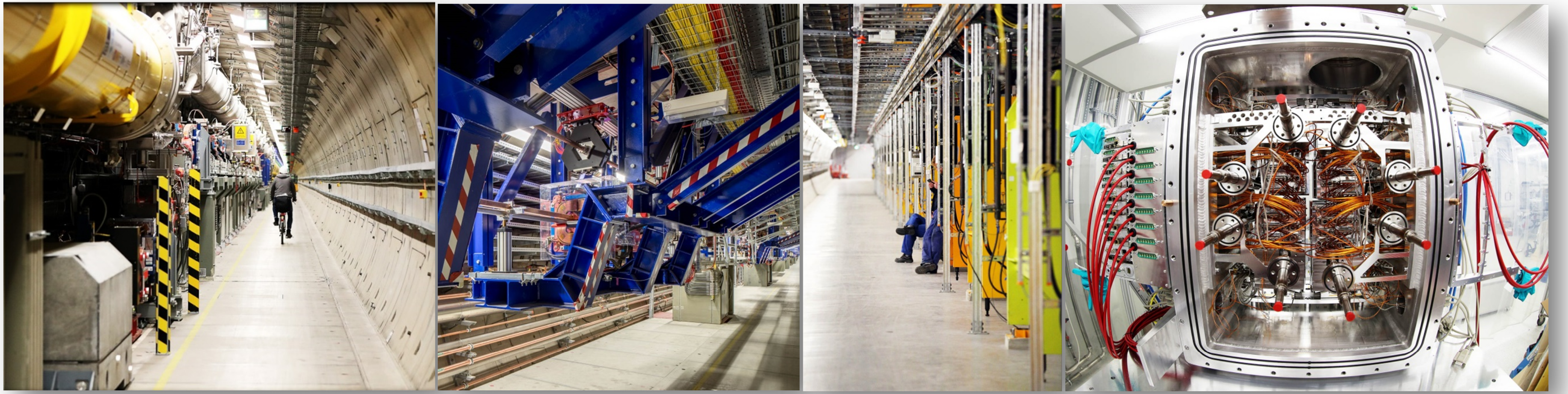
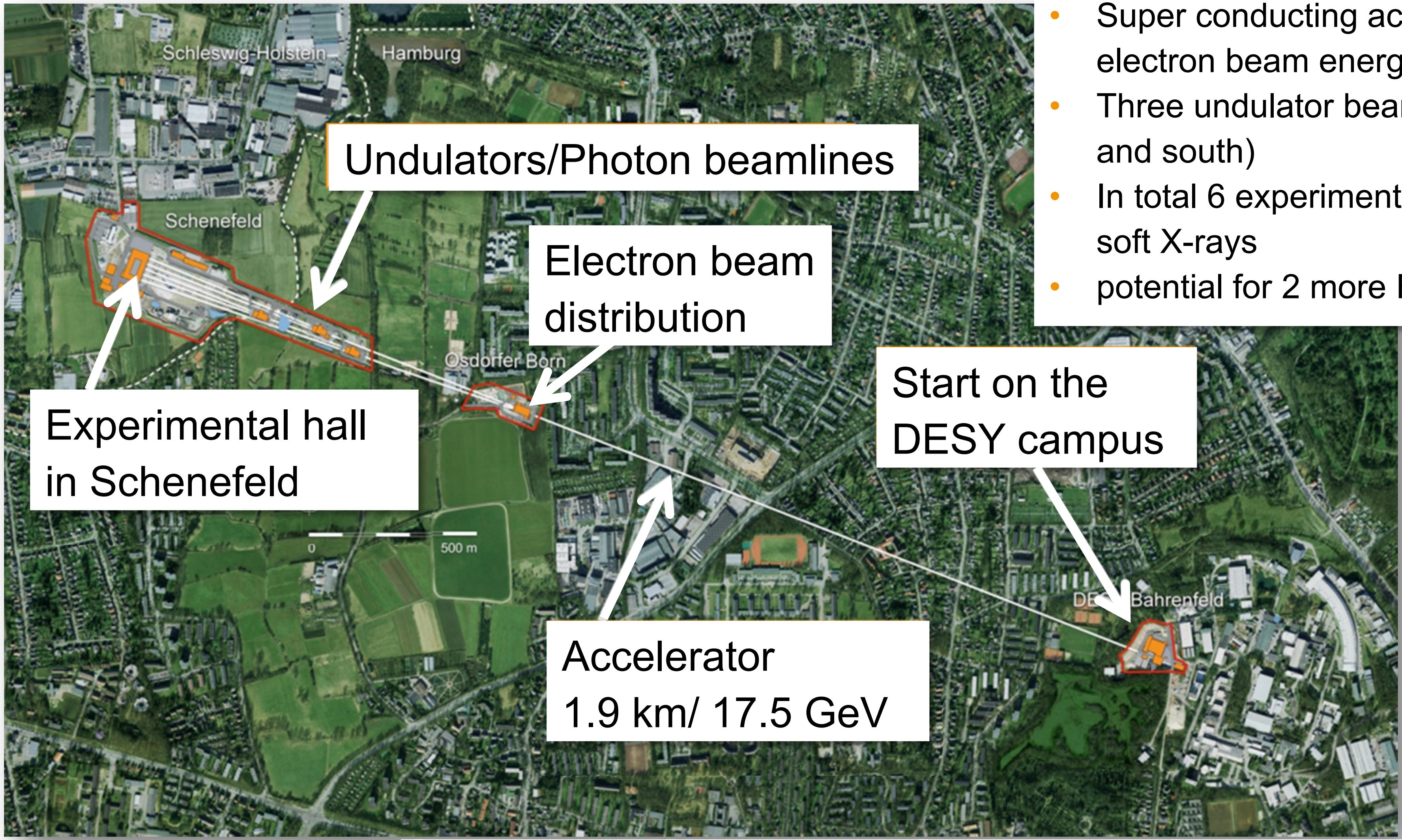
FEL Operation at the European XFEL Facility

Dirk Nölle for the EuXFEL Operation Team

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

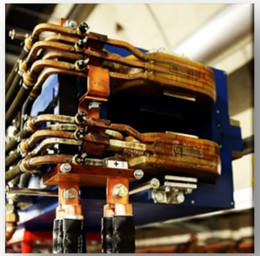


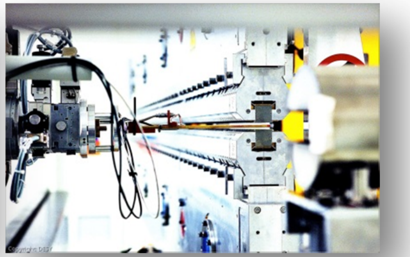
The European XFEL between Hamburg Bahrenfeld and Schenefeld

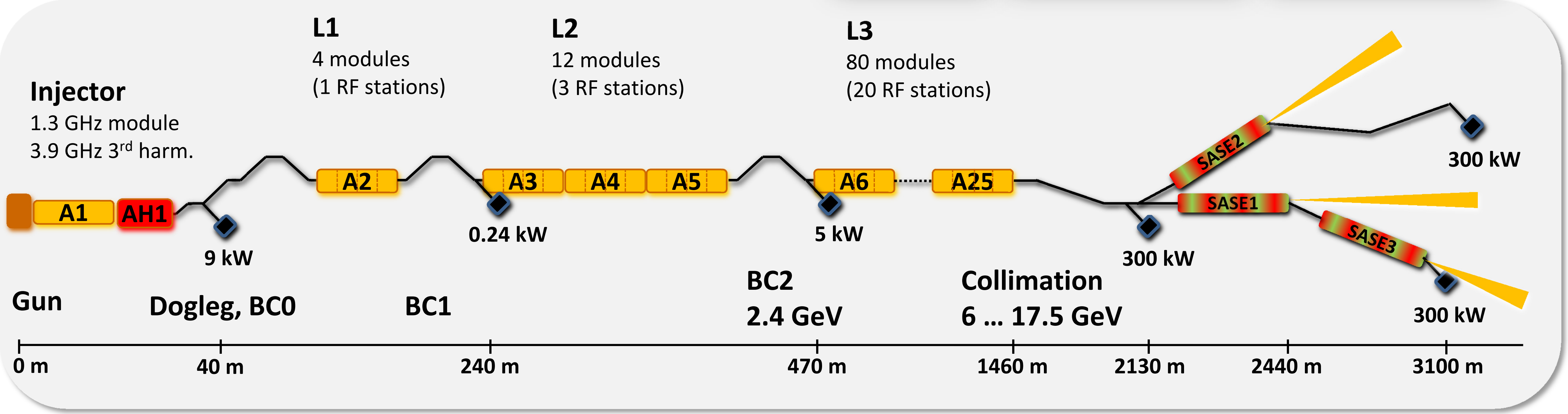


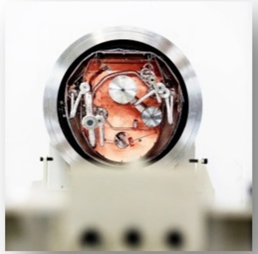
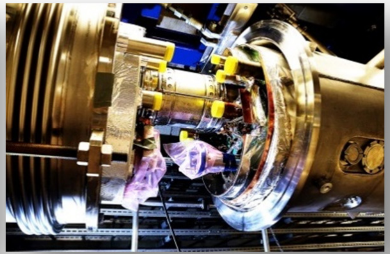
- Super conducting accelerator with up to 17.5 GeV electron beam energy
- Three undulator beamlines in two branches (north and south)
- In total 6 experiments, 4 for hard X-rays and 2 for soft X-rays
- potential for 2 more FELs

Schematic Accelerator Overview





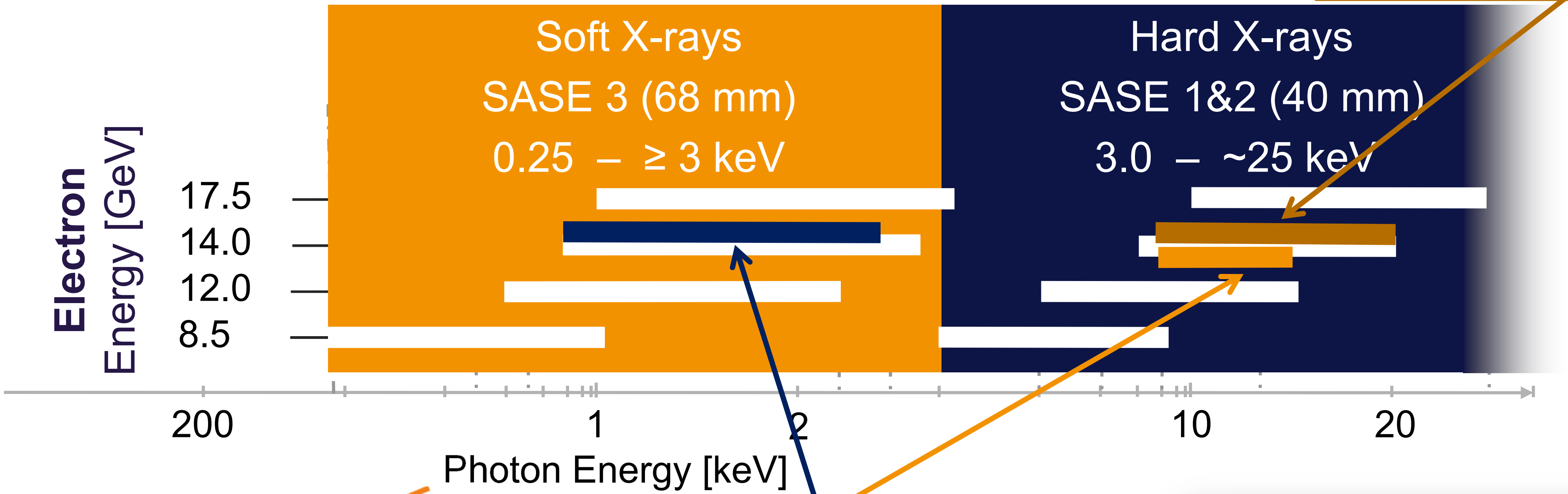


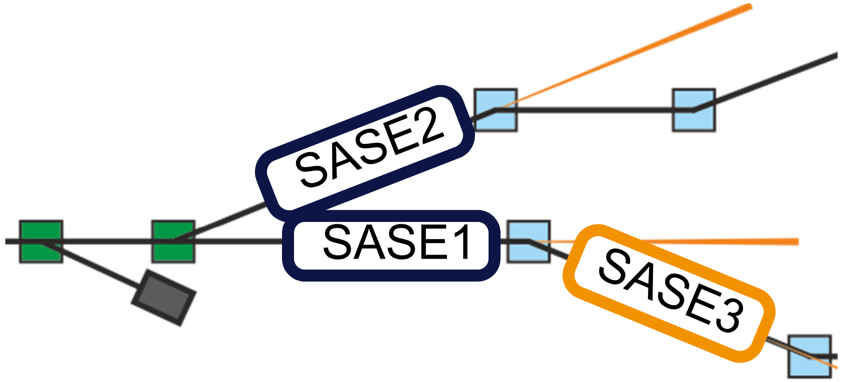




The European XFEL can cover Photon Energies from 0.25 keV to 25 keV

Explored during test runs:

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



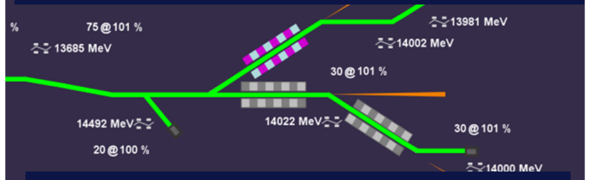


Working point during user runs:

- 14 GeV electron beam energy
- 5.8 - 14 keV photon energy (SASE1/2).
- 0.6 -2.4 keV SASE3

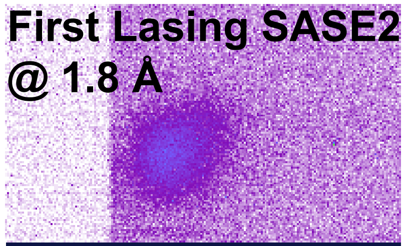
Operational Achievements

Flexible Beam Distribution



May - October, 2018

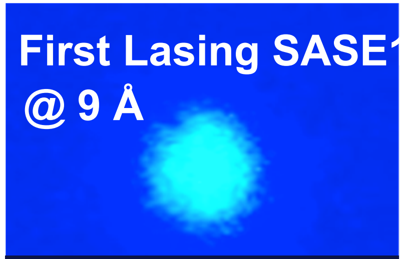
First Lasing SASE2 @ 1.8 Å



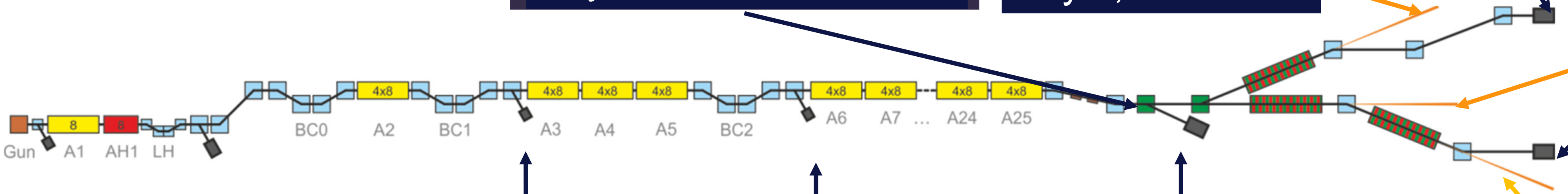
May 1, 2018

March 13, 2018

First Lasing SASE1 @ 9 Å

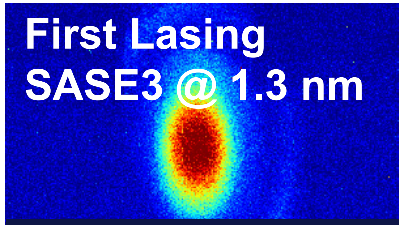


May 2-3, 2017



April 27, 2017

First Lasing SASE3 @ 1.3 nm



February 8, 2018

Jan 13, 2017

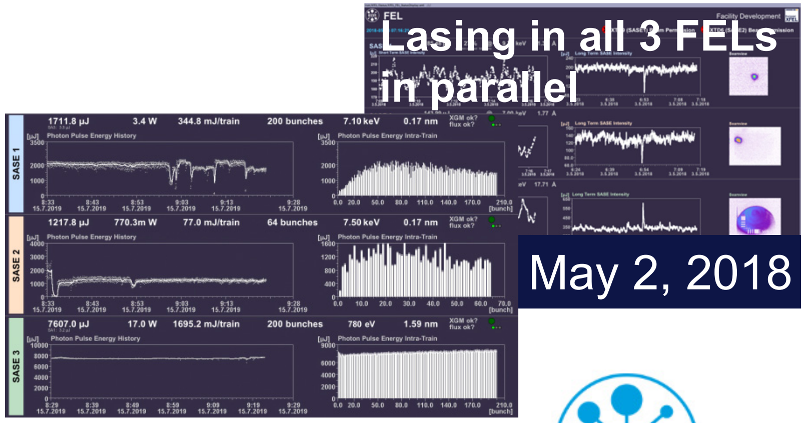
Feb 2, 2017: 600 MeV
Feb 22, 2017: 2.5 GeV

Feb 25, 2017: 2.5 GeV
April 8, 2017: 12 GeV
Oct 23, 2017: 14.9 GeV
July 12, 2018: 17.6 GeV

Jan 15, 2017: 130 MeV
Jan 19, 2017: 600 MeV

Nov 2, 2018: 2699 Bunches/RF pulse

Lasing in all 3 FELs in parallel

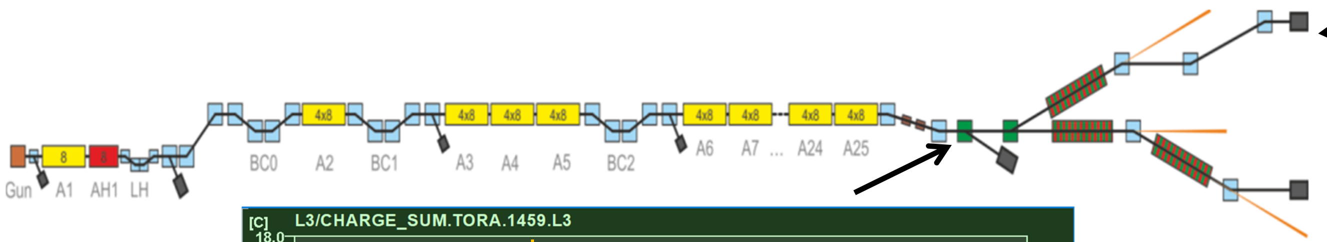


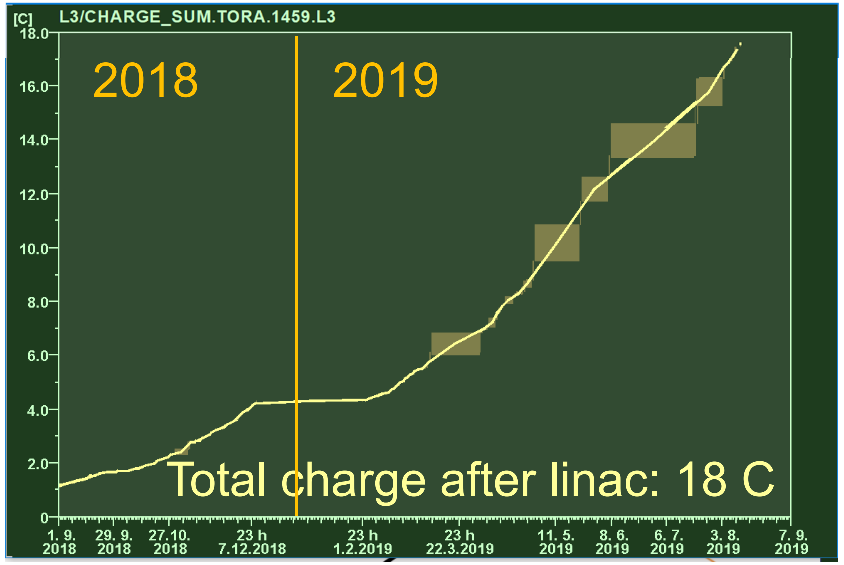
May 2, 2018

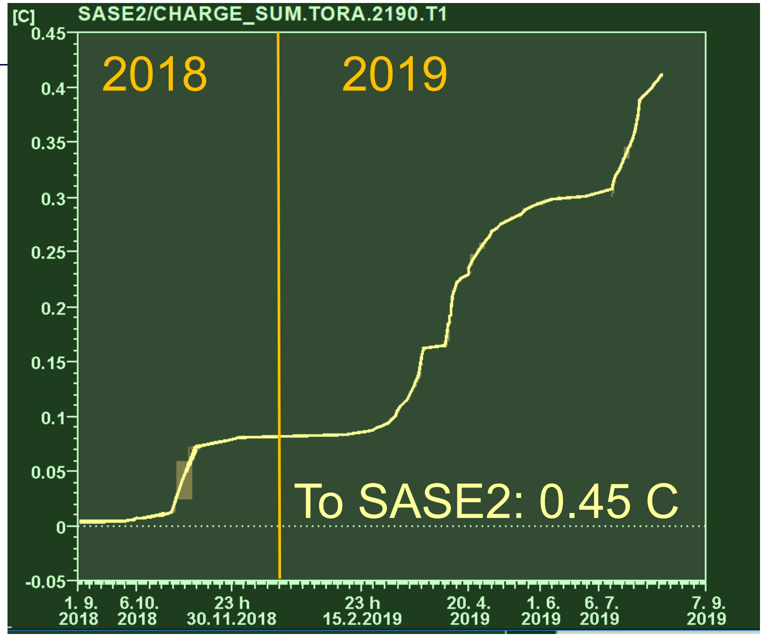
July 2019, 4.5 MHz User Operation

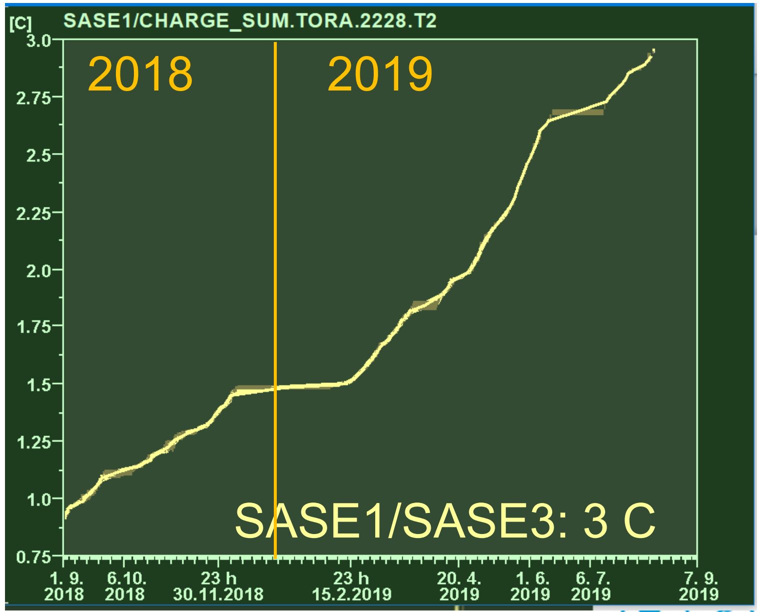
The Superconducting Linear Accelerator Performs to Design Specifications

Integrated Charge from 2018 to Aug. 15th 2019









- 600 µs 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

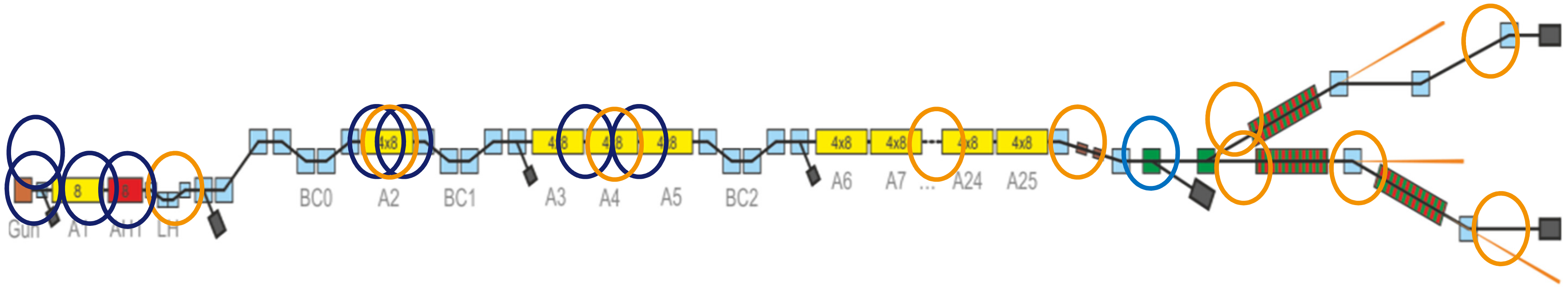
LINAC Operation with Longitudinal and Transverse Feedbacks

