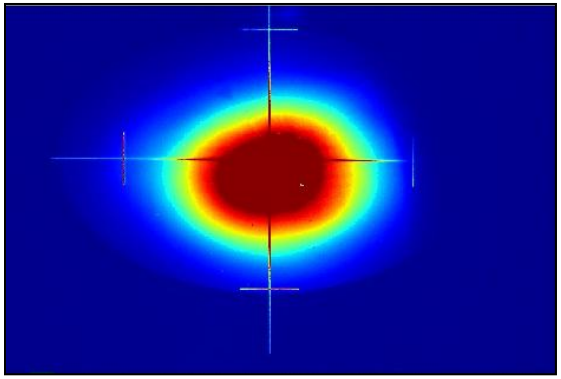
FLASH Upgrade and First Results

FLASH.
Free-Electron Laser
in Hamburg

FLASH free-electron laser user facility at DESY

Siegfried Schreiber
DESY

for the FLASH team



FEL 2010
Malmö, Sweden
Aug 23-27, 2010

HELMHOLTZ
GEMEINSCHAFT

DESY

FLASH at DESY in Hamburg

FLASH. Free-Electron Laser in Hamburg

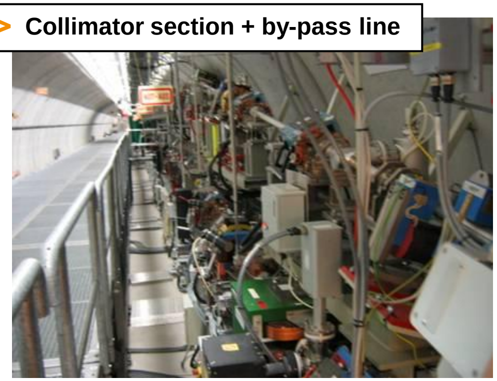
- Single-pass high-gain SASE FEL
  - **SASE = self-amplified spontaneous emission**
- Photon wavelength range from vacuum ultraviolet to soft x-rays
- Free-electron laser user facility since summer 2005
  - 1st period: Jun 2005 – Mar 2007
  - 2nd period: Nov 2007 – Aug 2009
  - 3rd period: Sep 2010 – Sep 2011
- FLASH is also a test bench for the European XFEL and the International Linear Collider (ILC)
- FLASH II, a second undulator beam line is in preparation

FLASH layout before upgrade (Sep-2007 – Sep-2009)

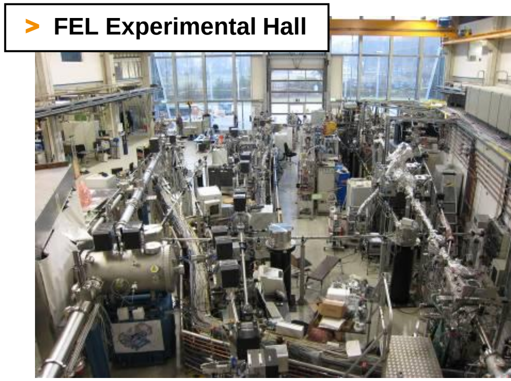
FLASH. Free-Electron Laser in Hamburg

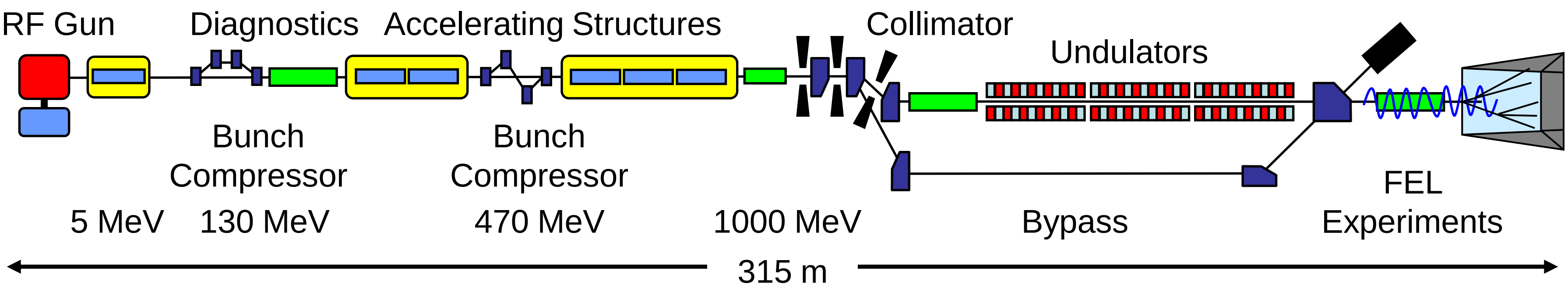
- Normal conducting 1.3 GHz RF gun
- Ce_2Te cathode
- Nd:YLF based ps photocathode laser

- Collimator section + by-pass line



- FEL Experimental Hall





- TESLA type superconducting accelerating modules
- Each module has eight 9-cell Nb cavities
- RF frequency at 1.3 GHz

- Fixed gap undulator
- Total magnetic length ~ 27 m
- Permanent NdFeB magnets

- FEL Experimental Hall

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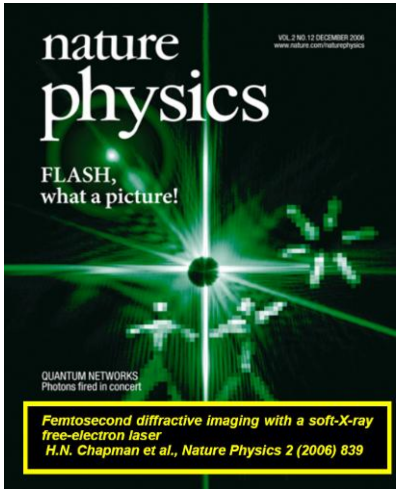
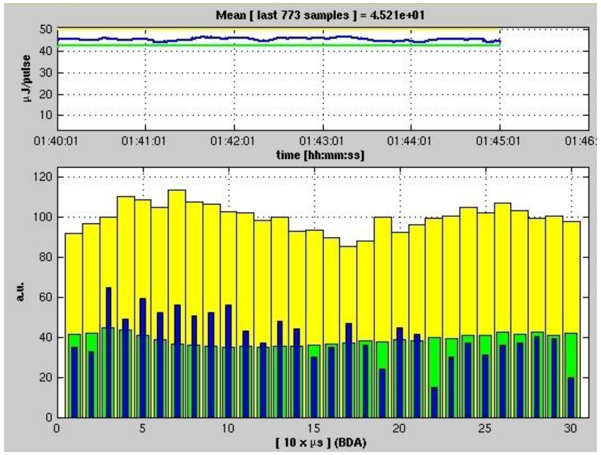
FEL performance 2nd user period (Nov-2007 – Aug-2009)

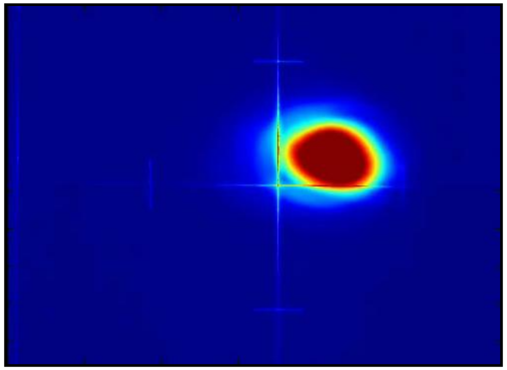
Typical user operation parameters 2nd user period

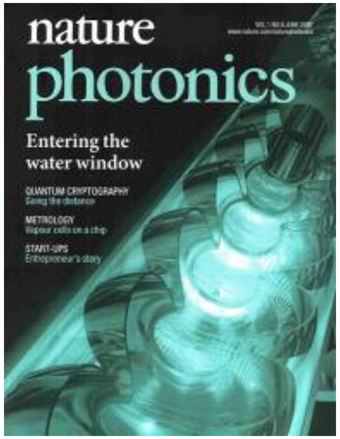
Wavelength range (fundamental)	6.8 – 40.5 nm
Average single pulse energy	10 – 100 µJ
Pulse duration (FWHM)	10 – 70 fs
Peak power (from av.)	1 – 5 GW
Average power (example for 500 pulses/sec)	~ 15 mW
Spectral width (FWHM)	~ 1 %
Peak Brilliance	10^{29} – 10^{30} *

* photons/s/mrad^2/mm^2/0.1%bw









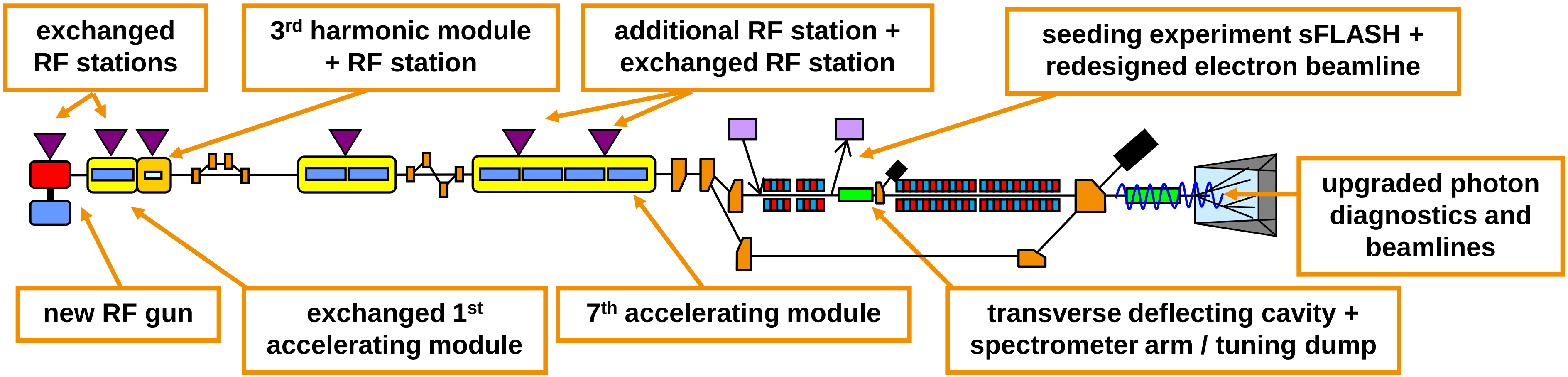
> more than 100 publications on photon science at FLASH in high impact journals

- http://hasylab.desy.de/facilities/flash/publications/selected_publications

Upgrade 2009 / 2010

FLASH.
Free-Electron Laser in Hamburg

> Upgrade shutdown: September 2009 – February 2010



- new diode pumped photocathode laser; upgraded old laser system
- new cabling/layout injector llrf electronics
- installation of a second master oscillator (as backup)
- exchanged injector corrector magnets
- new synchronization and feedback systems
- upgraded magnet controls
- optimized llrf controls
- upgraded and optimized waveguide distribution
- maintenance of infrastructure: water supplies, cryogenics
- improved survey and alignment of accelerator components (incl. SASE undulators)
- upgraded personnel interlock und radiation safety systems

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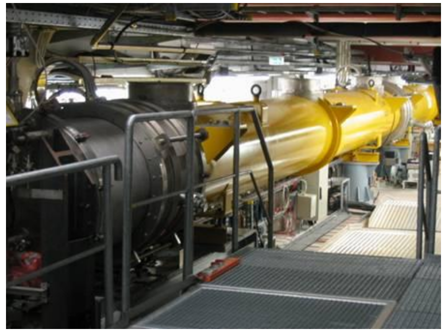
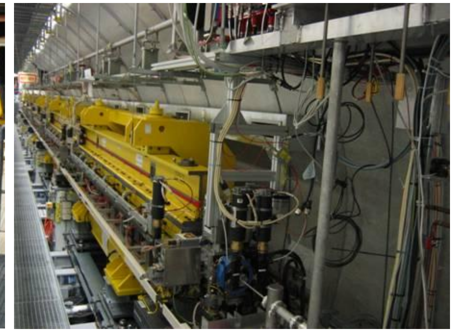
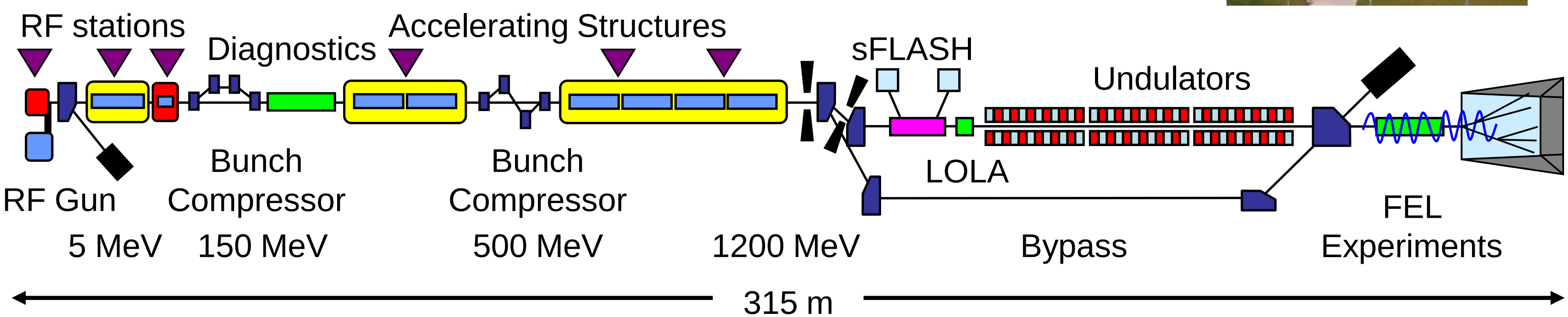
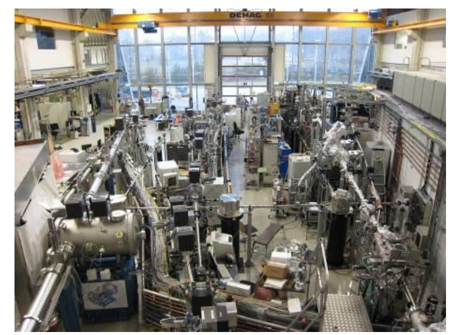
The new FLASH layout

FLASH. Free-Electron Laser in Hamburg



First Lasing at 4.45 nm

FLASH Undulators

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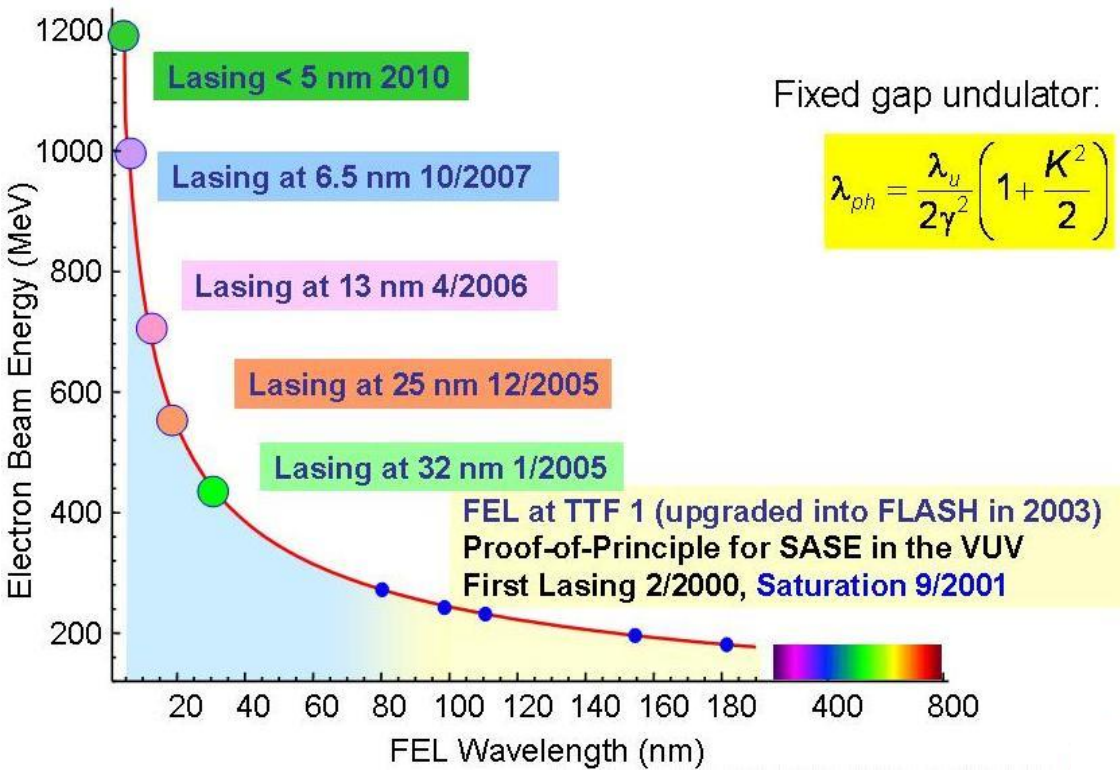
Free-Electron Laser in Hamburg

