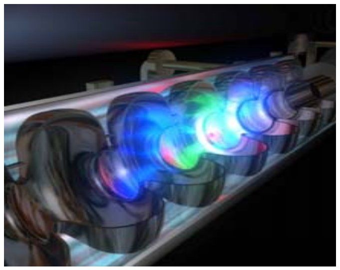
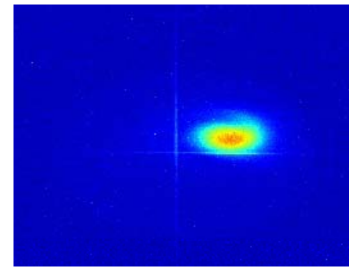
LINAC08
September 29 – October 3, 2008
Victoria, British Columbia, Canada

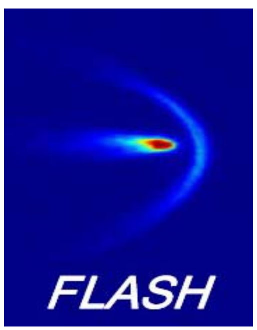
FLASH
Free-Electron Laser in Hamburg



Operation of FLASH as a user facility



Katja Honkavaara, DESY



FLASH – a free-electron laser user facility
Linac components
Performance and operational issues
Outlook

HELMHOLTZ
GEMEINSCHAFT

FLASH at DESY Hamburg

FLASH
Free-Electron Laser in Hamburg

- single-pass high-gain SASE FEL
  - SASE = self-amplified spontaneous emission
- FEL user facility since 2005
- photon wavelength range from vacuum ultraviolet to soft x-rays
- first lasings:
  - January 2005 – 32 nm
  - April 2006 – 13 nm
  - October 2007 – 6.5 nm
- user experiments
  - 1st period: June 2005 – March 2007
  - 2nd period: November 2007 – April 2009
- FLASH is also a test bench for the European XFEL

FLASH design goals reached

FLASH
Free-Electron Laser in Hamburg

Electron beam energy of 1 GeV

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.

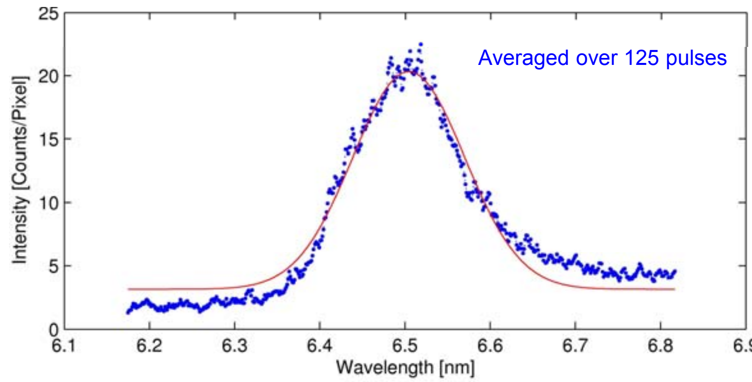
Während der letzten Wartungspause: Einbau des Beschleunigermoduls Nr. 6 in den FLASH-Tunnel.
During the last shutdown: Installation of accelerator module no. 6 in the FLASH tunnel.

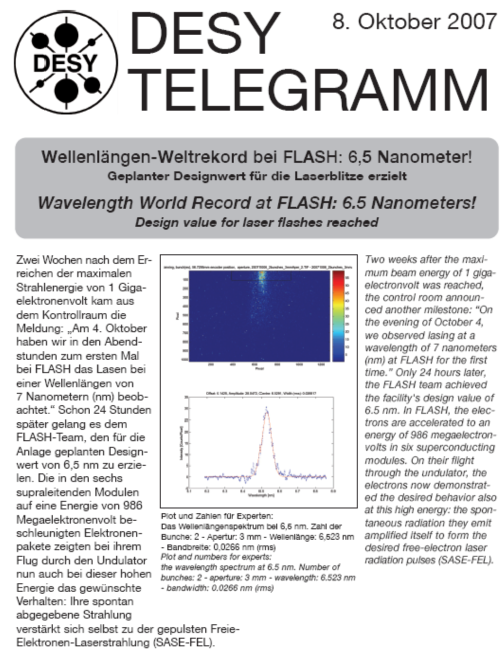
As usual, the breakthrough was achieved during a night shift, to be precise: on September 21 at 0:57 a.m. This time, the aim was to reach the planned maximum beam energy. "Goal: Operation to maximum energy—Achievements: 1 GeV!! Spectrum of spontaneous emission measured: ~ 6.3 nm," reads the entry in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

Das Team im Kontrollraum beobachtete im Wellenlängenspektrum der im FLASH-Undulator

For the first time, the team in the control room observed a peak around 6 nanometers in the

Lasing at 6.5 nm





DESY TELEGRAMM 8. Oktober 2007

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

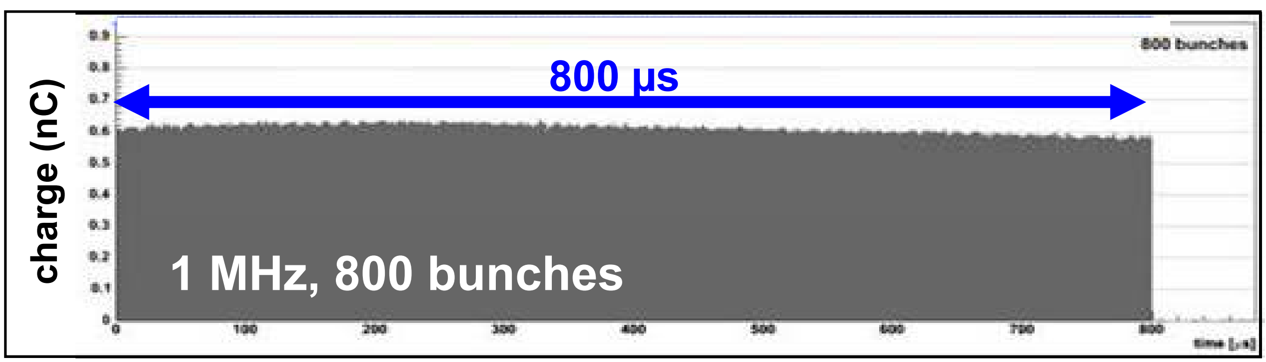
Wavelength World Record at FLASH: 6.5 Nanometers!
Design value for laser flashes reached

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 Anlage geplanten Designwert von 6,5 nm zu erzielen. Die in den sechs supraleitenden Modulen auf eine Energie von 986 Megaelektronenvolt beschleunigten Elektronenpakete zeigten bei ihrem Flug durch den Undulator nun auch bei dieser hohen Energie das gewünschte Verhalten: Ihre spontan abgegebene Strahlung verstärkt sich selbst zu der gepulsten Freie-Elektronen-Laserstrahlung (SASE-FEL).

