Progress at FLASH2 and Experience with Single Spike Lasing at FLASH in the Past 2.5 Years

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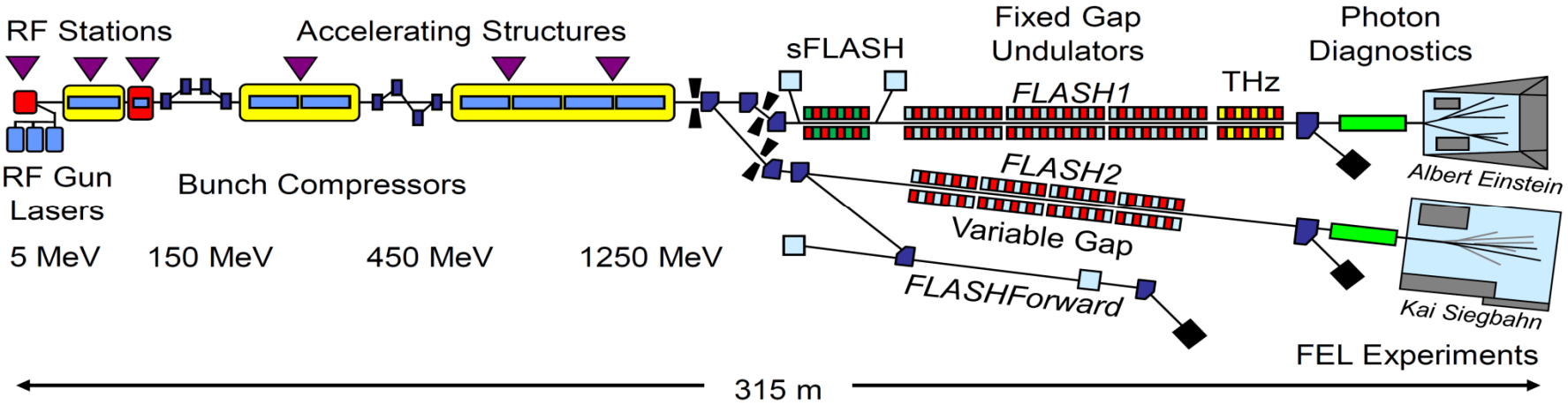
Accelerator Seminar,

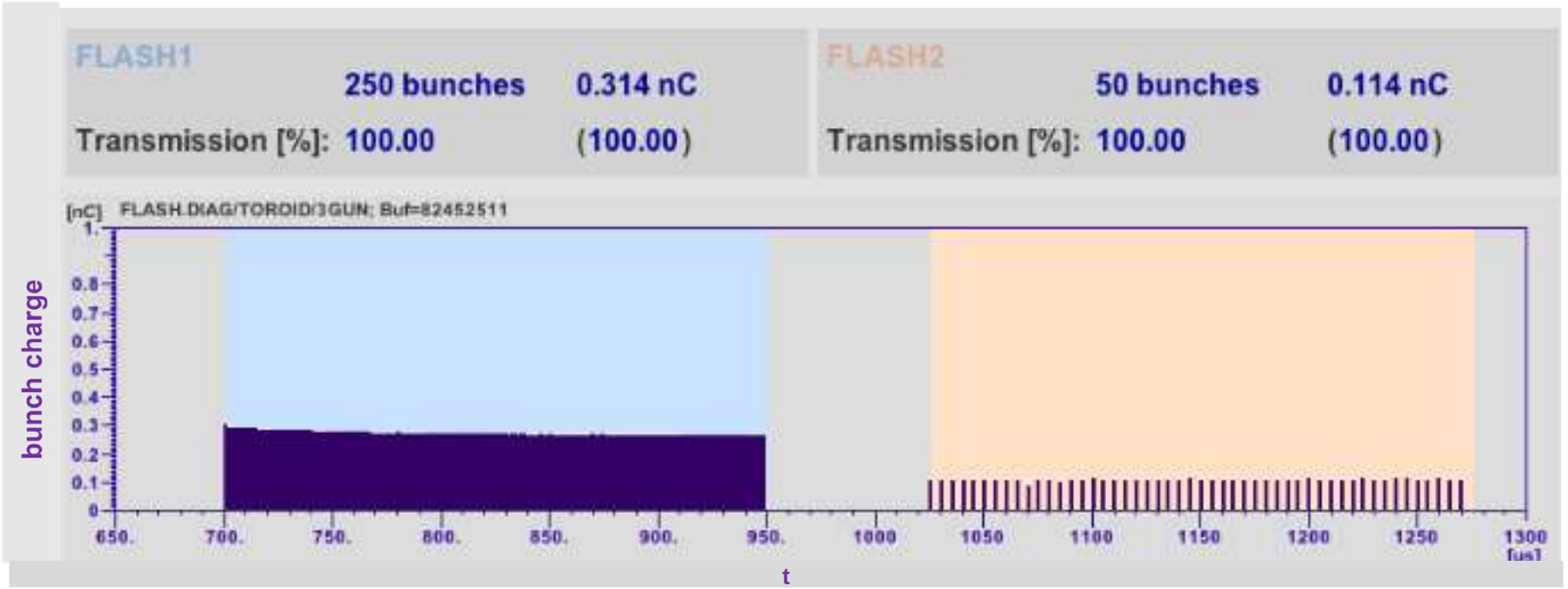
23rd of Januar 2018

Introduction

- Parallel operation of FLASH1 & FLASH2
  - Challenge operation with different charges
- SASE performance FLASH2
- Ultra short pulses
  - Challenges
  - Measurement of short FEL pulses
  - First user operation

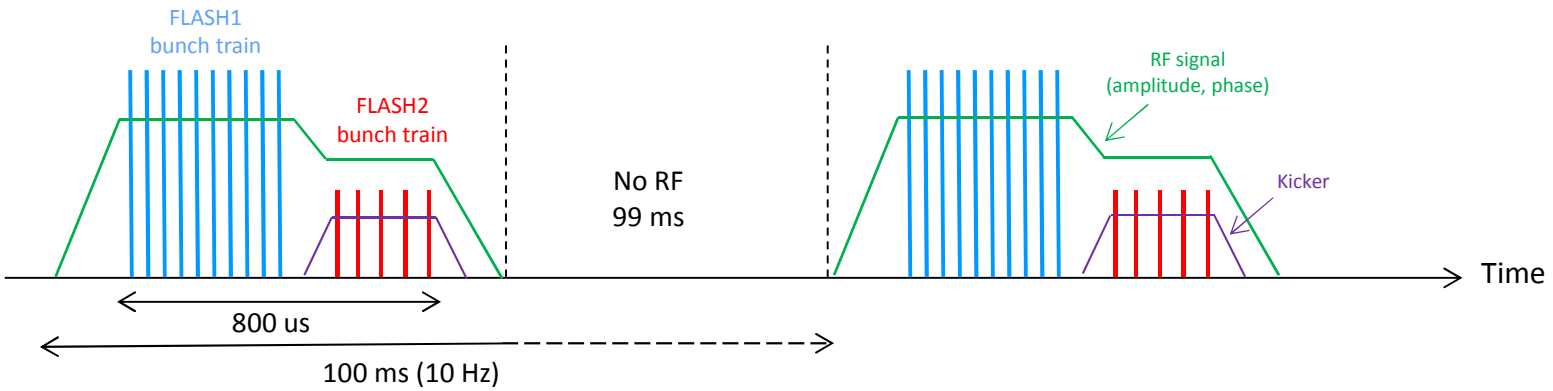
FLASH


RF Stations
Accelerating Structures
sFLASH
Fixed Gap Undulators
Photon Diagnostics
FLASH1
THz
RF Gun Lasers
Bunch Compressors
FLASH2
Albert Einstein
Variable Gap
FLASHForward
Kai Siegbahn
5 MeV
150 MeV
450 MeV
1250 MeV
FEL Experiments
315 m

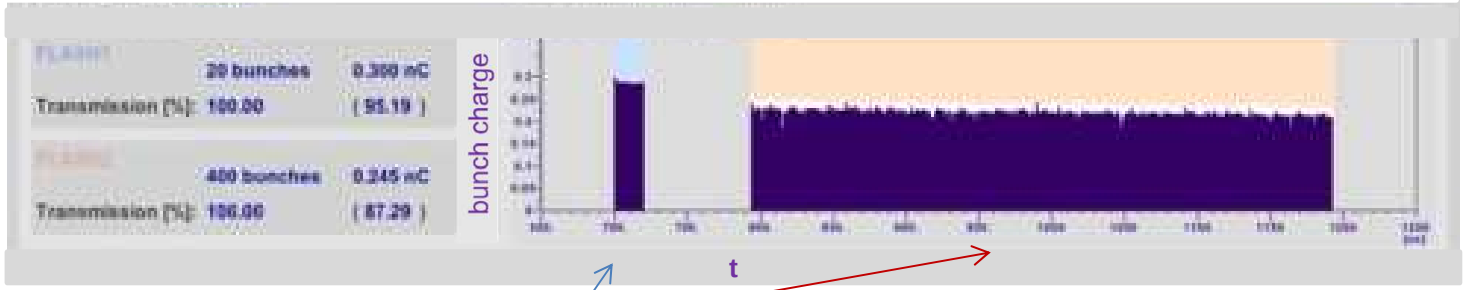

FLASH1
250 bunches
0.314 nC
Transmission [%]: 100.00
(100.00)
FLASH2
50 bunches
0.114 nC
Transmission [%]: 100.00
(100.00)
[nC] FLASH.DIAG/TOROID/3GUN; Buf=82452511
bunch charge
t

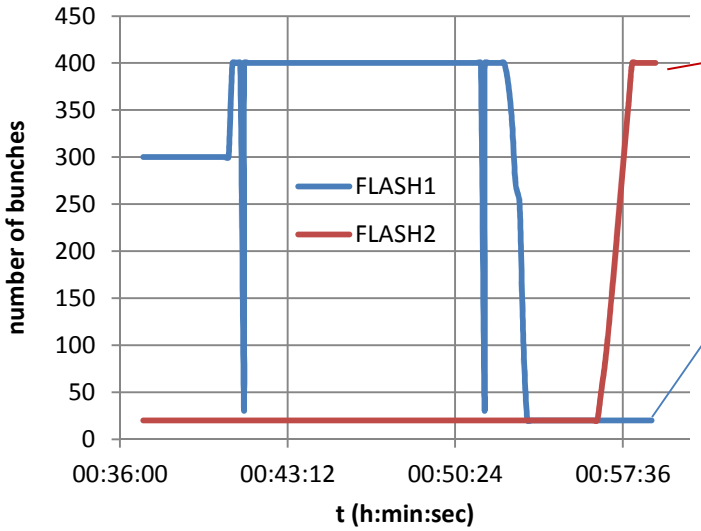
Simultaneous Operation

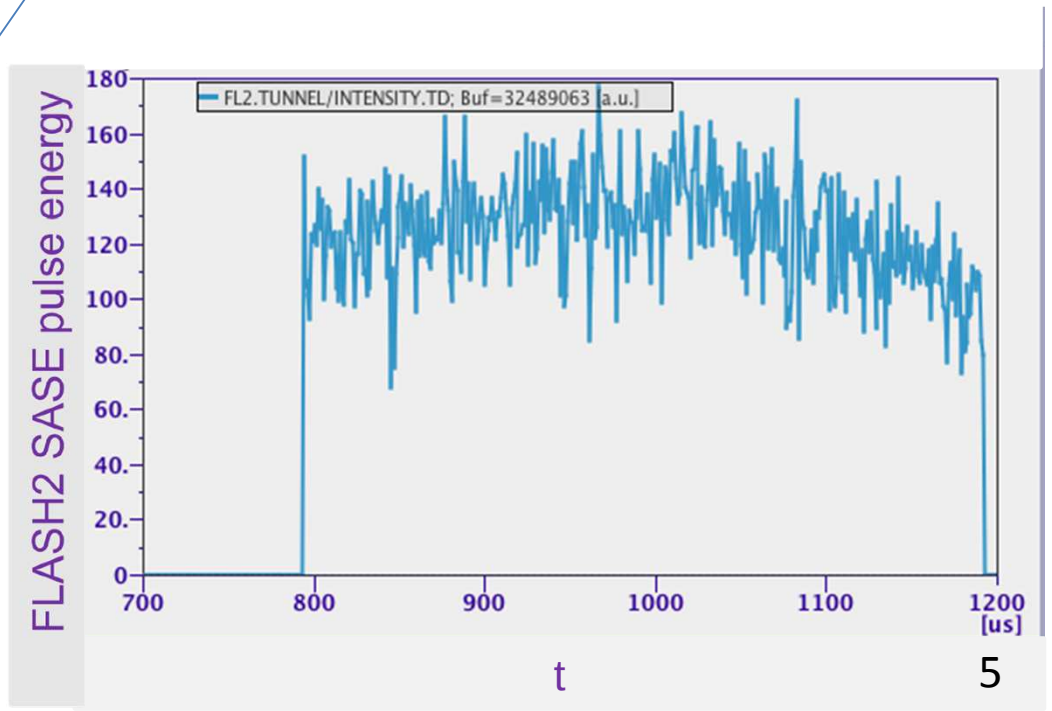
- Two photon experiments - one at FLASH1 and one at FLASH2 – are served simultaneously, both with a 10 Hz pulse train repetition rate
- Take advantage of superconducting accelerator: long RF pulse (1 ms) → long electron bunch train shared between FLASH1 and FLASH2
  - fast kicker and Lambertson septum to extract a part of bunch train to FL2
- Flexibility for photon experiments
  - two undulator beamlines → different wavelengths
  - three photocathode lasers → different bunch pattern and bunch charge
  - flexible RF-system → different amplitude and phase
  - different bunch charge and compression → different pulse durations



Long bunch trains at FLASH 1 & 2.



