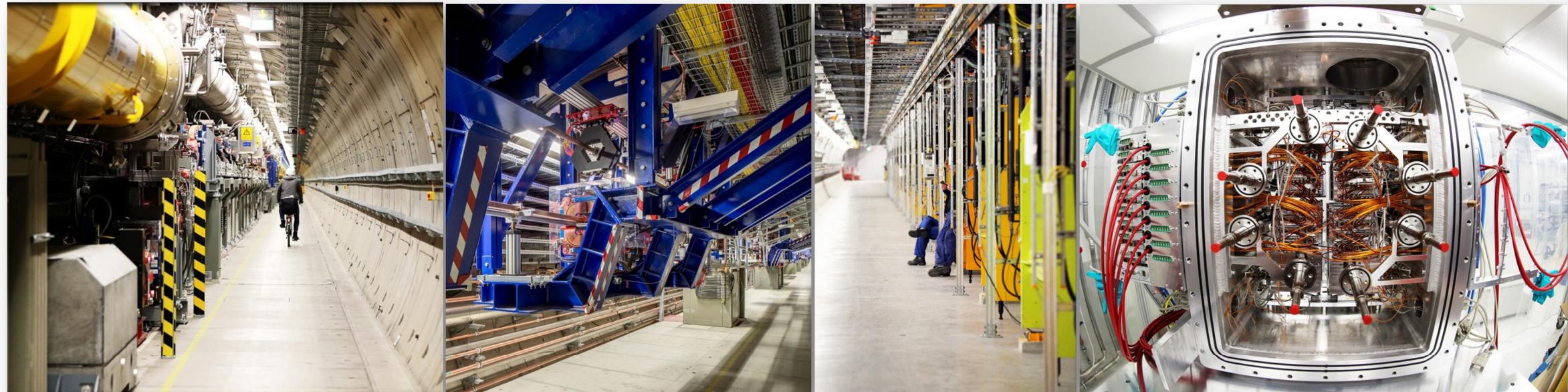


# FEL Operation at the European XFEL Facility

Dirk Nölle for the EuXFEL Operation Team

FEL 2019, 39<sup>th</sup> International Free-Electron-Laser Conference  
Hamburg, 26.-30. August 2019



# The European XFEL between Hamburg Bahrenfeld and Schenefeld

The map illustrates the European XFEL facility's layout. It shows the 1.9 km long accelerator tunnel starting from the DESY campus in Bahrenfeld, passing through Osdorfer Born, and ending at the Experimental hall in Schenefeld. The tunnel is marked with a red line and orange highlights for the undulators and photon beamlines. Labels include "Undulators/Photon beamlines", "Electron beam distribution", "Start on the DESY campus", "Accelerator 1.9 km/ 17.5 GeV", and "Experimental hall in Schenefeld". A scale bar indicates 0 to 500 m. The map also shows the surrounding areas of Hamburg and Schleswig-Holstein.

- Super conducting accelerator with up to 17.5 GeV electron beam energy
- Three undulator beamlines in two branches (north and south)
- In total 6 experiments, 4 for hard X-rays and 2 for soft X-rays
- potential for 2 more FELs

A photograph showing the interior of the circular accelerator tunnel. Two people are walking away from the camera, highlighting the enormous size of the structure. The tunnel walls are made of concrete with various markings and equipment visible.

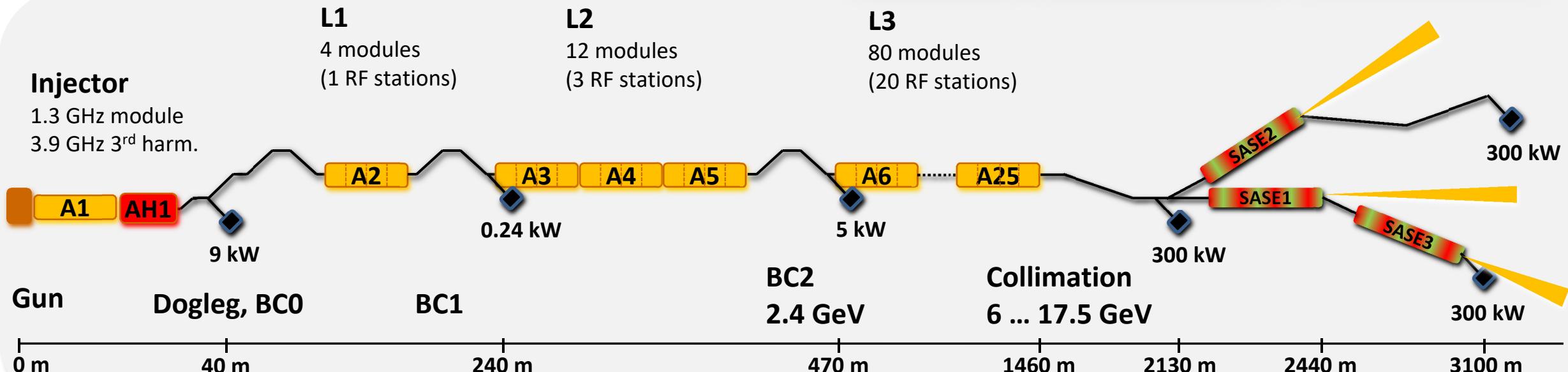
Copyright: DESY

The logo consists of a horizontal bar divided into segments representing the colors of the flags of the participating countries: Denmark, France, Germany, United Kingdom, Hungary, Italy, Poland, Slovakia, Spain, Sweden, and Switzerland.

The DESY logo, which includes the letters "DESY" and a stylized graphic element.

# Schematic Accelerator Overview

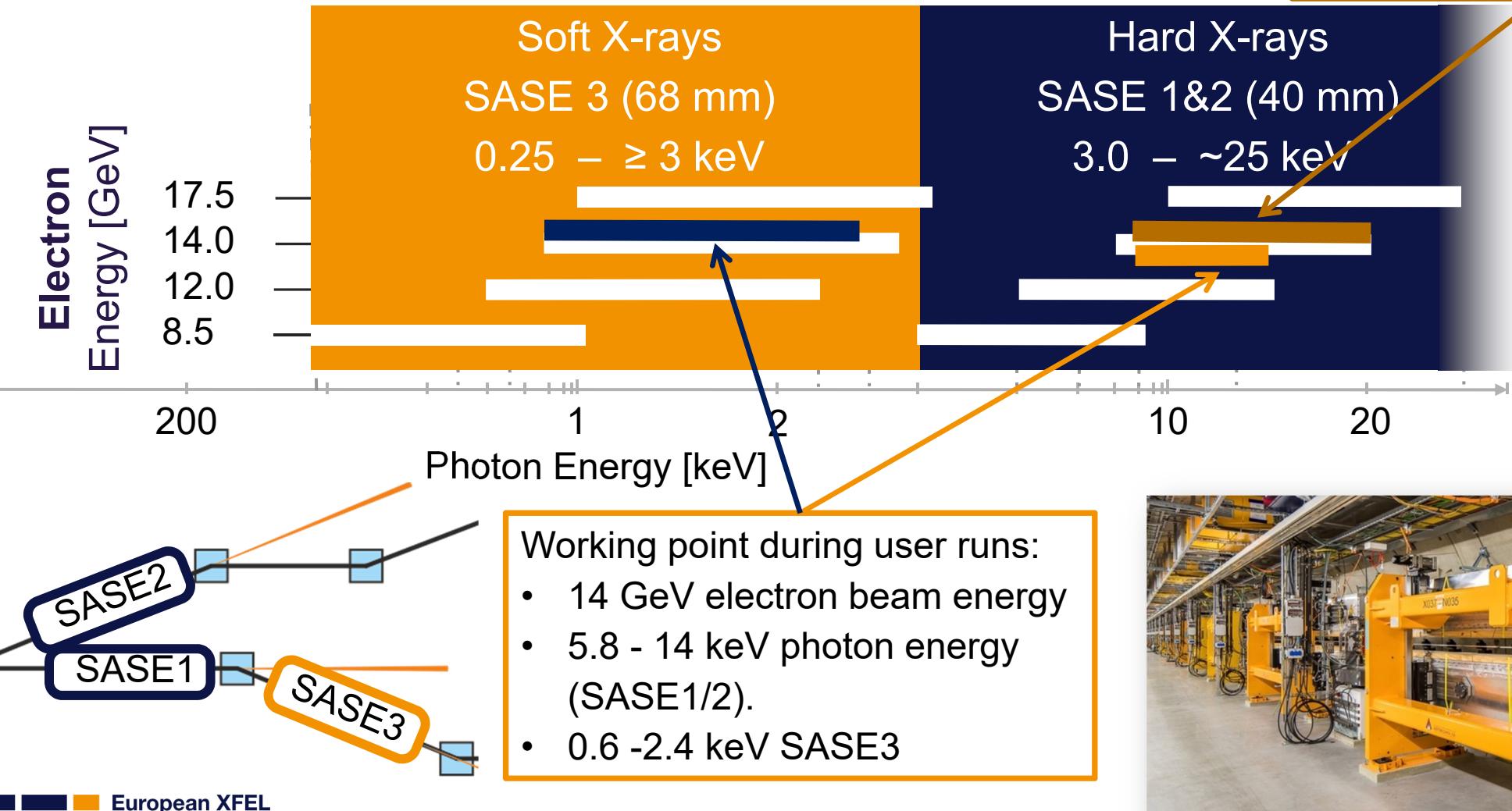
FEL19, Hamburg, 30.08.2019



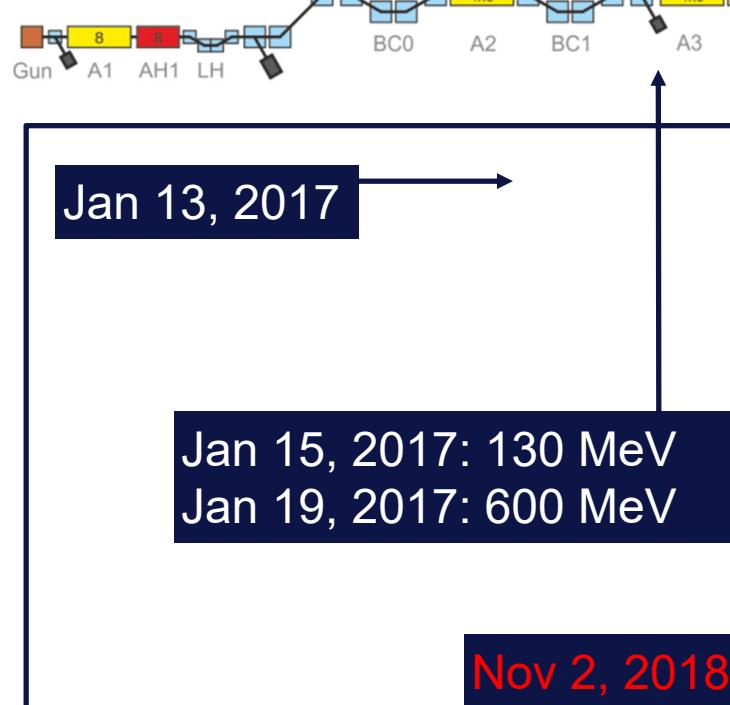
# The European XFEL can cover Photon Energies from 0.25 keV to 25 keV

Explored during test runs:

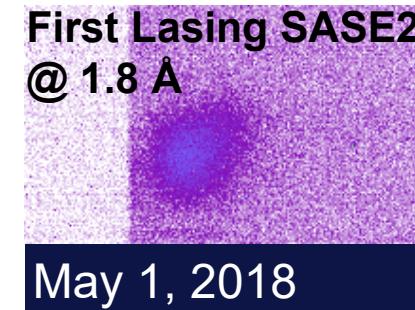
- 14 GeV
- 5.8 - 20 keV @ SASE1/2
- 0.6 – 4.5 keV @ SASE3