- 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

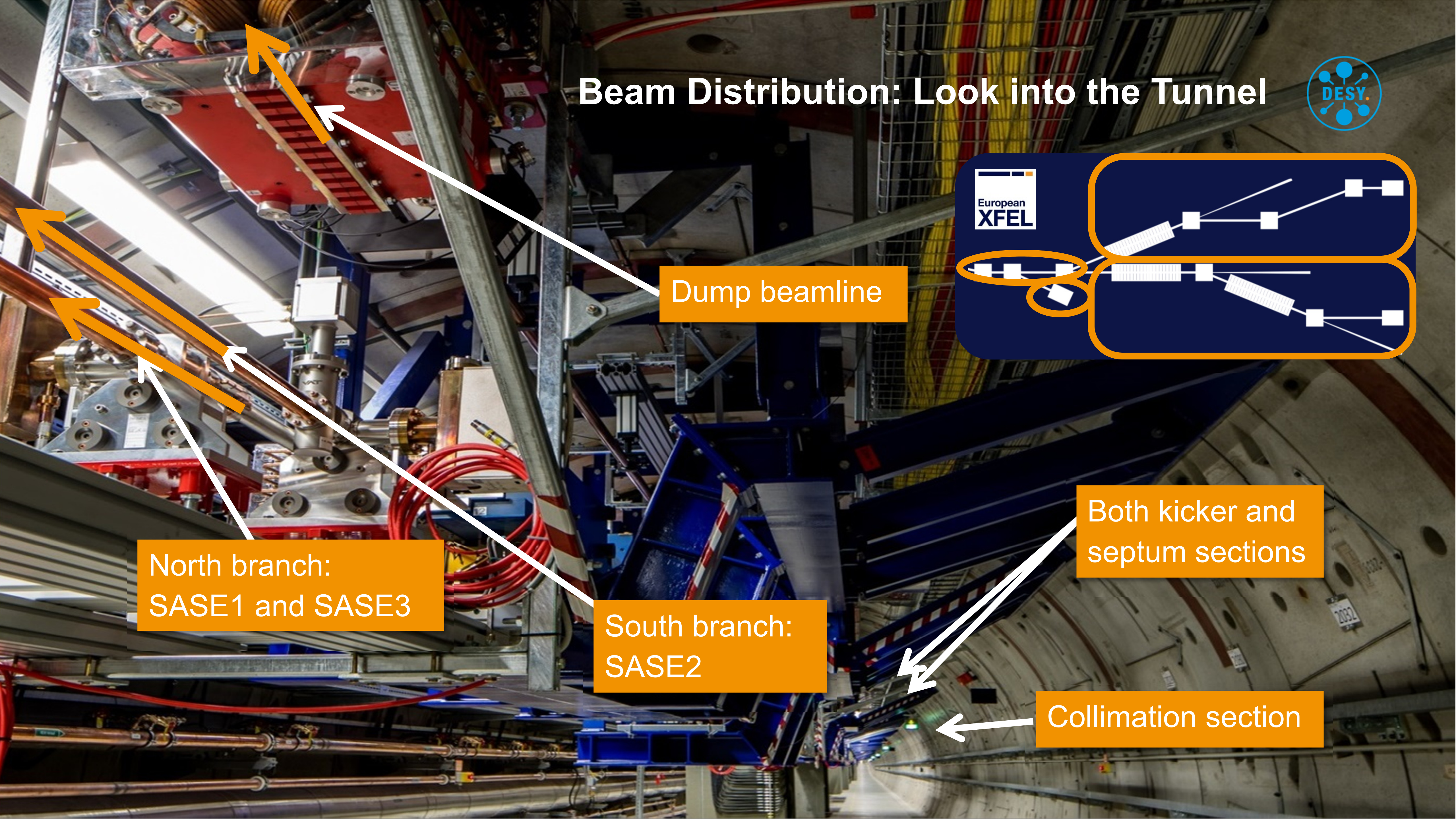
  Pointing stability at undulator (source point)
  - ≈ 0.1 σ bunch to bunch
  - ≈ 0.1 σ rf-pulse to rf-pulse (> 20 bunches)
  - ≈ 0.1 σ drift

- All numbers are expected to improve during advanced development of systems.

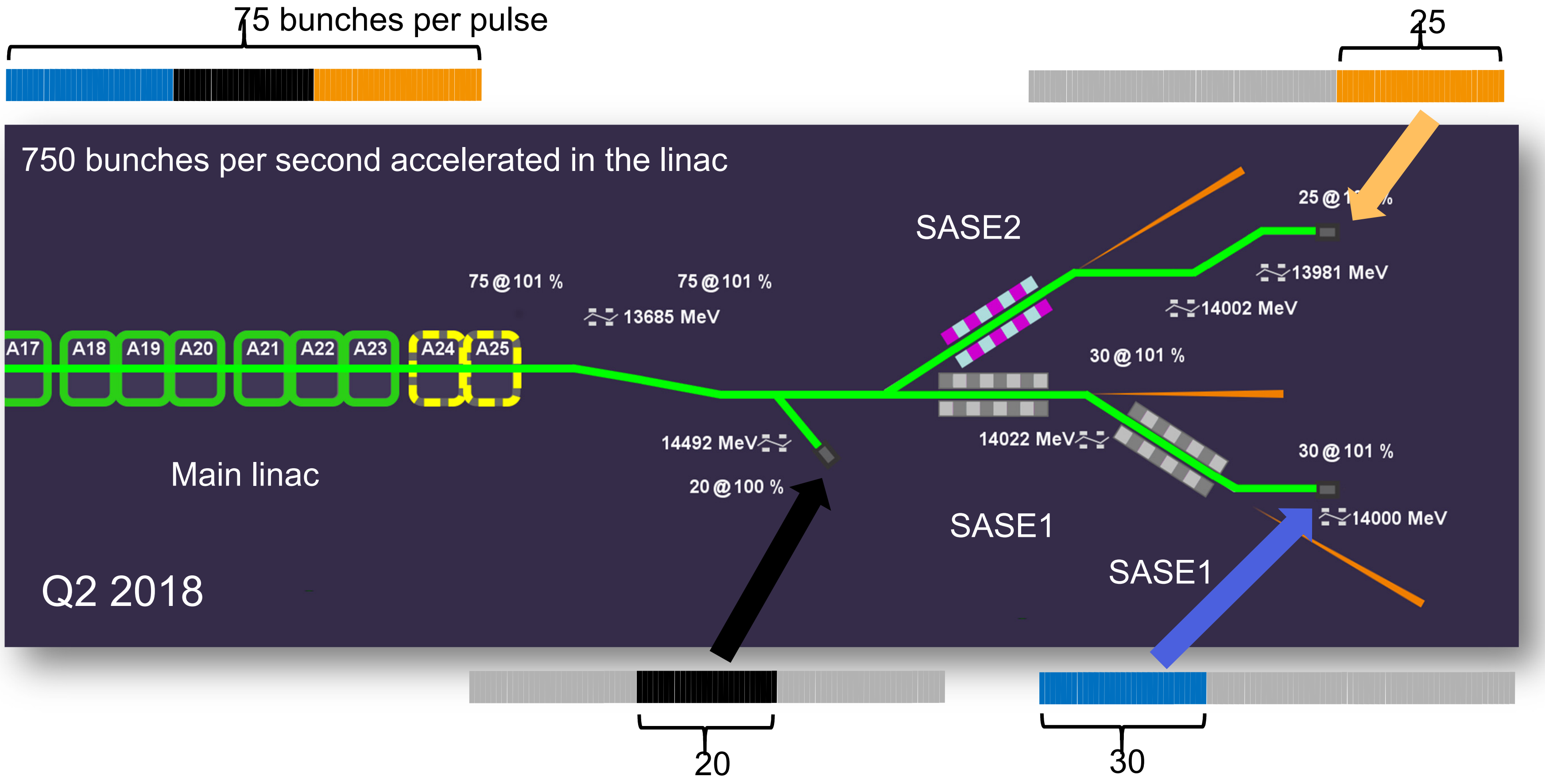


Beam Distribution: Look into the Tunnel

Beam Distribution: Look into the Tunnel

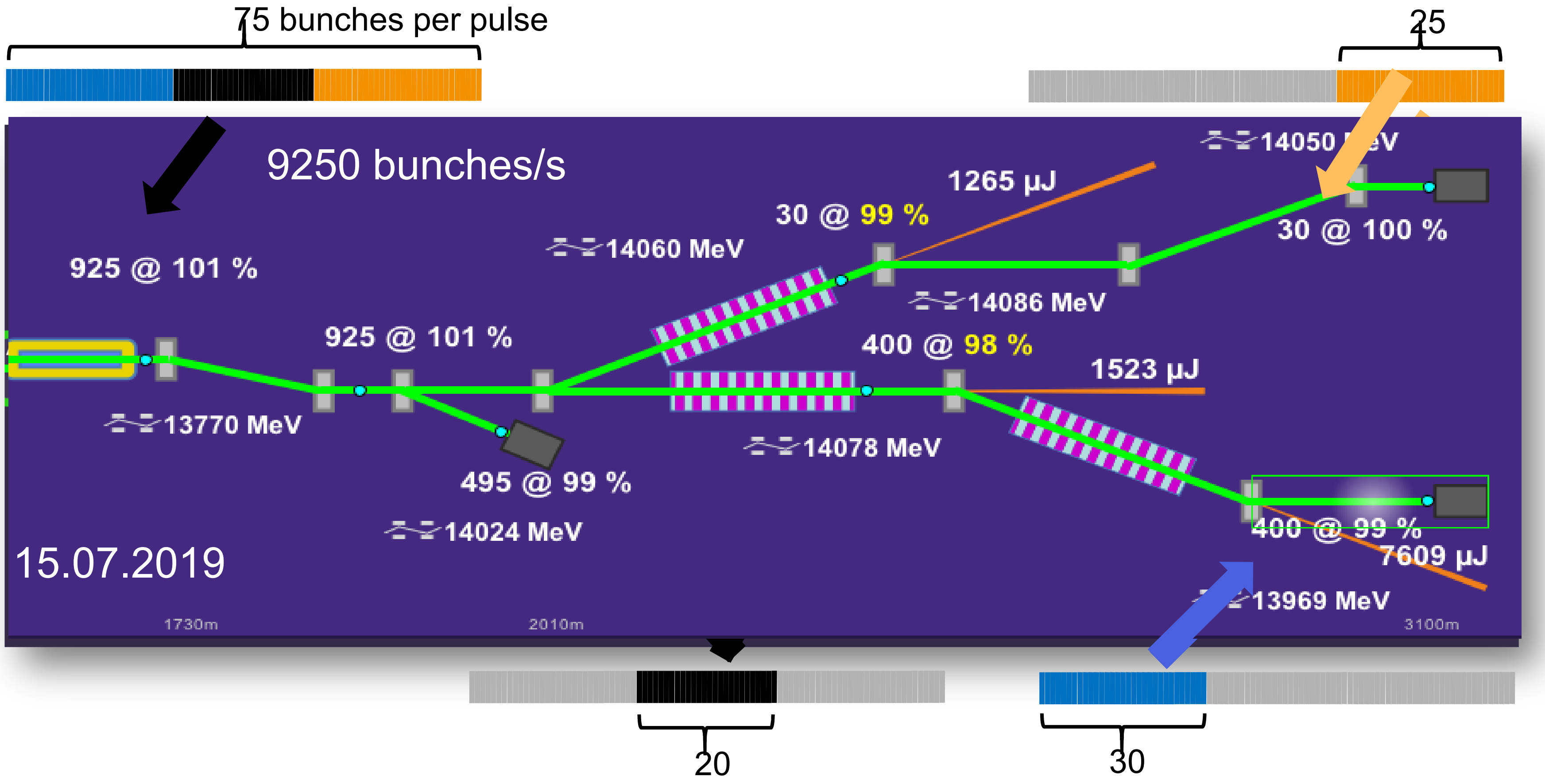


Parallel Operation of Beamlines - Flexible Electron Beam Distribution System Commissioned and further Developed



