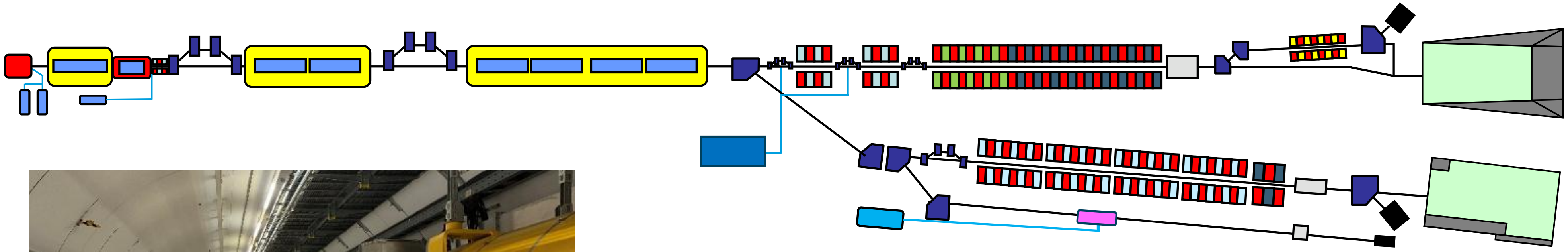
25 years of FEL Operation at FLASH (DESY)

FLASH: the pioneering FEL User Facility

Katja Honkavaara
for the FLASH Team

20-August-2026



DAEJEON LINAC2026

HELMHOLTZ

DESY.

FLASH – the Free-Electron Laser at DESY – today

DESY (Hamburg, Germany) is one of the world's leading centers for research on and with particle accelerators

- FLASH is based on TTF FEL
  - First lasing February 2000
- FLASH is an FEL User Facility since 2005
  - Driven by a **superconducting accelerator** using TESLA technology
  - Maximum electron beam energy 1.35 GeV
  - Provides several thousand photon pulses per second
  - **Two undulator beamlines** operated in parallel
    - FLASH1: **externally seeded**
    - FLASH2: **SASE**
  - Photon wavelength range from **XUV to soft X-rays** (85 nm to 3 nm)
  - Integrated electron beam driven **THz** source (1-30 THz)
  - Third electron beamline (FLASH3) hosts a PWFA experiment

TTF = TESLA Test Facility
TESLA = TeV Energy Superconducting Linear Accelerator

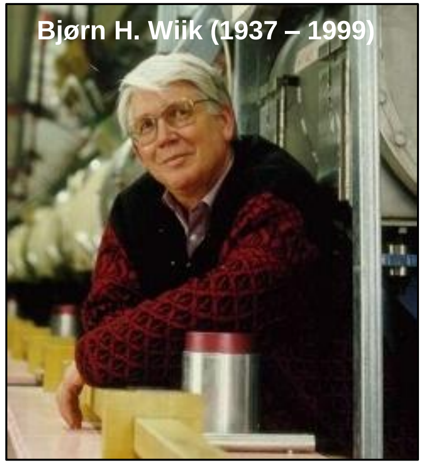
SASE = Self-Amplified Spontaneous Emission
Externally seeded = an external coherent light pulse initiates the lasing process
PWFA = Plasma WakeField Acceleration

VUV = Vacuum ultraviolet: 10 nm – 200 nm
EUV/XUV = Extreme ultraviolet: 10 nm – 100 nm
Soft x-rays < 10 nm

The FLASH story began already in 1990's

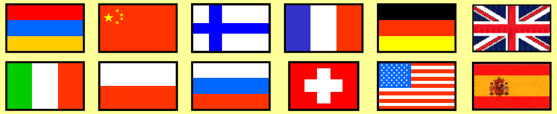
Lively discussions about the future accelerators for high energy physics and x-ray photon science

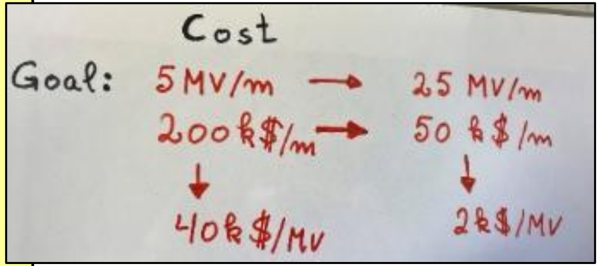
- Photon science community: synchrotron light sources already in operation, an **X-ray Laser** was still only **a dream**
- Particle physics community: a vision to built a TeV-scale **linear electron-positron collider**
- Accelerator community: several design proposals for the linear collider
  - Most experts had an opinion that the linear accelerator should be a **normal conducting copper linac**
  - Alternative possibility of **superconducting linac** started to be seriously considered
    - Superconducting linacs were already discussed and proposed in 1960's
- Bjørn H. Wiik (DESY director 1993-1999) had a vision of building **a superconducting $e^+ e^-$ linear collider with an integrated Röntgen Laser** within the international **TESLA collaboration**
  - TESLA Collaboration was established in early 1990's to develop "high-gradient, low-cost" superconducting accelerating cavities
  - DESY provided a site for Test Facilities (TTF, TTF Linac, TTF FEL, VUV-FEL@TTF2)


Bjørn H. Wiik (1937 – 1999)

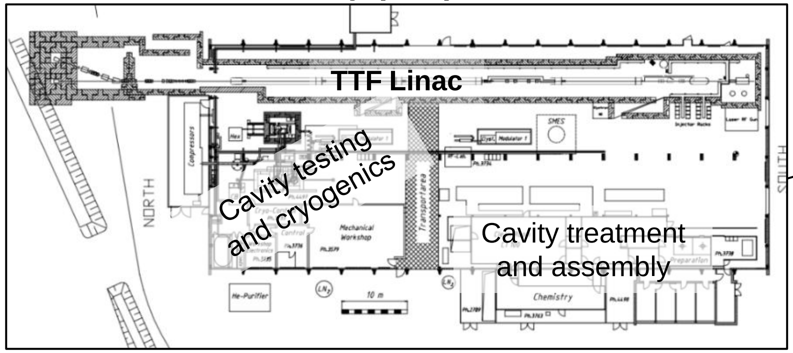
TESLA Collaboration

Almost all laboratories worldwide using superconducting accelerating cavities participated
(53 partners from 12 countries)

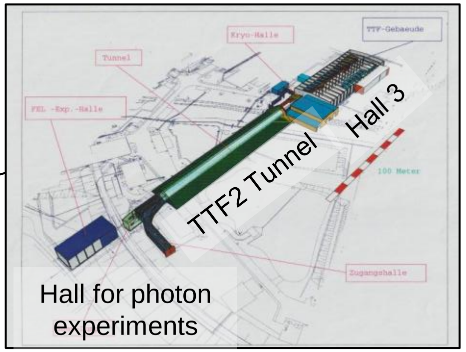




TESLA Test Facility (TTF) in Hall 3 at DESY



VUV-FEL @ TTF2

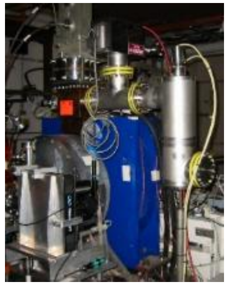


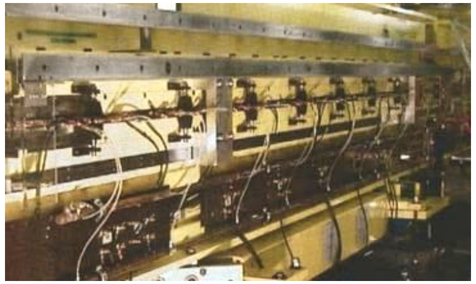
TTF FEL: the first SASE FEL worldwide in VUV range

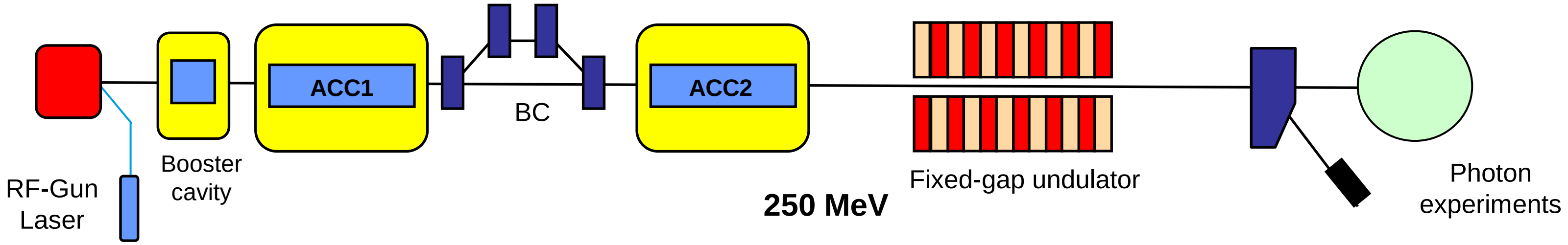
TTF Linac was about 100 m long, with maximum energy of 250 MeV, and located in Hall 3 at DESY

- **TTF Linac:** beam tests of the superconducting 1.3 GHz **TESLA accelerator modules** (1996 – 2002) and a driver of the **TTF FEL** Free-Electron Laser (1999 – 2002)
- TTF Linac and TTF FEL were installed step-by-step
  - First electron source (1996-1998) was a thermionic gun and subharmonic buncher, replaced by **a photo-injector** (RF-gun, Cs_2Te cathode, Laser) in late 1998
  - **Booster** ("capture") **cavity** installed in 1996, **first accelerator module** (ACC1) in spring 1997
  - ACC1 exchanged, **ACC2** and **bunch compressor** installed in 1998
  - Fixed-gap **undulato**r installed in summer 1999

TESLA cavity = 9-cell superconducting Niobium cavity
Booster cavity = one TESLA Cavity in a cryostat,
Accelerator Module = 8 TESLA Cavities in a cryostat