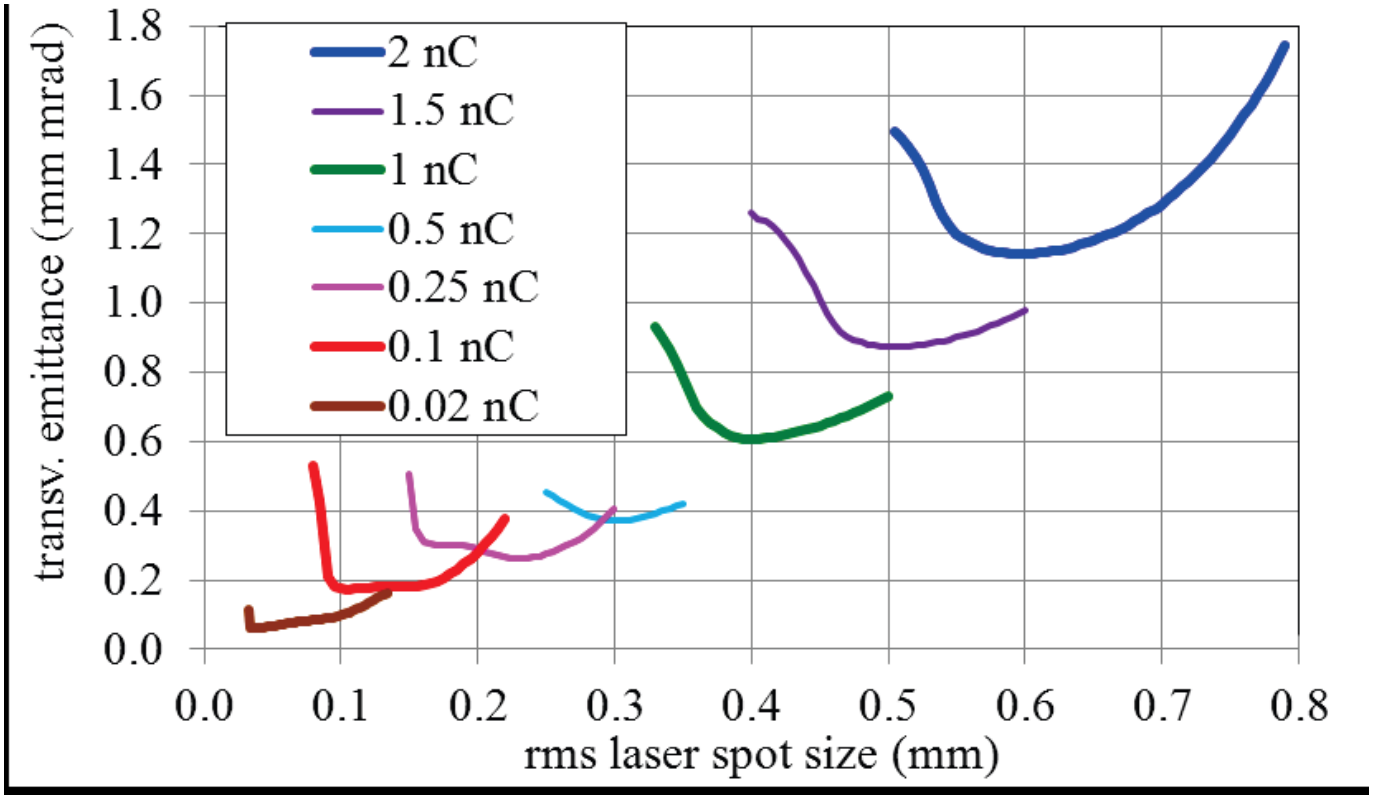




- Fix threshold for integrated losses
- Tolerances for losses are smaller for long bunch trains
- Reference files: both beamlines should be able to run with long bunch trains

Injector laser spot size

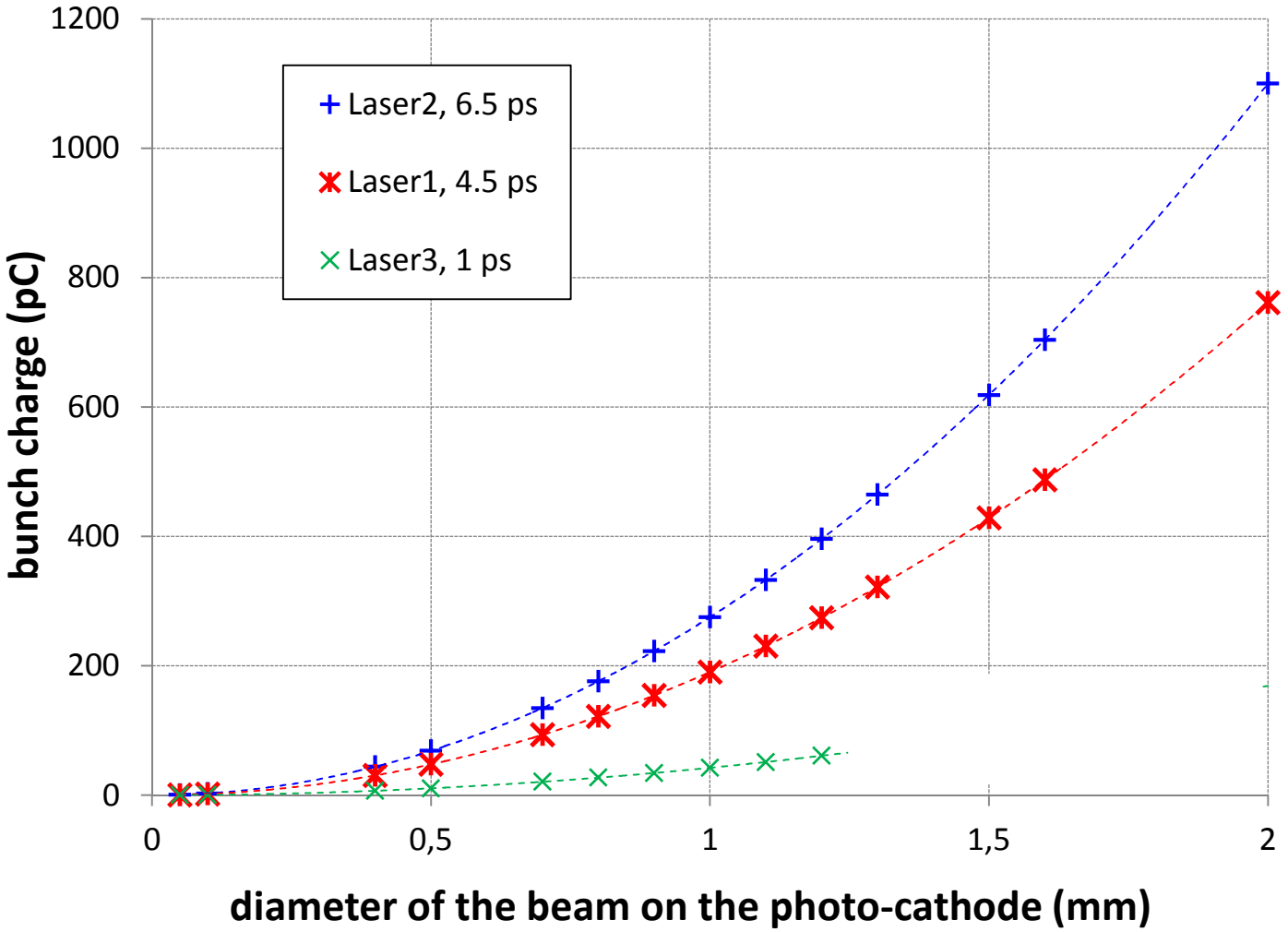
- Bunch charge is key parameter to optimize the FEL pulse properties
- Results from PITZ
- rms laser spot size at the cathode
- Too small spot size → space charge emittance degradation
- Too large spot size → RF & thermal emittance degradation
- The value depends on the laser pulse duration



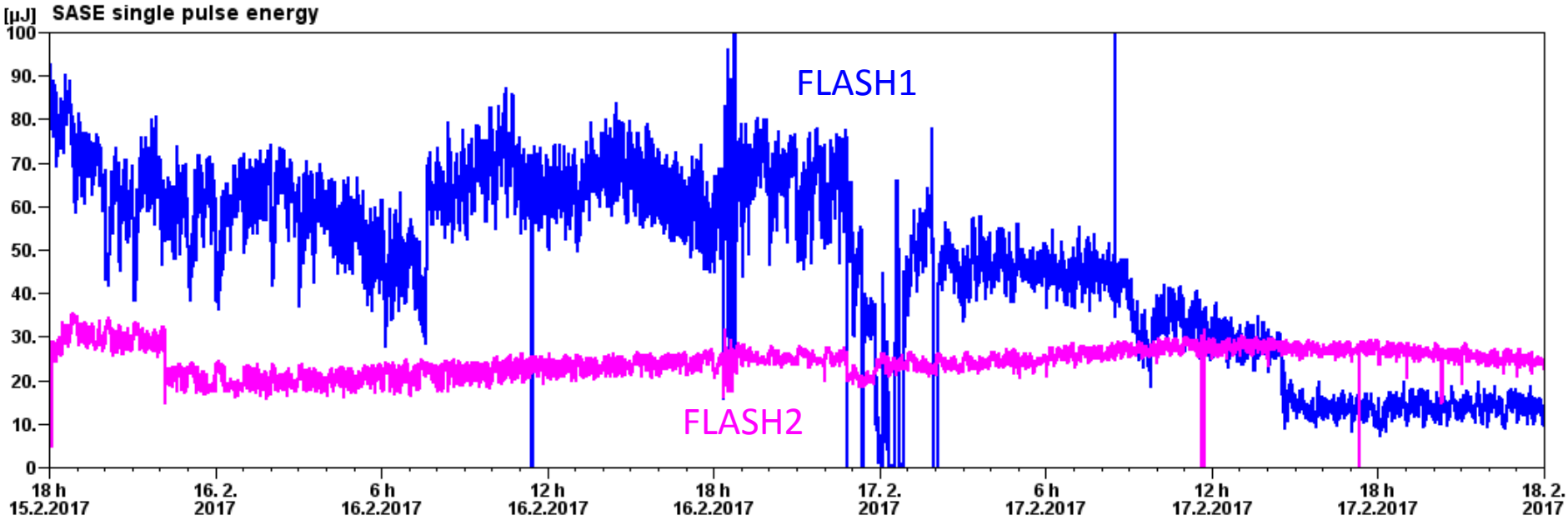
M. Krasilnikov et al., "**PITZ EXPERIENCE ON THE EXPERIMENTAL OPTIMIZATION OF THE RF PHOTO INJECTOR FOR THE EUROPEAN XFEL**", Proceedings of FEL2013, New York, NY, USA

Injector laser spot size

- The fit is based on emittance measurements at PITZ and adapted to FLASH settings assuming a transv. flat-heat distribution
- Flat head diameter of the beam at the cathode is defined by the BSA (beam shaping aperture)
- Laser1&2 share a BSA
- Laser3 has an independent BSA



