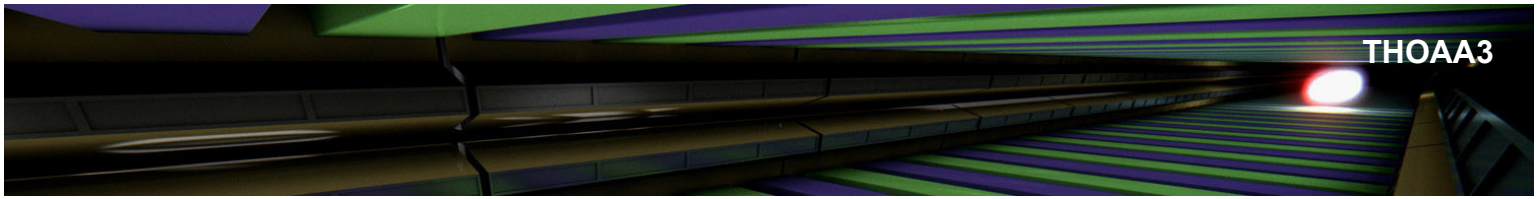


INSTALLATION AND FIRST COMMISSIONING OF THE LLRF SYSTEM FOR THE EUROPEAN XFEL

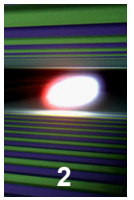
Julien Branlard, for the LLRF team

IPAC17

DESY

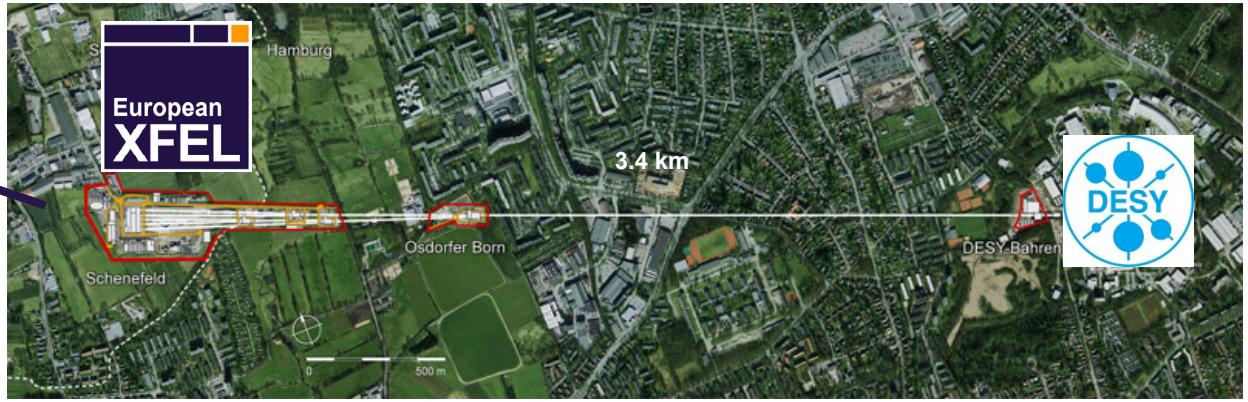
HELMHOLTZ ASSOCIATION

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

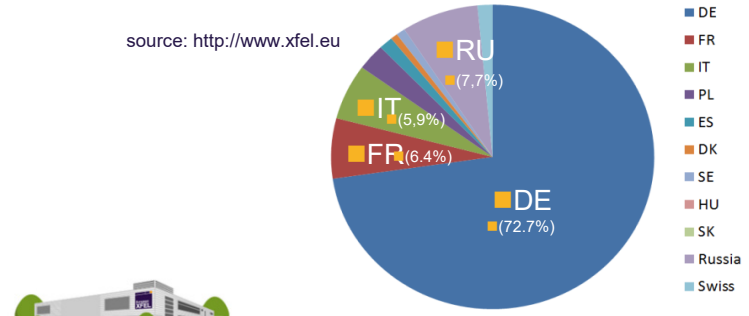
