LLRF commissioning at the European XFEL

Commissioning procedure and operation performance

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on behalf of the LLRF team

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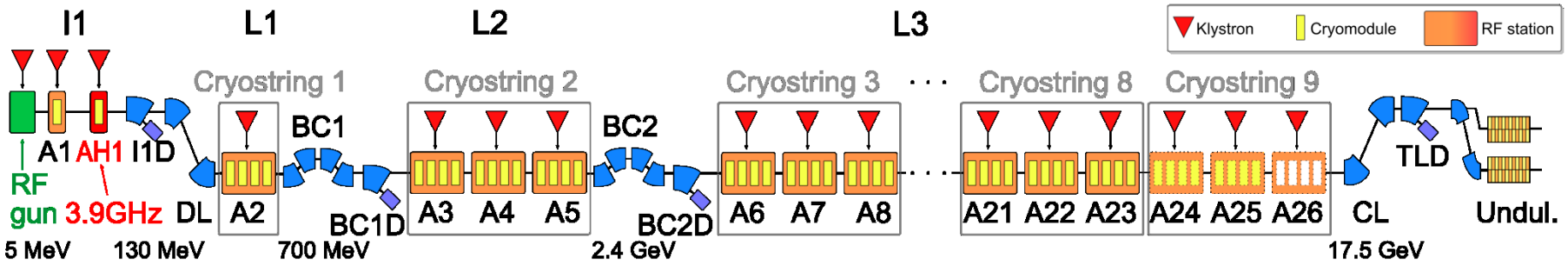
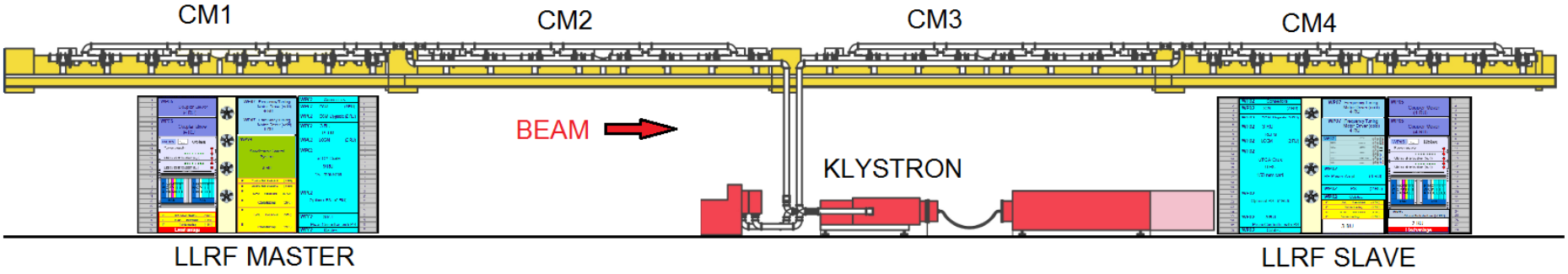
- Summary/Outlook

