Thomas Schietinger (on behalf of the SwissFEL team) :: Paul Scherrer Institut

Towards full performance operation of SwissFEL

9th International Particle Accelerator Conference,
Vancouver, BC, Canada, 28 April – 4 May 2018

Contents

- SwissFEL overview
- The big picture:
  machine evolution at a glance
- First pilot experiments
- Smaller pictures:
  status and plans for key systems
- Beam dynamics progress
- FEL setup and characterization
- Schedule Aramis (hard X-rays)
- Outlook Athos (soft X-rays)

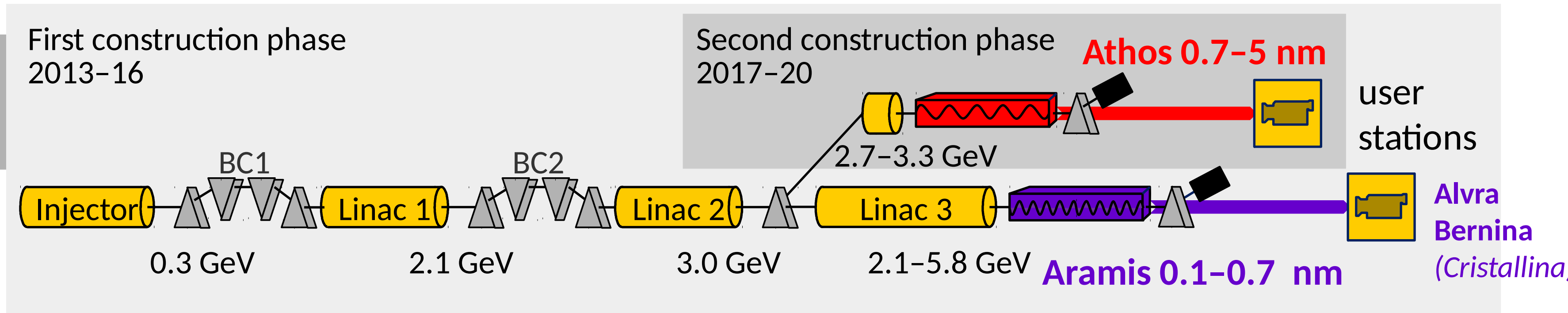
SwissFEL Overview

Athos:

Soft X-ray FEL, λ=0.65–5.0 nm

Variable polarization, Apple-X undulators

First users 2021



Aramis:

Hard X-ray FEL, λ=0.1–0.7 nm

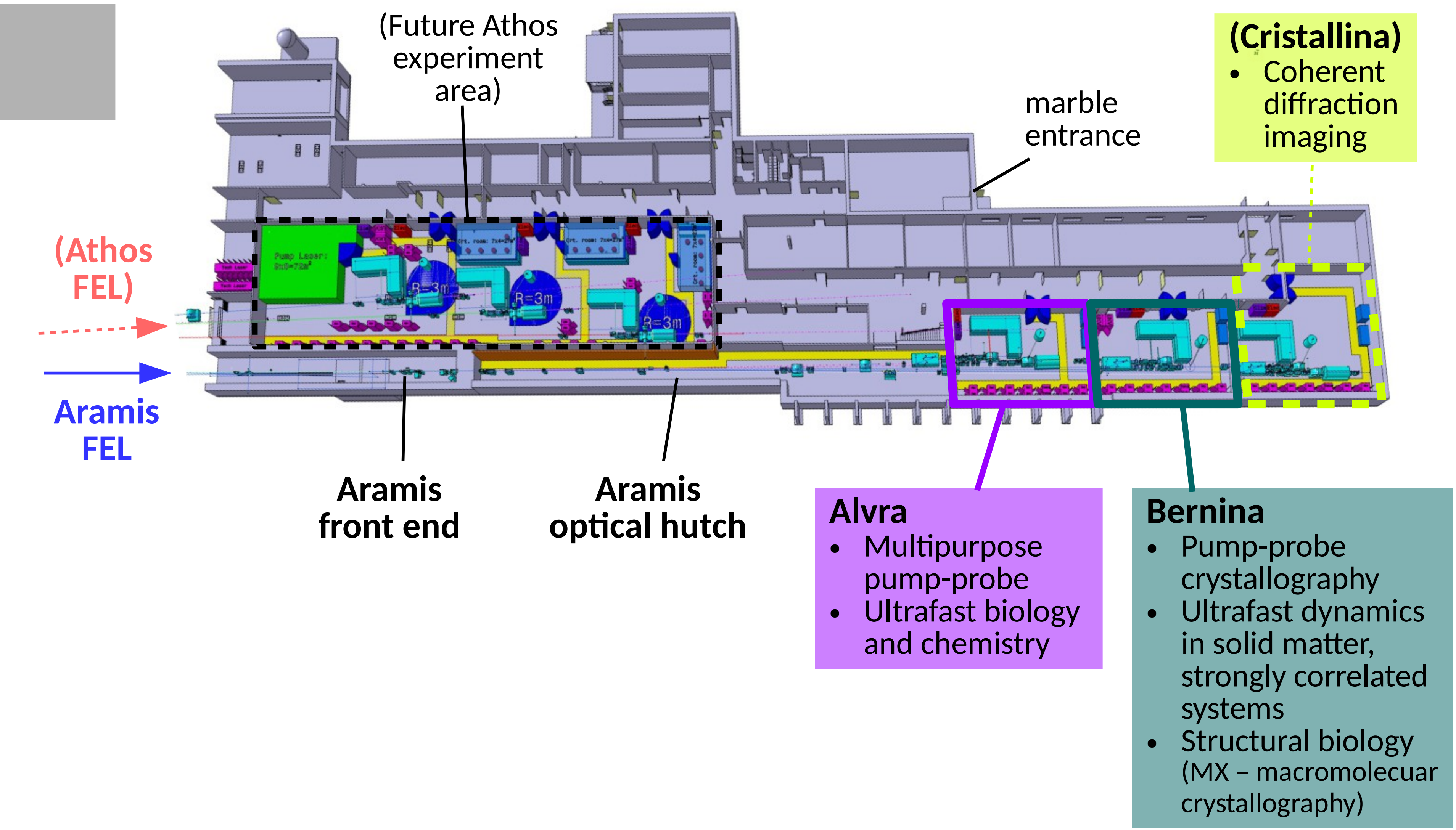
Linear polarization, variable gap, in-vacuum undulators

First users 2018

Main parameters:

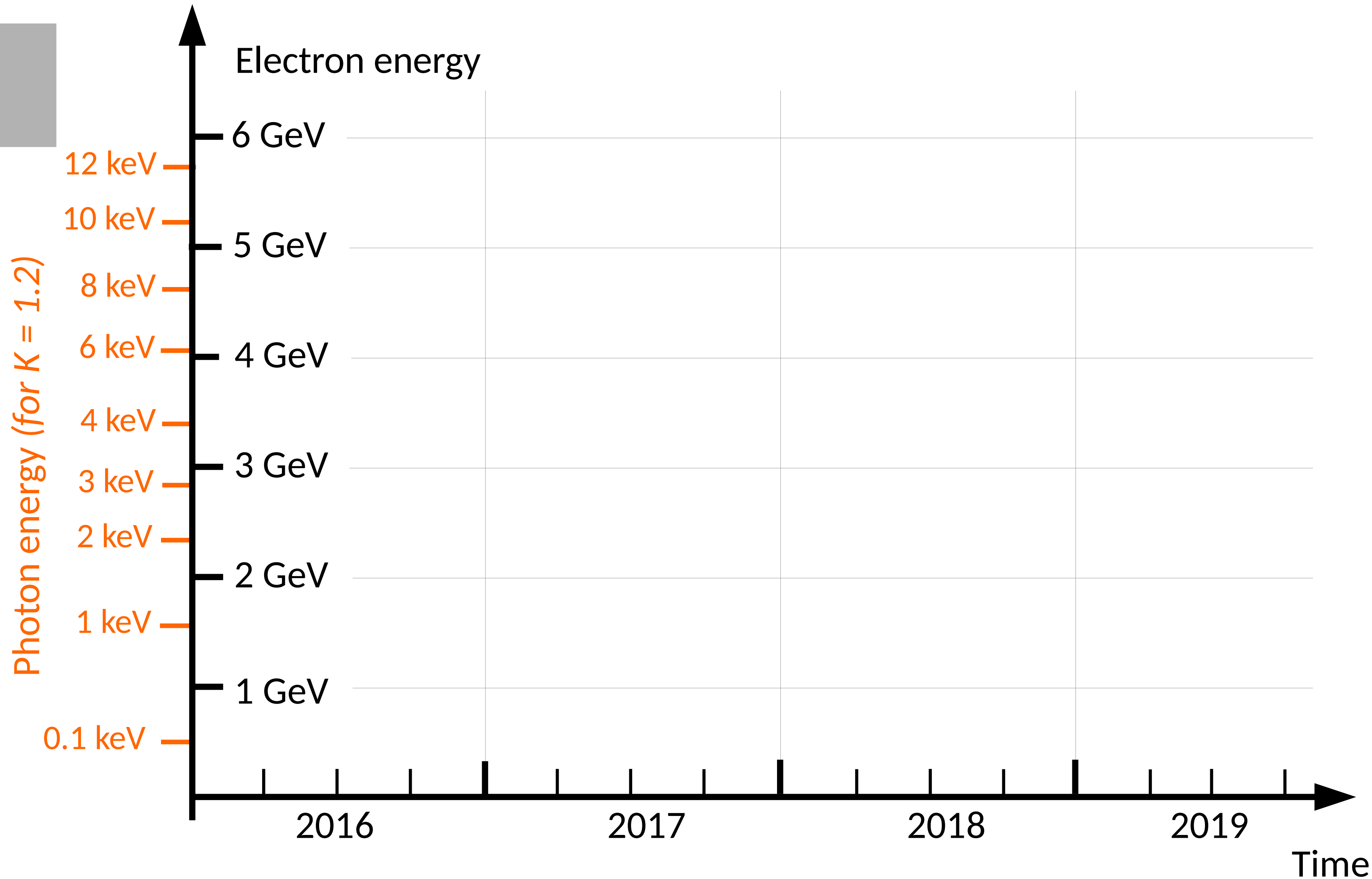
Photon wavelength	0.1–5 nm
Photon energy	0.2–12 keV
Pulse duration	1–20 fs
Electron energy	5.8 GeV
Electron bunch charge	10–200 pC
Repetition rate	100 Hz

