European XFEL Operational Experience

Tesla Technology Collaboration Meeting
19-21 Jan. 2021

Julien Branlard, for the **XFEL operation team**

Hamburg, 21.01.2021

OUTLINE

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  - Introduction
  - RF station
- **2020**
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  - COVID-19 de(re)tune
  - High-/low-V linac setup
- **Availability**
  - XTL report
  - Operation team
- **Automation**
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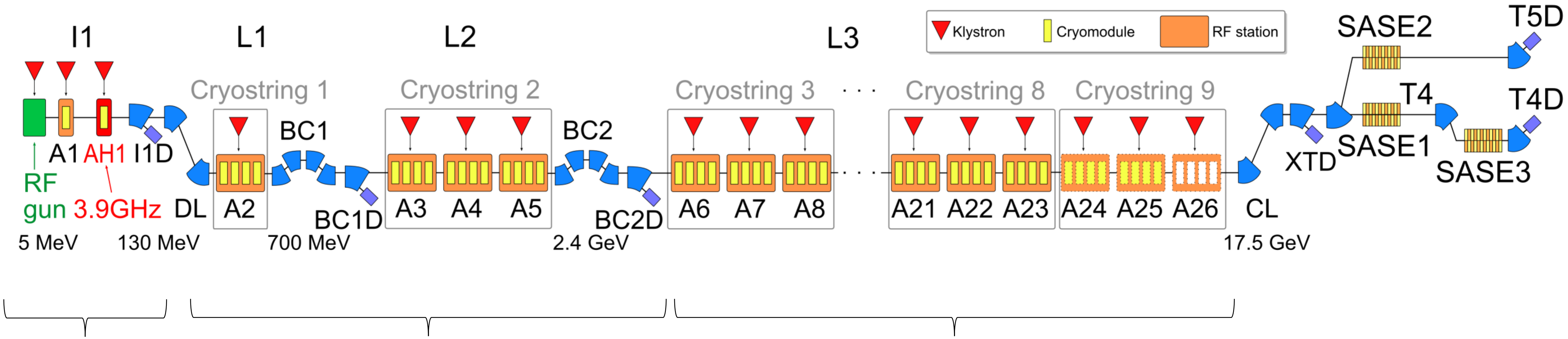
  - LFD piezo automation
  - FSM trip recovery
- **The high-V / low-V experiment**
  - Statistics
  - Trip examples
- **Outlook**
  - Example: “big data” analysis

The European XFEL Accelerator



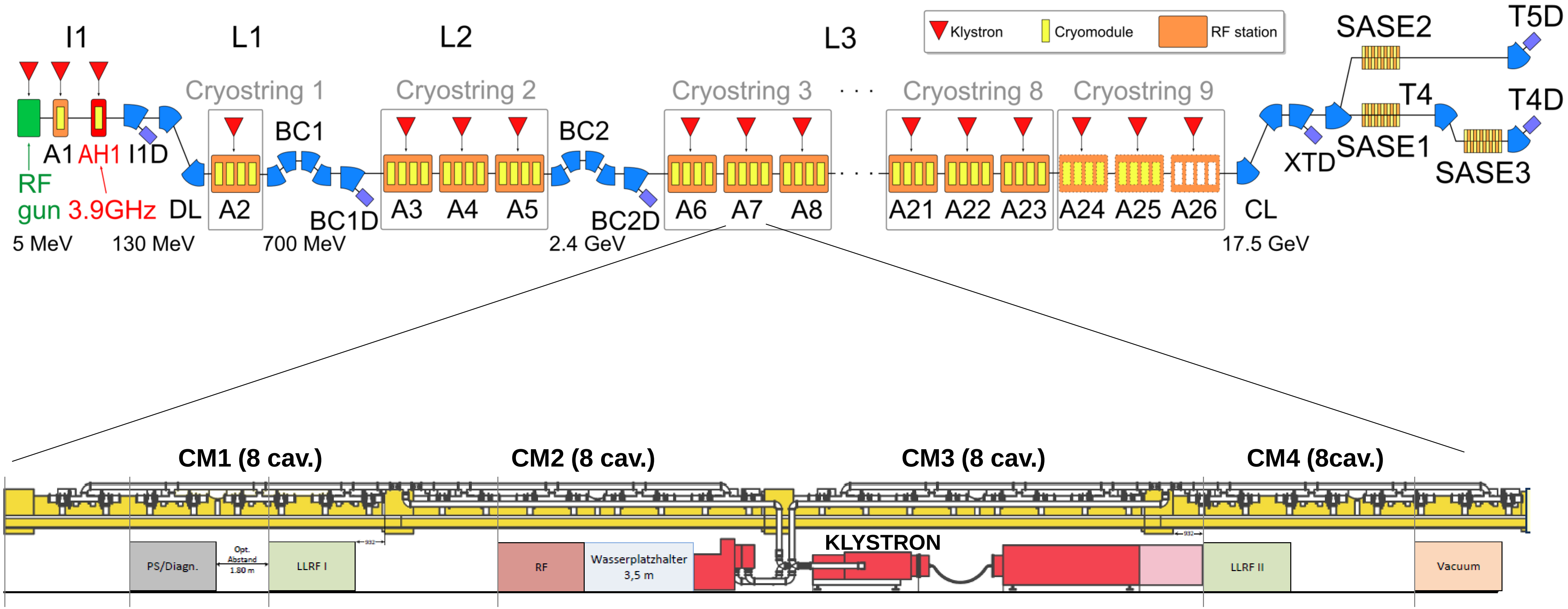
Injector
120 m
130 MeV
8× 1.3 GHz
8× 3.9 GHz

