

PAUL SCHERRER INSTITUT



Paolo Craievich (on behalf of the SwissFEL team) :: Paul Scherrer Institut

SwissFEL Linac commissioning status, current performance and future plans

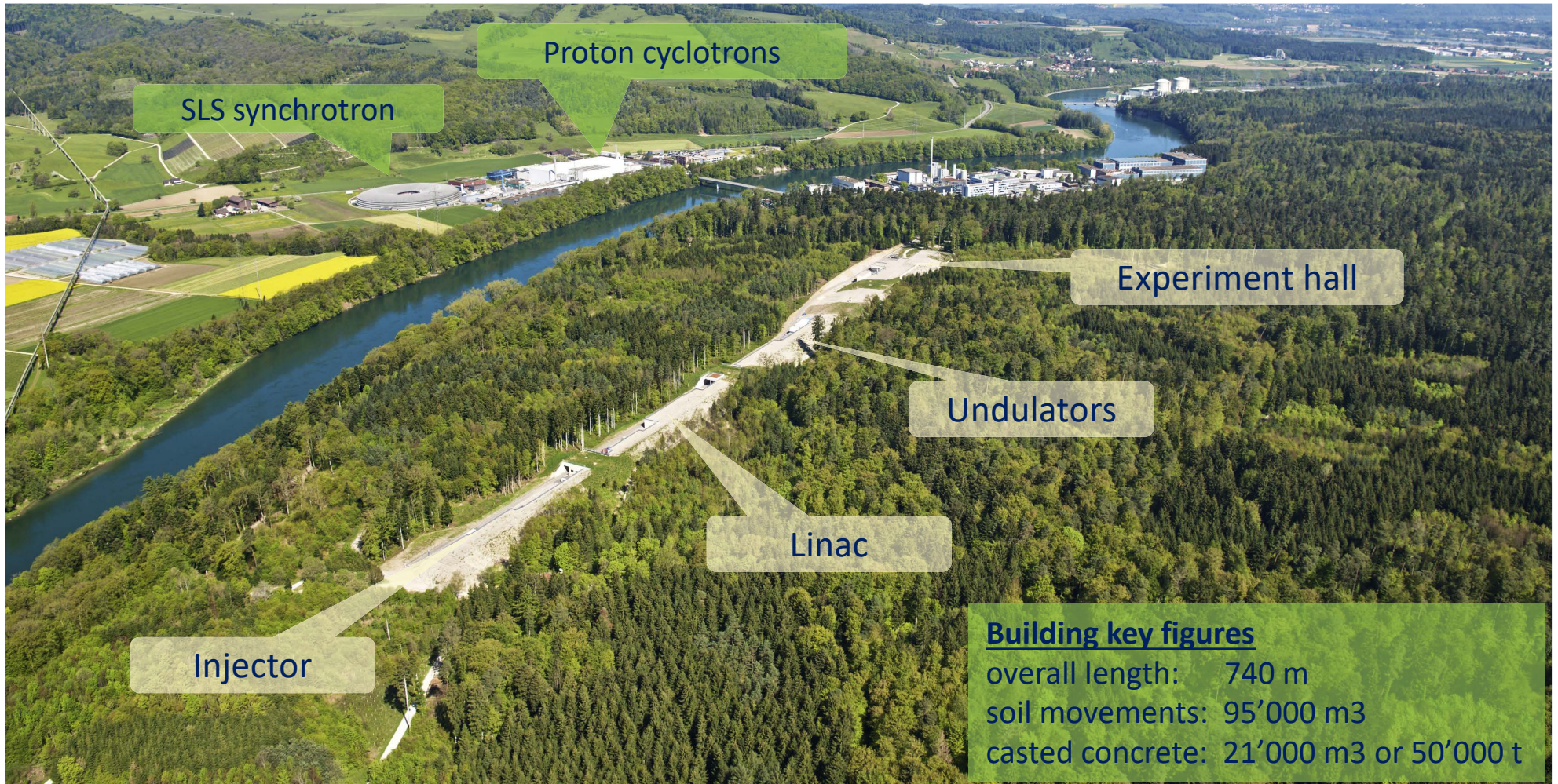
29th Linear Accelerator Conference, LINAC 18 - Beijing, China, 16 - 21 September 2018



- ❑ SwissFEL overview
 - Experimental area
 - Schedule Aramis (hard X-rays)
 - SwissFEL Machine Evolution
- ❑ Electron source - 2.5 cell S-band RF gun
- ❑ Beam dynamics progress
- ❑ C-band Linac and stability
- ❑ Undulator, FEL setup and characterization
- ❑ Outlook Athos (soft X-rays)

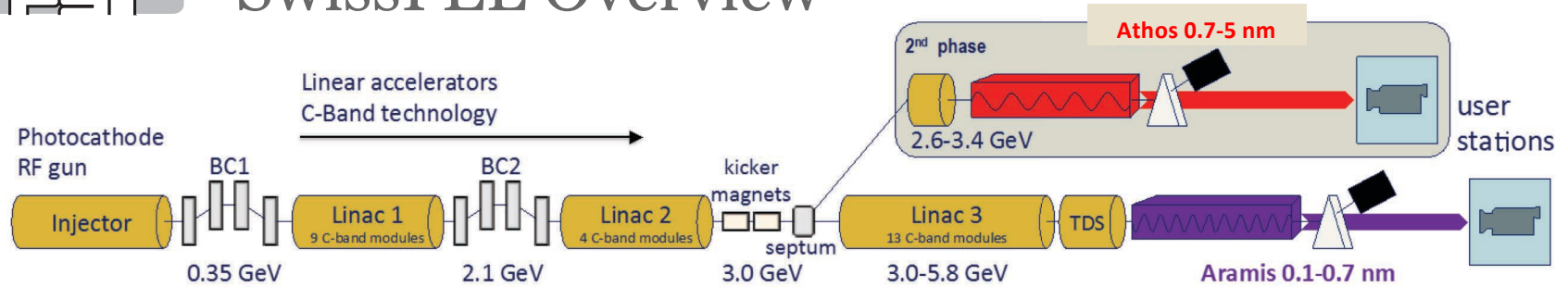


SwissFEL site





SwissFEL Overview



**Alvra
Bernina
(Cristallina)**

Main parameters

Wavelength from	0.1 nm–5 nm
Photon energy	0.2-12 keV
Pulse duration (rms)	1 fs - 20 fs
e ⁻ Energy (0.1 nm)	5.8 GeV
e ⁻ Bunch charge	10-200 pC
Repetition rate	100 Hz