European XFEL



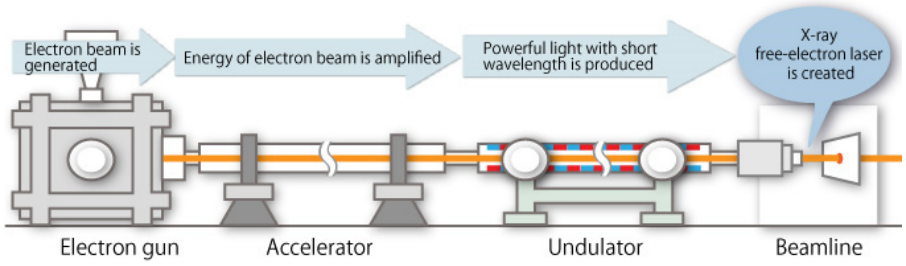
The European X-ray Free Electron Laser

- 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



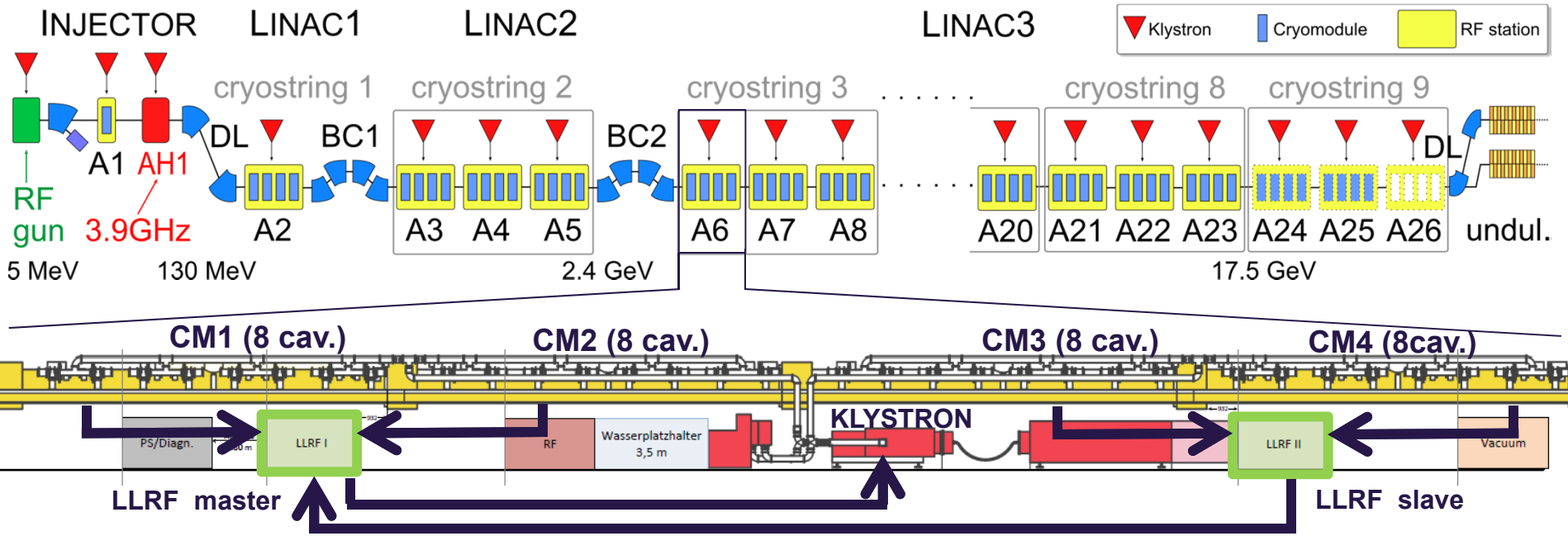
source: http://www.fis-landschaft.de

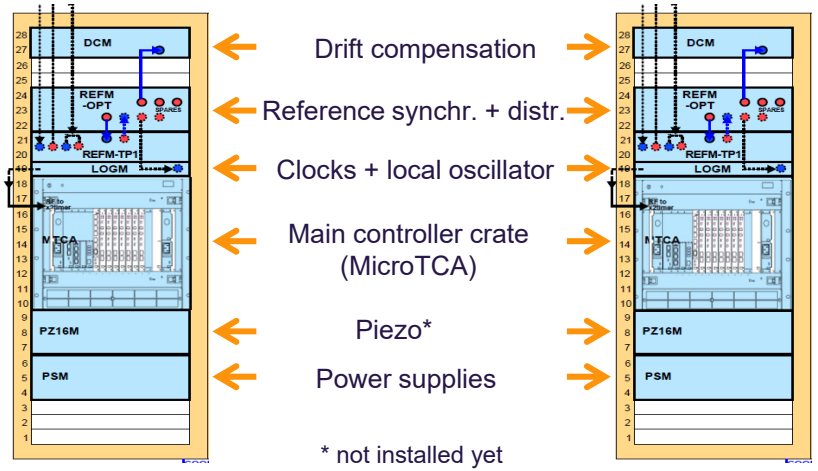


YouTube watch online:

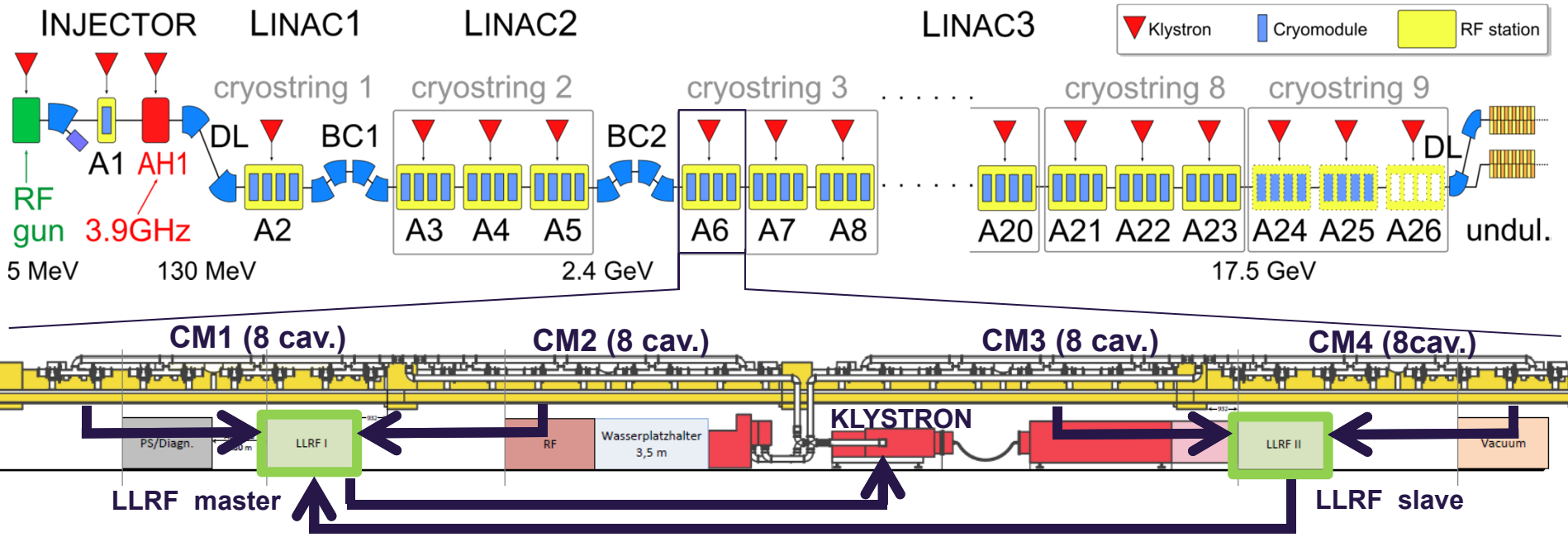
https://www.youtube.com/watch?v=p3G90p4glQA

