INSTALLATION AND FIRST COMMISSIONING OF THE LLRF SYSTEM FOR THE EUROPEAN XFEL

Julien Branlard, for the LLRF team
TALK OVERVIEW

- Introduction
  - Brief reminder about the XFEL LLRF system
  - Commissioning goals

- Commissioning
  - Planning
  - Steps description + automation
  - Results: some statistics

- Assessment
  - What went well, what didn’t
  - What’s done, what’s left
The European X-ray Free Electron Laser

- 17.5 GeV light source user facility
- TESLA superconducting 1.3 GHz RF cavities
- 1.4 msec RF pulses at 10 Hz
- e- beam 1.35 mA nom. - 4.5 mA max
- 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

source: http://www.xfel.eu

source: http://www.fis-landschaft.de

watch online:
https://www.youtube.com/watch?v=p3G90p4glQA
INTRODUCTION: the XFEL LLRF system

**INJECTOR**
- A1
- AH1
- RF gun
- 3.9 GHz
- 5 MeV

**LINAC1**
- cryostring 1
- A1
- DL
- BC1
- A2
- 130 MeV
- 2.4 GeV

**LINAC2**
- cryostring 2
- BC2
- A3
- A4
- A5

**LINAC3**
- cryostring 3
- A6
- A7
- A8
- A20
- A21
- A22
- A23
- A24
- A25
- A26
- 17.5 GeV
- undul.

**CM1 (8 cav.)**
- LLRF master
- Drift compensation
- Reference synchr. + distr.
- Clocks + local oscillator
- Main controller crate (MicroTCA)
- Piezo*
- Power supplies
- * not installed yet

**CM2 (8 cav.)**
- LLRF master

**CM3 (8 cav.)**
- LLRF slave

**CM4 (8 cav.)**
- LLRF slave

**LLRF master**
- LLRF master
- LLRF slave

**KLYSTRON**
- CM1
- CM2
- CM3
- CM4
- DM
- BPM
- PZ16M
- PSM
- LOGM
- DCM
- RF
- Wasserplatzhalter
- 3.5 m

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INTRODUCTION: the XFEL LLRF system

Technical commissioning represents >50% of the commissioning time

Intersystem commissioning is a key factor of the commissioning time
INTRODUCTION: 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..)
TALK OVERVIEW

- Introduction
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- Commissioning
  - Planning and milestones
  - Steps description + automation
  - Results: some statistics

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COMMISSIONING: planning

- Commissioning team
  - 8 LLRF experts
  - 6 trained colleagues from DESY
  - 6 colleagues from external facilities

Commissioning team of 20 people

- 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)
 Initial checks
  - LLRF system ready for commissioning?

 Cold coupler conditioning

 RF signal checks: Forward and Reflected
  - Cabling issues? Signal saturation?

 Frequency tuning
  - From parking position to resonance

 RF signal checks: Probe
  - Cabling issues? Signal saturation?

 Coupler tuning
  - Target $Q_L = 4.6e6$

 Power-based gradient calibration
  - Coarse

 Closed-loop operation
  - Feedback, learning feedforward, …
COMMISSIONING: LLRF milestones (2/2)

- Establish beam transport
  - 30 bunches, 0.5nC

- Cavity phasing
  - Using waveguide phase shifters

- Beam-based gradient calibration
  - Fine relative calibration
  - Absolute validation using energy server

- Estimated schedule
  - Injector (gun, A1, AH1) 2 weeks
  - L1 (1 RF station) 2 weeks
  - L2 (3 RF stations) 2 weeks
  - L3 (15 RF stations) 2 months

Example: beam induced transient during cavity phasing
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.
Cavity tuning
Cavity tuning
RF signal checks (1/2)

“what’s wrong with this picture?”

- Calibration
  - Probe
  - Forward
  - Reflected
- Limiters
  - Pre-Limit
  - Limit
- Phase Check
  - Peak
  - Phase

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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
Cabling issues
- 15 cabling issues (outer rack) identified before cool down
- 11 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
COMMISSIONING: multipacting commissioning
XFEL LLRF commissioning

COMMISSIONING: some statistics

- **4 out of 616** couplers shorted after test in XTL

- **5 out of 616** cavities not used due to AMTF results
  - A5.M1.C5 temporary, shorted pick up
  - A6.M3.C1 high FE/X-ray (10 MV/m limit)
  - A7.M2.C7 high FE/X-ray (11 MV/m limit)
  - A10.M1.C3 low Eacc BD (no FE) (13 MV/m limit)
  - A18.M4.C4 high FE/X-ray (23 MV/m limit + wrong P\textsubscript{FORW})

- **10 out of 19** RF stations actually have all cavities tuned
  - i.e only 50% of the RF stations have a 32-cavity vector sum
RF regulation (in-loop)

Intra-pulse $\sigma(dA/A) = 0.0057\%$

Pulse-to-pulse $\sigma(dA/A) = 0.0056\%$

Intra-pulse $\sigma(dP) = 0.0051\text{ deg.}$

Pulse-to-pulse $\sigma(dP) = 0.0024\text{ deg.}$

Specifications: $\sigma(dA/A) = 0.01\%$

$\sigma(dP) = 0.01\text{ deg.}$

Courtesy S. Pfeiffer
XFEL LLRF commissioning

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ASSESSMENT: what went well

- Install / test as much as possible, as early as possible
  - Individual component tests
  - Crate installation
  - Rack installation

- Automation
  - Simple scripts
  - Broken down into single, modular tasks

- Availability of cryomodule test data
  - Results from individual cryomodule tests
  - Cavity gradient limits, phase shifter limits, …
  - What to pay attention to (tune / don’t tune)
ASSESSMENT: what went well

- **Checklists + documentation**
  - Prepare the checklist
  - Test the checklist
  - Iterate the checklist
  - Stick to it

- **Machine operation**
  - Handed over RF station to operators after couple of days
  - Regular operator trainings
  - On-call LLRF experts
  - Finite State Machine: ramp up / down stations + recovery

- **Strong Team**
  - Large machine → large commissioning team
  - Beware of the installation burn out (2 years…)
  - External support (fresh eyes + enthusiasm)
ASSESSMENT: what didn’t go so well

- Initial checks of tuners drivers
  - More than 40% initial checks failed
  - Several iterations required → time consuming

- Triggered one cryo incident
  - Multipacting: “working here but quenching there”

- Too long recovery time ("phase jumps")
  - Intricate combination of timing + reset + clocks resulting in 240 deg. phase jumps (single boards) after a crate reboot

- Piezo driver
  - Piezo driver production was delayed > 2 years
  - To be installed and commissioned during maintenance this year
The baseline commissioning phase went relatively well
- Strong commissioning team
- Automation

Still a few milestones on our “to do” list
- Max energy?
- Piezo
- Performance assessment, stability, drifts (i.e. “advanced” commissioning)
- Improved diagnostics (aging, radiation, system health)

Further higher-level development
- Inter-RF station communication + automation
- Multi-beamline operation
THANK YOU FOR YOUR ATTENTION!

Photo Dirk Noelle