ANALYSIS OF DESY-FLASH LLRF MEASUREMENTS FOR THE ILC HEAVY BEAM LOADING TEST

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Abstract

In September 2008 the DESY-FLASH accelerator was run with up to 550, 3 nano-coulomb bunches at 5 Hz repetition rate. This test is part of a longer-term study aimed at validating ILC parameters by operation as close as possible to ILC beam currents and RF gradients. The present paper reports on the analysis that has been done in order to understand the RF control system performance during this test. Actual klystron power requirements and beam stability are evaluated with heavy beam loading conditions. Results include suggested improvements for upcoming tests in 2009.

INTRODUCTION

The DESY-FLASH electron beam accelerator [1] is today the best facility in the world to carry out the ILC experiment defined above. FLASH has 48 niobium superconducting RF cavities grouped in 8 cavities per cryomodule, with a technology similar to the one proposed for the ILC (Fig. 1). The last of the 3 FLASH RF units includes 3 cryomodules averaging over 20MV/m. The main objectives of the ILC 9mA studies are vast. They include among others:

- The operation of FLASH at the maximum RF gradients allowed.
- A demonstration of beam energy stability better than 0.1% with a long pulse and full beam loading over an extended period.
- Identification of gradient limits and a study of cavity quenches.
- Quantification of the minimum RF power overhead required for LLRF control.
- Machine protection faults and exception handling.
- Beam losses.
- Loss free beam transmission. (i.e. The LLRF system must support low beam loss during start-up).

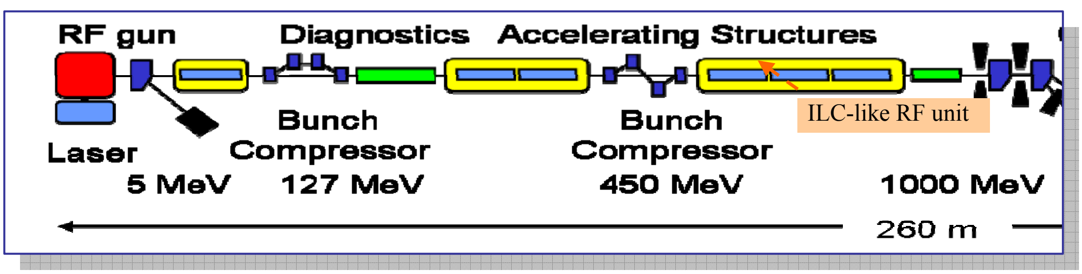

Figure 1: FLASH block diagram.

The ILC LLRF team for this experiment counts on the collaboration of LLRF groups from DESY, FNAL, KEK, SACLAY, ANL, and SLAC. During the two runs of September 2008 and January 2009 good progress has been made in preparation for the major two week test coming in September 2009 [2-3]. Much has been learned about running with long pulses and higher beam loading [3]. The experience confirms that this is a difficult test that pushes FLASH to limits it has not been pushed before. In particular the LLRF has observed and dealt with heavy beam loading, microphonics, Lorentz force detuning (LFD), RF power limits, machine trips and the limits of some LLRF equipment that have been in operation for over 10 years and are in the path to be upgraded.

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HEAVY BEAM LOADING TEST

In September 2008 FLASH was run with up to 550 3nC bunches at 1 μs bunch spacing.

Figure 2 shows the energy measured by the spectrometer at the dump. Despite of some transient behavior at the beginning and the end of the train, which are analyzed next, a very good performance was achieved.

Figure 3 shows that the total gradient during the test was 847 MeV; with average gradients close to 20 MeV/m in 5 out of 6 cryomodules. However, pushing gradients close to the limit was not part of the heavy beam loading part of the test.