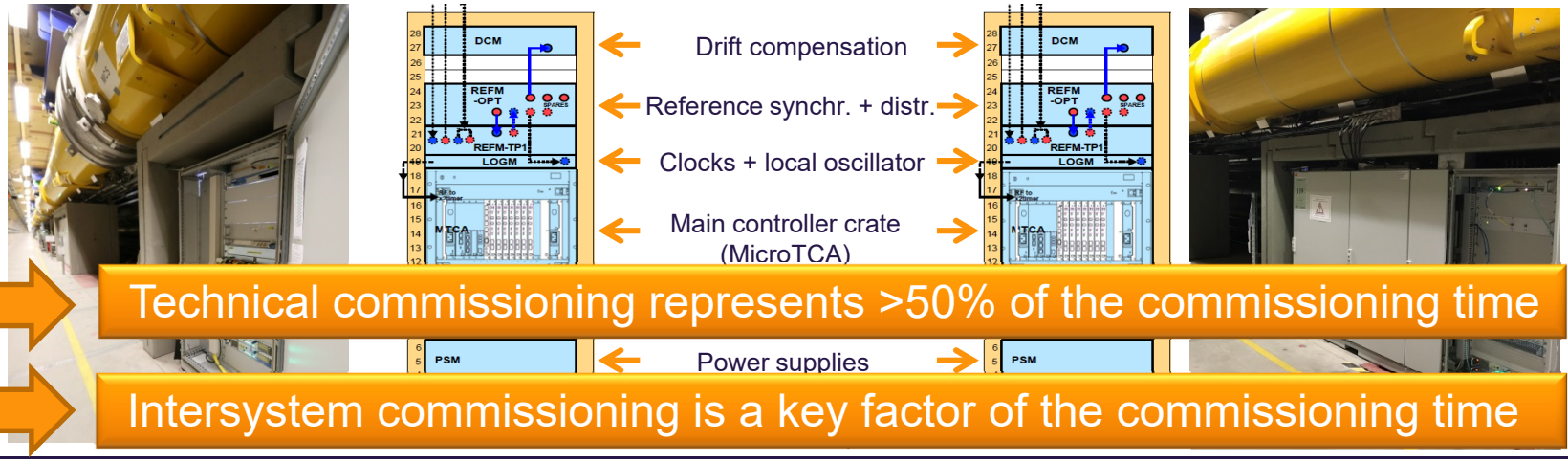
INTRODUCTION: the XFEL LLRF system





INTRODUCTION: the XFEL LLRF system

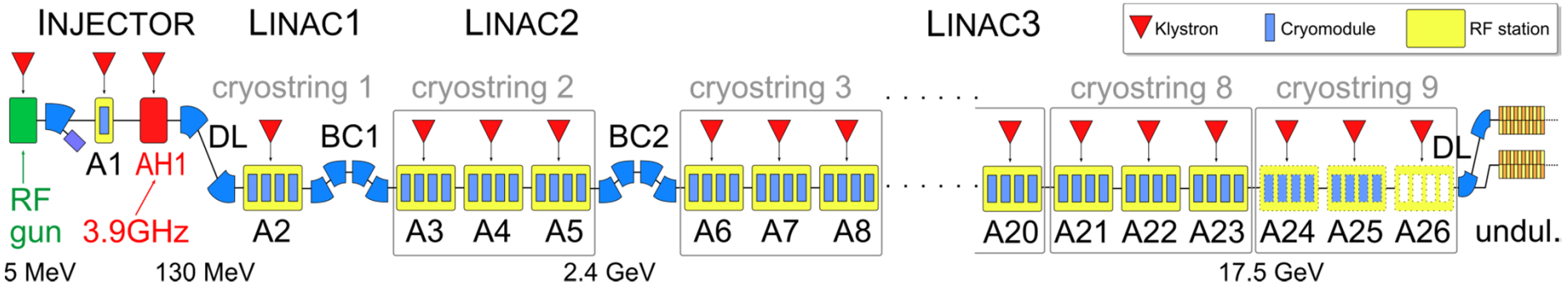




Technical commissioning represents >50% of the commissioning time

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

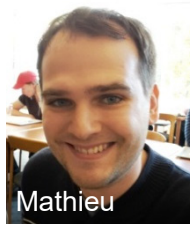
- Introduction
  - Brief reminder about the XFEL LLRF system
  - Commissioning goals
- **Commissioning**
  - Planning and milestones
  - Steps description + automation
  - Results: some statistics
- Assessment
  - What went well, what didn't
  - What's done, what's left

COMMISSIONING: planning

Commissioning team

- **8** LLRF experts
- **6** trained colleagues from DESY
- **6** colleagues from external facilities

→ **Commissioning team of 20 people**

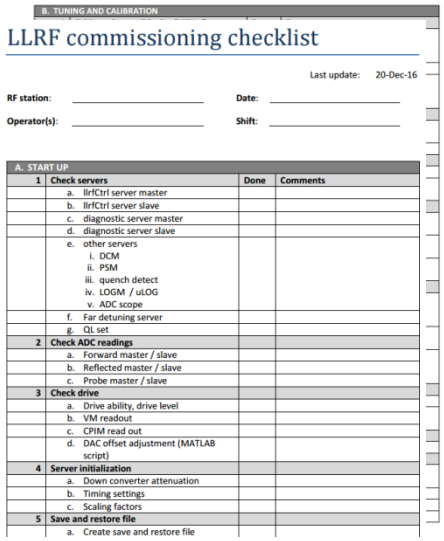


Commissioning shifts

- 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)



B. TUNING AND CALIBRATION

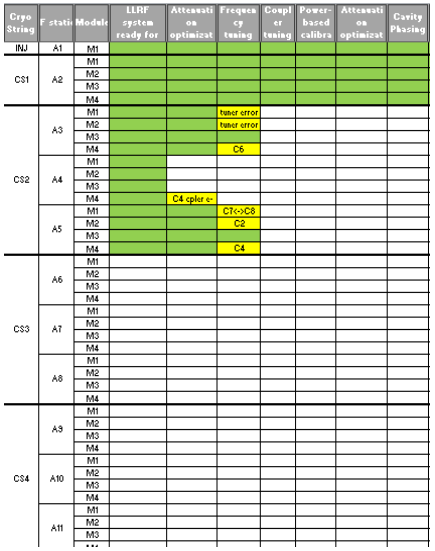
LLRF commissioning checklist

Last update: 20-Dec-16

RF station: Date:

Operator(s): Shift:

A. START UP				
1	**Check servers**		**Done**	**Comments**
	a.	llrfCtrl server master		
	b.	llrfCtrl server slave		
	c.	diagnostic server master		
	d.	diagnostic server slave		
	e.	other servers i. DCM ii. PSM iii. quench detect iv. LOGM / uLOG v. ADC scope		
	f.	Far detuning server		
	g.	QL set		
2	**Check ADC readings**			
	a.	Forward master / slave		
	b.	Reflected master / slave		
	c.	Probe master / slave		
3	**Check drive**			
	a.	Drive ability, drive level		
	b.	VM readout		
	c.	CPIM read out		
	d.	DAC offset adjustment (MATLAB script)		
4	**Server initialization**			
	a.	Down converter attenuation		
	b.	Timing settings		
	c.	Scaling factors		
5	**Save and restore file**			
	a.	Create save and restore file		



