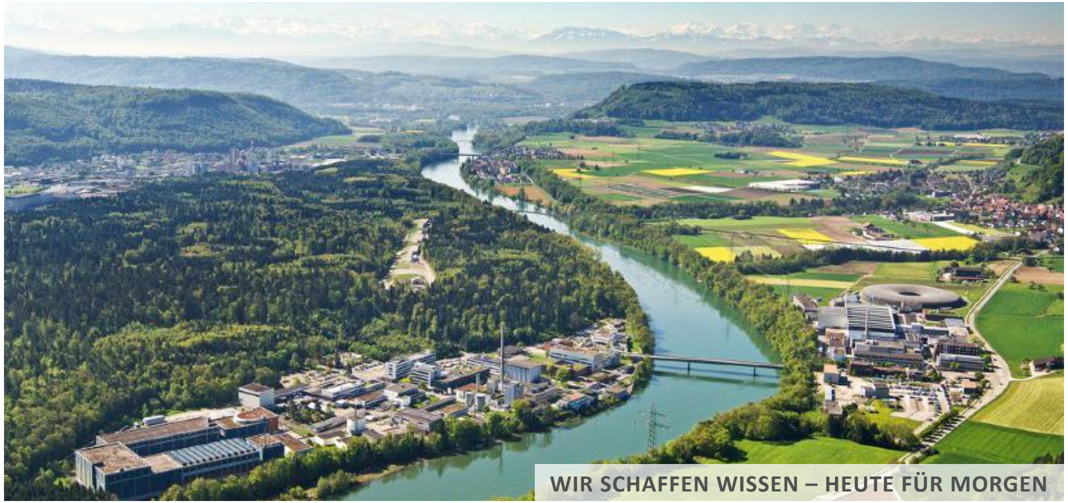


Nicole Hiller (on behalf of the SwissFEL & SLS teams) :: Paul Scherrer Institut

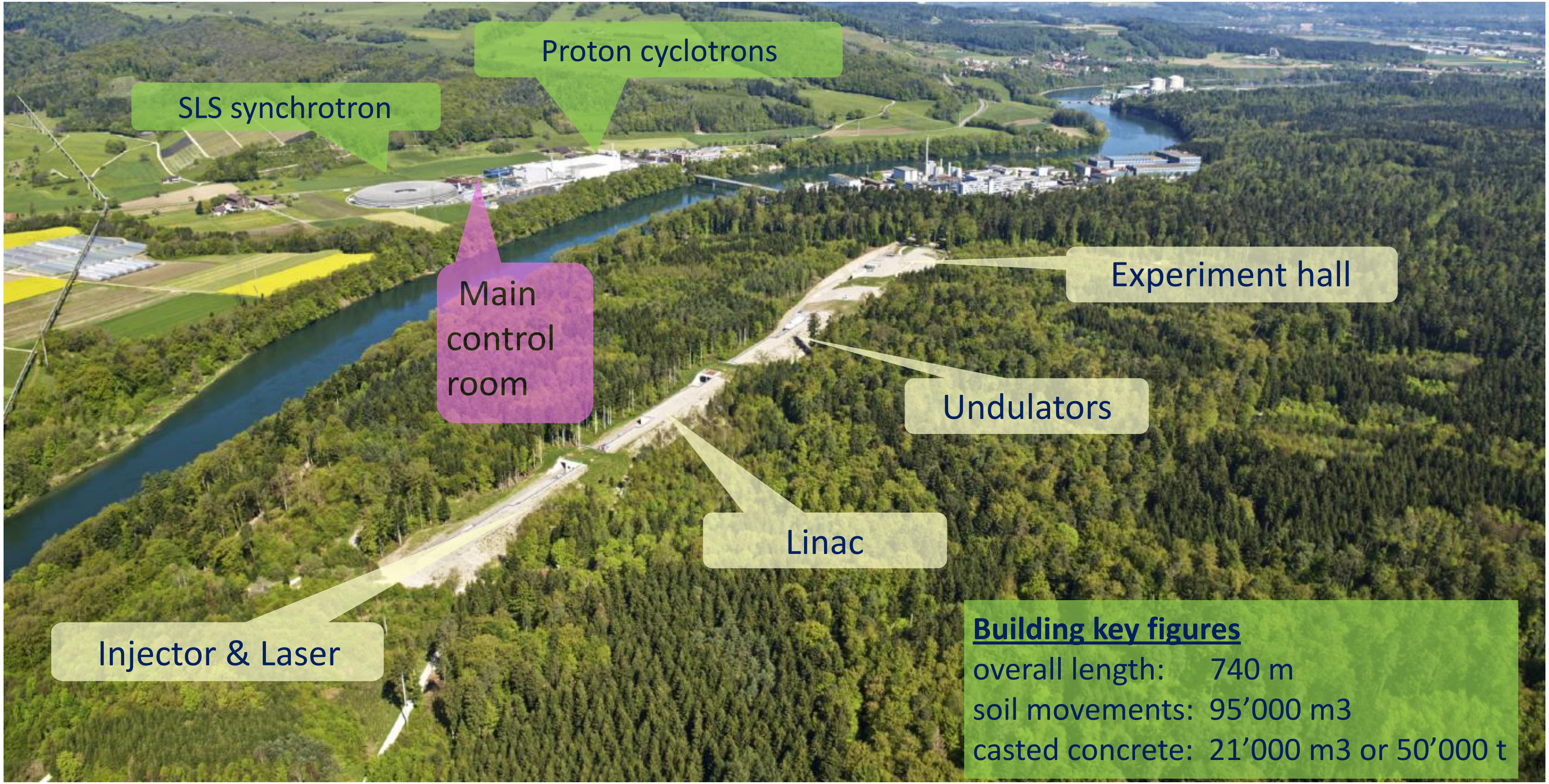
News from the operation of SwissFEL & the SLS

26th November 2018, XXVI ESLS Workshop, SOLARIS, Kraków, Poland

Outline

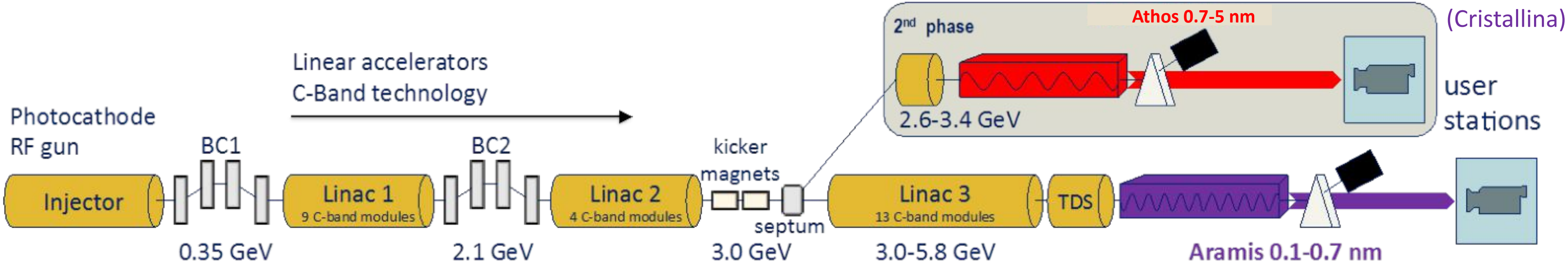
- ❑ SwissFEL overview
  - Experimental area
  - Schedule Aramis (hard X-rays)
  - SwissFEL machine evolution
  - ❑ Beam dynamics progress
  - ❑ C-band Linac and stability
  - ❑ Laser heater commissioning
  - ❑ Outlook Athos (soft X-rays)
- ❑ SLS Status & Outlook

SwissFEL site



Building key figures
overall length: 740 m
soil movements: 95’000 m3
casted concrete: 21’000 m3 or 50’000 t

SwissFEL Overview



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

ARAMIS

Hard X-ray FEL, λ=0.1 - 0.7 nm (12-2 keV)

Linear polarization, variable gap, 13 in-vacuum undulators

First users 2018

ATHOS

Beam Energy 2.7 – 3.3 GeV

Soft X-ray FEL, λ=0.65 - 5.0 nm (2-0.2 keV)

Variable polarization with Apple-X undulators (2-m long)

2nd construction phase 2017 – 2020

1st Undulator prototype just arrived!

