SRF Operation at XFEL: Lessons Learned After More Than One Year

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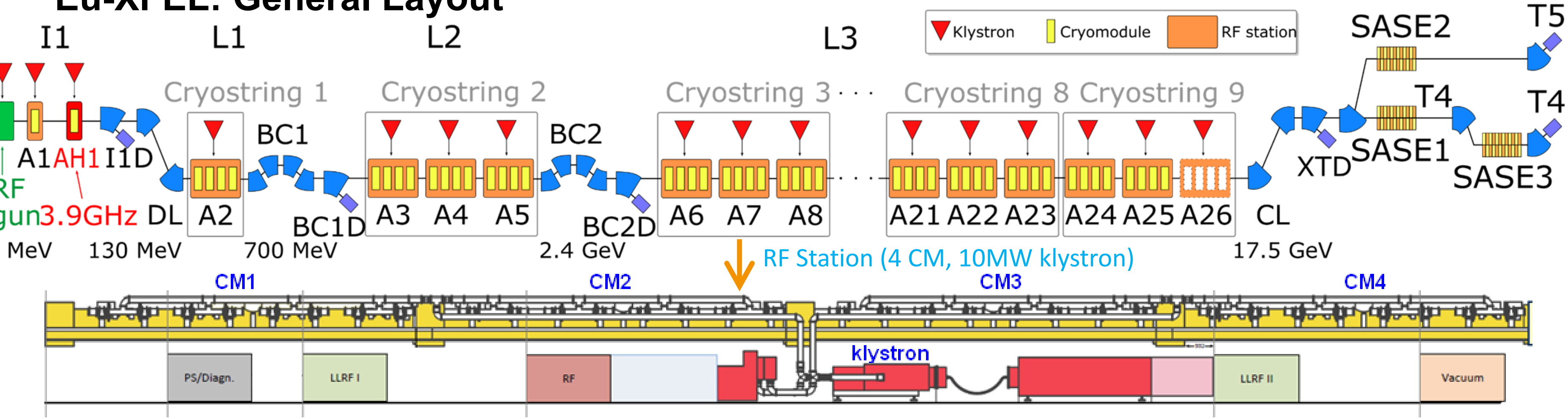
European XFEL – a great success story

- 17.5 GeV
- 27000 bunches/s

Outline

Eu-XFEL: General Layout



Length of accelerator: 1500 m

Length of facility: 3400 m

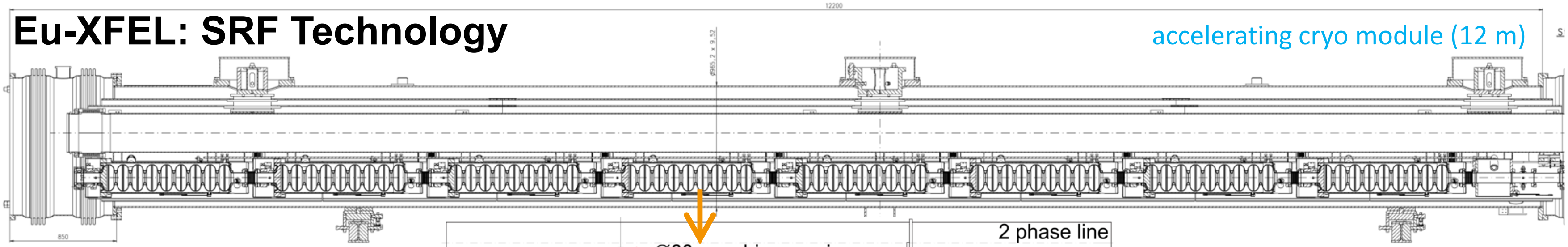
101 Cryo Modules (97 installed now)

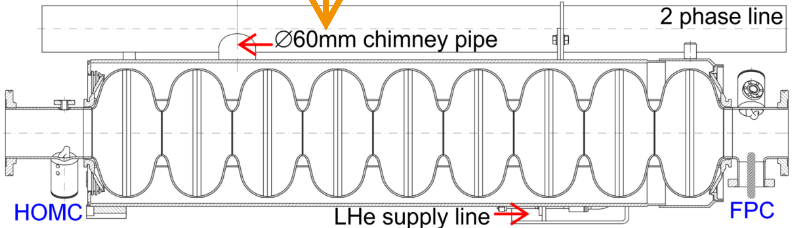
8 SRF 9-cell cavities per CM

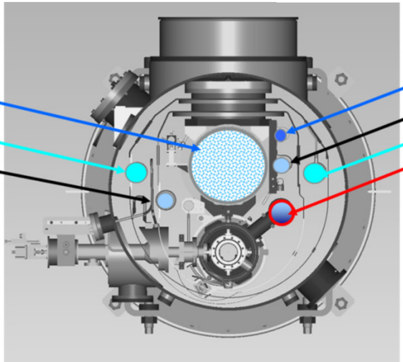
Beam pulse length	µs	**600**
Repetition rate	Hz	**10**
Max. # of bunches per pulse		**2700**
Min. bunch spacing	MHz	**4.5**
Bunch charge	nC	**≤ 1**
max. beam current	mA	**4.5**
Nominal beam DF	%	**0.65**
Average Gradient	MV/m	**23.6**

- 650 µs long RF pulse in gun and accelerating modules
- Operation energy 8 – 16.5 GeV
- LLRF takes into account electron beam induced fields
- Energy jitter over bunch train $<10^{-4}$
- No beam losses

Eu-XFEL: SRF Technology



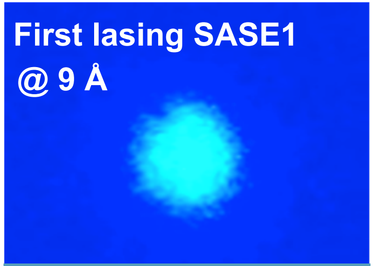




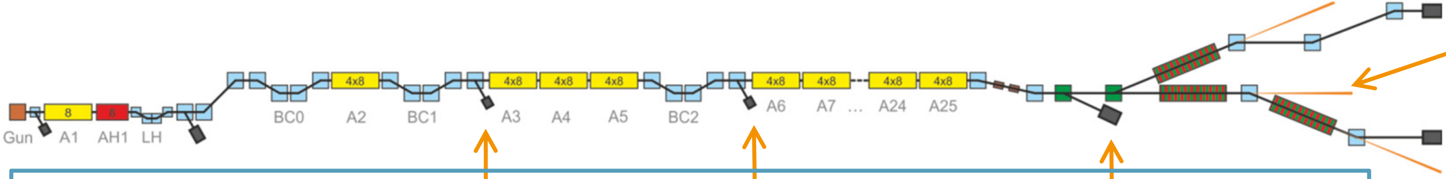
2-phase tube: ***240 W (20W/cryomodule)*** *is the estimated limit for one cryo string.*

