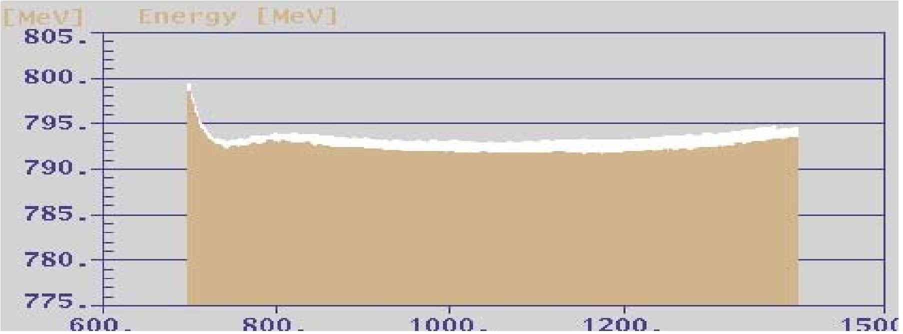
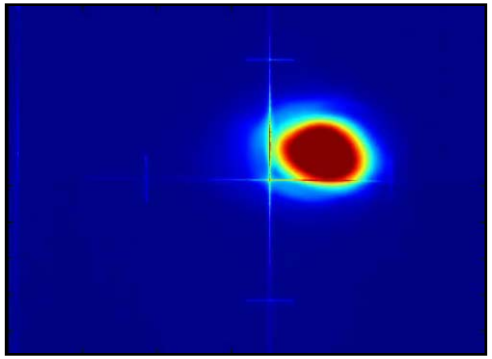
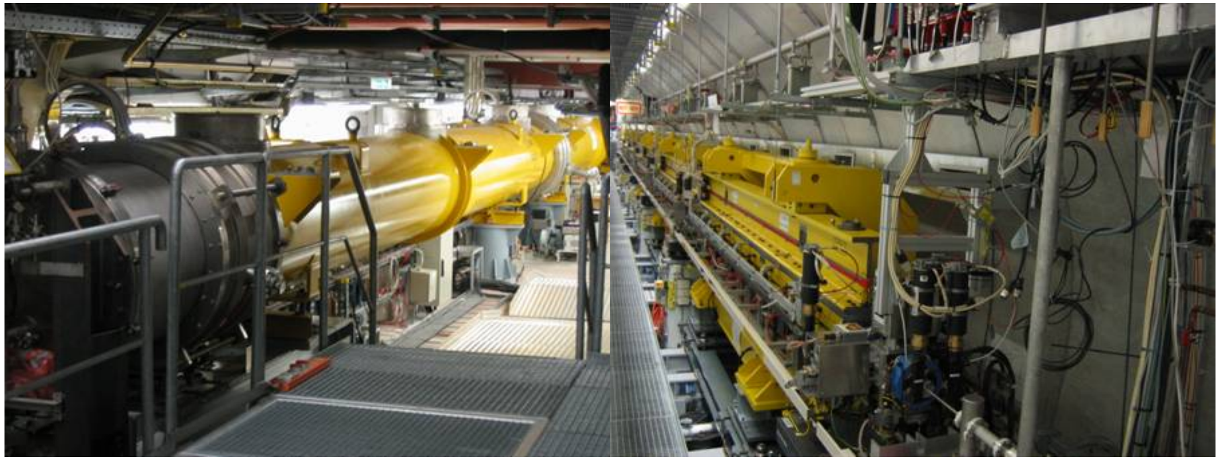
Full Beamloading at FLASH

FLASH.
Free-Electron Laser in Hamburg







Siegfried Schreiber, DESY
Nick Walker, DESY
John Carwardine, ANL

1st Annual RFTech meeting

DESY
29-30 Mar 2010

HELMHOLTZ
GEMEINSCHAFT

DESY

FLASH with PETRA and the European XFEL

FLASH.
Free-Electron Laser
in Hamburg

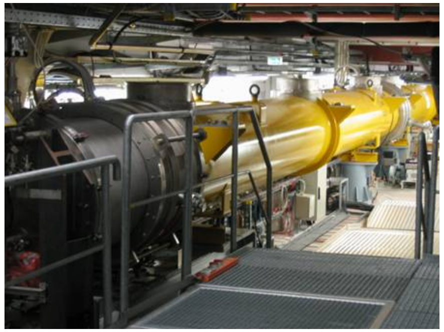
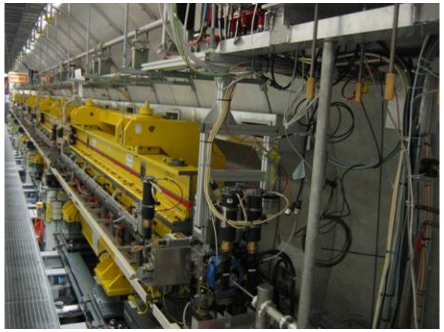
FLASH at DESY in Hamburg

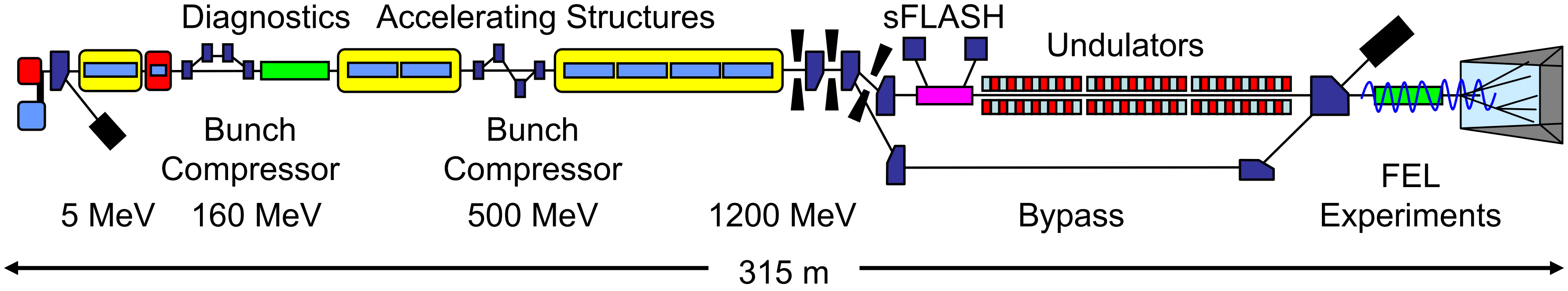
FLASH.
Free-Electron Laser
in Hamburg

- Single-pass high-gain SASE FEL
  - **SASE = self-amplified spontaneous emission**
- Photon wavelength range from vacuum ultraviolet to soft x-rays
  50 nm to 5 nm
- Femtosecond short coherent laser like radiation
- Free-electron laser user facility since summer 2005
  - 1st period: Jun 2005 – Mar 2007
  - 2nd period: Nov 2007 – Aug 2009
  - 3rd period: starting summer 2010
- FLASH is also a test bench for the European XFEL and the International Linear Collider (ILC)

