Lasing beyond 20 keV, recent achievements and future prospects

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European XFEL is the world leading FEL facility in terms of electron and photon energies. The new regime above 20 keV allows for novel photon science opportunities, especially in combination with the high repetition rate of EuXFEL. This presentation shows both the to-date achievements as well as future plans to strive for even higher photon energies within the next years.

Science Cases for Hard X-Rays

- Increased spatial resolution for scattering experiments
  - Allows measurement of amorphous pair distribution function

- Increased damage threshold
  - Lower photon cross section allows for more photons
  - High repetition rate allows to study µs-ms dynamics
  - Eg Bubble nucleation in metal foams

- Increased penetration depth for highly absorbent samples
  - Allows in situ studies of reactions
  - Allows to study phonon dynamics in the time domain by diffuse scattering

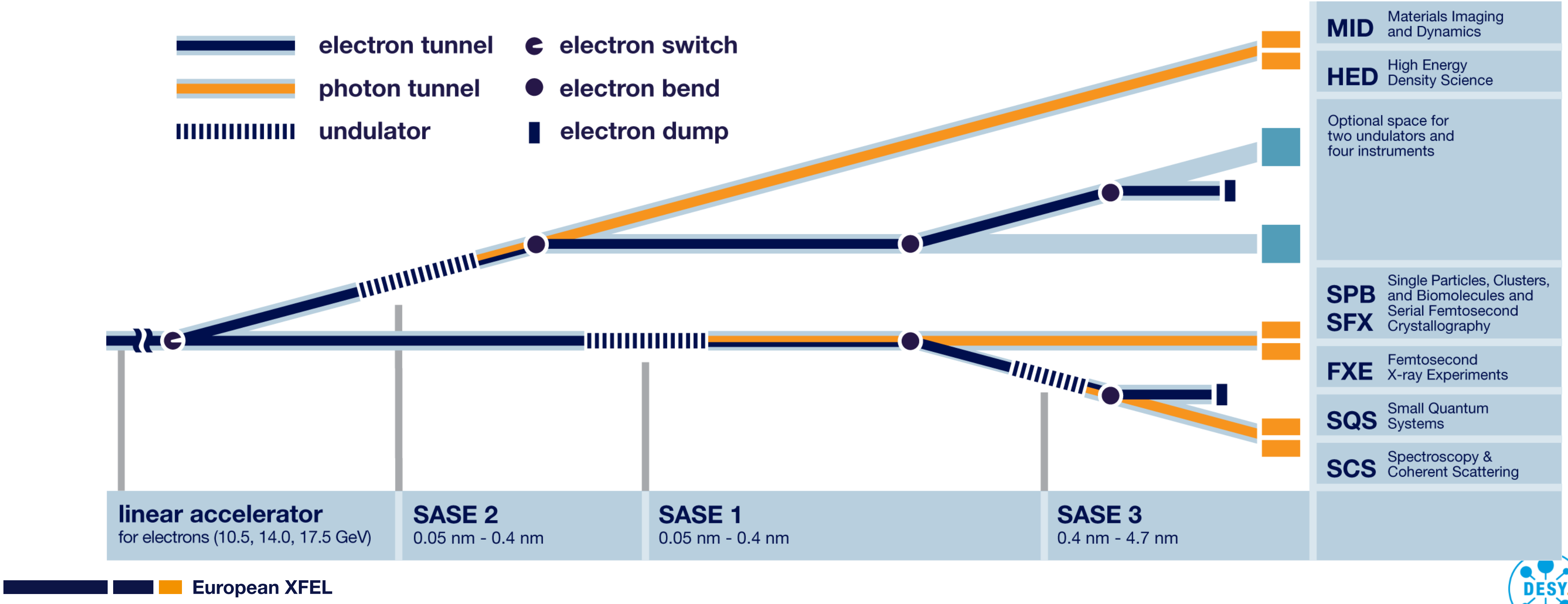
Science Cases for Hard X-Rays

- Structures and dynamics in disordered systems
  - liquids, melts, solutions
- Matter under extreme conditions
  - Diamond anvil cell with pulsed laser heating
- AMO
  - Beneficial to study compton scattering and recoil effects

