OPERATION OF THE FLASH LINAC WITH LONG BUNCH TRAINS AND HIGH AVERAGE CURRENT*

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Abstract

XFEL and ILC both intend to accelerate long beam pulses of a few thousand bunches and high average current, and it is expected that the superconducting accelerating cavities will eventually be operated close to their respective gradient limits as they are pushed to higher-energies. Additionally, a relative energy stability of $<10^{-4}$ must be maintained across all bunches. These parameters will ultimately push the limits of several sub-systems including low-level RF control, which must properly compensate for the heavy beam loading while avoiding problems from running the cavities close to their quench limits. An international collaboration led by DESY has begun a program of study to demonstrate such ILC-like conditions at FLASH, which serves as a prototype for both XFEL and ILC. This paper describes the program and reports on recent results.

INTRODUCTION

An important goal of the ILC Technical Design Phase is to demonstrate routine operation of a string of L-band superconducting cavities with full beam loading and at high gradients [1]. The ILC reference design uses a string of 26 cavities housed in three cryomodules fed from a single 10MW klystron and regulated using vector-sum control [2]. The reference operating gradient is 31.5MV/m averaged over the string. A program dubbed the '9mA' study is underway at the TTF/FLASH facility at DESY, which currently is the only operating electron linac capable of running ILC-like conditions.

The FLASH Accelerator

The layout of the FLASH linac is shown in Fig. 1. There are 48 L-band superconducting RF cavities housed in 6 cryomodules and powered from three high-power klystrons. The linac is designed to run bunch trains up to 800ms long, with an average current of 9mA and energy greater than 1GeV. Bunches are generated by a photocathode RF gun. Bunches from the linac are transported from the linac to the beam dump either through an undulator line for FEL operation or through a bypass transport line, the latter being used for the 9mA studies. Table 1 shows the beam parameters for the 9mA study alongside equivalent parameters for FLASH design and the DESY XFEL.

Table 1: Comparison of Machine Parameters

		9mA study	FLASH design	ILC	XFEL
Bunch charge	nC	3	1	3.2	1
Bunches		2400	7200	2625	3250
Pulse length	µs	800	800	800	650
Average current	mA	9	9	9	5

Particularly relevant to the ILC program are the last three cryomodules, ACC4/5/6, which are powered from a single 10MW klystron, a configuration that closely models the reference design RF unit in the ILC linacs.

Two previous accelerator study programs at TTF/FLASH are relevant to the 9mA studies. In 2000, TTF demonstrated 800µs-long bunch trains and 8mA average current through a string of 16 cavities in two cryomodules [3]. In 2007, TFF/FLASH demonstrated lasing of 800µs-long bunch trains with the present linac configuration at low average current [4]. Experience from this more recent study has been invaluable. Routine operation is with much lower beam powers, where there are typically 1-100 bunches and 1nC/bunch or less with a bunch-to-bunch distance between 1µs and 10µs.

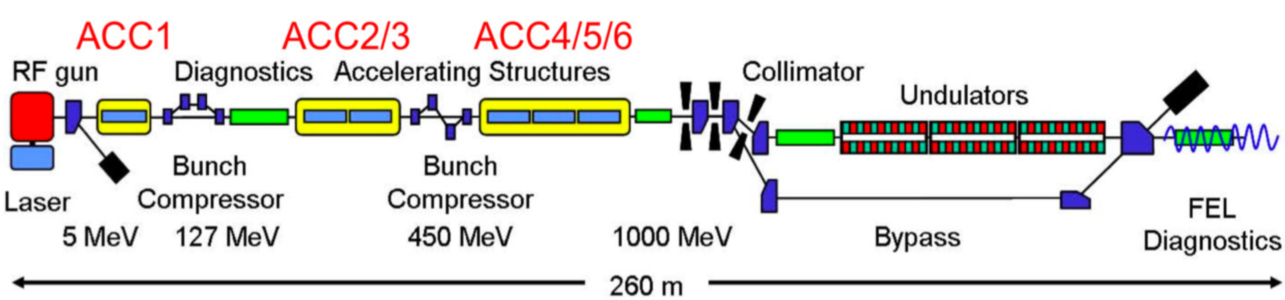

Figure 1: Layout of the FLASH linac.