# Operational Achievements



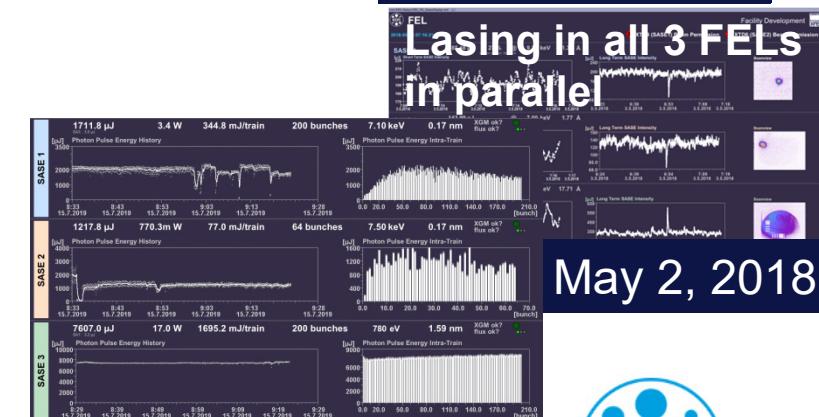
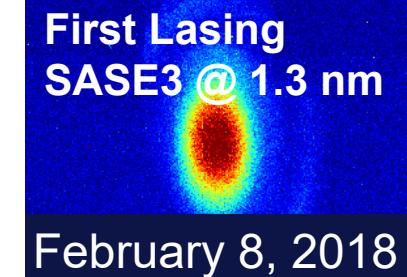
FEL19, Hamburg, 30.08.2019



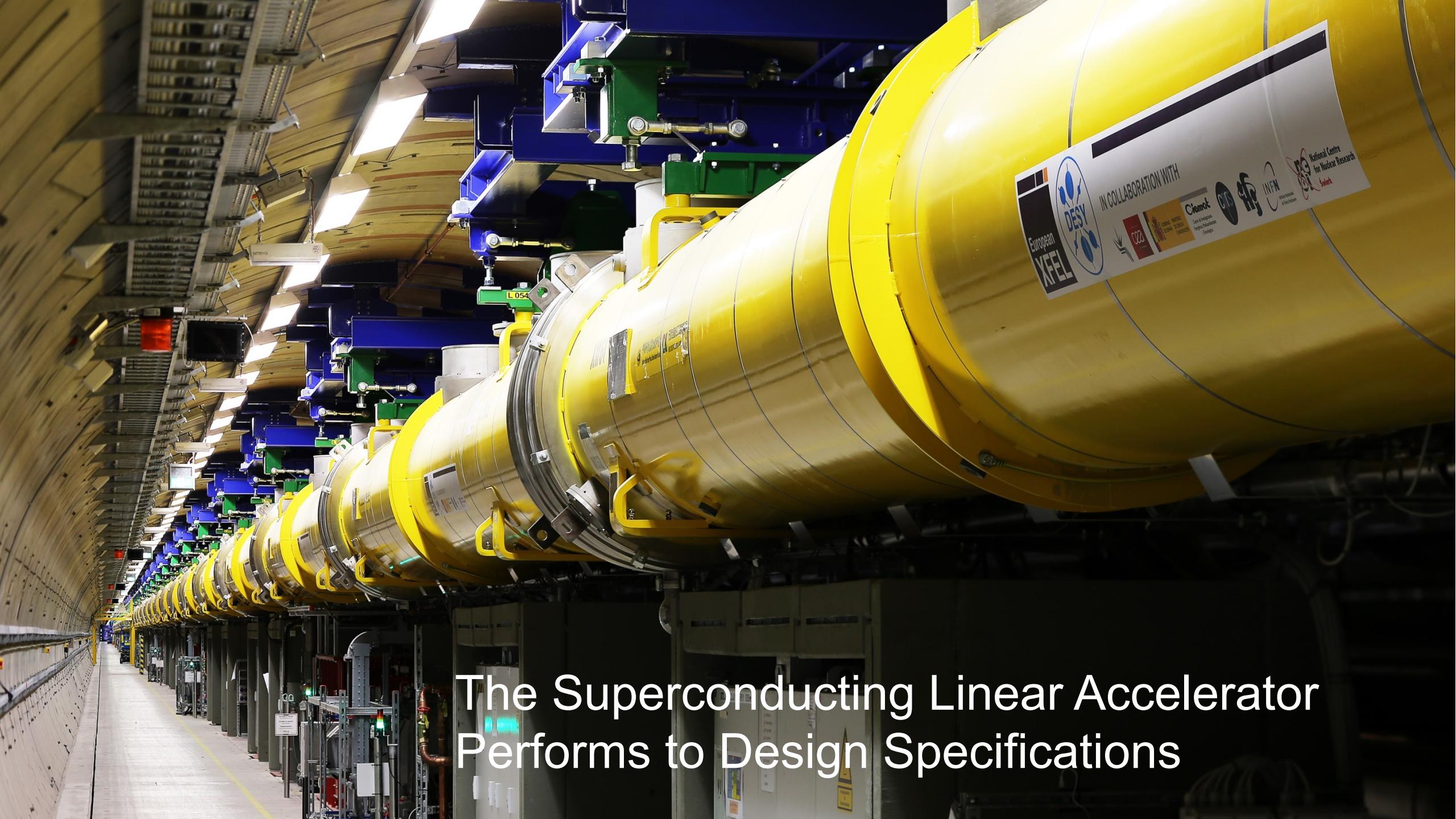
**March 13, 2018**



April 27, 2017

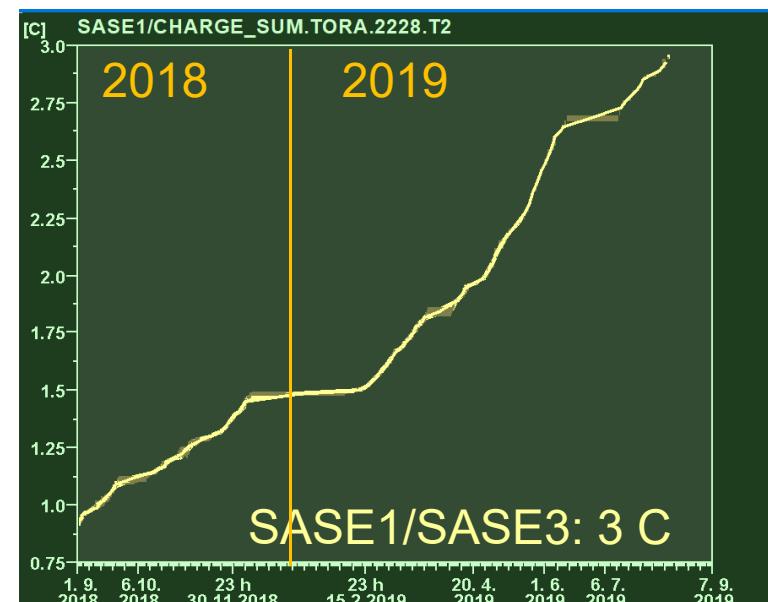
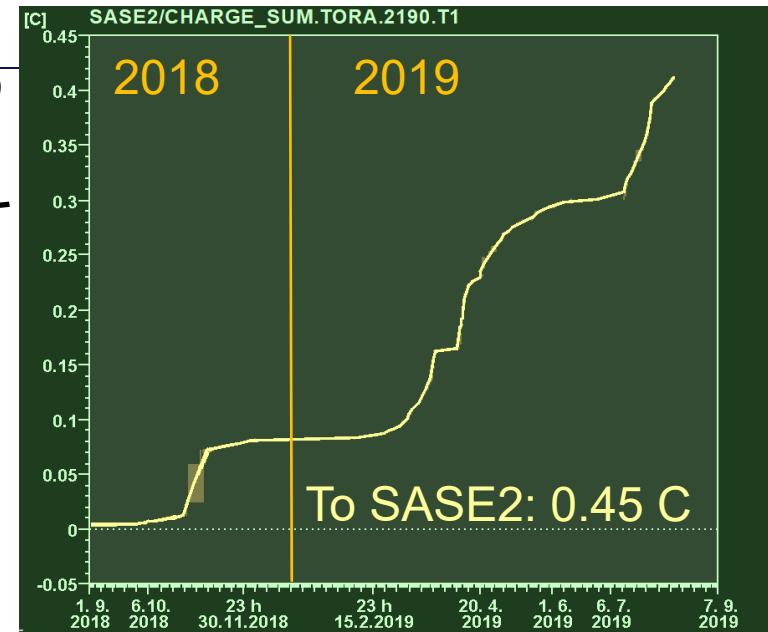


July 2019, 4.5 MHz User Operation



The Superconducting Linear Accelerator  
Performs to Design Specifications

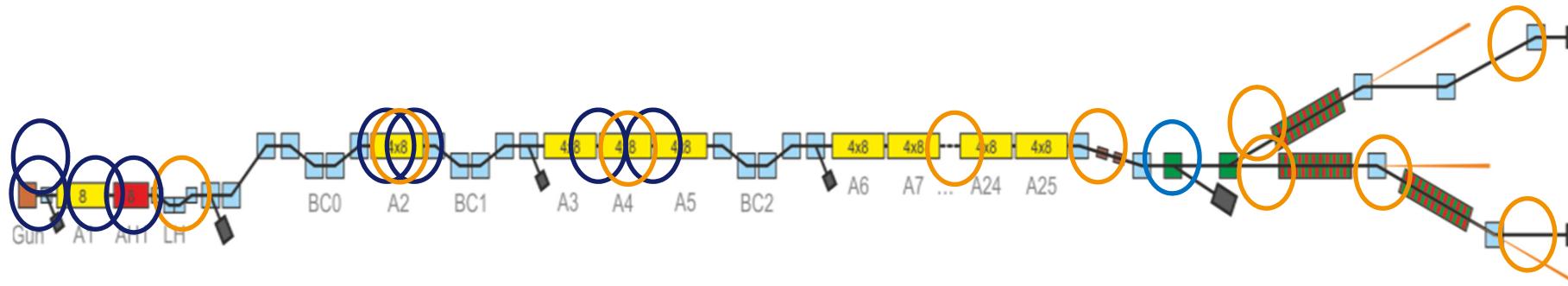
# Integrated Charge from 2018 to Aug. 15<sup>th</sup> 2019



- 600  $\mu$ s RF flattop available
- About 10% needed for stabilization, transition times and kicker gaps
- Up to now less than 20% of charge is used for photon production
- There is still a large potential to increase number of pulses on samples
- Just to mention: warm copper LINAC is less than 1 C/year

# LINAC Operation with Longitudinal and Transverse Feedbacks

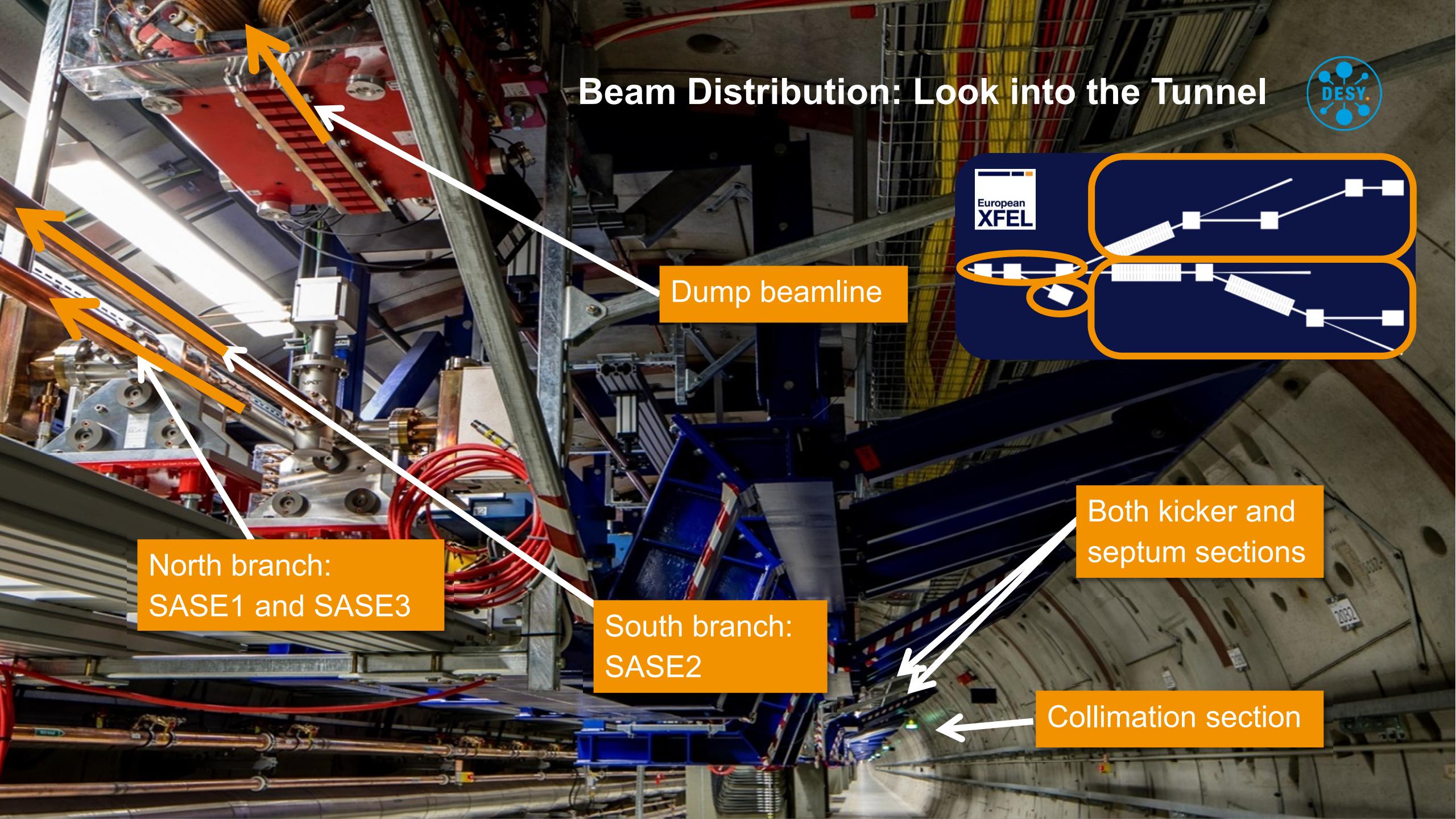
- 8 slow (rf-pulse to rf-pulse) *longitudinal* FB loops in operation
  - Charge stability < 0.7 % RMS
  - Energy stability < 2e-4 RMS
  - Arrival time jitter < 25 fs RMS
  - Arrival time drift 30 fs RMS
- Several **slow** (0.1 Hz) and one **fast** (bunch to bunch) *transverse* FB loops in operation
  - Pointing stability at undulator (source point)
    - $\approx 0.1 \sigma$  bunch to bunch
    - $\approx 0.1 \sigma$  rf-pulse to rf-pulse (> 20 bunches)
    - $\approx 0.1 \sigma$  drift
- All numbers are expected to improve during advanced development of systems.



