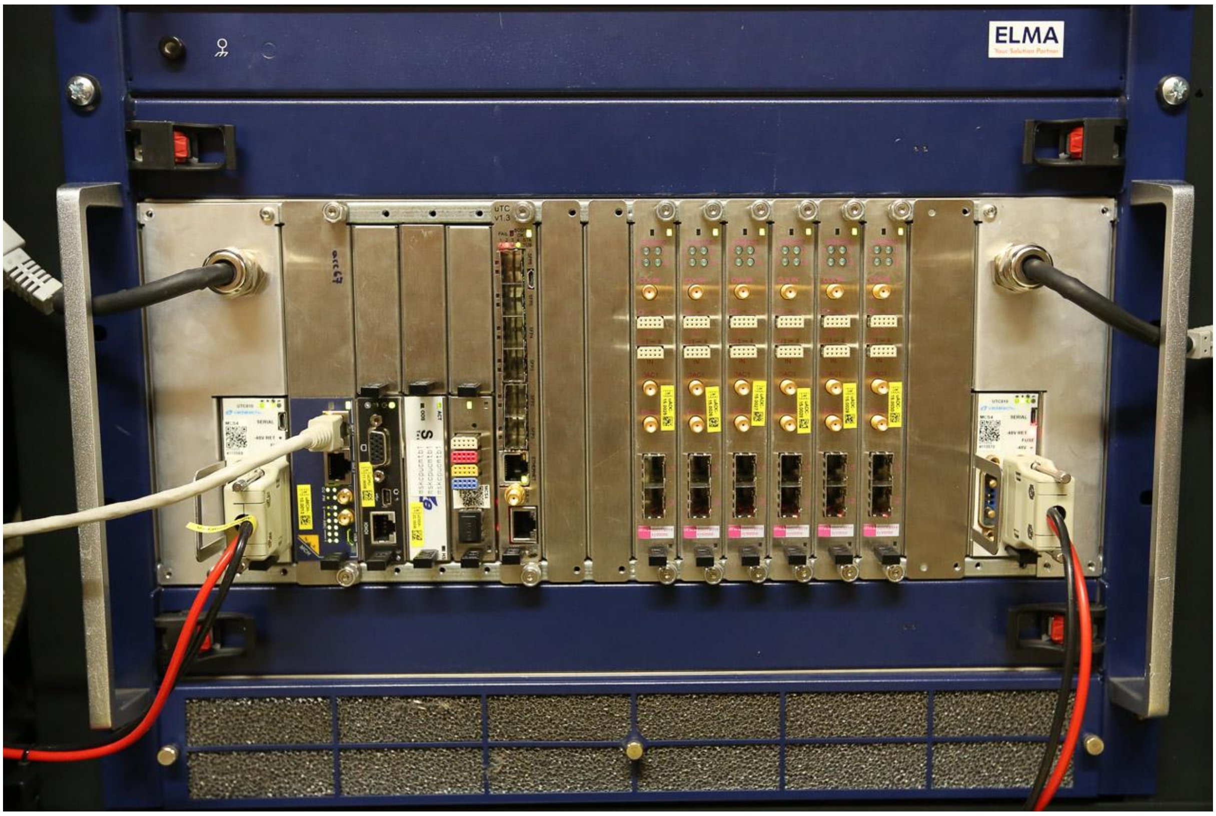

Figure 8 uTCA crate of LLRF system at ACC23

4. RESULTS OF TESTS AND ACHIEVED PERFORMANCE

The system component tests were performed routinely as a last stage of components production and were described in the milestones reports; therefore they will be not repeated here.

Using the installed system several tests have been done to evaluate the system performance and new functionality. However it must be underlined, that due to normal usage of FLASH as a user facility the beam time for LLRF tests was very limited and had to be shared between development and tests of a new system, and normal maintenance of the base system (old VME version). After the long shutdown related to the FLASH2 installation works the more complete and comprehensive tests will be performed. After the machine restart the uTCA system will become the base LLRF system at FLASH (however we are going to keep the old VME system ready to use for some limited time just in case of unforeseen problems).

The tests of uTCA-based system were divided into functional tests and performance tests. Both kinds of tests were successful, however many problems related to the system integration had to be solved during testing.

