System Integration: TTF/FLASH ‘9mA’ studies

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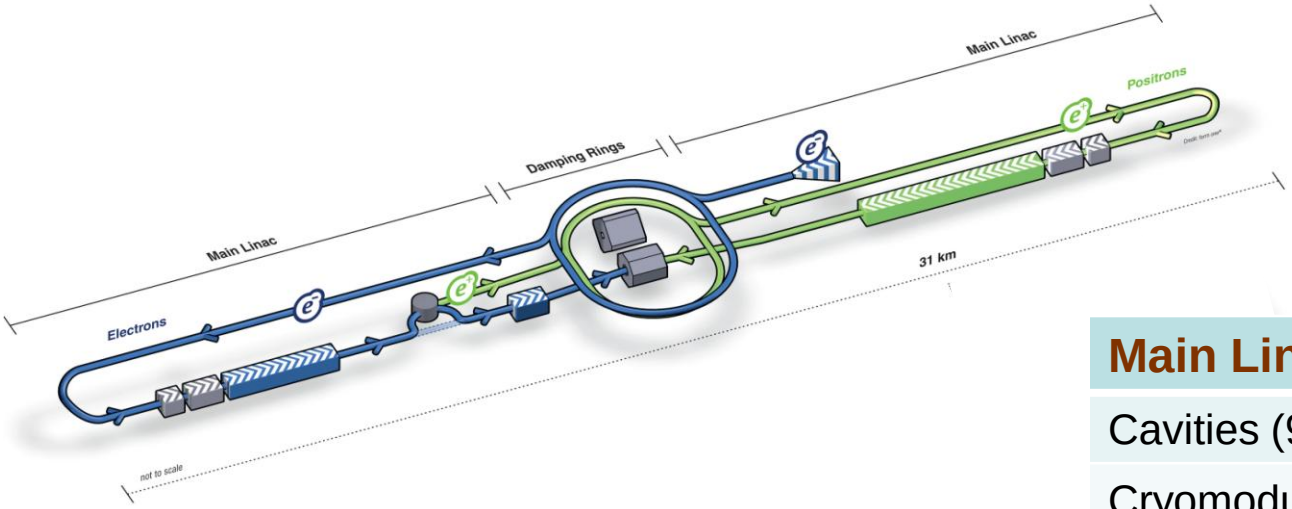
For the TTF/FLASH 9mA study team

Outline

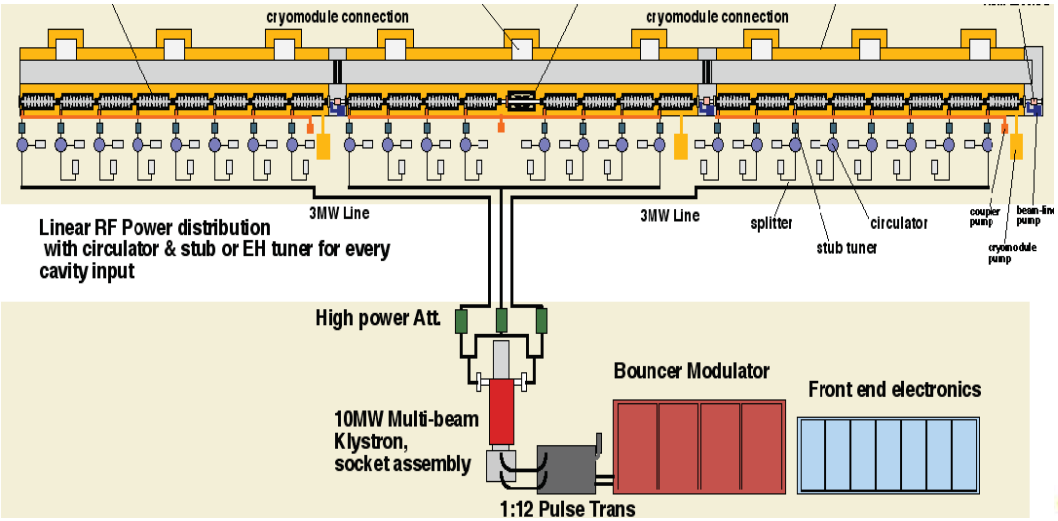
- **Motivation**
- **Overview of TTF/FLASH**
- **Studies highlights**
- **Upcoming studies program**
- **Wrap-up**

ILC Reference Design



Main Linacs	
Cavities (9-cell)	14,560
Cryomodules	1680
RF Units	560
Cavities per RF Unit	26
Avg. operating gradient	31.5MV/m
Gradient spread	+/-20%

Main Linac RF Unit



String Test: goals from R&D Plan

(Integration Tests)

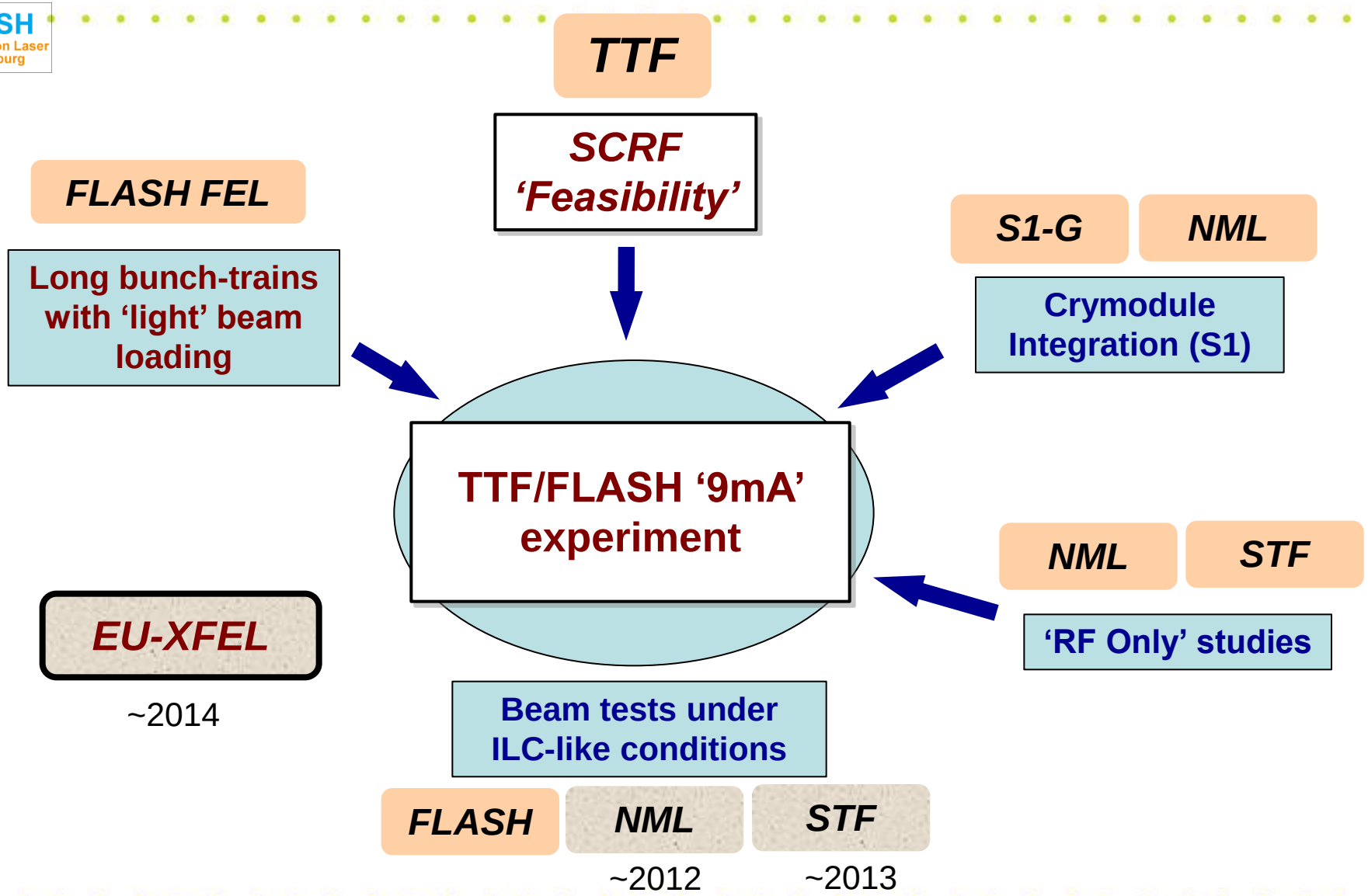
Demonstrate beam phase and energy stability at nominal current