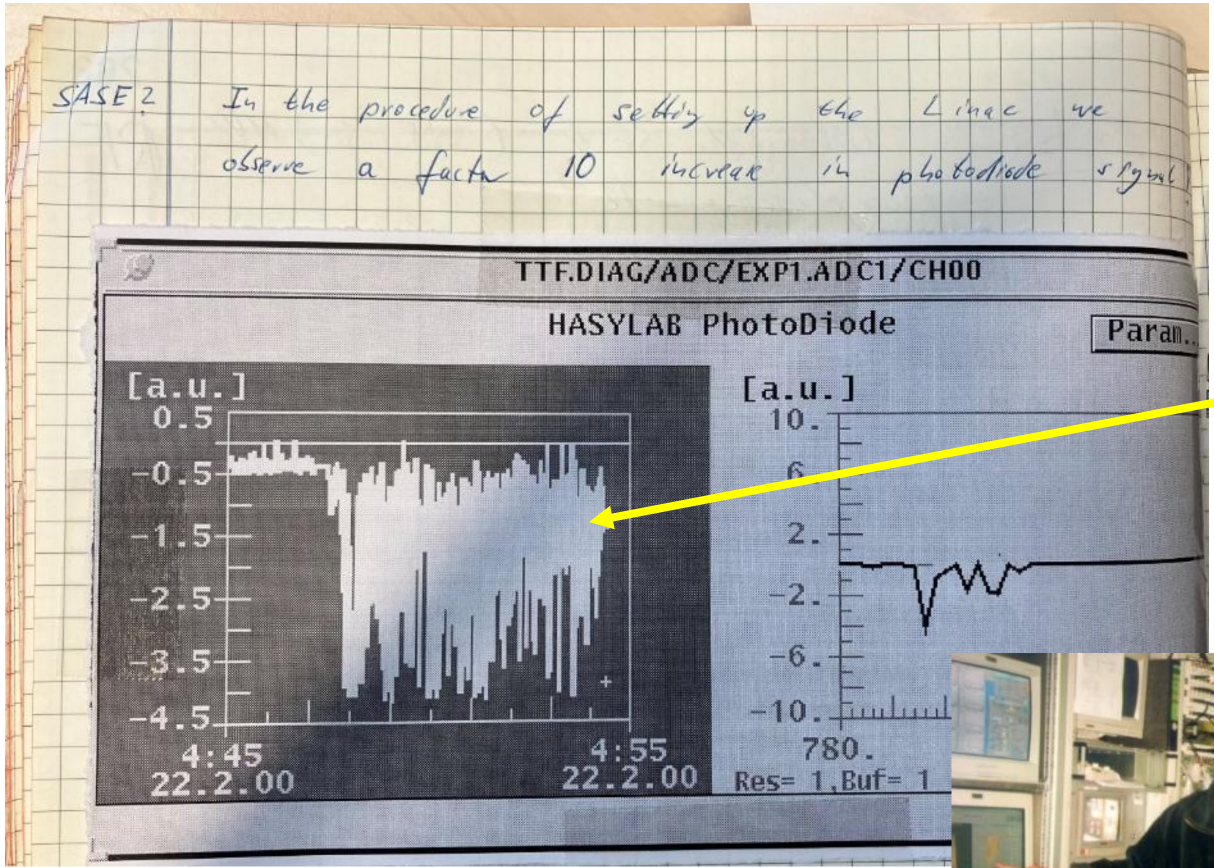


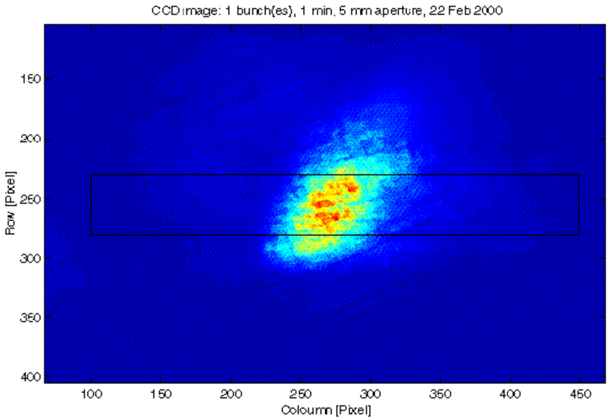


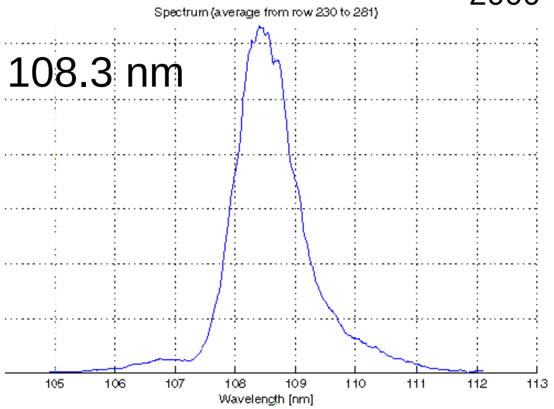


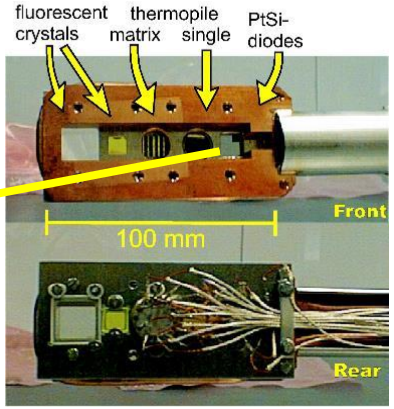
First Lasing at TTF FEL

22-Feb-2000 at 04:47: the first SASE lasing in VUV worldwide





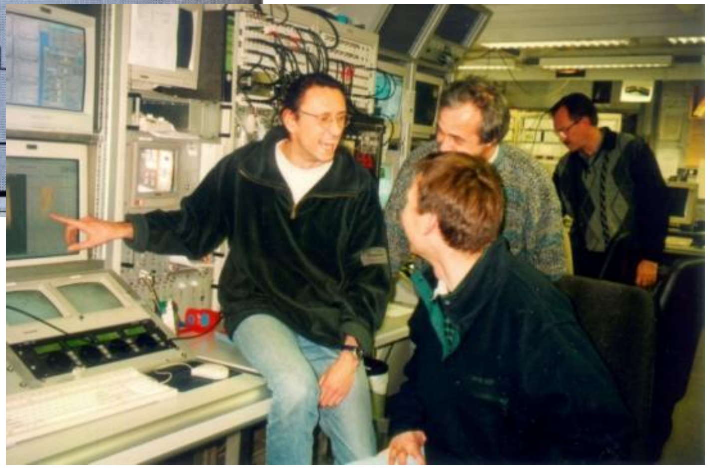




VOLUME 85, NUMBER 18 PHYSICAL REV

TABLE I. Main parameters of the TESLA Test Facility for FEL experiments (TTF FEL, phase 1).

Parameter	Measured value
Beam energy	233 ± 5 MeV
rms energy spread	0.3 ± 0.2 MeV
rms transverse beam size	100 ± 30 μm
Normalized emittance, ε_n	6 ± 3π mrad mm
Electron bunch charge	1 nC
Peak electron current	400 ± 200 A
Bunch spacing	1 μs
Repetition rate	1 Hz
Undulator period, λ_u	27.3 mm
Undulator peak field	0.46 T
Effective undulator length	13.5 m
Avg. betatron function horizontal/vertical	1.2 m/1.1 m
Radiation wavelength, λ_{ph}	109 nm
FEL gain	3 × 10^3
FEL radiation pulse length	0.4–1 ps



The success of TTF FEL encouraged the funding and construction **the first hard X-ray FELs** e.g. LCLS and European XFEL

Photon wavelength at TTF FEL
80 nm – 120 nm

First FEL experiments in VUV performed in autumn 2001

TTF completed FEL operation in March 2002

Damage of optical coatings; *J. Krzywinski, R. Sobierajski, et al.*

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Structure modifications in silicon irradiated by ultra-short pulses of XUV free electron laser

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Abstract

Structural modifications of solid Si (0 0 1) targets exposed to the XUV TESLA free electron laser radiation were studied. The samples were irradiated with the photon energy centered at 14 eV, in short pulses of only 80 fs and of peak power up to 1 GW. The FEL beam was focused on sample surfaces to microspots of size 10–100 μm. The energy density in the spots varied from below the ablation threshold up to far above this threshold. The structural modifications induced with the irradiation were studied by AFM, Nomarski contrast microscopy and by X-ray diffraction methods. A variety of morphological structures created in the damaged areas was found. The maps of the X-ray diffracted intensity distribution recorded around chosen spots on the Si surface made it possible to probe the damage distribution range around the spots. The observed features are related to the FEL irradiation fluencies applied.
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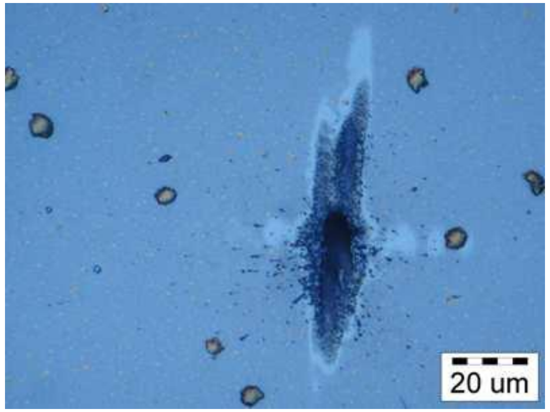
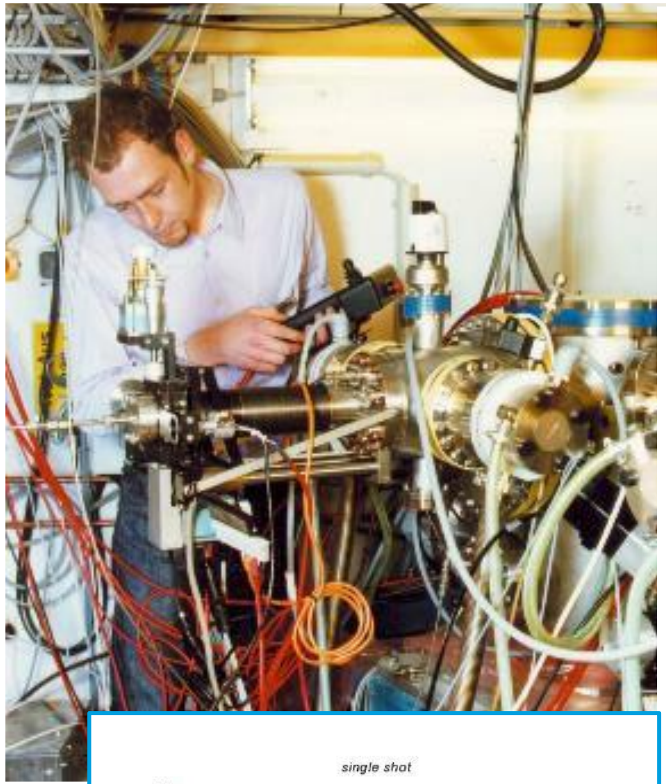
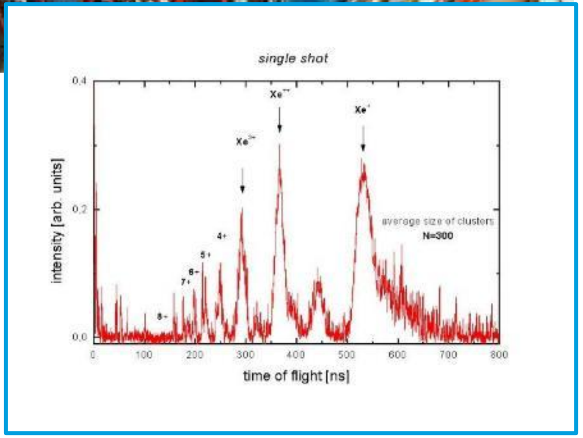
Keywords: Semiconductors; Laser processing; XUV free electron laser; Material modification; Ablation; Silicon



Creating highly charged clusters; *T. Möller, H. Wabnitz, et al.*





letters to nature

Multiple ionization of atom clusters by intense soft X-rays from a free-electron laser

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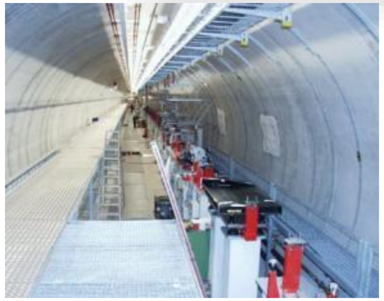
Intense radiation from lasers has opened up many new areas of research in physics and chemistry, and has revolutionized optical technology. So far, most work in the field of nonlinear processes has been restricted to infrared, visible and ultraviolet light[1], although progress in the development of X-ray lasers has been made recently[2]. With the advent of a free-electron laser in the soft-X-ray regime below 100 nm wavelength[3], a new light source is now available for experiments with intense, short-wavelength radiation that could be used to obtain deeper insights into the structure of matter. Other free-electron sources with even shorter wavelengths are planned for the future. Here we present initial results from a study of the interaction of soft X-ray radiation, generated by a free-electron laser, with Xe atoms and clusters. We find that, whereas Xe atoms become only singly ionized by the absorption of single photons, absorption in clusters is strongly enhanced. On average, each atom in large clusters absorbs up to 400 eV, corresponding to 30 photons. We suggest that the clusters are heated up and electrons are emitted after acquiring sufficient energy. The clusters finally disintegrate completely by Coulomb explosion.