Cavity type	TESLA
Number of cells	9
Cavity length	1.035 m
Operating frequency	1.3 GHz
R/Q	1030 Ω
Accelerating Gradient	20 – 31 MV/m
Quality factor, Q_0	$\geq 10^{10}$
Q_{ext} (input coupler)	4.6×10^6 (10^6 – 10^7)
Operating temperature	2 K

Eu-XFEL: Timeline



May 2-3, 2017



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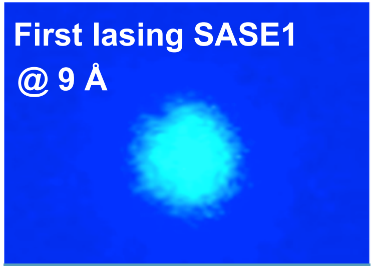

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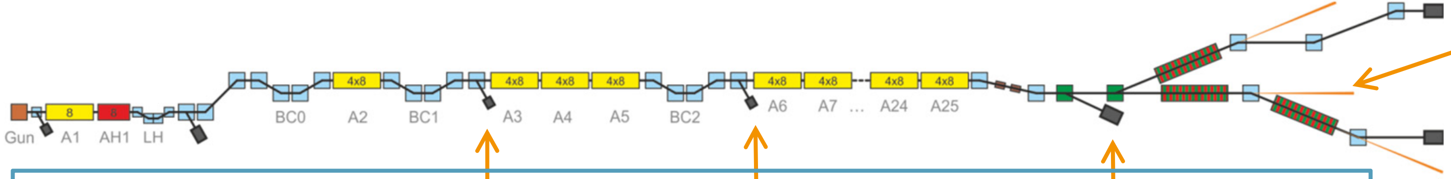

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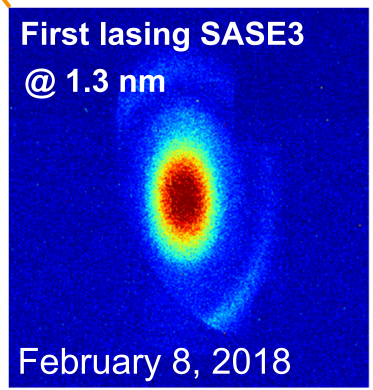

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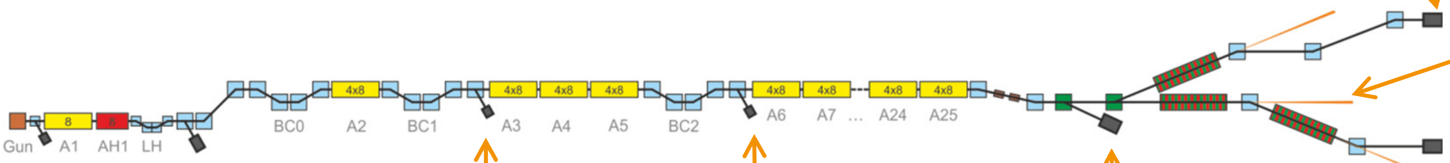
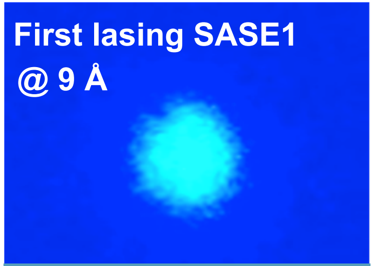


March 13, 2018



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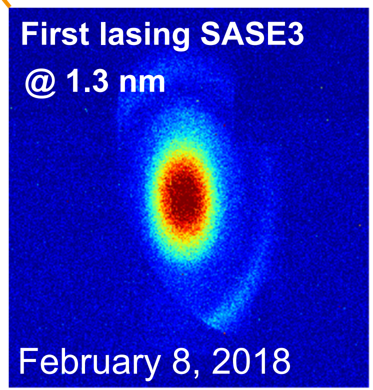

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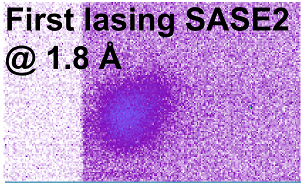

May 1, 2018

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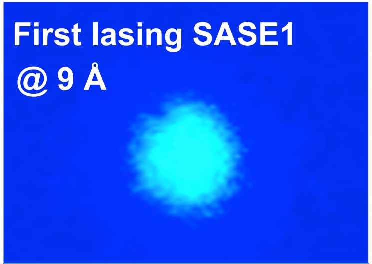

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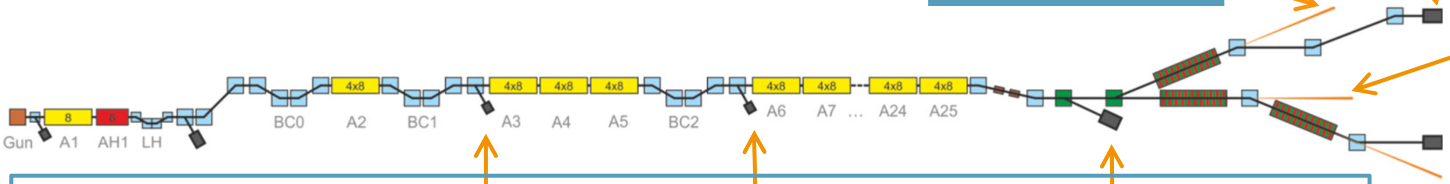

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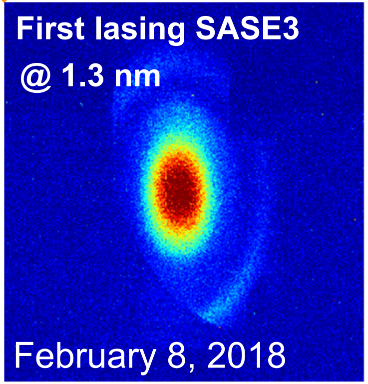
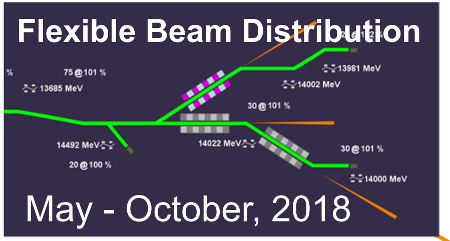
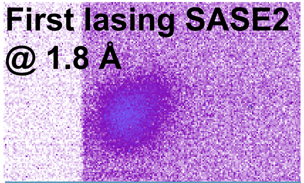


February 8, 2018

Eu-XFEL: Timeline





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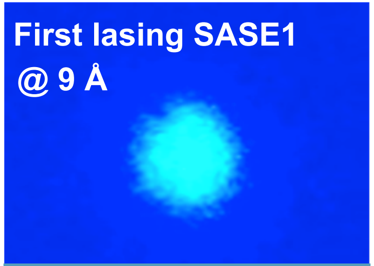