Figure 4 provides more detail on the last 10 minutes of operation when the number of bunches was being increased. It can be observed that about 5% of the bunch trains are terminated early by the machine protection system, which cause some problems to the LLRF systems as will be detailed below. Also, the increase in number of bunches is not monotonic due to reports of an increase in beam losses, when the beam loading was lowered and the optics readjusted. At that point increased beam losses caused a leakage due to thermal stress at the dump and the heavy beam loading test was aborted prematurely.

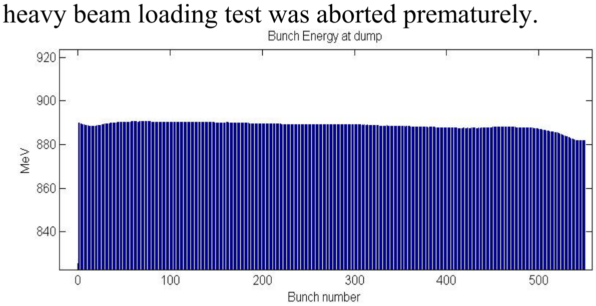

Figure 2: Energy measured by the spectrometer at the dump.

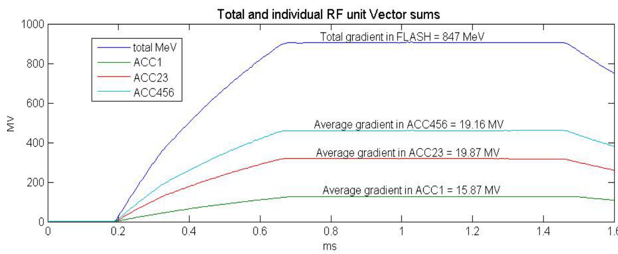

Figure 3: FLASH total gradient.

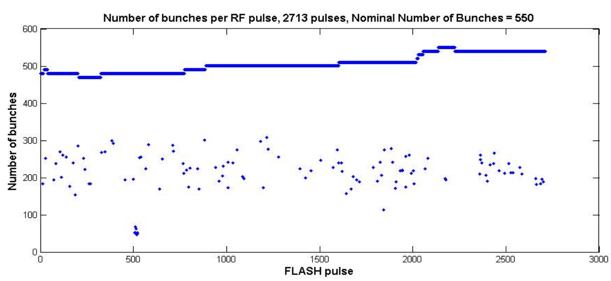

Figure 4: Number of bunches vs. time.

BEAM ENERGY STUDIES

A study of 2713 pulses at 5 Hz rate shows a peak energy stability ΔE/E=0.7% (Fig. 5). There is a high degree of correlation between the mean energy error and the number of bunches in the pulse train. Longer bunch trains have a larger energy dispersion, however as shown in Fig. 6 the 1st part of a long bunch train (i.e. about 300 bunches) is uncorrelated and has a mean ΔE/E~0.2%. This may be indicative of less stable RF fields when the beam loading is heavier.

LLRF PERFORMANCE

The LLRF system proved to be very adaptable to the large changes in operating conditions for the test. Quick generation of Matlab scripts and comprehensive DAQ allowed for timely adaptation for the study and for the post analysis. Figure 7 shows the amplitudes of the total FLASH gradient for 2713 over imposed pulses. There are some relevant features in this plot. There are 2 transients one at the beginning of the beam injection and the other one at the end of the beam loading compensation which may be responsible for the energy transients seen in Fig. 2. The first transient is due to not optimized feedforward compensation in cavities and couplers, combined with a relatively low LLRF feedback gain of 20. Perfectly coupling RF is a difficult task for superconducting cavities with very high Qs and subject to numerous disturbances and detuning. A higher RF closed loop gain is desired and one of the goals for the upcoming test of September 2009. As said before, about 5% of the RF pulses are cut short by machine protection trips. Since the LLRF does not receive beam current information the trips cause a gradient disturbance in part attenuated by the closed loop gain. The 2nd transient in Fig. 7 is due to imperfect synchronization between the end of the beam pulse and the start of the beam loading compensation. This transient could also be smooth out by incorporating real-time beam loading information into the LLRF.