Bunch compression
Two stage
354 m
2.4 GeV
L1 1× 1.3-GHz RF station
L2 3× 1.3-GHz RF stations

Main Linac
1180 m
17.6 GeV (max)
20× 1.3-GHz RF stations

3 photon beam lines
6 experiments
demonstr. photon energies
SASE1: 6-30 keV
SASE2: 6-19 keV
SASE3: 0.5-3.2 keV

The European XFEL Accelerator (RF station)

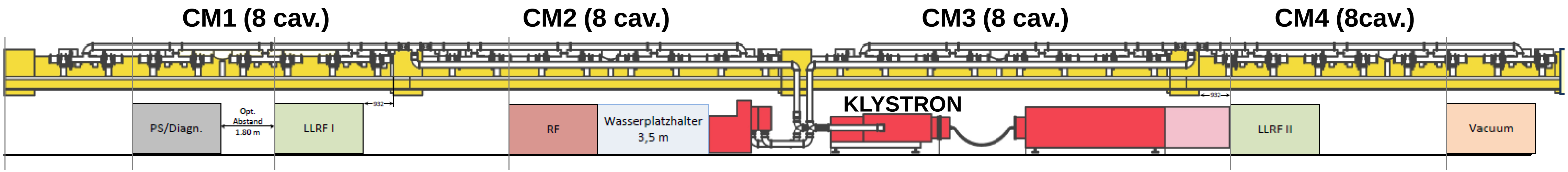


The European XFEL Accelerator (RF station)

One RF station comprises*:

- 1× 10 MW **klystron**
- 32× TESLA-type 1,3-GHz **cavities** housed in 4 **cryomodules**
- 32× motorized power **couplers**
- 32× motorized **tuners**
- 64× **piezo** (actuator actuator / sensor)
- 36× motorized phase shifters (1/ cav + 1/ cryomodule)
- 100+ LLRF channels (probe, forward, reflected)

