FLASH: Performance after the Upgrade and in the Future

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based on slides from:

B. Faatz, J. Feldhaus, K. Honkavaara, and S. Schreiber

HELMHOLTZ GEMEINSCHAFT

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DESY

Outline

- FLASH, the User Facilty
- FLASH Upgrade
- Energy Upgrade and the Water Window
- Linearized Bunch Compression
- From Long Pulses to Short Pulses
- Machine Stability and Feedback Upgrades
- sFLASH, a Seeding Experiment
- "FLASH-II"
- Summary

FLASH,

the User Facility

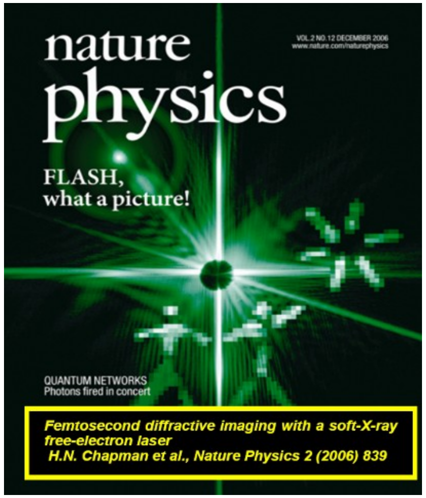
FLASH at DESY in Hamburg

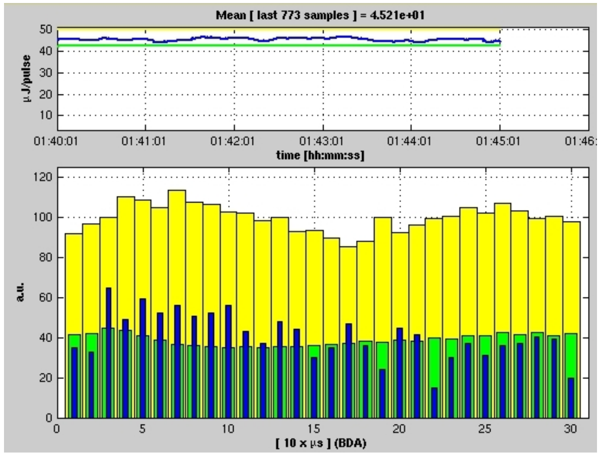
- Single-pass high-gain FEL
- Photon wavelength range from vacuum-ultraviolet to soft x-rays
- Free-electron laser user facility since summer 2005
- FLASH is also a test bench for the European XFEL and the International Linear Collider (ILC)
- sFLASH, a seeding experiment is in commissioning phase
- "FLASH II", a second undulator beam line is in preparation

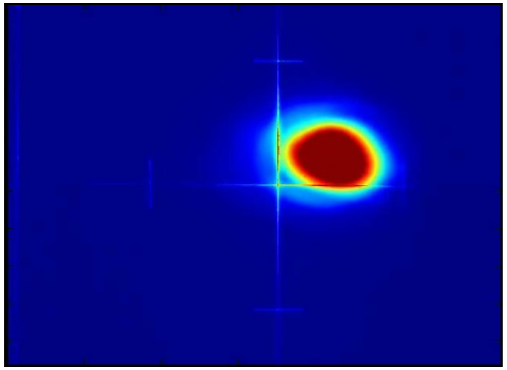
FEL Performance 2nd User Period (Nov-2007 – Aug-2009)

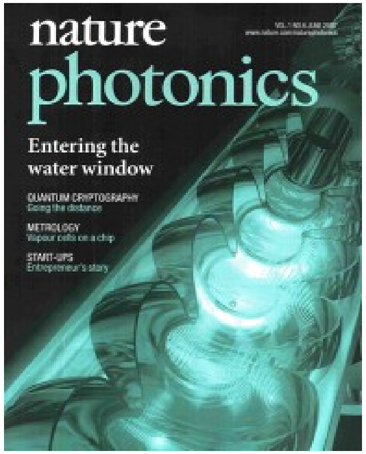
Typical User Operation Parameters 2nd User Period	
Wavelength range (fundamental)	6.8 – 40.5 nm
Average single pulse energy	10 – 100 µJ
Pulse duration (FWHM)	10 – 70 fs
Peak power (from avg.)	1 – 5 GW
Average power (example for 500 pulses/sec)	~ 15 mW
Spectral width (FWHM)	~ 1 %
Peak Brilliance	$10^{29} – 10^{30}$ *

* photons/s/mrad²/mm²/0.1%bw









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

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

FLASH Upgrade

Upgrade 2009 / 2010

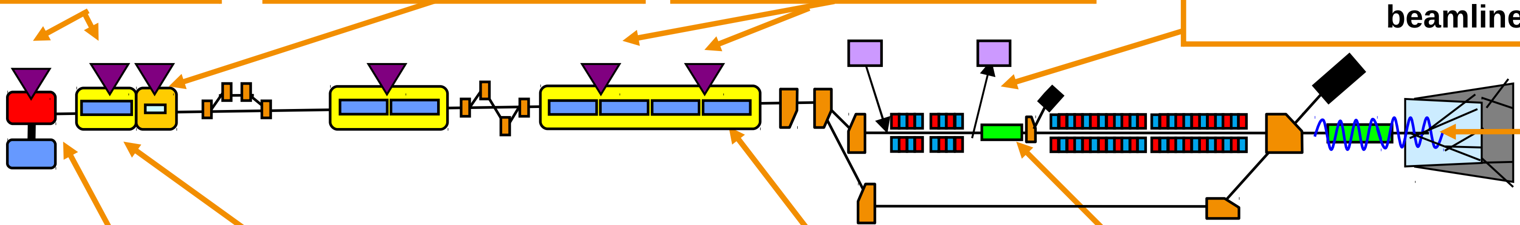
> Upgrade Shutdown: September 2009 – February 2010

exchanged RF stations

3rd harmonic module + RF station

additional RF station + exchanged RF station

seeding experiment sFLASH + redesigned electron beamline



upgraded photon diagnostics and beamlines

new RF gun

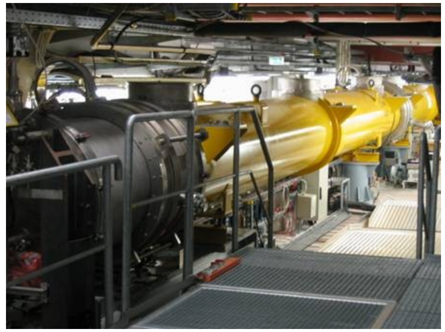
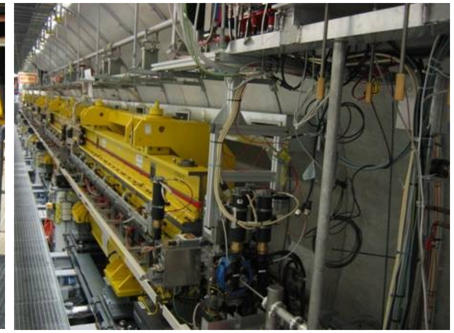
exchanged 1st accelerating module

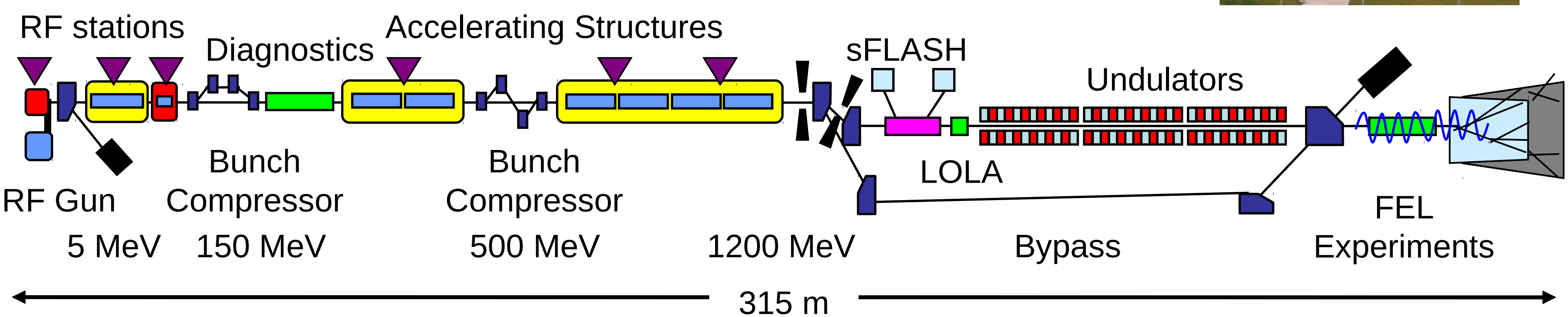
7th accelerating module

transverse deflecting cavity + spectrometer arm / tuning dump

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

The New FLASH Layout

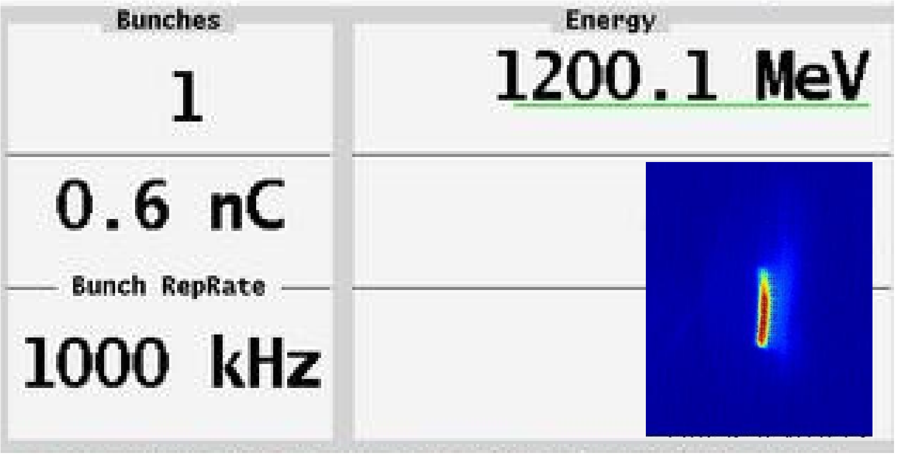



Energy Upgrade and the Water Window

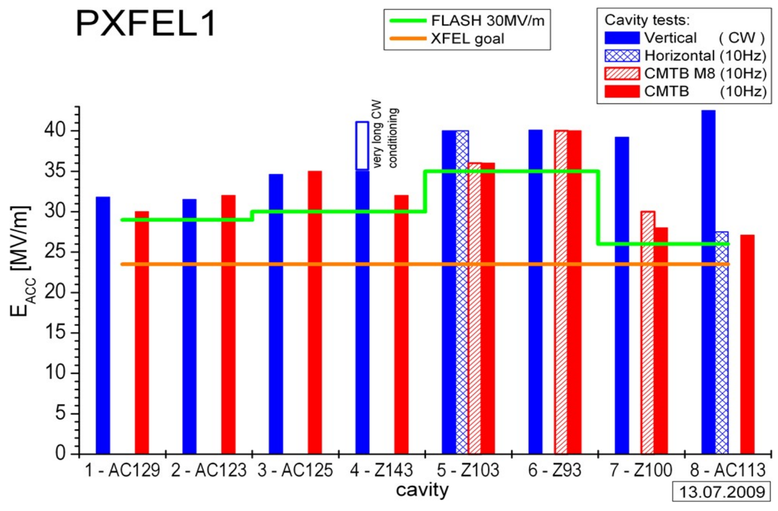
Energy Upgrade

- 7th superconducting TESLA type accelerating module installed
  - Prototype module for the European XFEL
  - Energy gain 240 MeV
- Electron beam energy 1.20 GeV
- Some optimization => 1.25 GeV

