

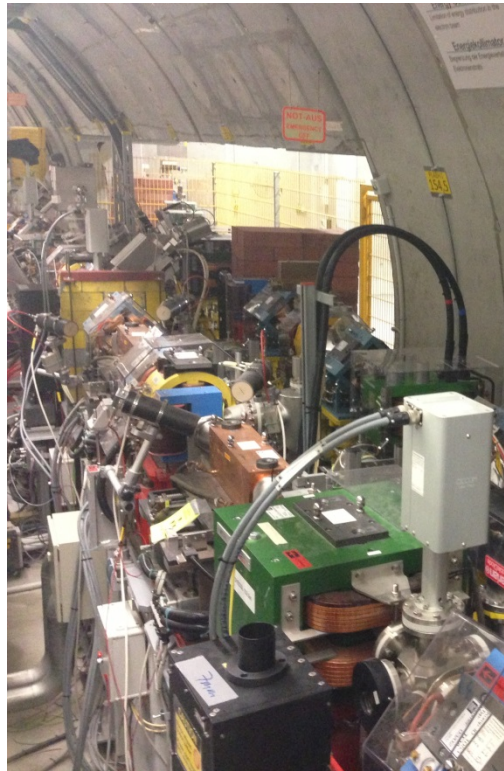
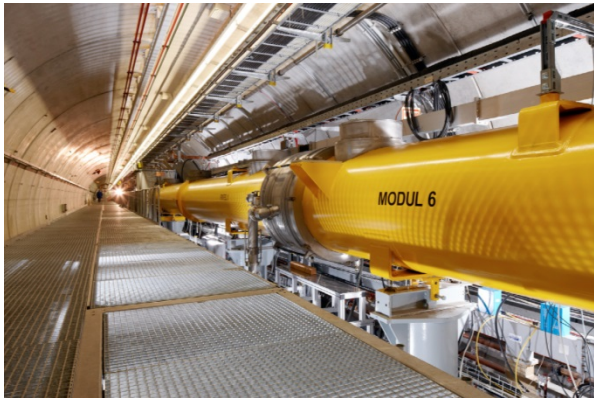
Operation of FLASH

FLASH.
Free-Electron Laser
in Hamburg

FLASH – Free-Electron Laser User Facility at DESY

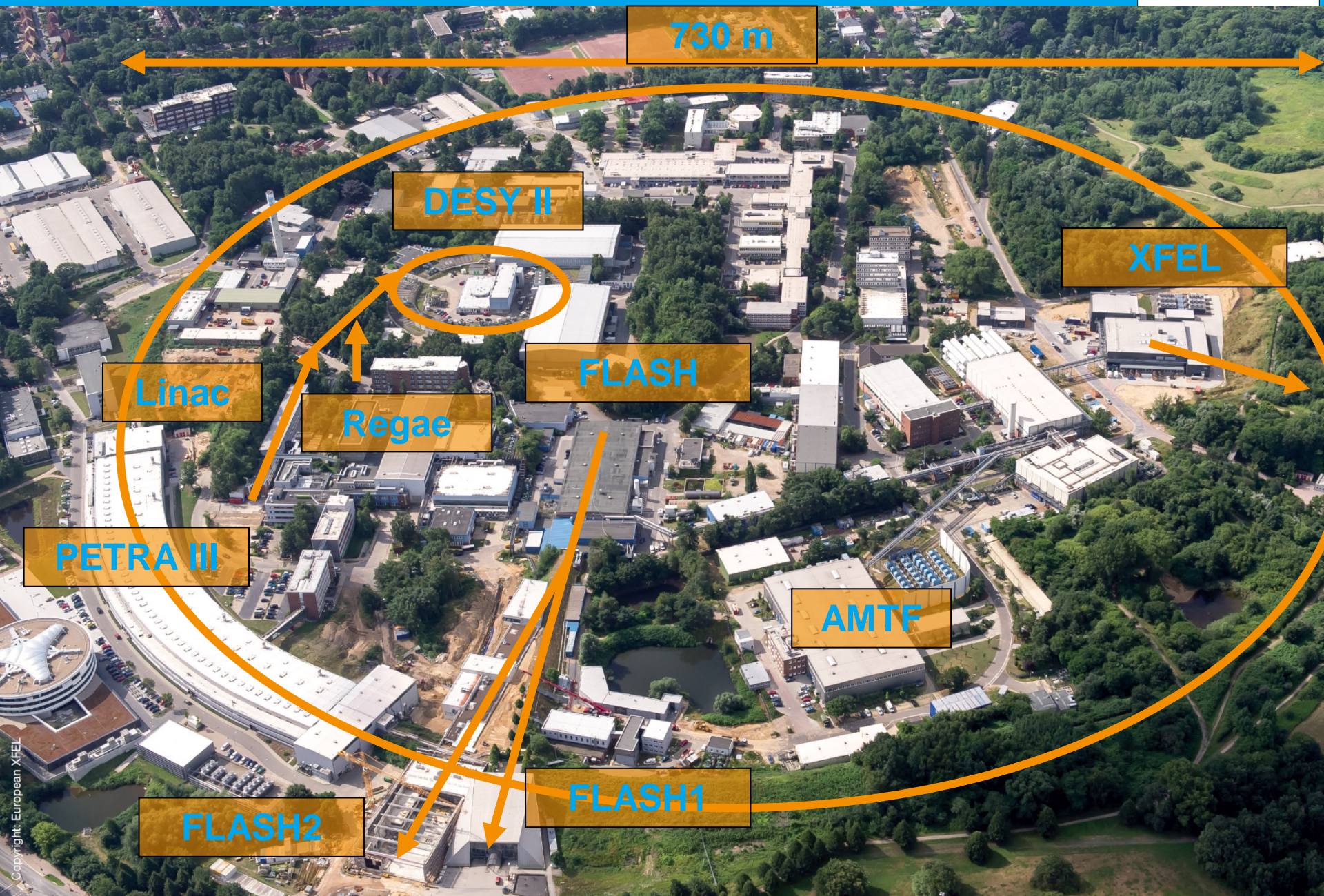
Siegfried Schreiber, DESY
for the FLASH team

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



DESY accelerators in operation

FLASH.
Free-Electron Laser
in Hamburg



FLASH Layout

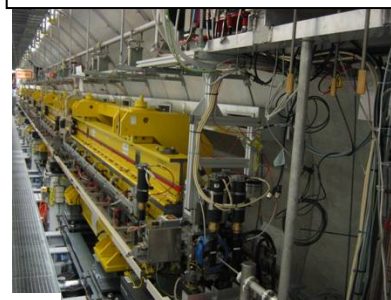
> 3rd harmonic sc module 3.9 GHz



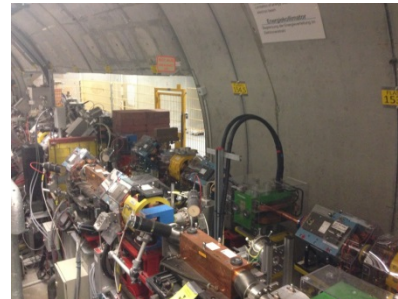
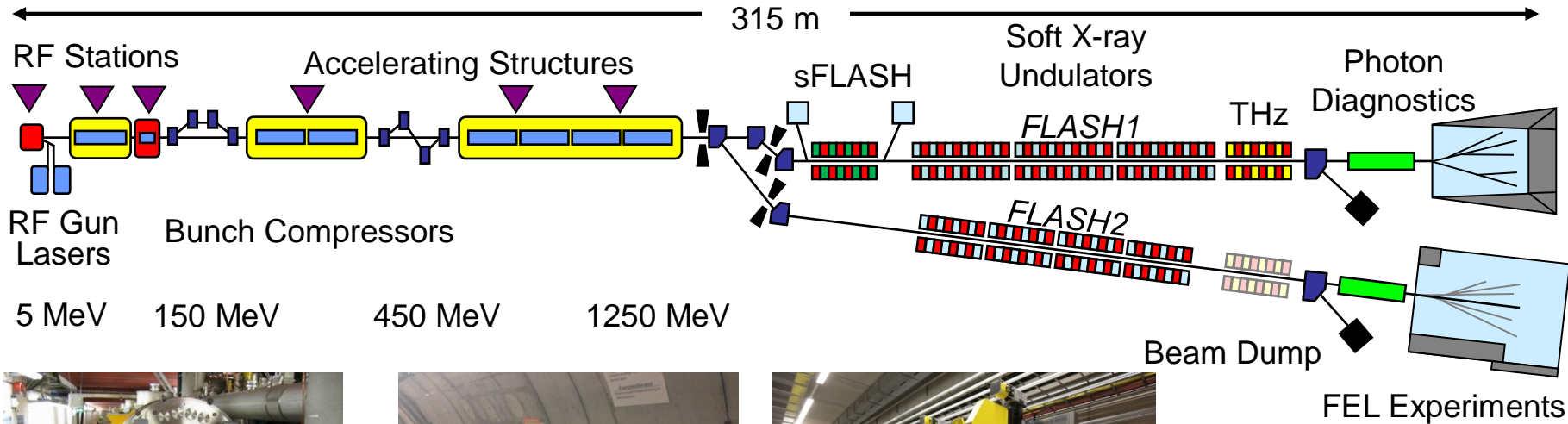
> TESLA type superconducting accelerating modules 1.3 GHz



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



> FLASH1 Experimental Hall



> Normal conducting 1.3 GHz RF gun
> Ce₂Te cathode
> Two Nd:YLF based ps photocathode lasers

> Extraction to FLASH2

> Variable gap undulator
> Total magnetic length ~ 30 m

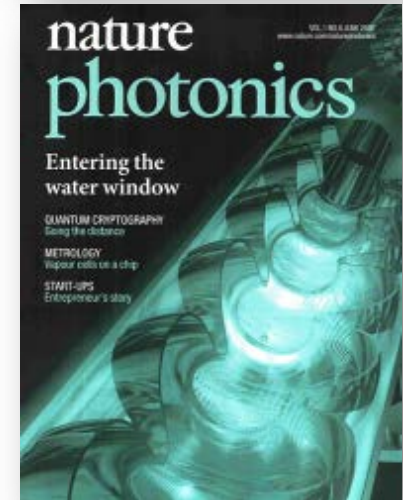
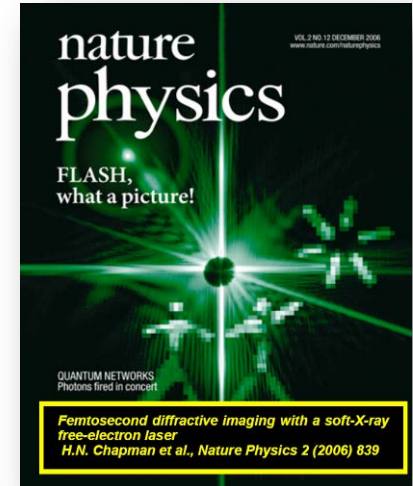
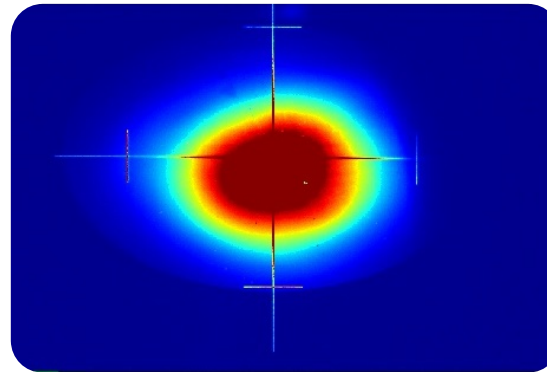
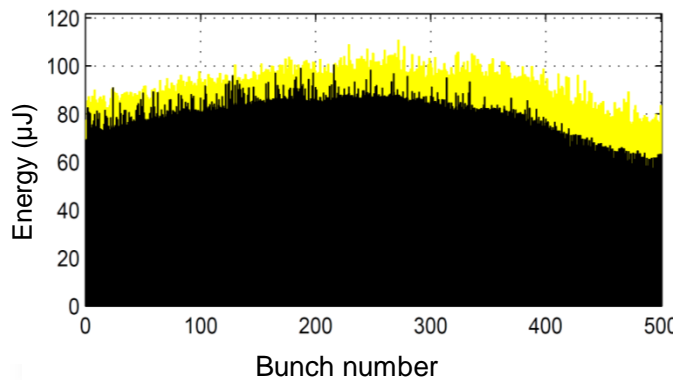
> FLASH2 Experimental Hall

User operation



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	$10^{17} - 10^{21} \text{ B}^*$
Peak Brilliance	$10^{29} - 10^{31} \text{ B}^*$
* photons/s/mrad ² /mm ² /0.1%bw	

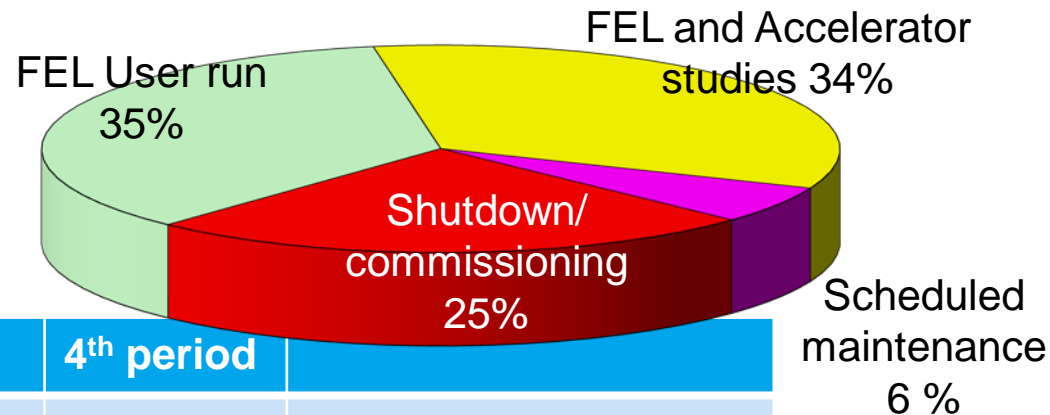


> more than 200 publications on photon science at FLASH,
many in high impact journals