25 RF Stations
- **25 Klystrons**
- **97 Cryomodules**
- **776 1.3 GHz cavities**



* Exception: A1 (injector) 1 CM

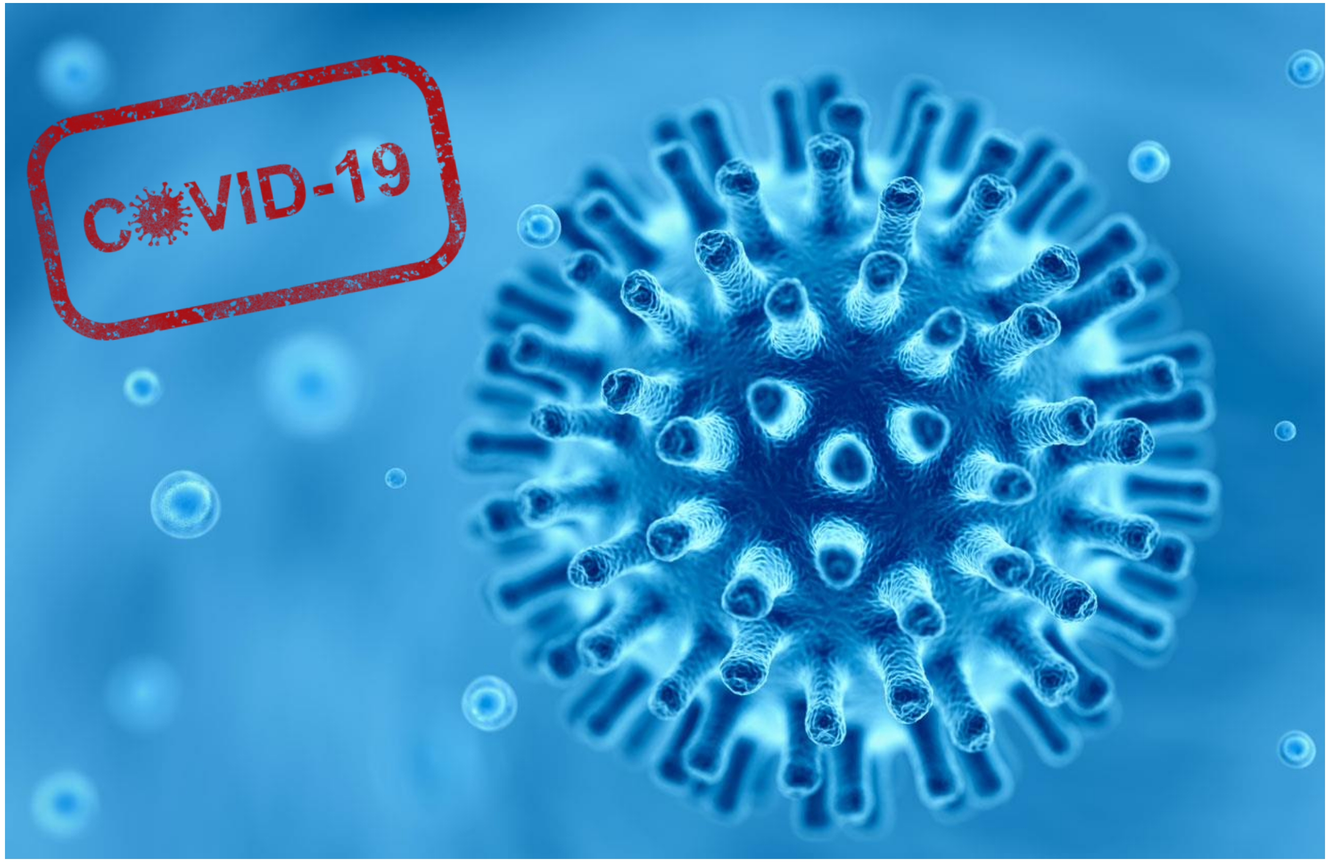
2020, year of the COVID-19

User stats

- 5640 operating hours
  - 6888 hours planned

- 1856 user hours (as planned)
  - with 95% availability

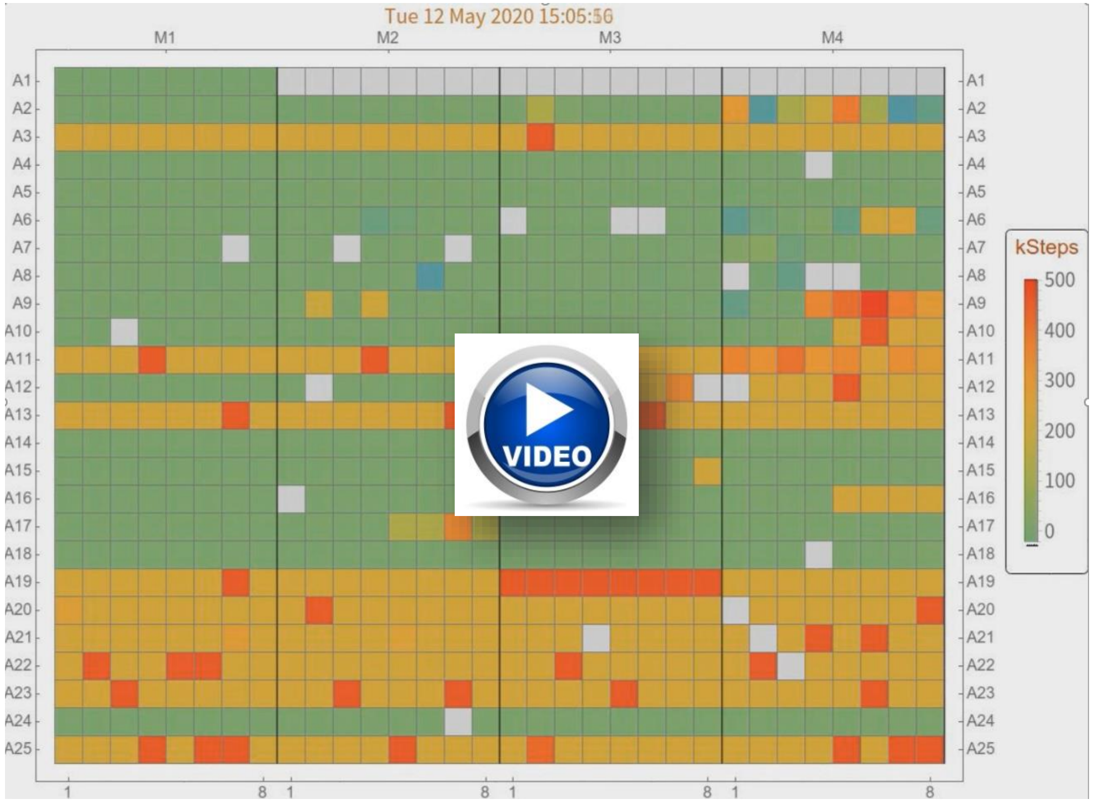
- 30 keV (world record) and
  17.8 keV (routine) photon energy



COVID (de)retune

- **March 2020**
  - Unclear if personnel on site could guarantee cold linac in case of cryo failure
  - Preventive measure: detuning all 776 SRF cavities
  - 2 shifts, 8 people
- **April 2020: lockdown (“light” shutdown)**
- **May 2020**
  - Remote facility operation possible
  - Retune all cavities (2 shifts, 8 people)
- **Lessons learnt**
  - Too long, too resource intensive
  - 1-button automatic detuning (design phase!)
  - Emergency plan ?