1.2 GeV demonstrated with beam in May 2010

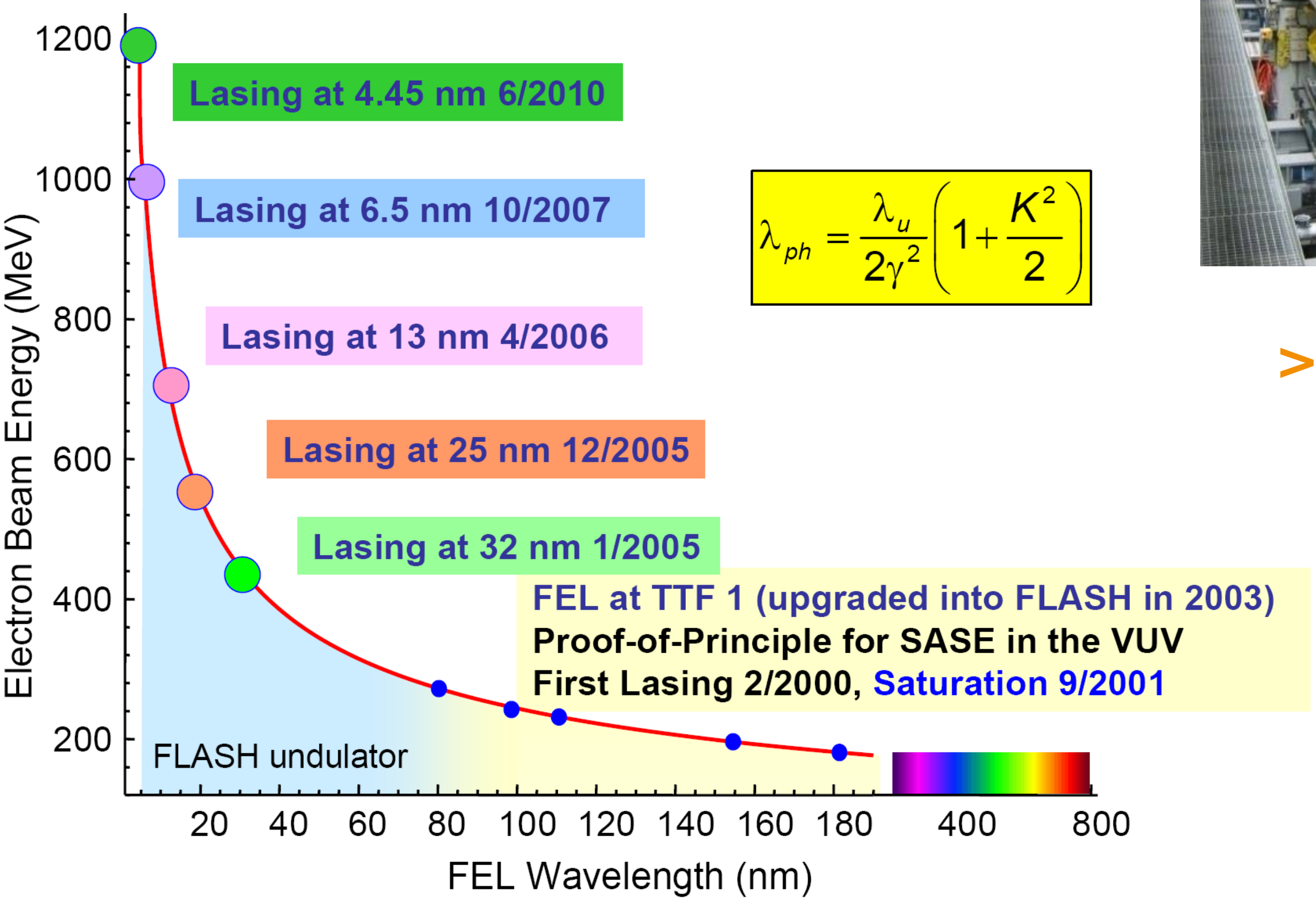


Results of cavity tests



FLASH Undulators

- 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

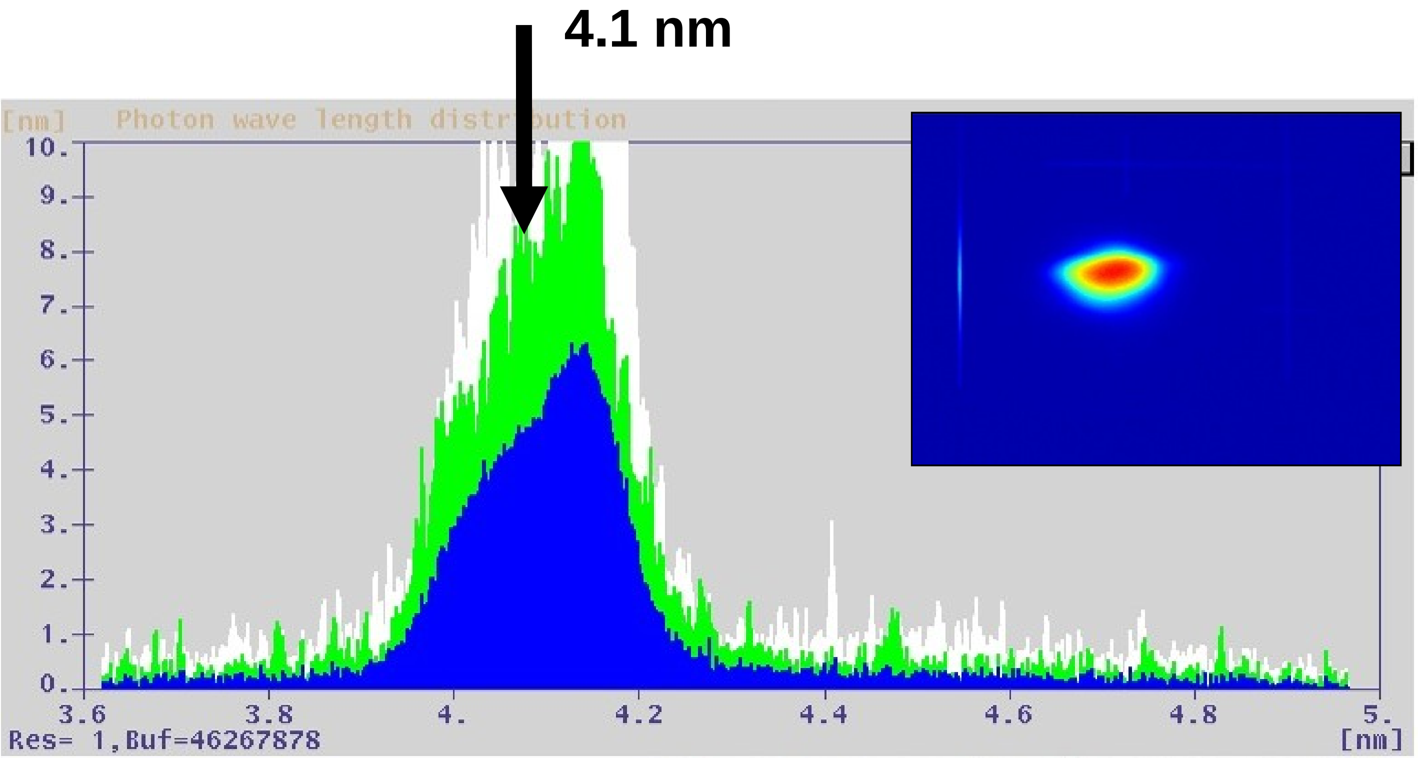


$$\lambda_{ph} = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

- change of wavelength ↔ change of electron beam energy

Access to the Water Window

- On 25-Sep-2010, we achieved to push the beam energy above 1.2 GeV
- First lasing in the water window at 4.12 nm with the fundamental
- Single pulse energy ~130 µJ (max), ~70 µJ (avg)

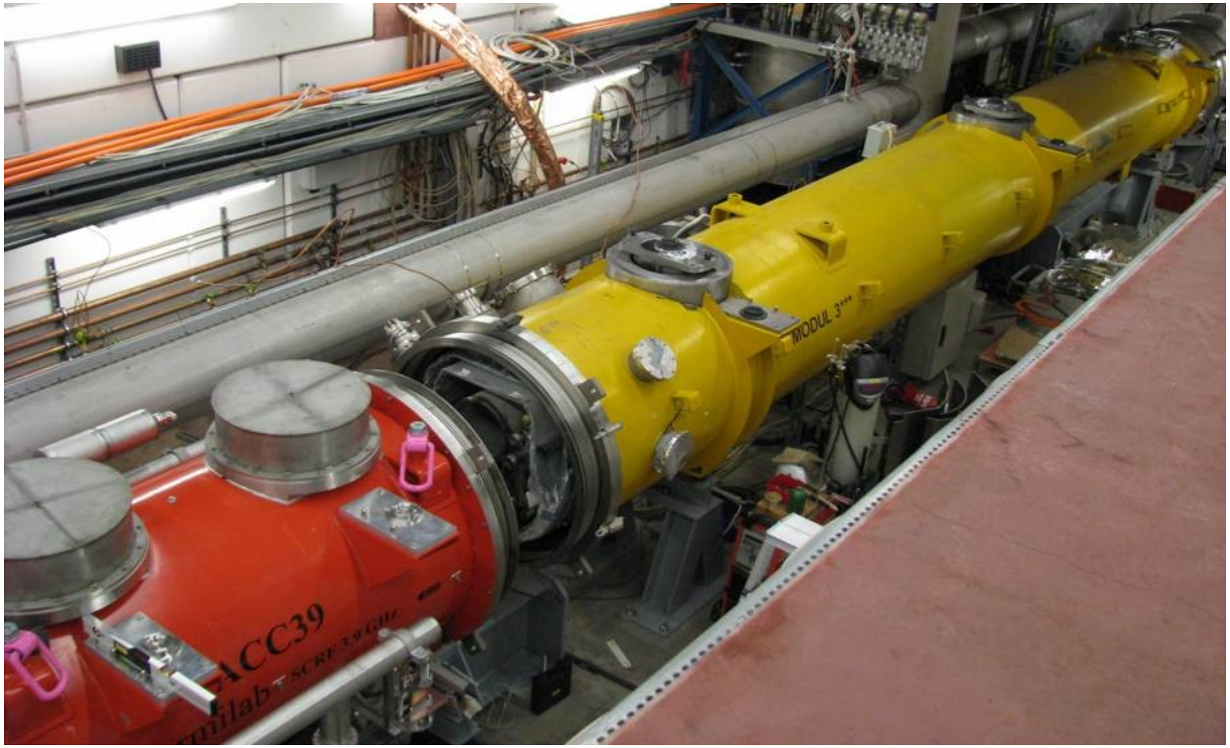


Linearized

Bunch Compression

3.9 GHz (3rd harmonic) Module and Module 1

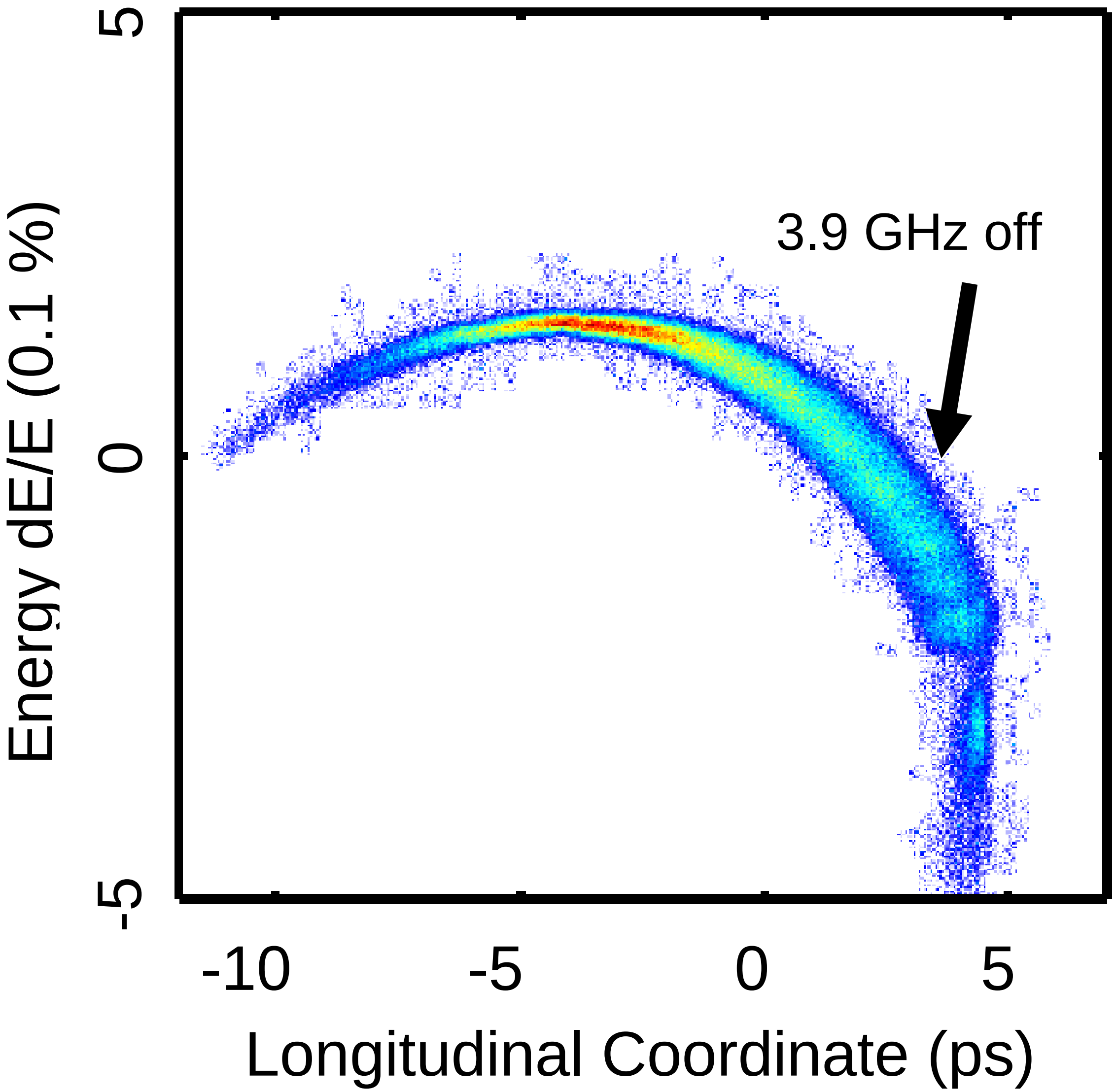
- New 1st accelerating module with improved cavities and Piezo tuners
- 3rd harmonic module with four nine-cell superconducting cavities operated at 3.9 GHz
  - includes RF system and LLRF regulation
  - built at FNAL (Fermilab) in a collaboration with DESY