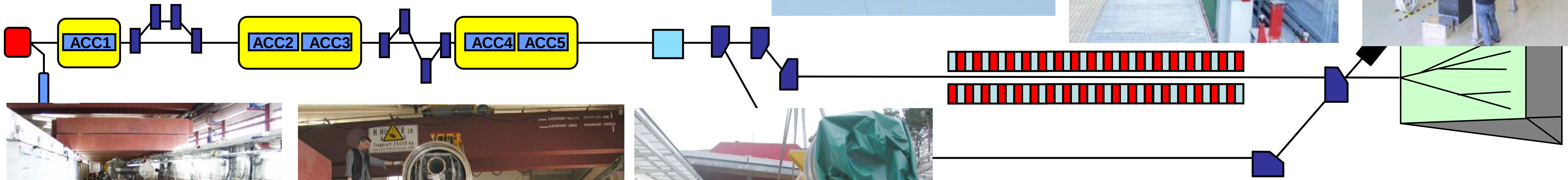
H. Wabnitz et al., Nature 420, 482-485 (2002)

VUV-FEL User Facility was part of the project since day one

SASE VUV-FEL (6 nm) @ TTF2 (1 GeV)

- Civil construction of a **new tunnel building** and an **experimental hall** started in 1999
  - as a part of the EXPO 2000 World Exhibition in Hannover (Germany)
  - June – October 2000: Science Exhibition **"Light for the New Millennium"** at DESY
- Installation and commissioning of electron and photon beamlines in 2003 - 2005

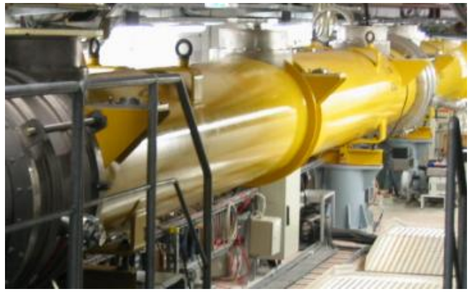


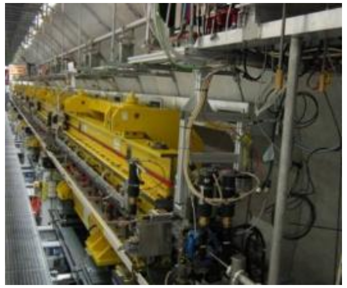


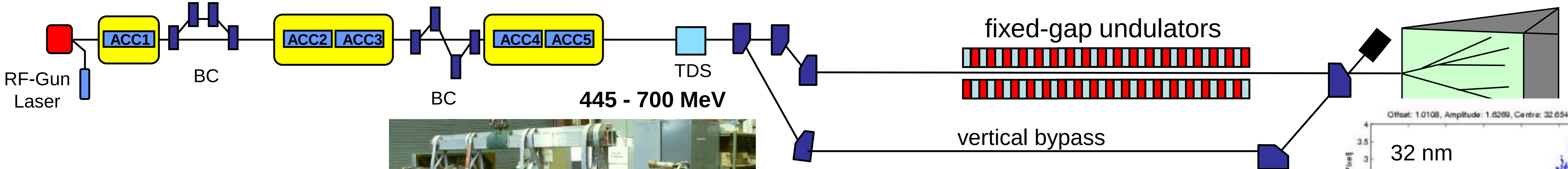
VUV-FEL@TTF2 starts operation

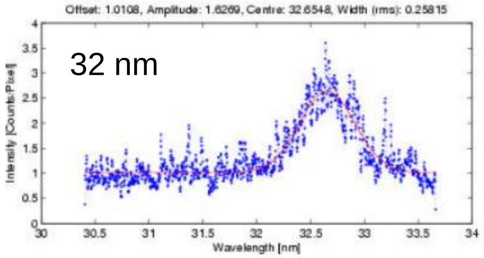
Electron beam operation started in 2004 with 445 MeV beam energy

- Total length ~ 300 m
  - **Photo-injector**, **five** TESLA type superconducting **accelerator modules**, **two bunch compressors** (C-type and S-type), transverse deflecting structure (**TDS**), **six fixed-gap undulators**, **photon diagnostics**, **experimental hall** (photon beamlines), **vertical bypass** line (to transport electron beam to dump w/o traversing undulators)
- **First lasing in January 2005 (32 nm)**





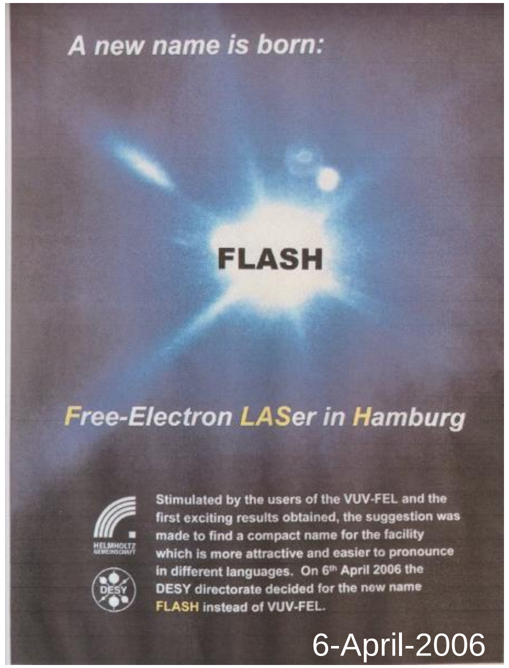




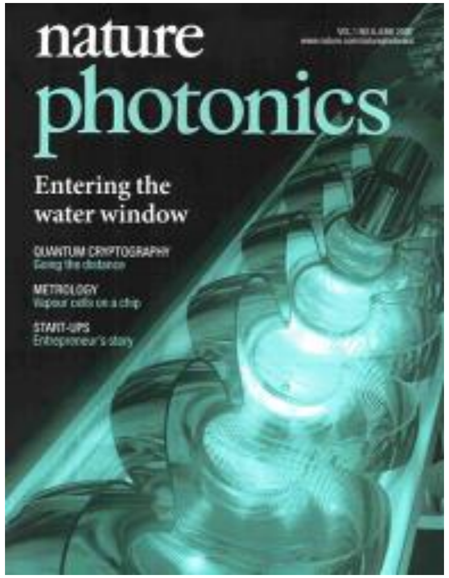
FEL User Facility FLASH is born

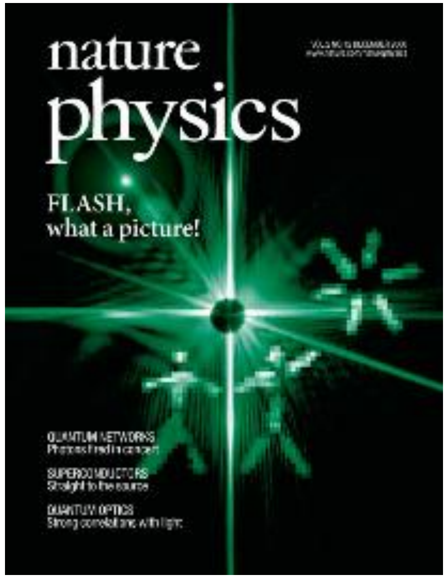
First round of user experiments from June 2005 to March 2007

- Autumn 2005: user experiments at 32 nm and 45 nm
- April 2006: **Renaming VUV-FEL @ TTF2 to "FLASH"**
  - A wish from user experiments, starting to publish their first results, to have a more exiting name for the facility
- 2006: Energy increased to **700 MeV**
  → **First lasing with the shortest wavelength: 13.1 nm** (April 2006)
- Spring 2006 – spring 2007: user experiments at wavelengths of **13.5 nm – 32 nm**

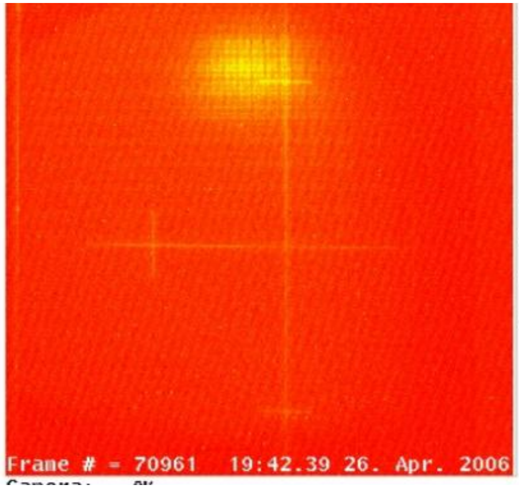


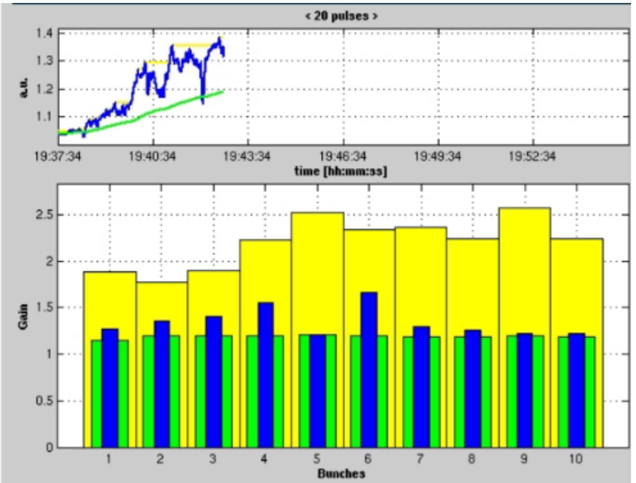
6-April-2006





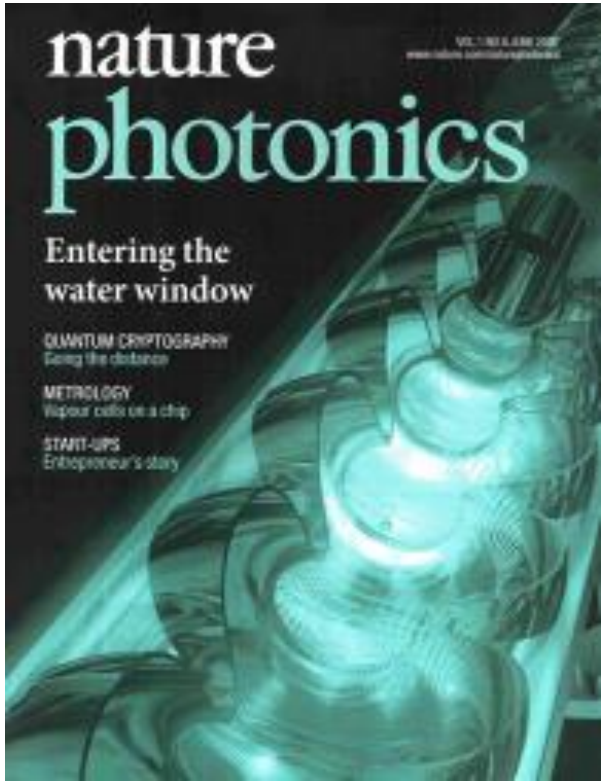
First lasing 13.1 nm 26-April-2006





Water window reached with the 5th harmonic

FLASH parameters 2006, as presented in *Nature Photonics* 1, 336–342 (2007)



nature photonics | VOL 1 | JUNE 2007 |

Operation of a free-electron laser from the extreme ultraviolet to the water window

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Published online: 1 June 2007; doi:10.1038/nphoton.2007.76

We report results on the performance of a free-electron laser operating at a wavelength of 13.7 nm where unprecedented peak and average powers for a coherent extreme-ultraviolet radiation source have been measured. In the saturation regime, the peak energy approached 170 μJ for individual pulses, and the average energy per pulse reached 70 μJ. The pulse duration was in the region of 10 fs, and peak powers of 10 GW were achieved. At a pulse repetition frequency of 700 pulses per second, the average extreme-ultraviolet power reached 20 mW. The output beam also contained a significant contribution from odd harmonics of approximately 0.6% and 0.03% for the 3rd (4.6 nm) and the 5th (2.75 nm) harmonics, respectively. At 2.75 nm the 5th harmonic of the radiation reaches deep into the water window, a wavelength range that is crucially important for the investigation of biological samples.

	FLASH-2006	Design
Electron beam		
Energy, MeV	700	1000
Peak current, kA	1.5-2.5	2.5
Emittance, norm., mm-mrad	1-2	2
# of bunches/train	600	7200
bunch train length, ms	0.6	0.8
Rep. rate, Hz	5	10
Undulator		
Period, cm	2.73	
Gap, mm	12	
Peak magnetic Field, T	0.48	
Undulator parameter K (rms)	0.87	
total length, m	27.3	
FEL radiation		
Wavelength, nm	13-47	6-60
Average pulse energy, μJ	100	500
Pulse duration (fwhm), fs	10-50	200
Peak power, GW	3	2-3
Average power, W	0.1	10-20

Water window reached with the 5th harmonic

"Water window" = the range of X-ray wavelengths (~2.3–4.4 nm) where water is relatively transparent but carbon-based organic compounds strongly absorb

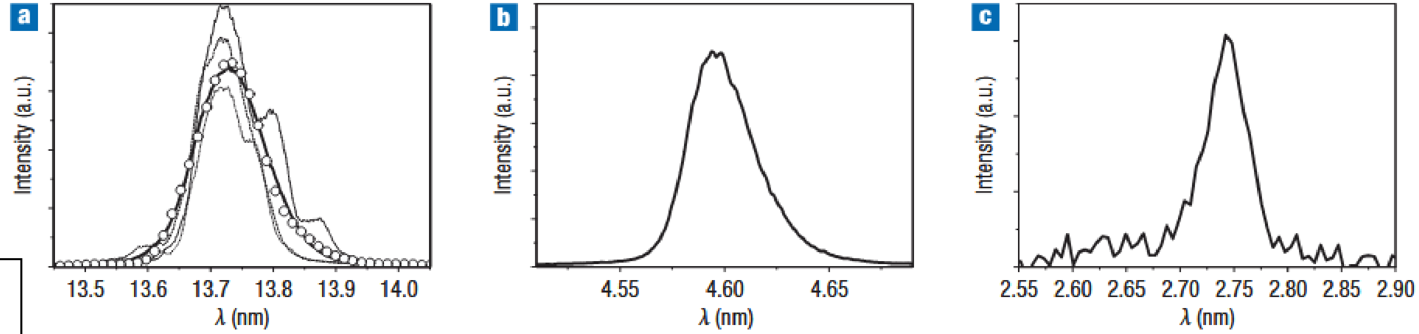


Figure 5 EUV spectra of the fundamental (a), 3rd harmonic (b) and 5th harmonic (c) contributions to the FEL output. Bold lines show averaged spectra (mean value of 300 shots), and thin lines show single-shot spectra. Circles in **a** represent averaged spectra simulated with the code FAST[38]. The average energy in the FEL pulse is 40 μJ.