Science opportunities with very hard XFEL radiation Workshop - 2021

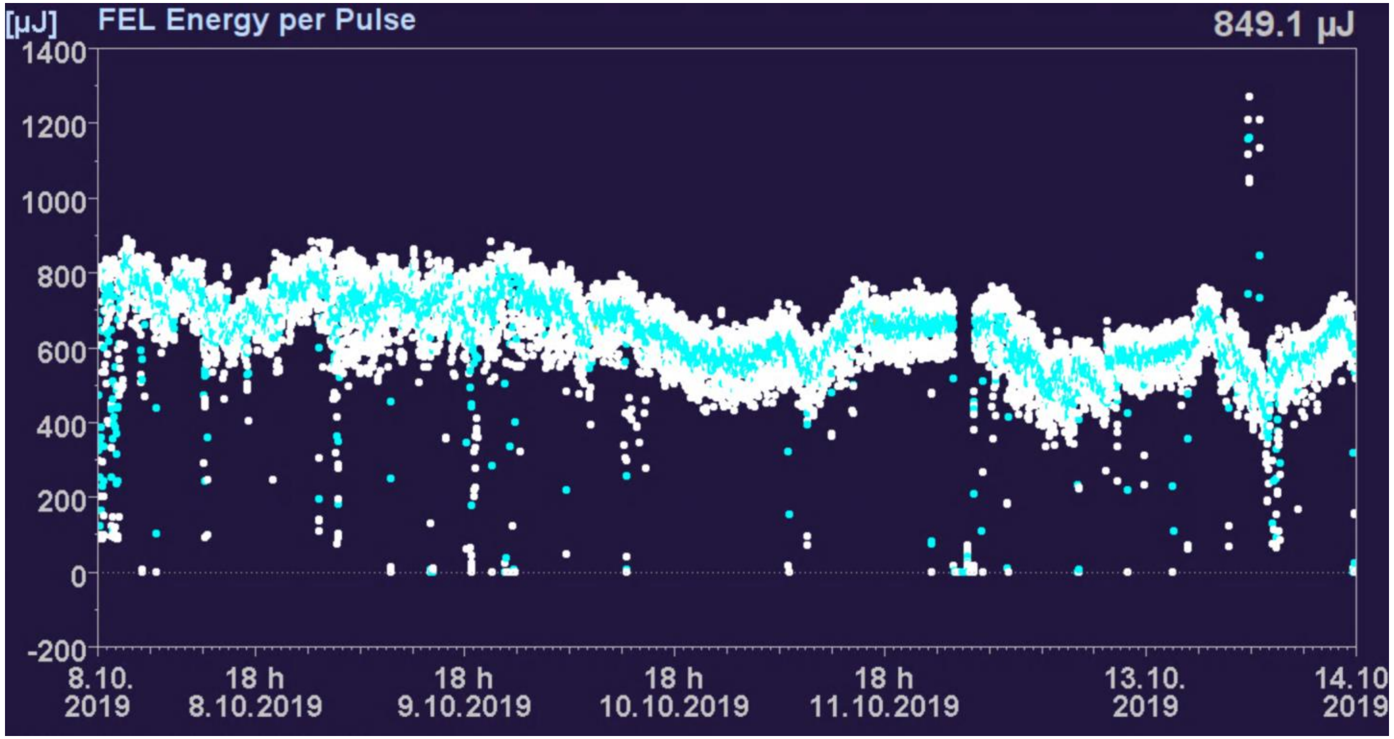
European XFEL

- The linac serves three beamlines
  - 2 Hard X-ray lines
  - 1 Soft X-ray line
- Design energies
  - Linac: 17.5 GeV
  - X-rays: <25 keV



User delivery: 17.8 keV

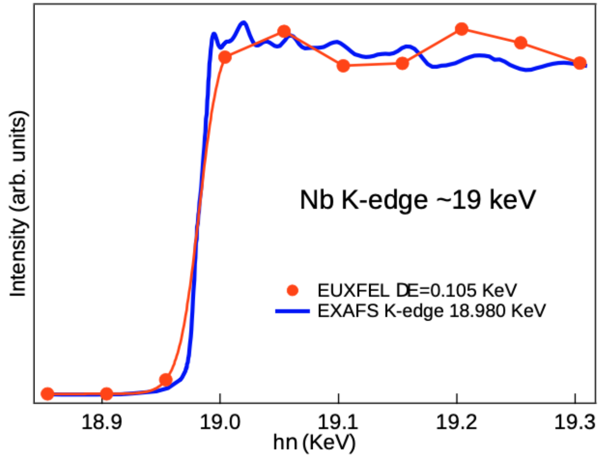
- Highest photon energy for user delivery for FELs
- Stable user delivery over one week
- Electron Energy 16.5 GeV

