Operation of the European XFEL Towards the Maximum Energy

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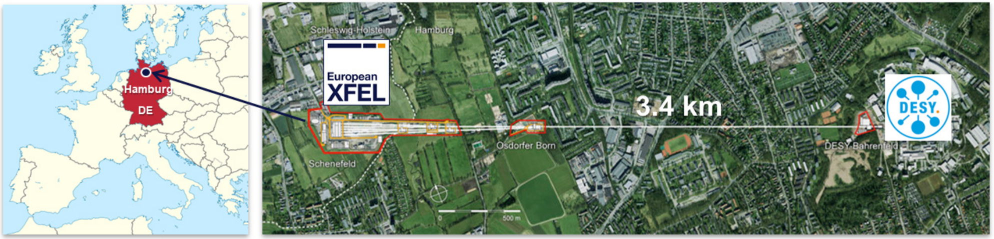
for the linac team

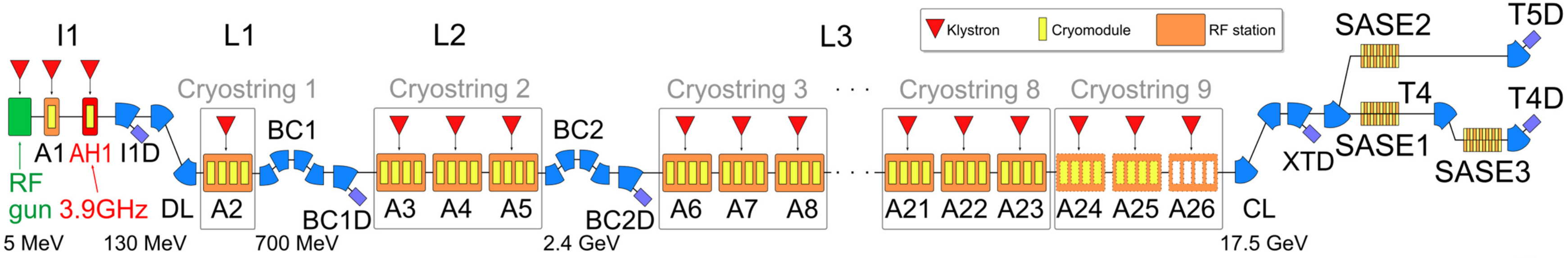
SRF 2019, Dresden, 01.07.2019

Contents

The European X-ray Free Electron Laser (XFEL)

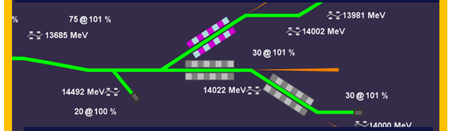
- Soft and hard X-ray light experiments
- ~800 TESLA-type cavities
- Resonance frequency 1.3 GHz
- 32 cavities per XTL RF station
- Design energy 17.5 GeV
- Pulsed operation at 10 Hz





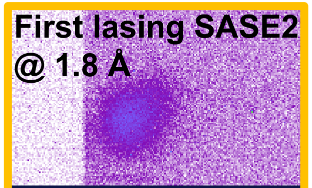
Commissioning Timeline

Flexible Beam Distribution



May - October, 2018

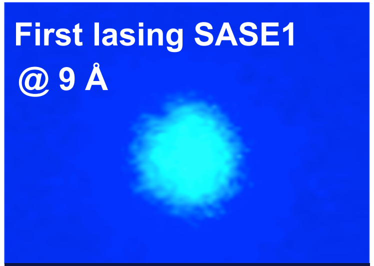
First lasing SASE2 @ 1.8 Å



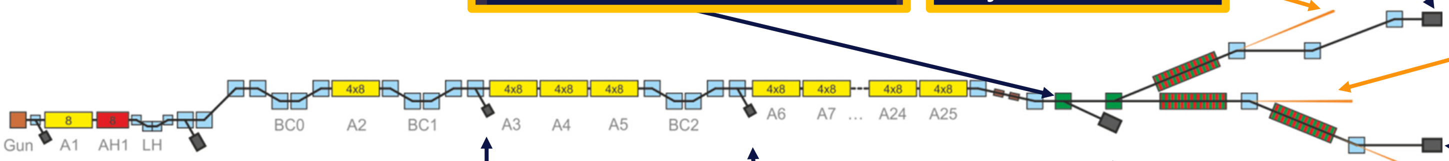
May 1, 2018

March 13, 2018

First lasing SASE1 @ 9 Å



May 2-3, 2017



April 27, 2017

Jan 13, 2017

Feb 2, 2017: 600 MeV
Feb 22, 2017: 2.5 GeV

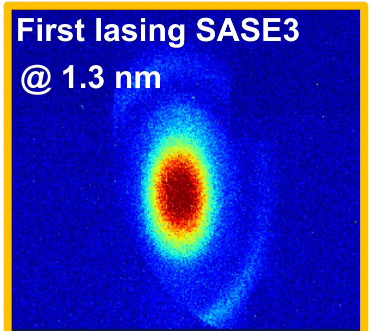
Jan 15, 2017: 130 MeV
Jan 19, 2017: 600 MeV