Original project goals reached

Beam energy up to 1 GeV, wavelength down to 6.5 nm, lasing with long bunch trains

- Energy upgrade in 2007
  - **ACC3** replaced by **a new module**
  - **Additional module ACC6** installed
- **1 GeV** energy reached in September 2007, lasing at **6.5 nm** in early October 2007
- Installation of an electromagnetic **THz Undulator**
  - Primary purpose was longitudinal electron bunch diagnostics, but its potential to produce **THz radiation for experiments** was soon recognized

DESY TELEGRAMM 21. September 2007

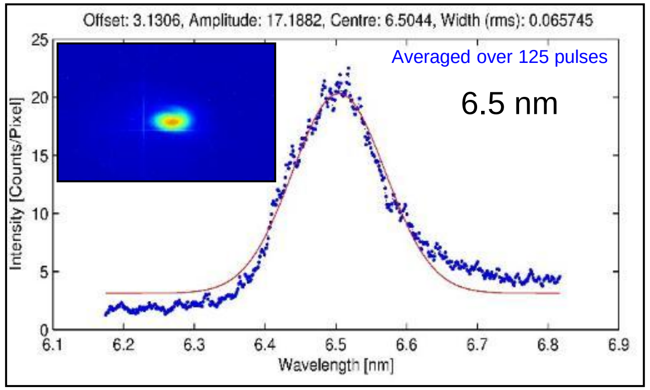
Design-Strahlenergie für FLASH erreicht!
Elektronenstrahl mit 6 Modulen erstmals auf 1 GeV beschleunigt

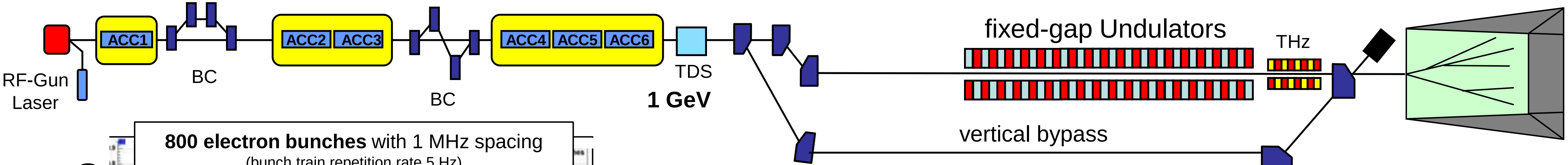
FLASH Reaches Design Beam Energy!
Electron beam accelerated to 1 GeV with 6 modules for the first time

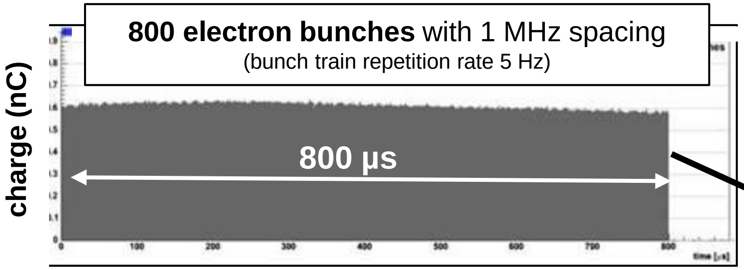
DESY TELEGRAMM 8. Oktober 2007

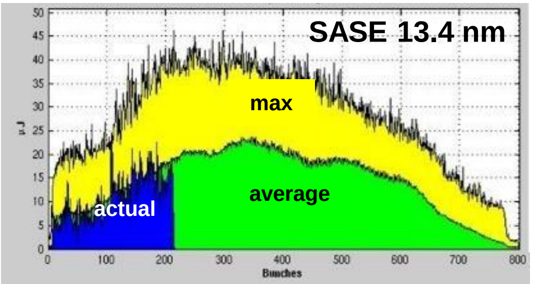
Wellenlängen-Weltrekord bei FLASH: 6,5 Nanometer!
Geplanter Designwert für die Laserblitze erzielt

Wavelength World Record at FLASH: 6.5 Nanometers!
Design value for laser flashes reached





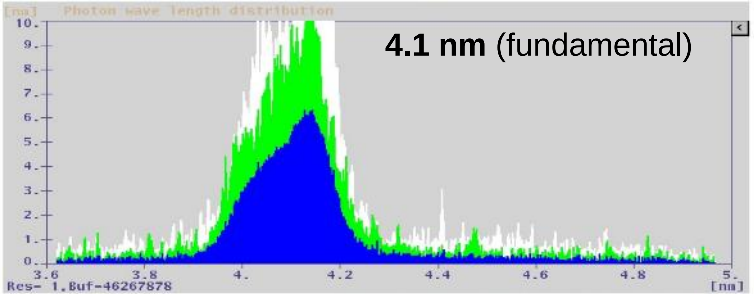


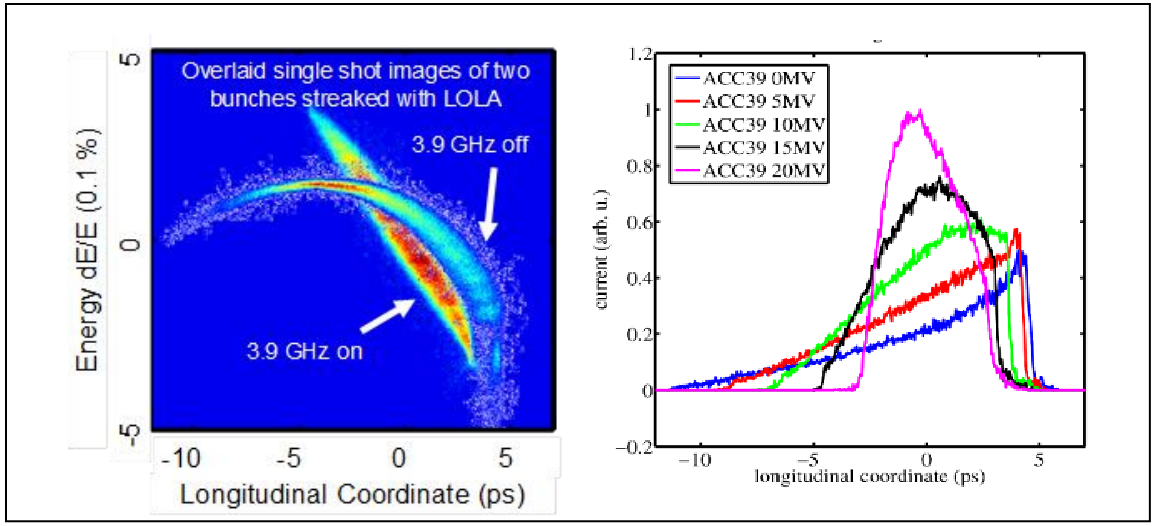


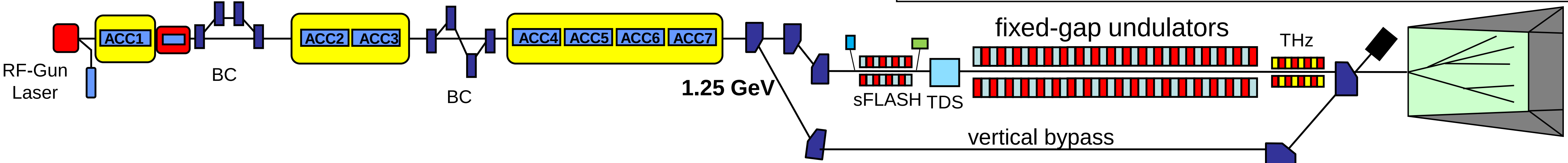
Next upgrade enables lasing (fundamental) in water window

3rd harmonic module linearizes the longitudinal phase space distribution: more regular longitudinal bunch shape

- Shutdown September 2009 to March 2010
  - Installation of an **additional module ACC7** (PXFEL1) → **1.25 GeV** → **4.1 nm**
  - Exchange of module ACC1 and installation of **3.9 GHz** (3rd harmonic) **module ACC39** (from Fermilab)
  - Installation of **sFLASH** seeding experiment
- Change to **10 Hz** operation (bunch train repetition rate)

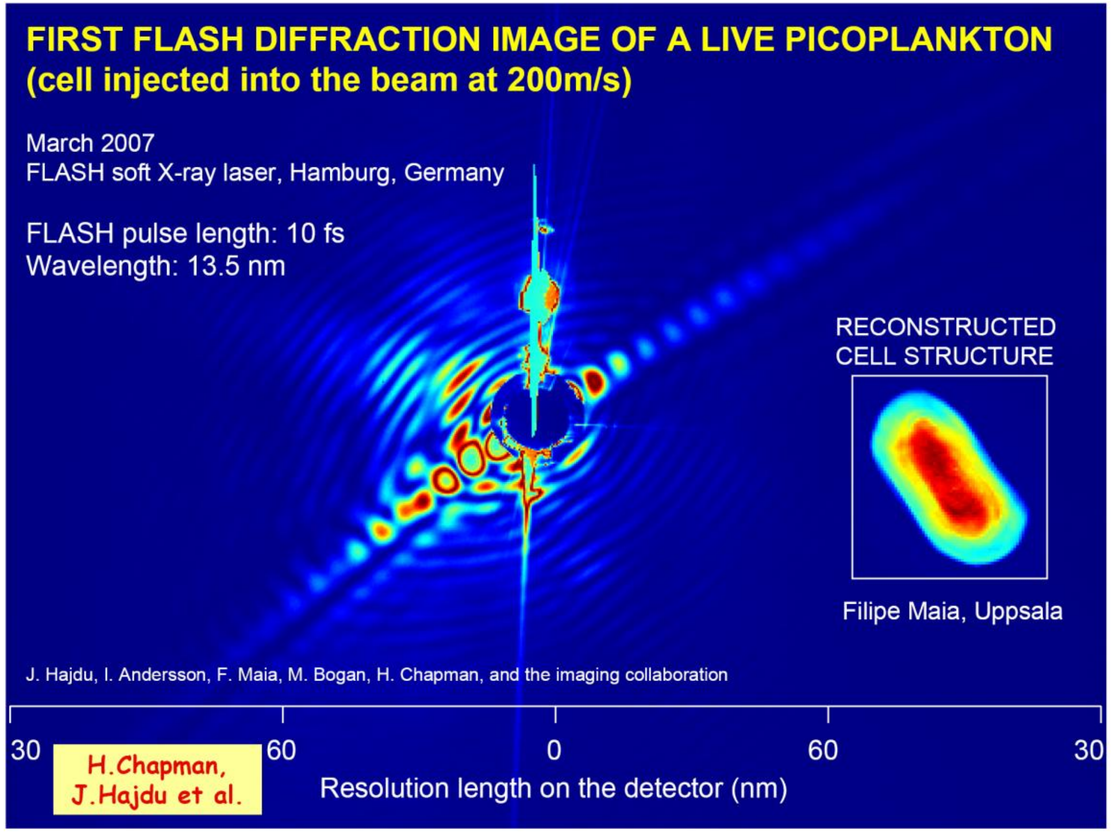






Experiments across different fields of science

Harvesting phase 2007 - 2013



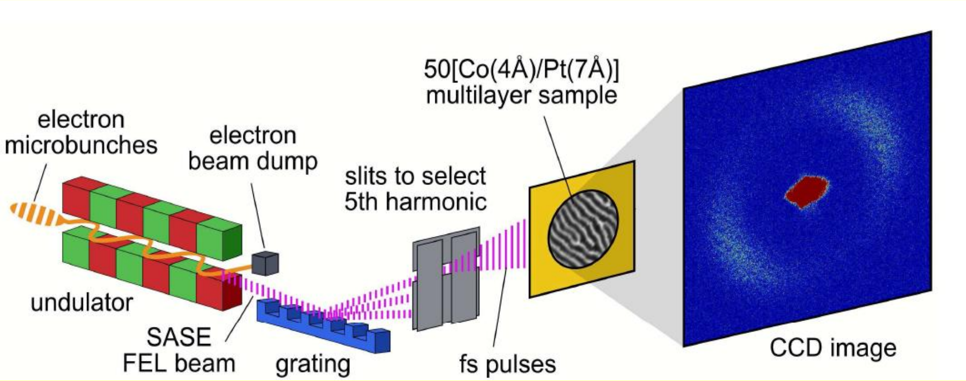
FEL Radiation Parameters 2010-2013

Wavelength range (fundamental)	4.2 – 45 nm
Average single pulse energy	10 – 500 μJ
Pulse duration (FWHM)	< 50 – 200 fs
Peak power	1 – 3 GW
Average power	up to 600 mW
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