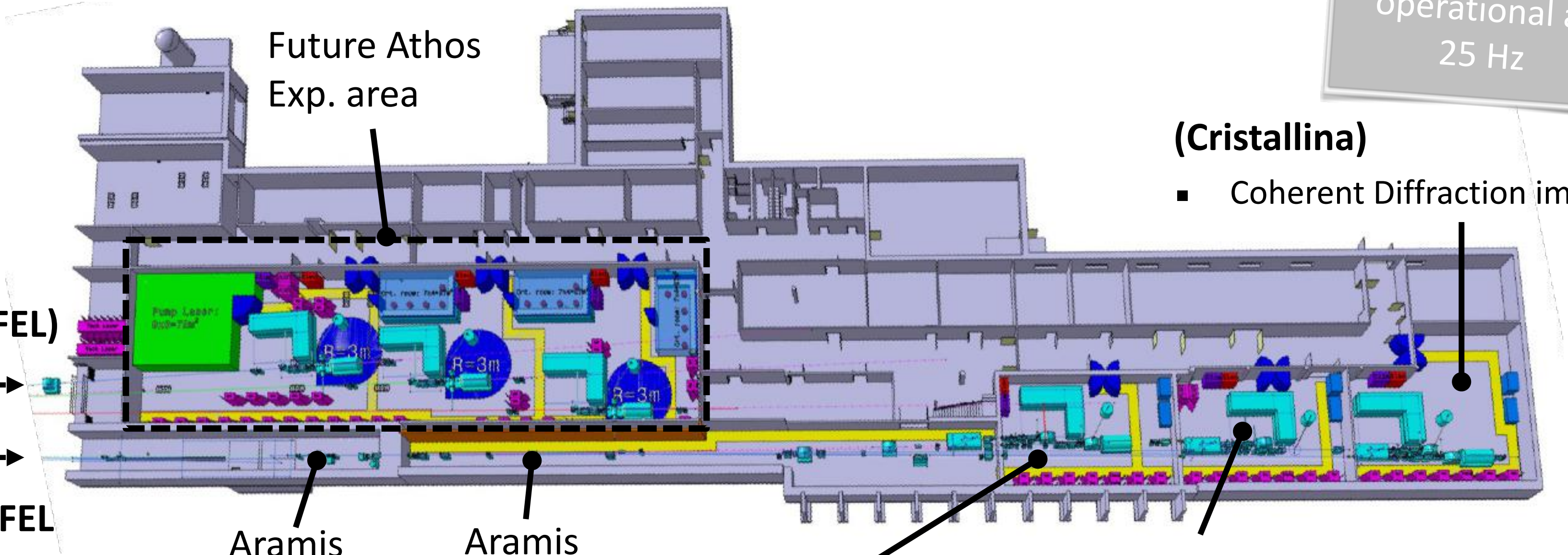
SwissFEL experimental area

Jungfrau Detector (32 MPixel) operational at 25 Hz

Future Athos Exp. area

(Athos FEL)

Aramis FEL



Aramis front end

Aramis optical hutch

(Cristallina)

- Coherent Diffraction imaging

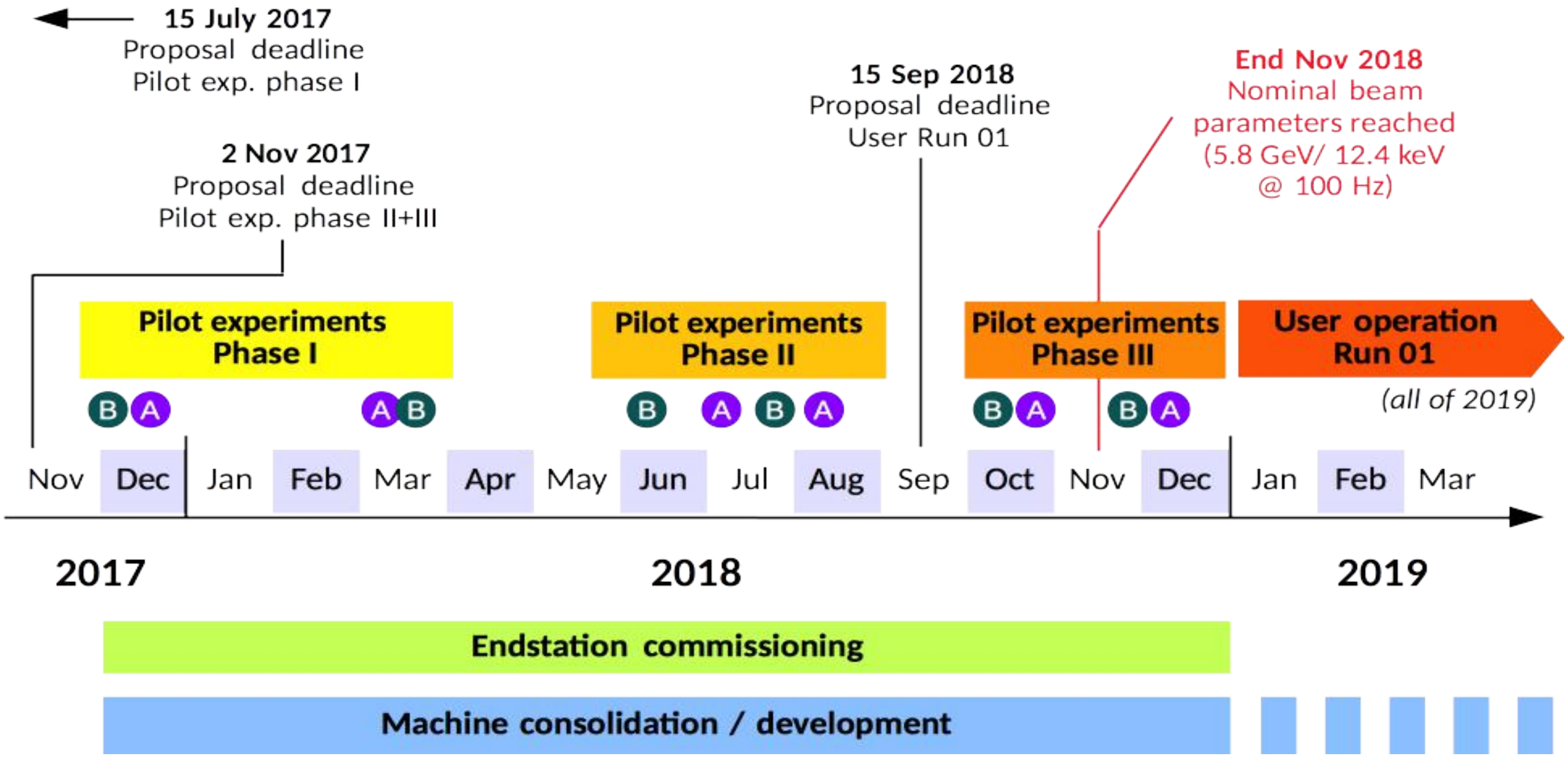
Alvra

- Multipurpose pump-probe
- Ultrafast biology and chemistry

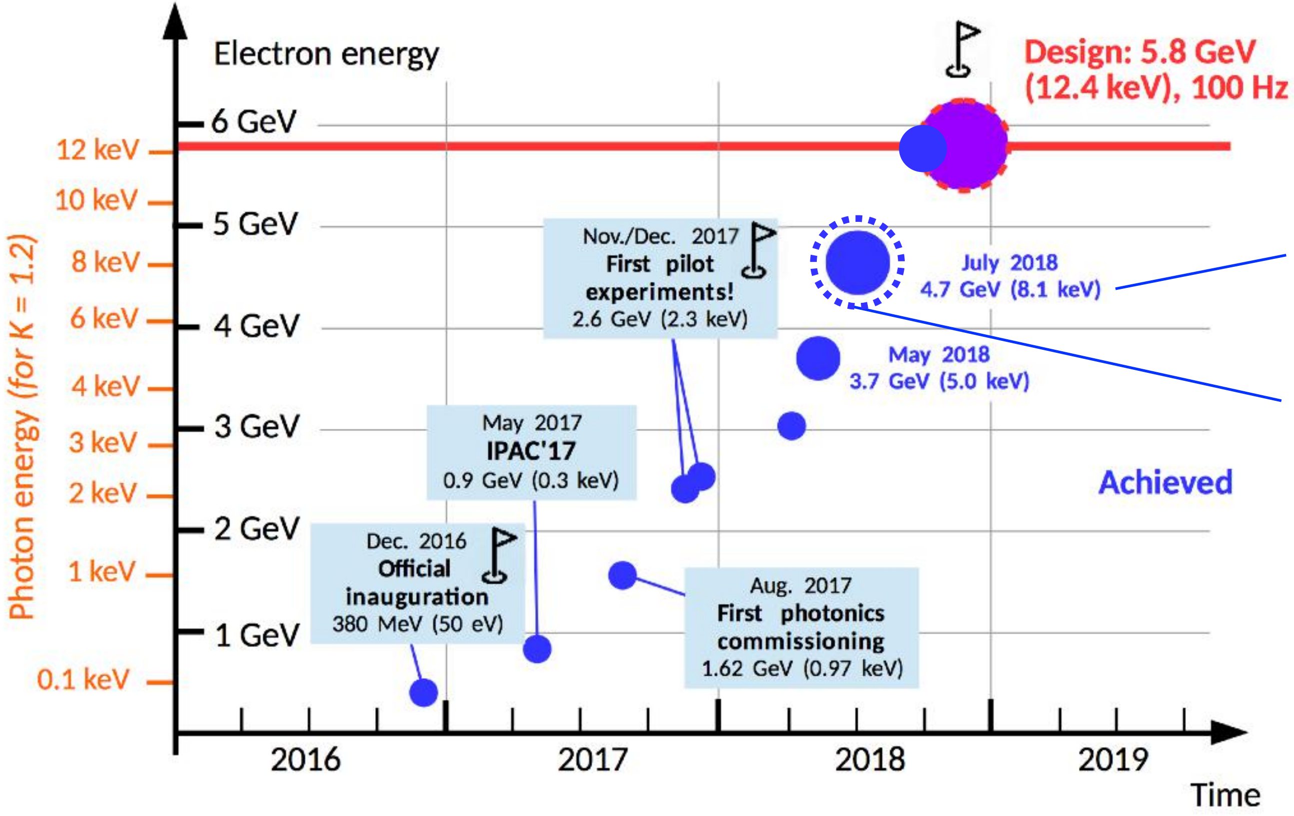
Bernina

- Pump-probe crystallography
- Ultrafast dynamics in solid matter, strongly correlated systems
- Structural biology (MX – macromolecuar crystallography)

Aramis schedule (hard-X-ray line)



SwissFEL Machine Evolution



Pushing for design parameters until the end of the year!