The best regulation precision achieved with a new system so far was $dA/A<9x10^{-5}$ for amplitude and dPh<0.008 deg. for phase. Certainly precise tuning and system calibration can improve it. However, achieved resolution allows observing influence of single bunches that was not possible with old system (Figure 9 and Figure 10).

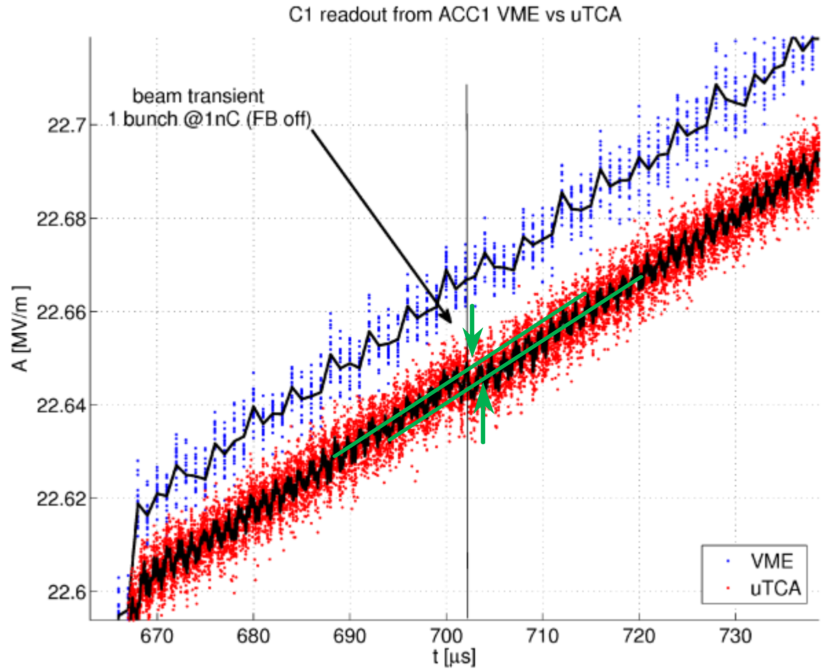

Figure 9 Single beam transient measured by old VME (blue) and uTCA (red) system.

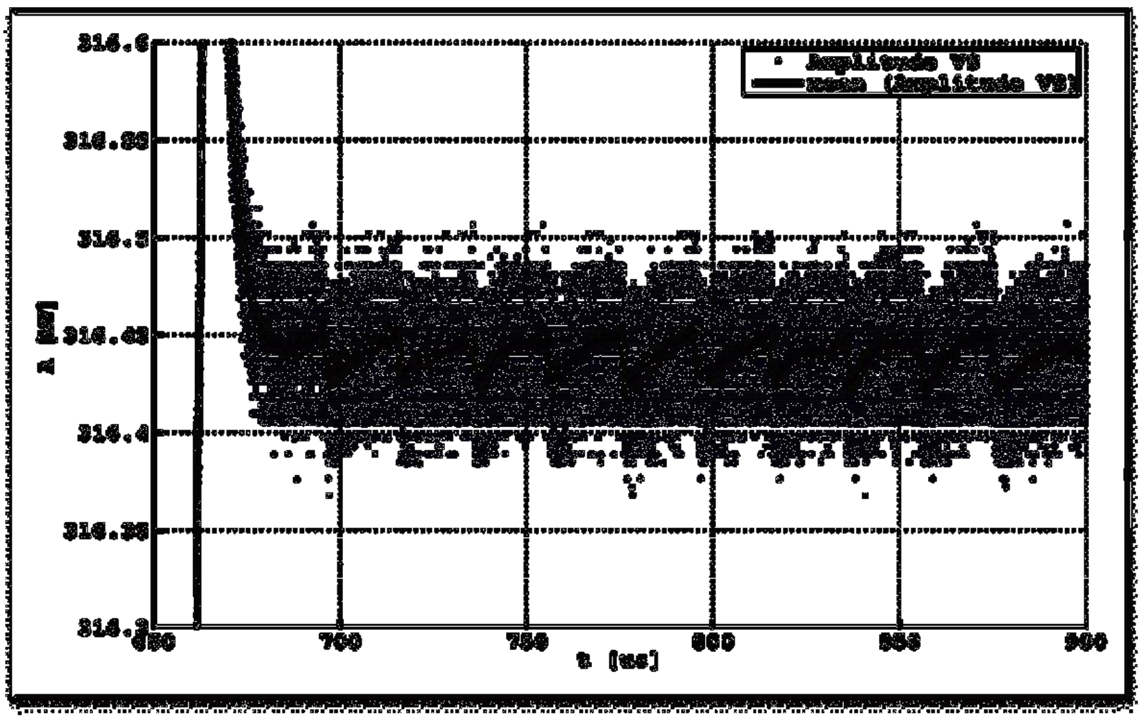

Figure 10 Vector sum regulation performance. There are vector-sum waveforms from many pulses plotted together with average value showing clearly the beam structure (each bunch drained some energy from the field, between bunches the field is recovering due to the RF supply).