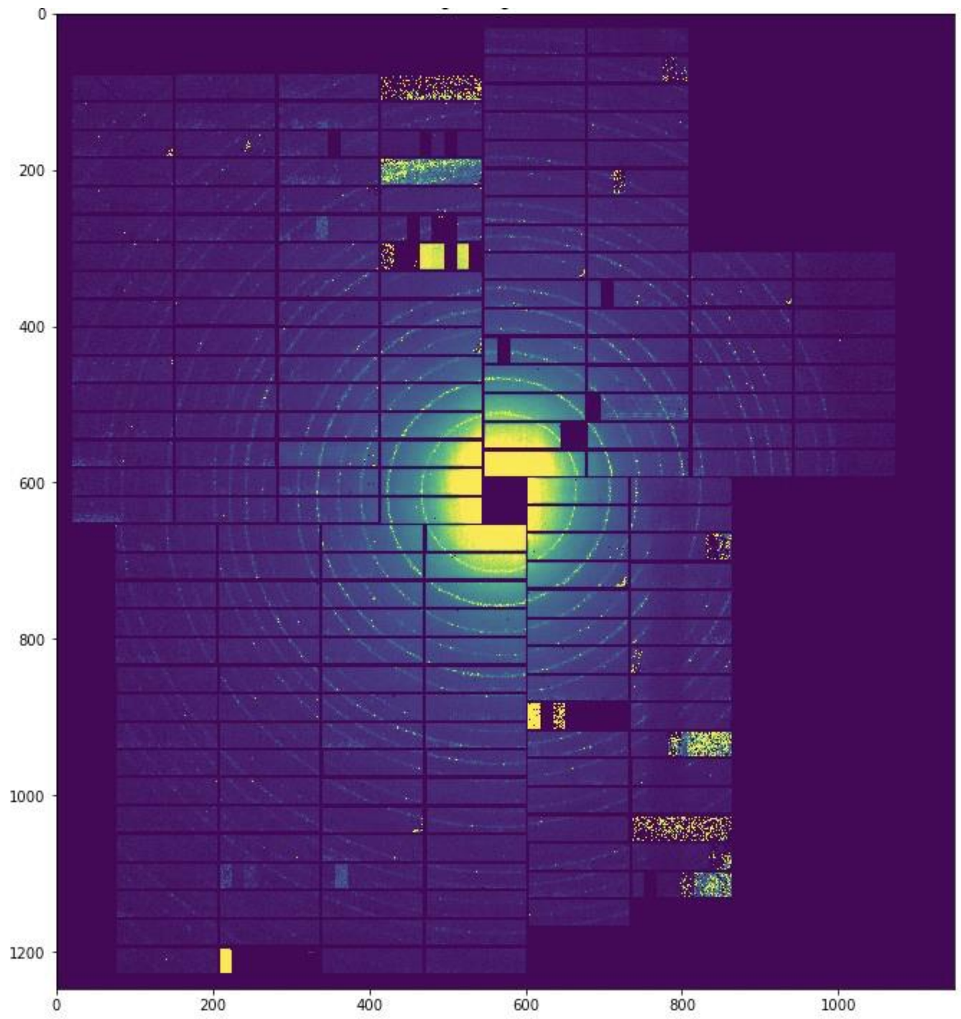


X-ray Commissioning: 20 keV

- Stable operation of photon beam at 20 keV at 1mJ level
- Electron Energy 16.5 GeV
- Commissioning experiments were performed at the FXE & SPB/SFX photon hutches

Unique opportunities at high X-ray energies!

