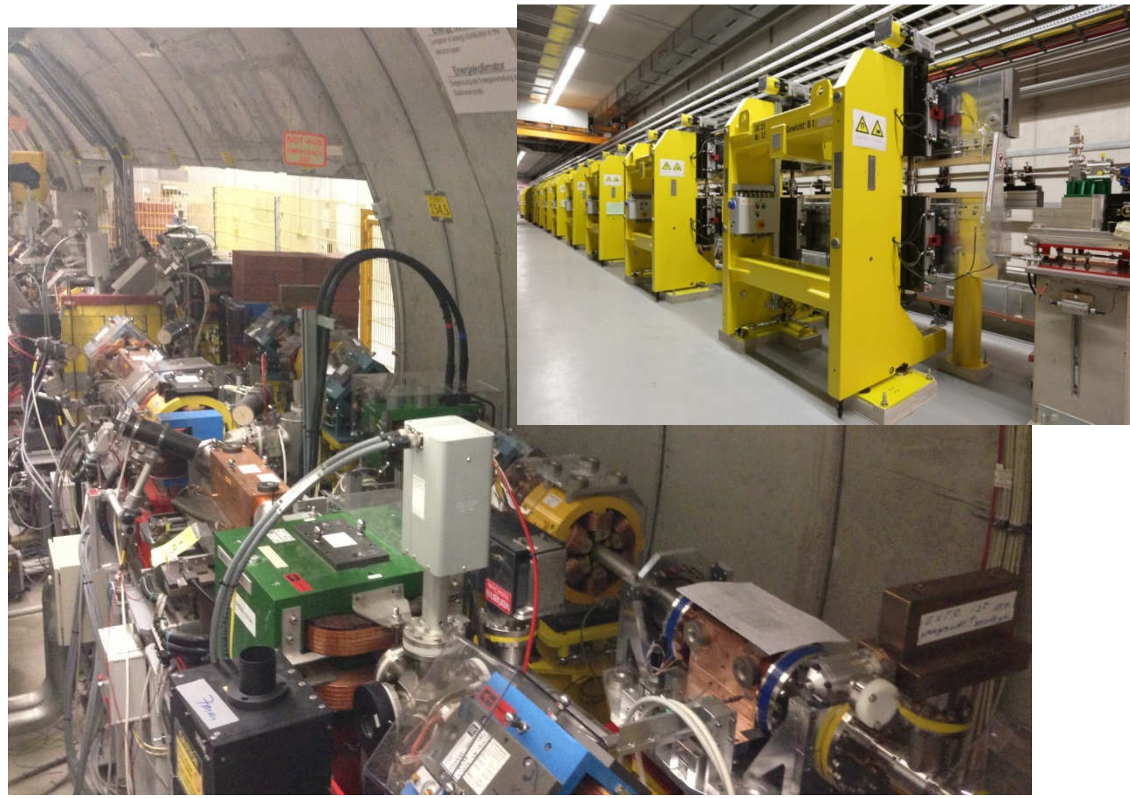
Operation of FLASH

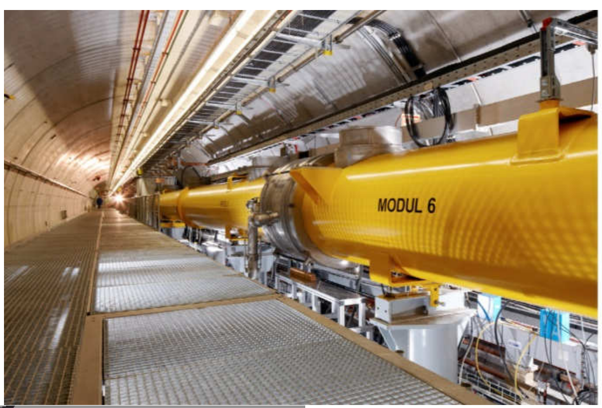
FLASH.
Free-Electron Laser
in Hamburg

FLASH – Free-Electron Laser User Facility at DESY

Siegfried Schreiber, DESY
for the FLASH team

SPIE Optics + Optoelectronics
Advances in X-ray Free-Electron
Lasers Instrumentation
Prague, 13-16 April, 2015





HELMHOLTZ
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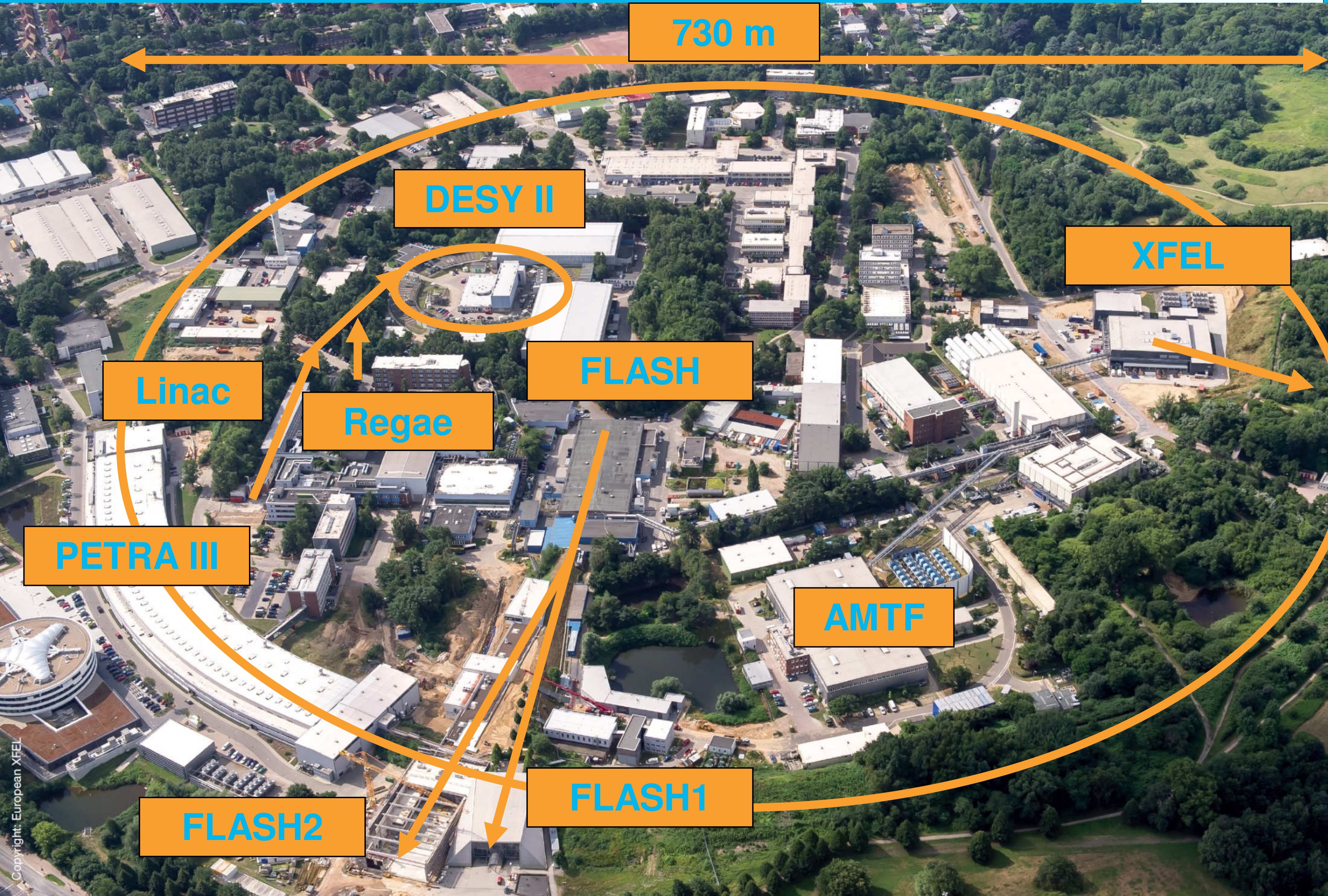
DESY

DESY accelerators in operation

FLASH.
Free-Electron Laser
in Hamburg



FLASH Layout

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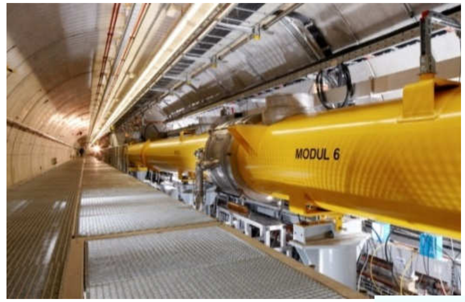
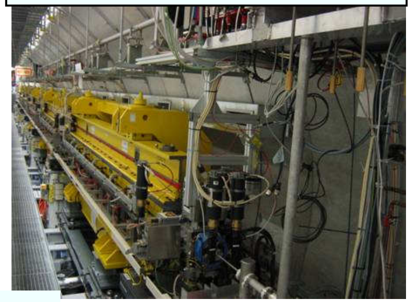
> 3rd harmonic sc module 3.9 GHz

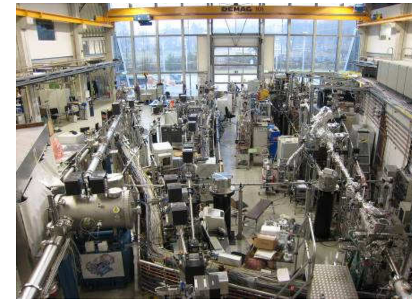
> TESLA type superconducting accelerating modules 1.3 GHz

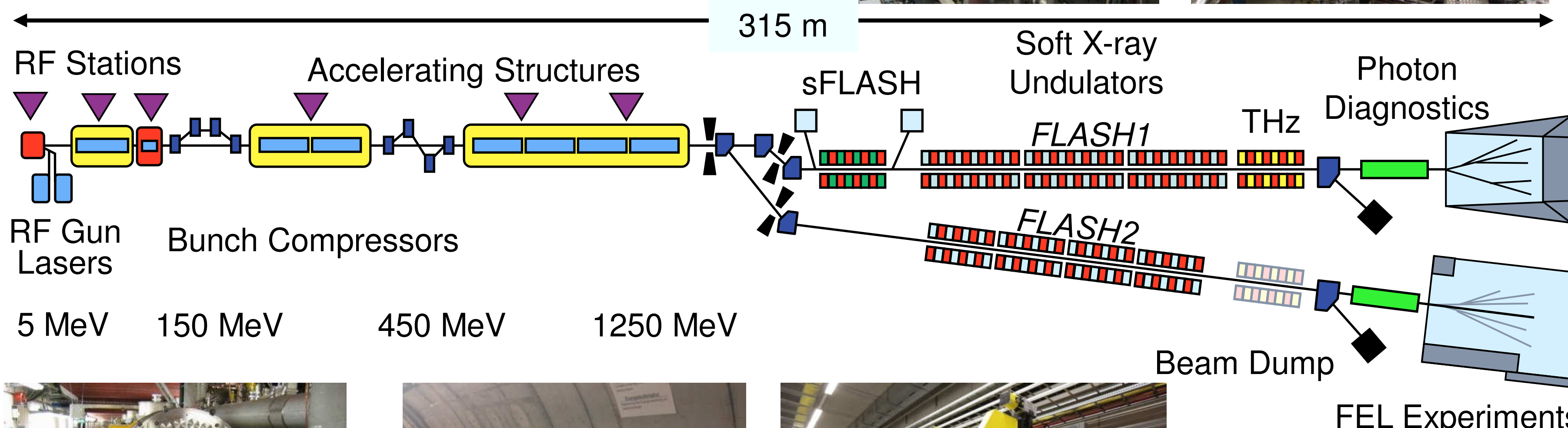


> FLASH1 fixed gap undulators
> Total magnetic length ~ 27 m



> FLASH1 Experimental Hall





> Normal conducting 1.3 GHz RF gun
> Ce_2Te cathode
> Two Nd:YLF based ps photocathode lasers

> Extraction to FLASH2

> Variable gap undulator
> Total magnetic length ~ 30 m

> FLASH2 Experimental Hall

User operation

FLASH1 Parameters 2014 / 2015

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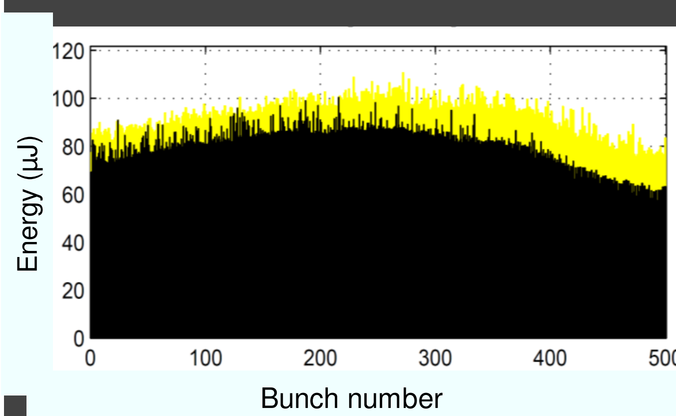
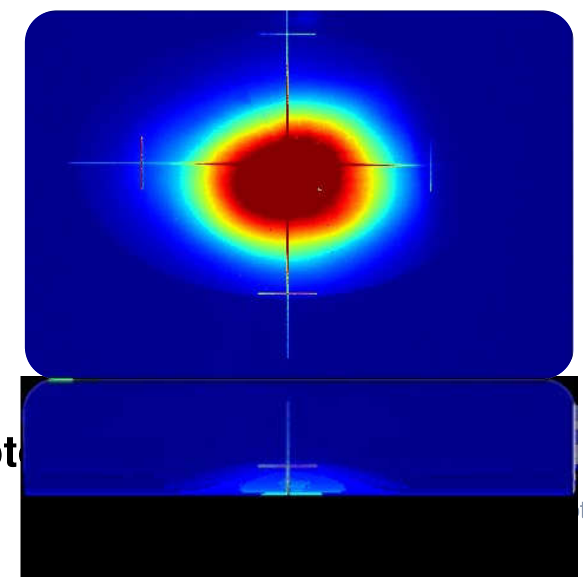
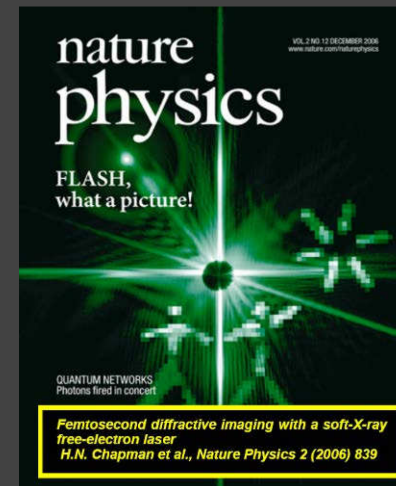
FEL Radiation Parameters 2014/2015

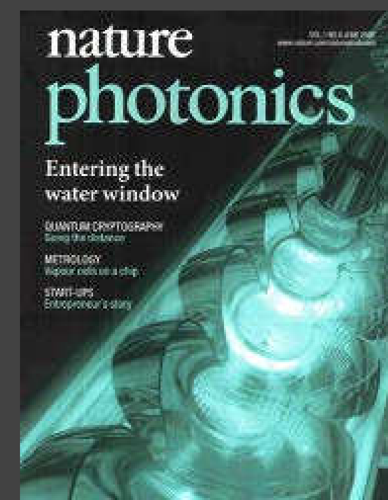
Wavelength range (fundamental)	4.2 – 52 nm
Average single pulse energy	10 – 500 µJ
Pulse duration (FWHM)	< 50 – 200 fs
Peak power (from av.)	1 – 3 GW
Pulses per second	10 – 5000
Spectral width (FWHM)	0.7 - 2 %
Photons per pulse	$10^{11} – 10^{13}$
Average Brilliance	$10^{17} – 10^{21}$ B*
Peak Brilliance	$10^{29} – 10^{31}$ B*

* photons/s/mrad²/mm²/0.1%bw









many in high impact journals

Beamtime Distribution and Bunch Pattern

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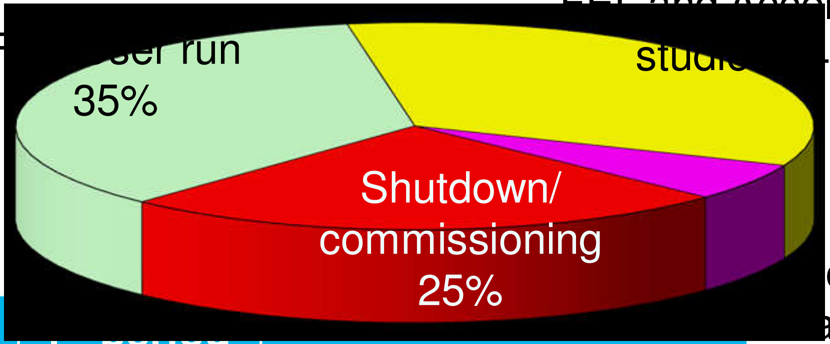
- Scheduled beamtime June 2005 – 2014