> Scheduled beamtime June 2005 – 2014

> >7500 hours / yr in operation

> 4500 hours / year
scheduled for users

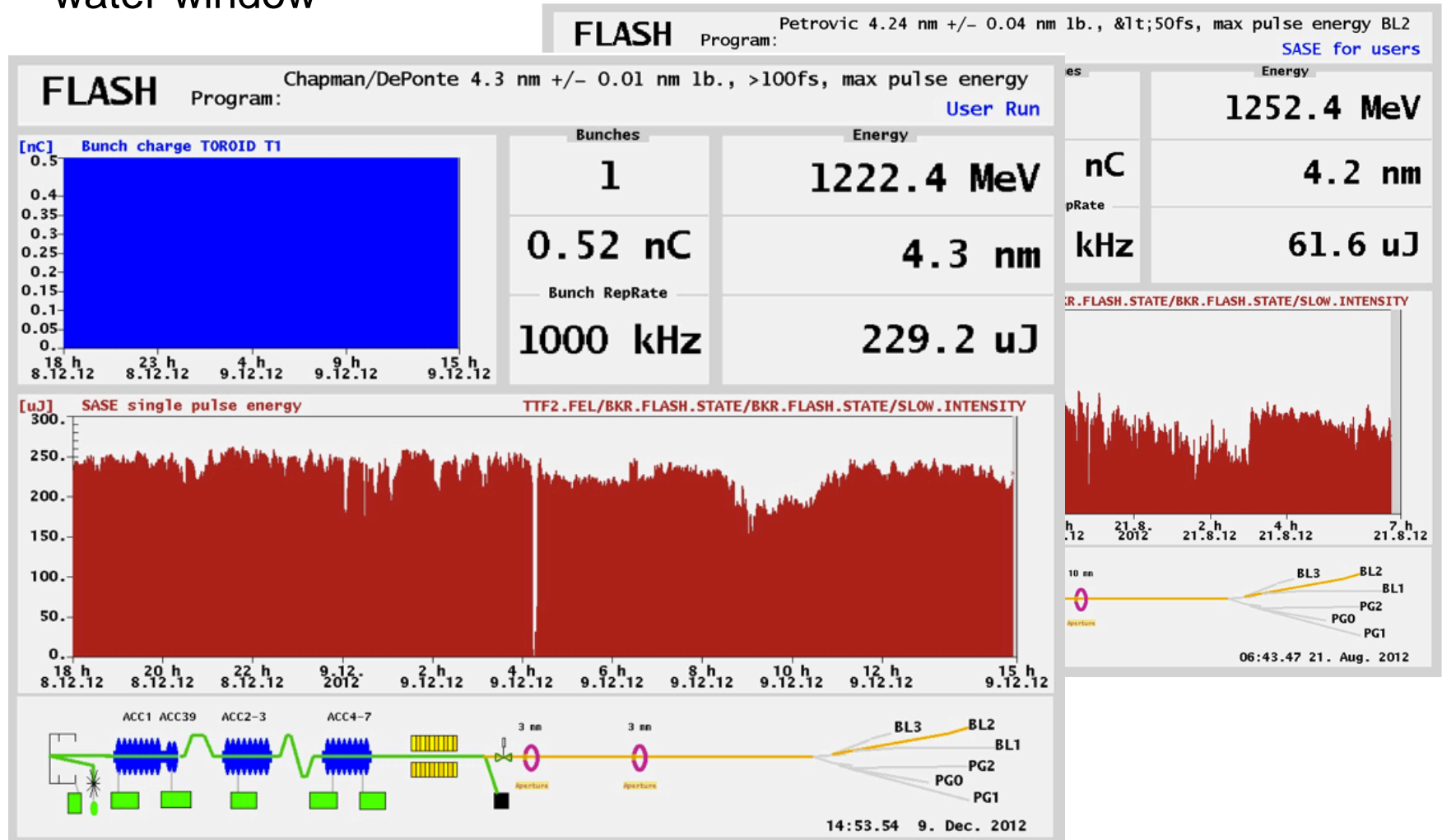


Requested Pulse Pattern		3 rd period	4 th period	
Single bunch		47%	47%	
Multi-bunch		53%	53%	35% >200 b.
Bunch spacing	1 MHz		30%	
	200 kHz		43%	
	other		27%	40, 100, 250, 500 kHz

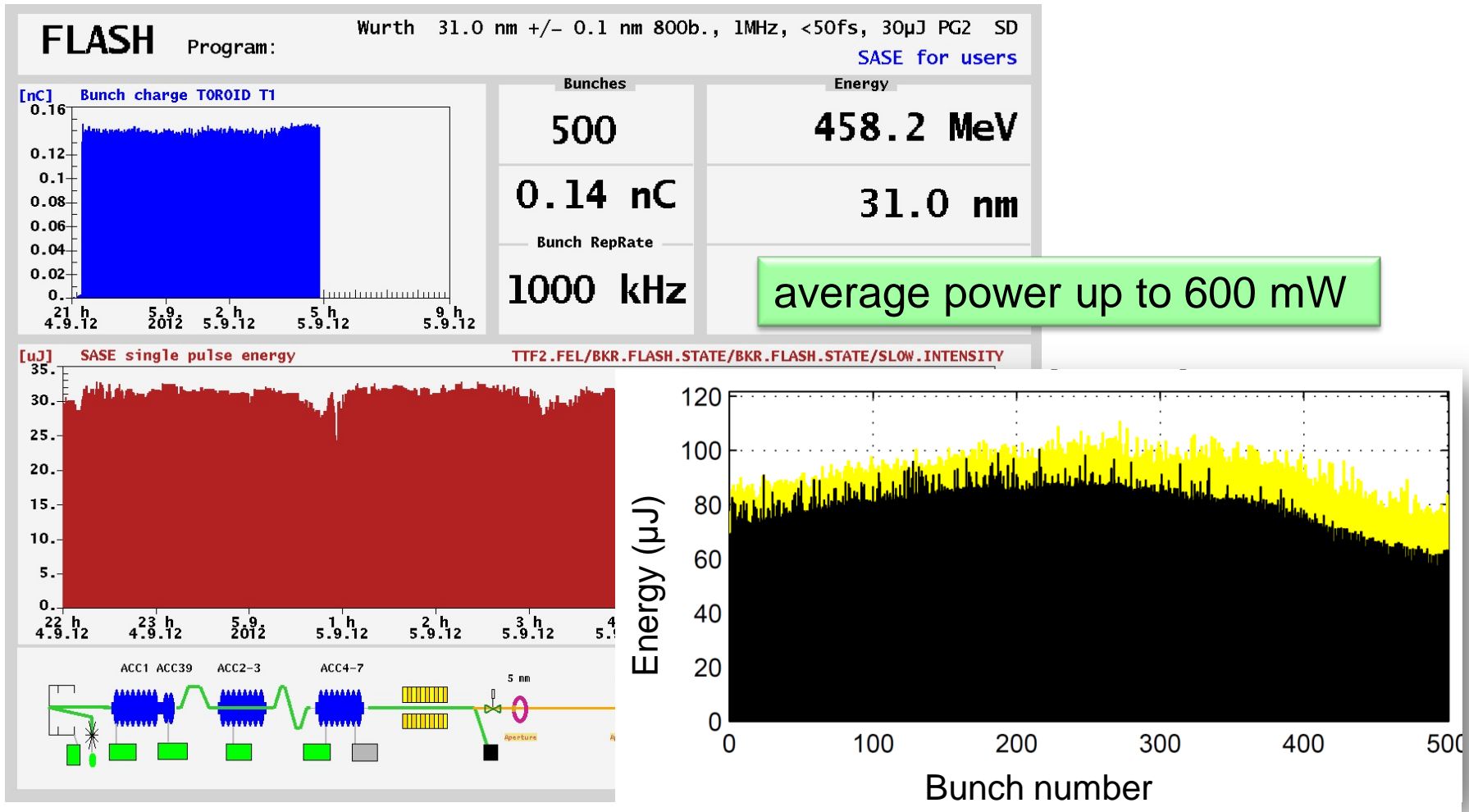
Requested FEL pulse duration				
< 50 fs fwhh		28%	42%	56% multi-bunch
50 -100 fs		54%	33%	64% single
not critical		18%	26%	83% max. energy

Water window experiments

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

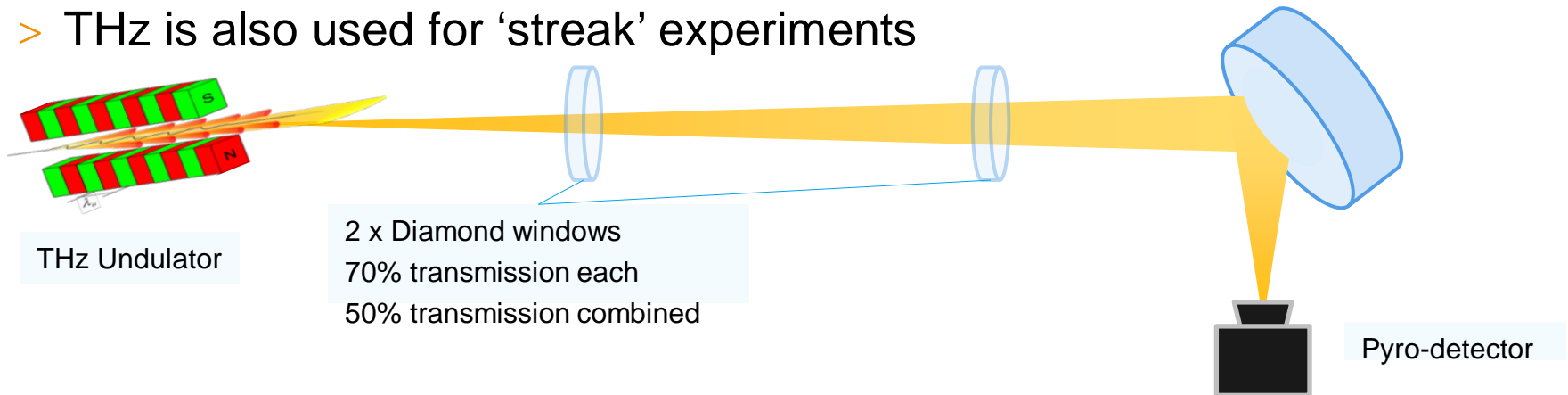


> 5000 SASE pulses/sec to experiments

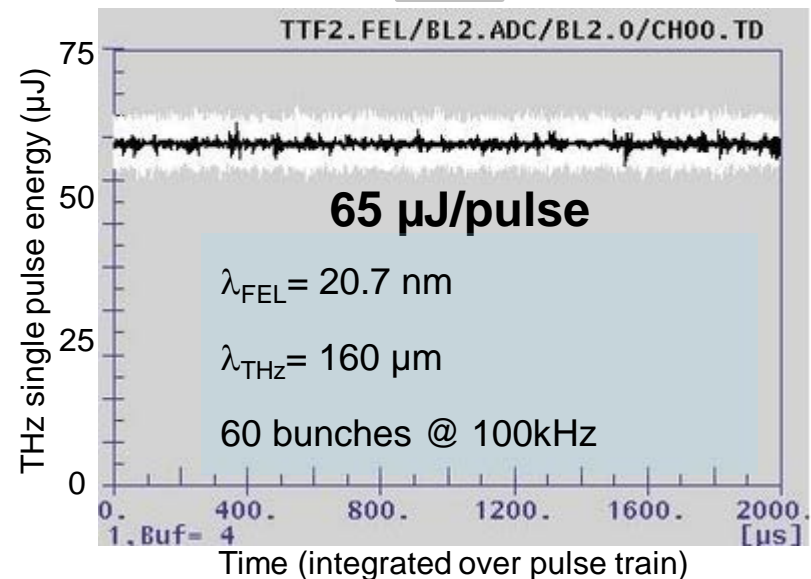


Experiments with THz radiation

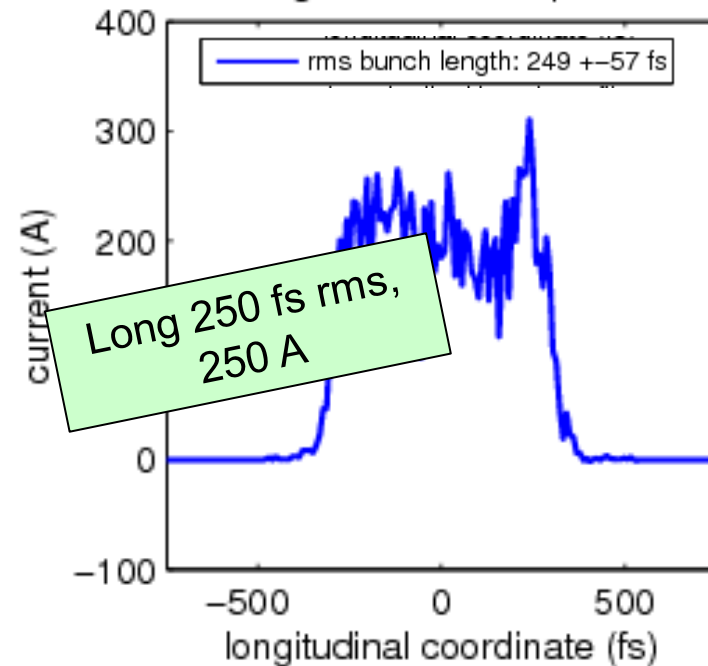
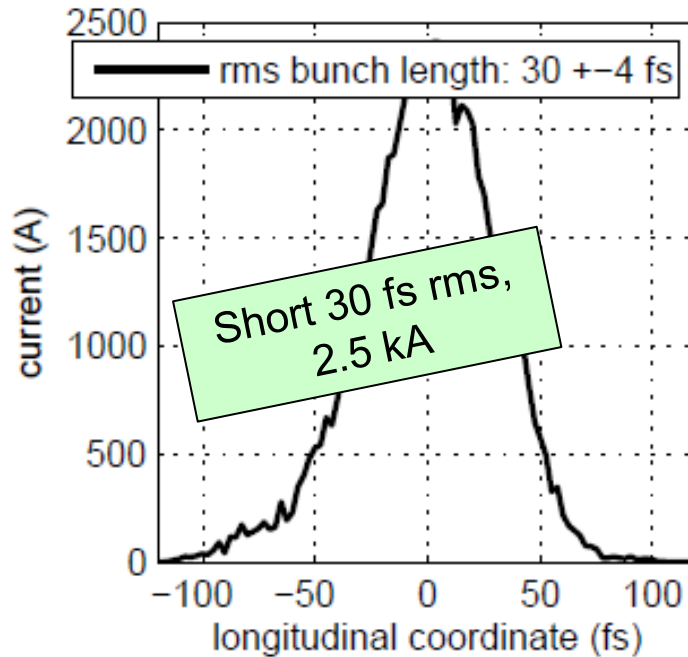
- > Several experiments use THz together with X-ray pulses and also optical laser for pump probe experiments
- > THz is also used for 'streak' experiments



- > 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



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

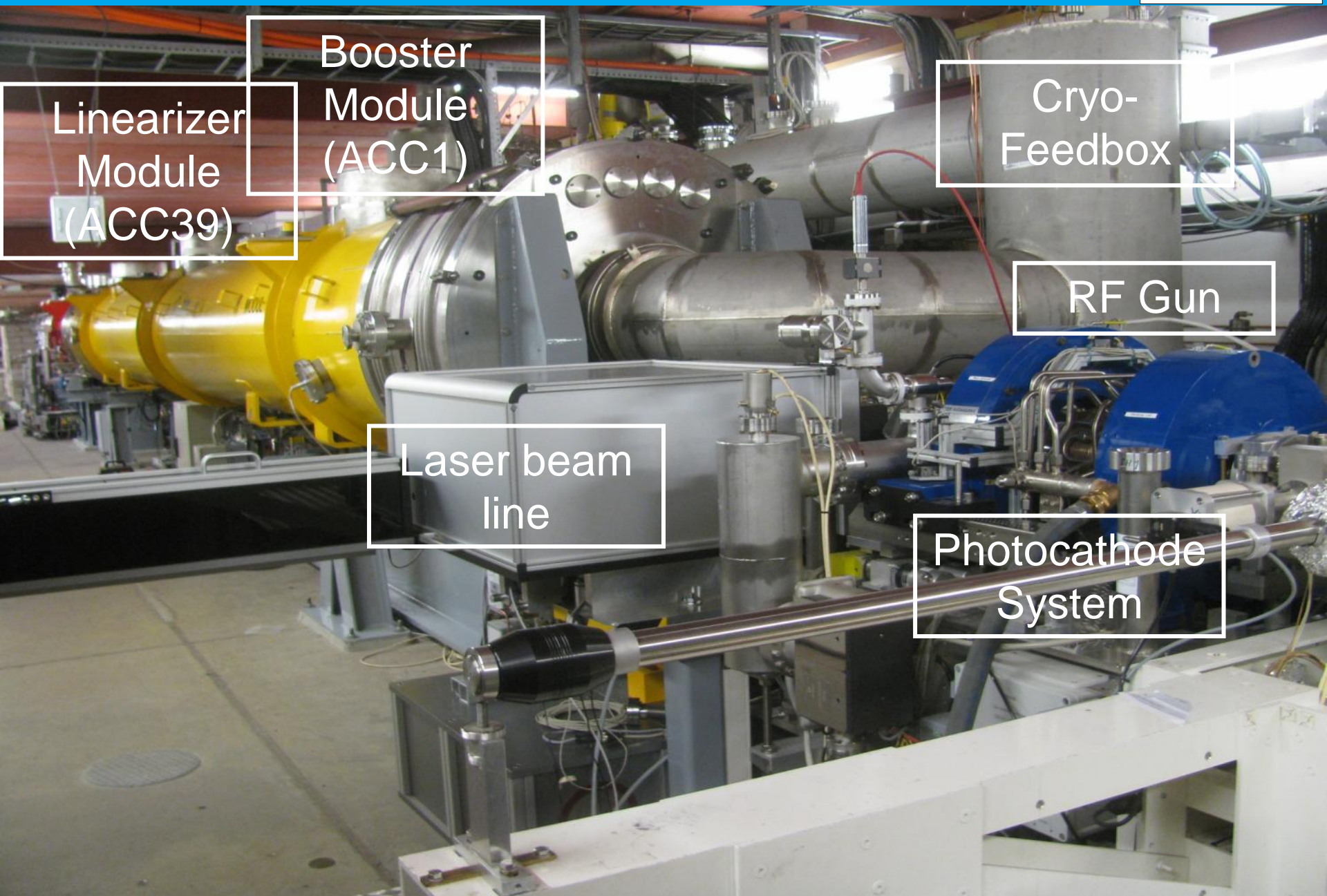


Electron Bunch length measured with our transverse deflecting cavity LOLA
(rms resolution $dt = 5...10$ fs, $dE/E = 1.4 \cdot 10^{-4}$)