PROGRAM GOALS

Specific goals of the 9mA studies are:

- Demonstration of 0.1% bunch-to-bunch beam energy uniformity and pulse-to-pulse energy stability over long bunch trains and with full beam loading.
- Characterization of issues which limit operation at high gradients and close to cavity quench.
- Quantification of klystron RF power overhead required for LLRF control.
- Study HOM absorber cryogenic loads.

Technically, the greatest challenge is considered to be achieving the required energy stability over all bunches in a train and over all bunch-trains, with fully beam-loaded cavities and at cavity gradient limits. Obtaining metrics on the performance trade-offs is a part of the study.

The 9mA Study in Context

These 'operation at limits' studies provide important input for the European XFEL development work and for planning future commissioning and operations. The studies are also a test bench for automation of RF system tuning and control, which will be an essential part of XFEL and ILC operation.

Several other in-construction or proposed superconducting linacs, either proposed or in construction, will also operate with long bunch-trains, high average currents, and high cavity gradients. They include STF at KEK, NML and Project-X at Fermilab. These projects will similarly benefit from the 9mA studies experience.

Benefits to FLASH come from necessary operational improvements, the additional focus on characterizing the machine, and from the accelerated progress towards routine high power long-pulse operation that will eventually be needed by the photon users.

Cavity Gradients at FLASH

Figure 2 shows gradient limits for the currently installed cavities. Average operating gradients of the FLASH cavities are below the 31.5MV/m of the ILC reference design. Nevertheless, much can be learnt about operation at high gradients and with high beam loading.

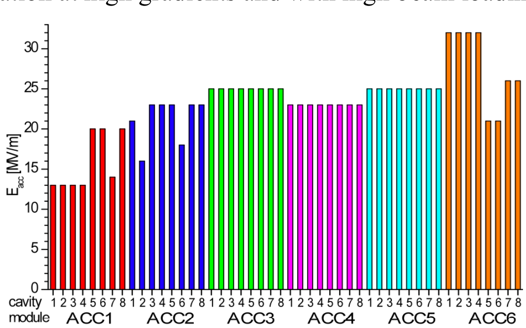

Figure 2: Operating gradient limits of cavities currently installed at FLASH.

The first four cavities in ACC6 have gradient limits of 34MV/m, giving an opportunity to study Lorentz-force detuning + piezo compensation, RF power overhead, and RF distribution, all at ILC gradients. The maximum operating gradient for ACC6 as a whole could exceed 25MV/m, with multiple cavities operating close to their respective quench limits. This will allow a broader study of running cavities close to quench with high beam loading and under vector sum RF field regulation.

INTERIM STUDIES REPORT

There have been three series of 9mA studies shifts to date, in May 2008, September 2008 and January 2009. The first steps towards high power operation were made during the September 2008 run. Stable operation was achieved over several hours with 450µs-long bunch-trains at an average current of 2.5mA (~2.5nC/bunch transported to the dump at 1MHz). Stable operation was also achieved with bunch-trains of 300 bunches at 500kHz, also with 2.5nC/bunch. The highest beam power reached was 6 kW comprising 550 bunches at 1MHz and 2.5nC/bunch at 5 Hz operation. Figure 3 shows the measured energy profile for such a bunch train. Over the bunch train, the peak-to-peak energy deviation over the entire bunch train is ~10MeV, with ~4MeV over the first 500 bunches.

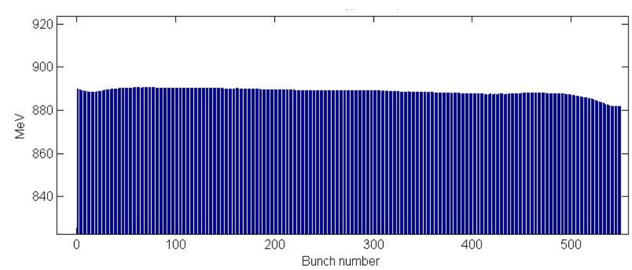

Figure 3: Bunch-by bunch energy profile for 550 bunches at 1MHz, ~2.5nC per bunch.

Increasing the bunch length from 450 bunches to 550 bunches at the 1MHz rate eventually caused a vacuum incident in the transport line immediately before the exit window to the dump, which terminated the studies.