- >7500 hours / yr in operation
- 4500 hours / year scheduled for users

Requested Pulse Pattern		3rd period		
Single bunch		47%	47%	
Multi-bunch		53%	53%	35% >200 b.
Bunch spacing	1 MHz		30%	
	200 kHz		43%	
	other		27%	40, 100, 250, 500 kHz
Requested FEL pulse duration				
< 50 fs fwhh		28%	**42%**	**56%** multi-bunch
50 -100 fs		54%	33%	64% single
not critical		18%	26%	83% max. energy

Water window experiments

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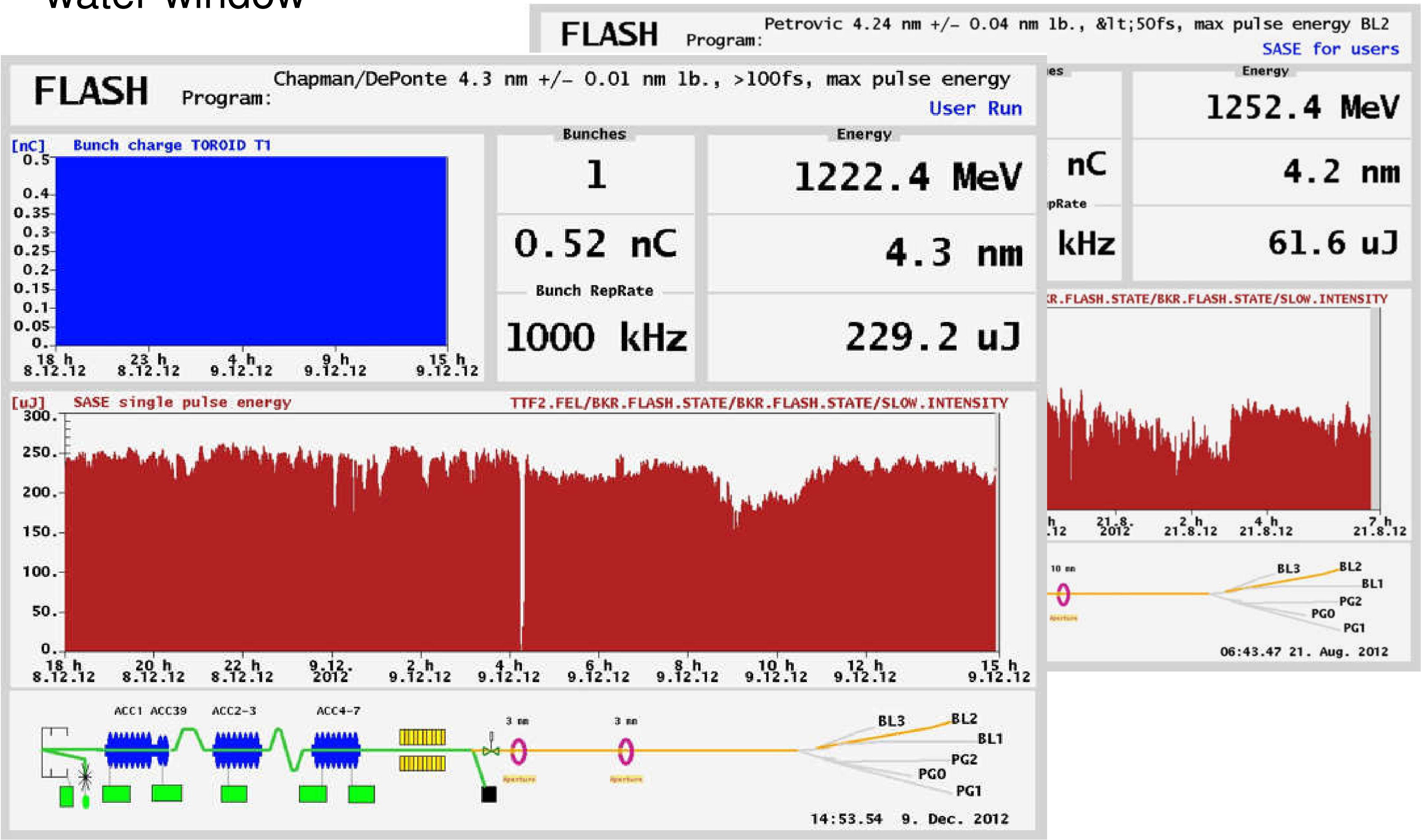
> Two examples of user experiment with 4.2 nm and 4.3 nm in the water window



SASE with high average power

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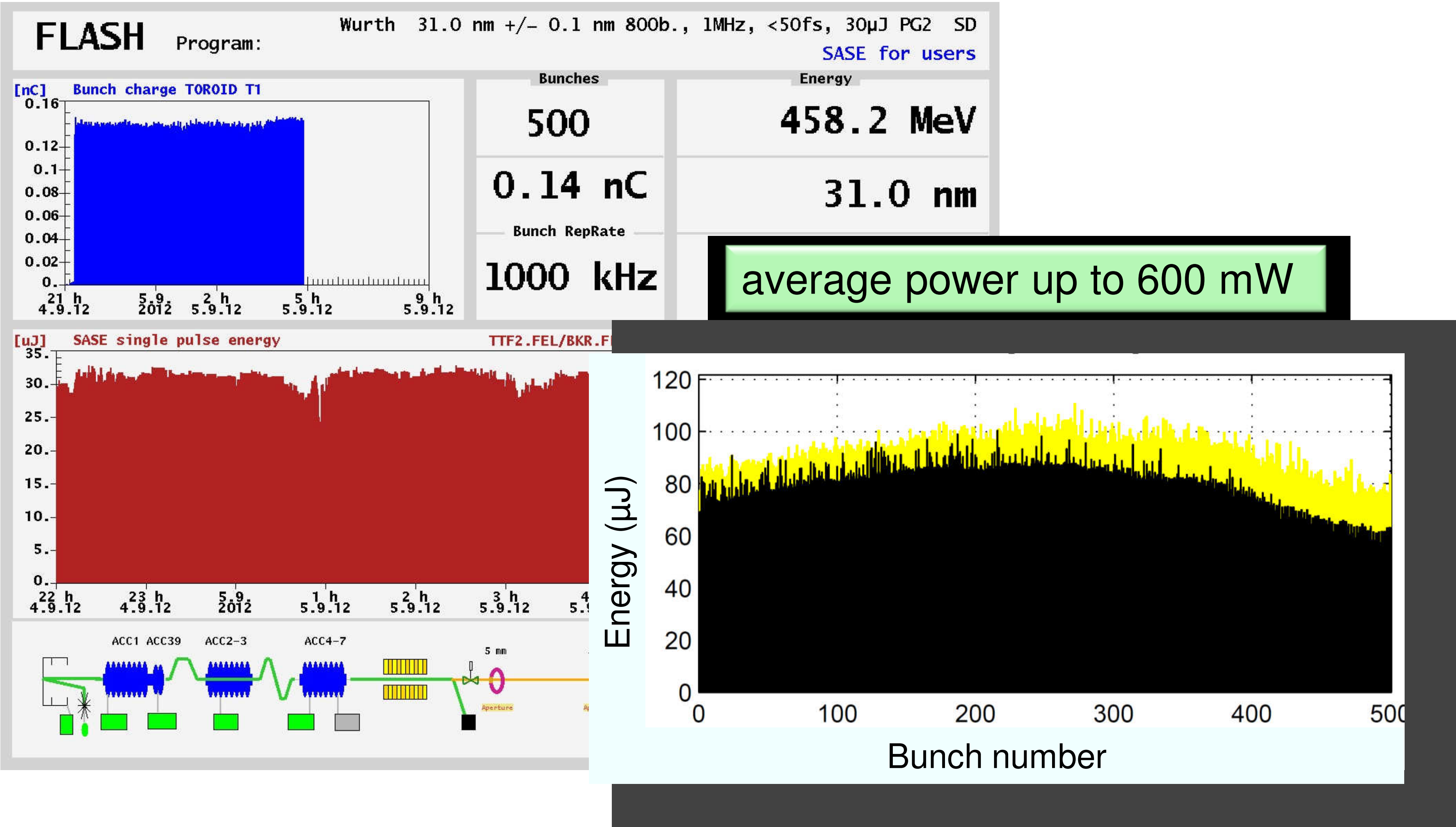
> 5000 SASE pulses/sec to experiments



Experiments with THz radiation

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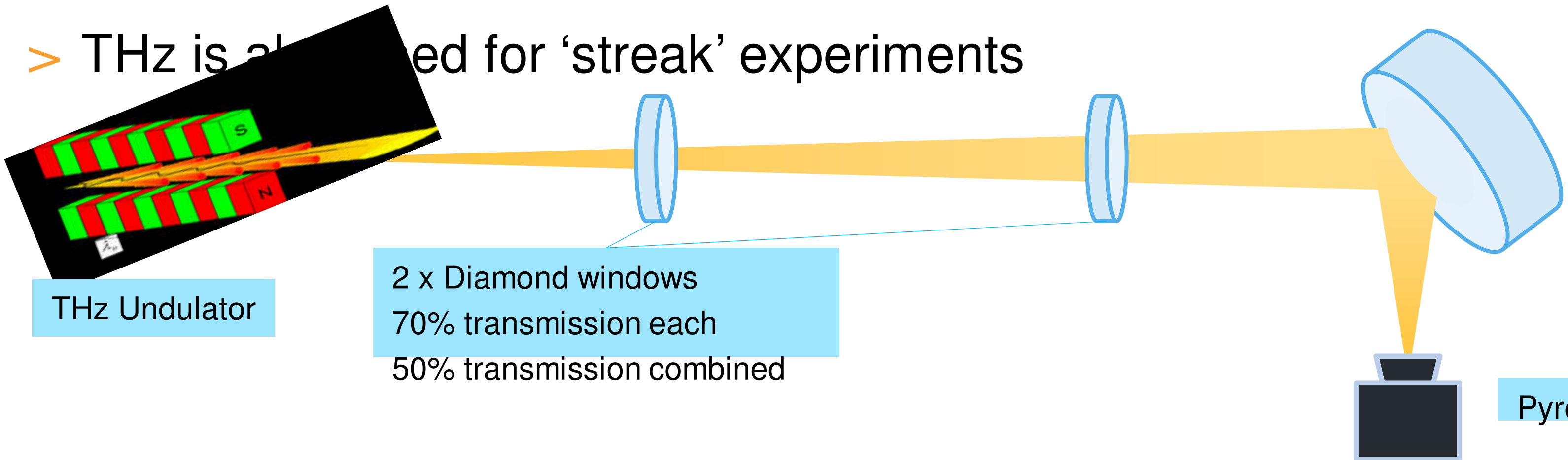
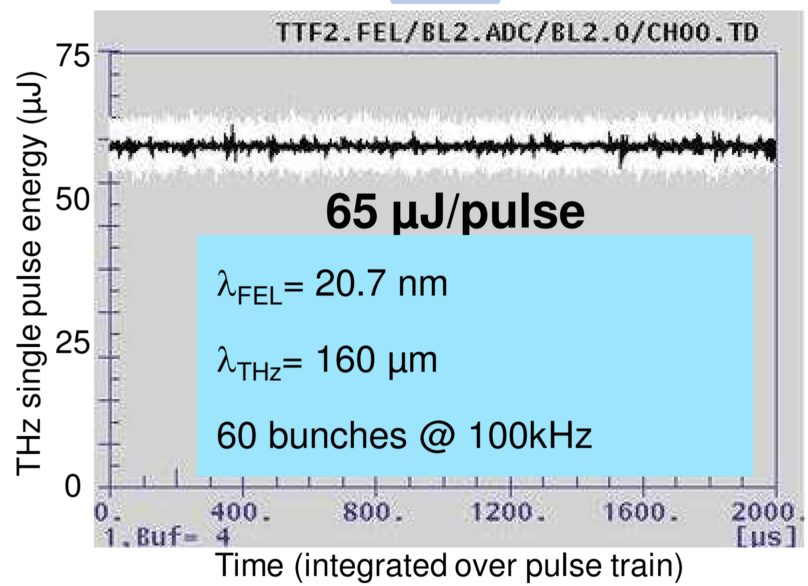
- Several experiments use THz together with X-ray pulses and also optical laser for pump probe experiments
- THz is al… ed for ‘streak’ experiments

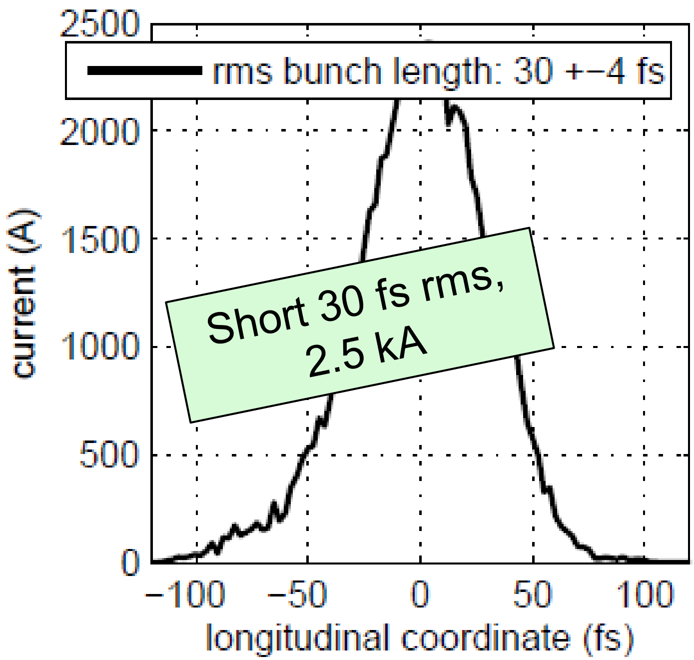


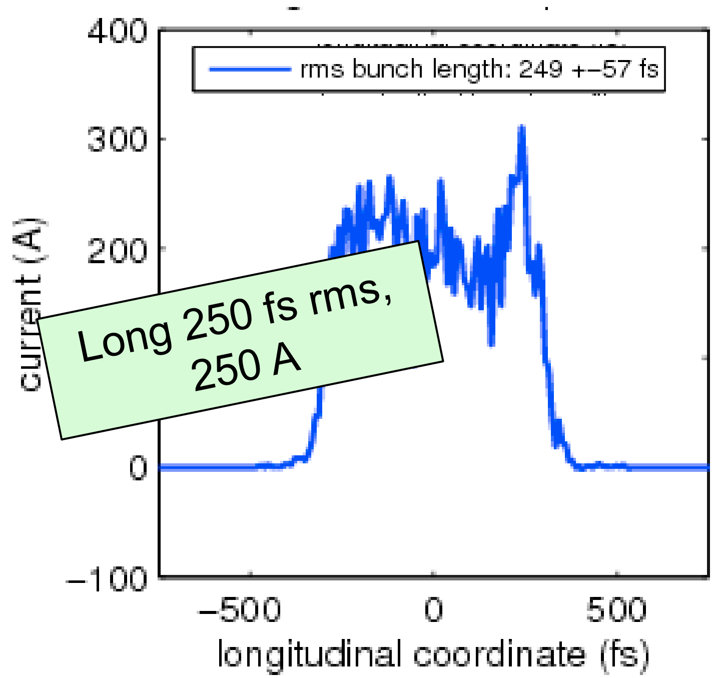
- FLASH is also a unique THz source worldwide
- Multibunch operation: many thousand pulses per second possible
- Perfect synchronization
- more than 100 µJ per pulse obtained



Tailored FEL pulses

- Experiments require various photon pulse lengths
- From short <30 fs rms ….. to long > 200 fs rms





Electron Bunch length measured with our transverse deflecting cavity LOLA
(rms resolution dt = 5…10 fs, dE/E = 1.4 10^{-4})