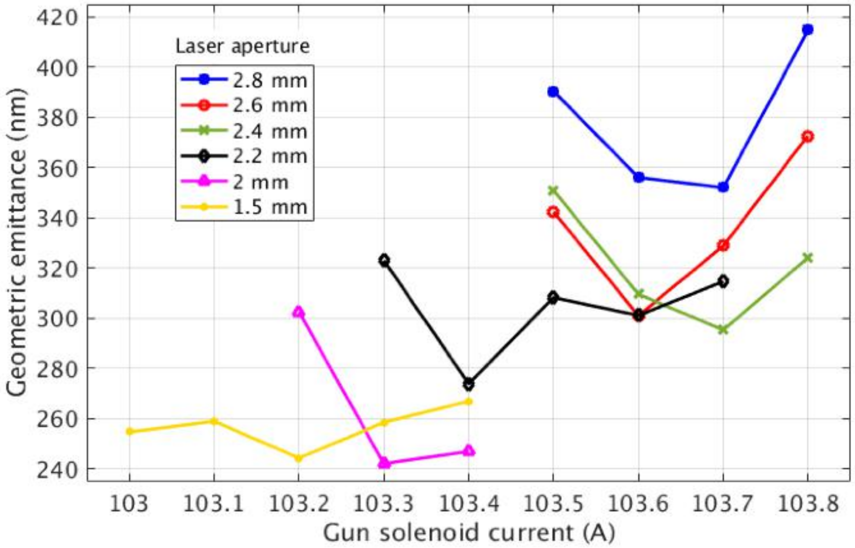
Aug 2018
First serial protein crystallography (SFX) experiments!

Summer/Fall 2018
Pump probe experiments becoming more established!
Reference measurements & availability of diagnostics)

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).

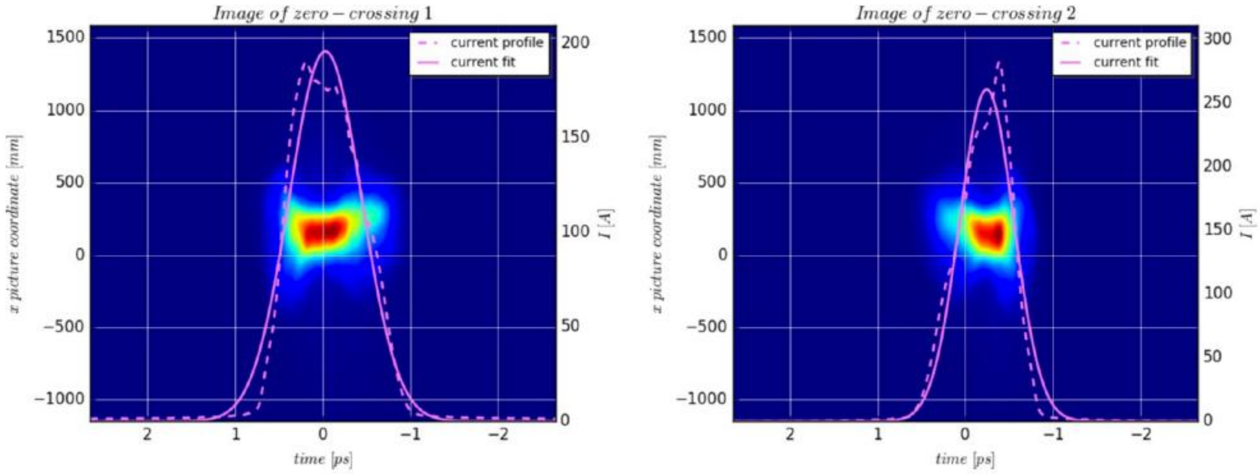


Ongoing studies about the emittance preservation through the machine! Hitting resolution limits of the screens…

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

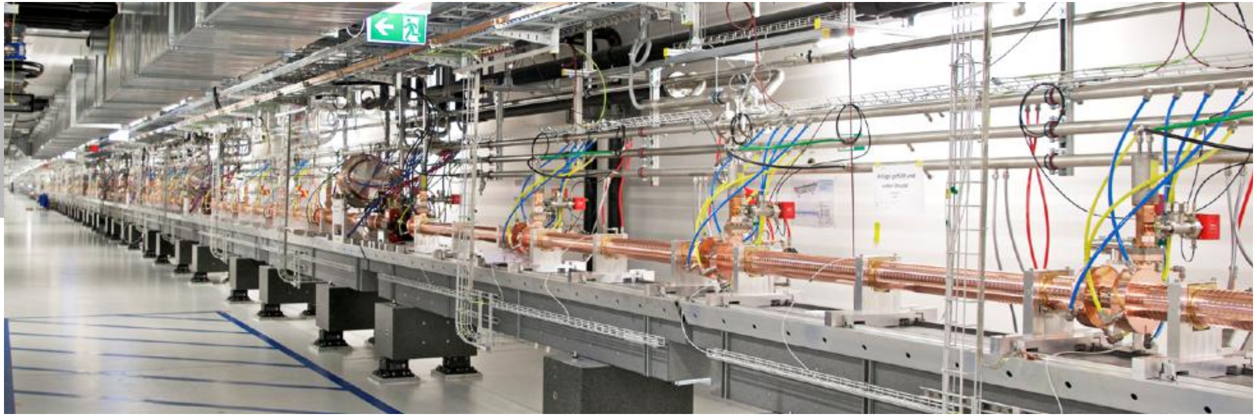


Example of bunch-length measurement after BC1

(two zero crossings of RF deflector)

PAUL SCHERRER INSTITUT PSI

C-band Linac



Solid State Modulators for C-Band

ScandiNova

K2-3 prototype for SwissFEL

13 modulators (Linac 3)

AMPEGON

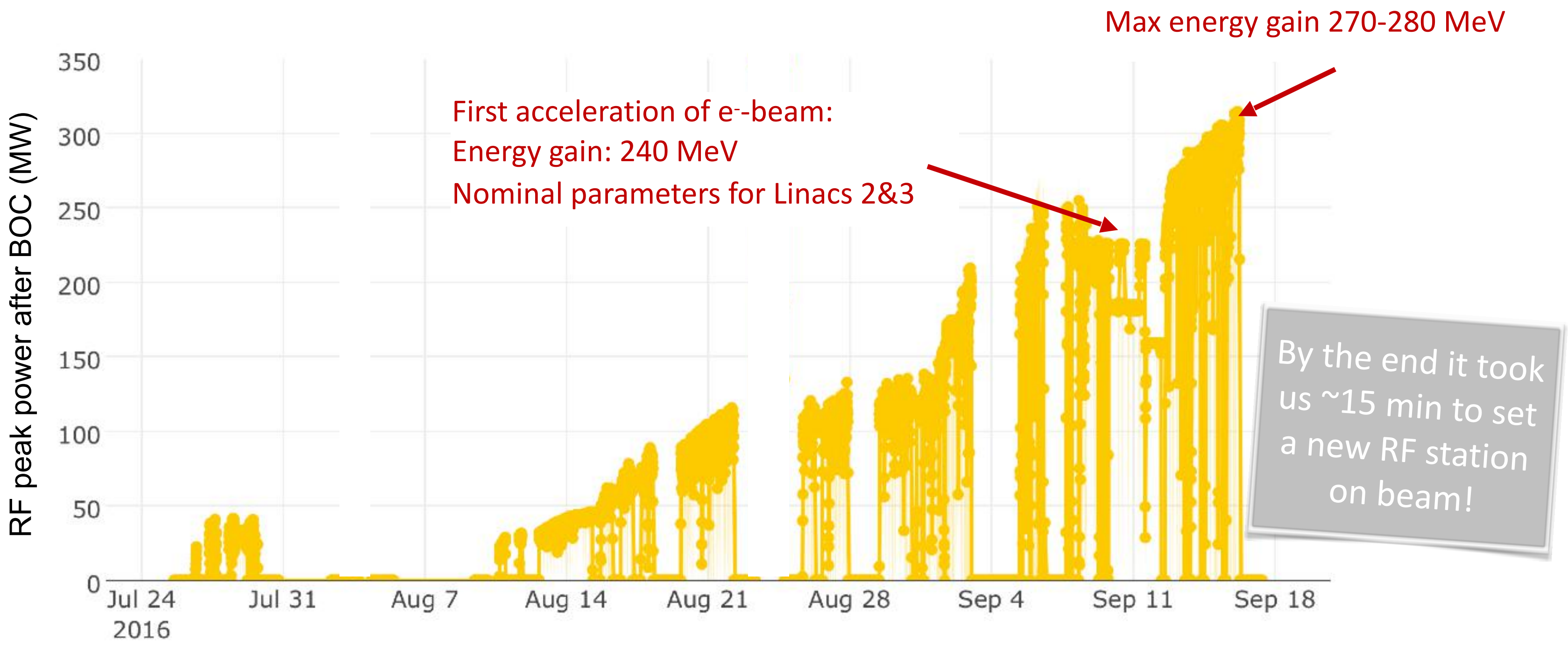
Type-μ prototype for SwissFEL

13 modulators (Linac 1, Linac 2)