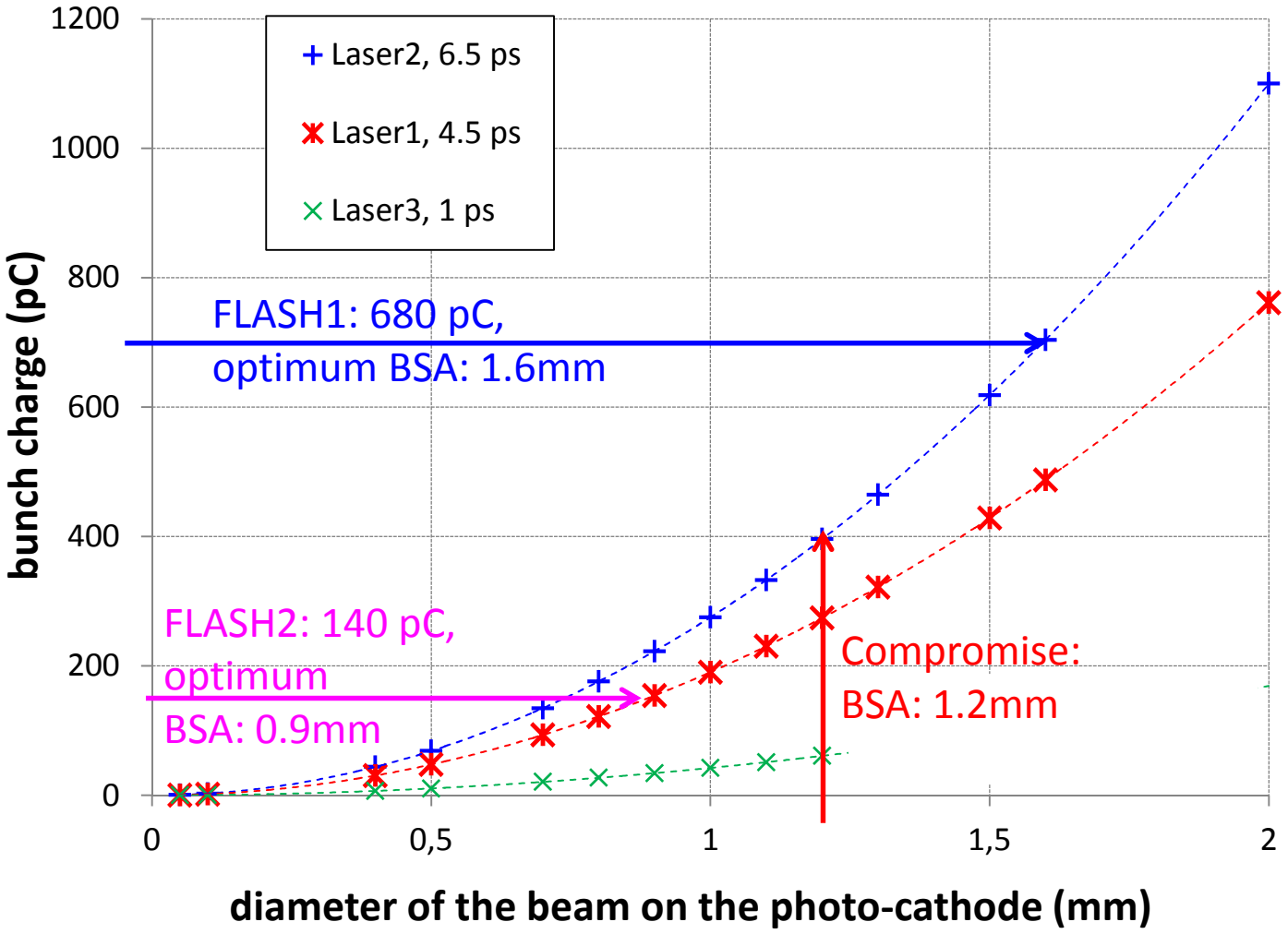
Example: Parallel operation (extreme case)



- SASE single pulse energy during 54 hours of the experiments in parallel operation
- FLASH1: 20.8 nm, single bunch with **680 pC**, THz-radiation was used
- FLASH2: 53 nm, 30 bunches with 10 µs spacing (100 kHz), and **140 pC**
- About a factor **5** charge difference

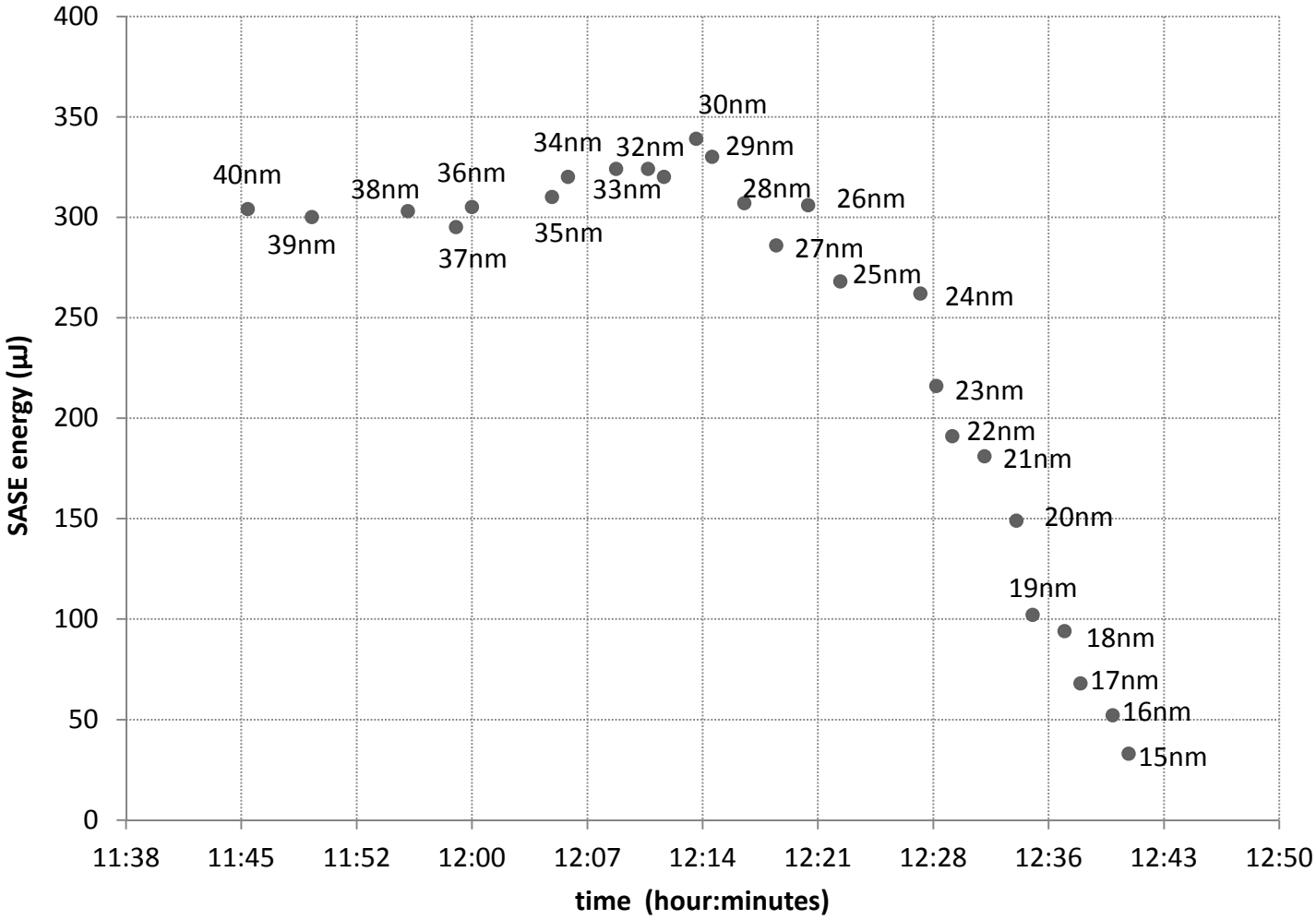
Injector laser spot size

- Laser1&2 share a BSA
- Laser3 has an independent BSA
- Solenoid can not be changed independently, but gun phase can be used



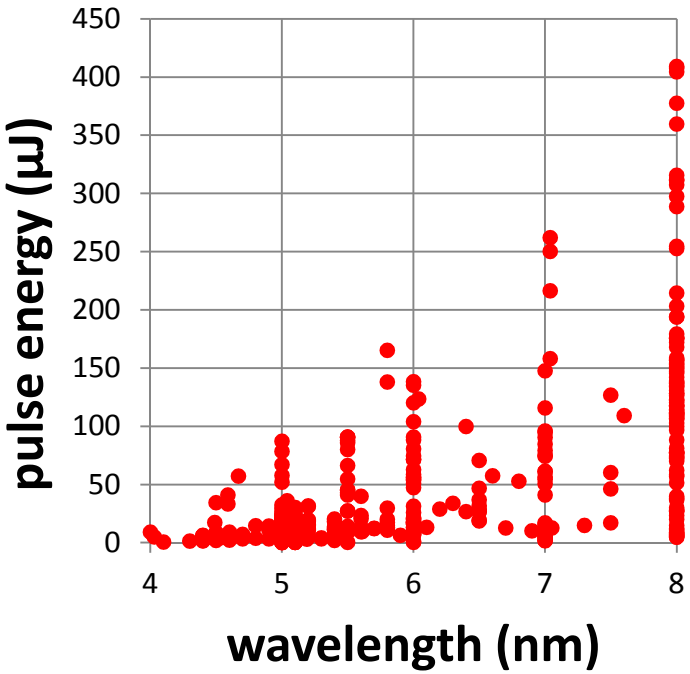
Fast tunability of FLASH2

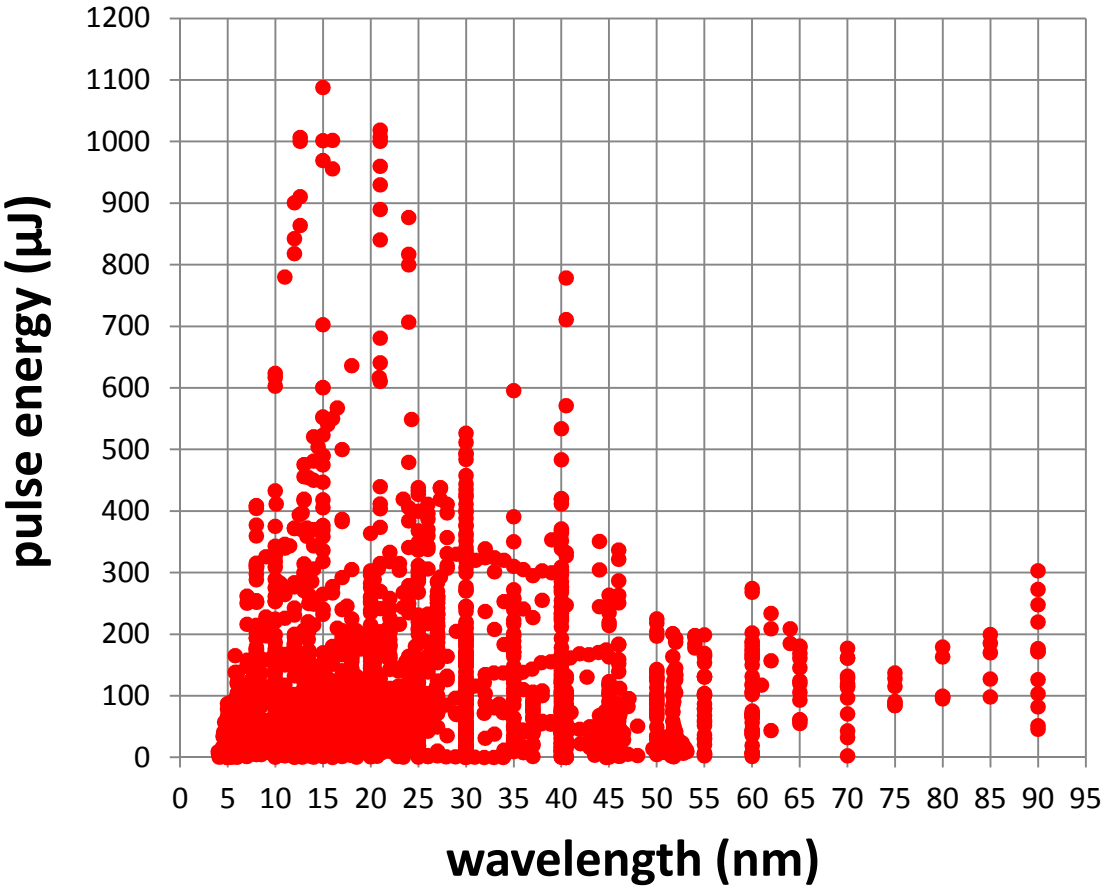
- FLASH1: 13.57 nm for users
- FLASH2: Wavelength scan from 40 to 10 nm
- 26 wavelength in 55 minutes
- -> change wavelength in a 1nm step took in average 2 minutes