- ***Important because of their potential cost impact:***
  - *demonstrate operation of a nominal section or RF-unit*
  - *determine the required power overhead*
  - *to measure dark current and x-ray emission*
  - *and to check for heating from higher order modes*

- ***Needed to understand linac subsystem performance:***
  - *develop RF fault recognition and recovery procedures*
  - *evaluate cavity quench rates and coupler breakdowns*
  - *test component reliability*

TTF/FLASH is currently the only facility where beam tests can be run

TDR-Phase System Integration (S2)



Specific objectives for the 9mA study

- **Long bunch-trains with high beam loading (9mA)**
  - 800μs pulse with 2400 bunches at 3MHz, 3nC per bunch
  - Vector Sum control of up to 24 cavities
  - +/- 0.1% energy stability
  - Cavity gradients approaching quench limits
  - Beam energy 700-1000MeV

Establish ILC-like operating conditions

- **Characterize operational limits**
  - Energy stability limitations and trade-offs
  - Cavity gradient overhead needed for LLRF control
  - Klystron power overhead needed for LLRF control
  - HOM absorber studies (cryo-load)

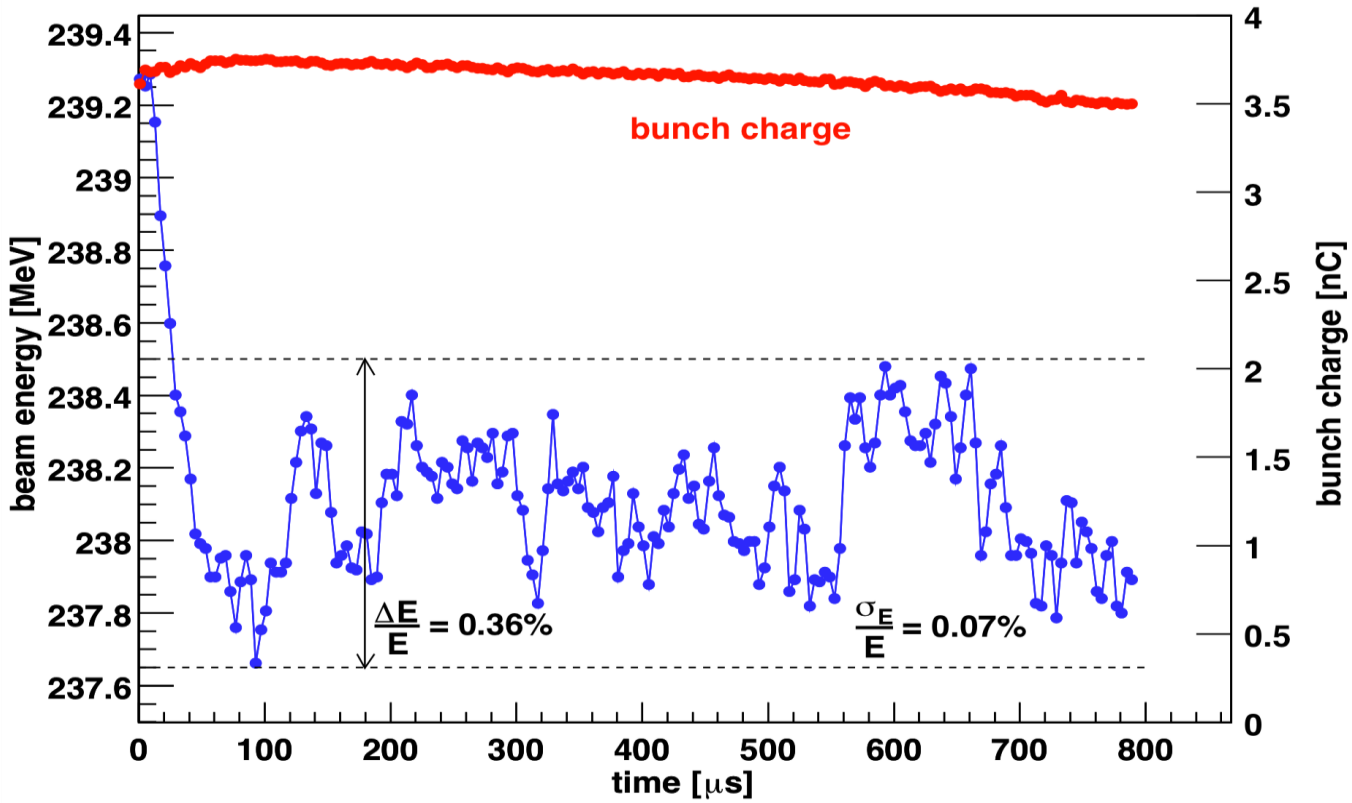
Studies under ILC-like operating conditions

- **Operation close to limits, eg**
  - Robust automation of tuning, etc
  - Quench detection/recovery, exception handling
  - Beam-based adjustments/optimization

TTF/FLASH facility

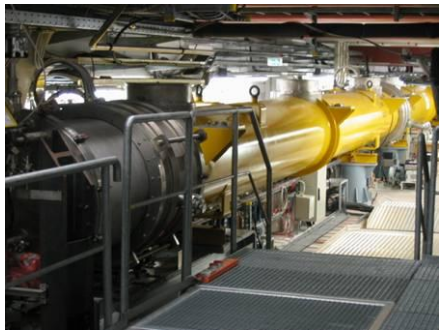
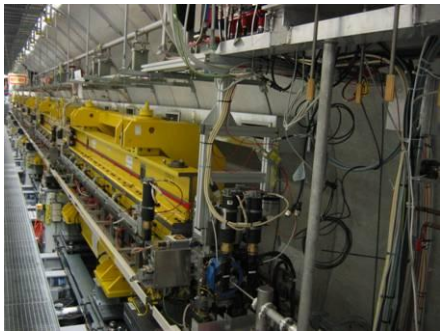
Feasibility demonstation at TTF (8mA, 800us)