Status

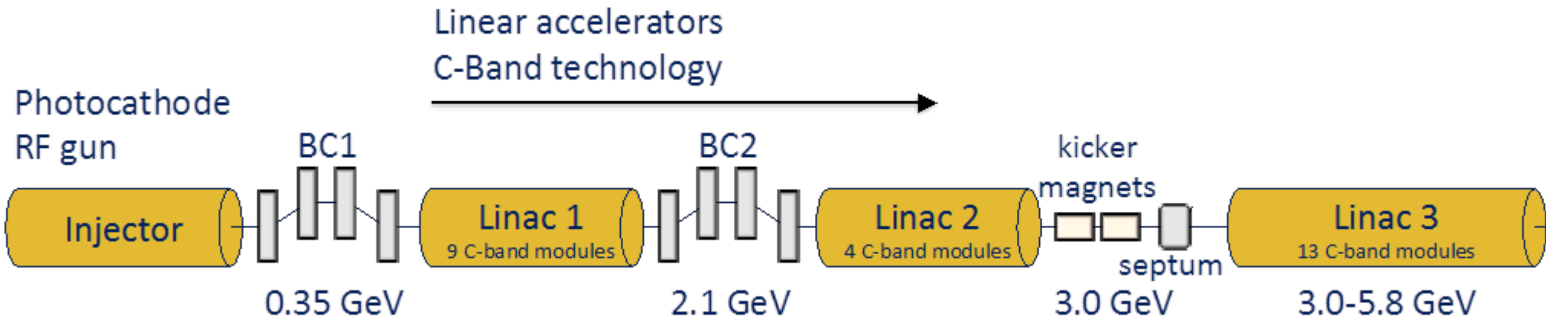
- 25 out of 26 modules on beam
  - Linac 1: all of the 9 modules
  - Linac 2: 3 module over 4
  - Linac 3: all of the 13 modules
- All modules run at 100 Hz
- **Reached nominal beam energy 5.8 GeV**
- Note: 300 MeV at injector exit (BC1)

Conditioning of first C-band module



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

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°

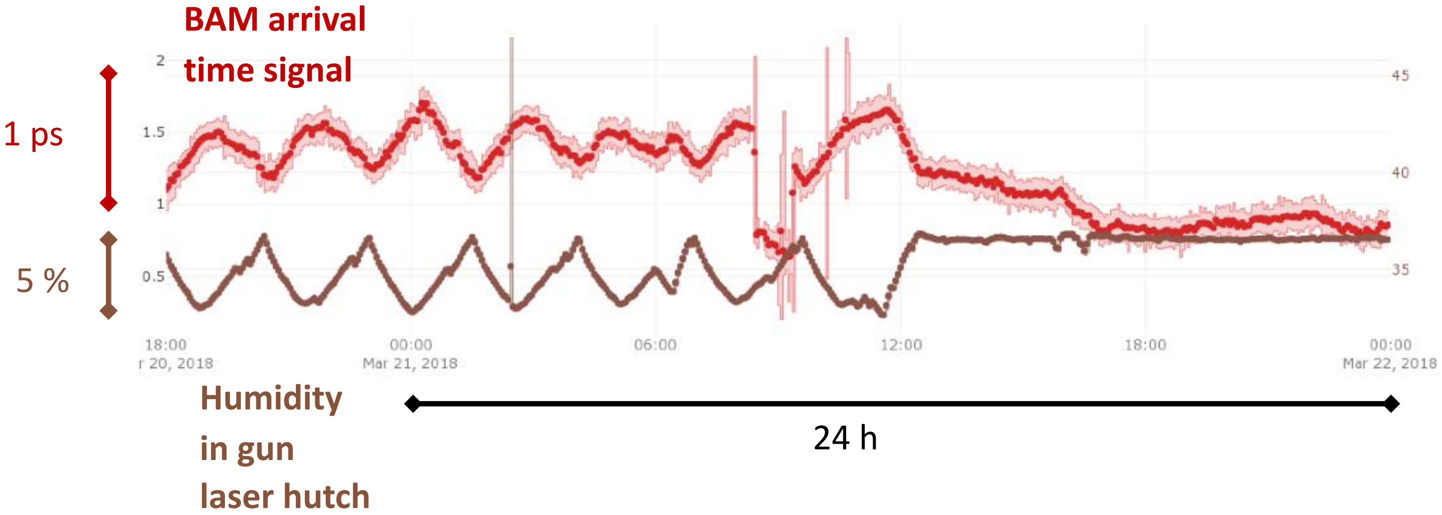
Pulse-to-pulse rel. ampli. jitter (rms)		
	Measured	Specs
S-band	0.01%-0.02%	0.02%
X-band	0.05%	0.05%
C-band	0.01%-0.02%	0.02%

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

Linac Stability (2)