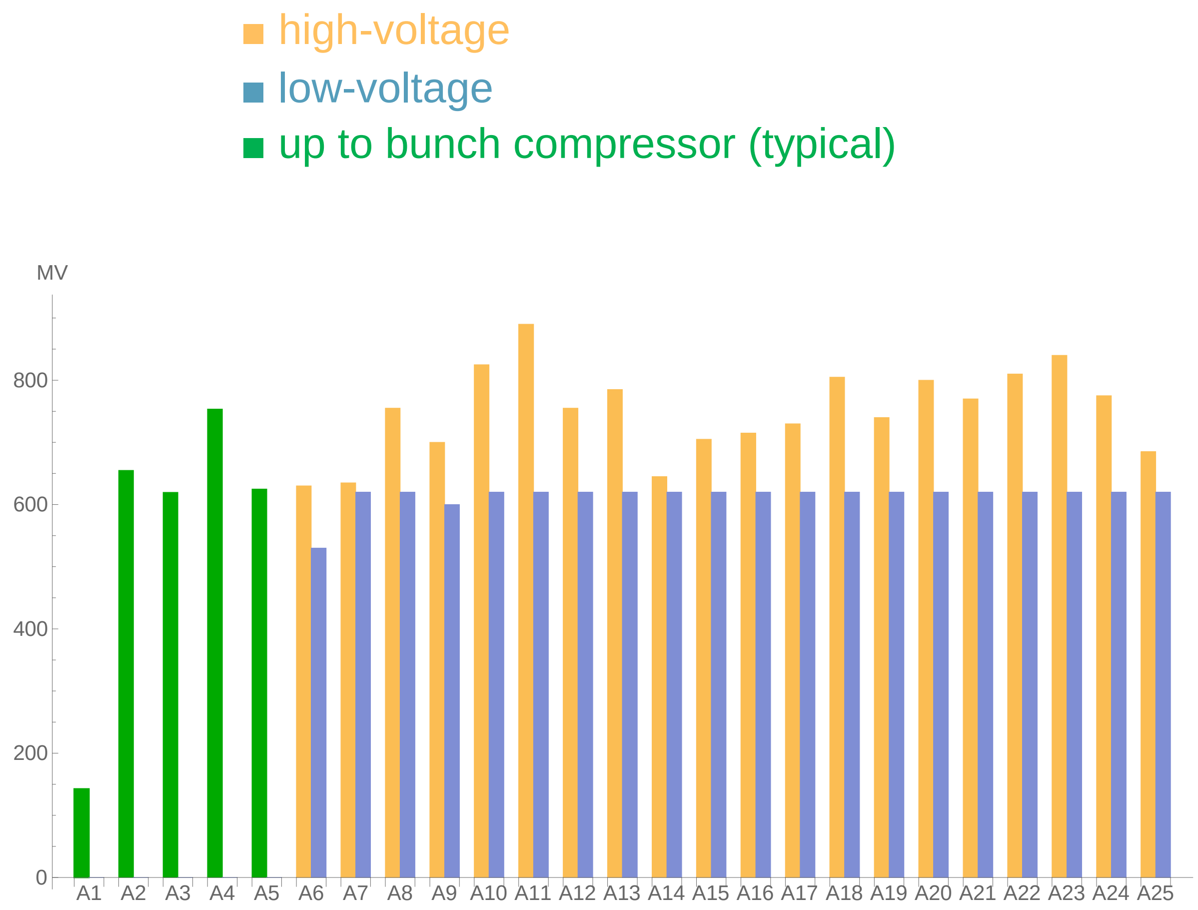
Movie credit N. Walker



Linac Setup

Two modes of operation:

- low-V : for beam energies 11.0 – 14.0 GeV
- high-V : for beam energies 14.5 – 16.5 GeV