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

RF Gun

Electron Source



Linearizer
Module
(ACC39)

Booster
Module
(ACC1)

Cryo-
Feedbox

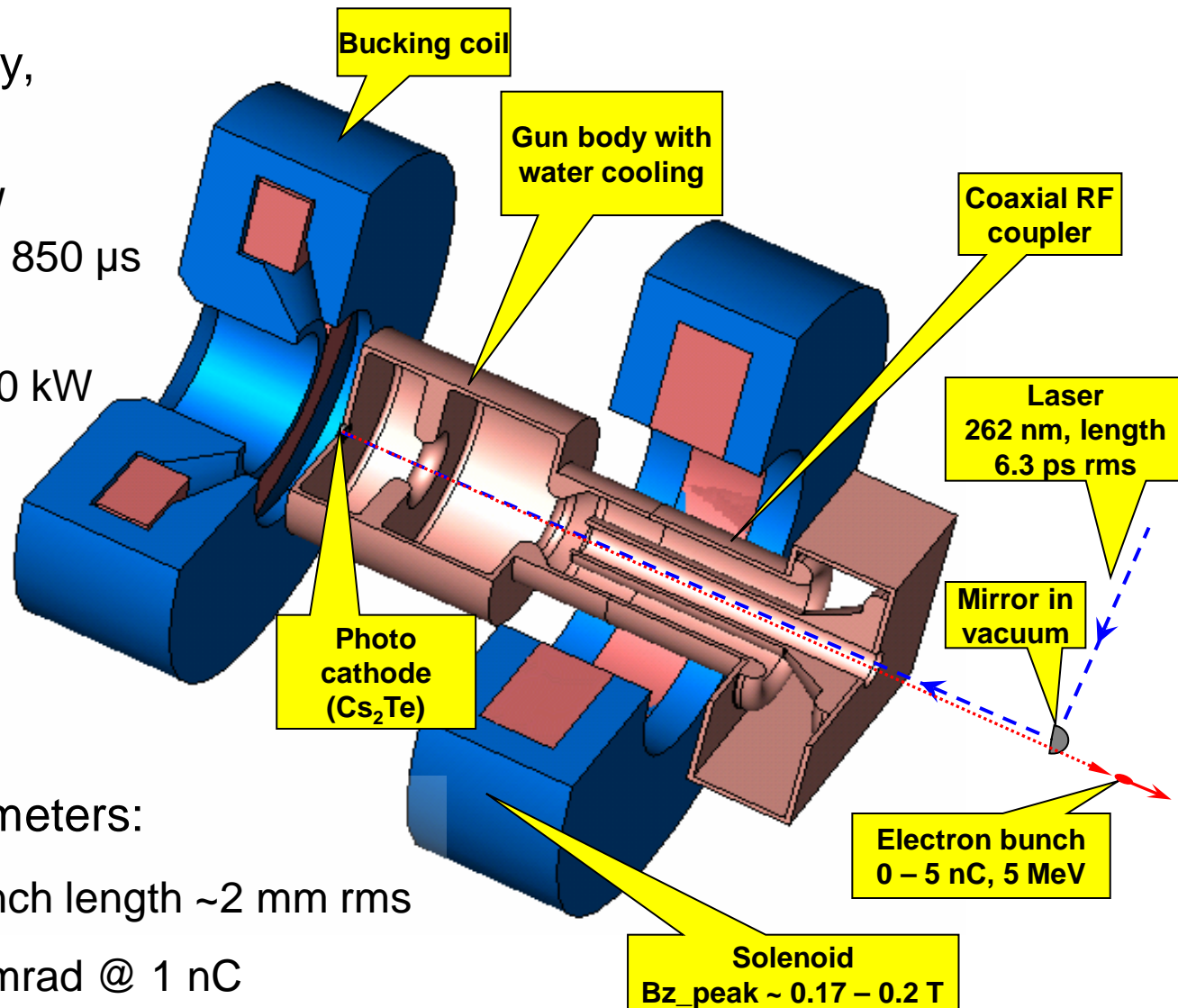
RF Gun

Laser beam
line

Photocathode
System

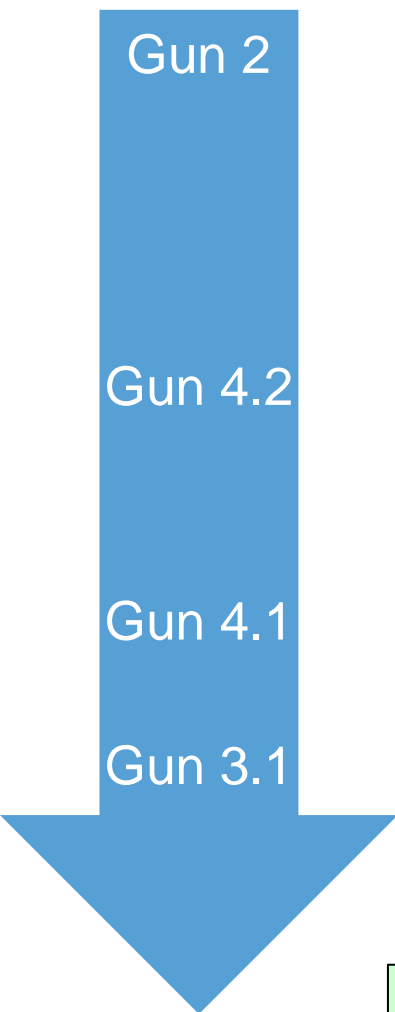
RF Gun (duty cycle 1:100)

- > 1.3 GHz copper cavity,
1 ½ cell
 - RF peak power 5 MW
RF pulse length up to 850 μ s
rep.rate 10 Hz
 - Av. RF power up to 50 kW
 - Cs₂Te 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



2004 Gun2: 5 Hz, 3.5 MW, 350 μ s, 5 kW, 680 GJ

Window: G29

2009 **Gun2 breakdown**

1/2010 Gun4.2: 10 Hz, 3.9 MW, 400 μ s, 15 kW, 1200 GJ

Window: Gxx

6/2010 Window break down; \rightarrow G67

9/2011 Window break down; \rightarrow G29

5/2012 **Gun4.2 breakdown**

6/2012 Gun4.1: 10 Hz, 4 MW, 550 μ s, 21 kW, 930 GJ

Window: G29

3/2013 **Gun3.1: 10 Hz, 5 MW, 550 μ s, 27 kW, 1200 GJ**

Window: Thales 5

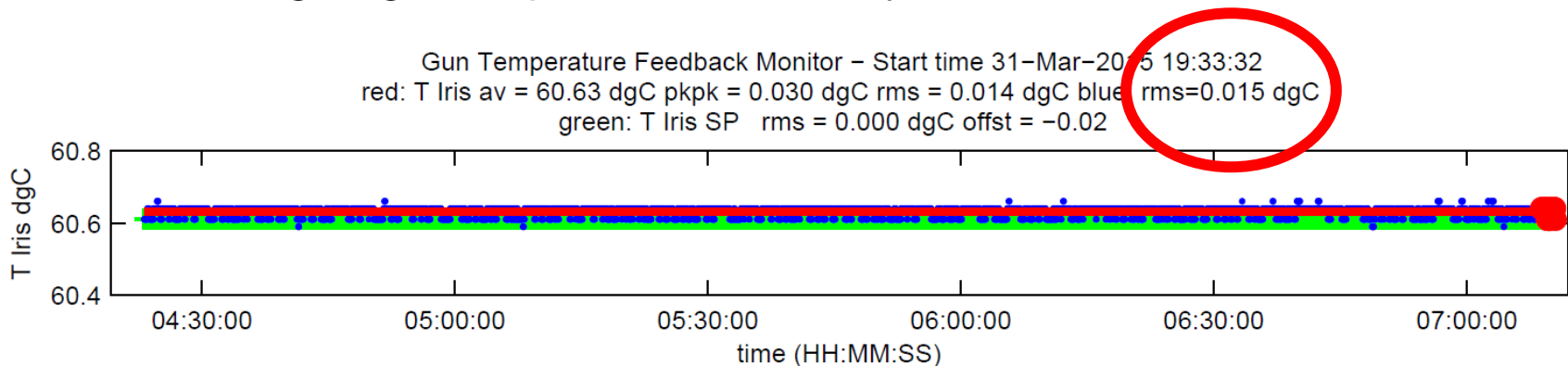
4/2014 Window leak; \rightarrow G64

**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 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

RF Gun water
circuit pressure
change

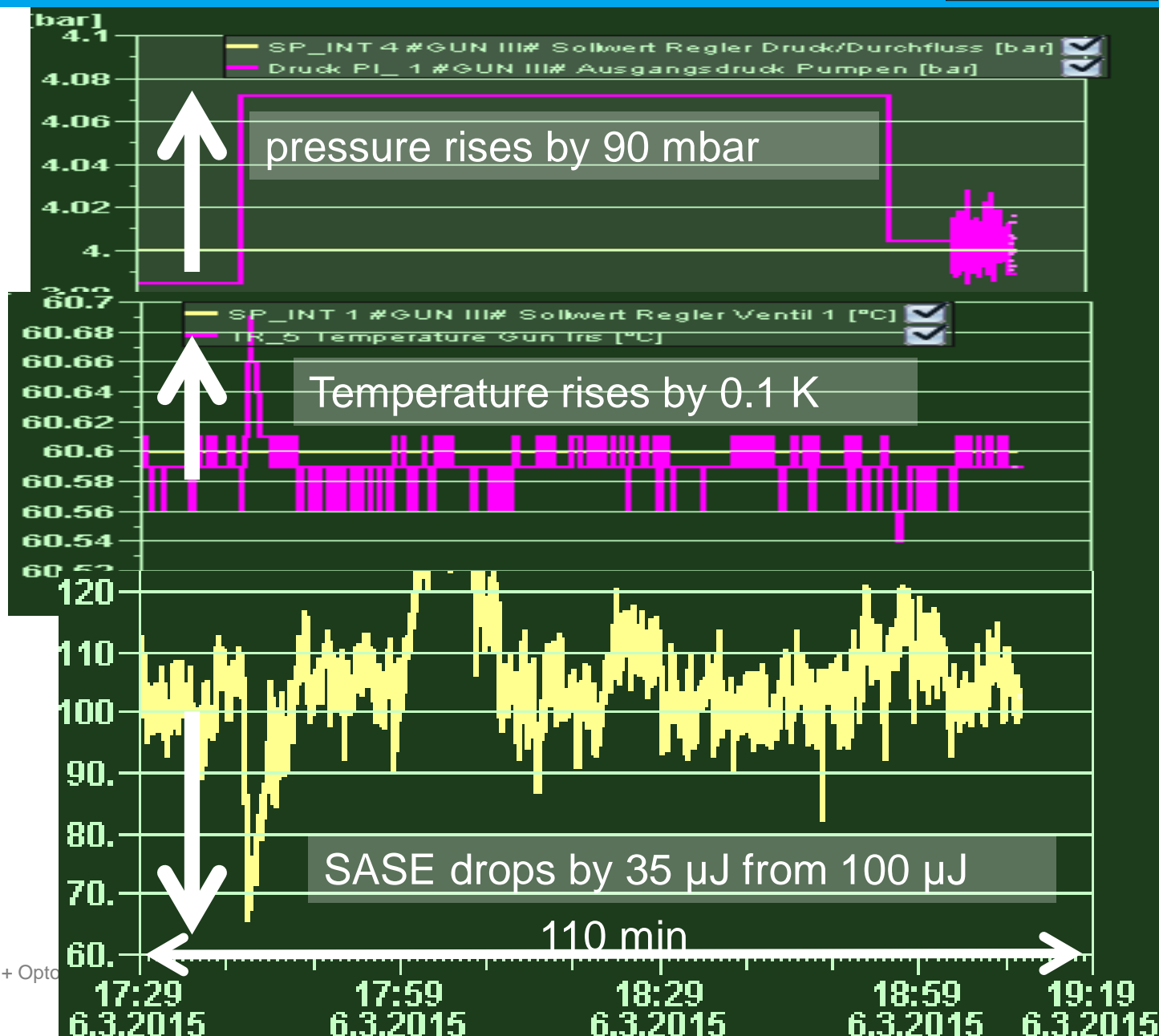
$$dP = 0.1 \text{ bar}$$



$$dT = 0.1 \text{ K}$$



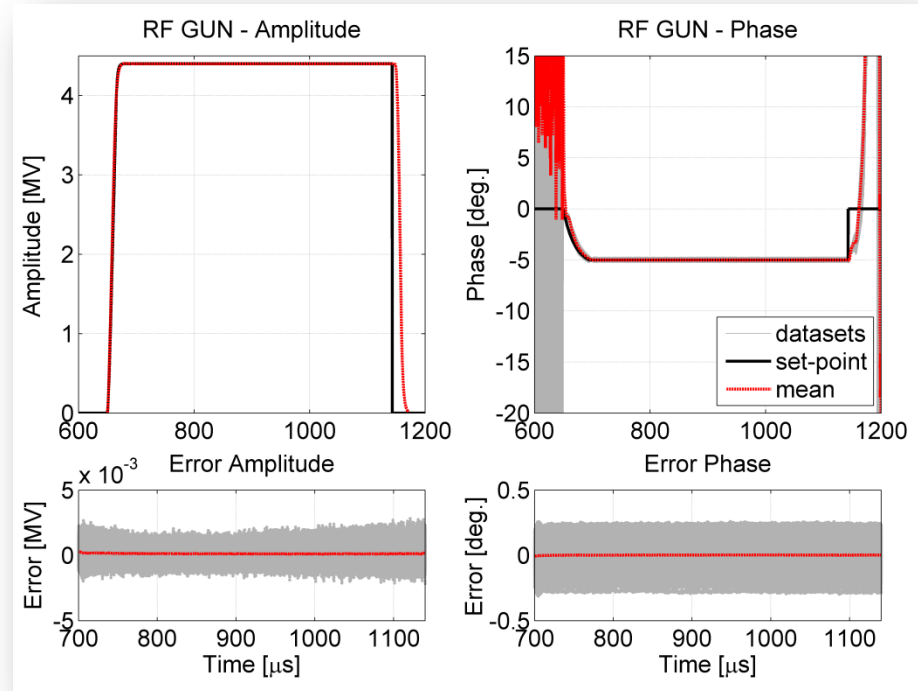
$$dE/E \text{ (SASE)} \\ = -30\%$$



- > New: based on MTCA.4 standard
- > System identification performed
 - Model found and controller designed
 - large loop latency compared to system bandwidth $\sim 1.4 \mu\text{s}$
- > Runs smooth and stable
- > Includes learning feedforward