Fermilab

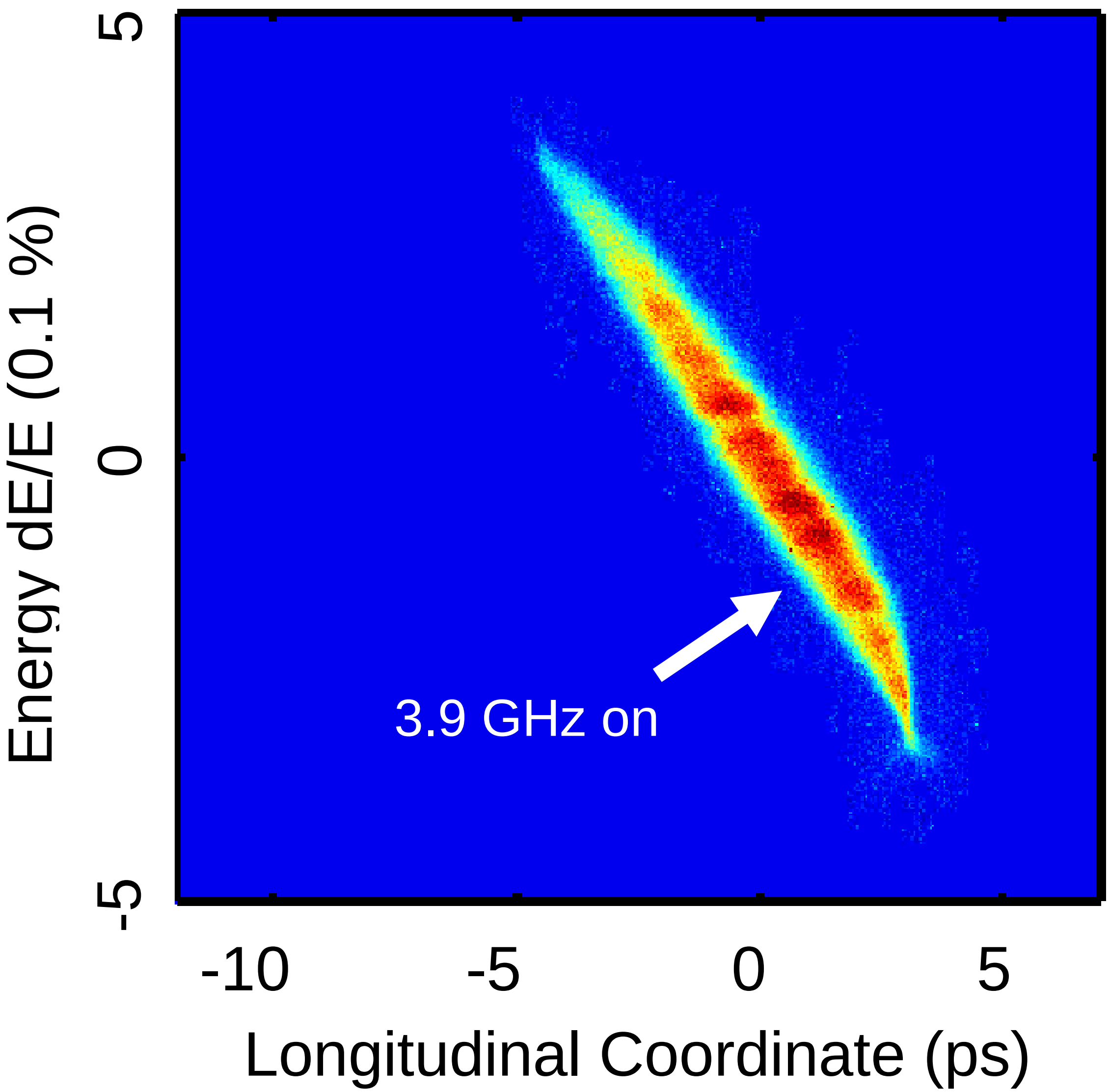
DESY

Bunch Compression Using 3rd-harmonic Cavities



- measured with LOLA
- dispersive section
- beam energy 700 MeV
- slight compression with 1st module (ACC1)
- 3.9 GHz cavities off

Bunch Compression Using 3rd-harmonic Cavities



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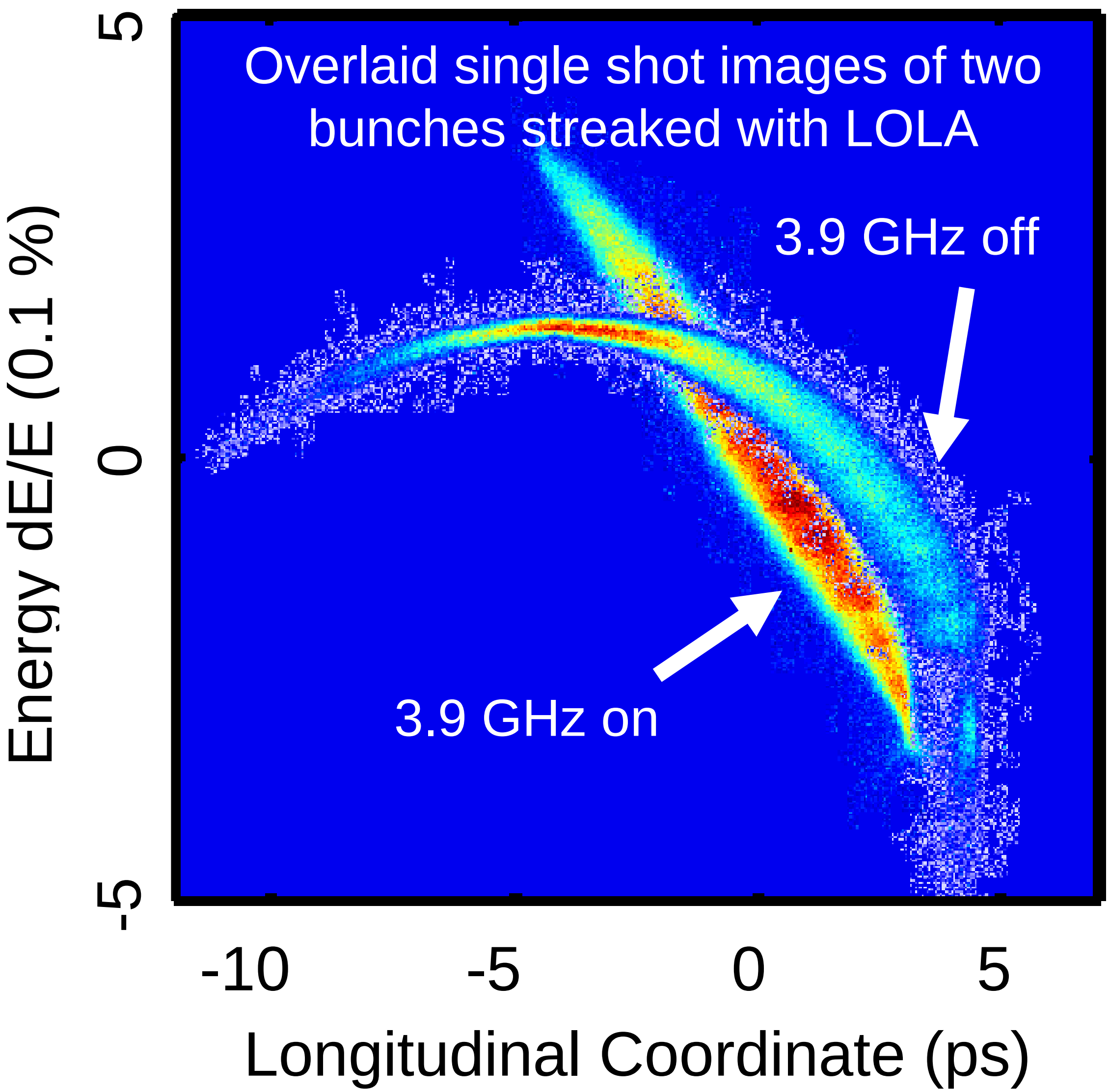
Bunch Compression Using 3rd-harmonic Cavities



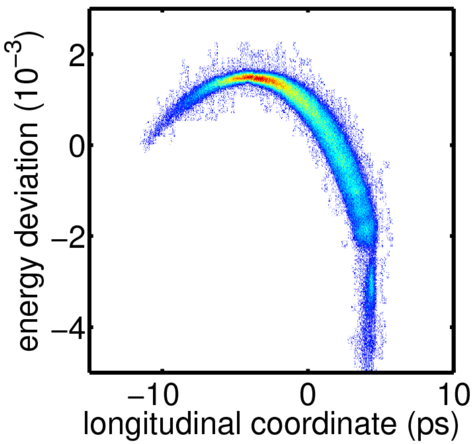
- measured with LOLA
- dispersive section
- beam energy 700 MeV
- slight compression with 1st module (ACC1)
- 3.9 GHz cavities on/off

Linearization of the Longitudinal Phase Space

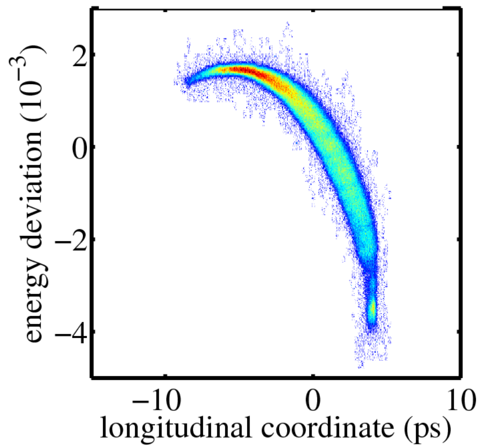
1st module (ACC1) set to moderate compression

Bunch shape measured for increasing voltage in the 3rd harmonic cavities

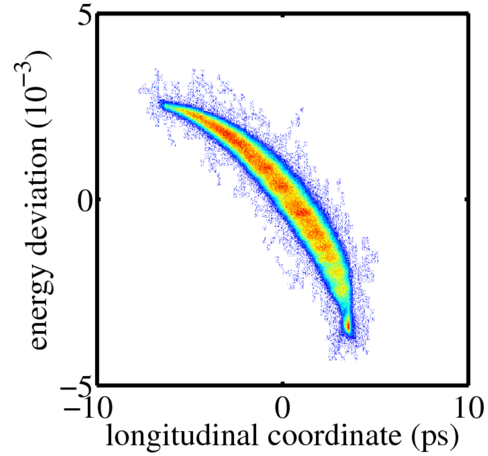
U_{39} = 0 MV



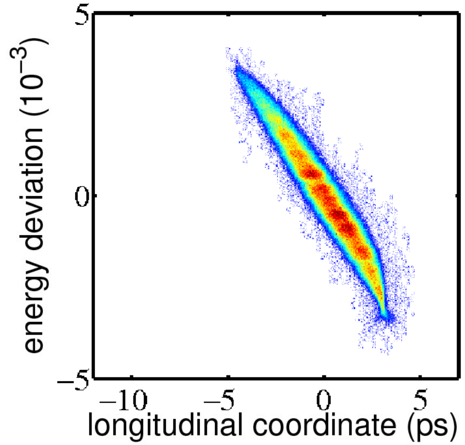
U_{39} = 5 MV



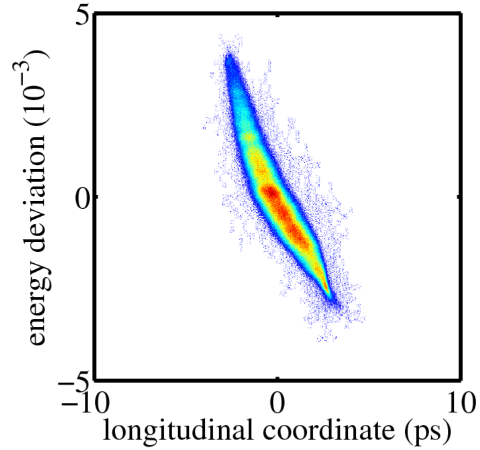
U_{39} = 10 MV



U_{39} = 15 MV



U_{39} = 20 MV

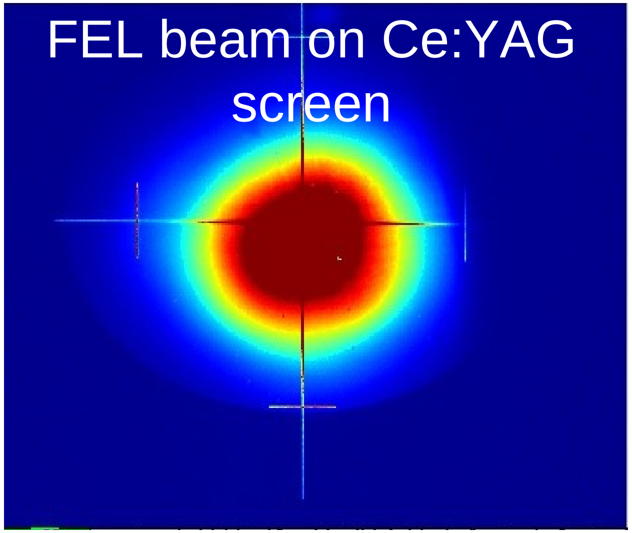


Examples of Lasing During Commissioning

- 10 Hz, between 1 and 120 bunches (1 MHz), compression using 3.9 GHz cavities

Examples:

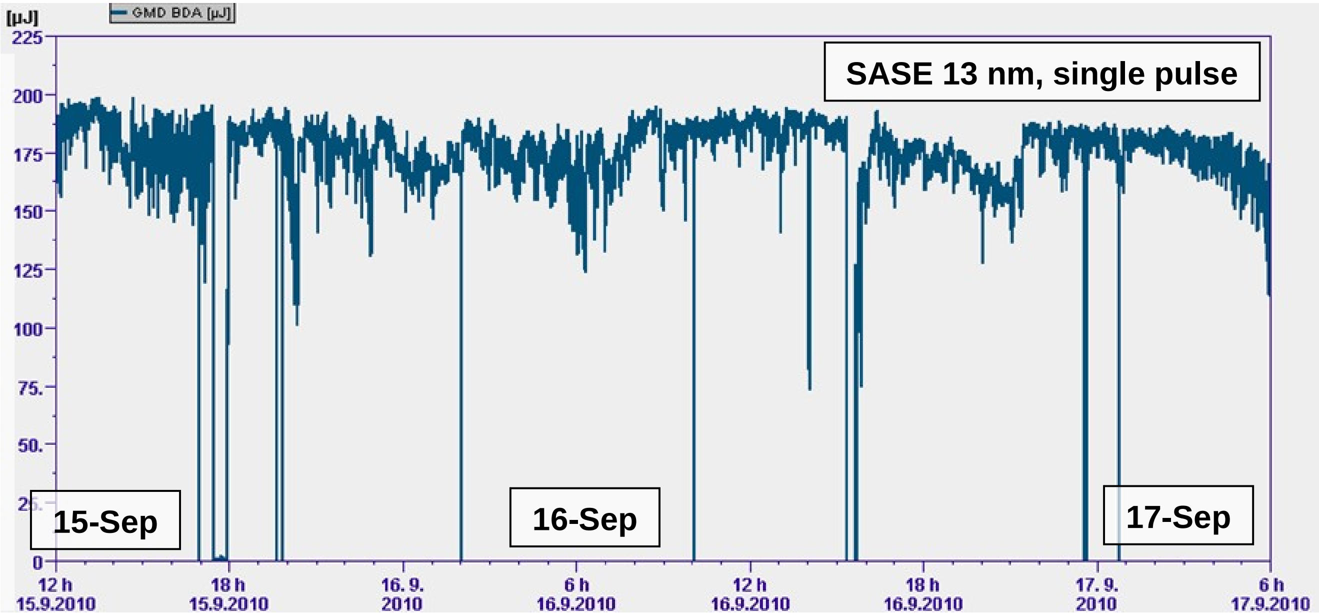
- 4.45 nm, 140 µJ max, average 75 µJ per pulse
- 12.4 nm, 105 µJ max, average 75 µJ per pulse
- 13.4 nm, 300 µJ max, average 250 µJ per pulse
- 19.2 nm, 350 µJ max, average 230 µJ per pulse
- 26.2 nm, 280 µJ max, average 160 µJ per pulse

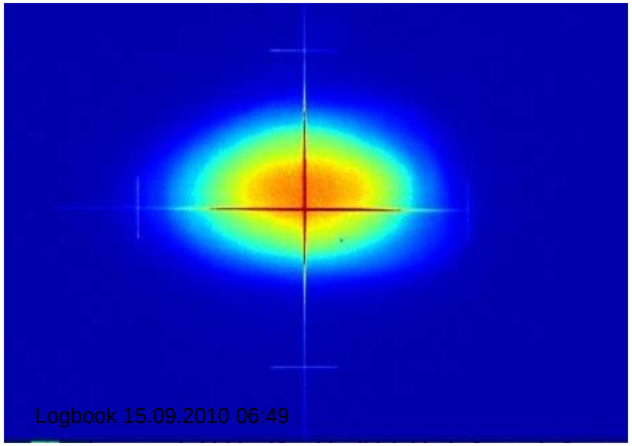


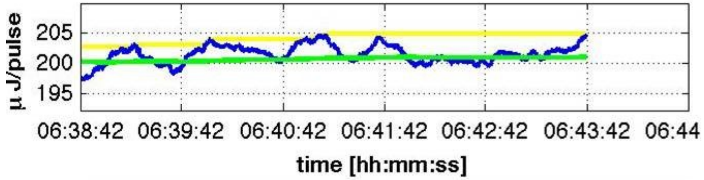
13.4 nm, distance to screen 23.5 m, ticks at 3 mm

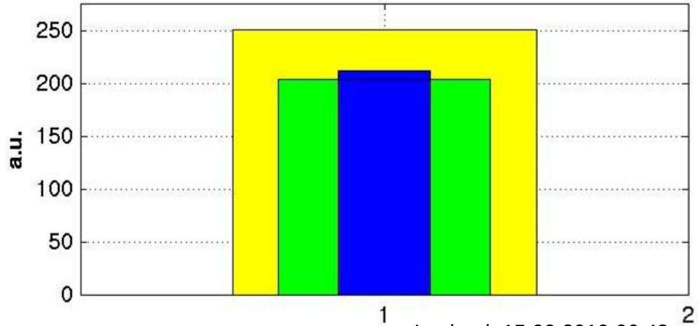
Radiation pulse energies are significantly higher and easier to tune compared to roll-over compression

Examples During User Run: 13 nm, Single Bunch



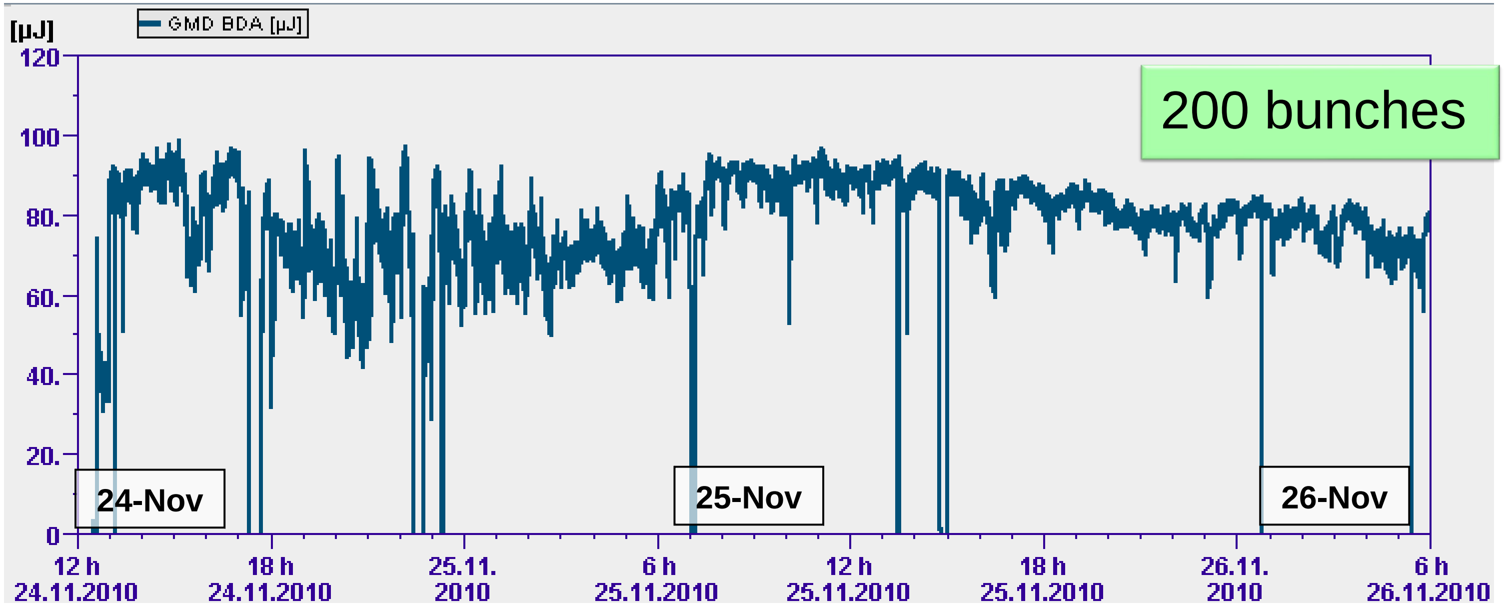


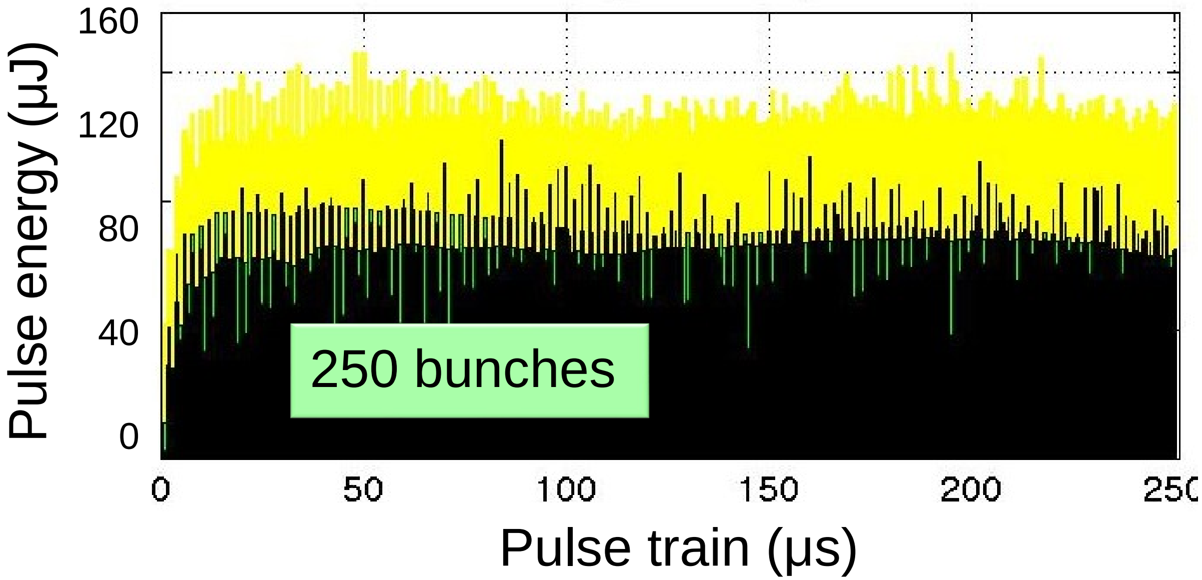




Logbook 15.09.2010 06:43

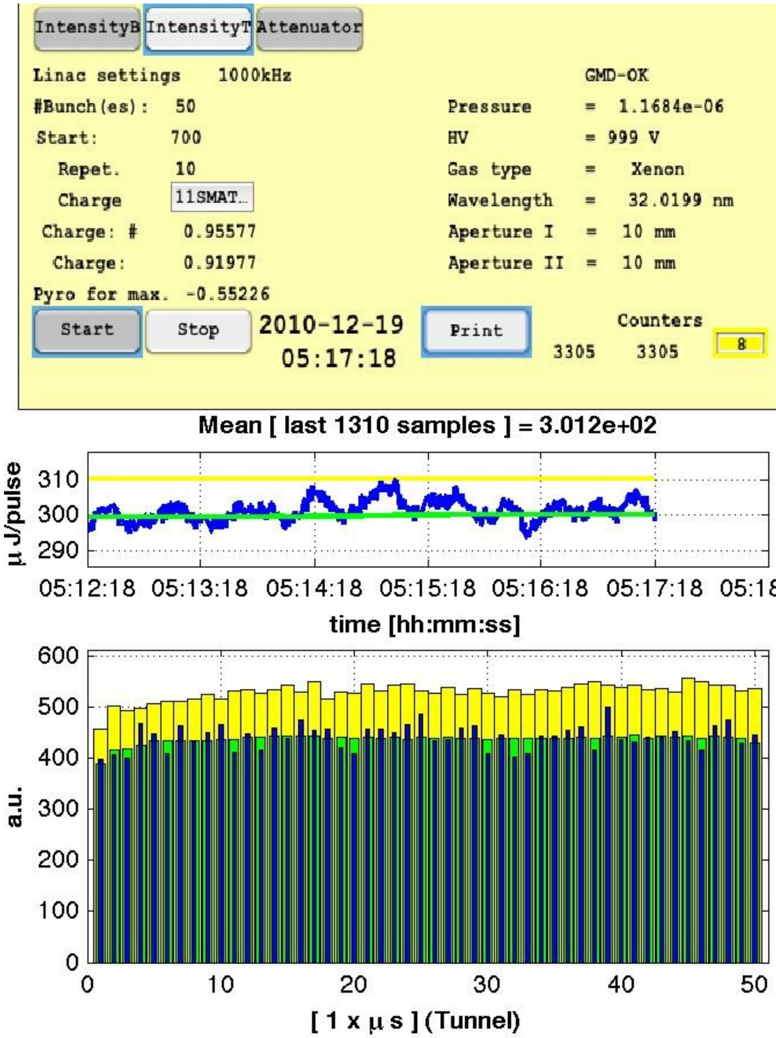
4.8 nm, 250 Pulses/Train, 1 MHz





New record for FLASH:
Average power 200 mW
(at 4.8 nm)