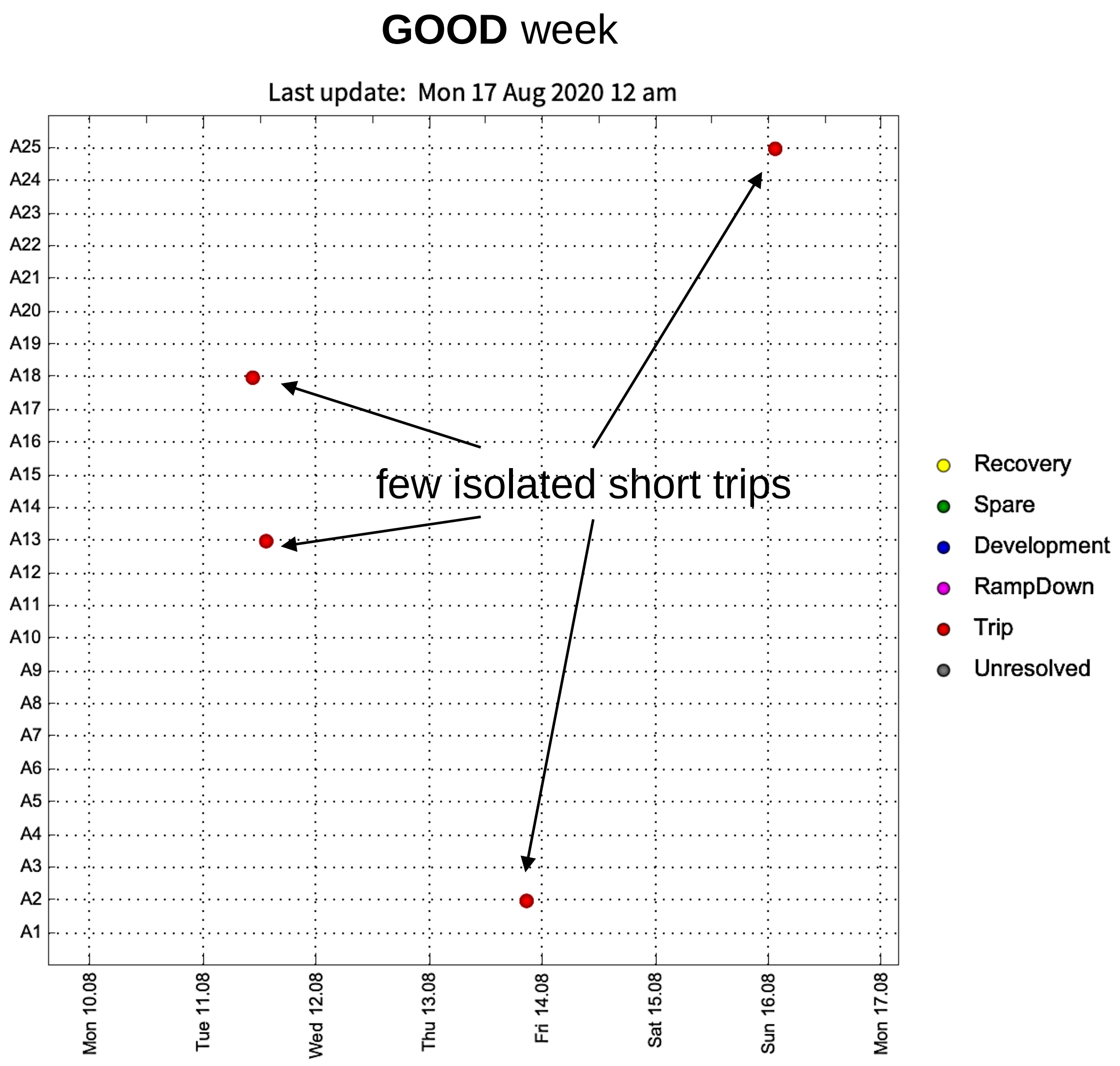


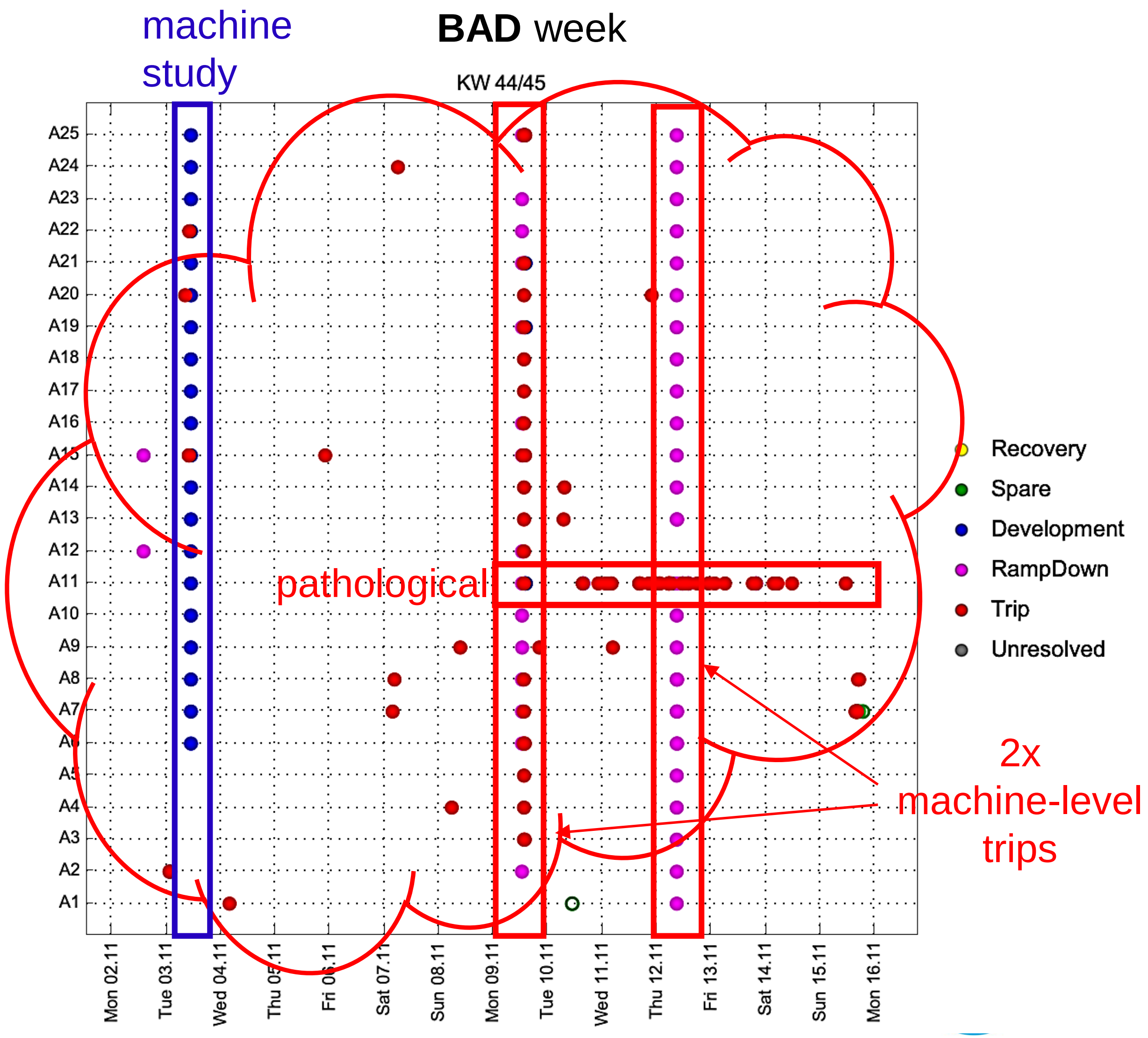
High-V

- Cavities operating at max gradient
  - ➔ **more radiation coming from RF**
- Cavities operating with almost no RF overhead
  - ➔ **almost at quench limit**
- Couplers, klystrons running with more power
  - ➔ **more arcs, sparks, etc..**
- Overall, operating on the edge
  - ➔ **more trips**

Monitoring the RF availability

XTL live report





The Linac Operations team

- **Cross-disciplinary team**
  - 5 – 6 regular members
    - ▶ Operations
    - ▶ Low and high power RF
    - ▶ Couplers and cavity