Feedback gain currently **not** sufficient to achieve a phase stability of $d\phi < 0.01 \text{ dg}$

- > Additional protection mechanism
 - amplitude limiter, fast switch off

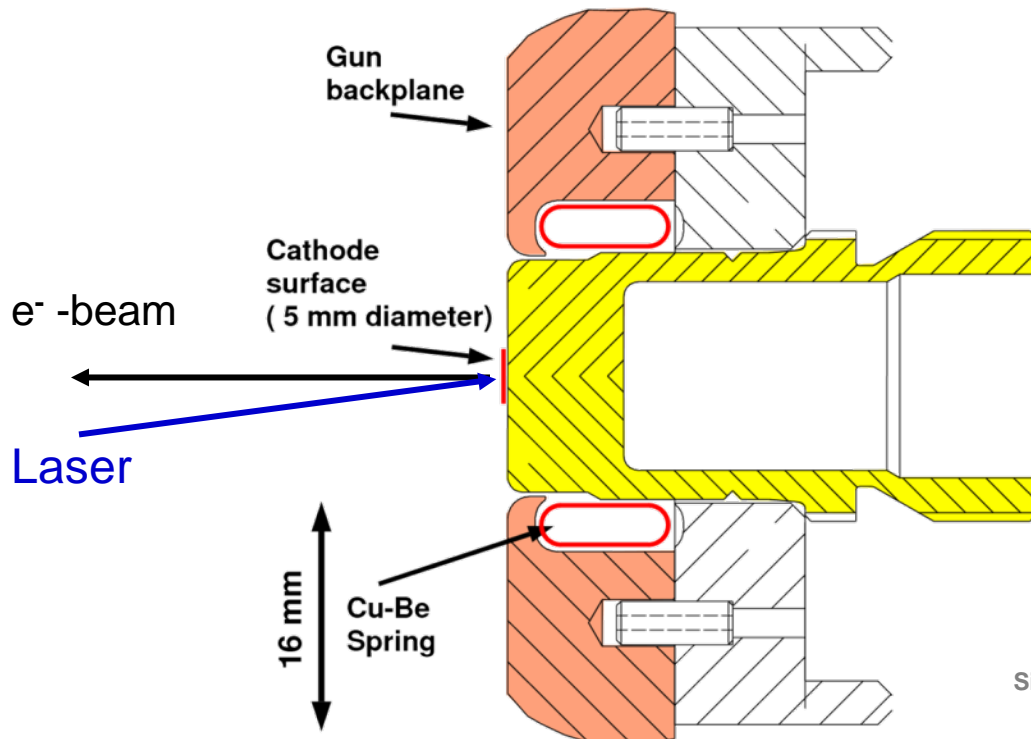


Regulation performance (rms)	Intra pulse (flattop)	Pulse to pulse (960 consecutive pulses)
Amplitude dA/A (%)	0.008	0.008
Phase $d\phi$ (dg)	0.007	0.076

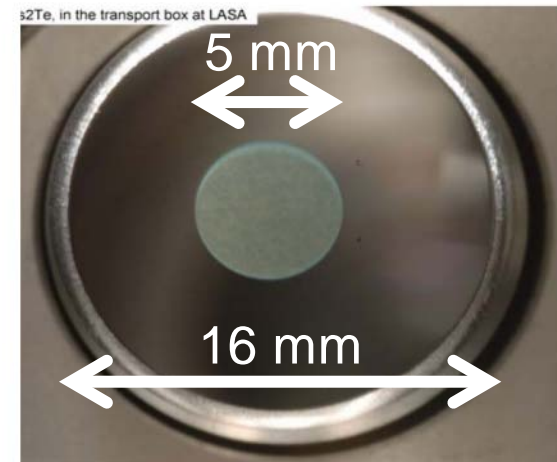
Goal: $< 0.01\%$ in amplitude and $< 0.01 \text{ dg}$ (rms) in phase

Cathode

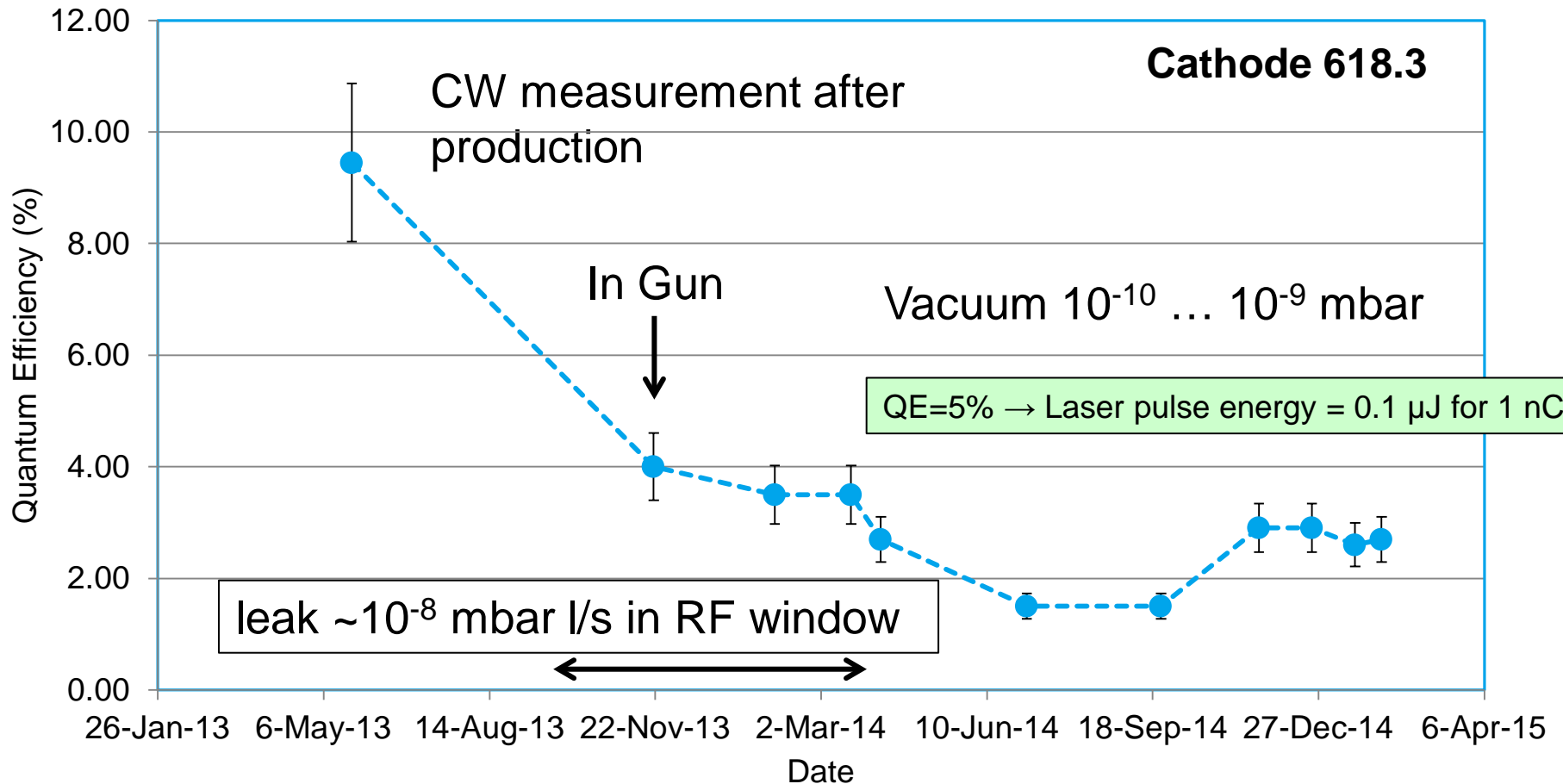
- > High initial quantum efficiency ~10 ... 15 %
- > Excellent lifetime > 1 year at FLASH
- > Preparation systems at LASA, Milano and DESY, Hamburg
 - UHV transport boxes
- > Requires UV laser 275 ... 250 nm



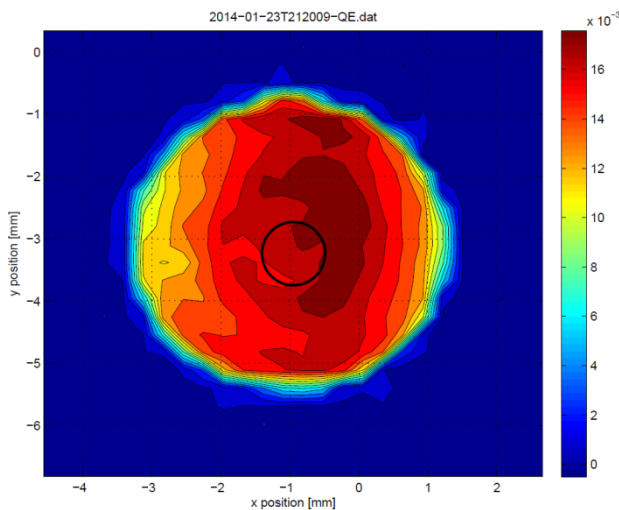
Thin film of Cs₂Te on
Mo plug



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

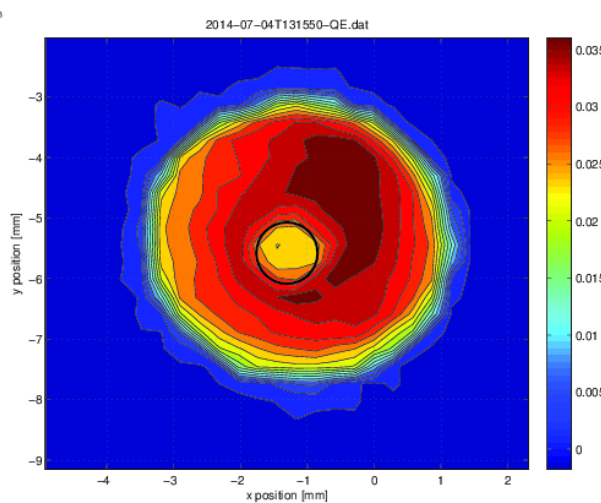


- > Cathode 618.3
- > Faster QE degradation where the laser hits
- > Rest of cathode degrades slower
- > Not clear, if QE actually recovered in the center, looks like “yes”