Cryo String	F station	Module	LLRF system ready for	Attenuation optimizat	Frequency tuning	Coupler tuning	Power-based calibra	Attenuation optimizat	Cavity Phasing
INJ	A1	M1							
CS1	A2	M1							
		M2							
		M3							
		M4							
CS2	A3	M1			tuner error				
		M2			tuner error				
		M3							
		M4			C6				
	A4	M1							
		M2							
		M3							
		M4		C4 cplar c-					
	A5	M1			C7<->C8				
		M2			C2				
		M3							
		M4			C4				
CS3	A6	M1							
		M2							
		M3							
		M4							
	A7	M1							
		M2							
		M3							
		M4							
	A8	M1							
		M2							
		M3							
		M4							
CS4	A9	M1							
		M2							
		M3							
		M4							
	A10	M1							
		M2							
		M3							
		M4							
	A11	M1							
		M2							
		M3							

COMMISSIONING: LLRF milestones (1/2)

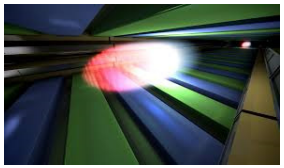
- **Initial checks**
  - LLRF system ready for commissioning ?
- ~~**Cold coupler conditioning**~~
- **RF signal checks: Forward and Reflected**
  - Cabling issues? Signal saturation?
- **Frequency tuning**
  - From parking position to resonance
- **RF signal checks: Probe**
  - Cabling issues? Signal saturation?
- **Coupler tuning**
  - Target Q_L = 4.6e6
- **Power-based gradient calibration**
  - Coarse
- **Closed-loop operation**
  - Feedback, learning feedforward, …

RF ONLY

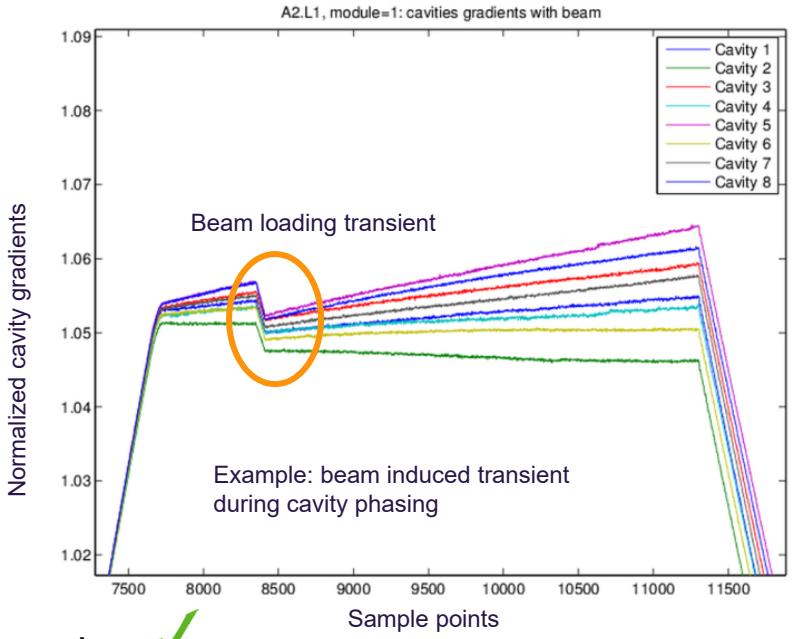
READY FOR BEAM

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



BEAM REQUIRIED



- **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 ✓

COMMISSIONING: tool automation

Cavity tuning

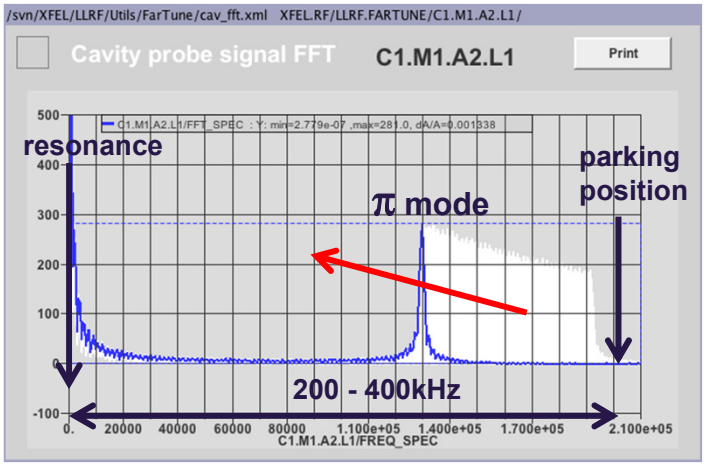
1. Perform initial check (1 motor turn ~ 15 kHz)

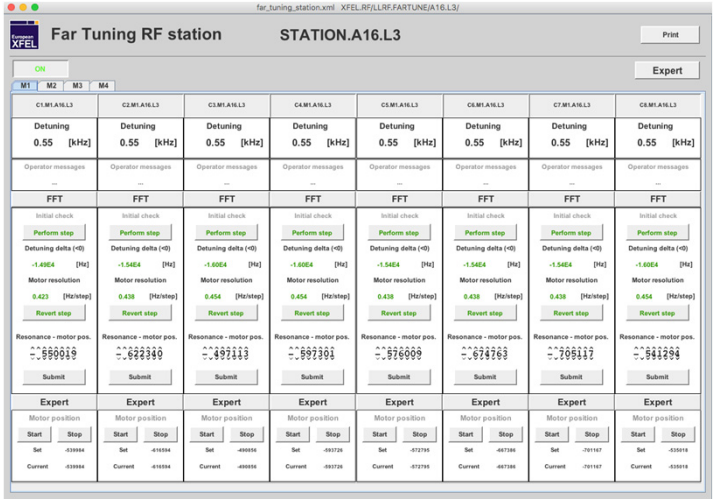
"Check that the detuning changes in the correct direction, in the proper amount and for the correct cavity"

2. if successful, tune to resonance (coarse)

"Based on step-to-resonance measured at AMTF"

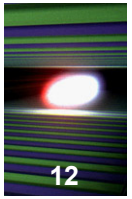
3. If successful, tune to resonance (fine)