Resonant magnetic scattering with fs-pulses at 1.59 nm

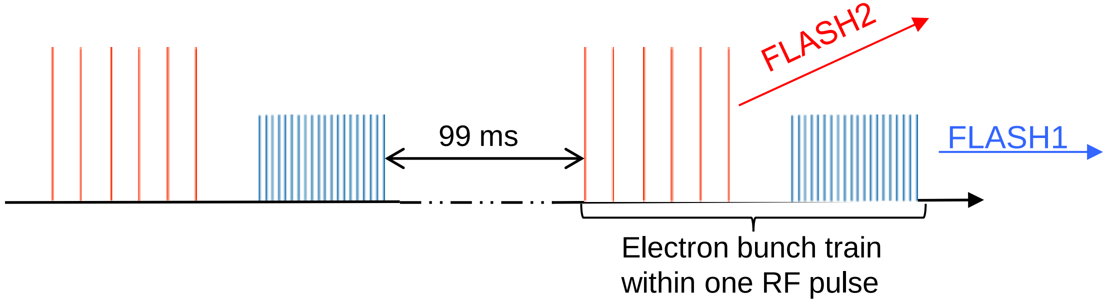
C. Gutt et al. 2007

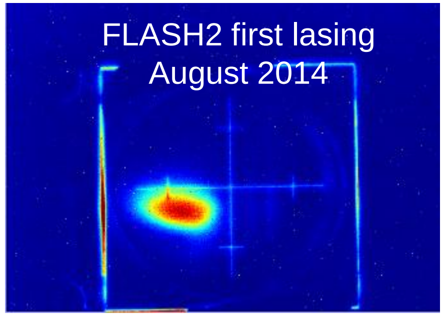


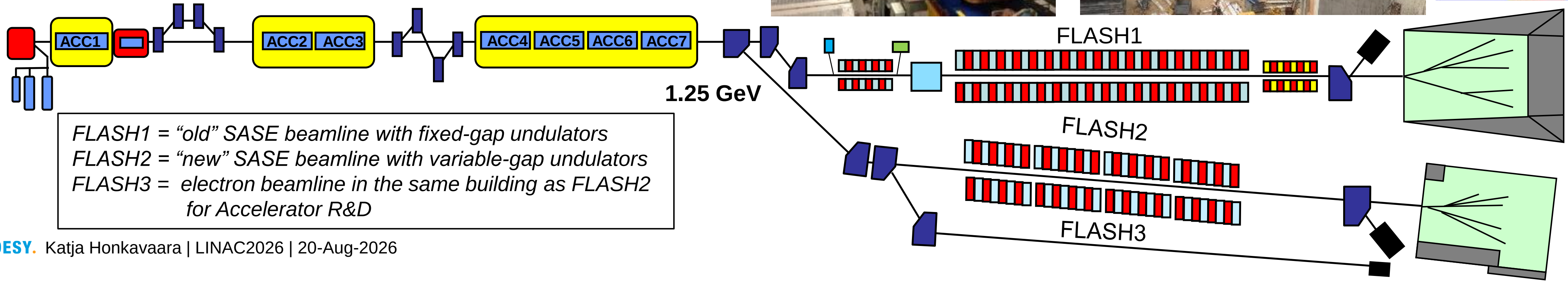
FLASH2: the second soft x-ray SASE undulator line

driven by FLASH linac, variable gap-undulators in a distinct building, and an own experimental hall

- The success of FLASH encouraged to construct **a second soft x-ray SASE undulator line**
- Civil construction started in 2011; connected to FLASH linac in 2013
- Simultaneous operation of two undulator beamlines, both at 10 Hz bunch train repetition rate
  - **Fast kicker** and **Lambertson septum** extracts a part of the bunch train to FLASH2
  - **Bunch/pulse parameters** (number, spacing, charge, duration) for FLASH1 and FLASH2 can be tailored nearly **independently,** thanks to sophisticated and flexible Injector laser(s) and LLRF system



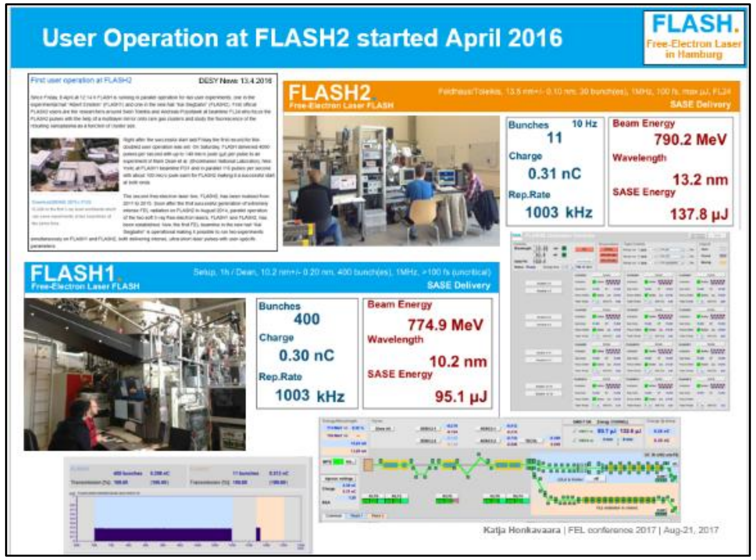




FLASH1 = "old" SASE beamline with fixed-gap undulators
FLASH2 = "new" SASE beamline with variable-gap undulators
FLASH3 = electron beamline in the same building as FLASH2 for Accelerator R&D

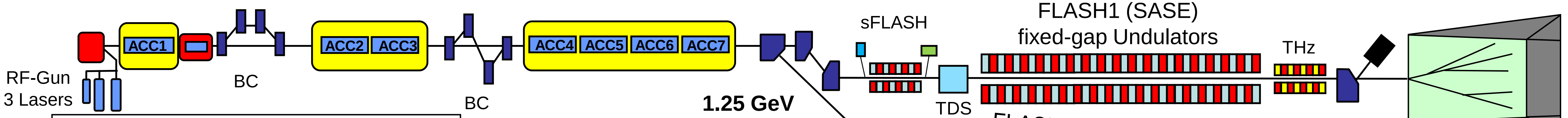
Two SASE undulator lines simultaneously in user operation

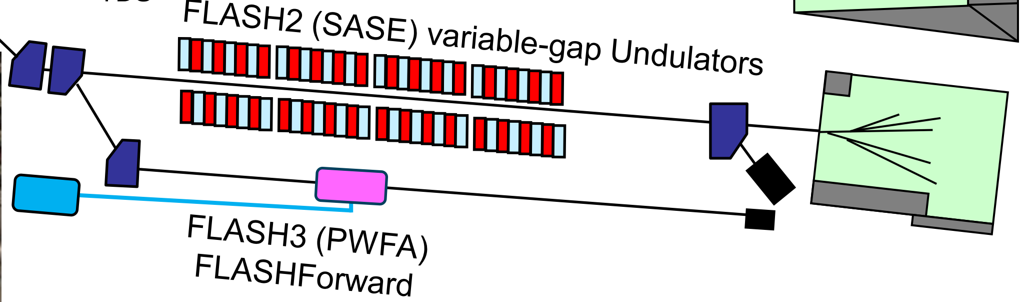
Harvesting phase 2016 – 2021 (last years hampered with the COVID-19 pandemic)



Parameters FLASH1 / FLASH2

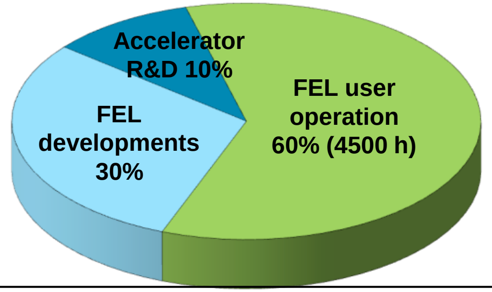
Wavelength (fundamental)	4.2 – 51 nm / 4 – 90 nm
Single pulse energy	1 – 500 µJ / 1 – 1000 µJ
Pulse duration (FWHM)	< 30 – 200 fs
Peak power	1 – 5 GW
Pulses per second	10 – 5000
Spectral width (FWHM)	0.7 – 2 % / 0.5 – 2 %
Photons per pulse	$10^{11} – 10^{14}$
Average Brilliance	$10^{17} – 10^{21}$ B*
Peak Brilliance	$10^{28} – 10^{31}$ B*





Scheduled beam time distribution

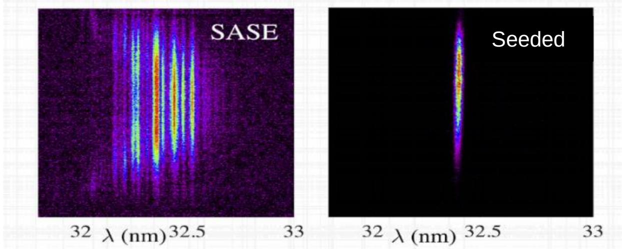
Scheduled yearly operation time: 7500 h



FLASHForward = Plasma wakefield acceleration (PWFA) experiment (experiments started in 2018)

FLASH2020+ upgrade project

Energy upgrade, high repetition rate seeding, variable polarization



Realization included **two long installation shutdowns**: 2021/22 (9 months), 2024/2025 (14 months)

Stage 1

Energy upgrade → exchange ACC2 & ACC3

New injector lasers — Laser heater

New movable BC2 — BC at FLASH2

TDS at FLASH2 — Afterburner FLASH2

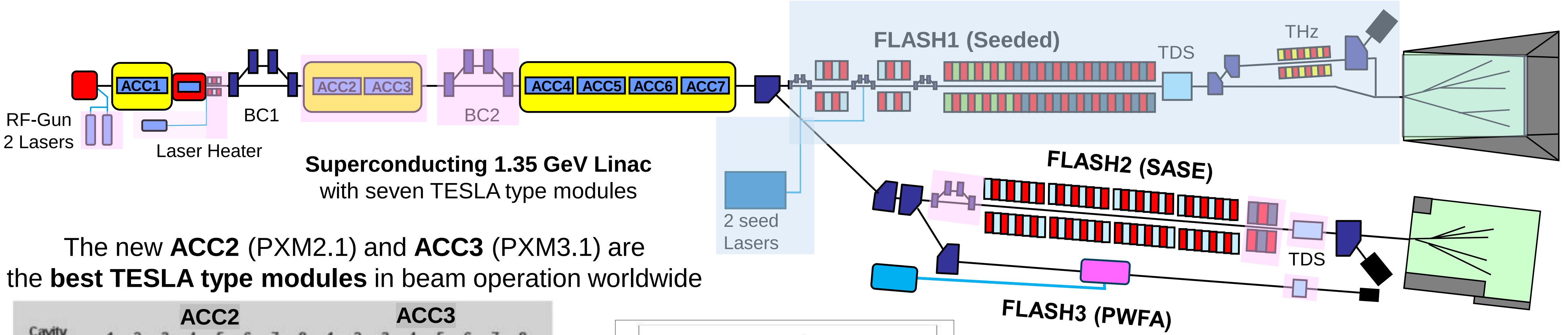
Stage 2 (FLASH1)

Infrastructure upgrade

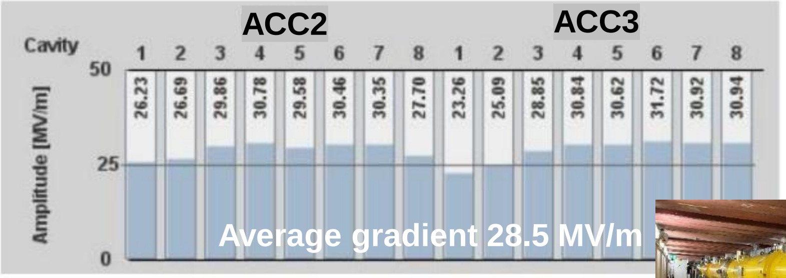
High repetition rate **seeding**

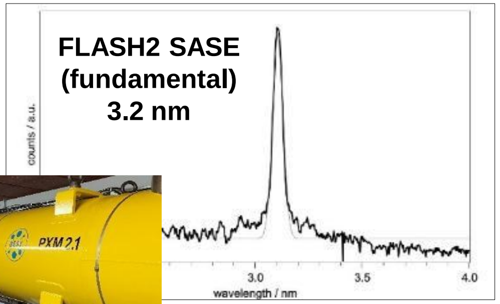
Photon diagnostics

Pump-probe laser FLASH1



The new **ACC2** (PXM2.1) and **ACC3** (PXM3.1) are the **best TESLA type modules** in beam operation worldwide