SwissFEL experimental areas

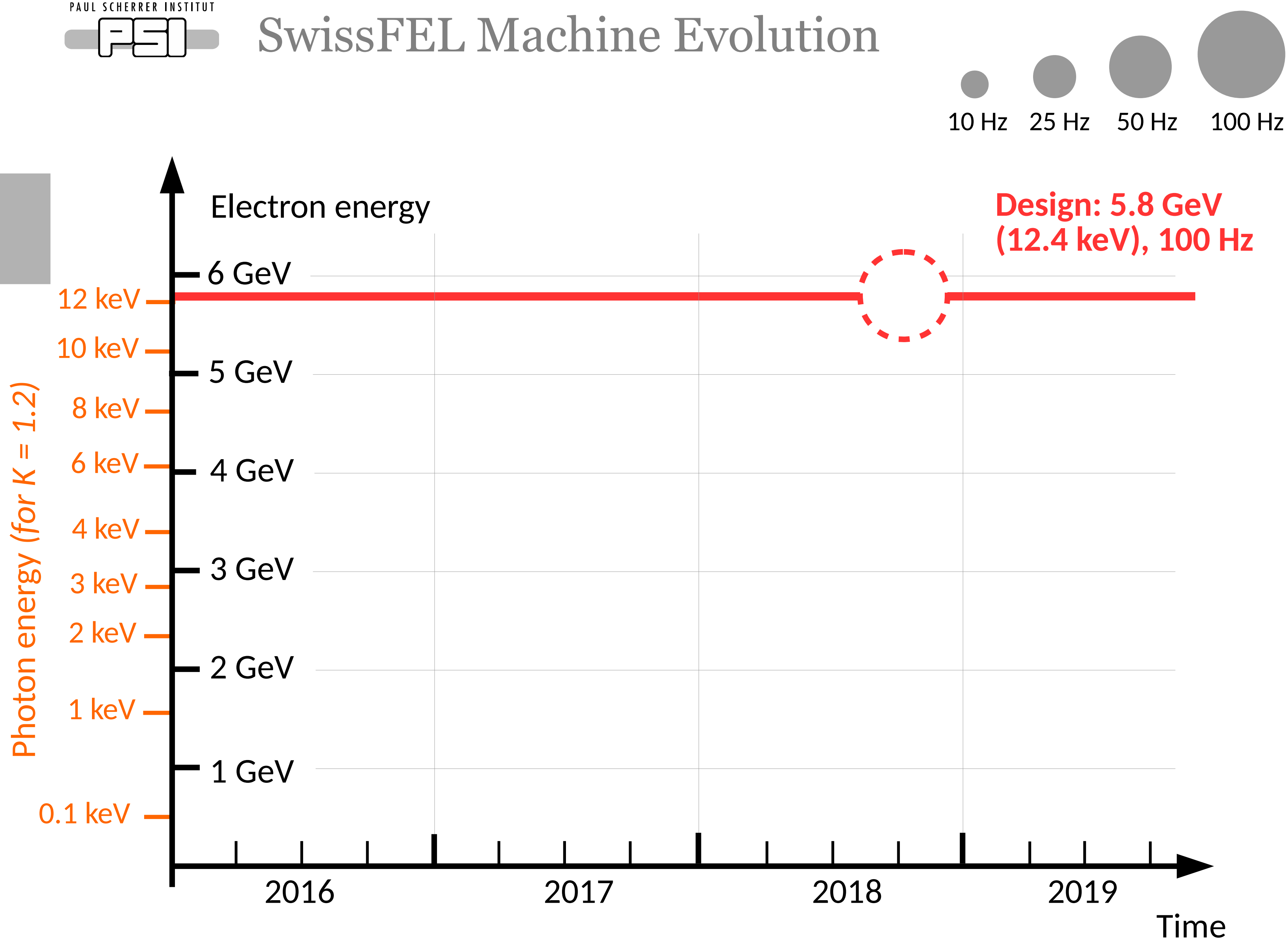


The big picture…

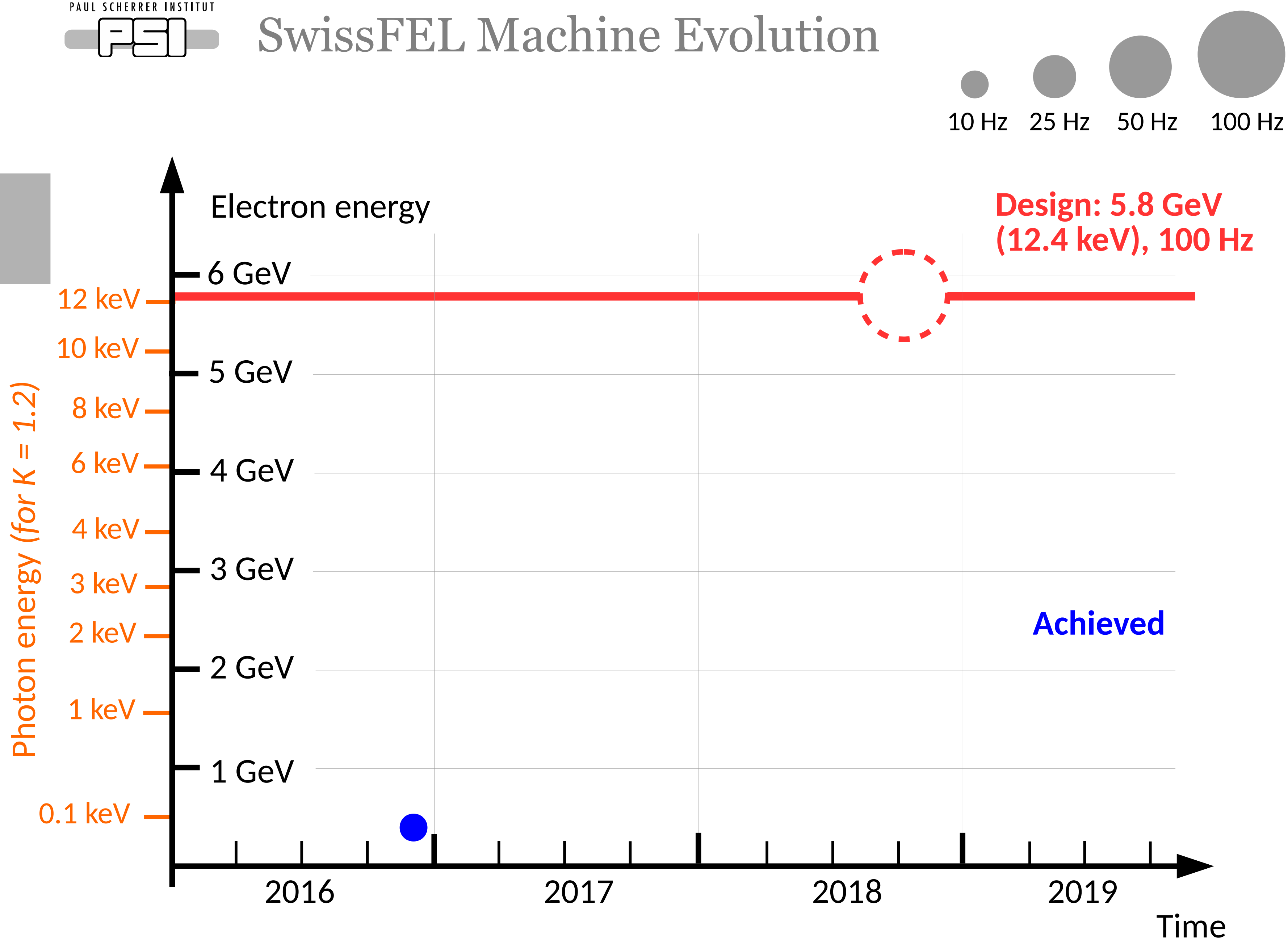
SwissFEL Machine Evolution



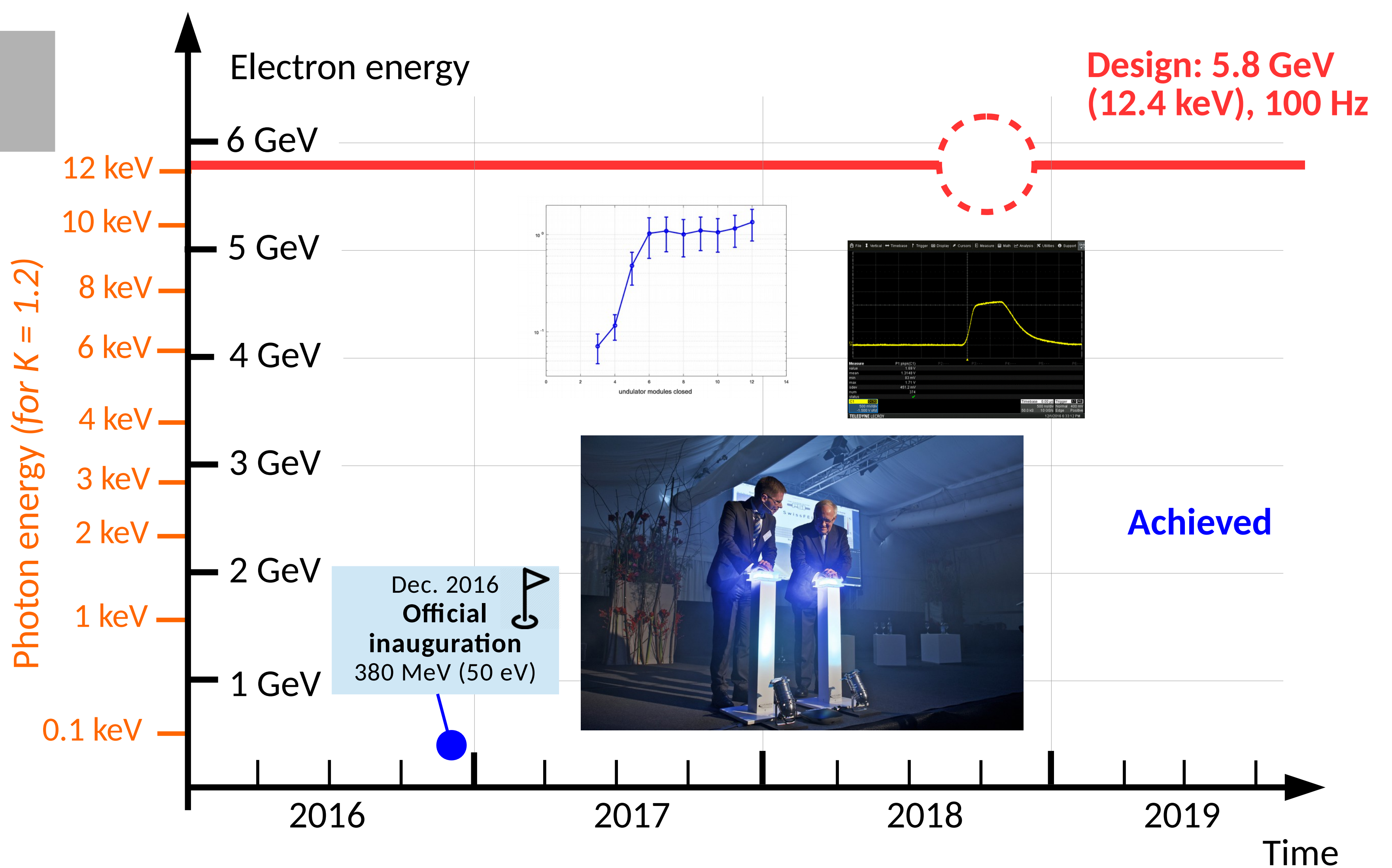
SwissFEL Machine Evolution



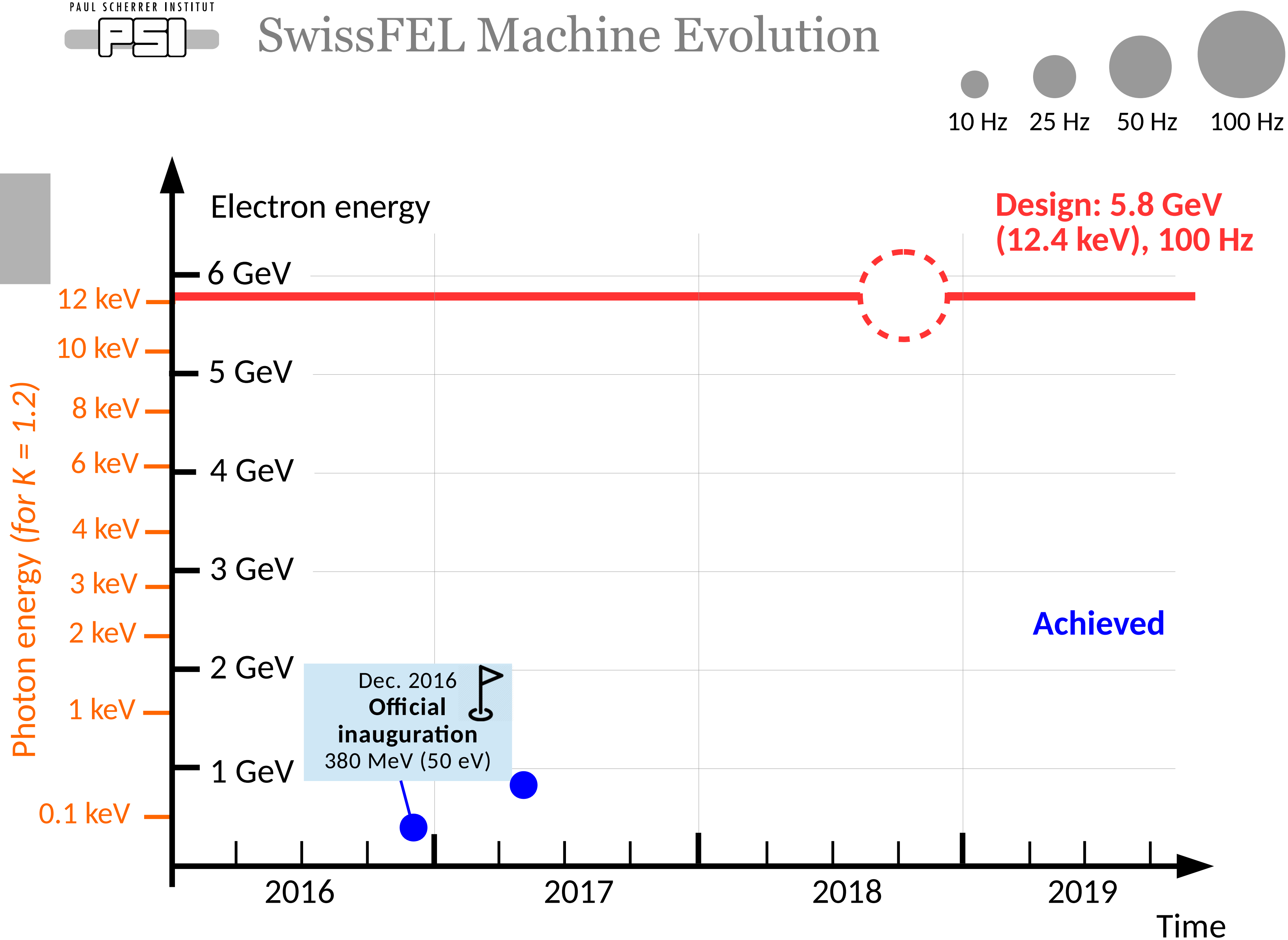
SwissFEL Machine Evolution



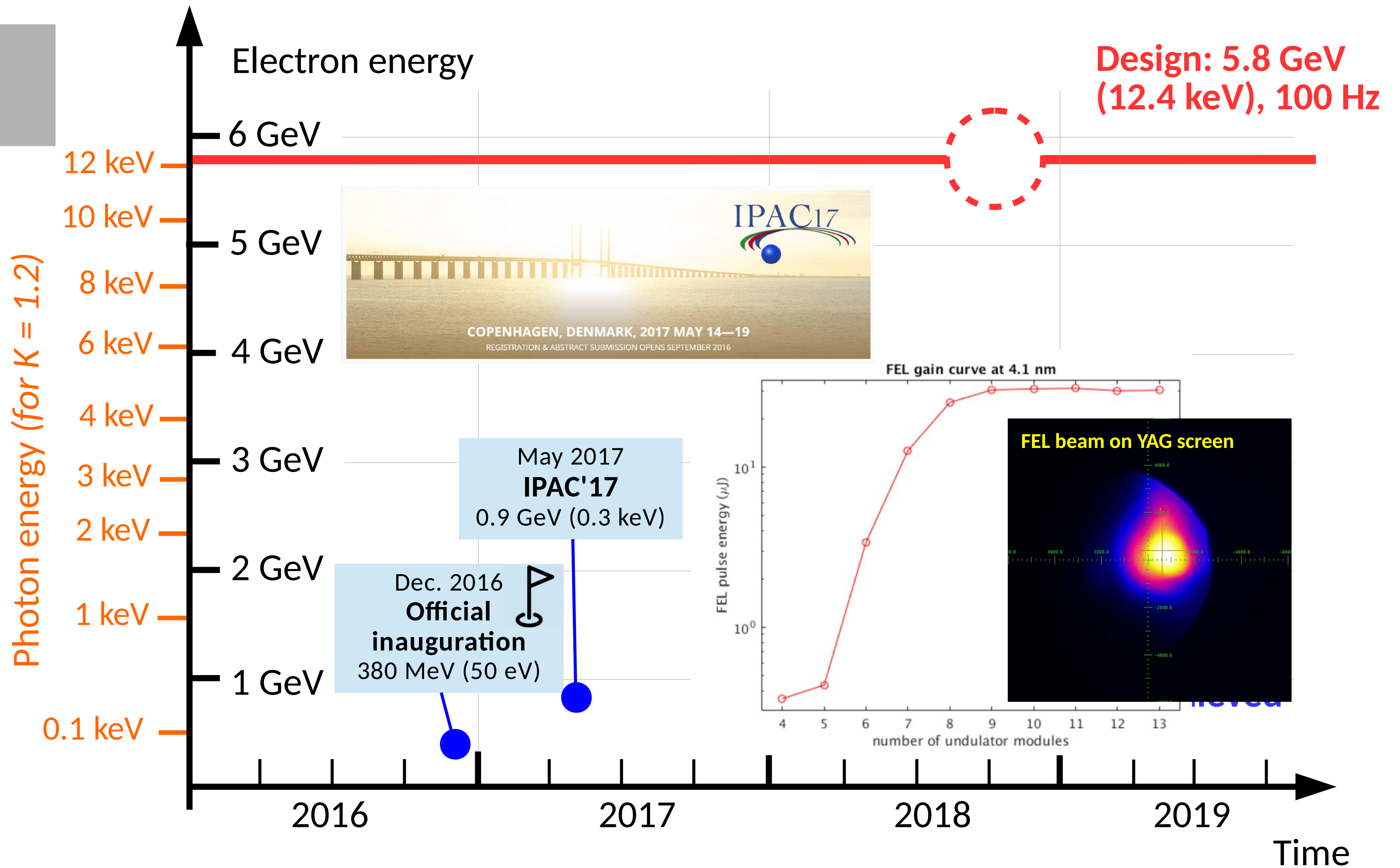
SwissFEL Machine Evolution



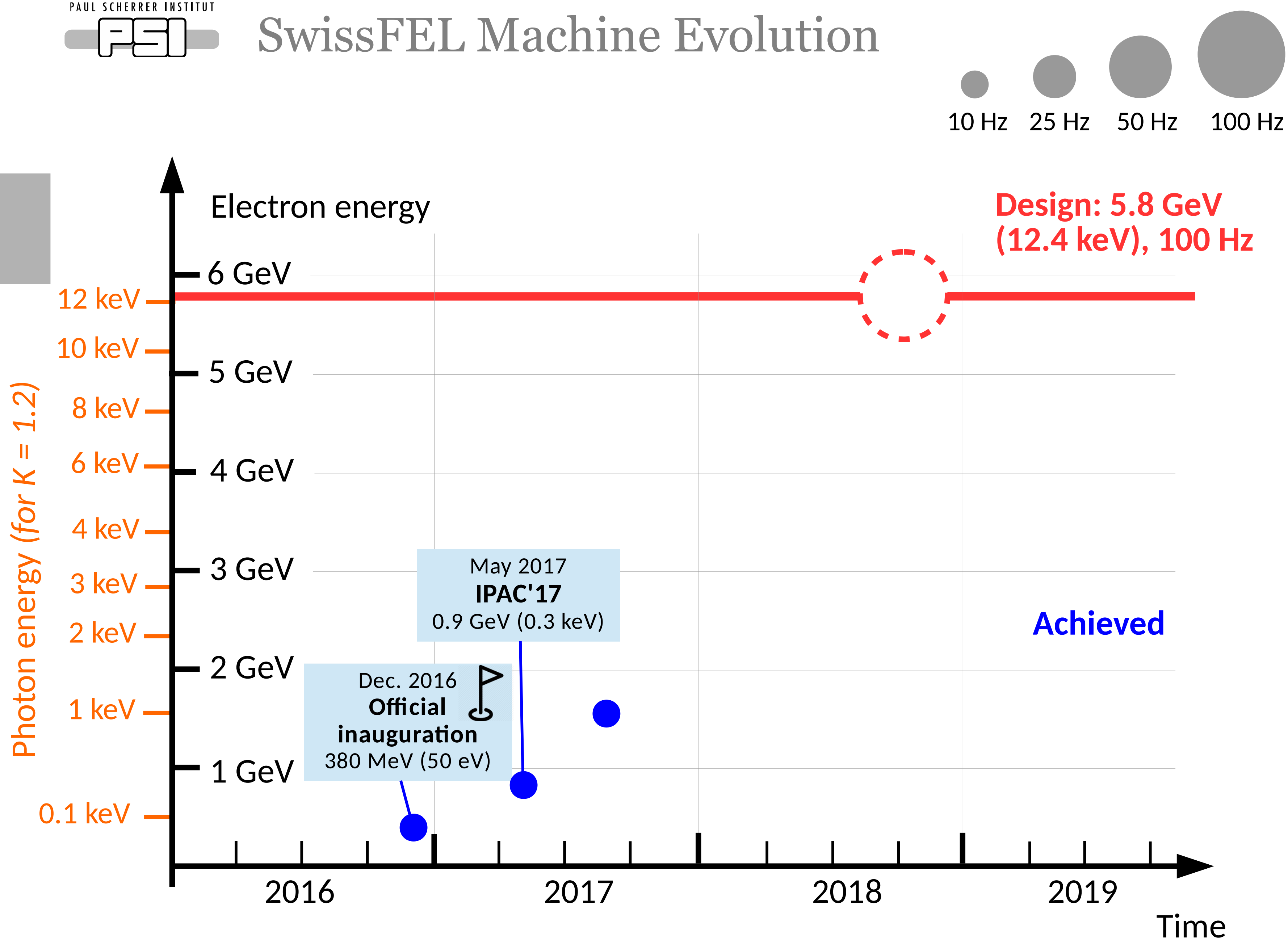
SwissFEL Machine Evolution



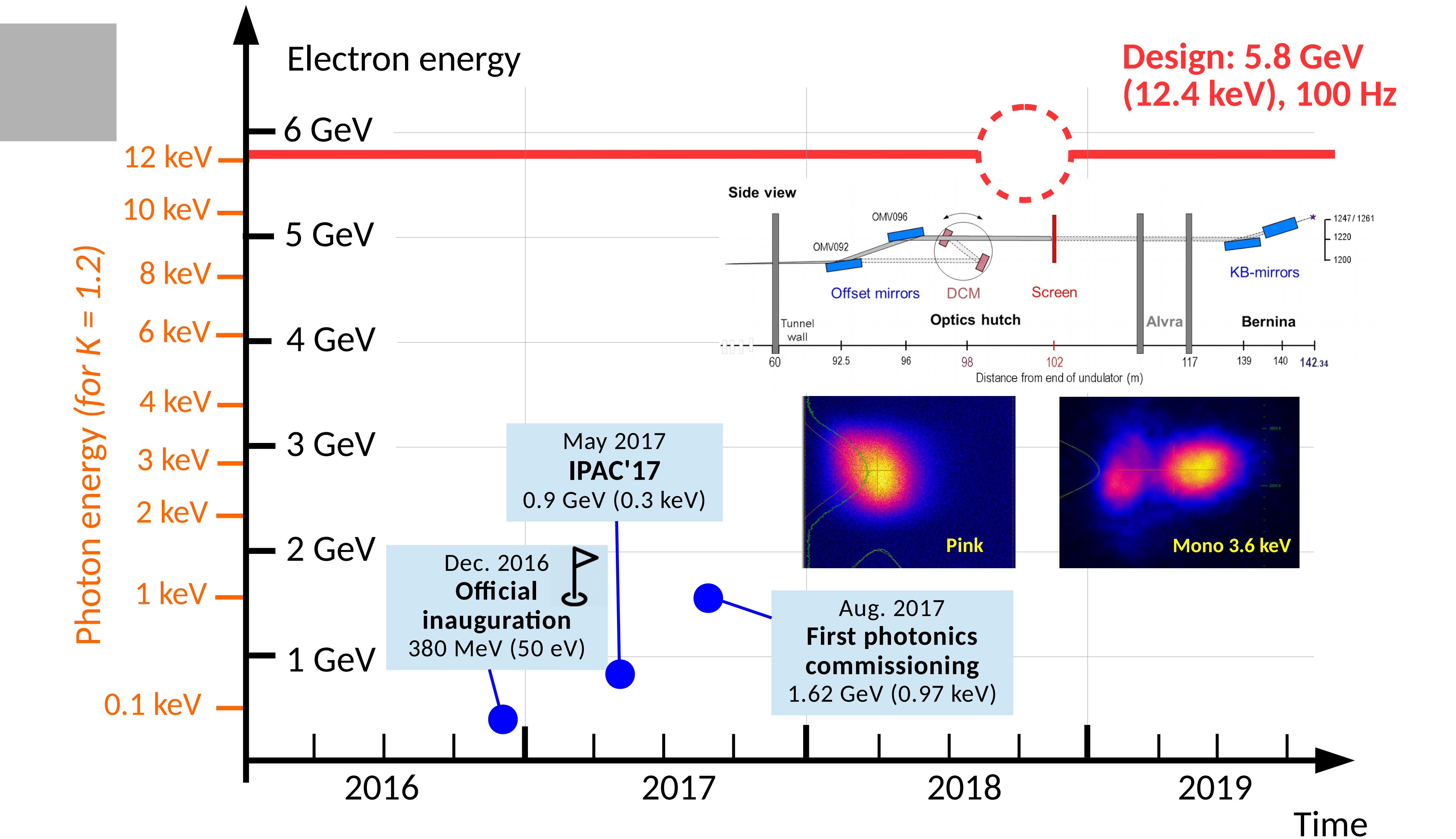
SwissFEL Machine Evolution



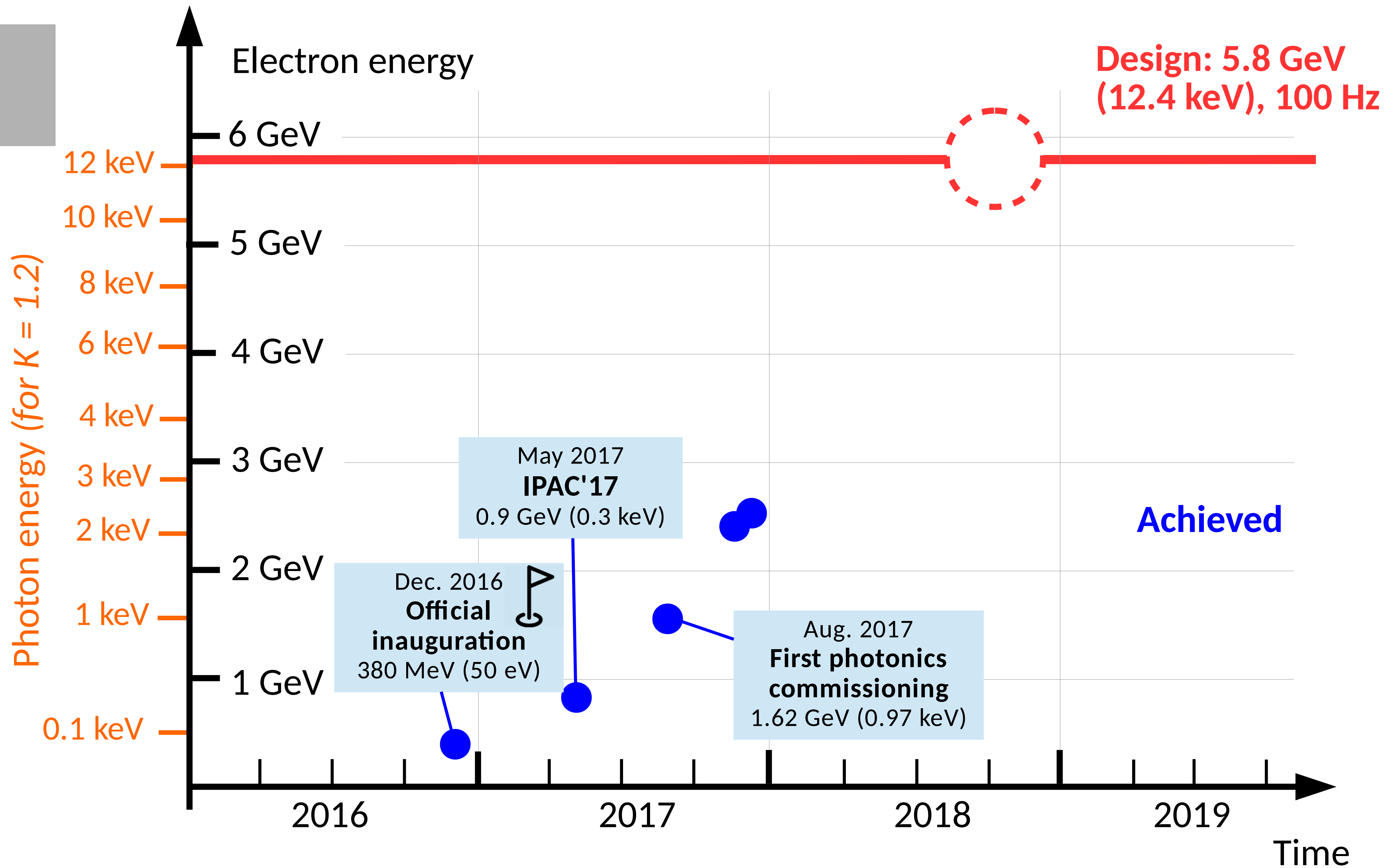