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

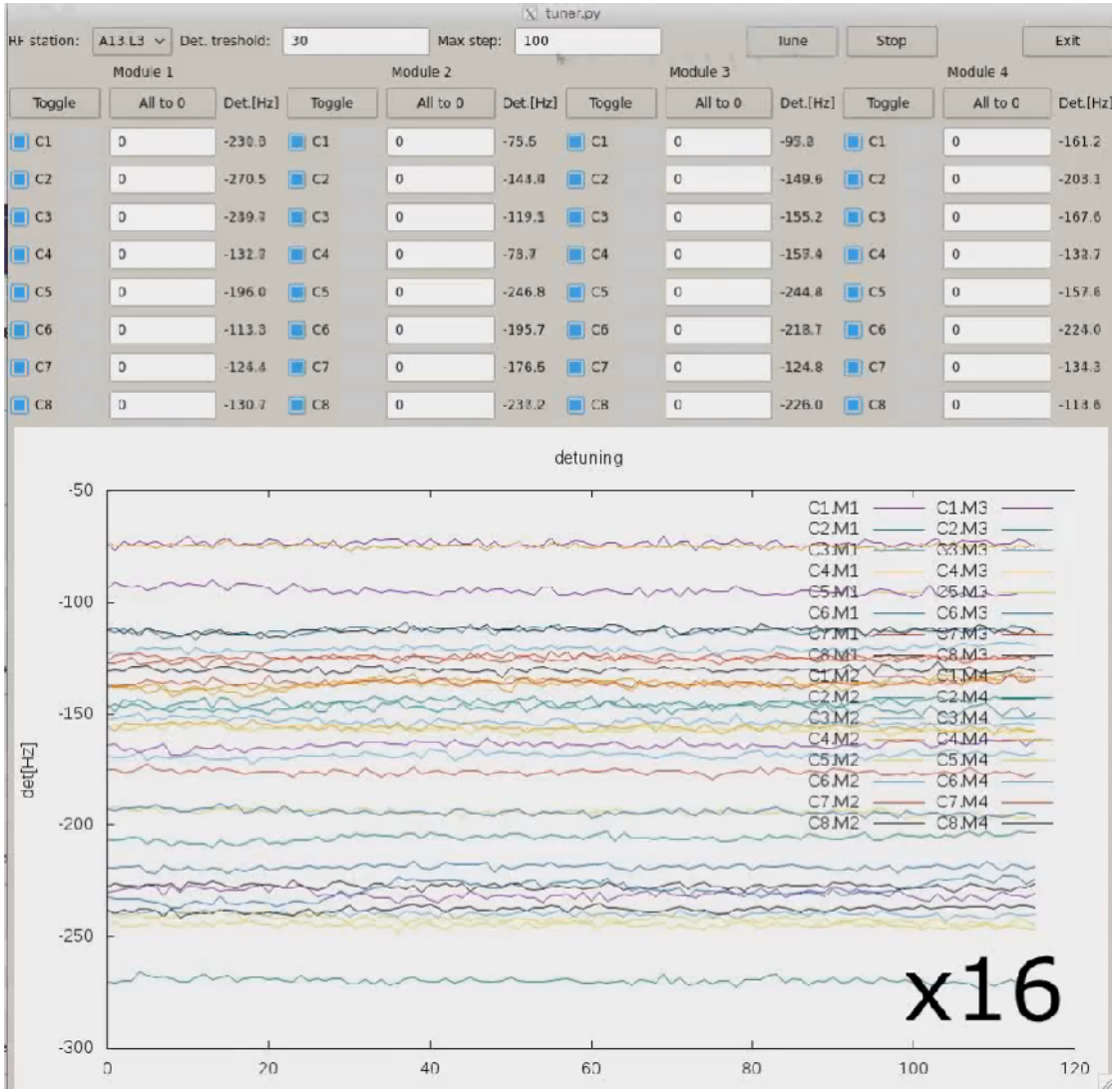
COMMISSIONING: tool automation



- **Cavity tuning**

COMMISSIONING: tool automation

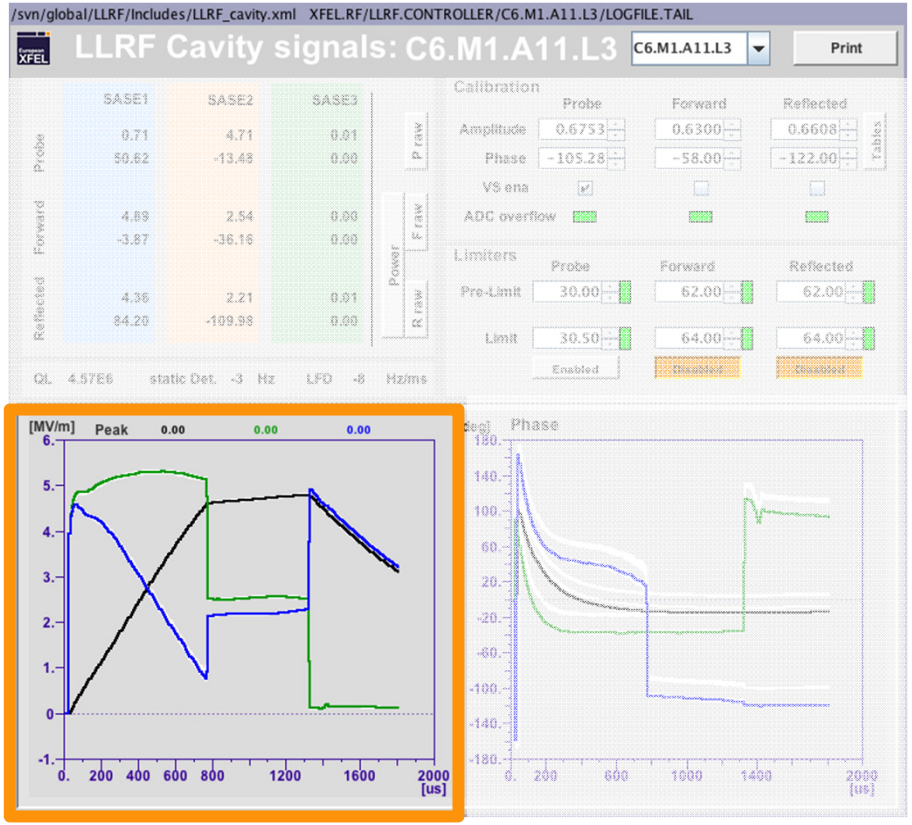
- **Cavity tuning**

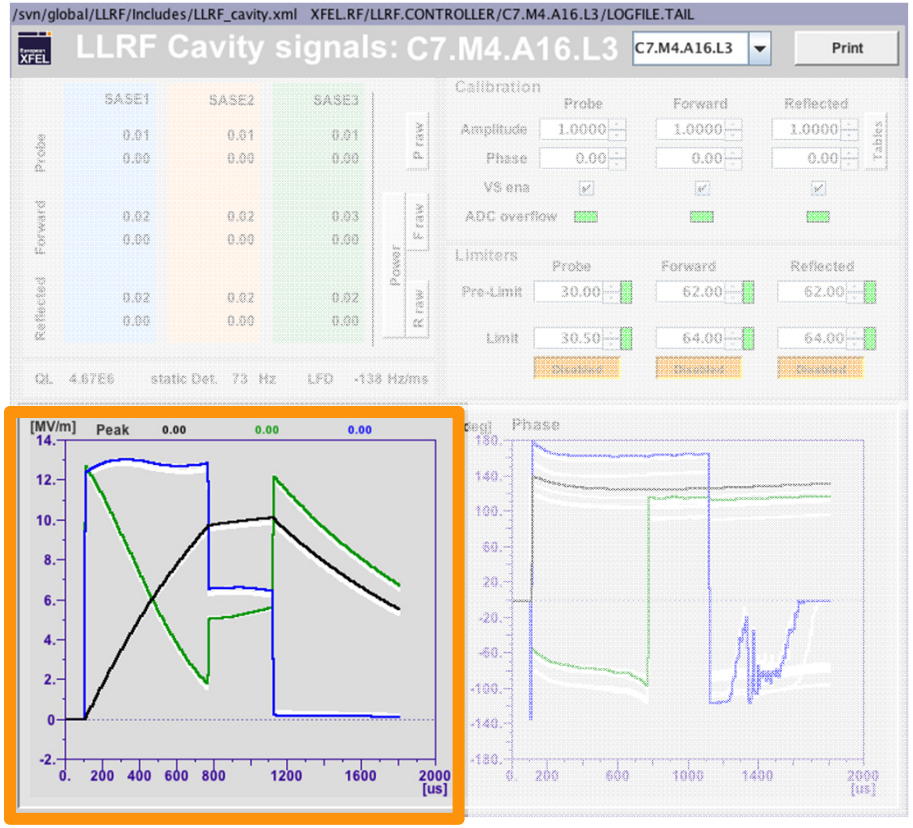


COMMISSIONING: tool automation

- **RF signal checks (1/2)**