- 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



- change of wavelength
  ↔
  change of electron beam energy

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Commissioning Step 4: Lasing below 5 nm

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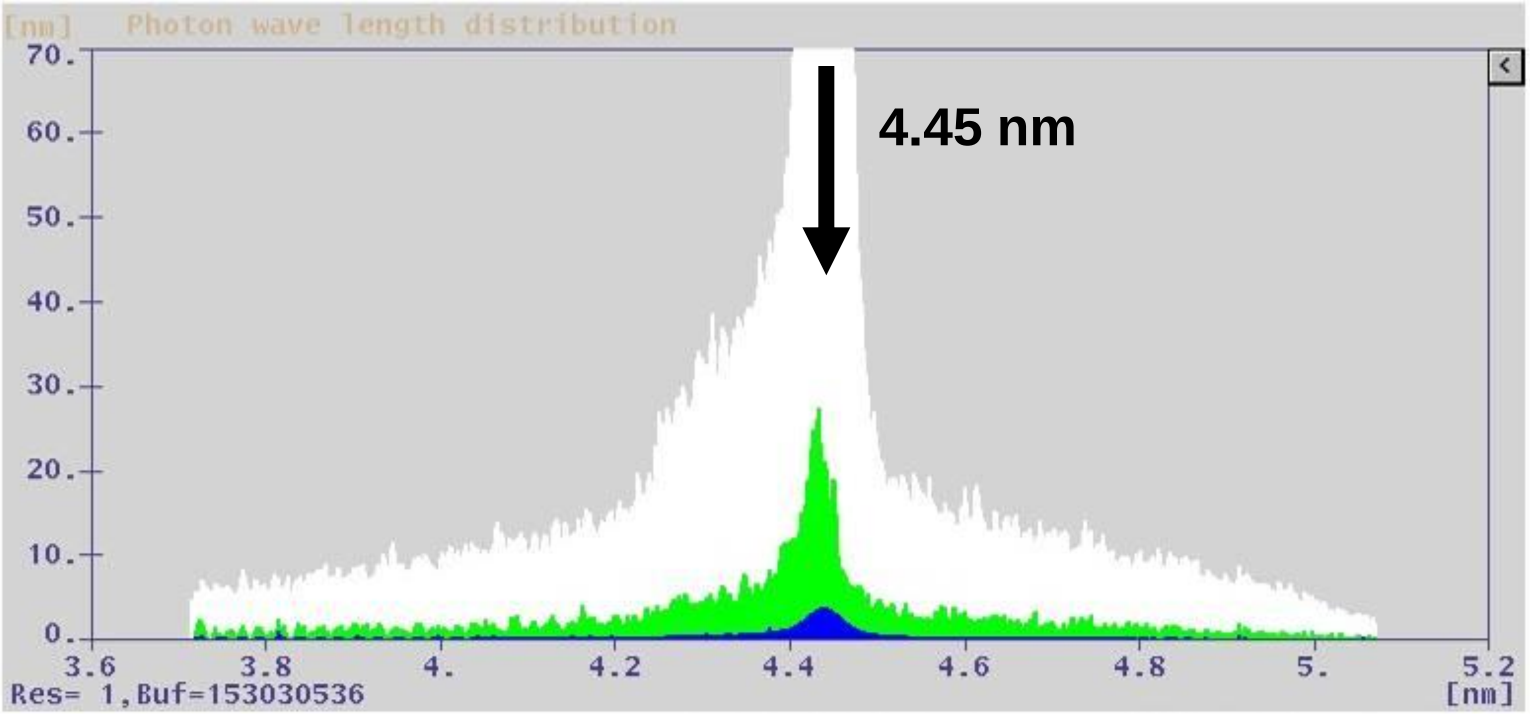
Free-Electron Laser in Hamburg

- Lasing at 4.x nm scheduled Jun-4 – Jun-11
- First lasing after upgrade in May-25 (12.5 nm)
- First lasing with linearized phase space (ACC39 on) in June-3 (12.5 nm)
- First lasing below 5 nm in June-6 @ 4.45 nm



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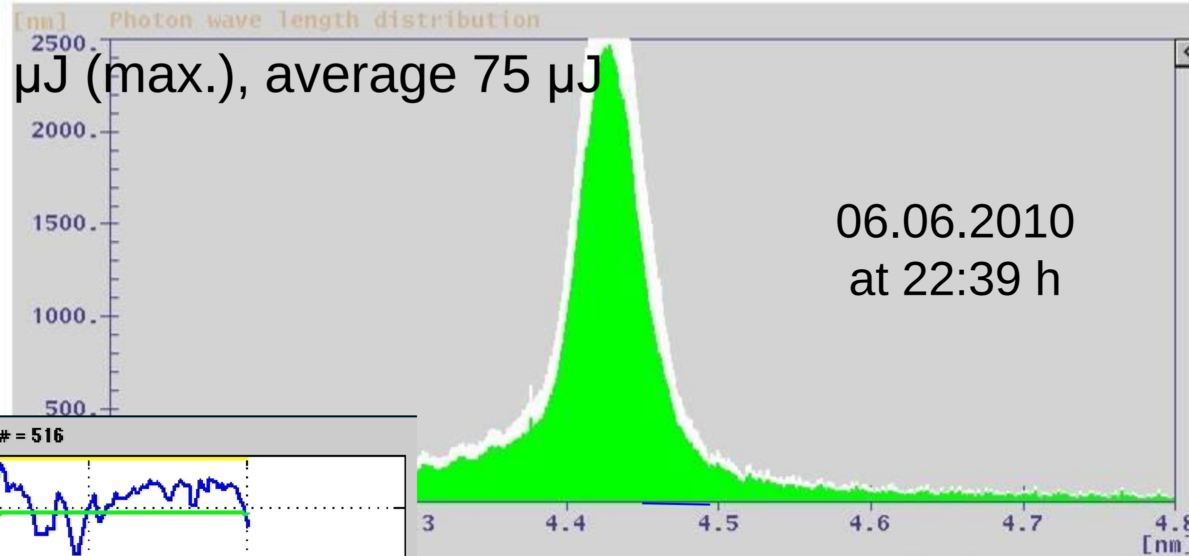
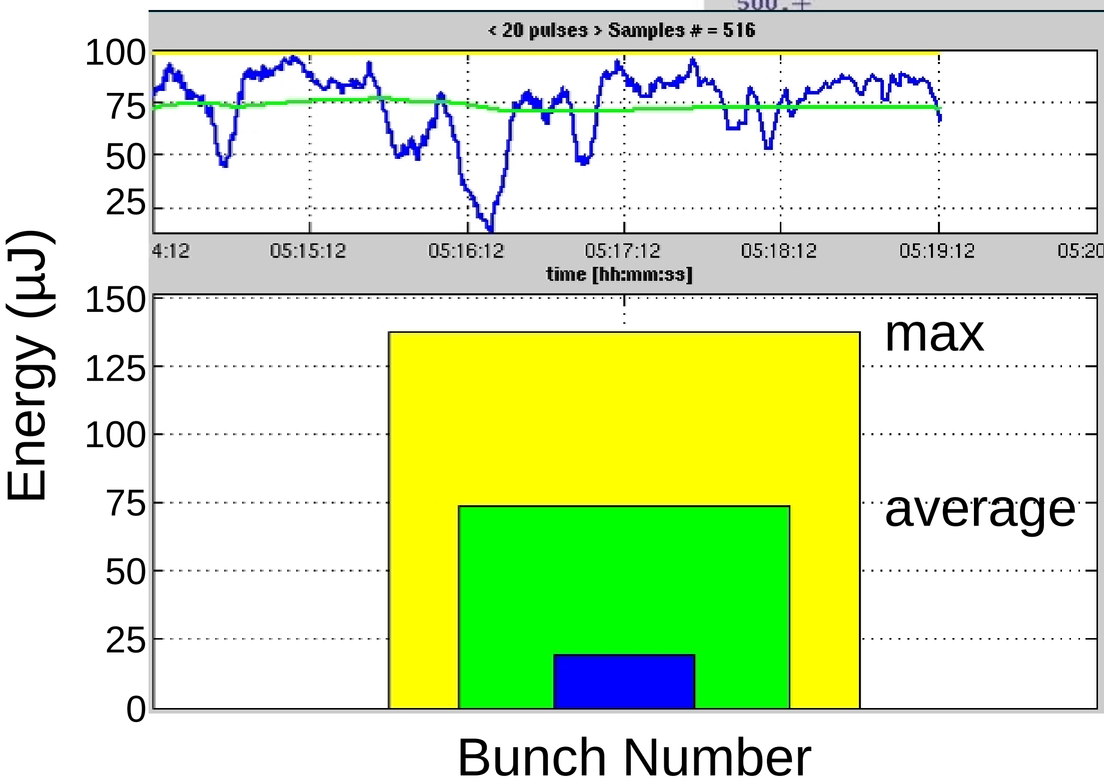
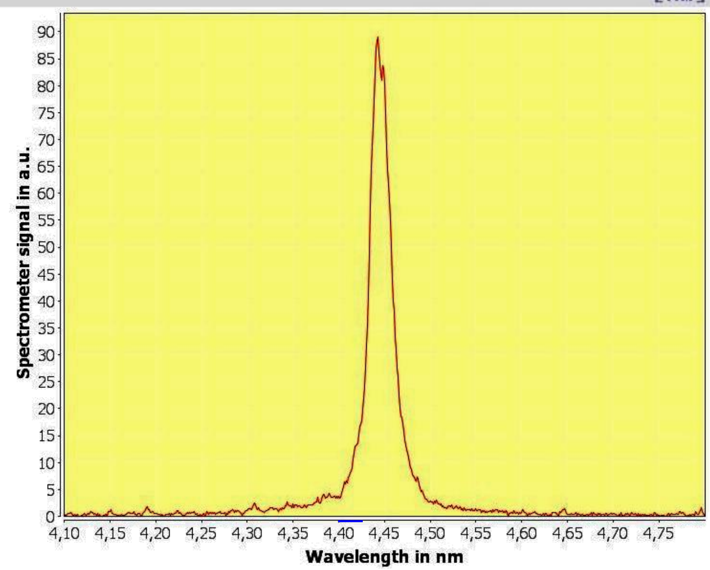
First Lasing at 4.45 nm

- Single pulse energy 140 µJ (max.), average 75 µJ
- Bandwidth ~0.25 % rms
- 10 Hz







SASE Parameters for 4.45 nm

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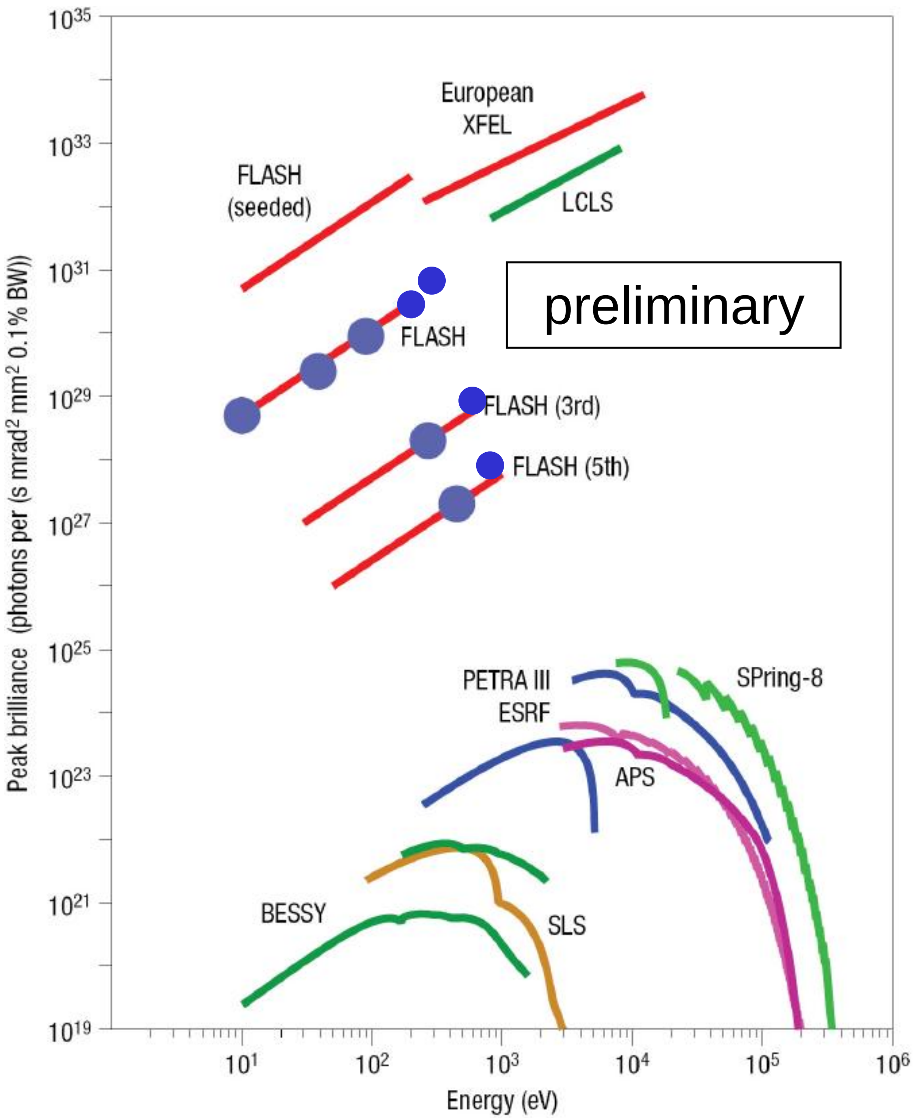
Preliminary data for 4.45 nm:

- Energy 140 µJ (max.)
- Peak power ~ 2 GW (estimate)
- bandwidth 0.25 % rms
- B ~ 10^{30} - 10^{31} photons/s/mrad²/mm²/0.1%bw



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Example for lasing at other wavelength

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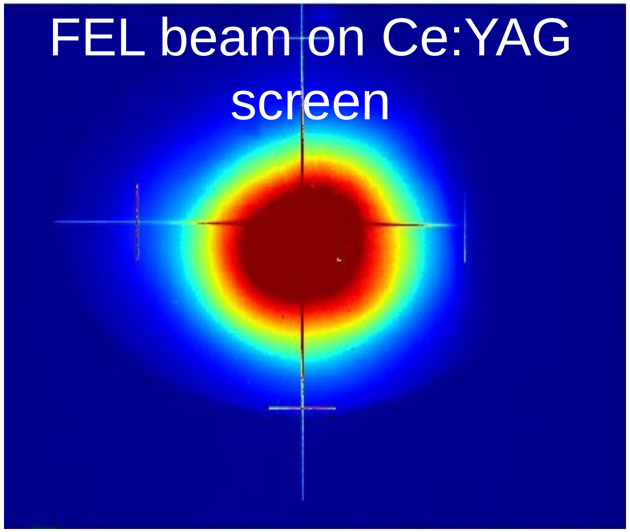
- For commissioning purposes, a couple of different wavelengths have already been set-up, many more to come
- 10 Hz, between 1 and 80 bunches per train so far, compression using 3.9 GHz cavities

Examples:

- 4.45 nm, 140 µJ max, average 75 µJ per pulse
- 12.4 nm, 105 µJ max, average 75 µJ per pulse
- 13.4 nm, 300 µJ max, average 250 µJ per pulse
- 19.2 nm, 350 µJ max, average 230 µJ per pulse
- 26.2 nm, 280 µJ max, average 160 µJ per pulse



13.4 nm, distance to screen 23.5 m, ticks at 3 mm

Radiation pulse energies are significantly larger and easier to tune compared to roll-over compression