Feb 25, 2017: 2.5 GeV
April 8, 2017: 12 GeV
Oct 23, 2017: 14.9 GeV

July 12, 2018: 17.6 GeV

Nov 2, 2018: 2699 bunches/RF pulse

First lasing SASE3 @ 1.3 nm



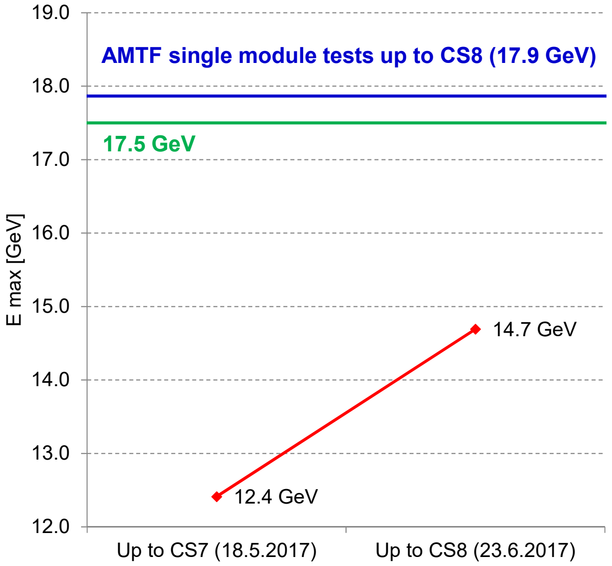
February 8, 2018

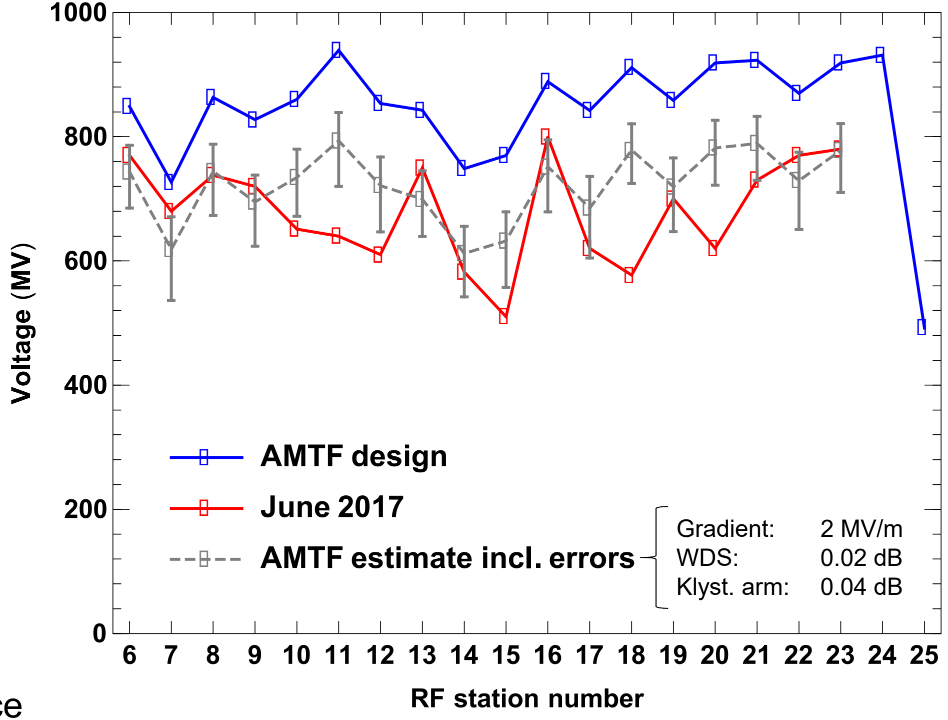
Achievements 2018

10th of June 2019: up to 250 µJ at 20 keV

- 14 GeV electron energy

Maximal Energy as of 23rd of June 2017

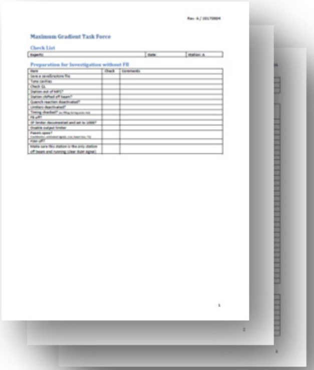


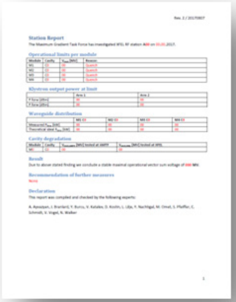


- Formation of the Maximum Gradient Task Force

Concept

- Team of experts (core team of 7 with more than 7 experts supporting)
- Investigation of single stations in parallel to regular beam operation, including user runs
- Investigation on single cavity granularity
- Checklist for unified testing procedure
- Work out solutions for maximal possible gradient (discussions, calculations, simulations, etc.)
- Document findings in station reports





Procedure

- Prepare RF station
- Perform study
  - VS voltage is slowly increased until one of the following limits is hit
    - ► Cavity quench
    - ► Field emission limit
    - ► High power chain limit
    - ► Waveguide sparking
  - If a cavity quenches in multipacting regime, try to condition it, other wise confirm quench limit, detune cavity and continue voltage increase
  - Field emission is measured with MARWIN drive-by, otherwise BLM signals give a hint
  - If klystron is close to saturation, klystron high voltage is increased
  - Sparking waveguide part is identified with sound detectors and exchanged when tunnel access is possible
  - Taking data at several points and typically close to the limits
  - The configuration, which yields highest VS voltage is kept and setup in closed loop
- Restore RF station for operation

Schedule

- First investigation on 21st of June 2017
- 40 investigations performed so far
- 20 of 20 stations in L3 investigated
- 20 of 20 stations reached final limit

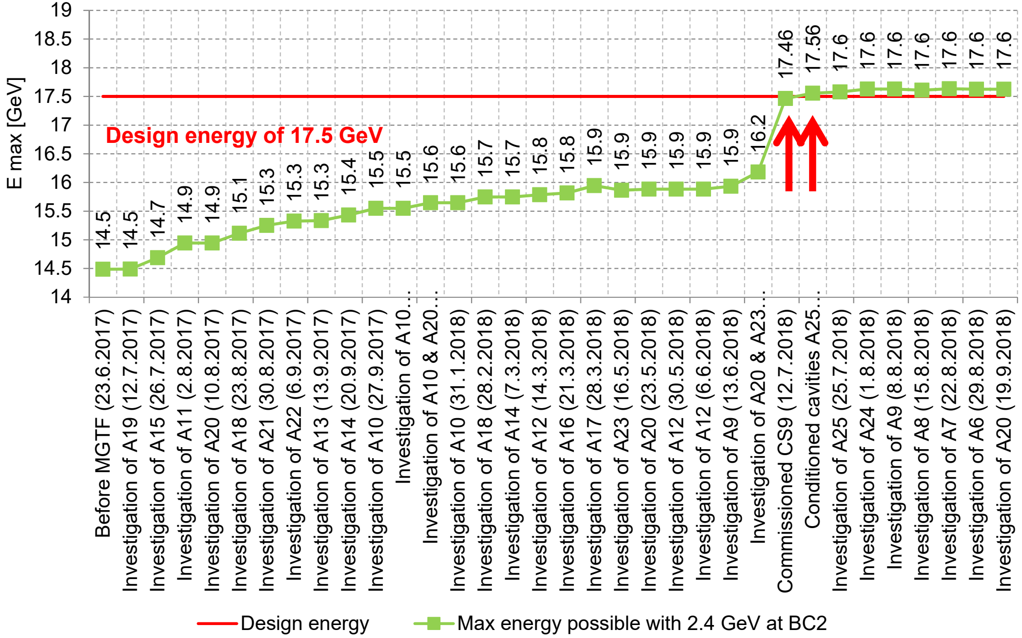
- 1 of 3 stations in L2 investigated
- 0 of 1 stations in L1 investigated
- 0 of 2 stations in injector investigated