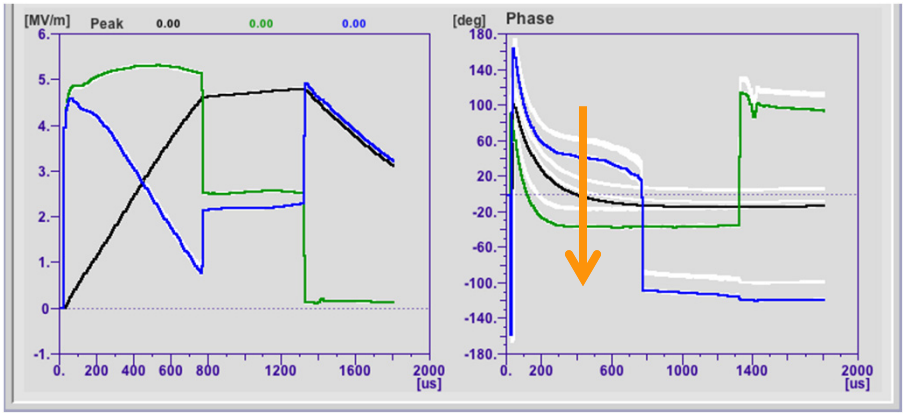
"what's wrong with this picture?"

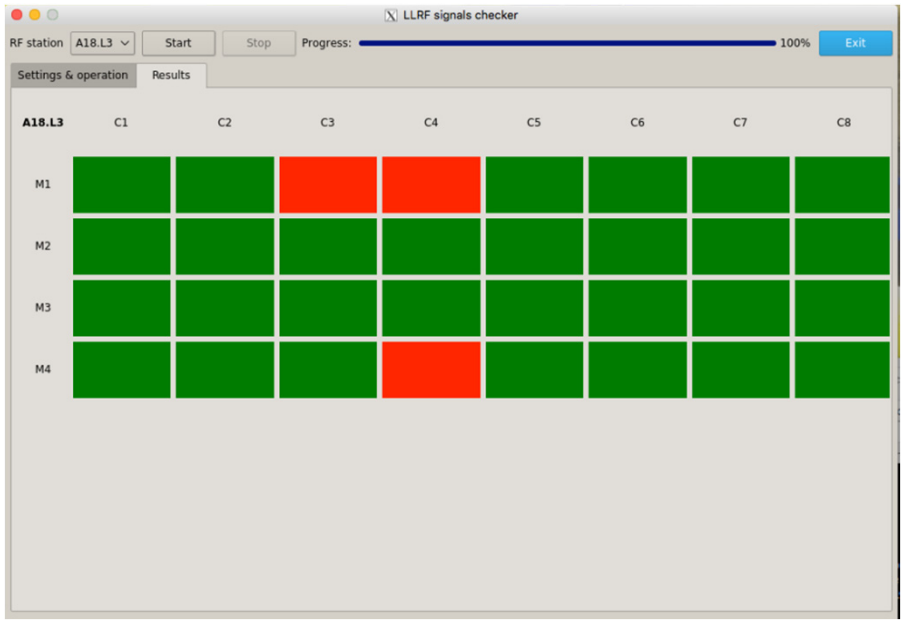




COMMISSIONING: tool automation

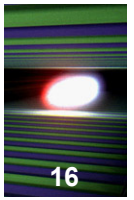
- **RF signal checks (2/2)**
  - 3-4 mins per RF station
  - Verify phase shifter functionality (32x)
  - Identify cabling errors:
    - ➔ FORW ↔ REFL
    - ➔ C1 ↔ C2