a) *b)*

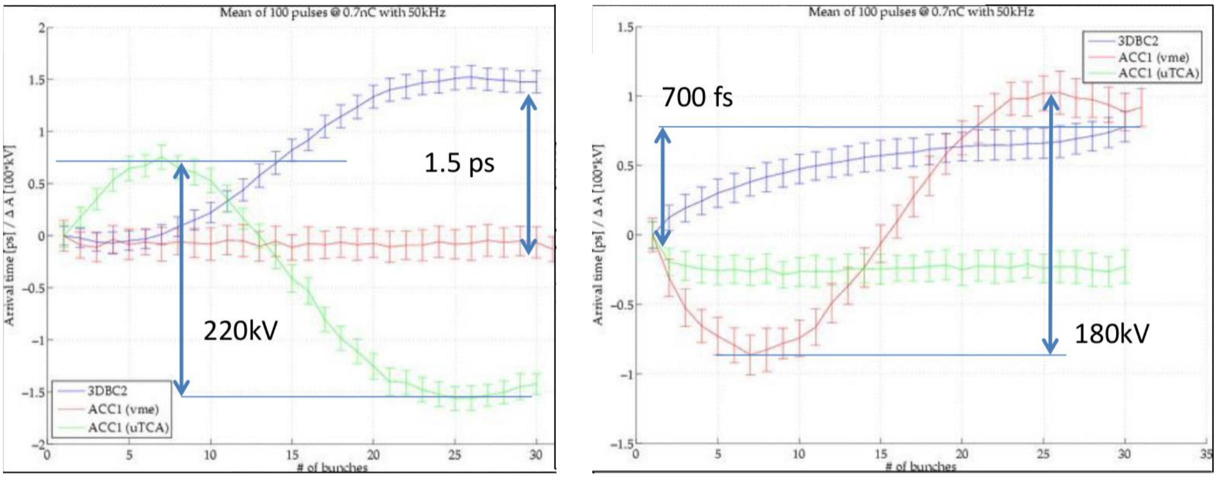

Figure 11 Beam arrival time measurements
a) VME regulation *b) uTCA regulation*

The beam energy stabilization was compared to the old VME based system using beam arrival time monitors after conversion of beam energy into the trajectory and finally into beam arrival time modulation. The initial measurements show the improvement by a factor of 2 (Figure 11).

The new uTCA system allows also to implement many new software application that were impossible to implement in the old system due to limited resources and performance. One of example is investigation of frequency characteristics of the 8/9pi mode of superconducting cavities. The results of these investigations are presented in Figure 12.

