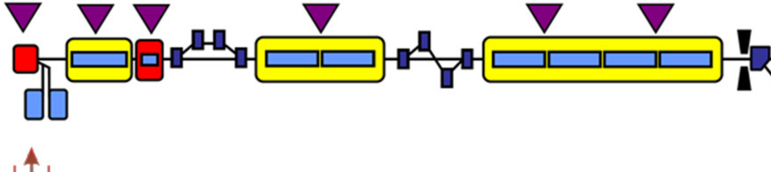
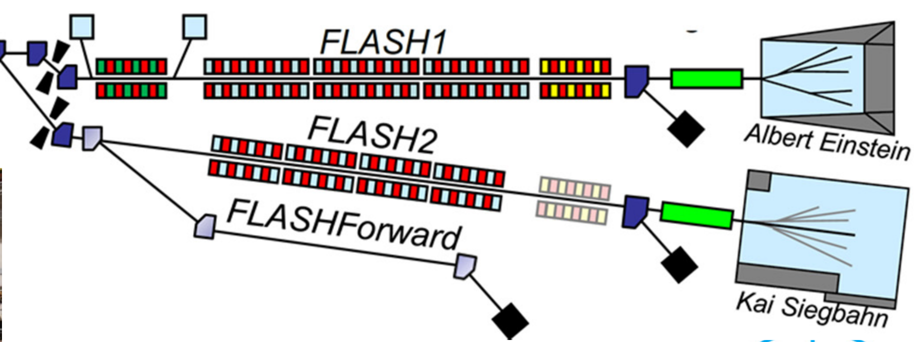
Recent FEL experiments at FLASH

FLASH.
Free-Electron Laser in Hamburg

FLASH: the first soft X-ray FEL operating two undulator beamlines simultaneously

Siegfried Schreiber,
Evgeny Schneidmiller,
Mikahil Yurkov,
Deutsches Elektronen-Synchrotron

FEL2017 Santa Fe, NM
Aug-22, 2017

HELMHOLTZ GEMEINSCHAFT

DESY

FLASH Layout 2017

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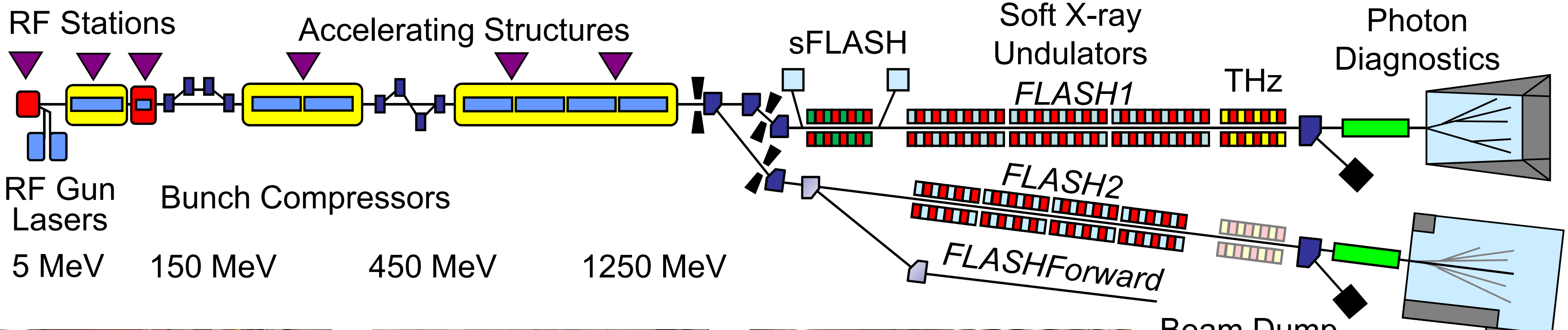
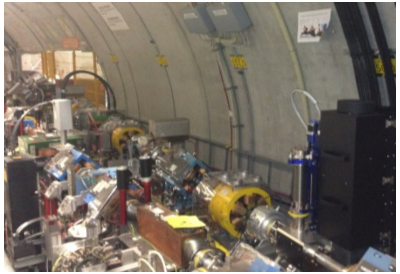
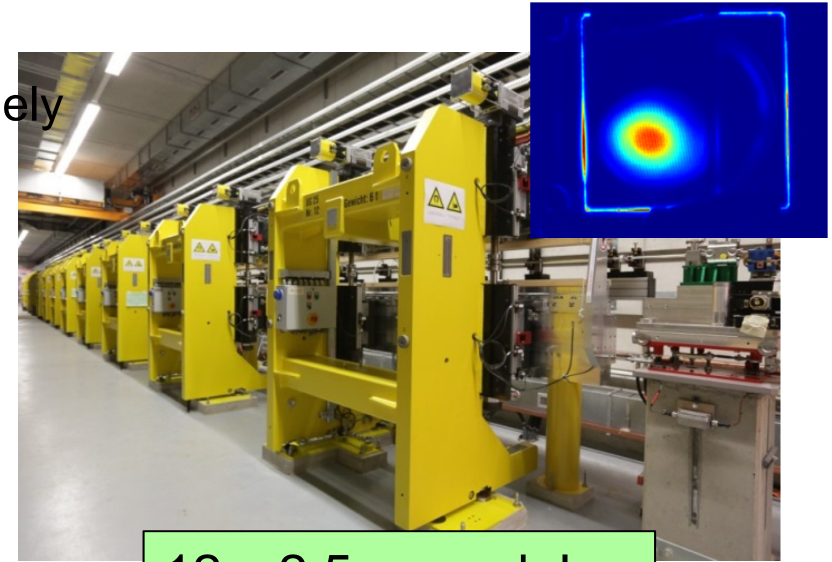


FLASH 2

FLASH2 with variable gap undulators

- FLASH2 variable gap undulators allow a variety of new type of experiments, not possible at FLASH1
- Linear and quadratic tapering is used routinely
  - up to 1 mJ single pulse energies
  - up to 10^{14} photons / single pulse
- Advanced operation modes:
  - Post-saturation taper
  - Harmonic lasing self-seeded FEL
  - Reverse tapering
  - Frequency doubling



12 x 2.5 m modules
Period 31.4 mm
K_{rms} = 0.7 - 1.9

Post-Saturation Taper

Post-Saturation Tapering

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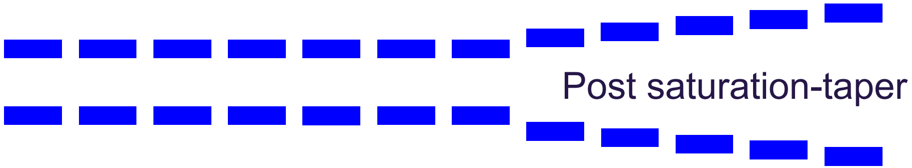
- Taper to keep undulators in resonance with electrons loosing energy during the amplification process
- We use statistical measurements for tuning optimum undulator tapering
- Optimum undulator tapering:
  - starting point = two field gain lengths before saturation
  - Saturation point = SASE fluctuations down by a factor of 3
- Quadratic tapering is applied



