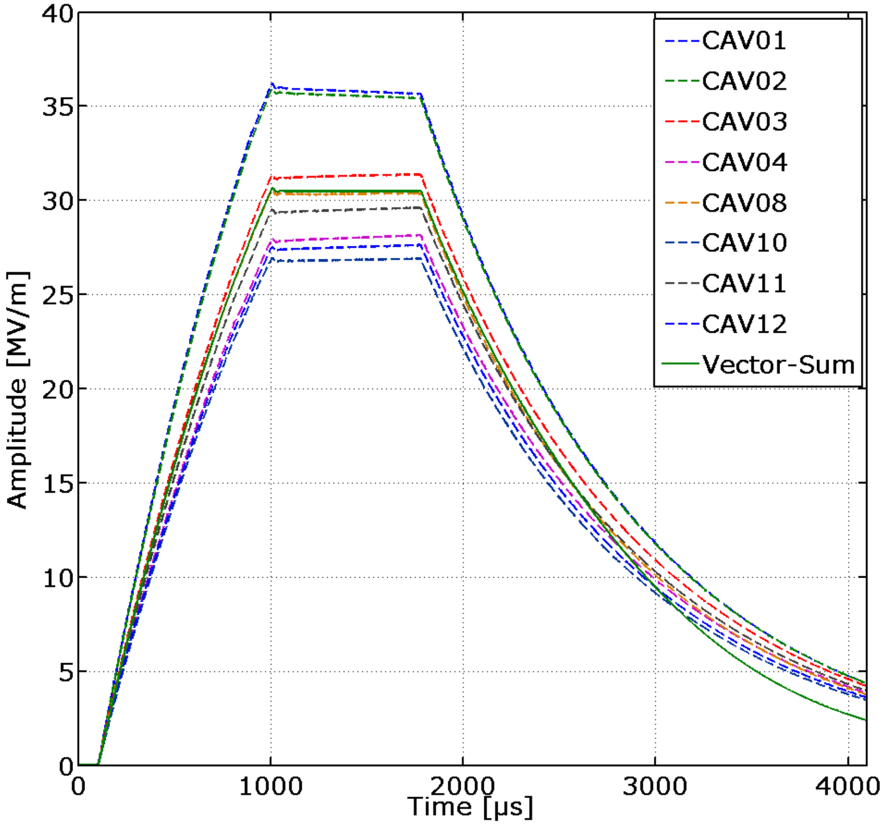
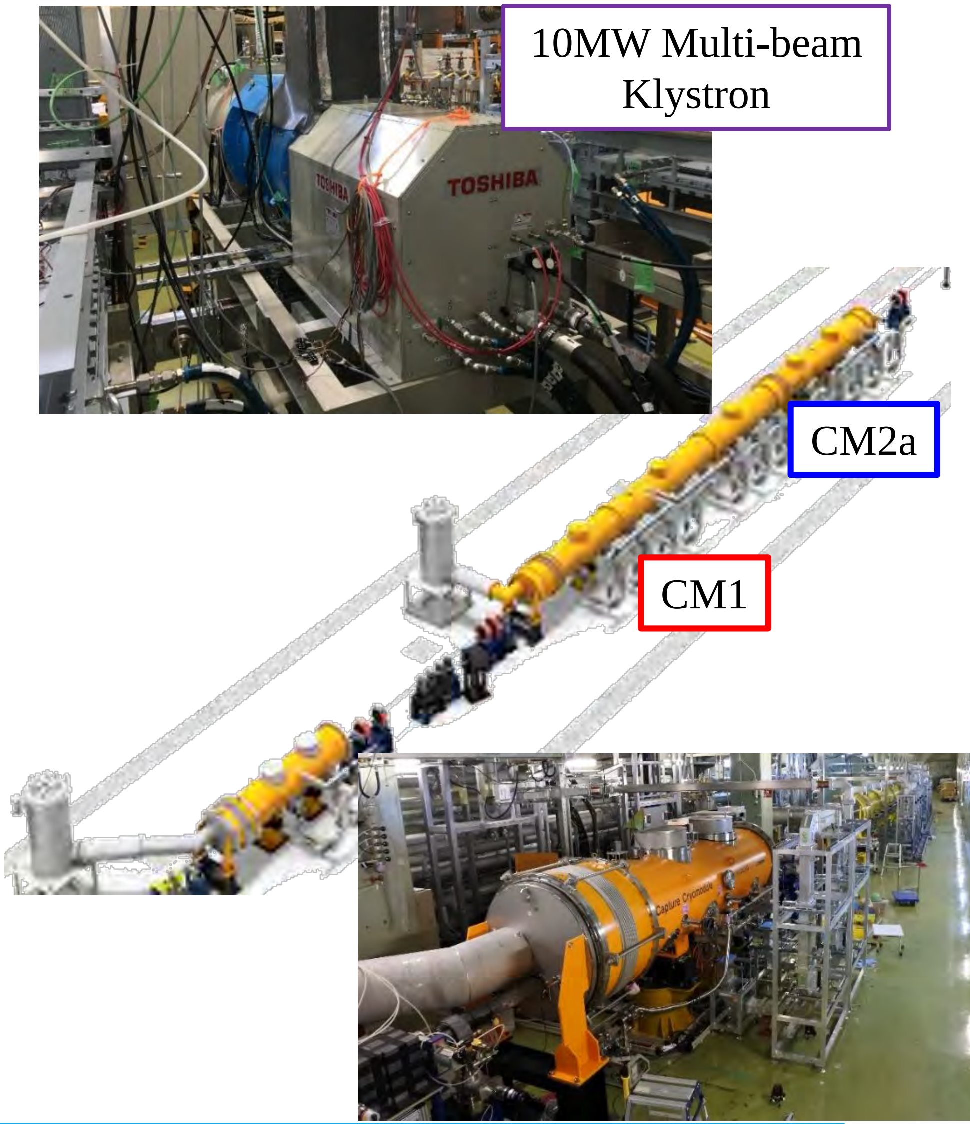
8 Cavities Operation by Vector-Sum@STF





8 Cavities were tuned on resonance by piezo, and vector-sum operation was done at 31MV/m.

SRF-Linac加速勾配、ビーム強度
FLASH 9mA study (TDR vol-3 part I, p.80)

complementary skills and resources of large accelerator laboratories and smaller university groups alike.