- Note: as a rough estimate, photon pulses are ~2 times shorter

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RF Gun

Electron Source

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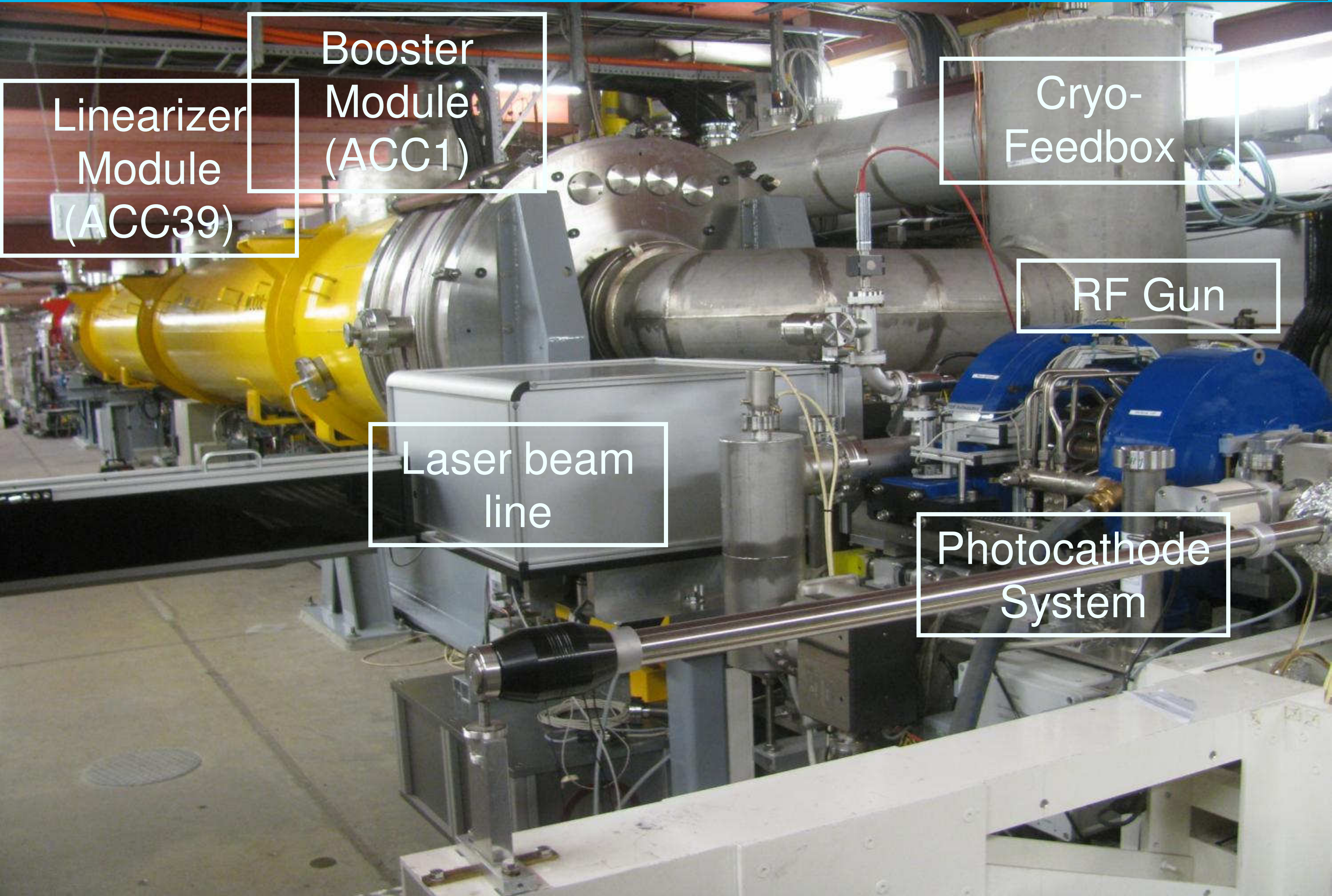

RF Gun (duty cycle 1:100)

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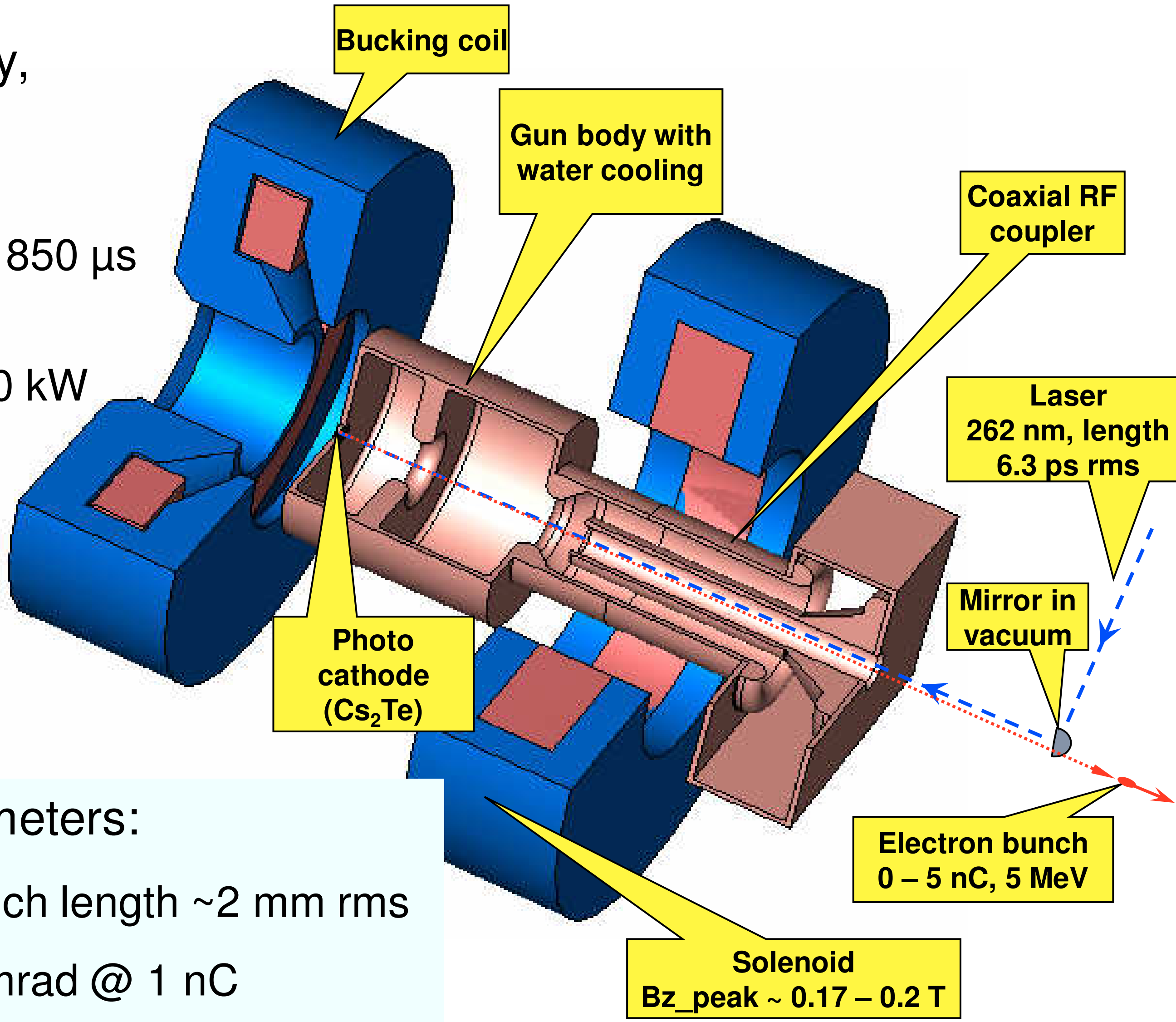
> 1.3 GHz copper cavity, 1 ½ cell

- RF peak power 5 MW
  RF pulse length up to 850 µs
  rep.rate 10 Hz
- Av. RF power up to 50 kW
- Cs_2Te photocathode
- UV burst-mode laser



> Electron beam parameters:

- Charge 0…5 nC, bunch length ~2 mm rms
- Emittance <1.5 mm mrad @ 1 nC
- Trains of thousands of bunches/sec

RF Gun's operated at FLASH since 2004

FLASH. Free-Electron Laser in Hamburg

Gun 2	2004	Gun2: 5 Hz, 3.5 MW, 350 µs, 5 kW, 680 GJ
		Window: G29
	2009	**Gun2 breakdown**
Gun 4.2	1/2010	Gun4.2: 10 Hz, 3.9 MW, 400 µs, 15 kW, 1200 GJ
		Window: Gxx
	6/2010	Window break down; → G67
	9/2011	Window break down; → G29
	5/2012	**Gun4.2 breakdown**
Gun 4.1	6/2012	Gun4.1: 10 Hz, 4 MW, 550 µs, 21 kW, 930 GJ
		Window: G29
Gun 3.1	3/2013	**Gun3.1: 10 Hz, 5 MW, 550 µs, 27 kW, 1200 GJ**
		Window: Thales 5
	4/2014	Window leak; → G64

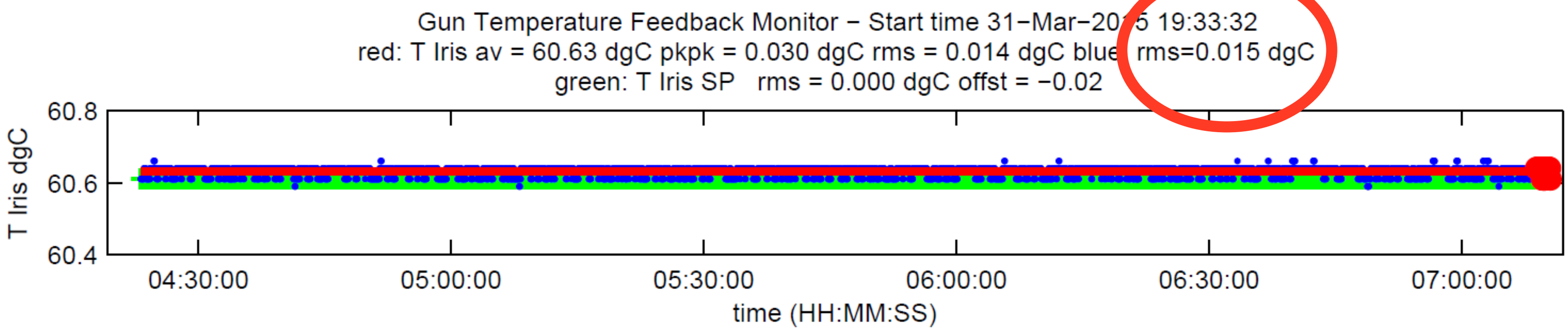
Integrated RF-power

No breakdown events or other trips since 8-Jun-2014

Note: maximum accepted trip rate by RF gun: <2 trips per week

RF Gun Temperature Stability

- RF gun has no tuning paddles
- Tuning to 1.3 GHz with its temperature
  - sensor in the iris separating full/half cell
- Stability measured: dT = 0.015 dgC rms (315 Hz; ~0.1 dg in RF phase)
- Measured RF phase stability <0.08 dg rms
- Work is ongoing to improve the stability further



Blue points: RF Gun temperature over 2.5 hours
(1 bit jump = 0.02 K)

Example for sensitivity of water temperature

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Free-Electron Laser in Hamburg

RF Gun water circuit pressure change

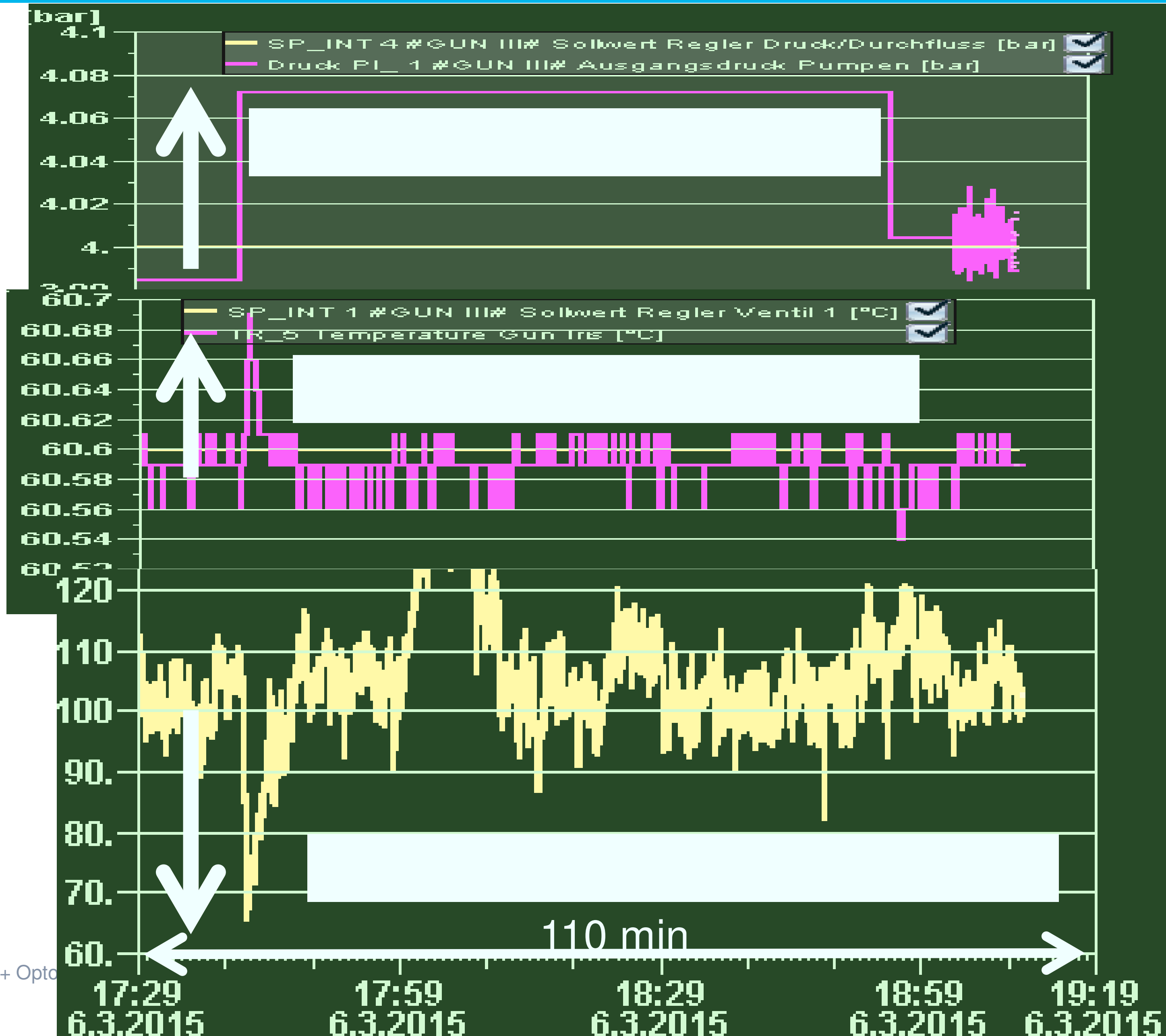
dP = 0.1 bar

↓

dT = 0.1 K

↓

dE/E (SASE) = -30%

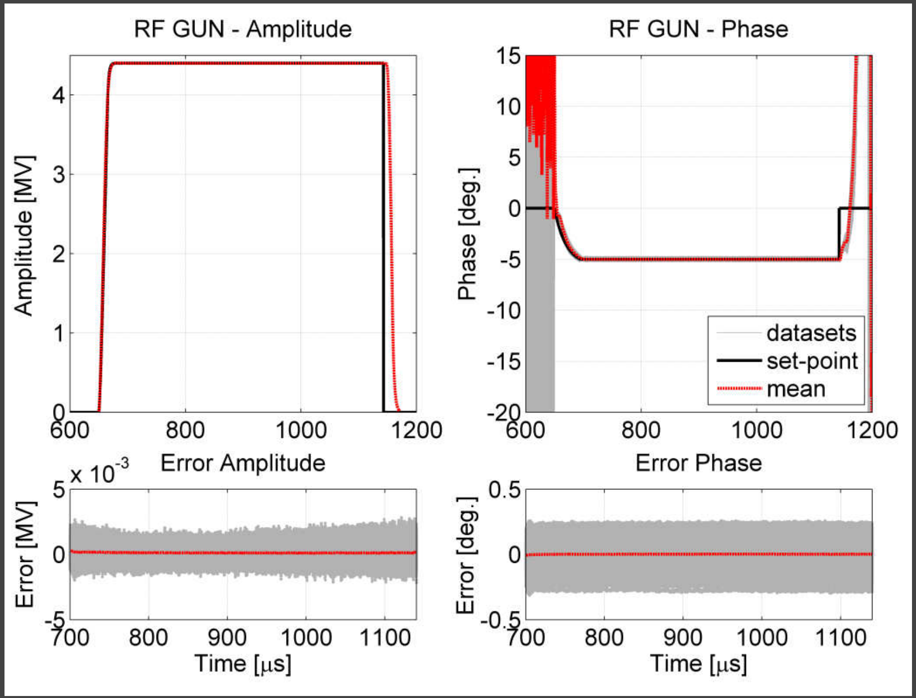


RF Gun Low Level RF

- New: based on MTCA.4 standard
- System identification performed
  - Model found and controller designed
  - large loop latency compared to system bandwidth ~1.4 µs
- Runs smooth and stable
- Includes learning feedforward

Feedback gain currently **not** sufficient to achieve a phase stability of dφ < 0.01 dg

- Additional protection mechanism
  - amplitude limiter, fast switch off



Regulation performance (rms)	Intra pulse (flattop)	Pulse to pulse (960 consecutive pulses)
Amplitude dA/A (%)	0.008	0.008
Phase dφ (dg)	0.007	0.076