Achievements FLASH2

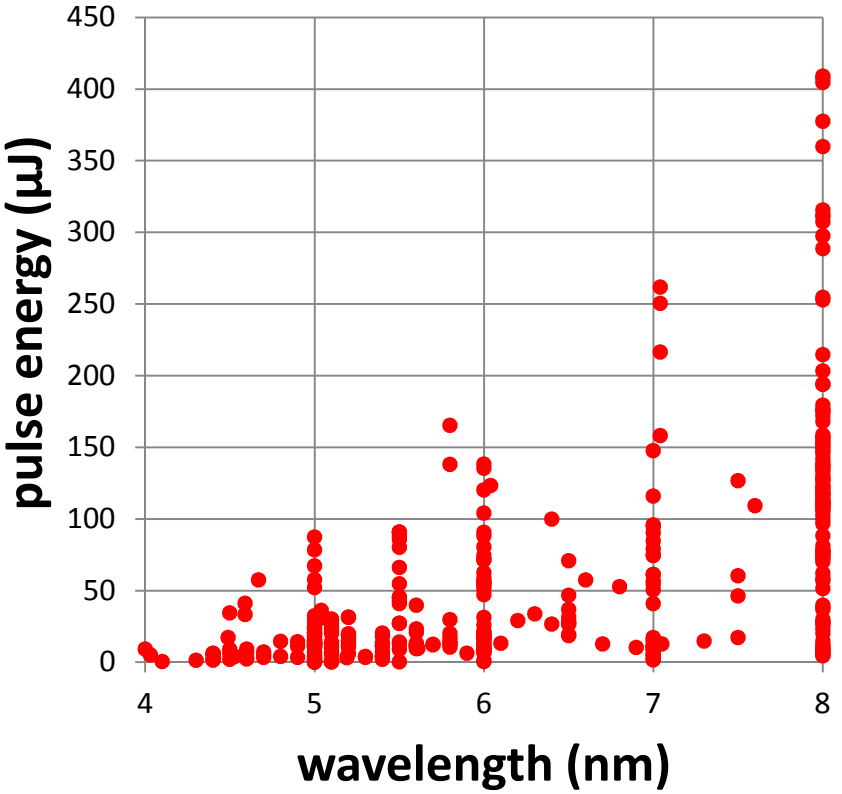
- FEL pulse energies:
  Sept 2015 – April 2017

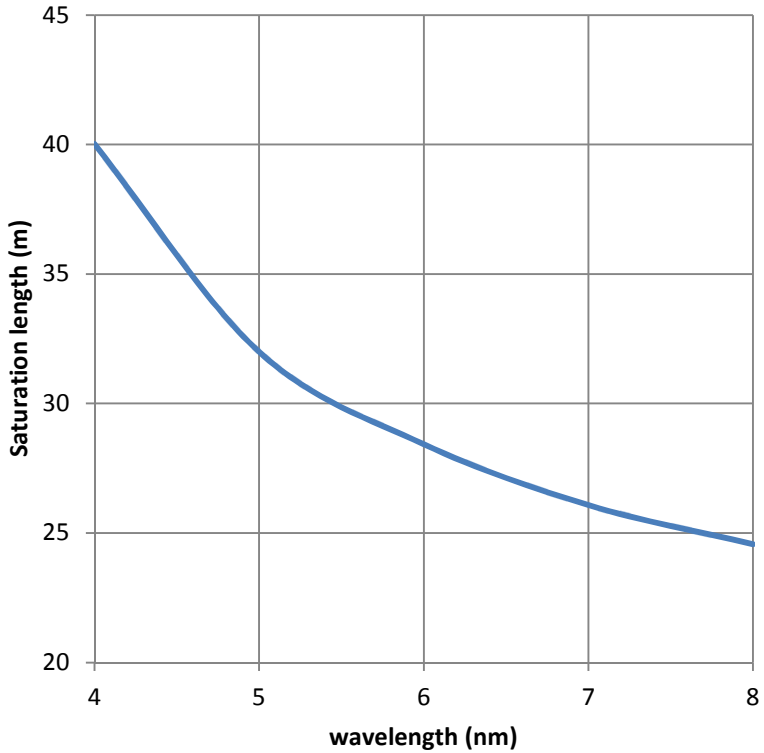




Achievements FLASH2

Small wavelength can only be achieved with small K, requires longer gain length

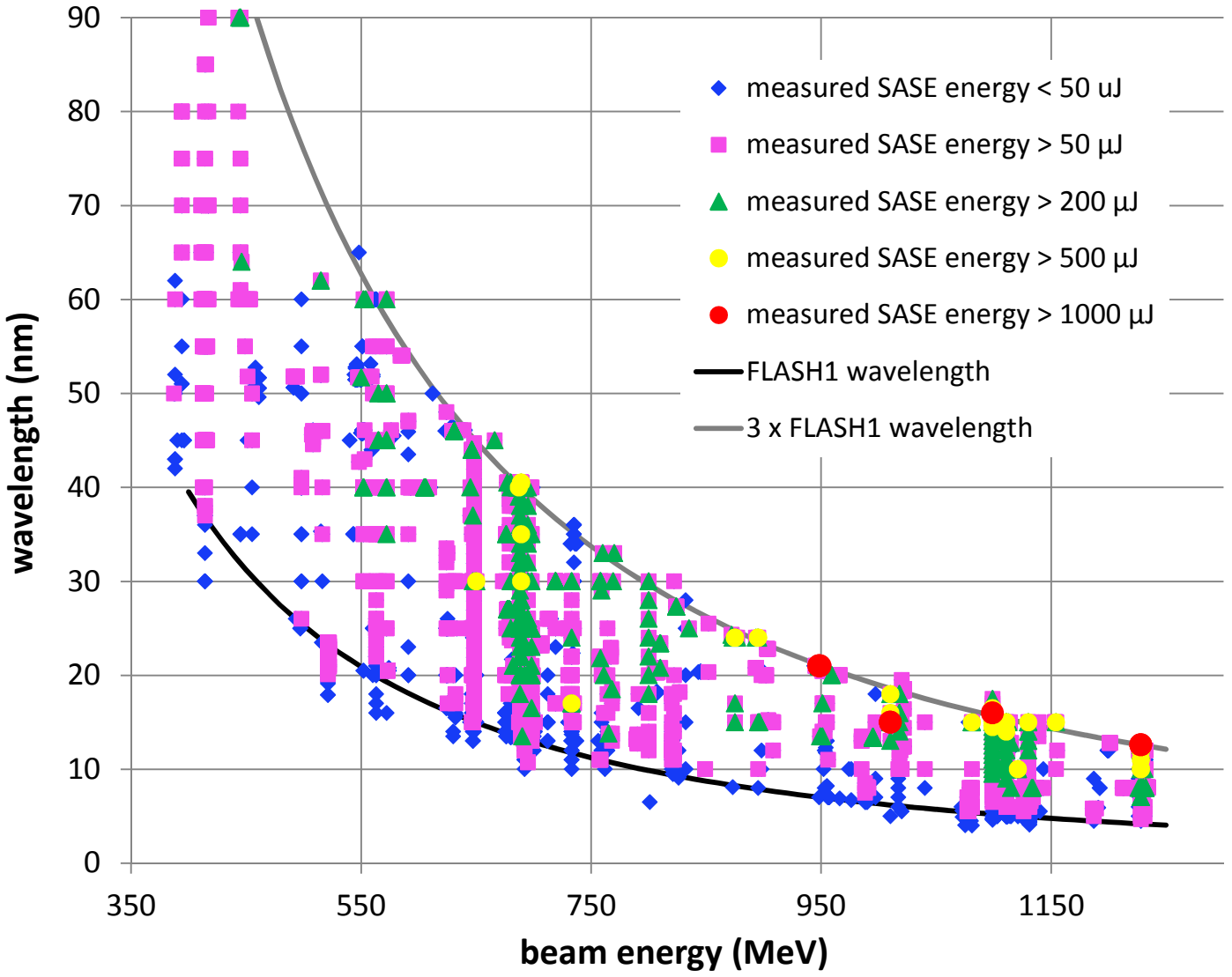




Beam energy:1.25 GeV,
Peak current. 1.5 kA,
Emittance: 1.4 mmrad,
Energy spread: 0.5 MeV

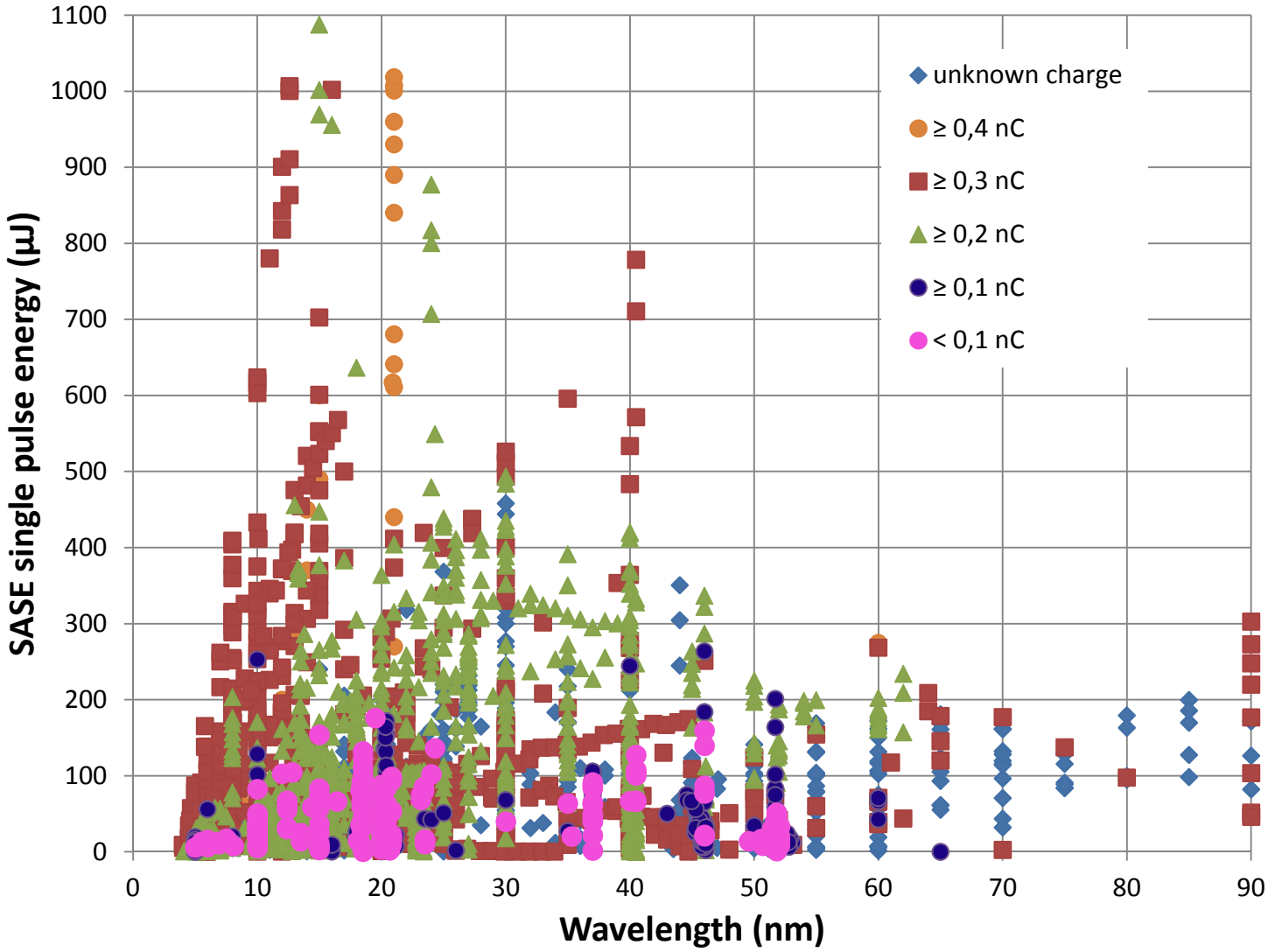
Achievements FLASH2

- wavelengths as a function of the beam energy (Sept 2015 – April 2017)
- An increase of the SASE pulse energy by up to a factor of two was observed