Example of SASE at 19.2 nm

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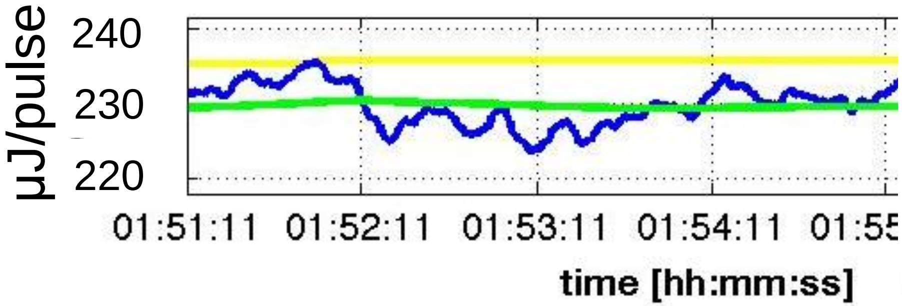
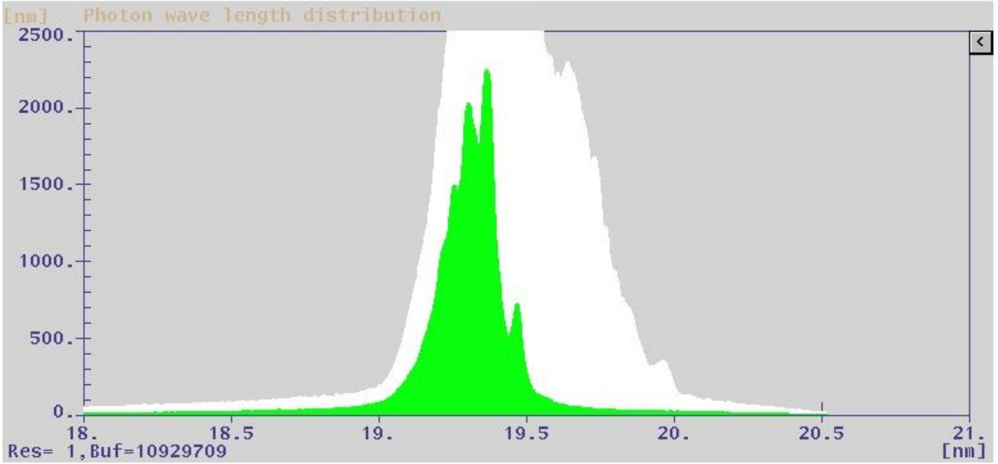
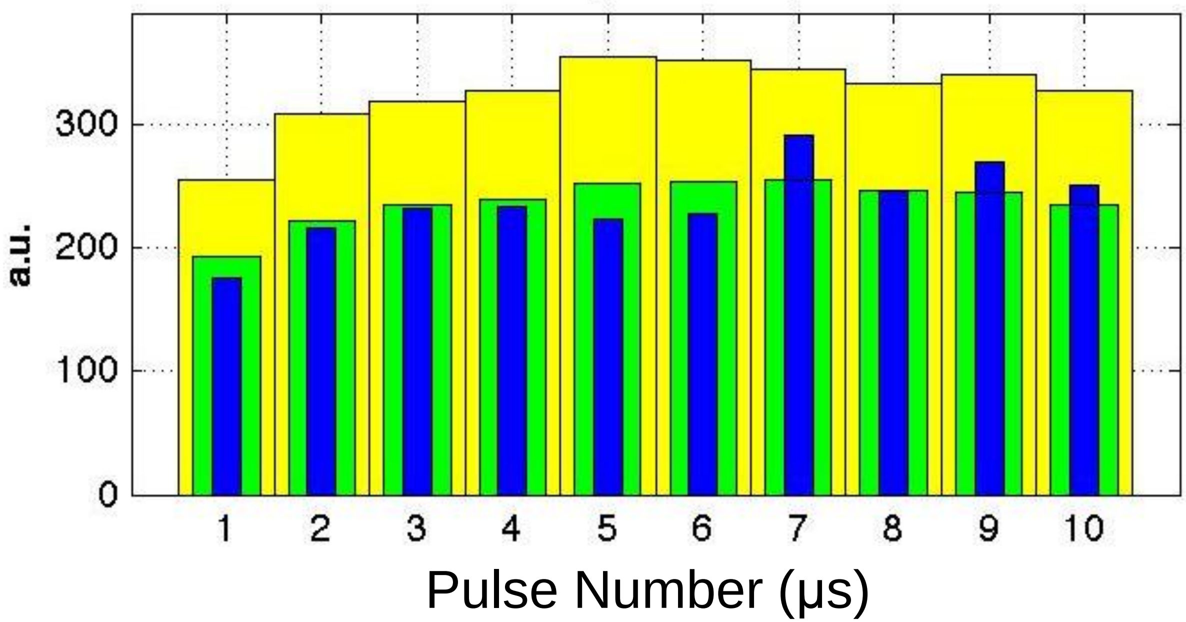
- 10 bunches/train, 10 Hz, max 350 µJ per pulse, av 230 µJ per pulse







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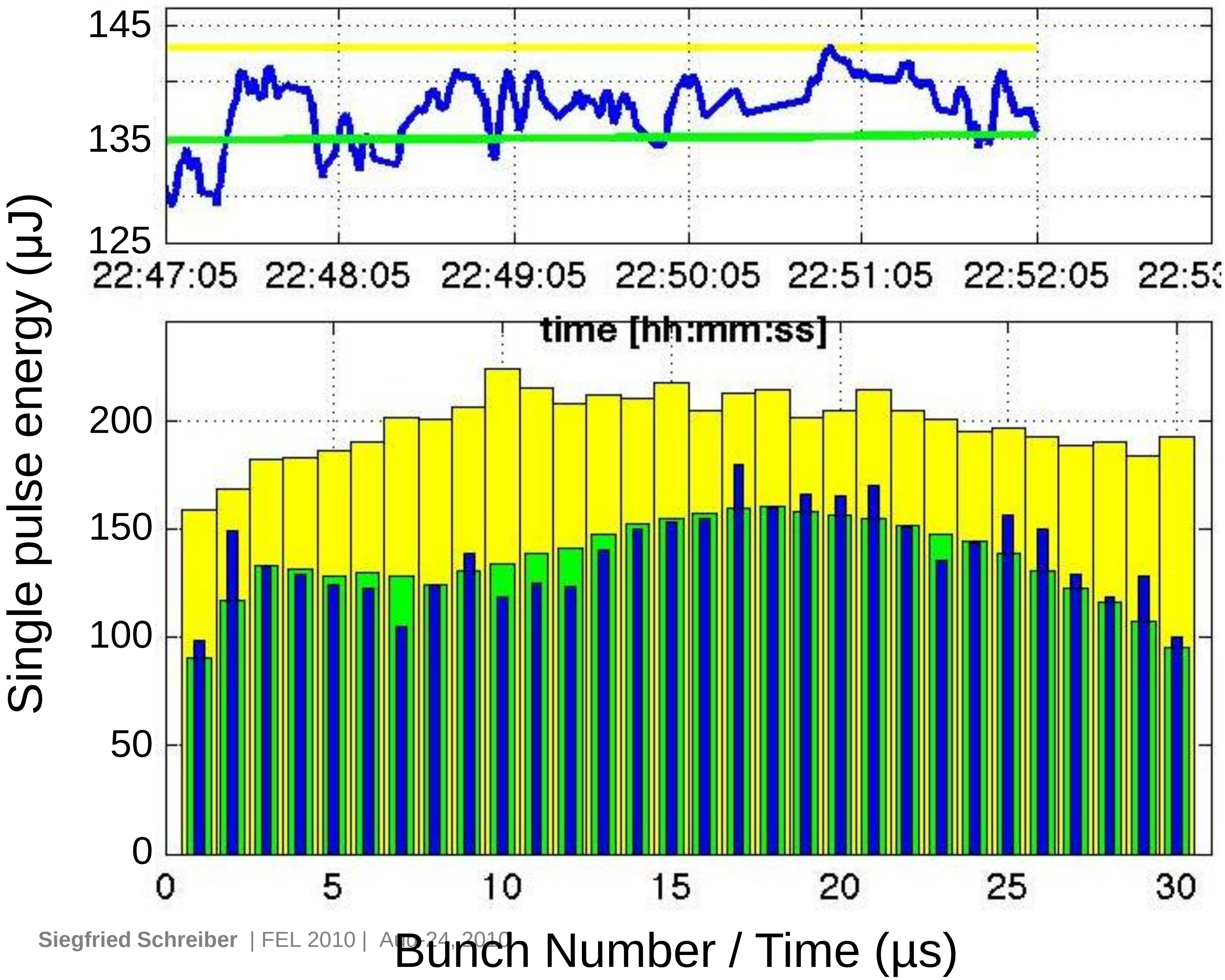
Example SASE at 13.4 nm

- 30 bunches/train, 10 Hz, max 225 µJ per pulse, av 140 µJ per pulse, average power 52 mW



3rd User Period

- The next, 3rd user period starts 2-Sep-2010
- Almost 400 12 h-shifts are scheduled until 11-Sep-2011
- Again, blocks of 4 weeks of user experiments are sandwiched by study weeks and beamline/user run preparation
- A few weeks of general accelerator studies are scheduled Jan 2010 and after the user run in Oct. 2011
- **Schedule available at flash.desy.de**

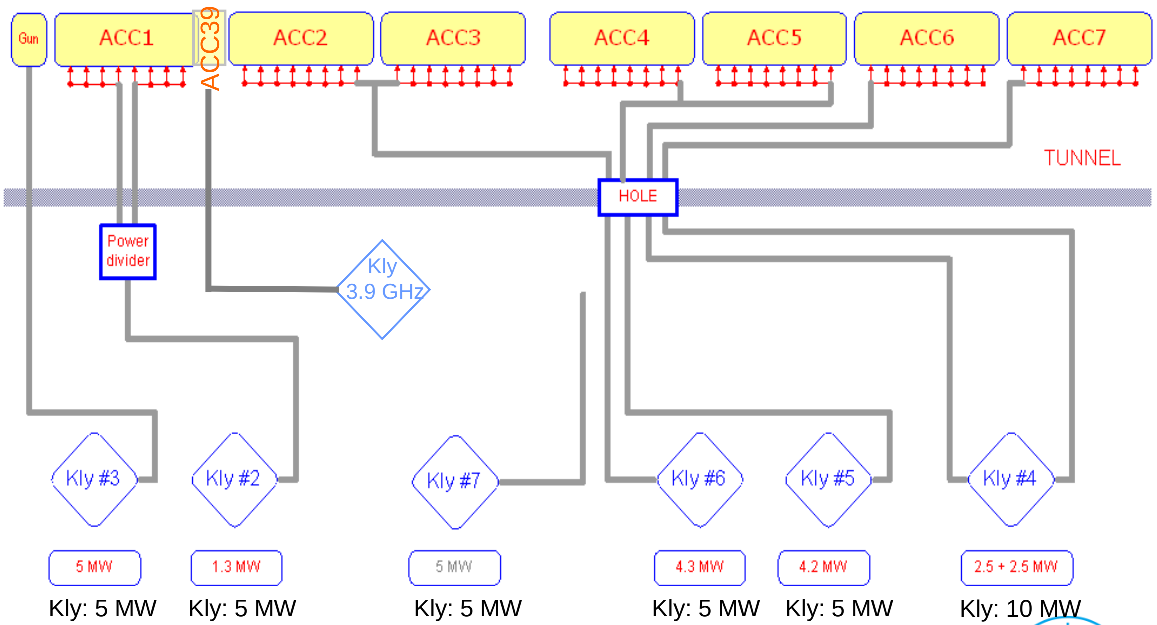
	27	5.Jul	-	11.Jul	7			school holidays HH	lasing with long trains
	28	12.Jul	-	18.Jul	7			school holidays HH/SH	
	29	19.Jul	-	25.Jul	2	FEL studies		school holidays HH/SH	
	30	26.Jul	-	1.Aug	2			school holidays HH/SH	
	31	2.Aug	-	8.Aug	3		preparation user run	school holidays HH/SH	
	32	9.Aug	-	15.Aug	3			school holidays HH/SH	
	33	16.Aug	-	22.Aug	3			school holidays HH/SH	photon beamlines commissioned
	34	23.Aug	-	29.Aug	3			**FEL Malmö**	**Start 3rd User Period**
	35	30.Aug	-	5.Sep	1	User Run		**Linac Tsukuba**	
	36	6.Sep	-	12.Sep	1				
	37	13.Sep	-	19.Sep	1				
	38	20.Sep	-	26.Sep	2	FEL studies			
	39	27.Sep	-	3.Oct	3		preparation user run		
	40	4.Oct	-	10.Oct	1	User Run			
	41	11.Oct	-	17.Oct	1				
	42	18.Oct	-	24.Oct	1				
	43	25.Oct	-	31.Oct	1				
	44	1.Nov	-	7.Nov	2	FEL studies			
	45	8.Nov	-	14.Nov	2				
	46	15.Nov	-	21.Nov	3		preparation user run		
	47	22.Nov	-	28.Nov	1	User Run			
	48	29.Nov	-	5.Dec	1				
	49	6.Dec	-	12.Dec	1				
	50	13.Dec	-	19.Dec	1				
	51	20.Dec	-	26.Dec	5	Maintenance			
January	52	27.Dec	-	2.Jan	5				
2011	1	3.Jan	-	9.Jan	4		preparation accelerator studies		***2011***
	2	10.Jan	-	16.Jan	4	Accelerator studies			
	3	17.Jan	-	23.Jan	4				
	4	24.Jan	-	30.Jan	2	FEL studies			
	5	31.Jan	-	6.Feb	2				
	6	7.Feb	-	13.Feb	3		preparation user run		
	7	14.Feb	-	20.Feb	1	User Run			
	8	21.Feb	-	27.Feb	1				
	9	28.Feb	-	6.Mar	1				

Example of upgraded components

Upgrade of RF stations and waveguide system

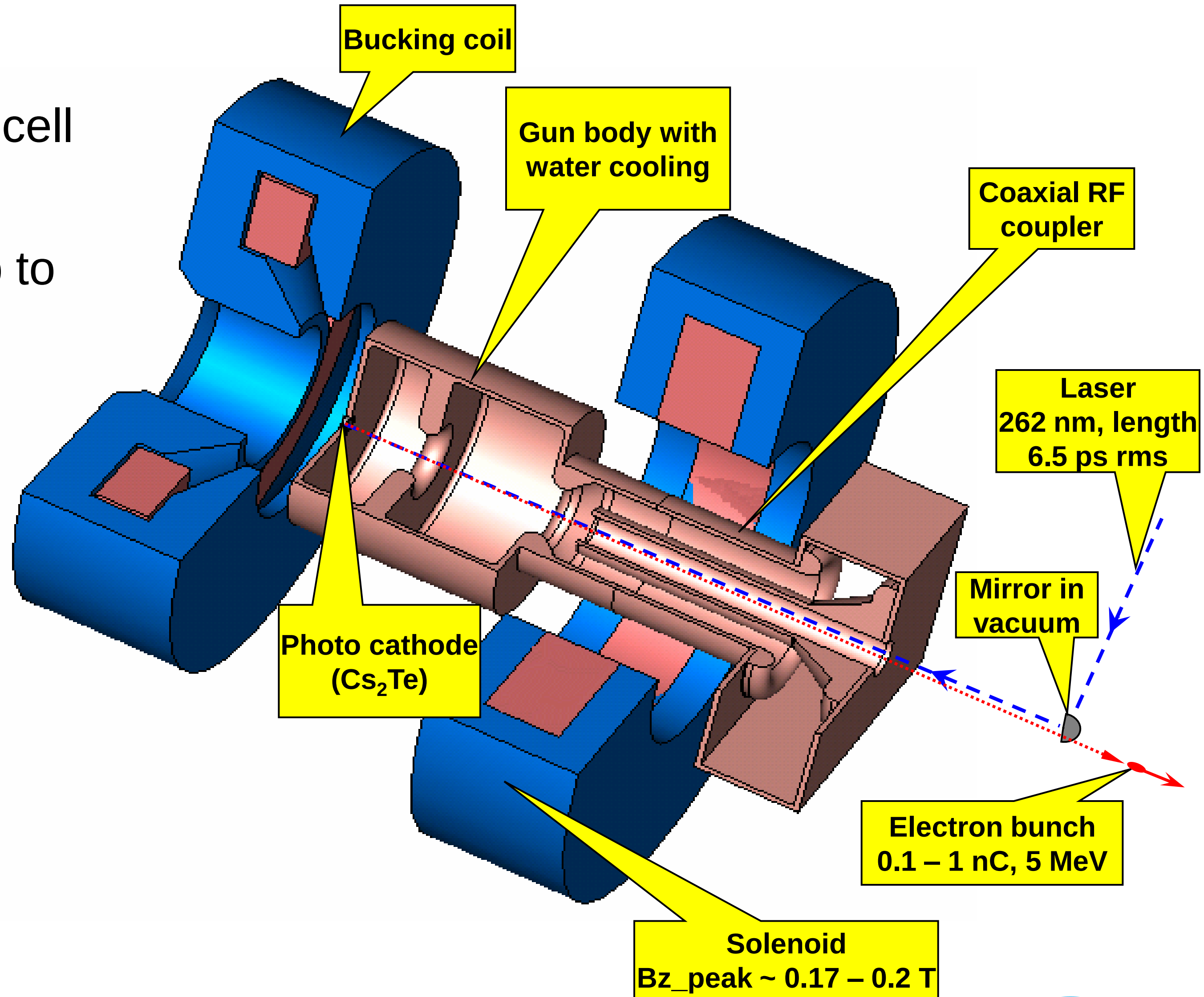
FLASH. Free-Electron Laser in Hamburg

- Two new 1.3 GHz RF stations + 1 modulator replaced
  - all stations of same type now
  - Four 5 MW klystrons, one 10 MW multi-beam klystron, 3.9 GHz klystron
- One additional RF station to optimize operation with seven accelerating modules
- Accelerating modules 1, 6, and 7 have the optimized XFEL type waveguide distribution