E. Schneidmiller, M. Yurkov, PRSTAB 18 (2015) 030705

Post-Saturation Tapering at FLASH2

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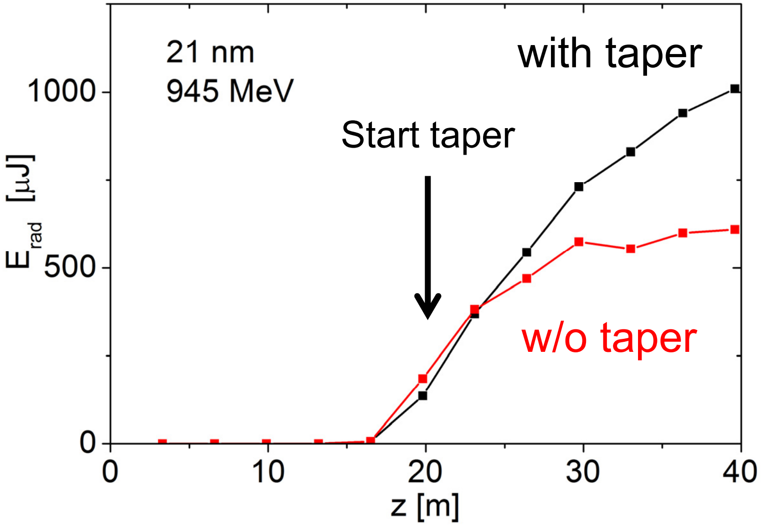
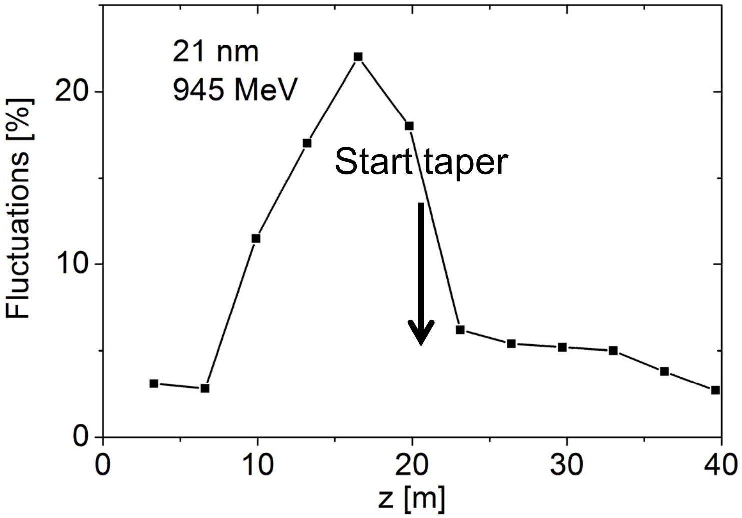
- Linear or quadratic tapering is a standard procedure at FLASH2
- With tapering, 1 mJ has been achieved at 21 nm: x2 more than w/o

A record of $1 \cdot 10^{14}$ photons per pulse





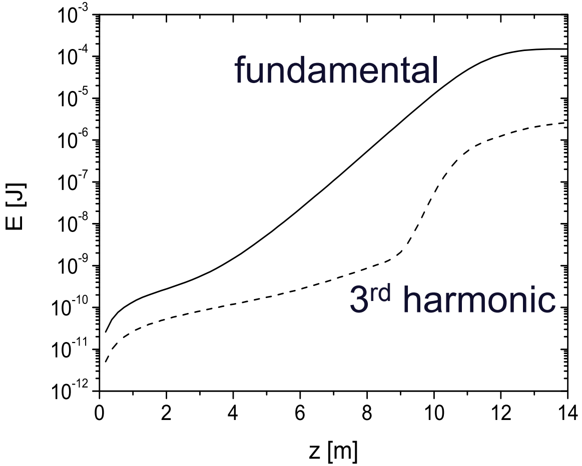
HLSS

There are two basic mechanisms in FELs:

- Nonlinear harmonic generation
- Harmonic lasing → harmonic lasing self-seeding (HLSS)

Nonlinear harmonic generation in SASE FELs

- When lasing at the fundamental frequency approaches saturation, the density modulation becomes nonlinear and thus contains higher harmonics
- Standard process, widely used (3rd, 5th, ..)
  - Power of 3rd harmonic is about 1% of saturation power of the fundamental
  - Relative bandwidth is about the same
  - Shot-to-shot intensity fluctuations are much stronger
  - Transverse coherence is worse



Non-linear harmonics are much less brilliant and less stable than the fundamental

3rd harmonic is driven by the fundamental

Harmonic Lasing

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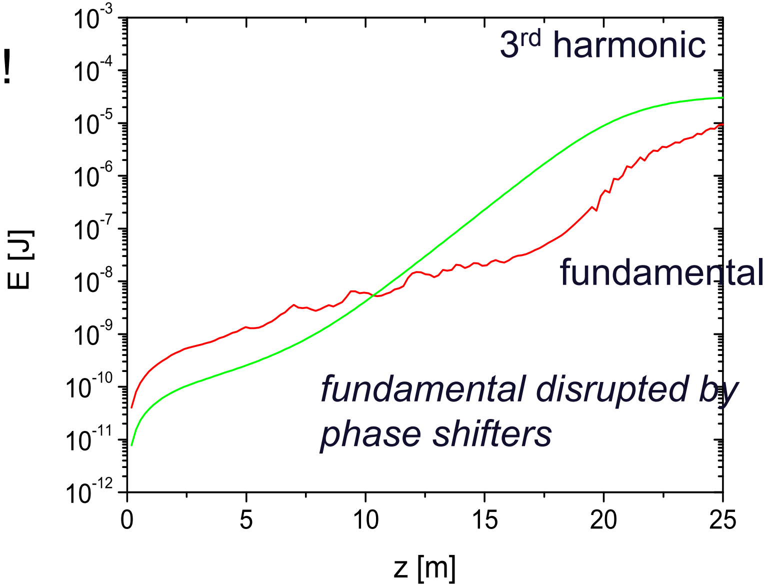
- Harmonic lasing is an FEL instability developing *independently* of the fundamental (in linear regime)

\- *in contrast to non-linear harmonic generation*!

→ We have to disrupt the fundamental to let the harmonic saturate

- Saturation efficiency of **h**-th harmonic and relative bandwidth scale as ~ λ_S / (**h** L_{sat})
- Shot-to-shot intensity fluctuations are comparable to fundamental
- Good transverse coherence



Brilliance is comparable to fundamental!

Harmonic Lasing – a long history actually

- Low-gain FELs:
  - First theoretical consideration >30 years ago (Colson, 1981)
  - Several successful experiments with FEL oscillators in IR (1988-2010)
- High-gain FELs:
  - 1D theory of harmonic lasing:

    Murphy, Pellegrini, Bonifacio, 1985
    Bonifacio, De Salvo, Pierini, 1990
    McNeil et al., 2005

  - 3D theory (everything included):

    Z. Huang and K.-J. Kim, 2000

Schneidmiller-Yurkov revision of harmonic lasing

- Simple parametrization of the gain length (included into FAST)
- Extended analysis of parameter space (with optimistic conclusions)
- New methods for suppression of the fundamental
  - Phase shifters, Spectral filtering, Switching between 3rd and 5th harmonics
- Discovered qualitatively new effect of anomalously strong harmonic lasing for thin electron beams
- Improvement of spectral brightness (HLSS-FEL)
- Considering practical applications for different facilities:
  → first experiments at FLASH

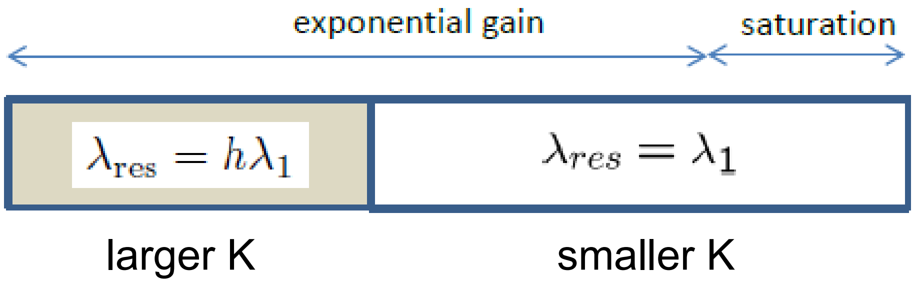
Our conclusion: this option must be seriously considered!