SwissFEL Machine Evolution



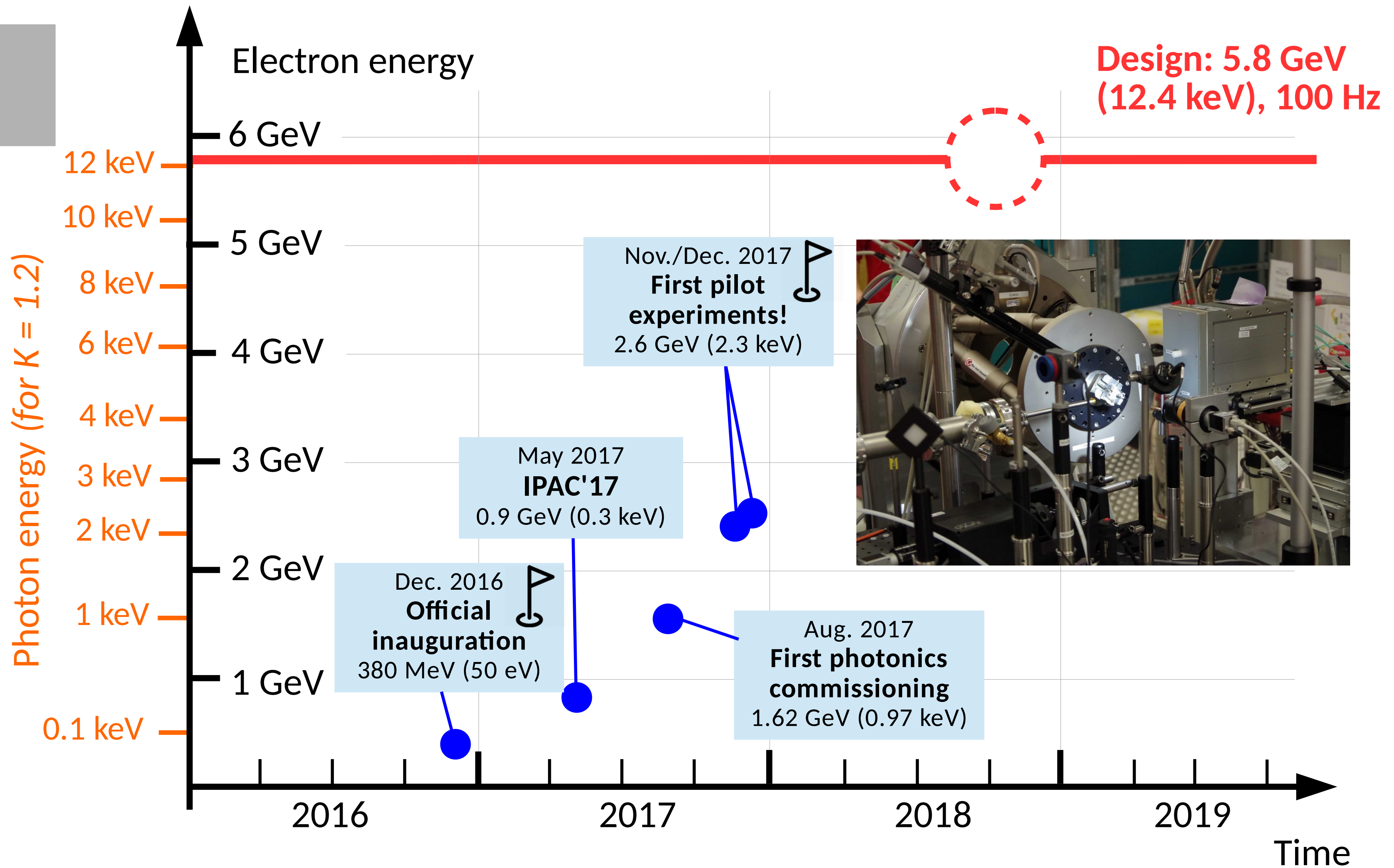
SwissFEL Machine Evolution



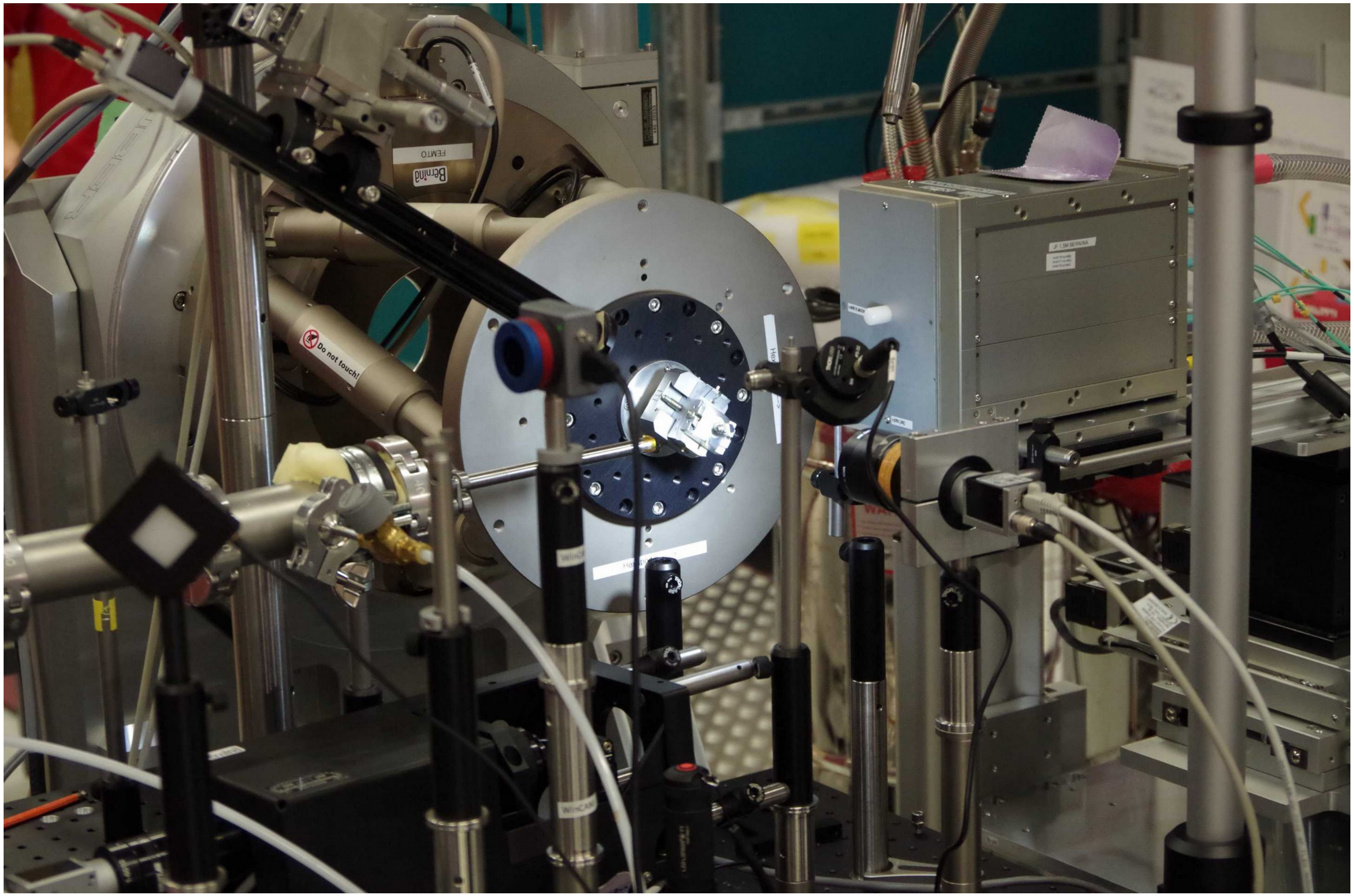
SwissFEL Machine Evolution



SwissFEL Machine Evolution



First SwissFEL sample (Bernina endstation)

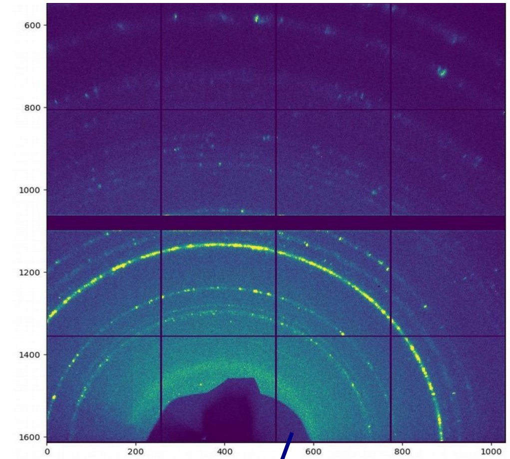


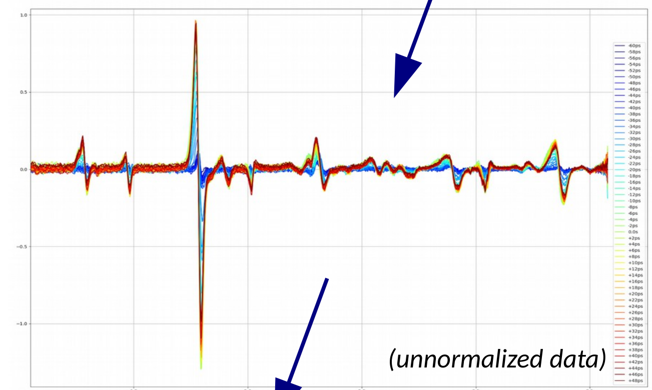
First pilot experiment at SwissFEL!

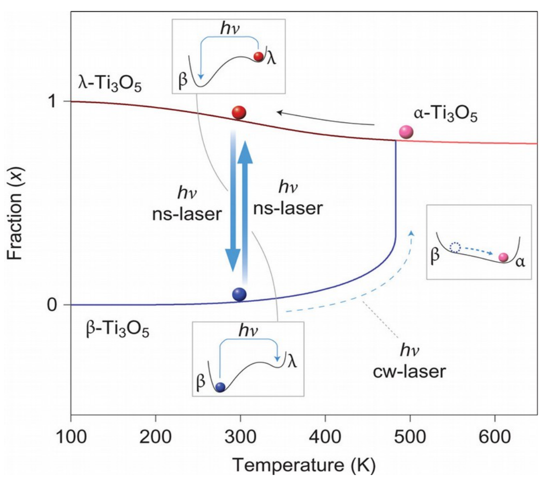
Experiment time: 27 Nov. – 4 Dec. 2017
Experimental station Bernina (ESB)
Collaboration: Univ. Rennes, ESRF, PSI
M. Cammarata, H. Lemke, G. Ingold et al.