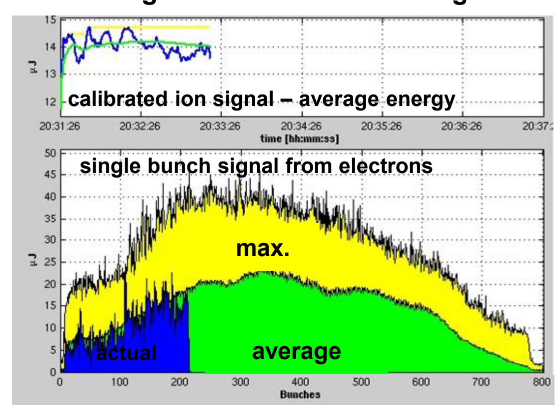
Plot und Zahlen für Experten:
Das Wellenlängenspektrum bei 6,5 nm. Zahl der Bunche: 2 - Apertur: 3 mm - Wellenlänge: 6,523 nm - Bandbreite: 0,0266 nm (rms)
Plot and numbers for experts: the wavelength spectrum at 6.5 nm. Number of bunches: 2 - aperture: 3 mm - wavelength: 6.523 nm - bandwidth: 0.0266 nm (rms)

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 modules. On their flight through the undulator, the electrons now demonstrated the desired behavior also at this high energy: the spontaneous radiation they emit amplified itself to form the desired free-electron laser radiation pulses (SASE-FEL).

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

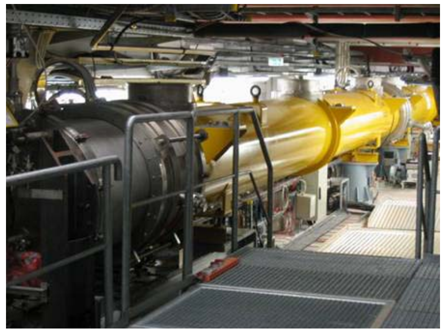
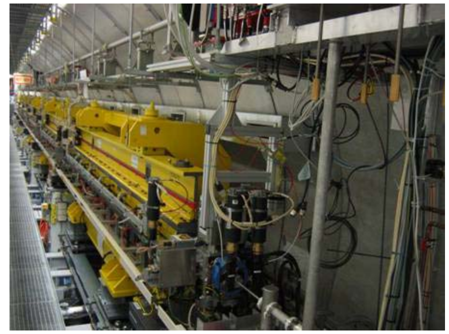