HLSS: Harmonic Lasing Self-Seeding FEL

- Improvement of spectral brightness in a gap-tunable undulator
  - First part of undulator: harmonic lasing in linear regime (narrow bandwidth!)

  → seeding the 2nd part of undulator with the harmonic
  - 2nd part of undulator: reducing K and reaching saturation at the now fundamental

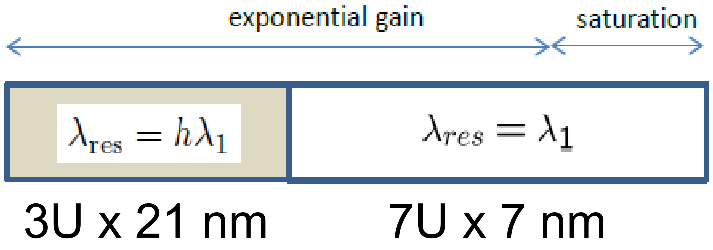
→ Then we have high power and narrow bandwidth

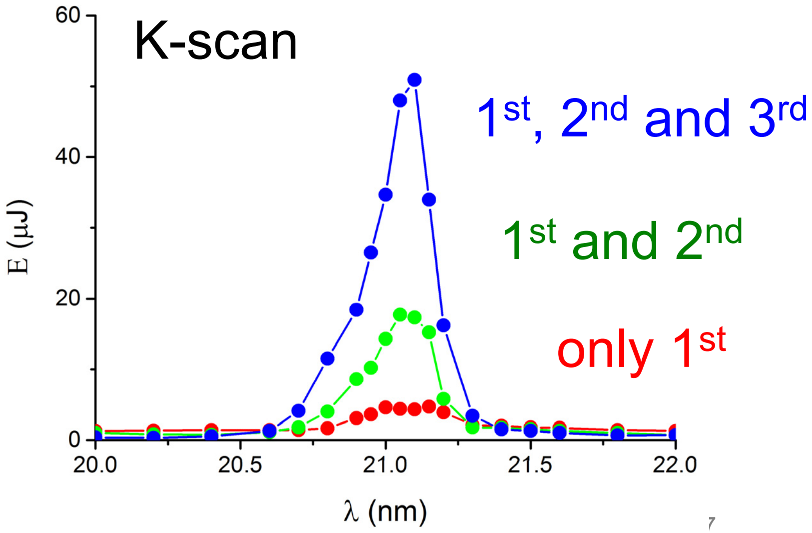


- Expected bandwidth reduction R = (0.6 to 0.9) * **h**
- Earlier saturation compared to SASE: **post-saturation taper** to improve FEL power

E. Schneidmiller, M. Yurkov, PRSTAB 15 (2012) 080702

HLSS at FLASH2: 1st harmonic lasing May 2016





E. Schneidmiller et al., PRAB 20, 020705 (2017)

- Experimental steps:
  - SASE at 7 nm in 10 undulators to 12 μJ (not in saturation, exponential gain)
  - Detuning first three undulators: sharp intensity drop
  - Scan K towards to 21 nm: sharp increase to 51 μJ, resonant behavior

  → gain length of 3rd harmonic (7 nm) is shorter than fundamental (7 nm)!

- Non-linear harmonic generation is absolutely excluded: pulse energy at 21 nm after 3 undulators was 40 nJ, 4 orders of magnitude below saturation.

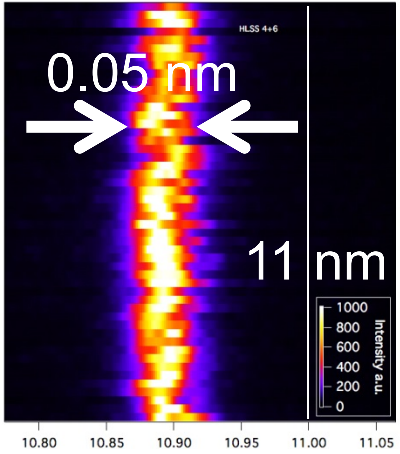
Results can only be explained by 3rd harmonic lasing at 7 nm

HLSS at FLASH2: reduction of bandwidth

- The HLSS experiment was repeated with 33 nm in 4 undulators (4U) + seeding in 6 undulators (6U) with 11 nm

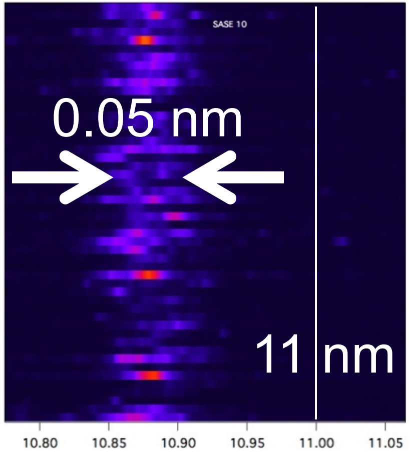
Courtesy M. Kuhlmann, DESY

HLSS (4U+6U)

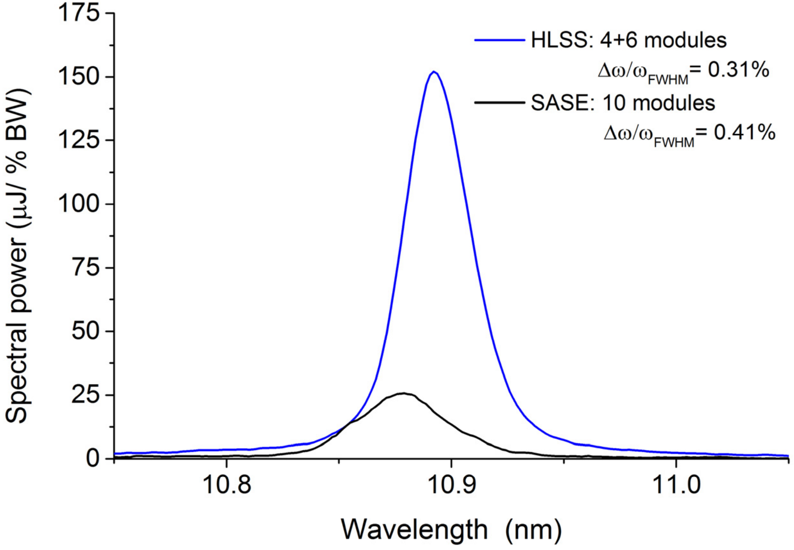


Wavelength (nm)

SASE (10U)



Wavelength (nm)



Measured: R = 1.3 (expected 1.7)