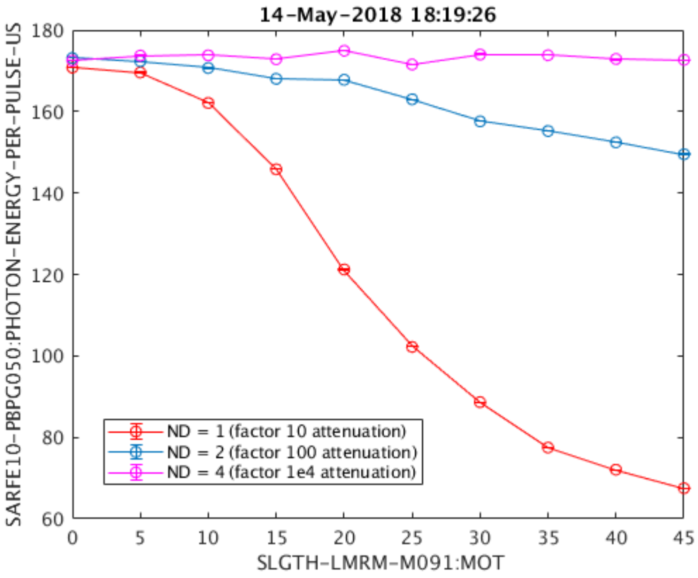
Arrival-time jitter

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



Laser Heater Commissioning

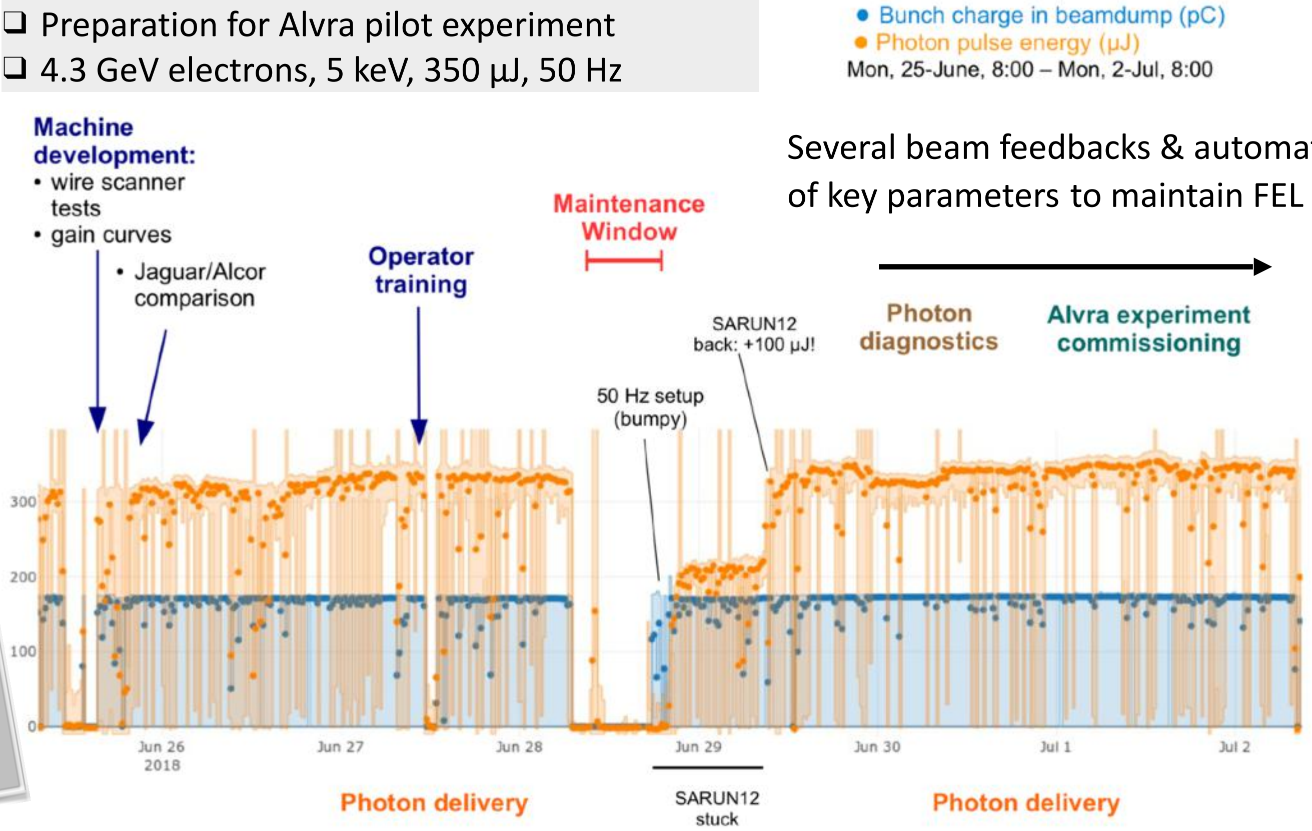
- **The mystery:** We cannot find an increase in FEL intensity for any settings of the laser heater, even when we compress a lot (3 kA pea current)! (Fermi & LCLS see up to 20% increase!)
- Setup / Alignment is completed & understood
- System produces uniform heating along the bunch & is strong enough to damp energy structures
- Investigated the effect for both gun lasers:
  - Alcor with stacked pulse and stretched Gaussian pulse
  - Jaguar with stretched Gaussian pulse
  - Similar results -> It is not caused by the laser profile
- **Conclusions so far:**
  - Microbunching instability is less detrimental than expected from simulations (assume 0 response time of cathode)
  - We suspect that our CsTe cathode has a slower response time & washes out most structures already



Example of FEL performance

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

Several beam feedbacks & automatic tweaking of key parameters to maintain FEL output

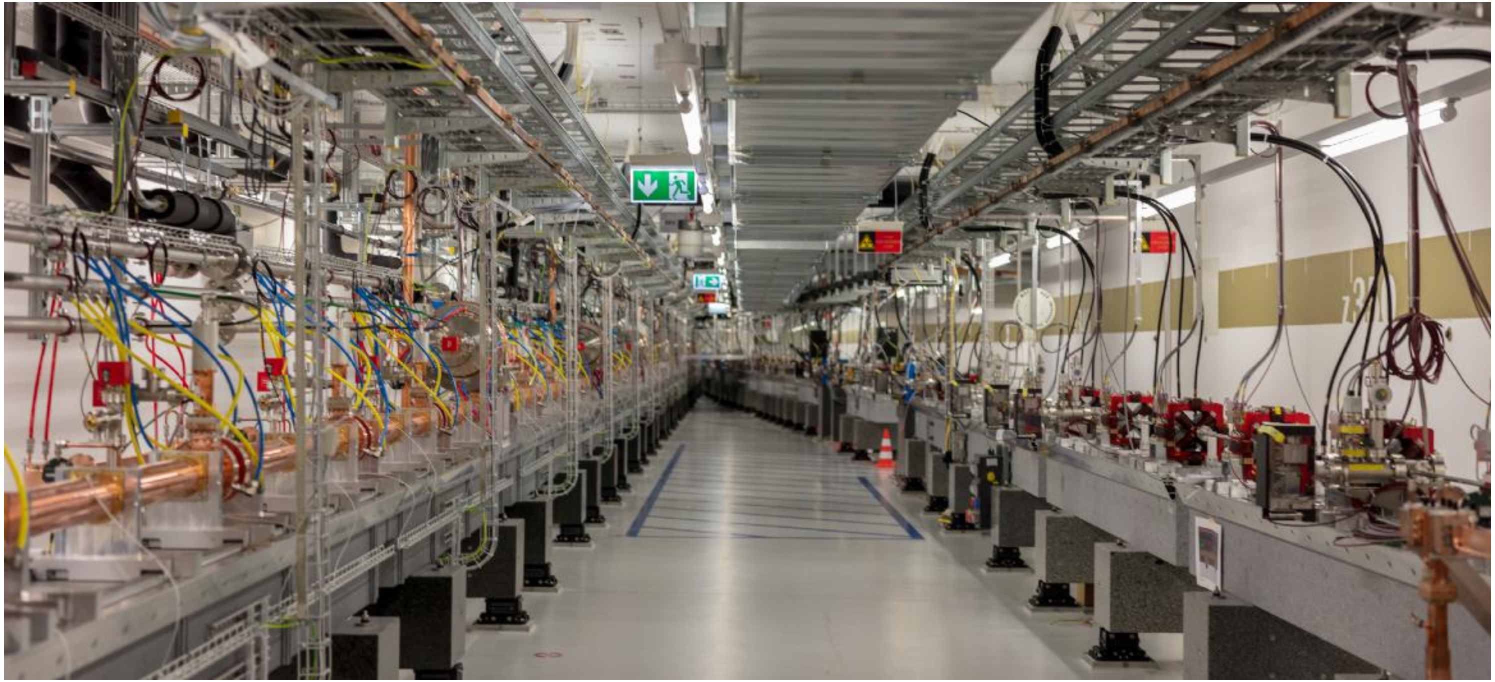


Most beam interruptions recover fully automatically

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

PAUL SCHERRER INSTITUT PSI

Outlook Athos (soft-X-ray line)

Athos schedule:

Athos dogleg in commissioning! Beam propagated through whole switchyard (21st Sept, 2018)

Resonant kicker system performs well!

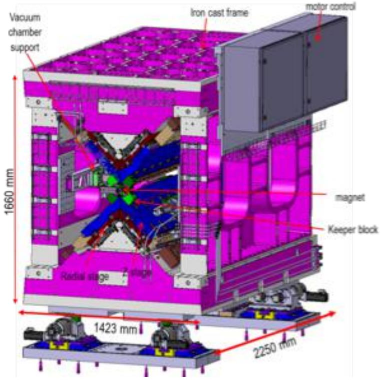
U38 module prototype delivered in November 2018

Delay chicanes in procurement

Undulator installation Jan. 2019 – March 2020

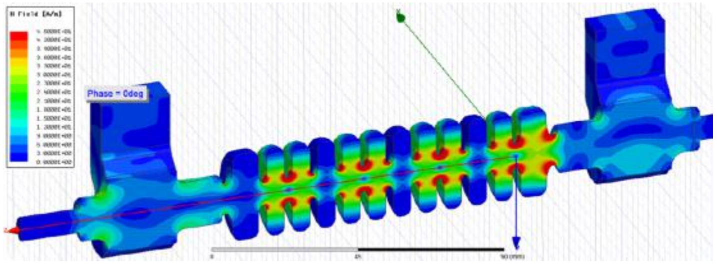
First pilot experiment end 2020

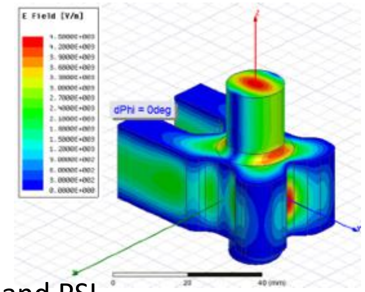
User operation from 2021



- 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)

Post-undulator X-band TDS with variable polarization





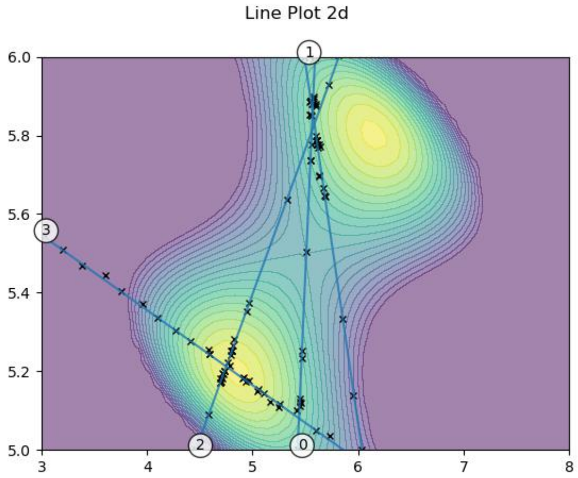
Collaboration between CERN, DESY and PSI

