First Commissioning Results of the European XFEL

Julien Branlard, on behalf of the DESY LLRF group
European XFEL Overview
- Project
- Cryogenics
- RF station

RF commissioning
- Planning
- Milestones
- Automation

First Results
- Beam
- RF
- Energy

* Note: many slides borrowed from Winni Decking’s IPAC 2017 invited oral presentation: MOXAA1: “Commissioning of the European XFEL Accelerator” W. Decking, H. Weise
The European X-ray Free Electron Laser
- 17.5 GeV light source user facility, 500kW beam power
- TESLA superconducting 1.3 GHz RF cavities
- 27000 pulses per second in 10 Hz burst mode
- 3 variable gap undulator section for hard and soft X-rays
- Dec. 18th 2015: first beam in injector
- 2015-2016: main tunnel installation
- Q1 of 2017: main linac commissioning
- May 4th 2017: first lasing!
- End of 2017: first user operation

Watch online: https://www.youtube.com/watch?v=p3G90p4gIQA
European XFEL: Commissioning Timeline

- 12/16: Cool down
- 01/17: Injector at 130 MeV (3 RF stations)
- 01/17: L1 commissioning (+1 RF station)
- 02/17: L2 commissioning (+3 RF stations)
- 02-04/17: L3 commissioning (+15 RF stations)
- 04/17: Beam through SASE1 undulator section
- 05/17: First Lasing + repeated
- 05-08/17: Commissioning SASE1 photon beamline and experiment
- 09/17: First user experiment (total 800 hours)
- 2018: Continue facility commissioning + 2000 user hours
- 2019: Routine operation with 6 experiments + 4000 user hours
**European XFEL: Cryogenics**

- Cryoplant cooling capability at 2K > 1.9 kW
- Linac is one 1.5 km long cryostring

**Temperature versus time at 9 positions along the linac**

- Cool down with one cold box
- Start asymmetrical operation of two cold boxes to speed up cool down
- Recovery of cold return flows in cold boxes to enhance cryogenic capacity
- Fast cool down at temperatures below liquid nitrogen (no more thermal stress)
- Reached 4K

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**2K line pressure fluctuation during normal operation**

- 2K pressure ±1%
- Sudden shutdown of 18 RF stations
- 7 hours

- Stability requirement for 2K pressure 2% peak (cavity detuning)
- Heaters to counteract dynamic heat load

*No cold leaks!*
First XFEL Commissioning Results

European XFEL: RF stations

Technical commissioning represents >50% of the commissioning time

Intersystem commissioning is a key factor of the commissioning time

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**RF COMMISSIONING: Goals**

- **INJ** (GUN, A1, AH1)
  - Already commissioned and in operation (cold) throughout 2016
  - Recommissioning necessary due to warm up/cool down + installation of new components

- **L1** (A2)
  - First time commissioning of a complete RF station (4 cryomodules)
  - “Commissioning” of the commissioning plan
  - First time 32 cavity vector sum feedback control

- **L2** (A3, A4, A5)
  - 3 times L1
  - “Validation” of the commissioning plan

- **L3** (A6 – A20)
  - 15 times L1
  - Hardware slightly different
  - Change strategy: horizontal commissioning (step 1 for all stations, then step 2, etc.)
RF COMMISSIONING: Planning

- Commissioning team
  - 8 LLRF experts
  - 6 colleagues from DESY
  - 6 colleagues from external facilities (SLAC / HZDR)

- Commissioning shifts
  - Two 8-hours shifts / day
  - Following DESY’s operator shift program

- Procedure
  - Parallel work (station-wise)
  - Follow detailed commissioning checklist
  - Gather issues.
  - Investigate/fix on maintenance day (once a week)
RF COMMISSIONING: Planning

IN operation
ON beam

IN operation but shifted OFF beam

Not ready for beam operation hence shifted OFF beam

Operation Mode: SASE1/3, TLD
Beam Mode: Short
Personal Interlock: XTL Beam Permission

Beam operation to T4D 11 GeV, 1 bunches, 0.5 nC, 1 Hz

L3 / CL / TLD

IN operation ON beam
IN operation but shifted OFF beam
Not ready for beam operation hence shifted OFF beam

Magnets
LINAC Mode: Grounded

1 @99 %
10381 MeV

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RF COMMISSIONING: LLRF milestones

- Initial checks
- RF signal checks: **Forward** and **Reflected**
- Frequency tuning
- RF signal checks: **Probe**
- Coupler tuning
- Power-based gradient calibration
- Closed-loop operation

**RF ONLY**

LLRF system ready for commissioning?
- Cabling issues? Signal saturation?
- From parking position to resonance
- Cabling issues? Signal saturation?
- Target $Q_L = 4.6e6$
- Coarse
- Feedback, learning feedforward, ...