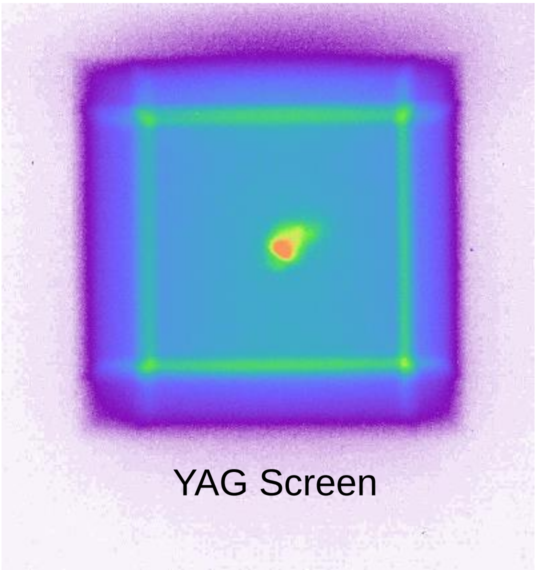


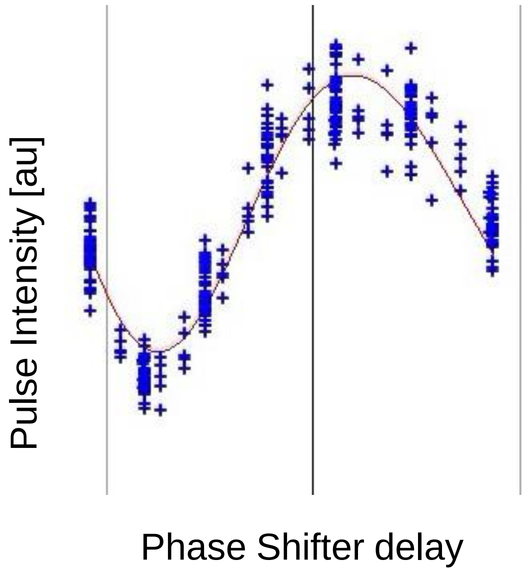


Large Pixel Detector at FXE

Machine Development: 30 keV

- Stable lasing at 30 keV
  - Electron energy 17.5 GeV
  - Observation of lasing on a screen
  - Outside of design parameters of the undulator system
- Only qualitative measurements of pulse intensity
  - Gas detector shows FEL intensity modulations
  - Low gas cross-section does not allow for absolute measurement
  - Further R&D is underway





Current Photon Energy Limitations

- Electron Energy is typically 14 GeV
  - Tradeoff for softer x-rays in SASE 3
    - ► Possible future mitigation by frequency mixing (proof-of-principle experiment was done)
    - ► Possible future mitigation by refurbishing undulator for longer periods
  - RF limitations
    - ► Permanent higher RF gradient testing is planned
    - ► Enough space for 4 more modules (currently 26 + 1 installed)

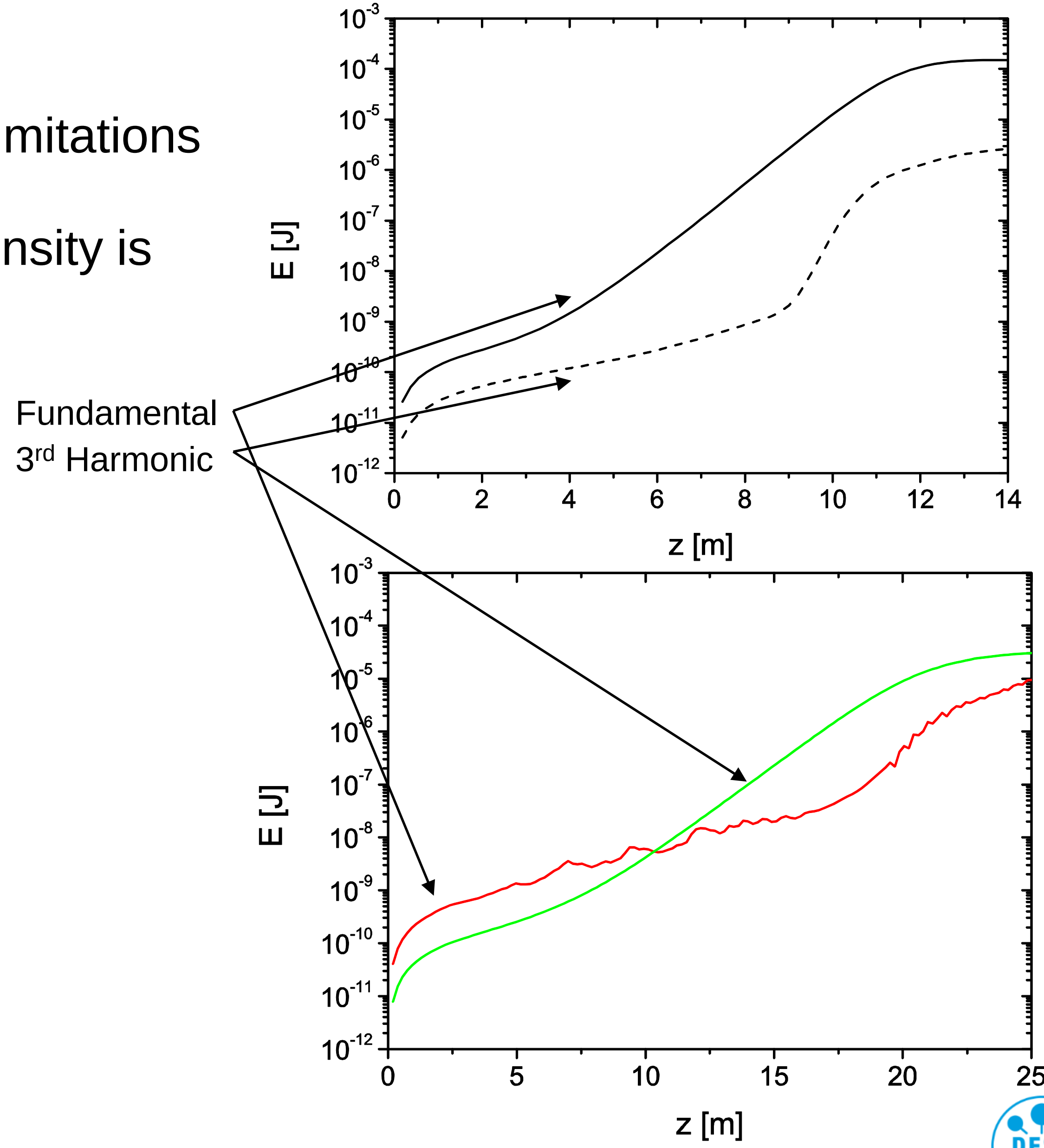
- Photon optics has limited wavelength acceptance
  - HED: 24 keV
  - FXE: 20 keV
  - MID: 18 keV
  - SPB/SFX: 16 keV