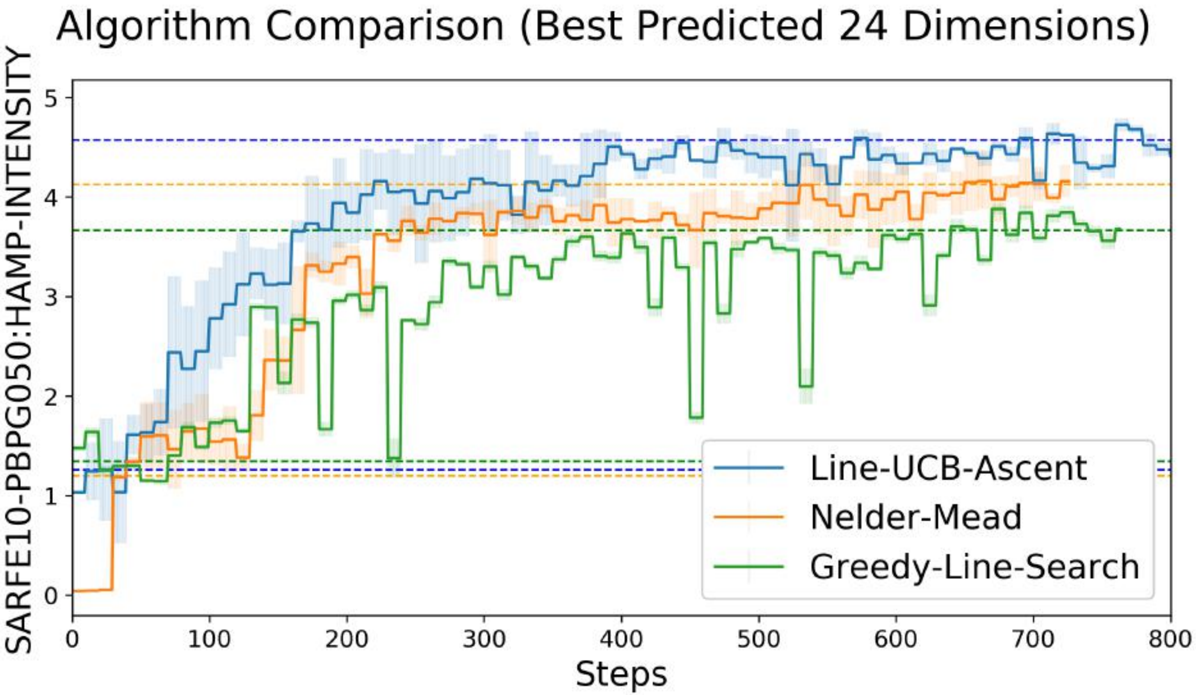
What is missing to achieve nominal performance?

- **Increase in repetition rate**
  - First tests at 100 Hz have been done
  - Load on some EPICS IOCs very high, network performance at limit, photonics detectors readout hitting the limit
- **Increase in beam / photon energy**
  - Nominal beam energy reached (want to have a bit more margin to operate comfortably, no proper "Virtual RF" control yet)
  - First very weak FEL light at 12.4 keV emitted -> Now we need to tweak this!
- **Increase in FEL intensity**
  - Tolerances for alignment of all components and the beam itself decrease with FEL energy -> much harder to lase with high intensity at 12.4 keV
  - More detailed jitter-investigation to identify sources
  - Systematic beam based alignment of whole machine, especially the undulator and X-band sections (first iteration done, but now a second iteration is required) -> ongoing
  - Study of the emittance preservation along the machine (we suspect our YAG screens to be saturated and measure too large bunches, cross-checks with the wire scanners are ongoing)
  - Systematic machine optimization (let's not get stuck in local optimum) -> That's why we started a collaboration with the ETHZ on machine learning based FEL optimisation -> poke me if you want to know more

Machine-Learning Based FEL Optimization

With: N. Hiller, M. Nonnenmacher, M. Mutny, F. Frei, A. Krause, R. Ischebeck

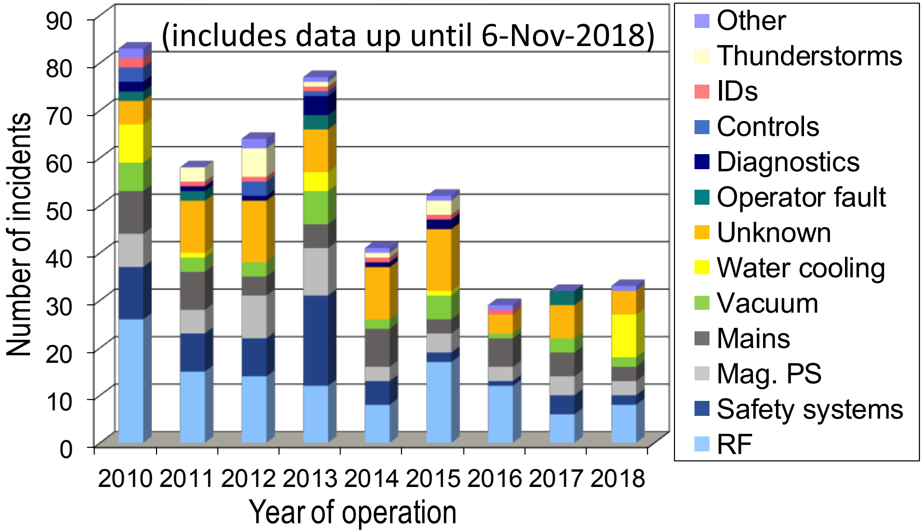


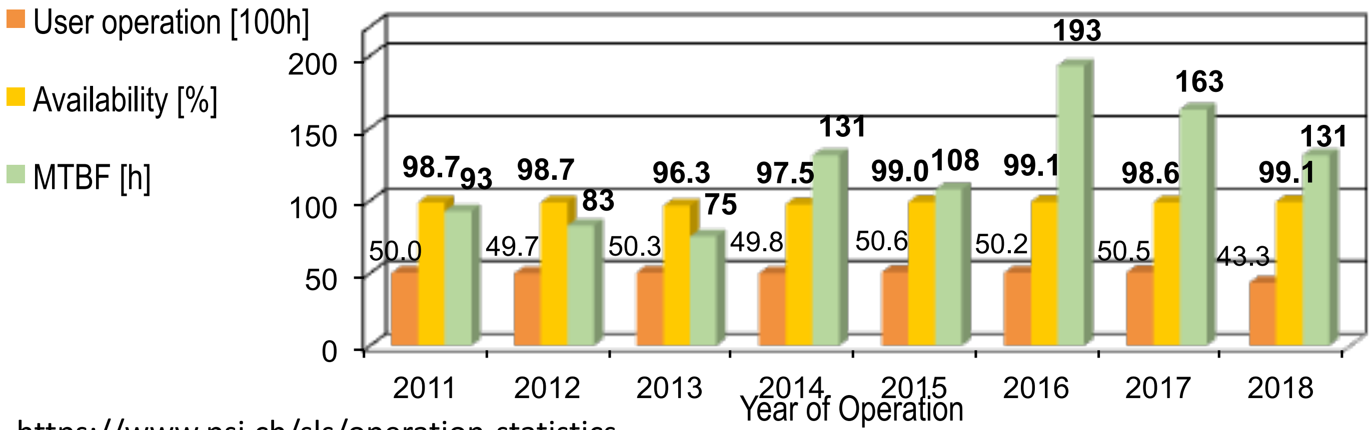


Preliminary results!

SLS Operation Statistics

- Very good year 2018 (so far):
- Excellent beam availability of 99.1%!
- Very good mean time between failures of 5.5 days
- Mean time between distortions very high: 66 hours
  - Very few BPM faults





- Jan/Feb 10 Water cooling interlocks -> took some time to understand what caused them
- X02DA-TOMCAT absorber water leak biggest interruption and we have 30 more of these installed…

https://www.psi.ch/sls/operation-statistics

Courtesy of A. Lüdeke

SLS - What has been going on in 2018

- RF upgrades in Linac (pulser board, thyratron replacement, ..)
- Since summer Shutdown: Booster operates with solid state RF amplifier (controls integration had been missing)

Detailed info in slides from ESLS-RF Workshop!