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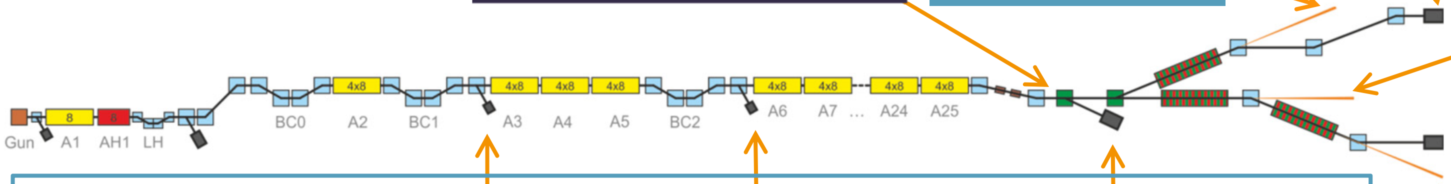

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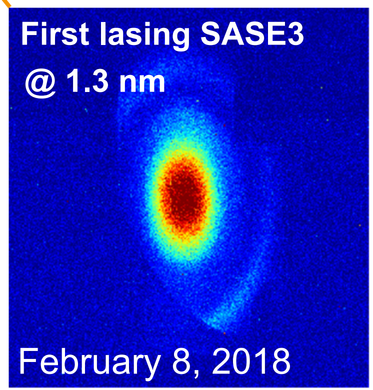
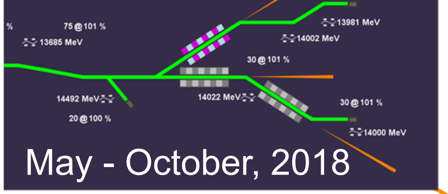


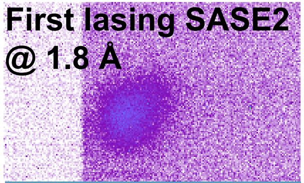
Eu-XFEL: Timeline

Flexible Beam Distribution



May - October, 2018

First lasing SASE2 @ 1.8 Å



May 1, 2018

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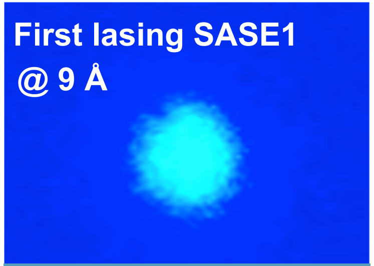
First lasing SASE1 @ 9 Å



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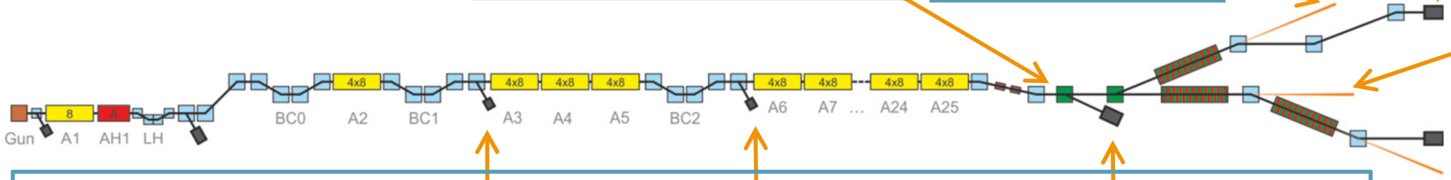

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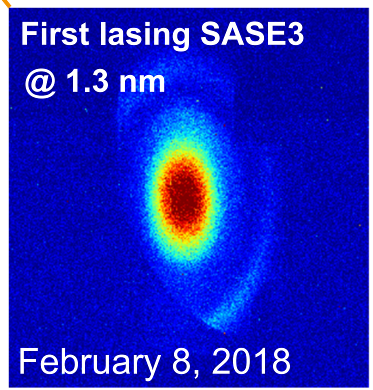
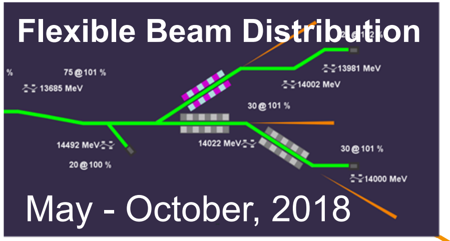
July 12, 2018: 17.6 GeV

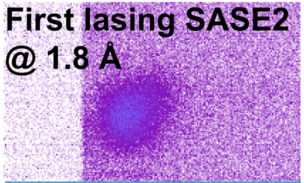
First lasing SASE3 @ 1.3 nm



February 8, 2018

Eu-XFEL: Timeline





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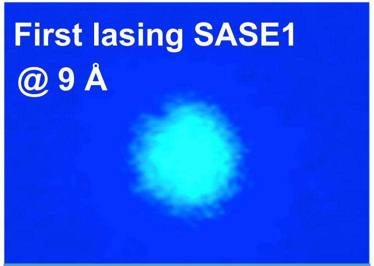

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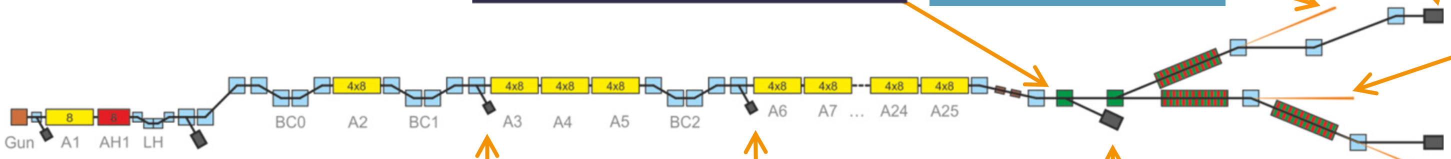

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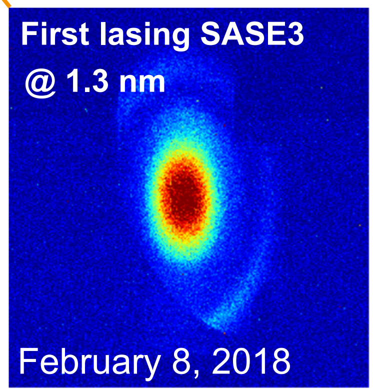
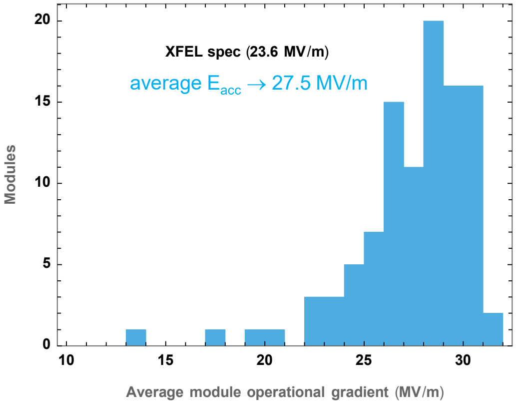
July 12, 2018: 17.6 GeV