  - Special topics:
    - ▶ Controls, cryo, MPS

- **Weekly meetings**
  - Review / tag the trip of the week
    - ▶ Availability
  - A.O.B.
    - ▶ Workflow, procedures
    - ▶ Accelerator development
    - ▶ Maintenance
    - ▶ Etc…

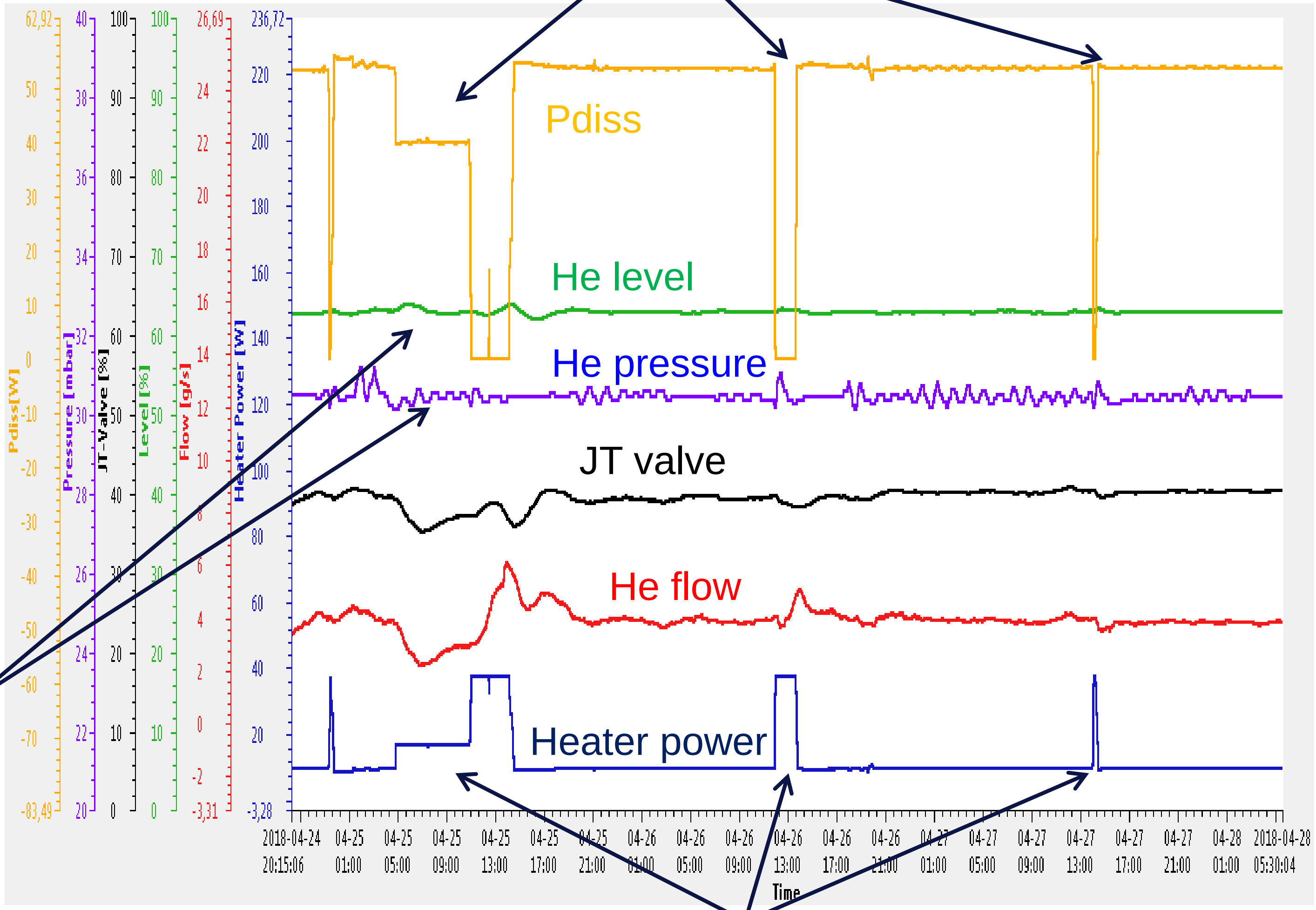
Stations	Type	Time	Duration	OnBeam	LinacDownTime	RootCause
A2–A21,A23–A25	LinacOff	Wed 18 Nov 2020 17:08:05	1.4 hours	On	1.4 hours	INFRASTRUCTURE : NETWORK_HARDWARE : NETWORK SWITCH
A22	Trip	Wed 18 Nov 2020 17:01:57	4.9 hours	On	43 seconds	LLRF : QUENCH_DETECT : {M3.C7}
A22	Trip	Wed 18 Nov 2020 16:25:38	4.9 hours	On	60 seconds	LLRF : QUENCH_DETECT : {M3.C7}
A22	Trip	Wed 18 Nov 2020 14:05:41	4.9 hours	On	22.1 minutes	LLRF : HARDWARE_FAULT : DCM / RADIATION
A11	RampDown	Wed 18 Nov 2020 13:36:20	15.5 minutes	On	62 seconds	KLYSTRON : MAINTENANCE
A18	Trip	Wed 18 Nov 2020 10:27:42	1.5 hours	On	1.5 hours	TIMING : COMMS_ERROR : REBOOT / RADIATION
A11	Trip	Tue 17 Nov 2020 16:20:09	2.3 minutes	On	2.3 minutes	KLYSTRON : GUN_ARC
A11	Trip	Tue 17 Nov 2020 14:57:27	2.2 minutes	On	2.2 minutes	KLYSTRON : GUN_ARC
A8	Trip	Tue 17 Nov 2020 13:05:10	1.8 minutes	On	1.8 minutes	LLRF : QUENCH_DETECT : {M2.C7}