RF Gun

- RF gun: 1.3 GHz copper cavity, 1 ½ cell
- RF power 3.8 MW, RF pulse length up to 850 µs, 10 Hz
- New gun tested and commissioned at PITZ (DESY-Zeuthen)



RF gun darkcurrent

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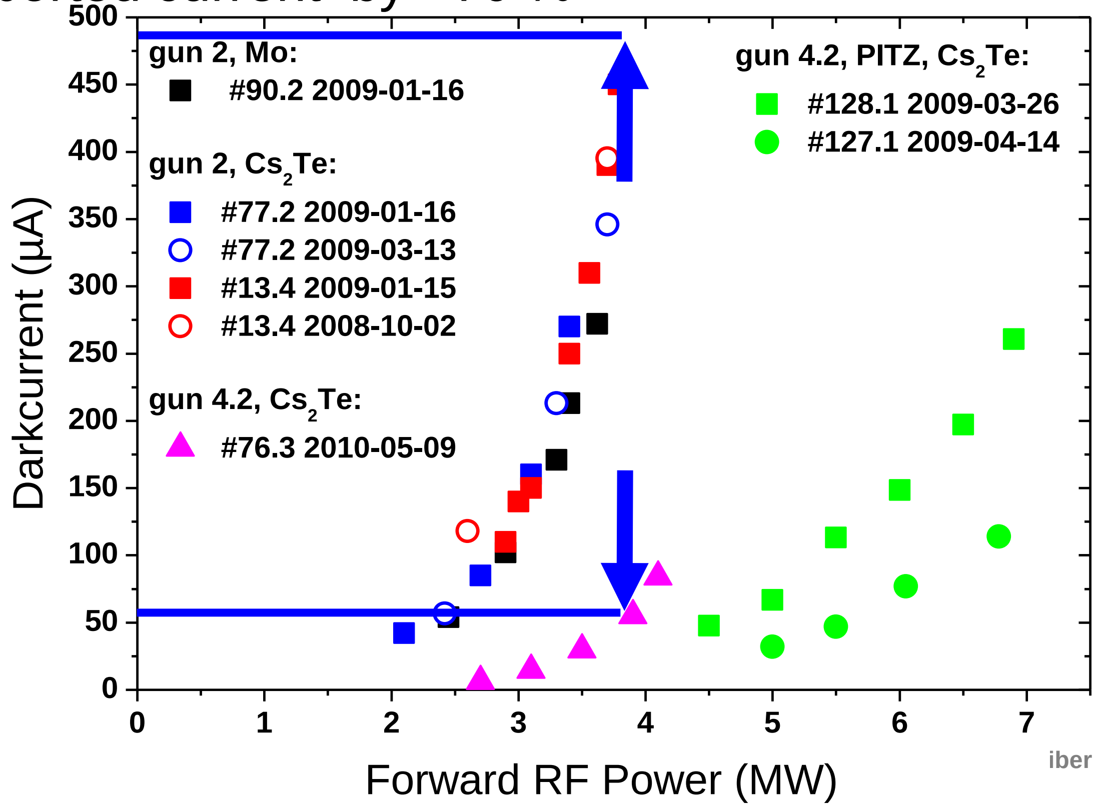
- Dry ice cleaned gun body
- Darkcurrent is reduced by a factor of 10 compared to previous guns
- This allows operation with 10 Hz and in the future with higher gradients
- Darkcurrent kicker + collimator at the gun exit to further reduce the transported current by ~70 %



DESY

3.9 GHz (3rd harmonic) Module and Module 1

- New 1st accelerating module with improved cavities and Piezo tuners
- 3rd harmonic module with four nine-cell superconducting cavities operated at 3.9 GHz
  - includes RF system and LLRF regulation
  - built at FNAL (Fermilab) in a collaboration with DESY

Fermilab DESY

Excellent performance of cavities

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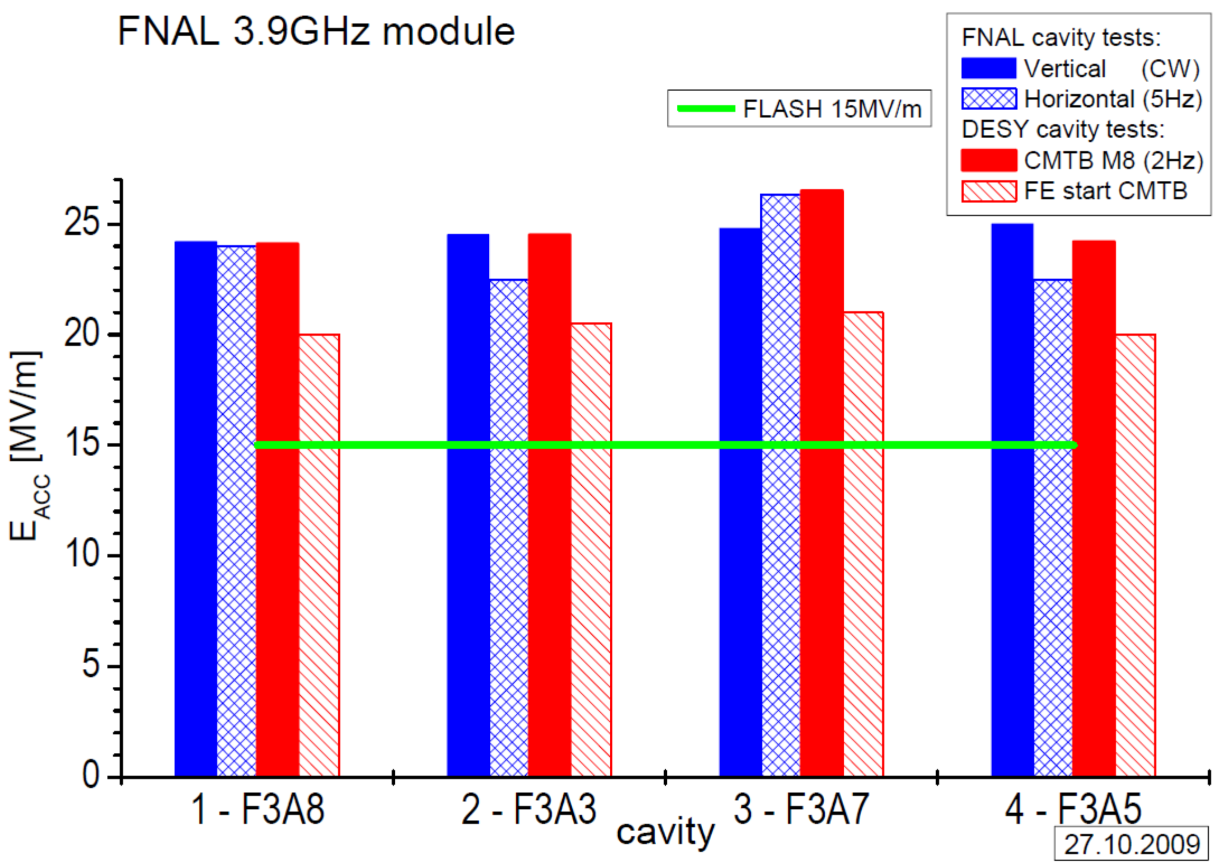
Free-Electron Laser in Hamburg

- 3.9 GHz cavities outperform design goal
  → routine operation with 21 MV (module)



Mounting of accelerating modules in injector

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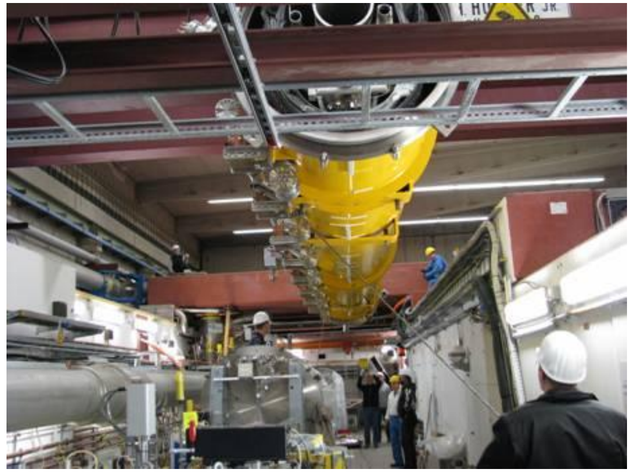
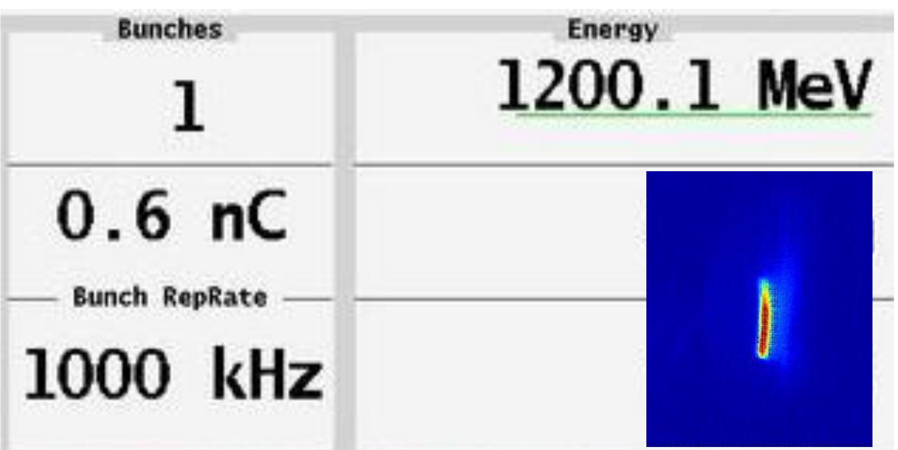


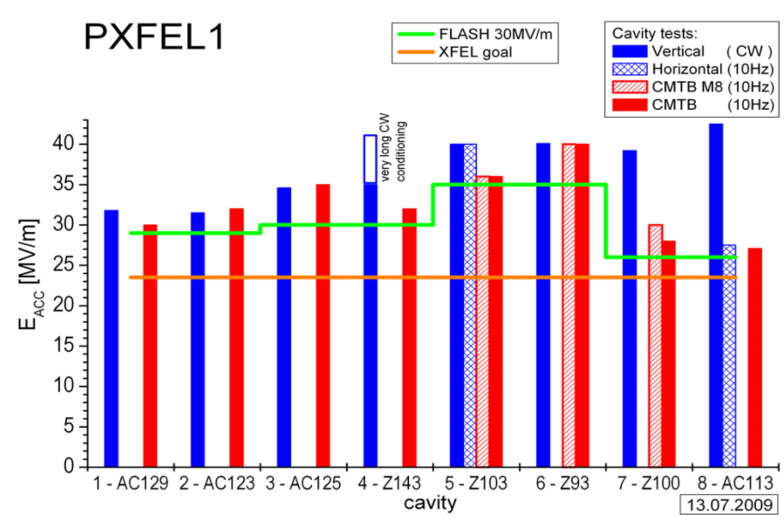
Energy upgrade

- 7th superconducting TESLA type accelerating module installed
  - Prototype module for the European XFEL
  - Energy reach 240 MeV
- Electron beam energy 1.2 GeV

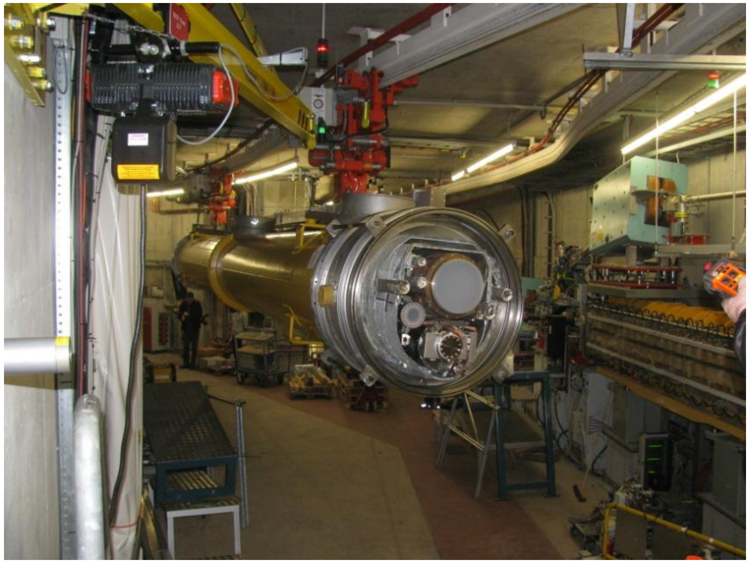
1.2 GeV demonstrated with beam in May 2010

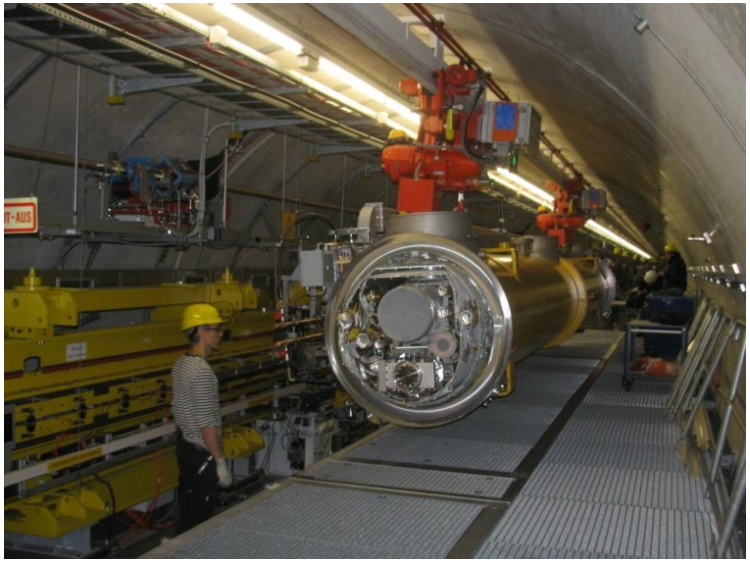


Results of cavity tests



Transport of 7th accelerating module



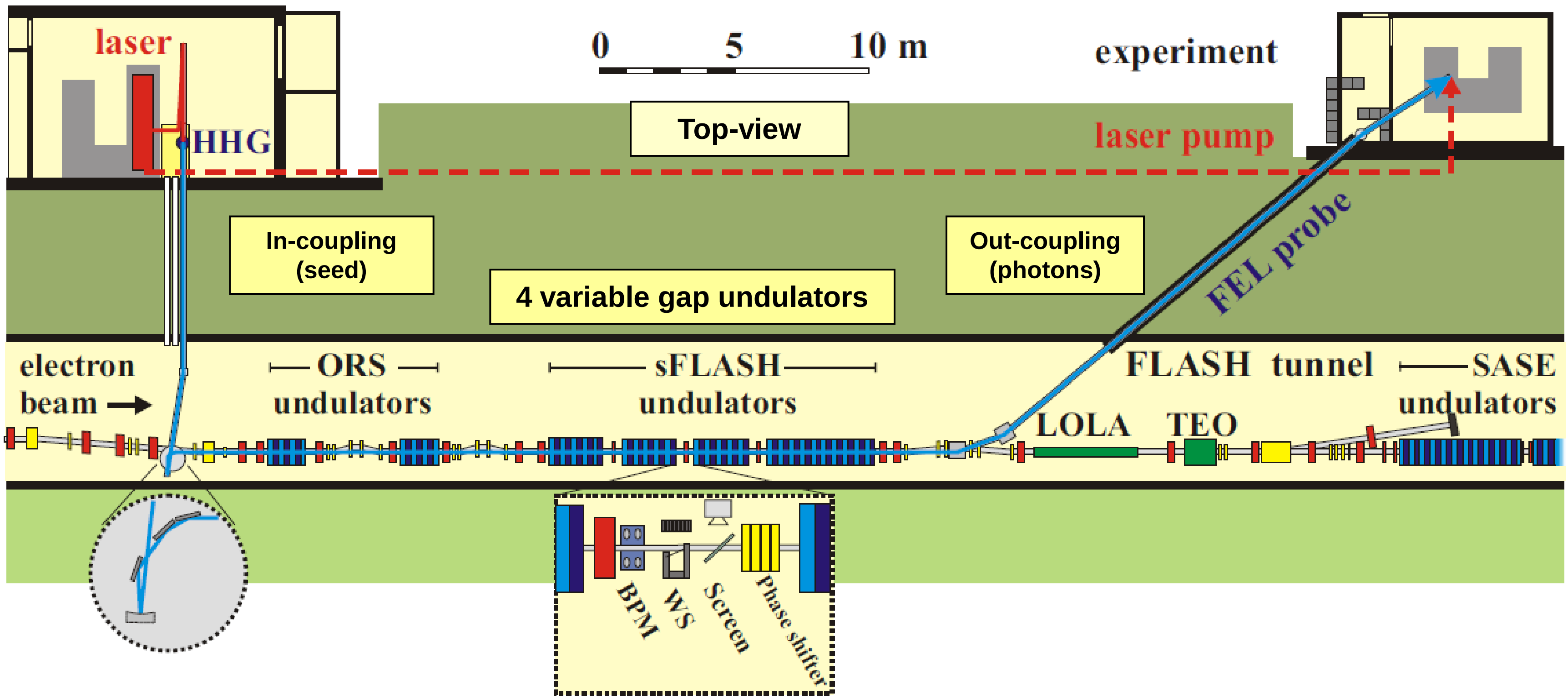


sFLASH

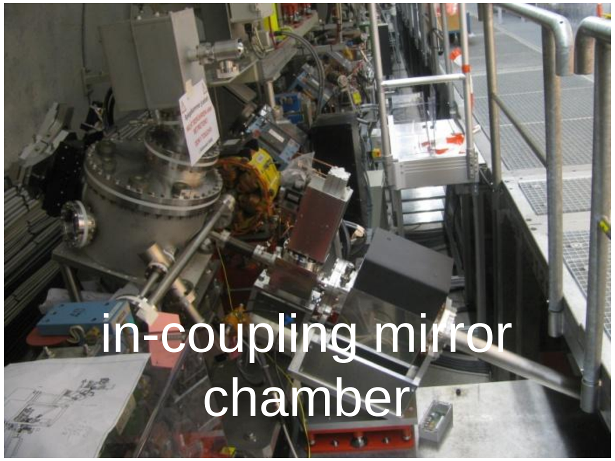
sFLASH: experiment for seeded FEL radiation