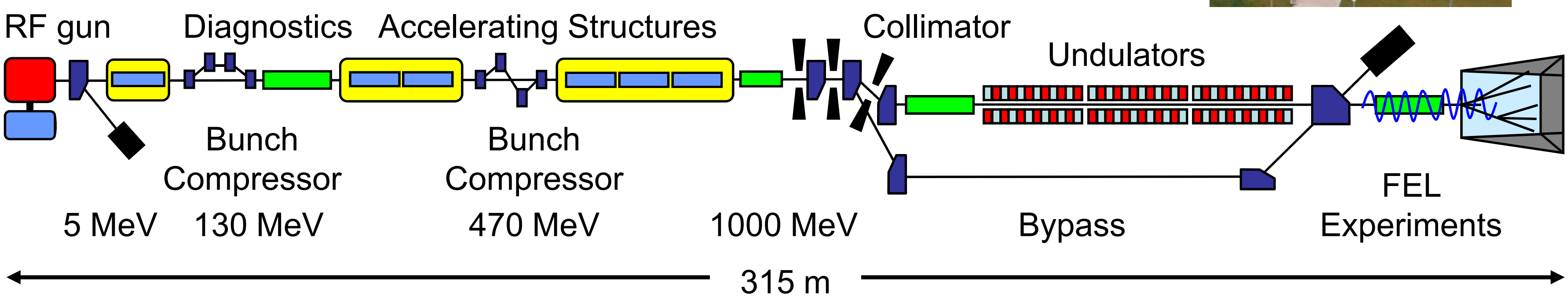
GMD - gas monitor detector - signal



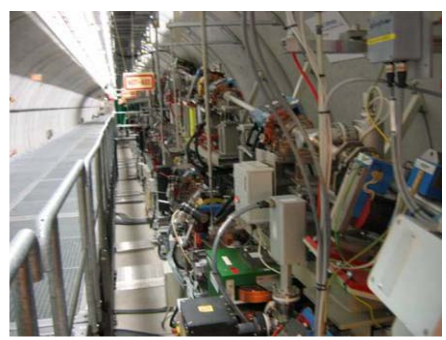
FLASH overview

FLASH
Free-Electron Laser in Hamburg

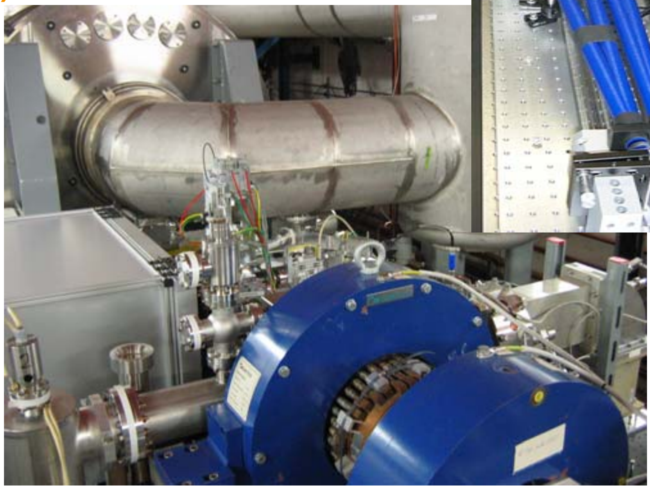








Electron source

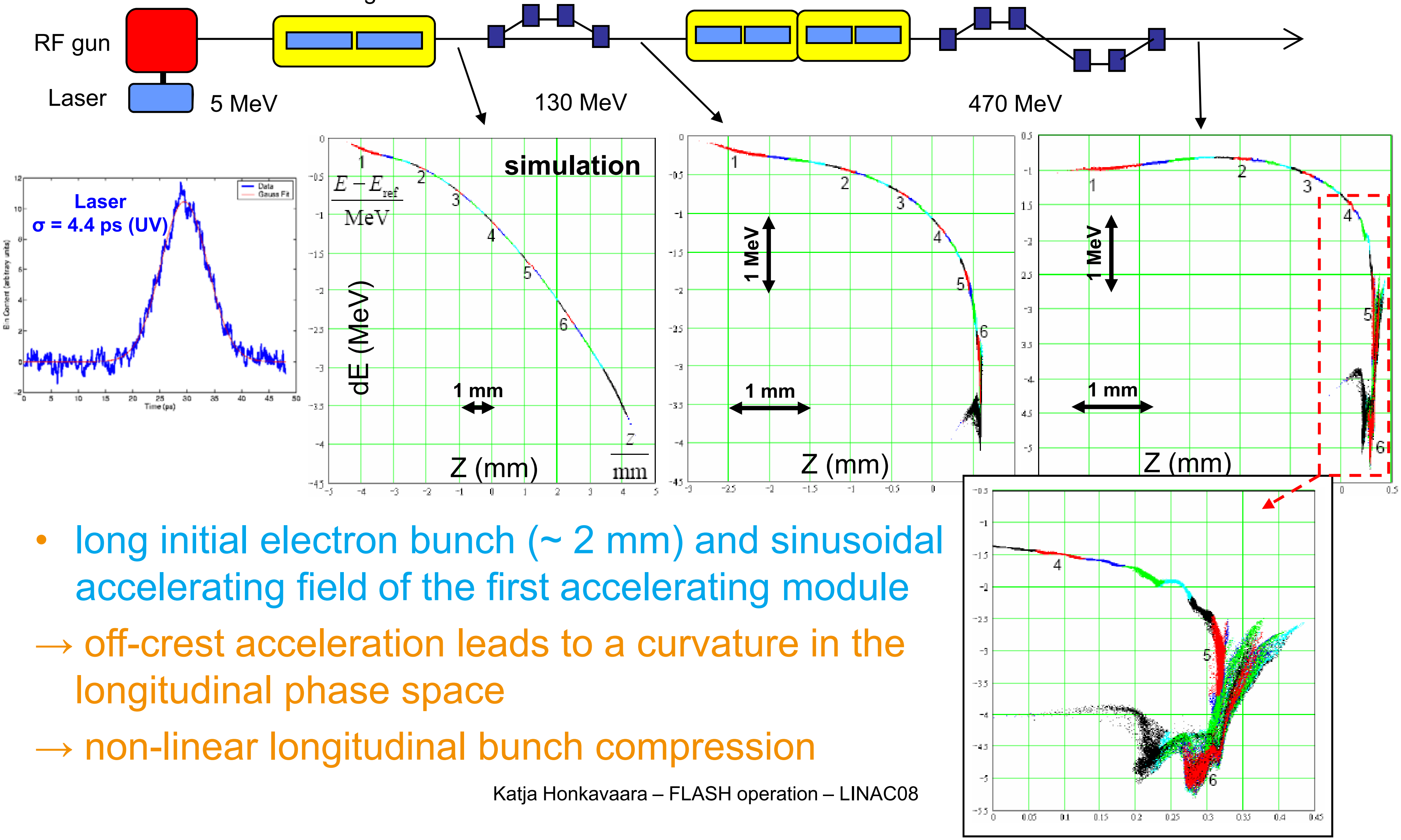
FLASH
Free-Electron Laser in Hamburg



- Nd:YLF based photocathode laser
  - designed for long pulse trains of up to 800 μs @ 10 Hz
  - 10 kHz to 1 MHz pulse separation within the train
- L-band (1.3 GHz) RF-gun
  - gradient on cathode 46 MV/m (max)
  - pulsed 5 Hz (10 Hz possible)
  - RF pulse length 100 to 900 μs
- Cs_2Te cathode
- charge variable to some extend
  - SASE operation: 0.5 nC – 1 nC
- macro-pulse repetition rate 5 Hz
  - number of bunches and bunch spacing within the train can be varied: 1 MHz (standard), 500 kHz, 200 kHz, 100 kHz , and others

Longitudinal phase space

FLASH
Free-Electron Laser in Hamburg



- long initial electron bunch (~ 2 mm) and sinusoidal accelerating field of the first accelerating module

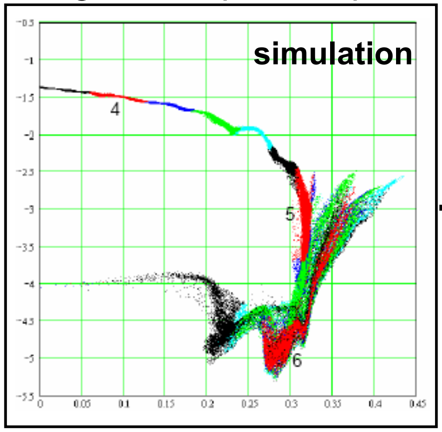
→ off-crest acceleration leads to a curvature in the longitudinal phase space

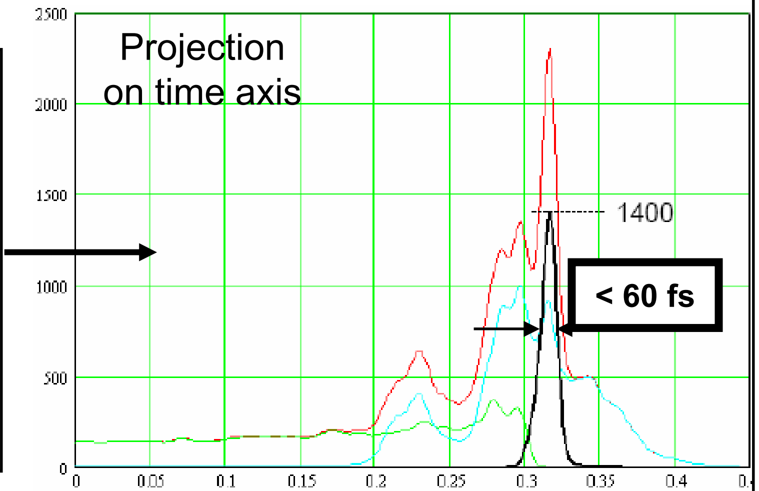
→ non-linear longitudinal bunch compression

Longitudinal bunch shape

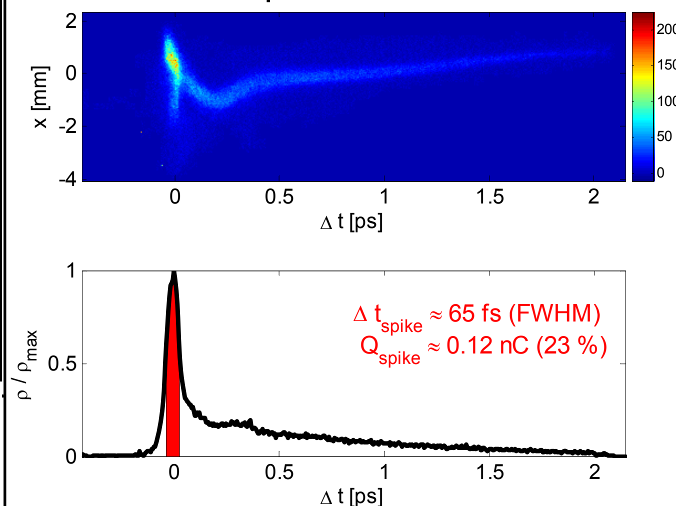
FLASH
Free-Electron Laser in Hamburg

Longitudinal phase space





Measured longitudinal shape of a compressed bunch



Measured by a transverse deflecting cavity placed after the last accelerating module

- ultra-short bunch spikes created (< 60 fs fwhm)
- difficult to measure relevant beam parameters
  - standard diagnostics measures projected parameters
- third harmonic (3.9 GHz) module to be installed in summer 2009
  - placed after the first accelerating module
  - flattening of the longitudinal phase space
  - → more regular compressed bunch shape

3rd harmonic module

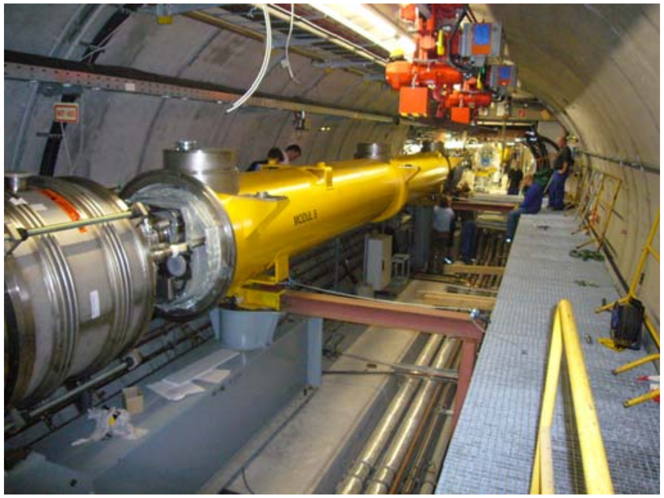
- four 9-cell superconducting cavities
- operated at 3.9 GHz
- collaboration DESY – FNAL