HLSS at FLASH2: increase in coherence time

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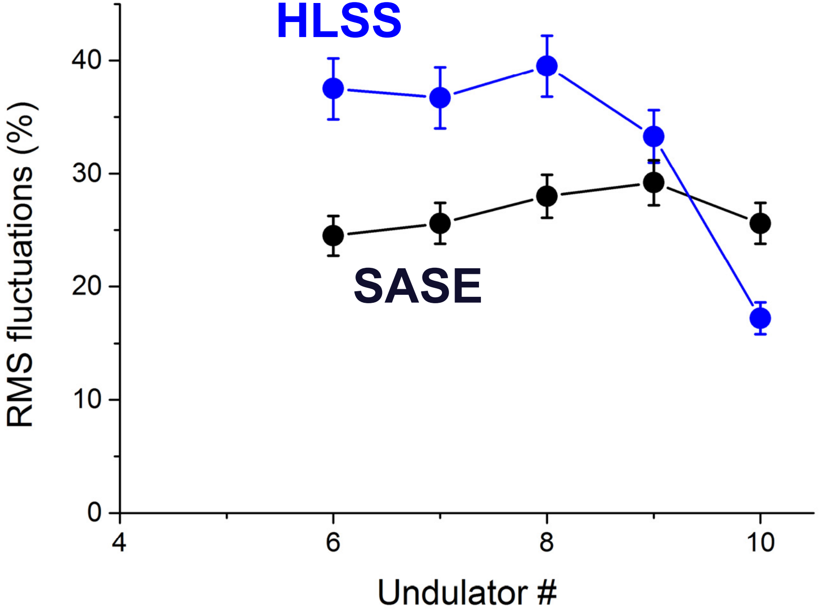
- Statistical determination of an increase of the coherence time



$L_{coh} \sim 1/M \sim \sigma^2$

Coherence time is proportional to the square of the rms SASE fluctuations

Measured:

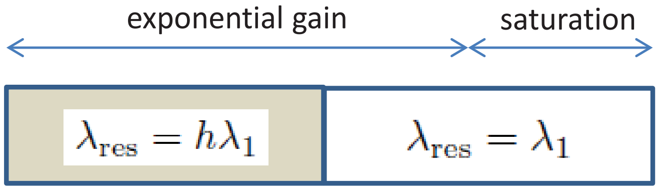
$R = \sigma^2_{HLSS} / \sigma^2_{SASE} = 1.8$

Expected: R = 1.7

HLSS at FLASH2: post-saturation taper

- Other HLSS experiments at 45 nm (4U) → 15 nm (8U) and at 13.5 nm (3U) → 4.5 nm (9U)
- Post-saturation taper is applied (for SASE **and** HLSS)

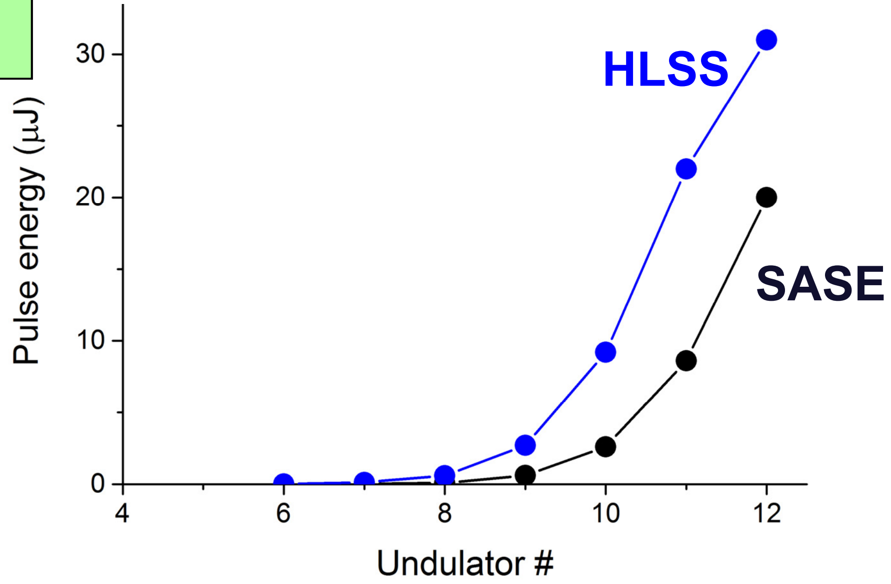
→ HLSS: significant increase in pulse energy compared to SASE



4 undulators
45 nm

8 undulators
15 nm

Note: FLASH2 has 12 undulators



HLSS Conclusions

- Successful demonstration of HLSS principle at FLASH2
- First evidence of harmonic lasing in a high-gain FEL and at a short wavelength (down to 4.5 nm)
- Harmonic lasing is a promising option for FLASH and also for the European XFEL
- Main features:
  - Bandwidth reduction and brilliance increase
  - Extension of photon energy range

    FLASH up to 1 keV
    European XFEL up to 60-100 keV

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Reverse Taper

Reverse taper for circular polarization

- Main SASE planar undulator + helical afterburner

→ The point is to get rid of the powerful linearly polarized radiation from the main undulator

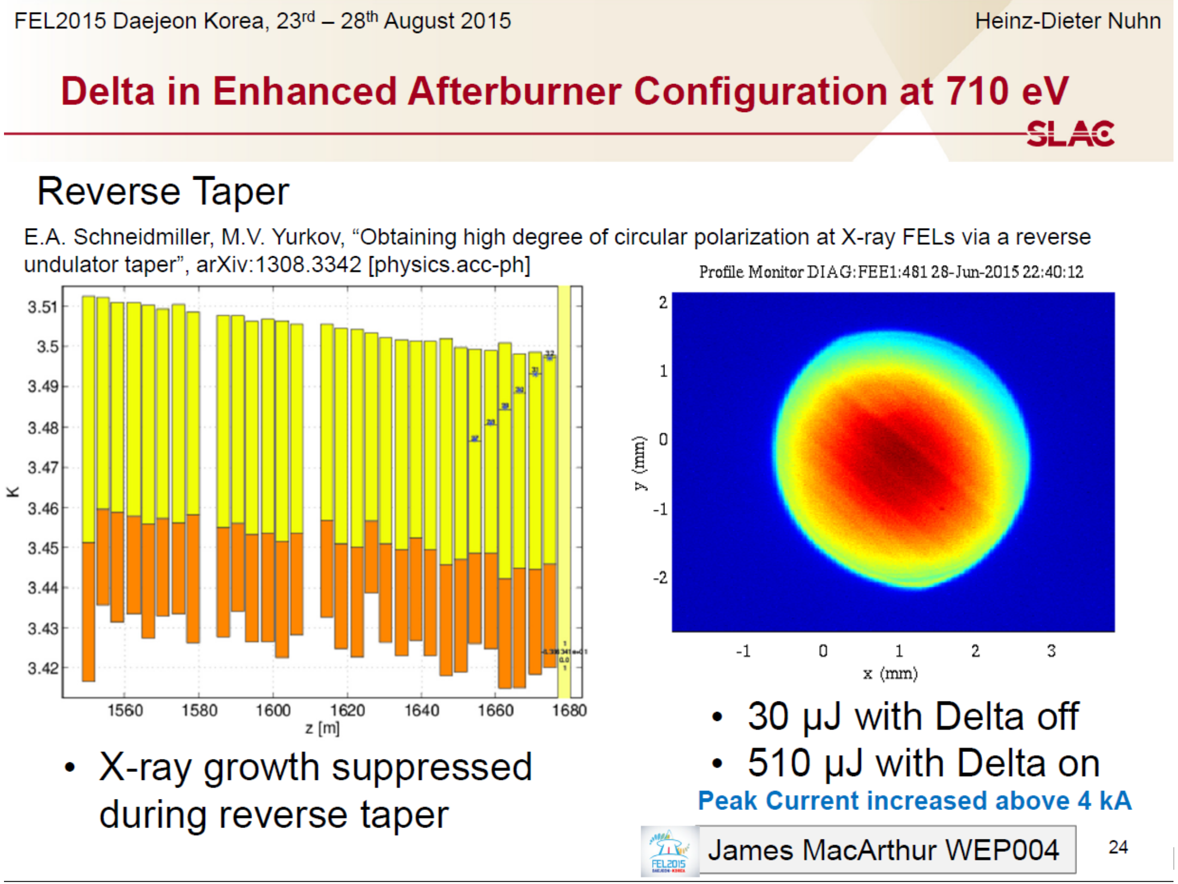
- Solution: reverse tapering

- Fully micro-bunched electron beam
- ! but strongly suppressed radiation power at the undulator exit