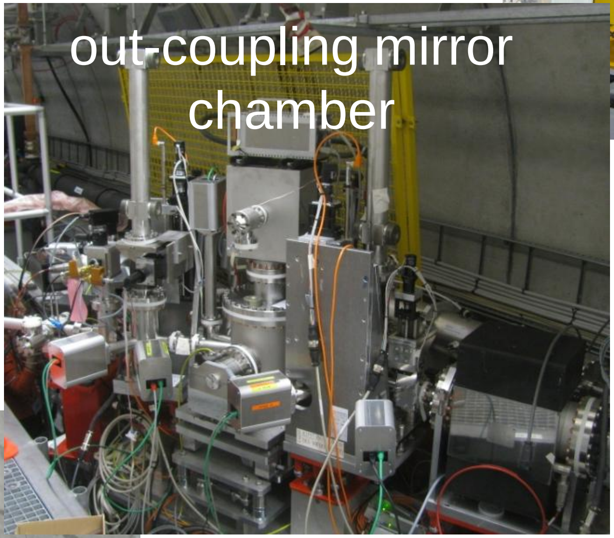
FLASH. Free-Electron Laser in Hamburg

- Goal: generation of seeded FEL radiation for piloting experiments
- Installed between the collimator and SASE undulators in the FLASH linac
  → new electron beamline with a length of ~ 40 m
- HHG (high harmonic generation) seeding at ~ 38 nm (~ 13 nm as an option)
- synchronisation goal for pump probe experiments: 10 fs
- Collaboration of DESY and University Hamburg



sFLASH section



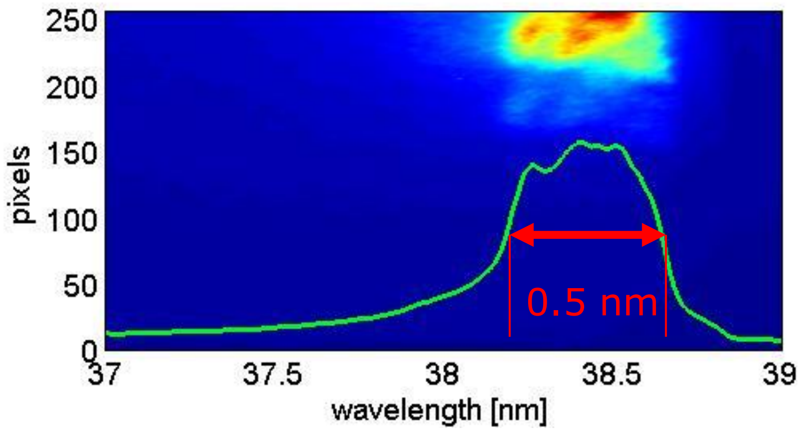


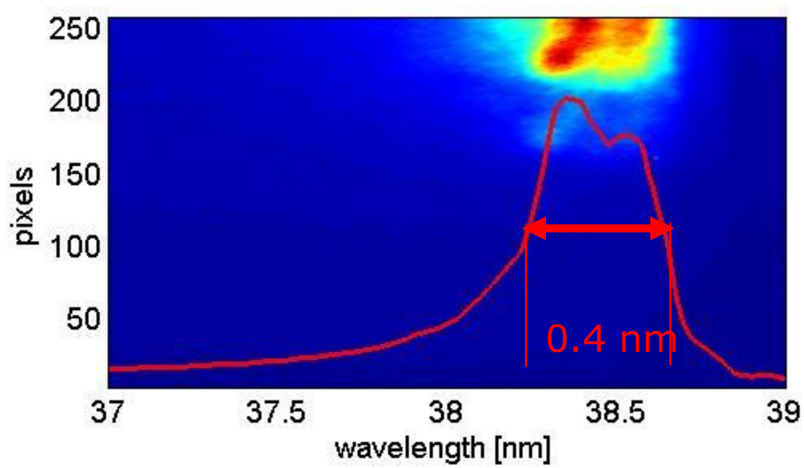
First SASE at sFLASH at 38.4 nm

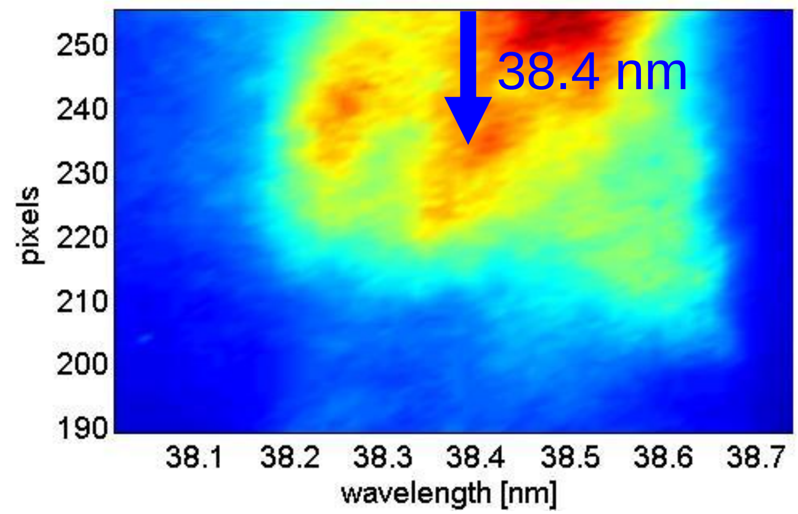
- SASE spectra, single shot
- Center wavelength 38.4 nm, width ~0.5 nm

Talk on We 9:00 h WEOAI2
by Joern Boedewadt,

Posters in the TUPB session







Photon Beamline

Photon diagnostics and photon lines

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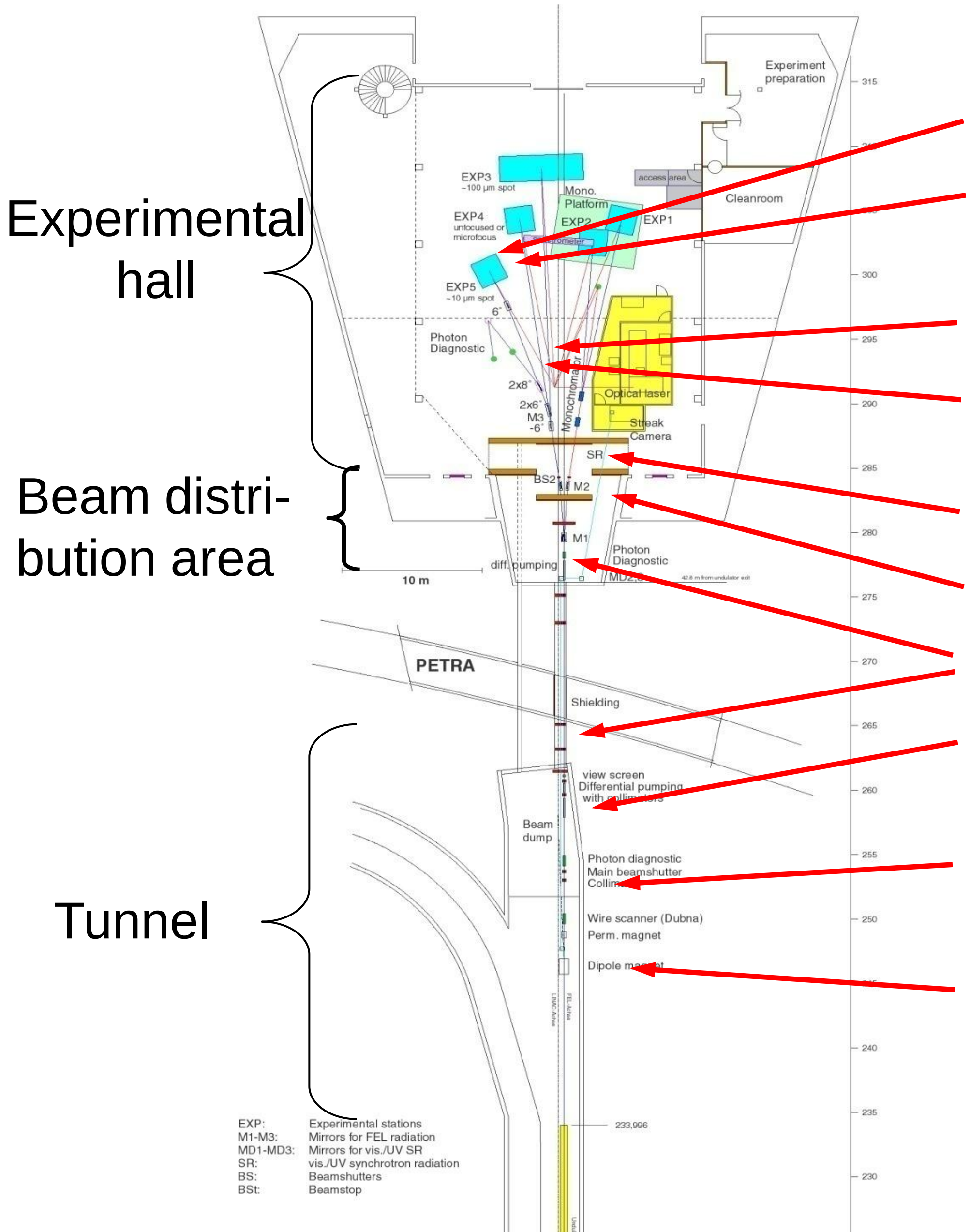

New installations / upgrades

- focusing mirror at BL3
- modification of differential pumping units of BL2 and BL3
- a fast switching mirror unit
- split and delay unit as a permanent device in the direct beam lines
- new filter units and new fast shutters
- repair of VLS spectrometer
- modification of differential pumping units
- additional photon BPMs with MCP / fluorescence screen monitor
- new online spectrometer based on atomic photo ionization (like GMD)
- installation of a MCP / fluorescence screen monitor in the MCP tool

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Bunch Compression

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Transverse deflecting cavity LOLA

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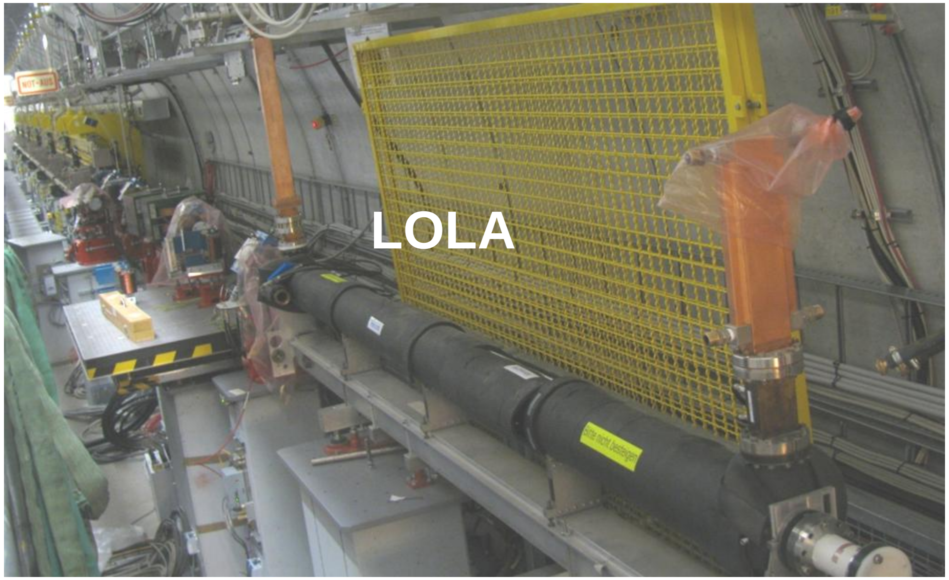
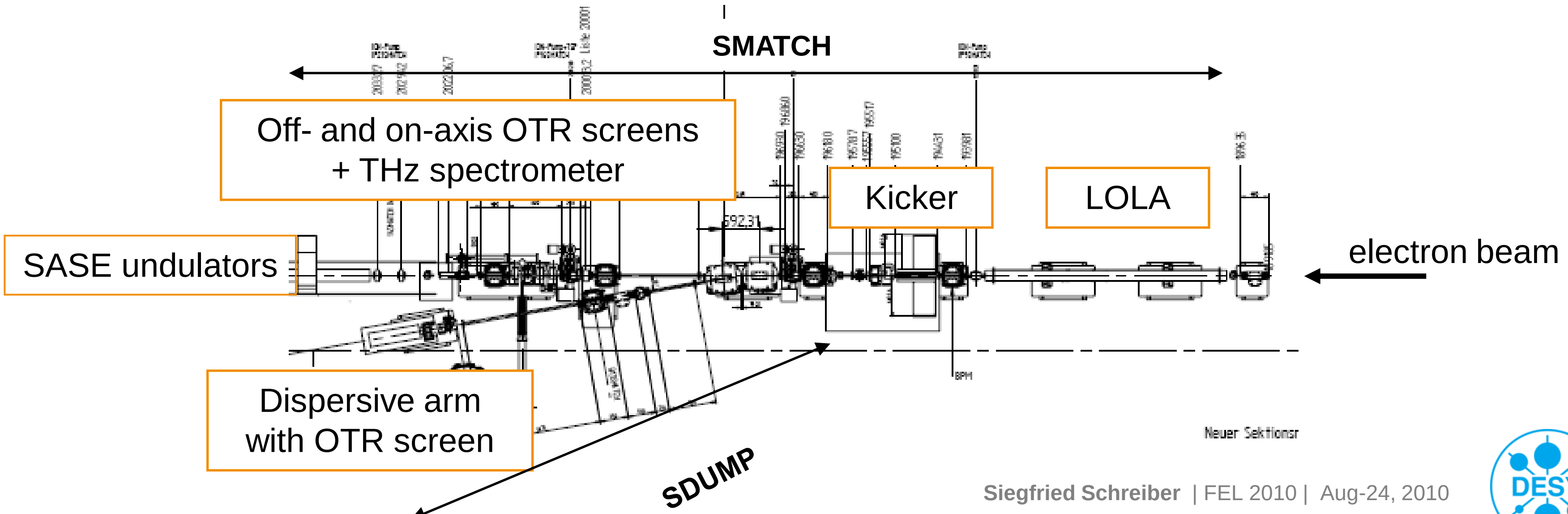
> Longitudinal bunch structure
  - LOLA is moved to a new location just upstream of the SASE undulators
  - time resolution 20 fs
  - energy resolution 1.4 10^{-4}

> Kicker and off-axis screen
  - on-line beam diagnostics, arbitrary pulse in the train can be picked