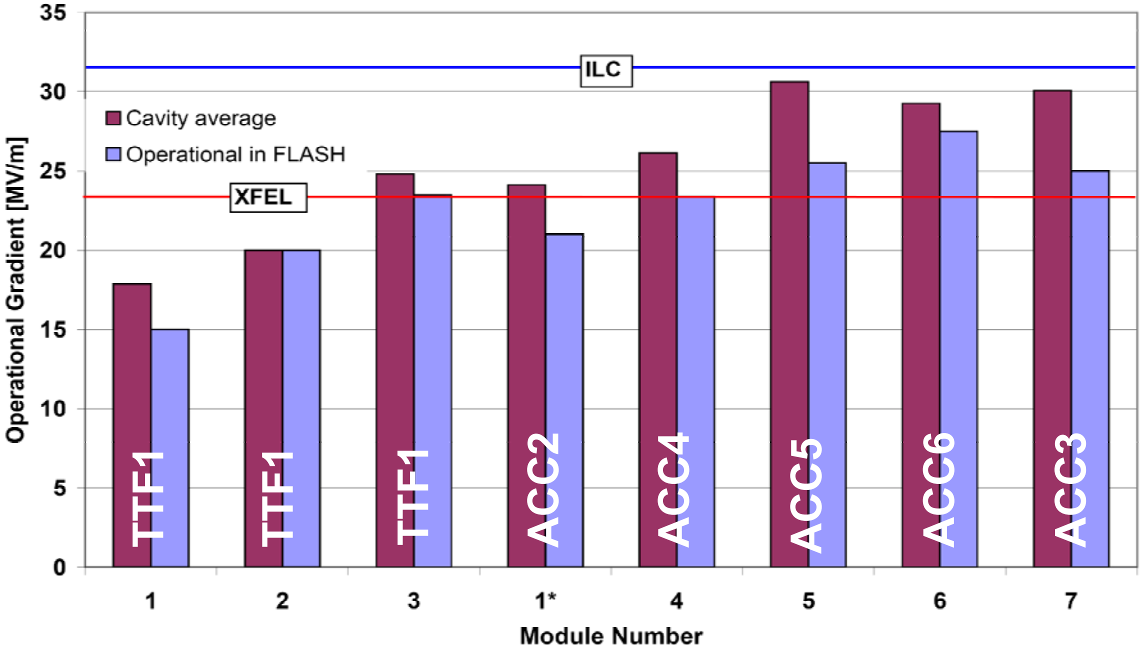
More details: Poster TUP034

Accelerating modules

FLASH
Free-Electron Laser in Hamburg

- six TESLA type accelerating modules
  - each having eight 9-cell superconducting niobium cavities operated at 1.3 GHz
- energy upgrade to 1 GeV in 2007
  - 6th module installed
  - 3rd module replaced by a new one
  - tuners of 5th module repaired
- both new modules ≥ 25 MV/m
  - 4 cavities of ACC6 reach even 30 MV/m

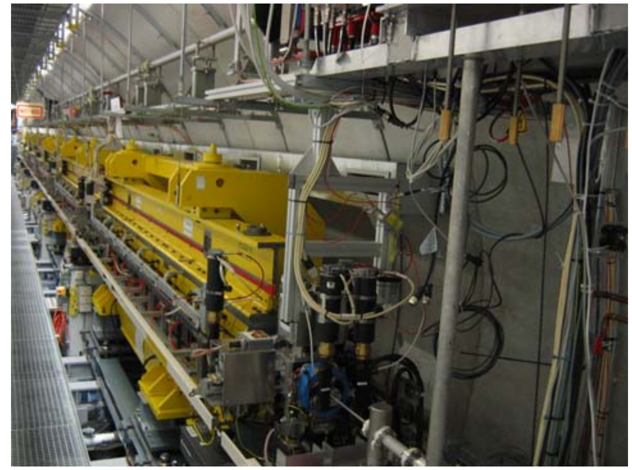




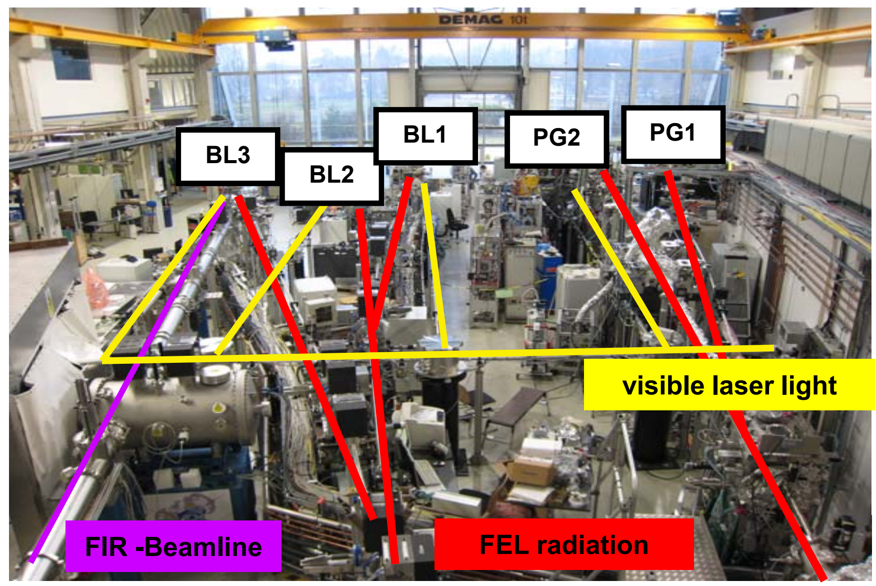
Undulator and photon beam lines

FLASH
Free-Electron Laser in Hamburg

- high-gain single-pass FEL requires a long undulator system
  - total length 27.3 m
  - permanent NdFeB magnets
  - fixed gap of 12 mm



- FEL radiation guided to the experimental hall
- five photon beam lines
  - large variety of experimental possibilities



SASE performance

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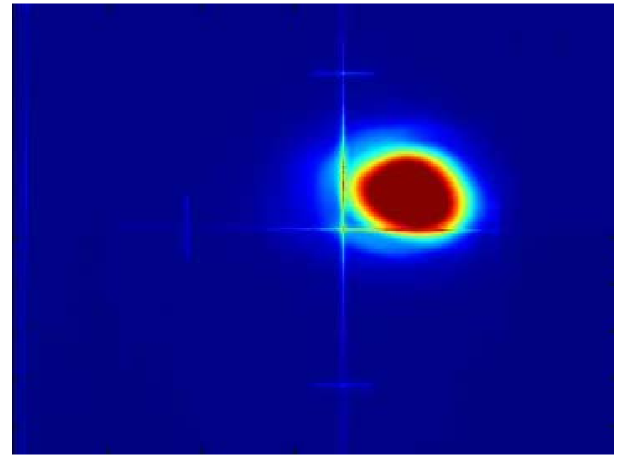
Free-Electron Laser in Hamburg