Example 32 nm, 50 bunches 1 MHz



Energy | Photons | Ph/sec

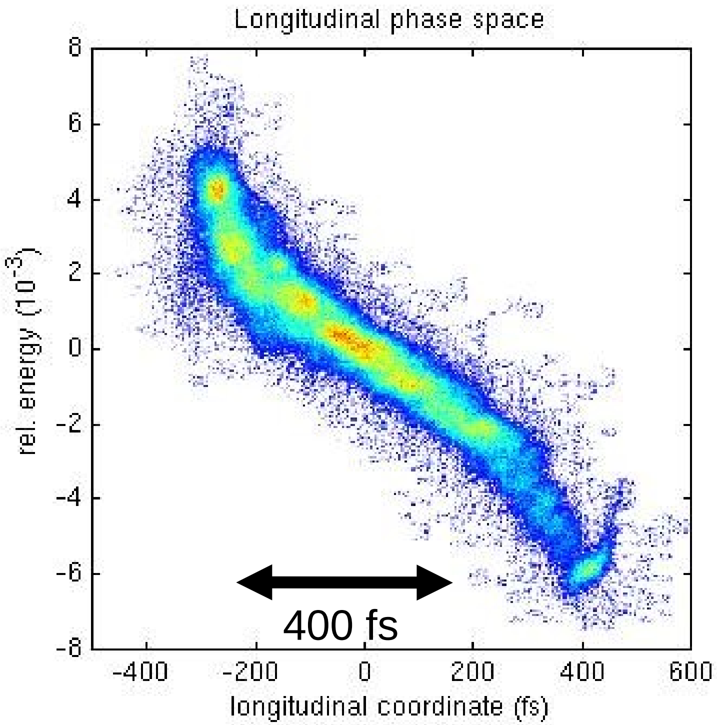
#	Signal	Max	Mean	RMS
Ion	2.985e+02	3.102e+02	3.002e+02	1.171e-02
All	4.415e+02	5.561e+02	4.369e+02	2.393e+01
1	3.971e+02	4.564e+02	3.888e+02	5.412e-02
2	4.058e+02	5.009e+02	4.162e+02	5.363e-02
3	3.999e+02	4.923e+02	4.185e+02	5.230e-02
4	4.676e+02	4.981e+02	4.246e+02	5.435e-02
5	4.471e+02	5.063e+02	4.338e+02	5.310e-02
6	4.089e+02	5.108e+02	4.340e+02	5.634e-02
7	4.645e+02	5.112e+02	4.332e+02	5.444e-02
8	4.319e+02	5.150e+02	4.342e+02	5.752e-02
9	4.501e+02	5.239e+02	4.335e+02	5.616e-02
10	4.664e+02	5.150e+02	4.363e+02	5.666e-02
11	4.116e+02	5.321e+02	4.369e+02	5.722e-02
12	4.480e+02	5.328e+02	4.398e+02	5.733e-02
13	4.155e+02	5.278e+02	4.402e+02	5.703e-02
14	4.589e+02	5.340e+02	4.428e+02	6.185e-02
15	4.379e+02	5.416e+02	4.437e+02	5.893e-02
16	4.753e+02	5.281e+02	4.438e+02	6.066e-02
17	4.538e+02	5.503e+02	4.426e+02	5.890e-02
18	4.570e+02	5.165e+02	4.386e+02	6.060e-02
19	4.198e+02	5.294e+02	4.418e+02	5.956e-02
20	4.094e+02	5.274e+02	4.390e+02	6.027e-02
21	4.564e+02	5.456e+02	4.414e+02	5.846e-02
22	4.560e+02	5.322e+02	4.381e+02	6.108e-02
23	4.506e+02	5.426e+02	4.409e+02	5.849e-02
24	4.654e+02	5.454e+02	4.372e+02	6.052e-02
25	4.856e+02	5.320e+02	4.405e+02	5.873e-02
26	4.339e+02	5.275e+02	4.386e+02	5.971e-02
27	4.351e+02	5.370e+02	4.402e+02	5.775e-02
28	4.589e+02	5.245e+02	4.379e+02	5.955e-02
29	4.631e+02	5.351e+02	4.388e+02	5.929e-02
30	4.083e+02	5.270e+02	4.369e+02	5.971e-02

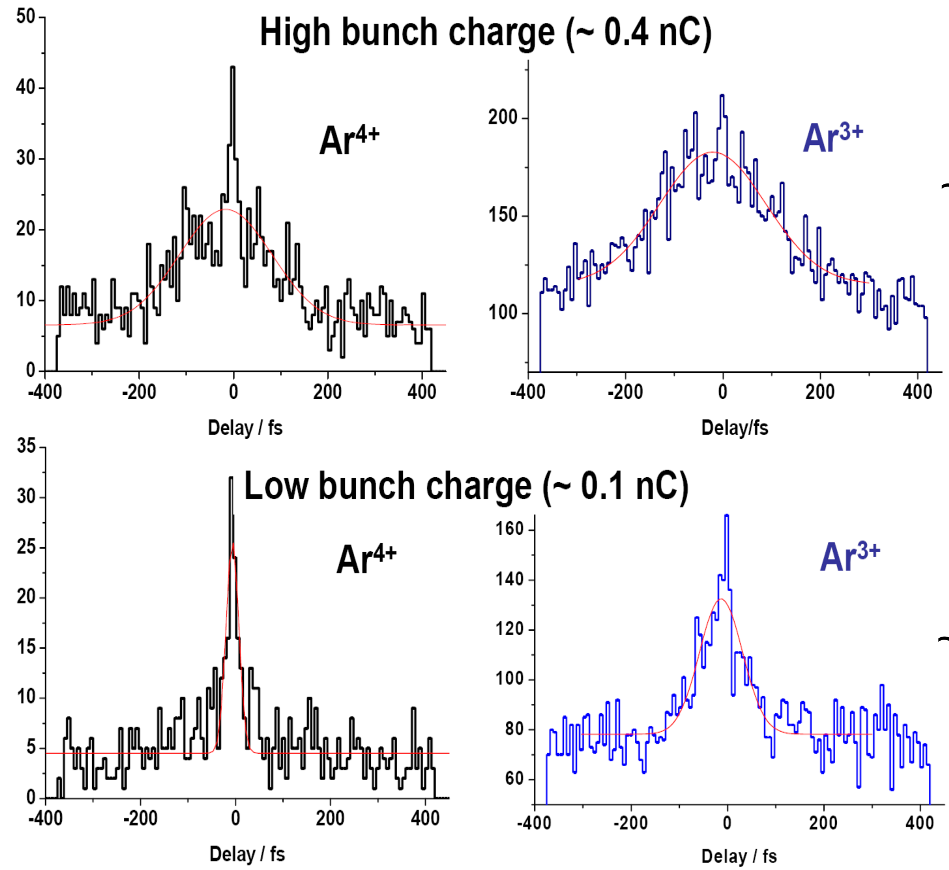
From Long Pulses

to

Short Pulses

Long Pulses: Short Pulses Wanted!





~200 fs

~70 fs

R. Moshammer, A. Rudenko

Longitudinal Phase Space
Measurements give just a hint!
But: Short Electron Bunches
=> (~~<=~~) Short Photon Pulses

Tuning and Characterisation of Short Electron Bunches and FEL Radiation Pulses at 14 nm

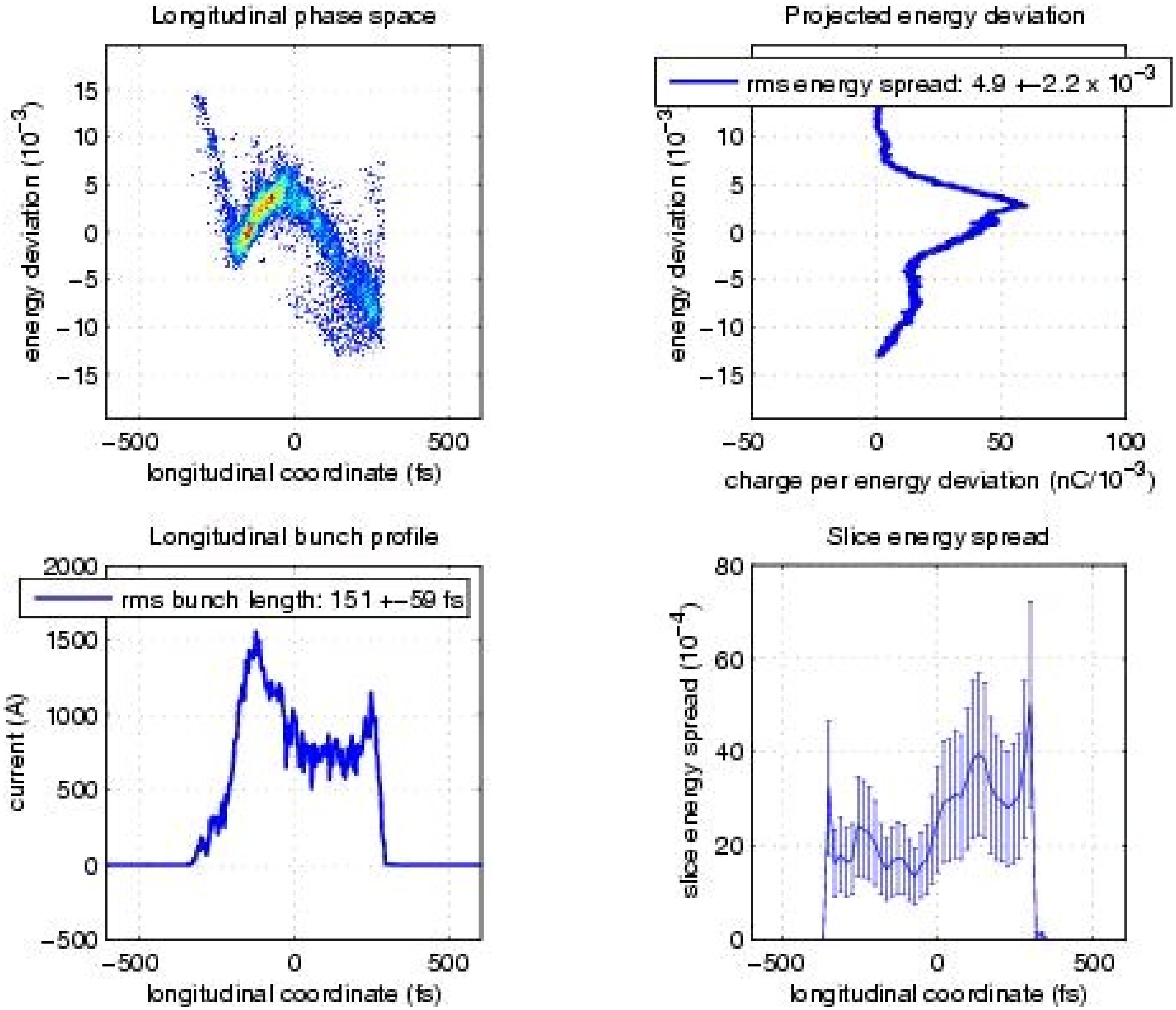
Short FEL photon pulses (<50fs) are desired!

For this reason, dedicated beam time was scheduled during the last accelerator studies in January 2011.