Beam tests done during the Technical Design Phase at other facilities are also important. For example, beam-coupling corrections applied at the Australian Synchrotron [117], have demonstrated beam emittance of 1.2 pm-rad, well below that needed for ILC.

3.2 FLASH 9 mA experiment

3.2.1 Introduction

The TESLA Test Facility (TTF) was constructed by the TESLA collaboration [118] to demonstrate that a linear collider based on superconducting accelerating cavities would be feasible and cost competitive with one based on conventional copper structures. Technical feasibility of ILC-type superconducting accelerating cavities was demonstrated in 2000 when an 800 microsecond-long 8-mA beam was accelerated through a single cryomodule to 168 MeV. The TTF was renamed FLASH (Free electron LASer in Hamburg) and became a user facility operating as a soft X-ray free-electron laser in 2005. The FLASH linac is a 1.25 GeV linac based on Tesla-type technology and operates 5000 hours per year on average. The '9-mA' program was proposed by the GDE in 2008 with the goals of demonstrating reliable operation of the TTF/FLASH linac with ILC-like bunch-trains and to characterise the limits of operation of gradient and RF power. Typical beam properties for FEL user operation (charge, number of bunches, average beam power) are far lower than those required for the 9mA studies. For DESY, however, these studies have been important for integration and operational issues associated with running long bunch trains and high bunch charge, both for FLASH itself and for the European XFEL (see Section 2.5).

The ILC main linac will accelerate a 5.8 mA (upgradeable to 9 mA) 726 microsecond beam pulse to 250 GeV with 0.1 % rms energy stability at a pulse-repetition rate of 5 Hz. The beam energy must be stabilised over two timescales: long-term pulse-to-pulse stability over minutes and hours; and energy stability within a bunch train. The ILC main linac also requires precision control of high-gradient SRF in the presence of heavy beam loading. Since gradient performance has the greatest cost impact, each cavity in the ILC will be set to a stable voltage near its gradient quench-limit. To leverage the most cost-effective performance, low-level RF controls are used to push the cavities to achieve the maximum practical gradient, expected to be within 5 % of the nominal maximum. Effects such as beam loss, beam turn-on, beam-current fluctuation, Lorentz-force detuning and errors in power input coupling should be properly managed and disturbances minimised in order to maintain stable operation. In addition, studies were made of the required high-level RF-power overhead needed for reliable operation.

The above scientific programme attracted strong interest and participation of low-level RF and machine experts from DESY and also internationally, from Argonne, Fermilab and KEK. The studies were performed over a total of about 5 separate week-long runs between September 2008 and September 2012.

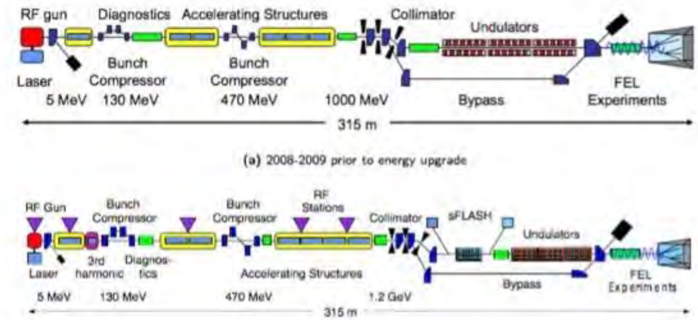
Table 3.2 compares beam parameters for the 9 mA Studies with the ILC Main Linac design parameters, and those of the European XFEL.

Table 3.2 Parameters for the 9 mA Experiment in context

	units	TDR Baseline	TDR Upgrade	European XFEL	FLASH 9 mA Expt.
Number of bunches per pulse		1312	2625	3250	2400
Bunch repetition rate	MHz	1.8	2.73	5	3
Beam pulse length	μs	727	960	650	800
Bunch Charge	nC	1.9	3	1	3
Beam current	mA	5.8	9	5	9

3.2.2 FLASH Main Linac

The main elements of the FLASH linac are shown in Fig. 3.1 before and after the energy upgrade in 2009/2010, when the number of accelerating cavities was increased from 48 to 56, increasing the maximum operating energy to 1.25 GeV. The injector comprises a 5 MeV laser-driven photo-cathode RF gun and a two-stage bunch compressor. The RF system of the first-stage compressor has eight cavities in a single cryomodule (module ACC1), while that of the second bunch compressor has 16 cavities in two cryomodules (modules ACC2 and ACC3). The main linac comprises modules ACC4 onwards. Prior to 2010, the main linac comprised modules ACC4, ACC5, ACC6 (24 cavities), all fed from a single klystron and regulated using vector-sum control.