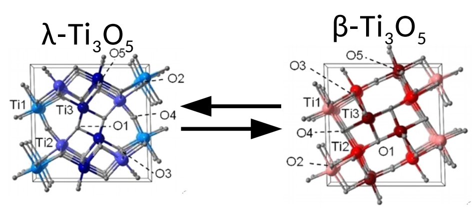
PSI press release:
www.psi.ch/media/first-experiment-at-swissfel-carried-out-successfully

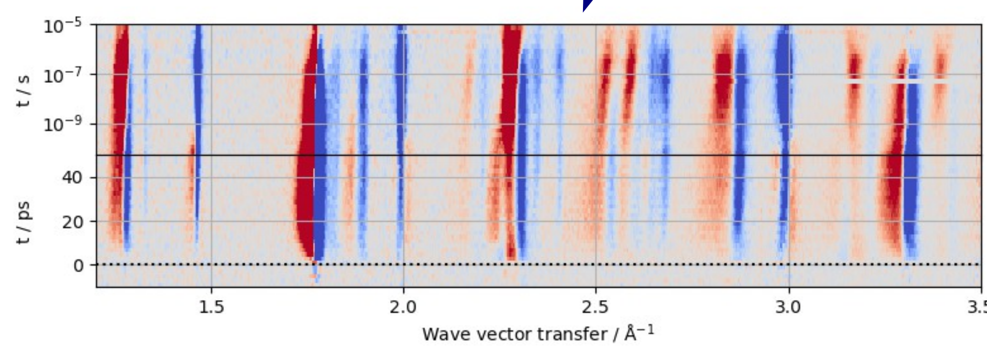
- Pump-probe investigation of the transition between metallic (λ) and semi-conducting (β) phase of titanium pentoxide (Ti_3O_5)
- Diffraction on nanocrystals, Jungfrau detector
- Pump: 800 nm, 42 mJ/cm^2 laser
- Probe: FEL 3rd harmonic 6.6 keV (fundamental 2.2 keV, 220 µJ)







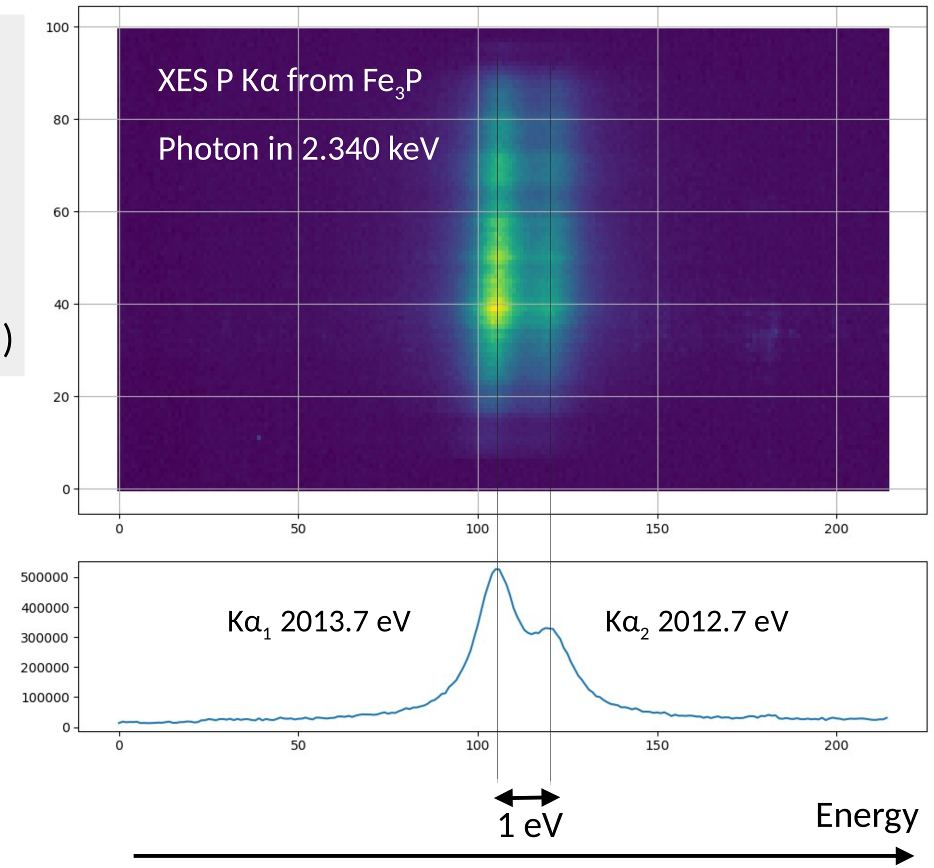


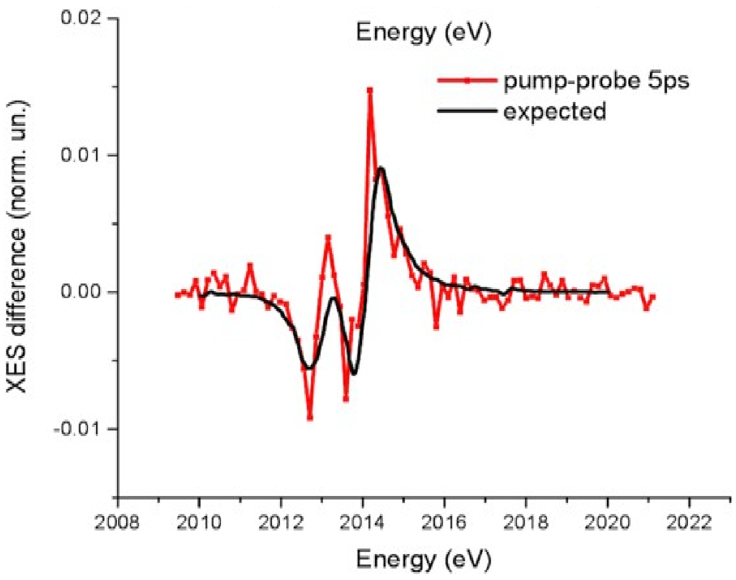


First X-ray emission spectra at SwissFEL

Experiment time: 11–17 Dec. 2017
Experimental station Alvra (ESA)
Collaboration: Inst Nucl. Phys. PAN Krakow, Univ. Bremen, PSI
J. Szlachetko, J. Czapla-Masztafiak, M. Kwiatek, M. Vogt, Ch. Milne. et al.

- UV photo-induced charge transfer in Cu/P based OLED system
- Time-resolved X-ray emission spectroscopy (XES)
- Pump: 355 nm, ~100 mJ/cm^2 laser
- Probe: FEL fundamental 2.34 keV (250 μJ)



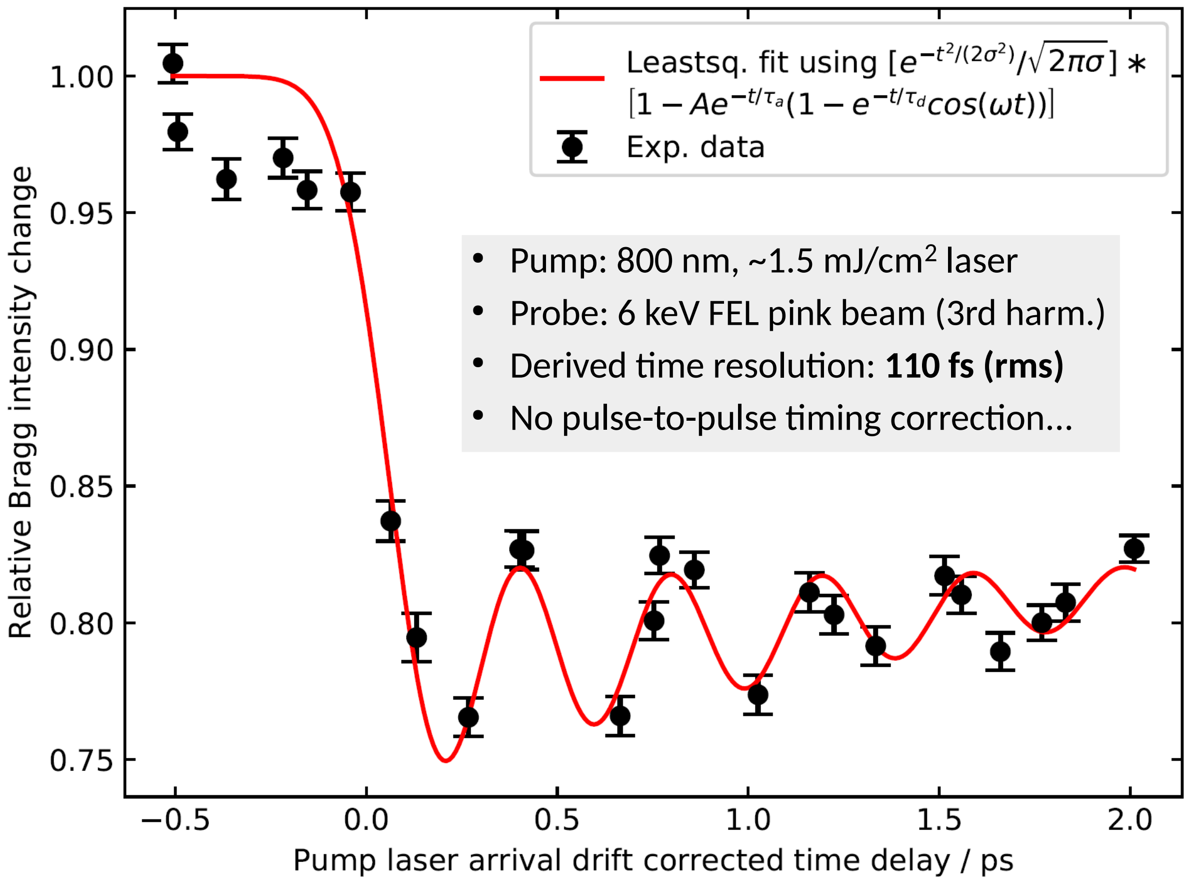


PAUL SCHERRER INSTITUT

Characterization of pump-probe timing jitter

Relative Bragg intensity as a function of pump-probe delay time, measured on Bi(111) film (modulation from optically pumped phonons, benchmark system)

Bernina, 21 March 2018

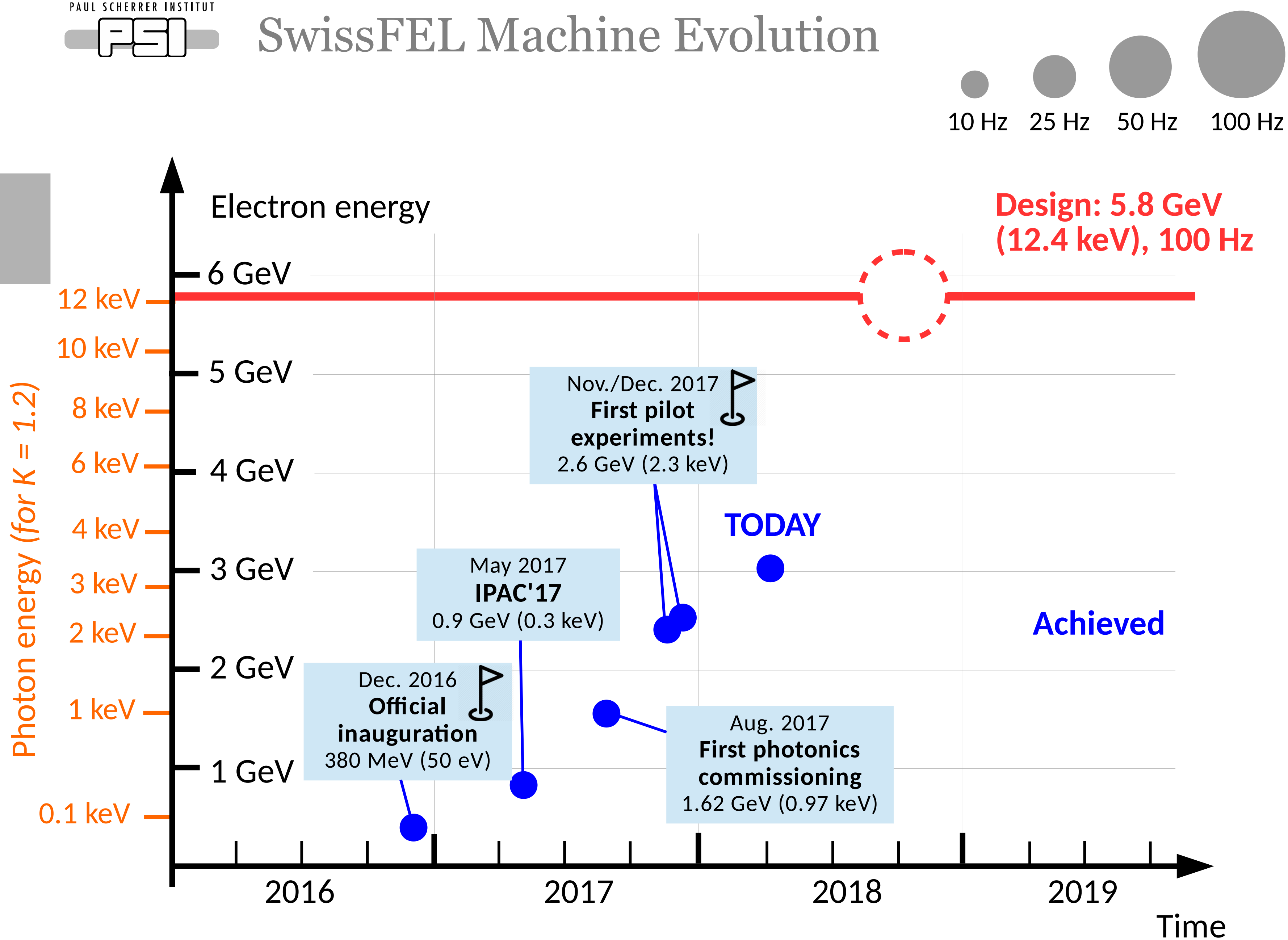


PAUL SCHERRER INSTITUT

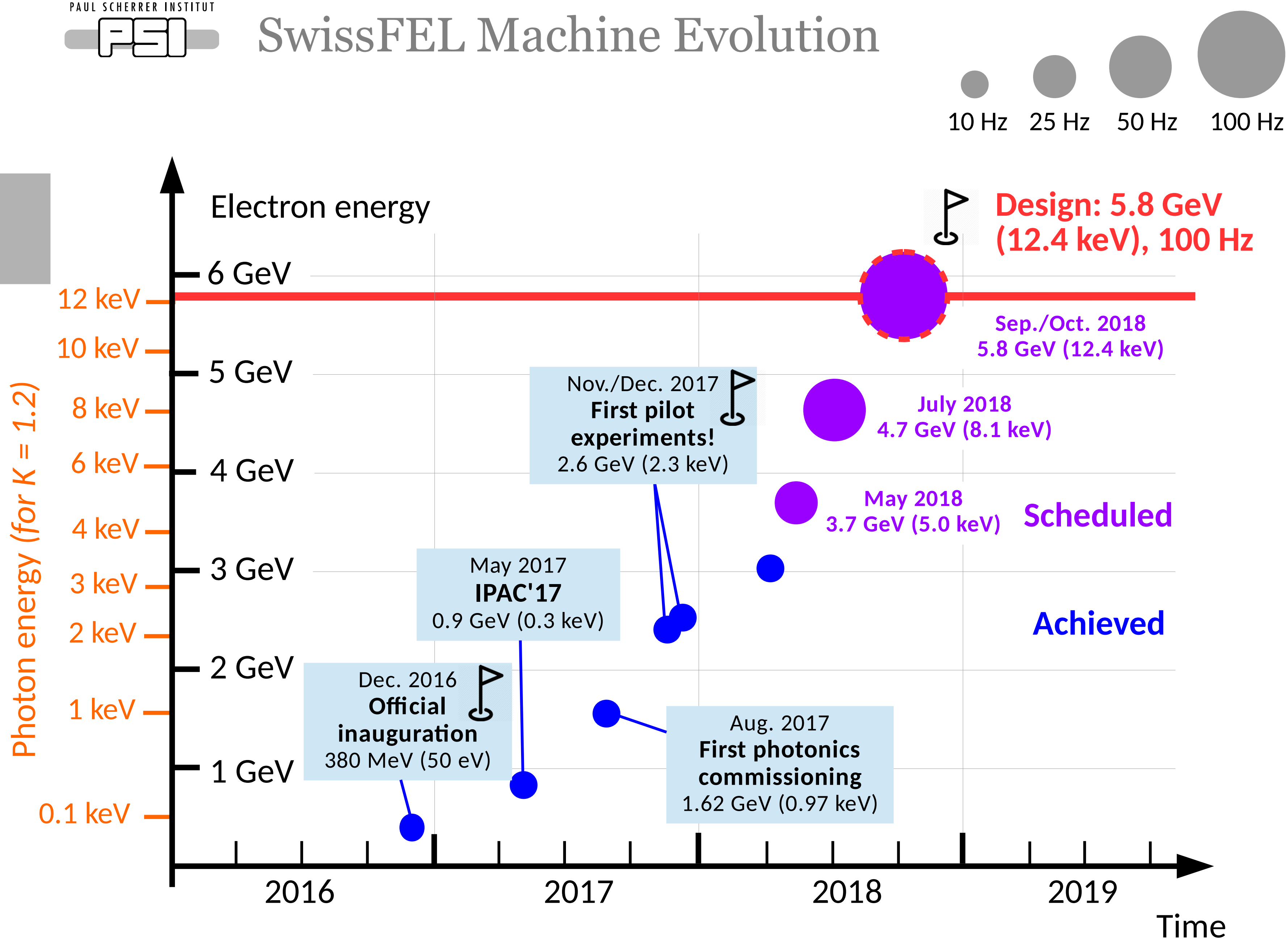
First SwissFEL lasings

Date	Purpose	Electron energy	Photon wavelength (energy)	Photon pulse energy	Comments
Dec. 2016	Inauguration	380 MeV	24 nm (50 eV)	Not measured	Backup gun laser; single-stage comp.
May 2017	IPAC'17	910 MeV	4.1 nm (300 eV)	30 μJ	Backup gun laser; single-stage comp.
Aug. 2017	1st photonics commissioning	1.62 GeV	1.28 nm (970 eV)	9.5 μJ	Backup gun laser; single-stage comp.
Nov. 2017	1st pilot experiment (Bernina)	2.45 GeV	0.55 nm (2.2 keV)	220 μJ	Main gun laser; dual-stage comp.; laser heater, tapering
Dec. 2017	2nd pilot experiment (Alvra)	2.6 GeV	0.54 nm (2.3 keV)	250 μJ	Main gun laser; dual-stage comp.; laser heater, tapering