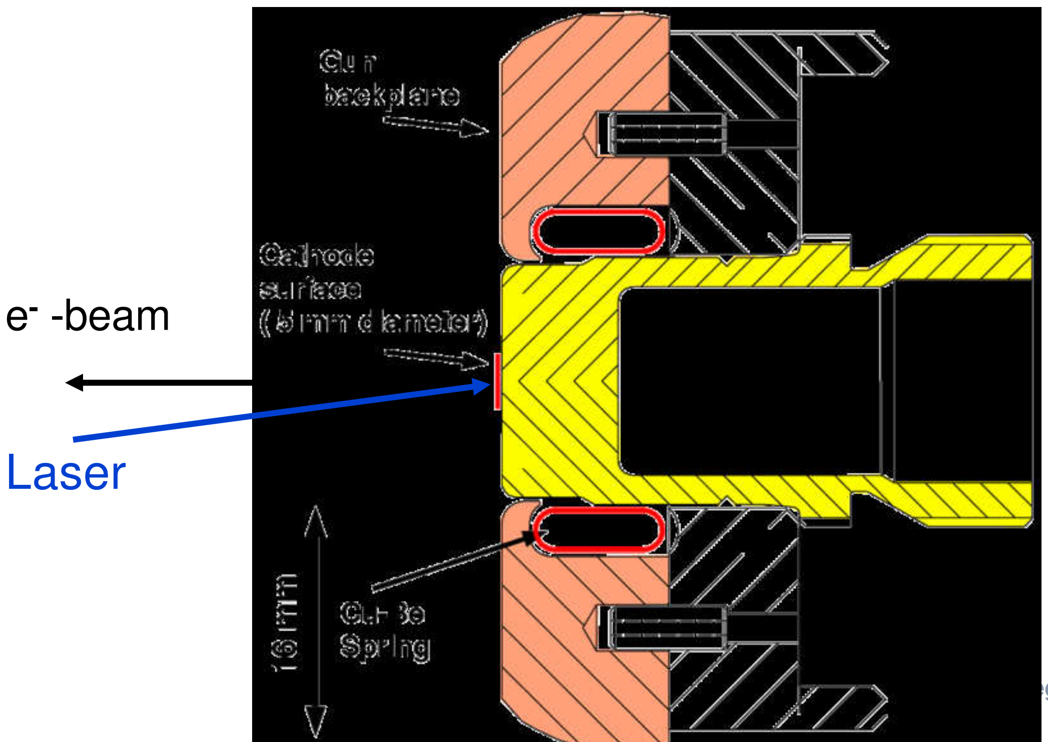
Goal: < 0.01% in amplitude and < 0.01 dg (rms) in phase

Cathode

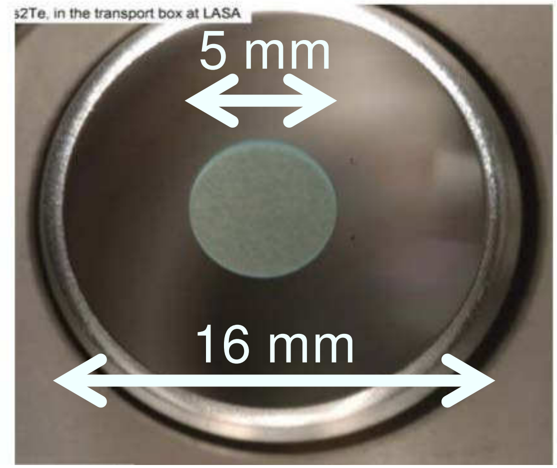
Cs_2Te Cathodes

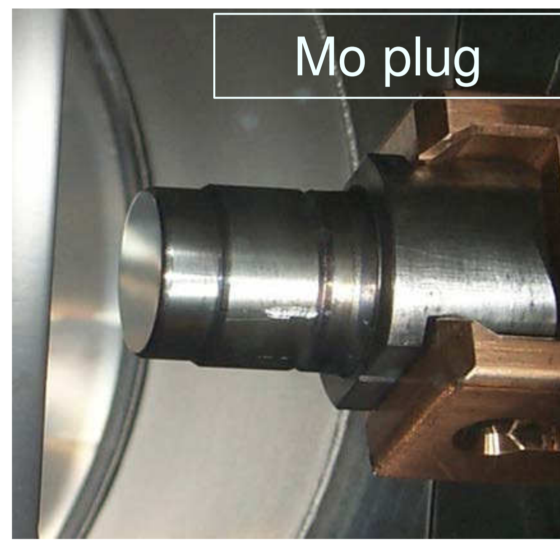
FLASH. Free-Electron Laser in Hamburg

- High initial quantum efficiency ~10 … 15 %
- Excellent lifetime > 1 year at FLASH
- Preparation systems at LASA, Milano and DESY, Hamburg
  - UHV transport boxes
- Requires UV laser 275 … 250 nm



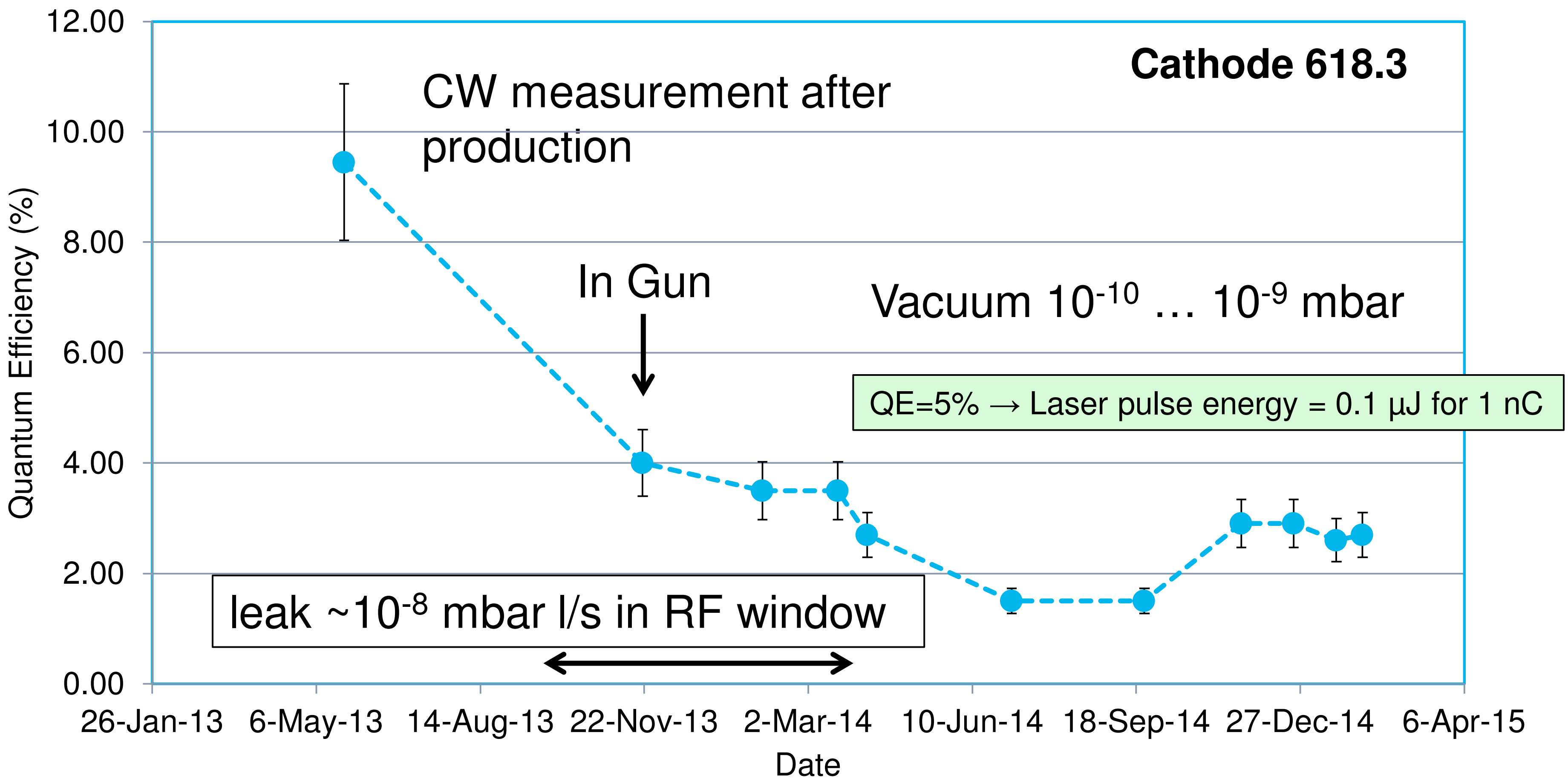
Thin film of Cs_2Te on Mo plug





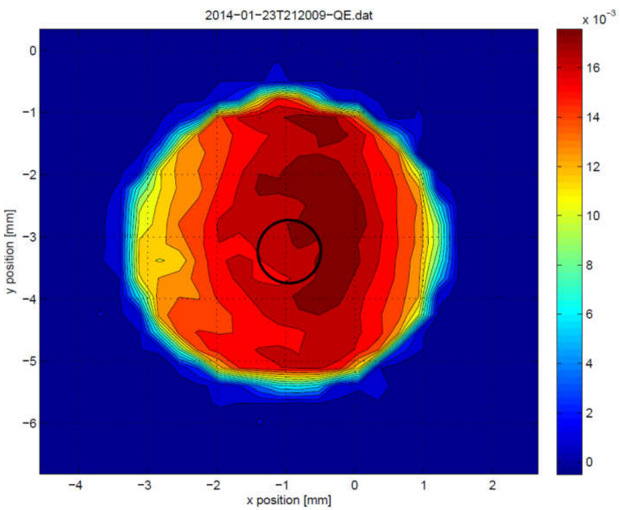
Cathode Lifetime

- Cathode 618.3: in use 21-Nov-2013 to 4-Feb-2015: **439 days**
- Total charge extracted: 3.2 C



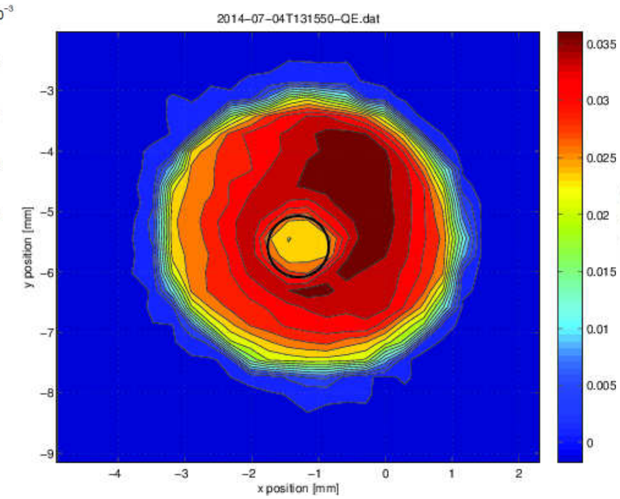
QE map

- Cathode 618.3
- Faster QE degradation where the laser hits
- Rest of cathode degrades slower
- Not clear, if QE actually recovered in the center, looks like “yes”



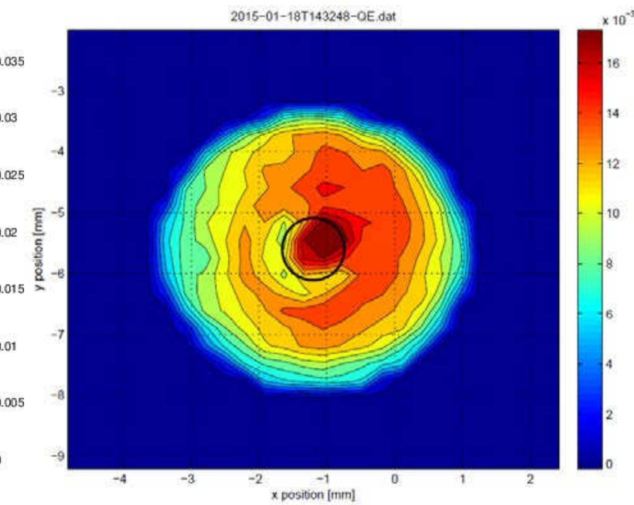
23-Jan-2014

QE=3.5%



4-Jul-2014

QE=1.5%



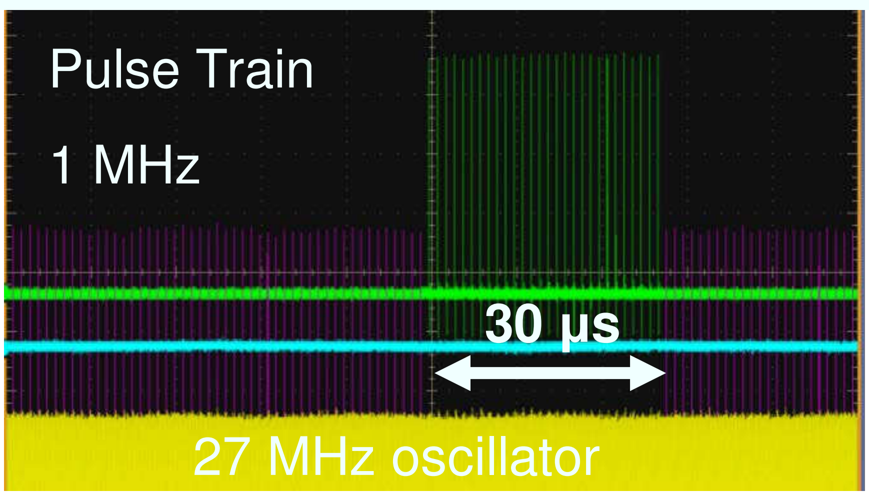
8-Jan-2015

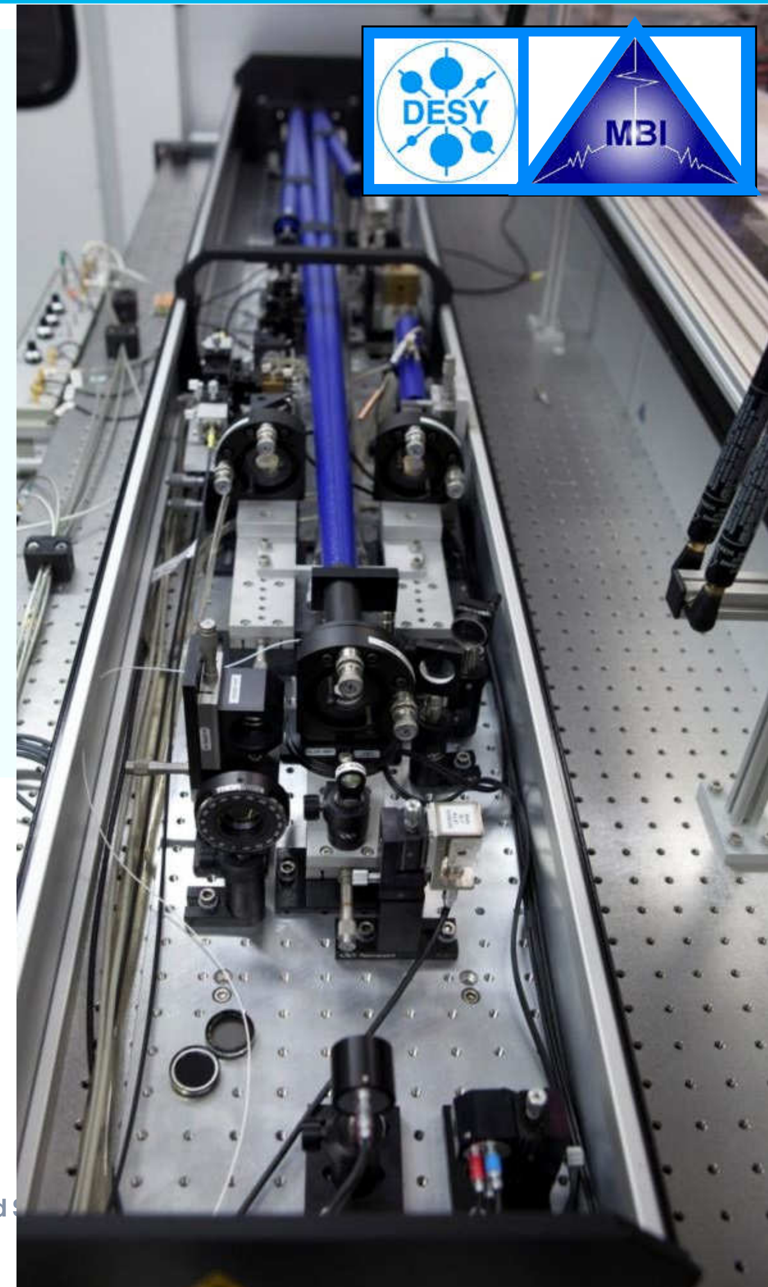
QE=2.6%

Photocathode Laser

Photoinjector Lasers

- 2 fully diode pumped Nd:YLF lasers
  - Compared to previous flashlamp pumped lasers:
  - Significant improvement in stability and reliability
  - Up to 50 µJ per pulse (UV)
  - Longitudinal gaussian shape
- Burst mode for long pulse trains (10 Hz)
- Number of pulses and pulse distance adjustable 1 MHz, 200 kHz, 100 kHz, …,
- 3 MHz option @ 5 Hz