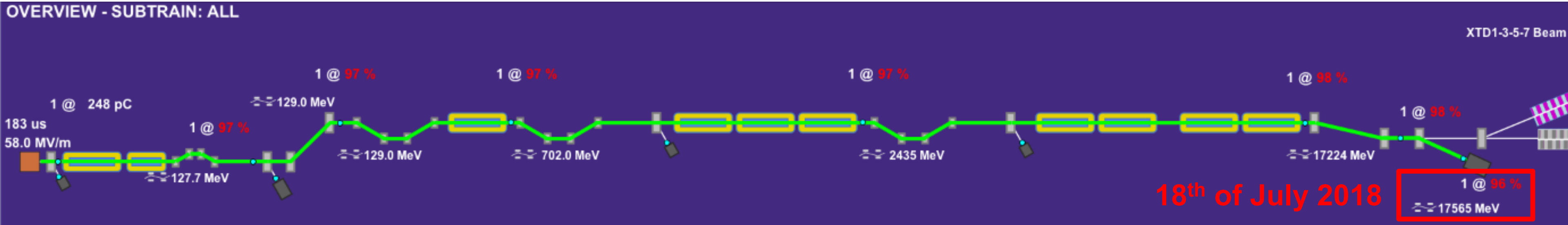
Date	Station	Comment
21.6.2017	A19	
12.7.2017	A19	
26.7.2017	A15	
2.8.2017	A11	
10.8.2017	A20	
23.8.2017	A20	
23.8.2017	A18	
30.8.2017	A21	
6.9.2017	A22	
13.9.2017	A13	
20.9.2017	A14	user run
27.9.2017	A10	user run
4.10.2017	-	maintenance
11.10.2017	-	maintenance
18.10.2017	-	maintenance
25.10.2017	-	
1.11.2017	A13	
8.11.2017	-	lack of spare station
15.11.2017	-	lack of spare station
22.11.2017	-	lack of spare station
29.11.2017	-	lack of spare station
5.12.2017	A13	quick check
6.12.2017	-	shutdown
13.12.2017	-	shutdown
20.12.2017	-	shutdown
27.12.2017	-	shutdown
3.1.2018	-	shutdown
10.1.2018	-	shutdown
17.1.2018	-	shutdown
24.1.2018	-	shutdown
31.1.2018	A13	
7.2.2018	-	TTC meeting
14.2.2018	-	He pressure test
21.2.2018	-	BBS Travemünde
28.2.2018	A18	
7.3.2018	A14	
14.3.2018	A12	

Date	Station	Comment
21.3.2018	A16	
28.3.2018	A17	
4.4.2018	-	shutdown
11.4.2018	-	shutdown
18.4.2018	-	shutdown
25.4.2018	-	
2.5.2018	-	
8.5.2018	A5	
16.5.2018	A23	
23.5.2018	A20	
30.5.2018	A12	
6.6.2018	A12	
13.6.2018	A9	
20.6.2018	-	shutdown
27.6.2018	-	shutdown
4.7.2018	-	shutdown
11.7.2018	-	
18.7.2018	-	
25.7.2018	A25	
1.8.2018	A24	
8.8.2018	A9	
15.8.2018	A8	
22.8.2018	A7	
29.8.2018	A6	
05.09.2018	-	
12.09.2018	-	
19.09.2018	A20	
26.09.2018	-	
03.10.2018	-	
10.10.2018	A23	aborded
17.10.2018	-	
24.10.2018	-	
31.10.2018	-	
07.11.2018	-	
14.11.2018	A23	
21.11.2018	A7, A25	

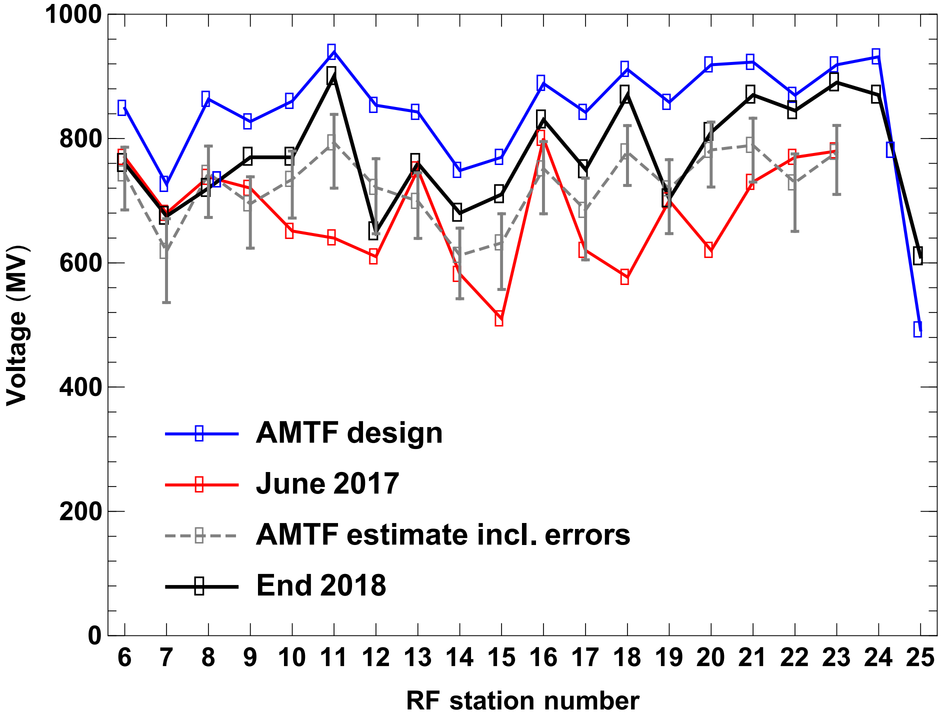
Milestone: Design Energy Reached

- 17.6 GeV at TLD on 12.7.2018
  - With 2.6 GeV after BC2
  - Further investigations followed
- 17.6 GeV at TLD on 18.7.2018
  - With design energy of 2.4 GeV after BC2
- Energy gain due to MGTF: 1.9 GeV
  - Nearly 11% of final energy
  - Equal to about 2.4 L3 RF stations