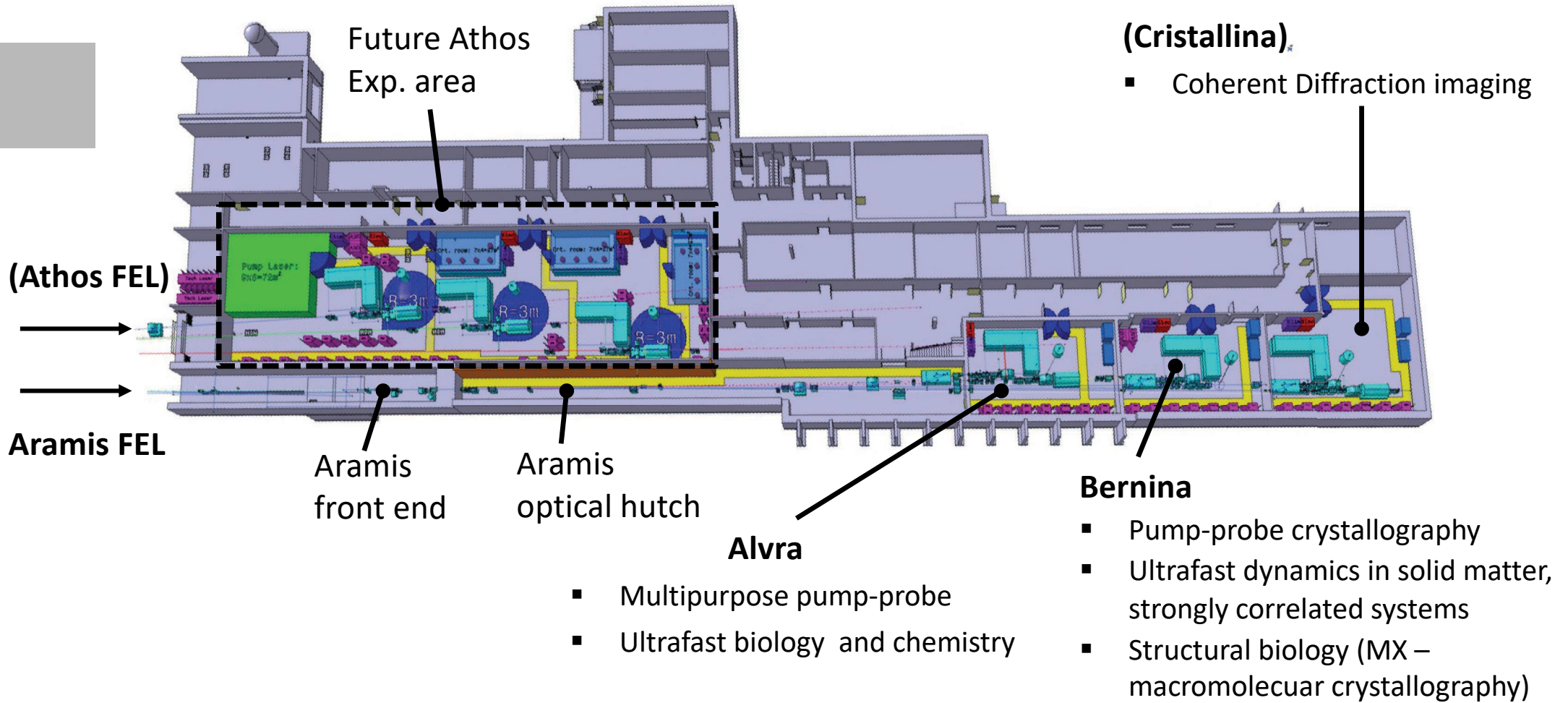
ARAMIS

Hard X-ray FEL, $\lambda=0.1 - 0.7$ nm (12-2 keV)
 Linear polarization, variable gap, in-vacuum undulators
 First users 2018

ATHOS

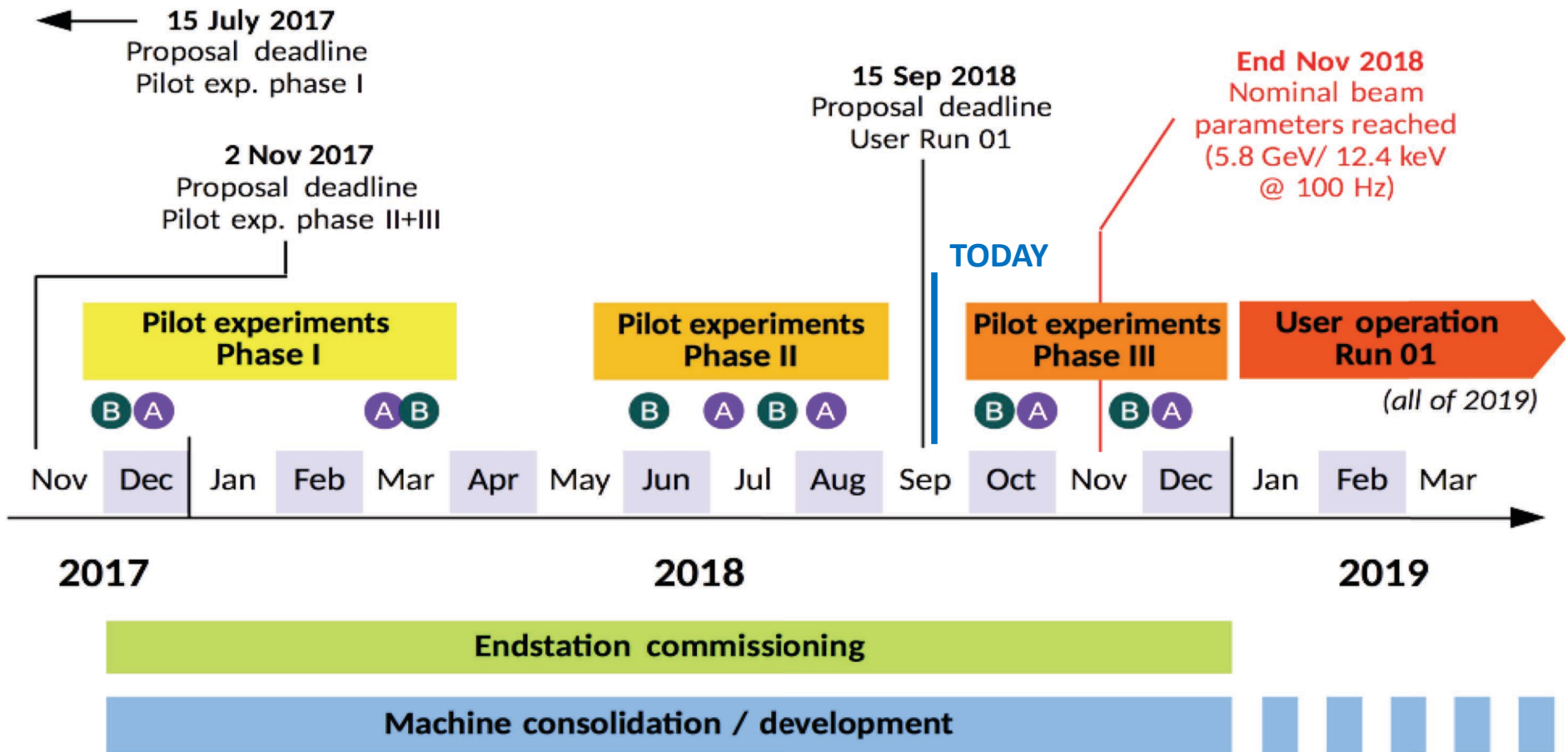
Beam Energy 2.7 – 3.3 GeV
 Soft X-ray FEL, $\lambda=0.65 - 5.0$ nm (2-0.2 keV)
 Variable polarization with Apple-X undulators (2-m long)
 2nd construction phase 2017 – 2020