> New installation includes a dispersive arm





DESY

Compression Scheme w/o 3rd Harmonic Cavities

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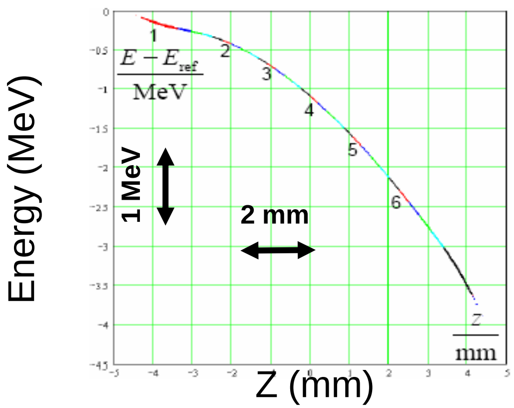
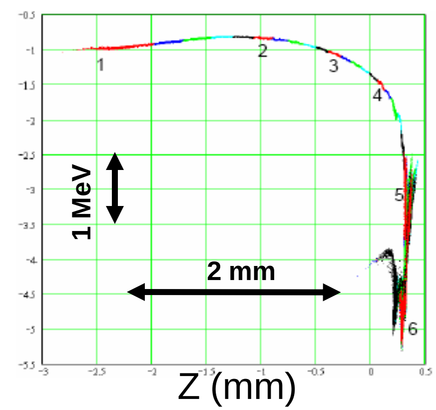
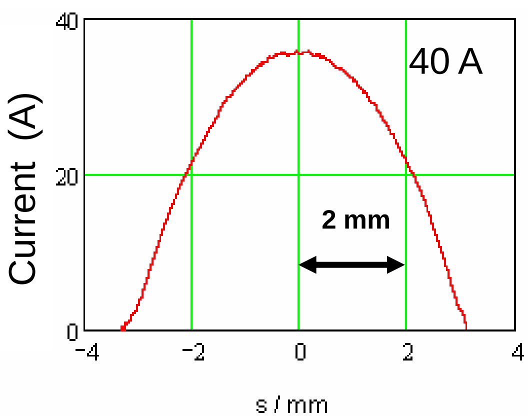
- Non-linearity in the longitudinal phase space leads to a roll-over compression
  → development of a sharp spike ~ 50 fs fwhh with high peak current

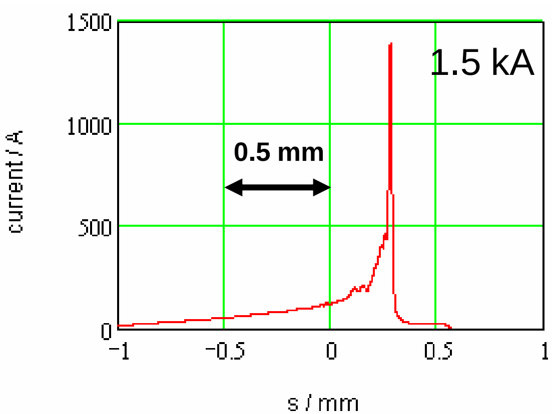
Before



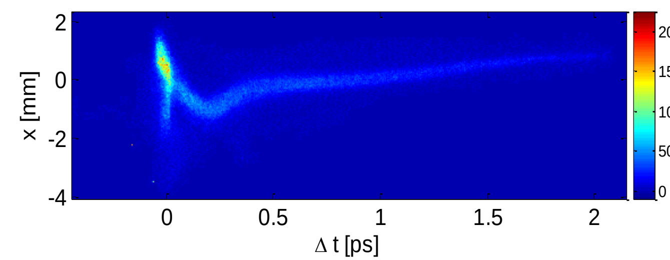
After compression

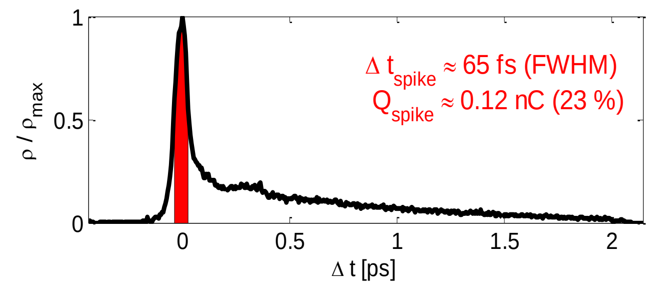






Measured longitudinal shape of a compressed bunch



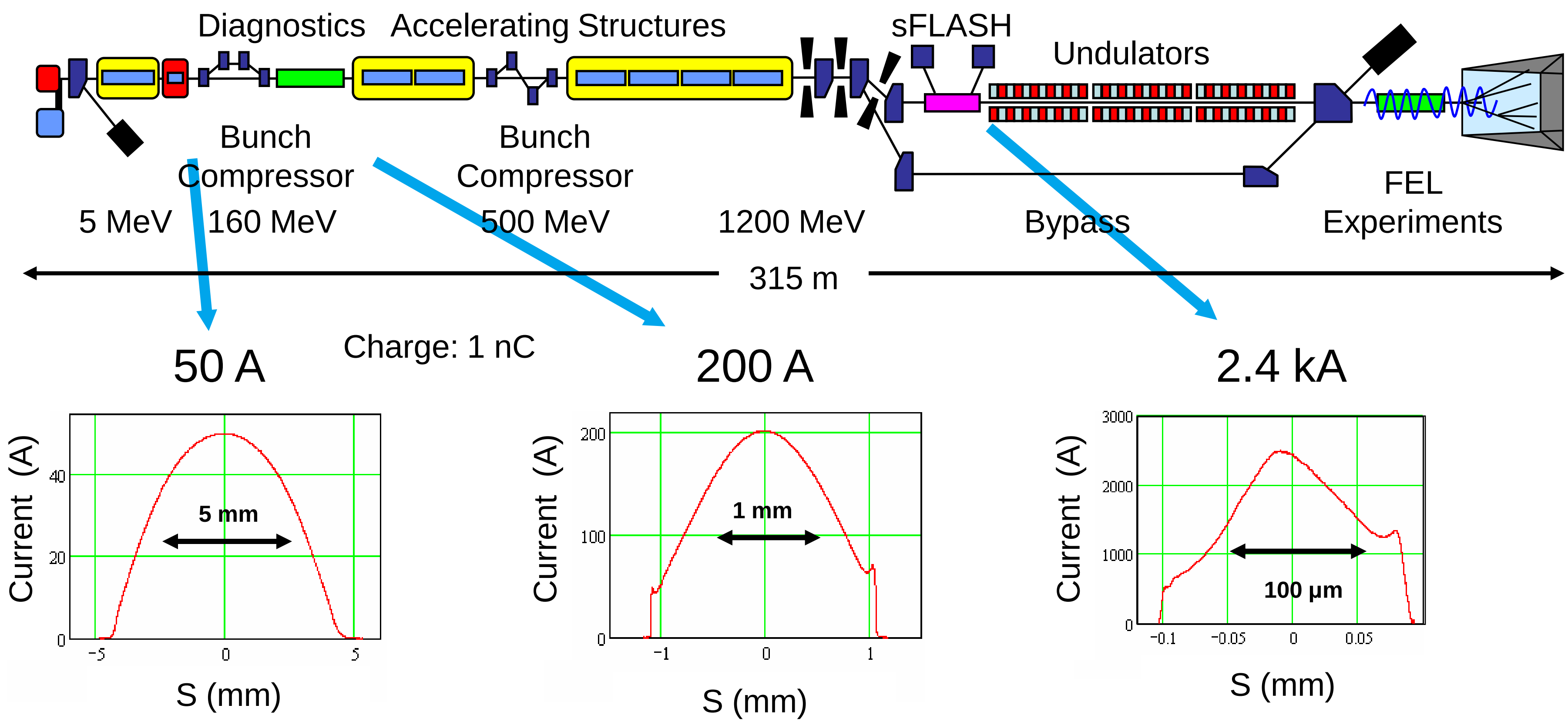


Measured by a transverse deflecting cavity placed after the last accelerating module

DESY

Regular Compression with 3rd Harmonic Cavities

- Flattening of the longitudinal phase space
- More regular compression with high peak current



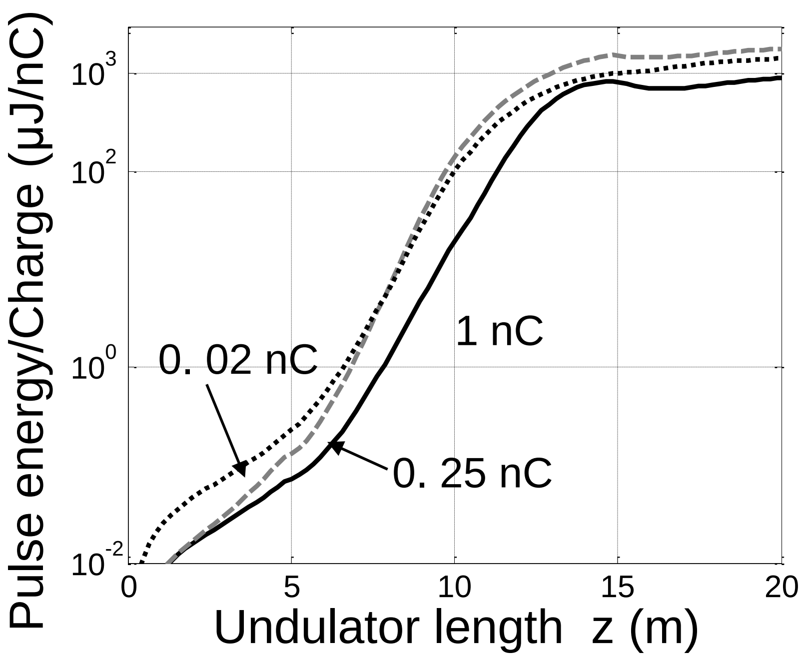
Expected photon energy and pulse length

FLASH.
Free-Electron Laser in Hamburg

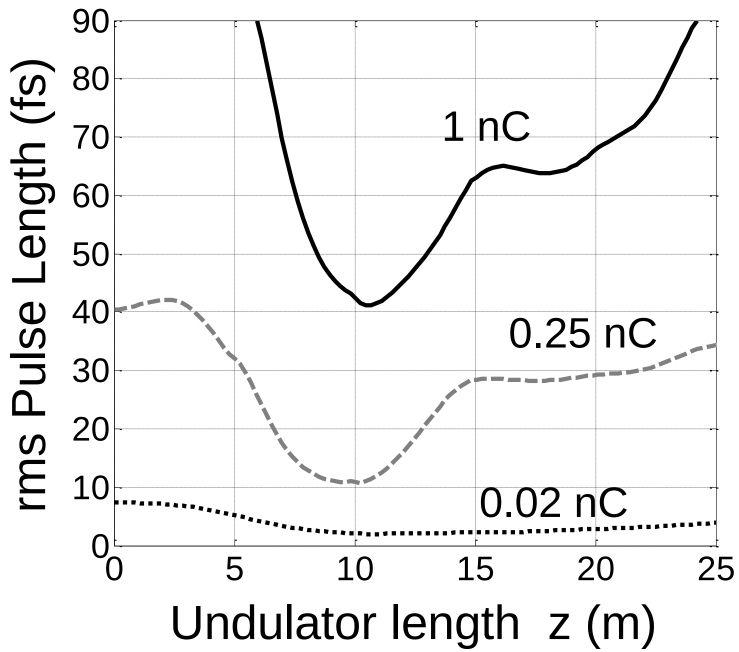
- Regular compression scheme with 3rd harmonic cavities, charge 1 nC
  → larger energy 1-1.5 mJ
  → photon pulse lengths ~30 fs rms

- Compression with lower bunch charge
  → charge from 0.02 to 1 nC
  → variable pulse length in the range of ~ 1 and 30 fs (rms)

Radiation pulse energy/charge



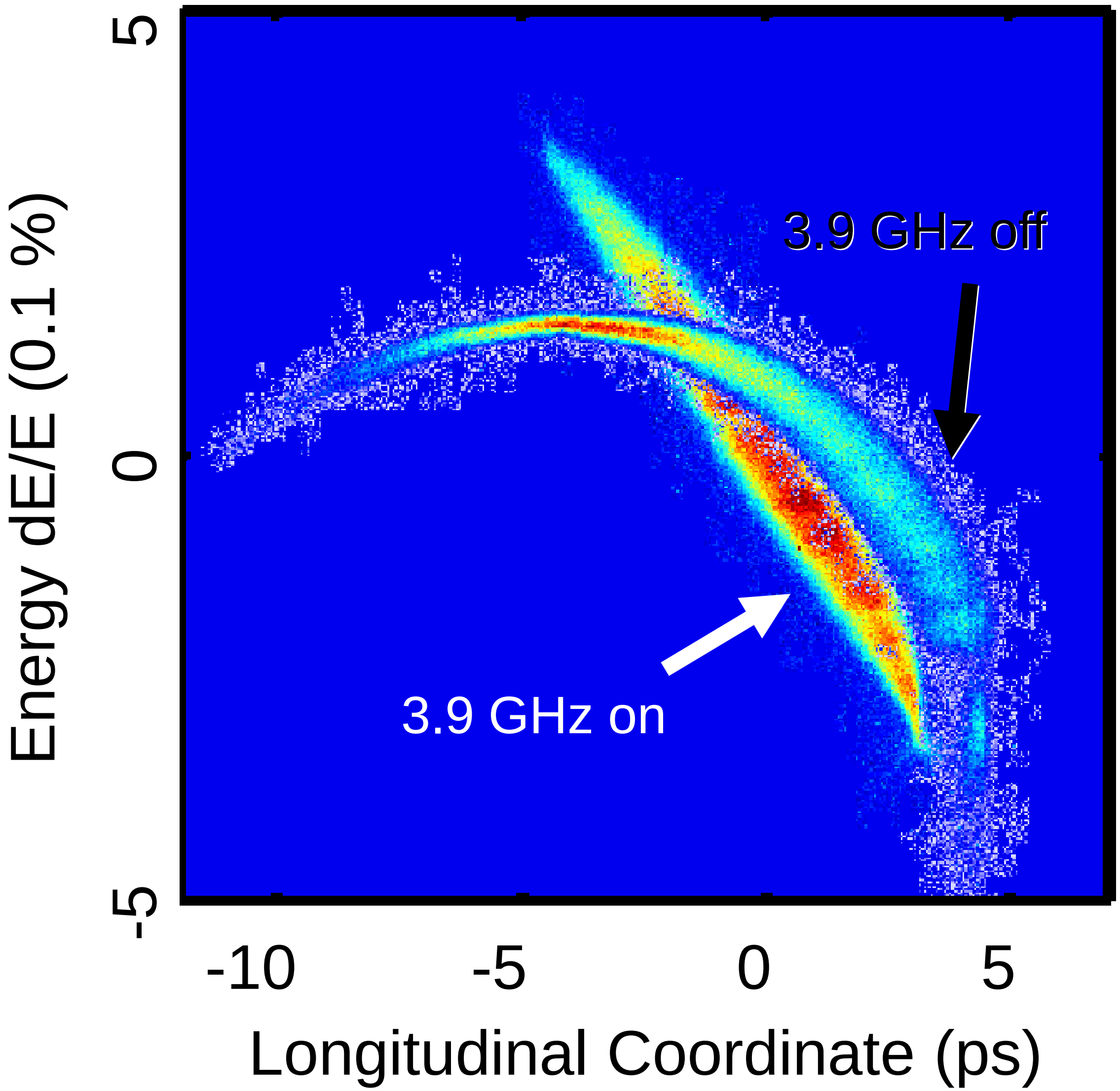
Radiation pulse width (rms)



→ talk of Igor Zagorodnov tomorrow at 11:00 h
WEOBI2 Ultra-Short Low Charge Operation at FLASH and the European XFEL

DESY

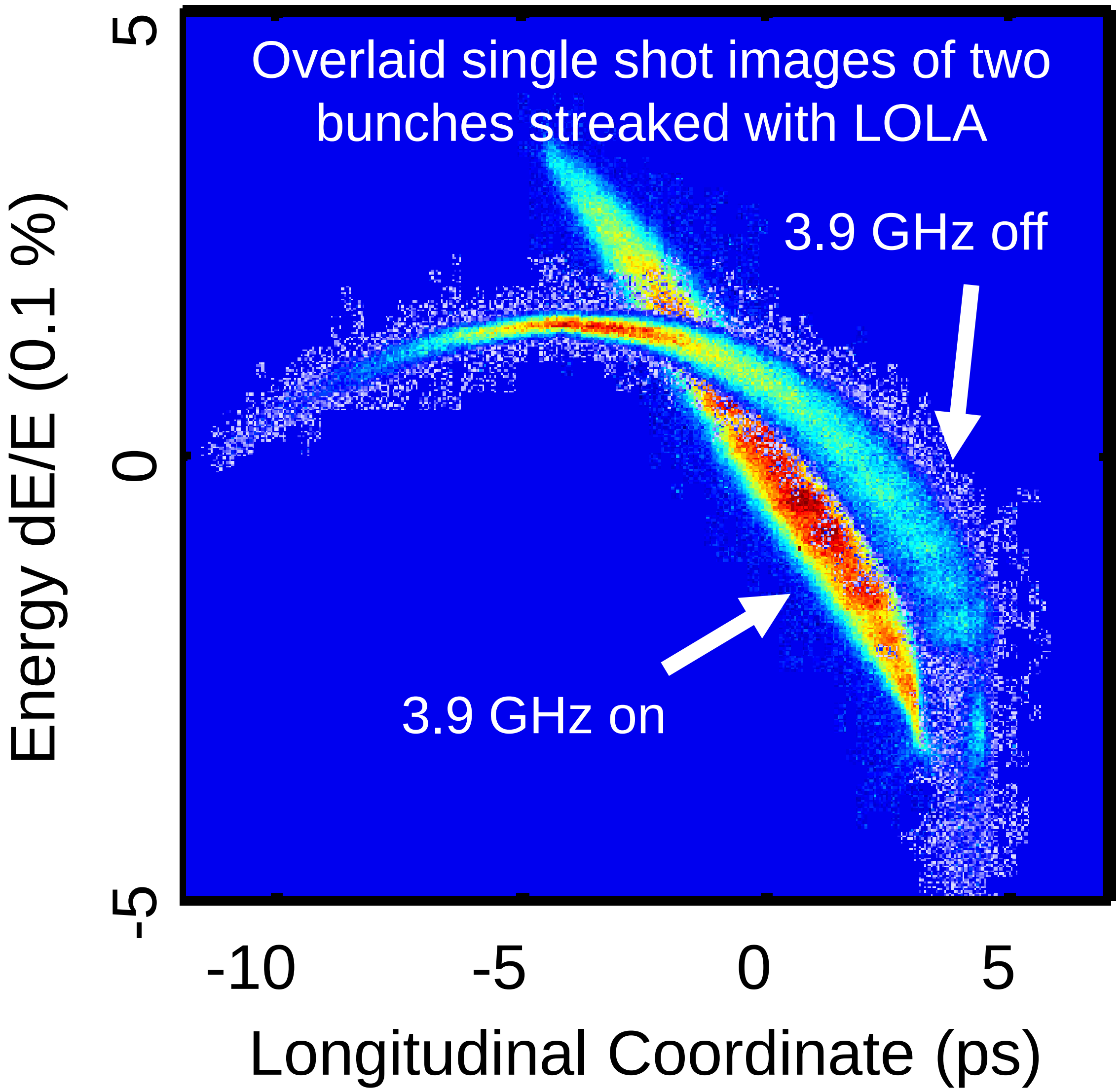
Linearization of the longitudinal phase space