→ The beam radiates at full power in the helical afterburner tuned to the resonance

E. Schneidmiller, M. Yurkov, PRST-AB 16 (2013) 110702

Reverse taper at LCLS



FEL2015 Daejeon Korea, 23rd – 28th August 2015 Heinz-Dieter Nuhn

Delta in Enhanced Afterburner Configuration at 710 eV

SLAC

Reverse Taper

E.A. Schneidmiller, M.V. Yurkov, "Obtaining high degree of circular polarization at X-ray FELs via a reverse undulator taper", arXiv:1308.3342 [physics.acc-ph]

- X-ray growth suppressed during reverse taper

- 30 µJ with Delta off
- 510 µJ with Delta on

Peak Current increased above 4 kA

James MacArthur WEP004

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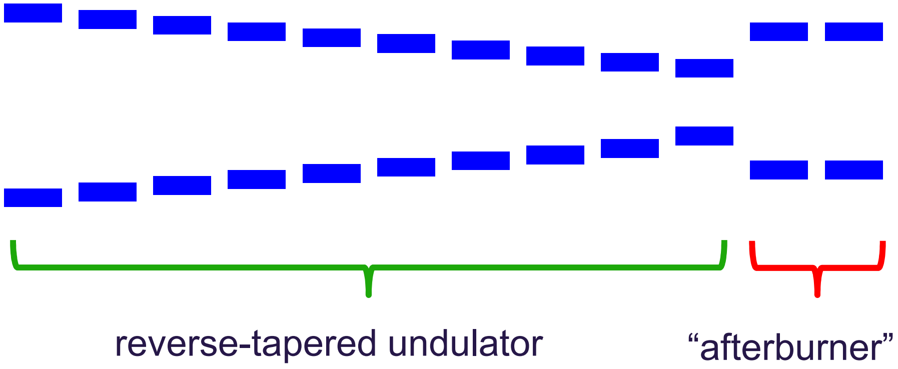
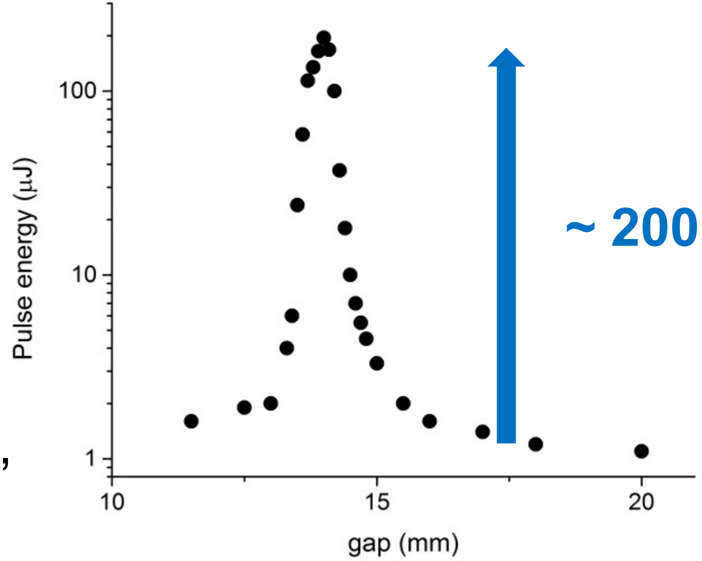
H.-D. Nuhn, FEL2015

Reverse taper experiment at FLASH2

- 10 undulators used for reverse tapering (10%), the last two act as the afterburner, 720 MeV, 17 nm



- Scan gap of “afterburner”



With the “afterburner” in resonance, the power increases by ~200

For a helical afterburner the power increase would be ~400

Reverse Taper and harmonic afterburner

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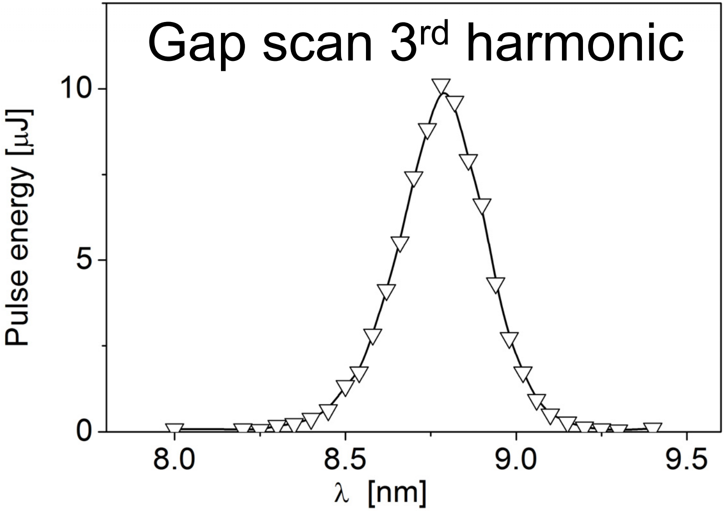
- This time with an “harmonic afterburner” simulated by 2 undulator modules
- Main undulator: 9 modules, 26.5 nm, with 5% reverse taper

Pulse energy after tapered undulators < 1 µJ

Afterburner tuned to the

- fundamental: 150 µJ
- 2nd harmonic: 40 µJ
- 3rd harmonic: 10 µJ

Reverse taper can be used for efficient background-free generation of harmonics in an afterburner



Reverse taper conclusion

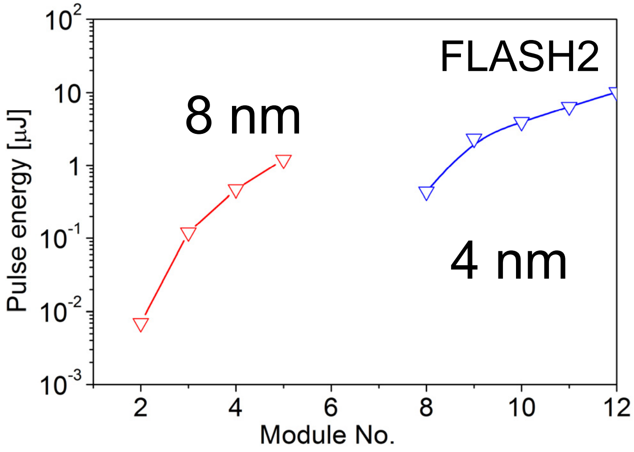
- Reverse taper is routinely used at LCLS and is shown to work nicely at FLASH2
- Reverse taper is a simple and elegant method for suppression of linearly polarized background and obtaining high degree of circular polarization
- FLASH2 plans to install a DELTA undulator in the afterburner configuration (2nd harmonic) for circular polarization
- Reverse taper can also be used for efficient background-free production of harmonics with energies much higher (orders of magnitude) than the harmonic content of SASE radiation.