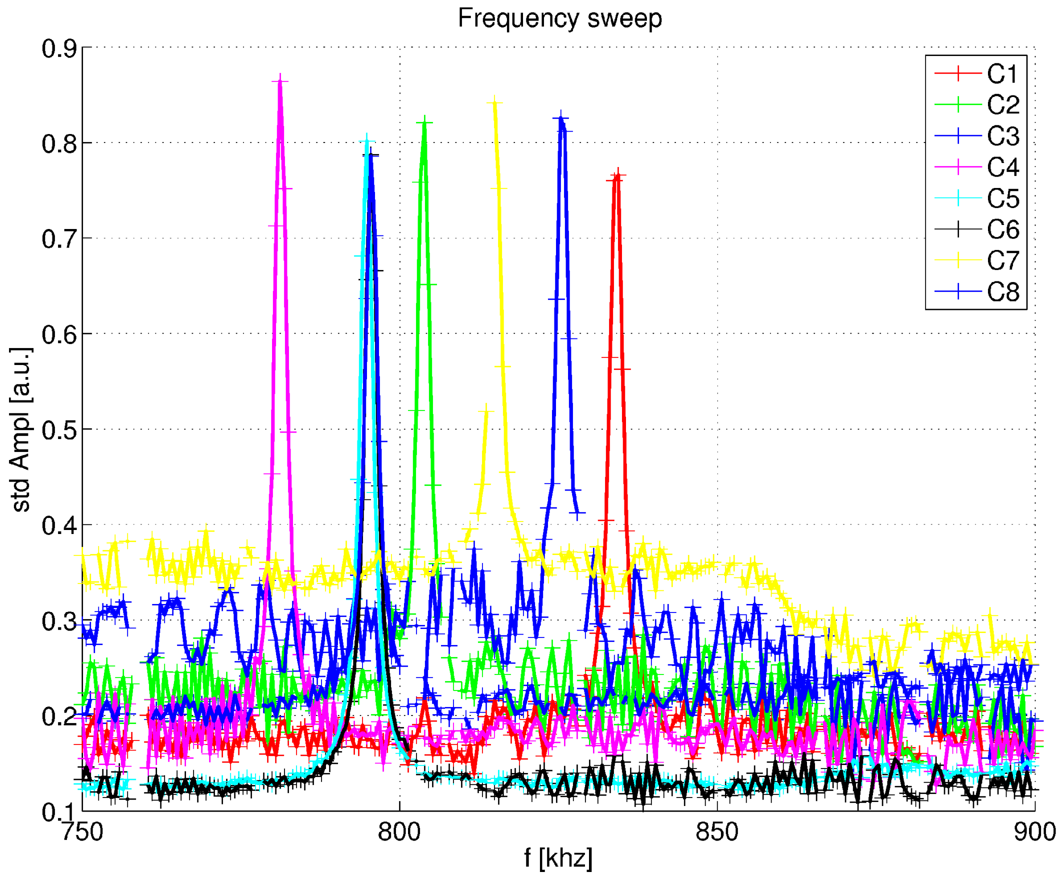

Figure 12 Excitation of the 8/9-Pi mode

Another new functionality implemented in uTCA based LLRF system is filtering of 8/9Pi modes. That helps to achieve stability of the regulation loop. The comparison of stability area for the regulation without and with filter is presented in Figure 13. It is clearly visible the filtering out of 8/9Pi modes significantly extends the stability area in the direction of higher loop gains.

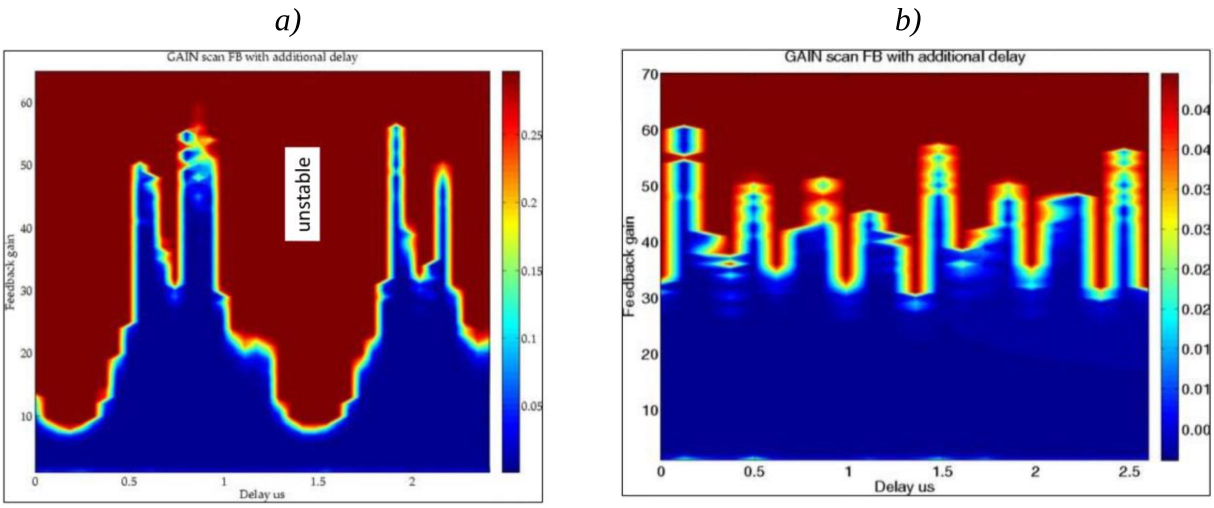

Figure 13 Feedback stability area
a) without 8/9Pi filter b) with 8/9Pi filter

Additional beam based feedback stabilizing the beam arrival time and thus beam energy can be used for further improvements. It allows to reduce the jitter in arrival time of subsequent bunches in the one bunch train (Figure 14), which means that the energy spread within one bunch train was reduced. The first several bunches were not stabilized, due to the latency in the feedback loop.