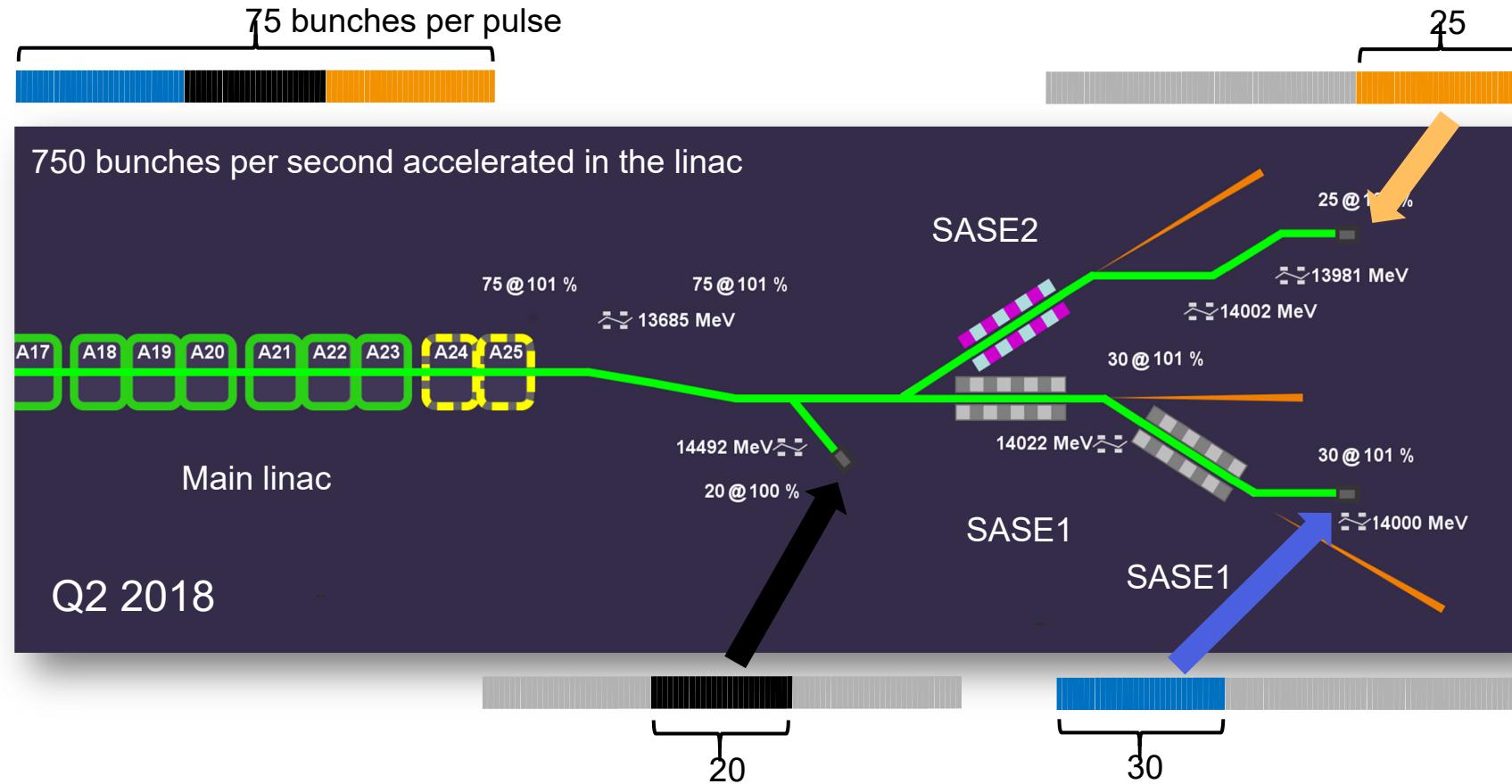
# Beam Distribution: Look into the Tunnel



# Beam Distribution: Look into the Tunnel

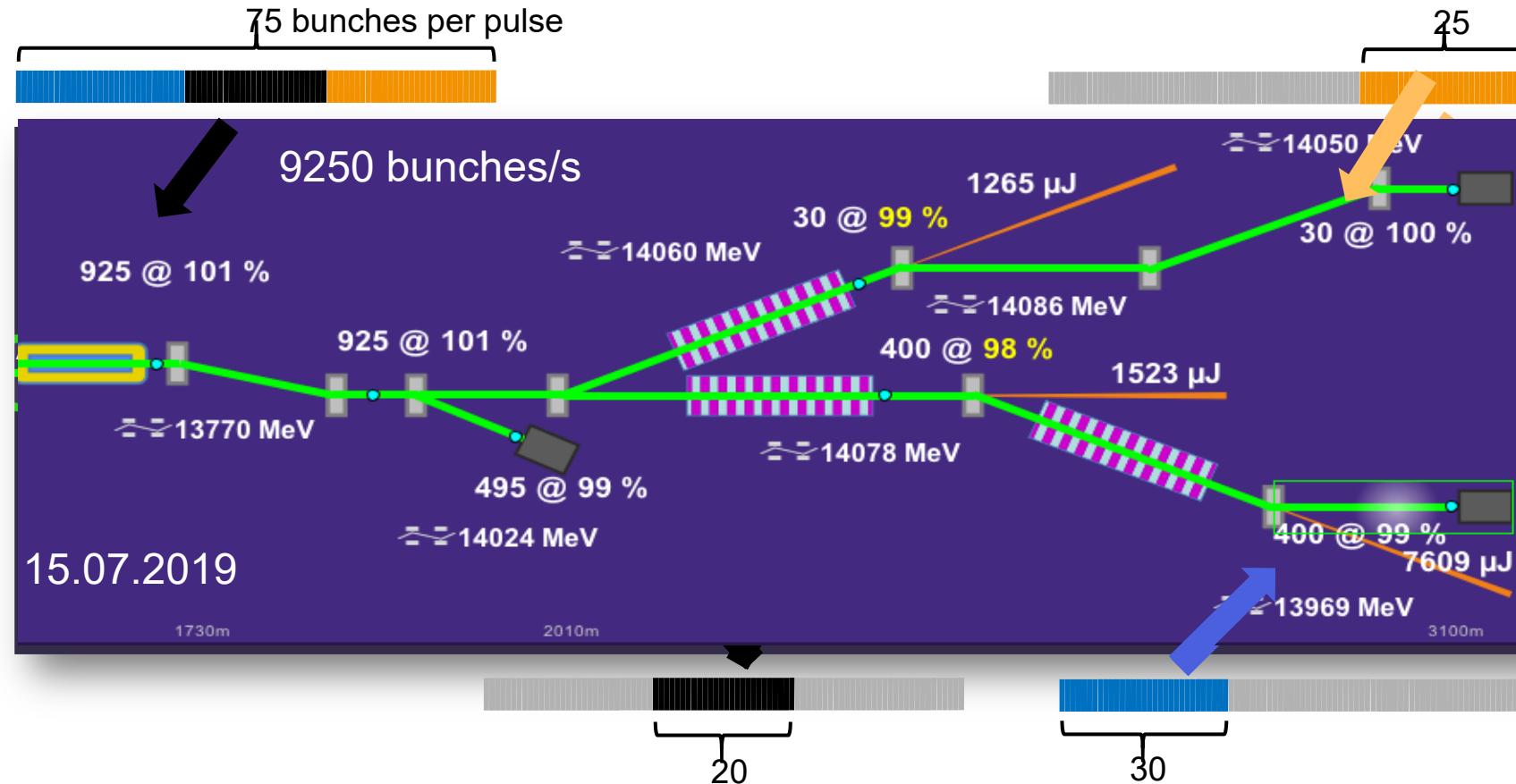


# Parallel Operation of Beamlines - Flexible Electron Beam Distribution System Commissioned and further Developed



- So-called user-defined timing patterns available since January 2018
- User controlled bunch numbers available since summer 2018
- Possibility to switch bunch pattern with 10 Hz since January 2019

# Parallel Operation of Beamlines - Flexible Electron Beam Distribution System Commissioned and further Developed



European XFEL

- So-called user-defined timing patterns available since January 2018
- User controlled bunch numbers available since summer 2018
- Possibility to switch bunch pattern with 10 Hz since January 2019



# Flexible Switchyard Needs/Allows Bunch Pattern Administration

[https://jdd-dxfel.desy.de/jdd/global/Util/bunch\\_pattern\\_server\\_pattern\\_builder.xml](https://jdd-dxfel.desy.de/jdd/global/Util/bunch_pattern_server_pattern_builder.xml) XFDL\_UTIL/BUNCH\_PATTERN/PATTERN\_BUILDER/PULSE\_TYPE\_0

**1. Injector Laser Properties**

ID Description	Bunch Charge	Trigger Bits	Add Laser
0 None	0.000 nC	<input type="checkbox"/> Laser 1 <input type="checkbox"/> Laser 2 <input type="checkbox"/> Laser 3	
1 Laser 1	0.250 nC	<input checked="" type="checkbox"/> Laser 1 <input type="checkbox"/> Laser 2 <input type="checkbox"/> Laser 3	
2 Laser 2	0.250 nC	<input type="checkbox"/> Laser 1 <input checked="" type="checkbox"/> Laser 2 <input type="checkbox"/> Laser 3	
3 Laser 1+2	0.250 nC	<input checked="" type="checkbox"/> Laser 1 <input checked="" type="checkbox"/> Laser 2 <input type="checkbox"/> Laser 3	

**2. Pulse Types**

ID Description	Inj. Laser	Destination	TDS & Kickers	Add Pulse Type
0 No bunch	0	None	<input type="checkbox"/> I1 <input type="checkbox"/> B1 <input type="checkbox"/> B2 <input type="checkbox"/> Soft kick <input type="checkbox"/> SA2 pre-kick	
D TLD	1	TLD	<input type="checkbox"/> I1 <input type="checkbox"/> B1 <input type="checkbox"/> B2 <input type="checkbox"/> Soft kick <input type="checkbox"/> SA2 pre-kick	
1 SA1	2	T4D	<input type="checkbox"/> I1 <input type="checkbox"/> B1 <input type="checkbox"/> B2 <input type="checkbox"/> Soft kick <input type="checkbox"/> SA2 pre-kick	
2 SA2	2	T5D	<input type="checkbox"/> I1 <input type="checkbox"/> B1 <input type="checkbox"/> B2 <input type="checkbox"/> Soft kick <input type="checkbox"/> SA2 pre-kick	
3 SA3	2	T4D	<input type="checkbox"/> I1 <input type="checkbox"/> B1 <input type="checkbox"/> B2 <input type="checkbox"/> Soft kick <input type="checkbox"/> SA2 pre-kick	
S SA2_SK	2	T5D	<input type="checkbox"/> I1 <input type="checkbox"/> B1 <input type="checkbox"/> B2 <input type="checkbox"/> Soft kick <input type="checkbox"/> SA2 pre-kick	
L TLDL	3	TLD	<input type="checkbox"/> I1 <input type="checkbox"/> B1 <input type="checkbox"/> B2 <input type="checkbox"/> Soft kick <input type="checkbox"/> SA2 pre-kick	