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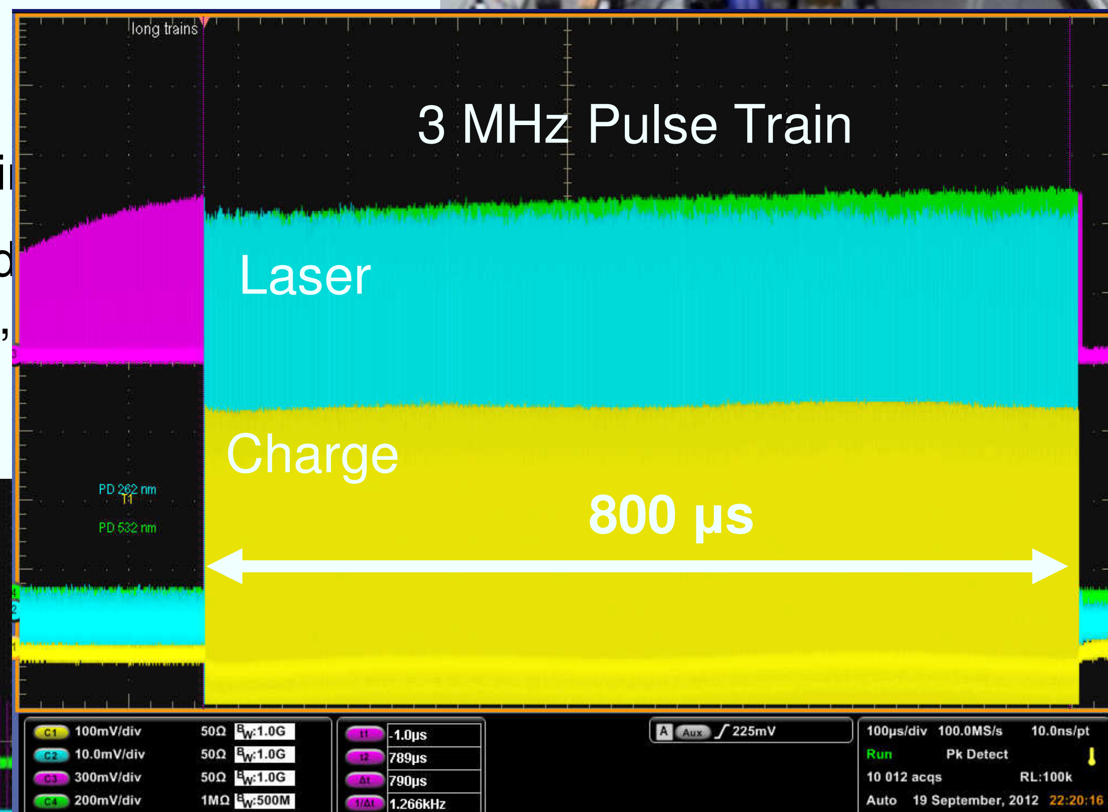

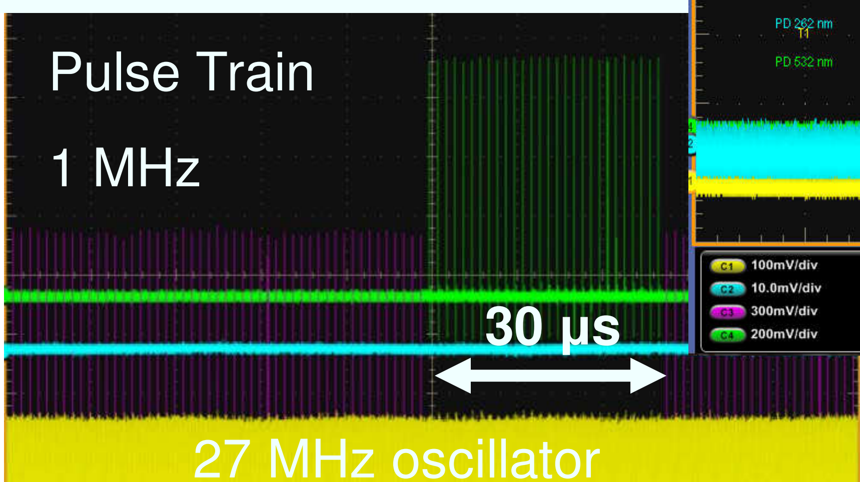

Photoinjector Lasers

FLASH.
Free-Electron Laser in Hamburg

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  - Significant improvement in stability and reliability
  - Up to 50 µJ per pulse (UV)
  - Longitu
- Burst mo
- Number c
  1 MHz, 2
- 3 MHz op

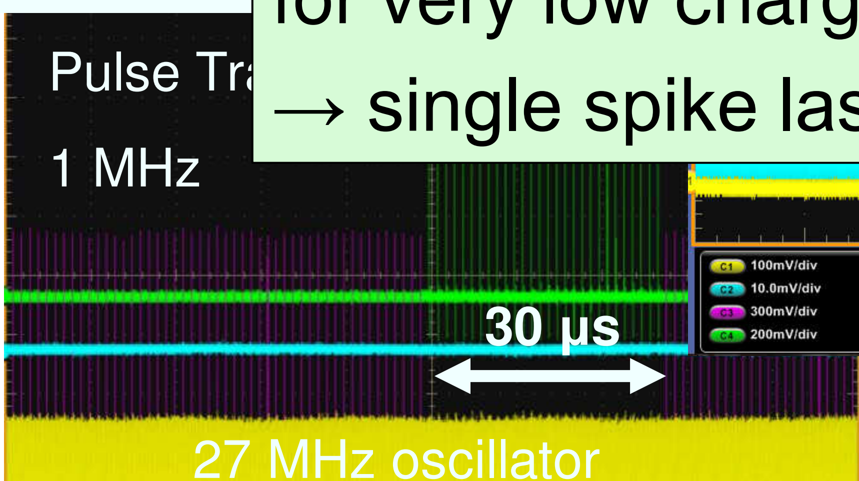
3rd laser in test phase

Feature:

variable pulse length 0.8 … 2 ps

for very low charge injection

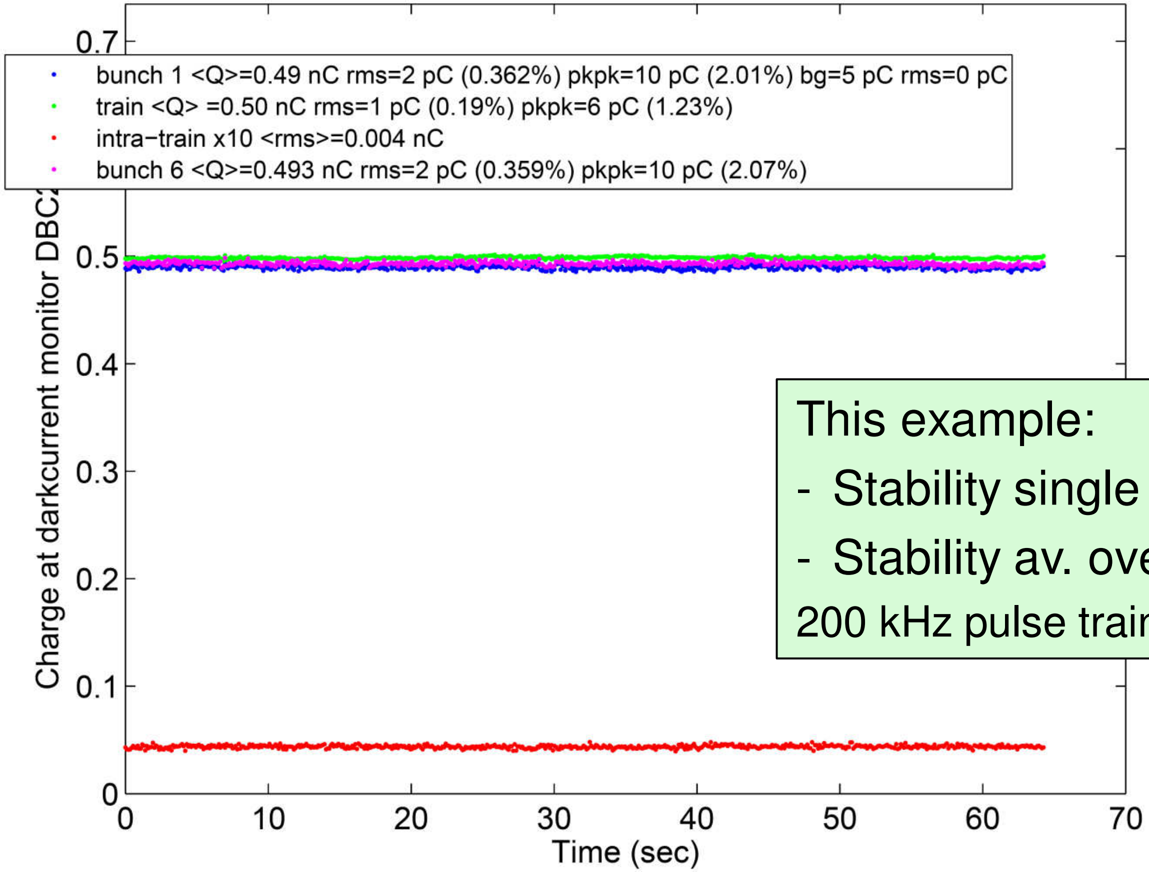
→ single spike lasing



Charge Stability

> Jitter at normal working point 0.3 ... 0.5 % rms

> Slow charge feedback to compensate drifts



This example:
- Stability single bunch: 0.36 % rms
- Stability av. over train: 0.19 % rms

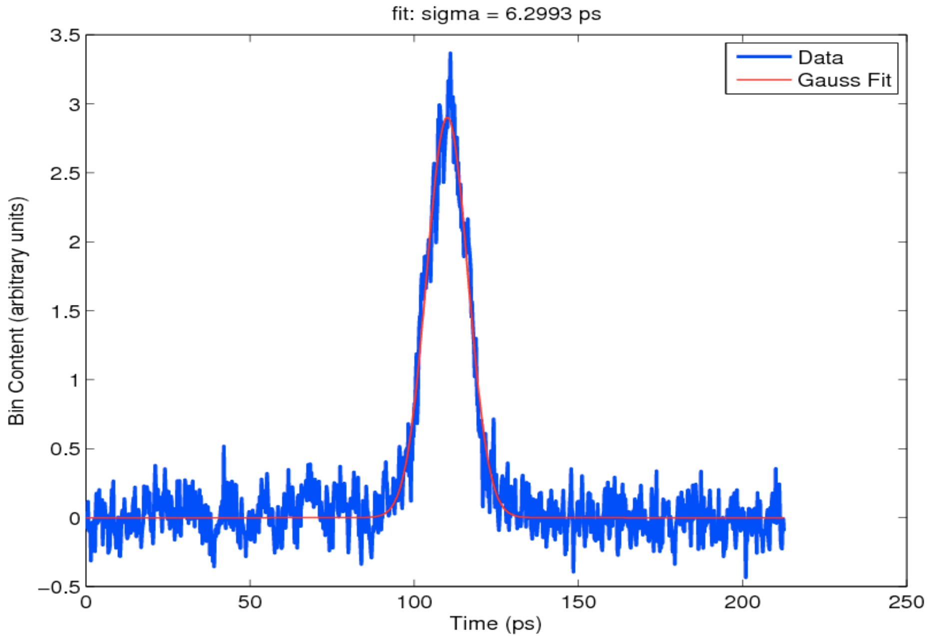
200 kHz pulse train with 125 bunches, 10 Hz

Laser Pulse Duration

> Only transverse shaping: overfilled hard edge aperture imaged on cathode

> no longitudinal shaping

> Gaussian shape, σ_L(from fit) = 6.3 +/- 0.1 ps (Laser 2, UV)

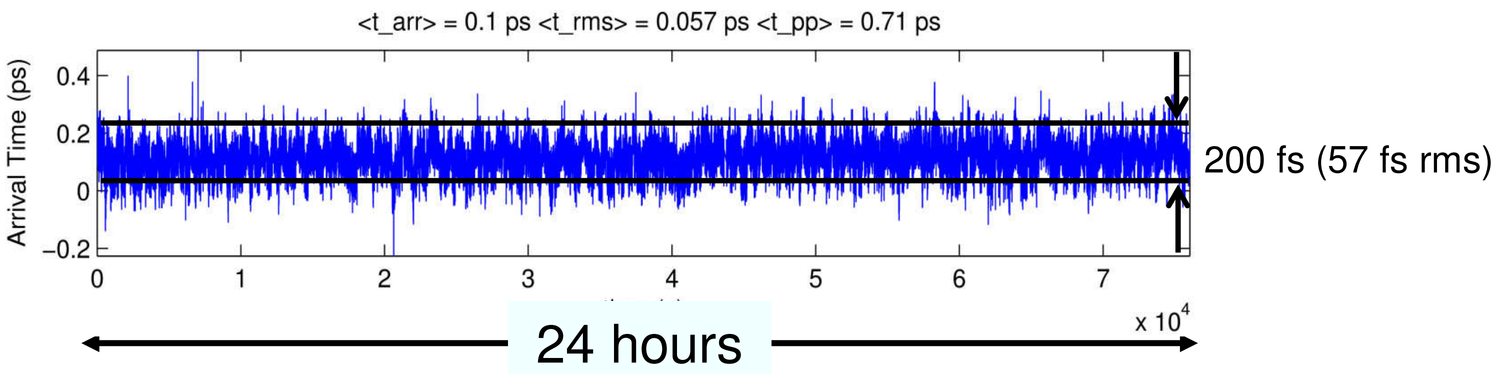


UV Laser Pulse duration (FESCA 200)

Arrival Time Stability and Synchronization

FLASH. Free-Electron Laser in Hamburg

- Phase stability is achieved with a 1.3 GHz EOM (active mode-locking)
- Long term mode-lock stabilization with slow feedback (Piezo acting on oscillator length, mainly against air pressure)
- Optical X-correlation against ultra-stable fiber laser of the FLASH synchronization system
  - Measured arrival time jitter 60 - 80 fs rms
  - Slow feedback acting on 1.3 GHz phase to compensate drifts



Reliability Laser System

FLASH. Free-Electron Laser in Hamburg

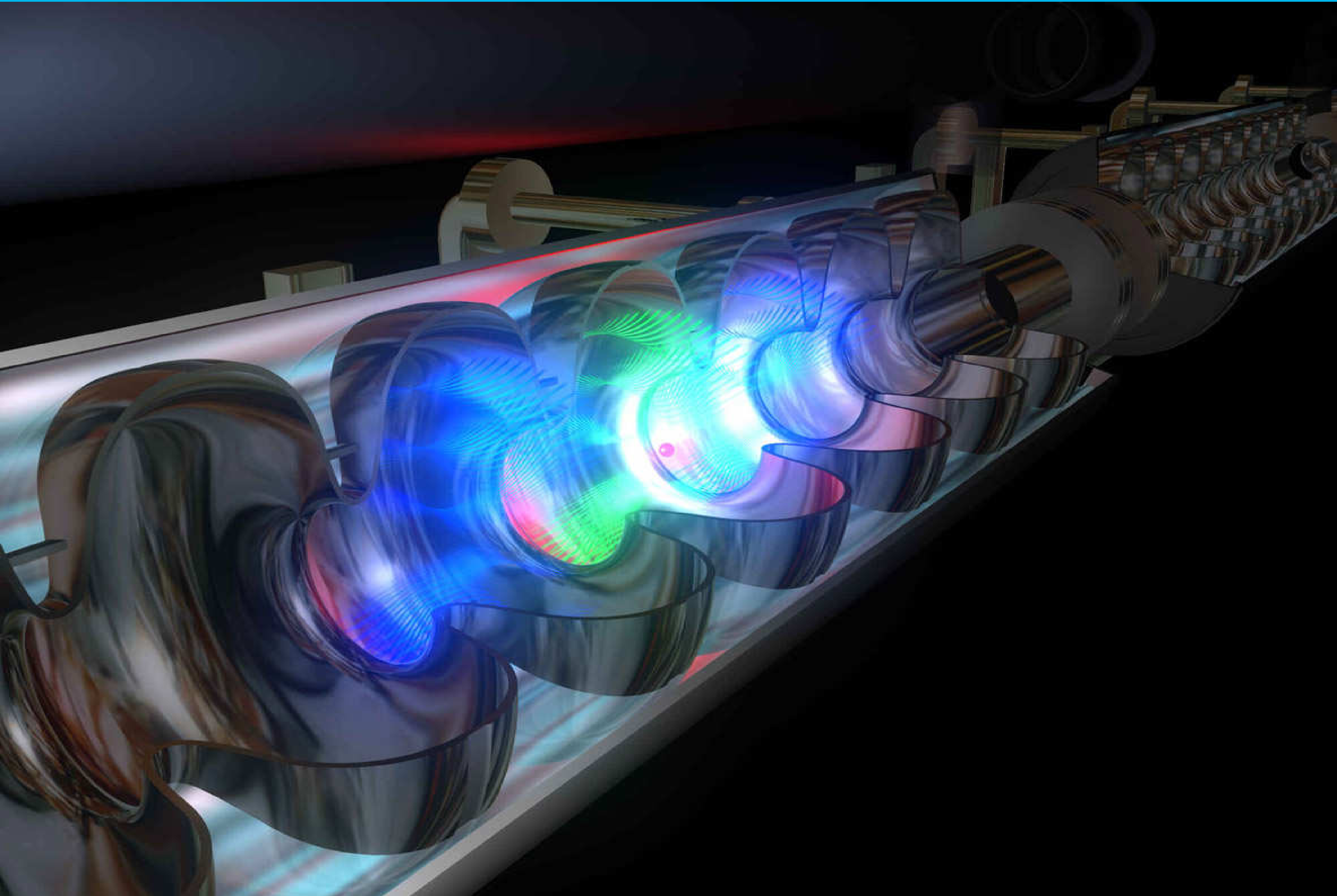
- Pump diode lasers are in continuous operation since their installation ~40,000 h up to now (1 ms, 10 Hz)
- Pump diodes of oscillator are in continuous operation for more than 50,000 hours (4.5 ms, 10 Hz)
- No failures of pump diodes up to now
- The whole laser system is remarkably robust and needs only little maintenance
- Total downtime of FLASH contributed to the laser system: 0.2 %