Post-mortem analysis of the vacuum incident in the transport line indicated the leak was the result of thermal cycling of a vacuum flange over the course of several hours caused by beam losses in the last few meters of the transport line that had gone undetected.

Controlling Beam Loss

Controlling localized beam loss has been the most difficult operational issue so far, and it will get more difficult as the beam power is increased.

Minimizing energy deviations over the long bunch trains is an important factor in controlling beam loss, and is largely the job of the low-level RF system. An example of the operational importance of energy stability is shown in Fig. 4, which shows the cavity vector sum and signal from a beam loss monitor after the final bend of the bypass line. The rapid increase in beam loss at the end of the bunch train correlates with a droop in the cavity vector sum corresponding to similar ~0.5% droop in the beam energy. (The energy profile in Fig. 1 shows a similar

similar signiture.) The droop is a result of beam-loading compensation in the LLRF system terminating prematurely. Analysis of this and other salient features in the vector sum profile is discussed in another paper in these proceedings [5].

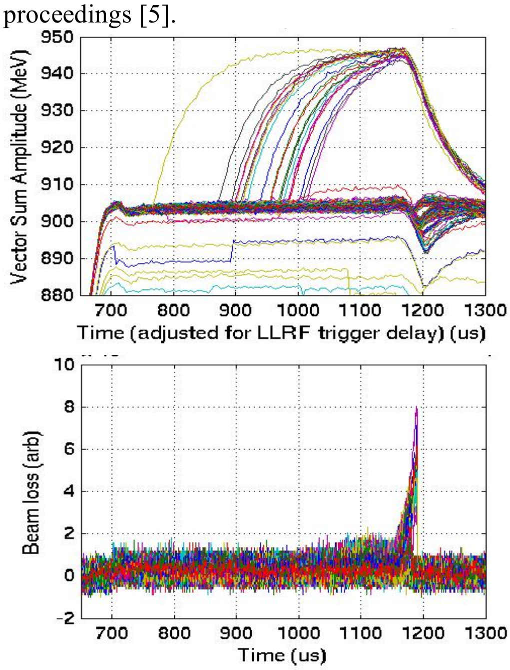

Figure 4: Cavity Vector Sum (top) and beam loss monitor in dump line (bottom) for many 500μs-long bunch trains (beam starts at T=700μs).

Studies in Support of the 9mA Program

The LLRF systems have been an important focus of the studies as means to improving energy stability both during the long bunch trains and from train to train. In addition to feedback regulator studies, there are ongoing studies to smooth the feed-forward tables and to optimize the high power RF drive control by cavity phase modulation during filling.

RF power overhead studies have also begun,, and they have yielded fresh information about cavity detuning jitter and Lorentz-force detuning at different gradients and with/without fast compensation using piezo tuners. These studies are discussed elsewhere in these proceedings [6].

PREPARATION FOR FUTURE STUDIES

As a result of the vacuum incident, several efforts have been initiated in order to better understand the loss scenarios and to have better diagnostics available for the next studies period. The additional diagnostics will comprise new Cerenkov fibers and long ion chamber beam loss monitors that will be installed along the transport line, a segmented diamond beam position monitor that will be installed on the exit window, and an in-air bpm that will be installed between the exit widow and the beam dump.

Improvements are also being made to the LLRF systems ahead of the September studies. The existing C67 DSP-based LLRF controllers in ACC456 are being upgraded to the most recent LLRF system design (either SimconDSP or an ATCA-based system), which offer better noise floors and faster loop times, and hence should allow the feedback gain to be significantly increased. Similarly, the LLRF Intermediate Frequency will be increased from 250kHz to 13MHz or 54MHz.

Additionally, results from more recent studies of loss scenarios and acceptance in the bypass lines are being used to improve the optics model for the transport line.

OUTLOOK

The 9mA studies program should provide important "operation at limits" experience to the ILC, XFEL, and for other superconducting linac projects. Good progress has been made in a relatively small number of studies shifts, while the vacuum incident has emphasized that the goals are operationally very challenging. An upcoming dedicated two-week studies period gives an excellent opportunity to make significant progress.

The ILC program could benefit tremendously from accelerator studies at FLASH when routine reliable high-power operation is finally achieved, and there is an increasingly long list of ILC and XFEL-related studies topics that go beyond the 9mA program as it is defined now.

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