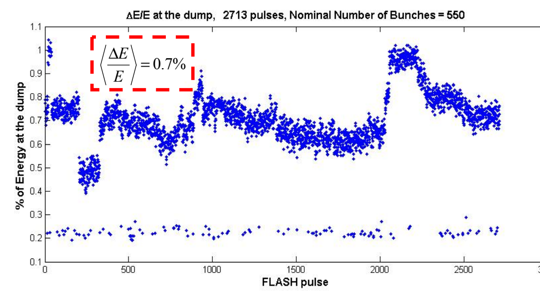

Figure 5: Peak energy stability ΔE/E.

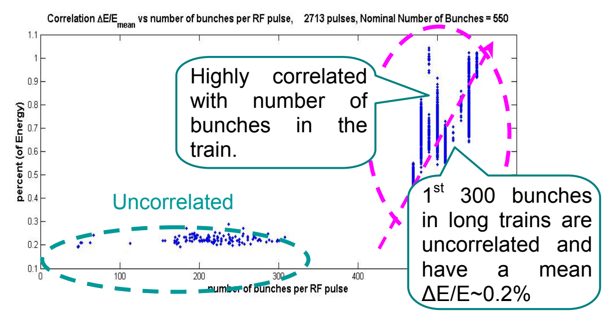

Figure 6: ΔE/E vs. bunch train length correlation.

It is also noticed that there are inconsistencies between energy and gradient fluctuations during the beam pulse (Fig. 8). The possible reasons for that may be imperfect vector sum calibration or bunch to bunch energy spread. More data analysis and calibration algorithms are being proposed to minimize this issues for the upcoming test.

CAVITY QUENCHES

In January 2009 cavity quenches were studied as part of testing gradient and power limits in preparation for the high voltage and heavy beam loading test of September 2009. Figure 9 shows cavity 1 in cryomodule 2 quenching at about 17 MeV.Vector sum setpoints were increased for ACC23 initially and subsequently for ACC456 until a cavity quenched. That cavity was then detuned and the setpoint increased further until the next cavity quenched, and so on. Table 1 shows the first few cavities that quenched in the order they quenched. The gradients at which they quenched agree quite well with the E_{max} values from the cavity database.

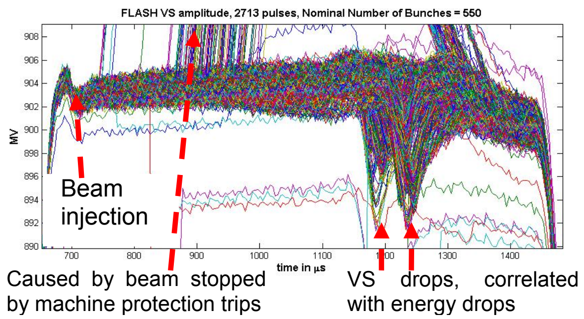

Figure 7: Amplitudes of FLASH gradient for 2713 over imposed pulses.

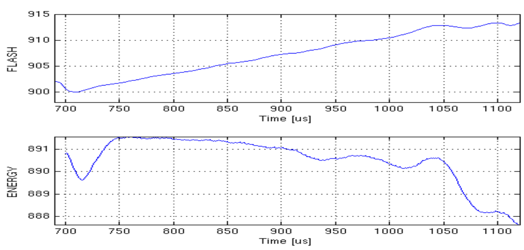

Figure 8: Total FLASH field and energy.

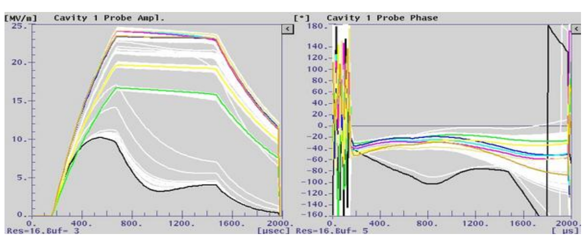

Figure 9: Cavity quench.