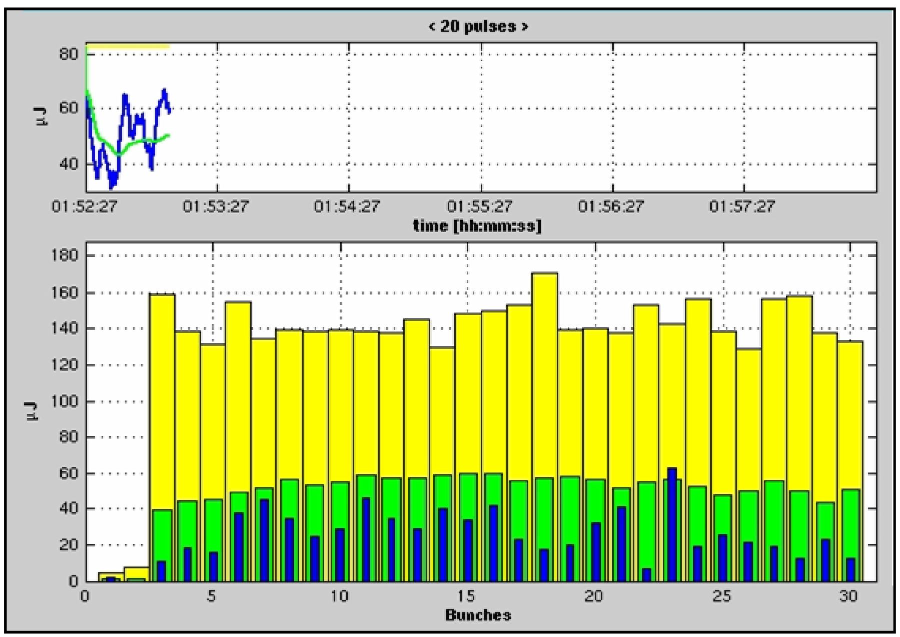
Typical user operation parameters:

• Wavelength range (fundamental)	7 - 47 nm
• Average single pulse energy	10 - 50 μJ
• Pulse duration (FWHM)	10 - 50 fs
• Peak power (from av.)	1 - 5 GW
• Average power (example for 500 pulses/sec)	~ 15 mW
• Spectral width (FWHM)	~ 1 %
• Brilliance	10^{29} - 10^{30} B



In saturation at 13.7 nm:

• Average energy	70 μJ
• Peak energy	170 μJ
• Pulse duration	10 fs
• Peak power	>10 GW
• Peak brilliance	(6 ± 3) 10^{29} B

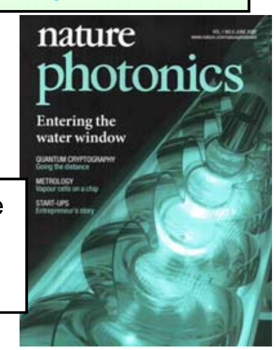


Multibunch SASE signal (μJ) recorded with MCP detector

max
single
average

"Operation of a free-electron laser from the extreme ultraviolet to the water window"

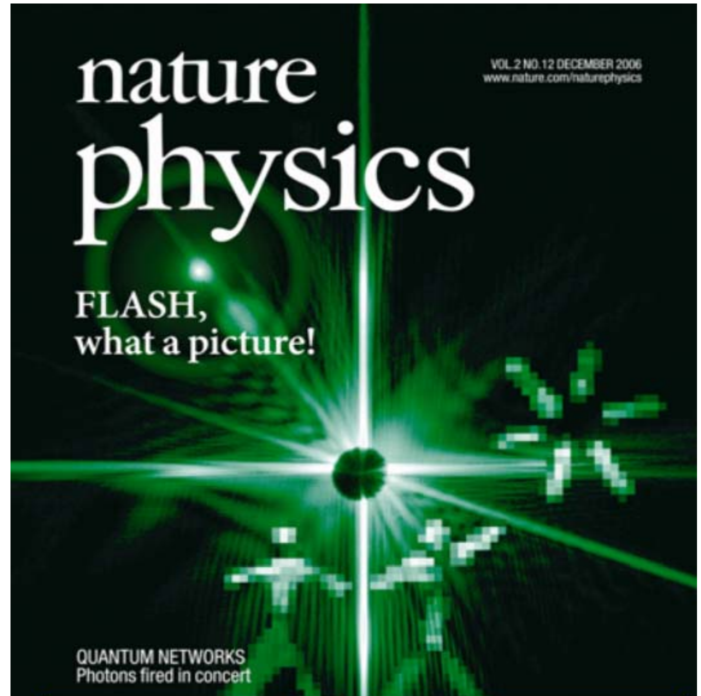
Nature photonics **1** (2007) 336



FEL user experiments

FLASH
Free-Electron Laser in Hamburg

- world-wide unique light source
  - ultra-short FEL pulses (femtosecond range)
  - unprecedented brilliance
  - photon wavelengths down to 7 nm
- experiments on
  - diffraction imaging
  - solid state-, plasma-, and cluster-physics
  - femtosecond-chemistry, molecular-biology
  - …
- single-shot measurements
- pump-and-probe experiments
- during the first user period (June 2005 – March 2007)
  - 18 projects received beam time
  - > 200 scientists, 60 institutes, 11 countries
- > 25 publications already, many more to come
  - http://hasylab.desy.de/facilities/flash/publications



Femtosecond diffractive imaging with a soft-X-ray free-electron laser
H.N. Chapman et al., Nature Physics 2 (2006) 839