- Measured with LOLA,
- dispersive section
- beam energy 700 MeV
- Slight compression with 1st module (ACC1)
- 3.9 GHz cavities on/off

Linearization of the longitudinal phase space

FLASH.
Free-Electron Laser in Hamburg



- Measured with LOLA,
- dispersive section
- beam energy 700 MeV
- Slight compression with 1st module (ACC1)
- 3.9 GHz cavities on/off

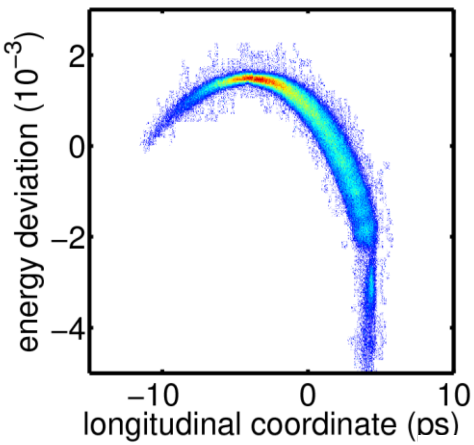
DESY

Linearization of the longitudinal phase space

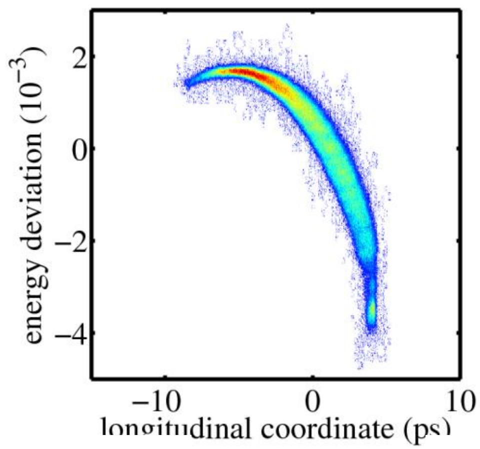
FLASH. Free-Electron Laser in Hamburg

- 1st module (ACC1) set to moderate compression
- Bunch shape measured for increasing voltage in the 3rd harmonic cavities

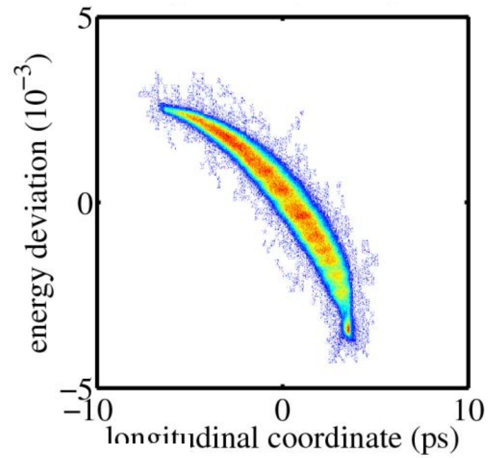
U_{39} = 0 MV



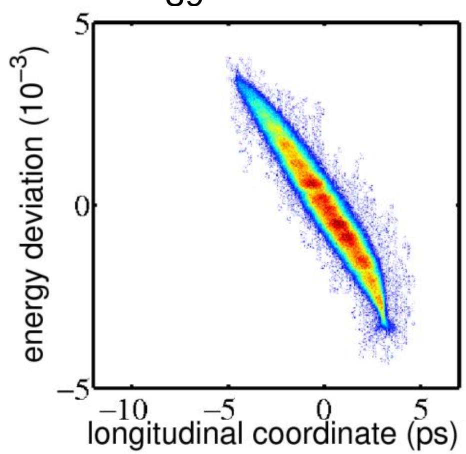
U_{39} = 5 MV



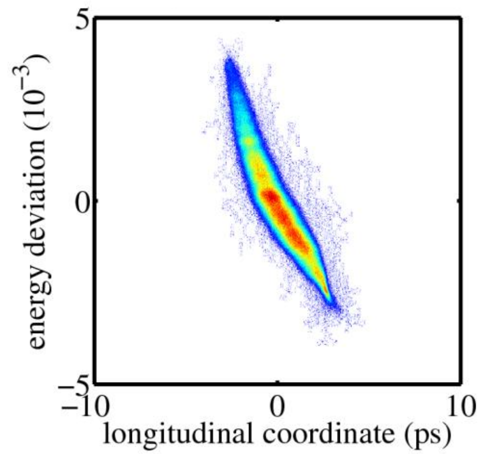
U_{39} = 10 MV



U_{39} = 15 MV



U_{39} = 20 MV



DESY

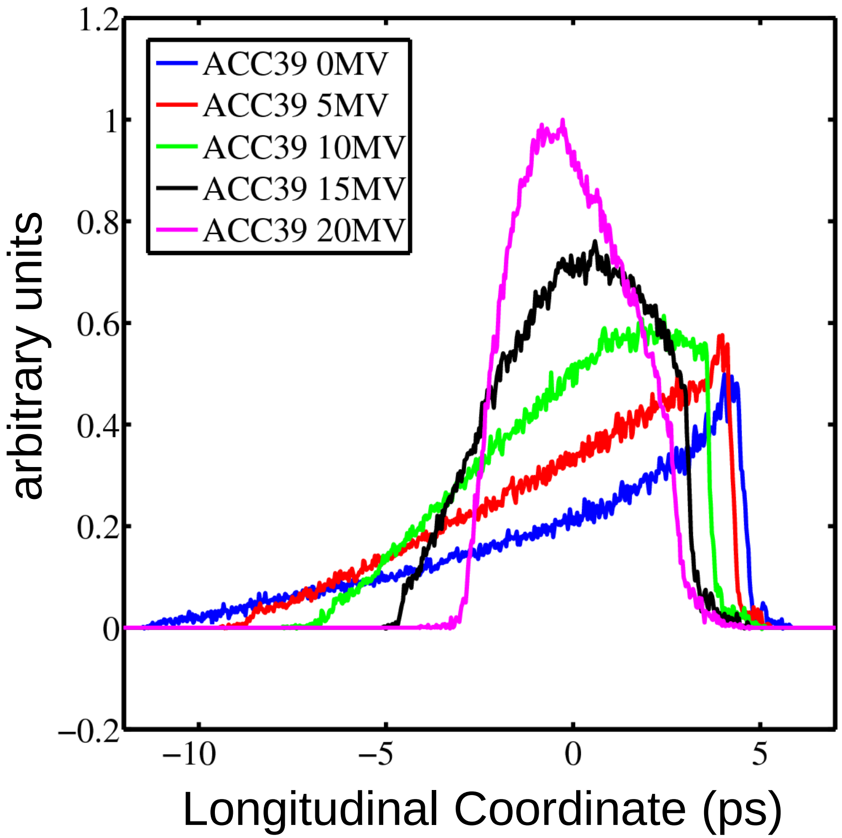
Longitudinal Bunch Shape

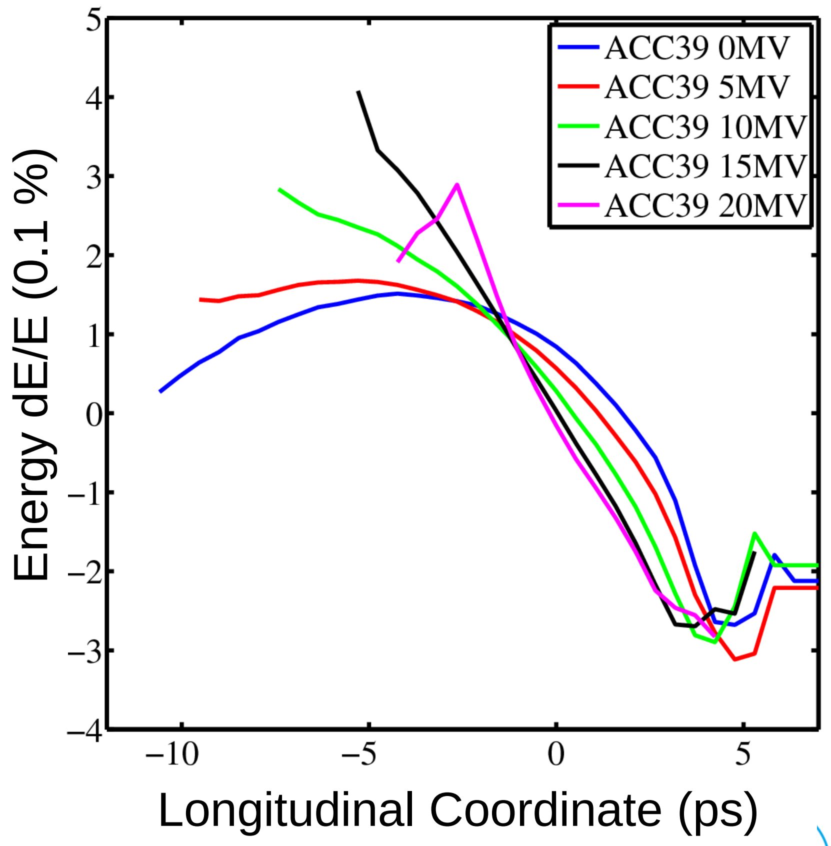
FLASH.
Free-Electron Laser in Hamburg

- Bunch shape for slight compression with first accelerating module
  - measured with LOLA at 700 MeV

MOPC08 Behrens, Gerth: Measurement of Sliced-Bunch Parameters at FLASH

- For different fields applied to the 3.9 GHz cavities (ACC39)





LLRF

Upgrade of the LLRF system

FLASH.
Free-Electron Laser in Hamburg

- Upgrade LLRF of all RF stations
  - Same type of hardware
  - SimconDSP controller
  - IF = 250 kHz, IQ-sampling scheme
  - Sampling rate 81 MHz (use averaging)
- RF control for 3.9 GHz
  - Probe, forward, and reflected signals
  - New RF downconverter & LO generation with
  - IF = 54 MHz, non IQ-sampling, LO = 3954 MHz
  - Sampling rate 81 MHz

10 Channel 14 bit ADCs
81 MHz clock rate
4 DAC, 14 bits
2 Gigalinks
FPGA: XILINX Virtex II pro

Upgrade Master-Oscillator and Gun/ACC1 LLRF

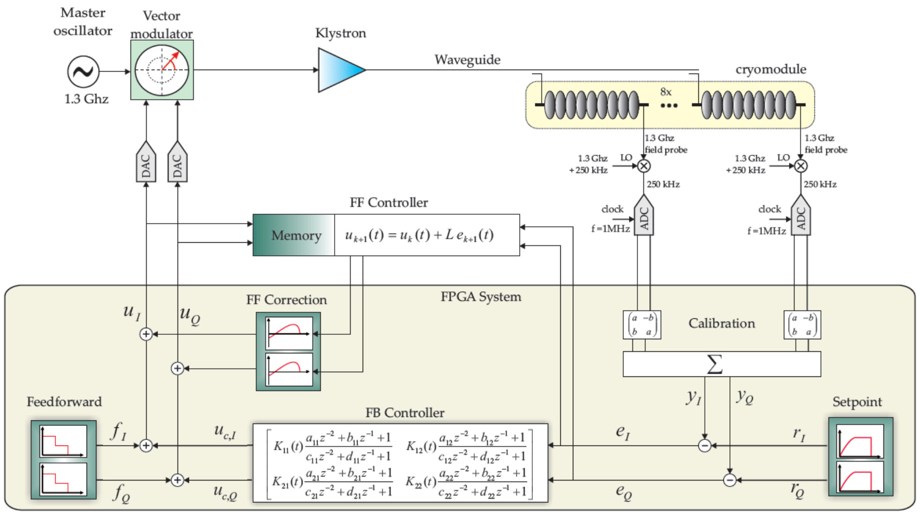
- New Master installed May 2008
- Finishing up with backup Master and refurbished cabling
  - New rack & cabling for RF gun and ACC1/ACC39
  - Enclosed racks for better temperature stability
  - Parallel cabling for development system
  - Careful noise investigation and power level adjustment of LO and RF signals

Upgrade LLRF system: FPGA controller

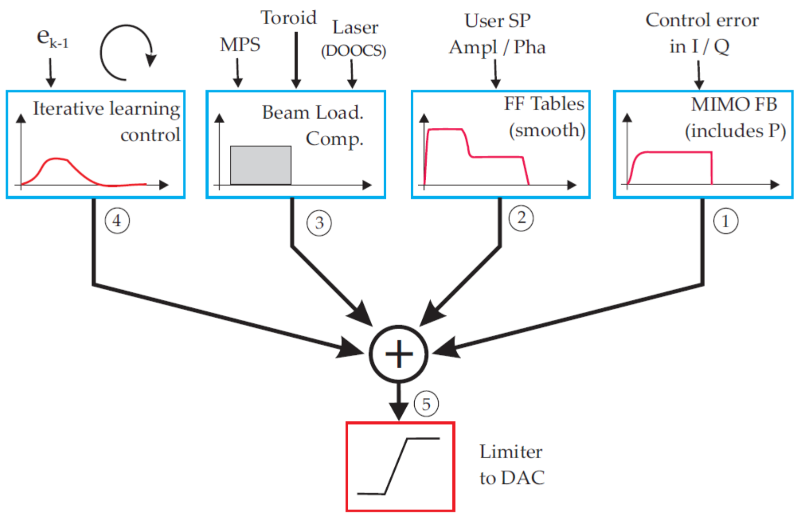
> Upgrade & unified FPGA controller firmware

- Multiple feed forward table (main/beam loading/correction)
- Multiple set point table (main/beam based correction)
- Model based Multiple-In-Multiple-Out (MIMO) controller
- Charge correction & intra-train beam based feedback
- Exception & Error handling, limiters
- Error and status displays