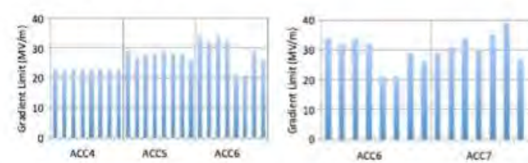


(b) 2010-2012, following upgrade to 1.25 GeV

Figure 3.1. Layout of the FLASH linac

The FLASH high-level RF systems are the basis of the HLRF system design for both the ILC and the European XFEL. The RF power is distributed from individual multi-beam klystrons of either 5 or 10 MW through a series of power-dividing elements to either one, two, or three groups of eight cavities. The relative power to each cryomodule (group of eight cavities) can be adjusted remotely. Pairs of adjacent cavities receive some fraction of the total RF power, with the power ratios having been set during fabrication based on measured quench limits of the cavities. These power-dividing ratios are not adjustable. Prior to 2010, the RF unit comprising the 24 cavities in ACC4,5,6 was of most interest for the 9 mA studies. In 2010, an additional cryomodule (ACC7) was added and the HLRF systems were reconfigured into two groups of 16 cavities each fed from it's own klystron (ACC4+5 and ACC6+7). Subsequent studies were focused on operation of ACC6 + 7. At the end of the linac, the beam is directed through a series of undulators for SASE FEL operation, or alternatively to a bypass line and then to the beam dump.

Figure 3.2 Measured cavity-gradient limits for the cavities in the FLASH Accelerator cryomodules for the 9 mA studies



(a) Modules ACC4,5,6 (2008-2009)　(b) Modules ACC6,7 (2010-2012)

高周波源

Comparisons with other facilities

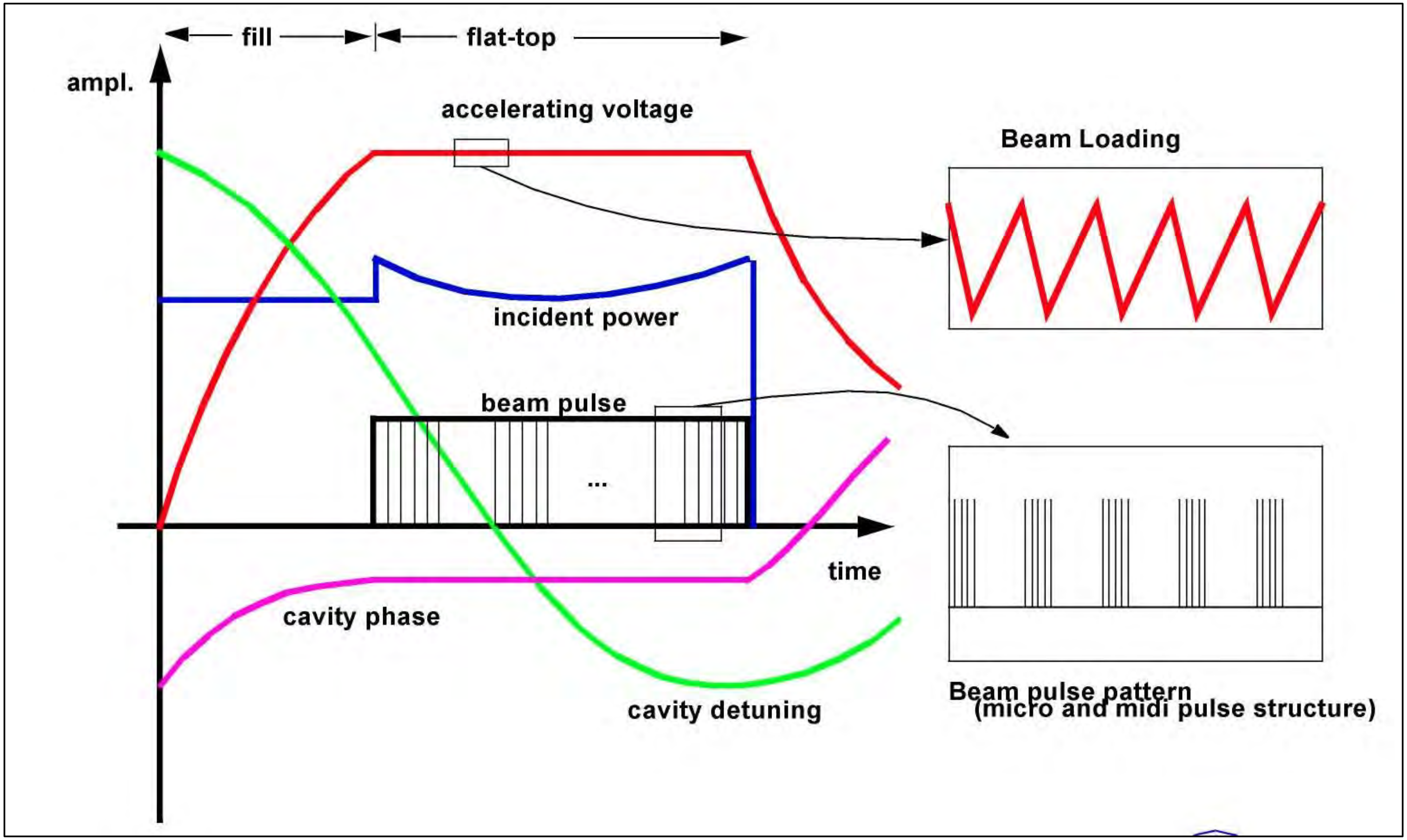
Parameter	ILC	FLASH	Euro XFEL	KEKB inj.	SLAC-SLC
Energy	**125 GeV*2**	**1.2 GeV**	**17.5 GeV**	**8 GeV**	**50 GeV**
Length	**20 km**	**200 m**	**1500 m**	**600 m**	**5000 m**
Cavity type	9-cell TESLA-type SSCs			NC	
Resonance frequency	1300 MHz			2856 MHz	
Cavity gradient (MV/m)	31.5±20%	20	23.6	40	
Loaded Q	3e6 ~ 10e6	~3e6	~3e6		
Number of cavities (e-,e+,RTML,ML)	~9,000	42	928	240	
Cavities per klystron	39	16	32	4	
Number of klystrons	**～240**	5	29	60	**245**
Beam pulse length	727 us	650 us	650 us		
Beam current	5.8 mA	3 mA	5.0 mA		