Variable polarization:

APPLE-III undulators

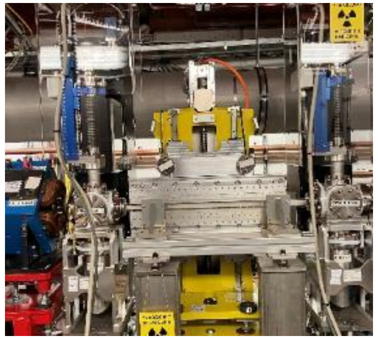
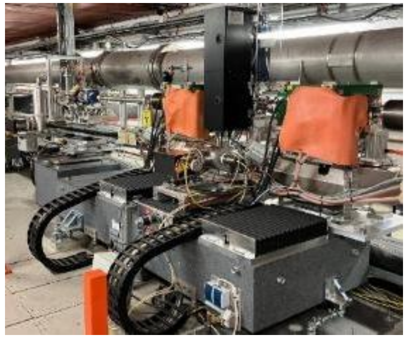
- FLASH1 radiator
  3 planar + 6 APPLE-III
- FLASH2 afterburner
  1 APPLE-III

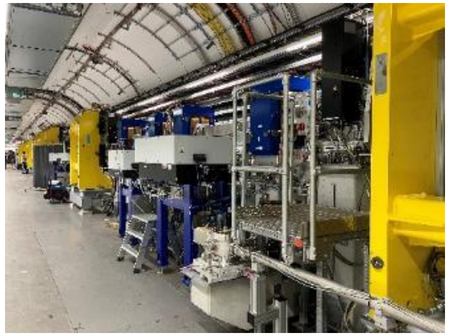
HGHG = High-Gain Harmonic Generation
EEHG = Echo-Enabled Harmonic Generation

FLASH is an unique FEL

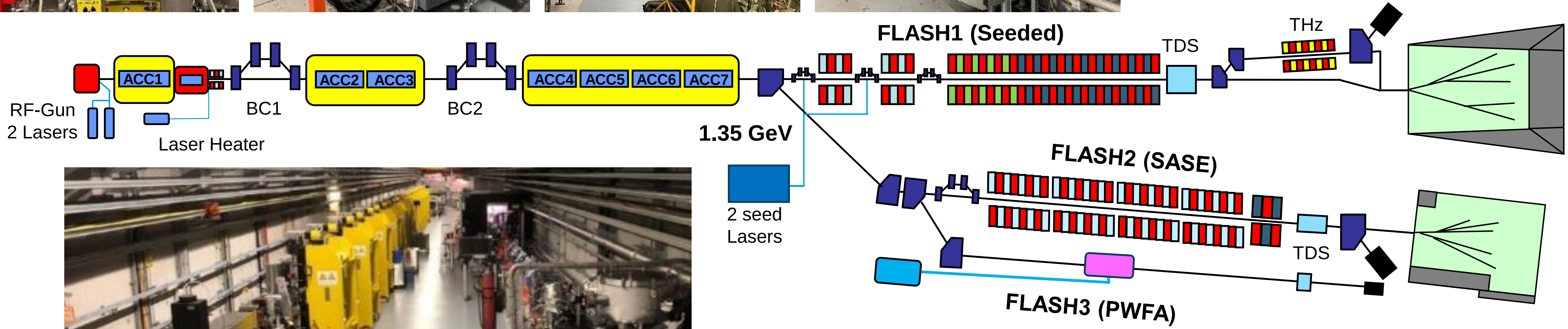
operating in parallel externally seeded FEL and SASE FEL with a high repetition rate

5000 photon pulses / second
shared between FLASH1 and FLASH2
500 bunches with 1 MHz spacing per train, train repetition rate 10 Hz



FLASH1: Externally seeded FEL
- HGHG and EEHG seedings
- Narrow spectral bandwidth
- Shot to shot stability
- Full coherence



FLASH2: SASE FEL
- High pulse energy
- Shortest pulses
- Transverse coherence

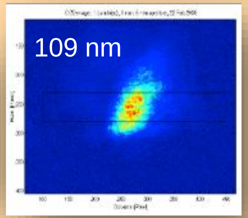
FLASH3: PWFA
- FLASHForward plasma wakefield acceleration experiment

FLASH is the forerunner of FEL user facilities worldwide

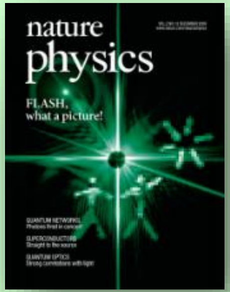
FLASH is continuously upgraded to define the state of the art in soft X-ray FEL technology

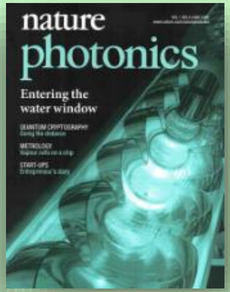
TTF Linac
demonstrated the feasibility of high gradient **superconducting** accelerator technology

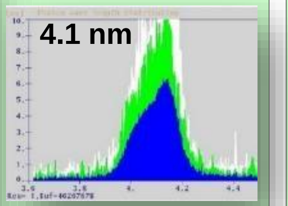
TTF-FEL
was the **first SASE FEL** in VUV range



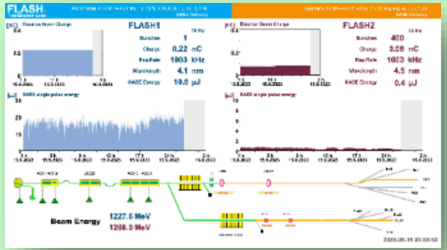
FLASH
was the **first** XUV-**FEL user facility**







FLASH1 + FLASH2
was the **first** facility operating **two** undulator beamlines **in parallel**



FLASH
is **unique** with
1 MHz seeding and parallel operation of **seeded and SASE** beamlines

1995 — 2000 — 2005 — 2010 — 2015 — 2020 — 2025

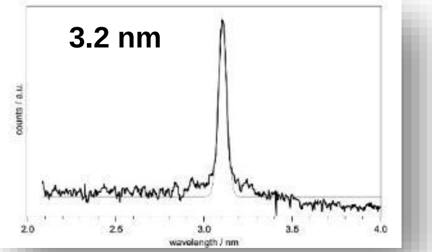
Beam energy up to **250 MeV**
Photon wavelength: **80 nm** – 120 nm

Beam energy up to **700 MeV**
Photon wavelength down to **13 nm**

2007 → Energy upgrade to **1 GeV**
Photon wavelength down to **6.5 nm**

2009/10 → Energy upgrade to **1.25 GeV**
Photon wavelength down to **4.1 nm**

2022 → Energy upgrade to **1.35 GeV**
FLASH2 photon wavelength down to **3.2 nm**



2024/25/26 →
FLASH1: **HGHG** and **EEHG** in parallel with FLASH2 SASE
FLASH2: photon wavelength down to ~ **1.5 nm** with 3rd harmonic afterburner
Variable polarization

Many of the key technologies for high performance FELs have been and are invented at TTF FEL and FLASH

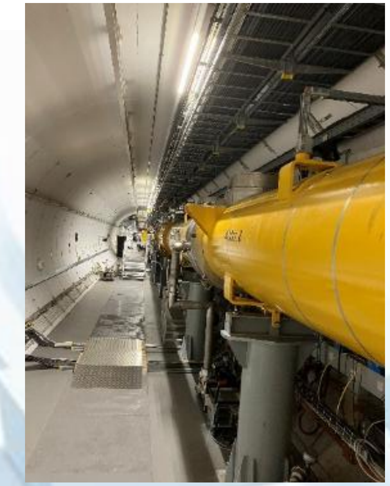
The key to success lies in a passionate and dedicated team

Thanks to everyone who has contributed to TTF/FLASH over the past 30 years!

Extra slides

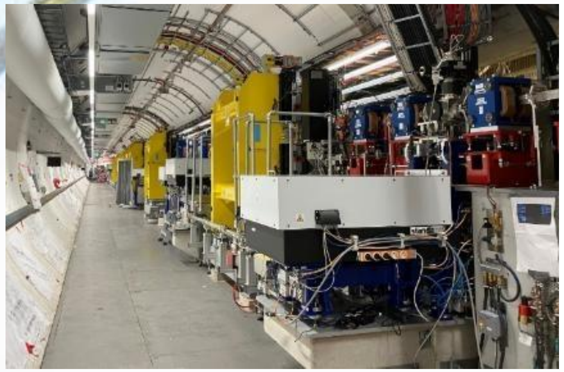
FLASH – the Free-Electron Laser at DESY – 2026

Machine parameters	FLASH
Electron energy (GeV)	0.35 - 1.35
Emittance RMS (µm) @ 0.4 nC	0.5
Energy spread (keV)	200
Bunch charge (nC)	0.01 – 1.2
Max peak current (kA)	2.5
Max bunches from gun (1/s)	15000



Lasing parameters	FLASH1 Seeded (expected)	FLASH2 SASE	FLASH1 THz (expected)
Photon energy (eV)	20.6 - 310	14 - 390 (- 890)*	0.015 - 0.124
Min FWHM bandwidth (%)	0.05	0.5	10
Max pulse energy (uJ)	< 20	1000	> 100
Pulse energy fluctuation (%)	≤ 10	10 – 100	
Pulse length (fs)	11 - 40	5 - 200	
Polarization	variable	horizontal (variable)*	horizontal

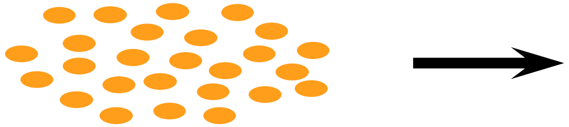
* with afterburner

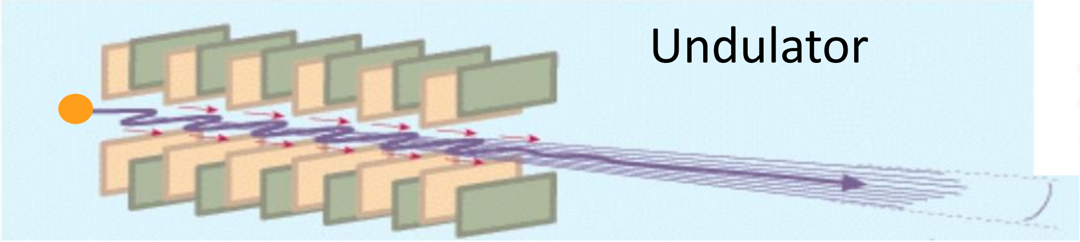


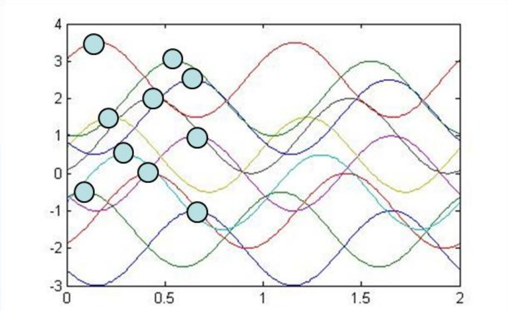
FEL principle

Ingredients:

Relativistic e-beam

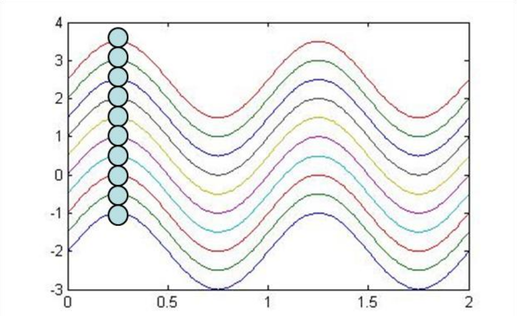






Incoherent ($\propto N$)

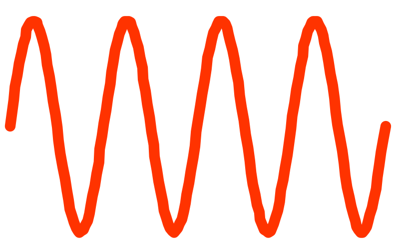
Up to here, we have “just” synchrotron radiation

