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PLANS FOR THE IMPLEMENTATION OF AN INTRA-PULSE FEEDBACK ON THE FERMI LINAC LLRF SYSTEM

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Abstract

FERMI is a single-pass linac-based FEL user-facility covering the wavelength range from 100 nm (12 eV) to 4 nm (310 eV) and is located next to the third generation synchrotron radiation facility Elettra in Trieste, Italy. The 1.5 GeV S-band linac is composed of fifteen 3 GHz 45 MW peak RF power plants powering the gun, sixteen accelerating sections and the RF deflectors. The requirements on beam quality impose tight specifications on the stability of the electromagnetic fields that can be achieved only installing high reliable and high performance state of the art LLRF systems. While these requirements are presently met by the system installed, the on-going upgrade of the processing board with the final one will allow to add new functionalities of the system. One of the possible developments is the implementation of an intra-pulse feedback that will allow to apply the corrections inside the RF pulse. This paper provides an overview of the additional benefits that could be achieved and discusses the requirements and the constraints for the implementation in the machine.

FERMI S-BAND LINAC RF SYSTEM OVERVIEW

FERMI is a FEL facility based on a warm linac followed by a single pass FEL. Two FEL lines are installed: FEL-1 and FEL-2.

The S-band warm linac [1] is presently composed of sixteen accelerating sections. The first nine sections are forward traveling wave (TW) ones, either 3 m or 4.5 m long. The last seven sections of the machine are 6.2 m long backward traveling wave (BTW), equipped with SLED systems. Two more accelerating sections will be added in the near future.

Fourteen S-band 45 MW, 4.5 µs. pulsed klystrons are installed plus an additional hot-spare one, powering the sections, the gun and the three RF diagnostic deflectors. Typical powering scheme is two sections per klystron for the TW case and one section per klystron for the BTW one. The system is in operation on a 24h/day basis and the total operating hours/year is higher than 6000.

LLRF SYSTEM OVERVIEW

FEL generation requires very high beam stability. For the S-band RF system this translates in a requirement for a stability in RF phase and amplitude within 0.1° rms and 0.1% rms respectively. In addition to a careful design of all the parts of the system, from modulators supplies to cables and waveguides temperature stabilization, meeting these targets requires a high performing LLRF system. The LLRF system measures the RF signals, and, according to the requirements and taking into account the beam feedbacks, controls the RF drive to the klystron. The system implemented in FERMI is an all-digital system [2] specifically designed in collaboration with Lawrence Berkeley National Laboratory.

Hardware

The basic hardware block of the LLRF is the LLRF chassis [3], see Fig. 1. This chassis includes mainly the RF front end, the processing board (AD board), the OCXO and all power supplies (see Fig. 2). The front end performs conversion between RF (3 GHz) an IF (99 MHz) and hosts all the frequency dependent components. The AD board, which hosts a Virtex5 FPGA, performs all controls, diagnostics and system communication. One LLRF chassis for each section is foreseen. In the case of one klystron powering two sections one chassis acts as the master, while the second one is used mainly to extend the number of measuring channels. At the present time all the master chassis have been installed, while the installation of the other chassis will be completed this autumn. All the components of the LLRF systems are installed in a shielded rack, temperature stabilised within ± 0.1 °C. Special care has been dedicated to all the RF cables and connections to ensure high reliability and stability.

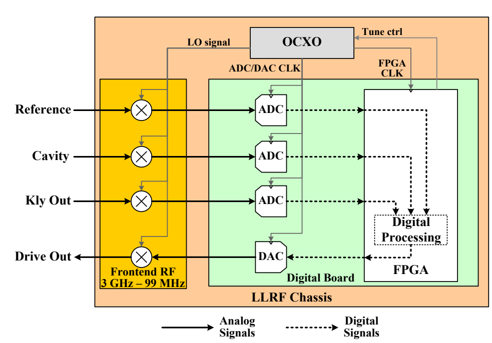

Figure 1: Internal chassis outline.

Firmware

The firmware presently in operation [4] implements all the basic loops needed: amplitude, phase, cable calibration, local oscillator phase drift and phase reference locking loops. All these are feed-forward loops. In addition, the control of the SLED phase reversal and phase modulation is also performed with the LLRF firmware. The present feedbacks are inter-pulse feedbacks and correct the RF drive to the klystron between pulses.