RF Performance as of End of 2018



- Reached an average of 93.6% of AMTF performance

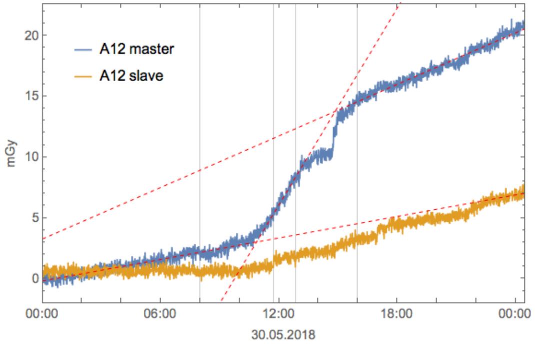
Main Limitations for VS Voltages

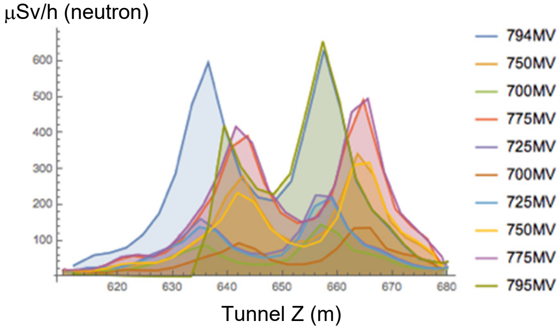
- Quench (soft quenching)
- Field emission (500 µSv/h neutrons)
- Power / missing piezo operation

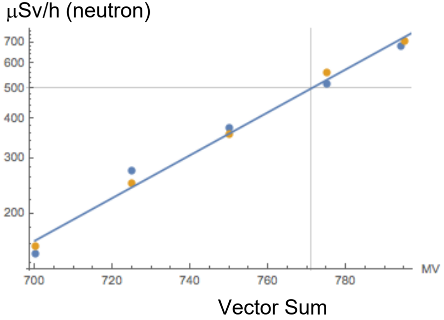
- Other limitations were overcome
  - Waveguide sparking
  - Too low klystron power
- In several cases the waveguide system is not optimal

A9 and A12 vector sums limited by dark current

- A12
  - Limit set to 720 MV (quench limited)
  - RADFET radiation rate too high
  - Reduced to 710 MV
    - ► M2.C2 detuned due to strong FE
- A9
  - First direct use of MARWIN to set operations limit
  - Ad hoc limit of 500 µSv/h neutron rate
  - Resulted in 770 MV operational limit
    - ► Quench limited at ~800 MV

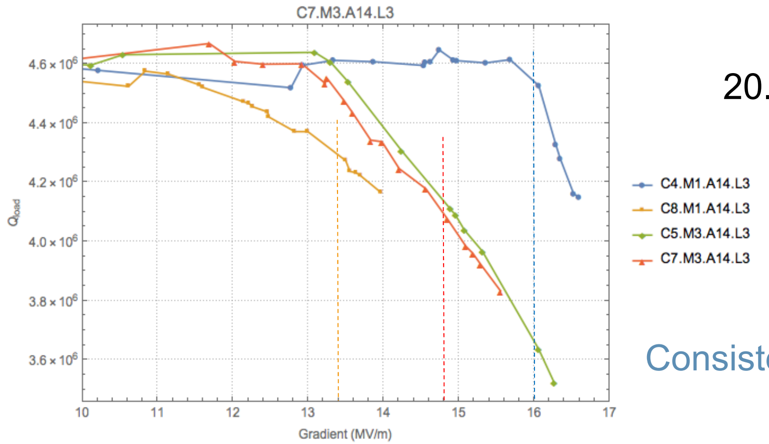






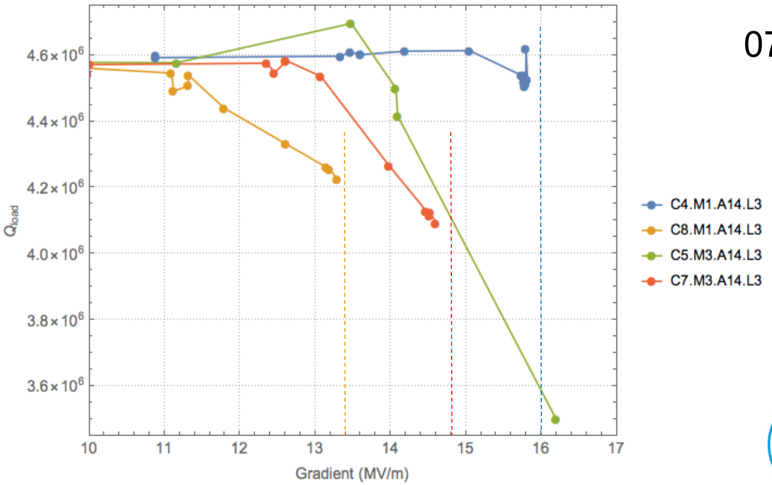
"Soft" Quenching: Example of A14

- Quench behavior reproducible
- Higher cryo load can be tolerated to a certain level
- We are operating this station without M3.C5 in the "soft" quench regime
  - M3.C5 creates too much cryo load
- VS limit at 680 MV
  - Corresponding cavity gradients marked in the plots by dashed lines