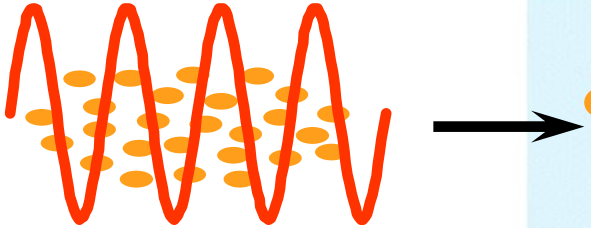


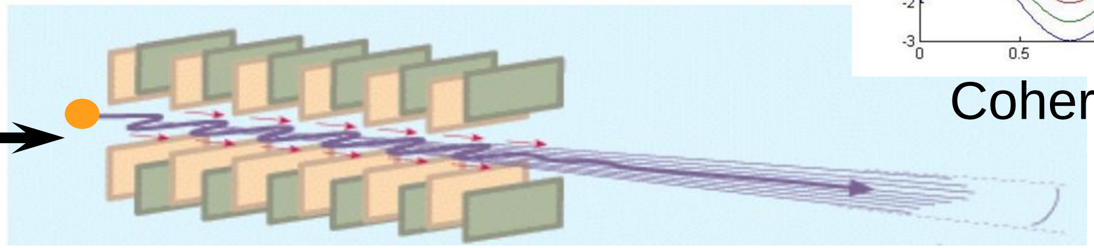
Coherent ($\propto N^2$)

We have to “convince” the electrons to radiate in phase, by adding a small ingredient:

Electro-magnetic wave





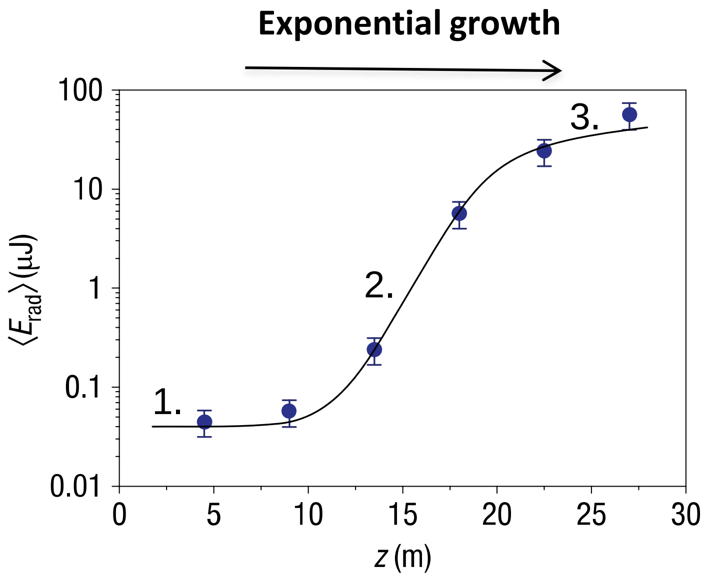


Amplification through energy transfer between e-beam and light

What is SASE?

Self-amplified spontaneous emission principle

1. The electron beam propagates in a long undulator and emits synchrotron radiation and starts interacting with the spontaneous emission
2. The spontaneous emission is, eventually, amplified
3. up to saturation (or to the undulator end)



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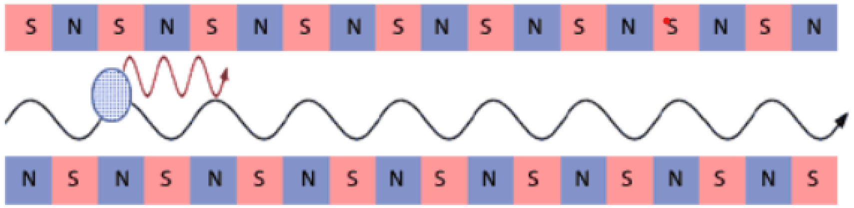

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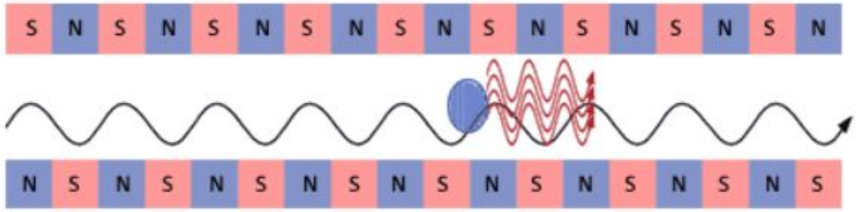

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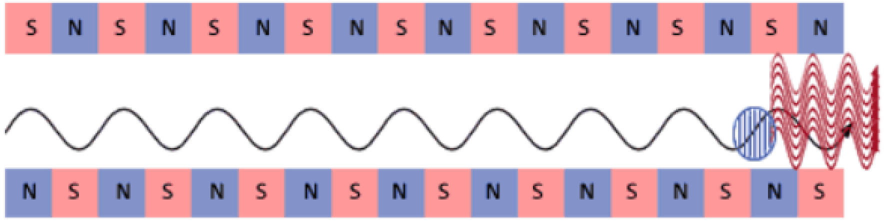
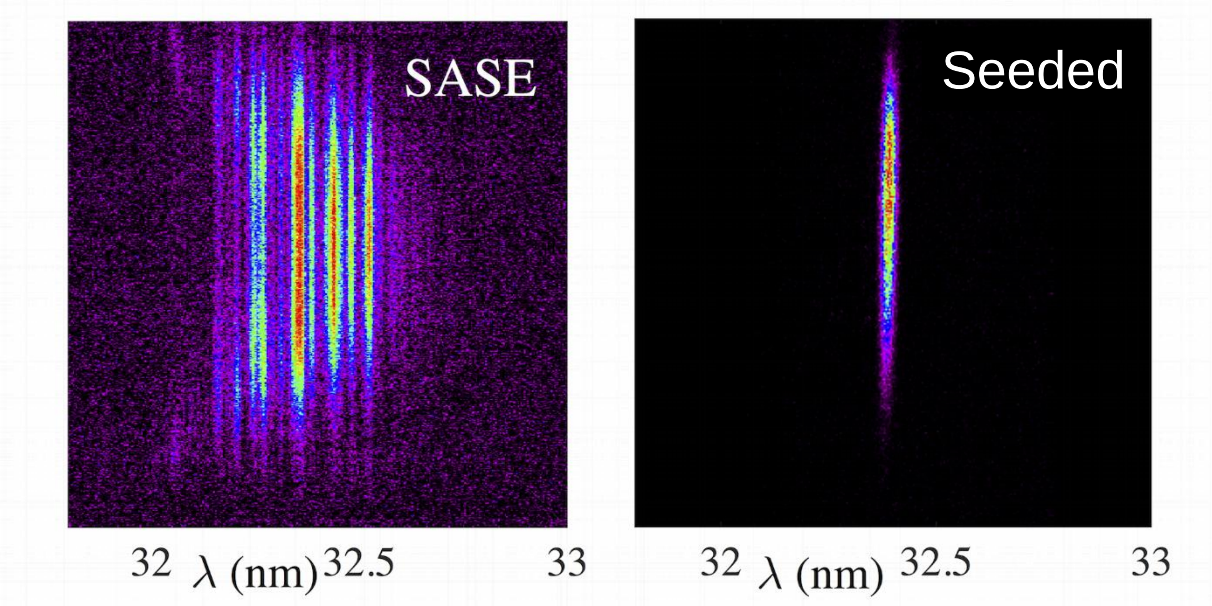


www-ssrl.slac.stanford.edu/lcls/glossary.html

What is seeding?

- Single-pass FELs can amplify the **noise** present in the electron beam density profile obtaining powerful SASE radiation.
- Using instead an “**external**” electromagnetic field (a seed) it is possible to initiate the FEL process in a deterministic way.
- The **properties** of the output FEL radiation are **inherited** and **determined** by the seed itself.

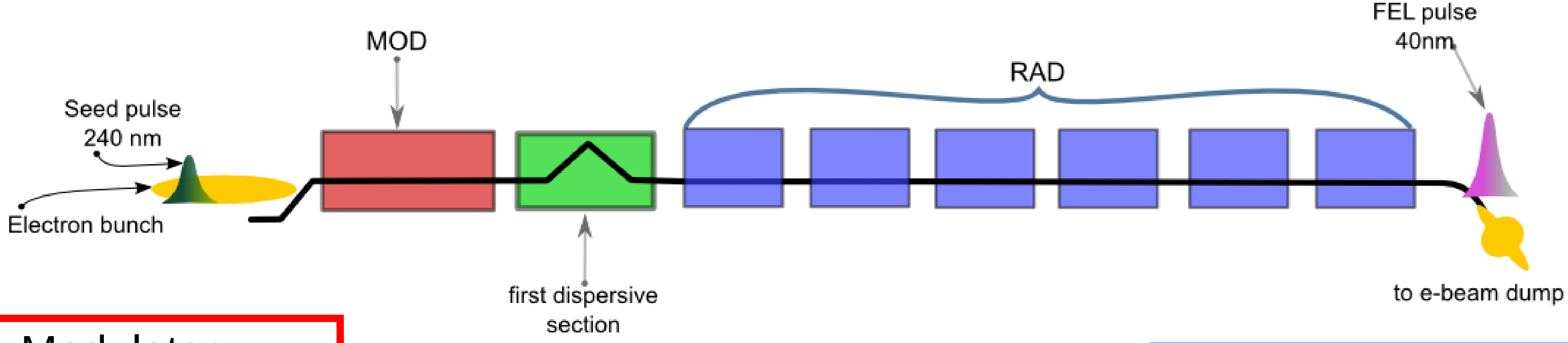


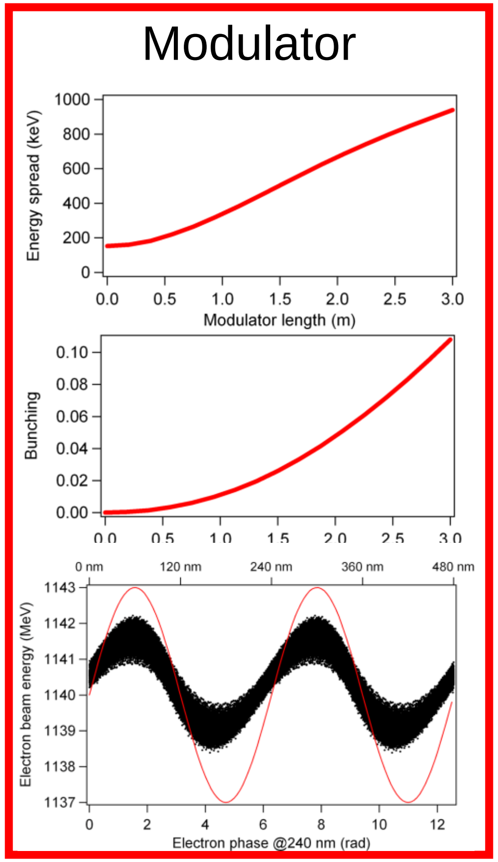
Compared to SASE devices, seeding can be more compact and produces nearly fully temporally coherent output.

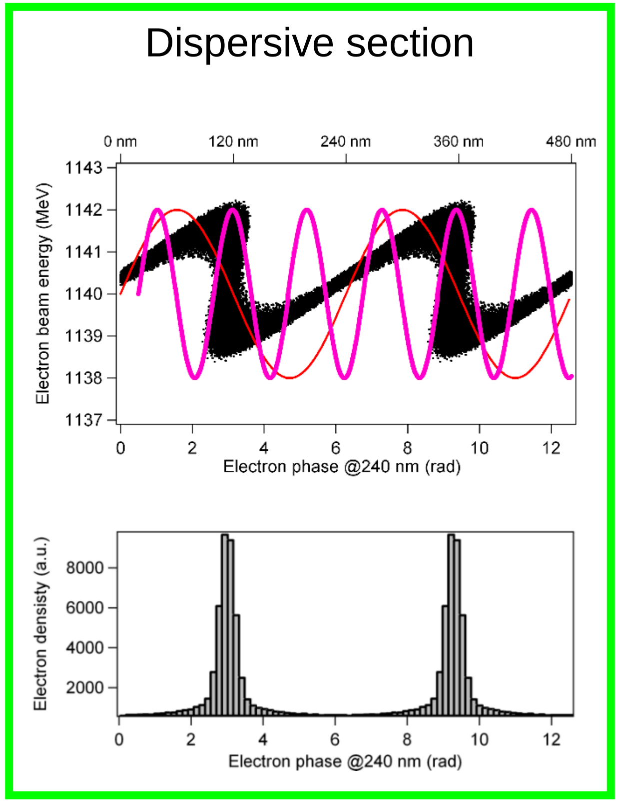
Spectral parameters can be controlled.