**Machine Pattern**

**BUNCH PATTERN SERVER: PATTERN BUILDER (MACHINE PATTERN)**

**3. Pulse Patterns**

Sequence:	[C]	[>]	[C]
Patterns:	[A] [B] [C]	Add Pattern	Remove Pattern
[C]	Base Frequency: 2257 kHz	Add Sub-Pattern	
Start Time	Description	Sub-Pattern	# Ticks # Repetitions
800.0 µs	TLD	D	^60 ^60.00
826.6 µs	SA2	D	^280 ^140.00
950.6 µs	Kicker Flat	D	^120 ^120.00
1003.8 µs	SA3	131D1D1D	^560 ^70.00

**6. Review Pattern** ... for train ID:

**7. Apply, Save & Load**

Enter a meaningful title for this pattern:  
100 TLD, 240 SA2, 120 TLD, 560 SA3 interleaved

**Pulse Types**

- No bunch
- SASE1
- SASE2
- SASE3
- Linac dump

**Cleanup**

**Final Bunch Pattern**

**# Bunches**

**Subpatterns**

**Assembled Pattern**

A typical bunch train is built by:

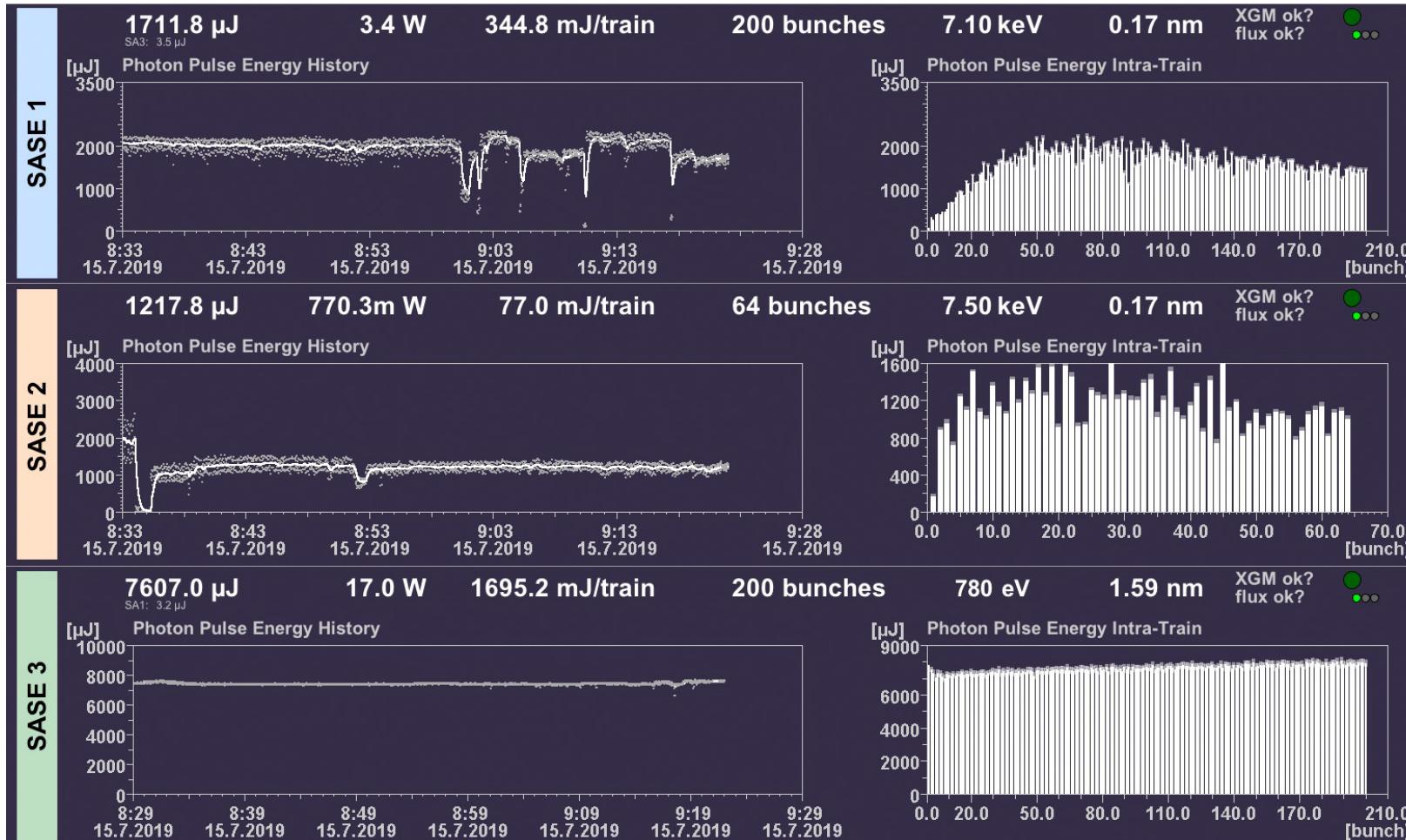
- Some pre-bunches
- Time slot for SASE2
- Kicker gap/RF transition time
- Time slot for SASE1 and SASE3
- SASE1/3 decoupled by „Soft Kick“
- Can get individual time slots
- Or run interleaved
- All bunches not required for SASE get removed
- Fast kickers allow for 4.5 MHz switching
- Sub-harmonics and even arbitrary bunch pattern
- bunch numbers already controlled by experiments
- Series of bunch pattern can be spooled





**SASE3 Undulator Section  
with Climate Enclosure**

# FEL Operation



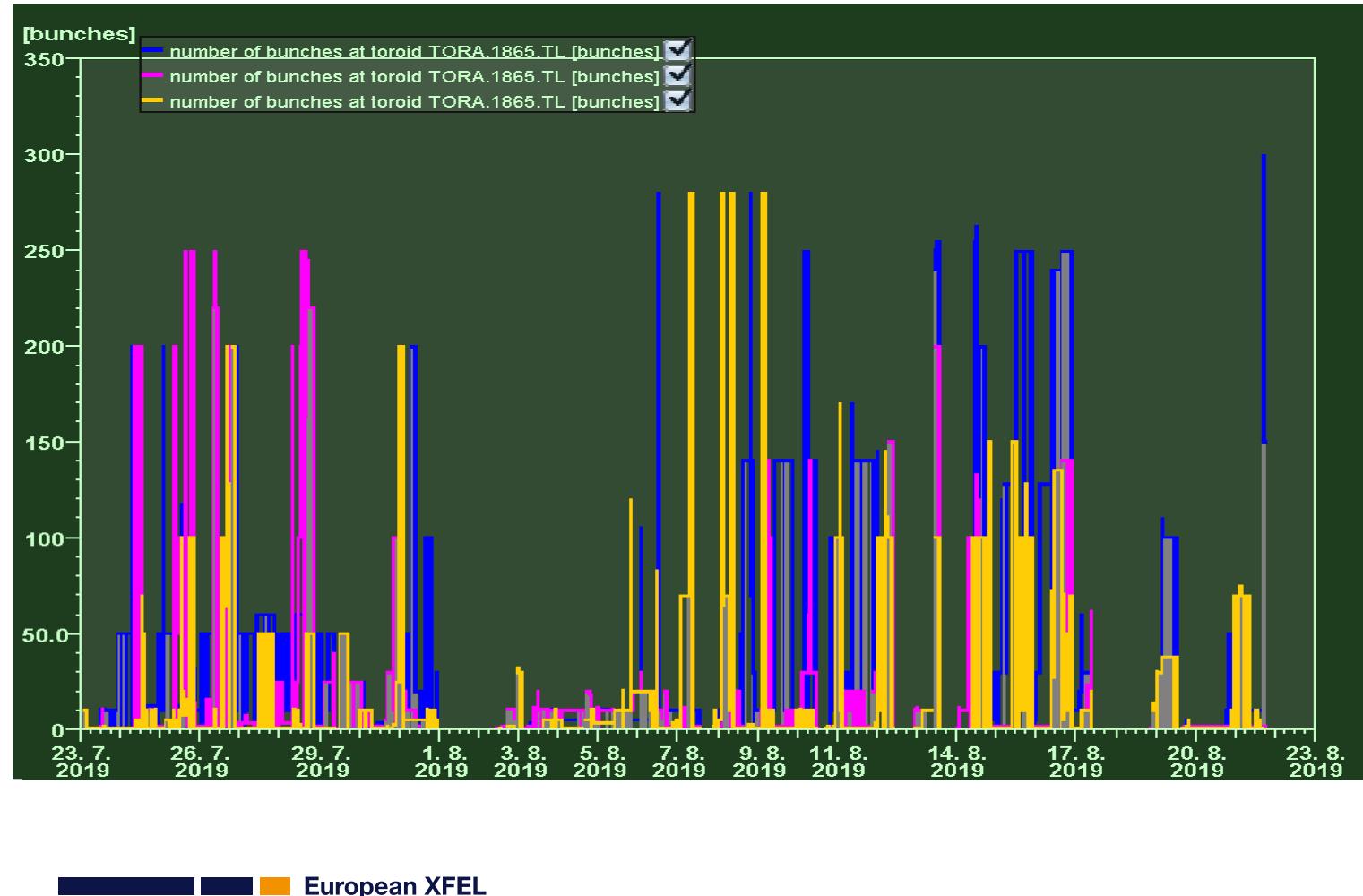
European XFEL

Average Power: 22 W! in 464 Bunches; SA2 at Actual Safety Limit

- Standard workingg point 14 GeV
- 3 FELs running simultaneously
- Experiments change every 12 h
- requested photon energy range
  - SA1/2: 5.8 – 14 keV
  - SA3: 0.6 – 2.4 keV
- Bunch numbers and average power currently restricted by safety
- Control given to users:
  - Bunch numbers/FEL
  - Photon energy; gaps
  - And they use it!