Frequency Doubler

Frequency-Doubler

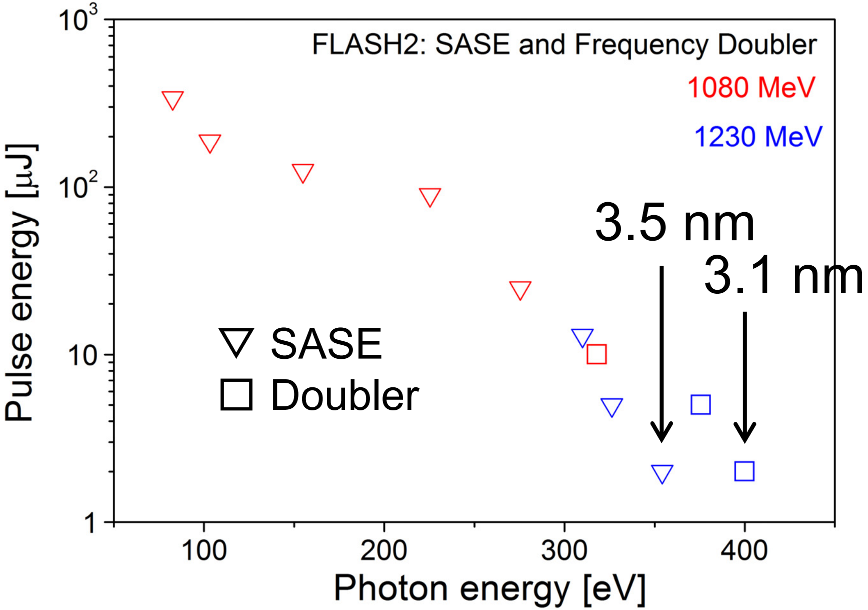
- The 2nd part of the undulator is tuned to the double frequency of the 1st
- The amplification process in the 1st part is stopped where non-linear higher harmonic bunching becomes pronouncing
  - While the radiation level is still too small to disturb the electron beam
- In the 2nd part of the undulator, the modulated beam efficiently generates radiation at the 2nd harmonic

The Frequency-Doubler allows
- two-color mode operation
- shorter wavelengths than standard SASE



Frequency-Doubler experiments at FLASH2

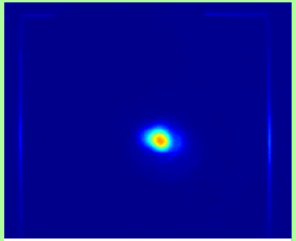
- Frequency-Doubler at 1080 MeV and 1230 MeV (highest energy of FLASH)
- SASE configuration: all 12 modules
- Doubler configuration: ν (5U) + 2ν (7U)



In the frequency-doubler mode, we demonstrated a wavelength reach shorter than SASE:

SASE: 3.5 nm

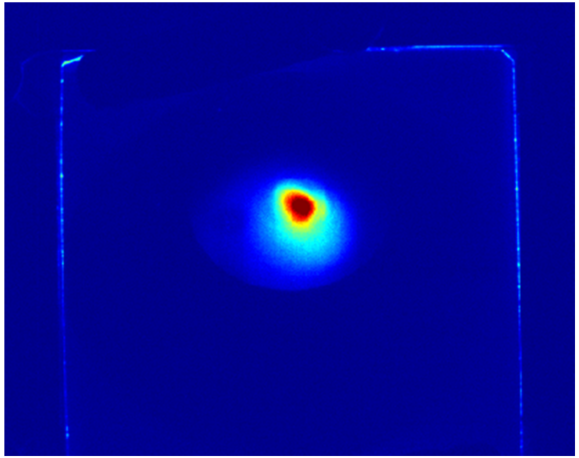
Doubler: 3.1 nm



3.1 nm from doubler

Two Color Operation at FLASH2

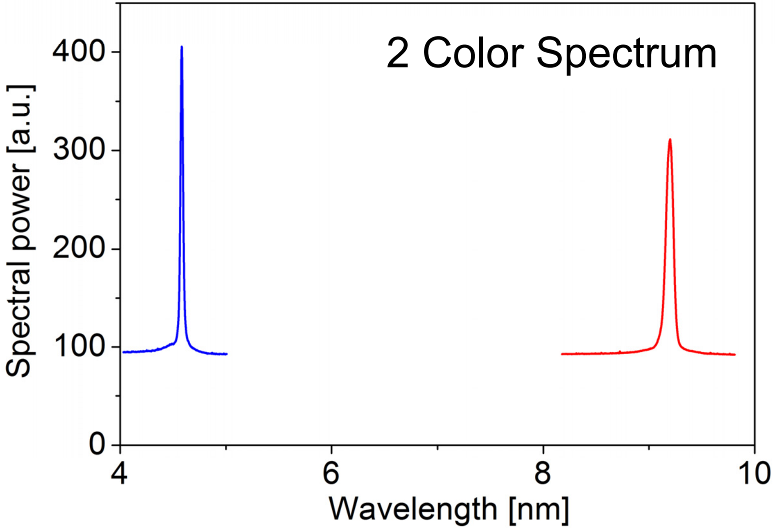
- Frequency doubler with two color mode of operation at 9 nm and 4.5 nm.
- Doubler configuration: ν (5U) + 2ν (7U)



Small red spot: 4.5 nm (2nd harmonic)

Larger blue spot: 9 nm (fundamental)

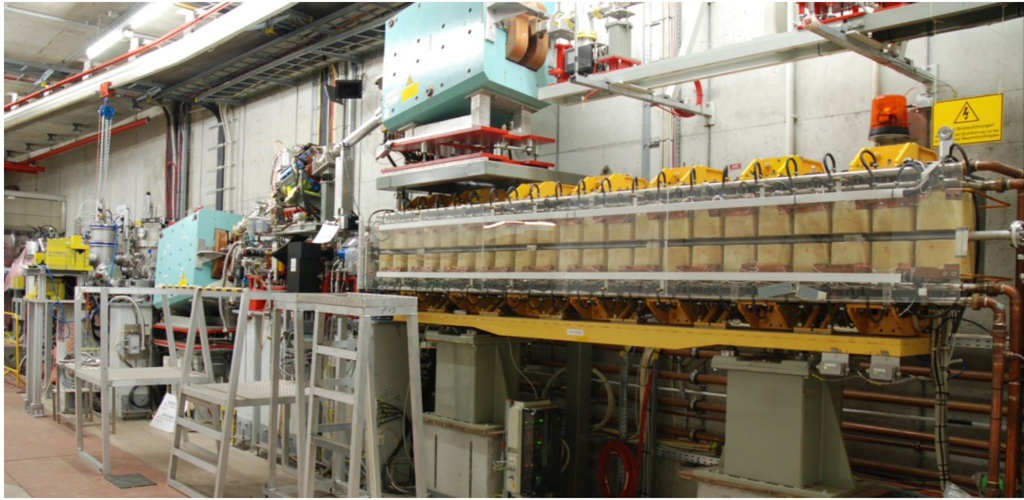
Courtesy M. Kuhlmann, DESY



THz-Doubler

THz-Doubler

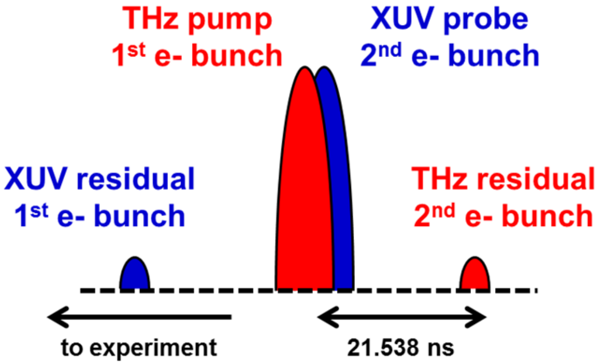
- THz undulator at FLASH1 downstream SASE undulators
- Goal: THz-pump / XUV-probe experiments with wavelength scan
  - Problem: THz beam has a path difference to XUV by 21.5 ns
  - Solution up to now: XUV is back-reflected to overlay with THz
  - Disadvantage: only good for a fixed wavelength (given by the mirror)