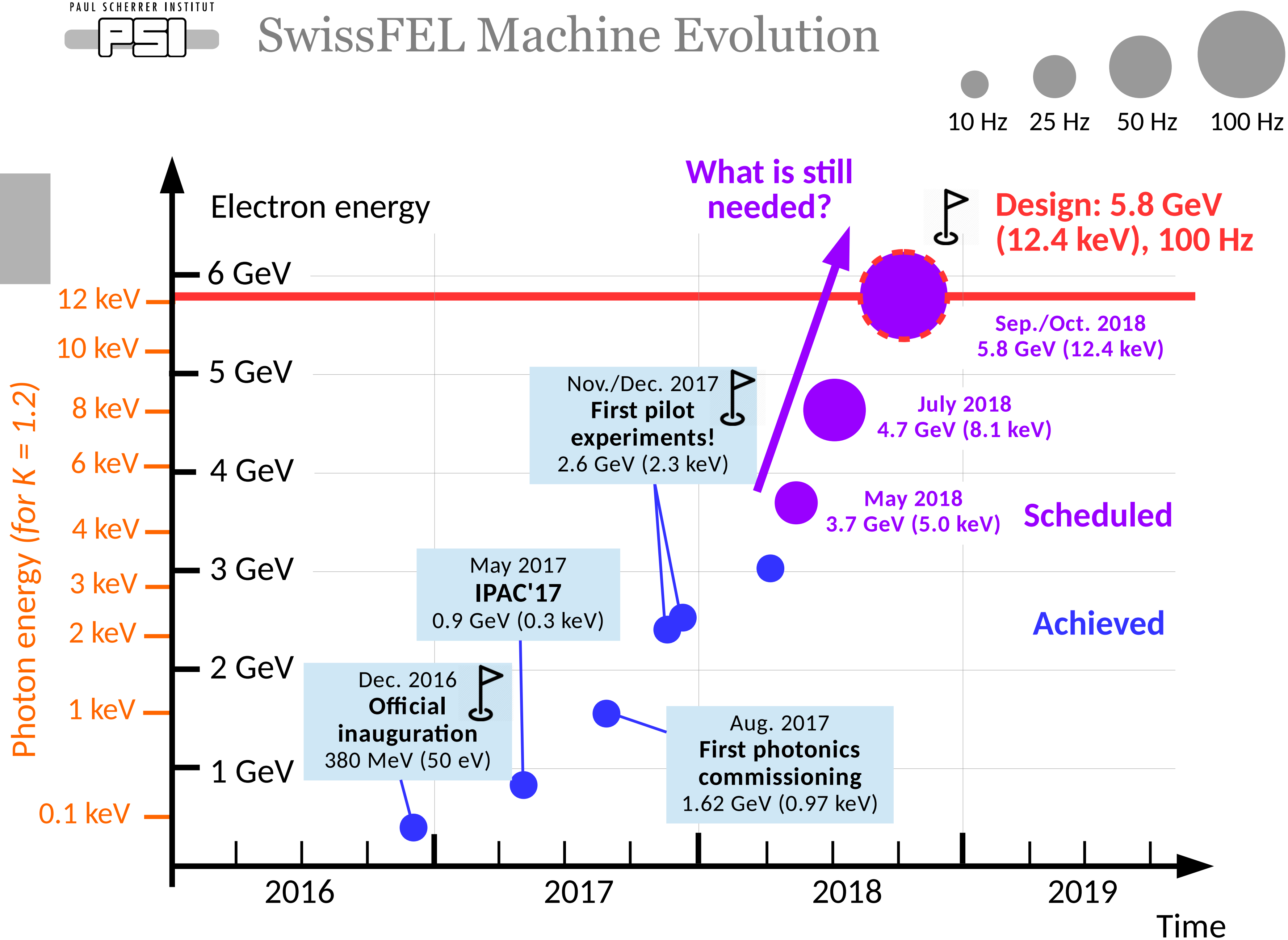
SwissFEL Machine Evolution



SwissFEL Machine Evolution



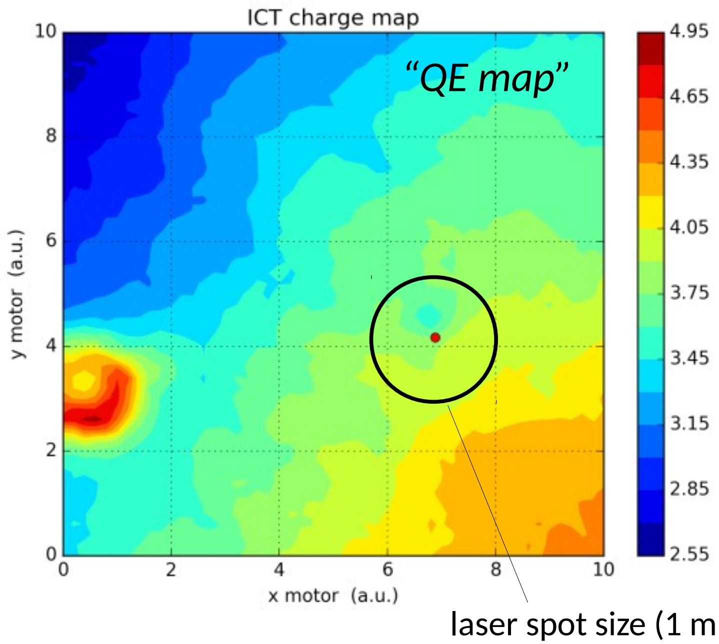
SwissFEL Machine Evolution

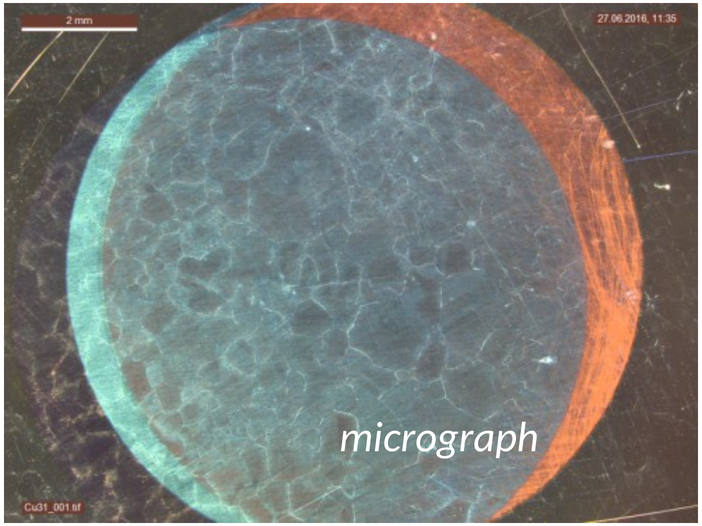


SwissFEL key systems: electron source (1)

Status

- **RF gun:**
  - Fully commissioned, 7.1 MeV nominal energy
  - Spare gun in production
- **Cathode:**
  - Cs_2Te coated copper cathode installed since July 2017.
  - Quantum efficiency stable at about 0.7% with uniform distribution around the laser spot.

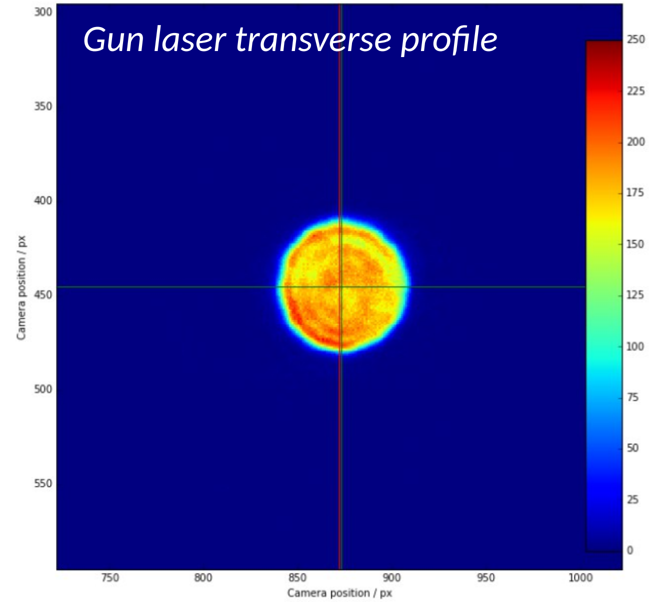


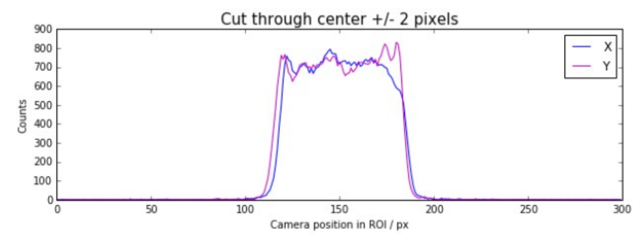


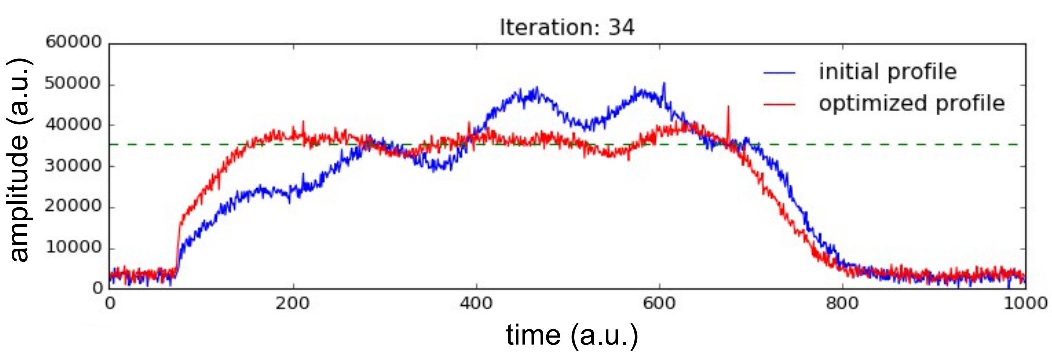
SwissFEL key systems: electron source (2)

Status

- **Gun laser system:**
  - Solid state $Yb:CaF_2$ chirped pulsed amplifier with excellent stability and uptime.
  - Variable circular aperture allows optimization of beam size on cathode (low emittance).
  - Approximate flat top profile with pulse stacking – beam based profile optimization.
  - Backup laser (Nd:YLF) with Gaussian profile available – switching is instant.
- *Standard operating procedure* for routine gun-laser check – fundamental for stability and reproducibility of the facility!







Gun laser longitudinal profile optimization (with RF deflected electrons)

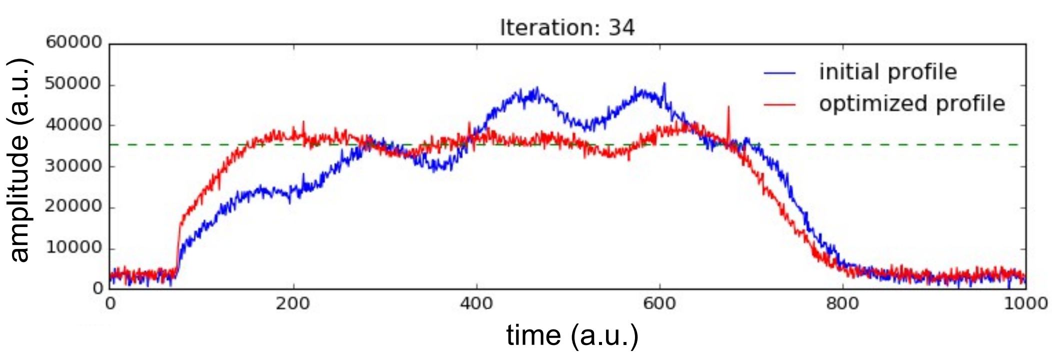
SwissFEL key systems: electron source (2)

Status

- **Gun laser system:**
  - Solid state $Yb:CaF_2$ chirped pulsed amplifier with excellent stability and uptime.
  - Variable circular aperture allows optimization of beam size on cathode (low emittance).
  - Approximate flat top profile with pulse stacking – beam based profile optimization.
  - Backup laser (Nd:YLF) with Gaussian profile available – switching is instant.
- *Standard operating procedure* for routine gun-laser check – fundamental for stability and reproducibility of the facility!

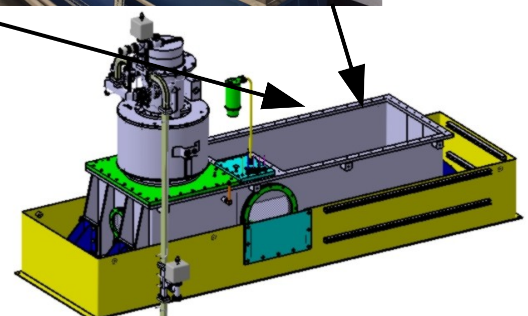
To do

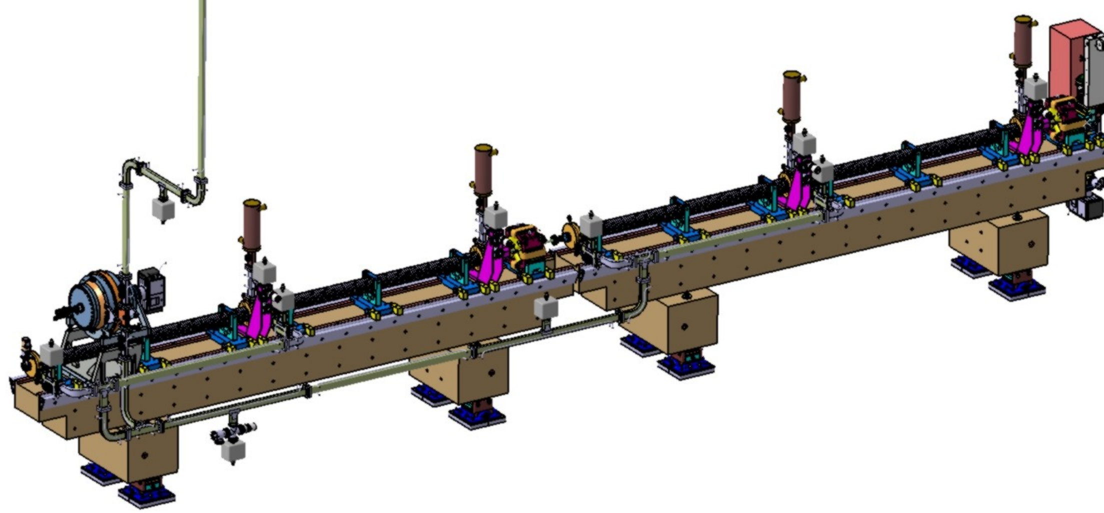
- Establish 100 Hz operation.
- Systematic comparison pulse-stacked versus stretched Gauss profile.
- UV arrival time monitor/feedback.
- Dual pulse generation setup (for soft-X-ray beamline).
- Procurement of identical backup laser system.