Harmonic Lasing

- One way to get around the electron energy limitations

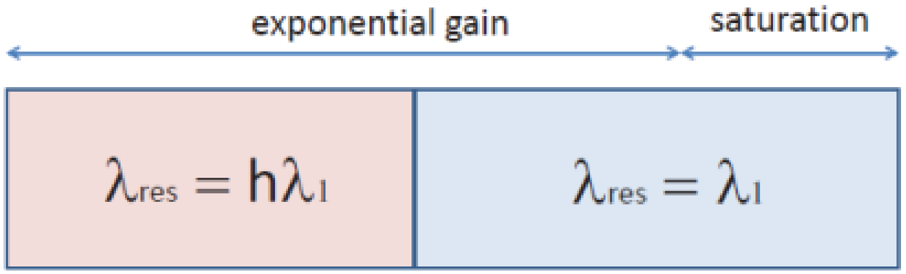
- Typically around 1% of the photon pulse intensity is in 3rd harmonic
  - Comes for free with a good SASE setup

- Suppress fundamental wavelength while leaving higher harmonic intact
  - Disturb fundamental with phase shifters
  - Leave higher harmonic unperturbed

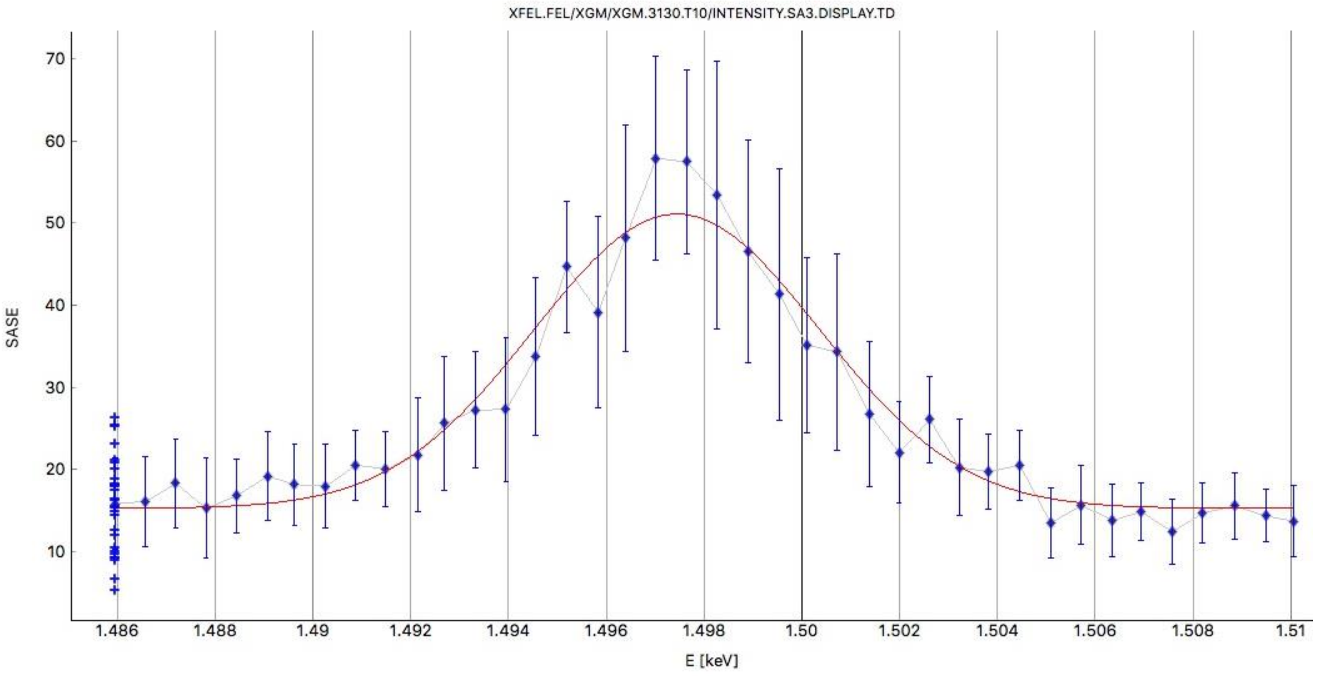


Harmonic Lasing Self Seeding

- Principle
  - Create bunching at the fundamental
  - Use an after-burner at the higher harmonic