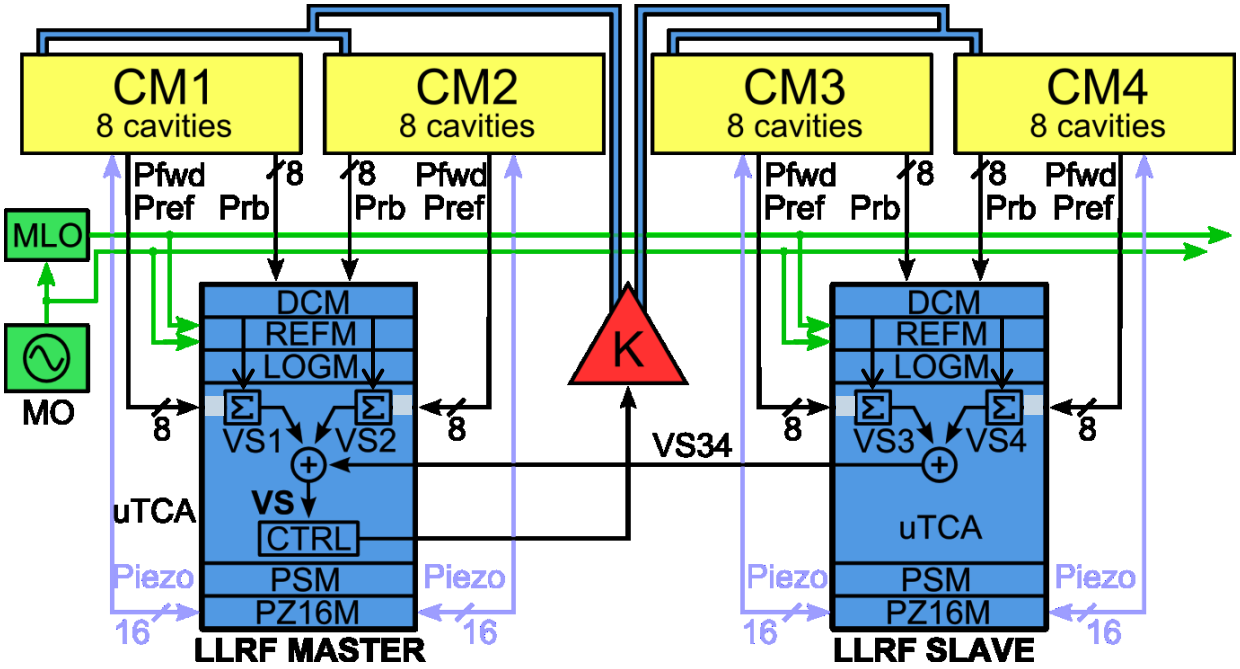
The European X-ray Free Electron Laser (XFEL)

- Soft and hard X-ray light experiments
- ~800 TESLA-type cavities
- Resonance frequency 1.3 GHz
- Design energy 17.5 GeV
- Pulsed operation 10 Hz
- First user September 2017



XTL RF Station: Semi-distributed LLRF System





DCM
Drift Calibration Module

REFM
RF Reference Module

LOGM
Local Oscillator Generation Module

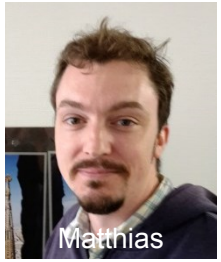
PSM
Power Supply Module

PZ16M
Piezo Driver Module

Commissioning Planning

Commissioning team

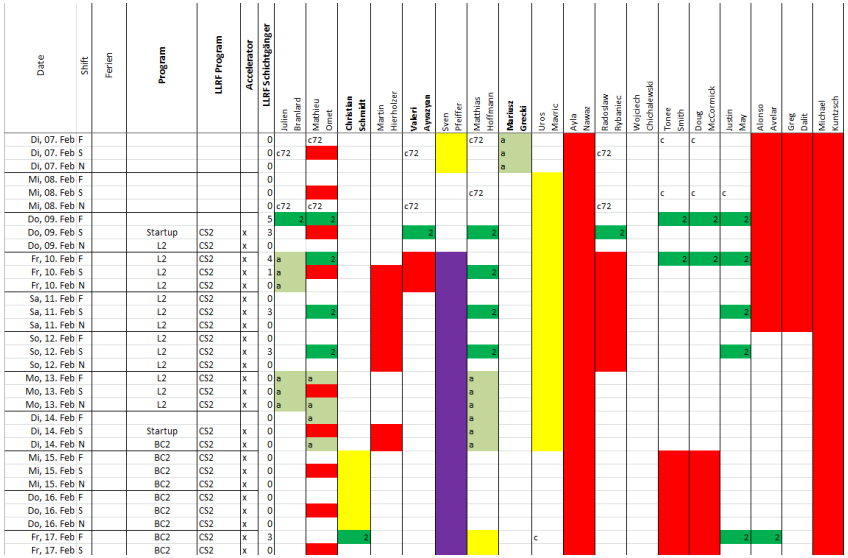
- 8 LLRF experts + 4 MSK colleagues
  - ►4x teams of 3
- Support from MHF-sl colleagues
  - ►2x
- Supporting colleagues from other facilities
  - ►SLAC (5)
  - ►HZDR (1)



Commissioning team of 20 people

Commissioning shifts

- Two 8-hours shifts / day
- Following DESY's operator shift program
- In practice, only a few week end shifts
- Hardly any night shifts



Commissioning Planning

Procedure

- Commission 1 cryo string at a time (3 RF stations)
- Parallel work
- Detailed check list to cover all commissioning tasks
- Gather issues and investigate 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

		Done	Comments
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 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 statio	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)