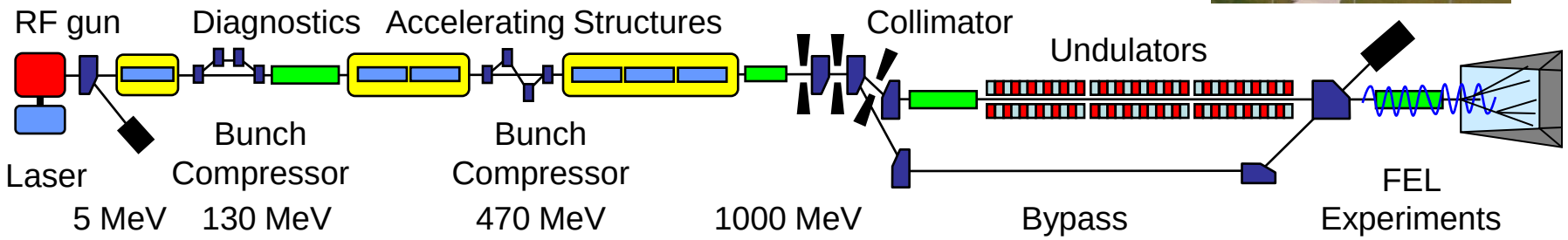
From ICFA Beam Dynamics Newsletter #24, April 2001



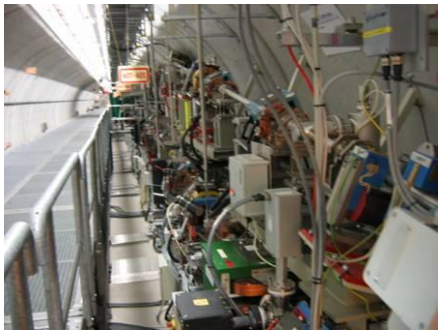
- 2 cryomodules, 8+8 cavities, single klystron
- 238MeV final beam energy
- 3.5nC/bunch 1800 bunches @ 2.25MHz

FLASH layout (2009)

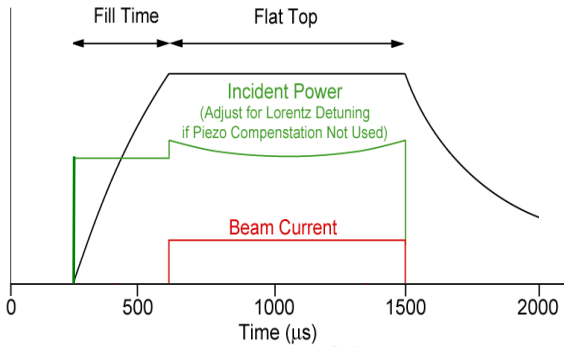




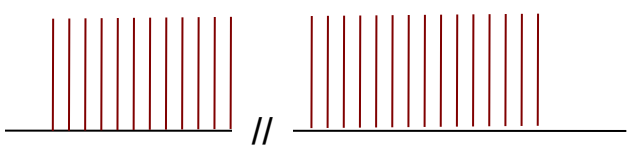


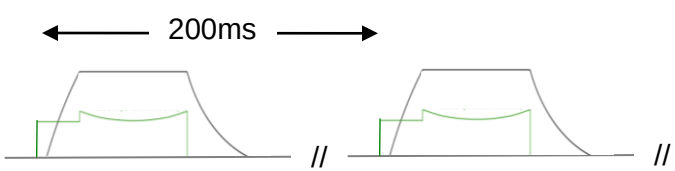



Comparison of machine parameters



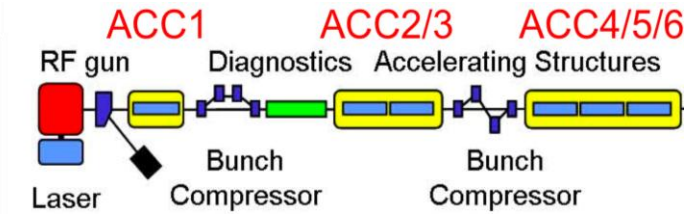
2400 bunches at 3MHz
(800 bunches at 1MHz)

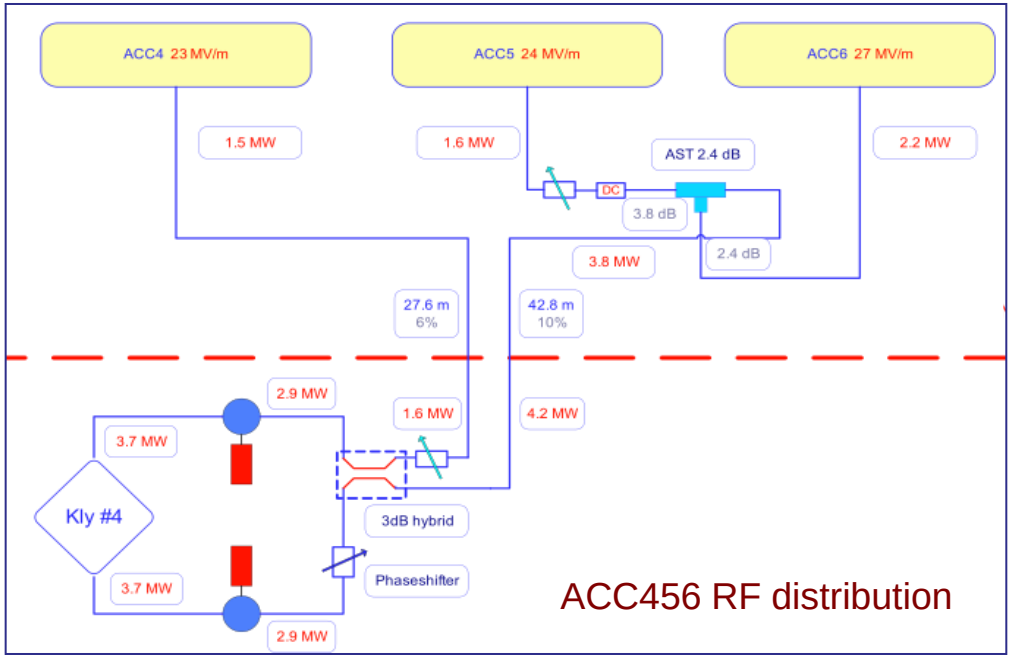


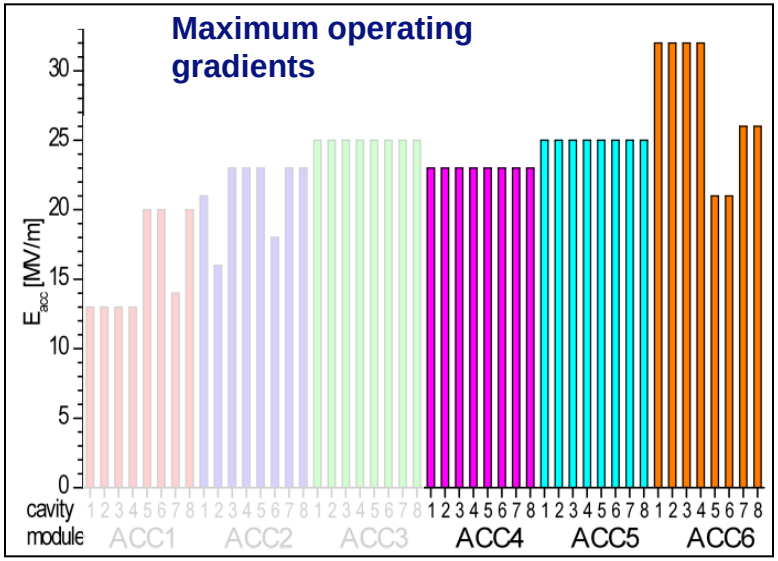


		XFEL	ILC	FLASH design	9mA studies
Bunch charge	nC	1	3.2	1	**3**
Bunch rate	MHz	5	2.7	9	**3**
# bunches		3250	2625	7200	**2400**
Pulse length	µs	650	970	800	**800**
Current	mA	5	9	9	**9**