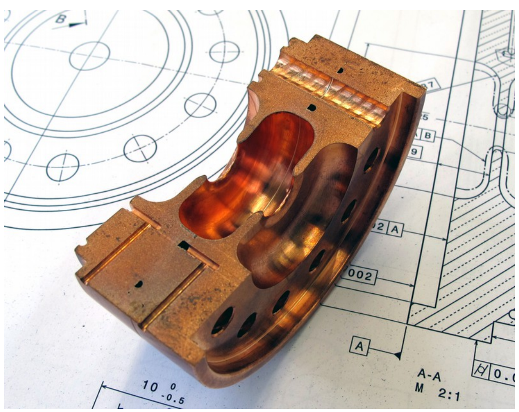
Gun laser longitudinal profile optimization (with RF deflected electrons)

SwissFEL key system: C-band linac





- 26 C-band modules (5.7 GHz) with 4 structures each
- Barrel Open Cavity (BOC) RF pulse compressors
- Modulators:
  - Ampegon (Linac-1, Linac-2)
  - Scandinova (Linac-3)
- Klystrons: Toshiba
- 50 MW for 3 µs, 370 kV/344 A
- ca. 200 – 280 MV per station (depending on conditioning status)



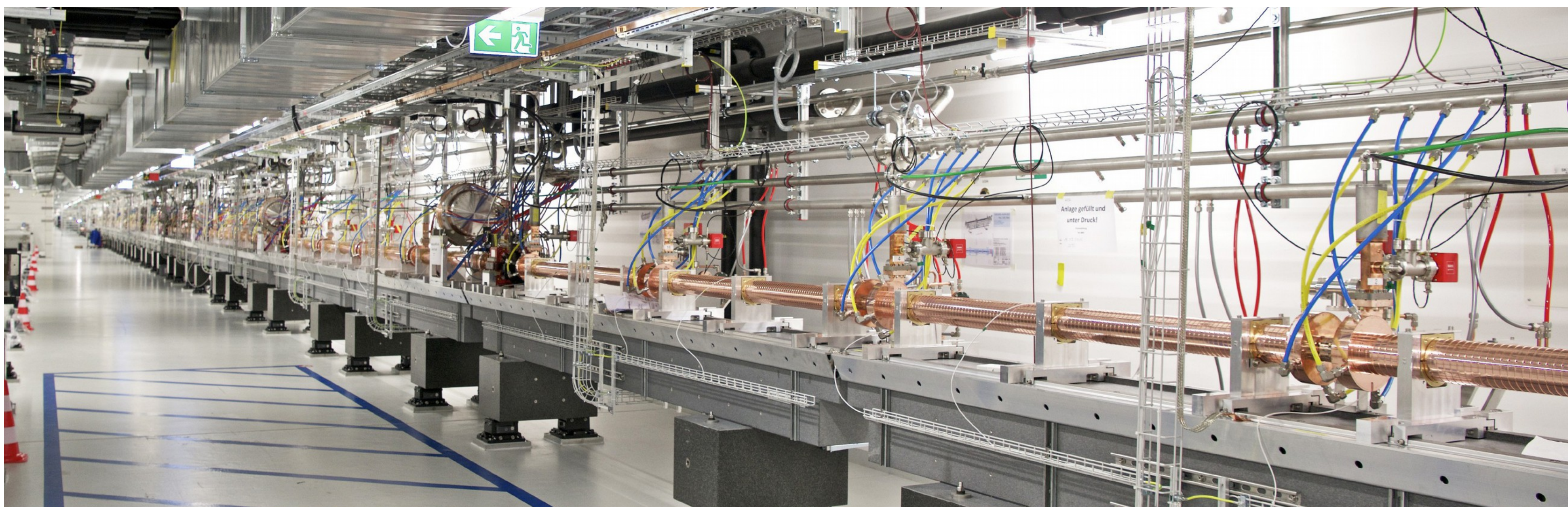
SwissFEL key system: C-band linac

Status

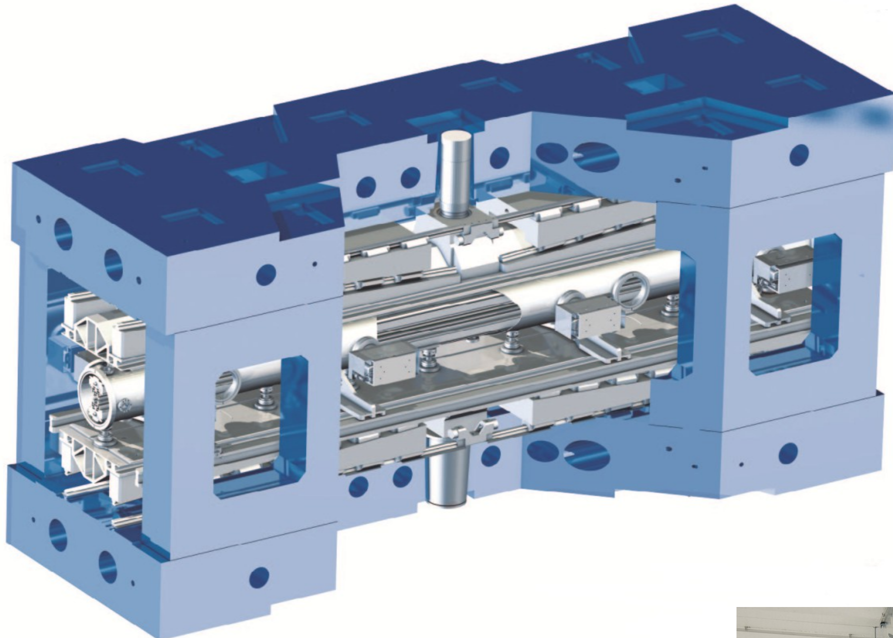
- **13 (out of 26) modules on beam**
  - all of linac-1 (9 modules, running 19° off-crest)
  - 1 module in linac-2
  - 4 modules in linac-3
- All modules currently run at 100 Hz (beam only at 10 Hz)
- Currently operating at a total energy of **3.0 GeV** (0.3 GeV from injector), with about 0.5 GeV reserve.

To do

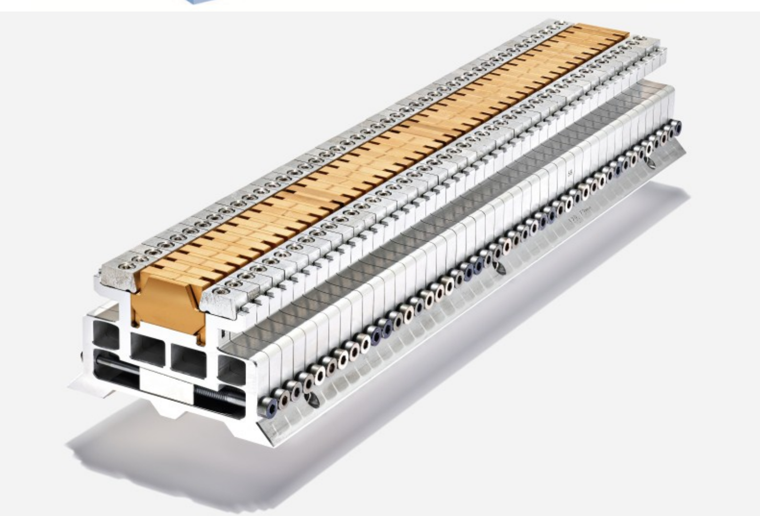
- Commissioning and conditioning of remaining modules!
- Current plan for energy increase:
  - **3.7 GeV** by mid May **(16 modules)**
  - **4.7 GeV** by mid July **(22 modules)**
  - **5.8 GeV** by mid September **(24 modules)**
  - with appropriate reserve!
- Beam tests at increasing repetition rate (25, 50, 100 Hz) – goal: 100 Hz beam operation by September 2018!

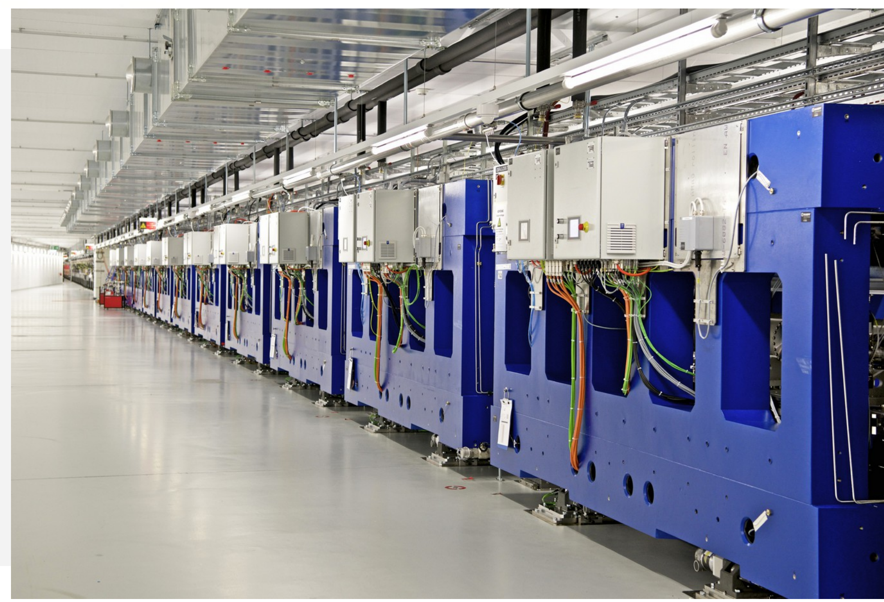


SwissFEL key system: Aramis undulator line



- In-vacuum, variable-gap undulators "U15"
- Undulator period 15 mm
- Nominal gap 4.5 mm for K = 1.2
- Array of 1060 permanent magnets (NdFeB with diffused Dy) per module
- 13 modules of 4 m length
  - Total length 65 m
  - Active length 52 m





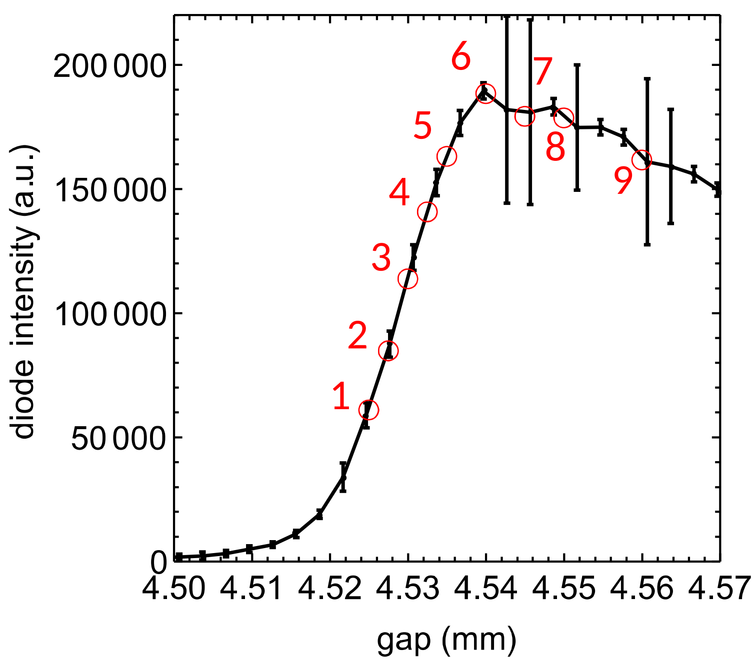
SwissFEL key system: Aramis undulator line

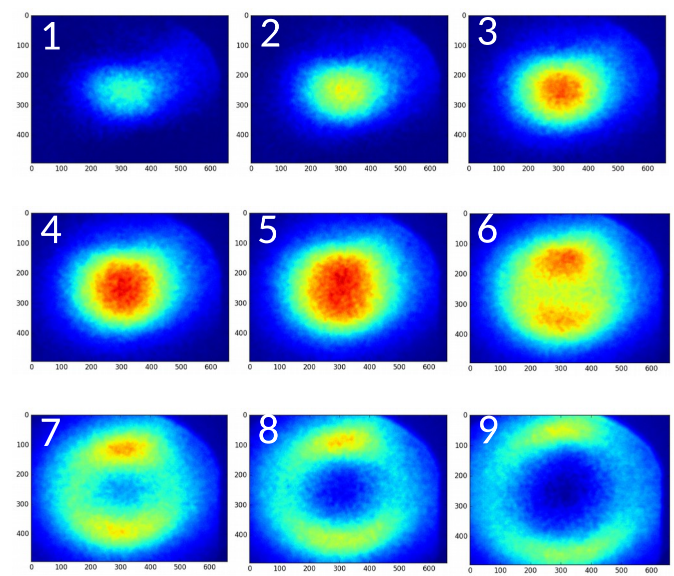
Status

- Basic commissioning and alignment of undulator line done
  - corrector-based electron-beam based alignment (BBA) done
  - alignment of undulators to BBA orbit with alignment quads
- Photon based procedure for undulator fine tuning implemented and tested
  - Using spontaneous radiation from a single undulator
  - Monochromator, photodiode/MCP for photon detection
  - Optimization of K values, undulator height and pitch

To do

- Systematic comparison of electron- and photon-based measurements
  - Some variations in contributions from modules not yet understood.
  - Some photon beam properties not yet understood (spatial chirp).
- Completion of photon-based fine tuning.
- Establishment of final BBA procedure

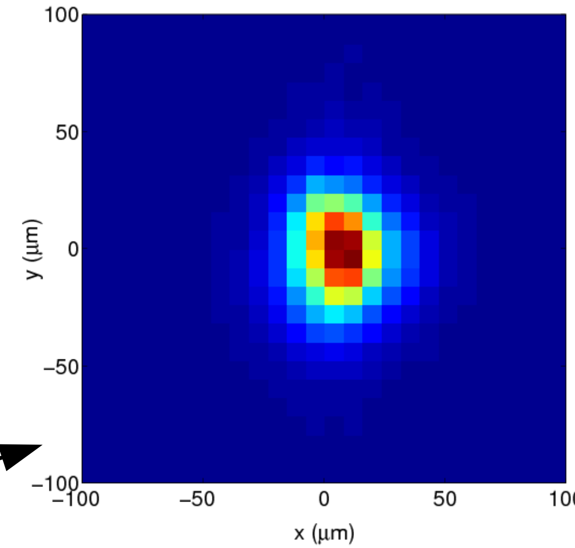




SwissFEL key systems: e-beam diagnostics

Status

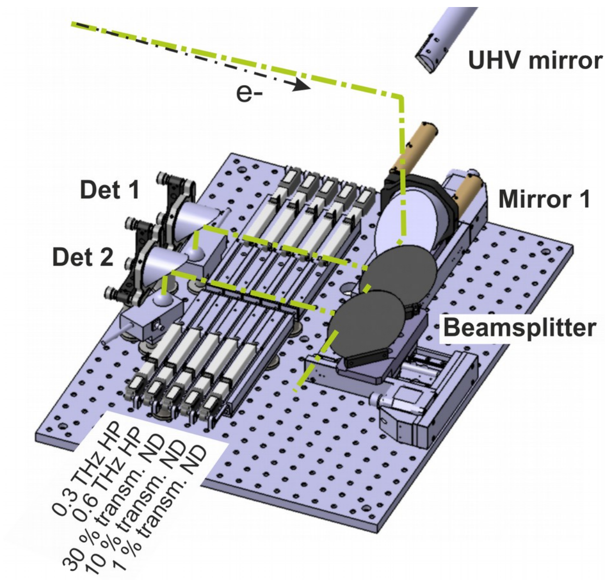
- For photon beam delivery:
  - **Resonator cavity beam-position monitors** (cBPMs) drive (slow) **orbit feedback** everywhere and **energy feedback** at three locations (BC1, BC2, energy collimator).
  - **Bunch compression monitor** based on THz detection drives **partial compression feedback** (BC1 only so far) – *next slide*
- For beam setup:
  - Use scintillating **YAG screens** (emittance)
  - with **RF deflector** for longitudinal measurements (bunch length, slice emittance)
- Initial commissioning of **bunch arrival time monitor (BAM)** – *next slide*
- Initial commissioning of **wire scanners**
- **Charge and loss monitors** fully commissioned

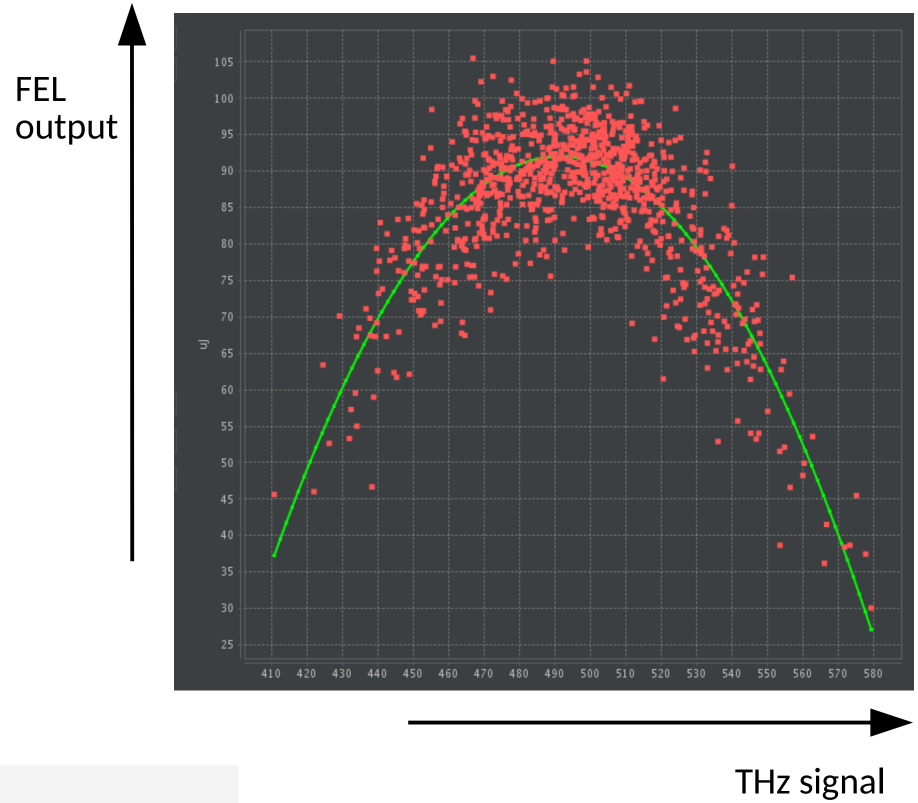


To do

- Commissioning compression monitor at BC2 (coherent diffraction radiation, later IR spectrometer)
- Commissioning bunch arrival time monitor and integration into global feedback.
- Wire scanner commissioning
- 100 Hz operation
- Advanced commissioning of all systems…

e-beam diagnostics highlights (1)