SwissFEL experimental area



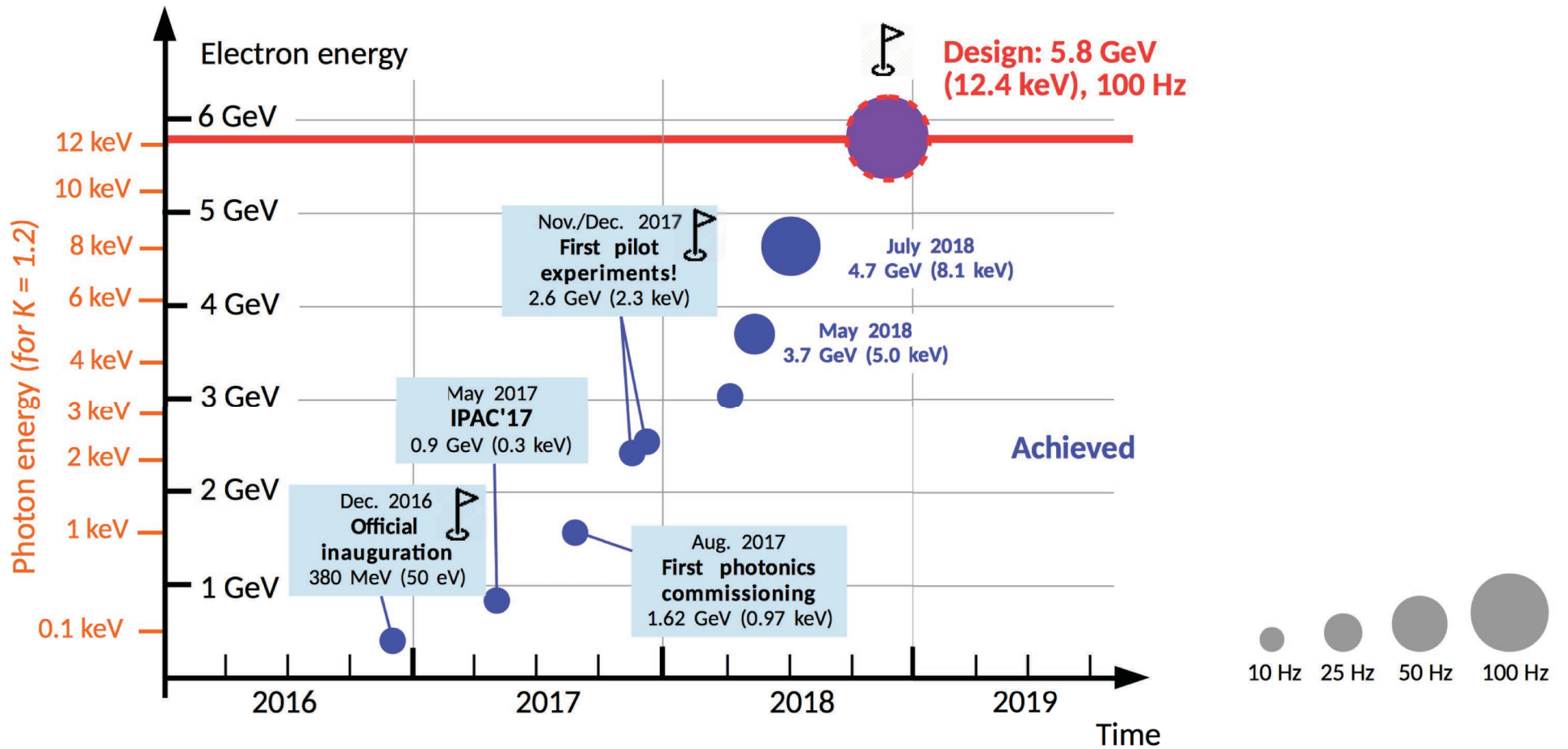


Aramis schedule (hard-X-ray line)



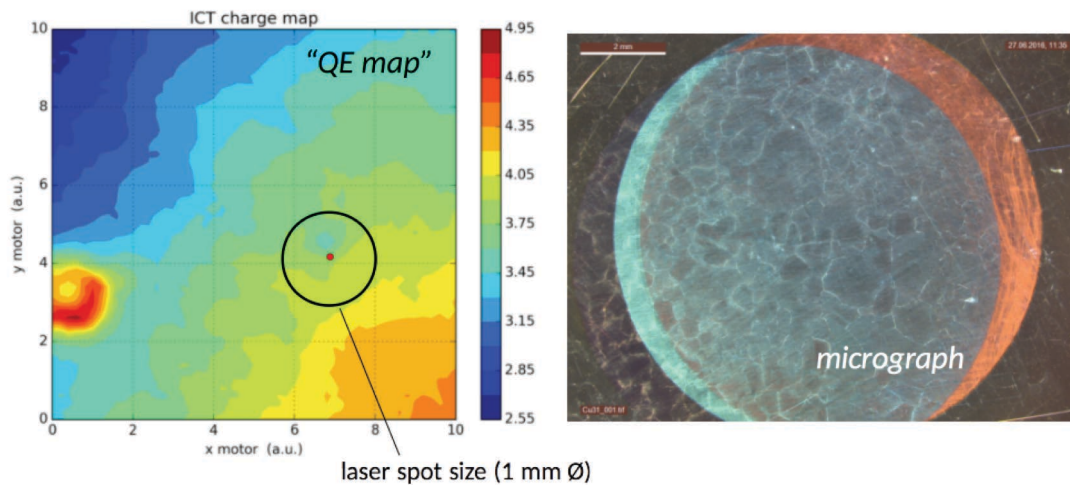
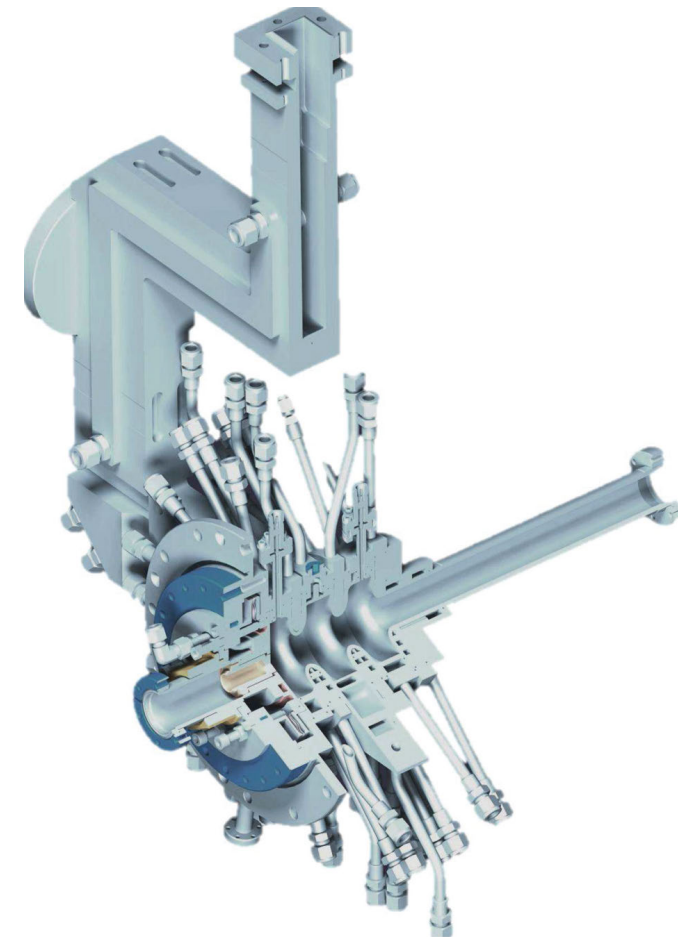


SwissFEL Machine Evolution



Electron source - 2.5 cell S-band RF gun

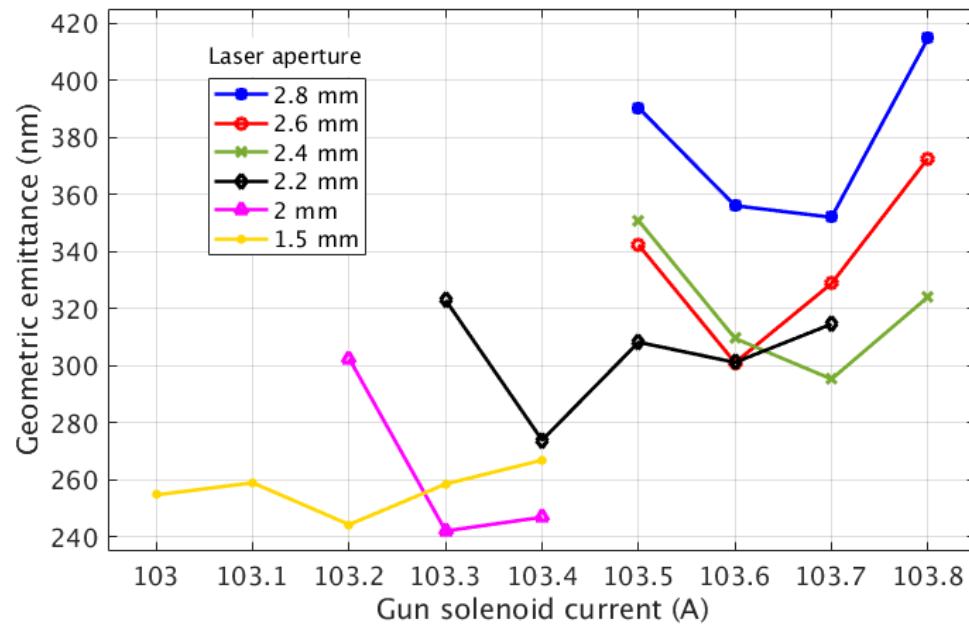
- ❑ RF gun:
 - Fully commissioned, 7.1 MeV nominal energy
- ❑ Cathode:
 - Cs₂Te coated copper cathode installed since July 2017
 - Quantum efficiency at about 0.7 % with uniform distribution around the laser spot
- ❑ Standard operating procedure for routine gun-laser check – fundamental for stability and reproducibility of the facility!