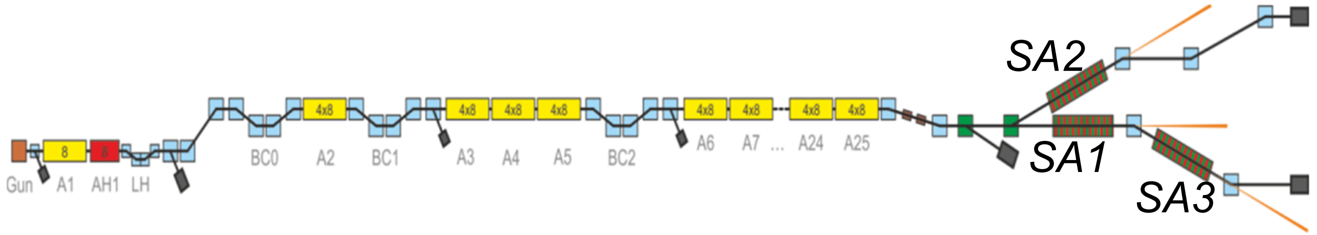
- So-called user-defined timing patterns available since January 2018
- User controlled bunch numbers available since summer 2018
- Possibility to switch bunch pattern with 10 Hz since January 2019

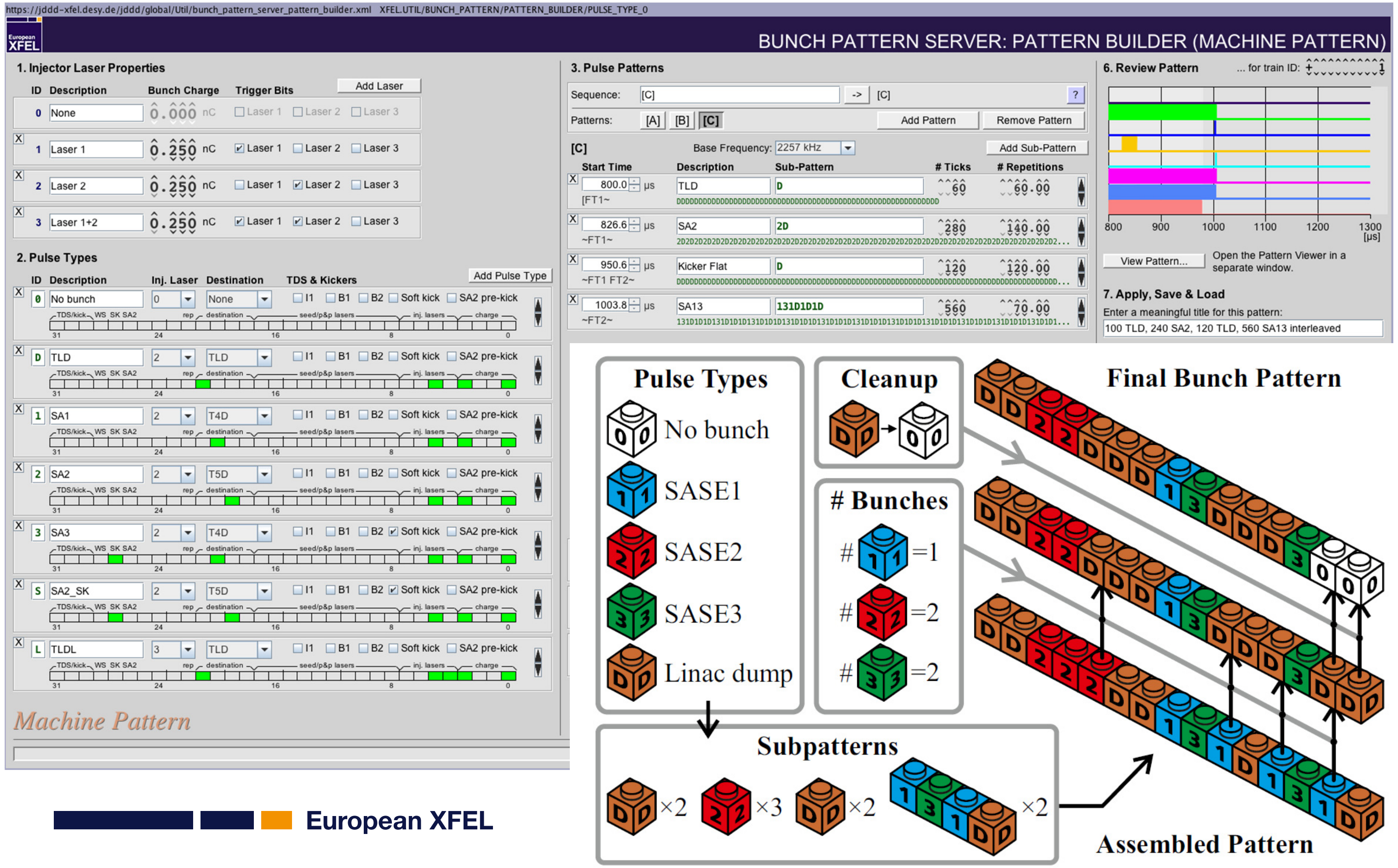
Parallel Operation of Beamlines - Flexible Electron Beam Distribution System Commissioned and further Developed



- 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



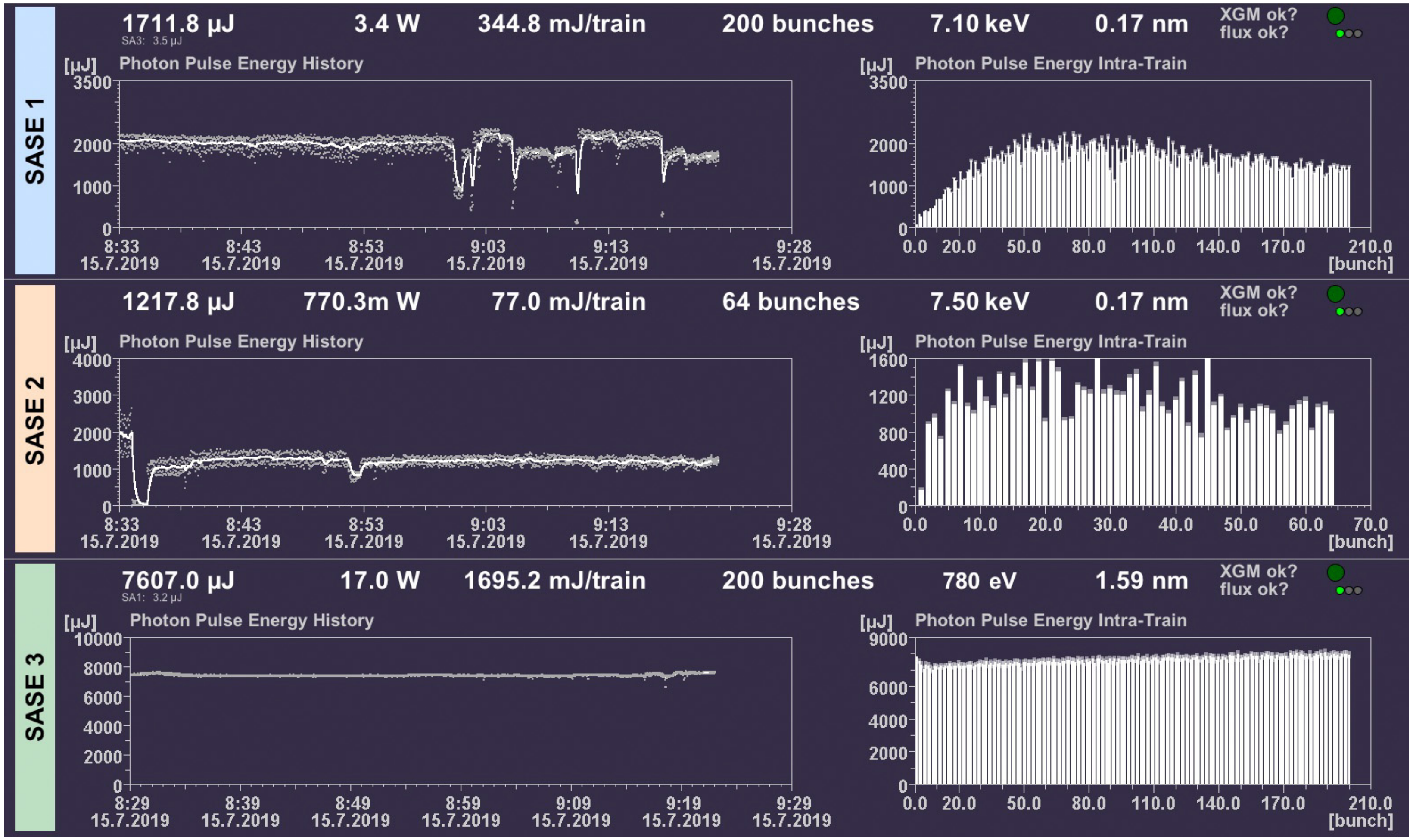


A typical bunch train is built by:

- 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

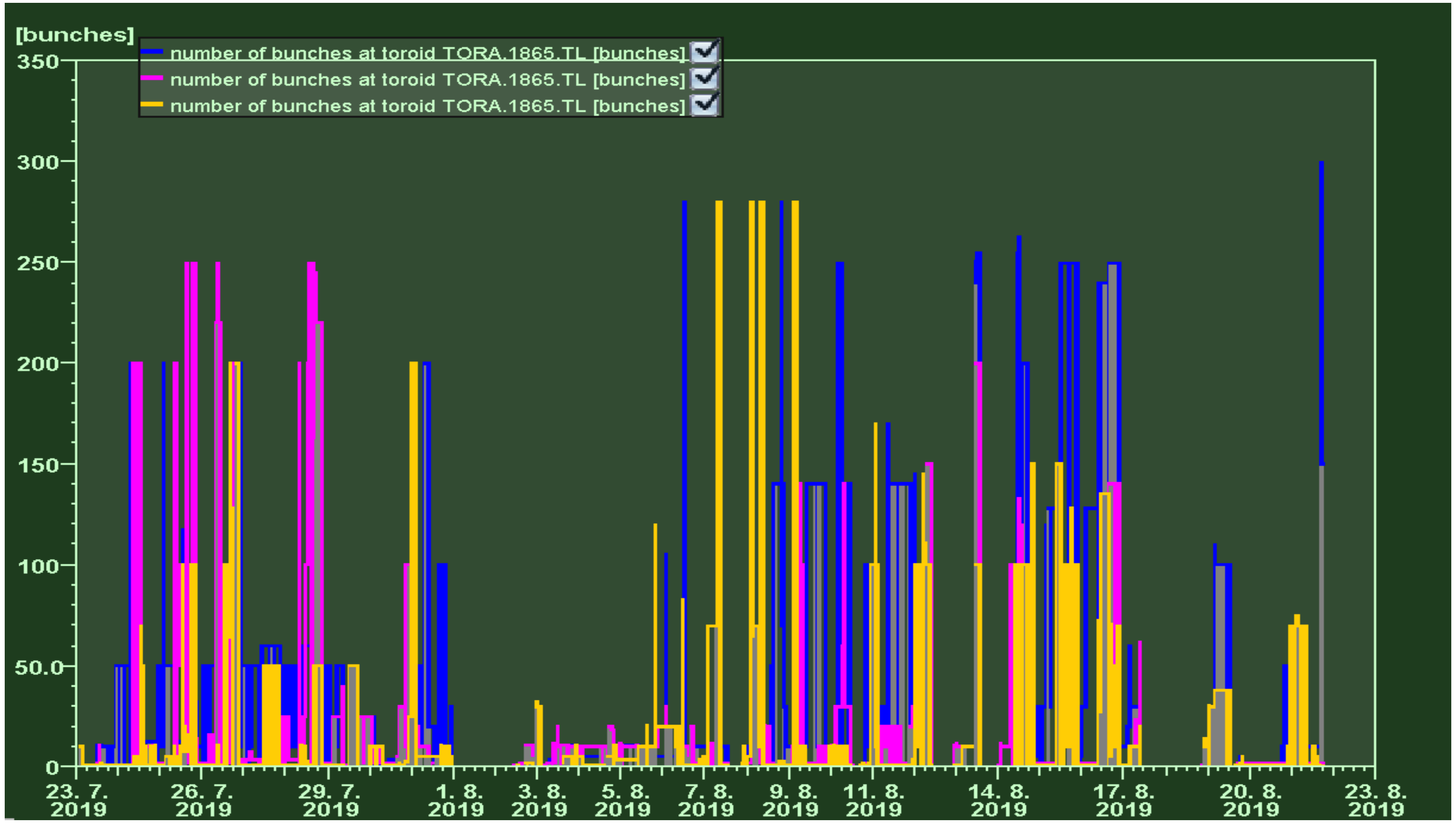
FEL Operation



- 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!