Vector Sum control of cavity fields



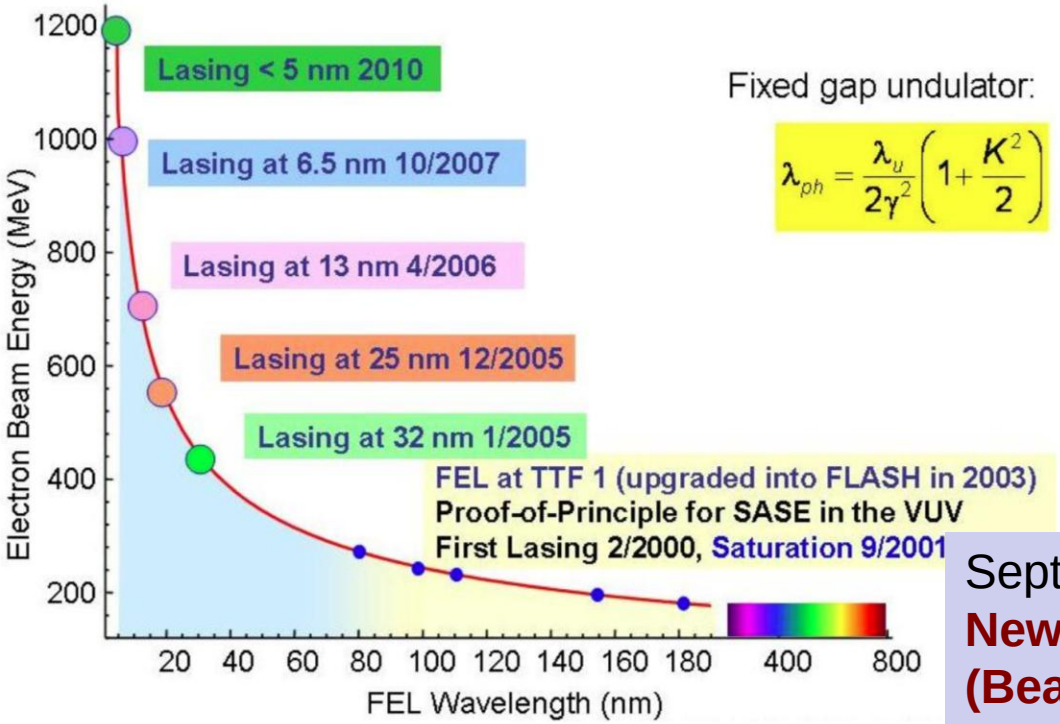




- A single klystron provides rf power to 24 cavities
- LLRF regulates the phase & amplitude of the vector sum of 24 cavity fields ("total energy gain")
- Critical issue: operating with a spread of gradients

FLASH is an operating FEL user facility
(5000hrs/year, 93% uptime)

- 6 undulator modules, total length 27 m
- Fixed gap of 12 mm
  - permanent NdFeB magnets
  - peak B = 0.48 T, K = 1.23, period of 27.3 mm



Fixed gap undulator:

$$\lambda_{ph} = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

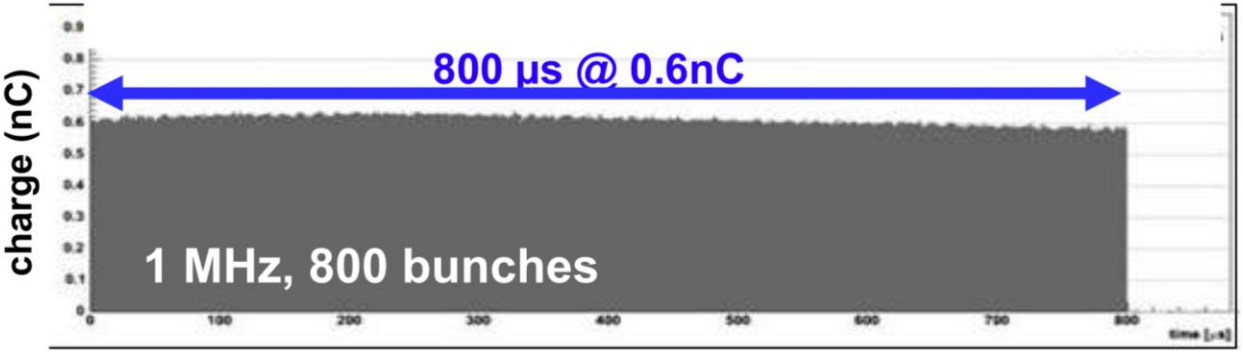
- change of wavelength
  ↔
  change of electron beam energy

September 26th
New record wavelength of 4.12nm
(Beam energy of 1.25GeV)

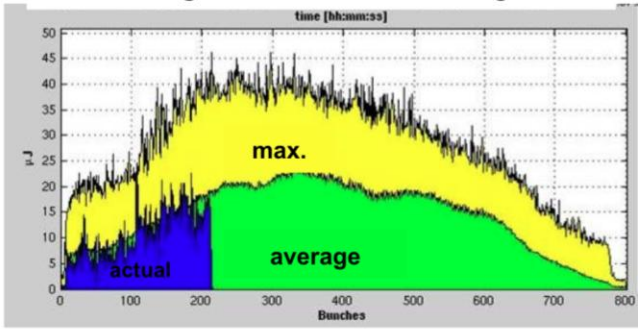
FLASH design goals reached in 2007

FLASH.
Free-Electron Laser in Hamburg

Lasing with a complete bunch train of 800 bunches at 13.4 nm



GMD - gas monitor detector - signal



Electron beam energy of 1 GeV and lasing at 6.5 nm

DESY TELEGRAMM 21. September 2007

Design-Strahlenergie für FLASH erreicht!
Elektronenstrahl mit 6 Modulen erstmals auf 1 GeV beschleunigt

FLASH Reaches Design Beam Energy!
Electron beam accelerated to 1 GeV with 6 modules for the first time

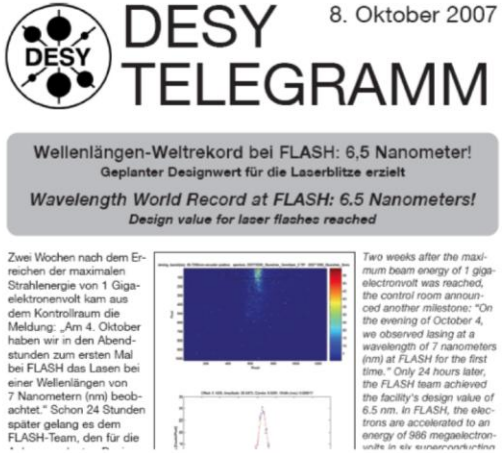
Der Durchbruch passierte wieder in einer Nachtschicht, genauer am 21.9.2007, um 0:57 Uhr. Dieses Mal ging es um das Erreichen der geplanten maximalen Strahlenergie. „Ziel: Betrieb mit höchster Energie – Ergebnis: 1 GeV Energie !! Gemessenes Spektrum der spontanen Emission: ~ 6,3 nm", so der Eintrag im elektronischen Logbuch.

Das Team im Kontrollraum beobachtete im Wellen-

Während der letzten Wartungspause: Einbau des Beschleunigermoduls Nr. 6 in den FLASH-Tunnel.
During the last shutdown: installation of accelerator module no. 6 in the FLASH tunnel.

As usual, the breakthrough was achieved during a night shift, to be precise: on September 21 at 0:57 a.m. This time, the aim was to reach the planned maximum beam energy. "Goal: Operation to maximum energy—Achievements: 1 GeV!! Spectrum of spontaneous emission measured: ~ 6.3 nm," reads the entry in the electronic logbook.