Achievements FLASH2

- FEL pulse energies depending on the bunch charge: Sept 2015 – April 2017



Towards short pulses

Compression Factor C

C ≈ 32-65

6500 fs initial bunch duration → **≈ 100-200 fs**

Q ≈ 1000 pC

The minimum radiation pulse duration :

$$\tau\,(\mathrm{FWHM}) = \frac{M\,\lambda_r\,L_{sat}(\lambda_r,\gamma,K)}{5\,c\,\lambda_u}$$

130 - 220

6500 fs → **≈ 30 - 50 fs**

250-100 pC

Space charge forces require to reduce the charge

6500 fs → ~~3 fs~~

2000

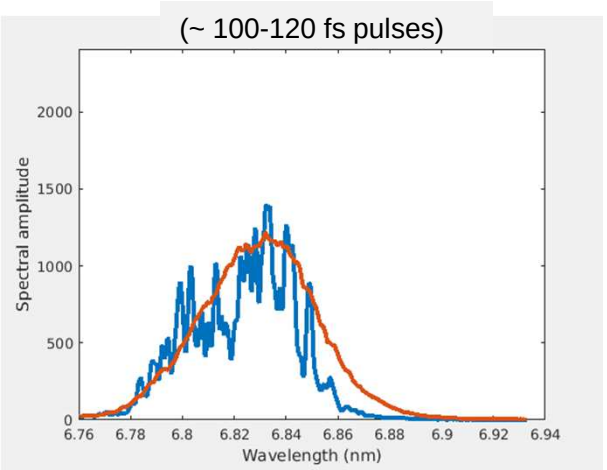
15 pC

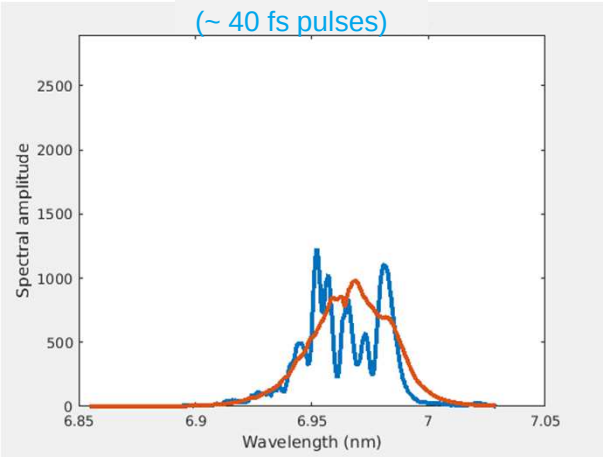
RF tolerances limit possible compression

C ≈ 50 → 330

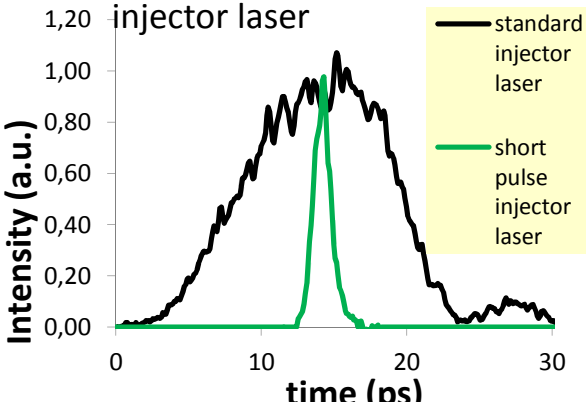
1000 fs → **30 fs → 3 fs**

Q ≈ 100 pC → 15 pC





Streak camera measurement of injector laser

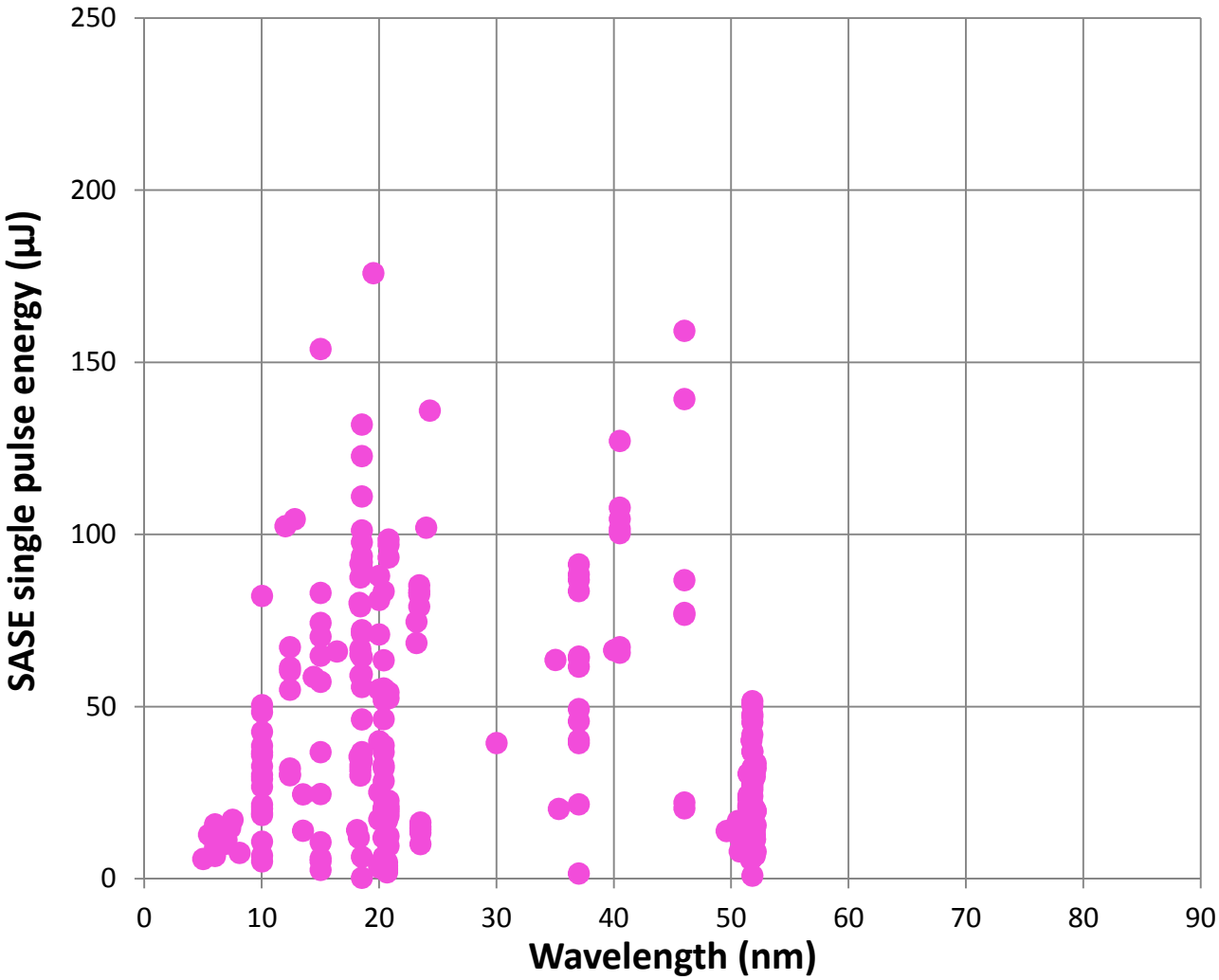


FLASH2 operation with Laser 3

- FLASH2 operation with charges <100pC
- FLASH2 diagnostics optimize for low charge operation

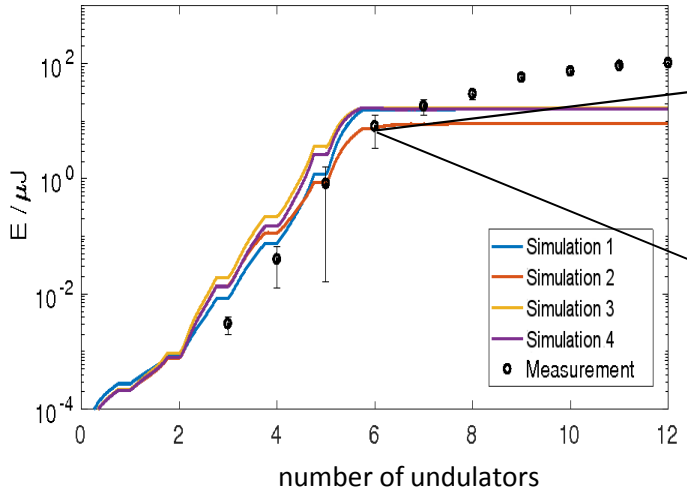
Difficulties

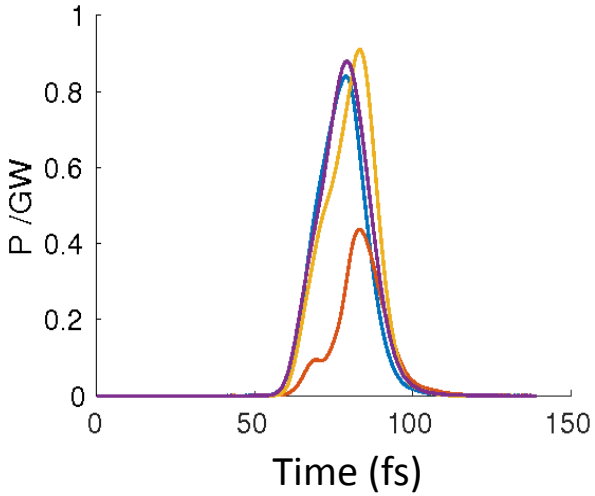
- currently no bunch length-diagnostics available
- spectrometer does not resolve single modes

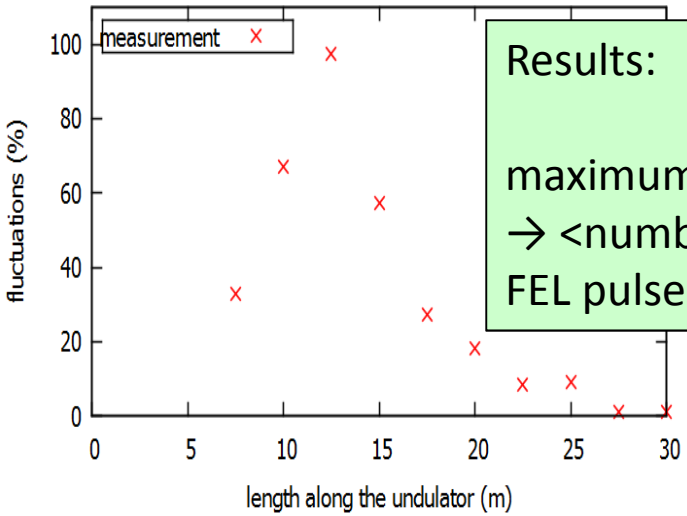


FLASH2: single-spike

For 41 nm XUV radiation at FLASH2

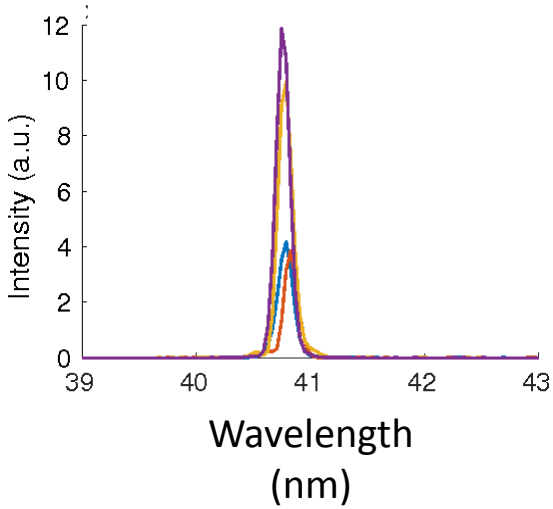






Results:

maximum fluctuation: 97%
→ <number of modes>: 1.05
FEL pulse duration: 6 fs (rms)



courtesy of F. Christie

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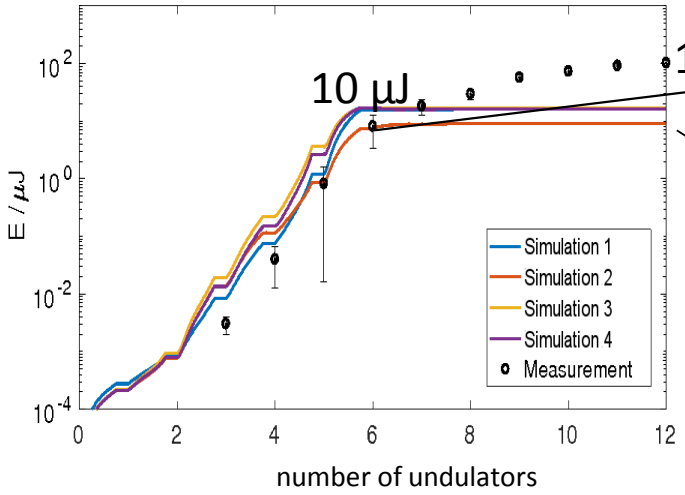
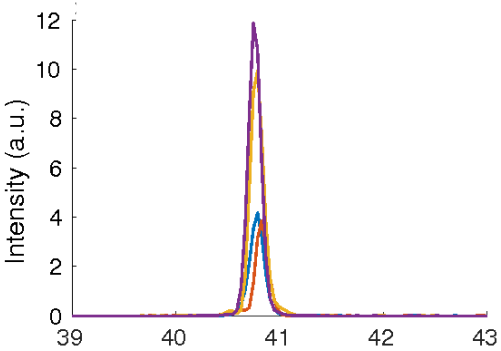
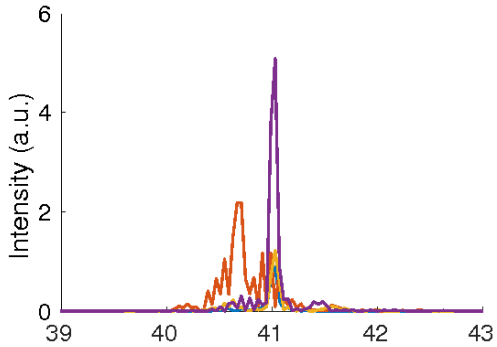


after the 6th undulator



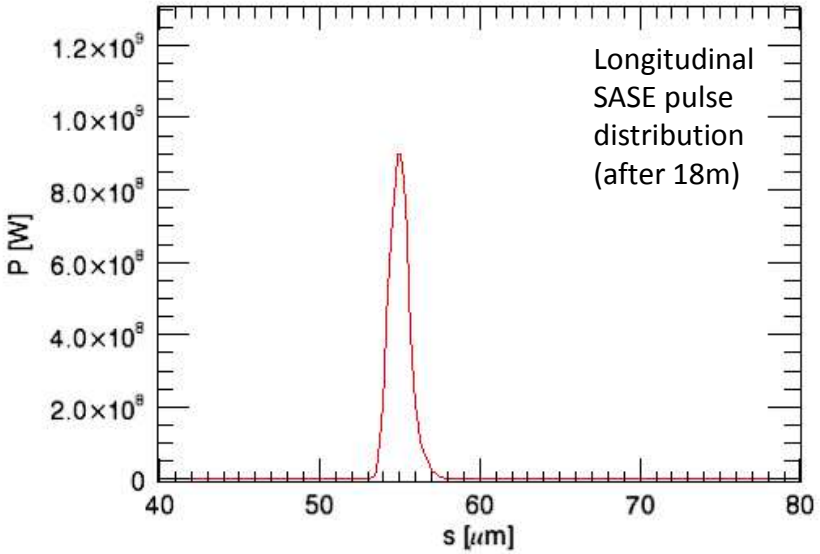
after the 12th undulator

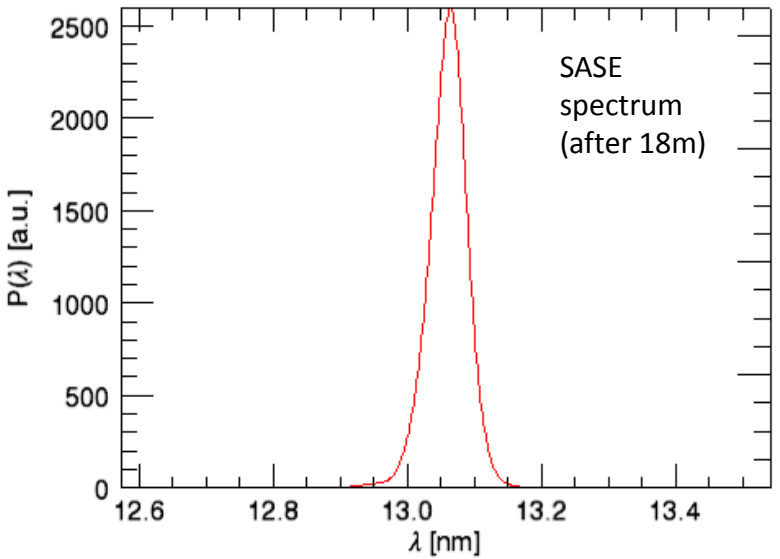


- Single spike pulses suffer from slippage effects elongating the bunch in saturation
- Variable gap undulator allows to chose the correct undulator number

courtesy of
F. Christie

FLASH1: single-spike

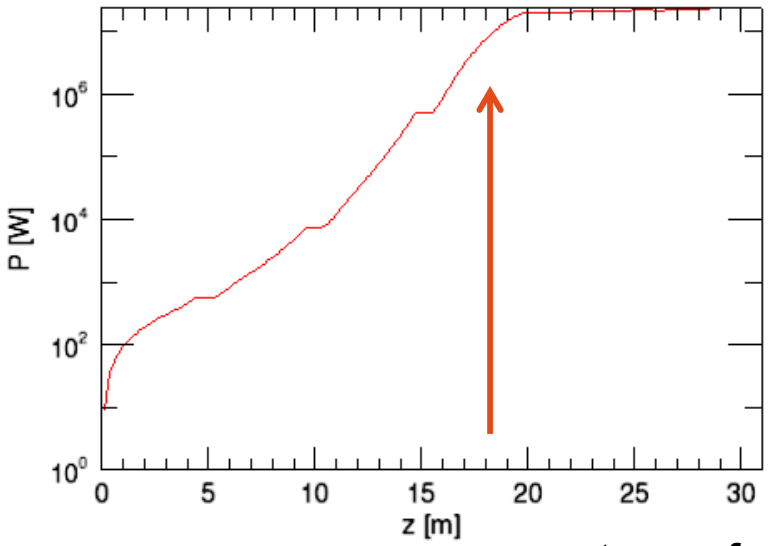




Genesis 1.3 simulation for FLASH 1

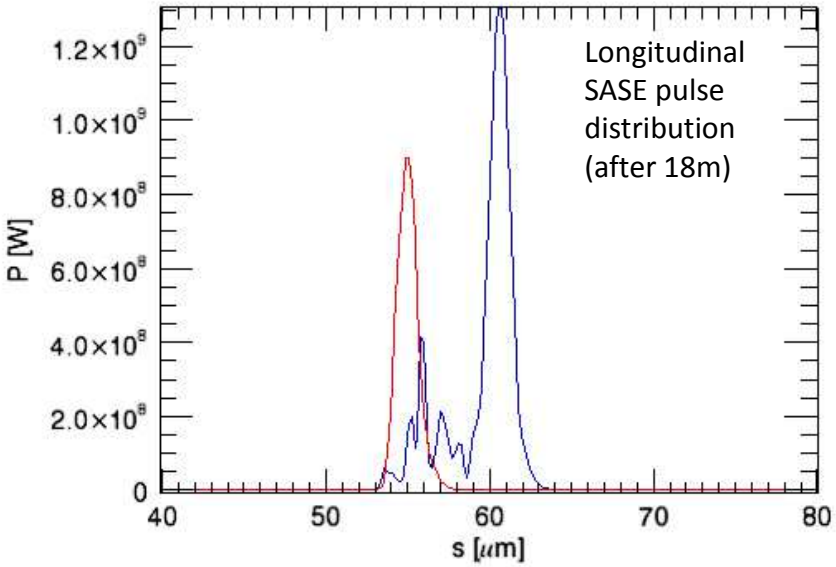
Bunch charge: 20 pC
Emittance: 1.4 mm mrad
Rms bunch length: 1.0 µm

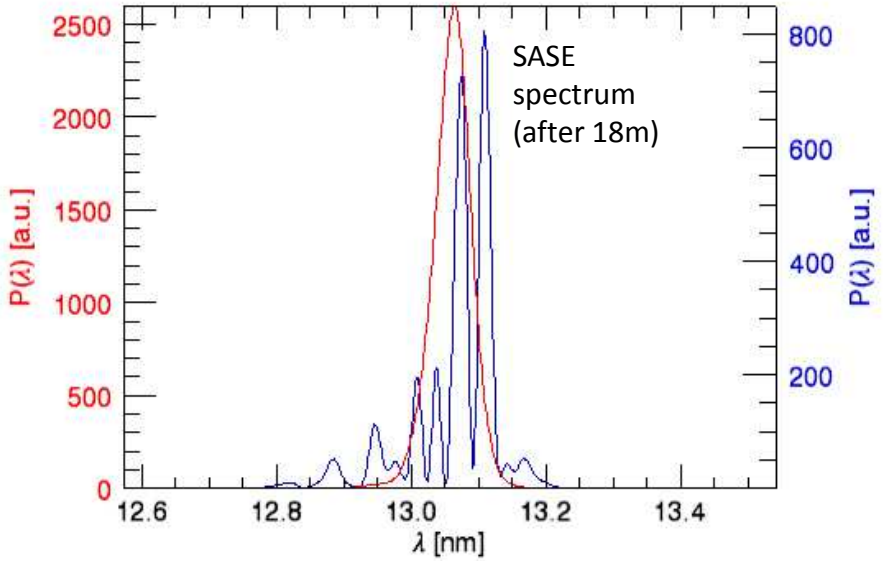
Gaussian bunch profile



courtesy of
M. Rehders

FLASH1: single-spike





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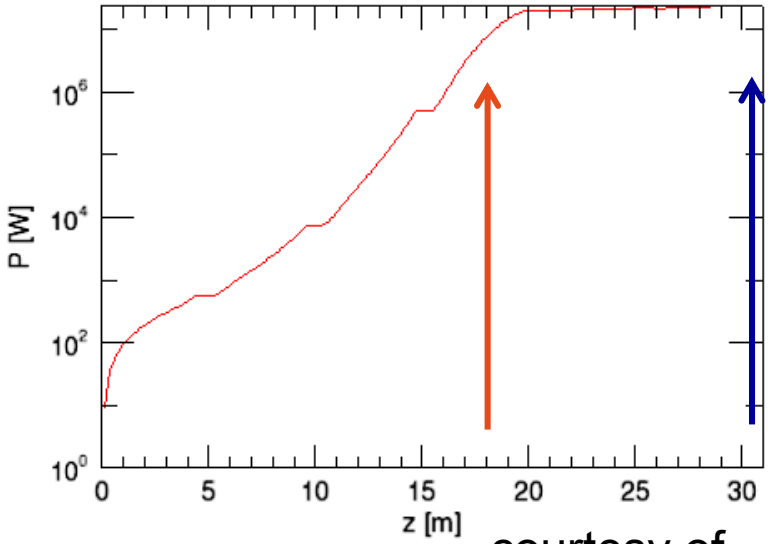
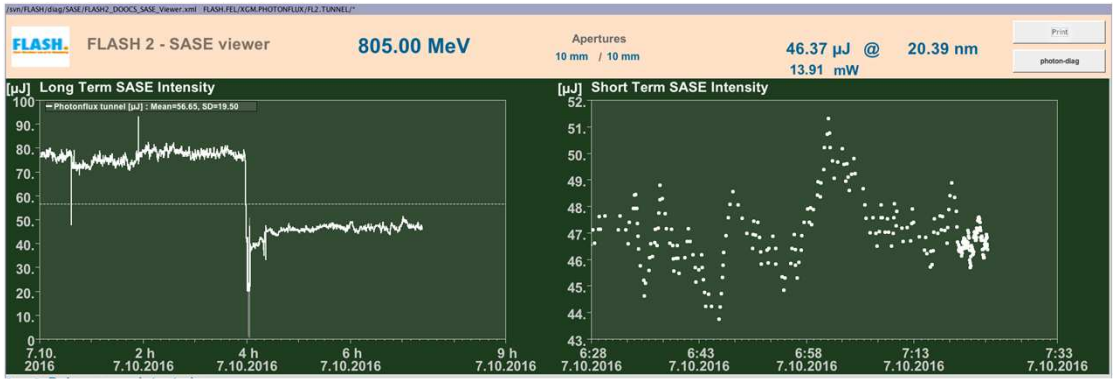