Comparisons with other facilities (2)

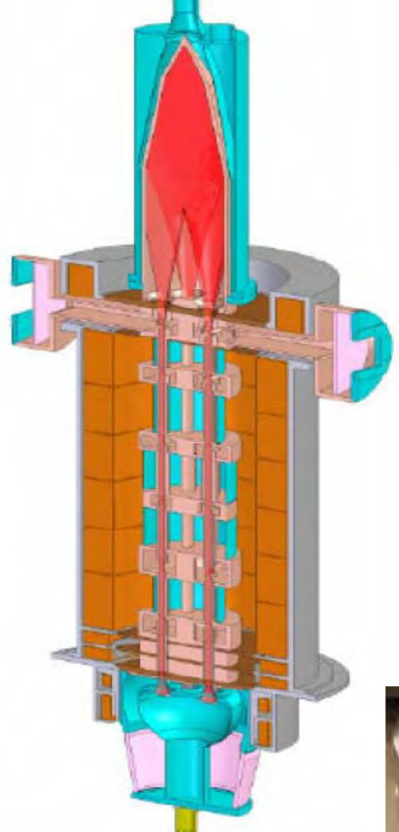
Parameter	ILC	FLASH	Euro XFEL	KEKB inj.	SLAC-SLC
Number of klystrons	**～240**	5	29	60	**245**
Klystron power	10 MW			50 MW	67 MW
Efficiency	65%			45%	45%
RF width	1650 us	1300 us	1400 us	4 us	3.5 us
Repetition rate	5Hz	5 Hz	10 Hz	50 Hz	180 Hz
Average rf power	83 kW	65 kW	140 kW	10 kW	42 kW
Modulator peak	17 MW (120 KV*140A)				
Modulator average	140 kW	100 kW	240kW	33 kW	150 kW

空洞数は多いが，クライストロンの本数はSLAC-SLCと同程度．
1クライストロン用の電源の規模は，ほぼ5045のものと同じ．（～150kW)

パルス超伝導空洞の運転模式図



マルチビームクライストロン

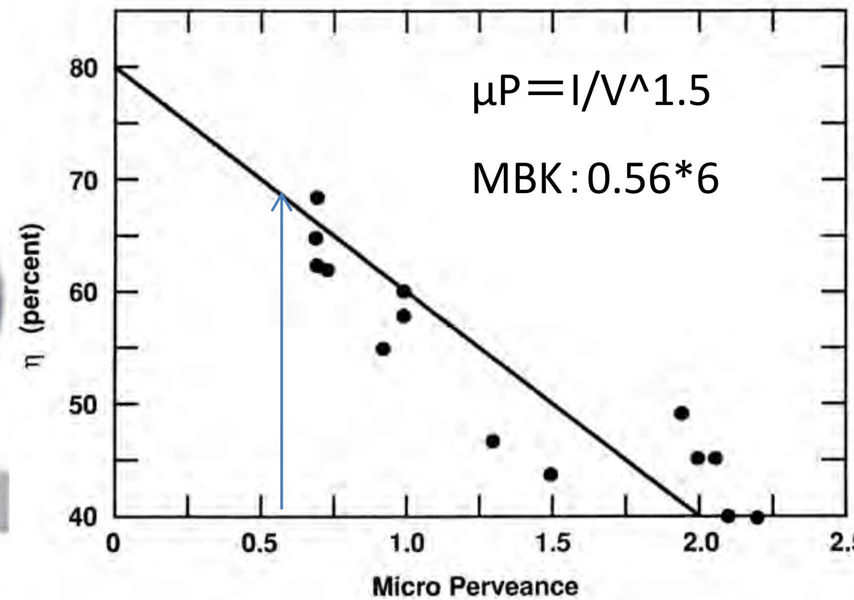


Parameter	Specification
Frequency	1.3 GHz
Peak power output	10 MW
RF pulse width	1.65 ms
Repetition rate	5.0 (10) Hz
Average power output (5 Hz)	82.5 kW
Efficiency	65 %
Saturated gain	> 47 dB