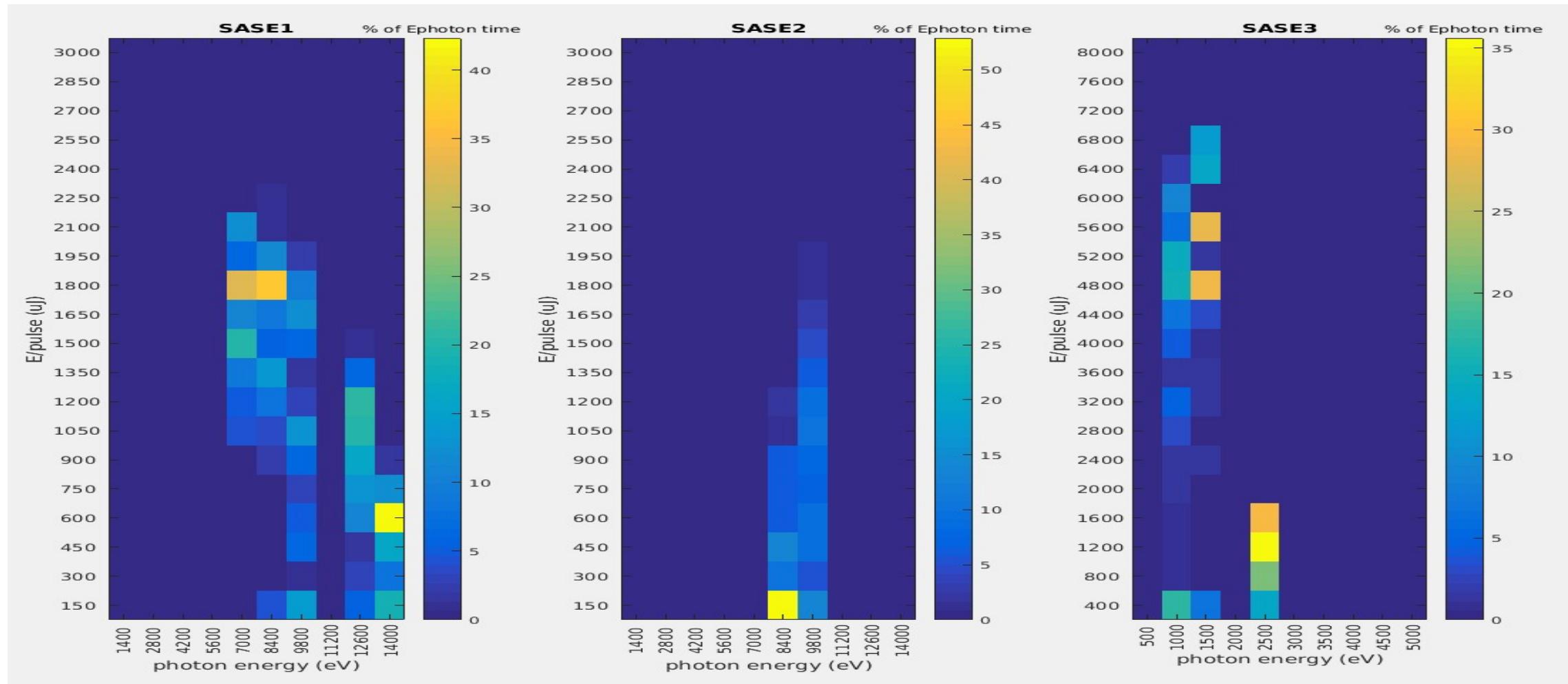


# Bunch Numbers: Set by Users

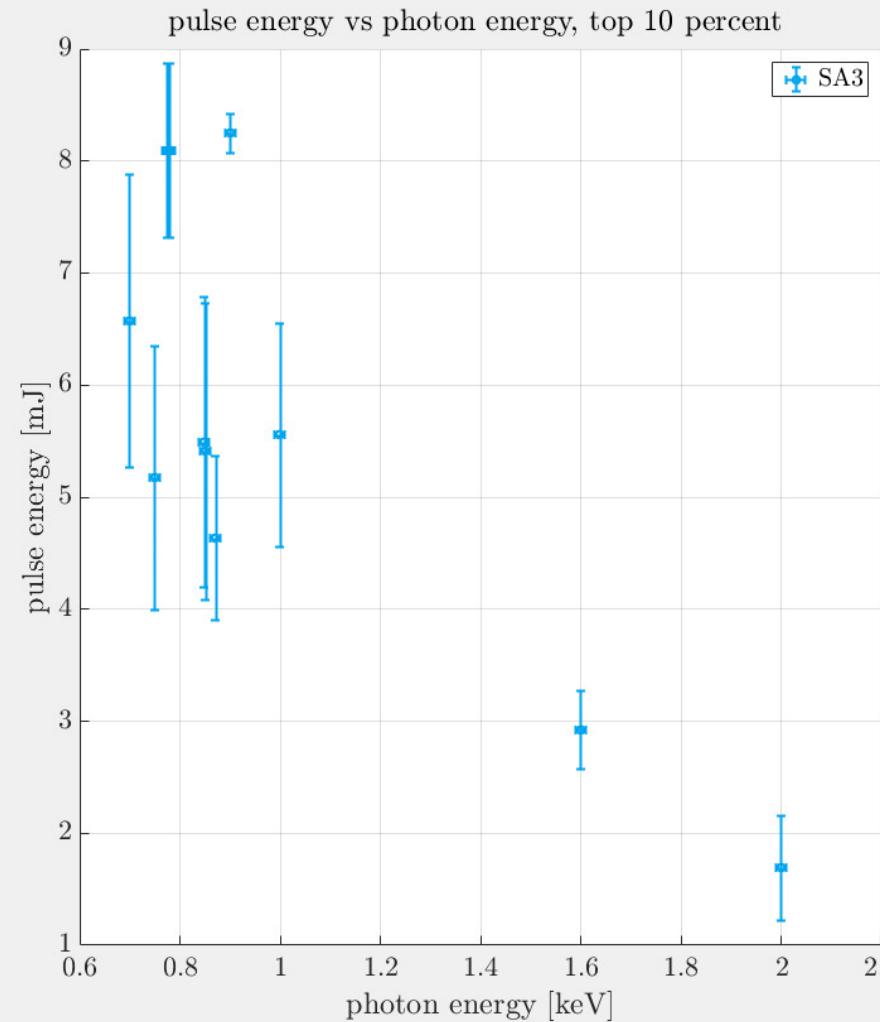
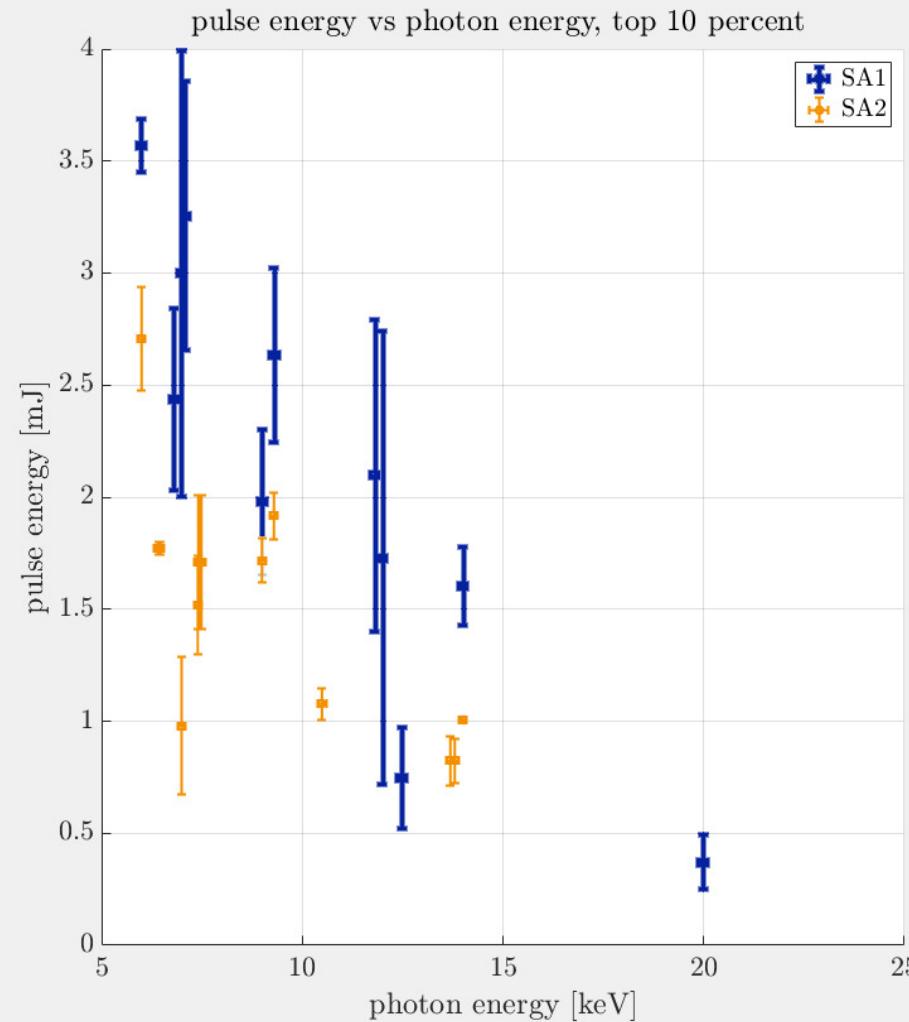


- Blue: SASE1
- Red: SASE2
- Yellow: SASE3
- Delivery schemes:
  - Single bunch for setup
  - Pulse on demand
  - Multi-bunch for data taking
  - Requirements differ depending on experiment
- Detectors make progress in accepting more data frames/RF pulse
- Demand for long trains increasing

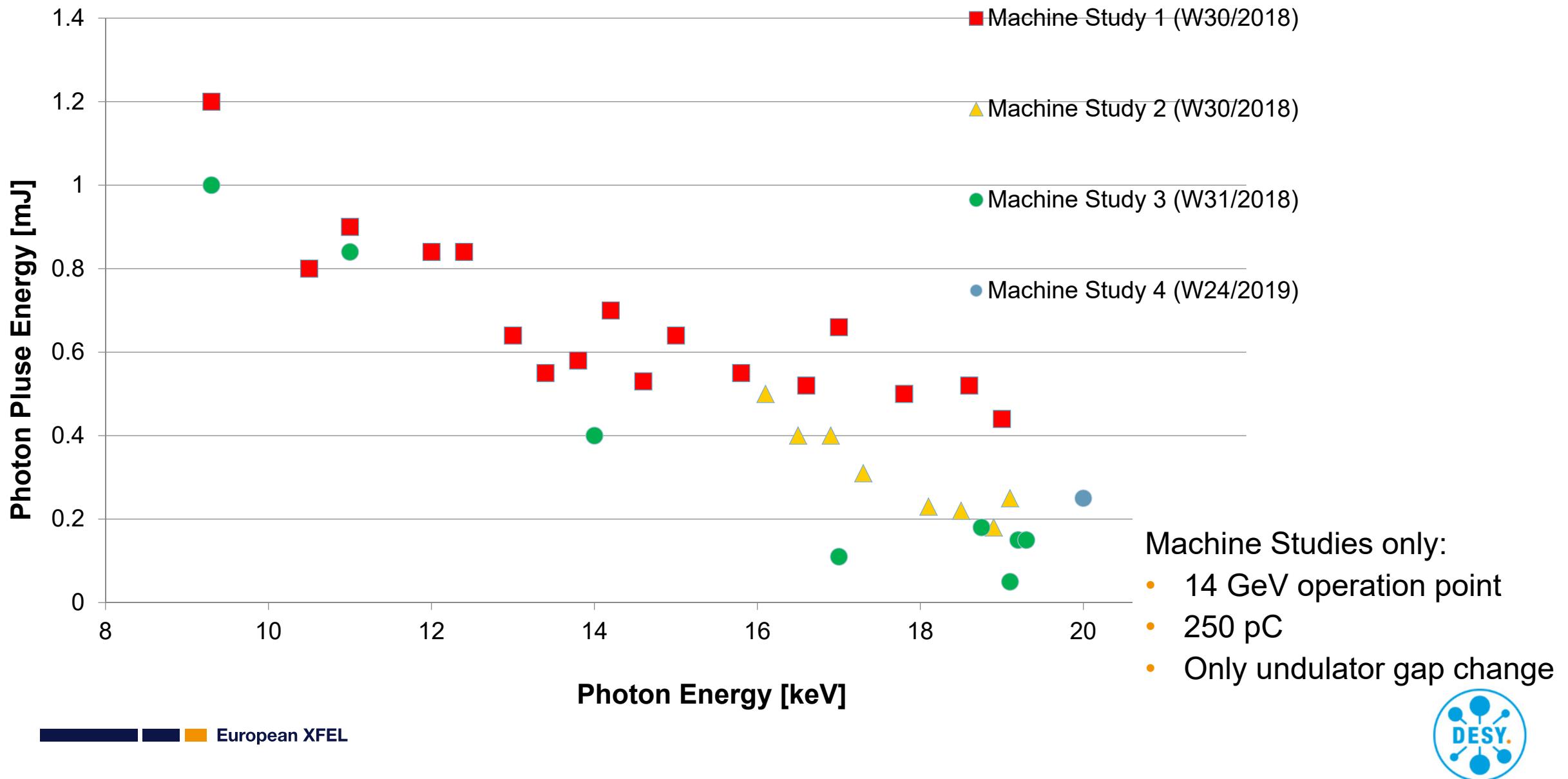
# Photon Energies and Pulse Energies during Photon Delivery