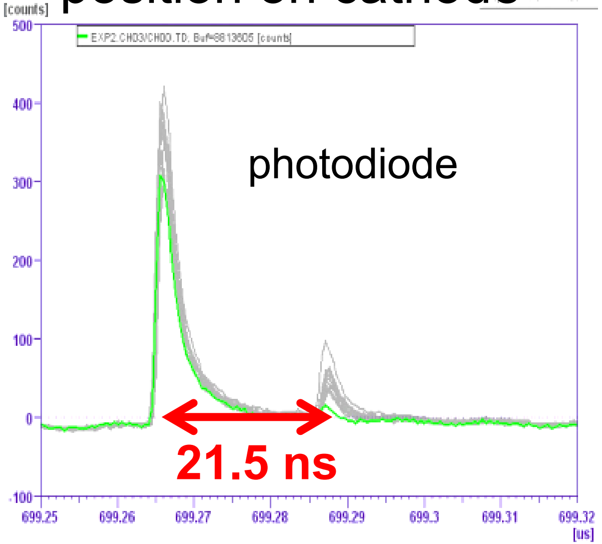


- Better solution: THz doubler
- Split & Delay of injector laser pulses, distance: a few RF-buckets (21.5 ns)
- The first bunch generates THz, the second XUV

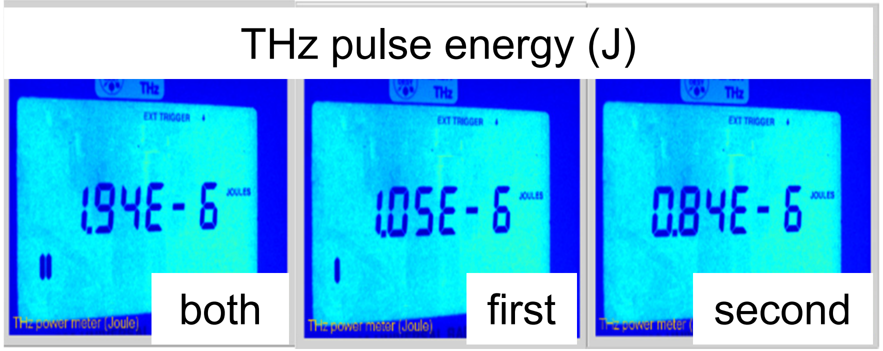
THz-Doubler

- First results: THz and SASE produced with THz-doubler at a delay of 21.5 ns
- Tuning of 2nd pulse with phase (delay change), charge (laser polarization), and position on cathode



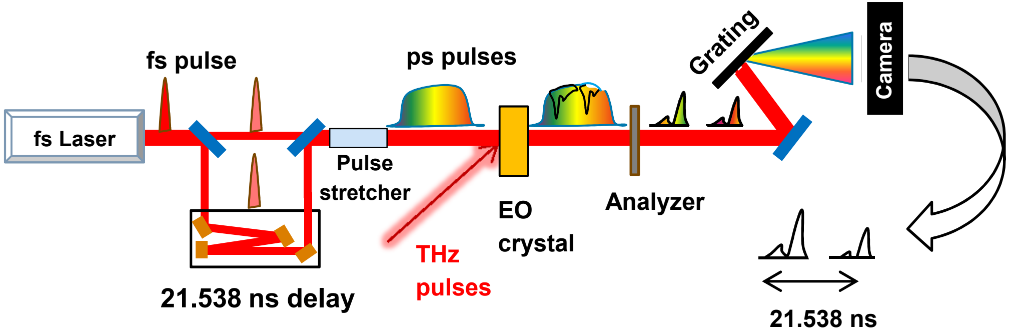


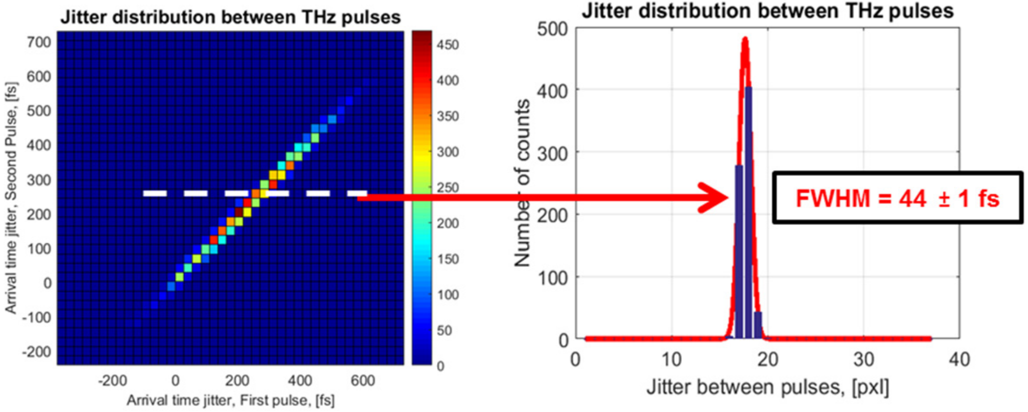
THz pulse energy (J)



THz arrival time measurements

- Measurement of timing jitter between double THz pulses using Spectral Decoding
  - jitter THz vs XUV from the same bunch < 5 fs
  - Measured jitter double pulses < 50 fs
  - limited by measurement resolution
- Next steps
  - improve arrival time measurement accuracy
  - XUV / THz benchmark experiment
  - extension of THz- doubler for further THz pulse shaping (e.g. spectral b/w control)