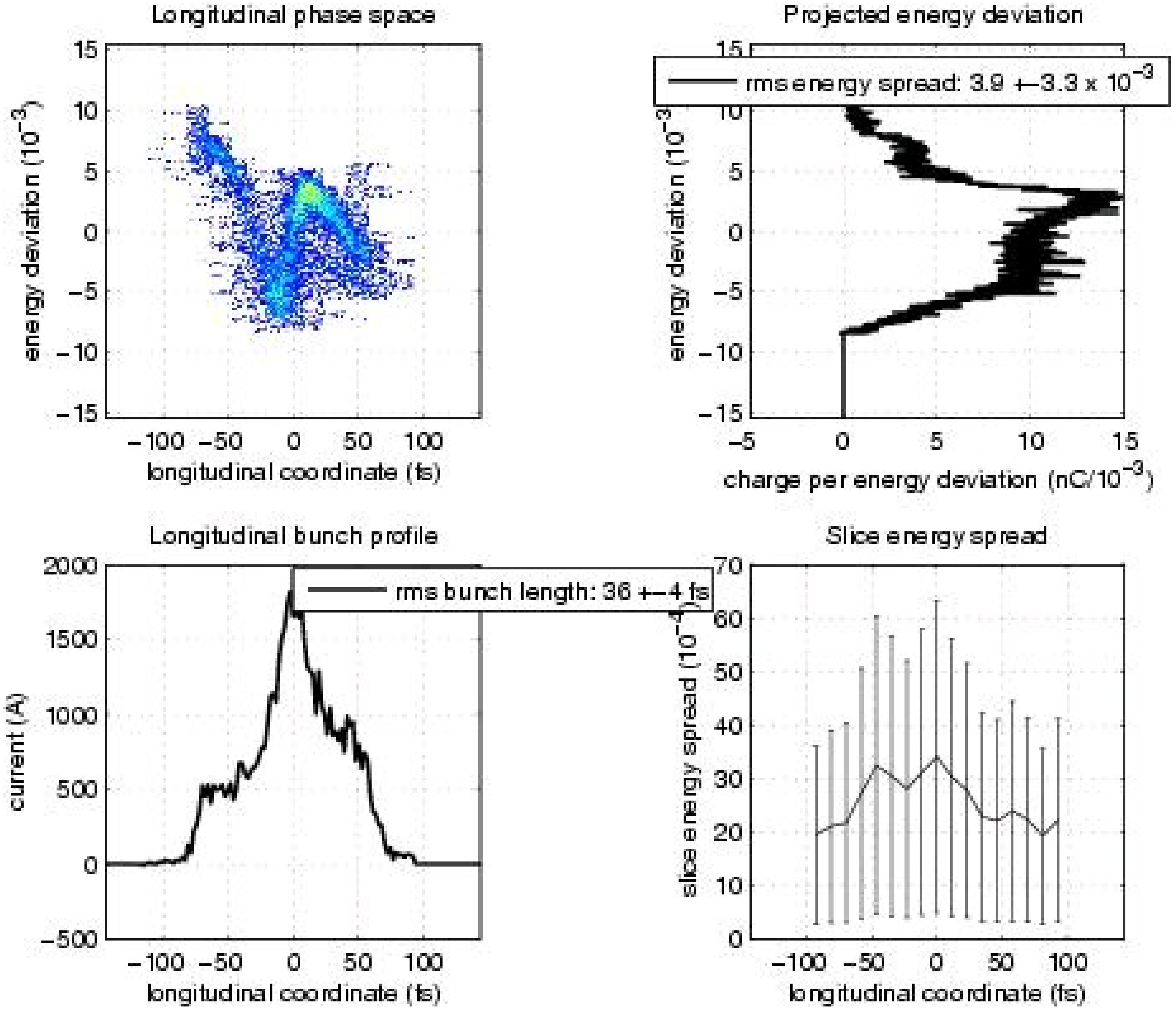
Characterisation Techniques

- Electron pulse:
  - LOLA (bunch shape)
  - Toroids (charge)
  - Pyro detectors (signal related to bunch shape and charge)
- Photon pulse:
  - Pulse energy (GMD and MCP)
  - Measurements of statistical fluctuations (MCP)
  - Spectral measurements (PGM)

LOLA images @ 500 pC



LOLA images @ 150 pC

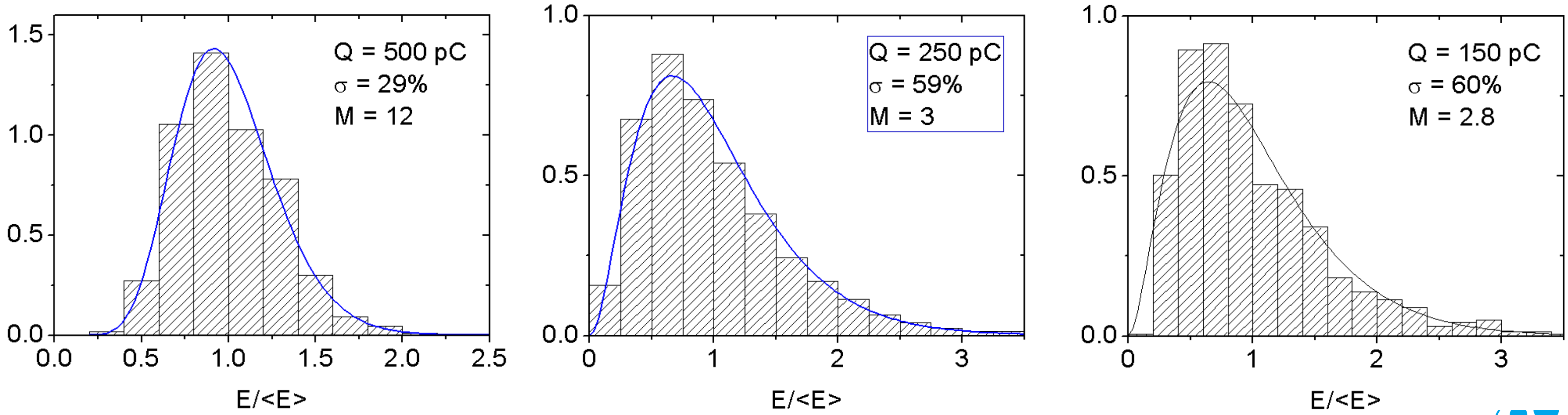


Results: Pulse Energy and Number of Modes

- SASE at 14 nm was tuned to max. pulse energy level for different charges:

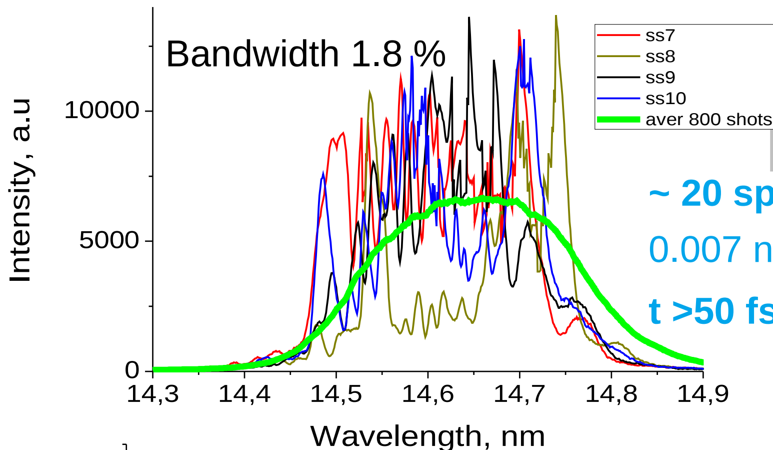
150 pC	25-35 uJ
250 pC	35 uJ
500 pC	>200 uJ

- Then the SASE process was suppressed in the undulator modules 5 and 6 (by orbit kick) in order to operate the FEL in the linear regime.
- The number of modes was determined by statistical measurements using MCP07 detector. Measured number of modes in the linear regime:



Results: Spectral Measurements

500 pC

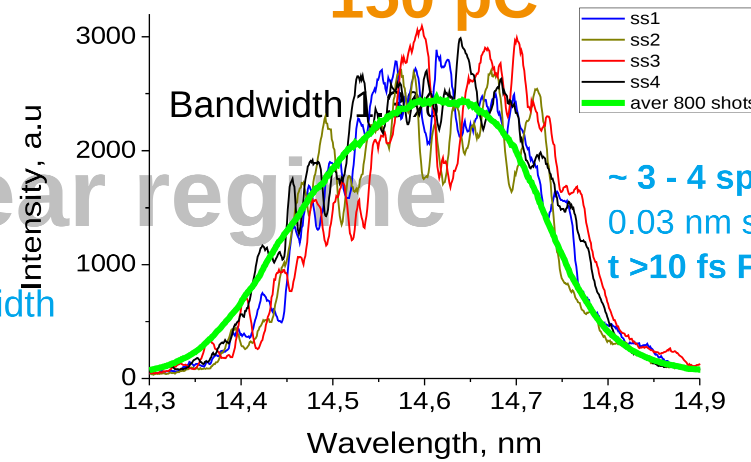


~ 20 spikes

0.007 nm spike width

t >50 fs FWHM

150 pC

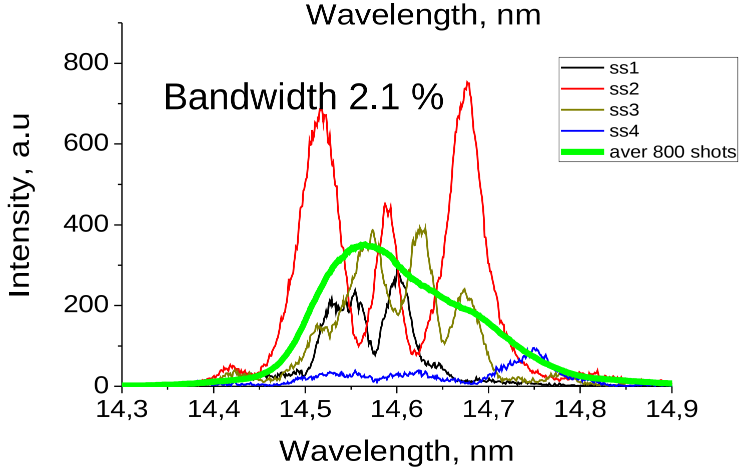


~ 3 - 4 spikes

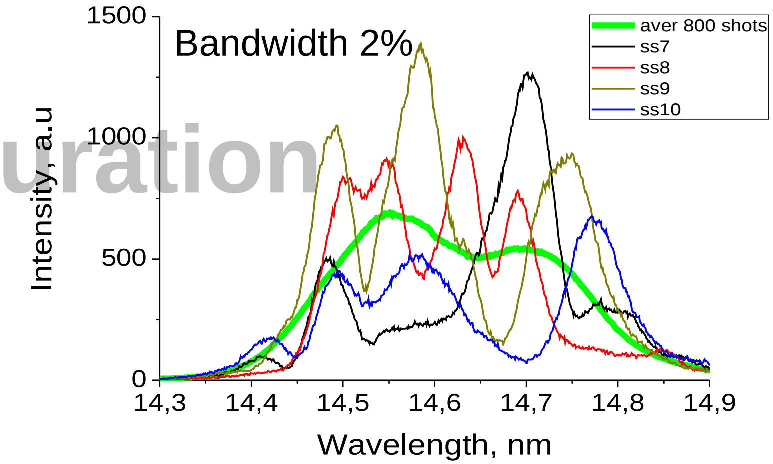
0.03 nm spike width

t >10 fs FWHM

Linear regime



Saturation



Statistics

500 pC: sigma = 29%, M = 12, T_rad ~ **60 fs** (+10 fs + 30 fs)

150 pC: sigma = 60%, M = 2.8, T_rad ~ **15 fs** (+10 fs + 7 fs)