RF ONLY

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

READY FOR BEAM

Commissioning: LLRF Milestones (2/2)

Establish beam transport

- 30 bunches, 0.5nC

BEAM REQUIRIED

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

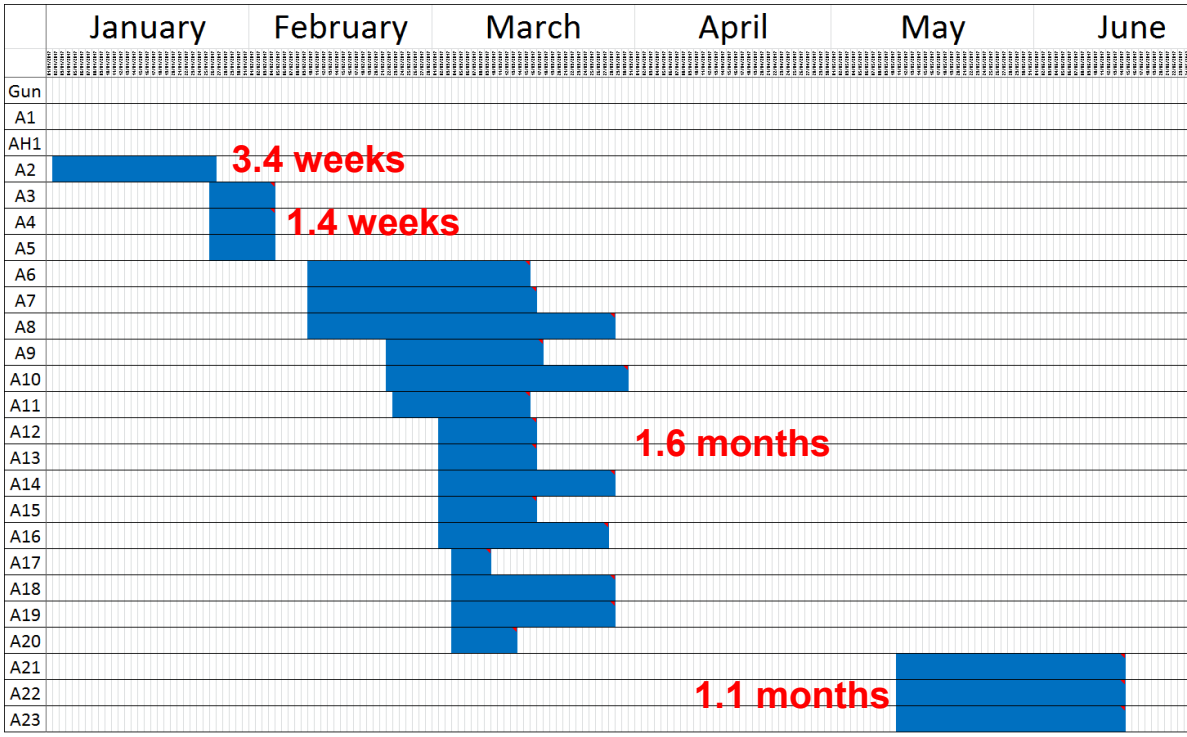
Commissioning Timeline (LLRF & General)

Injector

- 10.02.2015 Gun: first beam
- 18.12.2015 A1 operational (tuned cavities, QL values set, FB closed, nominal VS gradient of about 144 MV and beam acceleration
- 18.12.2015 AH1 operational (tuned cavities, FB closed and a VS gradient of about 41 MV)
- 18.06.2016 Gun: Maximum gradient (60 MV/m) reached first time

XTL

- 02.01.2017 Commissioning start
- 15.01.2017 First beam to B1D
- 26.01.2017 Finished basic LLRF commissioning of L1 / CS1
- 02.02.2017 First beam to B2D
- 04.02.2017 Finished basic LLRF commissioning of L2 / CS2
- 25.02.2017 First beam to TLD
- 30.03.2017 Finished basic LLRF commissioning of L3 / CS3-CS7
- 02.05.2017 First SASE
- 14.06.2017 Finished basic LLRF commissioning of L3 / CS8
- 23.06.2017 First beam to experimental hutch, first experiment