For the first time, the team in the control room ob-



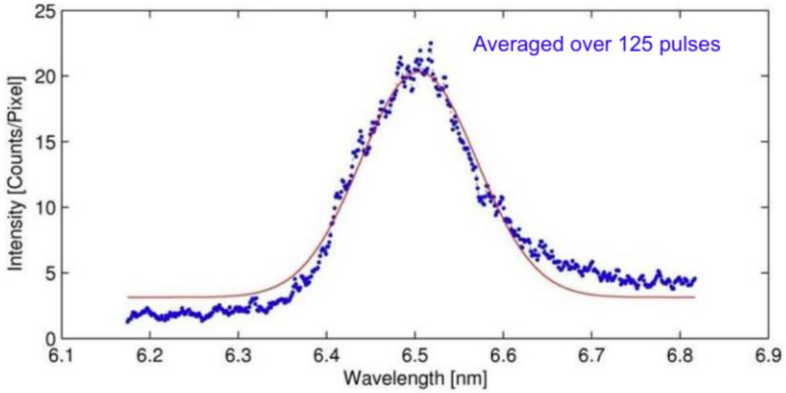
DESY TELEGRAMM 8. Oktober 2007

Wellenlängen-Weltrekord bei FLASH: 6,5 Nanometer!
Geplanter Designwert für die Laserblitze erzielt

Wavelength World Record at FLASH: 6.5 Nanometers!
Design value for laser flashes reached

Zwei Wochen nach dem Erreichen der maximalen Strahlenergie von 1 Gigaelektronenvolt kam aus dem Kontrollraum die Meldung: „Am 4. Oktober haben wir in den Abendstunden zum ersten Mal bei FLASH das Lasen bei einer Wellenlängen von 7 Nanometern (nm) beobachtet." Schon 24 Stunden später gelang es dem FLASH-Team, den für die

Two weeks after the maximum beam energy of 1 gigaelectronvolt was reached, the control room announced another milestone: "On the evening of October 4, we observed lasing at a wavelength of 7 nanometers (nm) at FLASH for the first time." Only 24 hours later, the FLASH team achieved the facility's design value of 6.5 nm. In FLASH, the electrons are accelerated to an energy of 986 megaelectronvolts in six superconducting



S. Schreiber
IWLC 2010 – J. Carwardine

Studies highlights

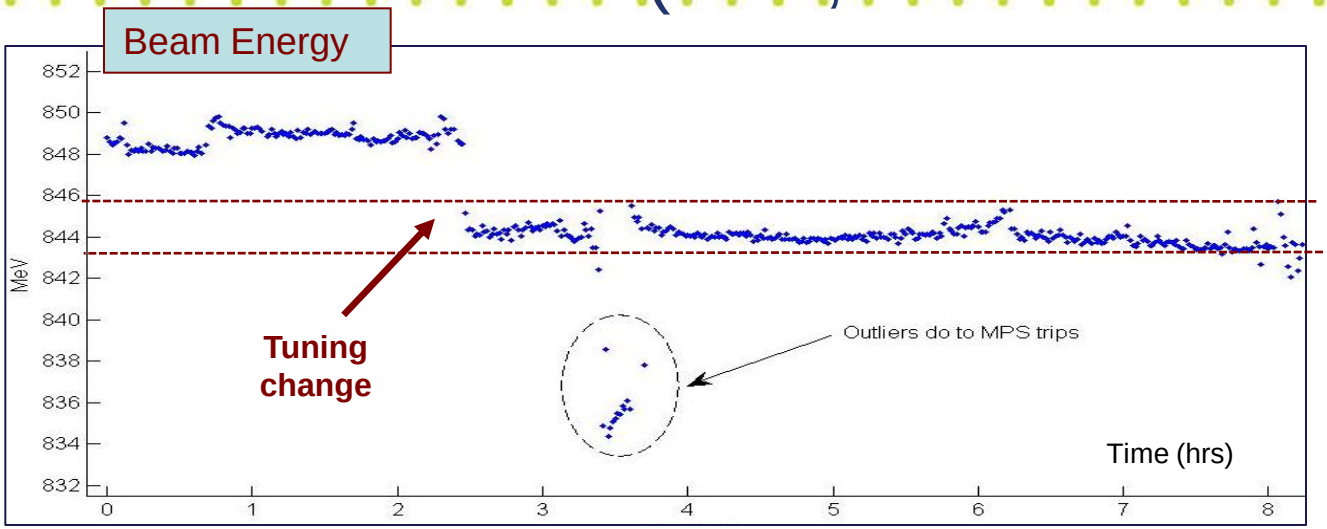
High power long bunch-train operation
(During 2 weeks of studies in Sept 2009)

Metric	ILC Goal	Achieved
Bunches per pulse	800 x 3nC (1MHz)	800 x 3nC
	2400 x 3nC (3MHz)	1800 x 3nC 2100 x 2.5nC ~2400 x 2nC
Charge in macro-pulse	7200nC @ 3MHz	5400nC @ 3MHz
Average beam power	36kW (7200nC, 5Hz, 1GeV)	22kW (5400nC, 5Hz, 800MeV)
Cavties operating at high gradients, close to quench	Up to 38Mv/m	Several cavities above 30MV/m

- 15 contiguous hours running with 3mA and 800us bunch trains
- Running at ~9mA with bunch trains of 500-600us for several hours
- Full pulse length (800us, ~2400 bunches) at ~6mA for shorter periods

- Energy deviations within long bunch trains: <0.5% p-p (7mA beam)
- Energy jittter pulse-pulse with long bunch trains: ~0.13% rms (7mA)

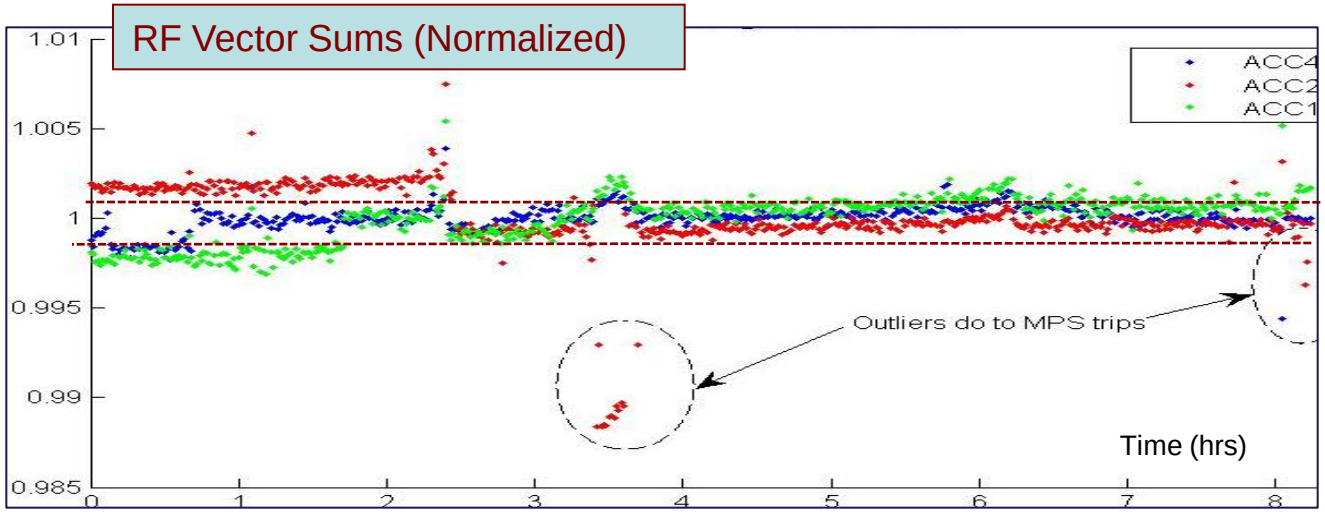
Energy stability over 8hrs
(3mA, 800us bunch trains)