DESY

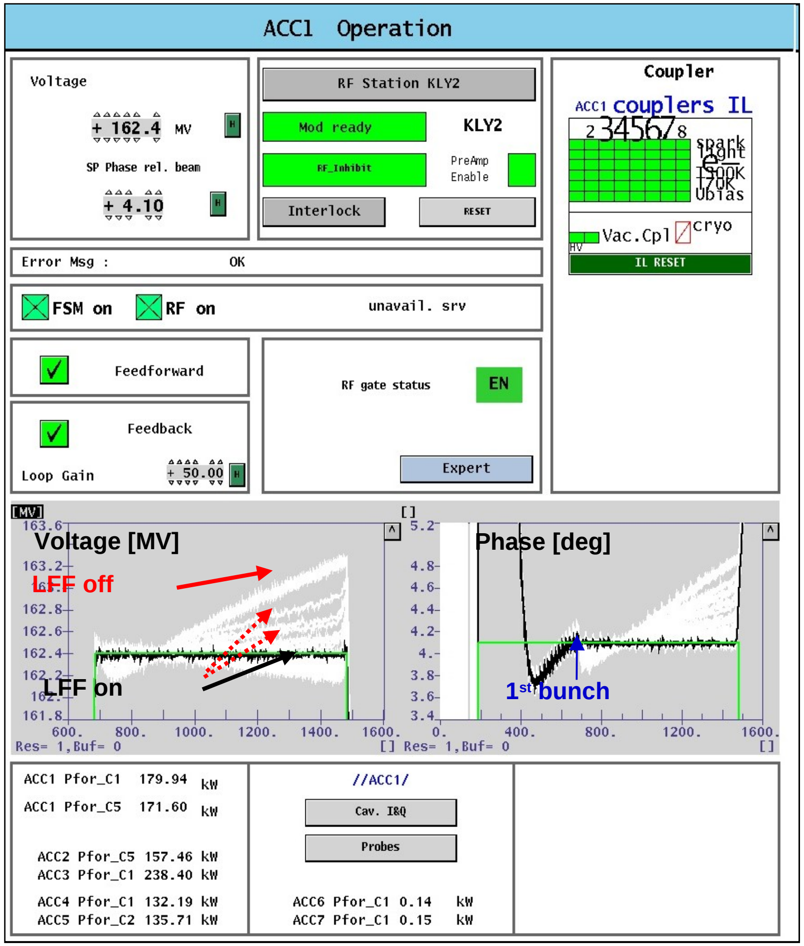
Machine Stabilty and Feedback Upgrades

Upgrade LLRF Control Software

> Unified and new control software

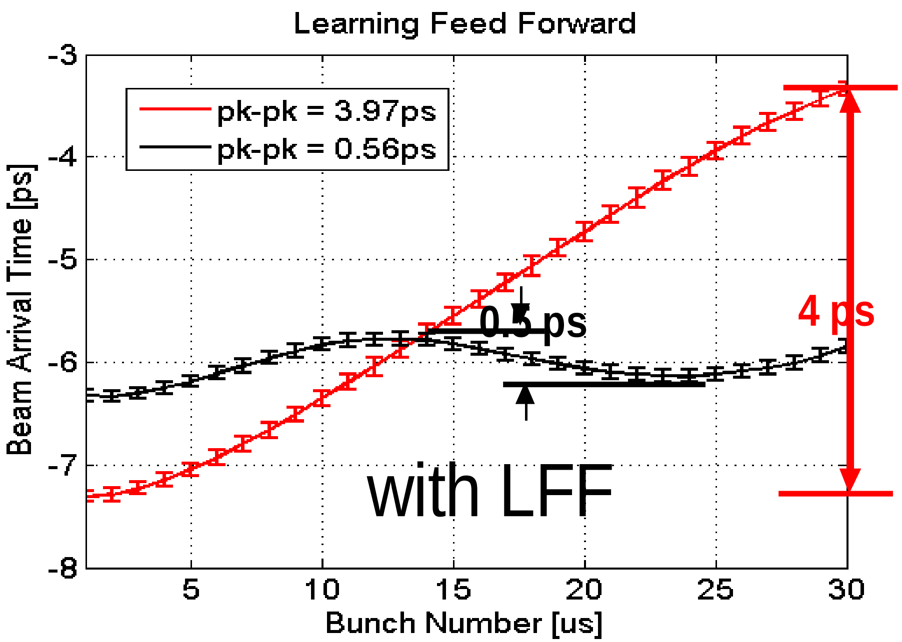
- New C++ architecture for front-end server
- Finite State Machine for automation
- High level software: diagnostics, calibration…
- Integration to data acquisition system
- Model based learning feed forward (LFF)
- Loop phase/gain correction
- Fast piezo control for cavity detuning comp.
- … and many more

Control software ~80 % completed
excellent progress in the last year

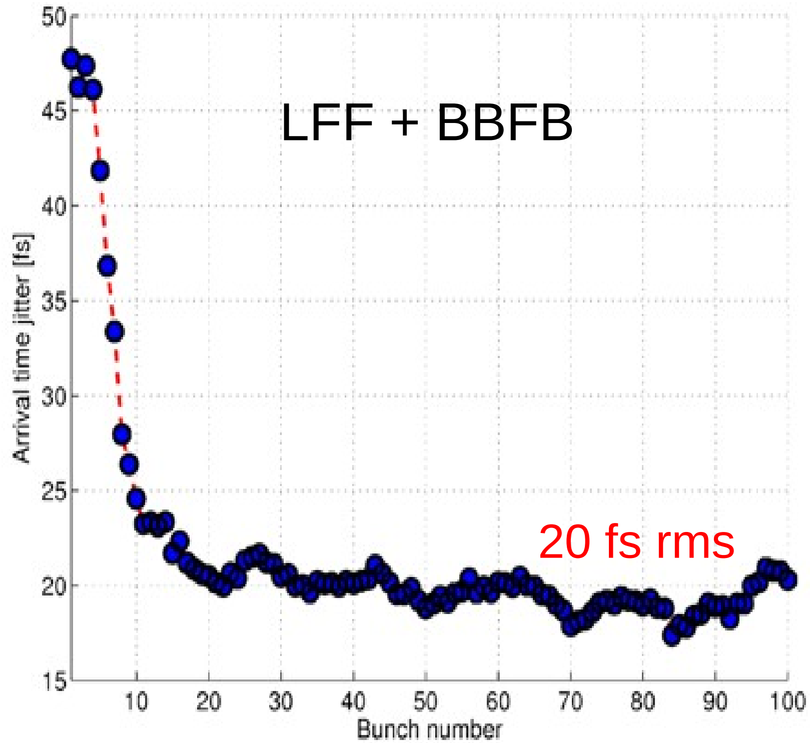


First Results on Stability and Beam-based Feedbacks

- Arrival time jitter (minutes) reduced from ~200 fs to 70 fs rms
  → dE/E (ACC1) < $1 \cdot 10^{-4}$



- Learning feedforward (LFF) and beam based feedbacks (BBFB)
  → 20 fs rms arrival time stability



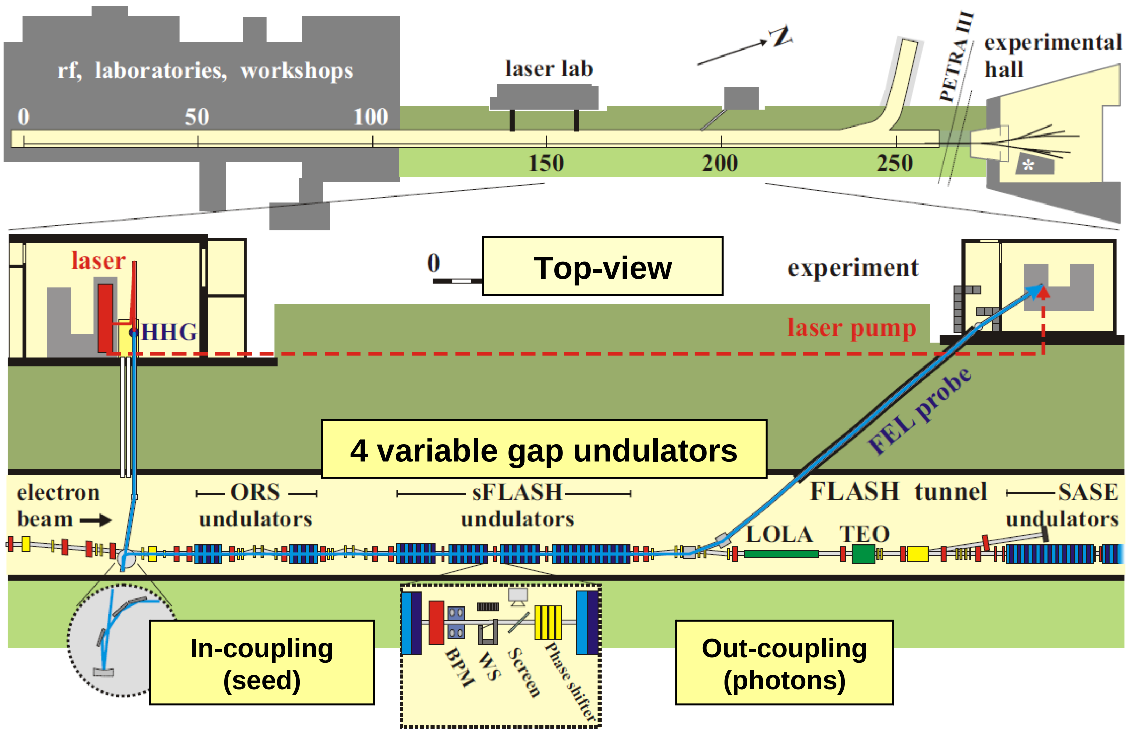
Still in R&D phase

sFLASH,

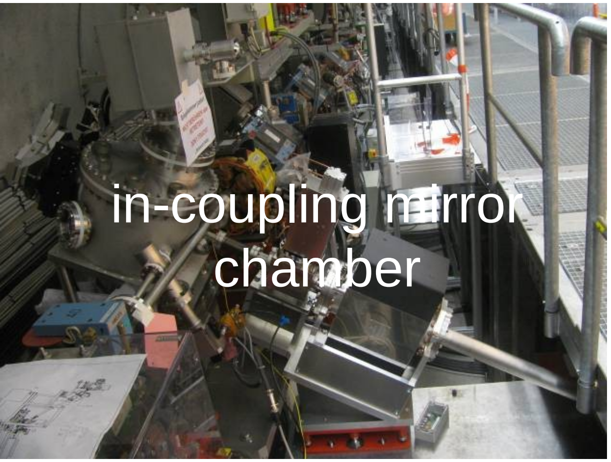
a Seeding Experiment

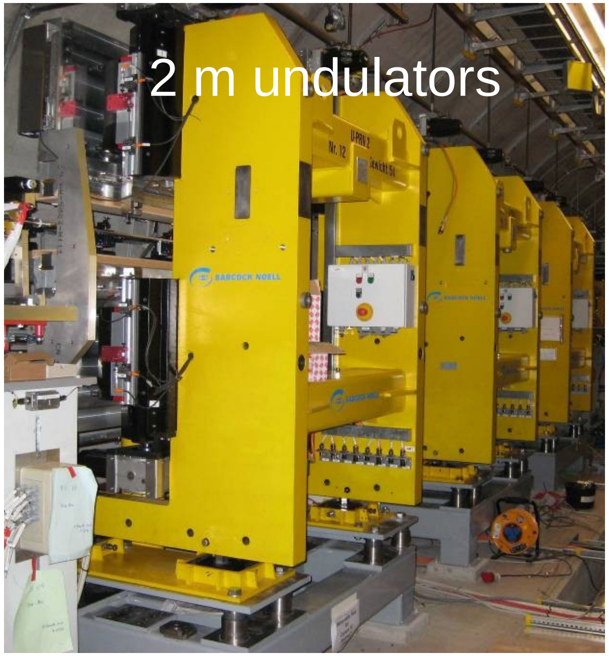
sFLASH: Experiment for Seeded FEL Radiation

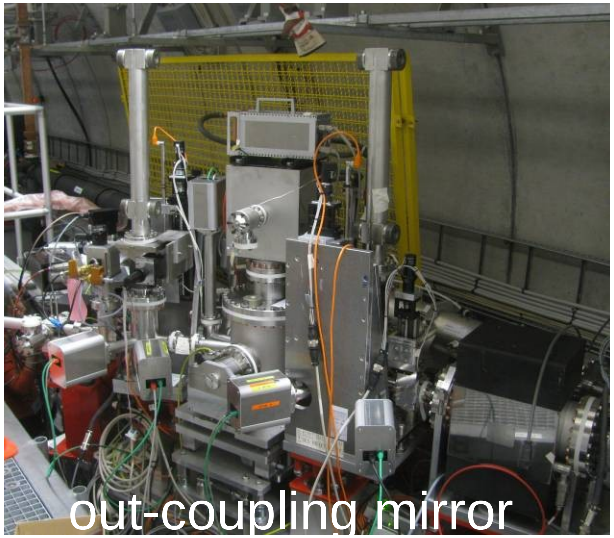
- Goal: generation of seeded FEL radiation for piloting experiments
- Installed between the collimator and SASE undulators in the FLASH linac
  → new electron beamline with a length of ~ 40 m
- HHG (high harmonic generation) seeding at ~ 38 nm (~ 13 nm as an option)
- Synchronisation goal for pump probe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