Commissioning Statistics

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

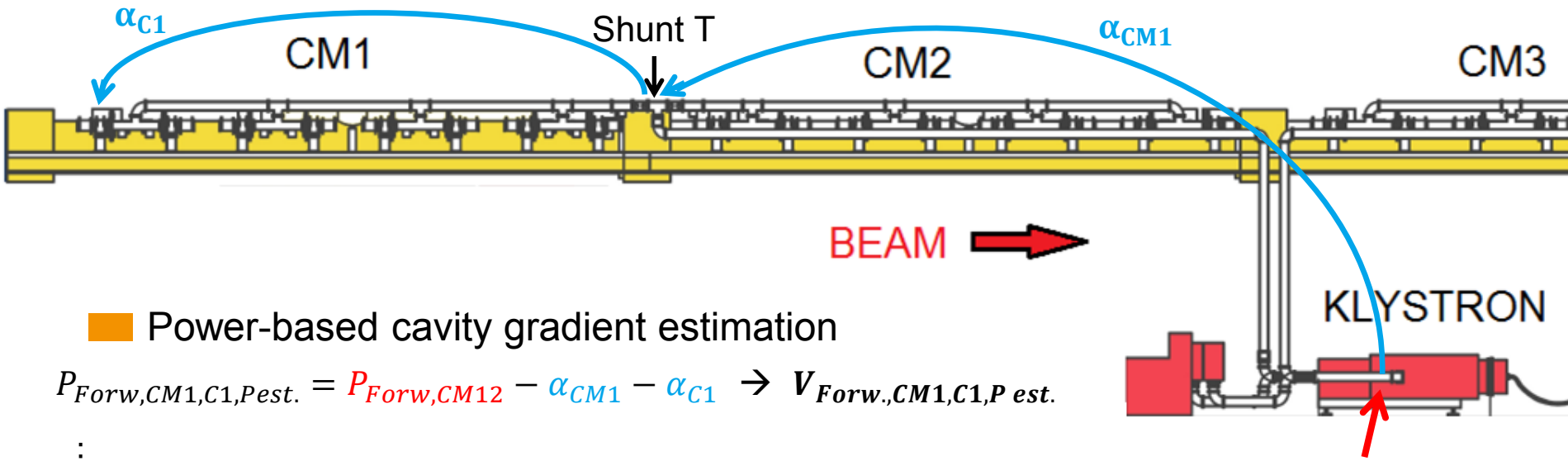
Multipacting

- 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)

Further information

- Poster by D. Kostin: “European XFEL LINAC RF System Conditioning and Operating Test”, SRF 2017, MOPB111
- IPAC’17 talks by W. Decking (MOXAA1) and J. Branlard (THOAA3)

Comparison of Power-based & Beam-based Calibrations



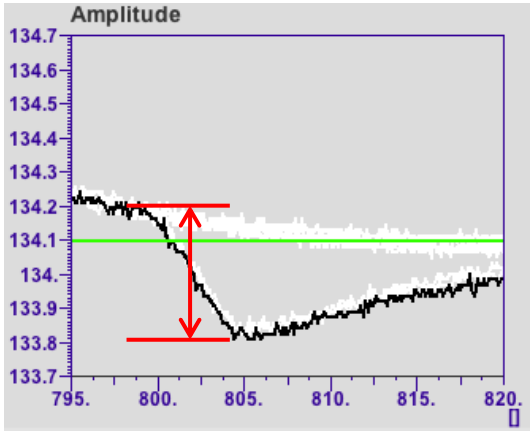
- Power-based cavity gradient estimation

$$P_{Forw,CM1,C1,Pest.} = P_{Forw,CM12} - \alpha_{CM1} - \alpha_{C1} \rightarrow V_{Forw.,CM1,C1,P\ est.}$$