FLASH layout

FLASH.
Free-Electron Laser
in Hamburg

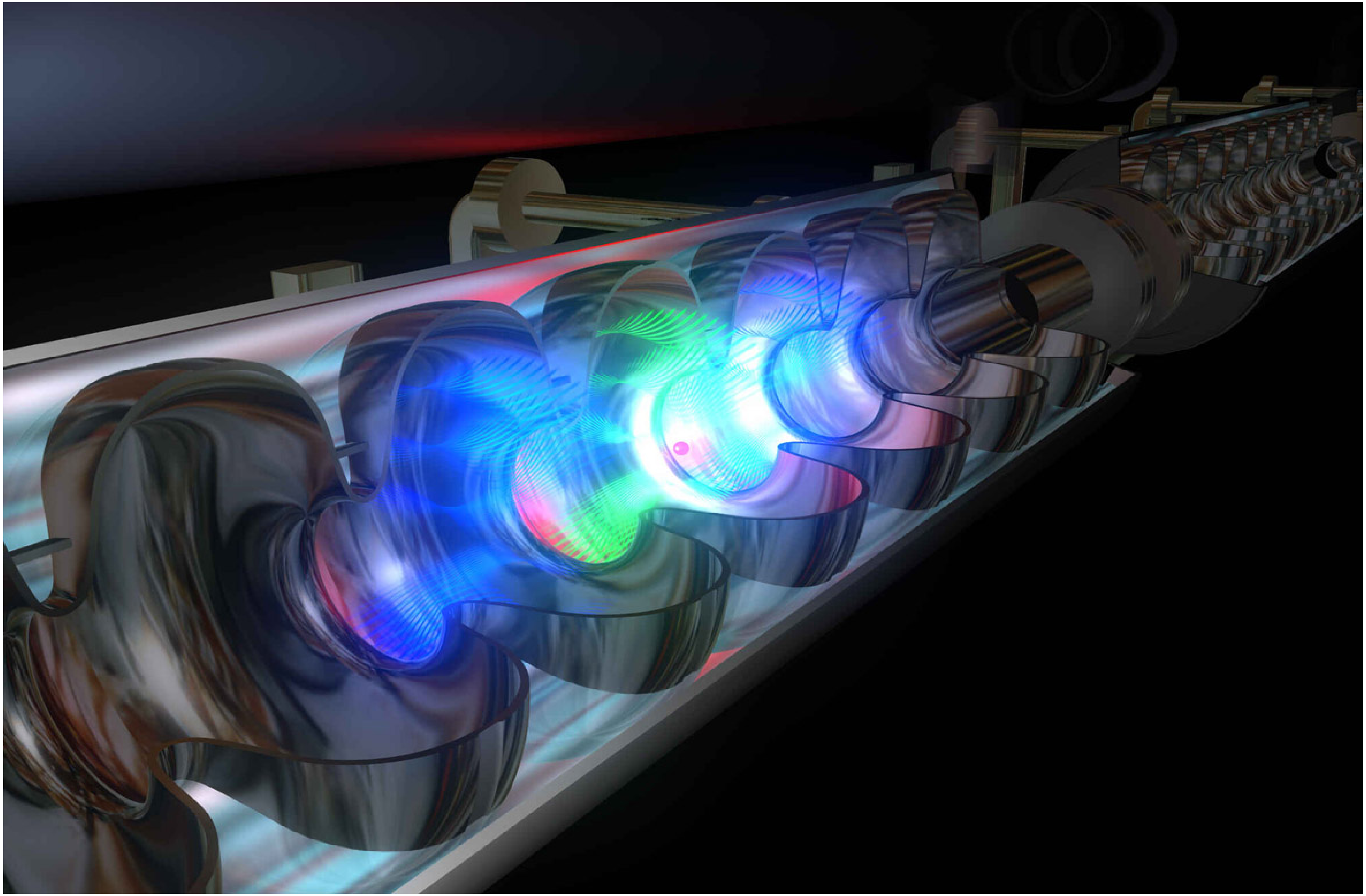




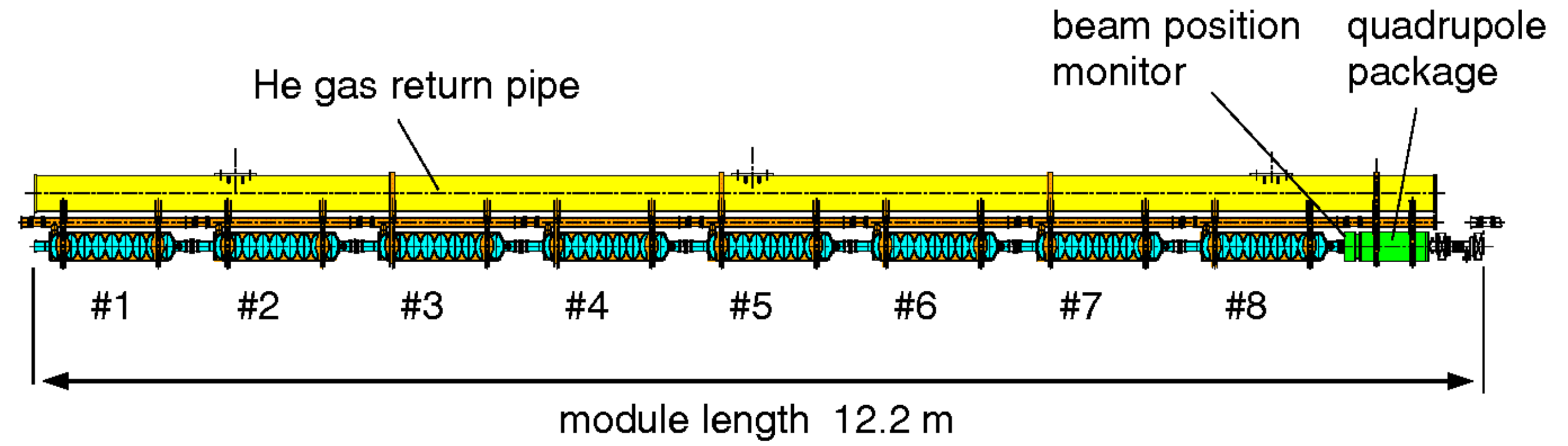


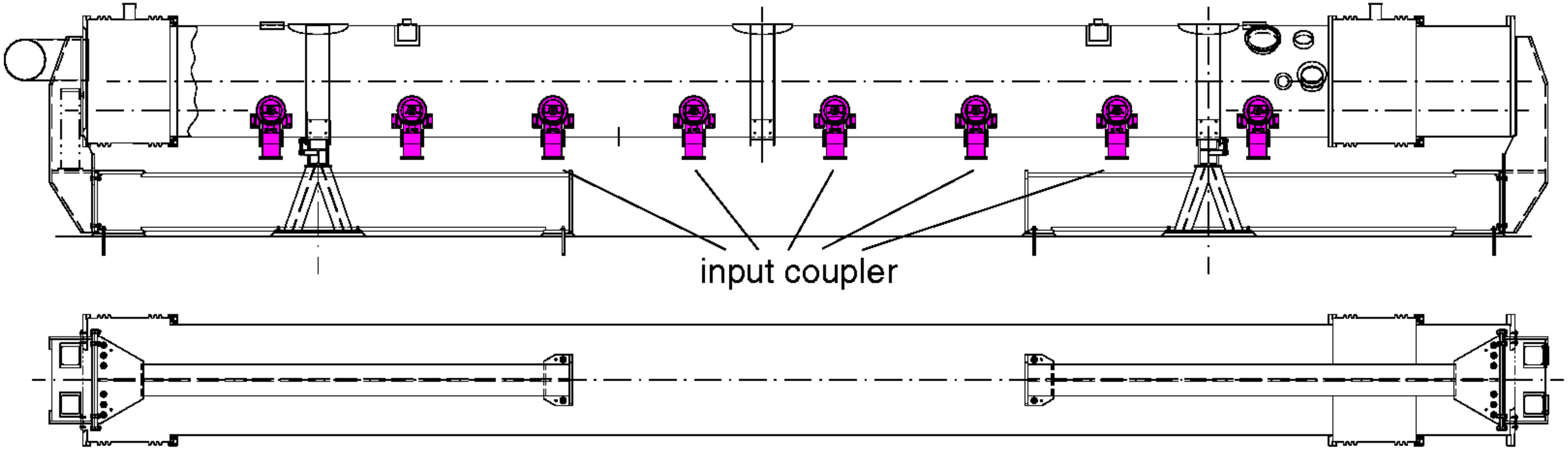

FLASH uses TESLA technology

FLASH.
Free-Electron Laser
in Hamburg



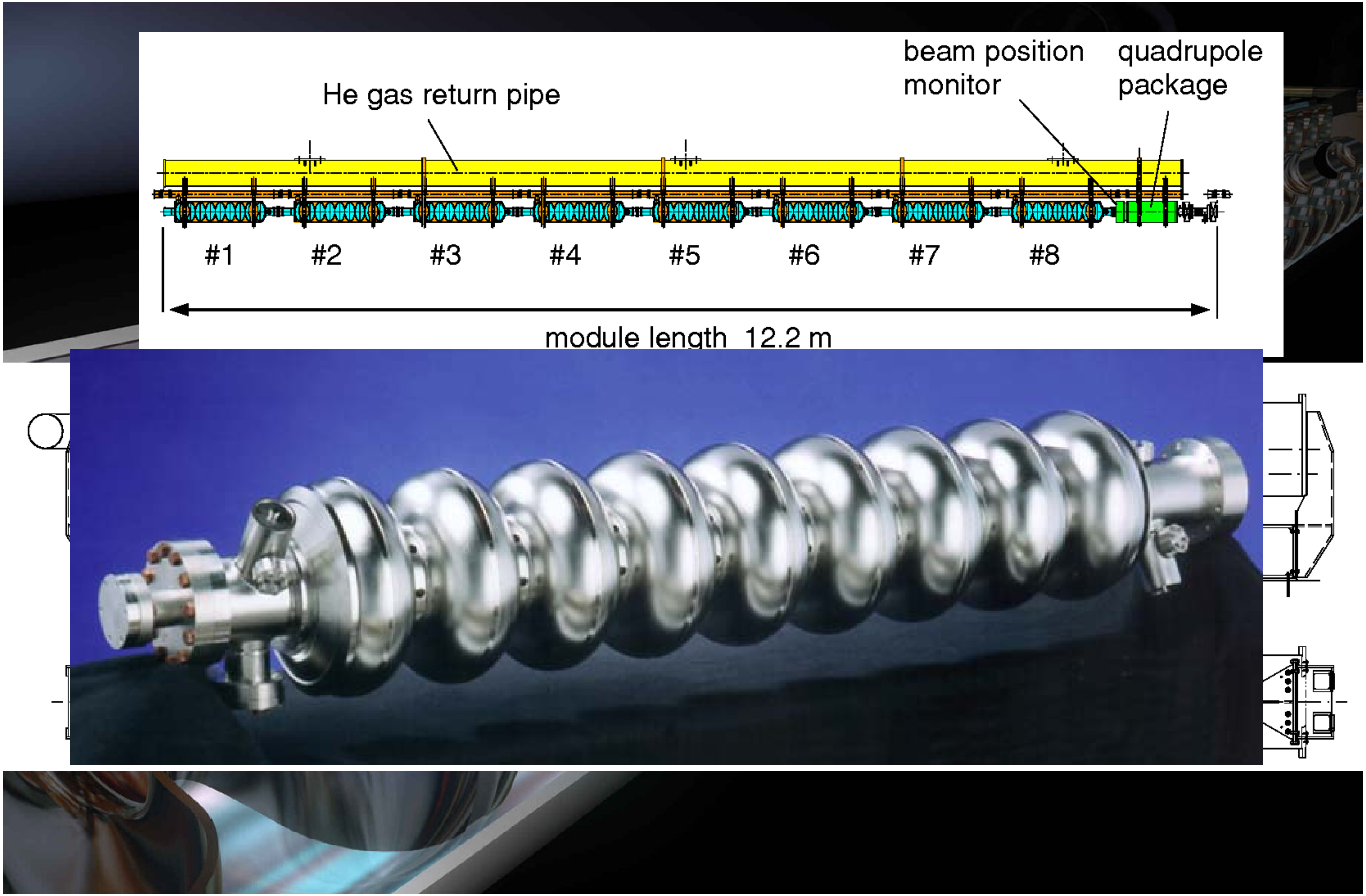
FLASH uses TESLA technology

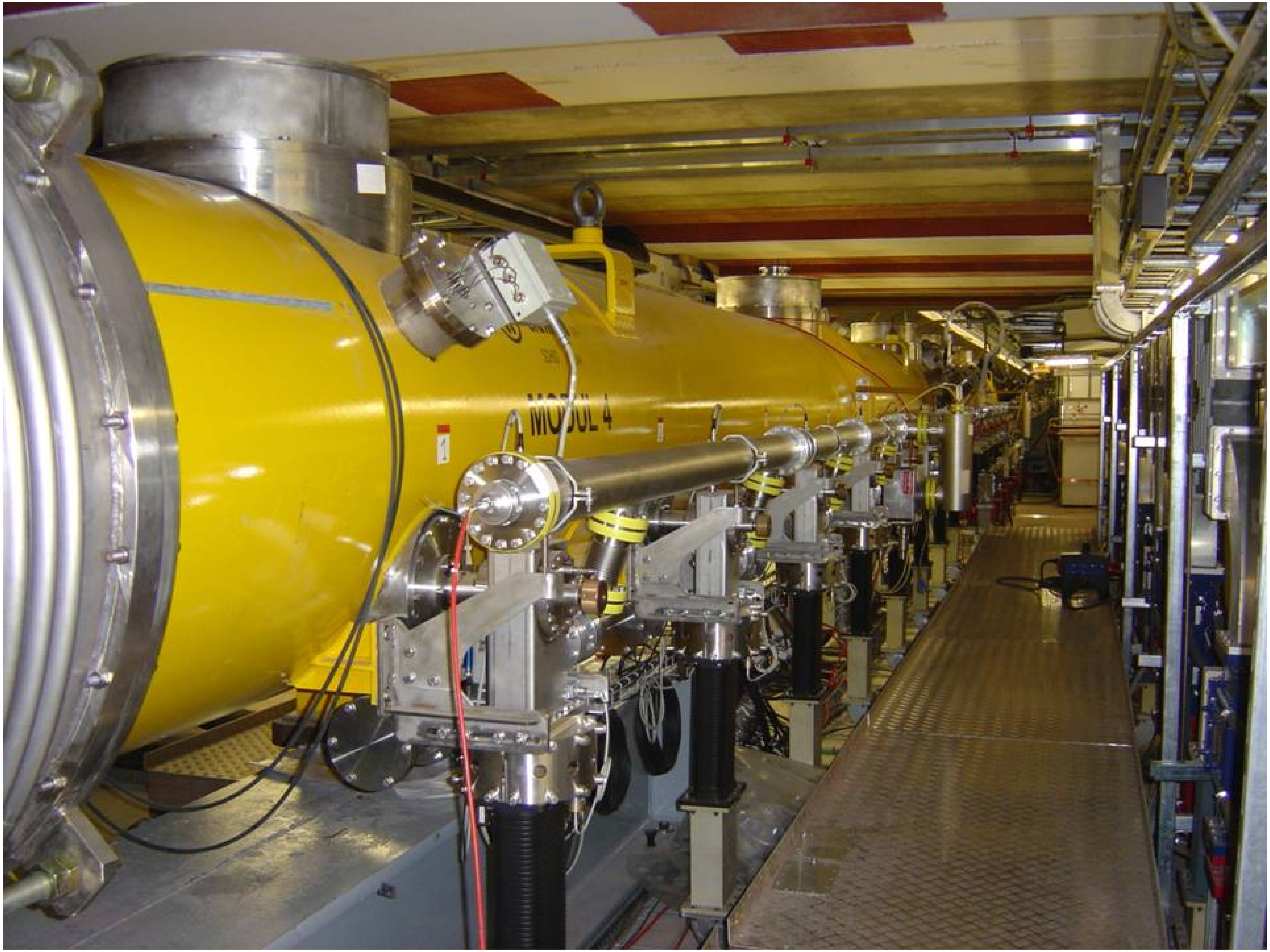




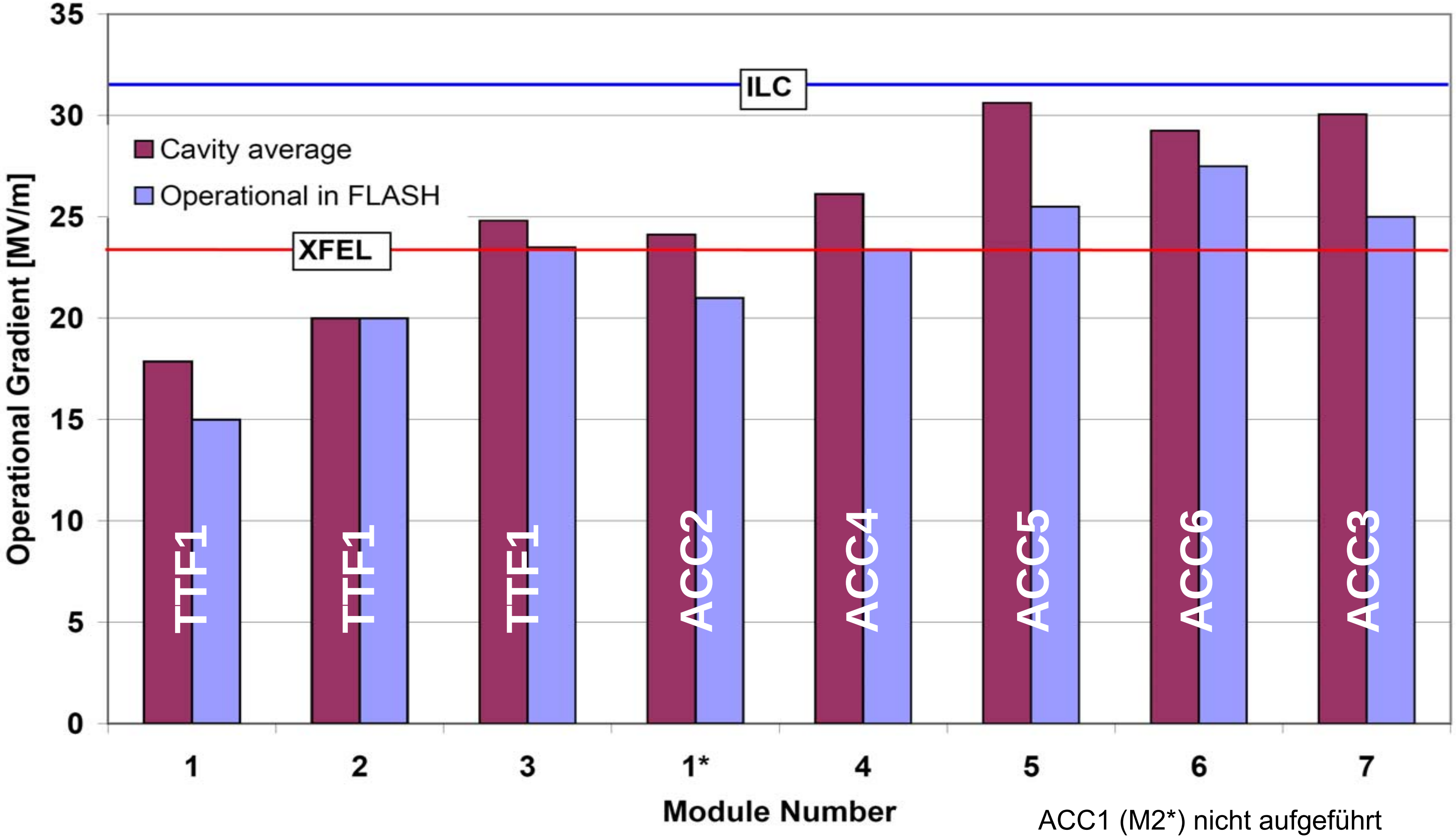
FLASH uses TESLA technology

FLASH.
Free-Electron Laser
in Hamburg




MODUL 4

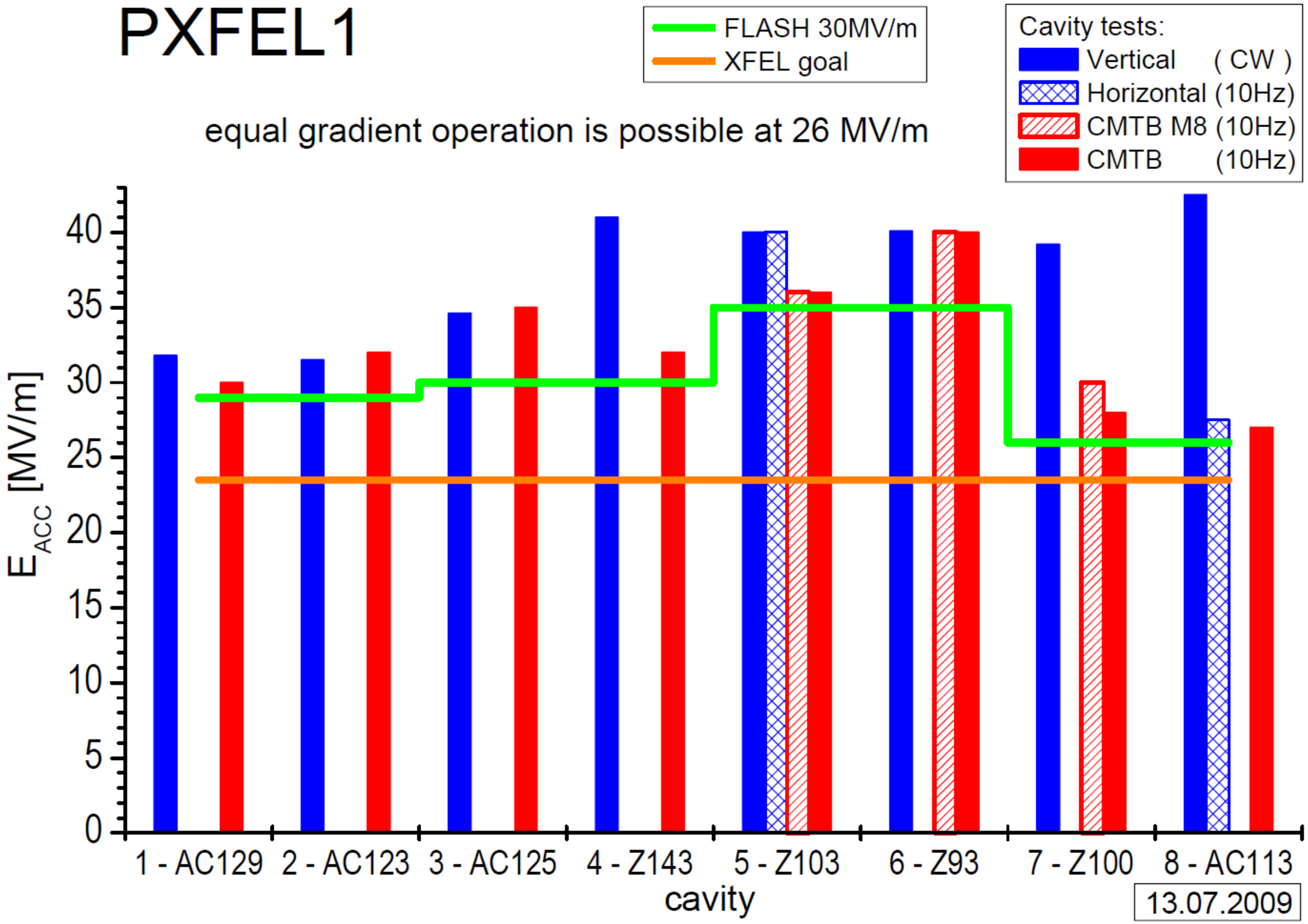
Accelerating gradient



ACC1 (M2*) nicht aufgeführt

Module PXFEL1 in FLASH – a prototype for XFEL

FLASH. Free-Electron Laser in Hamburg



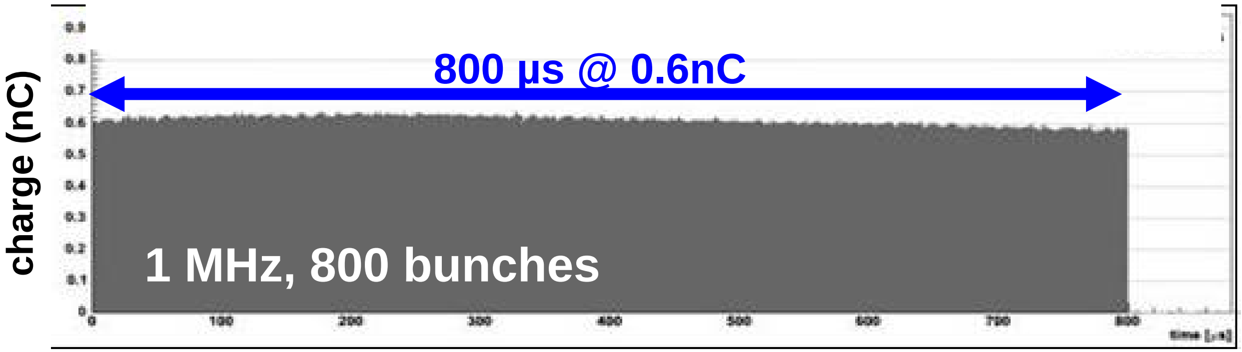
D.Kostin, 13.07.2009

Long Bunch Trains

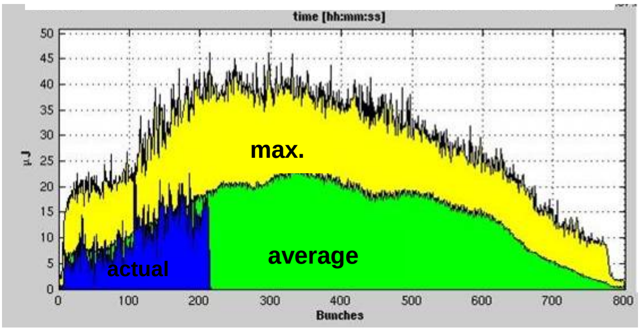
FLASH design goals reached in 2007

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

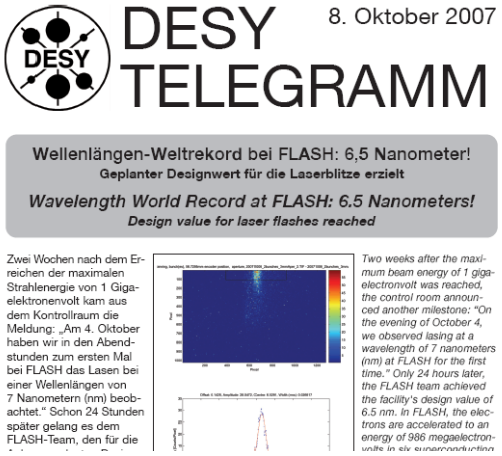