EuroーXFELと同じもの．東芝，Thalesが供給している．

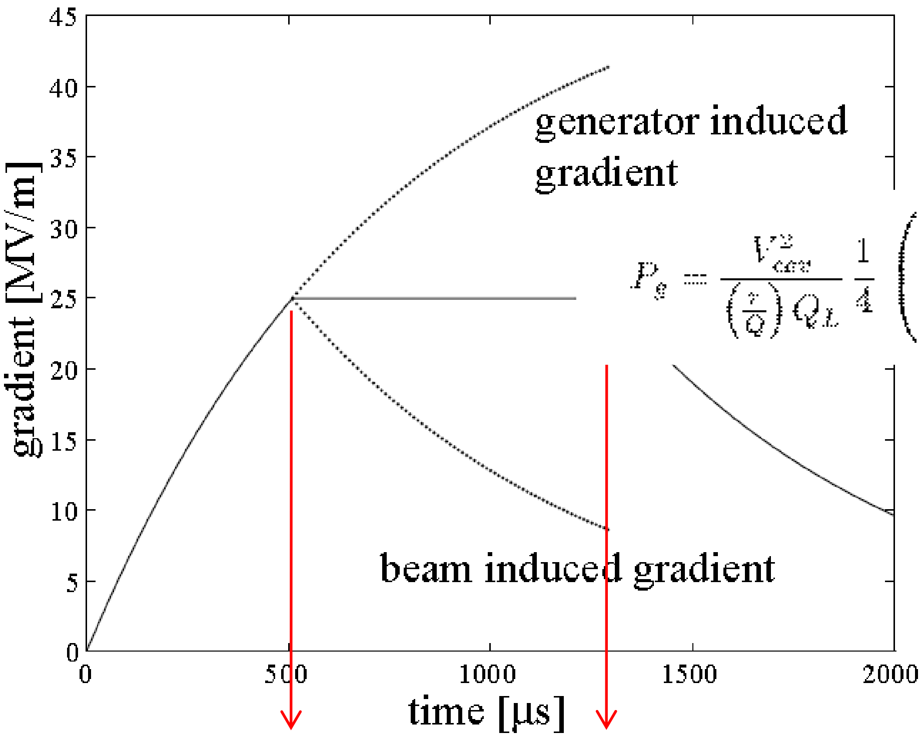
James Benford, John Swegle, Chapter 10 in High-power microwaves, Artech House, Boston, 1992.

東芝WEBより引用



ビーム安定度

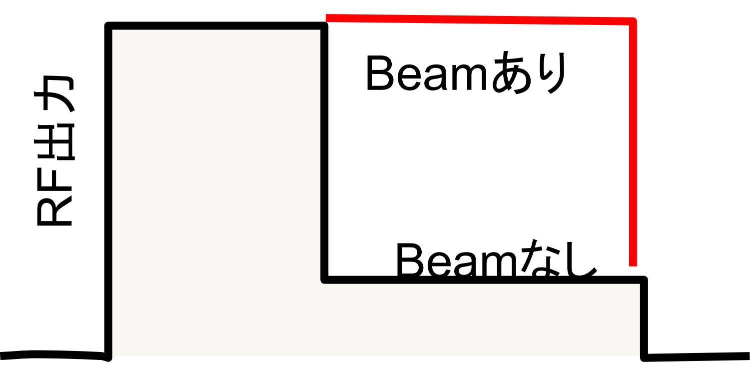
高周波の設定波形及び高周波出力



$$P_g = \frac{V_{cav}^2}{\left(\frac{r}{Q}\right) Q_L} \frac{1}{4} \left(\left[1 + \frac{\left(\frac{r}{Q}\right) Q_L I_{b0}}{V_{cav}} \cos\phi_b \right]^2 + \left[\frac{\Delta f}{f_{1/2}} + \frac{\left(\frac{r}{Q}\right) Q_L I_{b0}}{V_{cav}} \sin\phi_b \right]^2 \right)$$

Fillは設定電界の2倍の高さに空洞のQl値に対応して増加、設定値になった時点で維持

このような設定曲線で、離調がない理想的な場合は、ビームがある場合は矩形のRF出力。ビームなしの場合はFillの1/4の電力。



例：FLASH空洞のパラメータ

$V_{cav} = 25$ MV, $Q_L = 3 \cdot 10^6$; no beam:

$$P_g = 50kW \cdot \left(1 + \left(\frac{\Delta f}{f_{1/2}} \right)^2 \right)$$

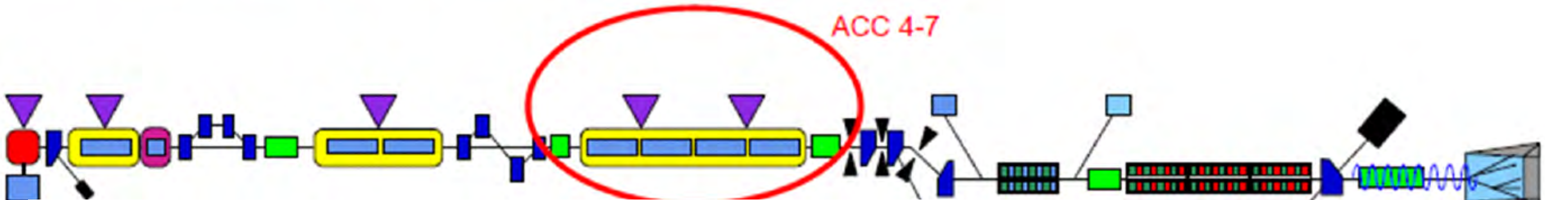
$V_{cav} = 25$ MV, $Q_L = 3 \cdot 10^6$; $I_b = 8$ mA; $\phi_b = 0°$ (on-crest):