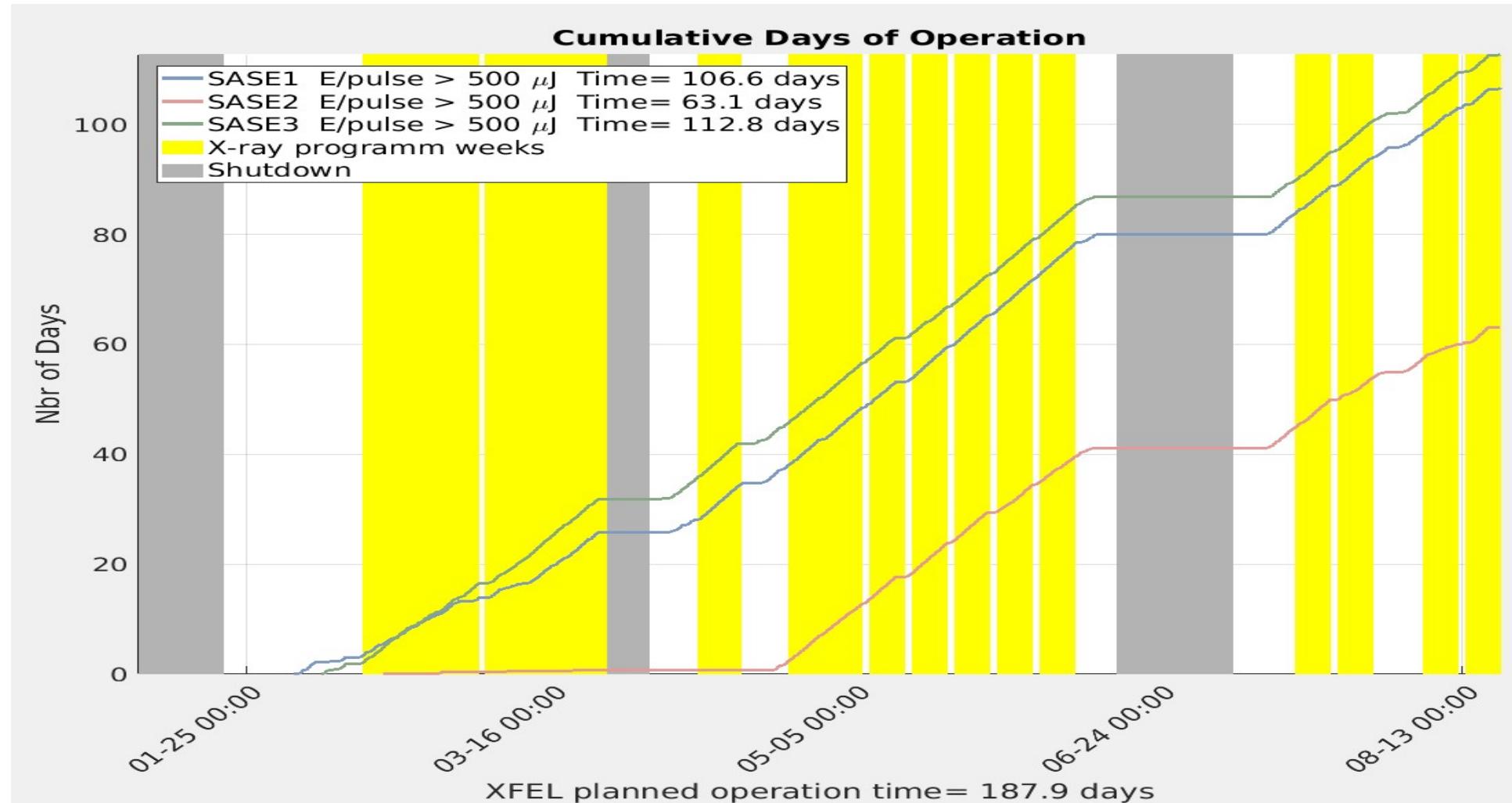
# Photon Energies and Pulse Energies during Photon Delivery 2019



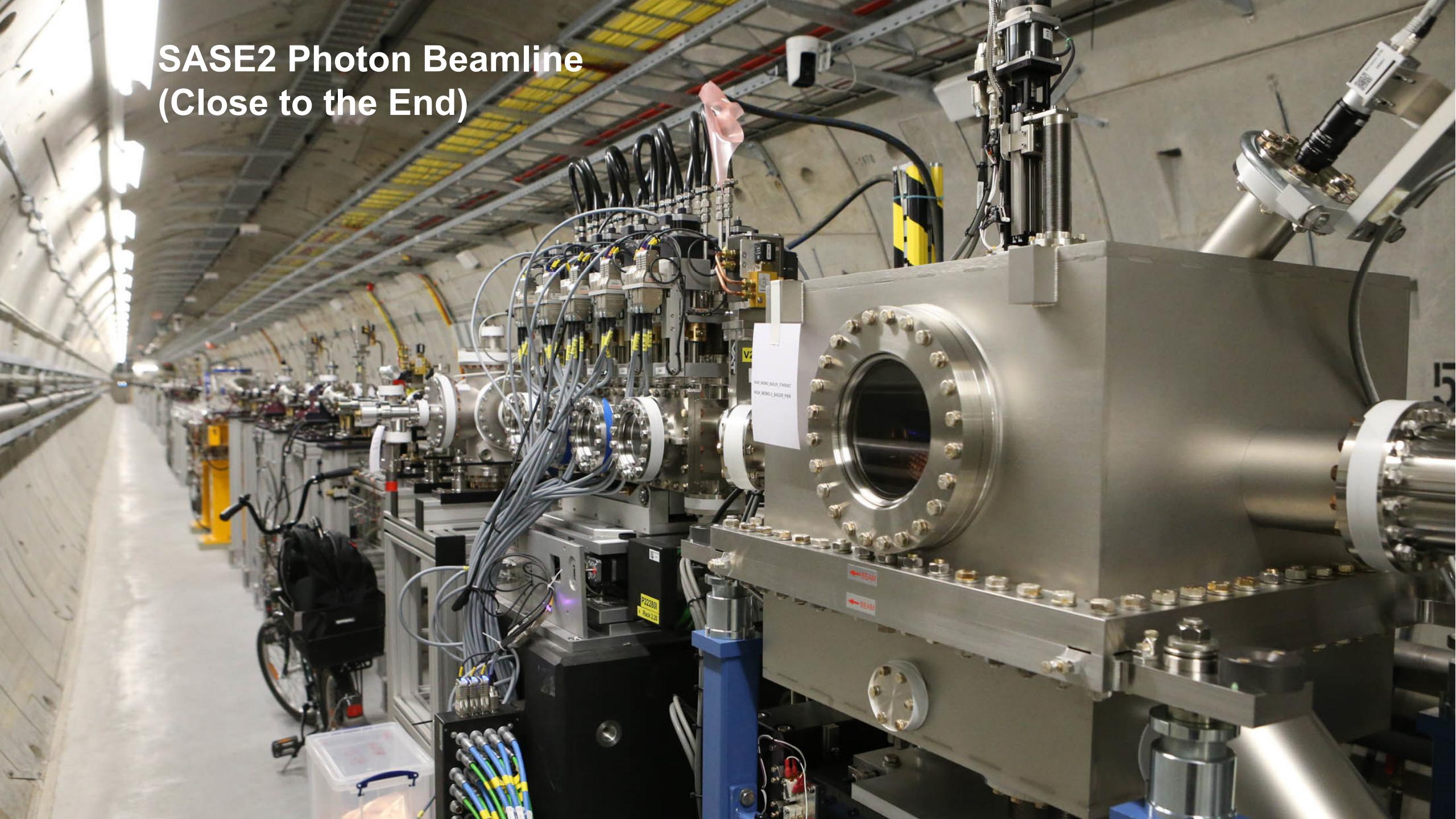
# High Photon Energy Operation at SASE1



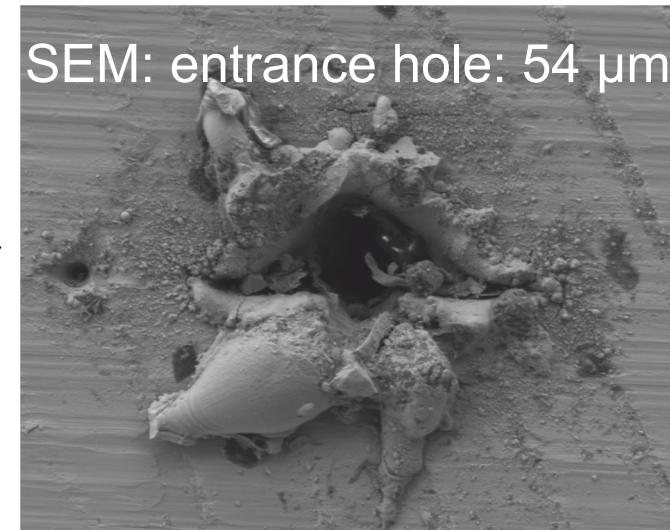
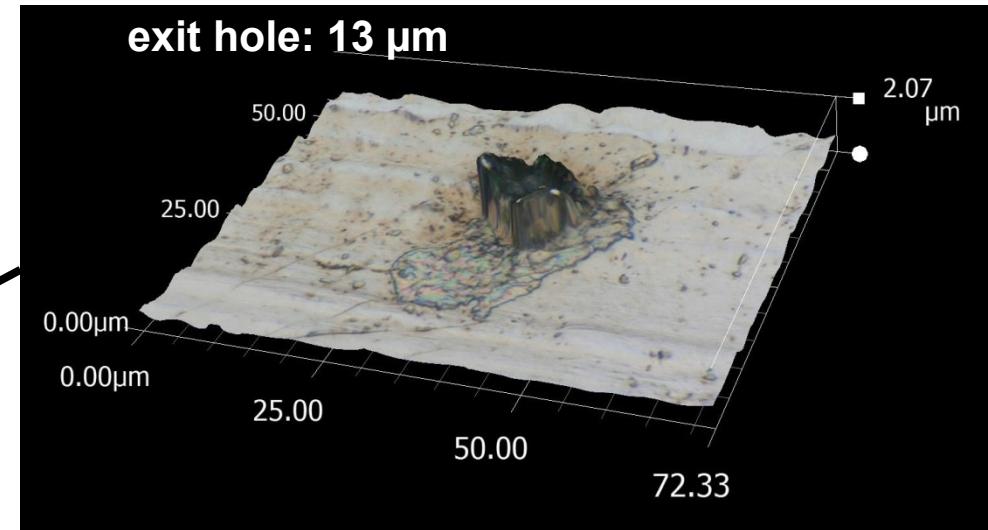
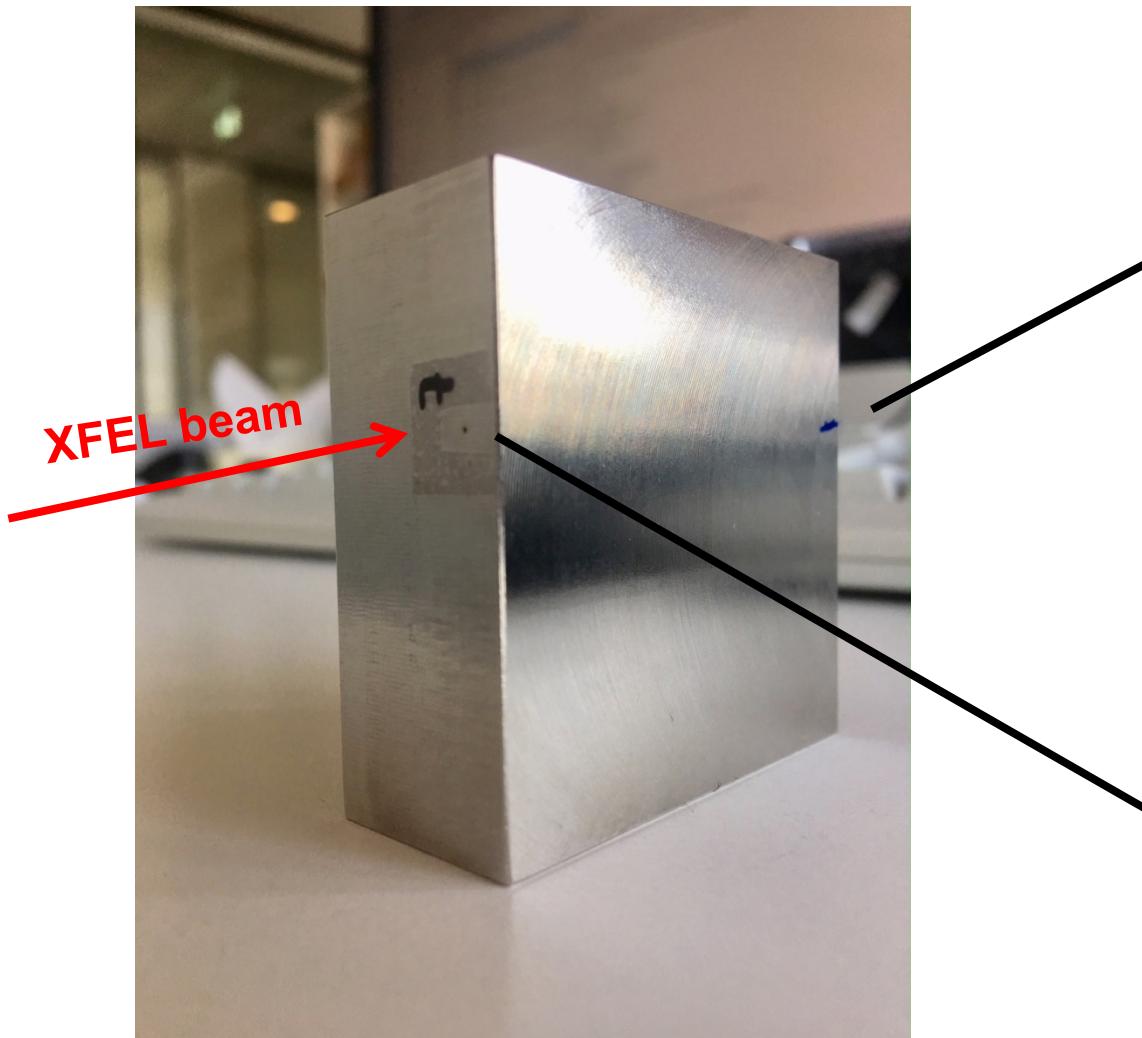
# SASE Delivery in 2019