20.09.17

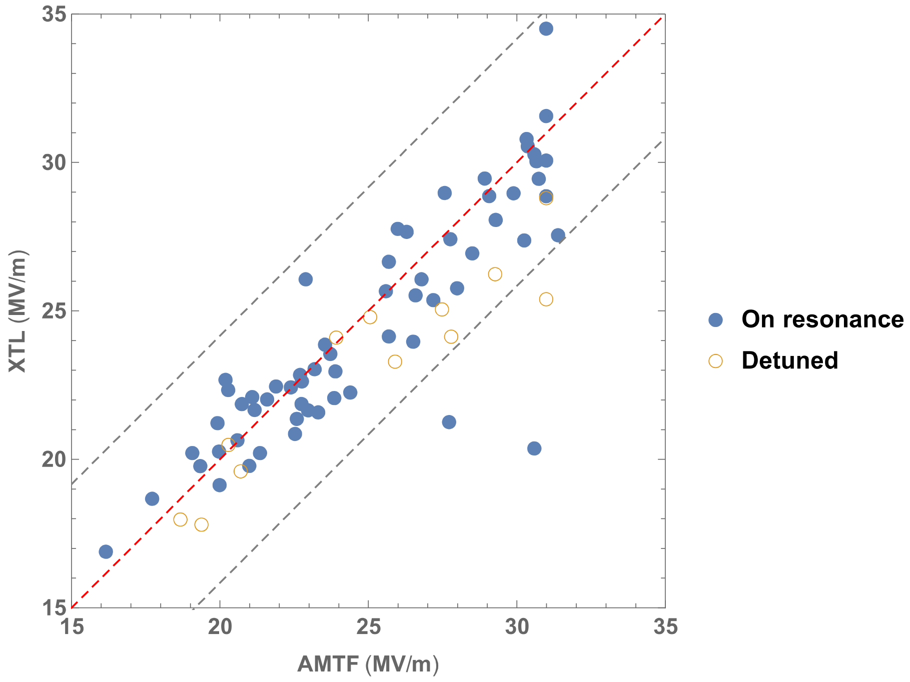
Consistent results



07.03.18

Single cavity performance (AMTF vs XTL)

- Quench limits of 76 cavities were determined
  - Not practical to re-measure all 800
  - Generally one per module (up to 3)
- Only 3 cavities identified as having degraded from AMTF test
  - Two were not limiting station performance
- Additional 12 cavities were detuned due to MGTF investigations
  - See next slide



Detuned cavities

Reason of detuning	Number of cavities
After AMTF tests (A)	5 (~0.6%)
After tests in XTL (A)	5 (~0.6%)
MGTF (0)	12 (~1.5%)
Sum	**22 (~2.8%)**

	A	O
Coupler 70k OH	4	
Strong FE	2	
MGTF (limiting VS)		9
BD degraded		2
Low BD	2	
High cryo load		1
Unknown	1	
WDS spec error	1	

	M1								M2								M3								M4							
	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
A2																																
A3																																
A4																												A				
A5																																
A6																	A				O	O										
A7							O				O				A																	
A8																									O			O	O			
A9																																
A10			A																													
A11																																
A12										O														O	A							
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- Coupler 70k OH
- Strong FE
- MGTF (limiting VS)
- BD degraded
- Low BD
- High cryo load
- Unknown
- WDS spec error

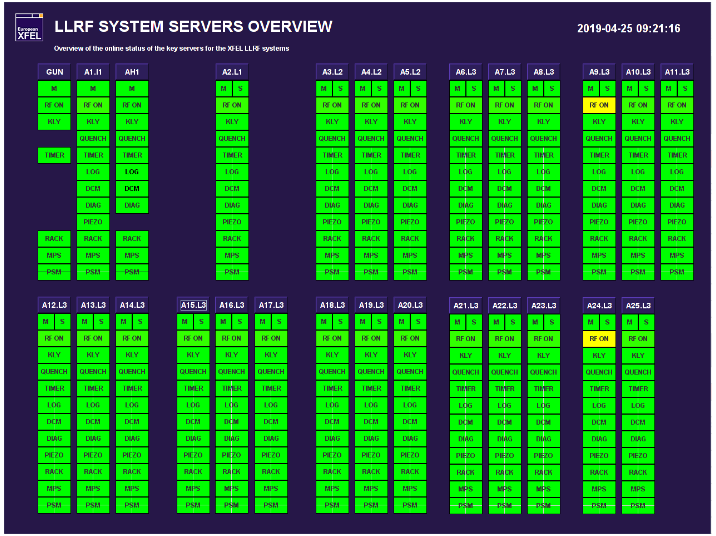
Status of Maximum Gradient Task Force

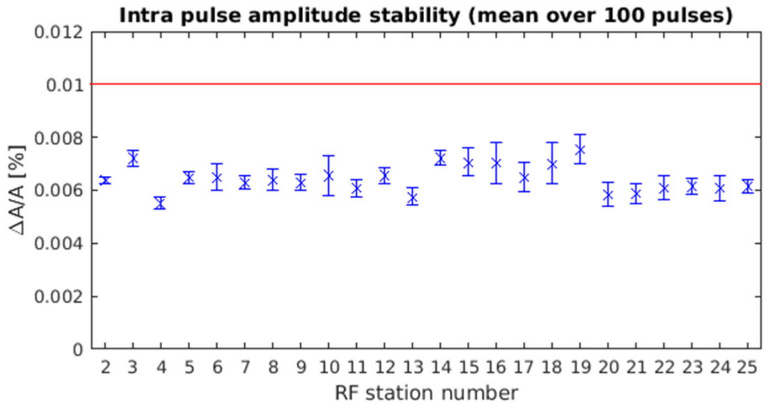
- Phase 1 ✓
  - Status survey ✓
  - Reach maximal VS voltages without hardware modifications ✓
  - Reaching 17.5 GeV ✓
- Phase 2 (Transition to Linac Operations Team)
  - Reach maximal VS voltages with hardware modifications
    - ► Cavity power optimization by waveguide distribution adjustments
    - ► Retune as many of the 22 cavities as possible
  - Investigations for keep operating all RF stations at established maximal VS voltages
  - Long time performance surveillance

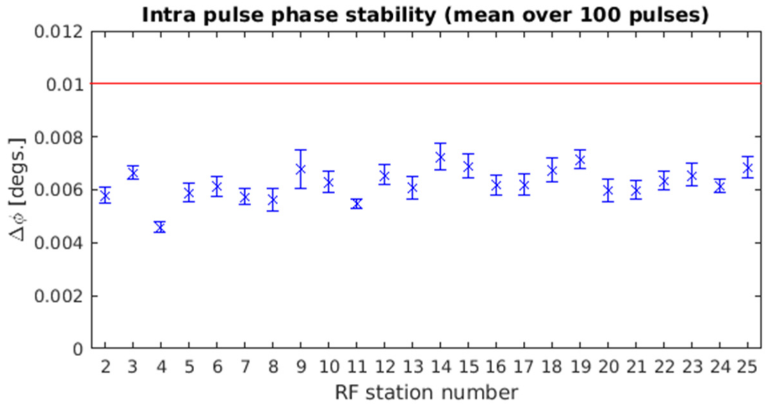
LLRF Regulation Performance and Health Tracking