Beam dynamics progress (1)

□ Optics and emittance

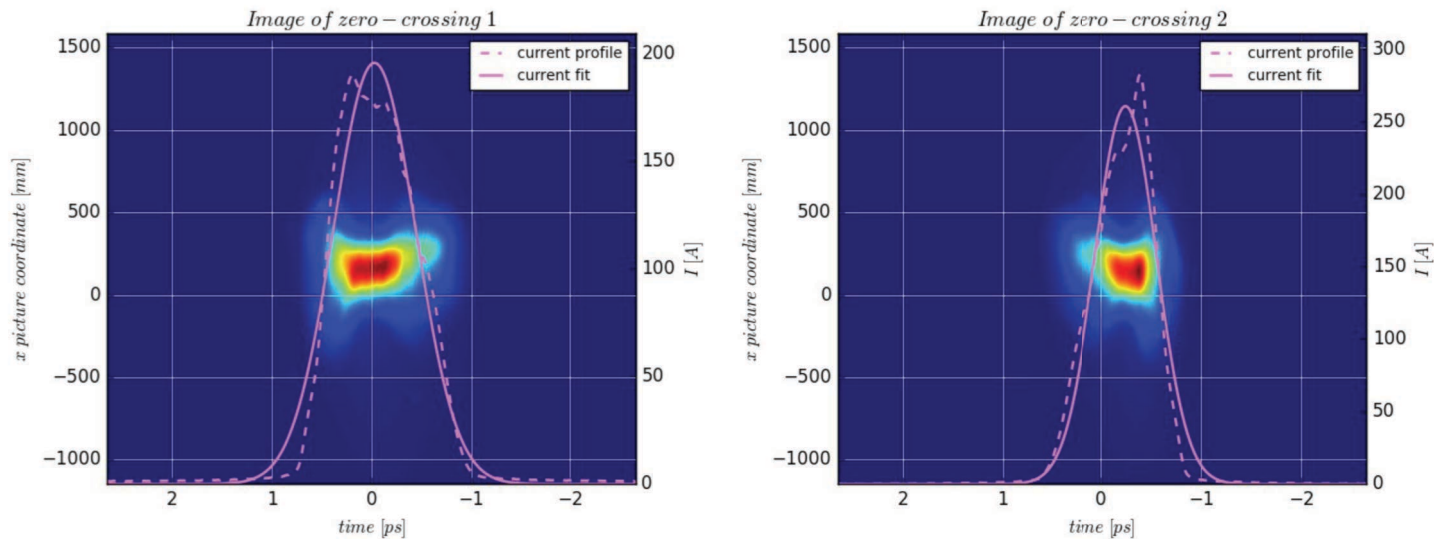
- After initial problems optics now well understood
- Emittance of uncompressed beam in injector optimized to ≤ 250 nm (projected), ≈ 150 nm (slice) for 200 pC bunch charge (10 ps rms bunch length).



Beam dynamics progress (2)

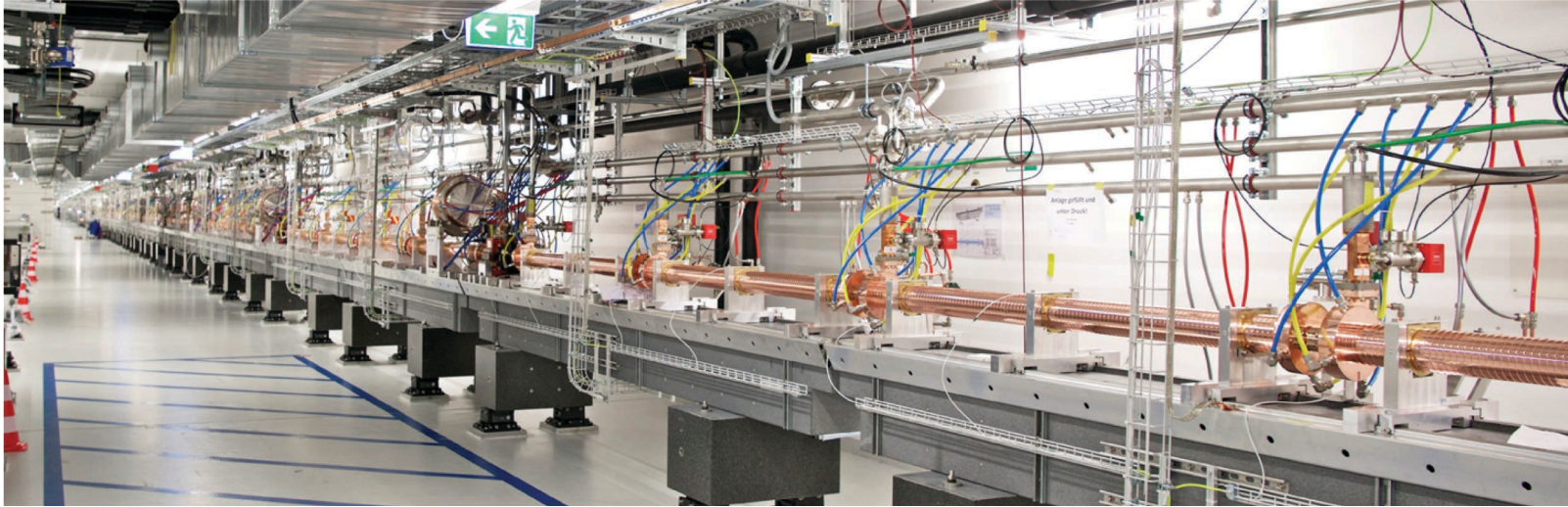
□ Compression setup

- 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



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

C-band Linac



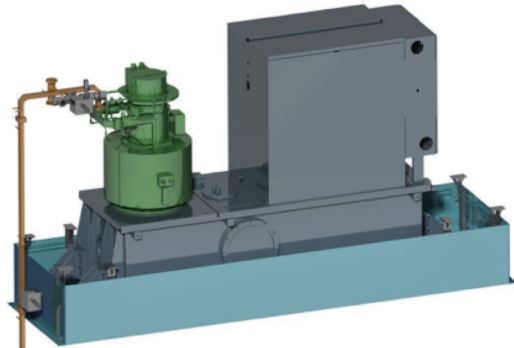
Status

- ❑ 25 out of 26 modules on beam
 - Linac 1: all of the 9 modules
 - Linac 2: 3 module over 4
 - Linac 3: all of the 13 modules
- ❑ All modules run at 100 Hz
- ❑ **Reached nominal beam energy 5.8 GeV**
- ❑ Note: 300 MeV at injector exit (BC1)

Station		MV	deg	Station		MV	deg
SINEG01	RF on beam	7.2	90.0	S20CB01	RF on beam	263.0	92.5
SINSB01	RF on beam	68.5	90.0	S20CB02	RF on beam	254.7	90.0
SINSB02	RF on beam	65.4	90.0	S20CB03	RF on beam	235.0	92.8
SINSB03	RF on beam	99.0	67.9	S20CB04	INIT	0.0	
SINSB04	RF on beam	99.0	67.8	S30CB01	RF on beam	207.4	90.0
SINXB01	RF on beam	19.9	264.4	S30CB02	RF on beam	253.5	90.1
SINDI01	RF on delay	4.2	256.9	S30CB03	RF on beam	260.2	90.0
S10CB01	RF on beam	243.8	77.8	S30CB04	RF on beam	249.9	90.0
S10CB02	RF on beam	242.9	77.8	S30CB05	RF on beam	239.6	90.0
S10CB03	RF on beam	249.2	77.8	S30CB06	RF on beam	235.2	90.0
S10CB04	RF on beam	212.7	77.8	S30CB07	RF on beam	235.0	91.8
S10CB05	RF on beam	262.3	77.8	S30CB08	RF on beam	244.1	90.0
S10CB06	RF on beam	253.6	77.8	S30CB09	RF on beam	241.9	90.0
S10CB07	RF on beam	228.5	78.5	S30CB10	RF on beam	265.3	90.0
S10CB08	RF on beam	193.5	77.8	S30CB11	RF on beam	254.0	90.0
S10CB09	RF on beam	237.7	77.8	S30CB12	Conditioning	0.0	196.3
				S30CB14	Conditioning	65.0	2.0