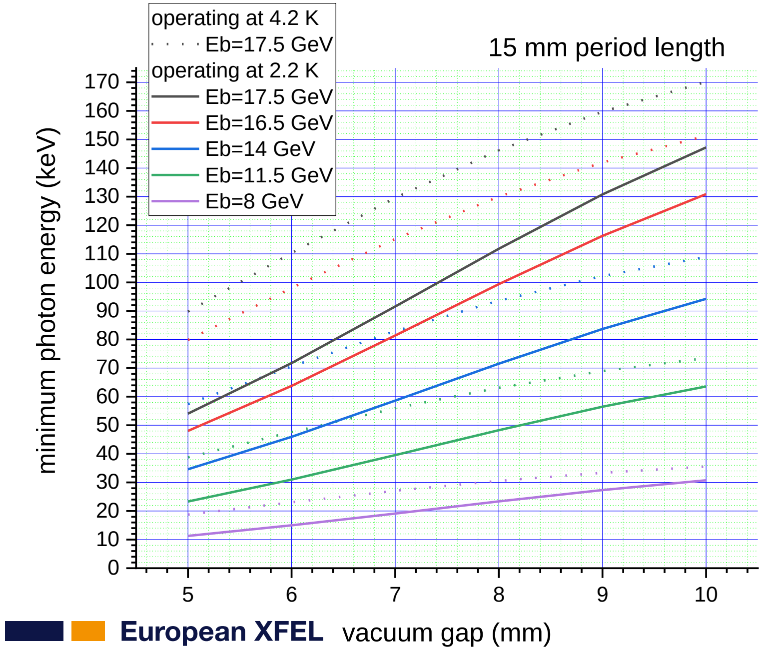
- Proof-of-principle experiment
  - 6 Undulators set to 1.5 keV
  - 6 Undulators set to 4.5 keV
  - Was also done with the 5th harmonic

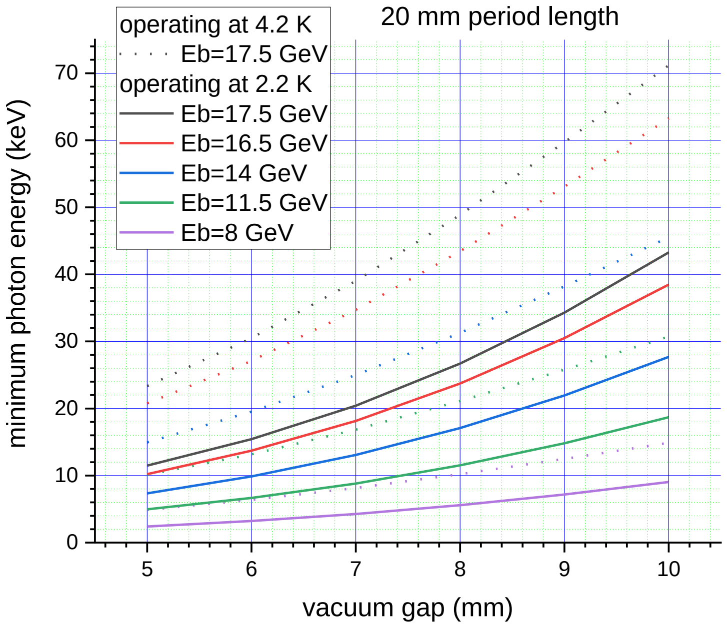


Scan of the undulators at the fundamental

Future prospects: Superconducting undulator afterburner

- Planned to be installed downstream of SASE2
  - 5 units with 2x2m SCU planar undulators with phase shifters
  - Undulator period either 15mm (SASE2 has 40 mm)
  - Under consideration for installation within the next 5 years
  - Targeting 10^9 photons at 50 keV