Nov 2, 2018: 2699 bunches/RF pulse



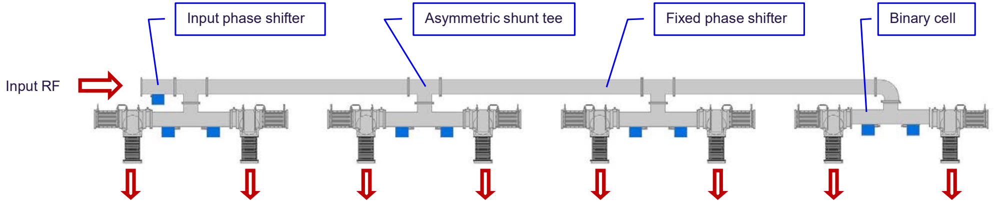
Cryomodule Waveguide Distribution System (WDS) tailored to match forward power to each cavity within practical limits

RF Power Distribution

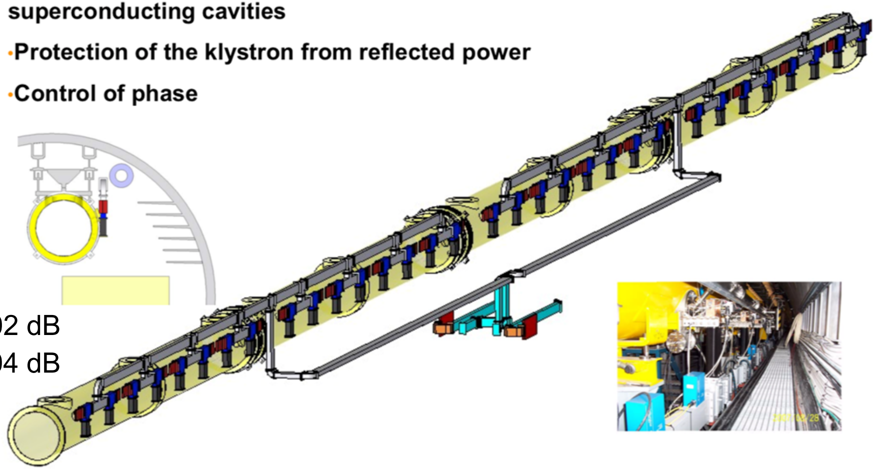


- All CM were cold-tested in **A**ccelerating **M**odule **T**est **F**acility (AMTF)
- Cavities operational limits:
  - Quench
  - Field Emission (X-ray monitor threshold 10^{-2} mGy/min)
  - 31 MV/m – power limit (administrative)
- E_{acc} measurement error ~10%

- CM WDS
- RF station (4 CM)



- **Distribution of klystron output power to the superconducting cavities**
- **Protection of the klystron from reflected power**
- **Control of phase**



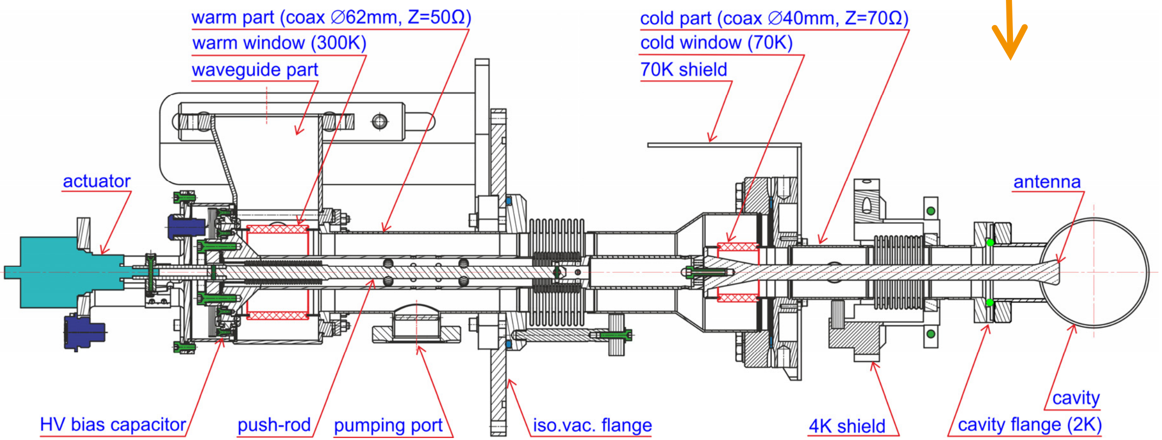
- Errors:
  - WDS: 0.02 dB
  - Klystron arm: 0.04 dB

- Module 'pairs' balanced (power requirement)
- Module power balance adjusted to match max. voltage (up to 3dB)

Fundamental Power Couplers

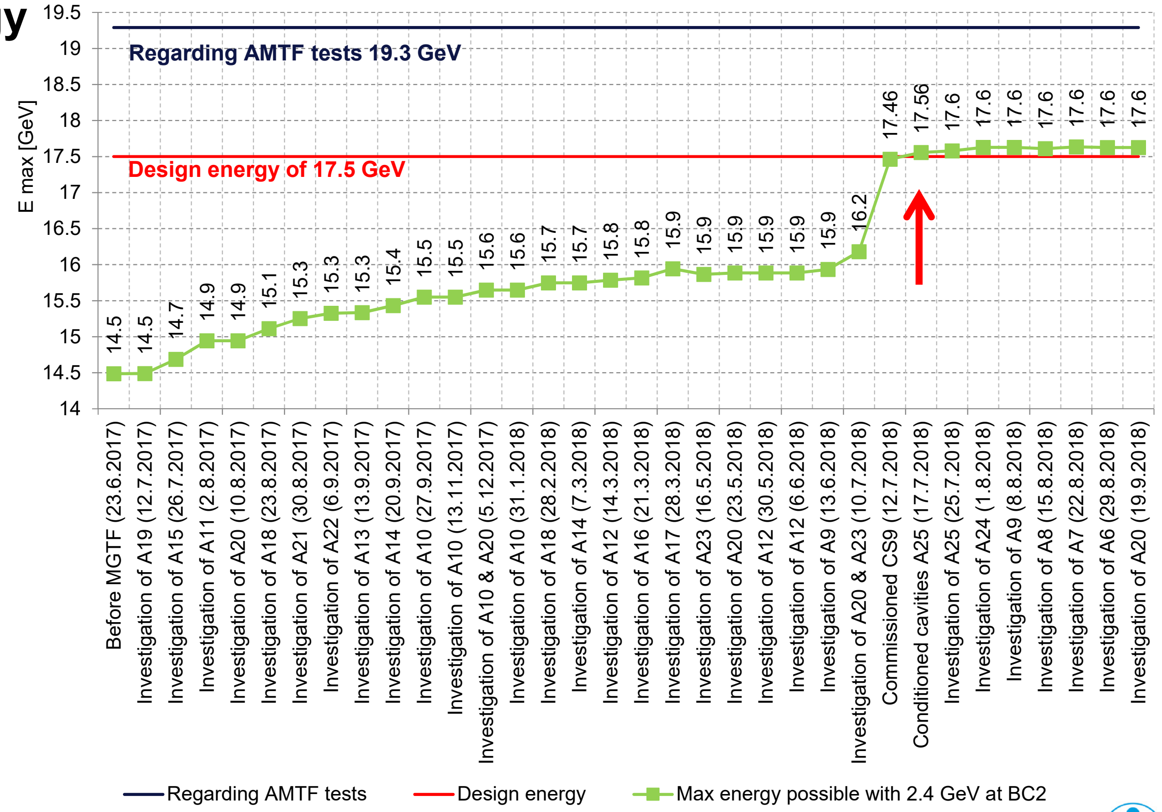
- Main coupler design for the Eu-XFEL linac is well established and proven.
- All of 25 Eu-XFEL RF stations 776 couplers are conditioned except
  - 4 FPCs were not conditionable and showing T70K overheating – shorted / disconnected from the RF source.
- Couplers operation stable since over two years of Eu-XFEL operation – no other shorted (not used) couplers.
- FPC cold window temperature (T70K) increase with high RF power on some couplers shows, that proper coupler cooling could be rather critical – currently it is not a problem for the operation.
- FPC conditioning (warm and cold) is important for the linac operation.