Der Durchbruch passierte wieder in einer Nachtschicht, genauer am 21.9.2007, um 0:57 Uhr. Dieses Mal ging es um das Erreichen der geplanten maximalen Strahlenergie. „Ziel: Betrieb mit höchster Energie – Ergebnis: 1 GeV Energie !! Gemessenes Spektrum der spontanen Emission: ~ 6,3 nm", so der Eintrag im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



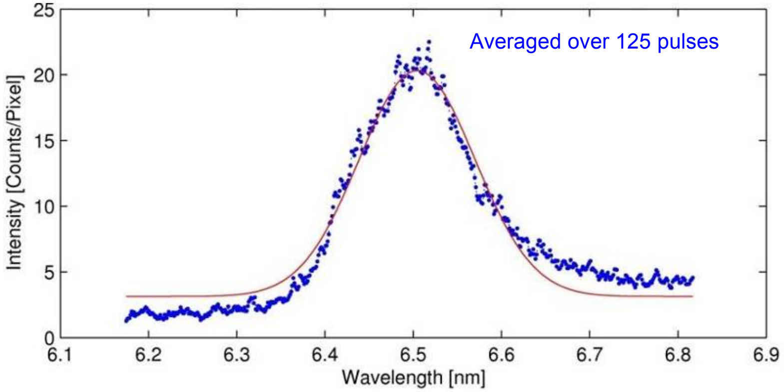
DESY TELEGRAMM 8. Oktober 2007

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

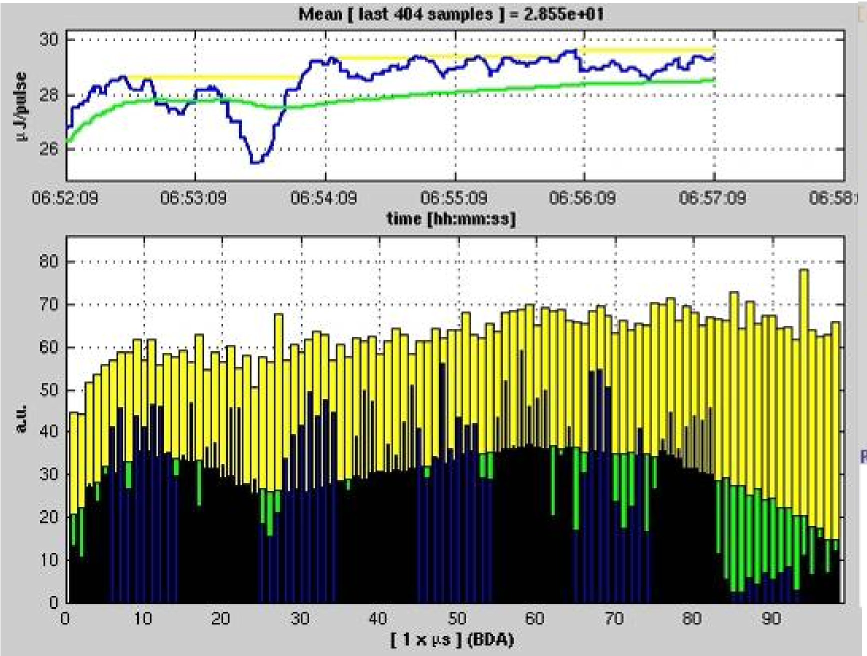
Two weeks after the maximum beam energy of 1 gigaelectronvolt was reached, the control room announced another milestone: "On the evening of October 4, we observed lasing at a wavelength of 7 nanometers (nm) at FLASH for the first time." Only 24 hours later, the FLASH team achieved the facility's design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



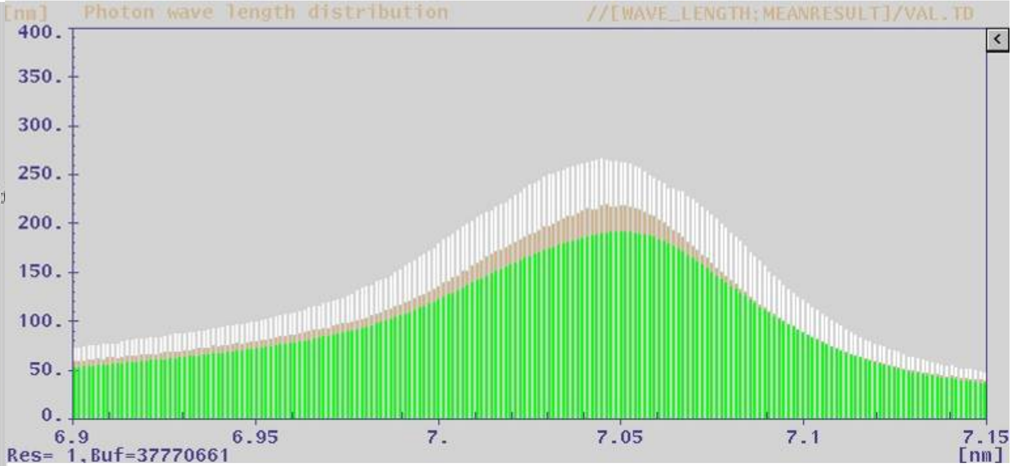
Long Bunch Train Run at 7 nm in 2008

FLASH. Free-Electron Laser in Hamburg

- 5 days continuous running with 100 bunches 500 kHz for two experiments in March 2008
- Wavelength: 7.05 ± 0.1 nm
- Average SASE level ~30 µJ (14 mW average power)



Bunch Number



Wavelength (nm)

Why Long Bunch Trains?