**READY FOR BEAM**

- Establish beam transport
- Cavity phasing
- Beam-based gradient calibration

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**Cavity tuning**

1. Perform initial check (1 motor turn ~ 15 kHz)
   “Check that the detuning changes in the correct direction, in the proper amount and for the correct cavity”

2. If successful, tune to resonance (coarse)
   “Based on step-to-resonance measured at AMTF”

3. If successful, tune to resonance (fine)

Example: A3.L3 1 RF station (32 cavities) tuned from parking position to resonance in 1h.
RF COMMISSIONING: Tool automation

- Cavity tuning
RF COMMISSIONING: Tool automation

- Cavity tuning
RF COMMISSIONING: Tool automation

- RF signal checks (1/2)

“what’s wrong with this picture?”

RF COMMISSIONING: Tool automation

- RF signal checks (2/2)
  - 3-4 mins per RF station
  - Verify phase shifter functionality (32x)
  - Identify cabling errors:
    - FORW ↔ REFL
    - C1 ↔ C2

- Reminder:
  - LLRF has 2500+ RF signals (Probe, forward, reflected)
  - x2 counting int/ext cabling

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First XFEL Commissioning Results

PRELIMINARY RESULTS: Lasing!

First lasing 02-03 May 2017
- E = 6.4 GeV
- K = 3.5
- 1.3 keV

Scientists say the ability to make images of individual molecules “marks the beginning a new era of research in Europe.”
PRELIMINARY RESULTS: RF stability

**RF regulation** (in-loop)

Specifications:

- \( \sigma \left( \frac{dA}{A} \right) = 0.01 \% \) ✓
- \( \sigma (dP) = 0.01 \text{ deg.} \) ✓

Intra-pulse \( \sigma \left( \frac{dA}{A} \right) = 0.0057 \% \)

Pulse-to-pulse \( \sigma \left( \frac{dA}{A} \right) = 0.0056 \% \)

Intra-pulse \( \sigma (dP) = 0.0051 \) deg.

Pulse-to-pulse \( \sigma (dP) = 0.0024 \) deg.

Courtesy S. Pfeiffer
The energy stability measured by them is roughly 1.6e-4 after the injector, 1.1e-4 after L3.

Energy stability:
1.6e-4 after the injector
1.1e-4 after L3

Energy measurements:
- **BC0**: $\sigma_y = 147 \, \mu m$, $D_y = -222 \, mm \Rightarrow \sigma_E/E = 6.6e^{-4}$
- **BC1**: $\sigma_y = 225 \, \mu m$, $D_y = -490 \, mm \Rightarrow \sigma_E/E = 4.6e^{-4}$
- **BC2**: $\sigma_y = 149 \, \mu m$, $D_y = -382 \, mm \Rightarrow \sigma_E/E = 3.9e^{-4}$

Courtesy: L. Fröhlich
First XFEL Commissioning Results

PRELIMINARY RESULTS: Energy reach

- Design accelerating gradient: 23.5 MV/m
- Average accelerating gradient: 26.0 MV/m (after module test and waveguide tailoring)
- After initial commissioning design gradient almost reached
- On-going measurement campaign to assess limits and reasons

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PRELIMINARY RESULTS: RF commissioning

- **4 out of 720** couplers shorted after test in XTL

- **6 out of 720** cavities not used due to AMTF results
  - A7.M2.C7: high FE/X-ray (11 MV/m limit)
  - A18.M4.C4: high FE/X-ray (23 MV/m limit + wrong $P_{\text{FORW}}$)

- **10 out of 22** RF stations actually have all cavities tuned
  - i.e only 50% of the RF stations have a 32-cavity vector sum
Cabling issues

- **15 cabling issues** (outer rack) identified before cool down
- **17 cabling issues** (outer rack) identified after cool down
- **0 cabling issues** (inner rack) identified so far

Multipacting

- Observed on nearly all stations
- Start appearing around 550-600 MV (i.e. ~17-18 MV/m)
- Up to 50% of cavities / cryomodule required conditioning (worse case)
- Conditionable on all stations
- Required couple of hours per station (@10 Hz)
- 3 GeV additional energy after conditioning

\[ \text{\{~1.5\%}} \]
First XFEL Commissioning Results

PRELIMINARY RESULTS: RF commissioning

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CONCLUSIONS and OUTLOOK

■ Baseline commissioning went well
  ▪ Strong commissioning team
  ▪ Automation
  ▪ Test as much as possible, as early as possible
  ▪ Availability of cryomodule test results
  ▪ Finite state machine to ramp up/down and trip recovery

■ Recent milestones (June 2017)
  ▪ CS8 commissioned: new energy reach 13.2 GeV
  ▪ Lasing at 2 Å, with 700 μJ
  ▪ Commissioning of undulators and photon beamline
  ▪ Light up to experimental hall

■ Looking ahead
  ▪ First user operation in September 2017
  ▪ Maximum gradient assessment
  ▪ Installing piezo drivers later this year
  ▪ CS9 commissioning (Spring 2018)
  ▪ Preparation for multi beamline operation
First XFEL Commissioning Results

THANK YOU FOR YOUR ATTENTION!

Photo Dirk Noelle

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