18.09.2018

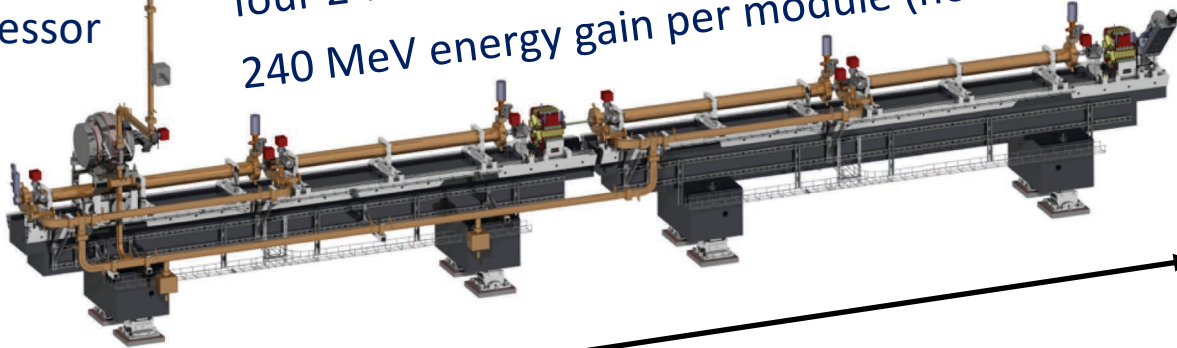
C-Band module



C-band-klystron
5.7 GHz, 50 MW, 3 μ s, 100 Hz

BOC
pulse
compressor

four 2-m long C-band structures,
240 MeV energy gain per module (nominal)



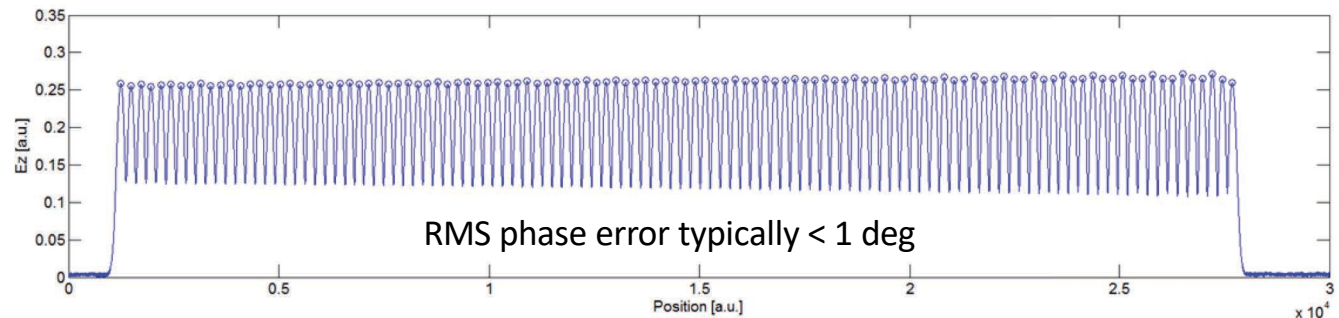
9 m

Main LINAC	#
LINAC module	26
Modulator	26
Klystron	26
Pulse compressor	26
Accelerating structure	104
Waveguide splitter	78
Waveguide load	104

C-band structures

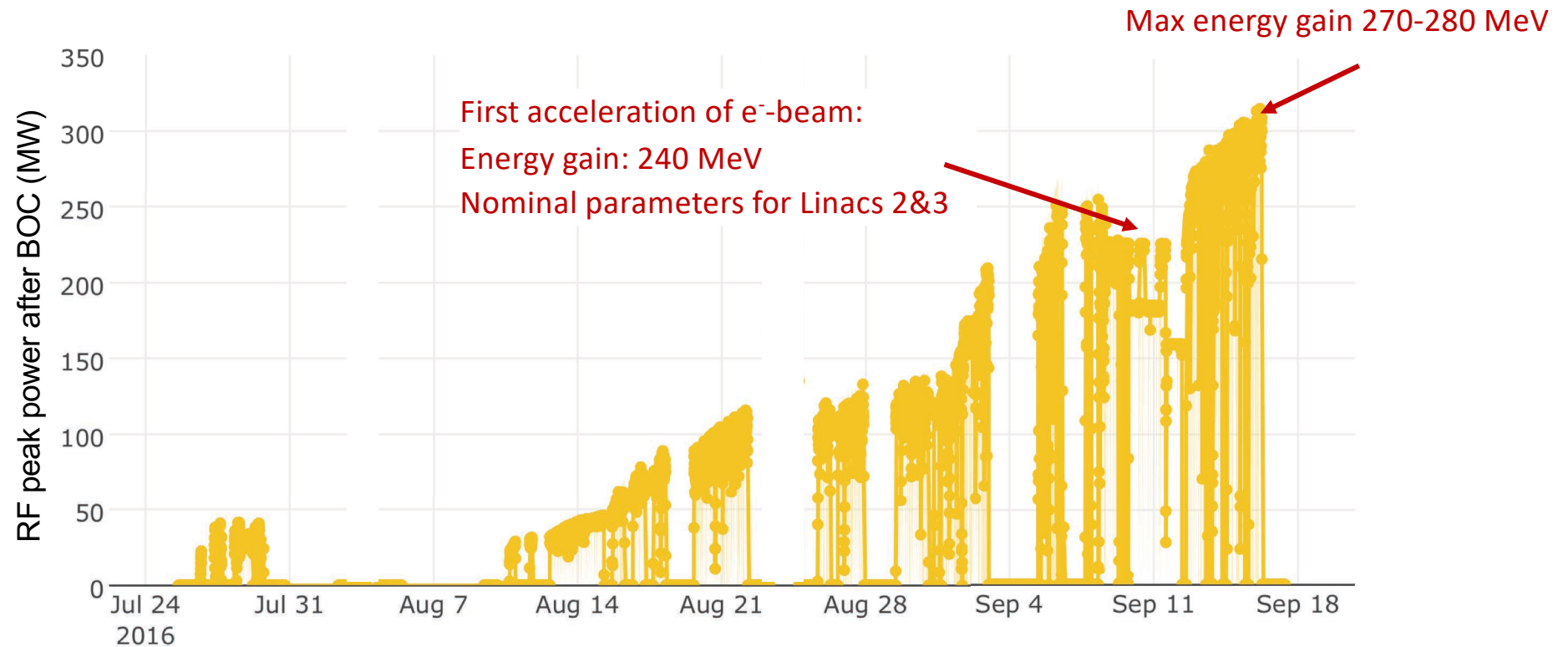


- ❑ Structures are machined “on tune”, no provisions for dimple tuning!
- ❑ Cup manufacturing with micron precision at VDL ETG Switzerland
- ❑ Coupler manufacturing at VDL ETG
- ❑ Stacked by robot and vacuum brazed at PSI
- ❑ Production rate: 1-2 structures/ week
- ❑ High power results for first structure:
 - Conditioned to 52 MV/m with BDR $\sim 2 \times 10^{-6}$
 - At nominal 28 MV/m, break-down rate negligible (well below the specified threshold of 10^{-8})



Bead pull measurement - No tuning

Conditioning of first C-band module



→ Usually a module is fully conditioned in 3-4 weeks (structures, waveguides and pulse compressor)

Consolidation of the RF technology at PSI

- ❑ PSI has developed a production line of high technological content for high-quality, high-gradient C-band accelerating structures for the SwissFEL project.
- ❑ PSI is interested in extending, consolidating and broadening its know-how to S-band and X-band frequencies
 - RF group is establishing international collaborations on different topics:
 - CERN-PSI: development of X-Band high-gradient accelerating structures structures in tuning-free C-band design;
 - CERN-DESY-PSI: development of innovative X-band tuning-free transverse deflecting structure with a novel variable polarization feature;
 - FERMI@Elettra-PSI: development of S-band high-gradient accelerating in tuning-free C-band design.
- ❑ *Consolidation of the exiting C- band technology in accelerators applications: development of C-band traveling-wave photo guns for the SwissFEL project and for a multipurpose compact photo-injectors.*



Solid-state modulators for C-band linac

- ✓ Two prototypes were tested at PSI for evaluation of the series.
- ✓ **50 MW / 3 μ s RF, 370kV / 344A**

AMPEGON

Type- μ prototype for SwissFL



- 13 modulators (Linac 1, Linac 2)