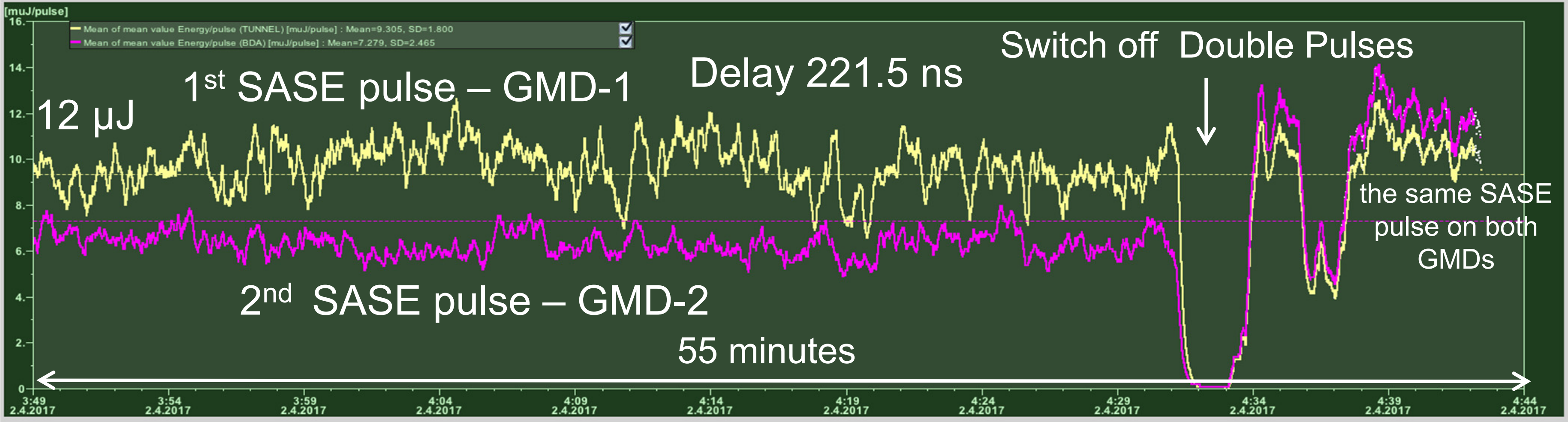


THz team: Nikola Stojanovic, Torsten Golz, Ekaterina Zapolnova, Rui Pan, THz-doubler: Karsten Klose, Siegfried Schreiber

Double Pulse with large delay

Double Pulses at FLASH

- SASE double pulses with variable nanosecond spacing
- Realized with simultaneous operation of 2 injector lasers in the same beamline
  - Delay adjustable by users in steps of 9.2 ns (108 MHz DAQ; finer steps on request only)
  - with a few adjustments of the 2nd laser (energy, phase, position on cathode, then slight orbit correction, slight compression correction), it is possible to have the same SASE level for both
- 2nd beamline operated in parallel with the 3rd laser



12 μJ

1st SASE pulse – GMD-1

Delay 221.5 ns

Switch off

Double Pulses

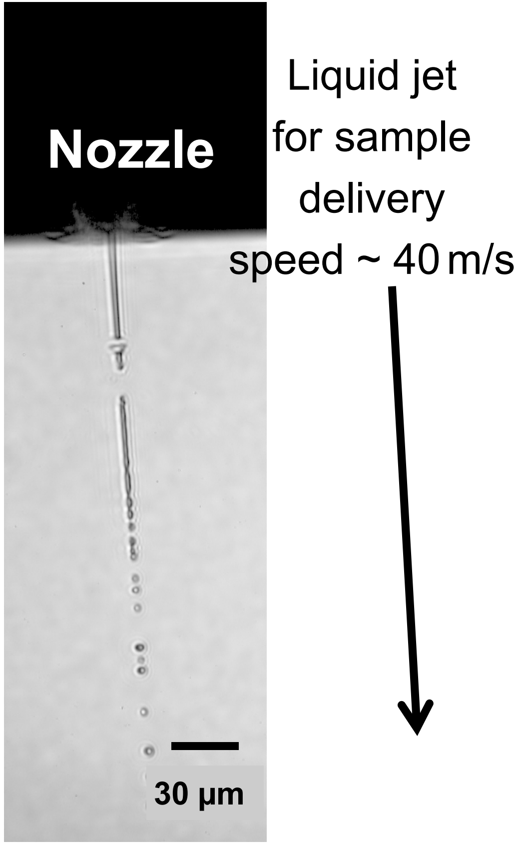
the same SASE pulse on both GMDs

2nd SASE pulse – GMD-2

55 minutes

User experiment with double pulses

- Double pulse scheme commissioned and operated for an external user experiment (Chapman et al.) April 2017
- 221.5 ns and 470 ns delays used by experiment
- Goal: Check recovery time of a liquid jet after hit by an FEL pulse (shock wave?)
- Mimic a high pulse repetition rate (e.g. European XFEL with 4.5 MHz)
- to check feasibility of liquid jet sample delivery for high repetition rate diffraction experiments



Liquid jet
for sample
delivery
speed ~ 40 m/s

User experiment with double pulses

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Wavelength 4.29 nm

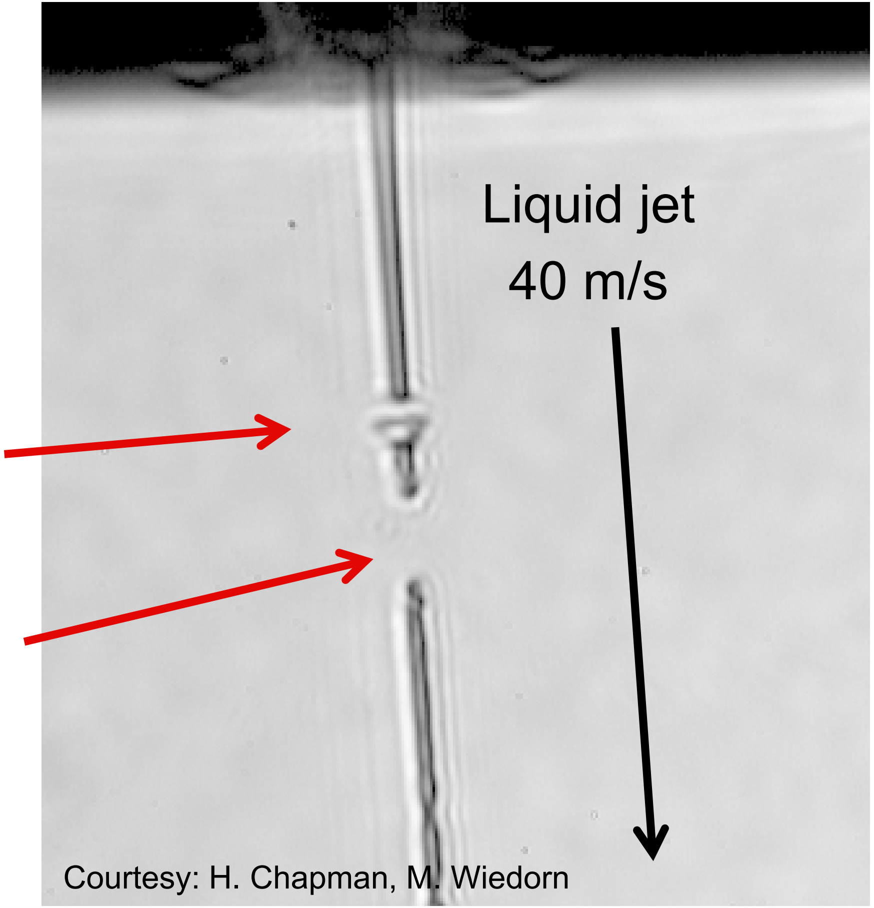
1st pulse: 18 µJ

2nd pulse: 10 µJ

Double pulse delay: 221.5 ns

2nd pulse
jet explosion starting

1st pulse
jet explosion propagated



Courtesy: H. Chapman, M. Wiedorn

Summary

FLASH.
Free-Electron Laser in Hamburg

- With the new FLASH2 variable gap undulators, FLASH used the opportunity to do a variety of undulator related experiments:
- Post-saturation tapering to double SASE pulse energy
- Harmonic lasing and harmonic lasing self-seeding (HLSS) to reduce bandwidth and improve pulse energy of higher harmonics – first experimental demonstration
- Reverse undulator tapering to suppress linear polarization or fundamental when using afterburner polarizers (eg DELTA) or 2nd harmonic afterburners
- Frequency doubling to extend the wavelength range and for two color operation
- THz doubler to ease THz-XUV pump-probe experiments
- Double pulses with adjustable ns-delay for certain class of experiments