- **Eu-XFEL fundamental power coupler** consists of warm, cold and waveguide main parts. Coaxial coupler is made of copper and copper plated (10/30μm) stainless steel with two alumina TiN coated ceramic windows.
- Motorized antenna tuning (±10mm) allows for Q_{load} adjustment ($10^6..10^7$). Operating Qload is 4.6×10^6.
- All FPCs are pre-conditioned up to 1 MW pulsed RF power up to 400 μs RF pulse length and up to 500 kW with 1.3 ms pulse, repetition rate is 10Hz.

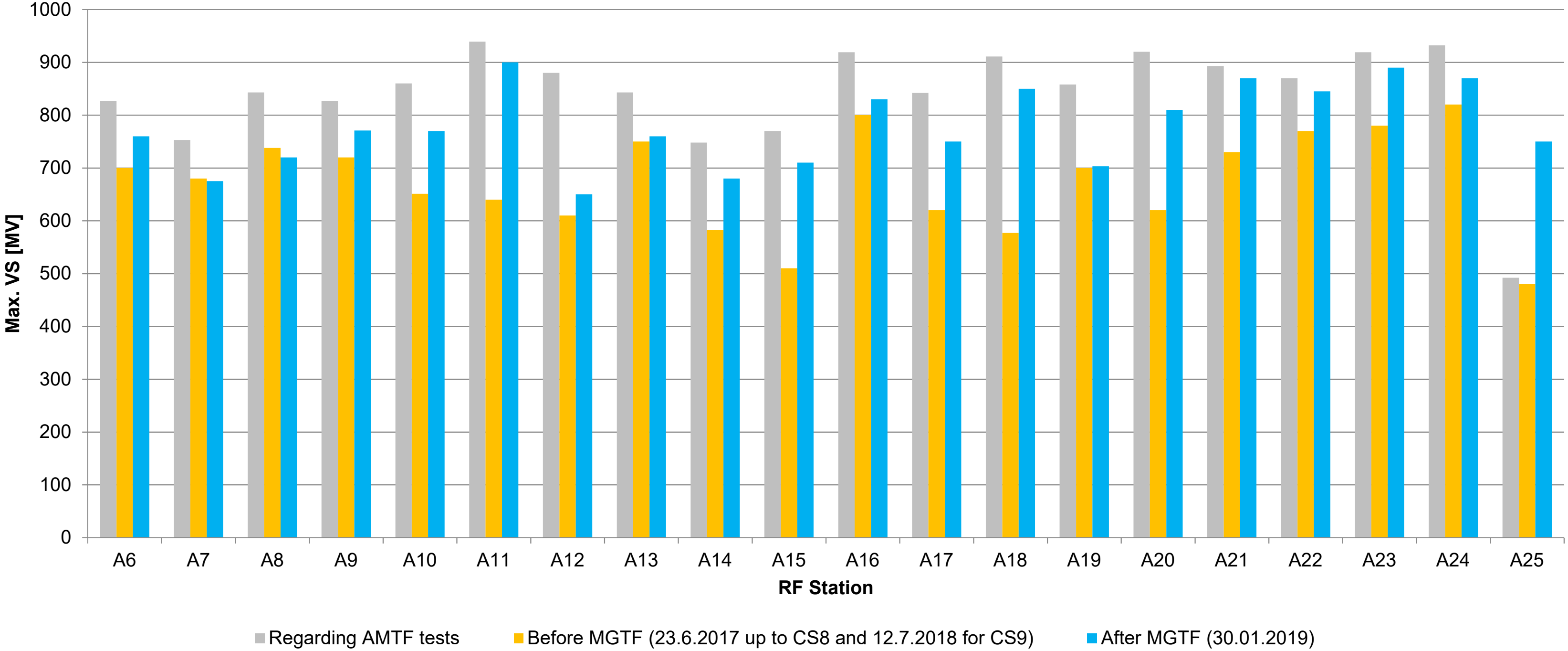


Reaching the Design Energy

- Maximum Gradient Task Force (MGTF)
  - start on 21.06.2017
  - 20 of 20 stations in L3 investigated
  - 1 of 3 stations in L2 investigated
  - 40 investigations done
- 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



SRF Cavities: Performance



Reached an average of 93.6% of AMTF performance

SRF Cavities: Limits

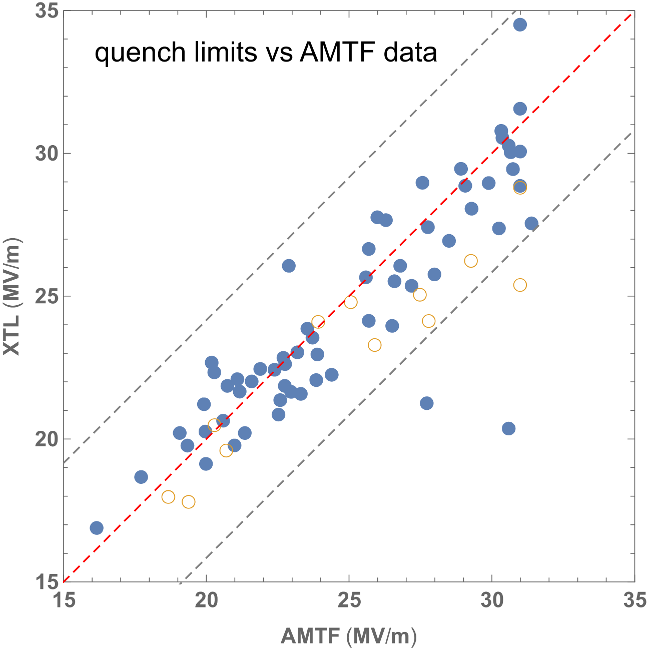
- Quench (soft quenching)
- Field emission (500 μSv/h neutrons)
- Power / missing piezo operation
- Other limitations → solved
  - Waveguide sparking
  - Too low klystron power
  - Cryogenics
- In some cases, there are potential energy gains from further optimization of the WDS