Organization of beam time

FLASH
Free-Electron Laser in Hamburg

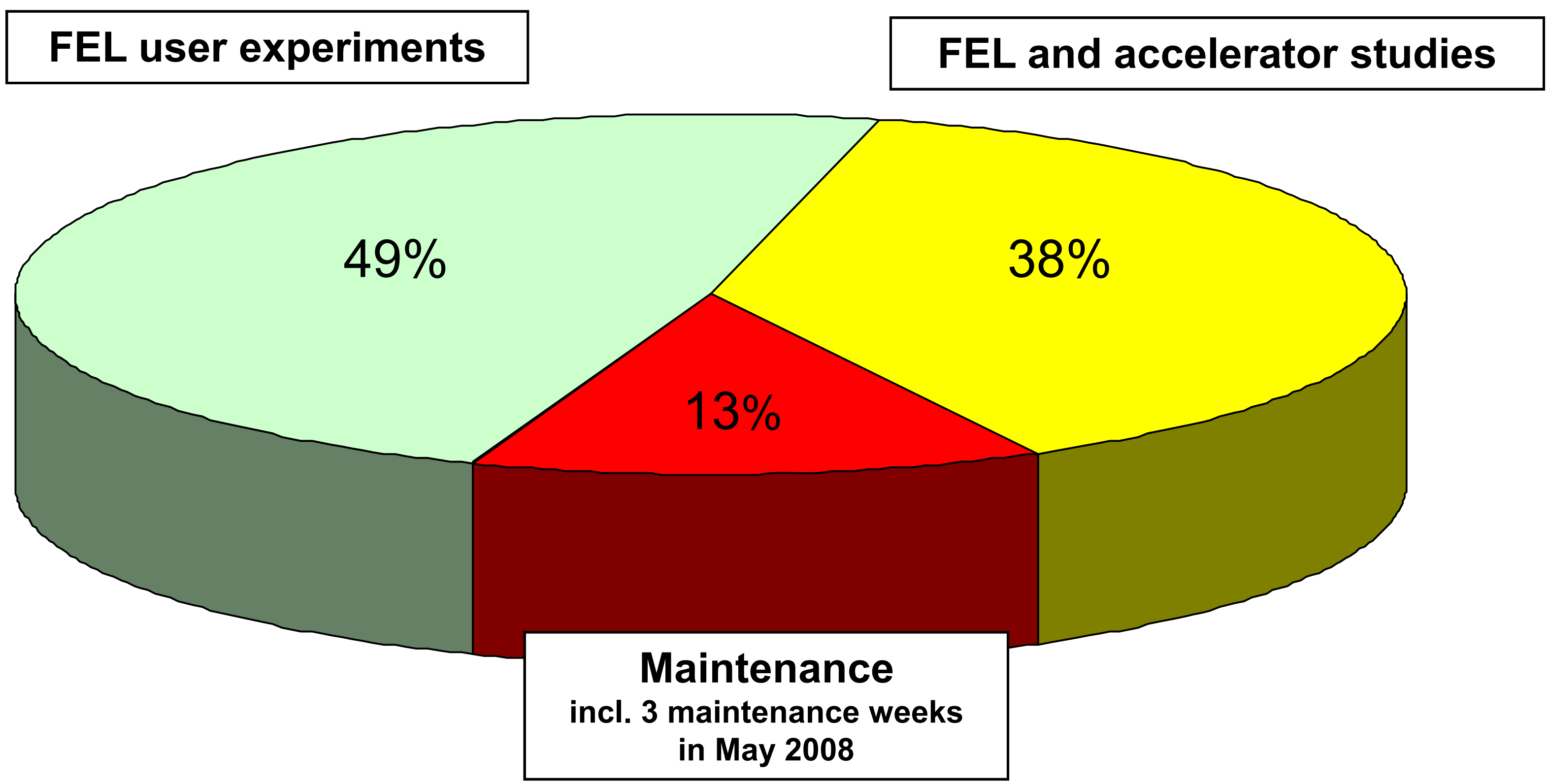
- FLASH runs 24 hours per day, 7 days per week
- beam time always overbooked
- the second user period started in November 2007 and continues until April 2009
  - ~ 250 days scheduled for user operation
  - distributed in 4-week blocks
- between user blocks, we have study weeks
  - FEL physics studies, improvements of the FLASH facility, preparation of next user blocks
  - general accelerator studies
    - 2-3 weeks three times per year
    - related to e.g. XFEL and ILC

	52	24.Dec - 30.Dec	5	Maintenance
January	1	31.Dec - 6.Jan	5	
2008	2	7.Jan - 13.Jan	4	Accelerator studies
	3	14.Jan - 20.Jan	4	
	4	21.Jan - 27.Jan	2	FEL studies
February	5	28.Jan - 3.Feb	2	
	6	4.Feb - 10.Feb	3	
	7	11.Feb - 17.Feb	1	User Run
	8	18.Feb - 24.Feb	1	
	9	25.Feb - 2.Mar	1	
March	10	3.Mar - 9.Mar	1	
	11	10.Mar - 16.Mar	2	FEL studies
	12	17.Mar - 23.Mar	2	
	13	24.Mar - 3.Jan	3	
April	14	31.Mar - 6.Apr	1	User Run
	15	7.Apr - 13.Apr	1	
	16	14.Apr - 20.Apr	1	
	17	21.Apr - 27.Apr	1	

Beam time distribution

FLASH
Free-Electron Laser in Hamburg

41 weeks from November 26, 2007 to September 7, 2008



User experiments

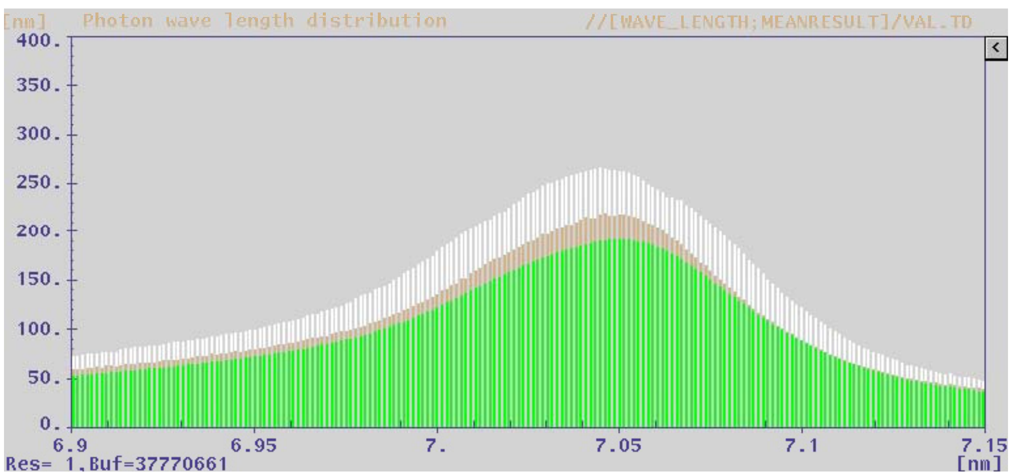
- typically two user experiments run in parallel (12 h shift)
  - scheduled, when possible, such that both experiments require similar SASE parameters
  - even with this, we have to change beam parameters between most of the shifts (every 12 h, mostly wavelength or bunch pattern)
- demands from users increase continuously
  - high radiation energy, good pointing stability
  - exact photon wavelength and/or all bunches lasing at the same wavelength (within 0.1 nm)
  - beam quality, e.g. narrow spectral bandwidth
  - wavelength scans, e.g. ± 0.5 nm around the wavelength
  - lasing with long bunch trains
  - experiments using higher harmonics of the FEL radiation

Operational highlights

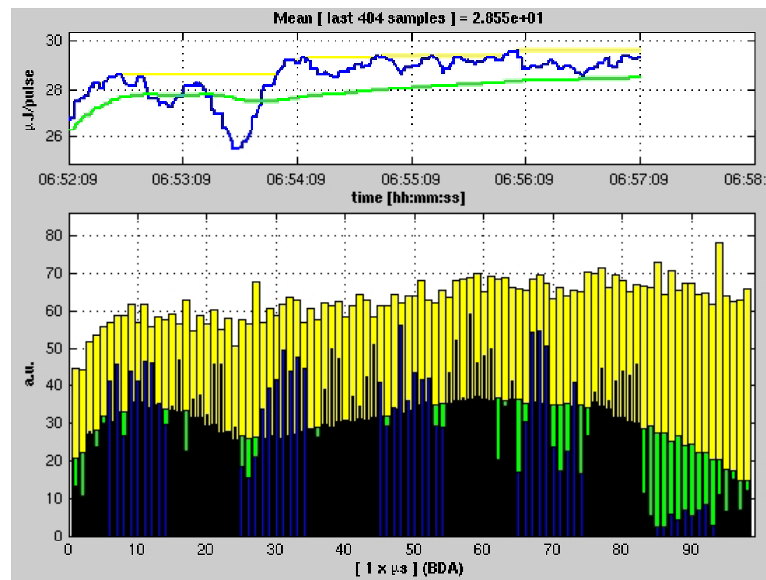
FLASH
Free-Electron Laser in Hamburg

- user experiment with 5th harmonics of 7.97 nm: 1.59 nm
- 5 days continuous running with 100 bunches @ 500 kHz for two user experiments
  - wavelength of 7.05 ± 0.1 nm
  - average SASE level ~30 μJ (14 mW average power)