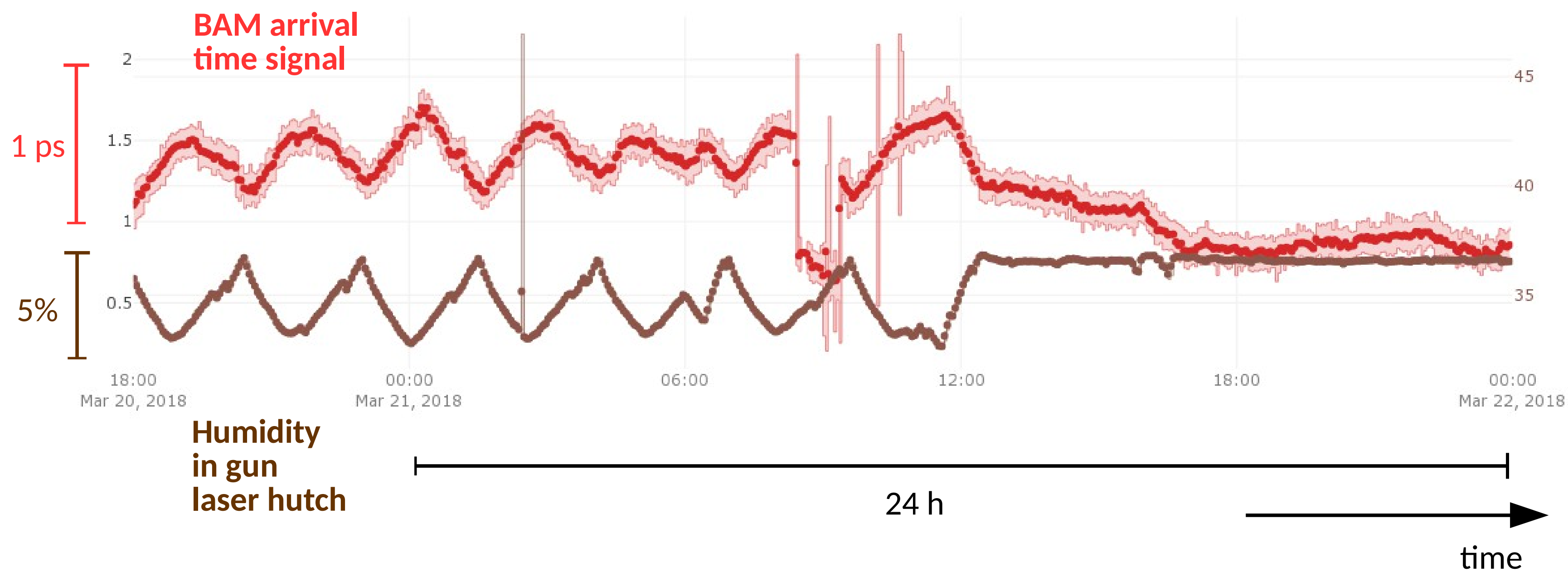
Bunch compression monitor

- Measure THz radiation from last compression dipole edge with Schottky diodes.
- Set of filters for spectral range selection.
- Pulse-to-pulse data available → feedback on FEL signal!

e-beam diagnostics highlights (2)

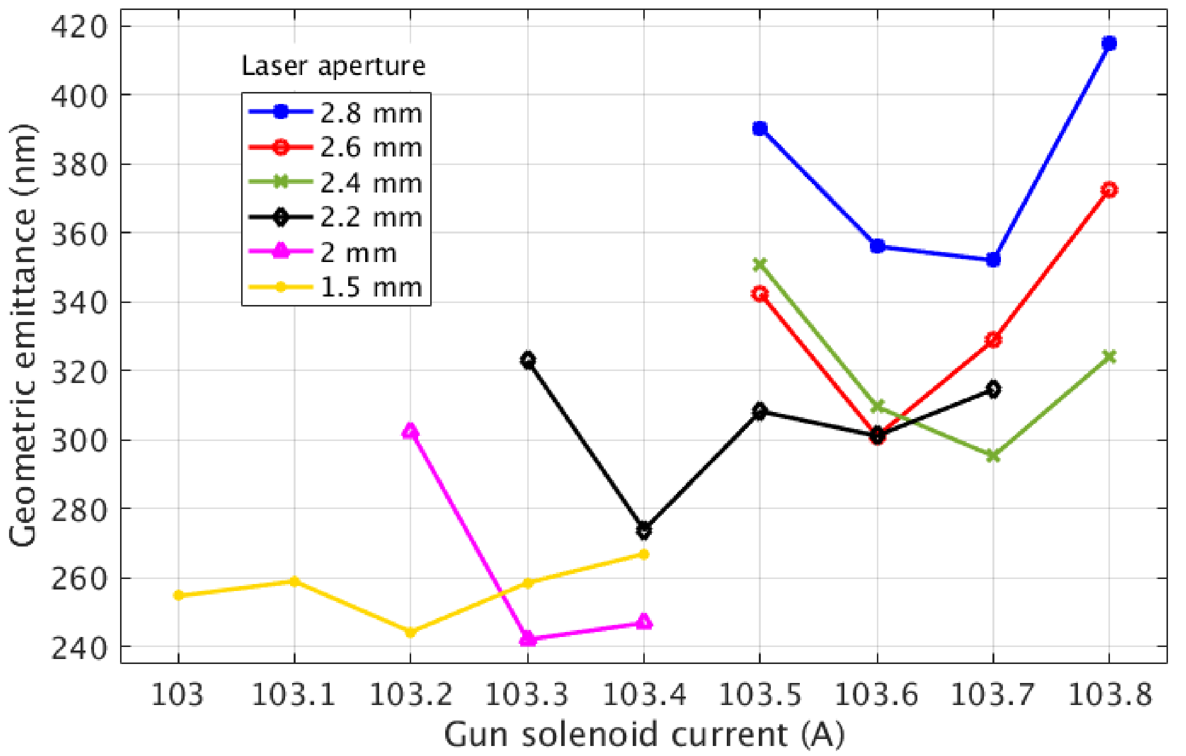
Bunch arrival-time monitor

- First bunch arrival-time monitor yielding data.
- Measurement resolution is ~5 fs.
- Measured (preliminary) arrival time jitter after BC1 is ~35 fs (will improve with new X-band preamps installed last week!)

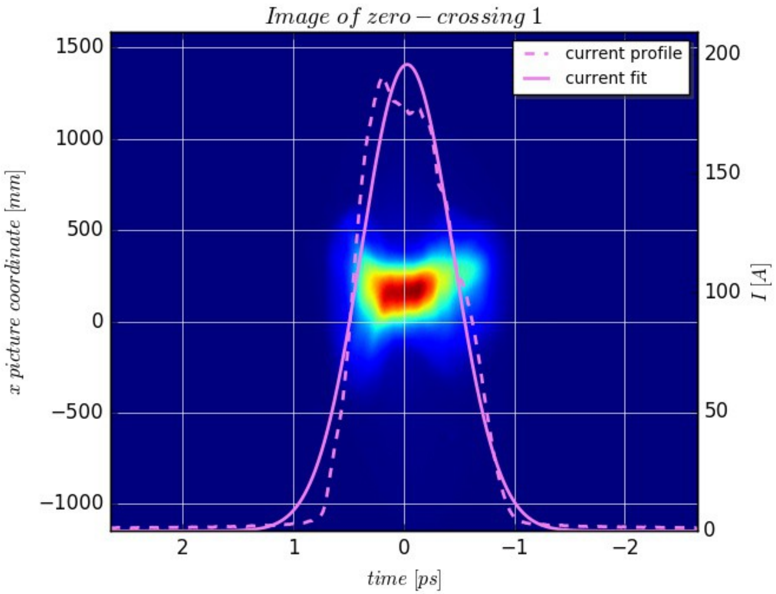


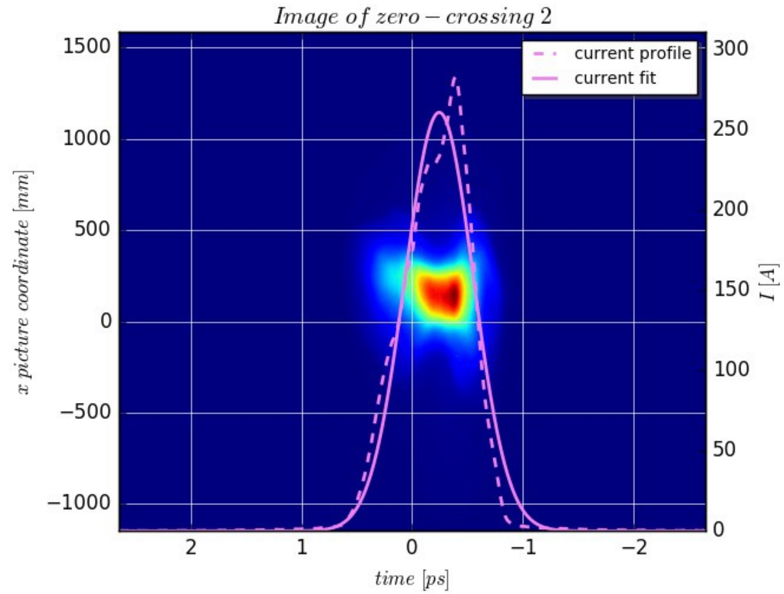
Beam dynamics progress (1)

- **Optics and emittance**
  - After initial problems optics now well understood.
  - Emittance of uncompressed beam in injector optimized to ≤250 nm (projected), ≈150 nm (slice) for 200 pC bunch charge (10 ps rms bunch length).



Beam dynamics progress (2)





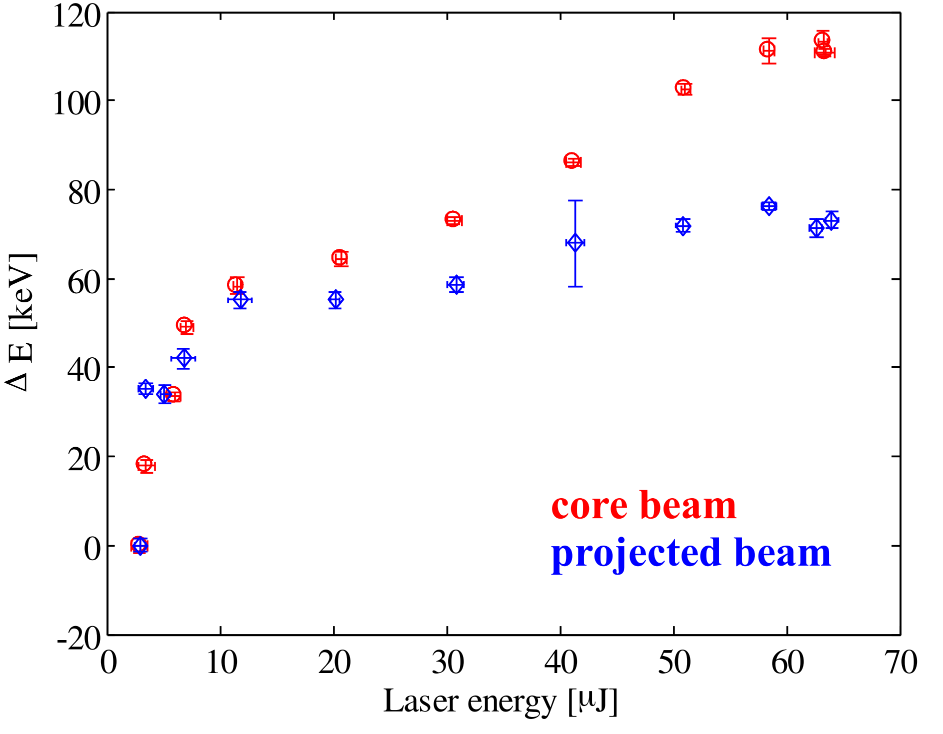
Example of bunch-length measurement after BC1 (two zero crossings of RF deflector)

- **Compression setup**
  - Systematic compression in BC1 down to ≈120 fs (rms) bunch length (compression factor ≈20) with two compression "knobs" constructed from S-/X-band amplitudes and phases. Slice emittance under control.
  - Preliminary setup of dual stage compression (BC1 and BC2) with C-band deflecting cavity (available since Jan. 2018) for final bunch length of 50 fs (rms).
  - Systematic optimization of dual stage compression still in progress…

Beam dynamics progress (3)

- **Laser heater**
  - Initial commissioning done: transverse and longitudinal overlap determined.
  - Characterization of laser-heater induced energy spread, also time-resolved (“heating shape”).
  - Detailed commissioning / characterization still needed!

Energie spread vs. laser heater energy

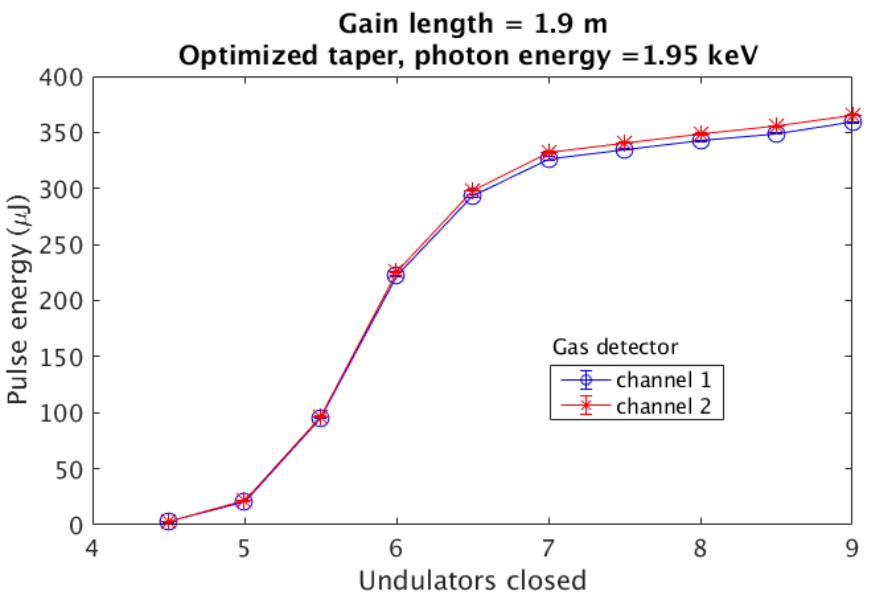


FEL setup and characterization

- **FEL setup:**

After optics and compression setup and verification, we apply the following steps for optimal FEL output:

1) Optimization of *pre-saturation taper* (linear)
   - Compensate for energy loss from wakefields
2) Adjustment of K values and phase shifters for uniform gain (if necessary)
3) [Optimize laser heater energy for max. pulse energy]
4) Optimization of *post-saturation taper* (linear and quadratic)
   - Compensate for energy loss from wakefields and from FEL
5) Readjustment of K values and phase shifters for uniform gain (if necessary).
6) Random walk optimization of electron orbit in undulator section.



Gain curve (gas detector), 14 March 2018

- **FEL characterization:**
  - Gain length around 2 m, in rough agreement with expectation
  - Photon pulse energy at saturation: 250 μJ for K = 1.2 at 2.6 GeV (2.3 keV photon energy) and 350 μJ for K = 1.45 at 2.3 GeV (2.0 keV).