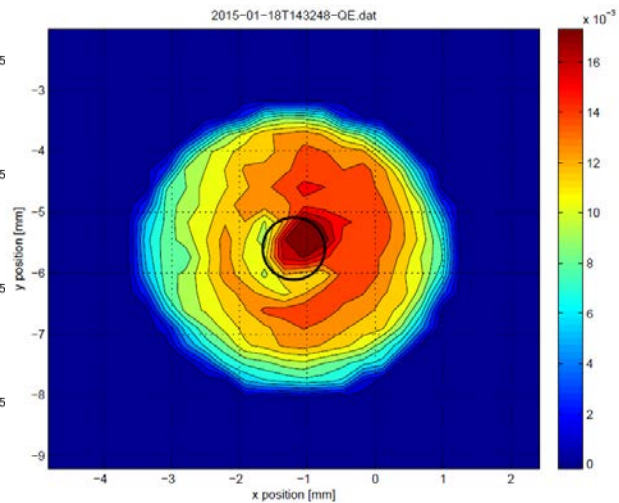
23-Jan-2014

QE=3.5%



4-Jul-2014

QE=1.5%

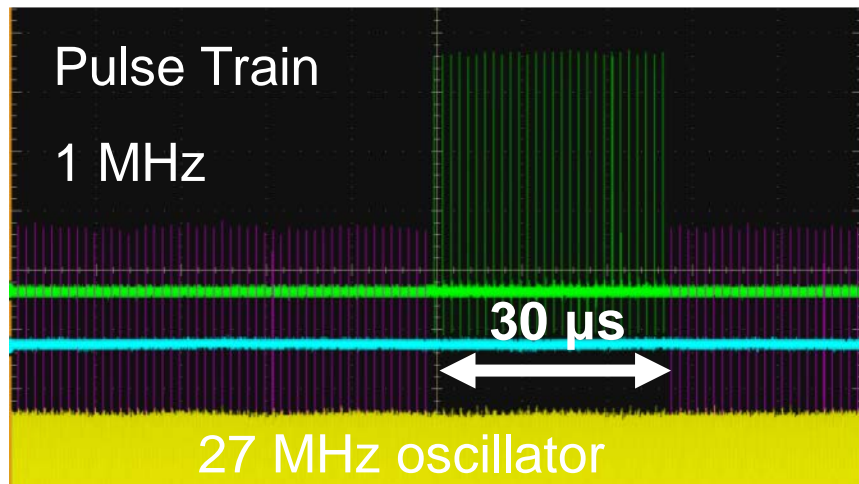


8-Jan-2015

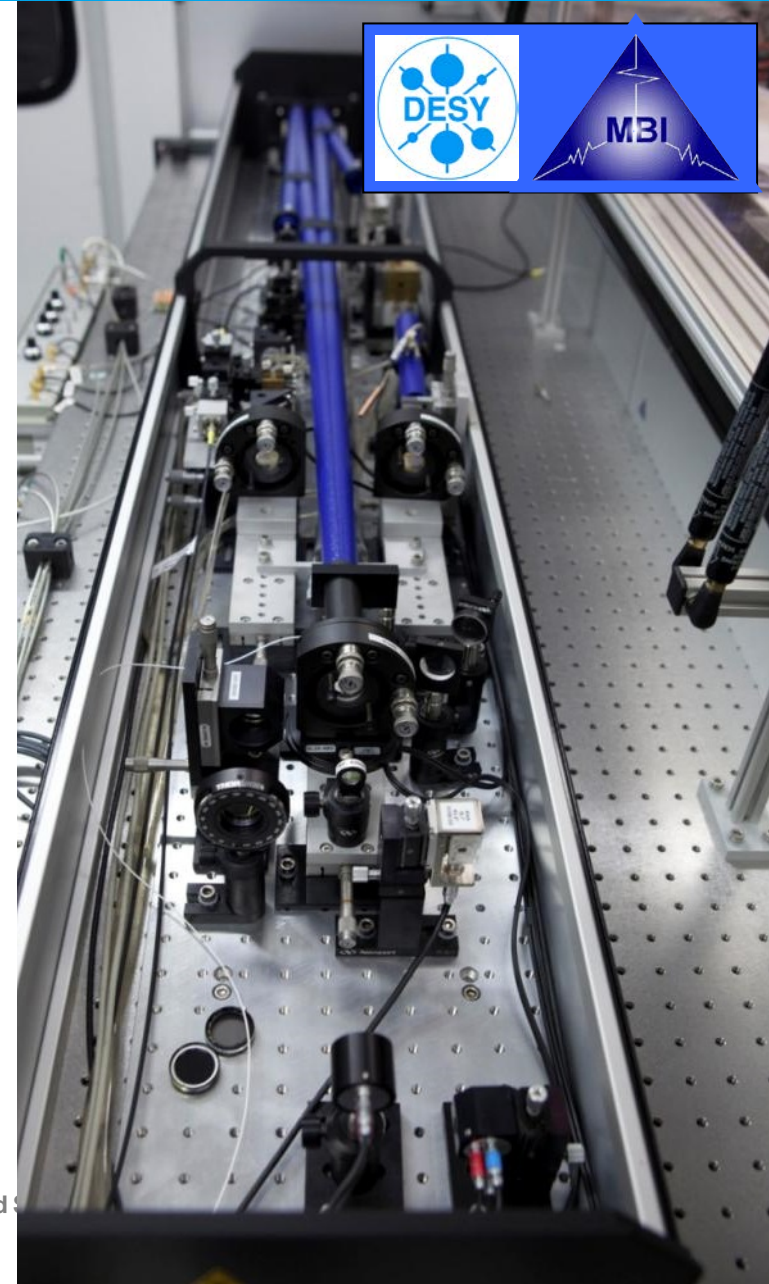
QE=2.6%

Photocathode Laser

- > 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

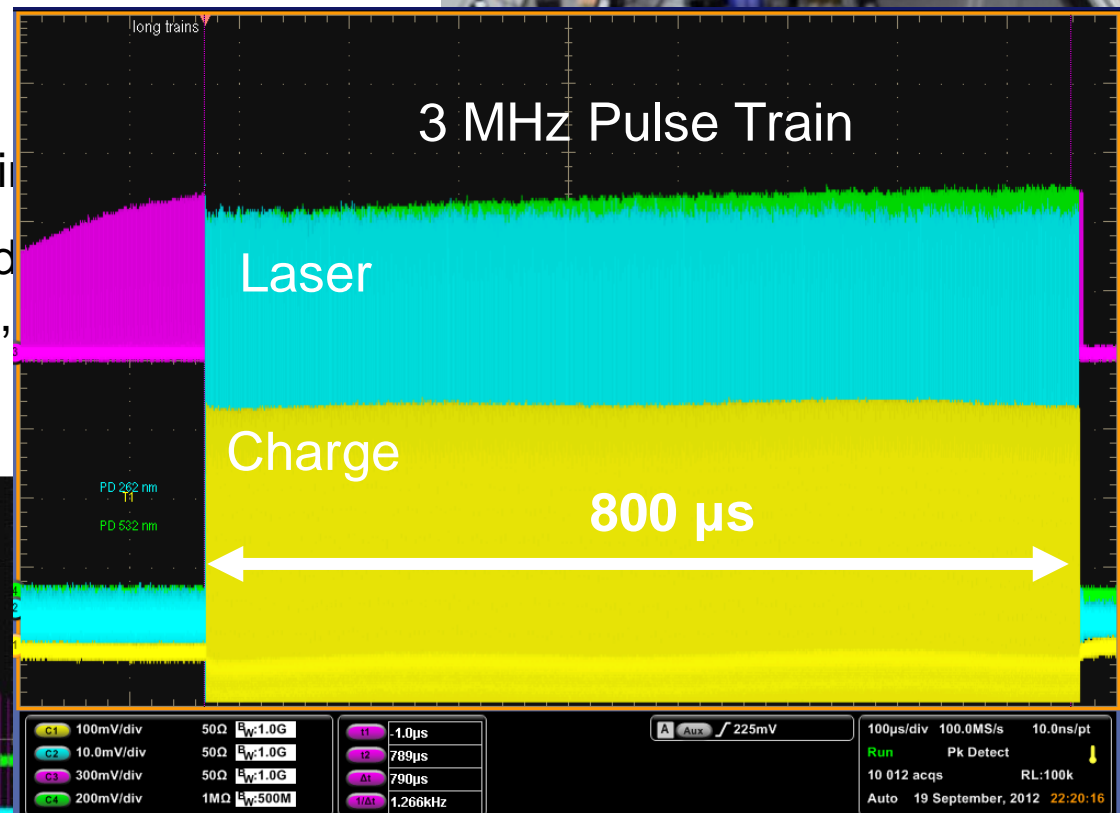
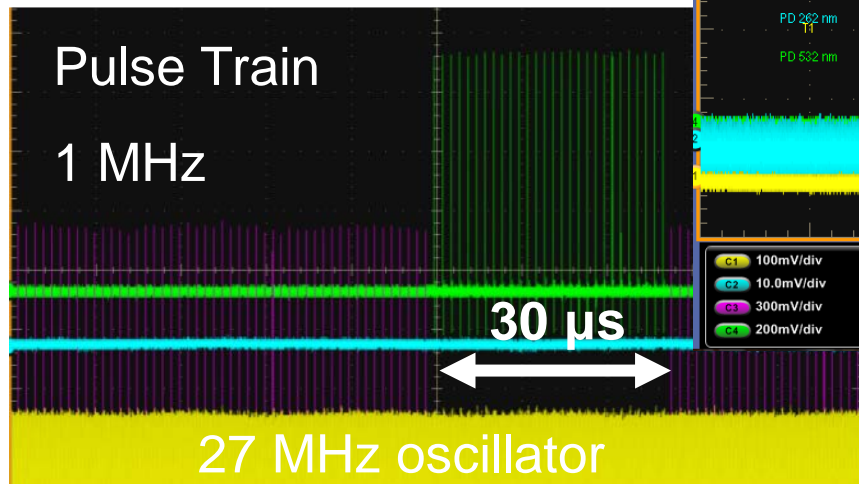


Siegfried



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 train
- > Number of pulses and pulse d
- 1 MHz, 200 kHz, 100 kHz, ...,
- > 3 MHz option @ 5 Hz



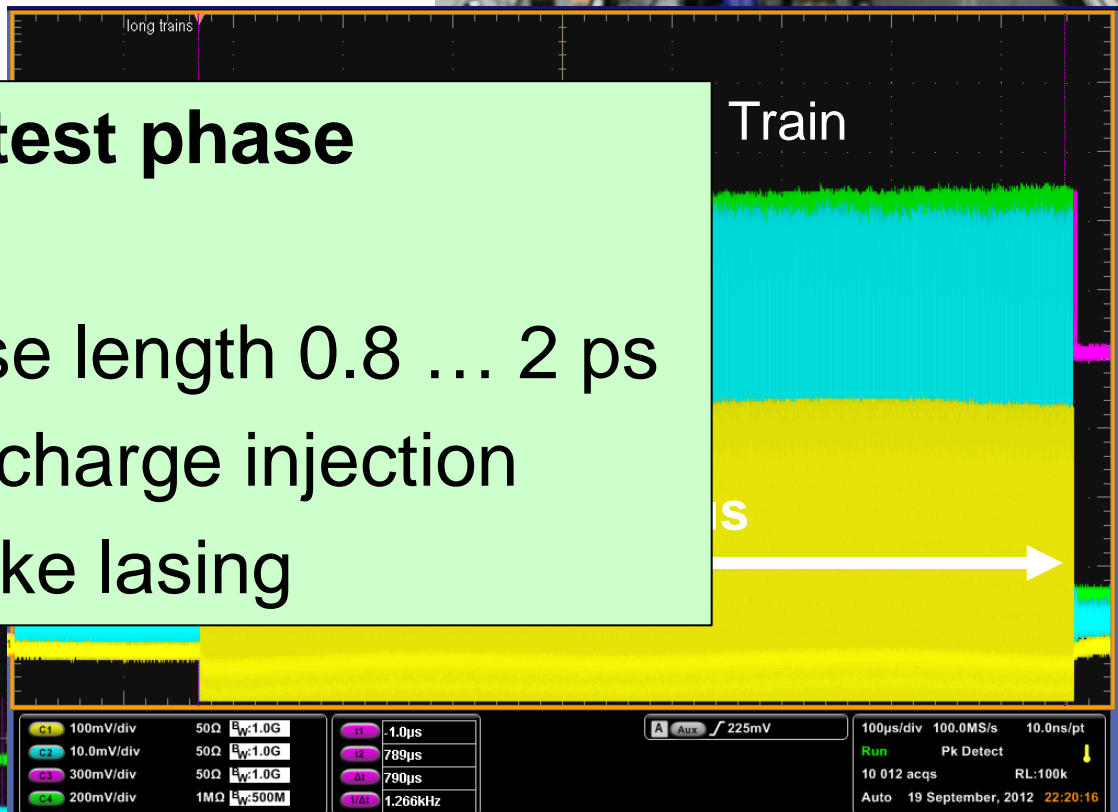
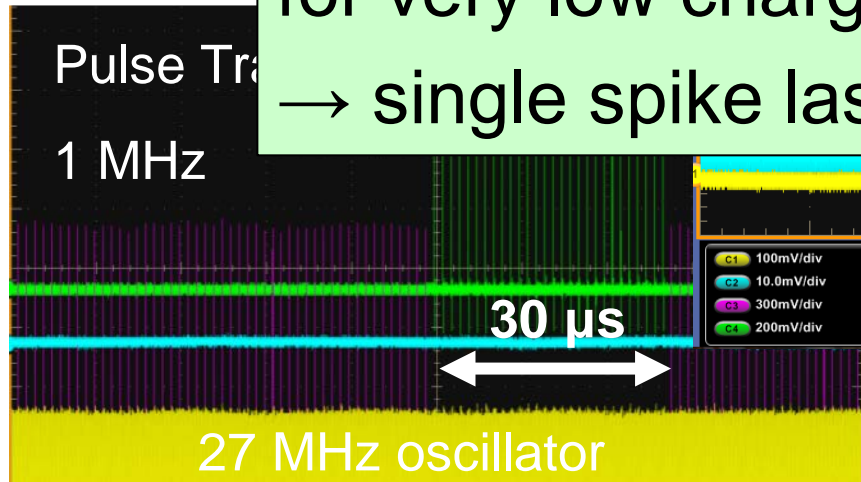
- > 2 fully diode pumped Nd:YLF lasers
 - Compared to previous flashlamp pumped lasers:
 - Significant improvement in stability and reliability
 - Up to 50 μJ per pulse (UV)
 - Longitudinally polarized

- > Burst mode
- > Number of pulses
- 1 MHz, 2
- > 3 MHz op

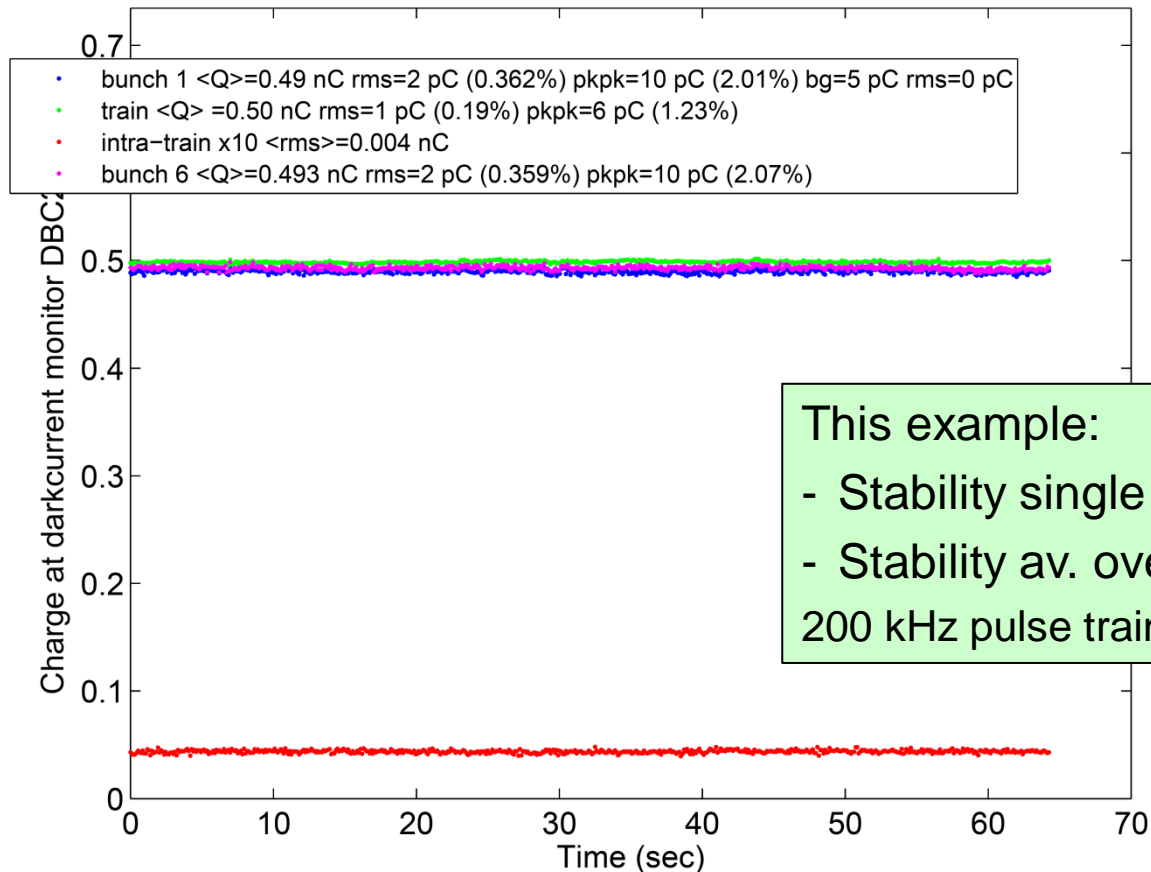
3rd laser in test phase

Feature:

variable pulse length 0.8 ... 2 ps
for very low charge injection
→ single spike lasing



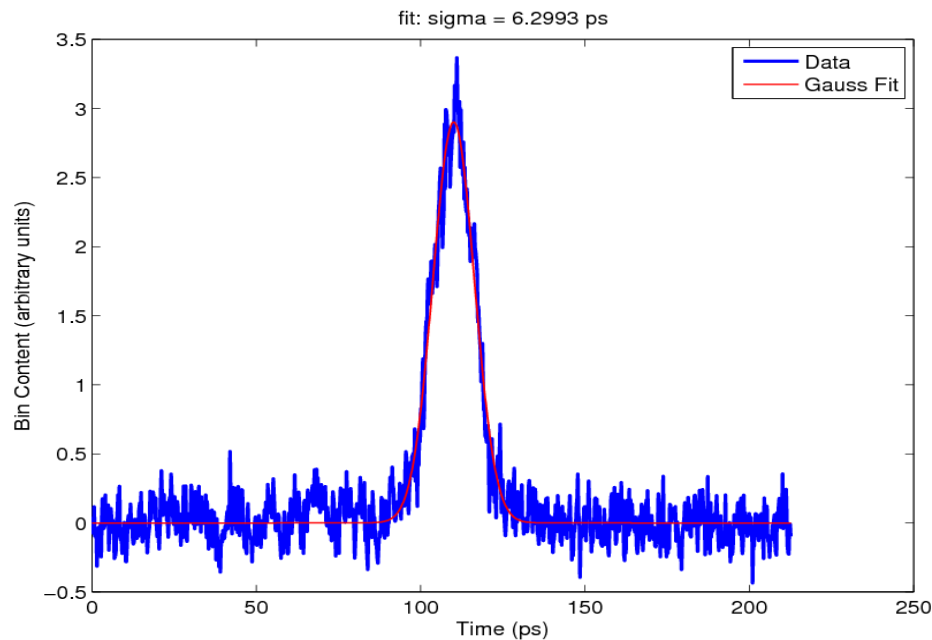
- > Jitter at normal working point 0.3 ... 0.5 % rms
- > Slow charge feedback to compensate drifts



This example:

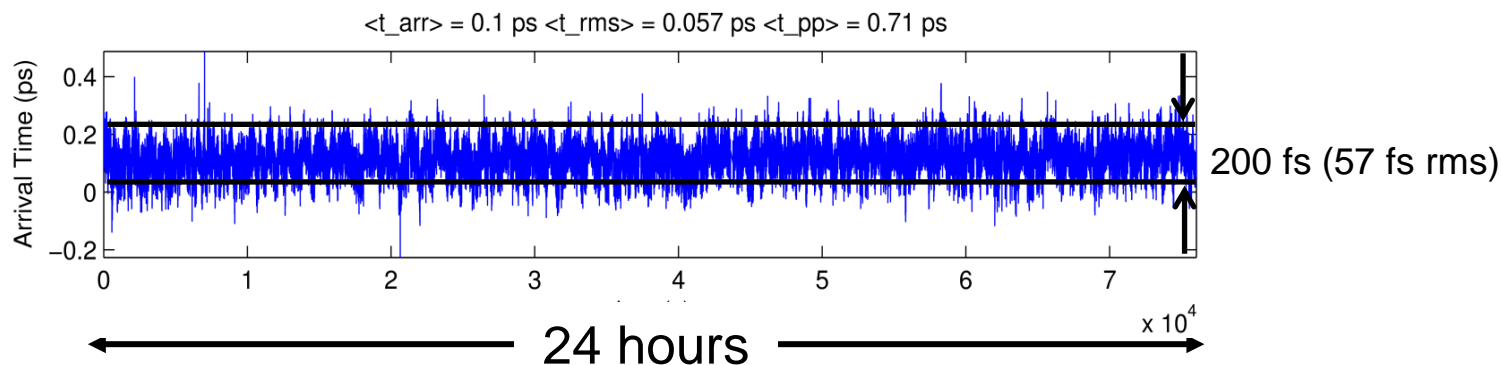
- Stability single bunch: 0.36 % rms
 - Stability av. over train: 0.19 % rms
- 200 kHz pulse train with 125 bunches, 10 Hz

- > 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)

- > 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

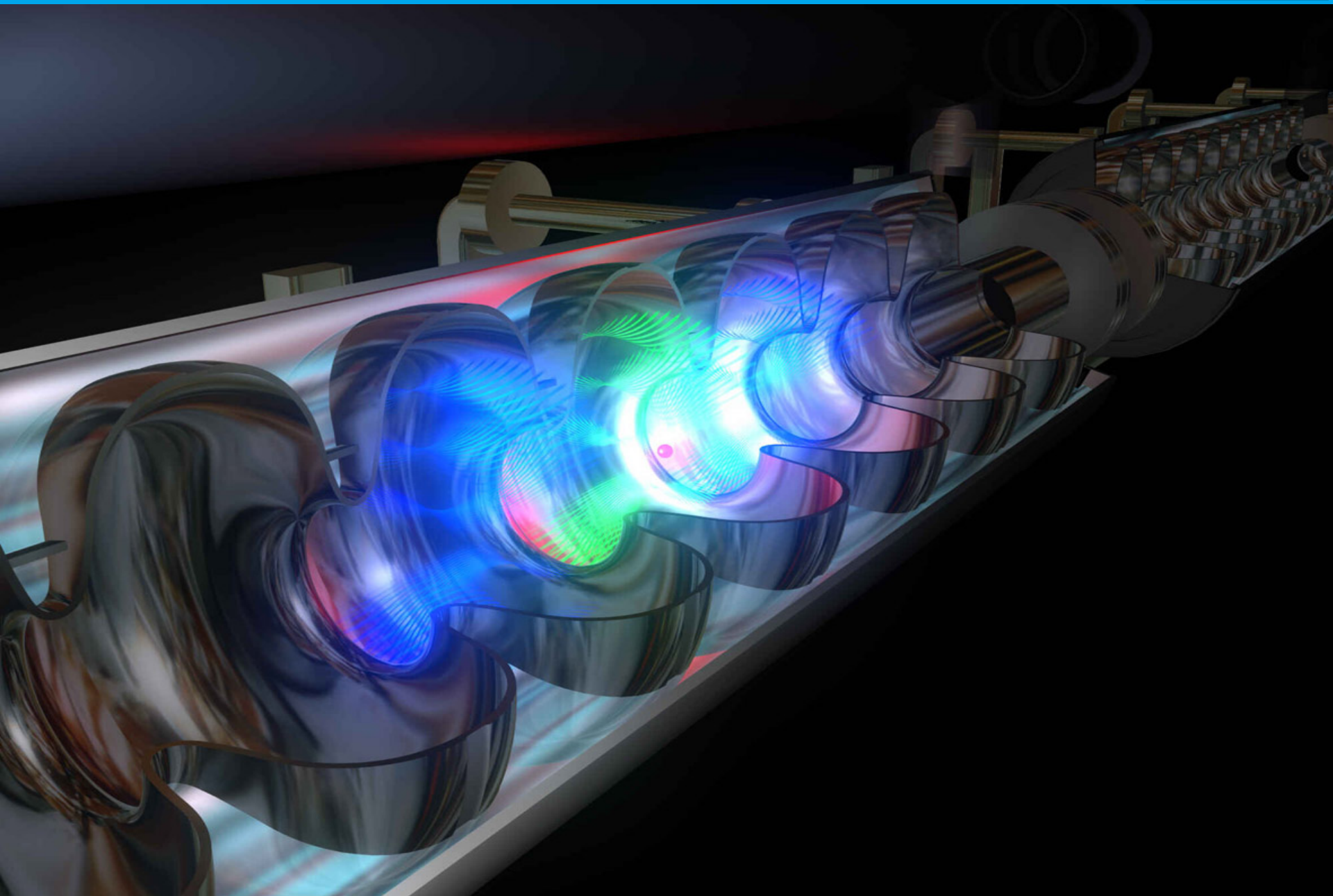


- > Pump diode lasers are in continuous operation since their installation ~40,000 h up to now (1 ms, 10 Hz)
- > Pump diodes of oscillator are in continuous operation for more than 50,000 hours (4.5 ms, 10 Hz)
- > No failures of pump diodes up to now
- > The whole laser system is remarkably robust and 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



Pure Niobium superconducting cavities
9-cells, 1.3 GHz

Burst mode: acceleration for $800\ \mu\text{s}$ at 10 Hz

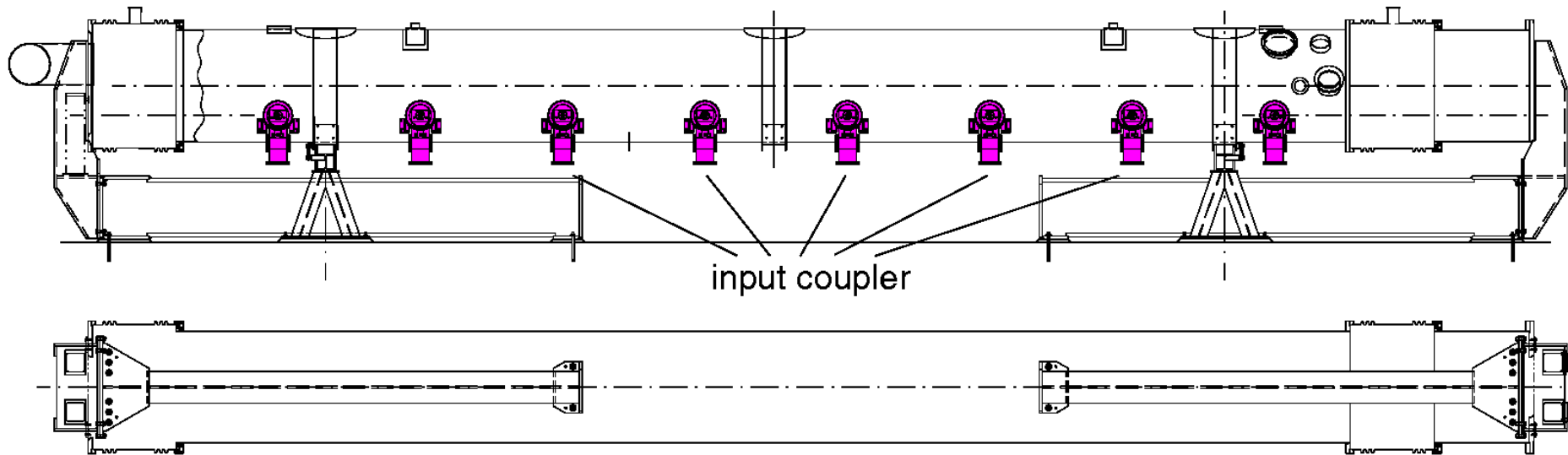
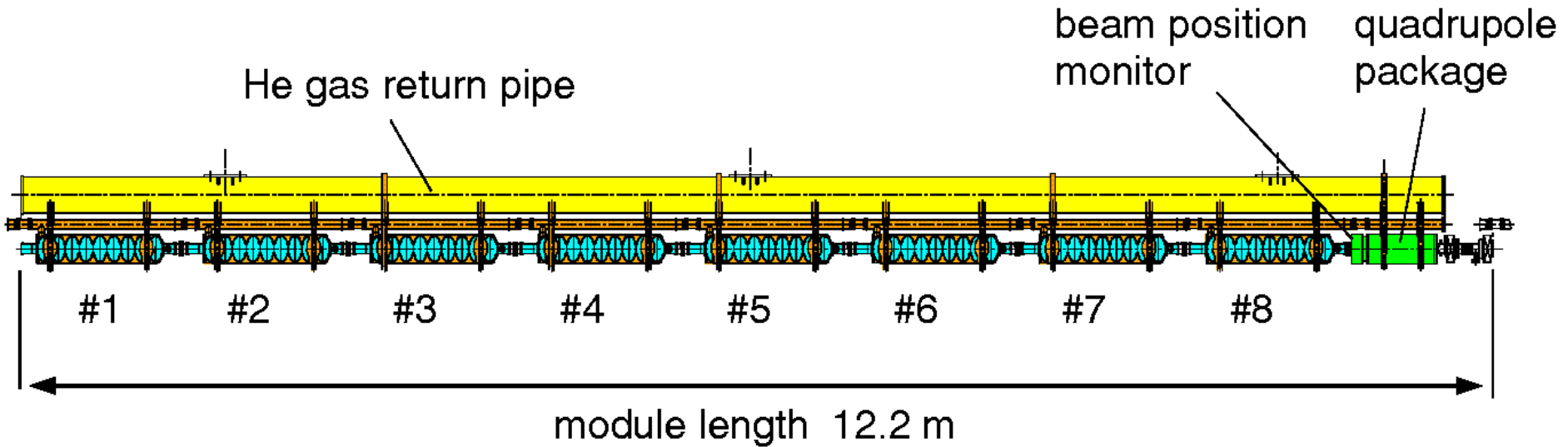
Efficient acceleration due to high $Q \sim 10^{10}$

Energy gain $\sim 25\ \text{MV/m}$

1 m



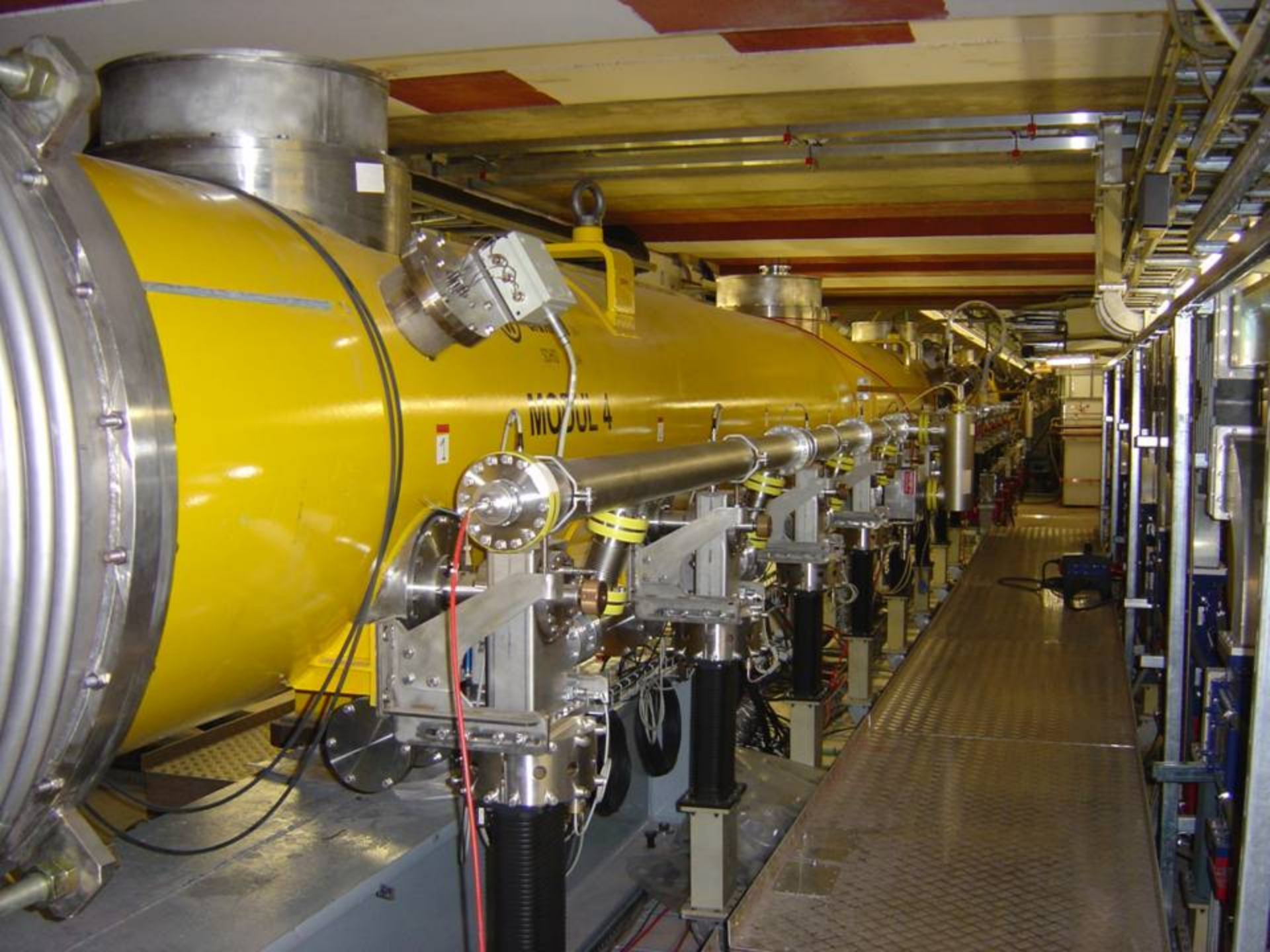
FLASH uses TESLA technology



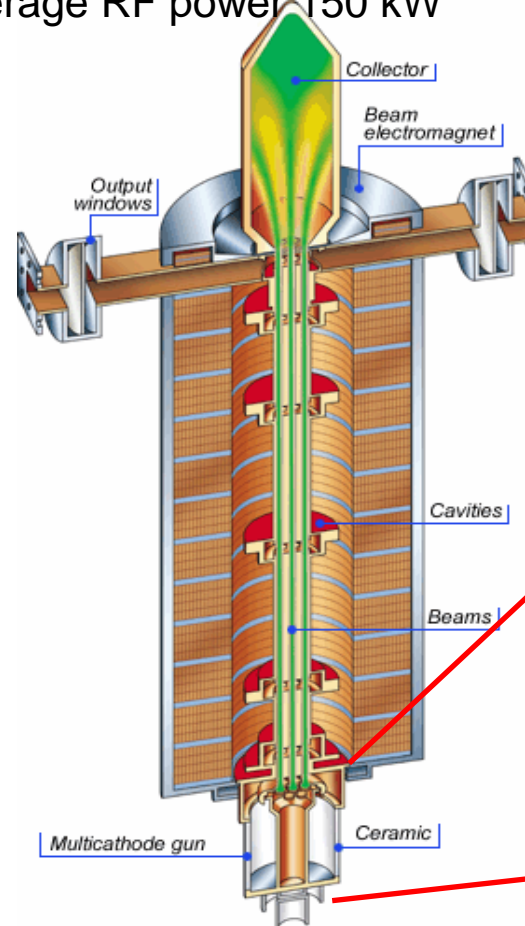
FLASH tunnel with superconducting modules