- RF flattop amplitude and phase stability (RMS)
  - XFEL specifications: ΔA ≤ 0.01%, ΔΦ ≤ 0.01 deg.
  - Constantly met since commissioning in 2017

- Keeping track of LLRF station health





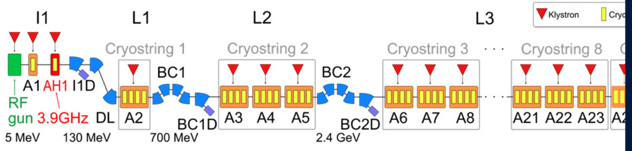


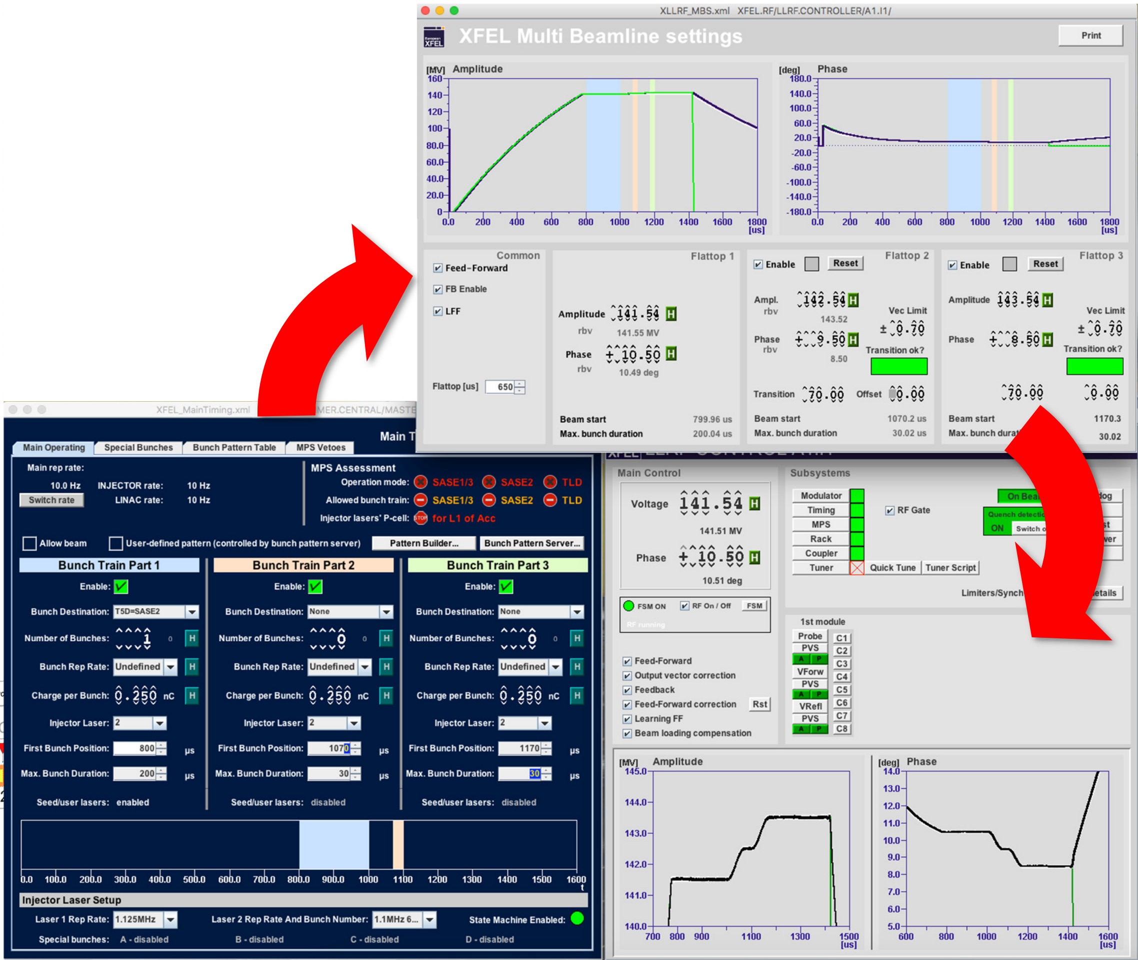
Piezo Status

- Driver electronics for piezos, which compensate cavity detuning during RF pulse
  - Installed at all XTL RF stations
- Cabling check
  - 61 issues found
  - Only 4 RF stations unaffected
- Completion of cabling repair and commissioning expected to be finished by summer 2019
- Piezo automation successfully tested
  - Full piezo operation demonstrated at A17 and A24

Multi Flattop Operation

- Definition of flattop regions via the timing system
- Setting different amplitude and phase set points via the LLRF systems
- Allows e.g. different compression settings for different bunch trains / beam lines
- Typically used in sections L1 and L2