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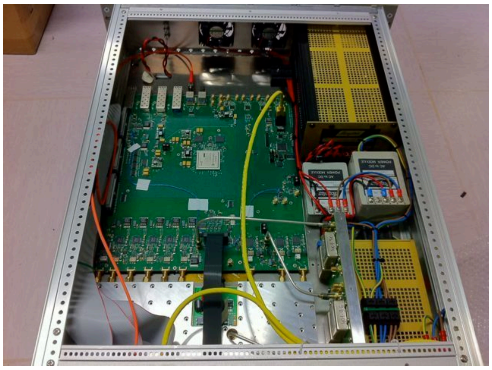

Figure 2: LLRF chassis.

Operational Results

The requirements of stability for machine operation are met [5]. Phase and amplitude stability is increased by means of the cable calibration loop that eventually compensates changes of the electrical length of the cables between the LLRF chassis in the service gallery and the sections in the linac tunnel. The measurements on the machine show that amplitude stability is around 0.030 %, while phase stability is around 0.046°.

MOTIVATION FOR AN INTRA-PULSE FEEDBACK

The present feedbacks are inter-pulse feedbacks and correct the RF drive to the klystron between pulses. This compensates mainly drifts in phase and amplitude, but does not correct random jitter contributions. Although the present stability and accuracy of the S-band RF system is adequate for the operation of the machine and satisfies the design requirements, possible future needs to push stability and accuracy to higher limits could require more stringent limits on jitters tolerances.

Random jitter contributions can be related to different reasons. One of the leading factors is caused by modulator instabilities, which can be related to the HV power supply or the pfn charging. Another important effects can be due to thyratrons, which trigger the line type modulators, especially since performance deterioration has been observed with aging of the tube. Contribution to the jitter can also be related to RF instabilities in the high power RF system, for example correlated to arcing or multipactoring.

These jitter contributions should be corrected by an intra-pulse feedback, where the information at beginning of the pulse is acquired and the correction applied inside the same pulse before the arrival of the beam. Therefore, while the inter-pulse feedback is adequate to correct drifts, an intra-pulse feedback can complement this feature adding the correction for shot to shot random instabilities that produce jitter in the beam acceleration.

TECHNICAL ANALYSIS

An intra-pulse feedback should measure, calculate and apply the correction within the RF pulse. This implementation requires high performance capabilities on the processing hardware that have been considered for the design of the system. A fundamental issue to be taken into account for an intra-pulse feedback is the latency time (see Fig. 3), which is depending on different contribution, such as the section filling time, the digital acquisition time and the digital processing time.

The main contributor to the latency times is the section filling time. In FERMI we have three types of S-band accelerating sections with filling times from 0.8 to 1.5 µsec. Since the RF pulses width is 4 µsec, it will not be efficient to include the section in the loop. It must be noted that this assumption is based on the consideration that waveguides and sections are not active components and any drift is related mainly to thermal issues and therefore are slow and already corrected by the inter-pulse or other slow feedbacks. Therefore a sample of the RF field at the output of the klystron will be acquired. In addition to eliminating the contribution of the section filling time this has also the advantage of having a minor contribution from shorter cables.

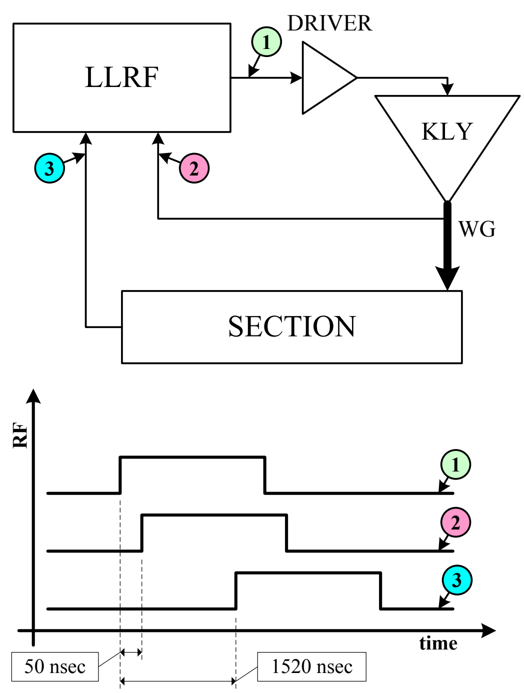

Figure 3: Layout (upper) and signal delays (lower).