- Fixed gap undulators does not allow simply to avoid slippage
- Interrupt SASE process to preserve the single spike.

courtesy of
M. Rehders

First users with the short pulse laser at FLASH2

- First users with ultra-short pulses
  - Parallel FLASH operation FLASH1 (Laser2) & FLASH2 (Laser3) …
- User experiment: ultra-fast magnetic dynamics, (30.9.2016 - 7.10.2016)
  18.5 nm, 100 bunches, 250 kHz, **<50 fs, 10 µJ**
- changing requirements to the beam:
  - 45µJ, 12 undulators, ~ 60pC
  - short: 13-20µJ (7µJ in the experimental hall), 9 undulators, ~60pC
- User experiment: Dynamics of Proton Transfer through a hydrogen bond,
  51.8 nm, 80 bunches, 200kHz, 50 fs, 10 µJ

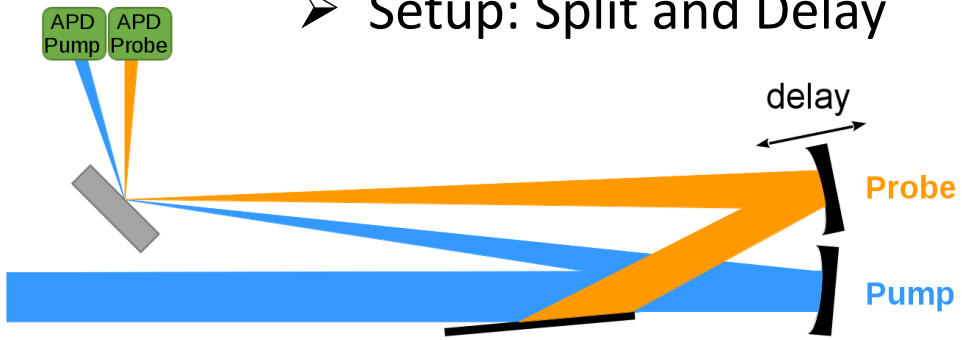


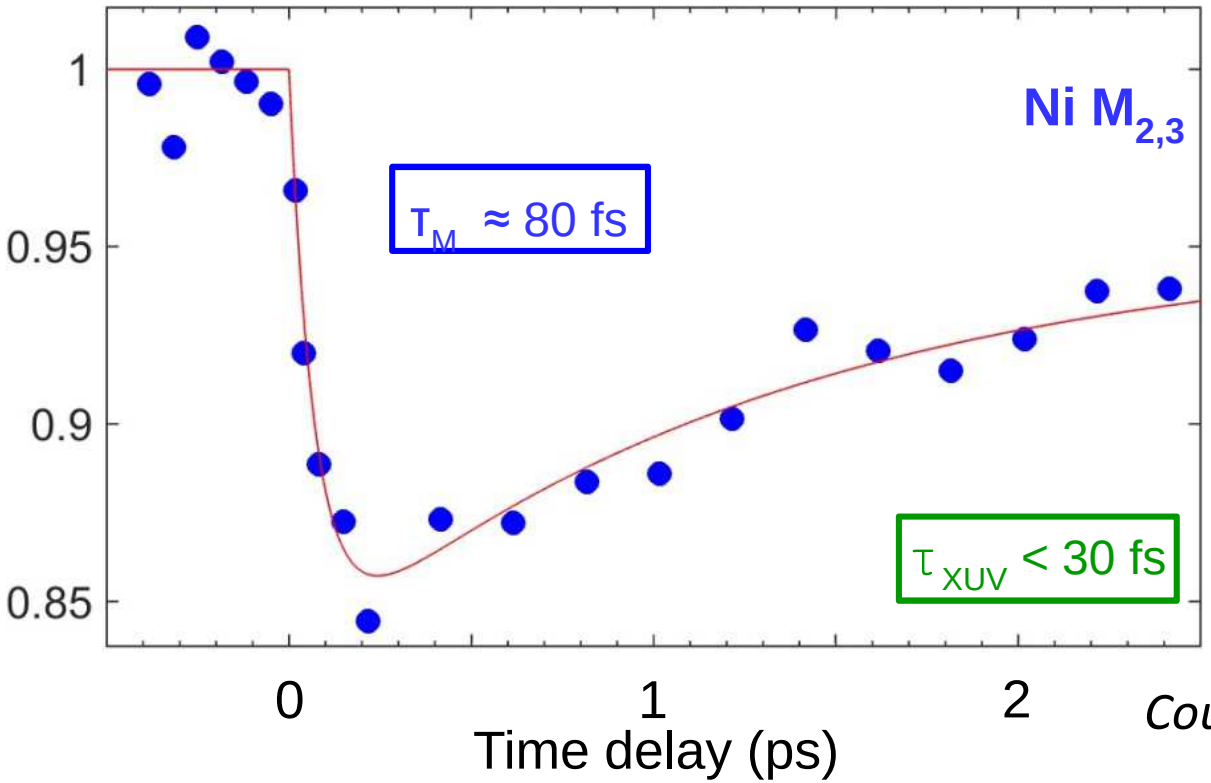
User experiment with ultra-short pulses

(Group: J. Lüning) : Ultra-fast demagnetization

- Goal: Measure demagnetization in Ni

- Setup: Split and Delay



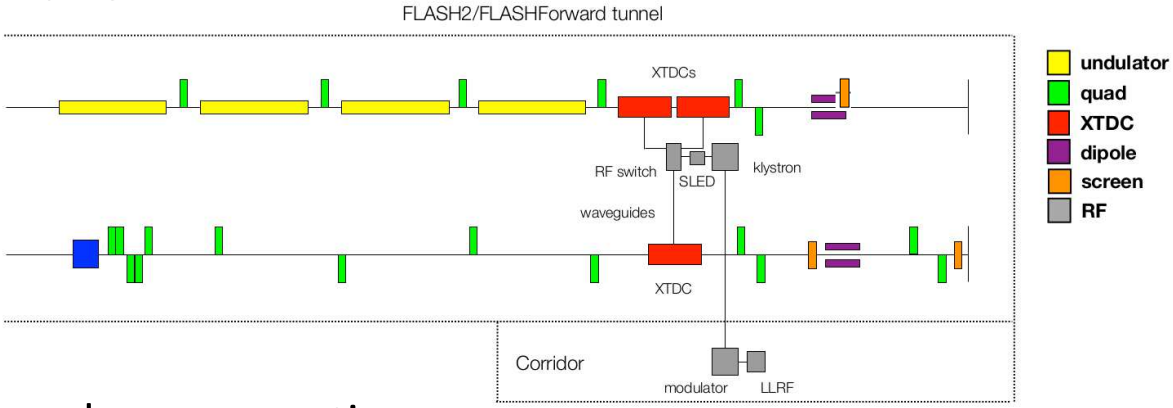


measurement resolution: <10 fs

Courtesy: J. Lüning

X-band deflecting cavity at FLASH2

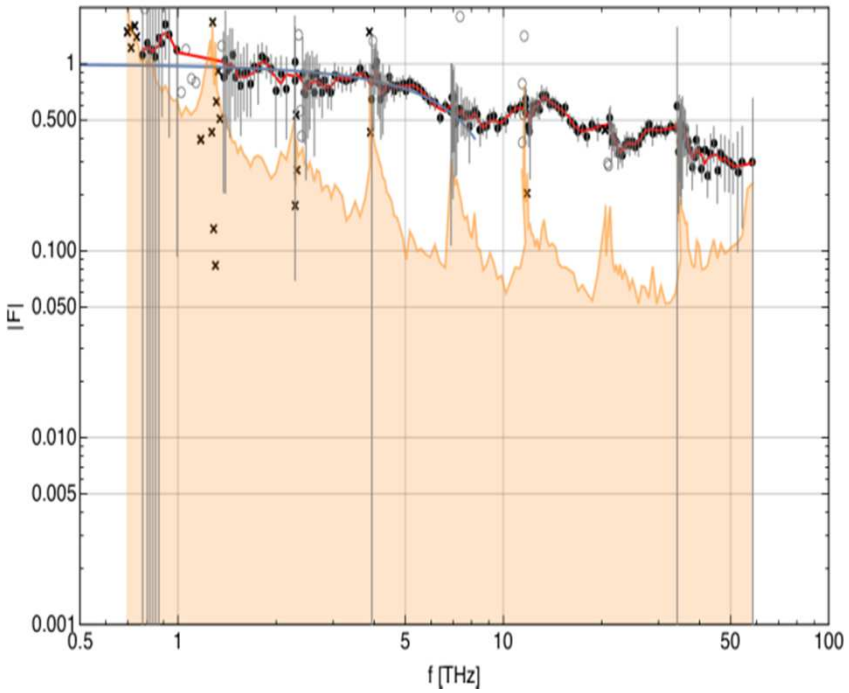
- Two X-band transversely deflecting cavities will be installed downstream of undulators sharing a klystron with FLASHForward
- Together with Simbad and FLASHForward
- Coordinated by B. Marchetti
- In cooperation with CERN and PSI
- Longitudinal phase space distribution can be measured with and without lasing

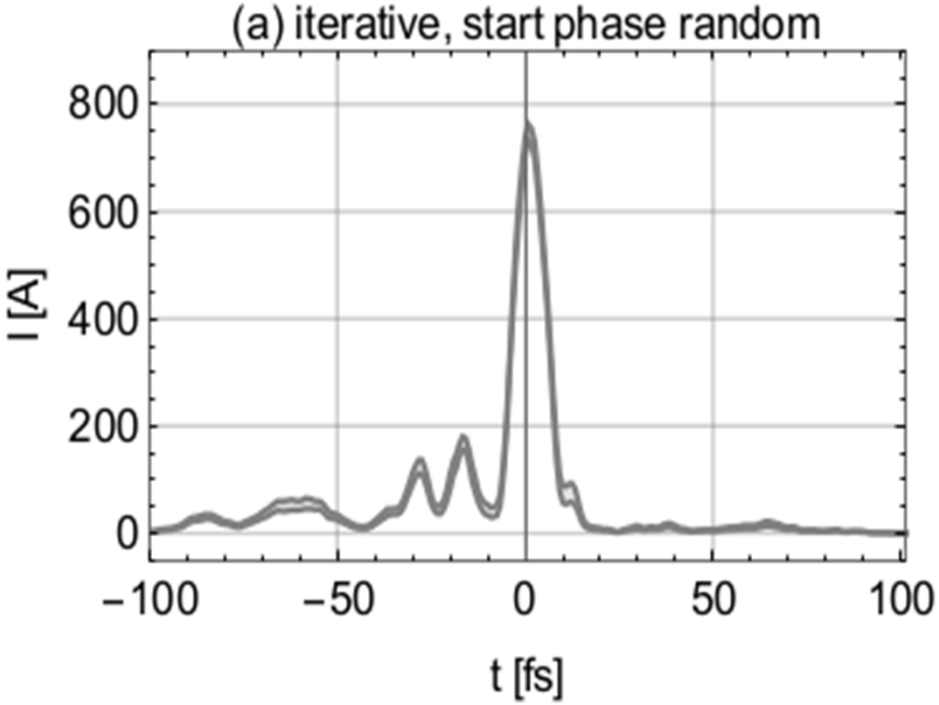


Courtesy: R. D'Arcy

- Worst case resolution for low charge operation: $\sigma_t = 1.7$ fs, $\sigma_E = 1.6 \cdot 10^{-4}$ ($\varepsilon_N = 1$ mm mrad, $\mathrm{p} = 1.2$ GeV, $\mathrm{V}_0 = 35$ MV)
- F. Christie (PhD student) is working on the FLASH2 design