LLRF RF controller schematics



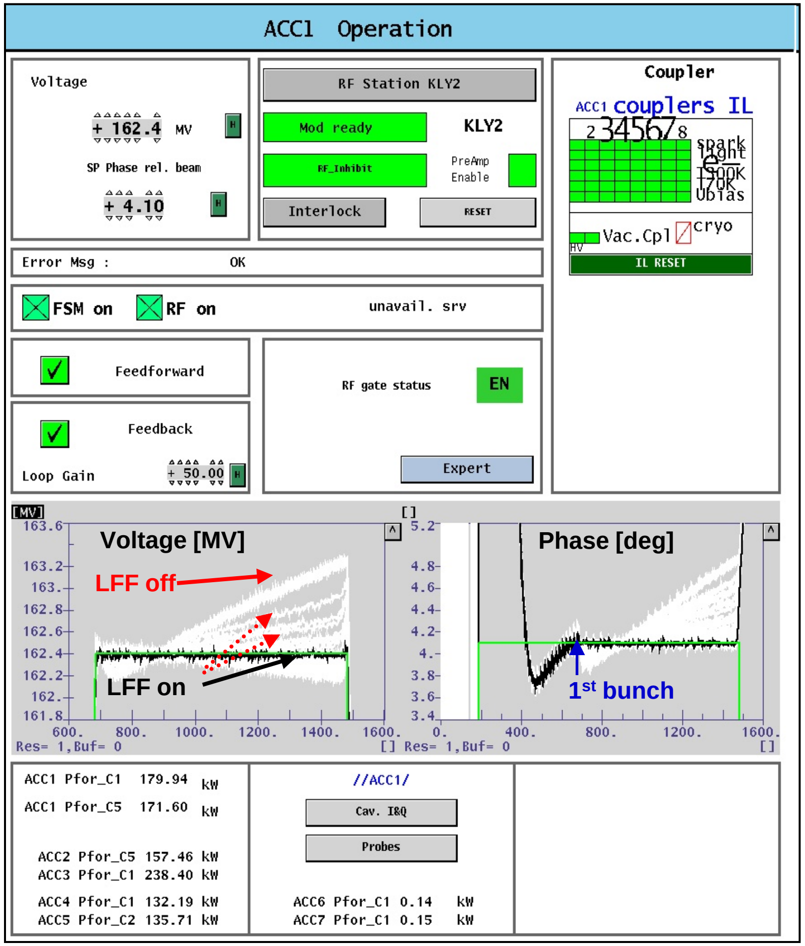
Feed forward table architecture



Upgrade LLRF control software

FLASH. Free-Electron Laser in Hamburg

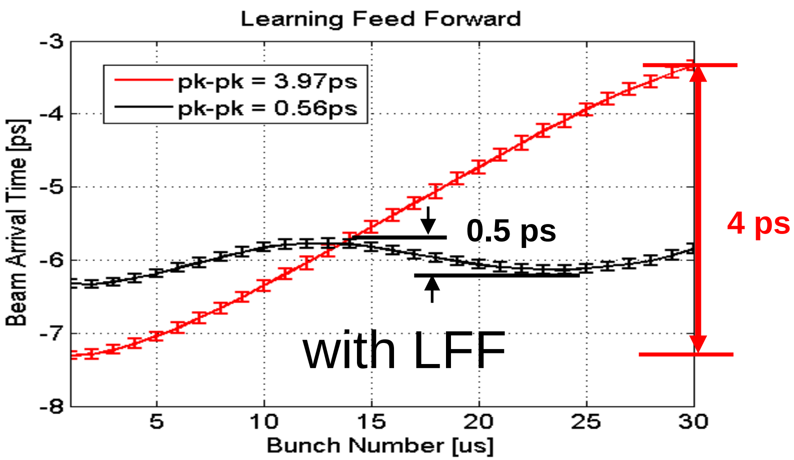
- Unified and new control software
  - New C++ architecture for front-end server
  - LLRF library based on SysML approach
  - Unified naming convention
  - Automatic firmware downloads
  - Finite State Machine for automation
  - High level software: diagnostics, calibration…
  - Integration to data acquisition system
  - Model based learning feed forward (LFF)
  - Loop phase/gain correction
  - Fast piezo control for cavity detuning comp.
  - … and many more
- Control software ~70 % completed

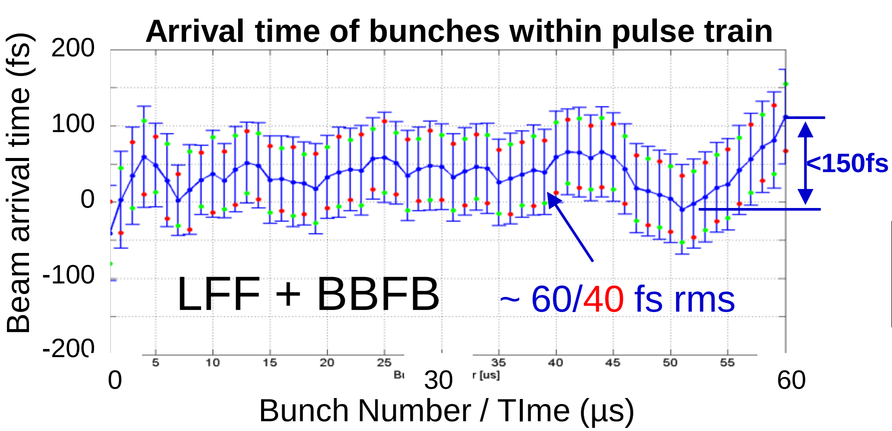


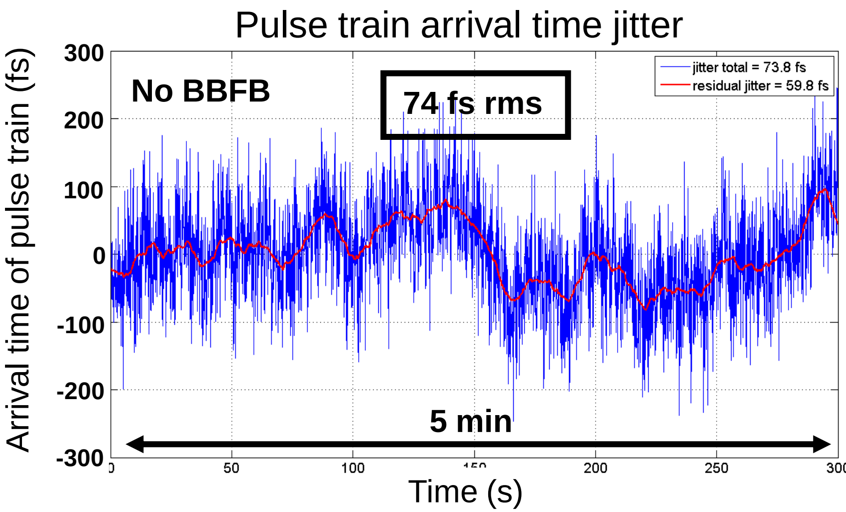
First results on stability and beam based feedbacks

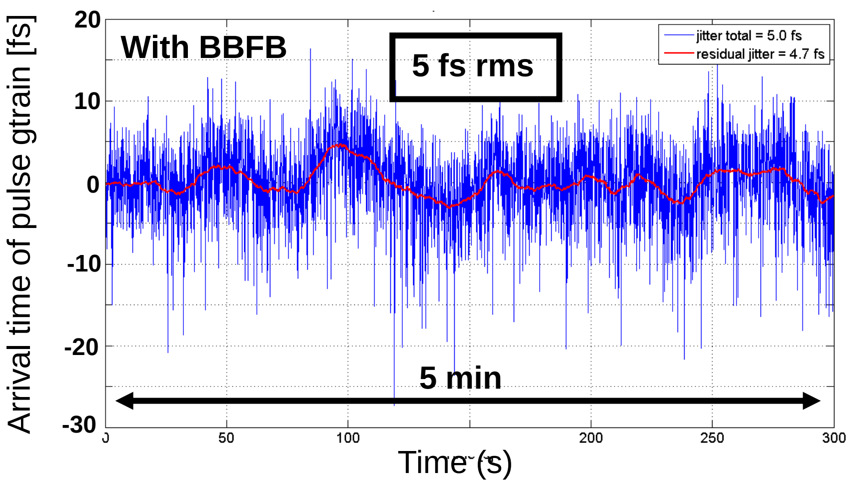
FLASH.
Free-Electron Laser in Hamburg

- Arrival time jitter ds 1st bunch compressor 70 fs rms (5 min) $\rightarrow$ dE/E (ACC1) $< 1 \cdot 10^{-4}$
- Learning feedforward (LFF) and beam based feedbacks (BBFB)







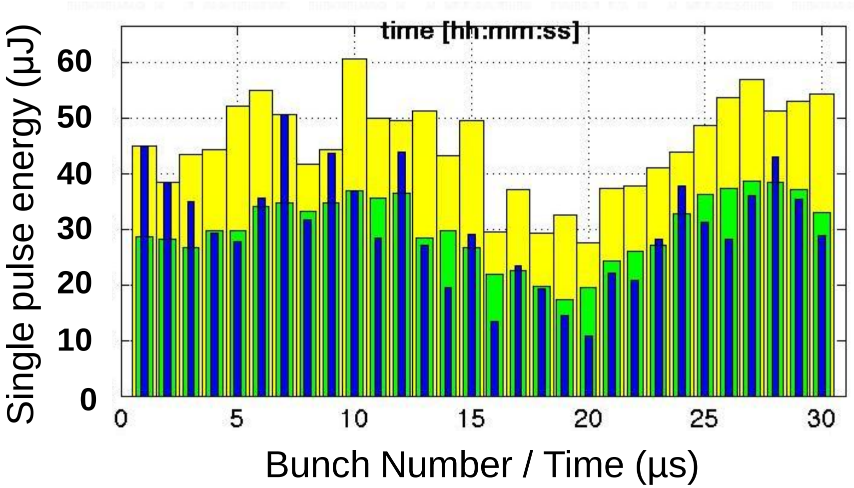


Talk on Thursday by W. Koprek, THOAI2
Intra-train Longitudinal Feedback for Beam Stabilization at FLASH

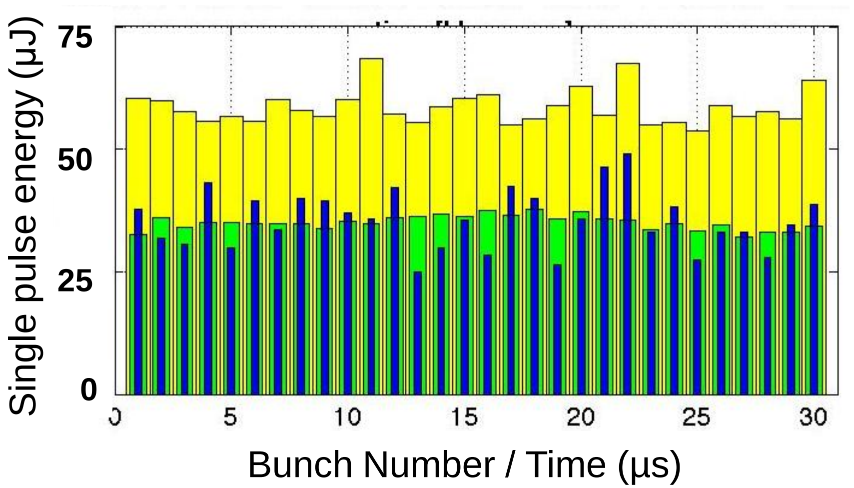
LLRF: example of flattening the pulse train

FLASH. Free-Electron Laser in Hamburg

> w/o adaptive feedforward



> adaptive feedforward applied

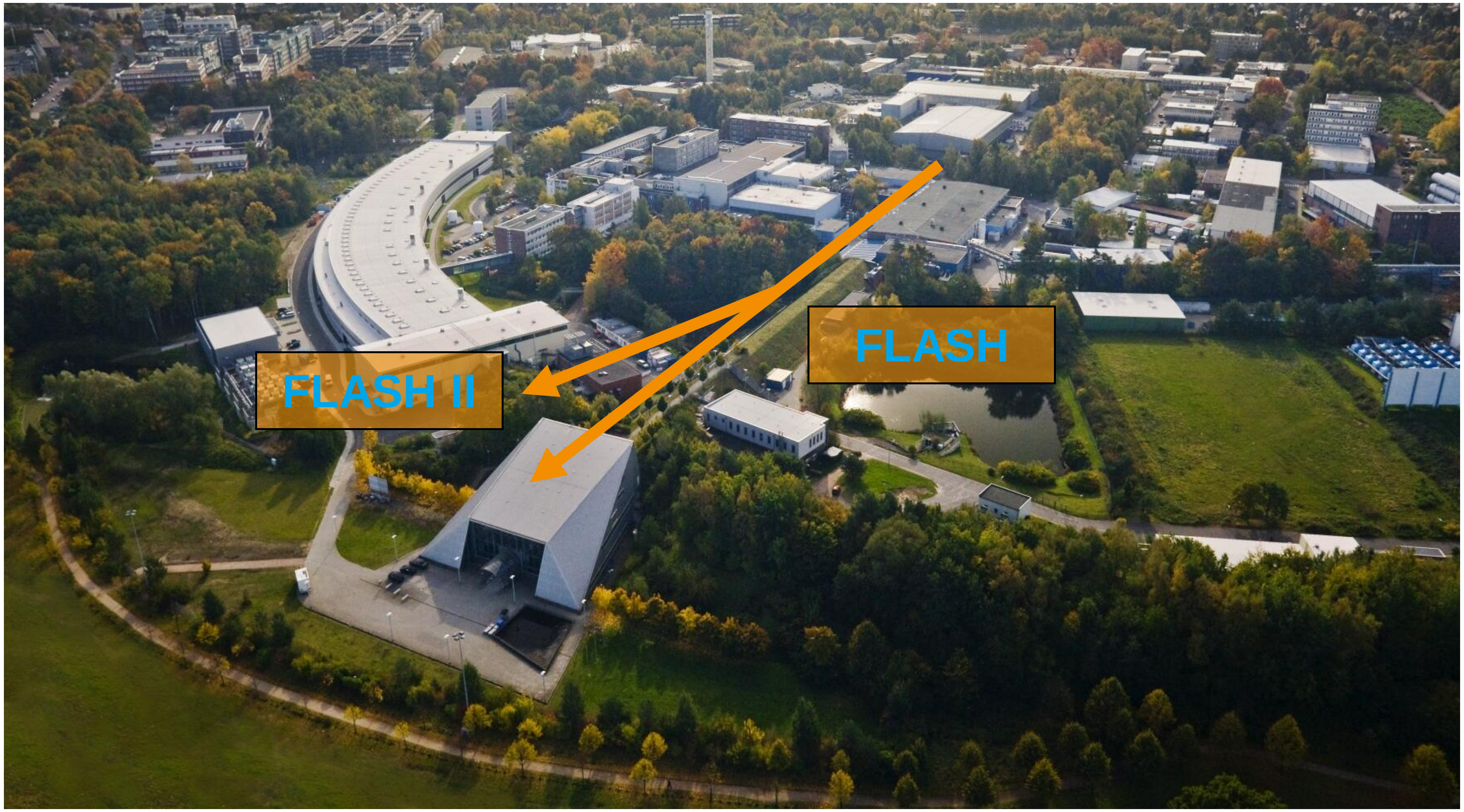


FLASH II

FLASH II

FLASH. Free-Electron Laser in Hamburg

- Second undulator line and experimental hall
- Common proposal by DESY and Helmholtz-Zentrum Berlin
- Project approved, construction starts end of 2011



DESY

Summary and outlook

FLASH. Free-Electron Laser in Hamburg

- FLASH finished in August 2009 the very successful 2nd user period
  - 5700 hours of delivered FEL radiation to user experiments
  - > 100 publications on photon science at FLASH in high ranked journals
- Upgrade shutdown from autumn 2009 to early 2010
- Major modifications
  - energy upgrade to 1.2 GeV (7th accelerating module installed)
  - installation of the 3rd harmonic module
  - sFLASH seeding experiment
- **Lasing at 4.45 nm June 6, 2010**
- Phase space linearization with 3rd harmonic works excellent
- Single photon pulse energies of up to 350 µJ
- 3rd FEL user period starts 2-Sep-2010
- FLASH II approved

DESY

Talks and posters about FLASH

FLASH.
Free-Electron Laser in Hamburg

- MOOAI3 First Lasing at FLASH with 4.45 nm
- MOPA01 FLASH II Status and Design
- MOPC04 Options of FLASH Extension for Generation of Circularly Polarized Radiation in the Wavelength Range Down to 1.2 nm
- MOPC08 Measurement of Sliced-Bunch Parameters at FLASH
- MOPC09 Upgrade of the FEL User Facility Flash
- MOPC10 Ytterbium Fibre Laser Based Electro-Optic Measurements of the Longitudinal Charge Distribution of Electron Bunches at FLASH
- MOPC11 Commissioning of an Electro-Optic Electron Bunch Length Monitor at FLASH
- MOPC09 Upgrade of the FEL User Facility FLASH
- TUOBI2 FLASH Upgrade and First Results
- TUPB20 Present Status and Commissioning Results of sFLASH
- TUPB21 Characterization of Seeded FEL Pulses at FLASH: Status, Challenges and Opportunities
- TUPB22 The XUV Injection Beam Line for Direct Seeding at sFLASH
- WEOAI2 sFLASH - First results of a direkt seeding at FLASH
- WEOBI2 Ultra-Short Low Charge Operation at FLASH and the European XFEL
- WEPB29 Simulations on Operation of the FLASH Injector in Low Charge Regime
- WEPB30 Multistage Bunch Compression
- THOAI2 Intra-train Longitudinal Feedback for Beam Stabilization at FLASH
- THOA3 RF-based Synchronization of the Seed and Pump-Probe Lasers to the Optical Synchronization System at FLASH
- THPA04 Longitudinal Bunch Arrival-Time Feedback at FLASH
- THPA05 Performance of the FLASH Optical Synchronization System Utilizing a Commercial SESAM-Based Erbium Laser
- THPA06 Real-Time Sampling and Processing Hardware for Bunch Arrival-Time Monitors at FLASH and XFEL
- THPC15 Status of Plane Grating Monochromator Beamline at FLASH
- FROBI1 Ultrafast Single-Shot Diffraction Imaging of Nanoscale Dynamics