844 MeV

2MeV (0.25%)

(Spec: +/-0.1%)

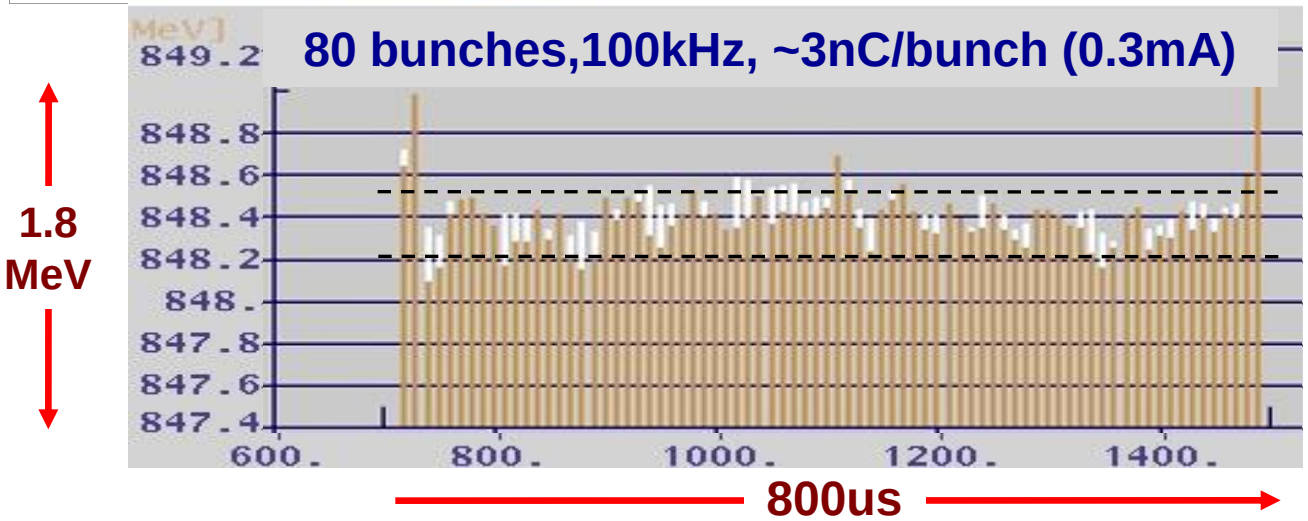


Nominal

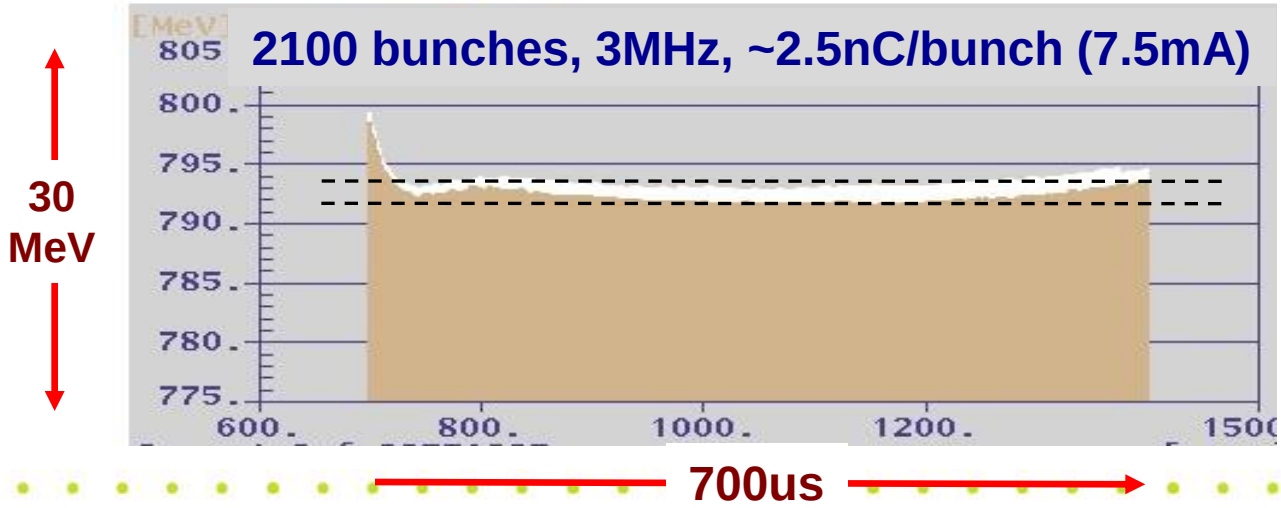
0.2%

8 hrs

Energy deviation along bunch train (examples)



Along pulse: 0.035% p-p



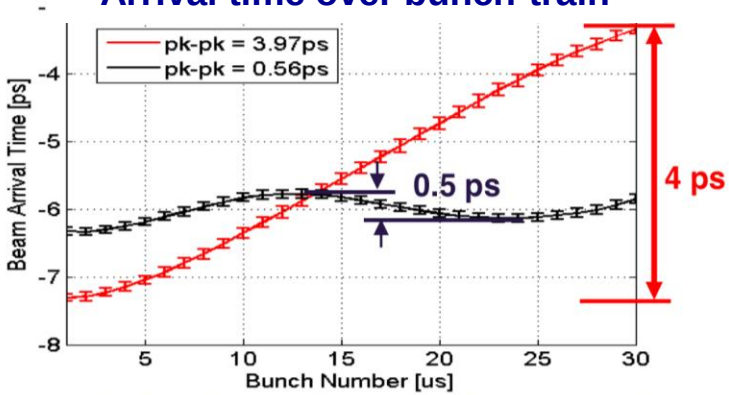
Along pulse: 0.5% p-p
Pulse-pulse: 0.13% RMS

LLRF upgrades to improve energy stability

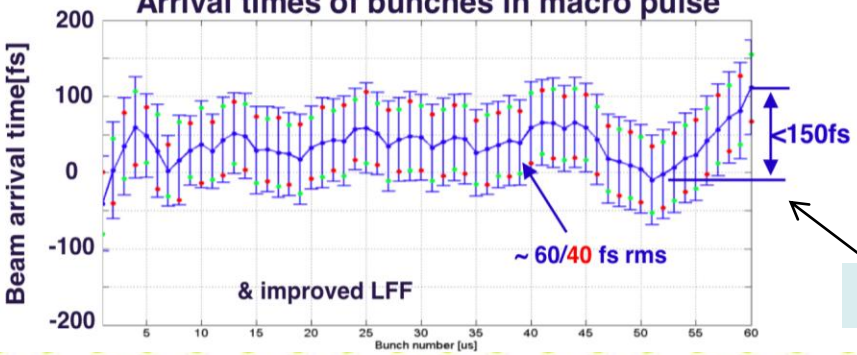
Energy stability after first bunch compressor:

$\Delta A/A < 0.01\%$

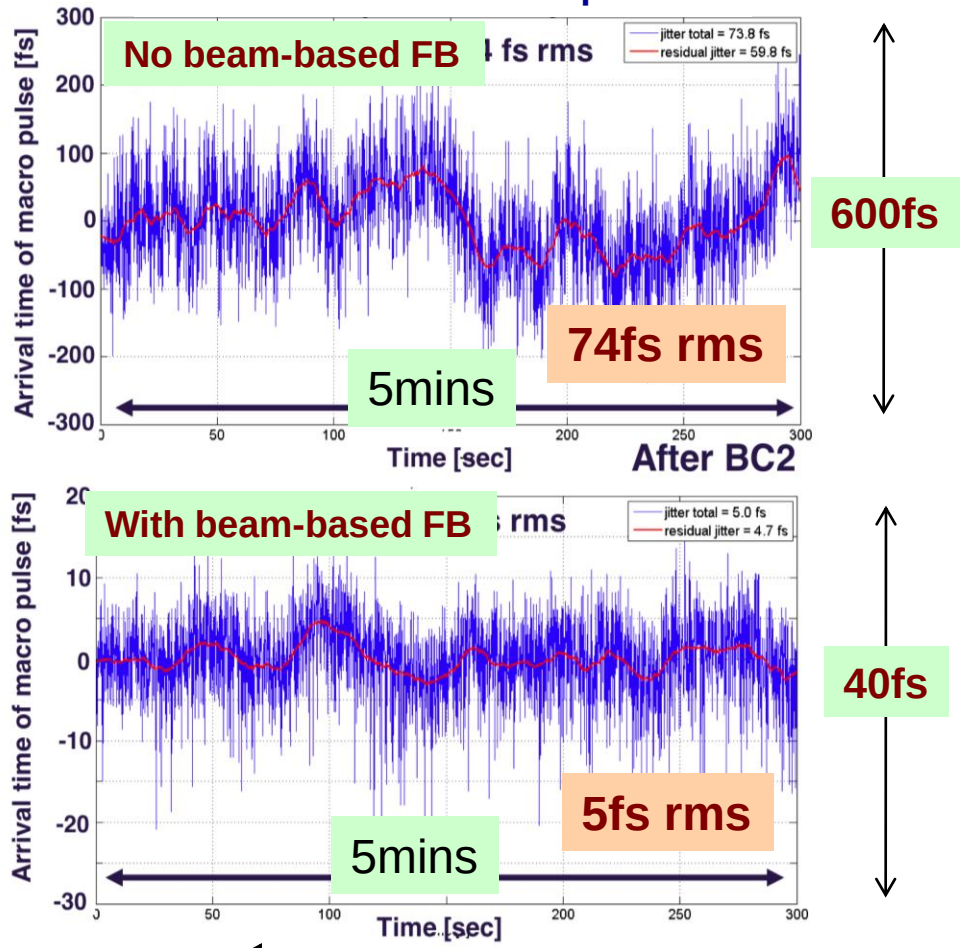
Arrival time over bunch-train



Arrival times of bunches in macro pulse



Arrival time of macropulse



Arrival time ≡ beam energy

H. Schlarb

Upcoming studies

Upcoming 9mA studies at FLASH

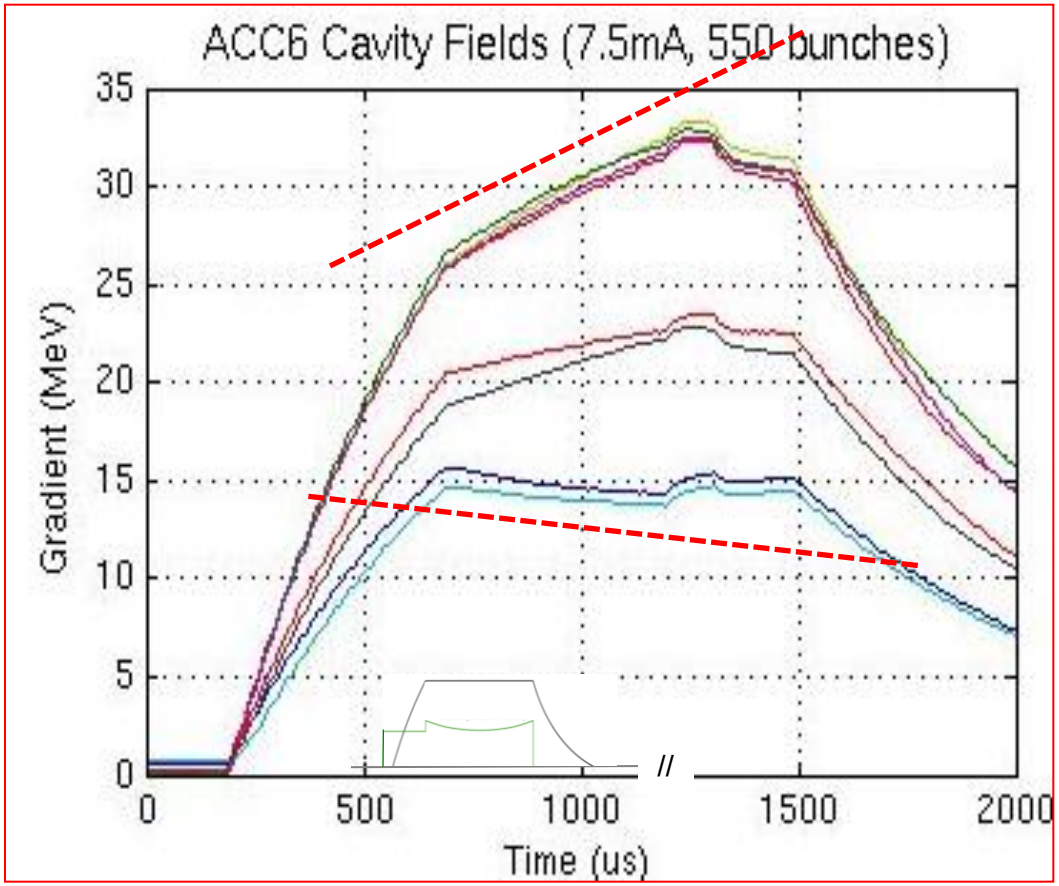
- **Future 9mA studies will benefit significantly from many recent machine improvements**

- **Characterize operation at gradient limits with beam loading**
  - Gradient ‘tilt’ studies (‘Pk/Qext’ tuning methodology)
  - Compensation of Lorentz-force detuning with piezo tuners
  - Operation at high gradients is also a priority for FEL studies – common program being developed

- **Input to 9mA program from other facilities**
  - Take advantage of recent piezo tuner studies at S1-Global
  - Utilize NML for ‘RF-Only’ studies to support and prepare for subsequent beam studies at FLASH

- **Next 9mA studies shifts expected in Jan 2010**

Cavity gradient tilts from beam loading



A ‘feature’ of running cavities with a spread of gradients from same RF source

Matched beam current with constant Pk:

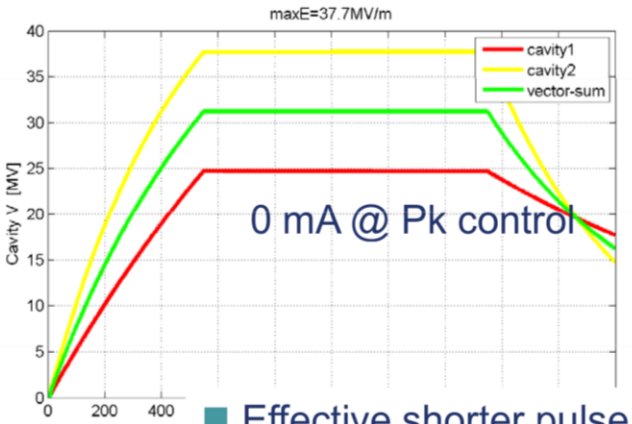
$$I_{matched} = \frac{V_k}{\left(\frac{r}{Q}\right) Q_{ext}}$$