> Long bunch trains with thousands of bunches per second are fundamental to the advantage of the TESLA superconducting RF accelerating technology

> FLASH or XFEL → more bunches, higher average brilliance

- Significant opportunities for experiments with X-rays
- Also a challenge for the experimental equipment
- Single-bunch parameters are critical (equal lasing of all bunches required!)
- Bunch charges may be low (< 9 mA), but with high peak current
- Need flexibility to serve several experiments at the same time

> International Linear Collider (ILC) → more bunches, more Luminosity

- Absolutely required to reach physics goals
- Design current in pulse train: 9 mA

Why Long Bunch Trains?

FLASH.
Free-Electron Laser
in Hamburg

> Long bunch trains with thousands of bunches per second are fundamental to the advantage of the TESLA superconducting RF accelerating technology

> FLASH or XFEL → more bunches, higher average brilliance

Long bunch-train operation is a defining capability of the DESY FEL light sources

  - Bunch charges may be low (< 9 mA), but with high peak current
  - Need flexibility to serve several experiments at the same time

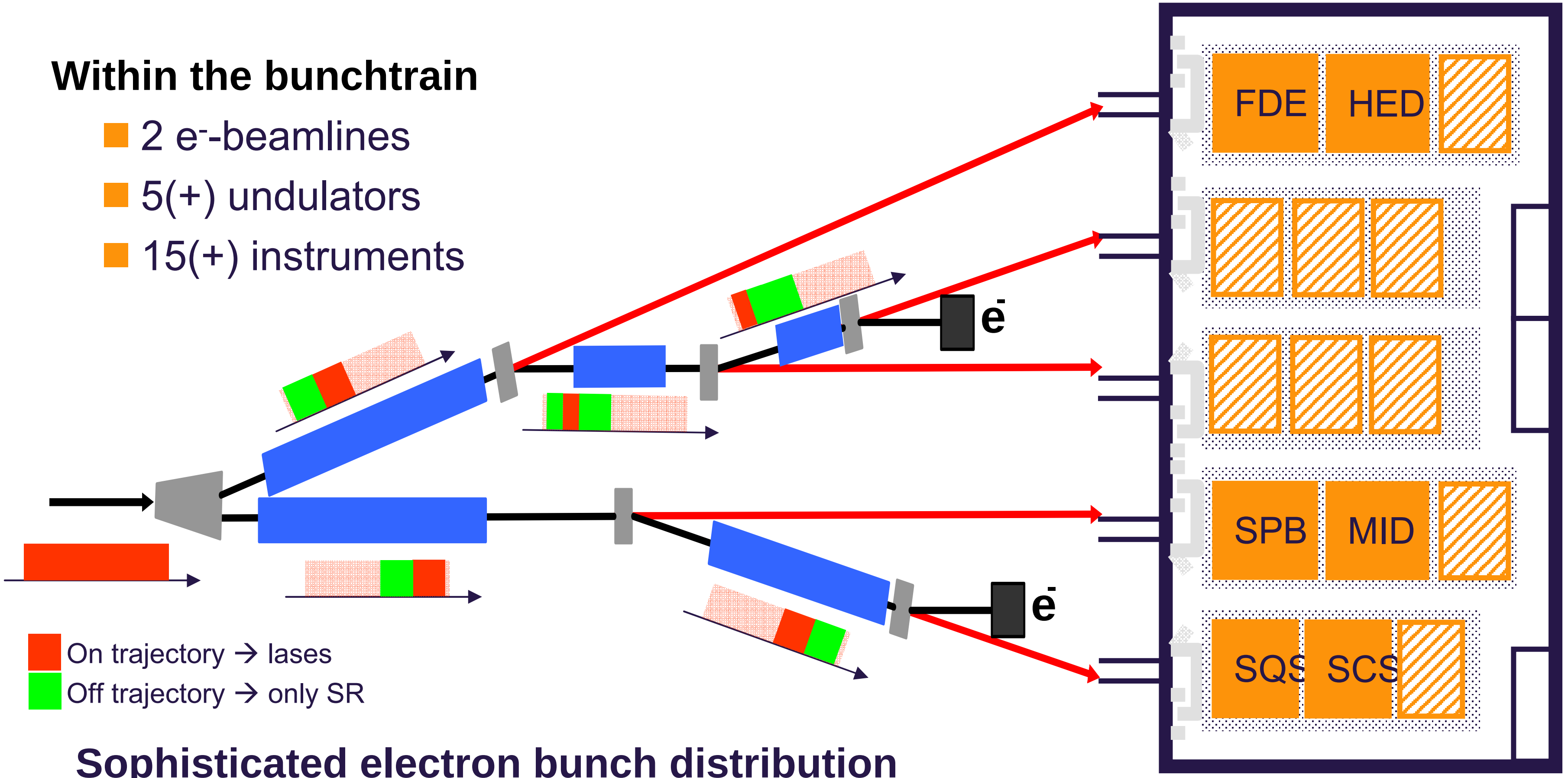
> International Linear Collider (ILC) → more bunches, more Luminosity

  - Absolutely required to reach physics goals
  - Design current in pulse train: 9 mA

Simultaneous operation of many instruments

Within the bunchtrain

- 2 e⁻-beamlines
- 5(+) undulators
- 15(+) instruments



Boxes only placeholders !

🟥 On trajectory → lases
🟩 Off trajectory → only SR

Sophisticated electron bunch distribution

- 27.000 bunches/sec to 5 beamlines
- in average 10-20 Hz and ~500 pulses/train
- using kicking methods to make bunches lase only in dedicated undulator

Bunch Pattern

	Macro-pulse repetition rate	Macro-pulse length	Max bunches per macro-pulse	Beam current during macro-pulse	Max bunches per second
LCLS	30 Hz - 120 Hz	n/a	1	n/a	30 - 120
FLASH (9 mA) *(Bypass mode)*	5 Hz	800 µs	800 @ 1 MHz 2400 @ 3 MHz	1 mA 9 mA	4000 12000
FLASH (2010)	10 Hz	800 µs	800 @ 1 MHz	1 mA	8000
European XFEL	10 Hz	650 µs	2900 @ 4.5 MHz	4.5 mA	29000
ILC (RDR)	5 Hz	970 µs	1000 - 5400	9 mA	5000 - 27000

> SC-based linacs operate in burst mode with thousands of bunches/sec

Full Beam Loading

Full Beam Loading

TESLA parameters:

8 mA for

loaded Q = $3\ 10^6$

fill time 500 µs

acc field 25 MV/m

ILC: 9 mA

Full beam loading program at FLASH

> ILC initiated: part of the Global Design Effort R&D

- Operation of an RF-unit (3 TESLA type modules) with ILC-like beams

> A DESY program with international participation

> Important for XFEL and FLASH

- XFEL

  - Close collaboration with world-wide LLRF groups
  - Essential “Operation at limits” experience
  - Focus development and planning for XFEL

- FLASH

  - Addresses important operational issues
  - Towards routine high-power long-pulse operation for users

Full beam loading studies at TTF and FLASH

1997	TTF (Injector I)	217 MHz	173600 bunches	37 pC	8 mA (130 MeV)
2002	TTF (Injector II)	1 MHz	750 bunches	2.8 nC	2.8 mA
2006	FLASH	1 MHz	800 bunches	0.8 nC	400 lasing
2007	FLASH	1 MHz	800 bunches	0.6 nC	800 lasing
2008	FLASH	1 MHz	550 bunches	2.7 nC	9 mA exp.
Shutdown to replace beam dump vacuum line					
2009	FLASH	1 MHz 3 MHz	800 bunches 2400 bunches	3 nC 2 nC	9 mA exp (1 GeV)

- Proof of principle has long been established
- Long bunch-train running always characterized by difficult set-up!
- Remaining goal is routine and stable operation for FLASH users
- 9 mA goals addresses operational limits (pushed by ILC requirements)

Objectives of the full beam loading experiment

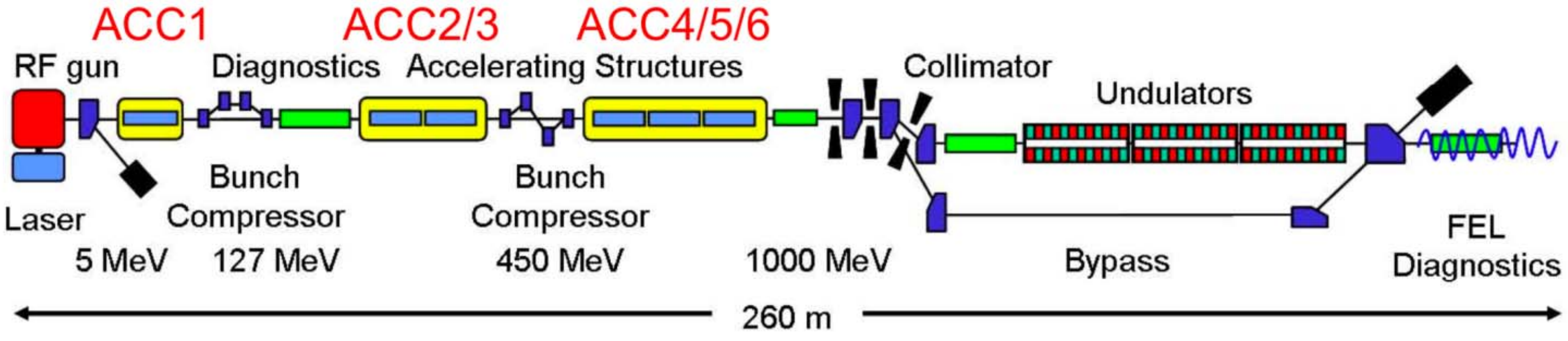
- Long-pulse high beam loading (9 mA) demonstration
  - 800 µs pulse length with 2400 bunches (3 MHz), 3 nC per bunch
  - Vector sum control of up to 24 cavities, ± 0.1 % energy stability
  - Cavity gradients approaching quench limits
  - Beam energy 700-1000 MeV
- Characterize operational limits
  - Energy stability limitations
  - Klystron overhead needed for LLRF control
  - HOM absorber studies (cryo-load)
- Operation close to limits, eg
  - Robust automation of tuning, etc
  - Quench detection/recovery, exception handling
  - Beam-based adjustments/optimization

Operational challenge for FLASH

Well beyond typical beam parameters for photon users

FLASH 9 mA experiment

FLASH.
Free-Electron Laser in Hamburg



Nominal experiment setup

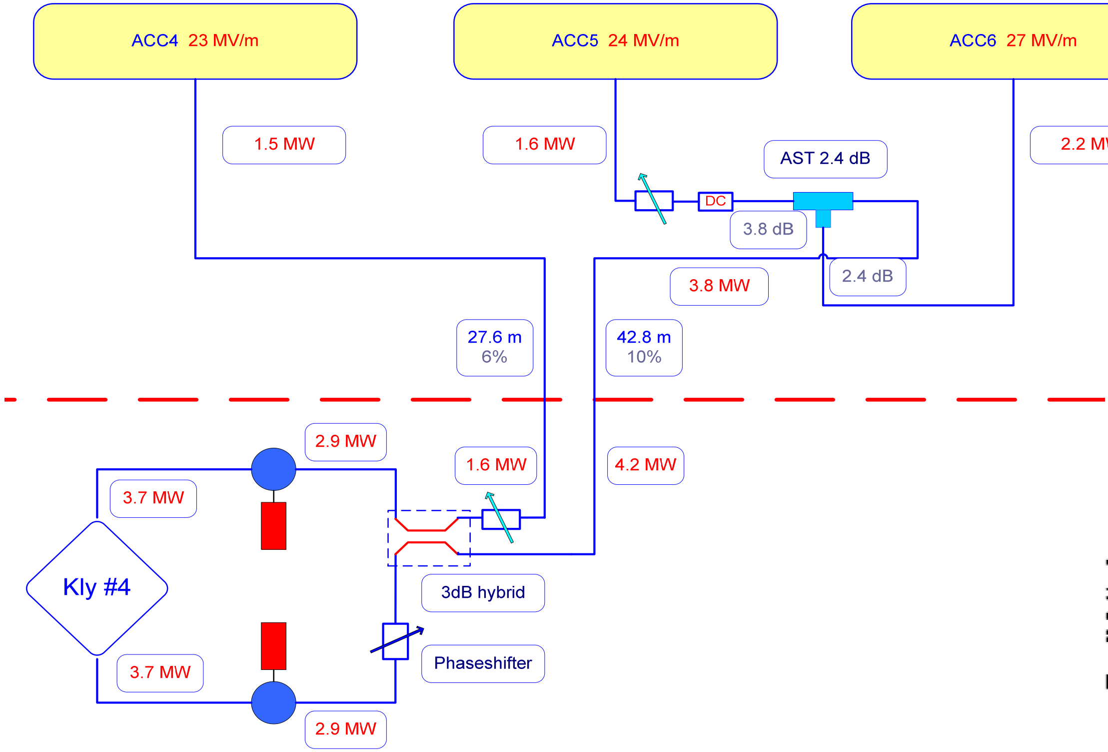
- 3 nC / bunch
- Bunch rates: 40 kHz – 3 MHz
- RF systems operating ‘on crest’
- BC magnets on, but no compression
- Beam through Bypass line to dump