Bunch duration measurements at FLASH 1





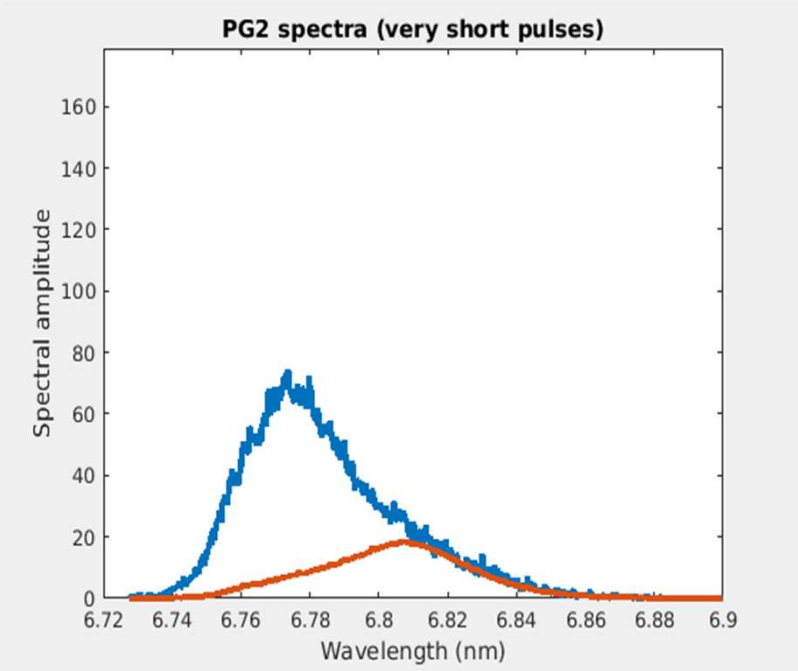
7+/-1 fs (FWHM)

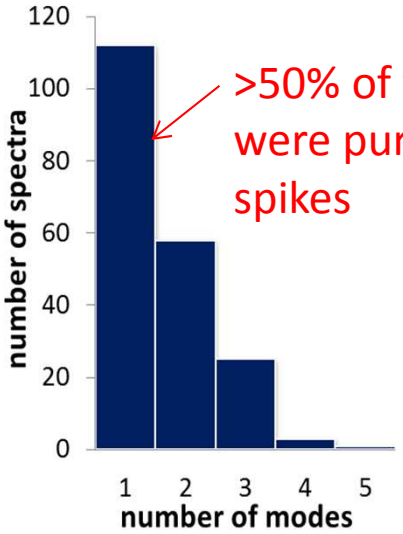
rms of the spike → ~3 fs

Courtesy: B. Schmidt

Single-spike operation

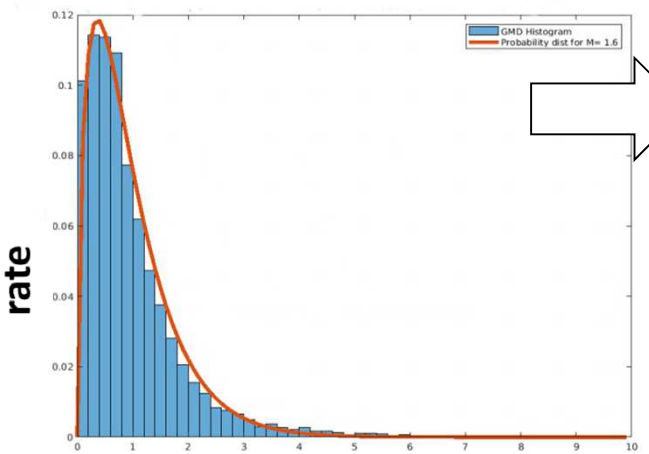
For 6.8 nm XUV radiation at FLASH1 (2016)





>50% of the shot were pure single spikes

M = 1.6

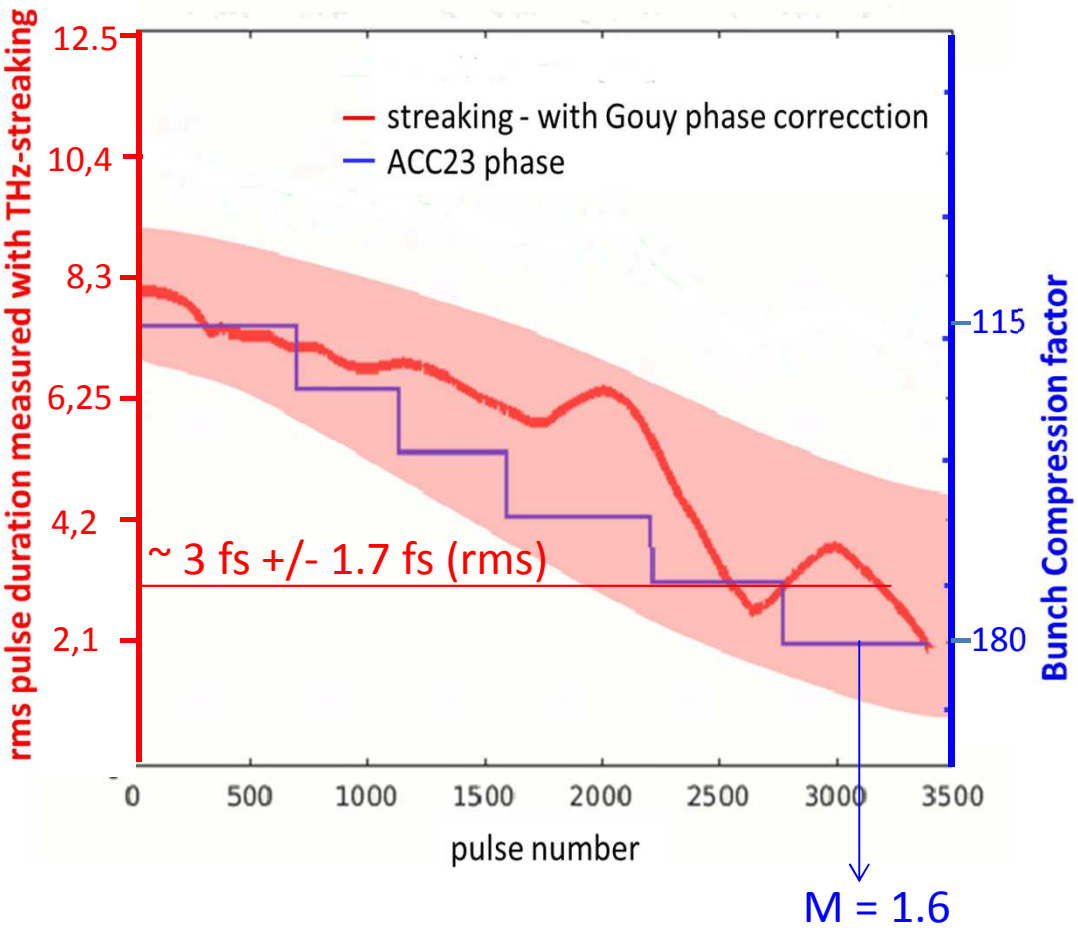


M = 1.6

Probability distribution of SASE energy and mode counting show comparable results.

Ultra-short pulses

For 6.8 nm XUV radiation at FLASH1



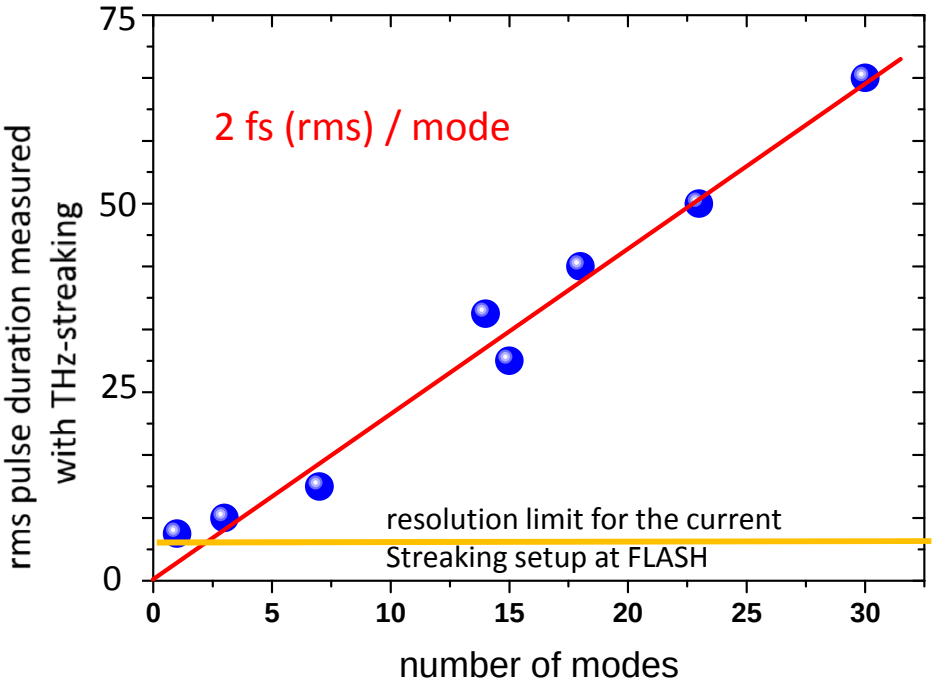
- The minimum radiation pulse duration :

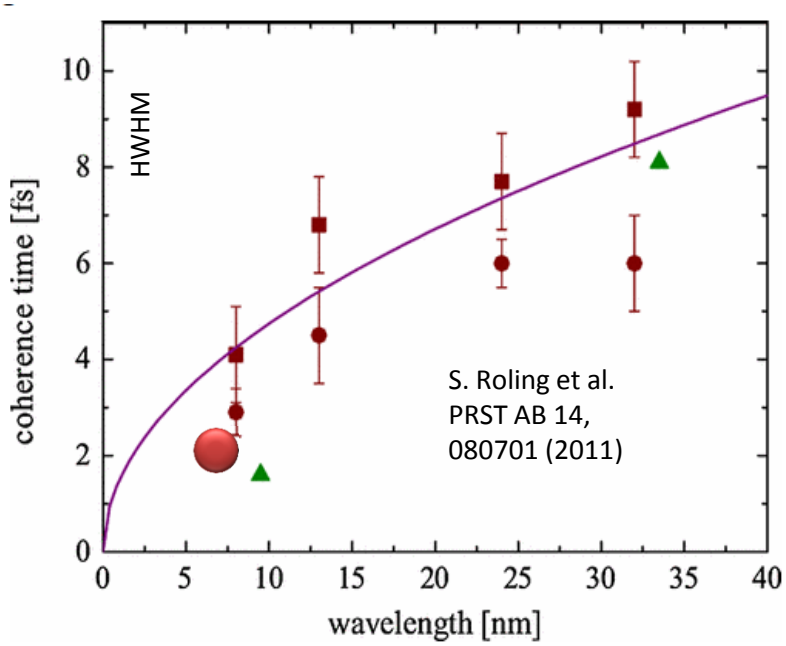
$$\tau\ (\text{FWHM}) = \frac{M\ \lambda_r\ L_{sat}(\lambda_r, \gamma)}{5\ c\ \lambda_u}$$

  - $M = 1.6$
  - $\lambda_r = 6.8$ nm
  - L_{sat} = 35 m +/- 3 m

- $\tau\ (rms)$ = 4 fs +/- 0.4 fs

Ultra-short pulses





Summary

- Routinely FLASH1 and FLASH2 run in parallel (98% of the time during user operation)
- High charge differences and in general high charges in FLASH1 are challenging to set-up
- Measurement of ultra-short FEL- pulses is not a standard diagnostic:
  - At FLASH1 spectral measurements and THz measurements can only be performed by experts of the FS group
  - At FLASH2 currently only gain curve measurements give an idea about the pule duration but bunch length and photon pulse length diagnostics is in preparation
- An X-band TDS is planed at FLASH2 allowing bunch duration and FEL pulse duration measurements down with 1.7 fs resolution

Summary

- Ultra-short pulses with single-spikes could be produced in FLASH1 & FLASH2
  - FLASH1: pulse duration: @ 7nm
    - 3.0 fs +/- 1.7 fs (rms) – THz-streaking,
    - 4.0 fs +/- 0.4 fs (rms) – mode counting
    - 1.6 modes in average
  - FLASH2: pulse duration: @ 41nm
    - 6 fs (rms) – gain curve measurement
    - 1.05 modes in average
- Ultra-short pulses available for user operation since end of 2016

Thanks for your attention

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