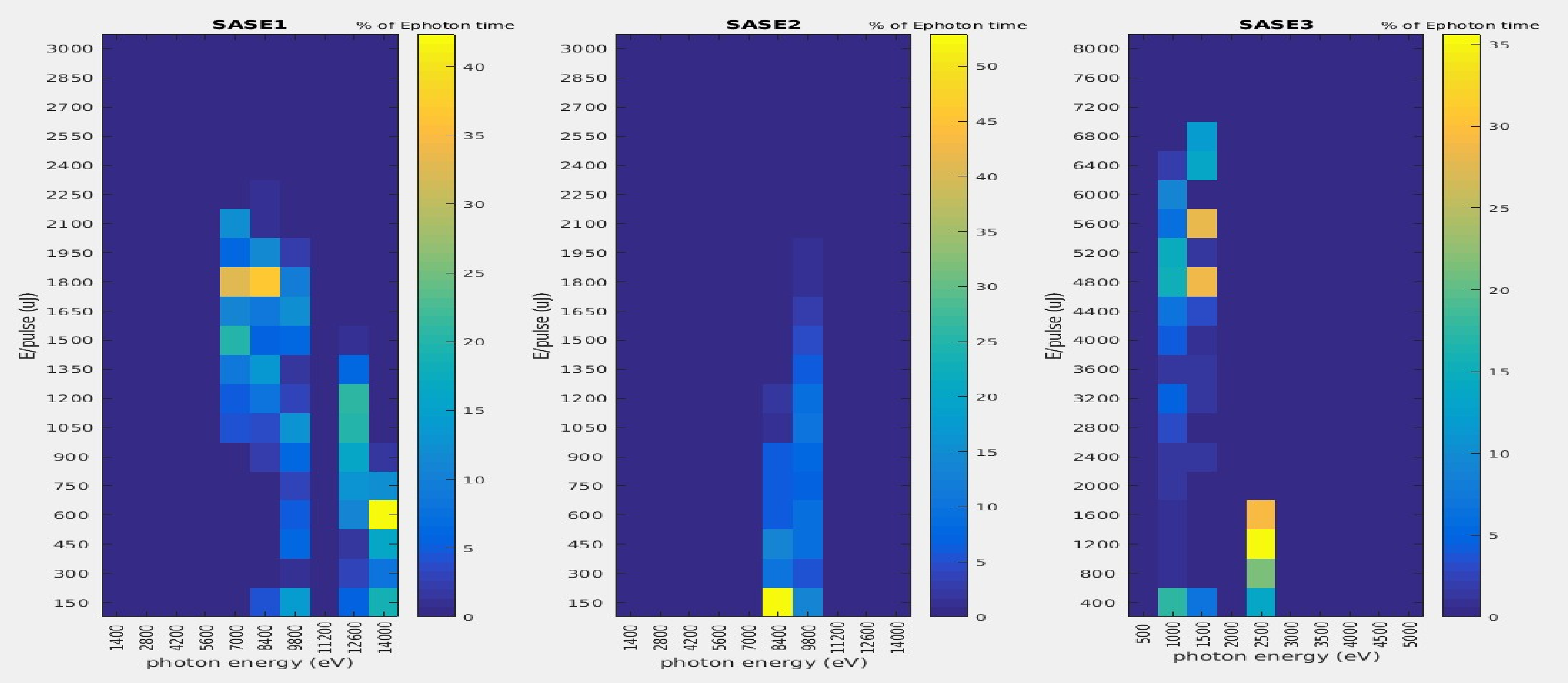
Average Power: 22 W! in 464 Bunches; SA2 at Actual Safety Limit

Bunch Numbers: Set by Users



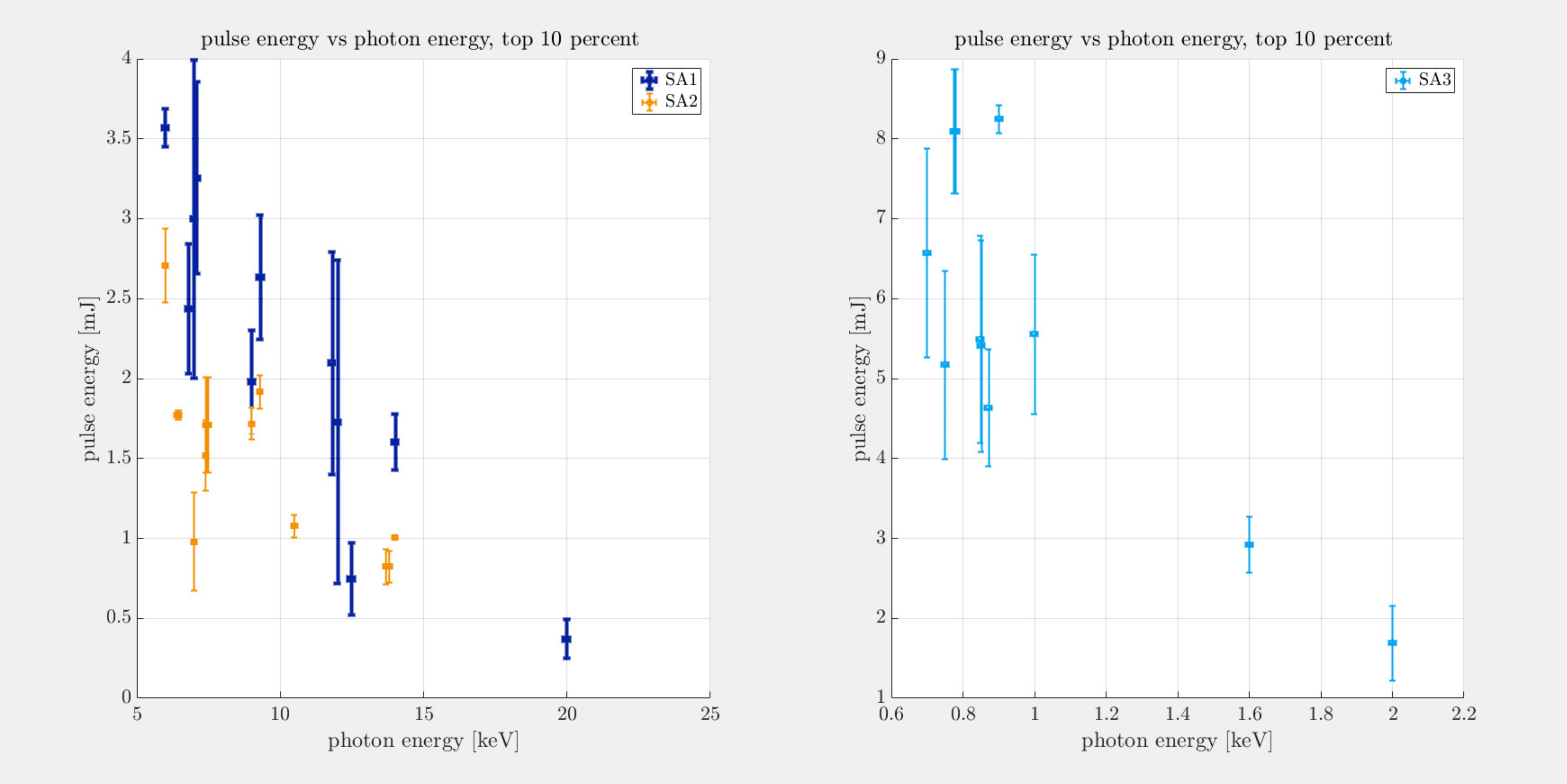
- Blue: SASE1
- Red: SASE2
- Yellow: SASE3
- Delivery schemes:
  - Single bunch for setup
  - Pulse on demand
  - Multi-bunch for data taking
  - Requirements differ depending on experiment
- Detectors make progress in accepting more data frames/RF pulse
- Demand for long trains increasing