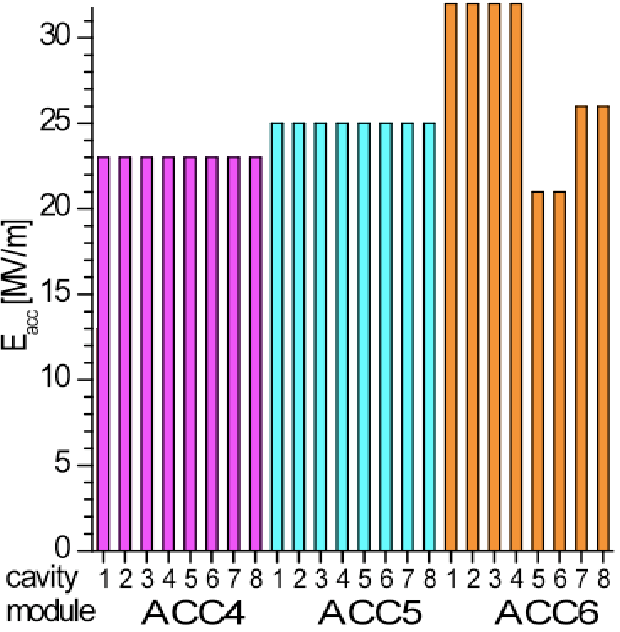
- RF gun – 1.5 cell L-band warm photoinjector
- ACC1 – 8 SC cavities
- ACC23 – 2x 8 SC cavities
- ACC456 – 3x 8 SC cavities
- LLRF – digital I/Q control of VS
- Piezo tuners – ACC3, ACC5, ACC6

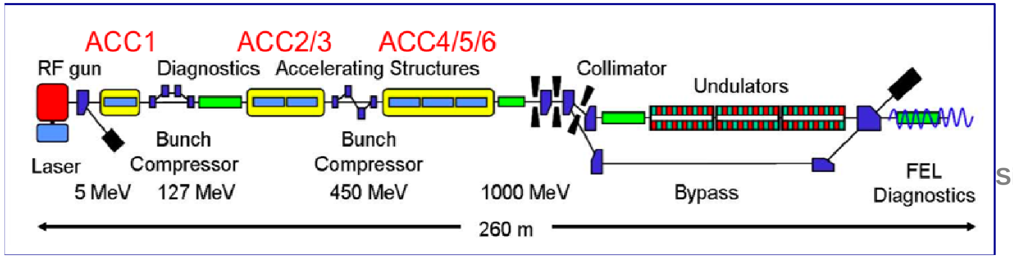
ACC456 – focus of the experiment

FLASH.
Free-Electron Laser in Hamburg

- the 3 modules ACC4, 5, and 6 build an ILC type accelerating unit powered by one 10 MW multi beam klystron







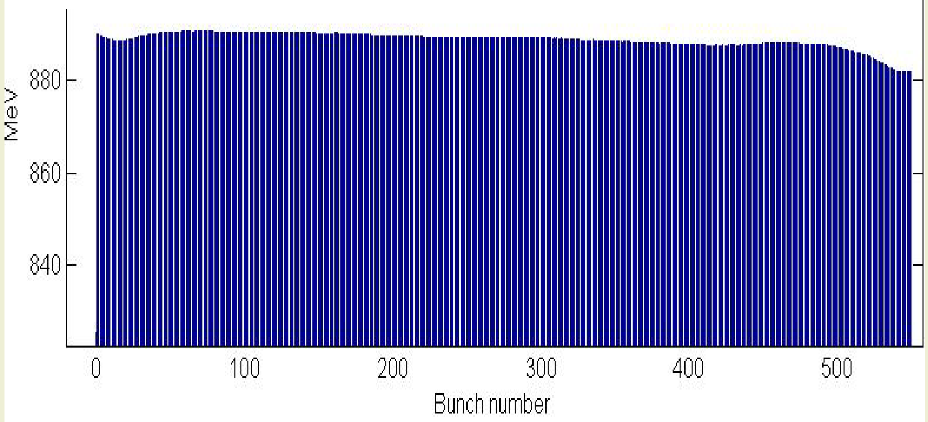
First run September 2008

FLASH.
Free-Electron Laser in Hamburg

High beam-loading long pulse operation

(550 bunches at 1 MHz, ~2.5 nC / bunch at dump, 890 MeV)

Beam Energy along 550 μs bunch train



Long bunch trains:

- **450 bunches @ 1 MHz**
- **300 bunches @ 500 kHz**

… terminated early by vacuum incident in dump line

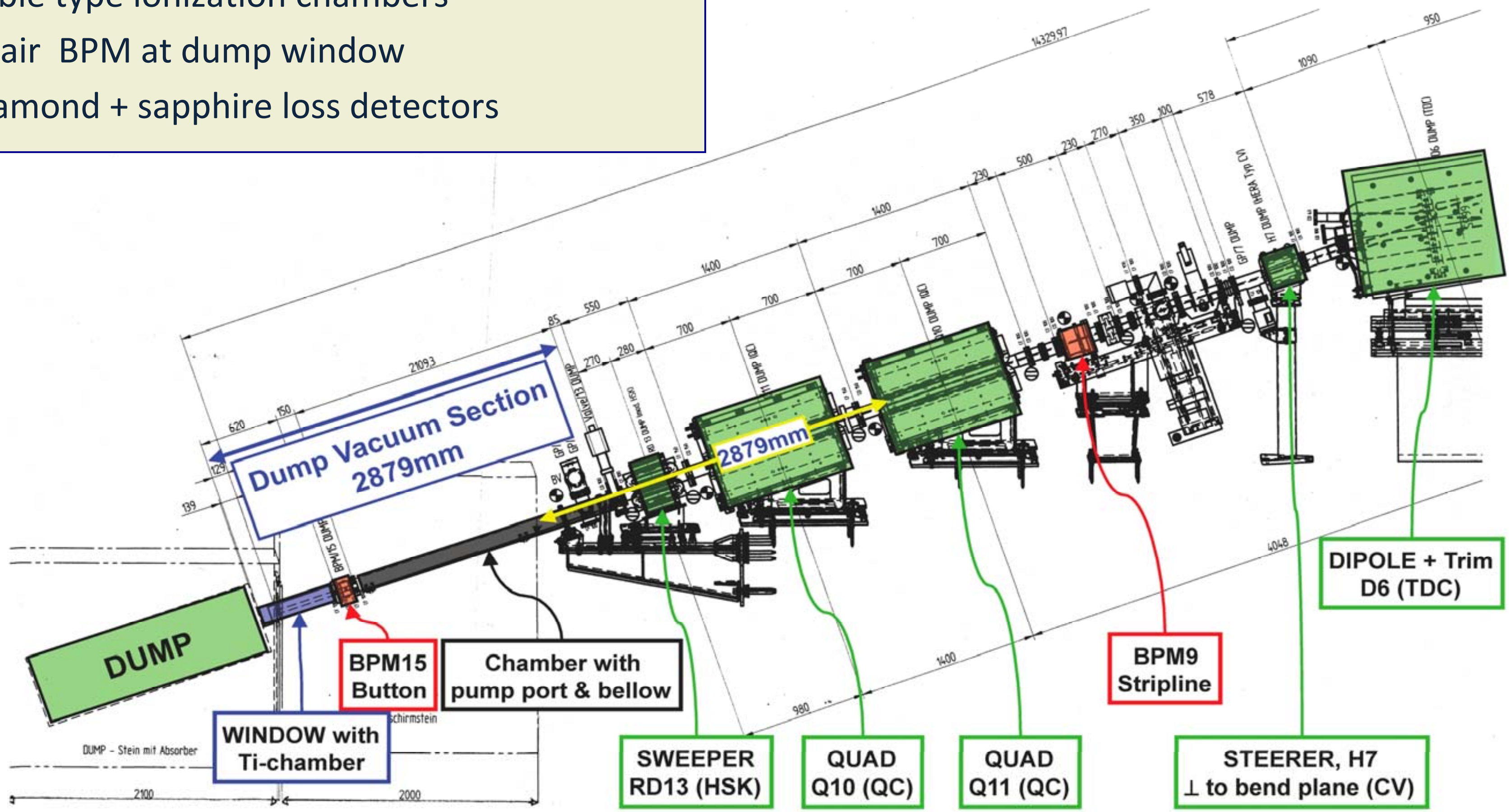
Biggest operational issue: minimizing beam losses

- High beam power (~6 kW)
- Narrow energy aperture, sensitive to LLRF tuning
- Insufficient beam loss information from dump line

Dump line section

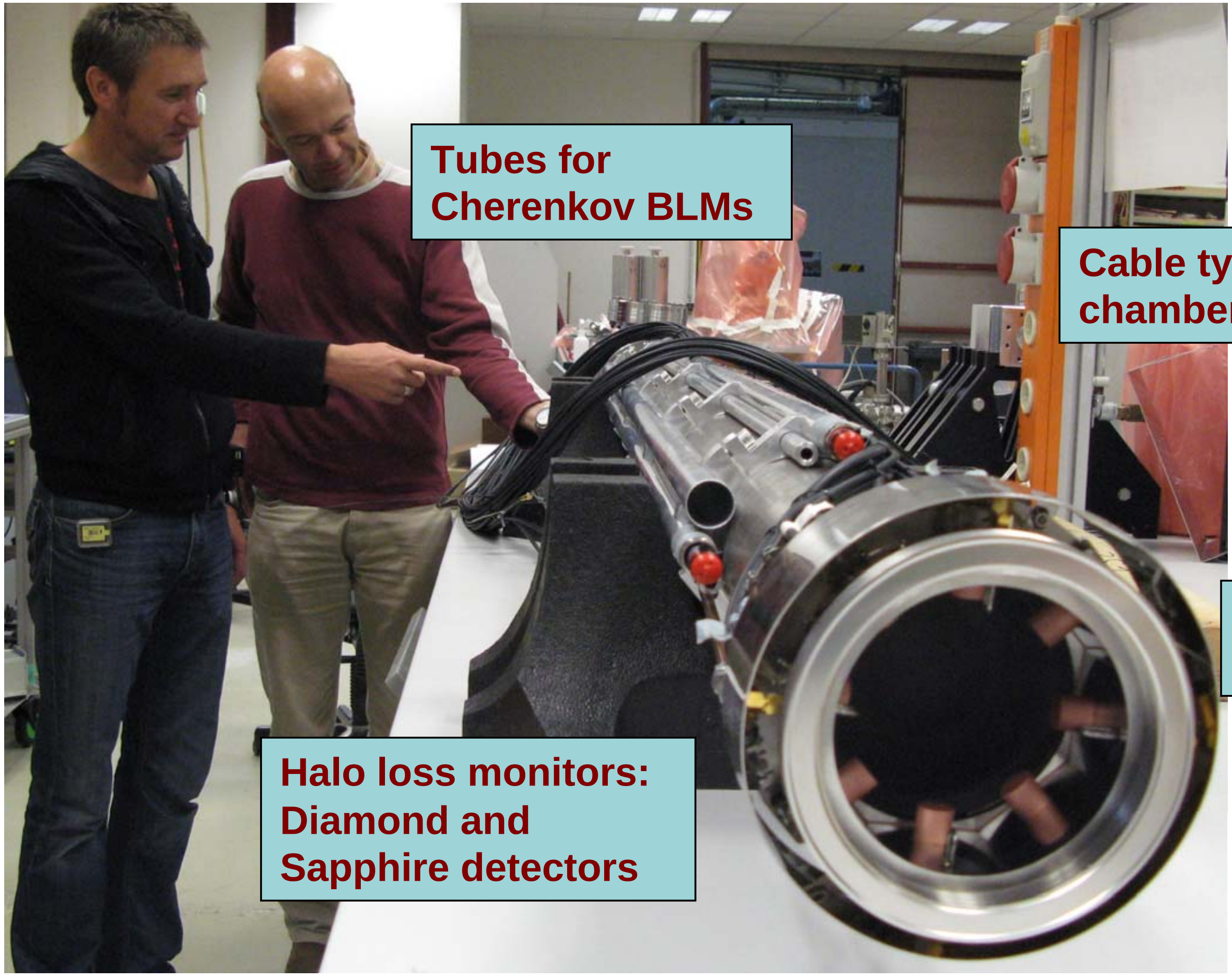
New dump line section with improved diagnostics

- New vacuum pipe (Ti)
- Cherenkov fibers
- Cable type ionization chambers
- In-air BPM at dump window
- Diamond + sapphire loss detectors