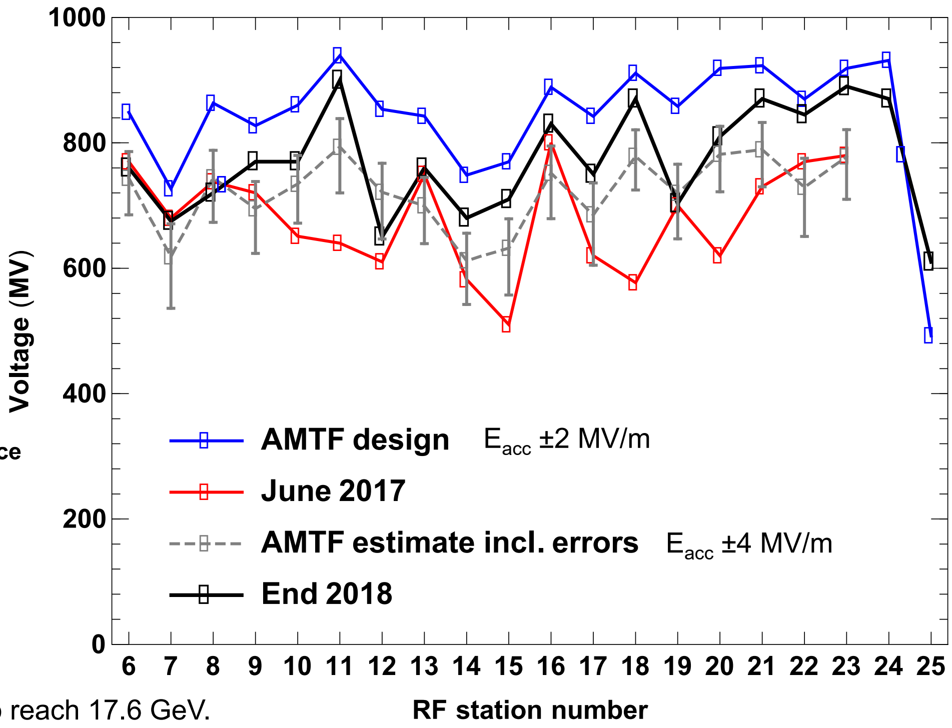
Detuned cavities (31.01.2019)

Reason of detuning	Number of cavities
After AMTF tests	5 (~0.6%)
After tests in XTL (coupler)	4 (~0.5%)
MGTF	12 (~1.5%)
Sum	**21 (~2.7%)**

- A4.M4.C4 coupler problem: T70K
- A6.M3.C1 cavity problem: high FE/X-rays (10MV/m limit)
- A6.M3.C5 MGTF: too much power to this cavity (higher V_VS without)
- A6.M3.C6 MGTF: too much power to this cavity (higher V_VS without)
- A7.M1.C7 MGTF: too much power to this cavity (higher V_VS without), degradation
- A7.M2.C3 MGTF: too much power to this cavity (higher V_VS without)
- A7.M2.C7 cavity problem: high FE/X-rays (11MV/m limit)
- A8.M4.C1 MGTF: too much power to this cavity (higher V_VS without)
- A8.M4.C4 MGTF: too much power to this cavity (higher V_VS without)
- A8.M4.C5 MGTF: too much power to this cavity (higher V_VS without)
- A10.M1.C3 cavity problem: low Eacc BD (no FE) (13MV/m limit)
- A12.M2.C2 MGTF: too much power to this cavity (higher V_VS without)
- A12.M3.C8 MGTF: too much power to this cavity (higher V_VS without)
- A12.M4.C1 coupler problem: T70K
- A14.M3.C5 MGTF: high cryo-losses (already at AMTF observed)
- A16.M2.C1 coupler problem: T70K
- A17.M3.C7 MGTF: too much power to this cavity (higher V_VS without)
- A18.M4.C4 wrong WG-distribution 31MV/m (FE limit at 23MV/m)
- A20.M4.C1 coupler problem: T70K
- A21.M3.C4 cavity problem: low Eacc BD (no FE) (14MV/m limit)
- A21.M4.C2 MGTF: too much power to this cavity (higher V_VS without), degradation

SRF Cavities: Operation

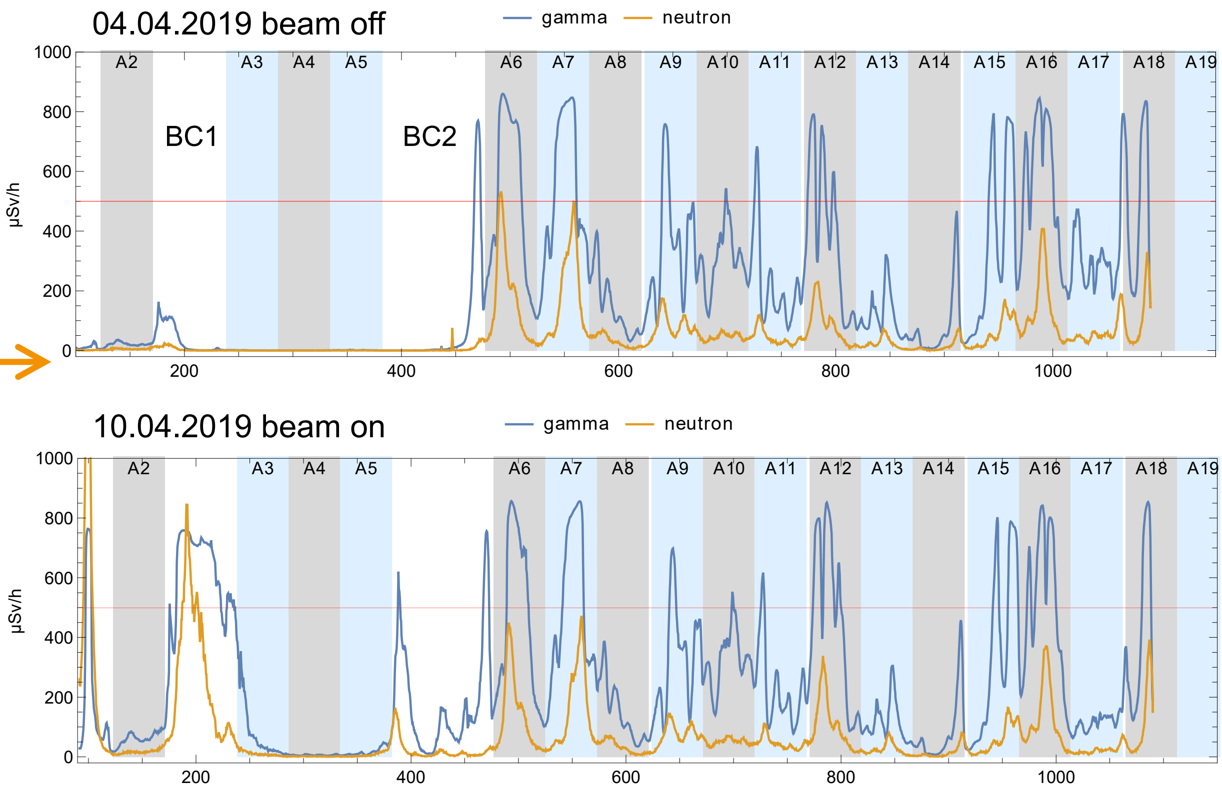




- Possible to reach 17.6 GeV.
- Quench limits of 76 cavities were determined operationally (1..3 per CM).
- 12 cavities are detuned to optimize the performance (max. energy).
- 1 RF station (A14) is limited by the cryo-load.
- 3 RF stations (A6, A9, A12) are limited by the tunnel radiation.
- Reached 93.6% AMTF test performance – within the error margins.