# SASE2 Photon Beamline (Close to the End)

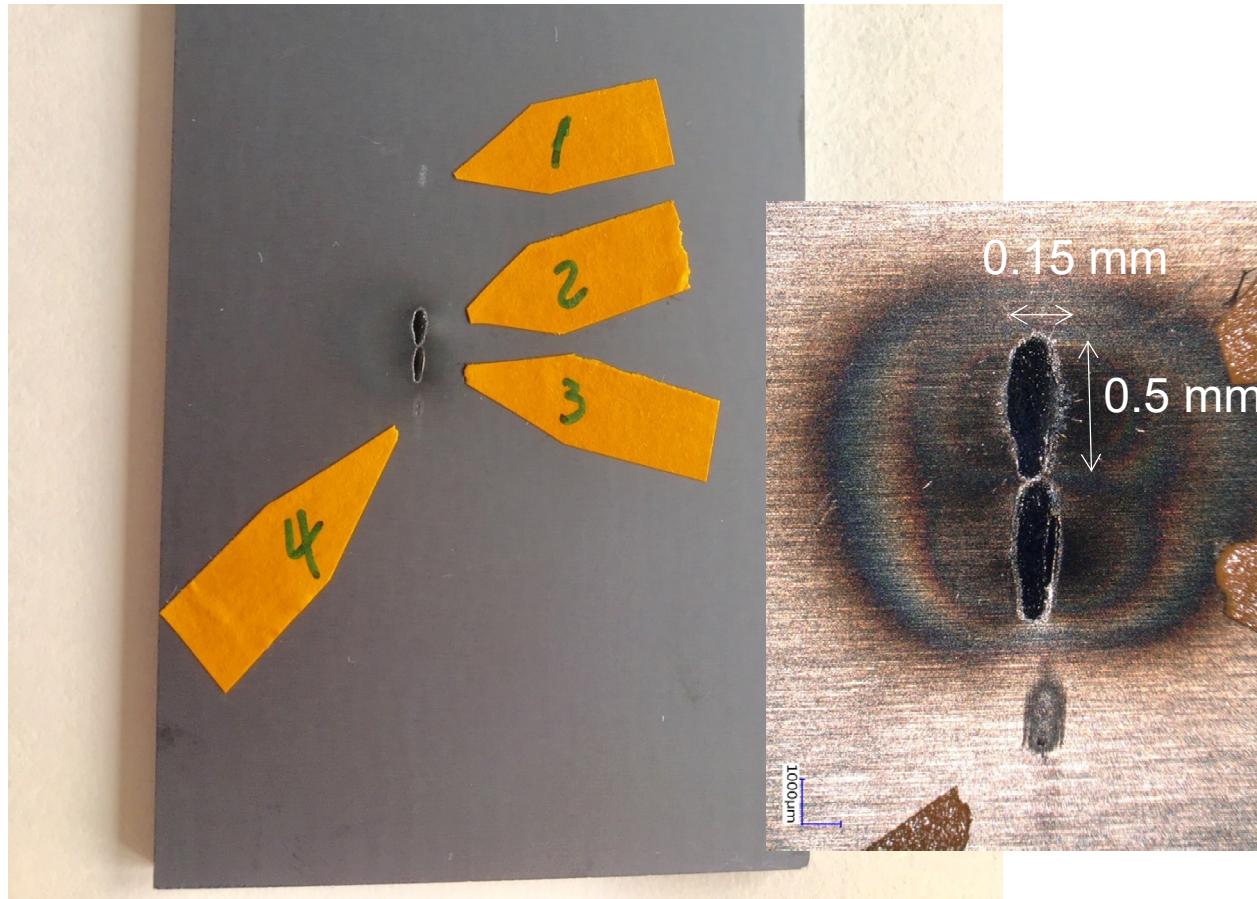


# April 2018: Drilling with XFEL Beam Through 50 mm of Steel in 26 Seconds



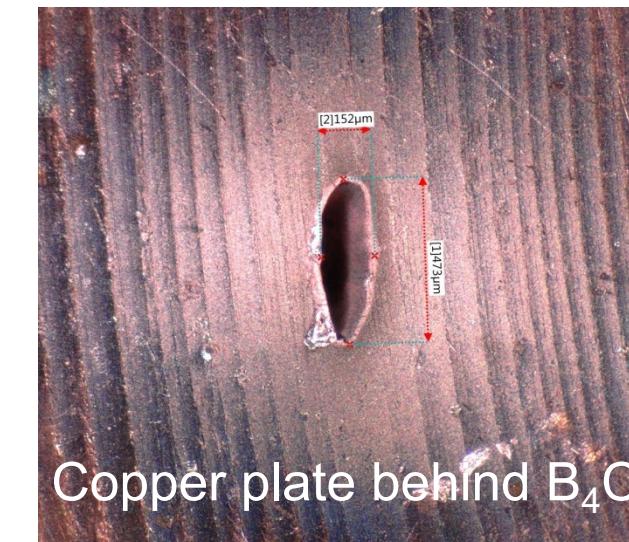
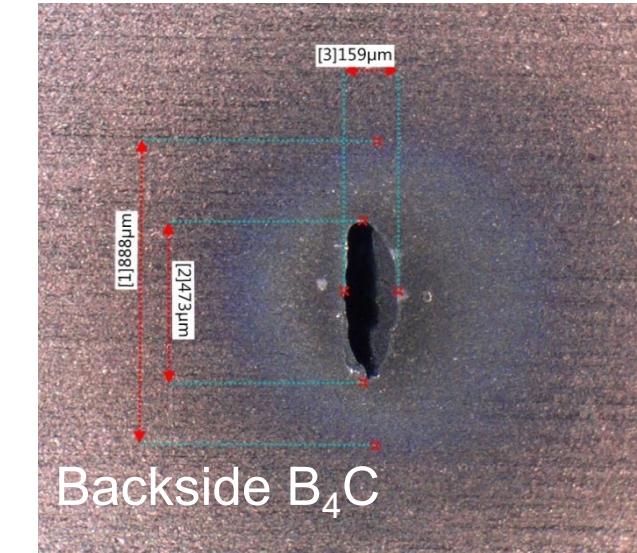
FXE instrument  
9.3 keV  
1 mJ/pulse  
20 µm beam size  
1500 pulses/sec

# August 2018: Drilling Tests at SASE3 (SCS, 700 eV, 300 x 4 mJx 10 Hz = 12 W)



Frontside of 4 mm thick  $B_4C$ , 10-20 min exposure

■ ■ ■ European XFEL



Copper plate behind  $B_4C$

# Performance Rise and Future Expectations

**Early 2018**  
~300 pulses/s/branch

**Up to 2019 (today)**

<4000 pulses/s/branch  
SASE1/2: 0.8 – 8 W  
SASE3: 30 W

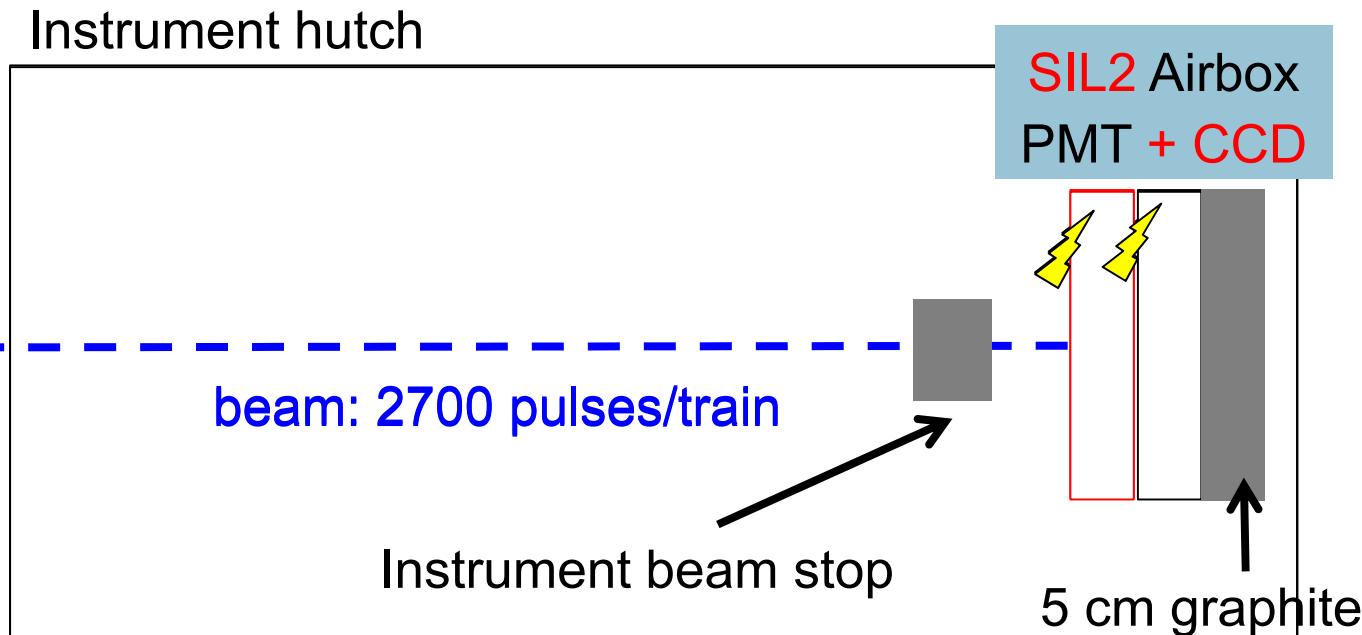
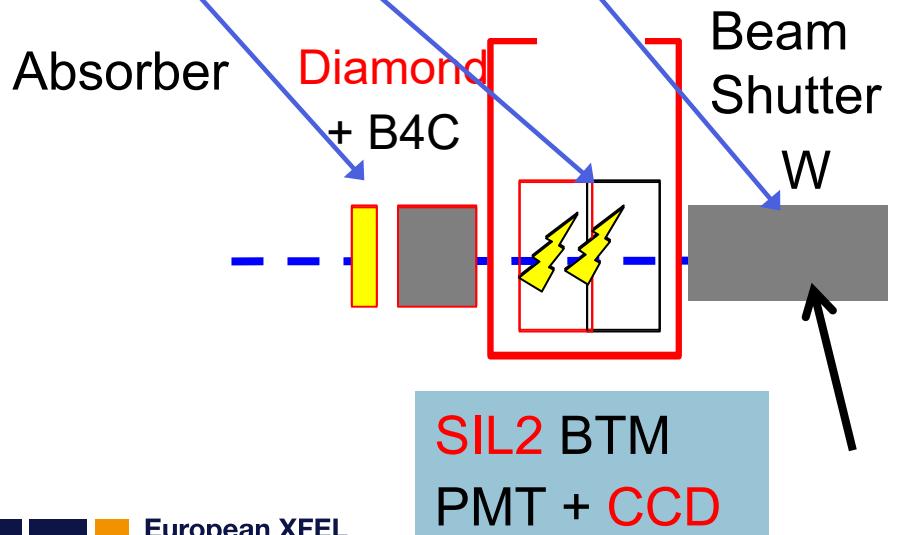
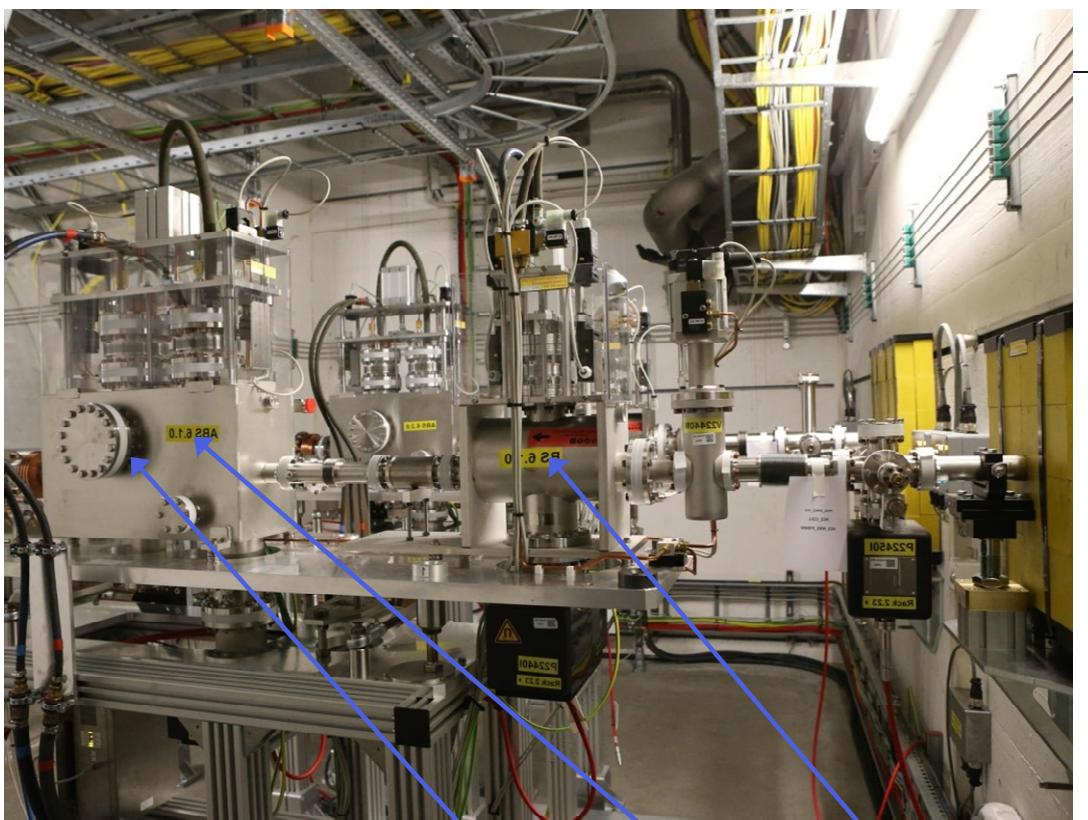
..., 2020, ...