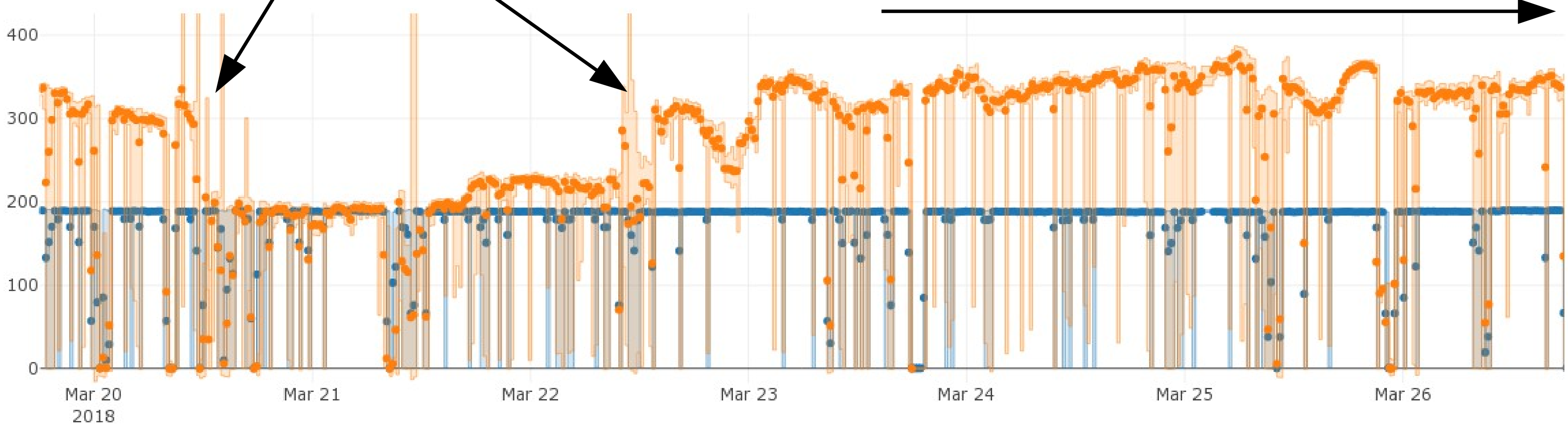
Example: FEL performance during pilot week

- Week 12/2018
- Second experiment at Bernina end station
- 2.5 GeV electrons, 2 keV photons (K = 1.45)
- Measurements on the 3rd harmonic (6 keV)

● Bunch charge in beamdump (pC)
● Photon pulse energy (μJ)
Mon, 19-Mar, 18:00 – Mon, 26-Mar, 18:00

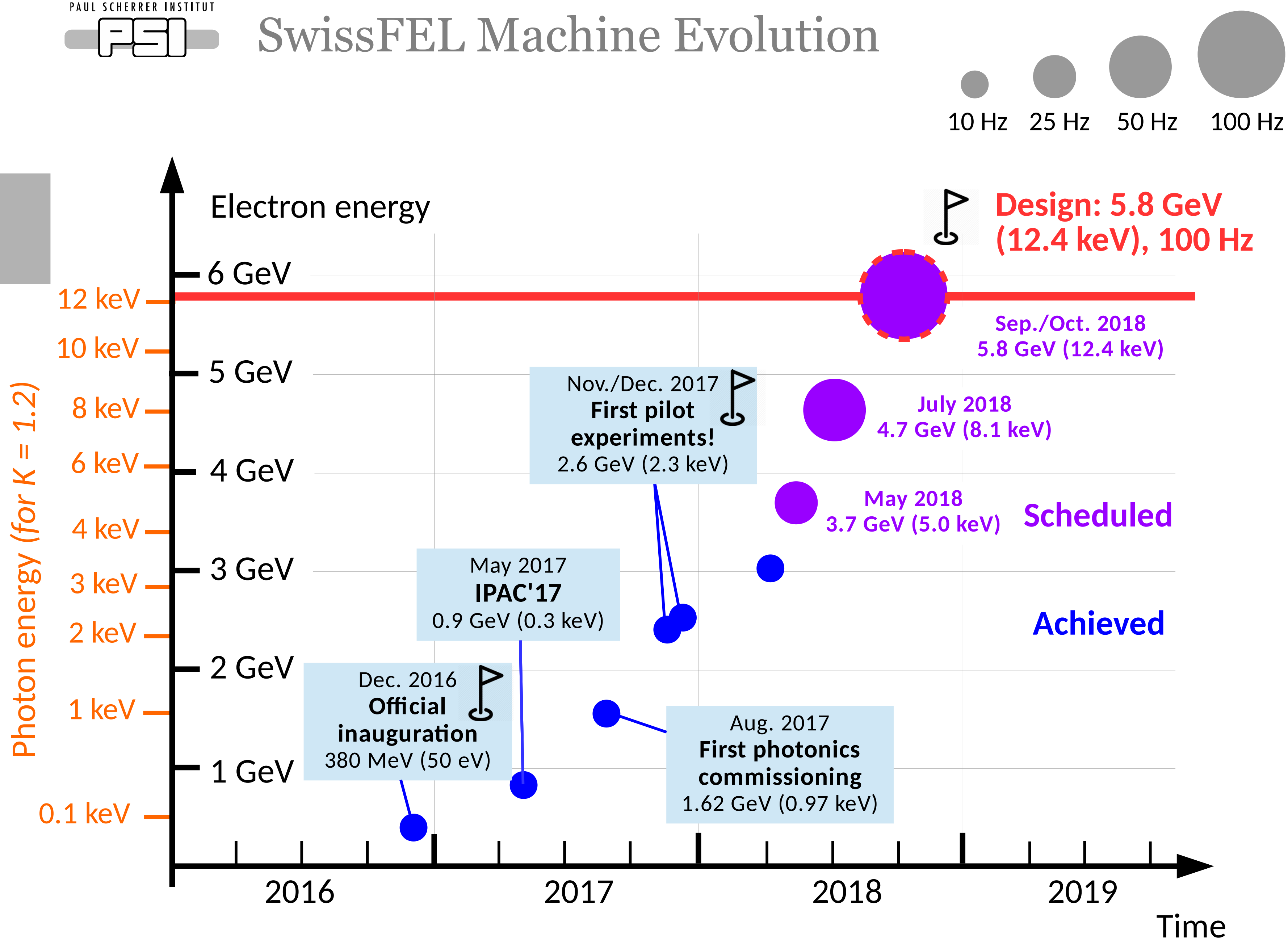
Changes in compression setup (different bunch length, output 3rd harmonic)

Automatic tweaking of key parameters to maintain FEL ouput

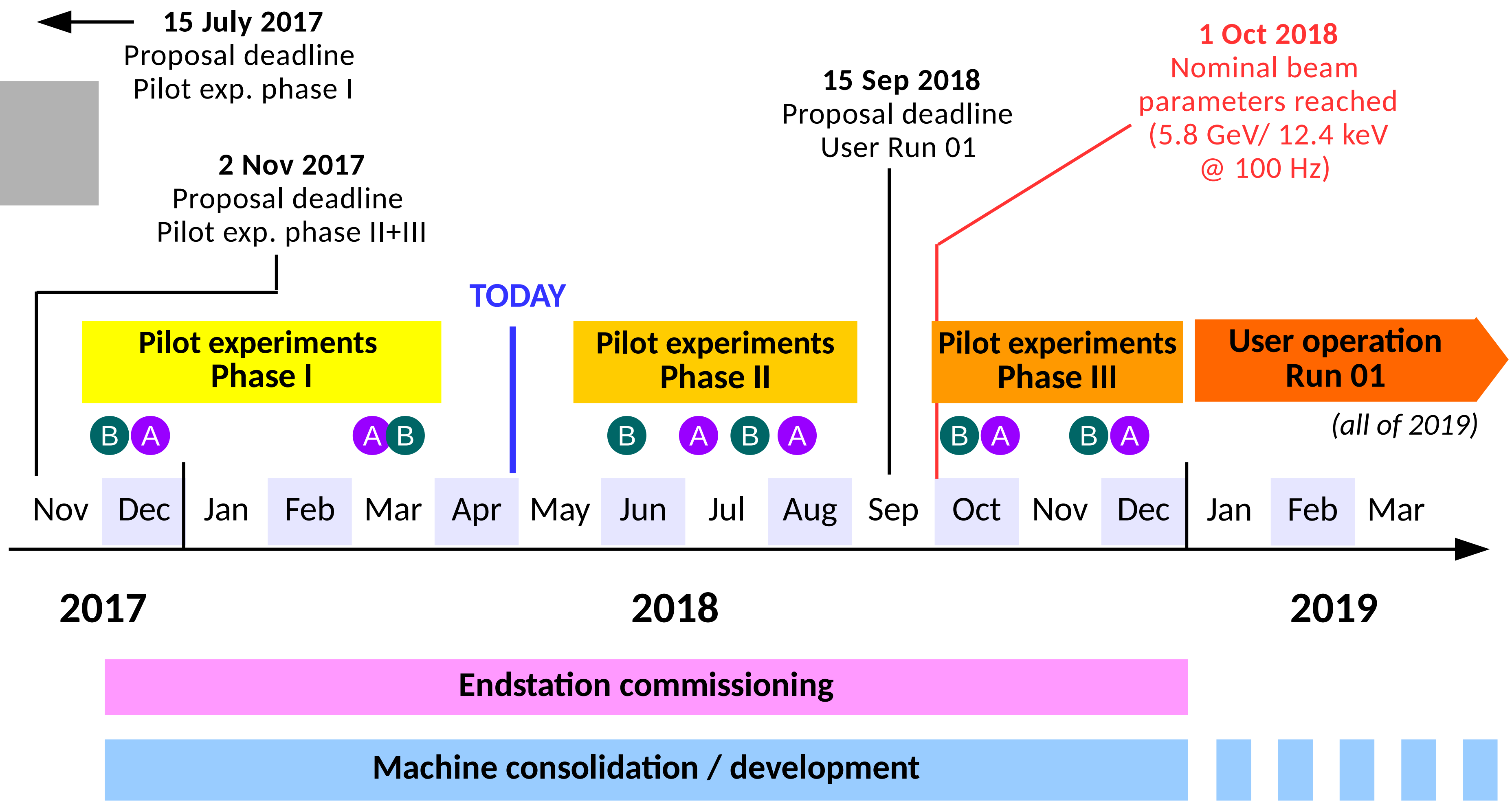


- Overall ~90% uptime
- Some downtime due to user requests to change setup / beam parameters

SwissFEL Machine Evolution



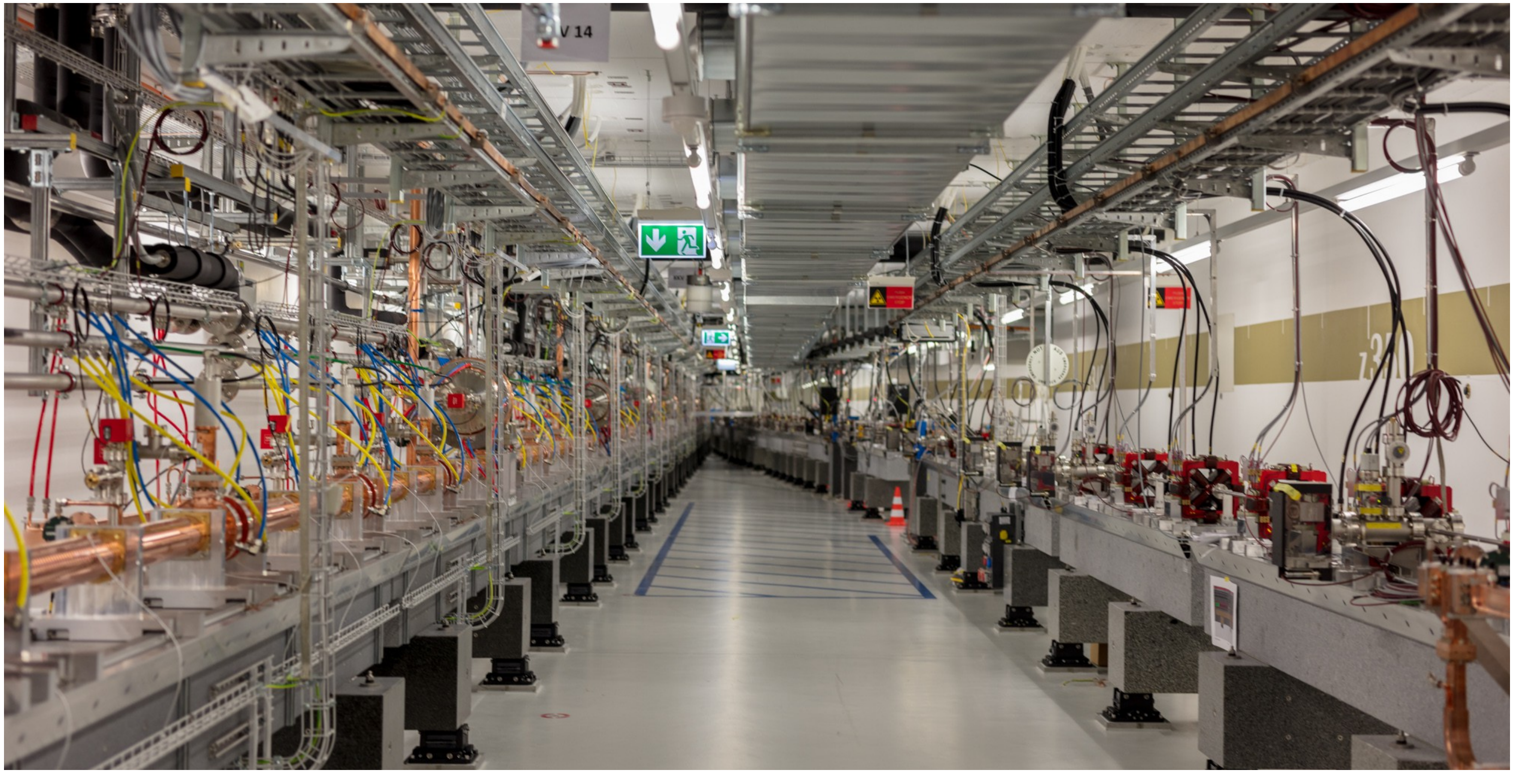
Aramis schedule (hard-X-ray line)



Outlook Athos (soft-X-ray line)

Flexible undulators and chicanes for a **compact** and **bright** beam line!

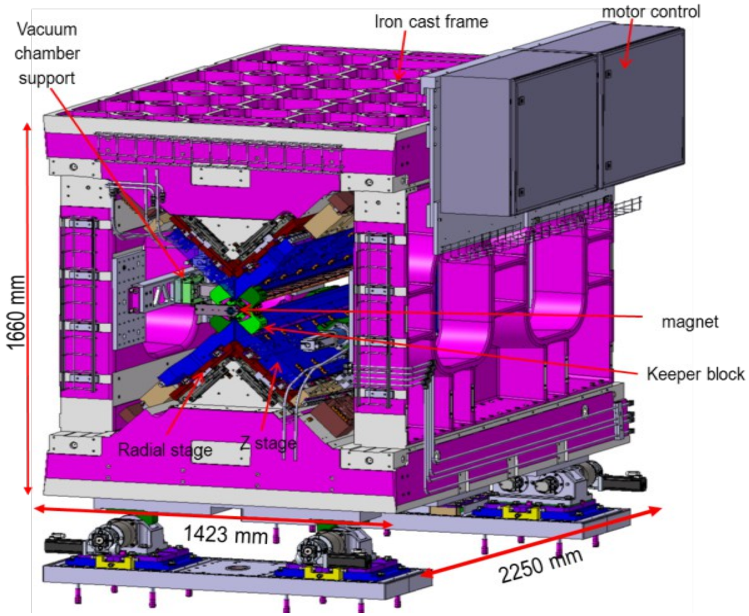
Aramis line
(hard X-ray)



Athos line
(soft X-ray)

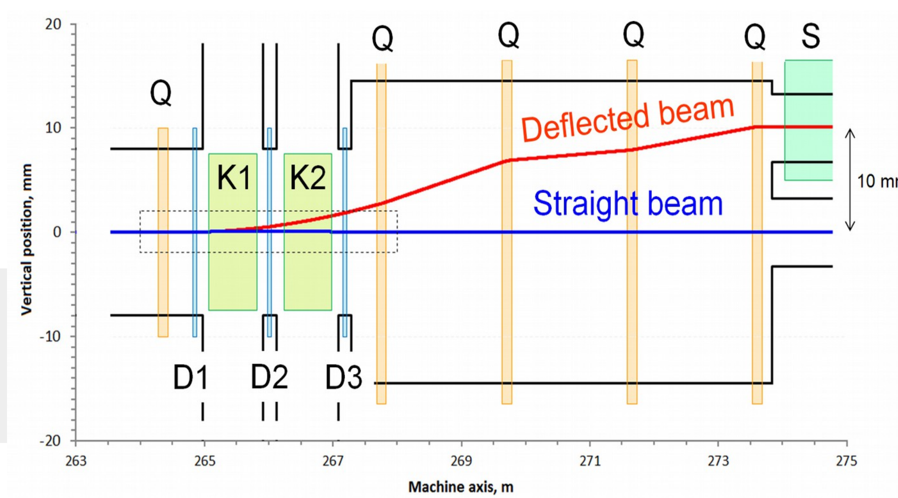
SwissFEL still under construction…

Outlook Athos (soft-X-ray line)



Athos U38 undulator concept

- Redesigned soft-X-ray undulator line featuring 16 **Apple-X U38** undulators:
  - full polarization control
  - independent K and polarization control
  - transverse gradient undulator (TGU)
  - symmetric force distribution (gap = slit)
- Small **interundulator magnetic chicanes** to enable
  - Optical klystron mode
  - High-brightness mode
  - Terawatt-attosecond mode
- One large **magnetic chicane** for two-color operation (delay between −10 fs and +500 fs)



- Custom-designed **resonant kicker magnet** to distribute bunches separated by 28 ns.
- Installed and successfully tested in March.

Outlook Athos (soft-X-ray line)

Flexible undulators and chicanes for a **compact** and **bright** beam line!

Athos schedule:

- Athos dogleg ready for commissioning by June 2018
- U38 module prototype delivery in June 2018
- Delay chicanes in procurement
- Undulator installation Jan. 2019 – March 2020
- **First pilot experiment end 2020**
- **User operation from 2021**

PAUL SCHERRER INSTITUT

Summary

- SwissFEL has reached its 2017 milestone of first pilot experiments (with reduced parameters – 2.2 keV photon energy at 10 Hz).

- Systems and beam development program on track to reach nominal beam parameters by the end of 2018 (12.4 keV photon energy at 100 Hz).

- Regular user operation to start in January 2019!

- New soft-X-ray beamline Athos on track for first users in 2021.