FLASH.
Free-Electron Laser
in Hamburg



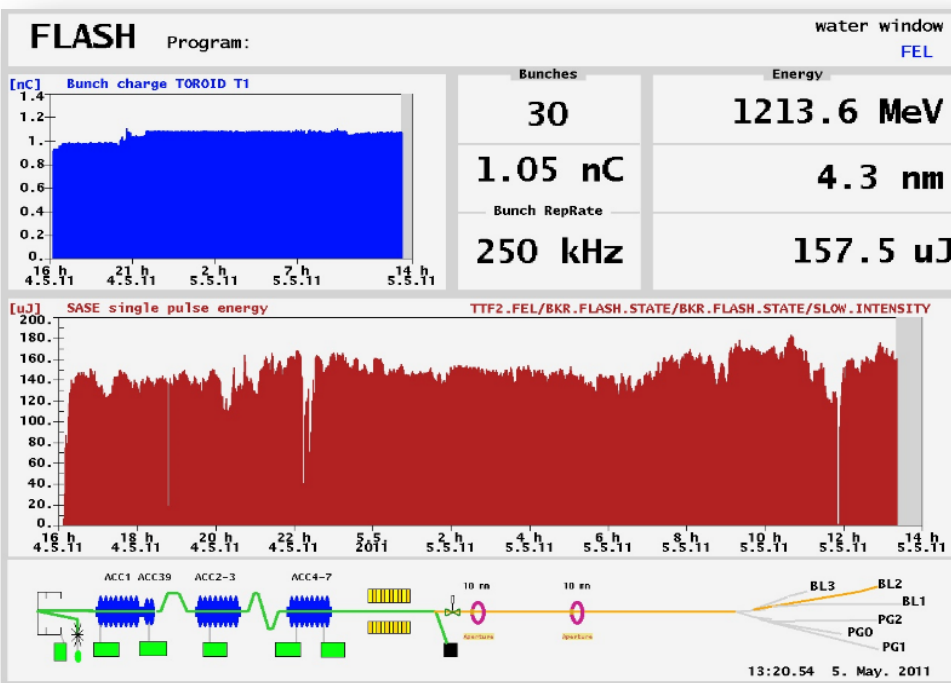


- > Thales 5 MW and 10 MW multi-beam klystron (TH1801)
 - Driven by 117 kV rectangular RF pulses (1.5 ms duration) at 10 Hz
 - Gain 48.2 dB, efficiency 65 %, average RF power 150 kW

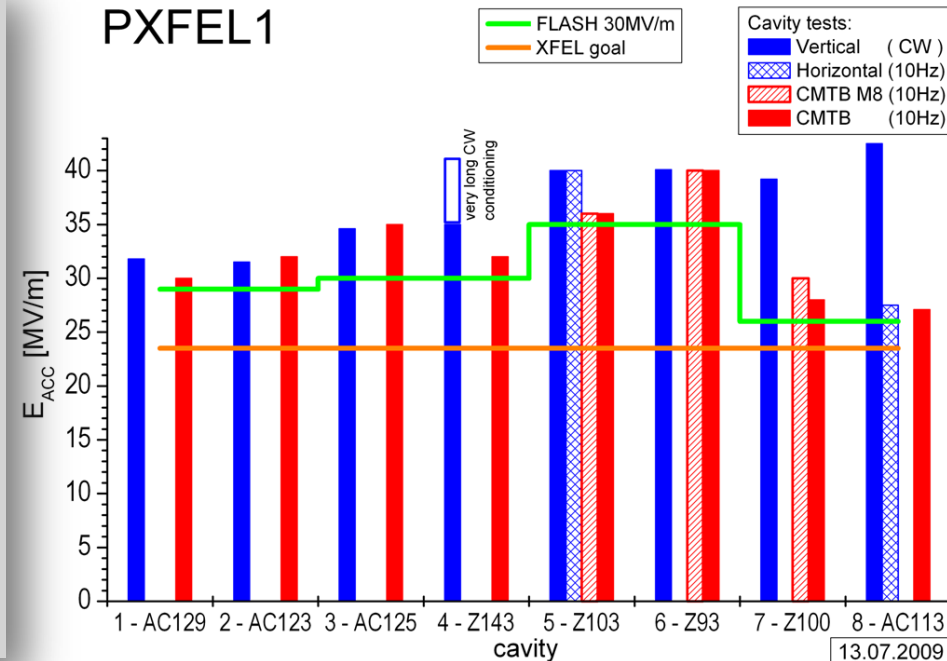


- > 7 TESLA type accelerating modules installed plus one 3rd harmonic module
- > Electron beam energy of 1.25 GeV possible → water window
- > 7 RF stations (four 5 MW, two 10 MW Thales klystrons, one 3.9 GHz)

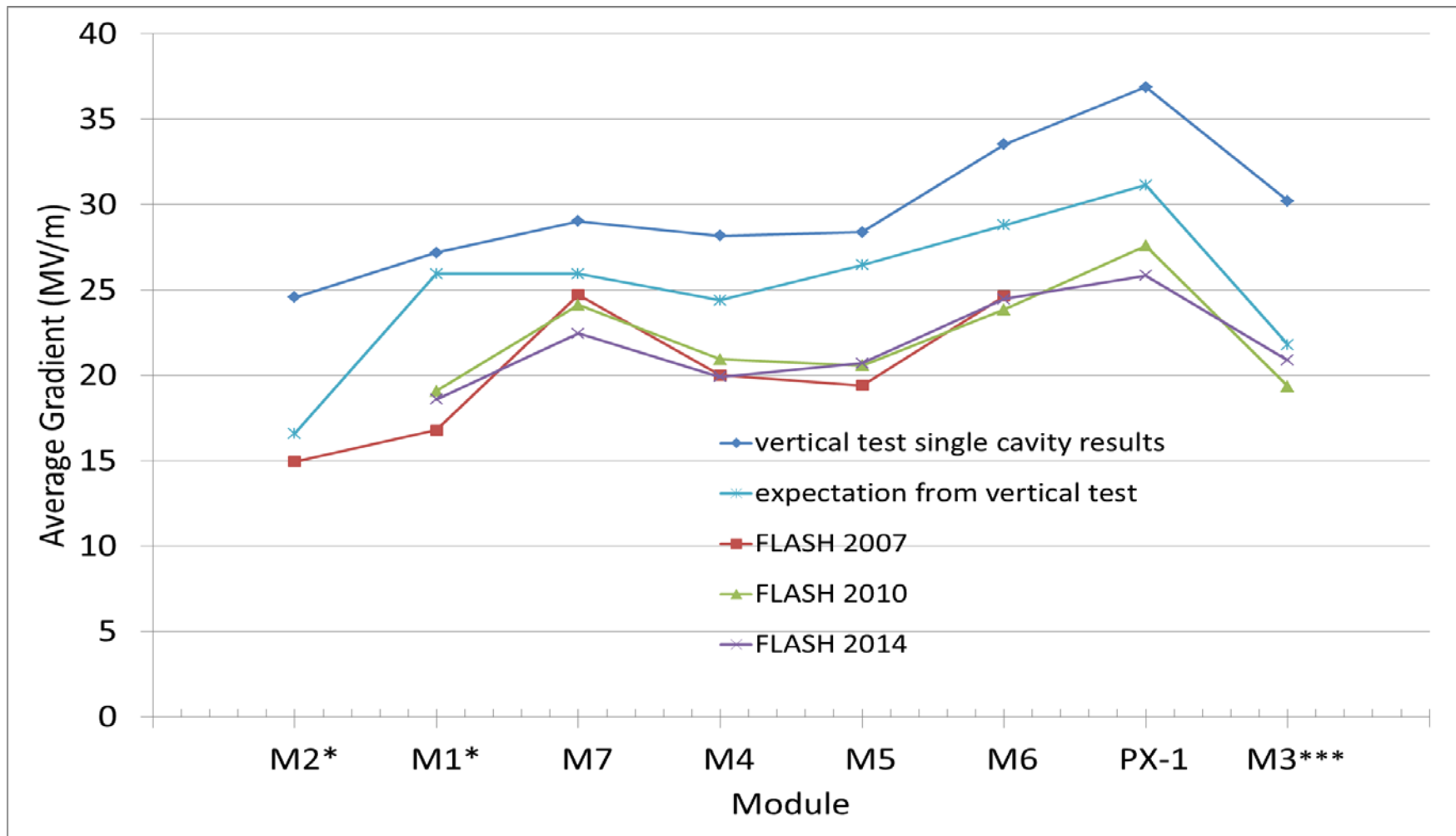
Module 7 is the 1st XFEL-prototype
with excellent performance



PXFEL1



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

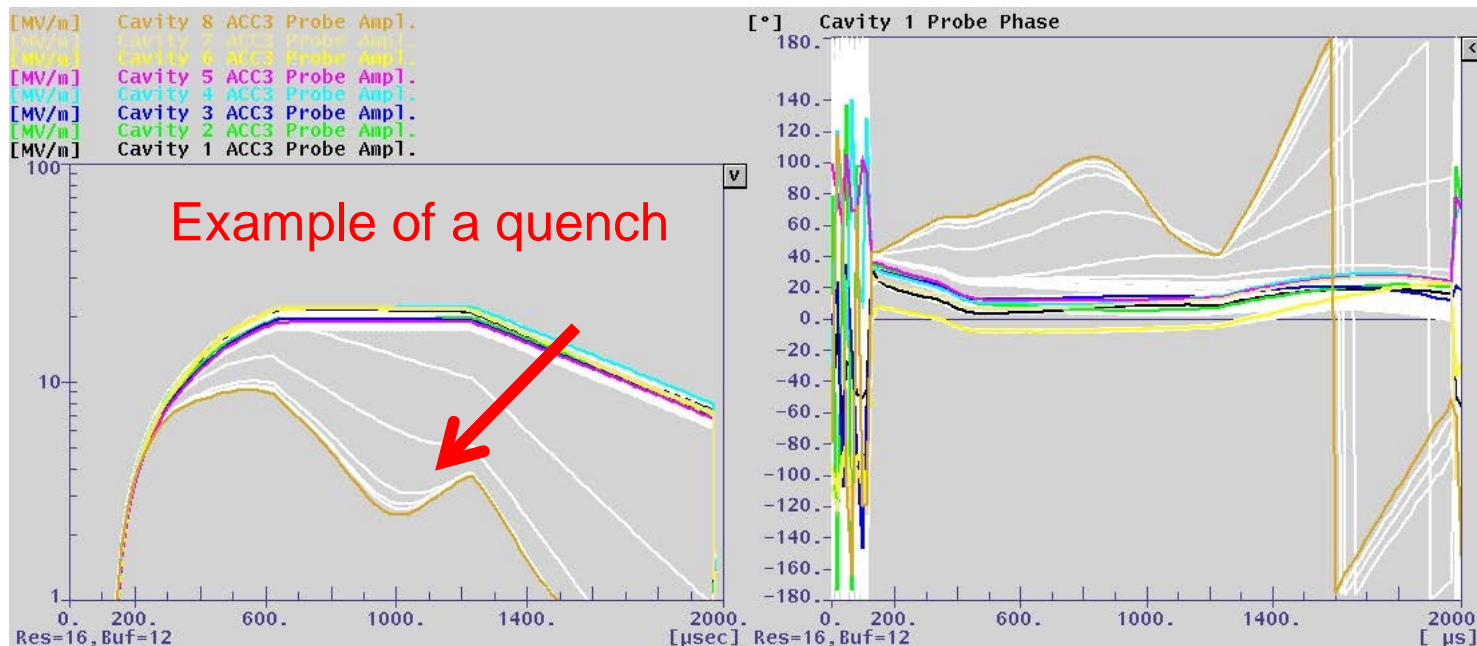


Cryogenics

- > 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

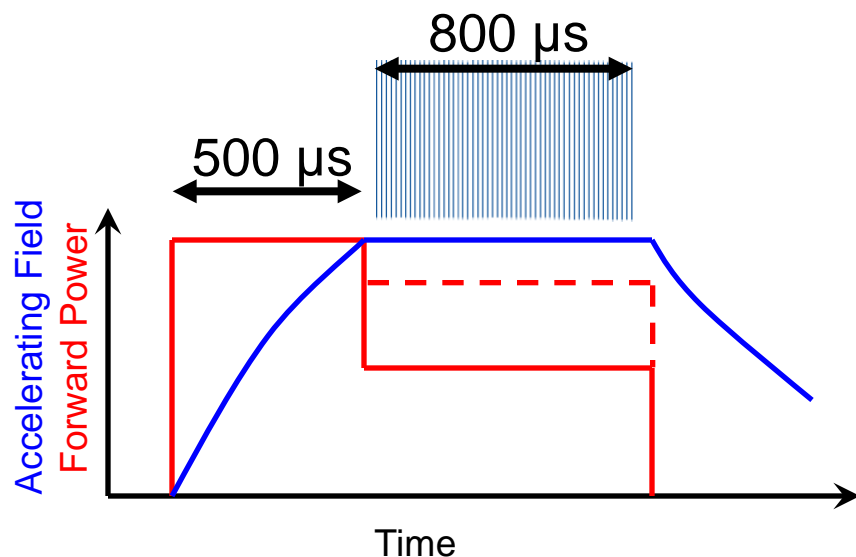
- > Cavities do not trip, but may quench (LLRF control issues)
 - > Cavity quenches do not necessarily lead to downtime but to instabilities
 - > He-pressure changes are measured with a large latency and are usually observed too late to prevent instabilities
- Software quench detection



Low Level RF

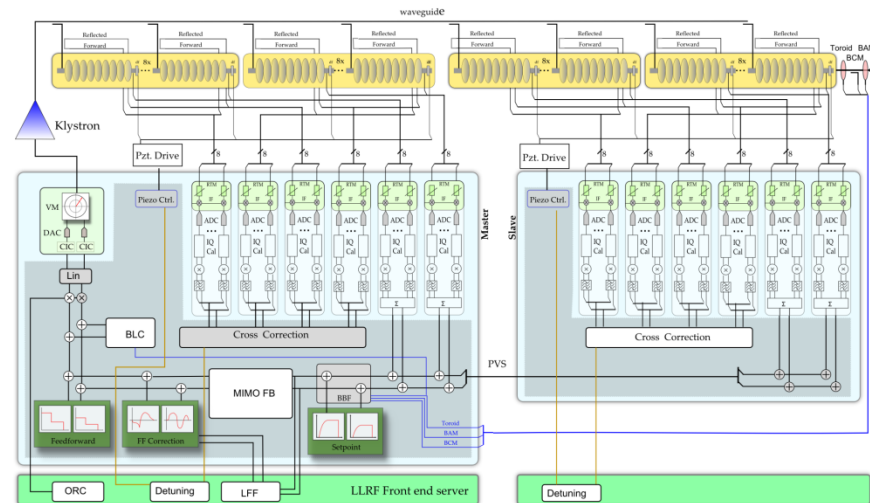
- > Take advantage of superconducting accelerating technology