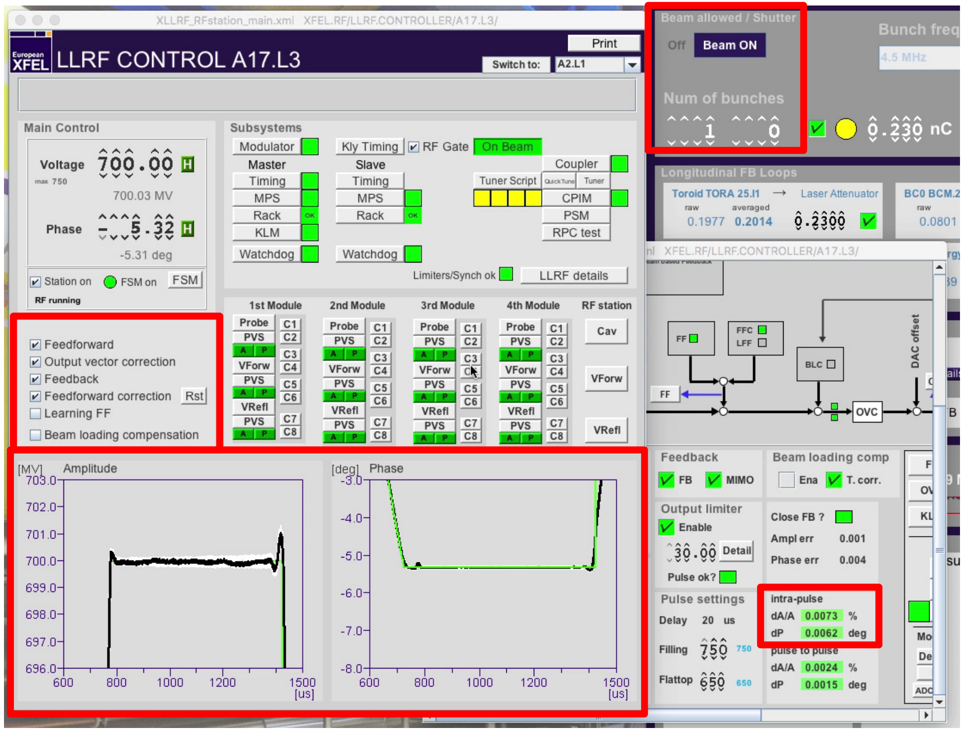




Beam Loading Compensation and Full Length Bunch Train Operation

- BLC compensates beam loading, assuring same energy gain for all electrons along bunch trains
- Commissioned on all RF stations

Beam Loading Compensation and Full Length Bunch Train Operation



Requirements
dA/A ≤ 0.01% ✓
dP ≤ 0.01 deg. ✓

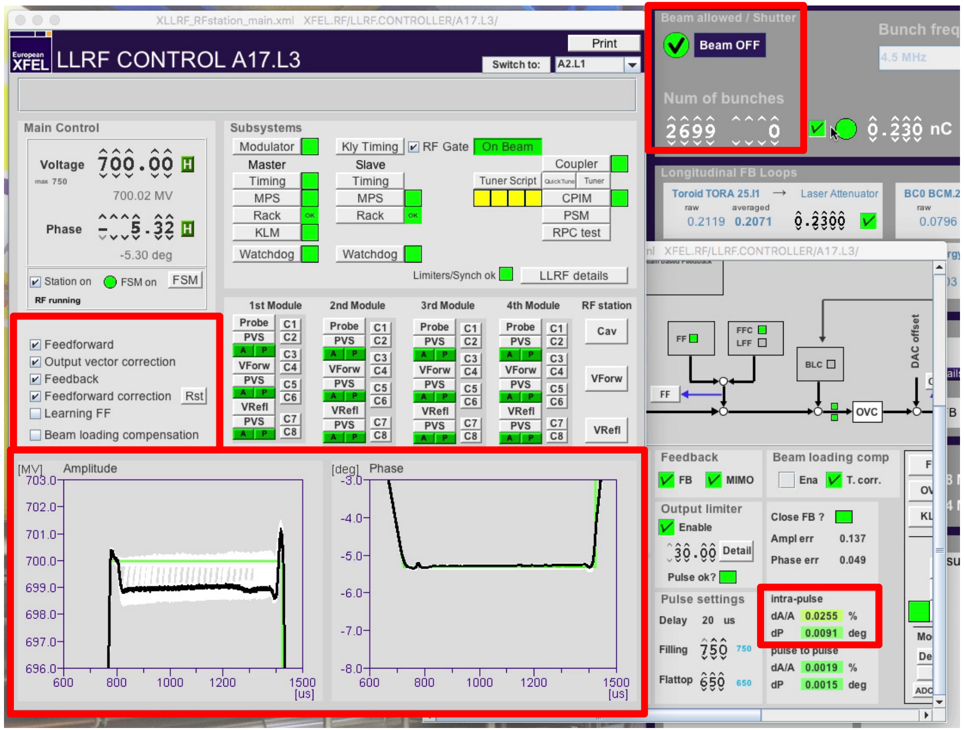
Beam Loading Compensation and Full Length Bunch Train Operation

Requirements

dA/A ≤ 0.01% ✘

dP ≤ 0.01 deg. ✘

Beam Loading Compensation and Full Length Bunch Train Operation



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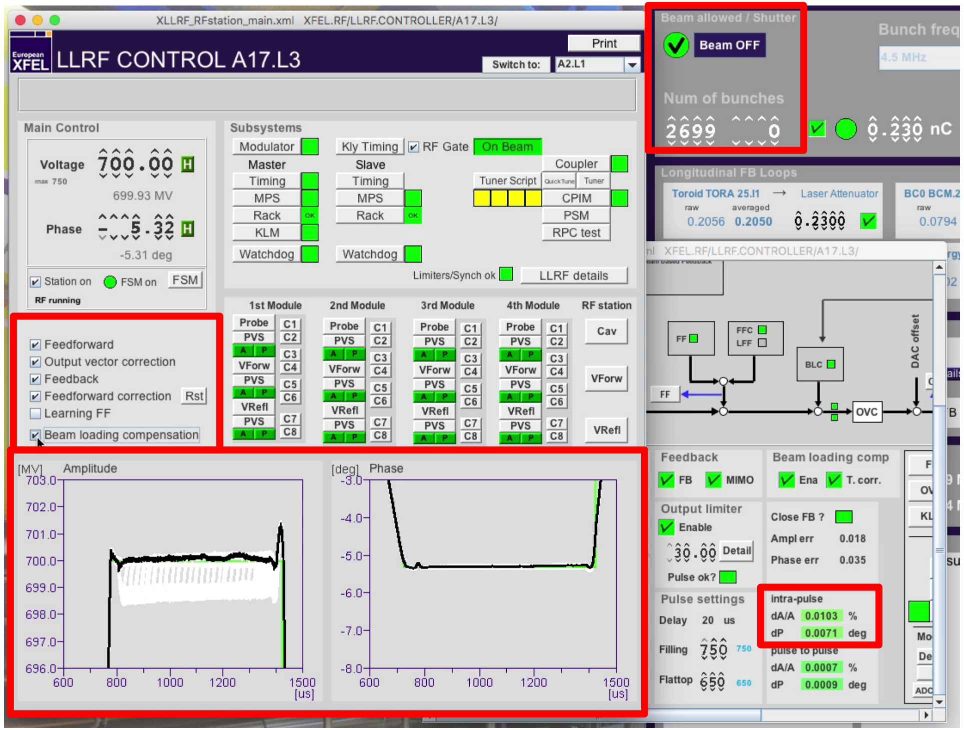
Beam Loading Compensation and Full Length Bunch Train Operation