User run at 7nm with 100 bunches



Wavelength (nm)

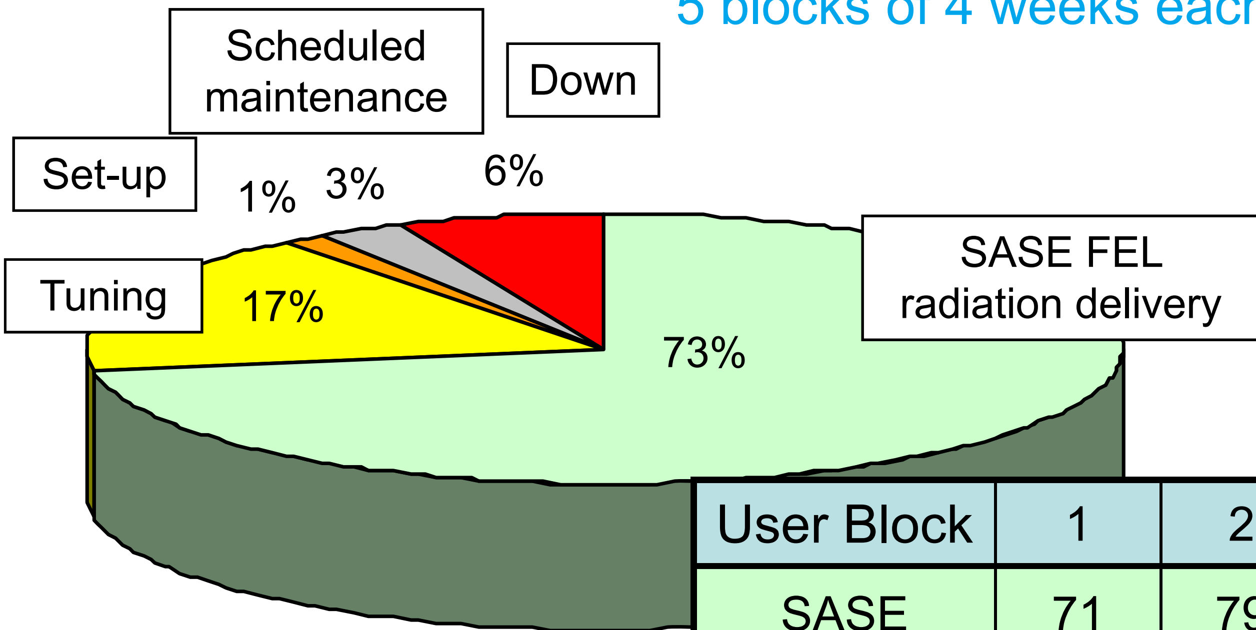


Bunch Number

Time distribution during user runs

FLASH
Free-Electron Laser in Hamburg

5 blocks of 4 weeks each (Nov-2007 to Sep-2008)



User Block	1	2	3	4	5
SASE	71	79	75	67	69
Tuning	14	13	16	24	18
Set-up	2	1	1	1	2
Maint.	4	4	2	2	1
Down	9	3	6	6	10

numbers in %

Tuning during user runs

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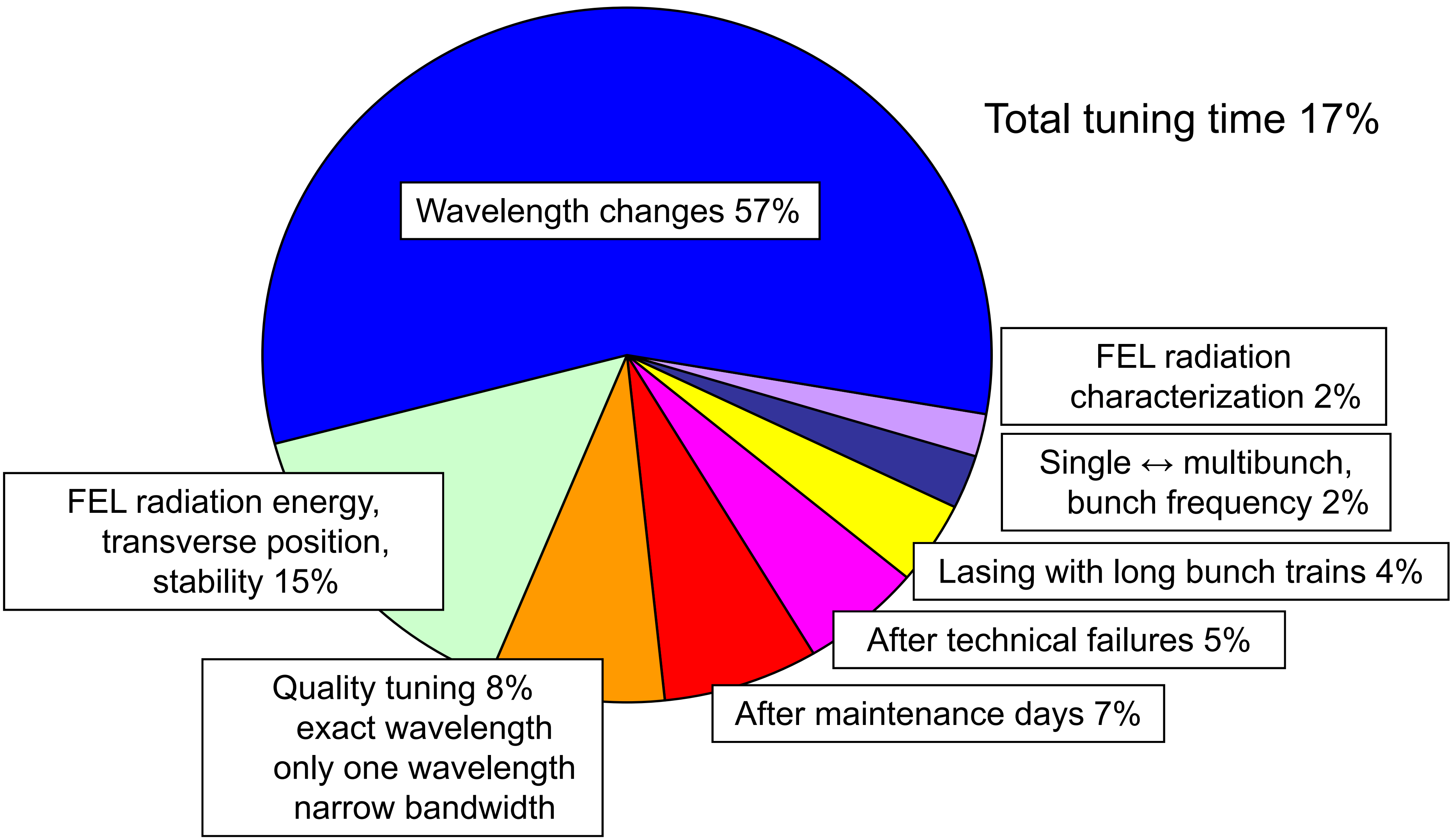
Free-Electron Laser in Hamburg