Tunnel Radiation

- Radiation (gamma and neutrons) measurement is an important tool to understand the machine operation.
- There are different techniques – Rad-FET, TLDs, BLMs, Gamma and Neutron Sensors – including a remote-controlled robot system (MARWIN).
- MARWIN measurement examples
- Radiation in the linac is almost entirely RF related (Field Emission / Dark Current).
- Radiation due to beam particle loss can be seen in collimation sections as expected
- Only three RF stations (A6, A9, A12) are limited by the radiation at max.energy.
- No degradation – radiation values do change with cavities accelerating gradient and tuning – understandable.



Cryogenics

- Eu-XFEL cryo-plant (4K) 2 years in the operation since successful commissioning
  - the performance results comply within the error margin with the specification: 2K cryo-losses set to ~5 W/CM, measured <6.3 W/CM at 17.5GeV
- The 2K pressure stability is excellent
  - 0.6% peak-to-peak, 0.3% RMS
  - The cascaded pressure regulation in combination with the automatic heat load compensation improved the pressure stability significantly
  - Even dynamic procedures (power ramping, RF-shutdown, etc.) can be compensated quite well without affecting the pressure stability drastically
- There are some problems with bearings of the cold compressor motors
  - New motor design is being developed, improvements are being done as well
  - The recovery effort after a cold compressor shutdown (e.g. bearing failure) is minimized by the automation and cryogenic system configuration

Eu-XFEL cryogenic system:

- 671 control valves
- 2647 temperature sensors
- 800 pressure sensors
- 212 flow sensors
- >100 level sensors
- 433 regulation loops
- > 22000 records
- > 220000 properties

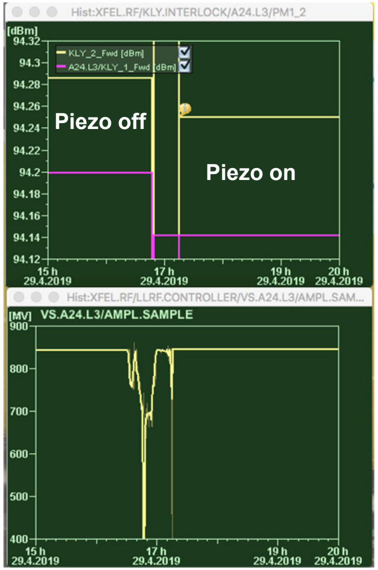
2K cryogenic heat load at 17.5 GeV (July 2018)

Cavity Piezo Drivers

Test run at A24

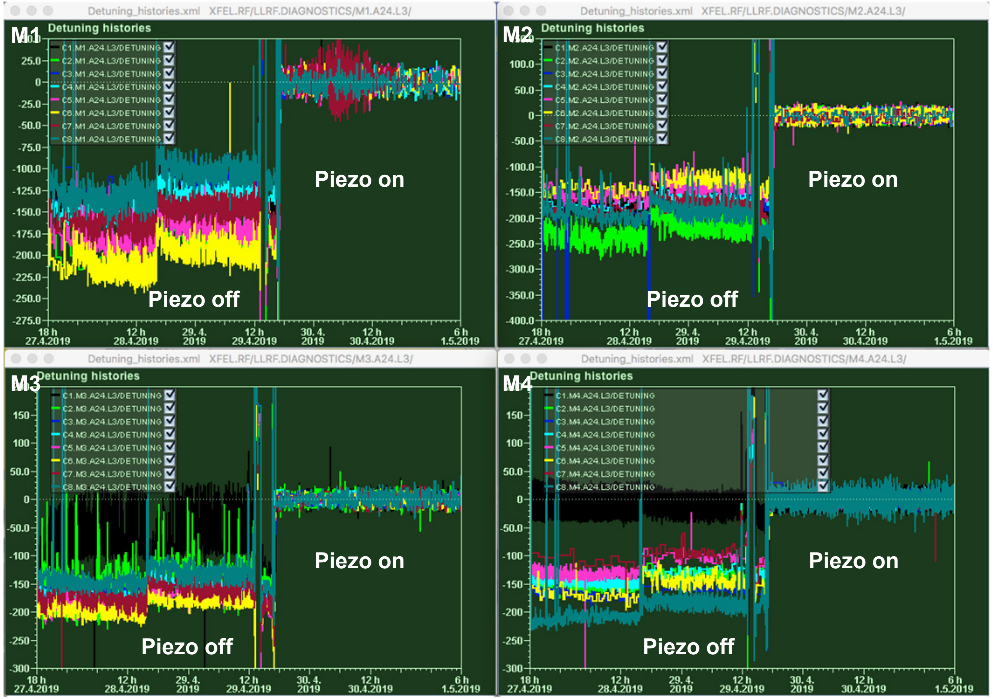
- Piezo driver electronics installed at all RF stations
- Cable checking is scheduled now, then…
  - Cable fixing
  - Commissioning
  - AC/DC feedback operation
- Test operation at A24 since end of April
  - Less forward power required for same VS voltage (-1.1%)
  - Detuning kept stably around 0 Hz

Klystron forward power of arm1 and arm2



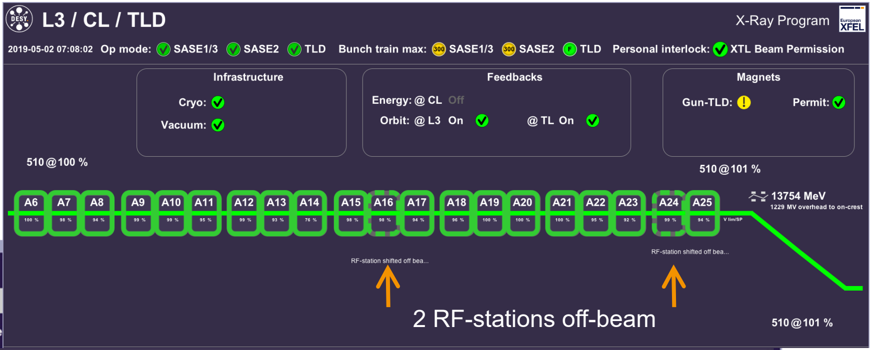
Vector Sum (VS)