⋮

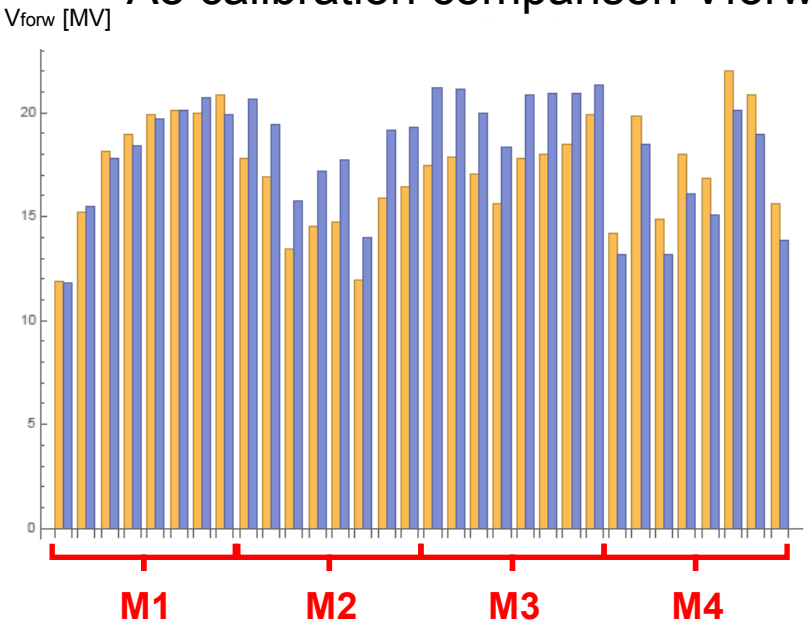
Power meter for arm 1 (CM1&2)
Power meter for arm 2 (CM3&4) on the other side

- Beam-based calibration
  - Evaluation of beam loading per cavity
  - Calibration of cavity probe signals
  - Calibration of forward signals → $V_{Forw.,CMx,Cy,Beam\ est.}$