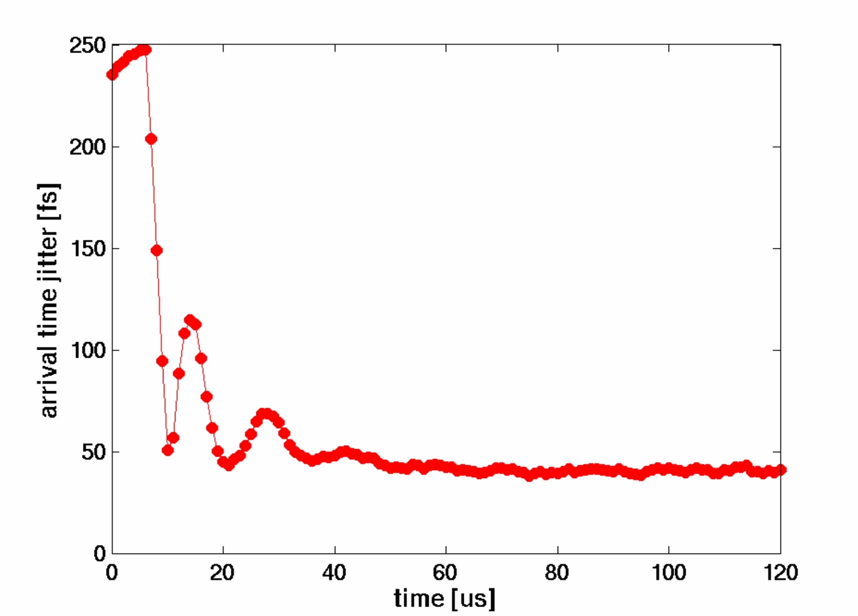

Figure 14 Arrival time jitter in one bunch train

Reduction of energy spread by reduction of the arrival time jitter, has significant influence on generated SASE radiation in the undulator. SASE generated without beam feedback, along the bunch train, is shown in Figure 15. In the best case (yellow color), the radiation in the undulator had the highest intensity in the beginning of the bunch train, and then this intensity decreases in the linear way, that around 150th bunch it is close to zero.

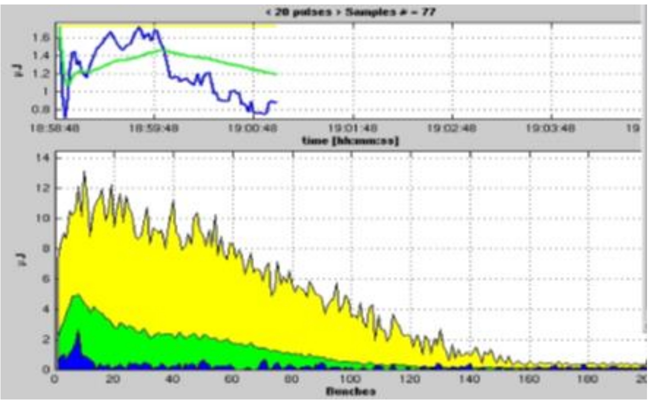

Figure 15 SASE without beam feedback

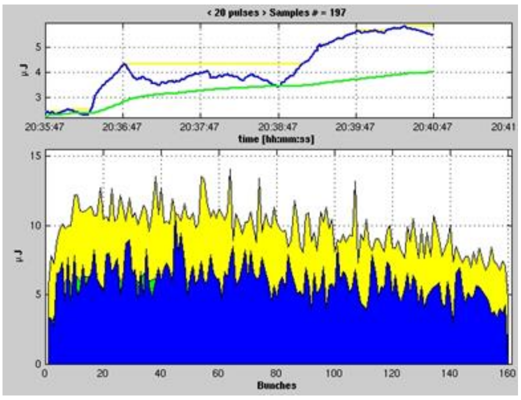

Figure 16 SASE with beam feedback

Usage of designed beam based feedback allows to easily extend the SASE process up 160 bunches.

5. PUBLICATIONS LIST

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