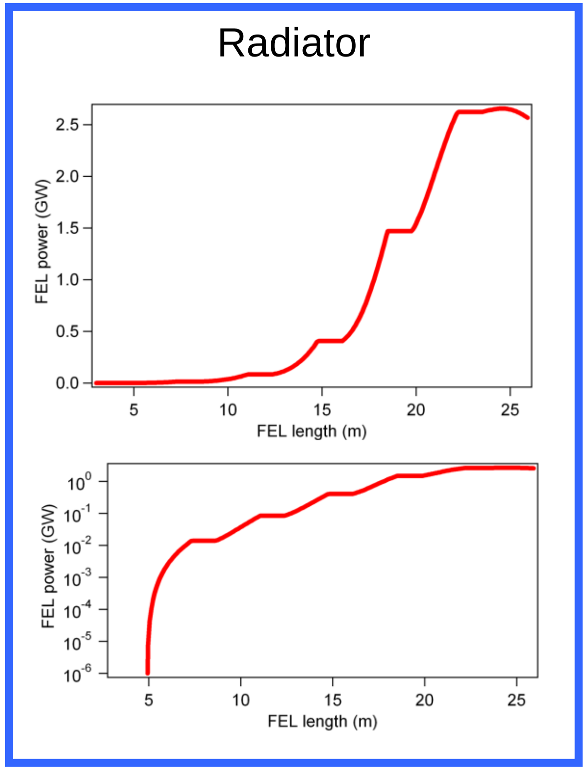
High Gain Harmonic Generation

HGHG



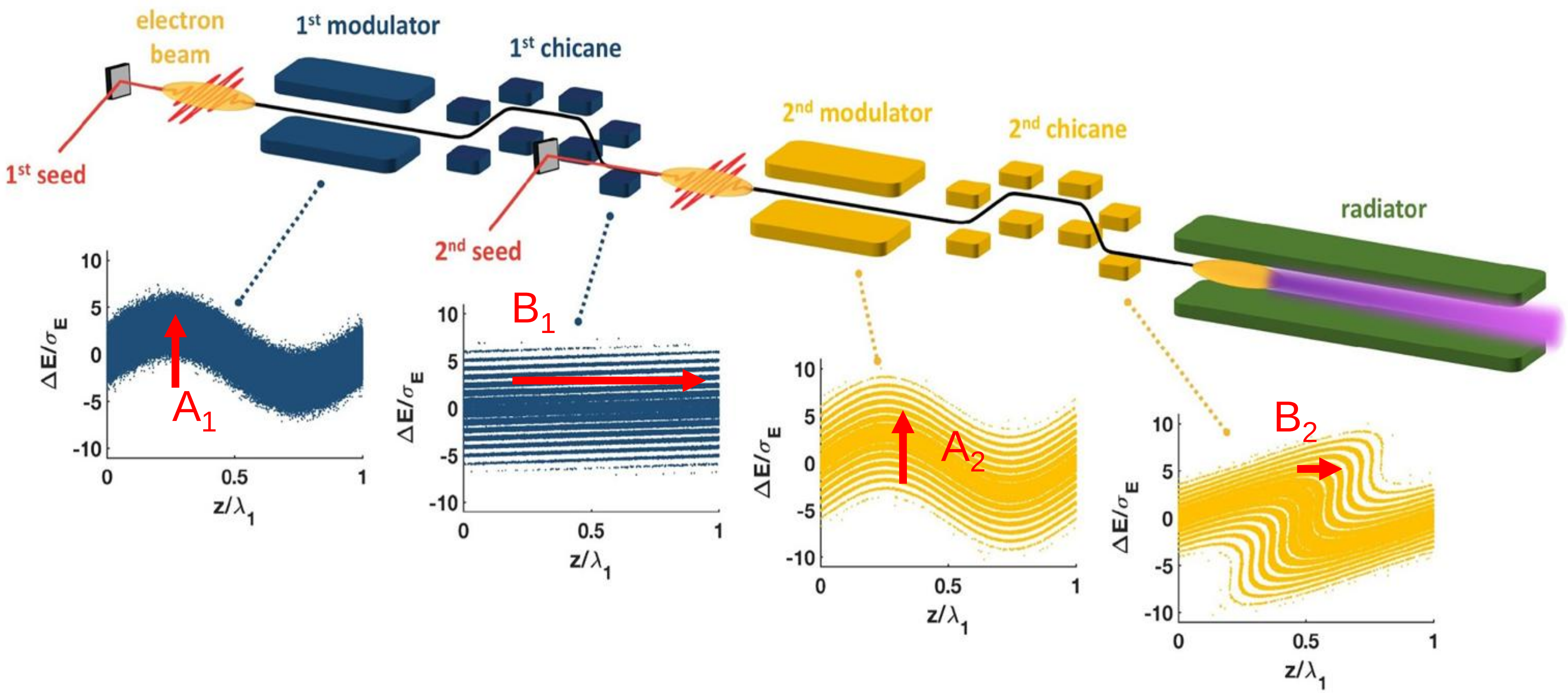




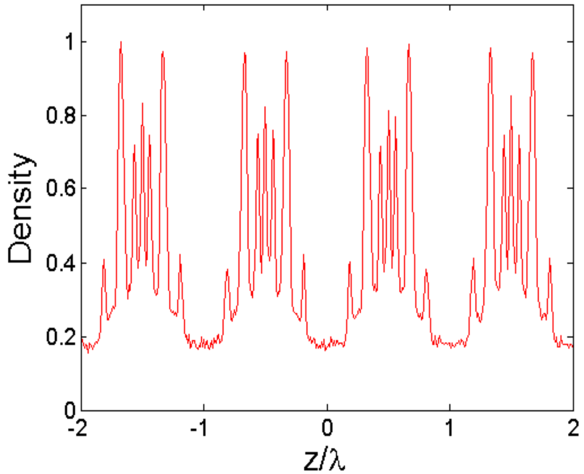


Echo Enabled Harmonic Generation

EEHG



- The first laser generates an energy modulation in electron beam.
- A strong chicane creates stripes in the longitudinal phase space.
- The second laser imprints an energy modulation.
- The second chicane converts the energy modulation into harmonic density modulation.

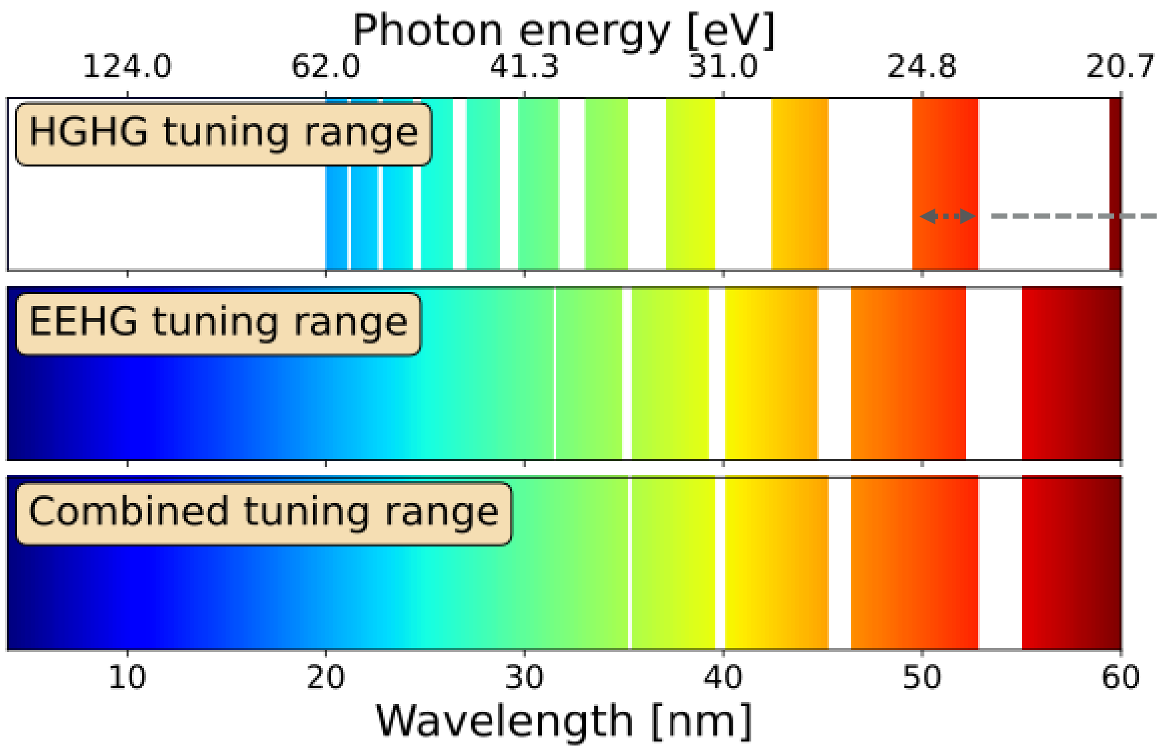


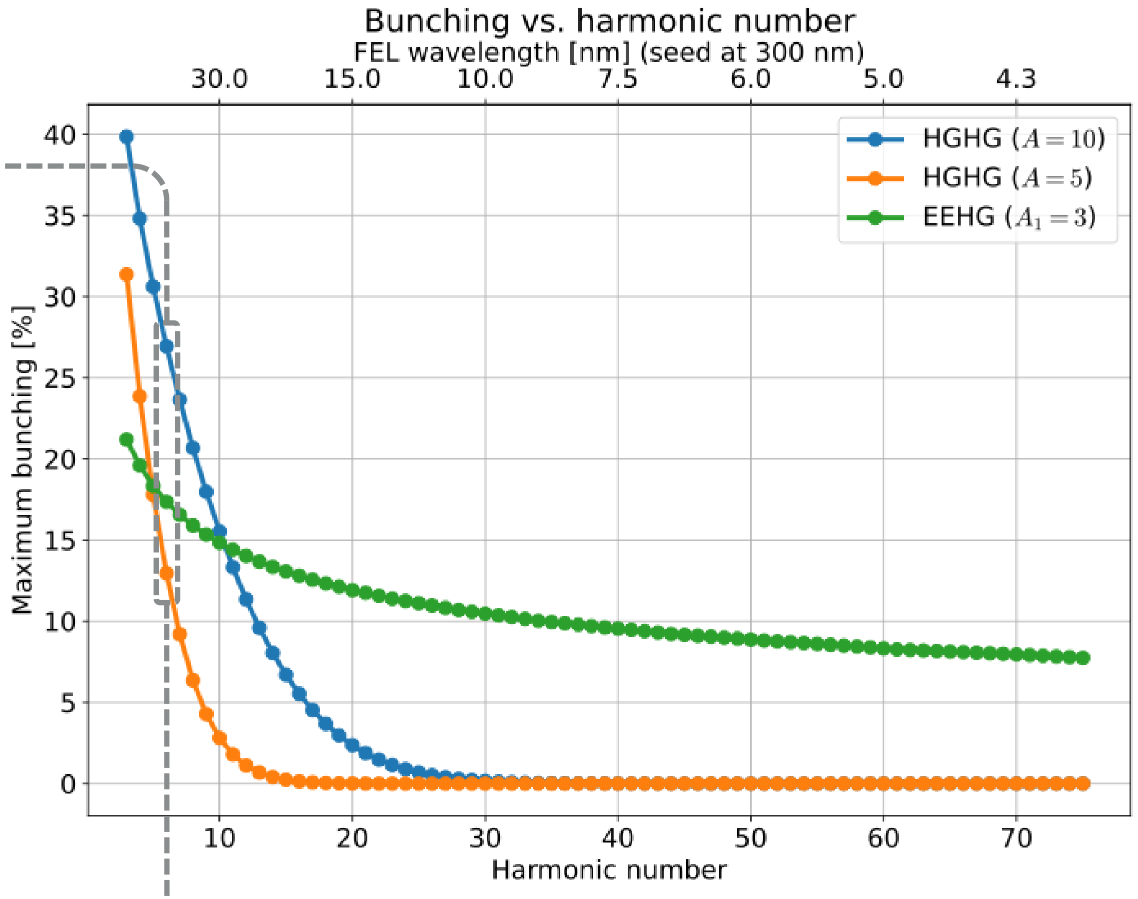
G. Stupakov, PRL, 2009

D. Xiang, G. Stupakov, PRST-AB, 2009

Wavelengths for FLASH1

60 nm to 4 nm by using 5th to 75th harmonic of seed laser





Seed 1: **343 nm, 100 MW, 500 fs**

Seed 2: **297-317 nm, 300 MW, 50 fs**