Dump line vacuum chamber

FLASH.
Free-Electron Laser in Hamburg



Tubes for Cherenkov BLMs

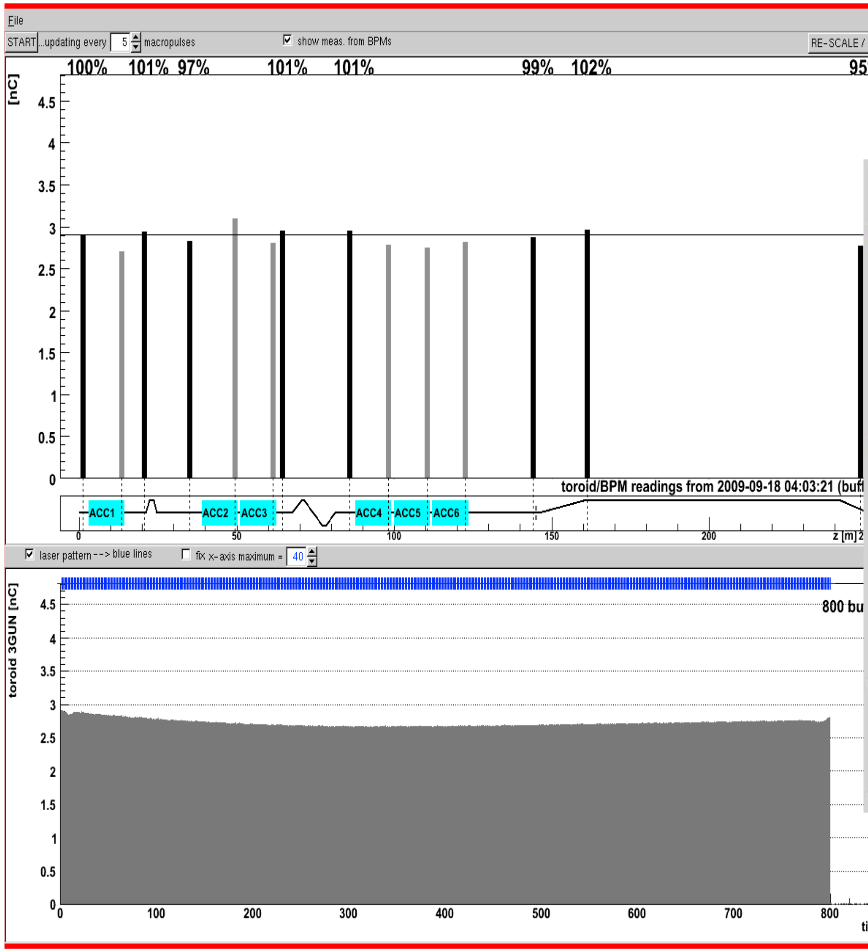
Cable type ionization chambers

In-air BPM (current loops)

Halo loss monitors: Diamond and Sapphire detectors

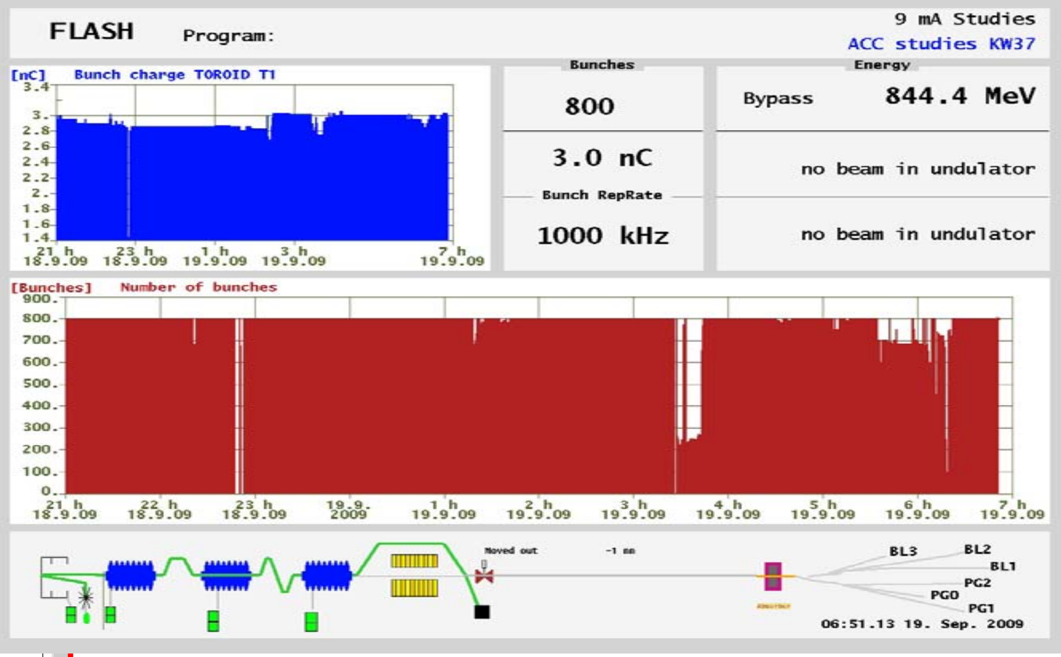
1st step: 800 bunches, 3 nC/bunch

**Bunch charge ~ 3 nC along the linac
and bunch train with 800 bunches at ~3 mA**



toroid/BPM readings from 2009-09-18 04:03:21 (buf

**stable beam with 800 bunches
at ~3 mA for 15 hrs**



FLASH Program: 9 mA Studies
ACC studies KW37

Bunches: 800

3.0 nC

Bunch RepRate: 1000 kHz

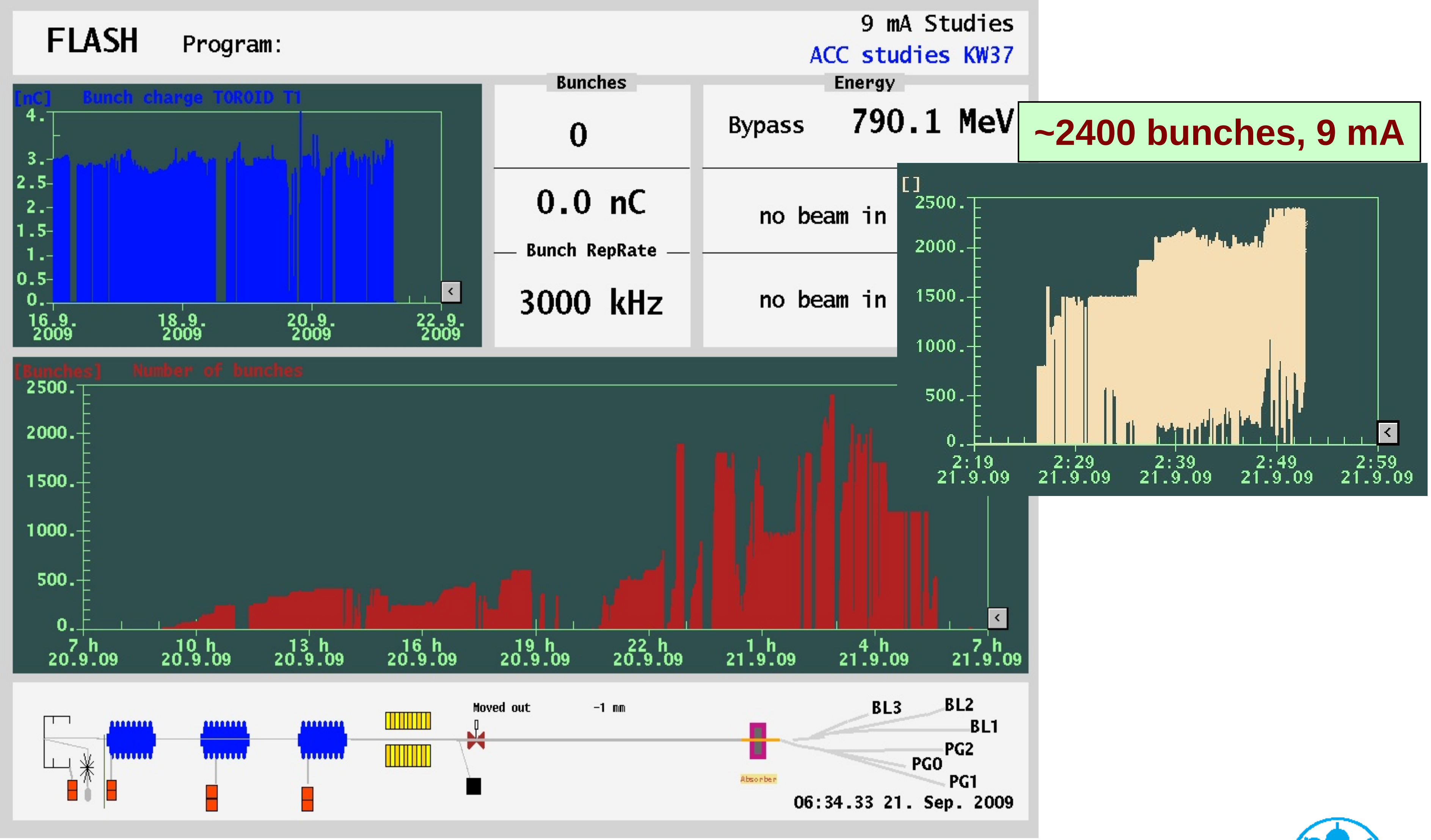
Energy: Bypass 844.4 MeV

no beam in undulator

no beam in undulator

06:51.13 19. Sep. 2009

2nd step: 2400 bunches 3 nC towards 9 mA



FLASH Program: 9 mA Studies
ACC studies KW37

Bunches: 0

0.0 nC

Bunch RepRate: 3000 kHz

Energy: Bypass 790.1 MeV

no beam in

no beam in

06:34.33 21. Sep. 2009

~2400 bunches, 9 mA

Major achievements Sept 2009

FLASH.
Free-Electron Laser
in Hamburg

Metric	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 per pulse	7200nC @ 3MHz	5400nC @ 3MHz
Beam power	36kW (7200nC, 5Hz, 1GeV)	22kW (6000nC, 5Hz, 800MeV)
Gradients close to quench	Up to 32Mv/m	Several cavities above 30Mv/m at end of long pulse

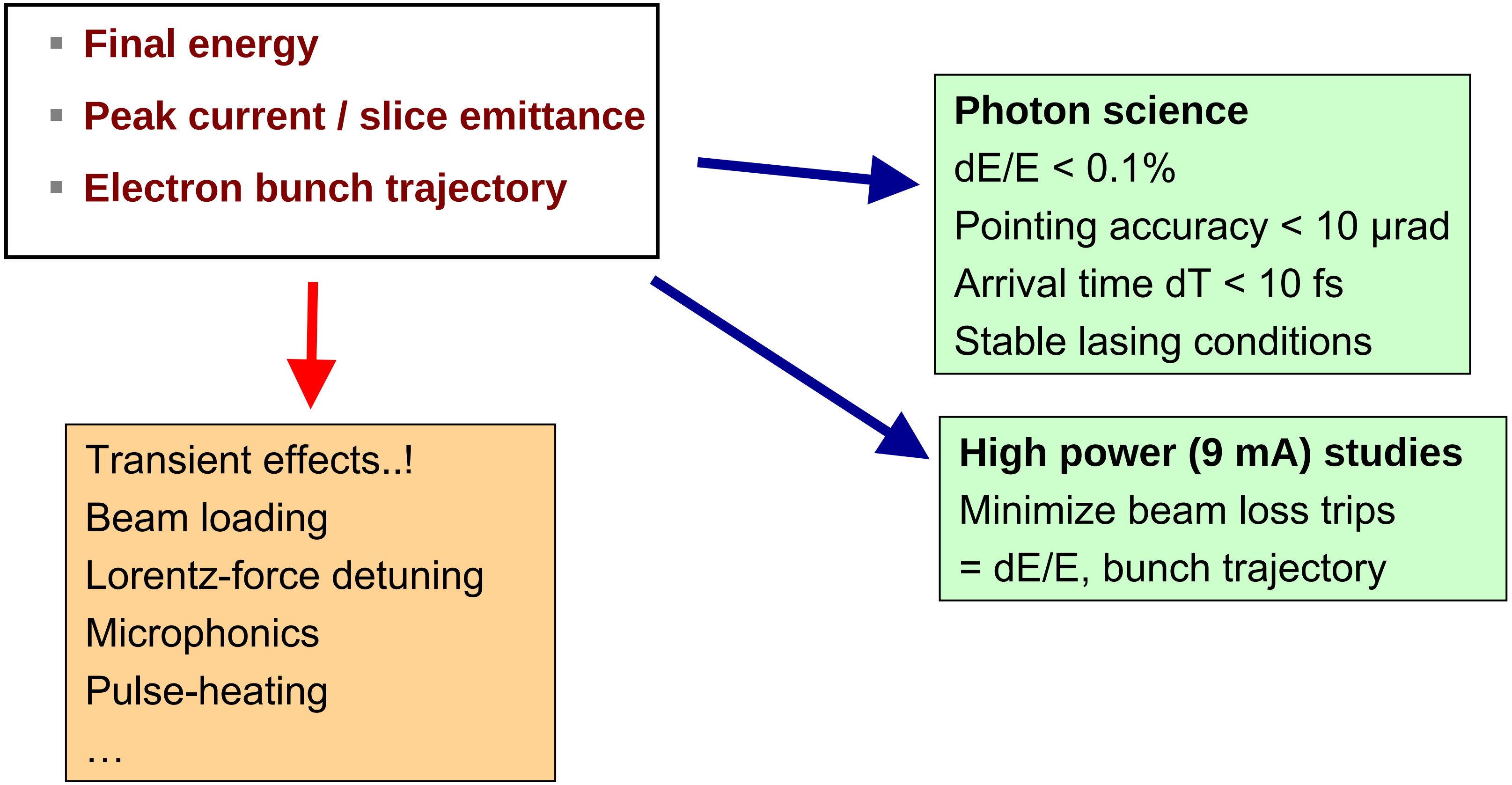
- 15 contiguous hours running with 3 mA and 800 µs bunch trains
- Running at ~9 mA with bunch trains of 500 - 600 µs for several hours
- Full pulse length (800 µs, ~2400 bunches) at ~6 mA for shorter periods