$$P_g = 50kW \cdot \left(4 + \left(\frac{\Delta f}{f_{1/2}} \right)^2 \right)$$

実際には空洞の離調があるため、これより波形はひずむ。

Motivation: 9mA experiment

TTF2/FLASH: unique worldwide facility



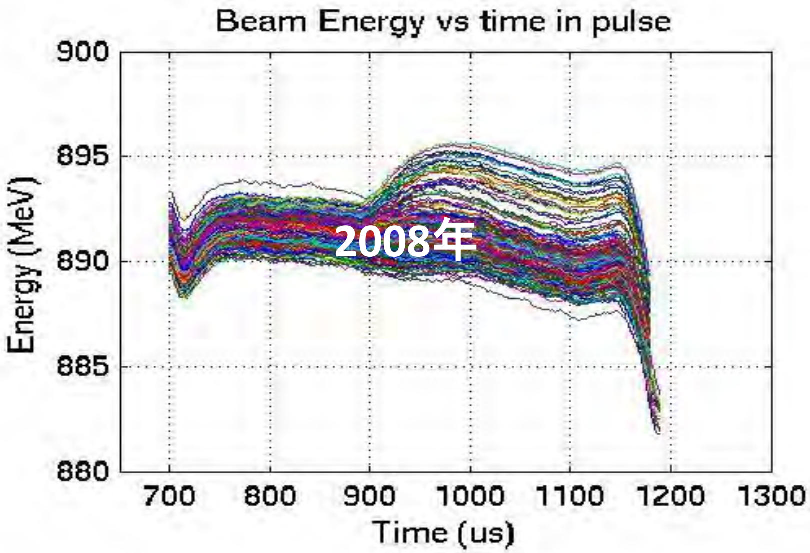
FLASHは当時は30バンチ運転(30us)
XFELのために長バンチ試験が必要であった.
ILCのためには，9mAロングバンチの確認が必要であった.
XFELとILCの両者にメリットのある共同実験

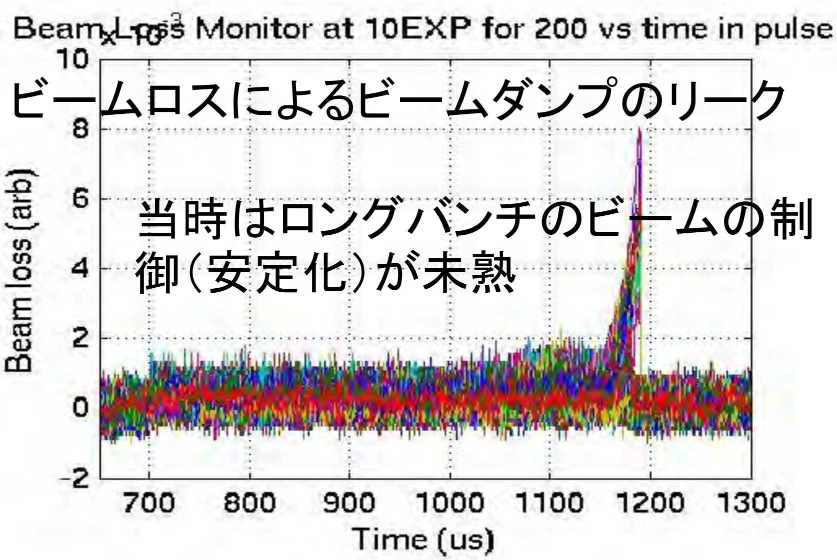
		XFEL X-Ray Free-Electron Laser	ilc	FLASH design	FLASH experiment
Bunch charge	nC	1	3.2	1	3
# bunches		3250*	2625	7200*	2400
Pulse length	µs	650	970	800	800
Current	mA	5	9	9	9