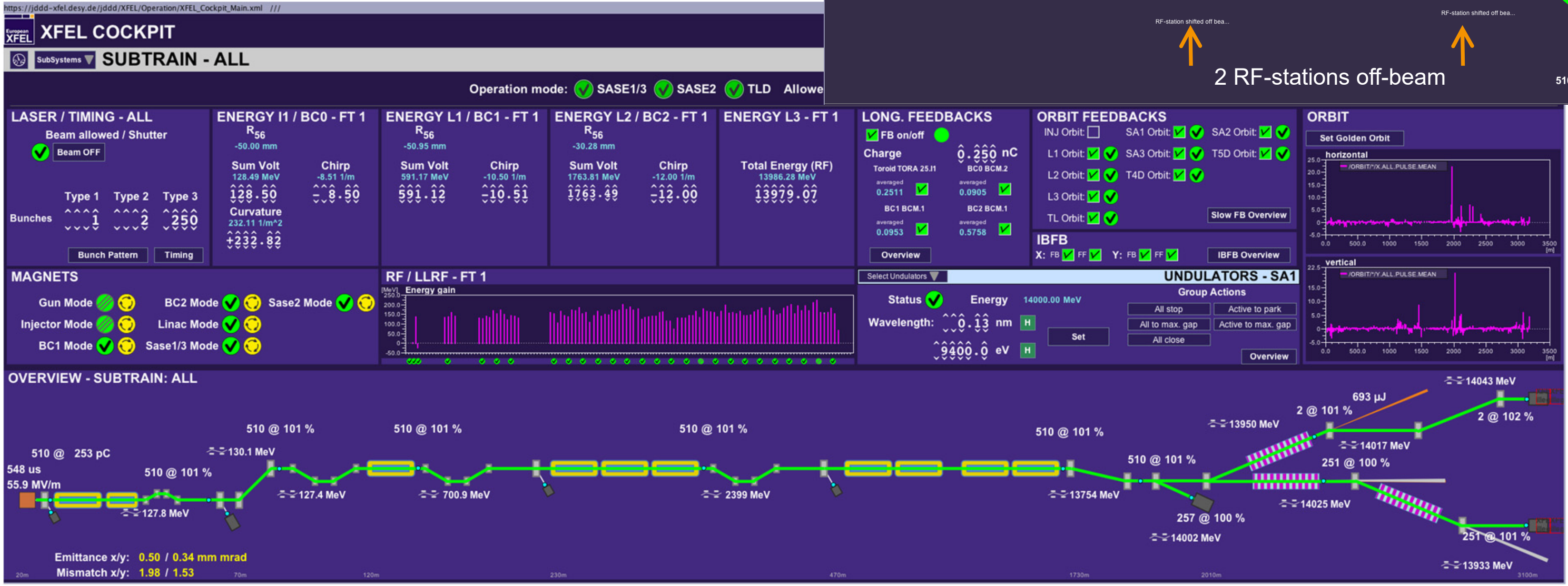
Detuning



Eu-XFEL: Current Operation

run with 1 or 2 RF-stations off-beam as a spare





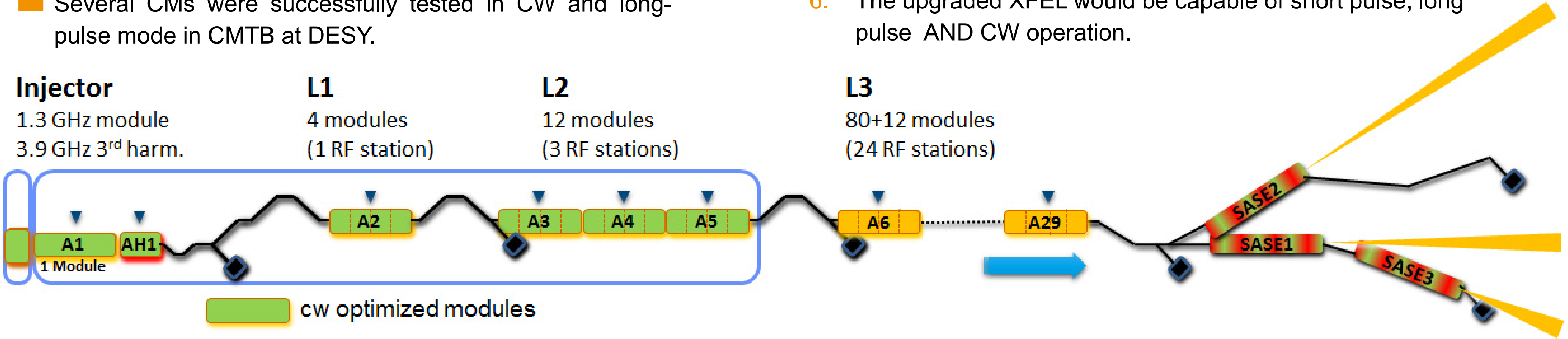
- Current beam energy: 14 GeV – 2 RF-stations off-beam (user operation).
- Next planned beam energy: 16.5 GeV – 1 RF-station off-beam (user operation).

Possible CW Upgrade

- Continuous Wave (CW) mode is the origin of the SRF accelerator technology. Eu-XFEL project was based on the Linear Collider (LC) technology (TESLA) operating in the pulsed RF power mode (10 Hz / 650 μs beam pulse). Many FEL user experiments will get an advantage (or become possible) with CW mode operation.
- Possible beam parameters: 25 μA (100 pC and 250 kHz) with 8 GeV (CW) and 12 GeV (long-pulse: ~100ms).
- Several CMs were successfully tested in CW and long-pulse mode in CMTB at DESY.

The Upgrade Plan:

1. Replace the front-end cryomodules (17x)
   - Larger cooling capability
   - CW optimized cavities
2. Install CW capable RF sources
   - 1× **IOT** per RF station
3. Double the cryo plant (cost driver)
   - 2.5 → 5kW
4. CW electron gun (preferred option: SRF gun).
5. The former front-end cryomodules can be installed at the end of the linac to lengthen L3 (+4 RF stations), no further action required in L3 (>1km).
6. The upgraded XFEL would be capable of short pulse, long pulse AND CW operation.



Summary

1. European XFEL operates since over two years – without major problems.
2. Important project milestones – **17.5** GeV and **27000** bunches/s (no lasing) – achieved.
3. Current beam energy: 8 – 16.5 GeV (user operation).
4. Initial achieved station voltages were consistent with production module tests projections including errors.
5. MGTF carefully studied and tuned each station individually, eventually achieving >90% of projected estimate.
6. Currently running with 21 cavities detuned - 12 detuned as a result of the MGTF studies.
7. Tunnel radiation (dark current): currently considered safely within limits, but will continue to monitor/study.
8. Focus now on maintaining identified max. limits operationally - root causes analysis of trips, etc.
9. A possible CW operation upgrade is under study.

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Thank You !