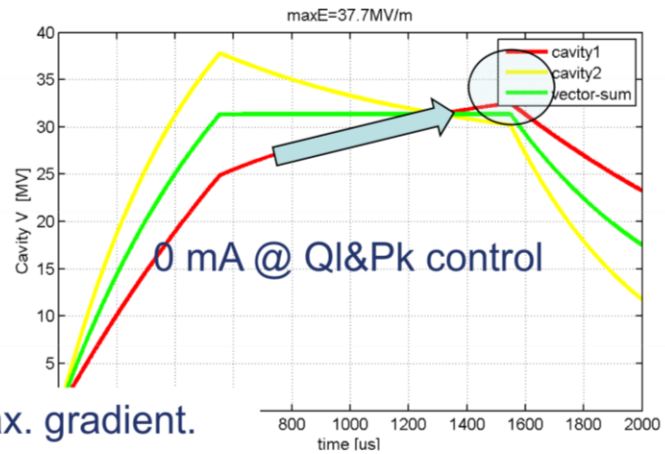
Knobs to correct cavity gradients tilts: Forward power, Loaded Q

Cavity gradient tilts: RF distribution schemes

All Qext equal
(FLASH standard setup)

Individually adjusted Qext
(ILC Reference Design)

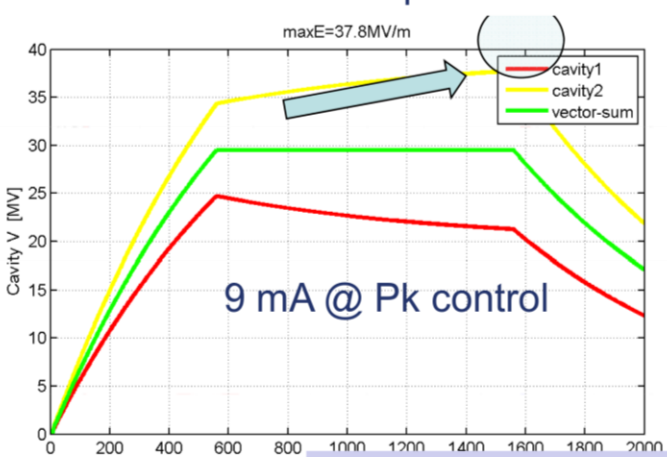


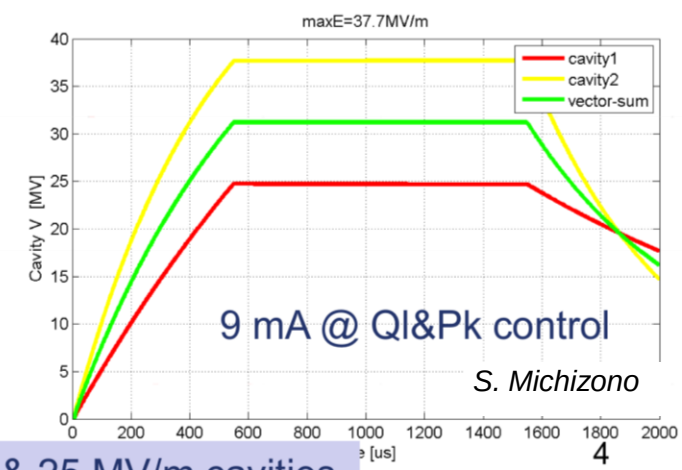


Matched beam current with constant Pk:

$$I_{matched} = \frac{V_k}{\left(\frac{r}{Q}\right) Q_{ext}}$$

- Effective shorter pulse at max. gradient.
- Same quench limit?





S. Michizono

FLASH cavities have remotely adjustable Loaded Qs (ACC67)

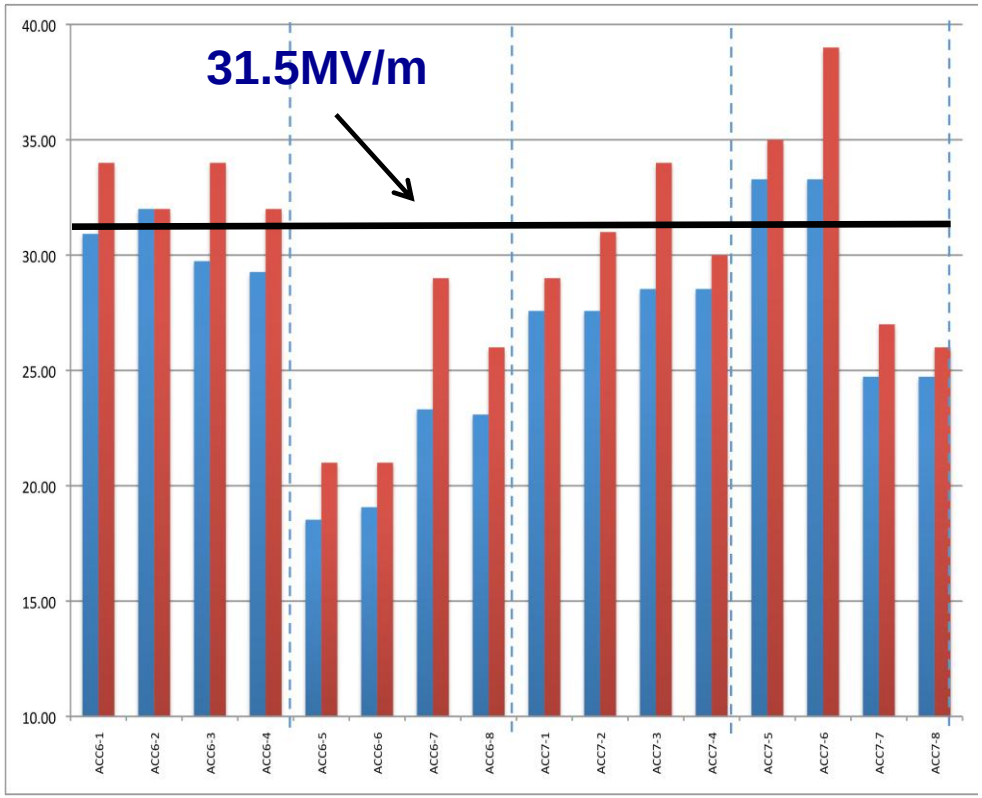
Solutions modeled to achieve flat gradients without adjusting Pk

Simulation for 38 MV/m & 25 MV/m cavities

Wrap-up

Extrapolating FLASH to ILC gradients

Gradient limits for 16 cavities in ACC6/7



Cavity quench limits and gradient spread are close to ILC design

Realistic conditions for 'Operation at the Limits' studies:

- **Gradient overhead, RF power overhead**
- **Vector-sum control**
- **RF distribution setup**
- **Lorentz-force detuning compensation**

Summary

- **'Near ILC-like' operating conditions achieved (Sept 2009)**
  - Reliable steady-state operation with 800us bunch trains at 3mA
  - Significant progress towards full spec: 9mA/600us, 6mA/800us
  - Energy stability (7.5mA): ~0.5% p-p
  - Energy stability (0.3mA): ~0.1% p-p

- **Continuing improvements for routine FEL user operation**
  - Cavity field regulation (June 2010, FEL op.): ~0.01% and <0.03 deg
  - Routine operation for users with trains of up to 200 bunches
  - Operation close to cavity gradient limits (up to 1.25GeV beam)

- **FLASH is 6% of XFEL which itself is 6% of ILC. The beam performance parameters are quite close.**
- **In many ways it is an excellent representation of full ILC performance**