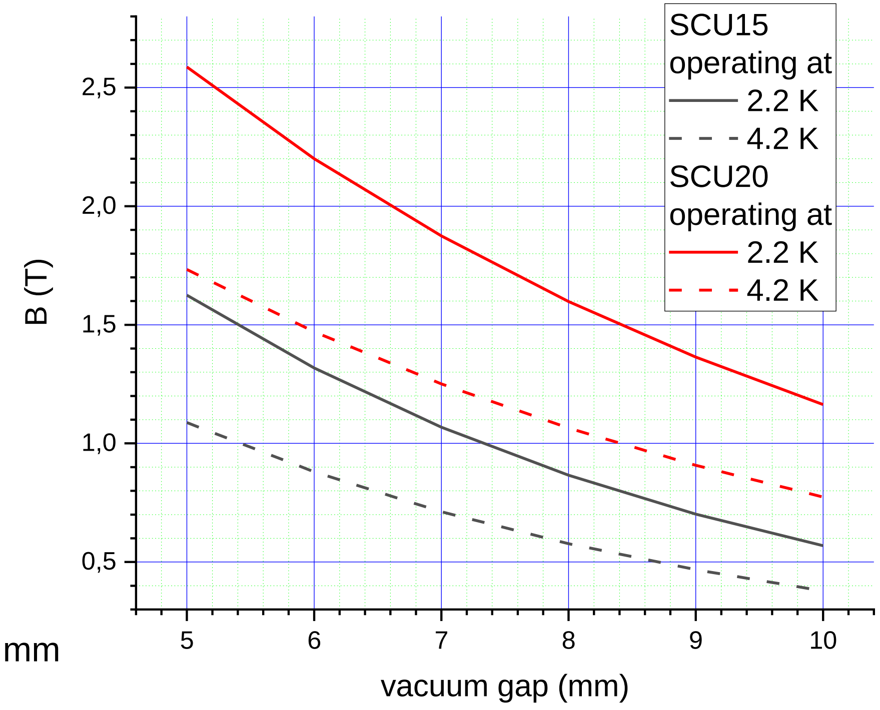


Comparison between existing Undulators and Superconducting After-burner

- The proposed afterburner scheme allows for increase in photon intensity
- Comparing 40 keV fundamental for SASE1/2 with after-burner configuration

17.5 GeV 250pC 20 m SCU20	17.5GeV 1nC 20 m SCU20	17.5 GeV 250pC 30 m SCU20	17.5GeV 1nC 30 m SCU20
7.5×10^{10} gain~4	3×10^{11} gain~4	$1.\times10^{11}$ gain~5.5	4.1×10^{11} gain~5.5

- Gain = $\frac{photons\ per\ pulse\ at\ x\ m\ SCU}{photons\ per\ pulse\ from\ 1st\ h.\ after\ SASE1/2}$
- Energy spread 5 MeV, gap= 7 mm operating at 4.2 K of with a v. gap = 9.6 mm



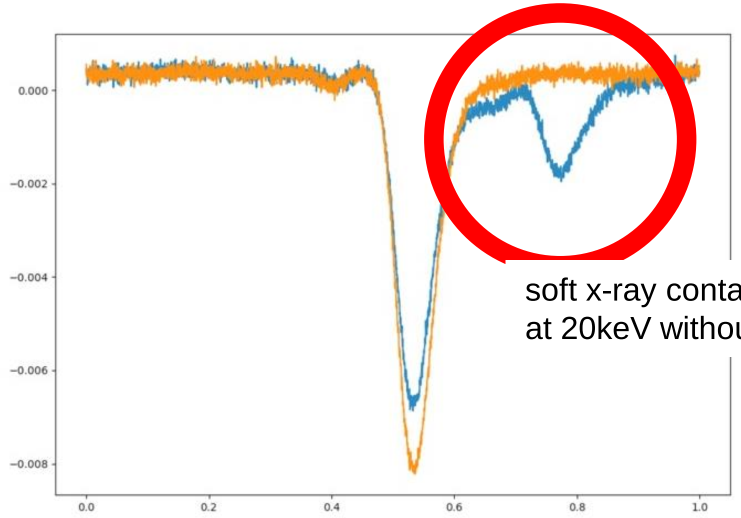
Photons per pulse with harmonic lasing (SASE1/2 set to 3rd harmonic)

	14 GeV 50 keV 250pC 20 m SCU	14 GeV 50 keV 250pC 30 m SCU	17.5 GeV 75 keV 250pC 20 m SCU	17.5 GeV 75 keV 250pC 30 m SCU
20 mm	1.4×10^9 gain~2.8	2.0×10^9 gain~3.7	5.8×10^8 gain~2.5	8×10^8 gain~3.4
15 mm	2.0×10^9 gain~3.9	2.8×10^9 gain~5.7	8.0×10^8 gain~3.4	1.2×10^9 gain~5.3

Slice energy spread 3 MeV (nominal)