Due to the high acquisition accuracy of the LLRF AD board (0.017°, 0.029 %), there is no need of averaging so we do not expect problems due to the digital acquisition time. The AD board features low latency ADCs, high FPGA clock frequency and double data rate DACs, so also the digital processing time issue should be very much under control.

Finally, the measurements taken on FERMI show that the phase and amplitude trend of the RF pulse can be considered constant between pulses. This leads to the conclusion that single amplitude and phase correction can be used within pulse.

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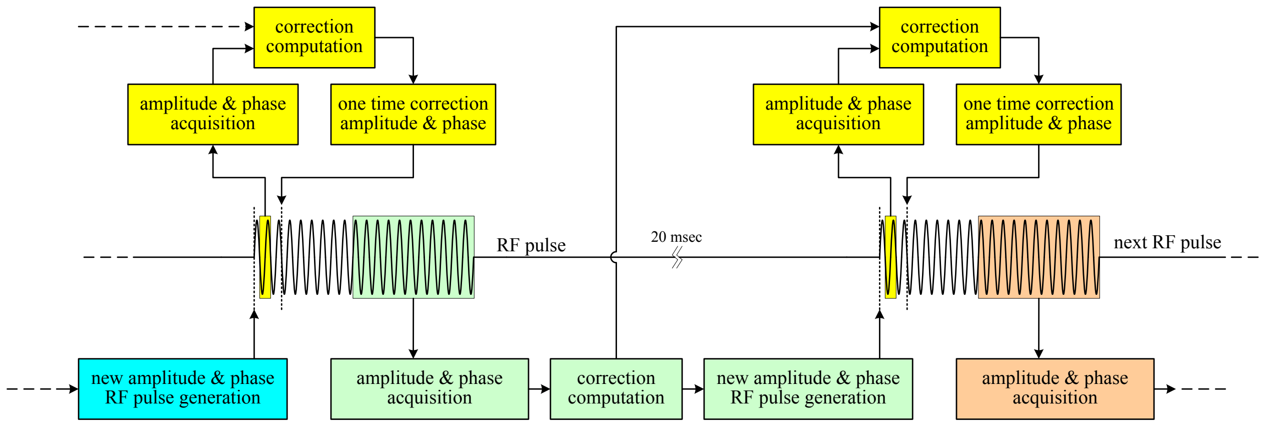

Figure 4: Scheme of principle of integration of inter and intra pulse feedbacks.

INTER AND INTRA-PULSE FEEDBACK INTEGRATION

The development of an intra-pulse feedback and its integration in the existing LLRF firmware will be based on the analysis of the different time constants involved, so there will not be interaction between the two algorithms and the operation of the two feedbacks will be decoupled. Figure 4 shows the scheme of principle of the integration between the two feedbacks. Intra-pulse calculations and corrections will be executed based on the klystron output measurements taken at the pulse beginning, while the inter-pulse feedback calculation will be based on the measurement of the section field made in the second part of the pulse, after the correction from the intra-pulse feedback has been applied. In this way both transient and repetitive error contributions, as well as drifts, should be compensated. Of course the intervention thresholds should be determined to avoid risks of loop instabilities.

FUTURE FIRMWARE DEVELOPMENTS PLANS

The present schedule of the activities on the FERMI LLRF is concentrated on the completion of the installation of the hardware and on the optimization of the existing firmware to fully exploit the capabilities of the system, also in connection with aspects like reproducibility, operability and maintainability. The installation of the second chassis on the plants where a klystron powers two sections will also allow to extend the number of measurements channels opening the possibility of further diagnostics of the operation. Development of firmware for the intra-pulse feedback is expected to start by the end of the present year. In the meantime, measurements on the RF plants are being performed to fully characterize all the parameters that could influence the implementation. Other aspect that will be evaluated is the implementation of the feedback in the case of the SLED equipped sections.

CONCLUSIONS

The specifications on phase and amplitude stability of the FERMI linac put stringent requirements on the LLRF control hardware and firmware, both in terms of performance results and operability. Design specifications on phase and amplitude stability are met with the FERMI LLRF now on and running. Developments are planned in the next months to extend the capability of the LLRF system with the implementation of an intra-pulse feedback thus pushing stability and accuracy to higher limits in parallel with the continuous efforts on the reliability and capabilities extension of the system.

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