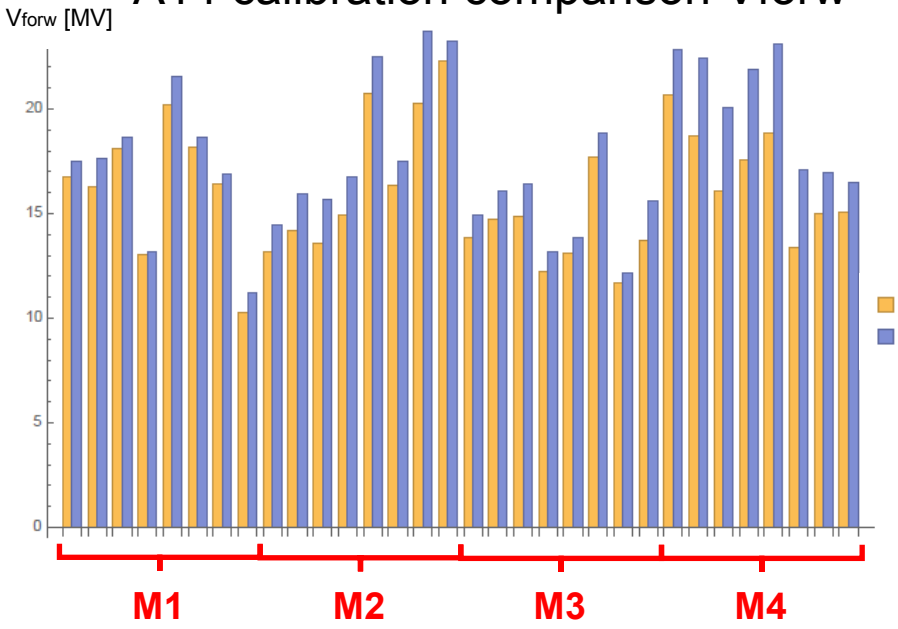


Comparison of Power-based & Beam-beased Calibrations

A8 calibration comparison Vforw

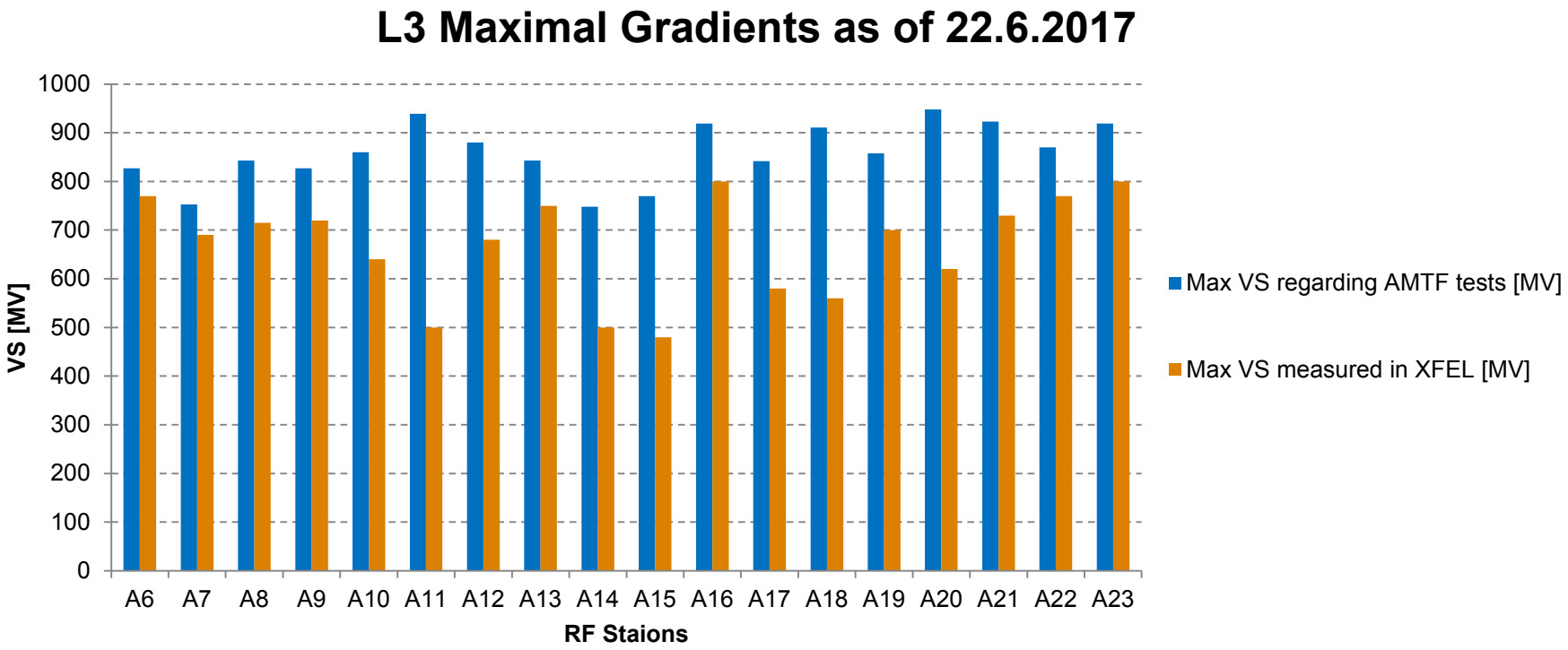


A14 calibration comparison Vforw



- Waveguide tailoring on module level confirmed
- Waveguide tailoring between modules in few cases not optimal
- Work in progress: cross-checks with power meters imminent

Maximal Gradients



- Calibrations at AMTF power-based, at XFEL beam-based
- Yields a theoretical maximal beam energy of 15.2 GeV (for now)
- Standard operation includes safety margin
  (1 MV/m below individual cavity quench limit)

Beam Energy Record

- On 22.6.2017 stable beam operation at 14.1 GeV (1 bunch, 0.5 nC)

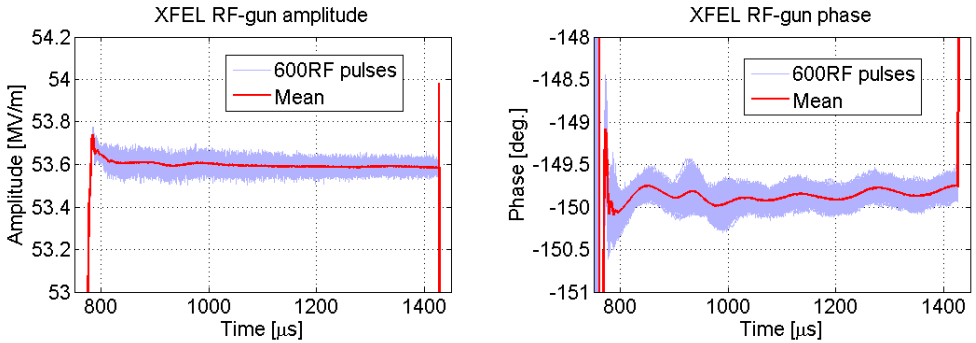
- Investigations for pushing maximal operational gradients ongoing

Injector Station Performance

- Stabilities reached (intra pulse RMS values)

	Gun	A1	AH1
Amplitude stability ΔA [%]	0.03	0.008	0.018
Phase stability ΔΦ [°]	0.06	0.008	0.024