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

COMMISSIONING: some statistics



Cabling issues

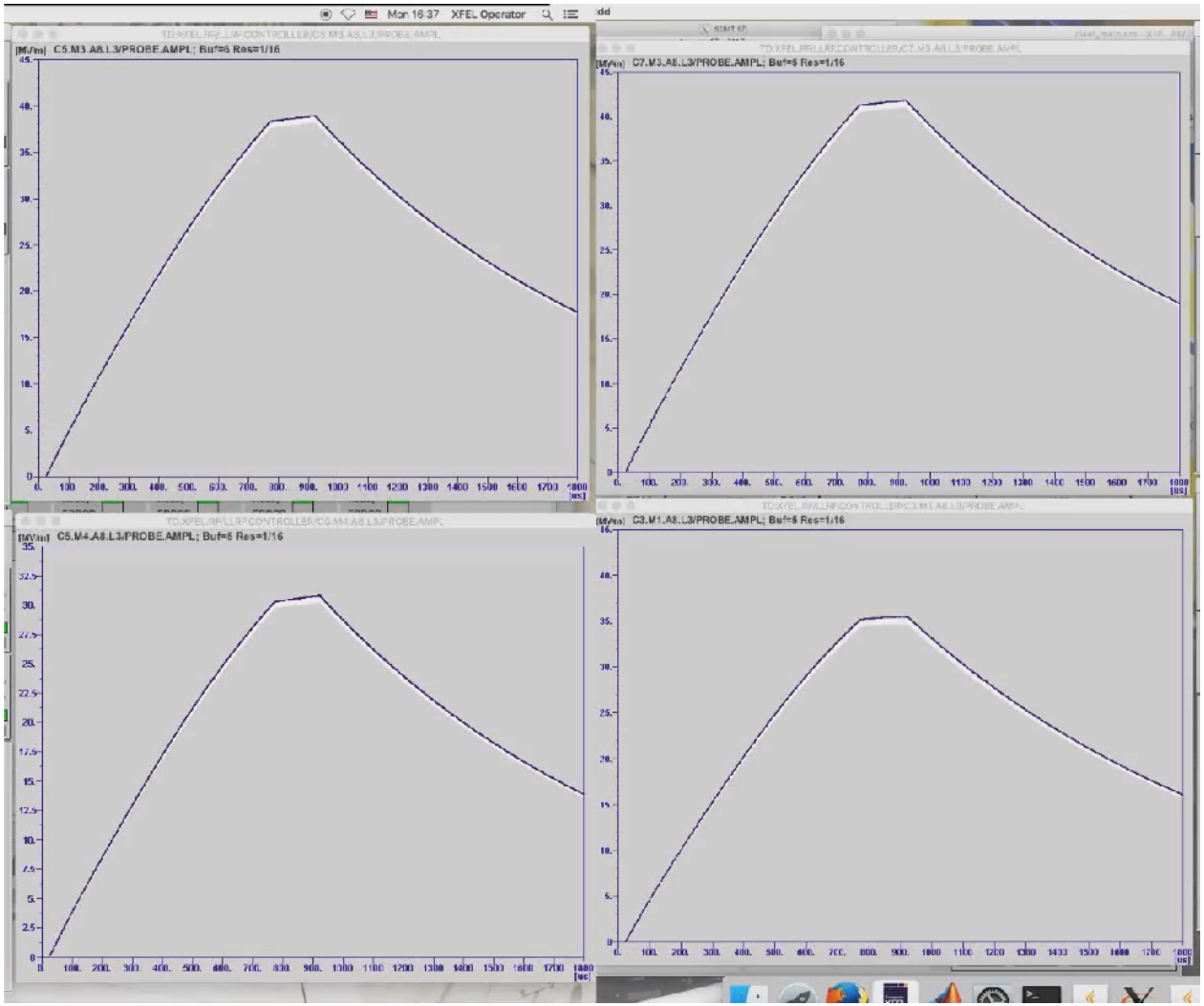
- **15 cabling issues** (outer rack) identified before cool down
- **11 cabling issues** (outer rack) identified after cool down
- **0 cabling issues** (inner rack) identified so far

} < 1%

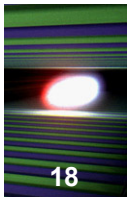
Multipacting

- 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



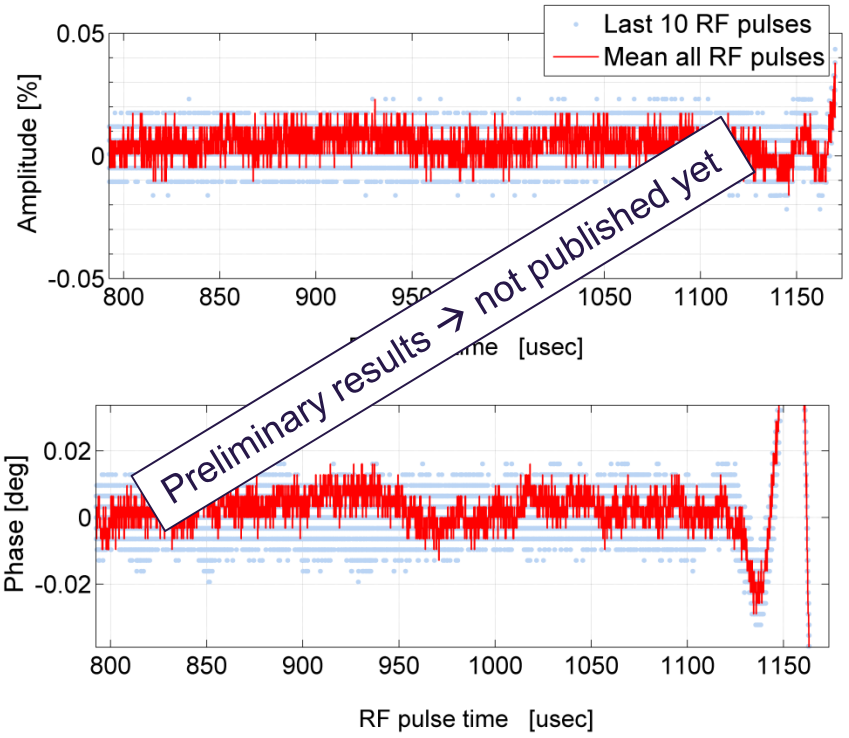
COMMISSIONING: some statistics

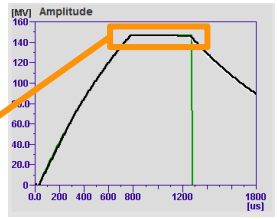


- **4 out of 616** couplers shorted after test in XTL
  - A4.M4.C4 coupler problem: T70K [shorted]
  - A12.M4.C1 coupler problem: T70K [shorted]
  - A16.M2.C1 coupler problem: T70K [shorted]
  - A20.M4.C1 coupler problem: T70K [shorted]
- **5 out of 616** cavities not used due to AMTF results
  - A5.M1.C5 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_{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

COMMISSIONING: some statistics

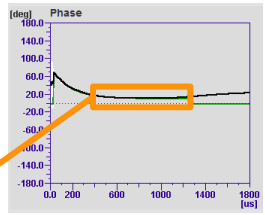
- **RF regulation** (in-loop)