Requirements

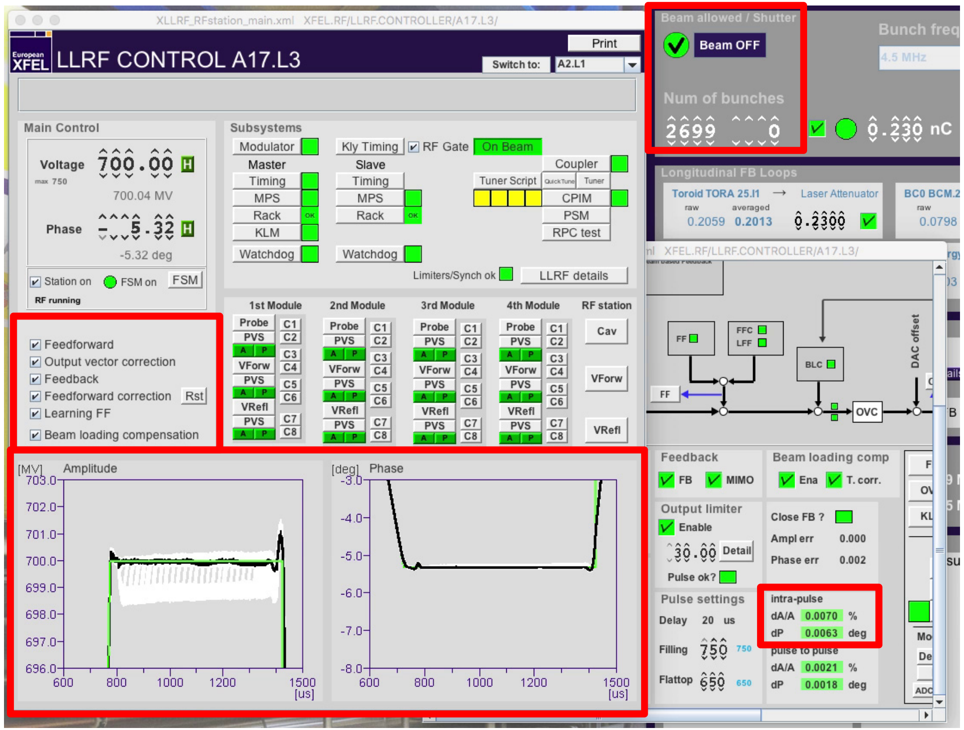
dA/A ≤ 0.01% ✘

dP ≤ 0.01 deg. ✓

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Beam Loading Compensation and Full Length Bunch Train Operation



- 650 μs long RF pulse in gun and SRF modules
- Energy jitter over bunch train < 5E-4
- No losses, 80 kW beam power safely distributed to beam dump

Requirements

dA/A ≤ 0.01% ✓

dP ≤ 0.01 deg. ✓

2nd of November 2018

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Summary

- General introduction
- Commissioning timeline
- Reaching design electron energy
  - Basic commissioning of the RF stations did not yield design electron beam energy → Formation of MGTF
  - All 20 L3 RF stations have been systematically investigated and reached their preliminary limits
  - Maximum beam energy increase: 1.9 GeV
  - Demonstrated beam acceleration at 17.6 GeV to TLD
  - Identified only three cavities, which one could classify as degraded
- Effort to stay at maximal voltages
- RF operation
  - Reliably meeting RF stability requirements since commissioning
  - Piezo driver electronics under commissioning
  - Multi flattop operation
  - Commissioned beam loading compensation allows acceleration of full bunch train length of 2700 bunches

Thank you very much for your attention! Questions?

- Live status of the European XFEL:
  http://tesla.desy.de/status_PNGs/XFEL_StatusPublic.png

- SRF2019 DESY contributions:

ID	Title	Author
Tutorial	LLRF Controls and RF Operation	J. Branlard
MOFAA2	RF Operation and Reaching Design Energy at the European XFEL	M. Omet, et al.
MOP023	NITROGEN INFUSION SAMPLE R&D AT DESY	C. Bate, et al.
MOP024	Vacancy-Hydrogen Dynamics in Samples during Low Temperature Baking	M. Wenskat, et al.
MOP025	Cavity Cut-Out Studies of a 1.3GHz single-cell cavity after a failed Nitrogen Infusion Process	M. Wenskat, et al.
MOP026	A Cross-Lab Qualification of Modified 120°C Baked Cavities	M. Wenskat, et al.
MOP034	European XFEL: Accelerating Module repair at DESY	D. Kostin, et al.
MOP070	Investigation of the Critical RF Fields of Superconducting Cavity Connections	J. Wolff, et al.
MOP082	Measurement of the vibration response of the EXFEL RF coupler and comparison with simulated data (Finite Element Analyses)	K. Jensch, et al.
TUFUA6	Surface Analysis of Niobium After Thermal/gas Treatments via Samples - Review	A. Dangwal-Pandey, et al.
TUP020	Statistical Analysis of the 120ºC Bake Procedure of Superconducting Radio Frequency Cavities	L. Steder, et al.
TUP023	Experience of LCLS-II Cavities Radial Tuning at DESY	A. Sulimov, et al.
TUP024	Radial Tuning Devices for 1.3 GHz TESLA Shape Cavities	J. Thie, et al.
TUP033	Modal analysis of the EXFEL 1.3 GHz cavity and cryomodule main components and comparison with measured data	S. Barbanotti, et al.
TUP099	Particulate sampling and analysis during refurbishment of prototype European XFEL cryomodule	N. Krupka, et al.
THP004	Design and Fabrication of a Quadrupole-Resonator for Sample R&D	R. Monroy-Villa, et al.
THP073	Advanced LLRF system setup tool for RF field regulation of SRF cavities	S. Pfeiffer, et al.
THP080	Status of the All Superconducting Gun Cavity at DESY	E. Vogel, et al.
THP092	STATUS OF CRYOMODULE TESTING AT CMTB FOR CW R&D	A. Bellandi, et al.
THP100	Insight into DESYs Test Laboratory for Niobium Raw Material and Semi-finished Products	J. Iversen, et al.
FRCAB08	Systematic Studies of the Second Sound Method for Quench Detection of Superconducting Radio Frequency Cavities	L. Steder, et al.