Photon Energies and Pulse Energies during Photon Delivery



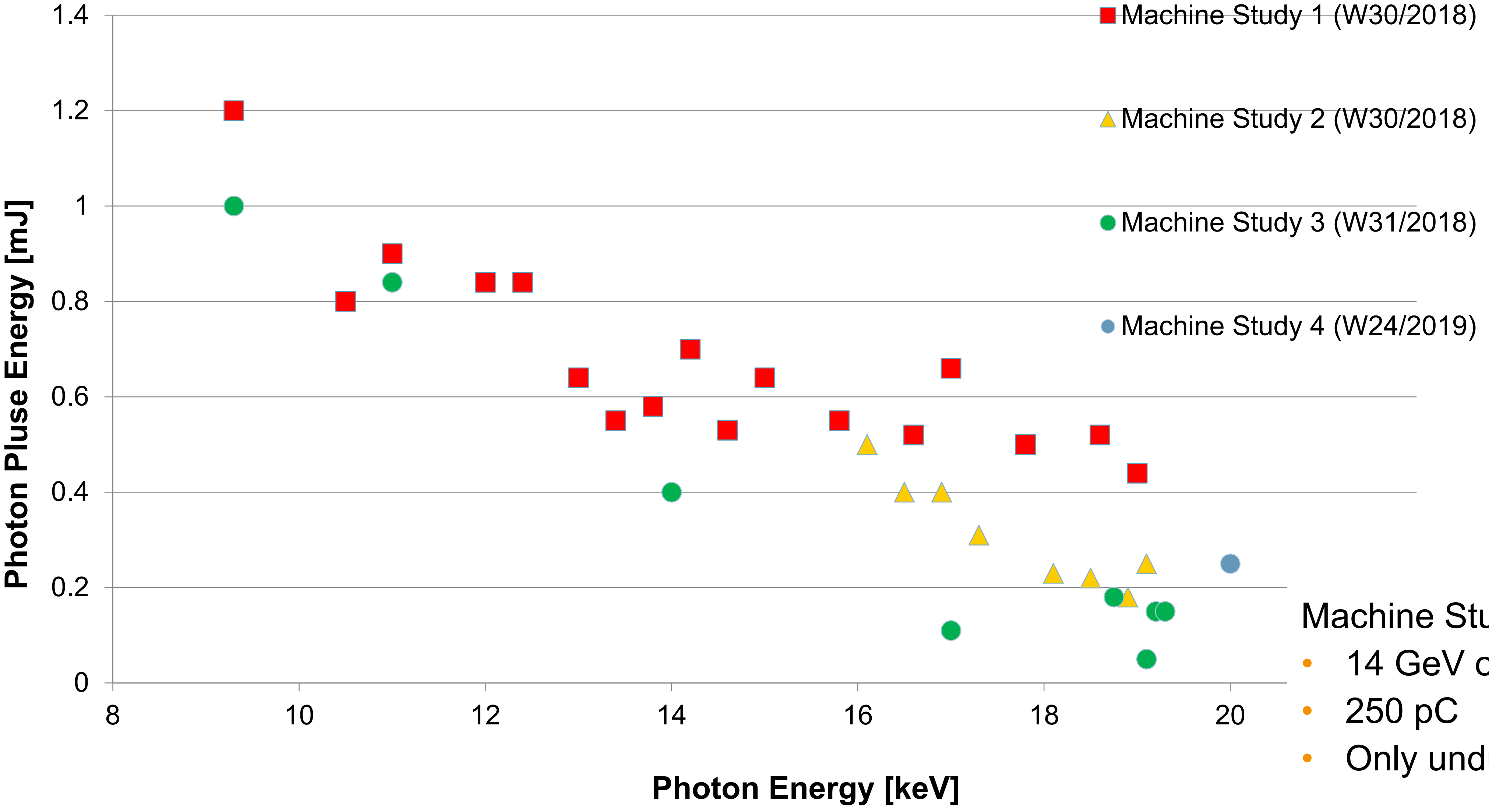
Week 30/2019

Photon Energies and Pulse Energies during Photon Delivery 2019



2019 Data

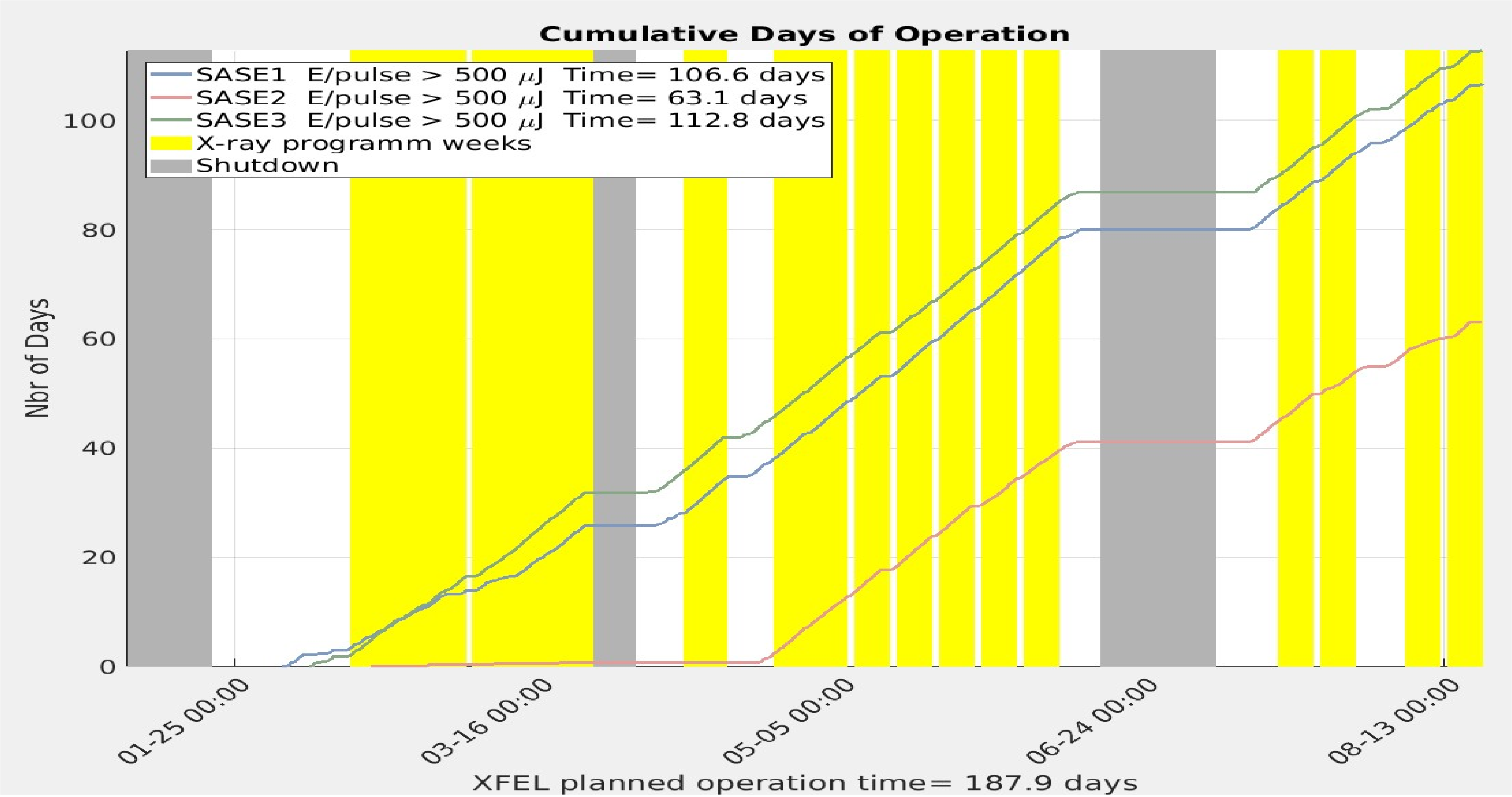
High Photon Energy Operation at SASE1

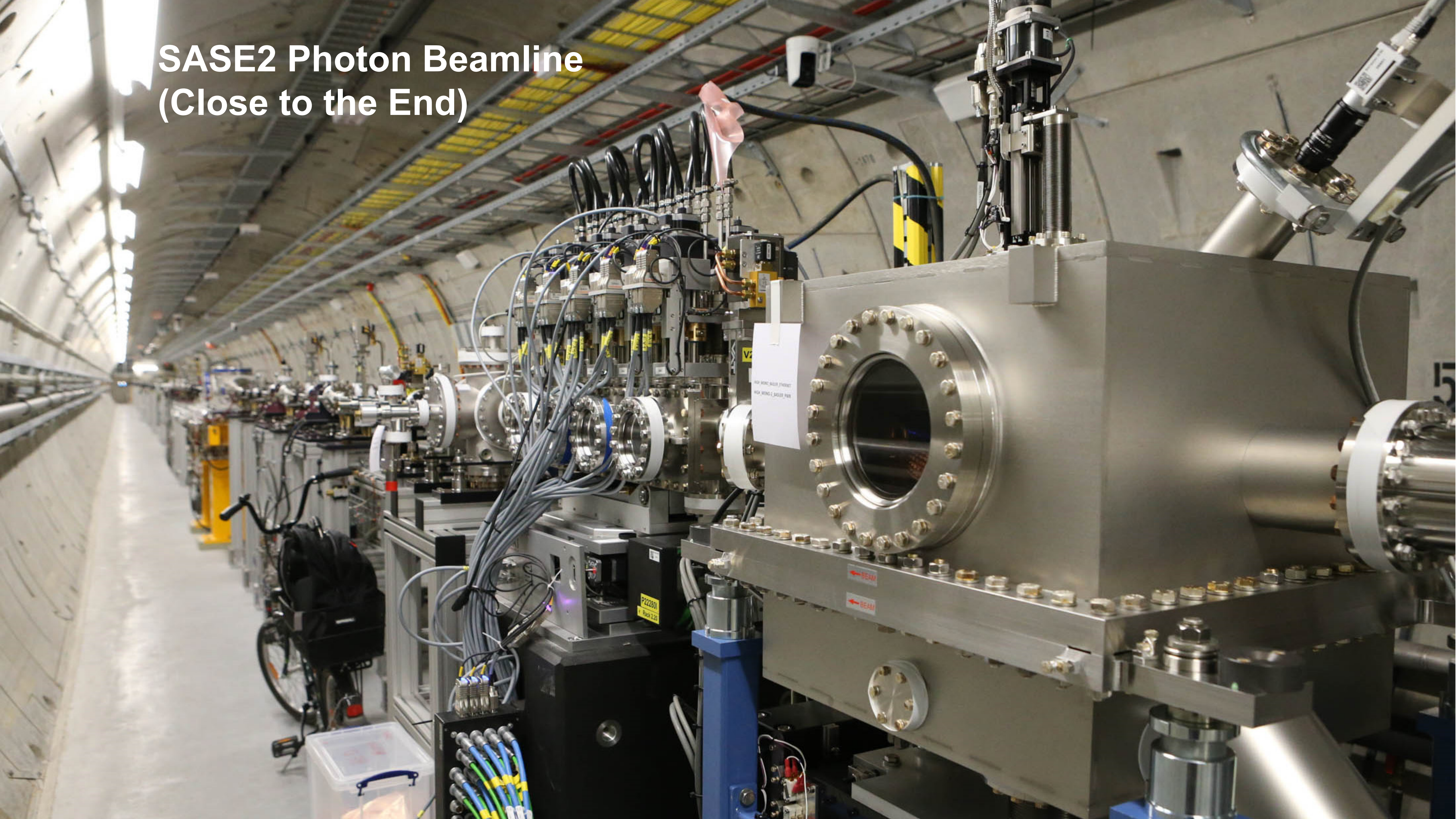


Machine Studies only:

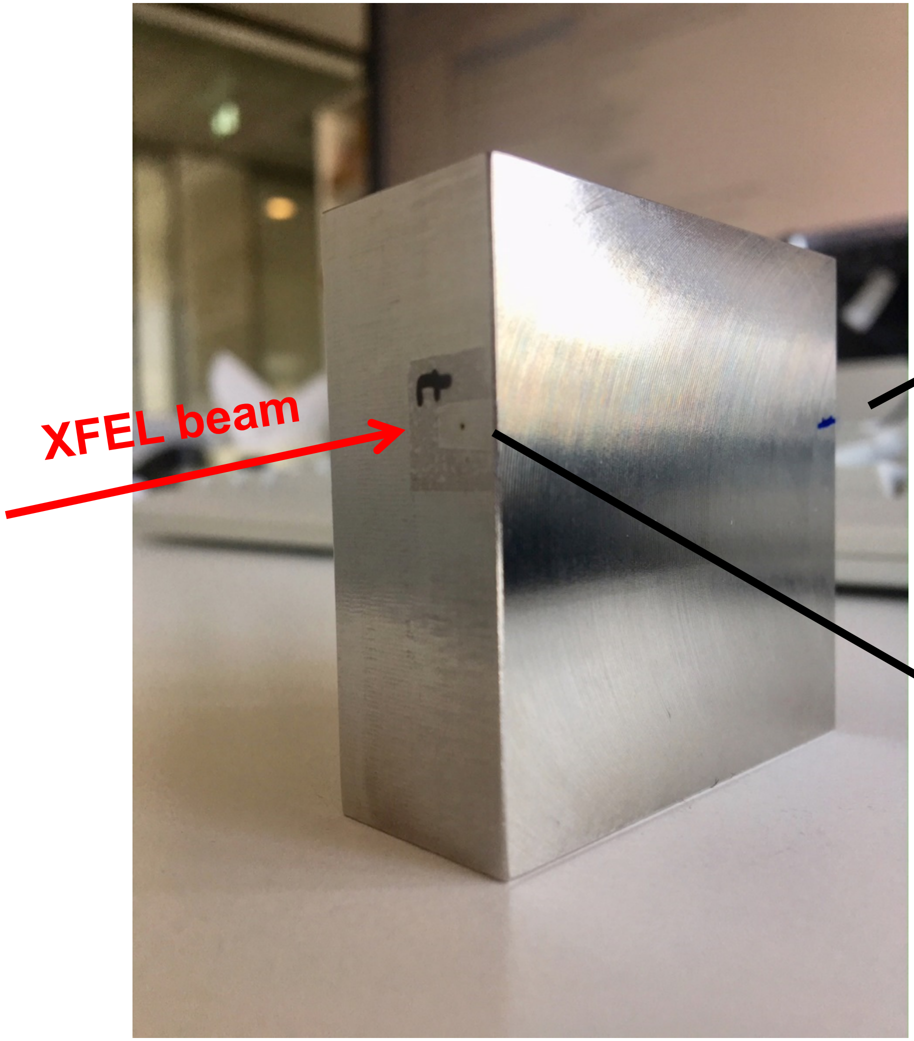
- 14 GeV operation point
- 250 pC
- Only undulator gap change

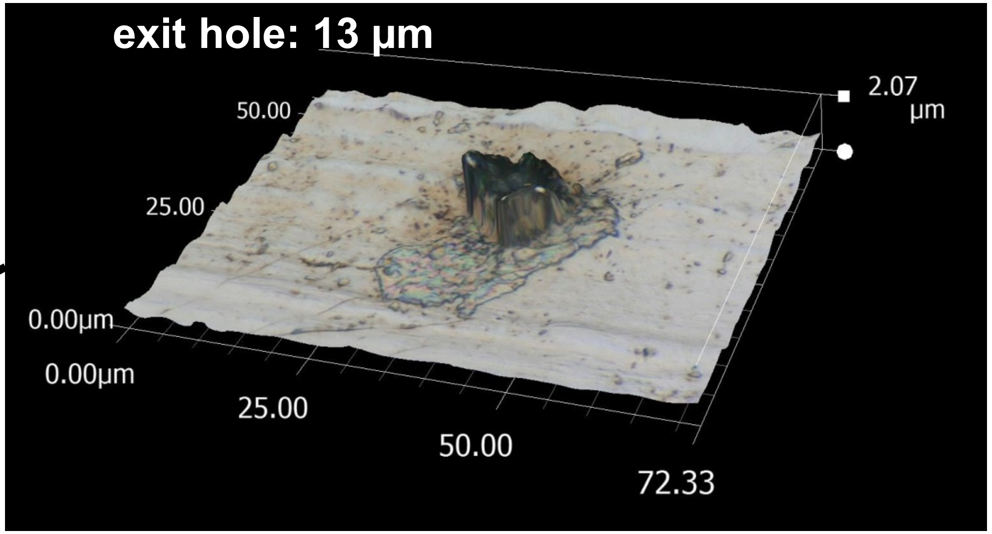
SASE Delivery in 2019

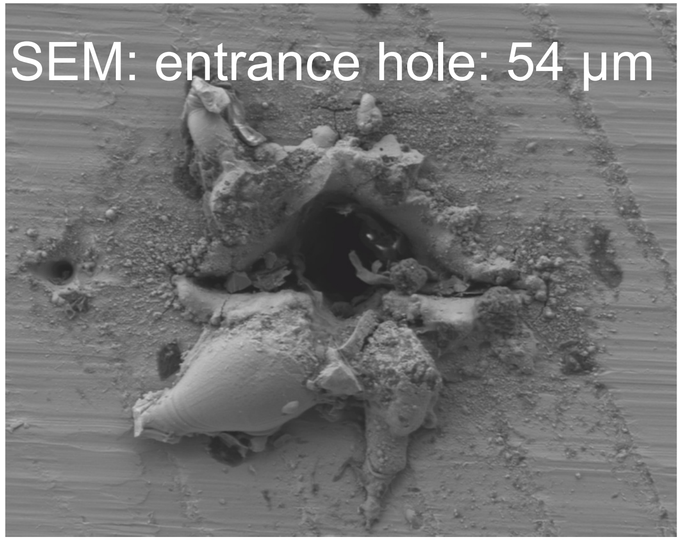



SASE2 Photon Beamline
(Close to the End)