Table 1: First Five Cavities in ACC23 that Quenched

Cavity	Quenched at: (MV/m)	Ecav max: (MV/m)
ACC2 C1	~22	22
ACC2 C3	~24.5	25
ACC2 C7	~25.5	25
ACC2 C8	~25.5	24
ACC3 C6	~26	26

FEEDBACK GAIN

LLRF control relies on a combination of feed-forward and feedback. RF units ACC23 and ACC456 are normally operated at a closed loop gain of 20, limited by the group delay in the loop. The group delay of about 7 µ is due to slow hardware technology and will be upgraded for the upcoming September 09 test.

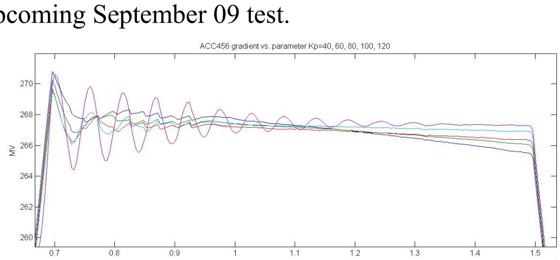

Figure 10: Total FLASH field as a function of the feedback control proportional gain.

Figure 10 shows the effects of increasing the feedback gain from 20 up to 120. As expected, a higher gain is able to reduce disturbances such as LFD at the end of the RF pulse but makes the system less stable, creating oscillations at the beginning of the pulse. The field oscillations are translated to the beam energy.

LF DETUNING COMPENSATION

Piezoelectric tuners are installed in all 16 cavities of cryomodules 5 and 6. DESY has done extensive R&D in SCRF resonant frequency control [ref]. Piezoelectric tuners were successfully tested in January 2009. Figure 11 shows how a feed-forward control algorithm compensates the LFD in Module 6, Cavity 3 at 35 MV/m from 600 Hz down to 30 Hz. In September 09 when FLASH is operated close to quenching gradients and full beam loading the piezoelectric tuner control will play an essential roll since cavity detuning translates into higher klystron power requirements.

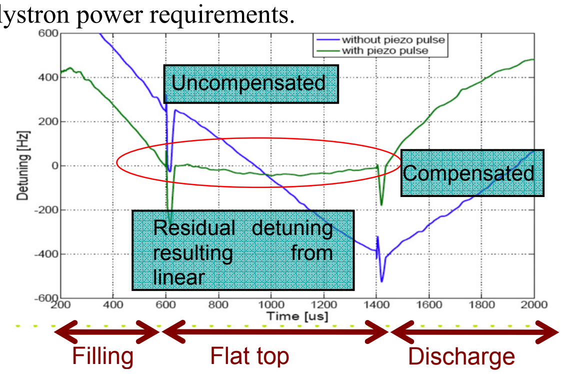

Figure 11: Resonant frequency control using piezoelectric actuators.

LLRF UPGRADES

Excellent LLRF performance is essential to achieve the ILC 9 mA experiment objectives. Henceforth, there is a plan to upgrade the old LLRF systems of the last two RF units (i.e. cryomodules 2 to 6) with new LLRF controllers and down-converters by September 2009. The controllers have already been developed by DESY and one is currently in operation in the 1st cryomodule. The new down-converters will operate at a higher IF frequency, decreasing group delay and removing spurious responses in the receiver. This migration path will allow us to operate the LLRF systems with a higher feedback gain with good stability margins. The LLRF upgrade will be completed with refined calibration procedures such us feed-forward compensations and vector-sum calibration.

REFERENCES

[1] http://flash.desy.de
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[3] S.L. Pei, et al, "Data Analysis of LLRF Measurement with Beam at FLASH," these proceedings.
[4] `Dynamic Lorentz Force Compensation with a Fast Piezoelectric Tuner', M. Liepe, W.D.-Moeller, S.N. Simrock, PAC 2001.