65 kW 500 MHz SSPA @ SLS

Outlook

- Infrastructure / Diagnostics need renewing (esp. with SLS 2.0 on the horizon)
  - LLRF Upgrade of Linac & Ring (SwissFEL solution for Linac)
  - BPM Upgrade (Electronics) required ideally before SLS 2.0
  - Feedbacks in need of upgrades:
    - Fast Orbit Feedback
    - Fast Adaptive / ID Gap Feed Forwards

SLS Renewal Workshop, Windisch, 30.-31.10.2018

Summary

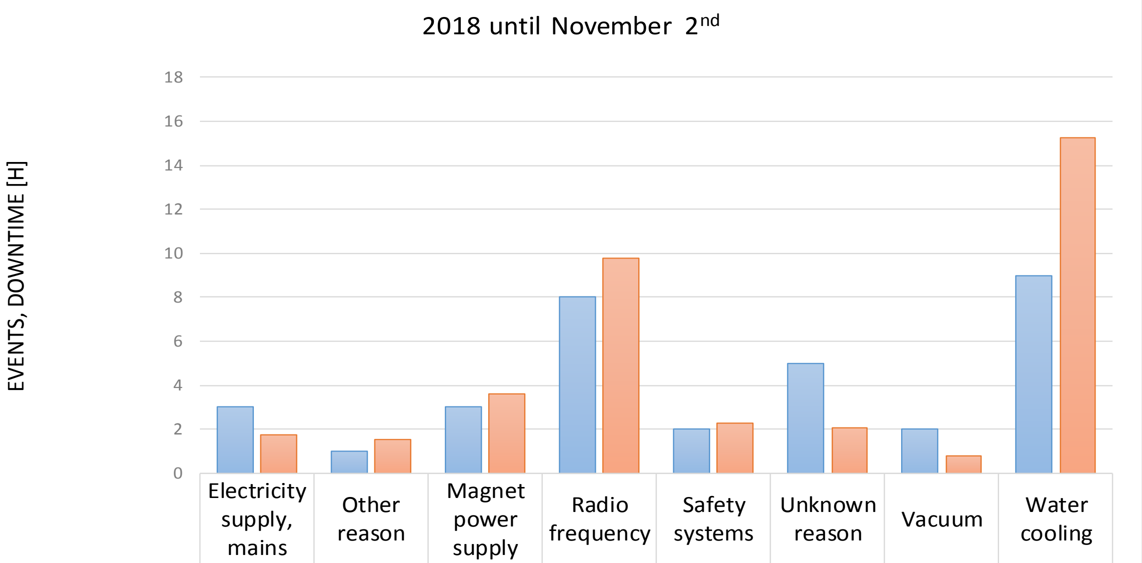
- SwissFEL has reached its 2017 and 2018 milestone of pilot experiments
- Systems and beam development program on track to reach nominal beam parameters by the end of 2018 (12.4 keV photon energy at 100 Hz).
- Reached nominal e-beam energy of 5.8 GeV!
- Regular user operation to start in 2019!
- New soft-X-ray beamline Athos on track for first users in 2021.
- SLS had another great year & is preparing for the SLS 2.0 upgrade

Bernard will tell you more about this!

SwissFEL: Many thanks to Thomas Schietinger, Paolo Craievich for providing a large portion of the presented slides that include the work of the whole commissioning team. And of course, to the whole SwissFEL and operation teams for making all this progress possible in the first place.

SLS: Many thanks to Andreas Lüdeke for the SLS operation statistics, Lukas Stingelin for input concerning the RF operation & many other colleagues for their valuable input.

SLS Operation Statistics - RF



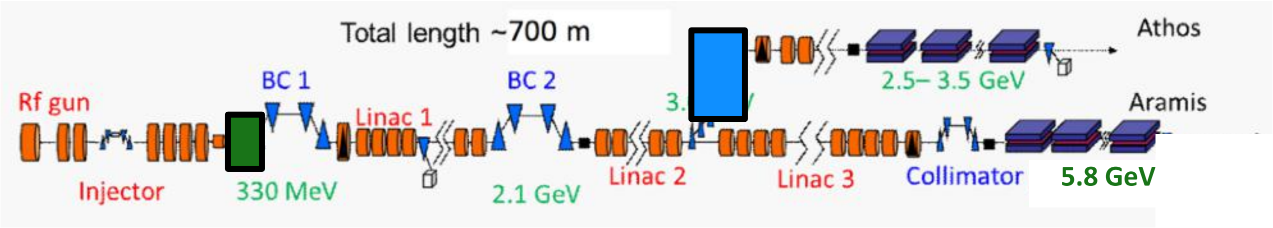
	Electricity supply, mains	Other reason	Magnet power supply	Radio frequency	Safety systems	Unknown reason	Vacuum	Water cooling
Events	3	1	3	8	2	5	2	9
Down time [h]	1.76	1.53	3.61	9.77	2.25	2.04	0.8	15.26

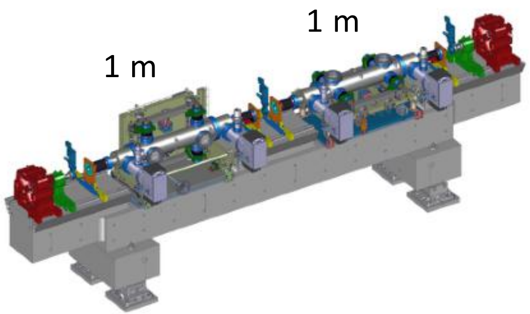
Main reasons for RF events:

- Drifts and settings of interlock thresholds (~4h)
- Klystron vacuum and modulation anode overcurrent (~3h)
- Loose contact in cooling rack (~1.5h)
- Flow switches (~1h)

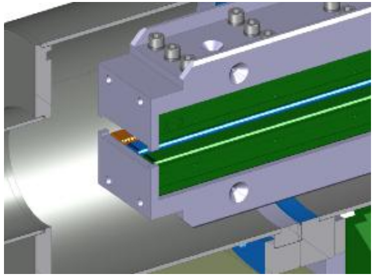
Courtesy of Lukas Stingelin (Shown at 22nd ESLS-RF workshop, 2018)

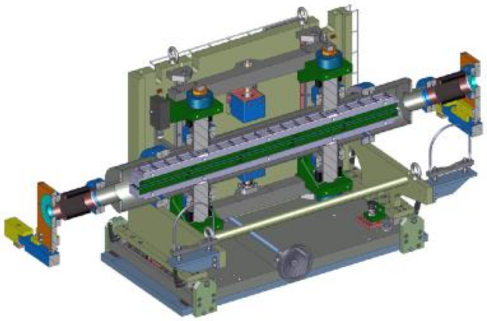
Beam manipulation in SwissFEL linac





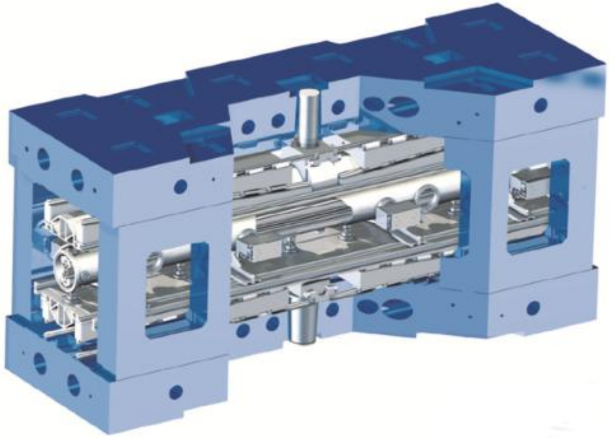
- ❑ Passively streak the beam (1-10 ps bunch length): 1 mm ≤ λ_W ≤ 6 mm
- ❑ Test the two-color generation via wakefield excitation: λ_W = 1 mm
- ❑ Alternatively linearize: λ_W = 6 mm
- ❑ Remove the chirp residual from the compression: λ_W = 2 mm
- ❑ Passively streak the beam at higher energy and shorter bunch length (~10-500 fs)





Aramis Undulator Line

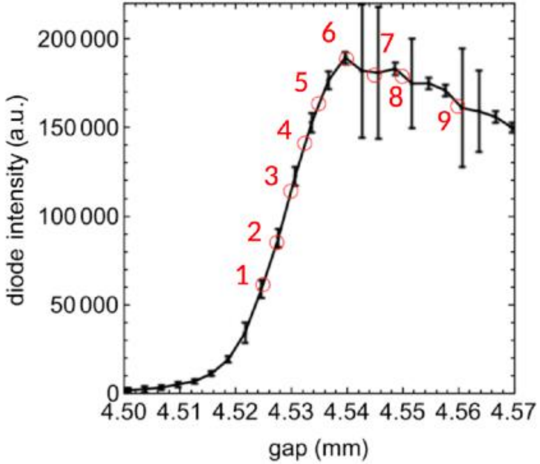
- In-vacuum, variable-gap undulators “U15”
- Undulator period 15 mm
- Nominal gap 4.5 mm for K = 1.2
- Array of 1060 permanent magnets per module
- 13 modules of 4 m length
  - Total length 65 m
  - Active length 52 m