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

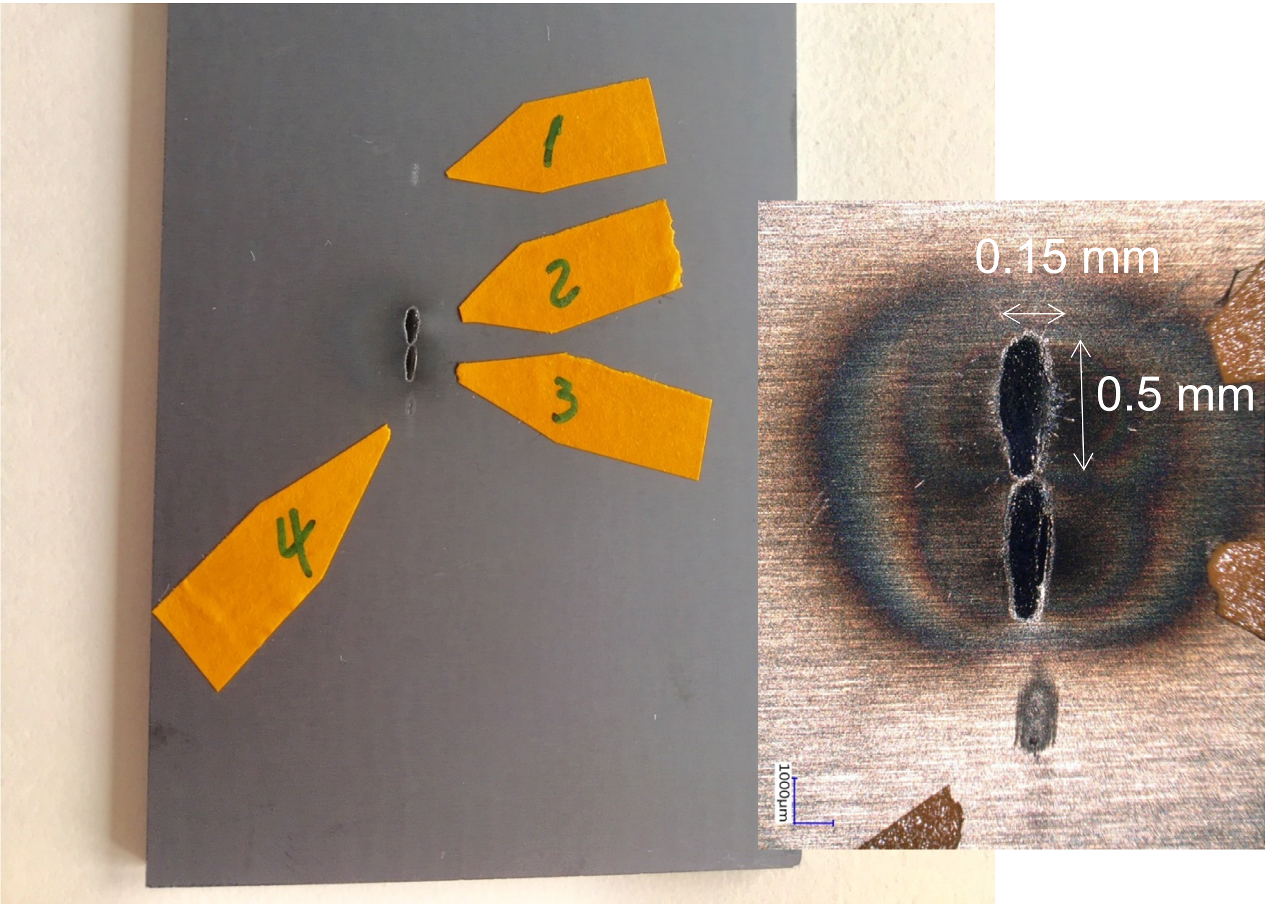




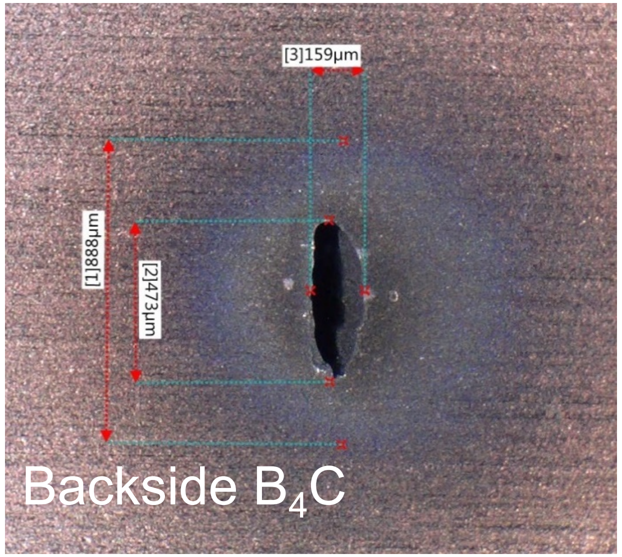


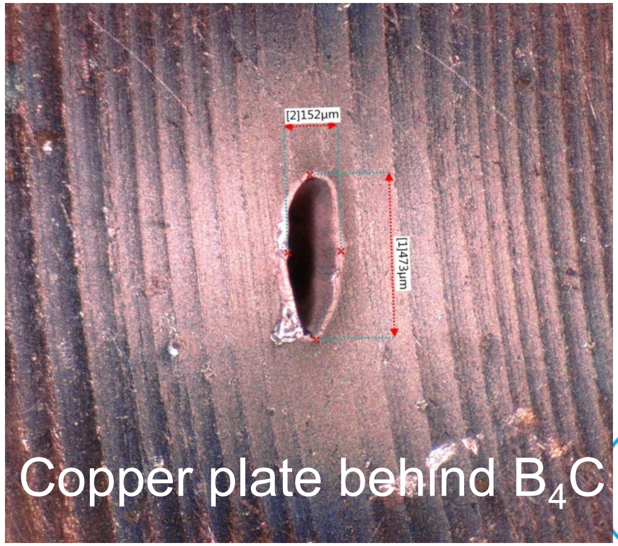
FXE instrument
9.3 keV
1 mJ/pulse
20 µm beam size
1500 pulses/sec

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





Performance Rise and Future Expectations

Early 2018
~300 pulses/s/branch

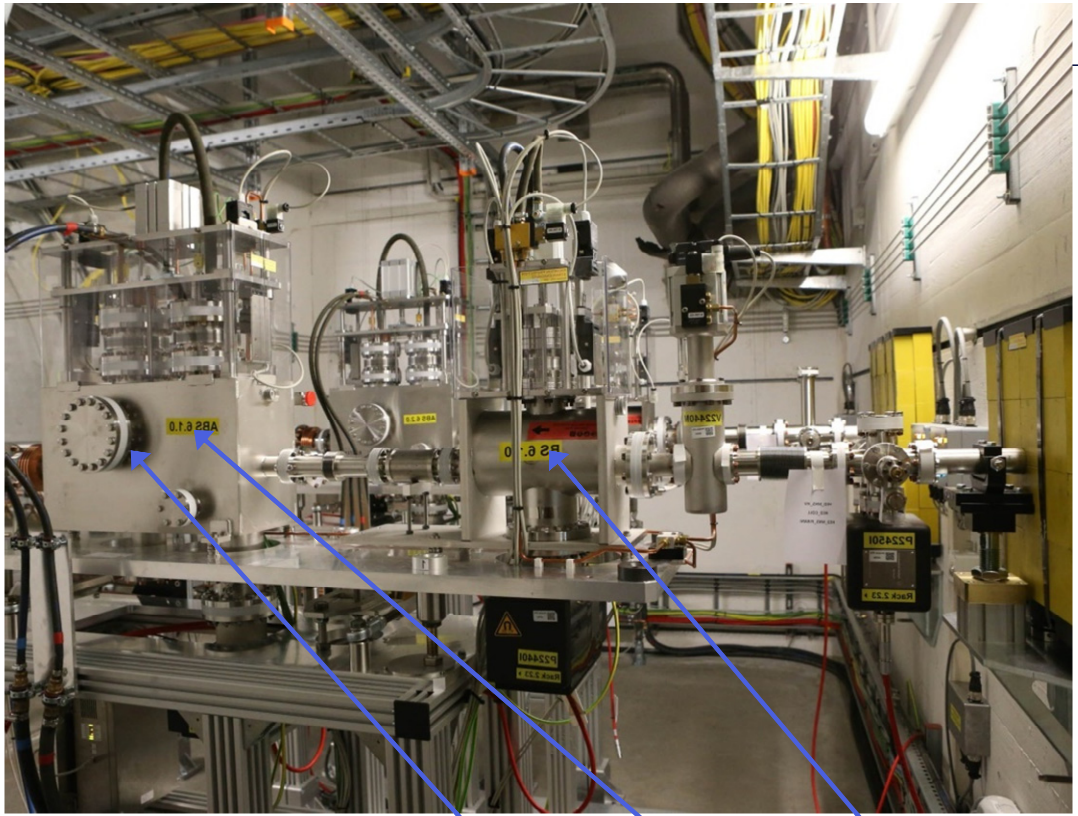
Up to 2019 (today)