  Laser: 0.09 %, Beamline: 0.09%, Controls: 0.03%

Super-conducting Acceleration

FLASH uses TESLA technology

FLASH.
Free-Electron Laser
in Hamburg



FLASH uses TESLA technology

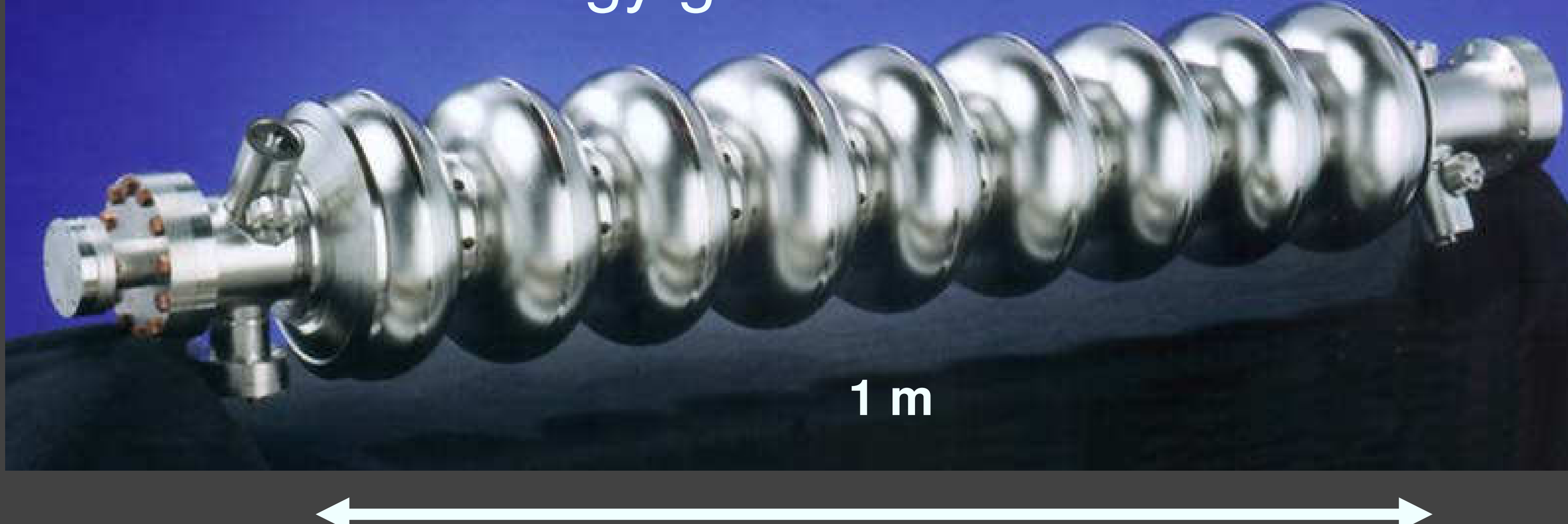
FLASH. Free-Electron Laser in Hamburg

Pure Niobium superconducting cavities
9-cells, 1.3 GHz

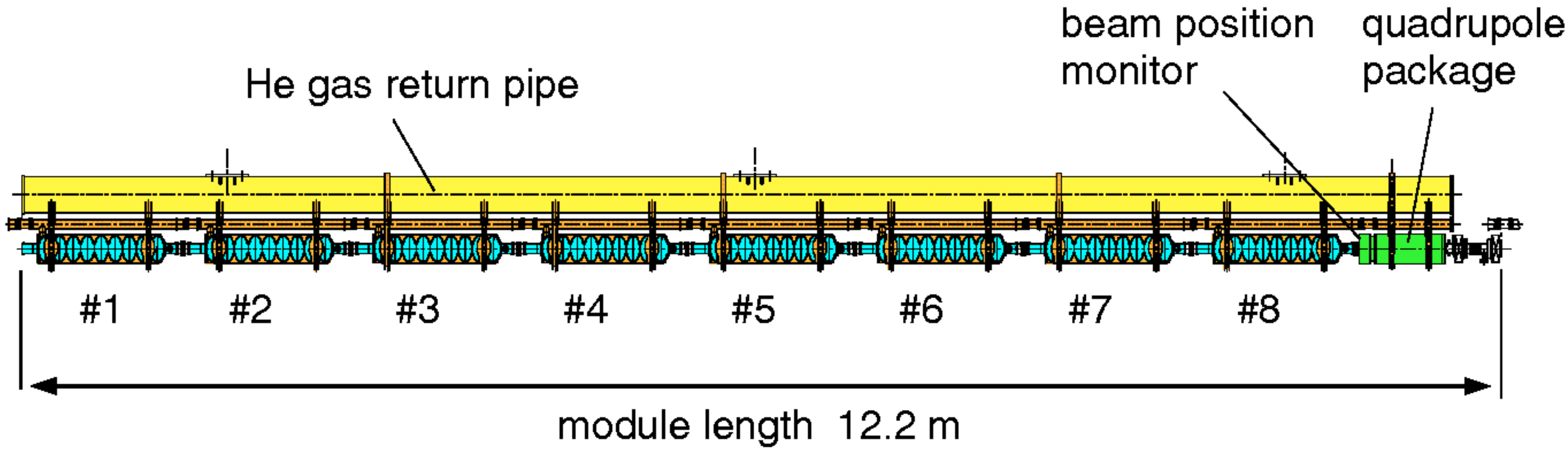
Burst mode: acceleration for 800 μs at 10 Hz

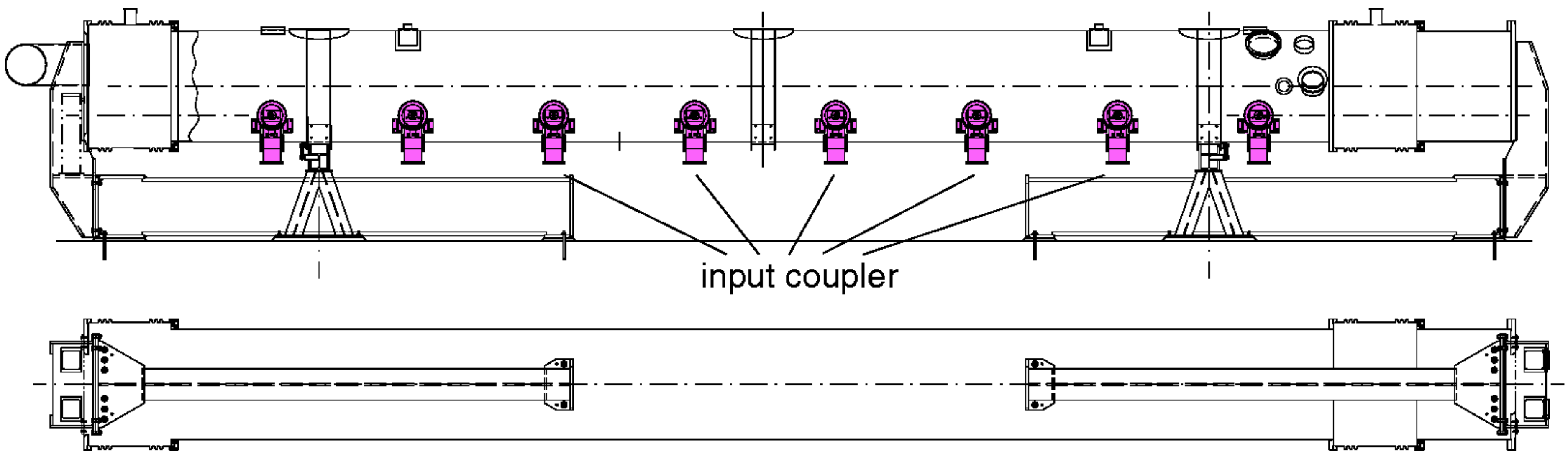
Efficient acceleration due to high Q ~ 10^{10}

Energy gain ~25 MV/m



FLASH uses TESLA technology





FLASH tunnel with superconducting modules

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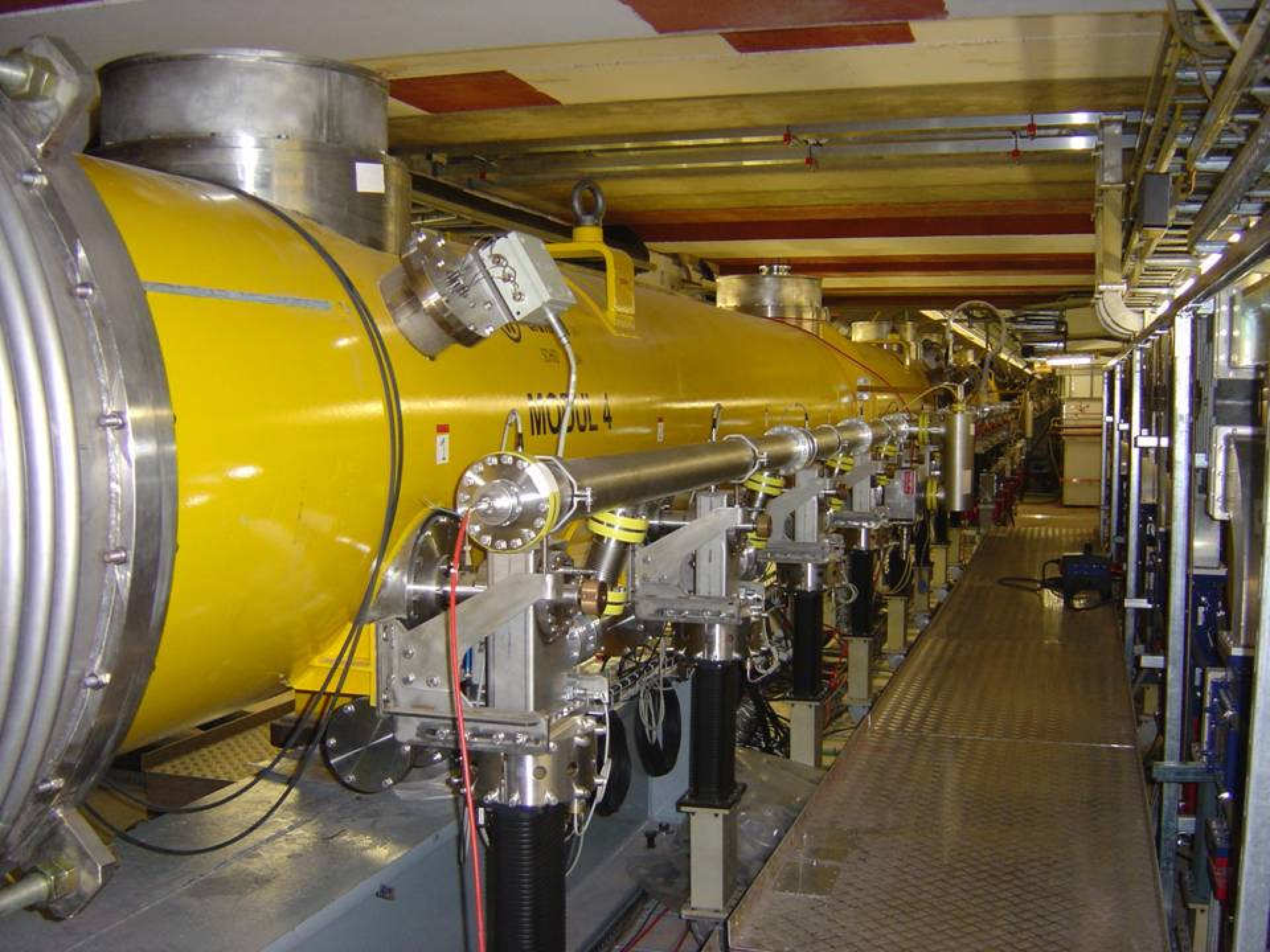
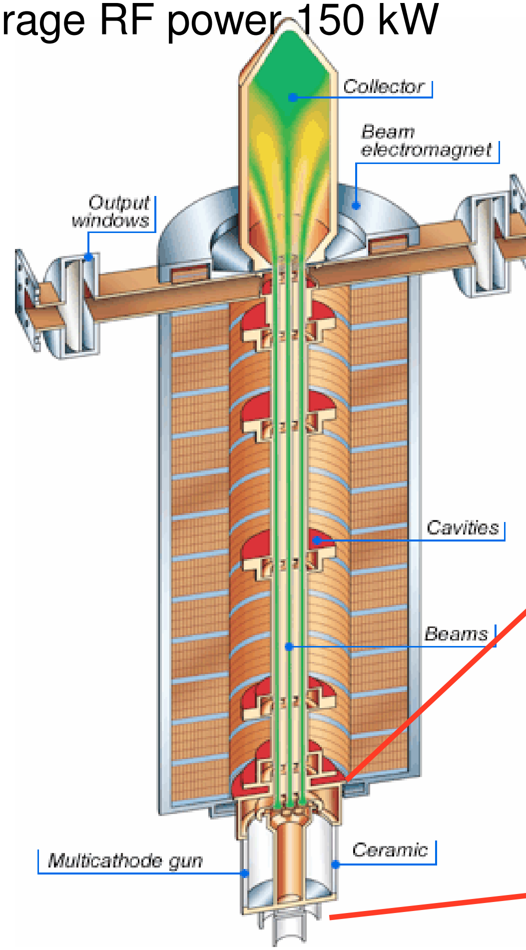

MODUL 4

Klystrons

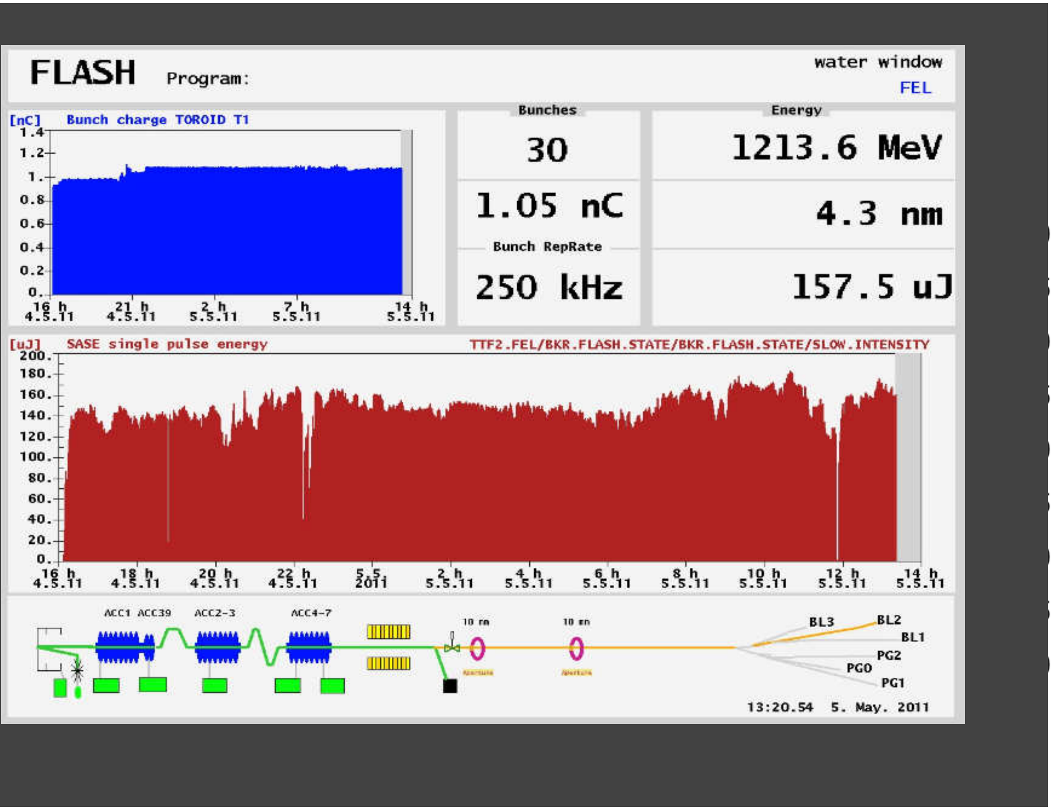
> Thales 5 MW and 10 MW multi-beam klystron (TH1801)