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

Specific Issues concerning LLRF

Long bunch trains issues versus single bunch

- All the challenges with setting up and running the machine are magnified when running long bunch trains
- Requires consistent and stable bunch properties over the bunch train



- **Final energy**
- **Peak current / slice emittance**
- **Electron bunch trajectory**

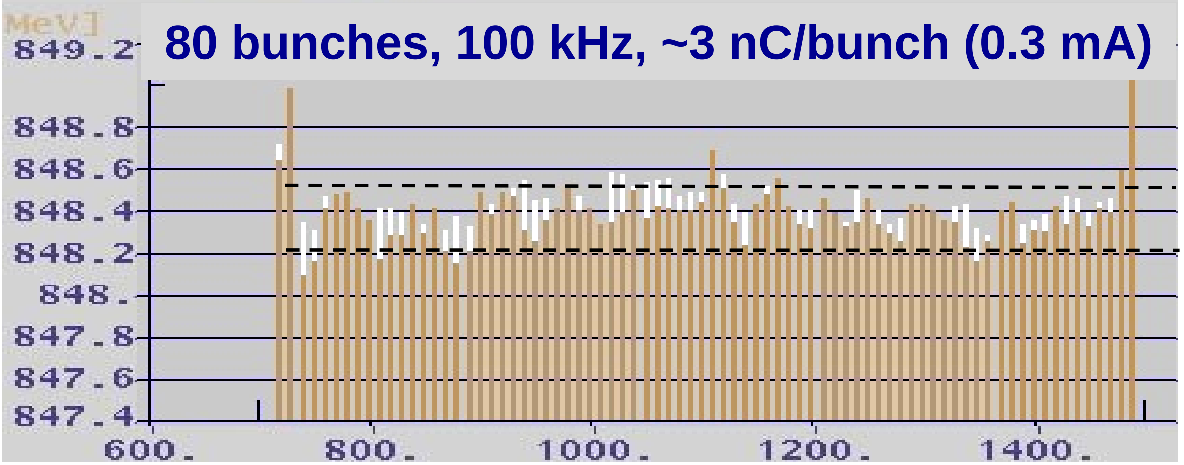
Photon science
dE/E < 0.1%
Pointing accuracy < 10 µrad
Arrival time dT < 10 fs
Stable lasing conditions

High power (9 mA) studies
Minimize beam loss trips
= dE/E, bunch trajectory

Transient effects..!
Beam loading
Lorentz-force detuning
Microphonics
Pulse-heating
…

Example: energy of bunches in the train

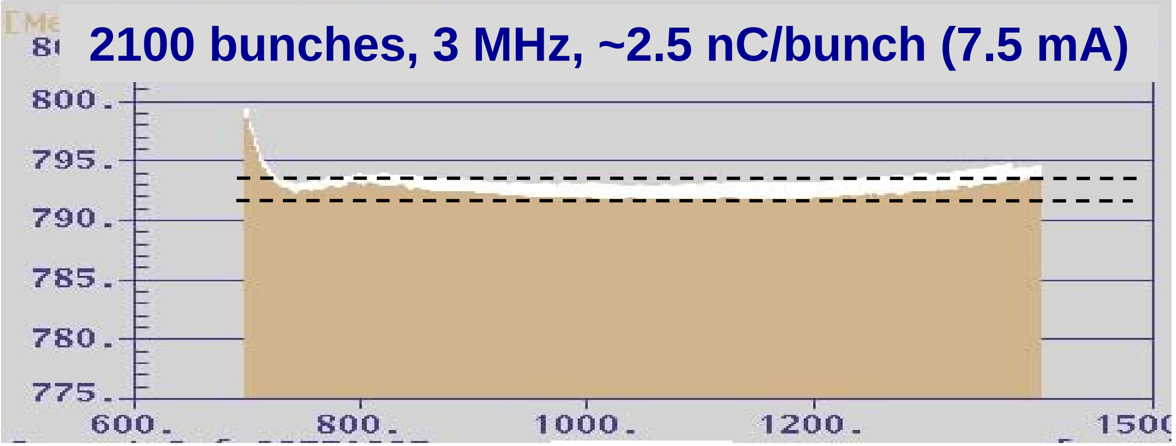
1.8 MeV


80 bunches, 100 kHz, ~3 nC/bunch (0.3 mA)

800us

Along pulse: 0.035 % p-p

30 MeV


2100 bunches, 3 MHz, ~2.5 nC/bunch (7.5 mA)

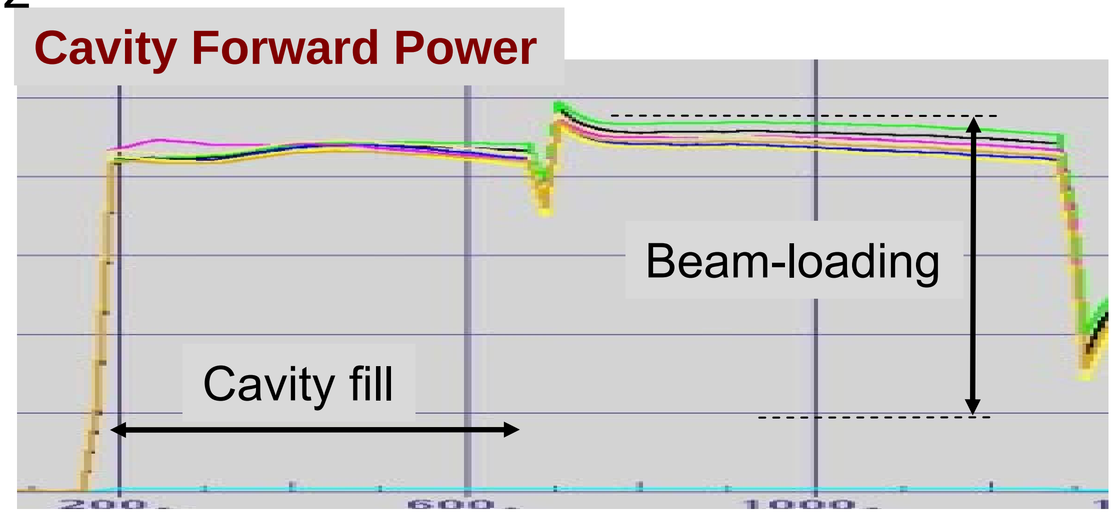
700us

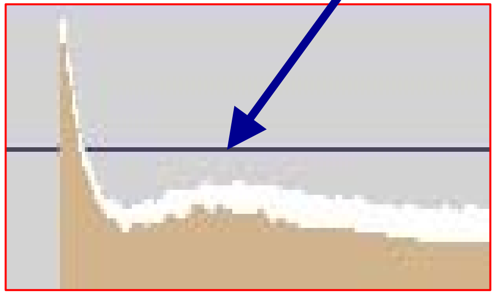
Along pulse: 0.5 % p-p
Pulse-pulse: 0.13 % rms

Transient examples with full beam loading

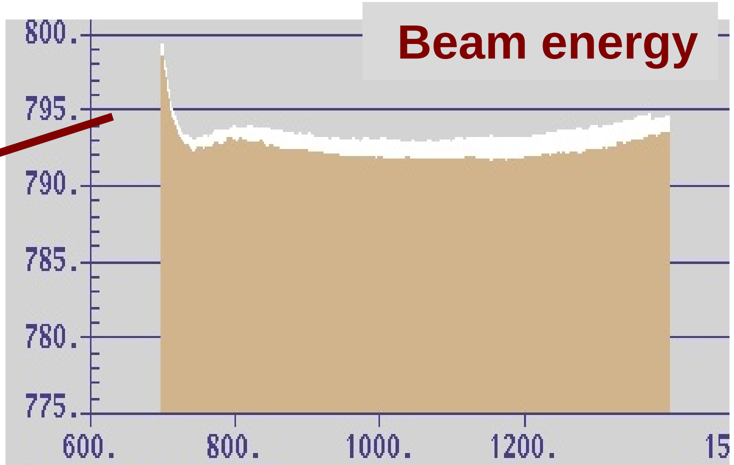
7.5 mA ~2100 bunches, 3 MHz

LLRF tuning/optimization:
RF feed-forward waveforms
Beam loading compensation
Cavity pre-detuning
…


Cavity Forward Power

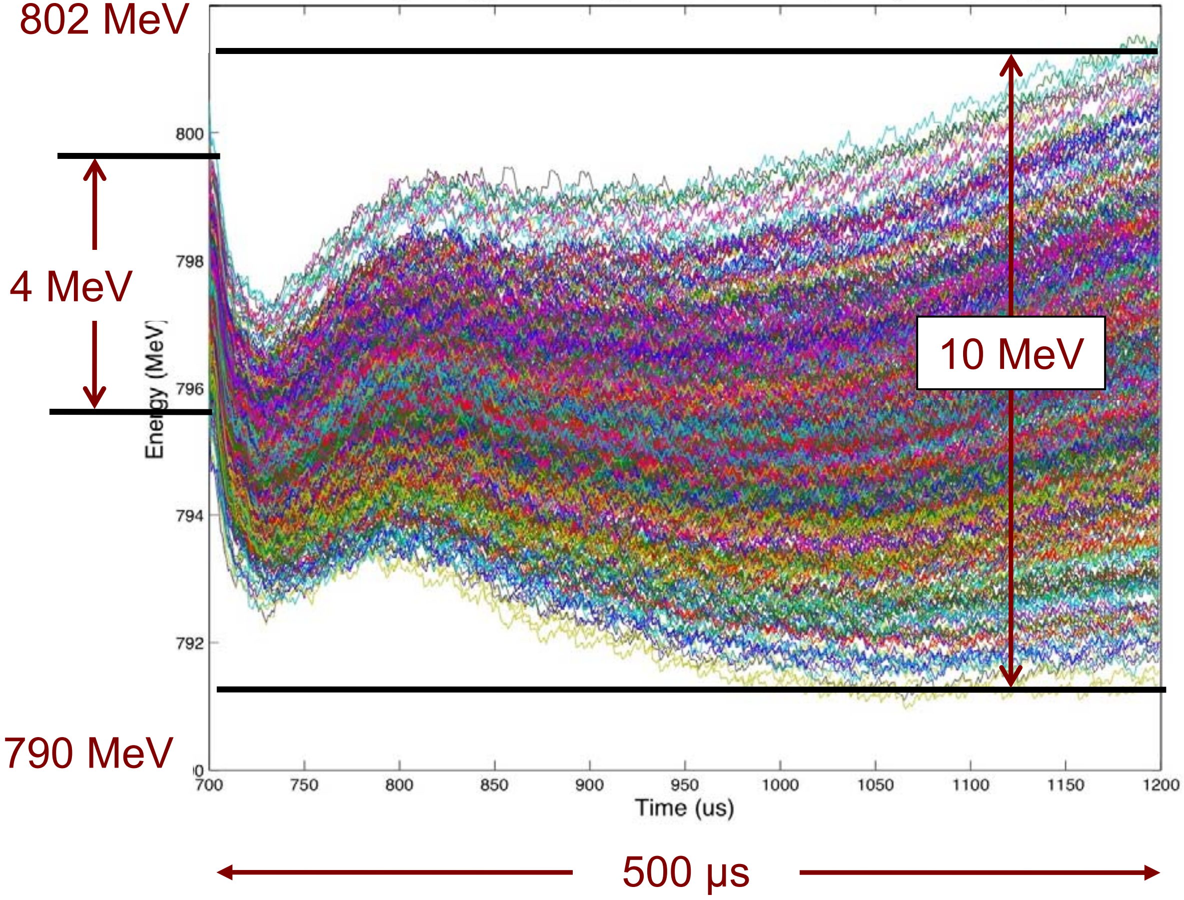

Beam-induced transient

Response of LLRF regulator


Beam energy

Example: energy jitter

500 bunches @ 1 MHz, 3 nC/bunch
(overlay of 200 consecutive pulses)



802 MeV

4 MeV

10 MeV

790 MeV

500 µs

Jitter (first bunch):
4 MeV pp (0.5 %)