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

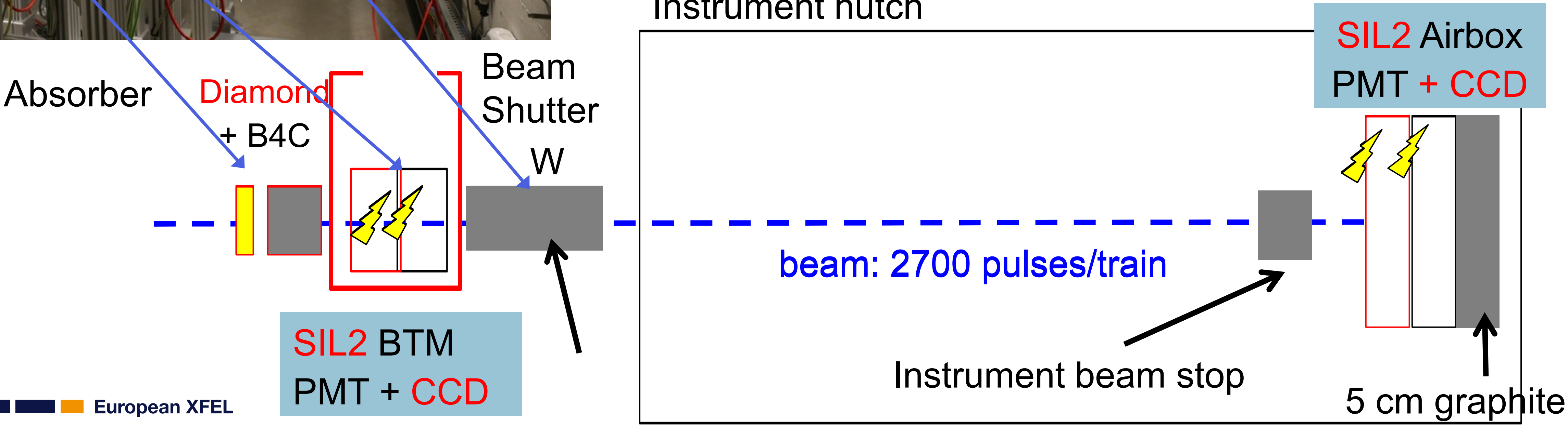
…, 2020, …

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

Safety Upgrade in Winter Shutdown 19/20



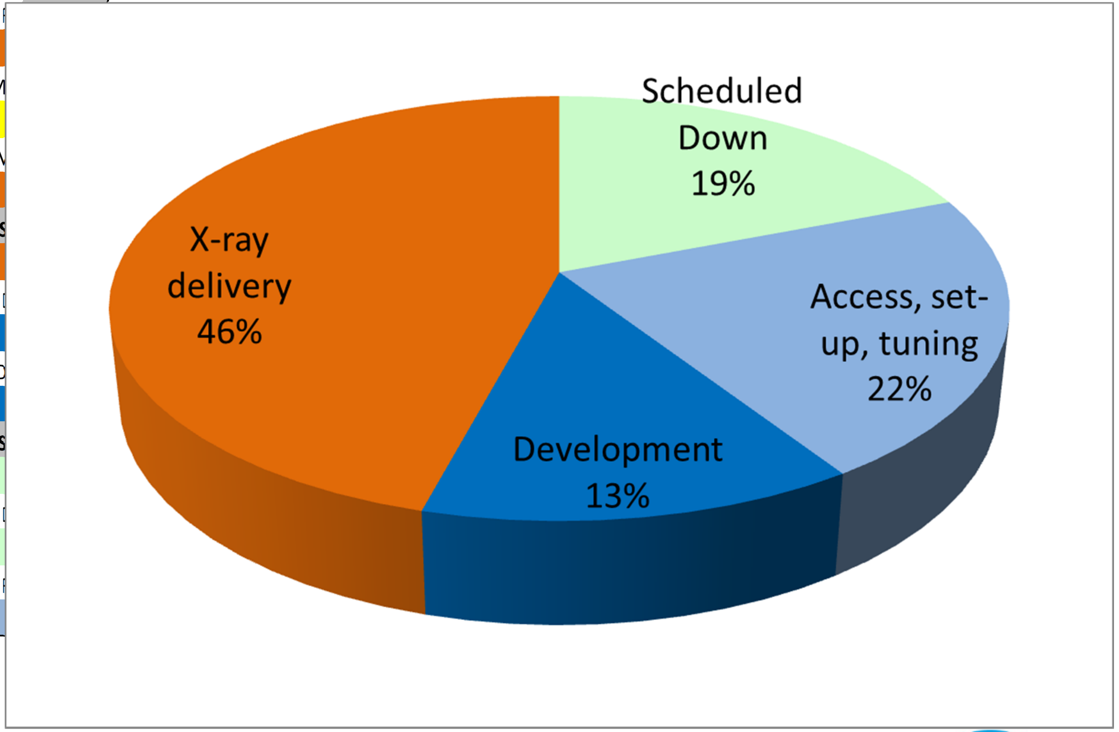
- Include active element between absorber and beam shutter
- Similar elements to ensure hutch integrity
- Development of *Burn Through Monitor* with required safety level (SIL2) available for Winter shutdown
- Diamond absorbers can take more power (than B_4C)
- Beam shutter has to “survive“´ latency 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
Jan	Mi	Do	Fr	Sa	So	Mo	Di	Mi	Do	Fr	Sa	So	Mo	Di	Mi	Do	Fr	Sa	So	Mo	Di	Mi	Do	Fr	Sa	So	Mo	Di	Mi	Do	Fr
Feb	Sa	So	Mo	Di	Mi	Do	Fr	Sa	So	Mo	Di	Mi	Do	Fr	Sa	So	Mo	Di	Mi	Do	Fr	Sa	So	Mo	Di	Mi	Do	Fr	Sa		
Mrz	So	Mo	Di	Mi	Do	Fr	Sa	So	Mo	Di	Mi	Do	Fr	Sa	So	Mo	Di	Mi	Do	Fr	Sa	So	Mo	Di	Mi	Do	Fr	Sa	So	Mo	Di
Apr	Mi	Do	Fr	Sa	So	Mo	Di	Mi	Do	Fr	Sa	So	Mo	Di	Mi	Do	Fr	Sa	So	Mo	Di	Mi	Do	Fr	Sa	So	Mo	Di	Mi	Do	
Mai	Fr	Sa	So	Mo	Di	Mi	Do	Fr	Sa	So	Mo	Di	Mi	Do	Fr	Sa	So	Mo	Di	Mi	Do	Fr	Sa	So	Mo	Di	Mi	Do			
Jun	Mo	Di	Mi	Do	Fr	Sa	So	Mo	Di	Mi	Do	Fr	Sa	So	Mo	Di	Mi	Do	Fr	Sa	So	Mo	Di	Mi	Do	Fr	Sa	So	M		
Jul	Mi	Do	Fr	Sa	So	Mo	Di	Mi	Do	Fr	Sa	So	Mo	Di	Mi	Do	Fr	Sa	So	Mo	Di	Mi	Do	Fr	Sa	So	Mo	Di	M		
Aug	Sa	So	Mo	Di	Mi	Do	Fr	Sa	So	Mo	Di	Mi	Do	Fr	Sa	So	Mo	Di	Mi	Do	Fr	Sa	So	Mo	Di	Mi	Do	Fr	S		
Sep	Di	Mi	Do	Fr	Sa	So	Mo	Di	Mi	Do	Fr	Sa	So	Mo	Di	Mi	Do	Fr	Sa	So	Mo	Di	Mi	Do	Fr	Sa	So	Mo			
Okt	Do	Fr	Sa	So	Mo	Di	Mi	Do	Fr	Sa	So	Mo	Di	Mi	Do	Fr	Sa	So	Mo	Di	Mi	Do	Fr	Sa	So	Mo	Di	Mi	D		
Nov	So	Mo	Di	Mi	Do	Fr	Sa	So	Mo	Di	Mi	Do	Fr	Sa	So	Mo	Di	Mi	Do	Fr	Sa	So	Mo	Di	Mi	Do	Fr	Sa	S		
Dez	Di	Mi	Do	Fr	Sa	So	Mo	Di	Mi	Do	Fr	Sa	So	Mo	Di	Mi	Do	Fr	Sa	So	Mo	Di	Mi	Do	Fr	Sa	So	Mo			
Jan	Fr	Sa	So	Mo	Di	Mi	Do	Fr	Sa	So	Mo	Di	Mi	Do	Fr	Sa	So	Mo	Di	Mi	Do	Fr	Sa	So	Mo	Di	Mi	Do			

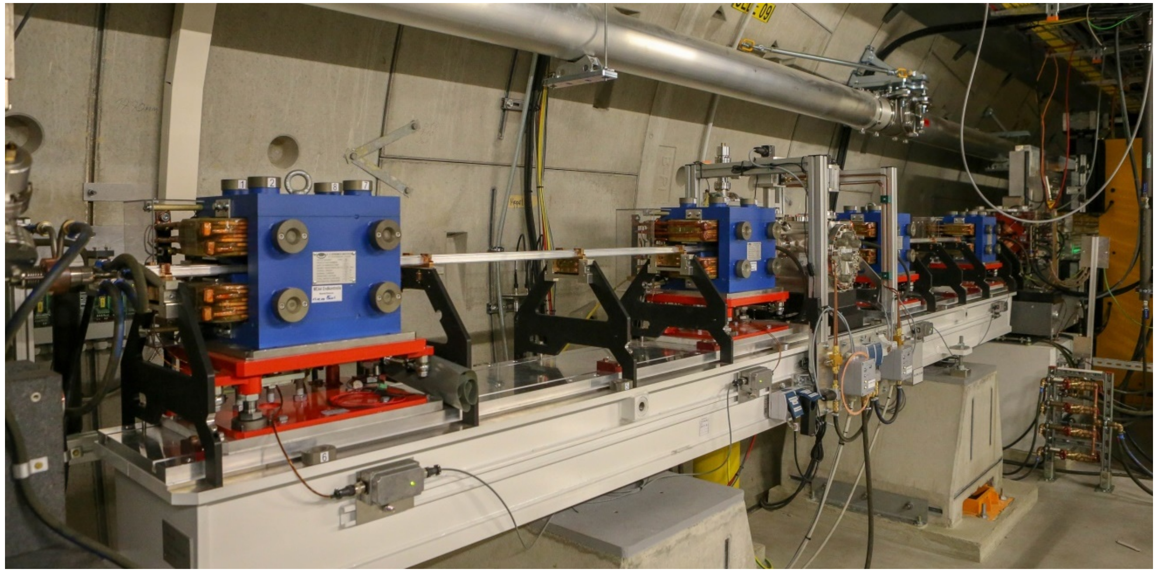
- Scheduled down: 70 d
- Operation: 7100h
  - Access, setup and tuning: 1902 h
  - Facility development: 1176 h
  - X-ray delivery: 4026 h



(Accelerator) Parameter Space (as of Today)

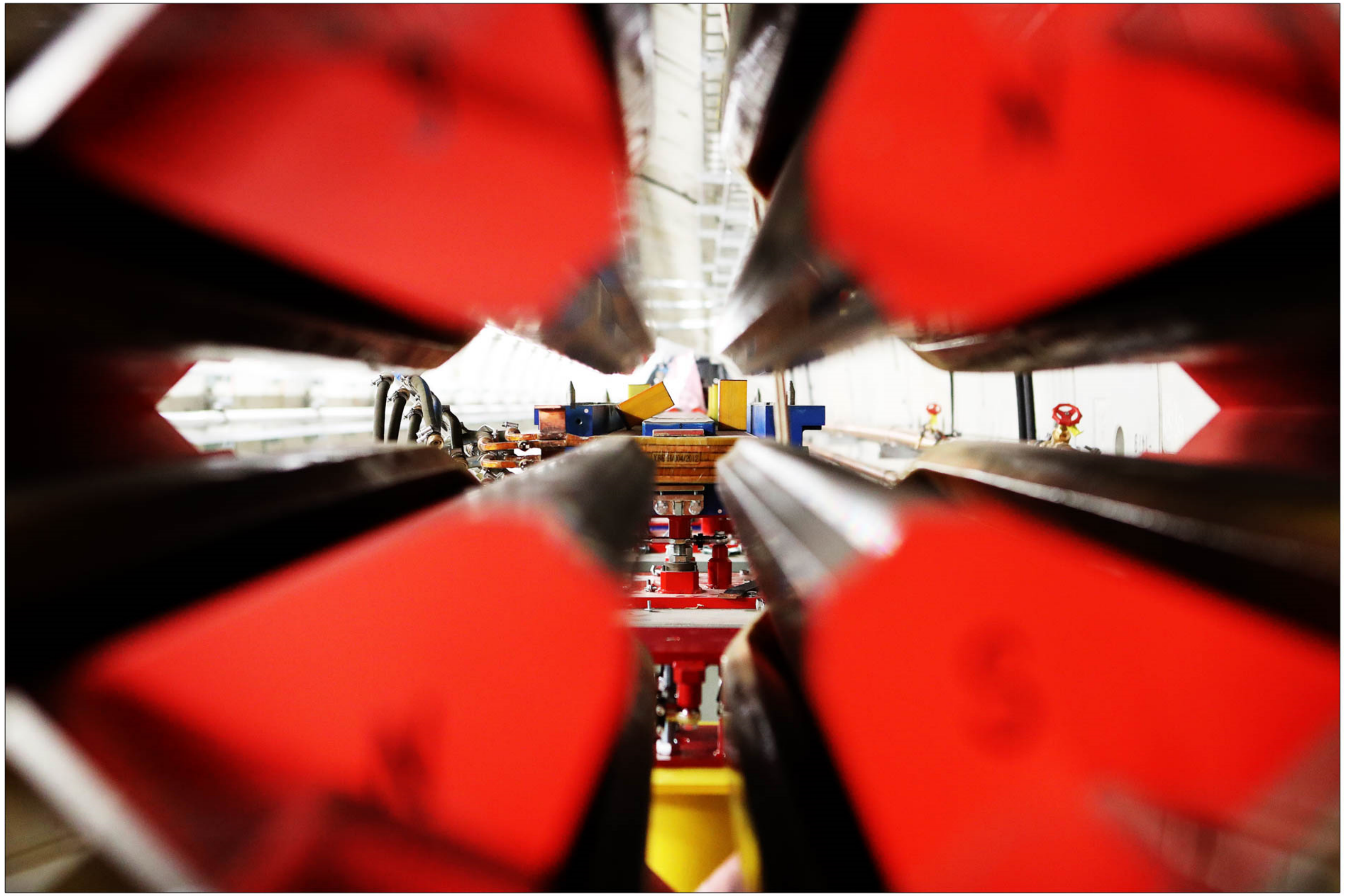
Quantity	Unit	Project Goal	Achieved	Routine
electron energy	GeV	8 – 17.5	6 – 17.5	14
bunch repetition within pulse	MHz	Up to 4.5	Up to 4.5	1.13 - 4.5, plus subharmonics
bunch charge	pC	20 – 1000	100 – 500	250
max. beam power	kW	500 kW	80 kW	40 kW
undulators in operation (lasing)		SASE1-3	SASE1-3	SASE1-3
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!