- Driven by 117 kV rectangular RF pulses (1.5 ms duration) at 10 Hz
- Gain 48.2 dB, efficiency 65 %, average RF power 150 kW

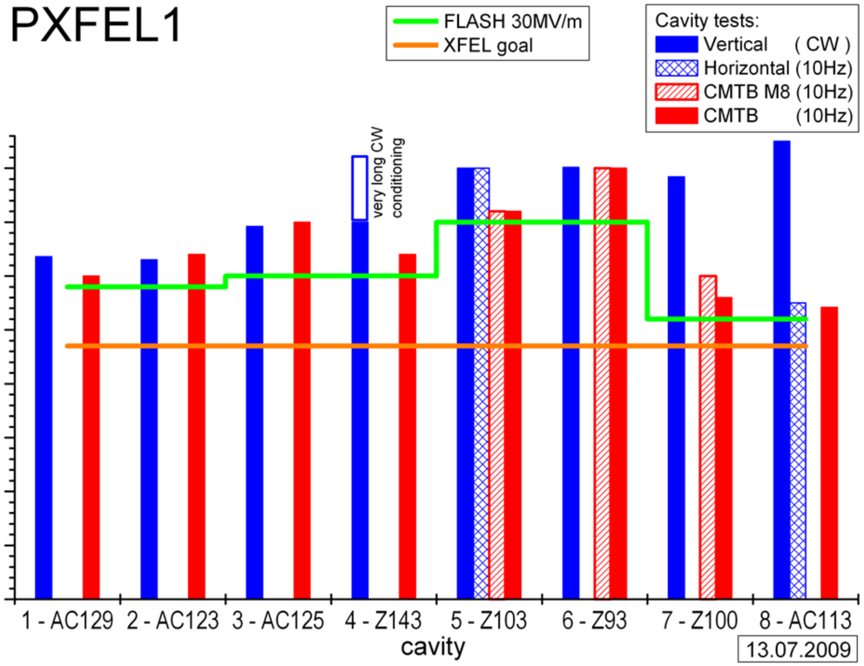


FLASH Energy Reach

- 7 TESLA type accelerating modules installed plus one 3rd harmonic module
- Electron beam energy of 1.25 GeV possible → water window
- 7 RF stations (four 5 MW, two 10 MW Thales klystrons, one 3.9 GHz)



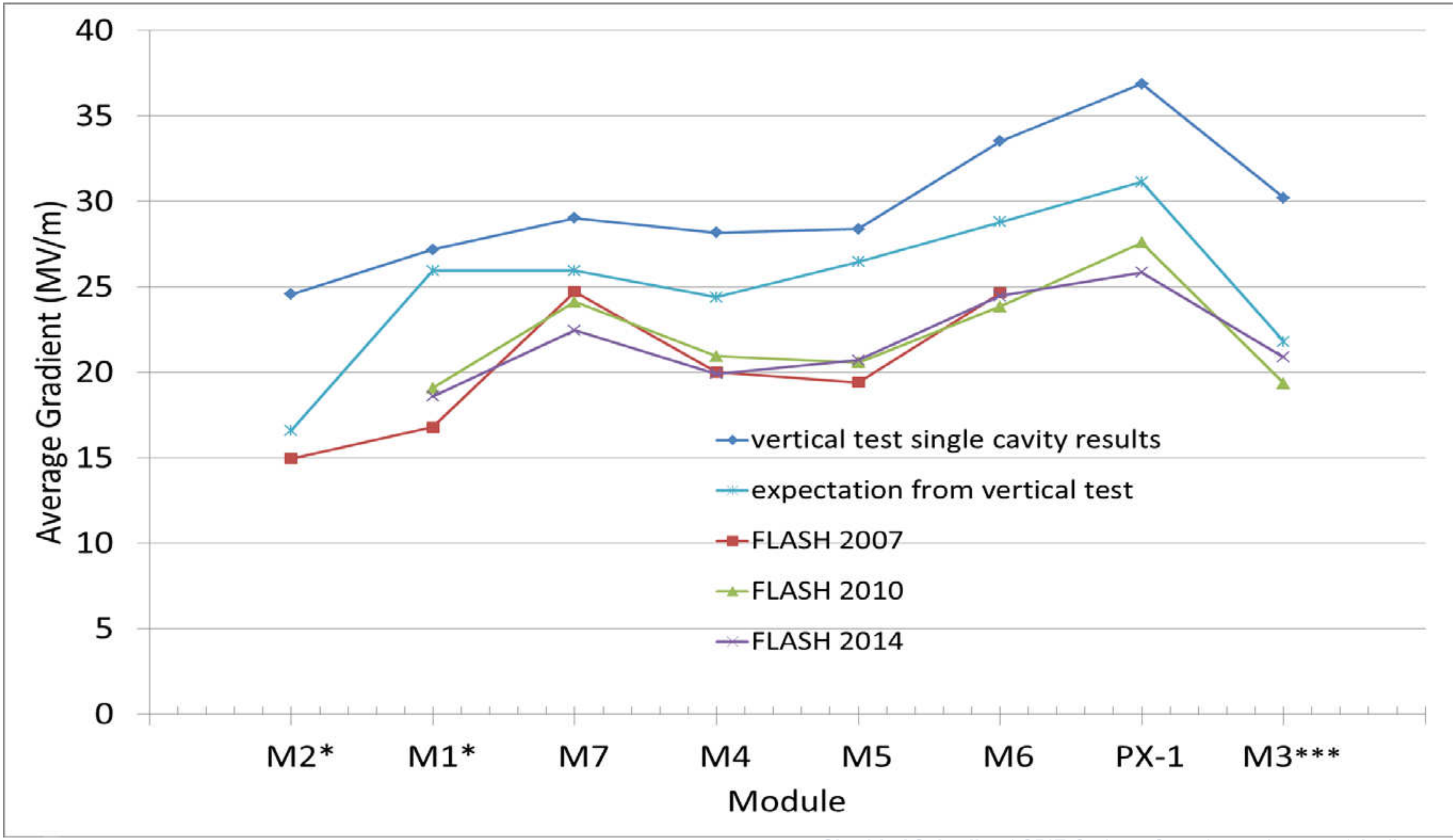
Module 7 is the 1st XFEL-prototype with excellent performance



Average Module Gradients

FLASH.
Free-Electron Laser in Hamburg

> Performance of cavities at FLASH in average 84% of the expectation from vertical test results – no degradation since installation observed



Cryogenics

Cryogenics

FLASH. Free-Electron Laser in Hamburg

> Cryogenic supply absolutely reliable
  - large cryo overhead: ~1 kW available
  - usually, only about half the capacity is used

> Downtime due to cryogenics issues ~0.2%

> Since 2002, FLASH has seen 6 cool-downs and 5 warm-ups

> Average cool-down/warm-up time: ~10 days each

Module	Location	in	out	cool downs	warm ups	
1*	ACC2	2002		6	5	
2*	ACC1	2004	2009	2	2	
3*	ACC3	2004	2007	1	1	
3***	ACC1	2009		3	2	
4	ACC4	2004		5	4	
5	ACC5	2004		6	5	CMTB Test
6	ACC6	2007		5	4	CMTB Test
7	ACC3	2007		5	4	CMTB Test
PXFEL1	ACC7	2009		4	3	CMTB Test
39	ACC39	2009		3	3	CMTB Test

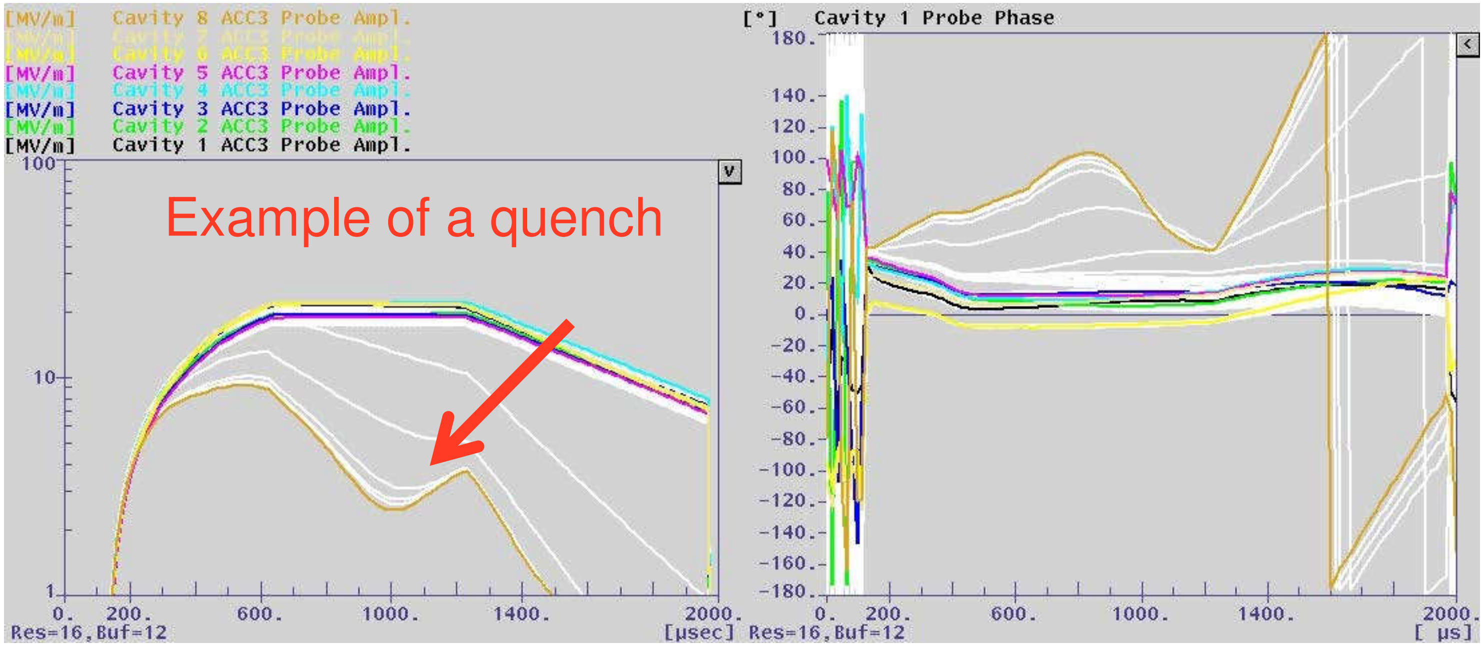
Cavity Quenches

> Cavities do not trip, but may quench (LLRF control issues)

> Cavity quenches do not necessarily lead to downtime but to instabilities

> He-pressure changes are measured with a large latency and are usually observed too late to prevent instabilities

→ Software quench detection

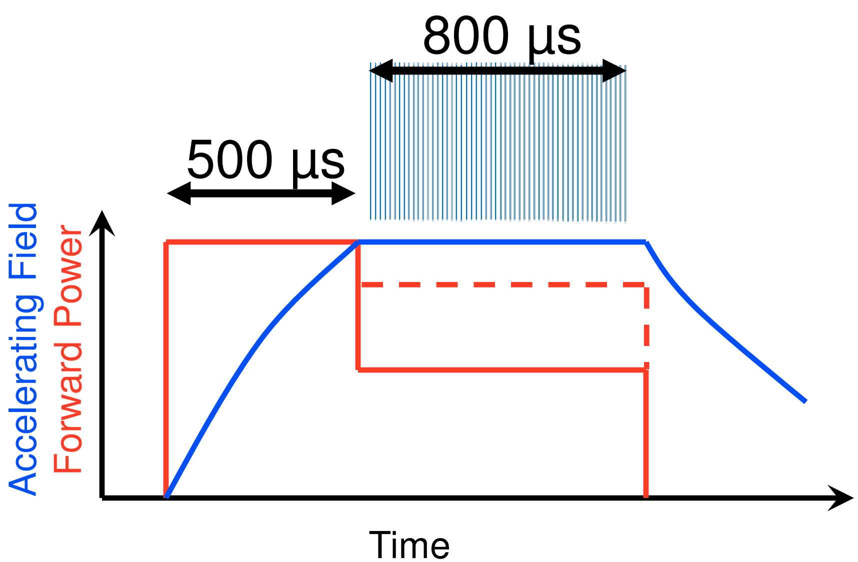


Low Level RF

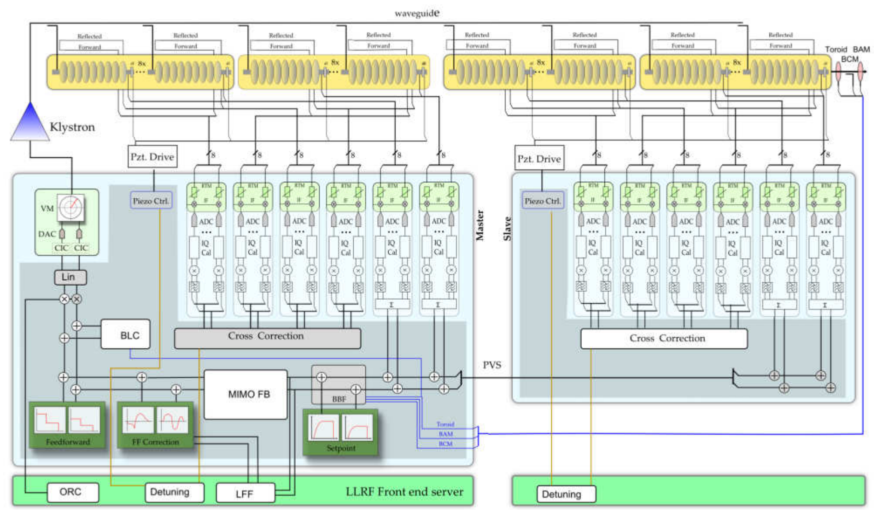
Low Level RF System (MTCA.4 since Aug-2013)

FLASH. Free-Electron Laser in Hamburg

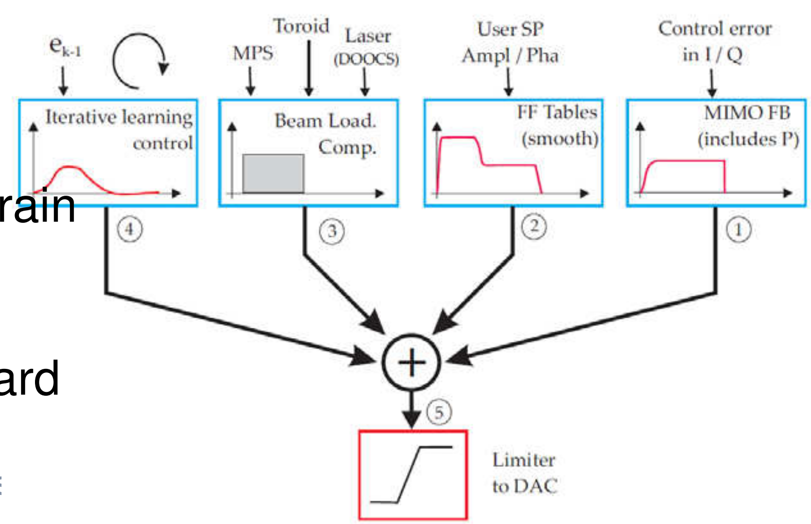
> Take advantage of superconducting accelerating technology
  - Burst mode – long bunch trains @ 10 Hz