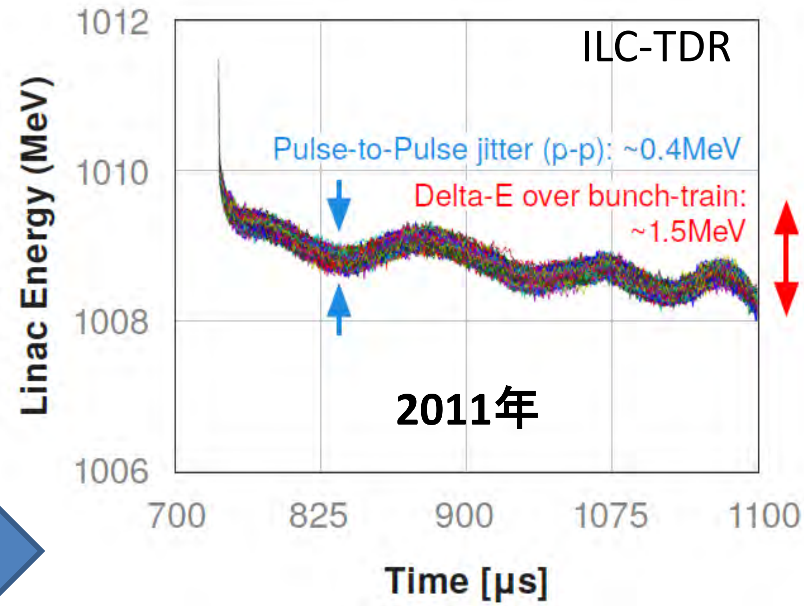
Courtesy: N. Walker

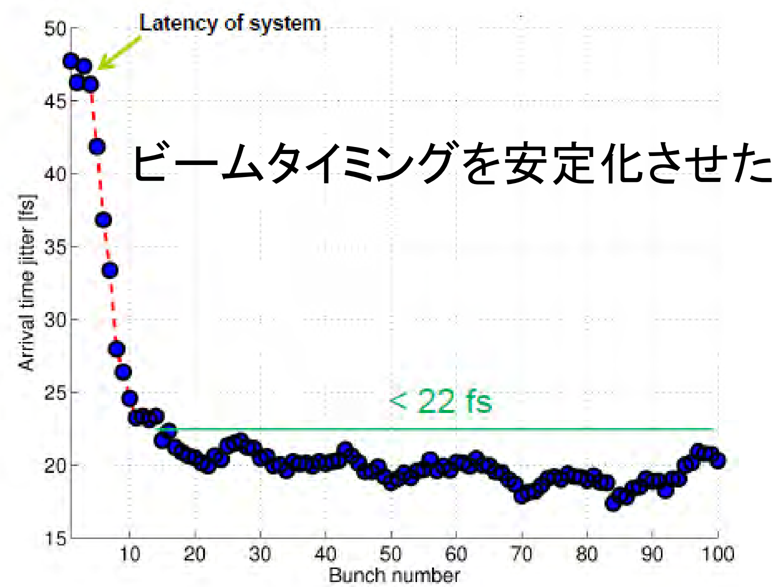
Proposal to operate FLASH
Similar to XFEL (4.5MHz, 4.5mA)

ビームエネルギー安定化









G. Cancelo（FNAL）

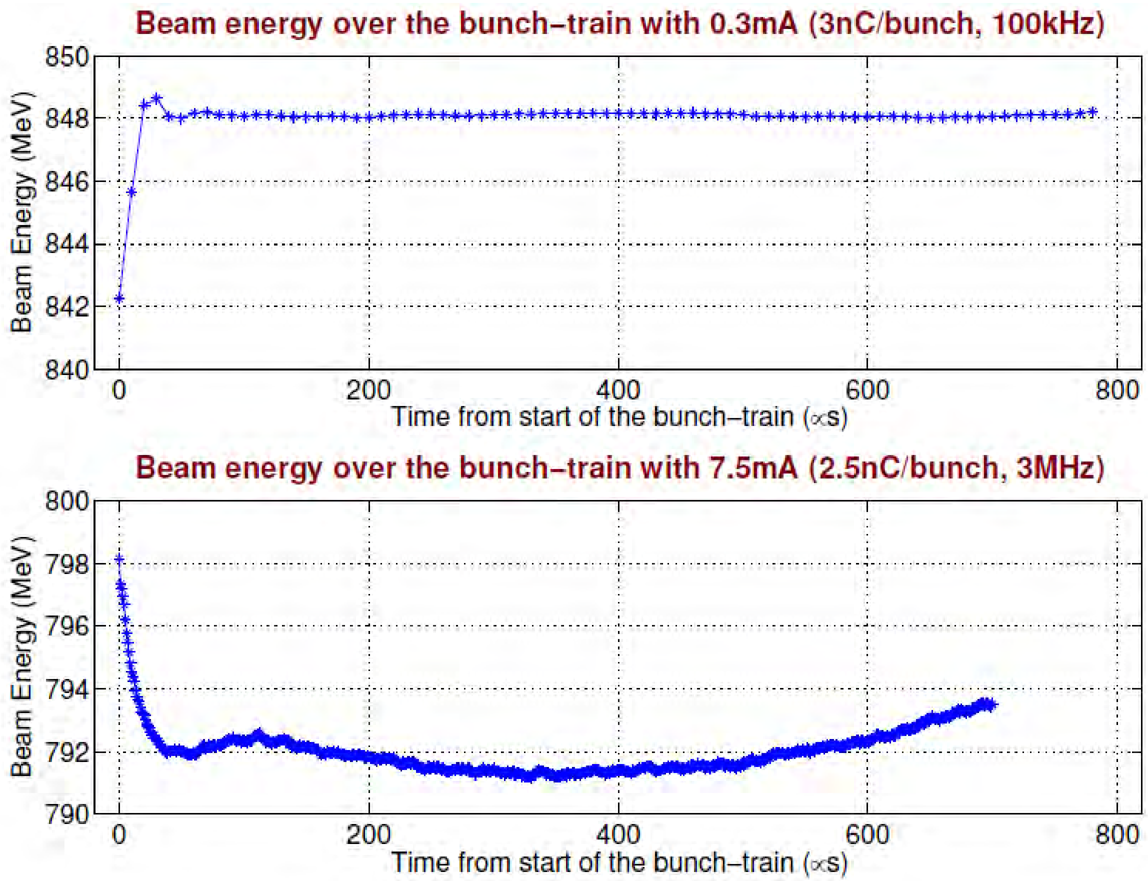


Figure 3.4
Linac energy profiles from 2009 study at 0.3 mA (top) and at 7.5 mA (bottom)