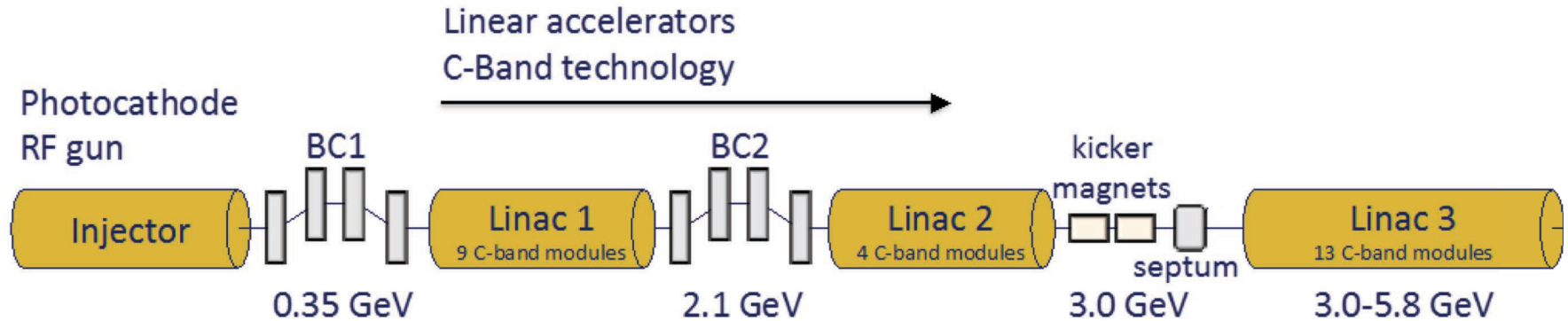
K2-3 prototype for SwissFEL



13 modulators (Linac 3)

- ✓ **Measured stability pulse to pulse at 100 Hz < 15 ppm**

Linac Stability (1)



Pulse-to-pulse phase jitter (rms)

	Measured	Specs
S-band	0.010°-0.04°	0.018°
X-band	0.05°	0.072°
C-band	0.018°-0.04°	0.036°

Pulse-to-pulse rel. ampli. jitter (rms)

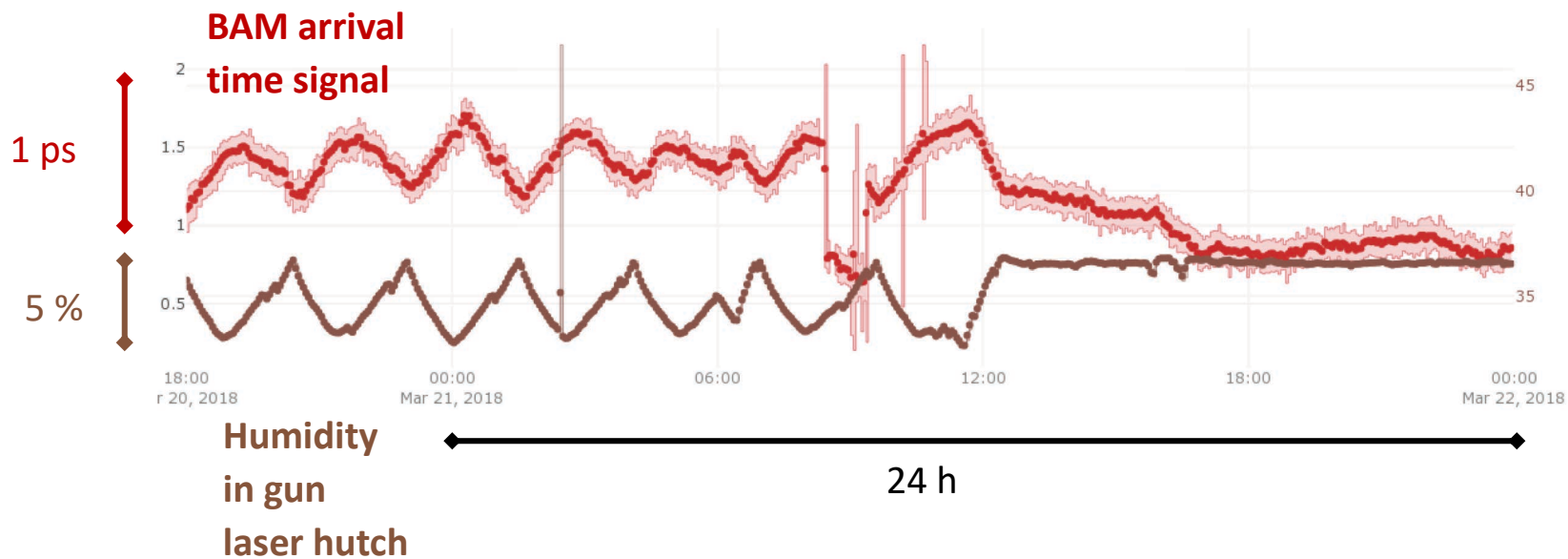
	Measured	Specs
S-band	0.01%-0.02%	0.02%
X-band	0.05%	0.05%
C-band	0.01%-0.02%	0.02%

✓ Relative energy jitter at the Linac end (@4.7 GeV) ~0.01%, spec. 0.05%

Linac Stability (2)

Arrival-time jitter

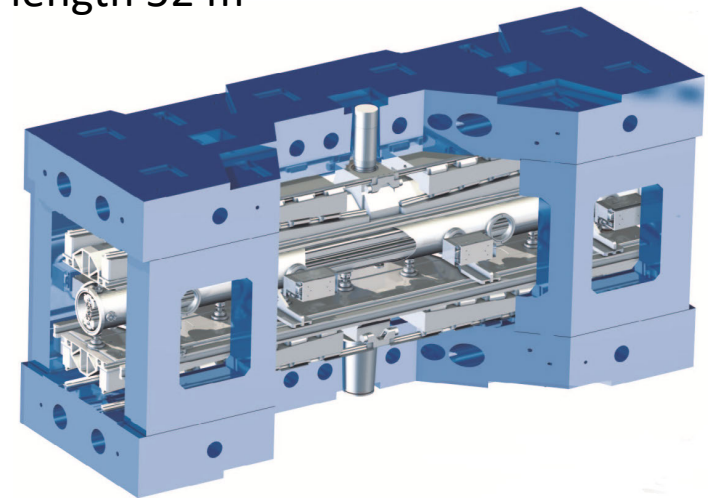
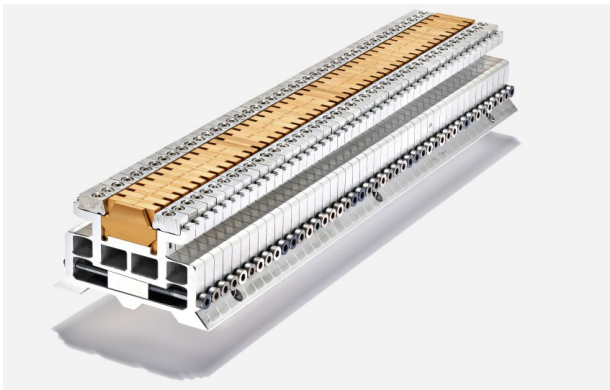
- ❑ First bunch arrival-time monitor yielding data
- ❑ Measurement resolution is ~ 5 fs
- ❑ Measured arrival-time jitter after BC1 is ~ 35 fs – preliminary and not at Linac-end



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 per module
- ❑ 13 modules of 4 m length
 - Total length 65 m
 - Active length 52 m



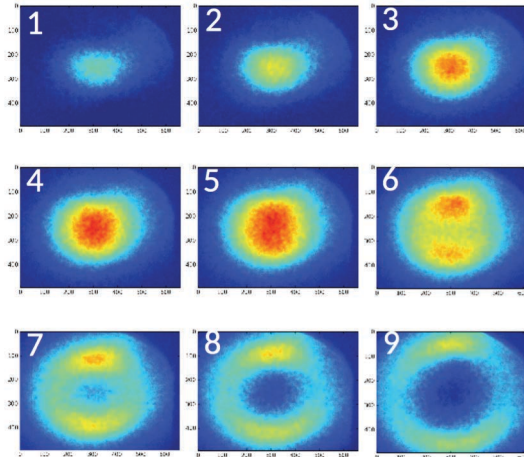
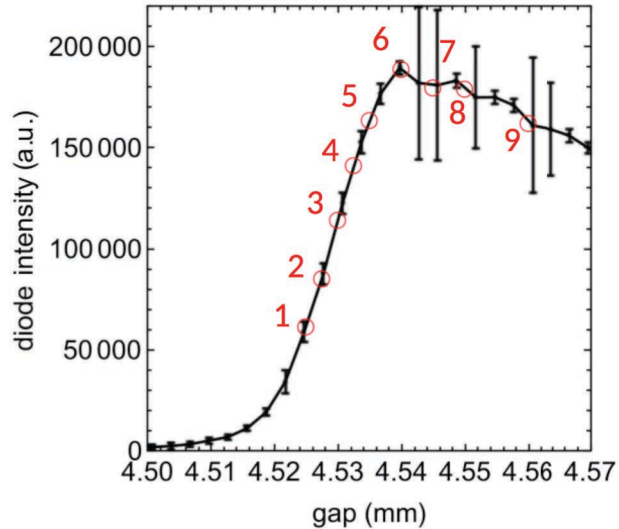
Aramis undulator line