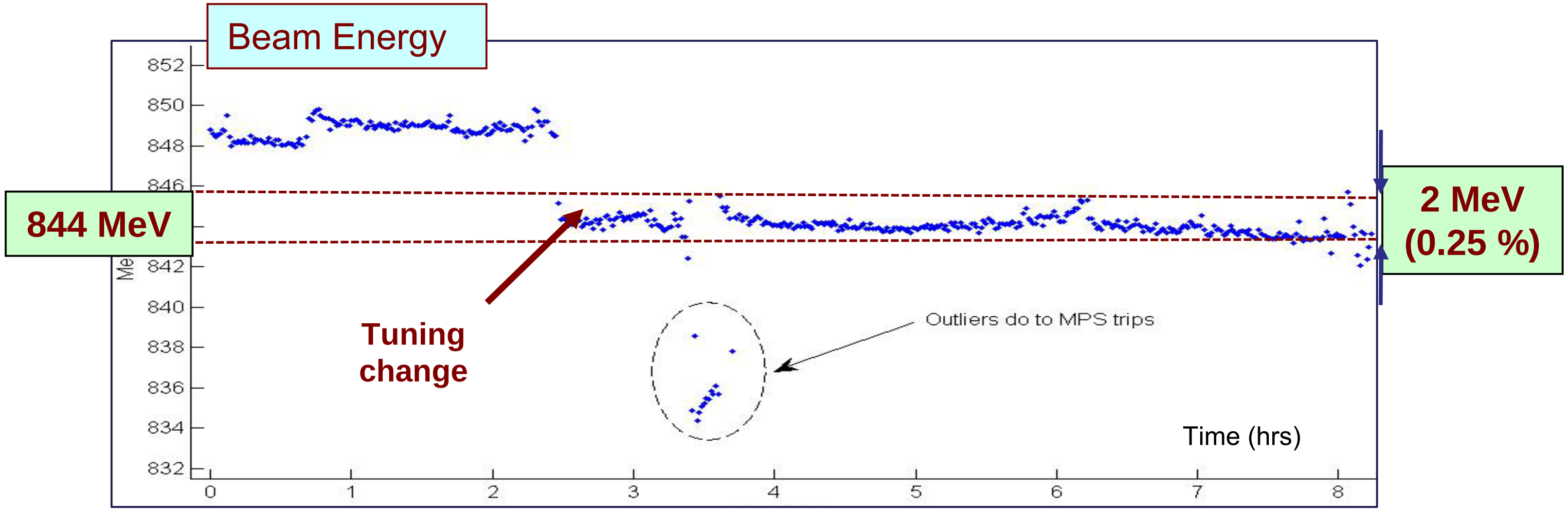
Jitter (all bunches): 10 MeV

Energy spread within bunch-train: 5 MeV

Single-bunch: tune a single point in the RF flat-top (profile doesn’t matter)

Bunch train: minimize deviations over the whole RF flat-top

Long term energy stability

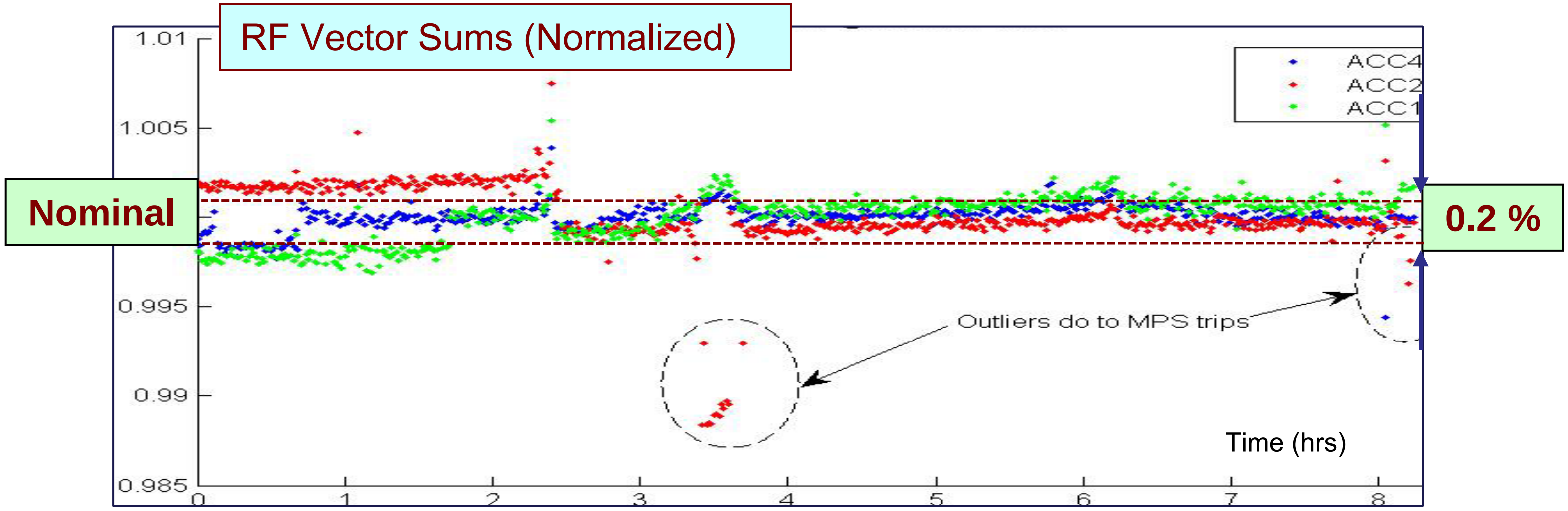


Beam Energy

844 MeV

2 MeV (0.25 %)

Tuning change



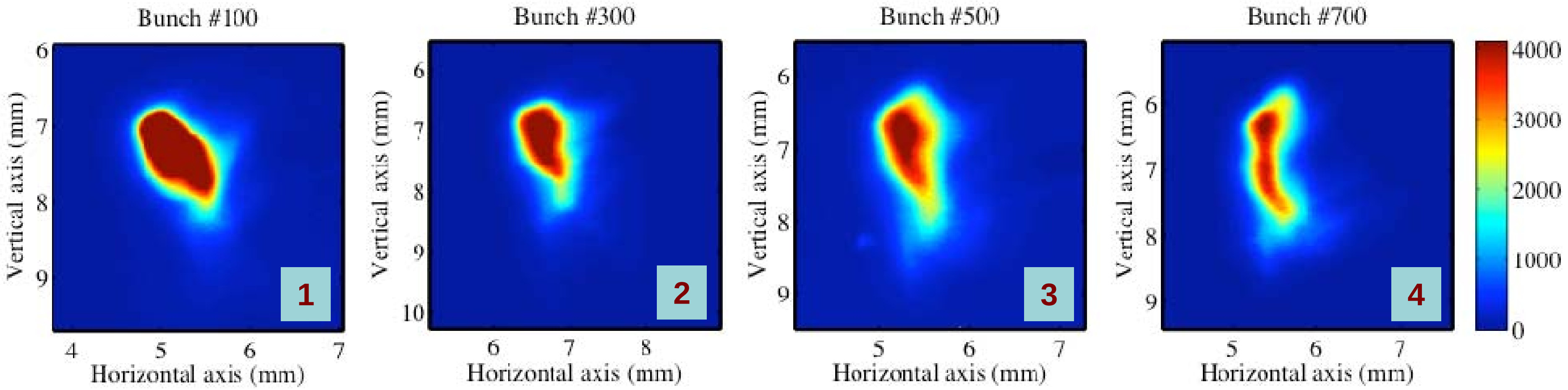
RF Vector Sums (Normalized)

Nominal

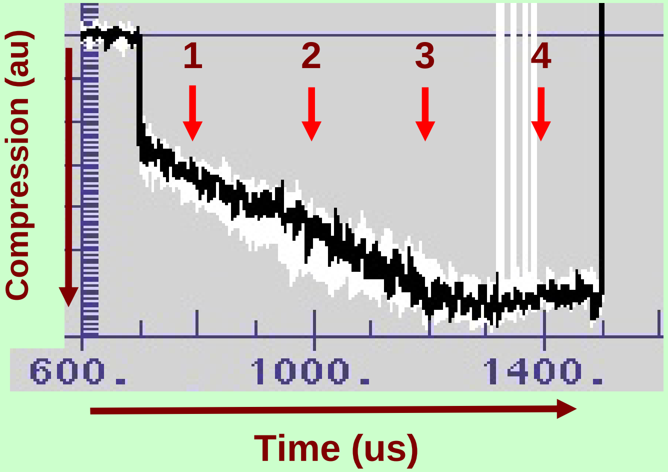
0.2 %

8 hrs

Transverse bunch shape along the train



Bunch compression during 800 µs bunch train



Transverse bunch distributions clearly show changes in bunch size and shape over the long bunch train

Compression slope is explained by a slope in bunch arrival phase at the bunch compressor

800 bunches @ 1 MHz, ~3 nC/bunch

ILC-specific study examples

- **Energy stability studies with full beam loading**
  - Impact of running close to quench
  - Operation close to zero–crossing (ILC RTML studies)

- **RF power overhead with full beam loading**
  - Power overhead needed to meet spec over extended periods
  - How effectively we can minimize detuning errors
  - How close to klystron saturation we can run, and still meet spec

- **Gradient studies**
  - How close to quench can we operate reliably with full beam loading?

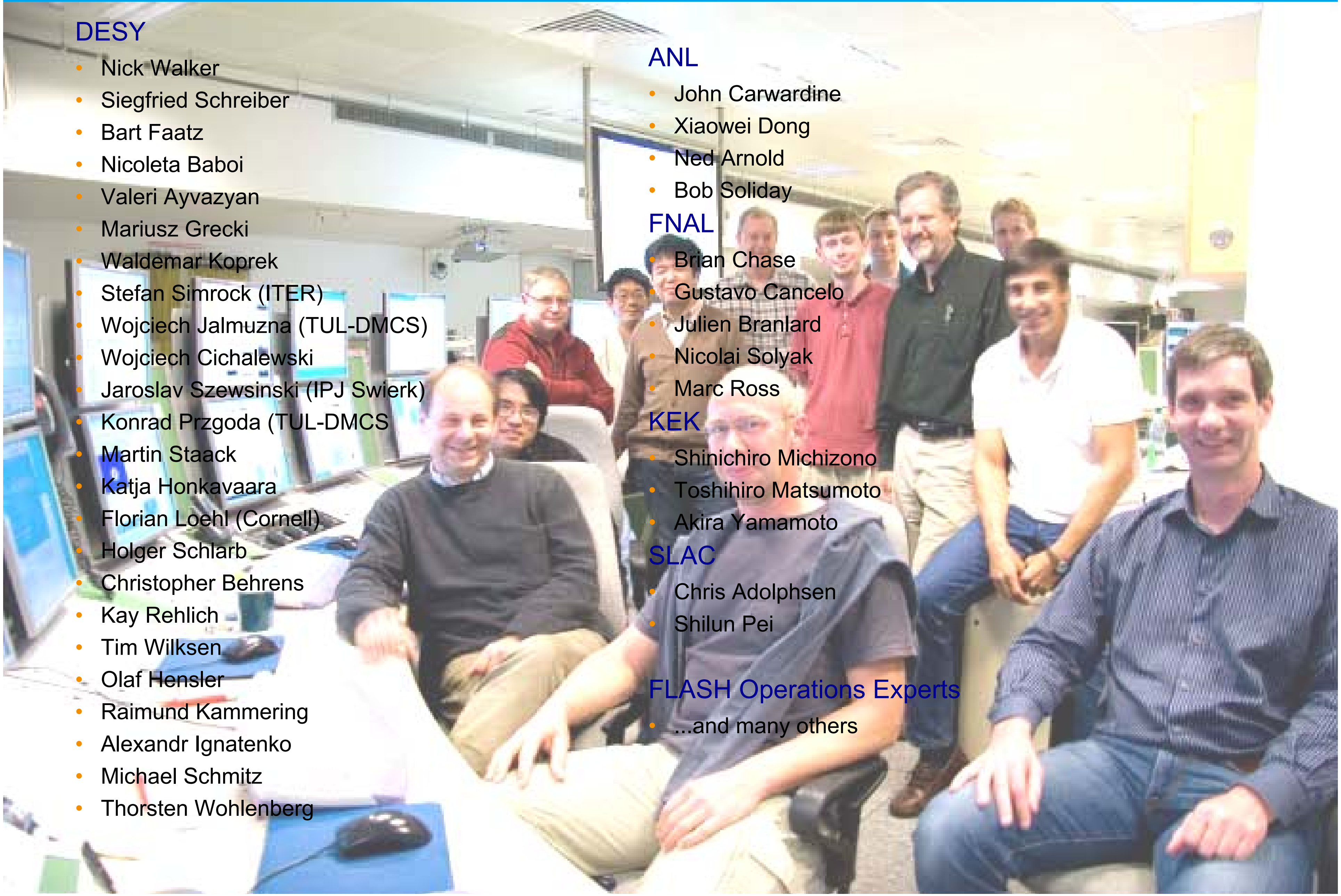
- **HOM cryo load with full beam loading**
  - Run with different bunch lengths

LLRF 09, "Recent results from the TTF/FLASH 9mA Studies" (J. Carwardine)

Next Experiments

- FLASH will provide for the next user run routinely with long bunch trains
  – tough not with full beam loading
- Full beam loading experiments will be prepared together with the FLASH long pulse train effort
  – since many issues can be studies even with partial beam loading
  – to gain experience in long term user runs
- Next dedicated full beam loading experiment at FLASH to be expected early 2011
- Experimental test facilities in preparation at FNAL and KEK

9 mA study team



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