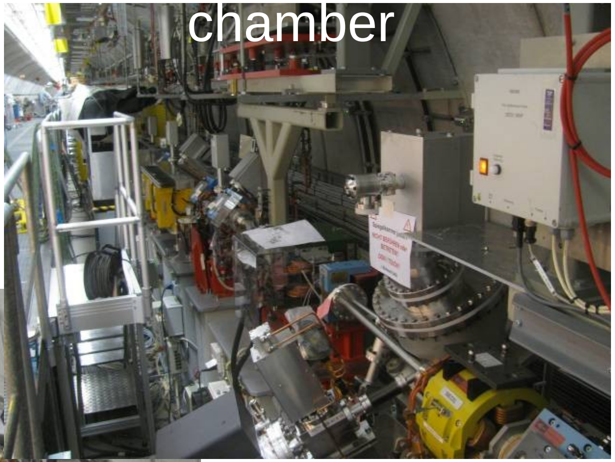


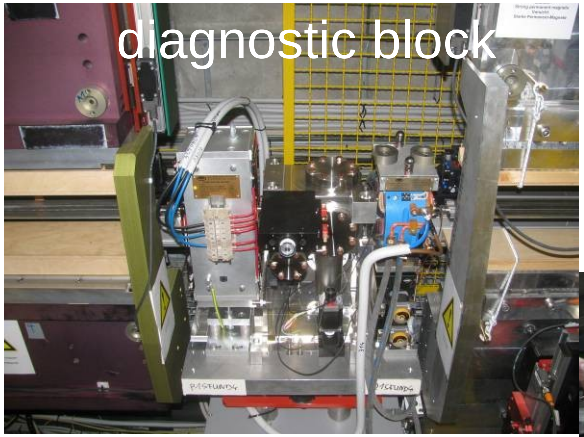
sFLASH Section











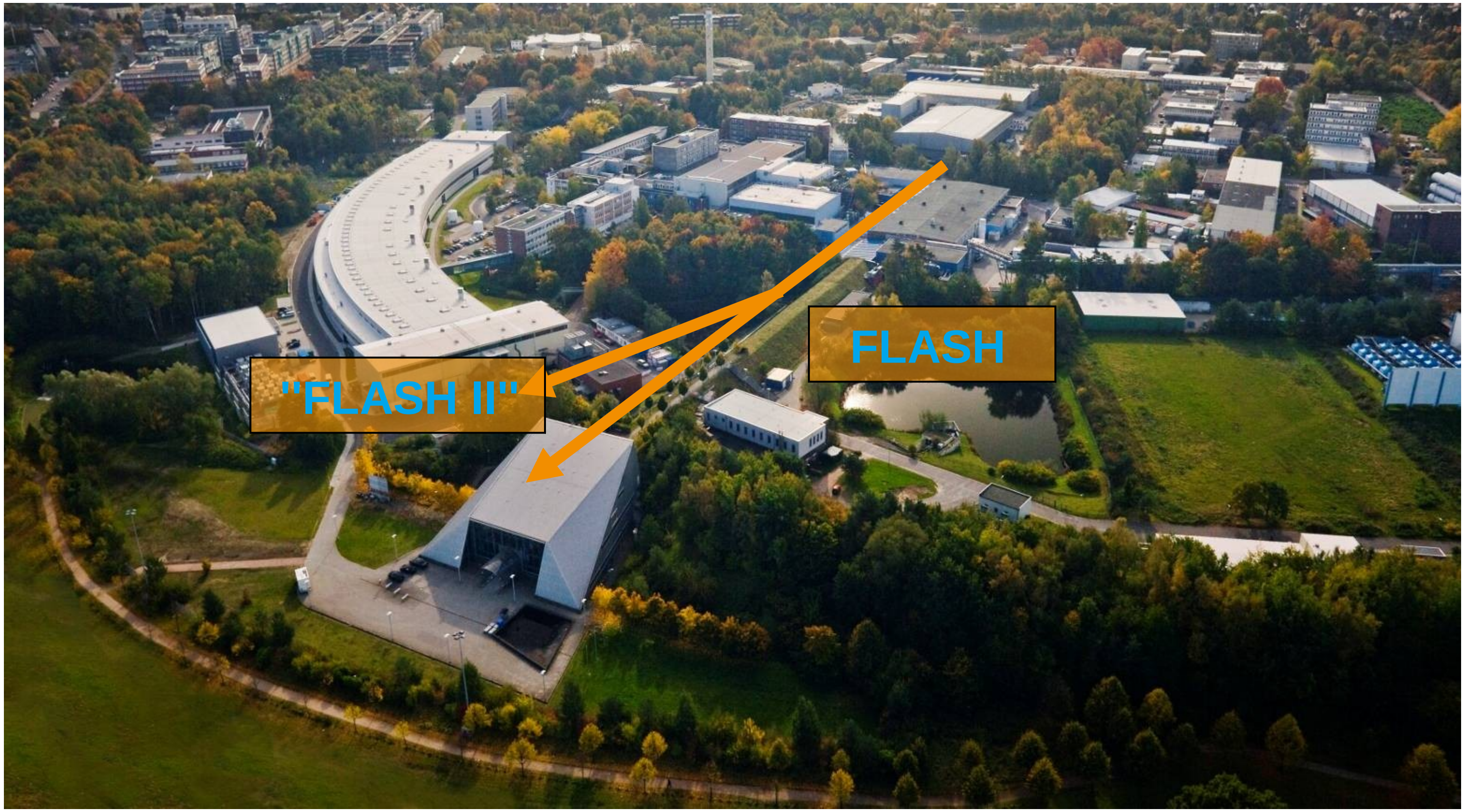
"FLASH-II"

"FLASH II"

Second undulator line and experimental hall

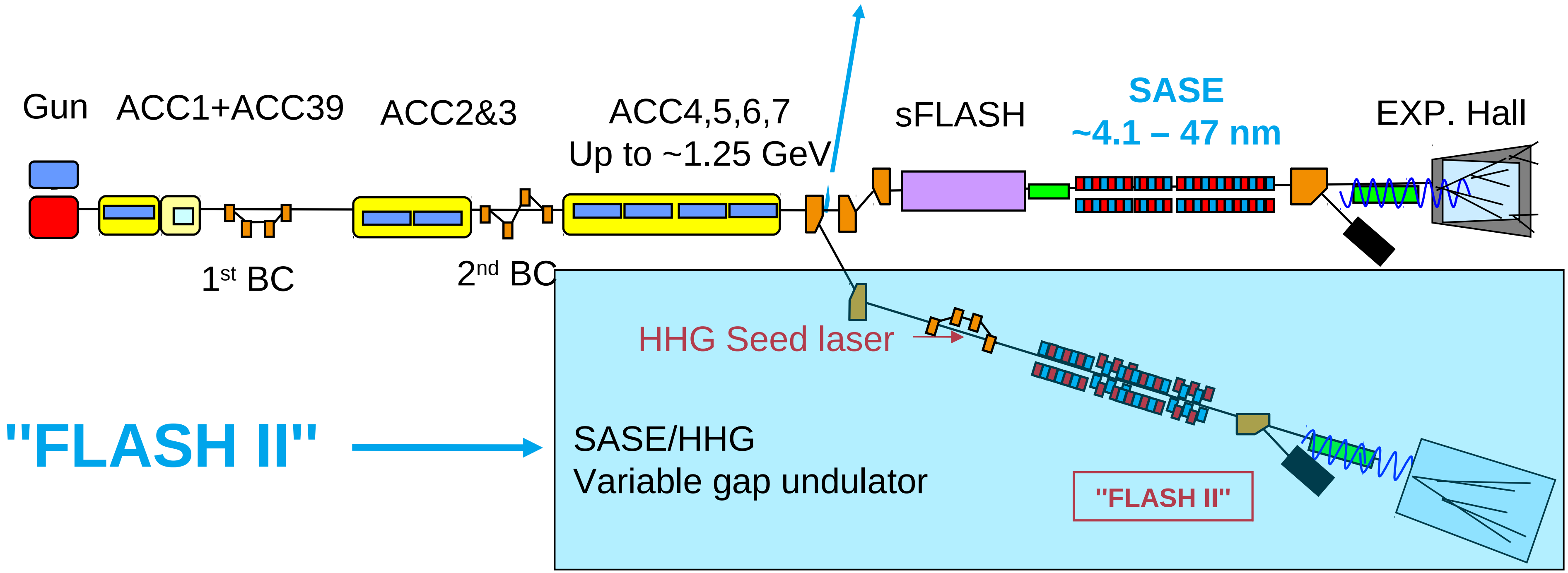
Common proposal by DESY and Helmholtz-Zentrum Berlin (HZB)

Project approved, construction starts end of 2011



Layout after Upgrade for "FLASH II".

- Separation FLASH and "FLASH II" behind last accelerator module
- Tunability of "FLASH II" by undulator gap change
- Extend user capacity with SASE and HHG seeding
- Use of existing infrastructure up to last accelerating module



"FLASH II": foreseen operation modes.

Self Amplified Spontaneous Emission (**SASE**) mode: Start from density fluctuations
spiky, but at full rep.rate and short and long pulses possible.

SEEDING SCHEME PHASE 1:

High Harmonic Generation (**HHG**) mode (see also sFLASH):

Amplify an external, frequency multiplied seed laser.

Only short pulses, but close to single mode down to ~10 nm.

Study for seeding towards shorter wavelength:

High Gain Harmonic Generation (**HGHG**) mode:

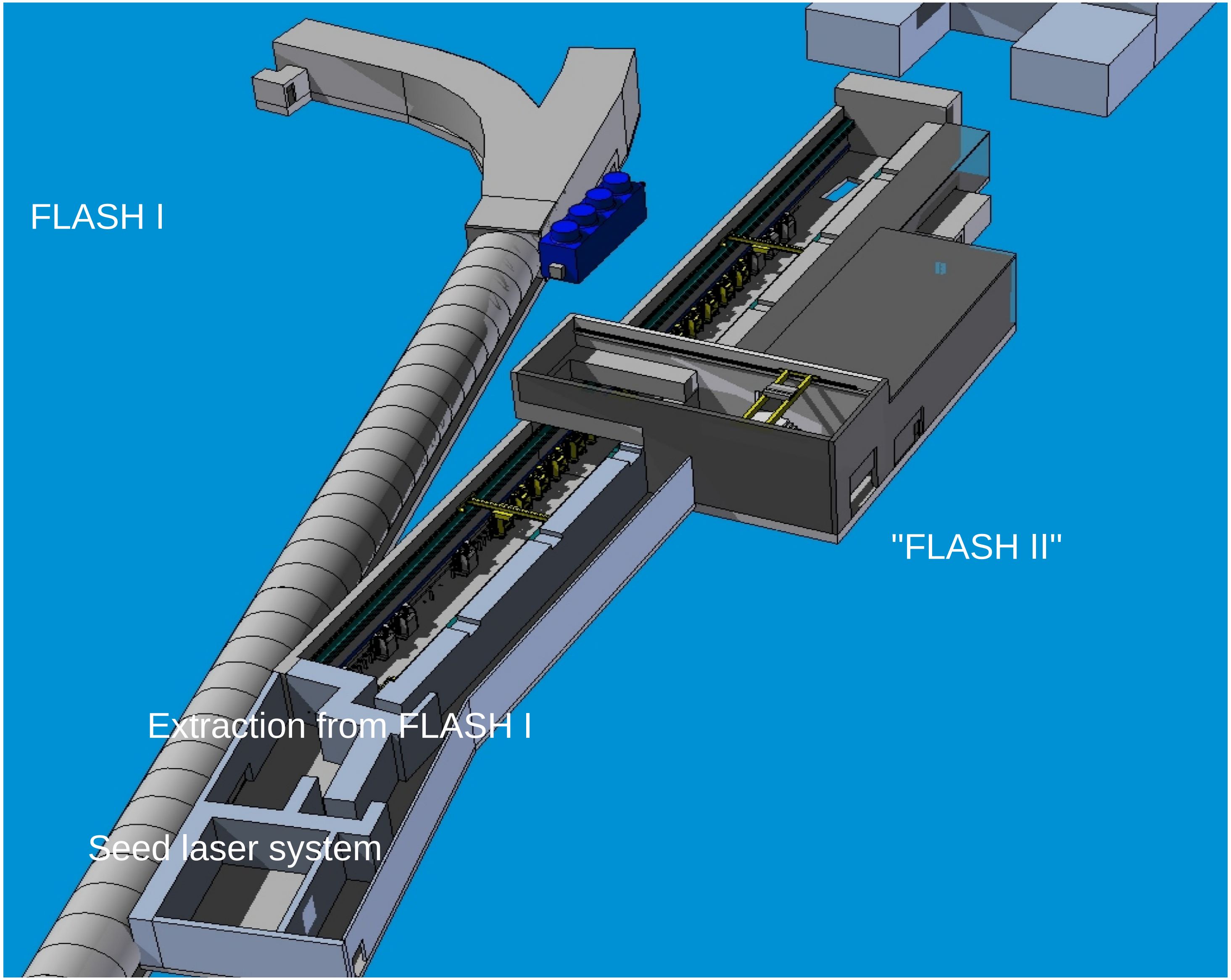
Amplify a long wavelength seed and apply frequency multiplication in FEL process.

Only short pulses (up to ~5-30 fs), but close to single mode down to ~4 nm.

Echo Enabled Harmonic Generation (**EEHG**) as option.

Hybrid mode: HGHG with HHG source

Tunnel Layout



Time Schedule

Starting now : Preparation of "FLASH II" construction

September 2011 : Start of tunnel construction
Needs ~3 months interruption of FLASH operation

Late Spring 2012 : Start to install technical infrastructure

Summer 2012 : Start to mount hardware

Winter/Spring 2013 : Vacuum connection with FLASH I

Early Summer 2013: Start commissioning of "FLASH II" with beam

Spring 2014(?) : Start of user operation "FLASH II"

Summary

- Successful re-start of FLASH after the upgrade
- We have reached the water window
- FEL beam more intense and stable than ever, tuning easier
- Tuning of short pulses is possible with linearized compression scheme
- LLRF and beam-based feedbacks have been significantly improved
- Photon beamlines and diagnostics have been significantly improved
- The seeding experiment sFLASH is in commissioning phase
- FLASH-II is approved and funded