LLRF RF controller schematics



Feed forward table architecture



> Feedback to keep gradient flat along pulse train

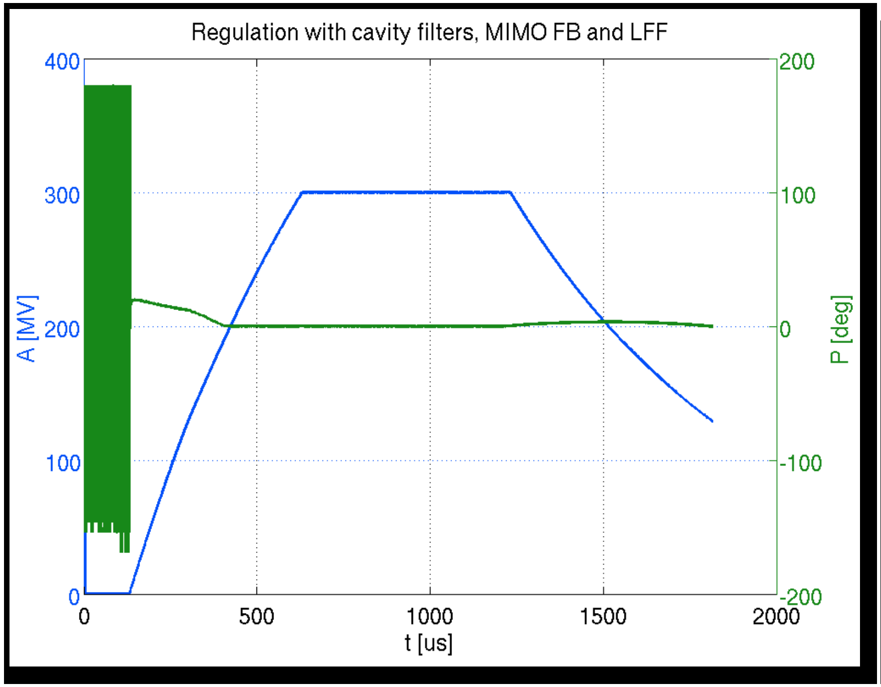
> Beam loading compensation

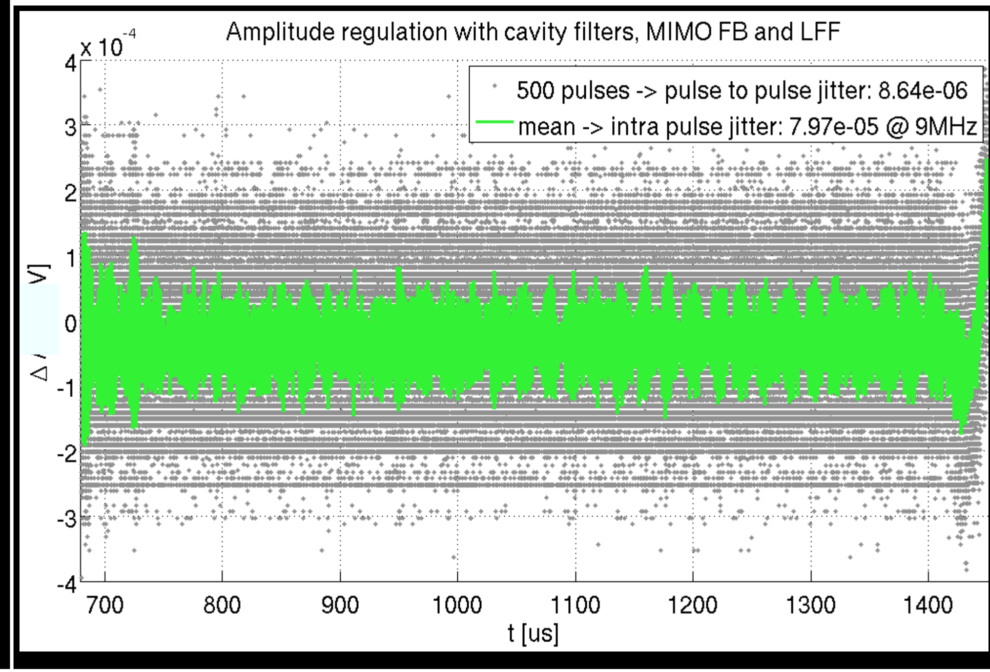
> Beam based corrections, learning feed forward

> Exception handling

RF Stability measurements (in-loop regulation)

FLASH. Free-Electron Laser in Hamburg





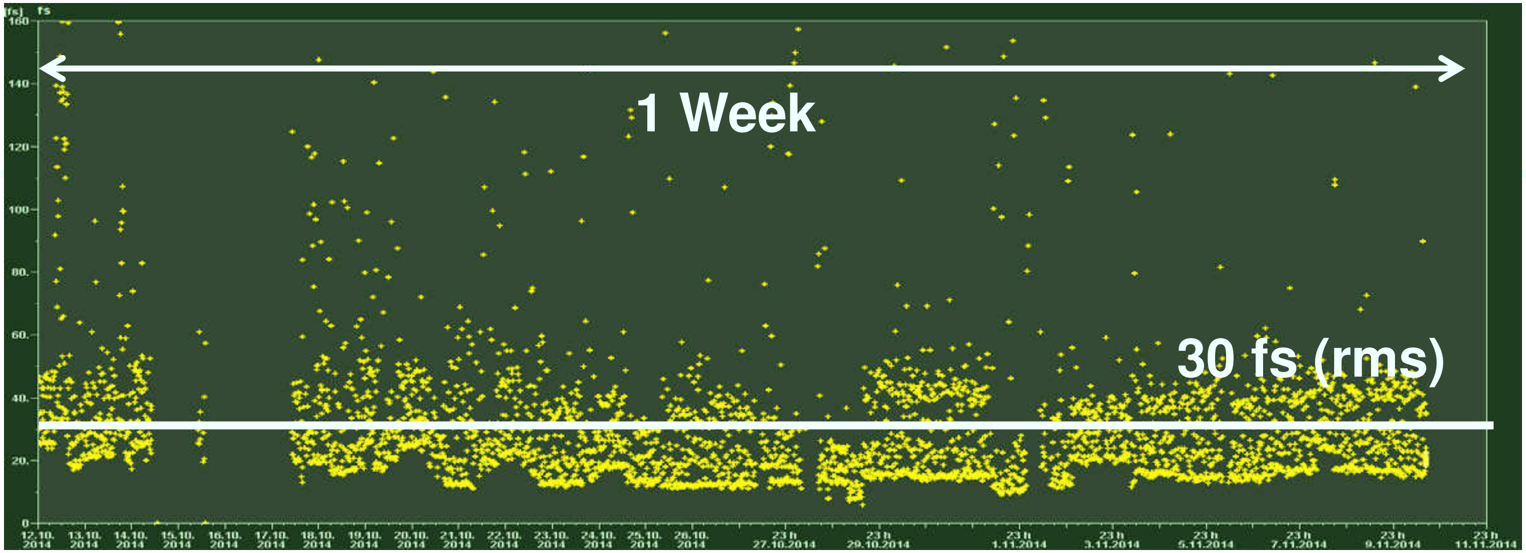
Stability (rms) @ 9 MHz	ACC1	ACC39	ACC23	ACC45	ACC67
Ampl. intra pulse **(10^{-4})**	**0.7**	2.7	0.5	0.8	0.7
Ampl. pulse to pulse **(10^{-4})**	**0.2**	0.5	0.1	0.09	0.2
Phase intra pulse (dg)	**0.01**	0.02	0.007	0.01	0.009
Phase pulse to pulse (dg)	**0.003**	0.01	0.002	0.002	0.003

Goal achieved: < 0.01% in amplitude and < 0.01 dg in phase

Arrival time jitter

FLASH.
Free-Electron Laser in Hamburg

- Dominated by RF amplitude jitter 1st module before 1st compressor (R56=0.18 m)
- With the new MCTA.4 based system improved from 70 fs to <40 fs rms
- Remaining long term drifts in RF amplitude and phase mainly due to humidity changes in MTCA crates:
- active compensation (DCM) is being tested in one module now

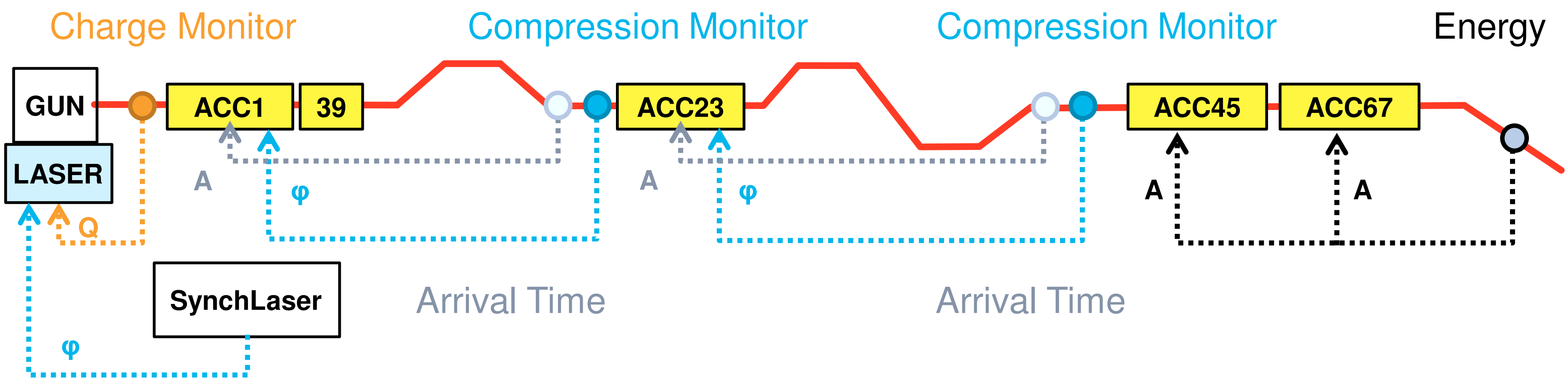


Slow Feedbacks

Slow Feedbacks

FLASH. Free-Electron Laser in Hamburg

> Slow "longitudinal" feedbacks to compensate drifts are essential for a stable running



Charge FB

Monitor: Toroid

Actuator: attenuator laser beamline (half wave plate)

Laser Arrival time FB

Monitor: Optical Cross-Correlator to Synchronization Laser

Actuator: RF phase laser oscillator

Compression FB's

Monitor: diffraction radiation with pyro-electric detectors

Actuator: RF phase of nearby module

Beam arrival FBs

Monitor: beam arrival time monitor X-correlated to Synchronization Laser

Actuator: RF amplitude of nearby modull

Energy FB

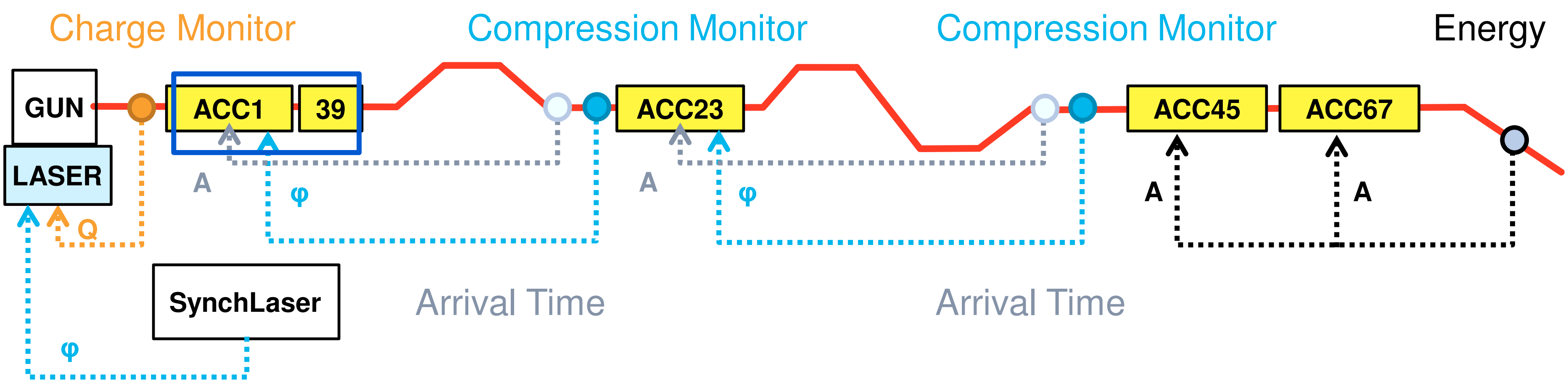
Monitor: Orbit around dispersive section + dipole current

Actuator: RF amplitude of last modules

Slow Feedbacks on “physical quantities”

FLASH. Free-Electron Laser in Hamburg

- Advanced mode: regulate on physical quantities
- Include compression properties like pulse length and chirp
- Feedback on a combination of ACC1 and ACC39 (third harmonic linearizer module)



Compression FB
Actuator: Chirp in E-phi space

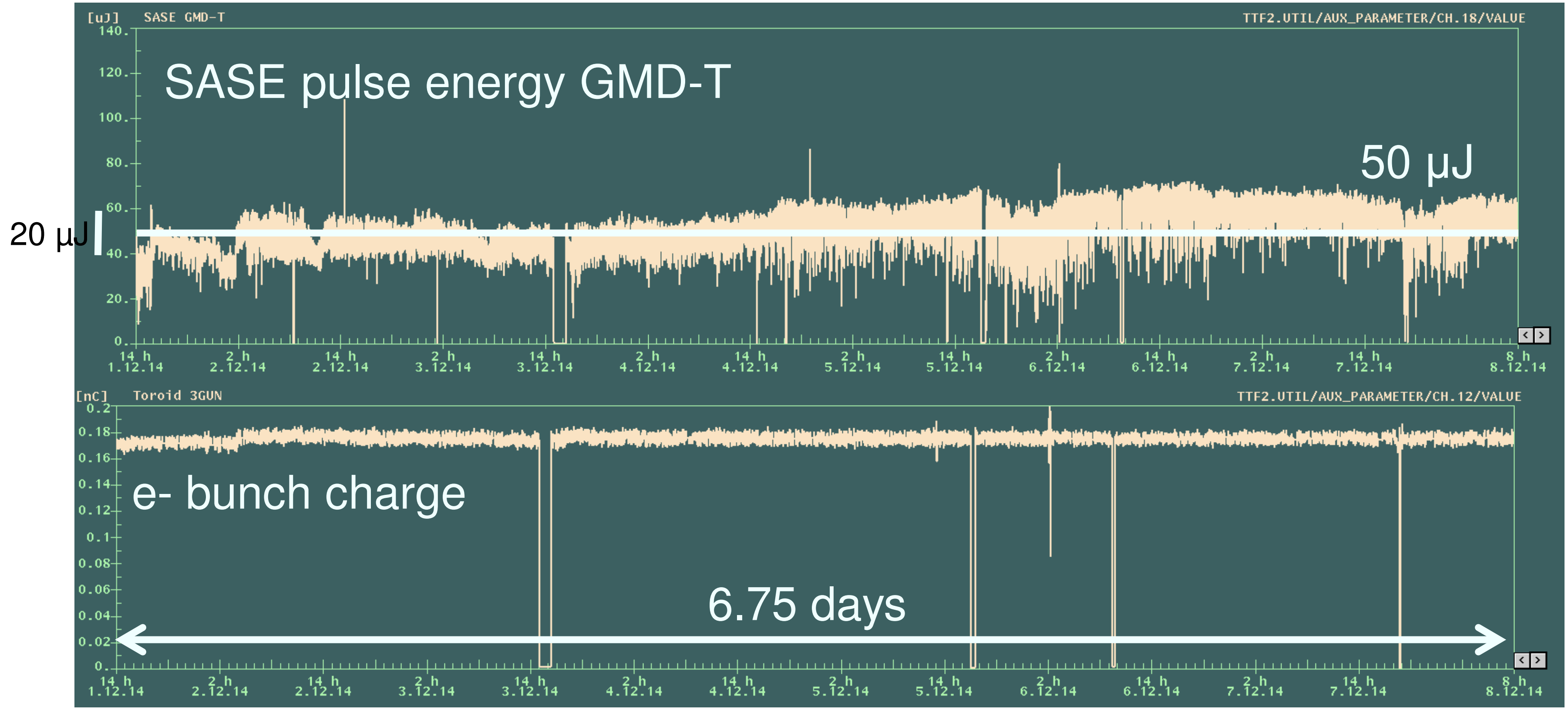
Beam arrival FBs
Actuator: Sum voltage ACC1 and ACC39

Example SASE for 1 experiment in 1 week

FLASH. Free-Electron Laser in Hamburg

> SASE Delivery: 96%, tuning 2%, down: 2%

> 11.5 nm, 1 bunch, 0.18 nC, apertures 3 mm



> Simultaneous operation of FLASH2 for commissioning

Summary

> FLASH is a user facility since 2005

> Growing demand of user experiments lead to constant upgrades of the facility

> With a beam energy of 1.25 GeV, FLASH reaches the water window with its fundamental 4.1 nm

> Stable operation of accelerating modules
  - Low level RF: excellent stability, upgraded to MTCA.4
  - Cryogenics: perfect!

> No degradation of superconducting cavities during operation at FLASH

> RF Gun: issue with limited life time of the gun and the RF window

> Cathode, laser systems: satisfactory

> Slow feedbacks essential to compensate drifts for stable user operation

> FLASH2 simultaneous operation → talk by K. Honkavaara