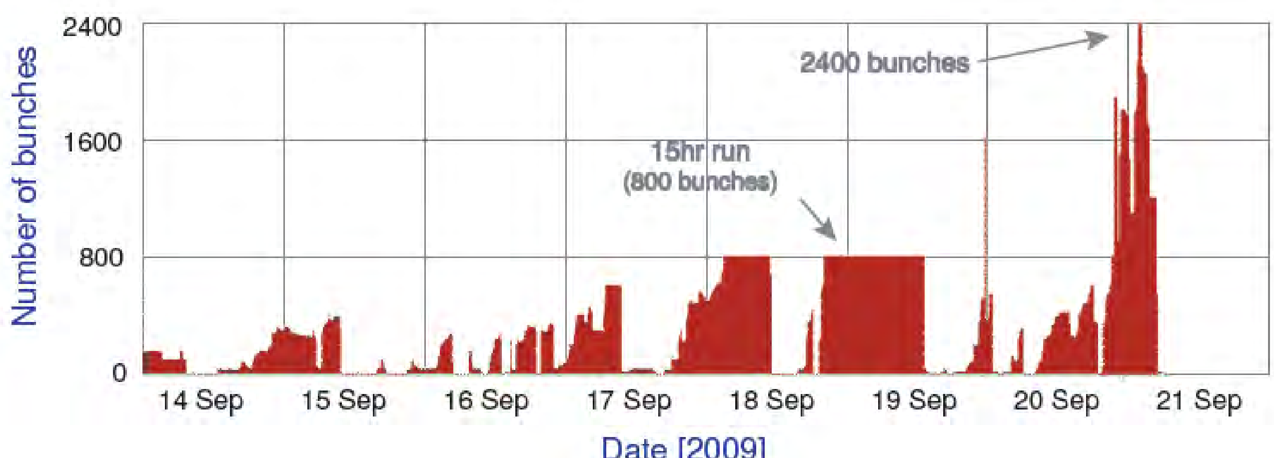


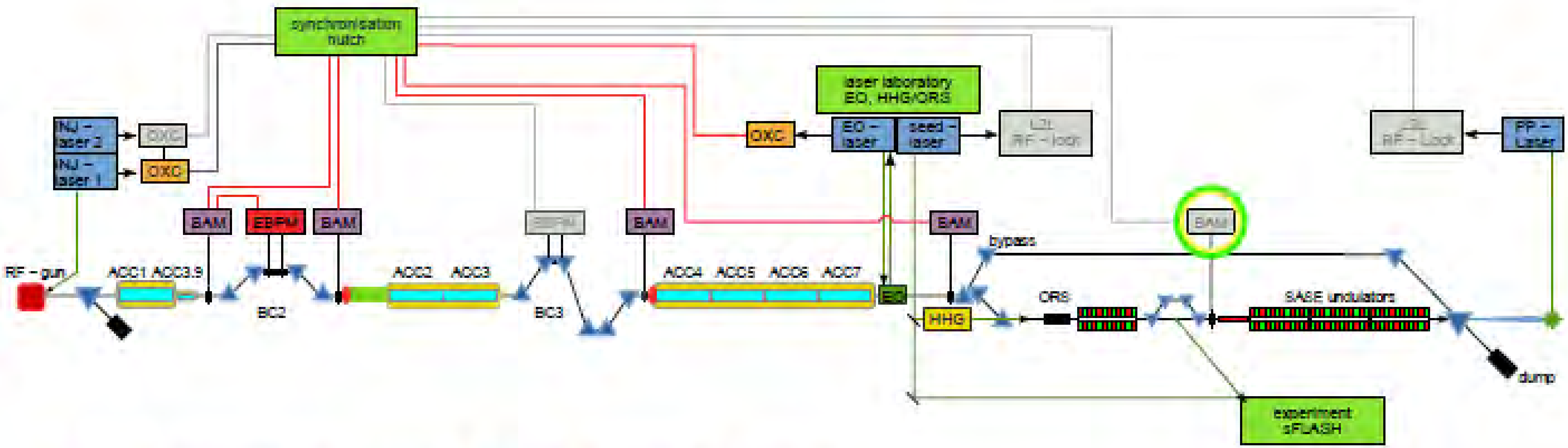
Figure 3.5
Number of bunches and bunch charge over 7 days of studies.

Table 3.3
Results of high-power beam studies

Metric	Goal	Achieved
Pulse length & current	800 μs and 9 mA	▪ 800 μs pulses and current up to 6 mA ▪ 9 mA current and pulse lengths up to 600 μs
Charge per pulse	7200 nC	▪ 5400 nC (600 μs, 9 mA)
Average power	36 kW (7200 nC, 5 Hz, 1 GeV)	▪ 22 kW (5400 nC, 5 Hz, 800 MeV)
Operating gradients with beam loading	31.5 MV/m nominal average	▪ Several cavities above 30 MV/m ▪ 13 cavities totalling 380 MV/m with 13 cavities
Gradient flatness	2 % $\Delta V/V$ (800 μs, 5.8 mA)	▪ $<$ 0.3 % $\Delta V/V$ (800 μs, 4.5 mA) (800 μs, 9 mA) ▪ Automated the cavity-gradient flattening algorithm
Gradient margin	All cavities operating within 3 % of quench	▪ Some cavities within $\sim$ 5 % of quench (800 μs, 4.5 mA) ▪ First tests of operations strategies for gradients close to quench
Energy Stability	$<$ 0.1 % rms at 250 GeV	▪ $<$ 0.15 % p-p (400 μs pulses $<$ 0.02 % rms 5 Hz)
RF power overhead	Stable operation at ILC design parameters	▪ First tests of operation within 5 % of klystron saturation with 800 μs pulse lengths and 4 mA ▪ First tests of klystron linearisation close to saturation
Linac operations	▪ 15 hrs continuous running with 3 mA and 800 μs pulses ▪ Several hours operation close to 9 mA with bunch trains of 500-600 μs ▪ Energy deviations within long bunch trains: less than 0.5 % pulse-pulse at 7 mA ▪ Energy jitter pulse-to-pulse with long bunch trains: $\sim$ 0.13 % rms. at 7 mA ▪ Recovery to 2400 bunches and 4.5 mA on the first pulse after a beam-inhibiting cryo event	

Laser-based Synchronisation Infrastructure at FLASH.

Locations of Bunch Arrival Time Monitors



- 1. Generation: BAM 4DBC3 and 18ACC7
- 2. Generation: BAM 1UBC2 - installed in 2009
- 3. Generation: BAM 3DBC2 - installed May 2010
- 4. Generation: BAM 1SFELC - scheduled for 2012