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

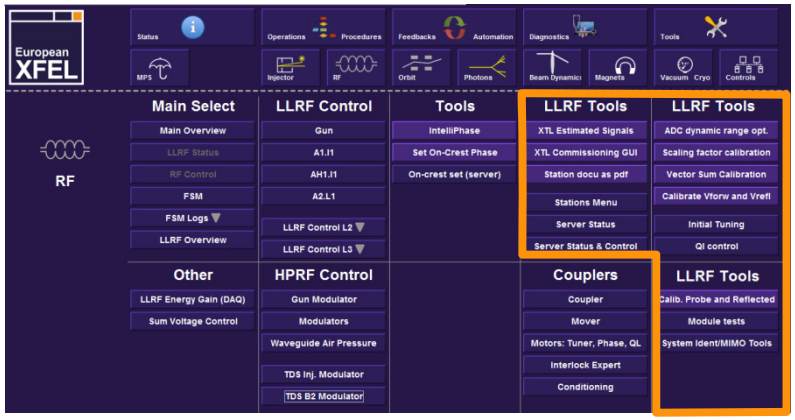
TALK OVERVIEW

- 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

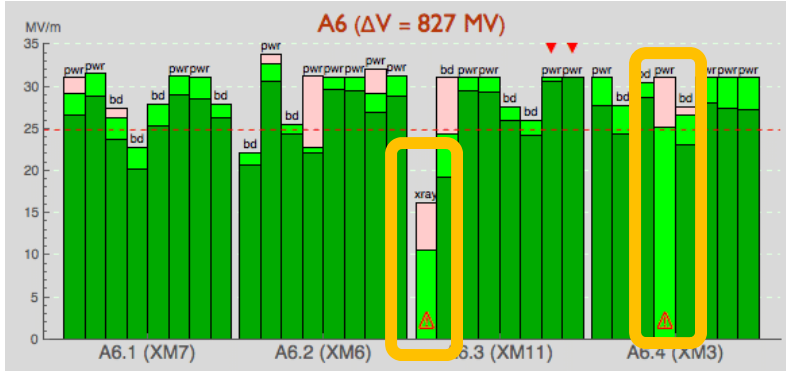
ASSESSMENT: what went well

- **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



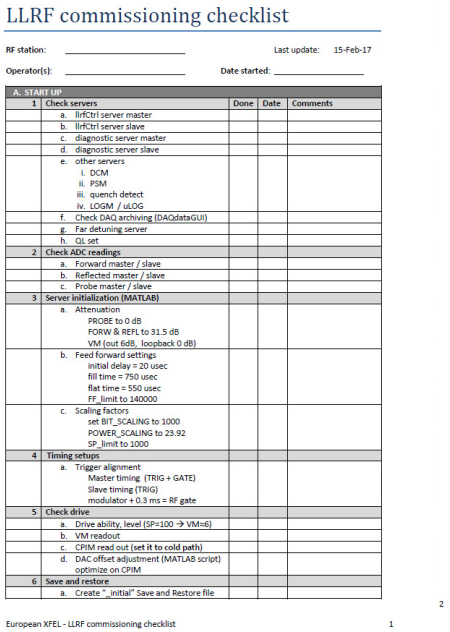
- **Availability of cryomodule test data**
  - Results from individual cryomodule tests
  - Cavity gradient limits, phase shifter limits, …
  - What to pay attention to (tune / don't tune)



ASSESSMENT: what went well

Checklists + documentation

- Prepare the checklist
- Test the checklist
- Iterate the checklist
- Stick to it



LLRF commissioning checklist

RF station: _____ Last update: 15-Feb-17

Operator(s): _____ Date started: _____

			Done	Date	Comments
A. START UP					
1	Check servers				
	a.	llrfCtrl server master			
	b.	llrfCtrl server slave			
	c.	diagnostic server master			
	d.	diagnostic server slave			
	e.	other servers i. DCM ii. PSM iii. quench detect iv. LOGM / uLOG			
	f.	Check DAQ archiving (DAQdataGUI)			
	g.	Far detuning server			
	h.	QL set			
2	Check ADC readings				
	a.	Forward master / slave			
	b.	Reflected master / slave			
	c.	Probe master / slave			
3	Server initialization (MATLAB)				
	a.	Attenuation PROBE to 0 dB FORW & REFL to 31.5 dB VM (out 6dB, loopback 0 dB)			
	b.	Feed forward settings initial delay = 20 usec fill time = 750 usec flat time = 550 usec FF_limit to 140000			
	c.	Scaling factors set BIT_SCALING to 1000 POWER_SCALING to 23.92 SP_limit to 1000			
4	Timing setups				
	a.	Trigger alignment Master timing (TRIG + GATE) Slave timing (TRIG) modulator + 0.3 ms = RF gate			
5	Check drive				
	a.	Drive ability, level (SP=100 → VM≈6)			
	b.	VM readout			
	c.	CPIM read out (set it to cold path)			
	d.	DAC offset adjustment (MATLAB script) optimize on CPIM			
6	Save and restore				
	a.	Create "_initial" Save and Restore file			

2

European XFEL - LLRF commissioning checklist 1

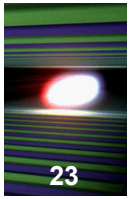
Machine operation

- 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

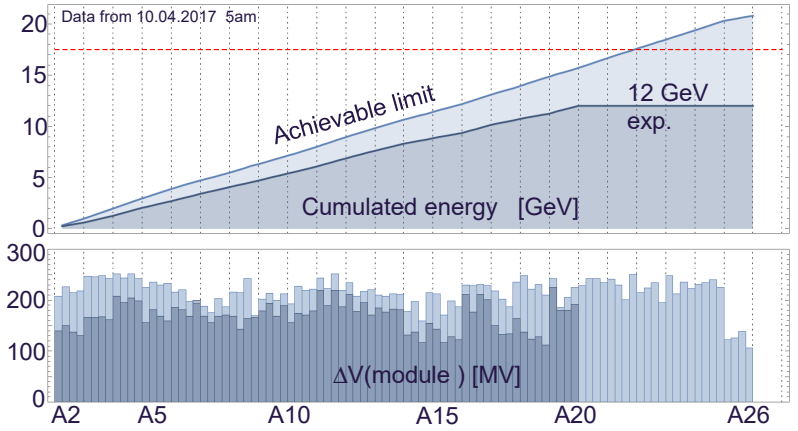


- **Initial checks of tuners drivers**
  - More than 40% initial checks failed
  - Several iterations required → time consuming
- **Triggered one cryo incident**
  - Multipacting: "working here but quenching there"
- **Too long recovery time ("phase jumps")**
  - Intricate combination of timing + reset + 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

CONCLUSIONS / OUTLOOK

- **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)



Courtesy N. Walker

- **Further higher-level development**
  - Inter-RF station communication + automation
  - Multi-beamline operation

THANK YOU FOR YOUR ATTENTION !

Photo Dirk Noelle