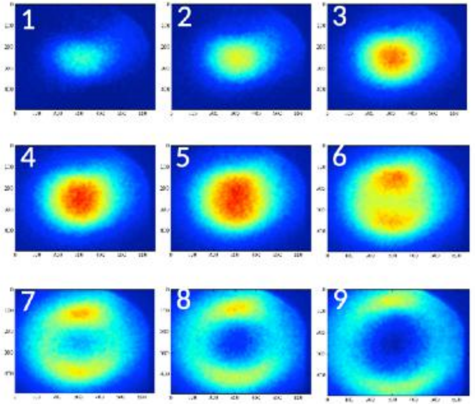


Aramis undulator line

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

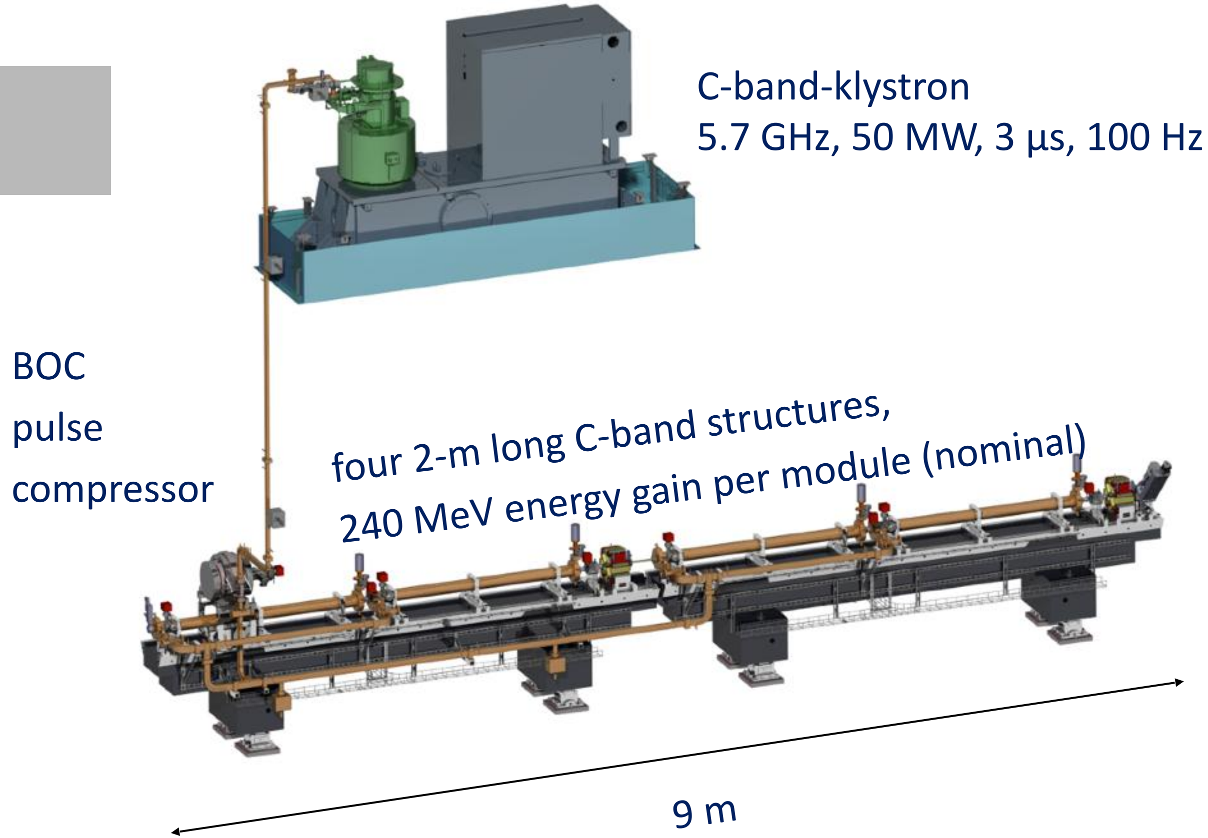
- Systematic comparison of electron- and photon-based measurements
  - Some variations in contributions from modules not yet understood.
  - Some photon beam properties not yet understood (spatial chirp).
- Completion of photon-based fine tuning
  - Establishment of final BBA procedure

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.*

Slide courtesy of P. Craievich

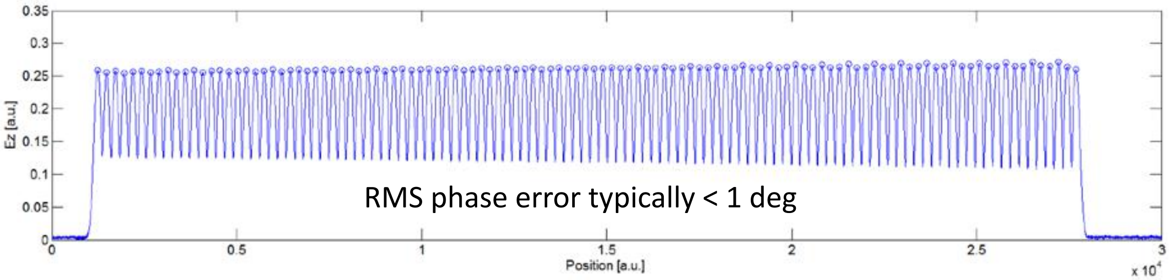
C-Band module



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

C-band structures

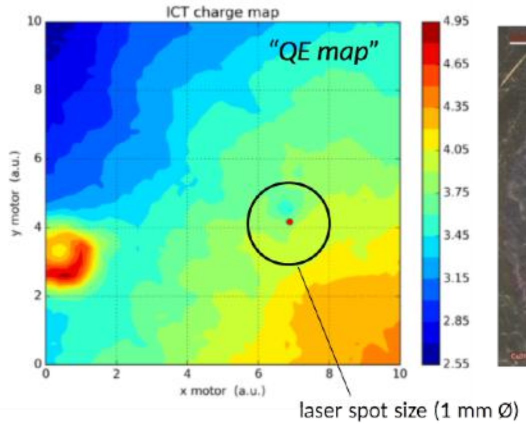
- Structures are machined “on tune”, no provisions for dimple tuning!
- Cup manufacturing with micron precision at VDL ETG Switzerland
- Coupler manufacturing at VDL ETG
- Stacked by robot and vacuum brazed at PSI
- Production rate: 1-2 structures/ week
- High power results for first structure:
  - Conditioned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

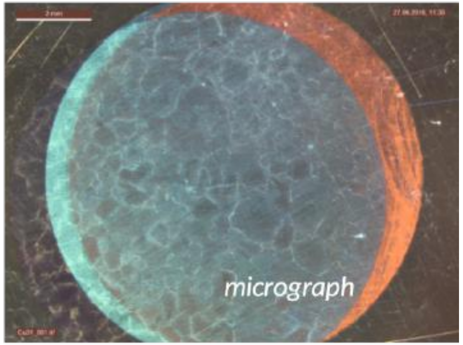


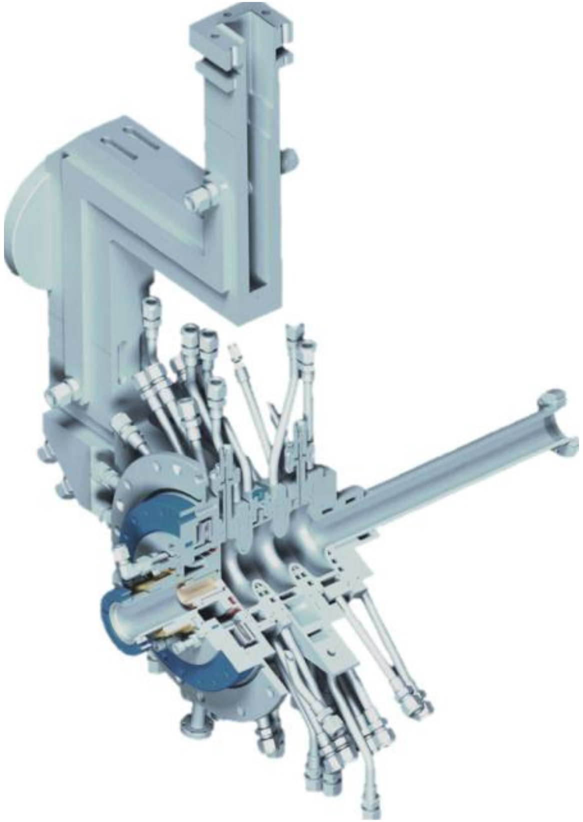
Bead pull measurement - No tuning

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, very low dark current
- Standard operating procedure for routine gun-laser check – fundamental for stability and reproducibility of the facility!





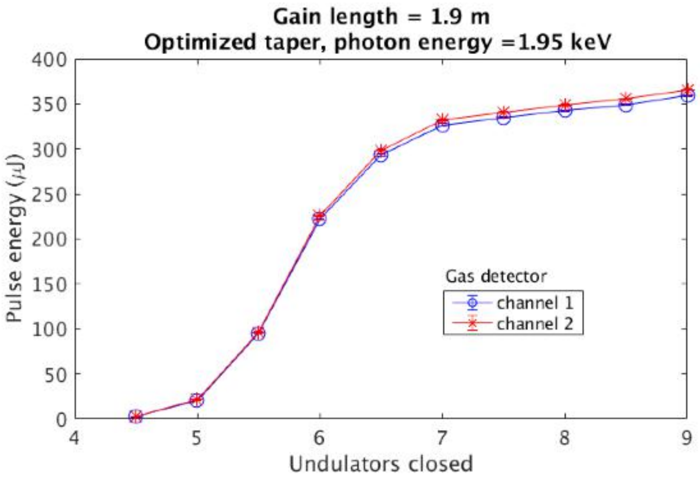


FEL setup and characterization

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] – ongoing
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. Empirical 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