Wavelength change

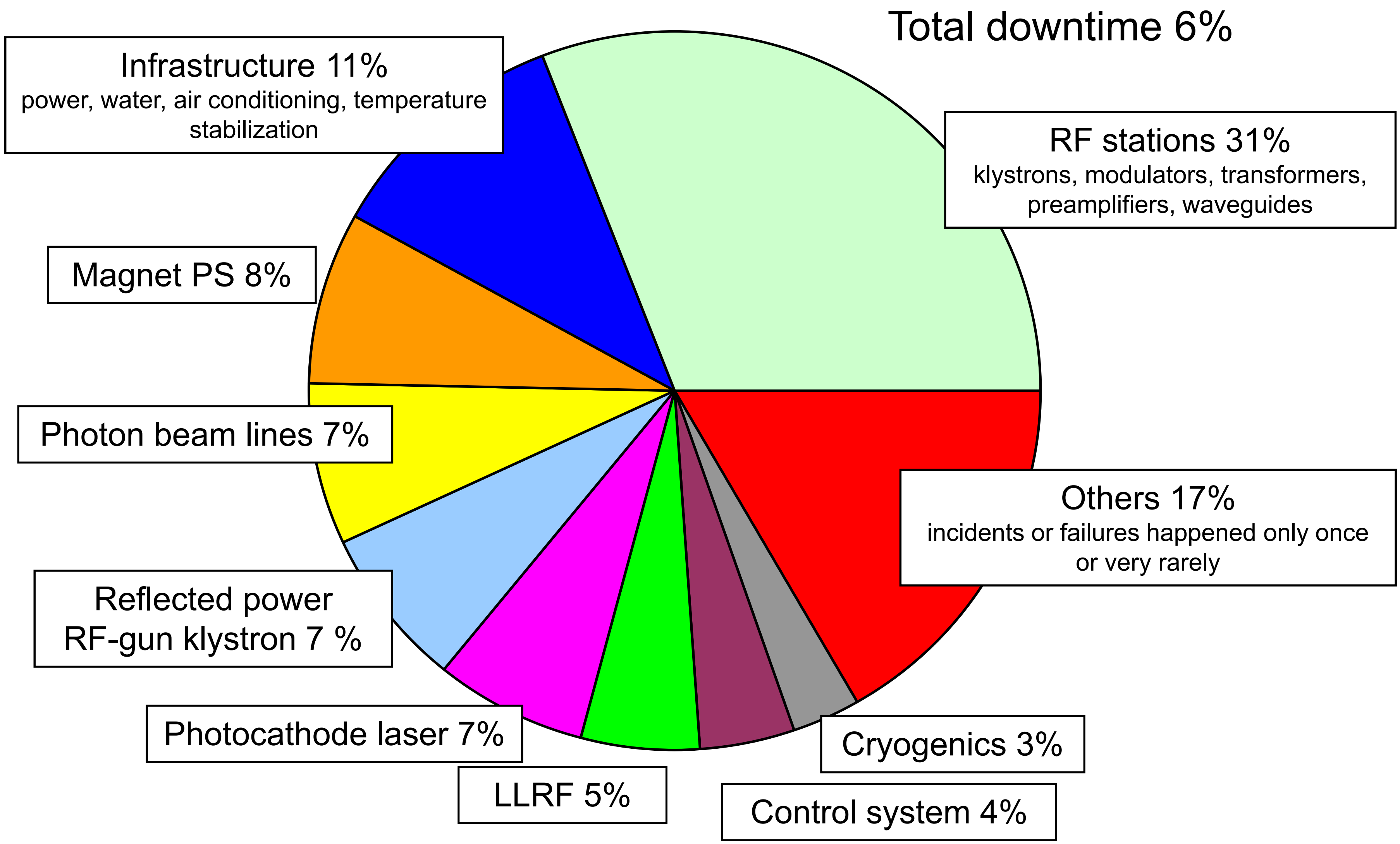
FLASH
Free-Electron Laser in Hamburg

- fixed gap undulator → change of photon wavelength requires change of electron beam energy → adjustments of
  - accelerating gradient and phases
  - beam optics
  - orbit through undulator
  - often also bunch compression
- by now, during the second user period: wavelength changed > 60 times, 24 different wavelengths between 27 nm and 7 nm delivered to users
  - many more wavelengths will come
- during the first user period: several other wavelengths from 47 nm to 13.5 nm delivered as well

Wavelengths delivered for users November 2007- September 2008	
7 nm	15.7 nm
7.05 nm	17 nm
8 nm	19.2 nm
9.65 nm	20.2 nm
10.6 nm	20.9 nm
12.4 nm	22.8 nm
12.6 nm	23.2 nm
12.7 nm	24 nm
13.3 nm	25.5 nm
13.5 nm	25.9 nm
13.7 nm	26.1 nm
14.8 nm	27 nm

Downtime during user runs

FLASH
Free-Electron Laser in Hamburg



Stability

- important issue to ensure continuous SASE operation
- many actions taken and on-going to improve stability
  - curing of electro-magnetic interference sources

    for example:
    - low noise magnet power supplies installed
    - new grounding scheme in the injector area
  - temperature stabilization of injector LLRF racks
  - LLRF developments
    - hardware upgrades (FPGA)
    - control algorithms to improve phase and amplitude regulations
  - replacement of the old master oscillator
  - slow feedbacks to correct drifts: beam energy, charge, arrival time, bunch compression, orbit
  - beam optics, beam-based alignment, dispersion corrections
  - better understanding of non-linear beam dynamics

Outlook

FLASH
Free-Electron Laser in Hamburg

- continuous beam operation until summer 2009
  - user FEL experiments
  - FEL and accelerator physics studies
- shutdown in 2009: major modifications
  - installation the 3rd harmonic (3.9 GHz) module
  - installation of the 7th accelerating module → energy up to ~ 1.2 GeV
  - installation of an experiment for seeded VUV radiation "sFLASH"
    - replacement of complete electron beam line between collimators and SASE undulators (~ 40 meters)
  - exchange of the RF-gun
  - upgrades of RF stations and waveguide distribution
- commissioning in winter 2009
- the third FEL user period is foreseen to start in spring 2010

Summary

FLASH
Free-Electron Laser in Hamburg

- FLASH is a world-wide unique light source
  - photon wavelength range from ~ 50 nm down to 7 nm
  - ultra-short FEL pulses (femtosecond range)
  - unprecedented peak brilliance
- since summer 2005 user FEL experiments successfully performed in many different fields
- during user experiments FEL radiation delivered in average 73% of the time to experiments
  - tuning 17%, set-up 1%, down 6%, scheduled maintenance 3%
- continuous beam operation until shutdown in summer 2009