- Burst mode – long bunch trains @ 10 Hz

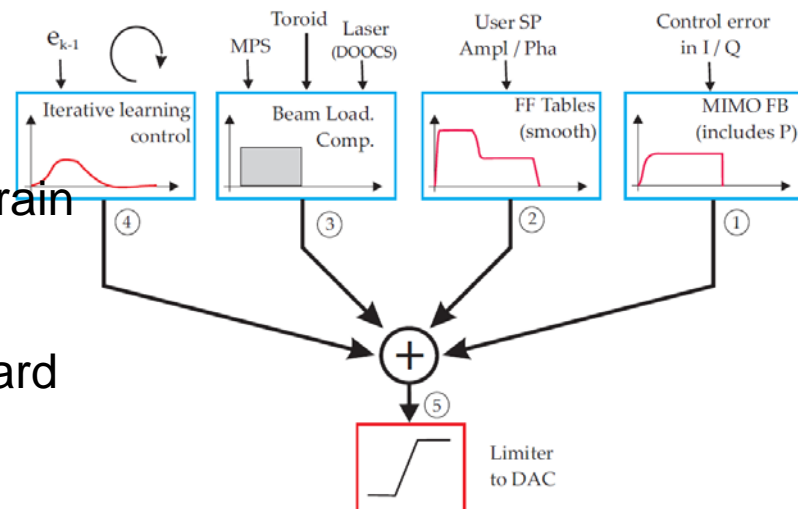


- > Feedback to keep gradient flat along pulse train
- > Beam loading compensation
- > Beam based corrections, learning feed forward
- > Exception handling

LLRF RF controller schematics

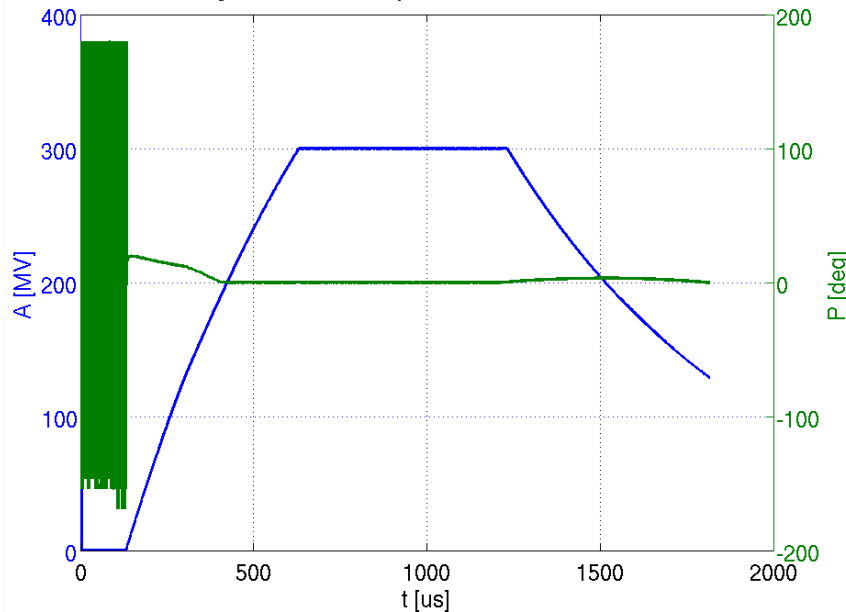


Feed forward table architecture

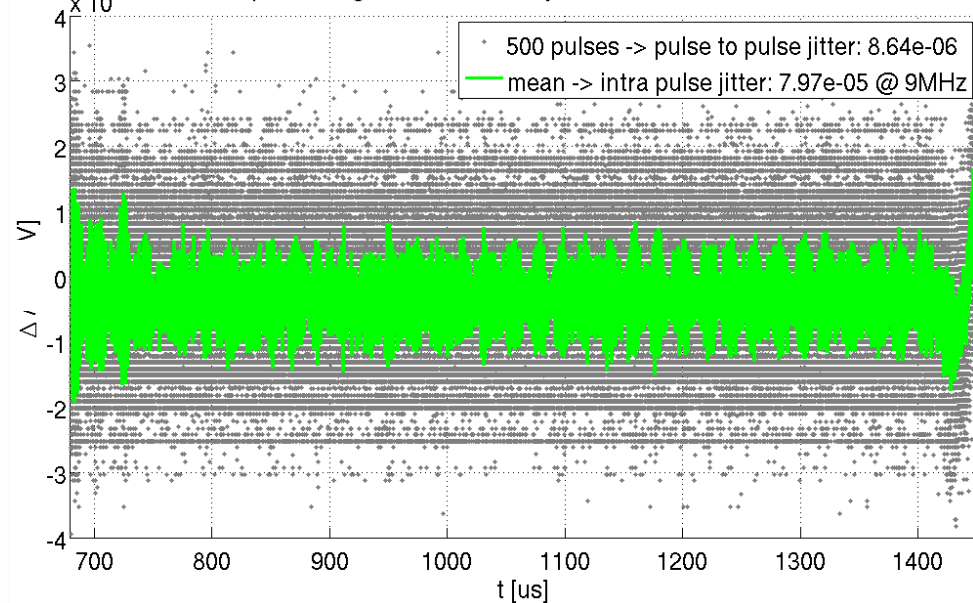


RF Stability measurements (in-loop regulation)

Regulation with cavity filters, MIMO FB and LFF



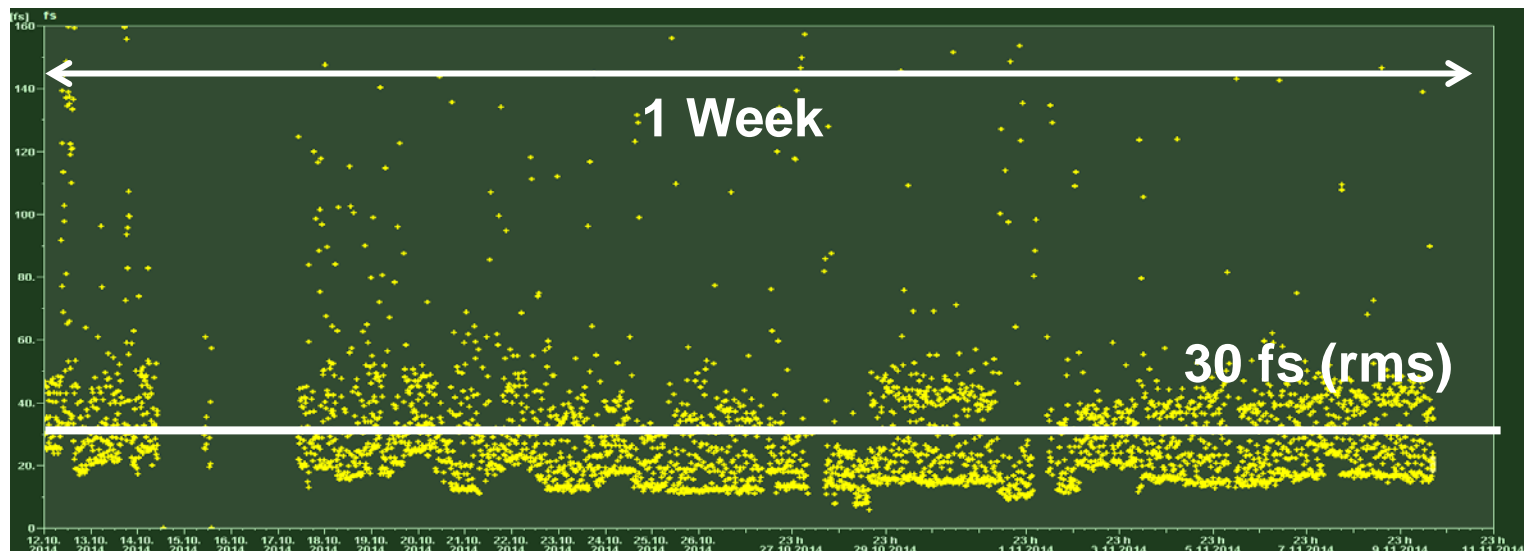
Amplitude regulation with cavity filters, MIMO FB and LFF



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

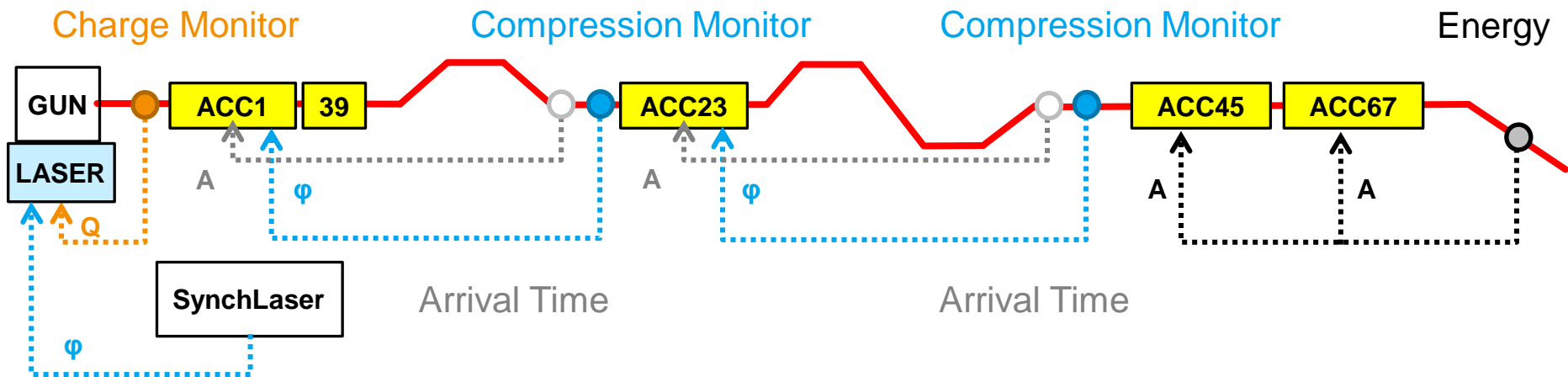
Goal achieved: $< 0.01\%$ in amplitude and < 0.01 dg in phase

- > 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 “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

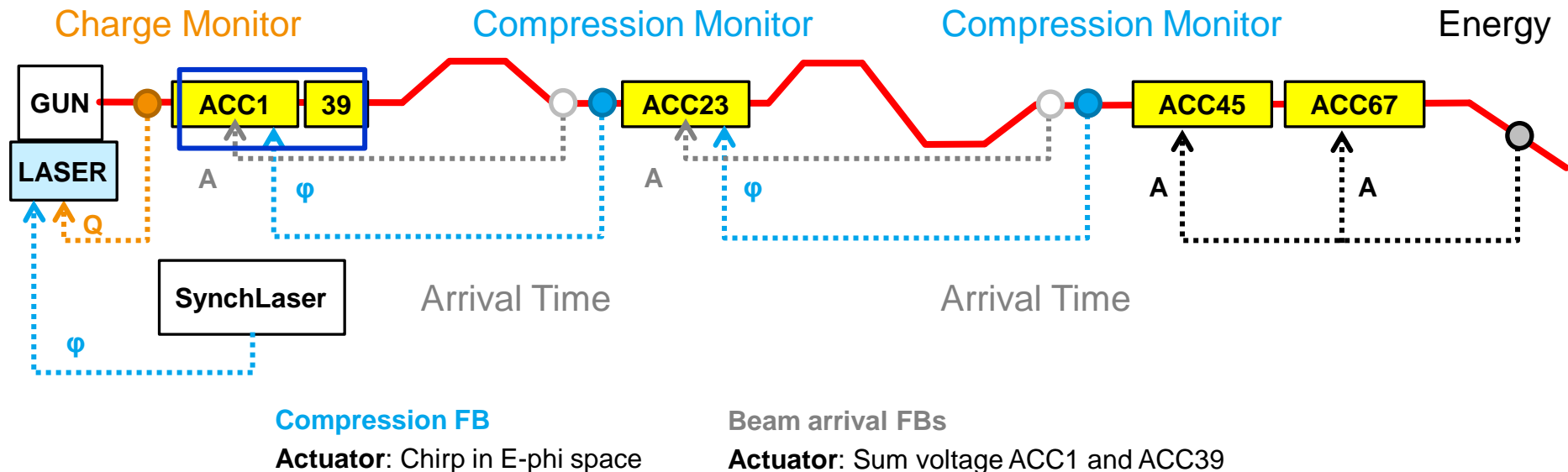
Energy FB

Monitor: Orbit around dispersive section + dipole current

Actuator: RF amplitude of last modules

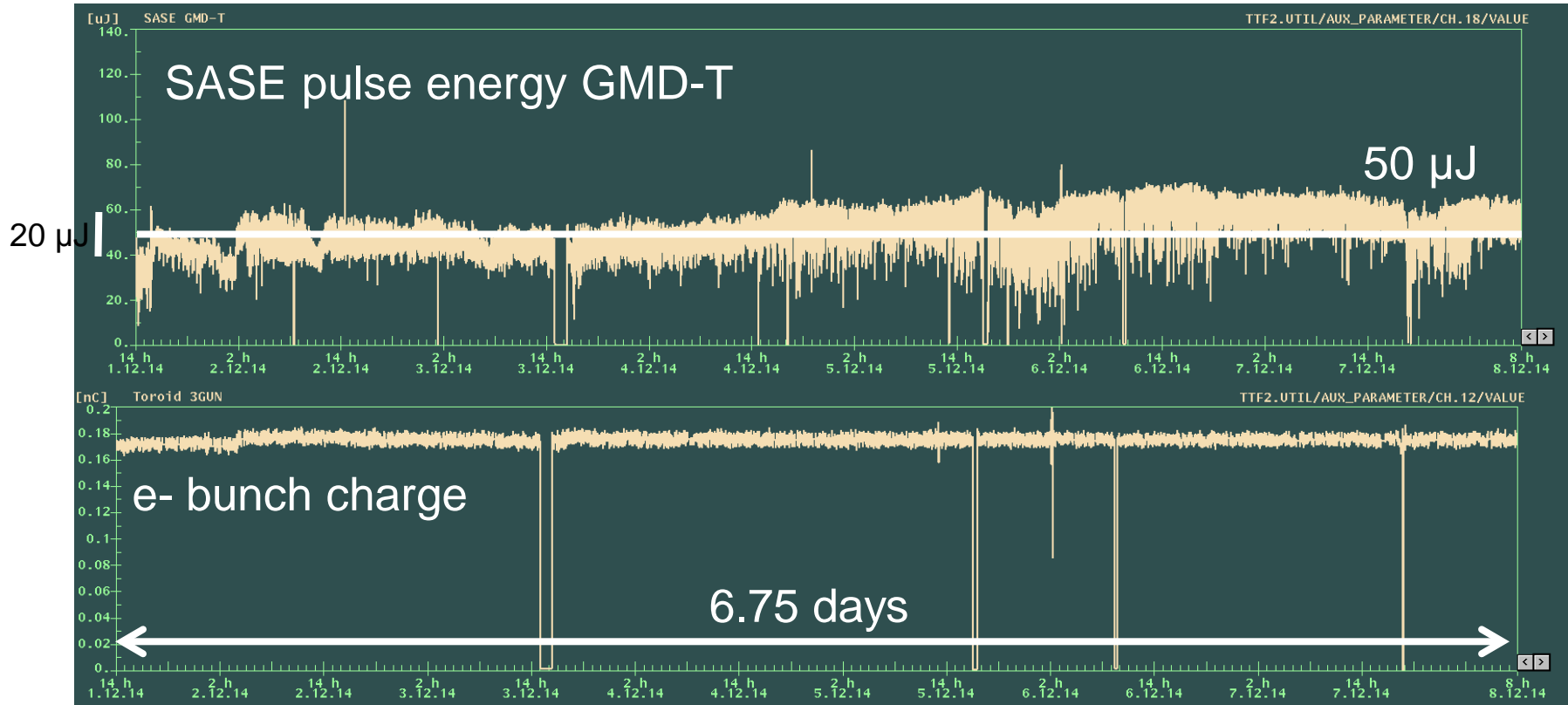
Slow Feedbacks on “physical quantities”

- > 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)



Example SASE for 1 experiment in 1 week

- > SASE Delivery: 96%, tuning 2%, down: 2%
- > 11.5 nm, 1 bunch, 0.18 nC, apertures 3 mm



- > Simultaneous operation of FLASH2 for commissioning

- > 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