**Full performance:**  
27000 pulses/s  
4.5 MHz  
SASE1/2: 10..100W  
SASE3: 300 W



# Safety Upgrade in Winter Shutdown 19/20

- Include active element between absorber and beam shutter
- Similar elements to ensure hutch integrity
- Development of *Burn Through Monitor* with required safety level (SIL2) available for Winter shutdown
- Diamond absorbers can take more power (than  $B_4C$ )
- Beam shutter has to “survive” latency of PPS system
- Absorbers protected by machine protection measures (no SIL)

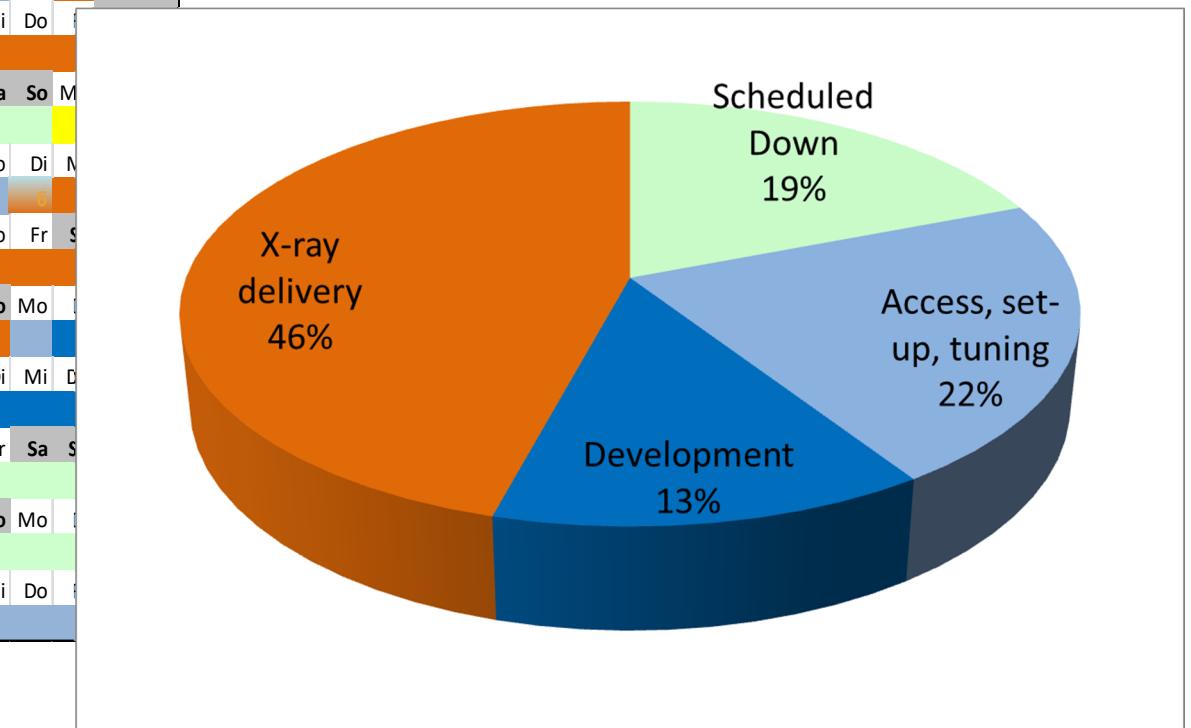


# Operation Schedule 2020

2020	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	
	Mi	Do	Fr	Sa	Sa	Mo	Di	Mi	Do	Fr	Sa	Sa	Mo	Di	Mi	Do	Fr	Sa	Sa	Mo	Di	Mi	Do	Fr	Sa	Sa	Mo	Di	Mi	Do	Fr	
Jan																																
Feb	Sa	Sa	Mo	Di	Mi	Do	Fr	Sa	Sa	Mo	Di	Mi	Do	Fr	Sa	Sa	Mo	Di	Mi	Do	Fr	Sa	Sa	Mo	Di	Mi	Do	Fr	Sa			
Mrz																																
Apr	Mi	Do	Fr	Sa	Sa	Mo	Di	Mi	Do	Fr	Sa	Sa	Mo	Di	Mi	Do	Fr	Sa	Sa	Mo	Di	Mi	Do	Fr	Sa	Sa	Mo	Di	Mi	Do		
Mai	Fr	Sa	Sa	Mo	Di	Mi	Do	Fr	Sa	Sa	Mo	Di	Mi	Do	Fr	Sa	Sa	Mo	Di	Mi	Do	Fr	Sa	Sa	Mo	Di	Mi	Do				
Jun	Mo	Di	Mi	Do	Fr	Sa	Sa	Mo	Di	Mi	Do	Fr	Sa	Sa	Mo	Di	Mi	Do	Fr	Sa	Sa	Mo	Di	Mi	Do	Fr	Sa	Sa	Mo			
Jul																																
Aug	Sa	Sa	Mo	Di	Mi	Do	Fr	Sa	Sa	Mo	Di	Mi	Do	Fr	Sa	Sa	Mo	Di	Mi	Do	Fr	Sa	Sa	Mo	Di	Mi	Do	Fr	Sa			
Sep	Di	Mi	Do	Fr	Sa	Sa	Mo	Di	Mi	Do	Fr	Sa	Sa	Mo	Di	Mi	Do	Fr	Sa	Sa	Mo	Di	Mi	Do	Fr	Sa	Sa	Mo	Di	Mi	Do	
Okt	Do	Fr	Sa	Sa	Mo	Di	Mi	Do	Fr	Sa	Sa	Mo	Di	Mi	Do	Fr	Sa	Sa	Mo	Di	Mi	Do	Fr	Sa	Sa	Mo	Di	Mi	Do	Fr	Sa	
Nov																																
Dez	Di	Mi	Do	Fr	Sa	Sa	Mo	Di	Mi	Do	Fr	Sa	Sa	Mo	Di	Mi	Do	Fr	Sa	Sa	Mo	Di	Mi	Do	Fr	Sa	Sa	Mo	Di	Mi	Do	
Jan	Fr	Sa	Sa	Mo	Di	Mi	Do	Fr	Sa	Sa	Mo	Di	Mi	Do	Fr	Sa	Sa	Mo	Di	Mi	Do	Fr	Sa	Sa	Mo	Di	Mi	Do	Fr	Sa		

European XFEL

- Scheduled down: 70 d
- Operation: 7100h
  - Access, setup and tuning: 1902 h
  - Facility development: 1176 h
  - X-ray delivery: 4026 h

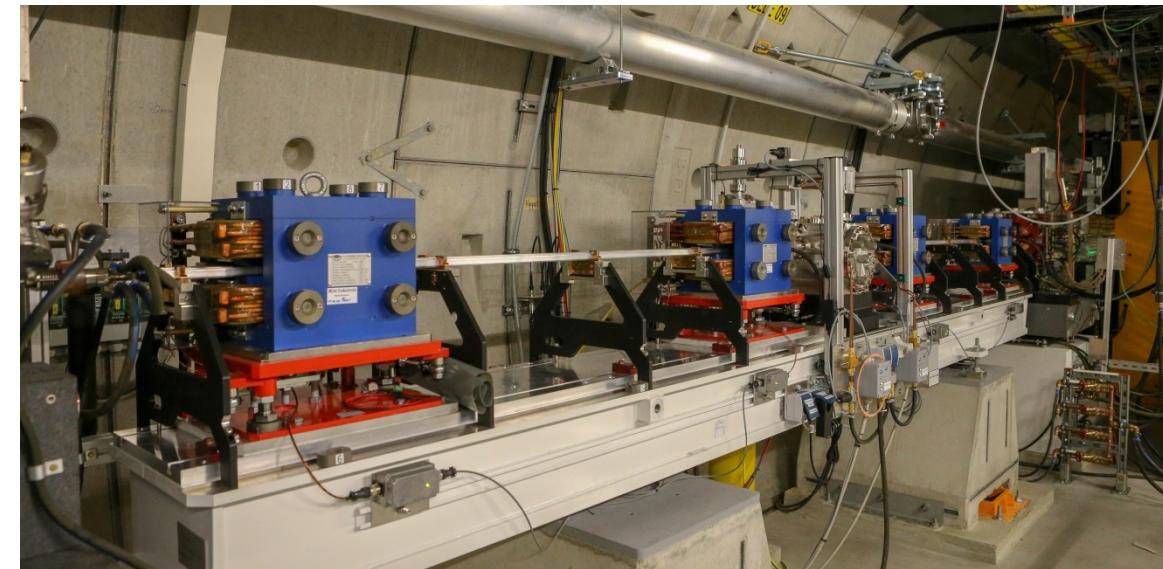


# (Accelerator) Parameter Space (as of Today)

Quantity	Unit	Project Goal	Achieved	Routine
electron energy	GeV	8 – 17.5	6 – 17.5	14
bunch repetition within pulse	MHz	Up to 4.5	Up to 4.5	1.13 - 4.5, plus subharmonics
bunch charge	pC	20 – 1000	100 – 500	250
max. beam power	kW	500 kW	80 kW	40 kW
undulators in operation (lasing)		SASE1-3	SASE1-3	SASE1-3
photon pulses / s / undulator		27000	5000	<3000
photon energy	keV	0.25-25	0.4-4.5; 5.8-20	0.6-2.2; 6 – 14
photon pulse intensity (SASE1) @ 14 GeV, 250 pC, 9.3 keV	mJ		2.5	2
photon pulse intensity (SASE3) @ 14 GeV, 250 pC, 600 – 900 eV	mJ		10	6-8
photon pulse intensity SASE2 (@ 14 GeV, 250 pC, 9 keV)	mJ		2.2	1.7

# After Commissioning is Before Upgrade

- ❑ Self Seeding in the hard X-ray regime:
  - ❑ SASE2 chicanes installed and operational
  - ❑ Commissioning with beam started in SASE2
- ❑ SASE3 Helical Afterburner and Two Color Scheme
  - ❑ Hardware installation starts in Winter shutdown 2019/2020
  - ❑ Hardware complete and first photons in 2021
- ❑ Still two empty tunnels suitable for FELs; Let's call them SASE4 and SASE5
  - ❑ Ideas to extend photon energy range in hard and soft x-ray regime are developed
  - ❑ Technical and scientific cases are explored
  - ❑ Proof of principle tests, e.g. Harmonic Lasing Self-Seeding (HLSS) have already been demonstrated at SASE3 reaching 4.5 keV
- ❑ Not to mention CW R&D or the option for a complete second fan



**Thanks to All Colleagues from DESY and European XFEL ...**



**... and You ...**

**for Your Attention!**