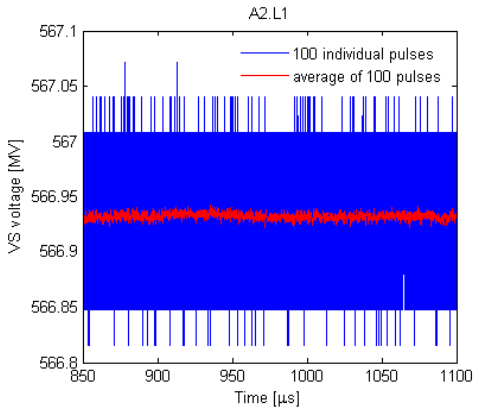
- Gun was not running latest controller optimizations

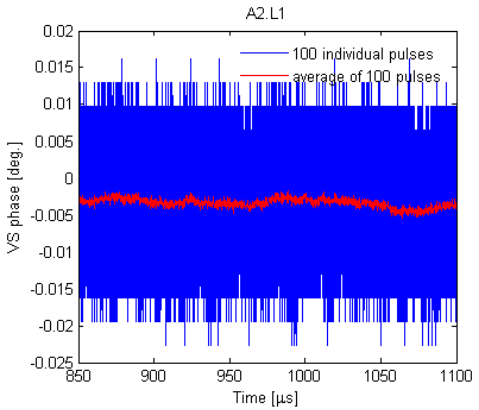


- Overall stable operation

XTL Station Performance

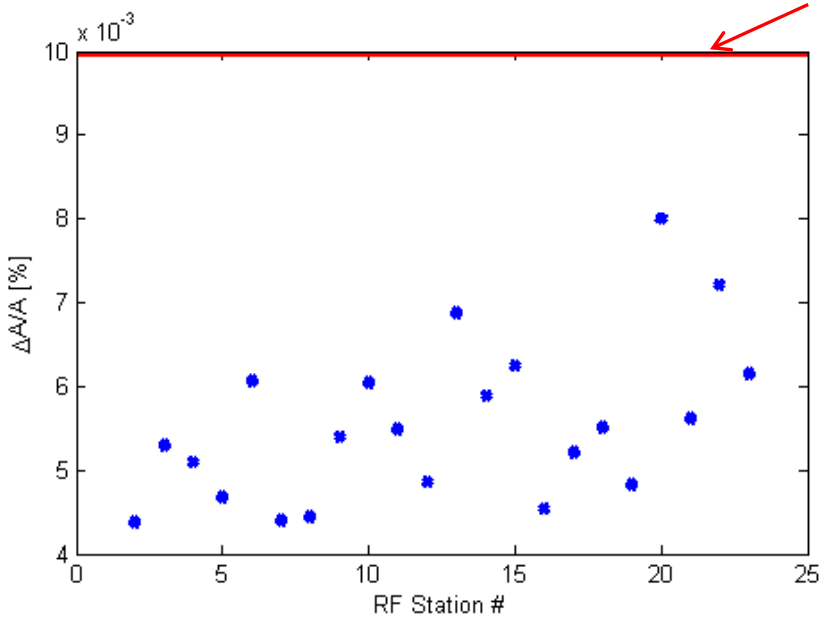
- A2 as an example

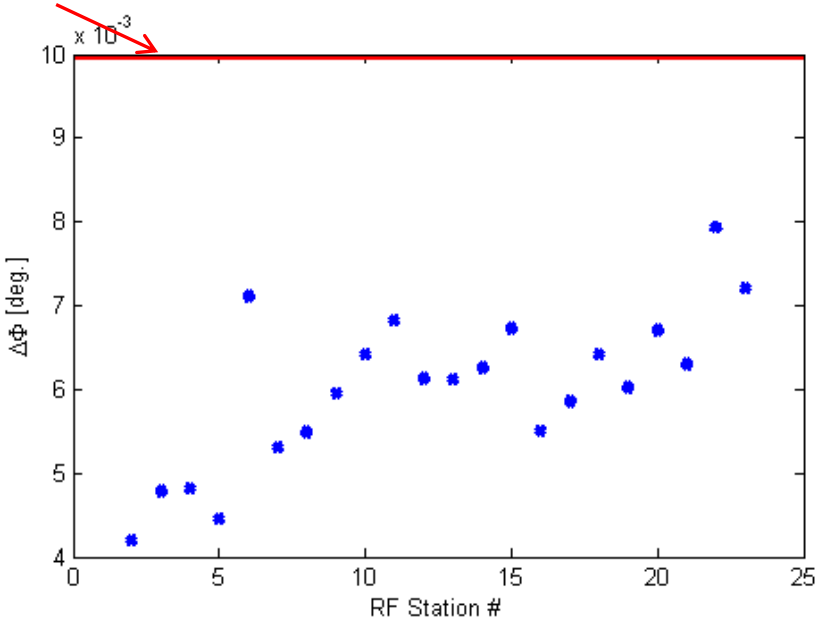




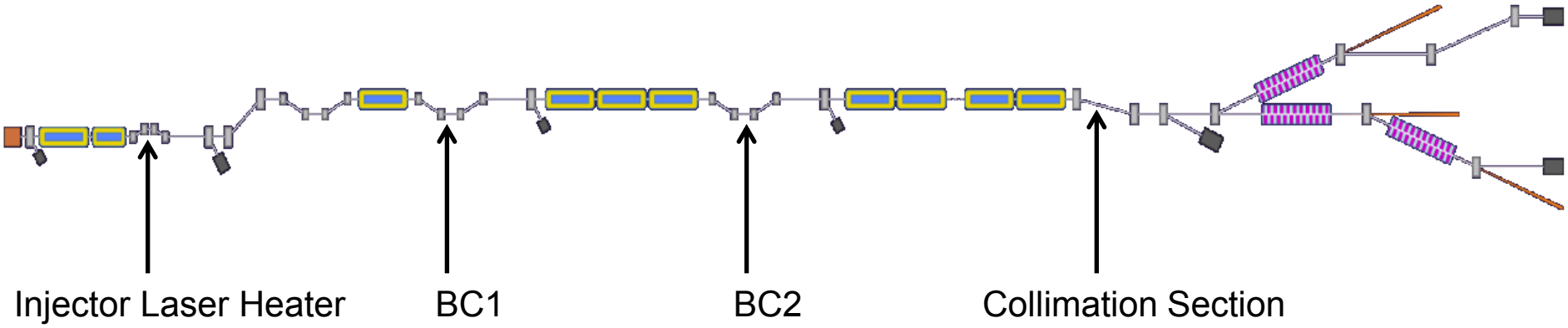
- All XTL Stations

XFEL specifications: ΔA ≤ 0.01%, ΔΦ ≤ 0.01 deg.





Energy Stability Measured with Energy Server



	Collimation Section
$\bar{E}$ [MeV]	13489
σE [MeV]	0.3104
$\sigma E/\bar{E}$	**(0.0023 ± 0.0023)%**

Requirement: 0.01%

Evaluation of 1000 pulses on 22.06.2017

Further Operation Experience

- Phase jumps of 240° on probe, forward and reflected channels
  - Frequency dividers were not triggered correctly + drifts of master timing
  - Firmware in LLRF system and timing system (bugfix of drift compensation) updated
  - Phase jumps only after LLRF crate reboot possible → initialisation script
- Have to revise output vector correction (OVC) algorithm
  - Was diverging in closed loop operation
  - Algorithm was revised and is being tested
- (Hardware) failures
  - Four cases, in which x2timer RTM was found in M1 state (issues on management level)
  - Once case, in which files were corrupted on a CPU and the OS had to be reinstalled
  - Once case, in which the communication between master and slave rack was lost
- At FLASH we see radiation related failures, at XFEL none so far
- Automation (FSM, etc.) and scripts (cavity tuning, etc.) key to smooth operation
- From LLRF point of view stable operation

Summary / Outlook

- Basic LLRF commissioning up to CS8 done
- Commissioning of CS9, when preparation work (cabling) finished
- Advanced LLRF commissioning ongoing (DCM, Piezo driver, REFM-OPT, etc.)
- So far maximal beam energy achieved: 14.1 GeV (goal 17.5 GeV)
- Investigations for pushing maximal operational vector sum gradients ongoing
- Intra-pulse amplitude and phase stabilities about factor two better than specifications
- Energy stability well below requirement
- Repeat LLRF tests performed at AMTF (E.g. QL range, frequency tuner, fundamental modes, etc.)

Questions?

- Thank you very much for your attention!