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 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 be done

- ❑ 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

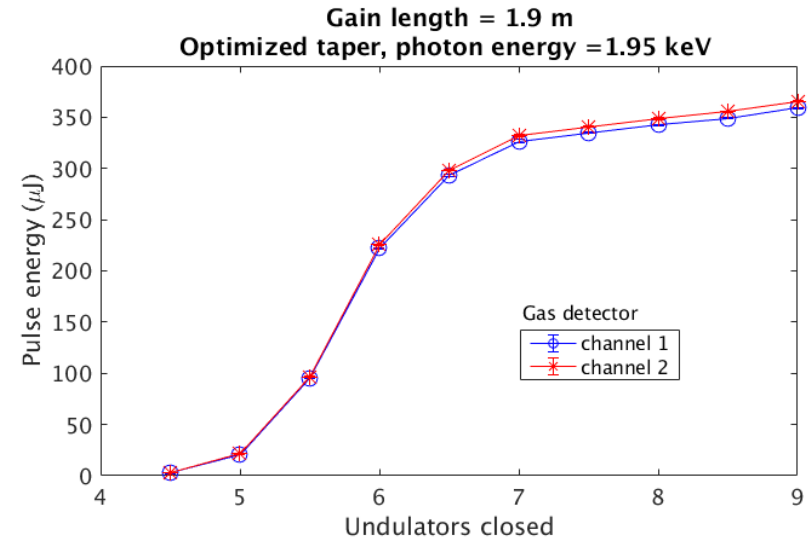


FEL setup and characterization

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]
 - on going
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.



FEL characterization:

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

→ Lasing on 18.09.2018: 8.9 keV (photon energy) at 5.8 GeV and e-beam at 25 Hz

Example of FEL performance

- ☐ Week 26/2018
- ☐ Preparation for Alvra pilot experiment
- ☐ 4.3 GeV electrons, 5 keV, 350 μJ , 50 Hz

● Bunch charge in beamdump (pC)
 ● Photon pulse energy (μJ)
 Mon, 25-June, 8:00 – Mon, 2-Jul, 8:00

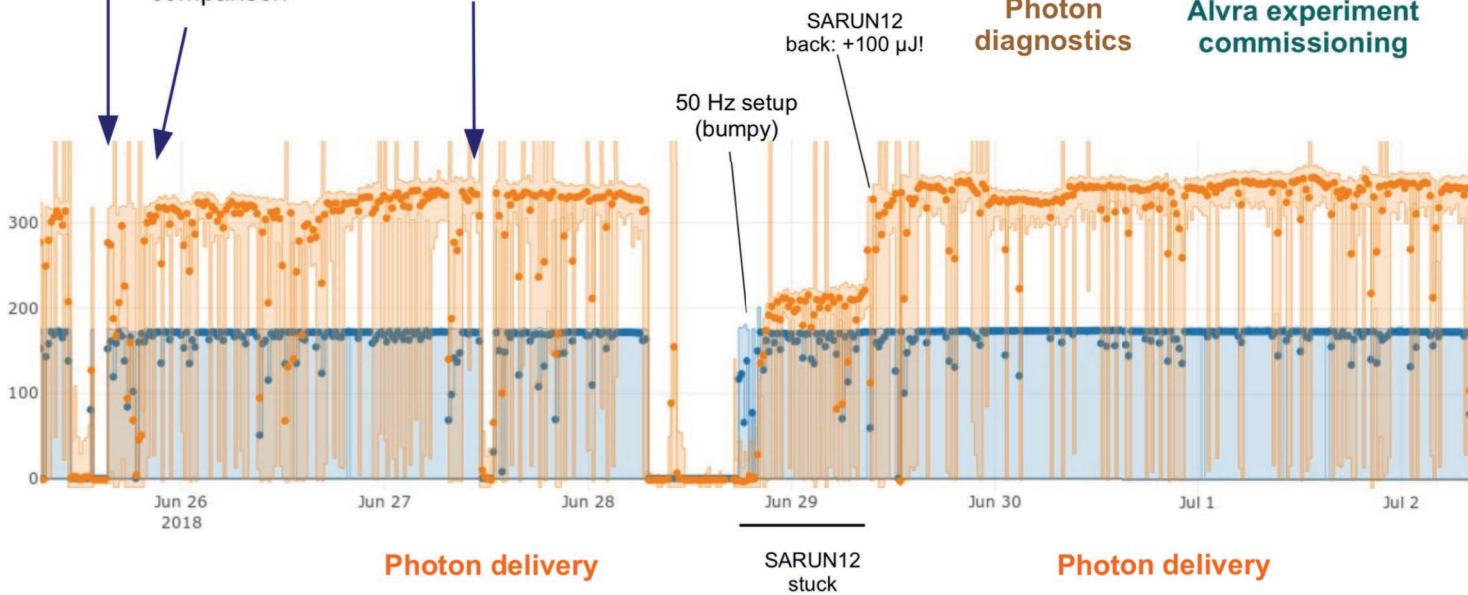
Machine development:

- wire scanner tests
- gain curves
- Jaguar/Alcor comparison

Operator training

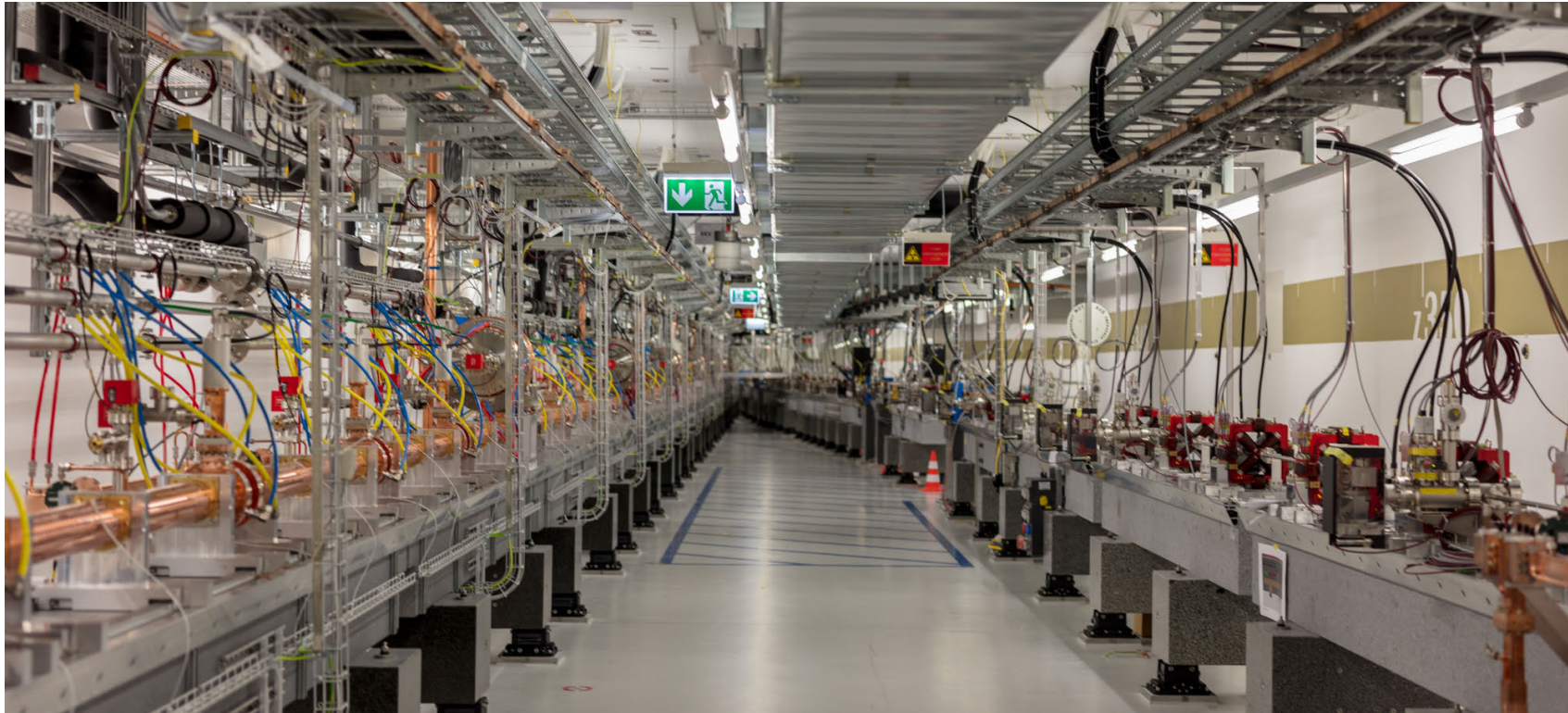
Maintenance Window

Automatic tweaking of key parameters to maintain FEL output



Outlook Athos (soft-X-ray line)

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



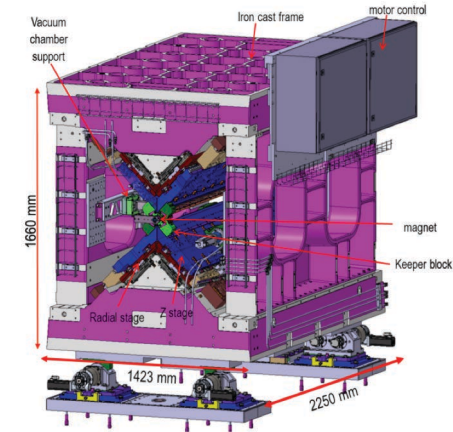
Aramis line
Hard X-ray

Athos line
Soft X-ray

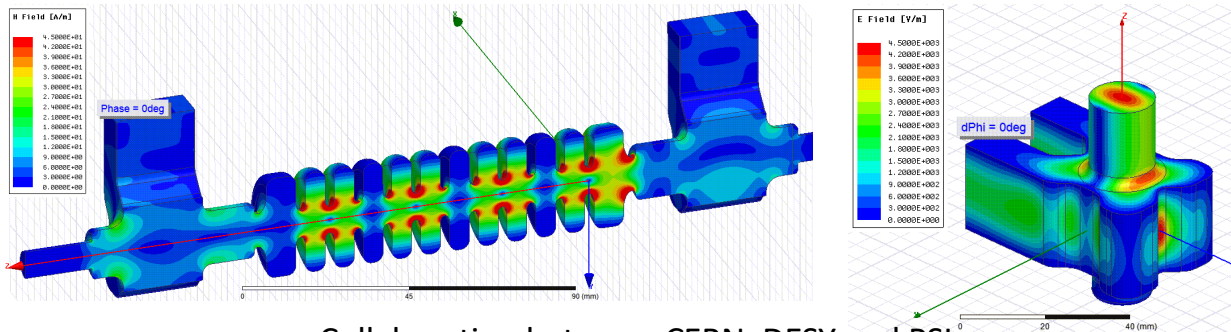
Outlook Athos (soft-X-ray line)

Athos schedule:

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



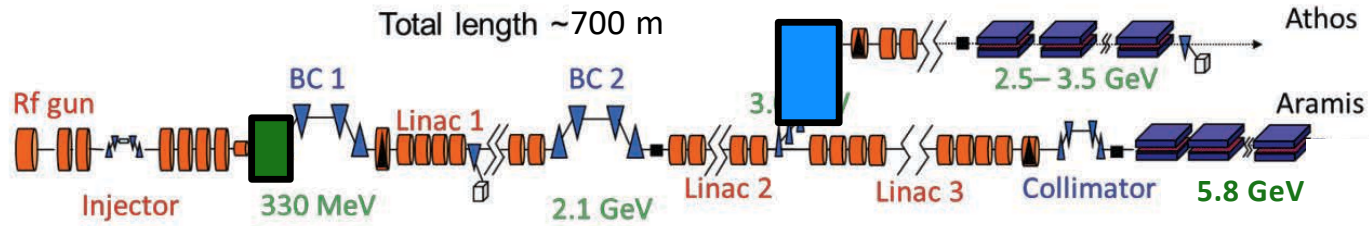
Post-undulator X-band TDS with variable polarization



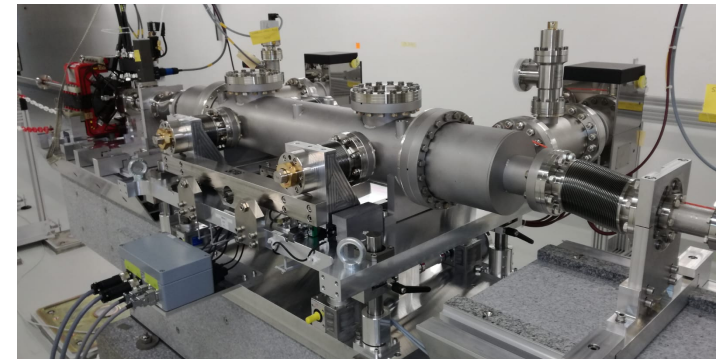
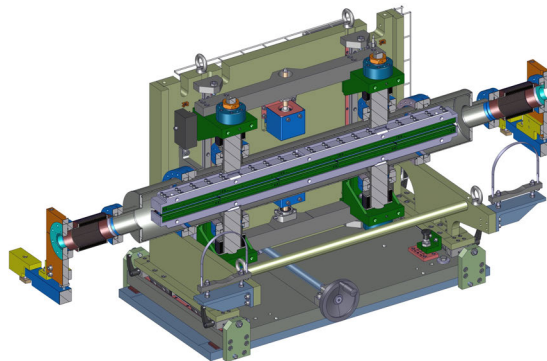
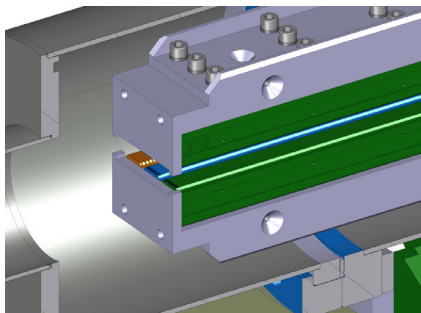
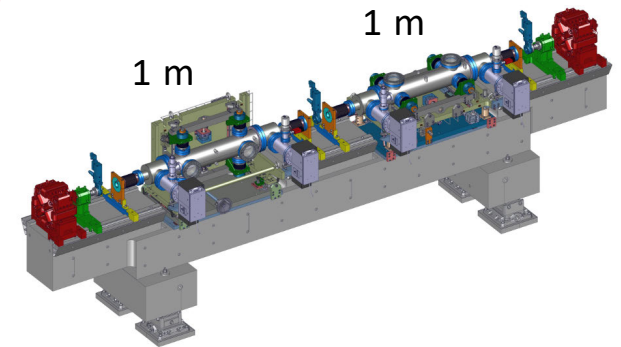
Collaboration between CERN, DESY and PSI

- 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)

Beam manipulation in SwissFEL linac



- ❑ Passively streak the beam (1-10 ps bunch length): $1 \text{ mm} \leq \lambda_w \leq 6 \text{ mm}$
- ❑ Test the two-color generation via wakefield excitation: $\lambda_w = 1 \text{ mm}$
- ❑ Alternatively linearize: $\lambda_w = 6 \text{ mm}$
- ❑ Remove the chirp residual from the compression: $\lambda_w = 2 \text{ mm}$
- ❑ Passively streak the beam at higher energy and shorter bunch length ($\sim 10\text{-}500 \text{ fs}$)



Summary

- ❑ SwissFEL has reached its 2017 and 2018 milestone of pilot experiments
- ❑ 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).
- ❑ Reached nominal e-beam energy of 5.8 GeV!
- ❑ Regular user operation to start in January 2019!
- ❑ New soft-X-ray beamline Athos on track for first users in 2021.