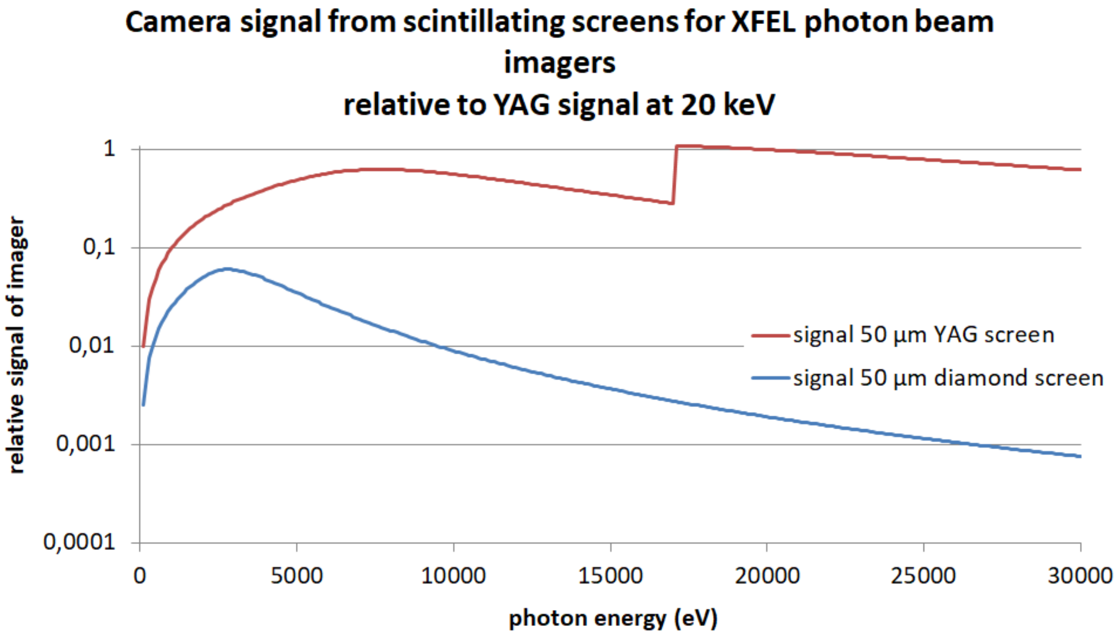
X-Ray Diagnostic Beyond 20 keV

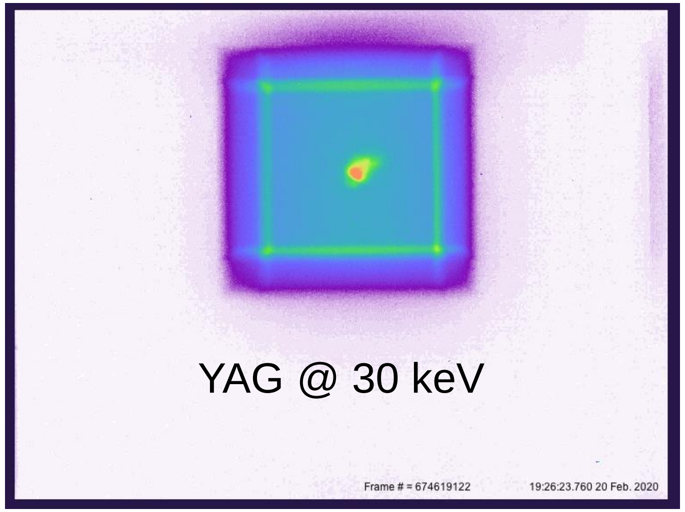
- Currently installed diagnostics is limited in its wavelength range
- X-ray gas monitor
  - Parasitic measurement
  - Pulse resolved
  - Sensitive to soft x-ray contamination (can be filtered)
  - Calibrated up to 25 keV
  - Further R&D is needed to increase its range (new gas types, calibrations, …)



X-Ray Diagnostic Beyond 20 keV

- YAG Scintillator
  - Limited to 2 pulses
  - Has a good signal response above 20keV
- Diamond Screen
  - Allows for longer pulse trains
  - Good response above 20 keV due to sufficient photon flux in FEL
  - Currently being investigated to further increase the photon range





Summary

- European XFEL is already pushing into the area of harder x-ray lasing
  - Photon user experiment: 17.8 keV
  - Commissioning experiments: 20 keV
  - Fundamental lasing of the machine: 30 keV

- Current limitations
  - Default electron energy is lower than design energy for harder x-rays
  - Photon energy acceptance of instruments: <25 keV

- Future prospects
  - Go to higher harmonics
  - Install super conducting afterburners with shorter wavelengths
  - Increase electron energy
  - Extend current photon diagnostics for higher photon energies

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