Automation for RF operations

Dynamic heat load compensation

- Cold compressors need a regular He flow
- Avoid disturbance induced by RF changes
  - Quenches
  - Sudden massive gradient changes
- Dynamic heat load fluctuations compensated by heaters

XFEL RF shutdowns



Stable He level and pressure

Heater compensation

Pdiss computation based on RF gradient, flat top duration, and quench alarms

Automation for RF operation

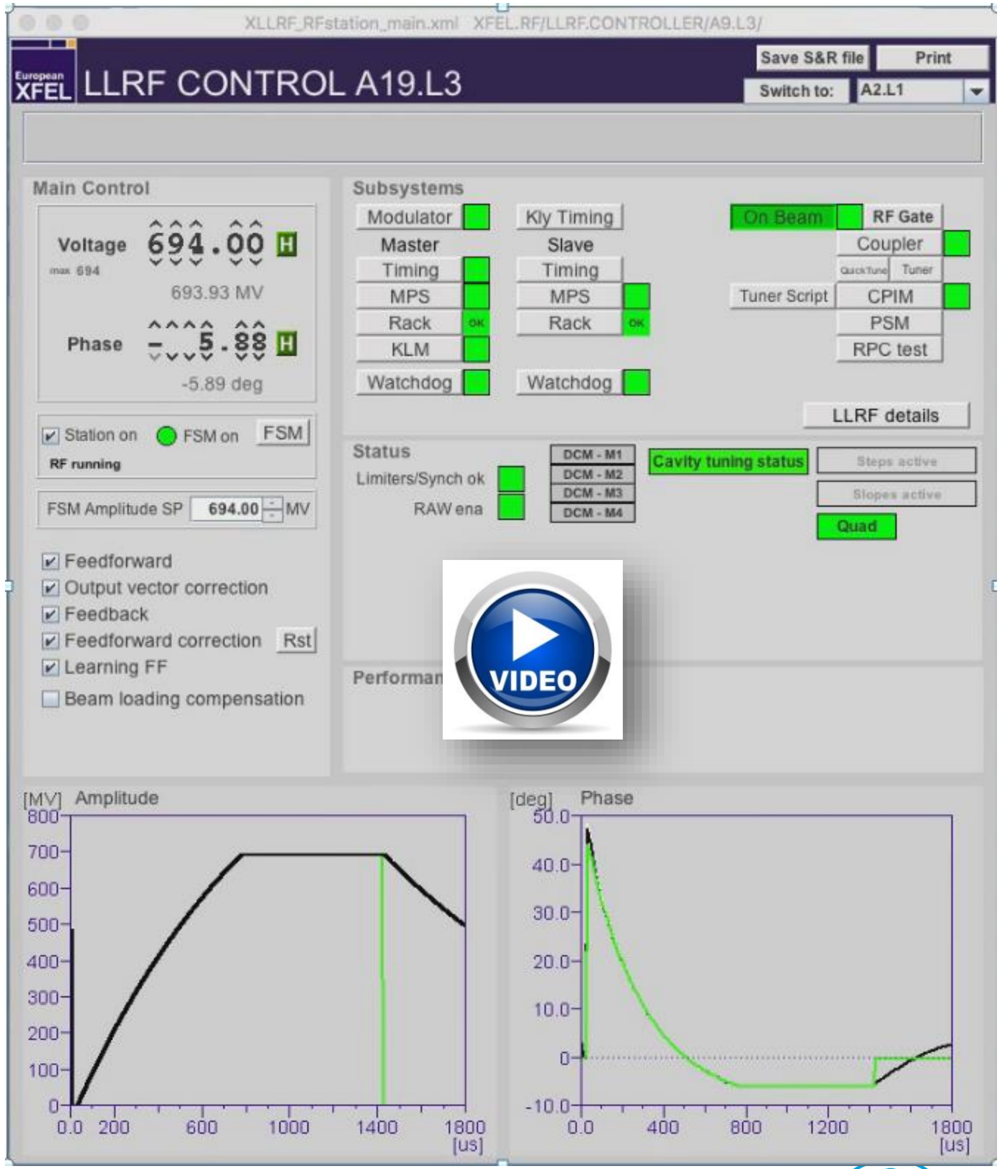
Lorentz force detuning compensation

- Following a gradient change
  - LFD compensation adaptation
  - 32 cavities simultaneously tuned
  - (16 cavities shown)

Automation for RF operations

Finite State Machine

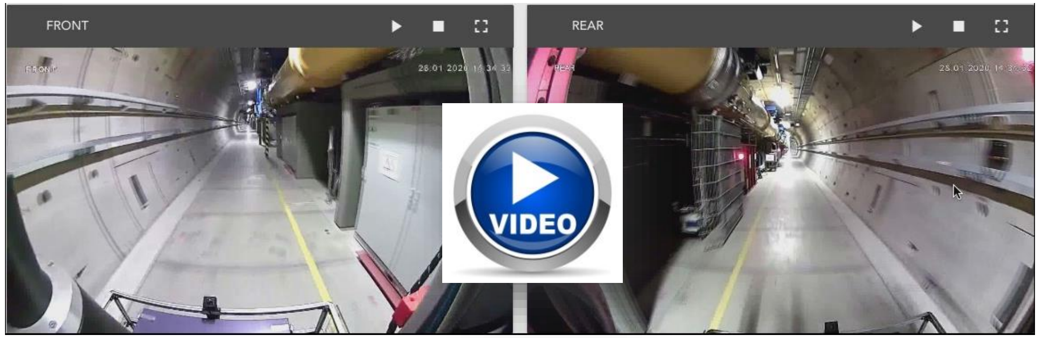
- Ramp up example (trip recovery):
  - Starts the modulator and wait for HV to be stable
  - Notify cryo that a station will be ramped up
  - Ramps up RF open loop at given pace
  - Recovers previous operating gradient
  - Scales output drive to match set point (fine adjust.)
  - Closes the loop (FB)
  - Clears learning feed forward corrections and starts LFF
  - Start piezo tuning
  - (Enables beam loading compensation)
  - Places station on beam (if was previously on-beam)



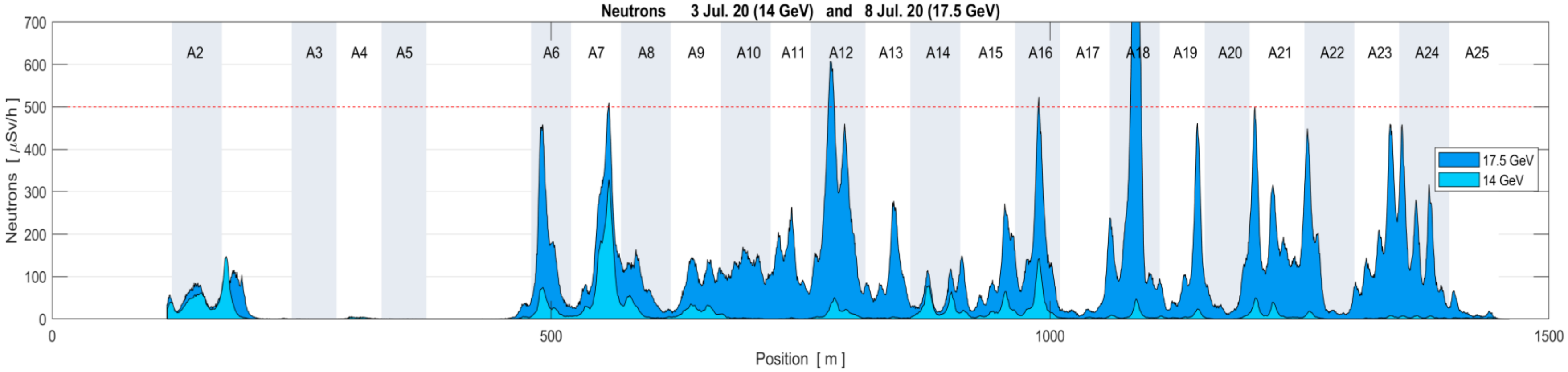
High-Voltage (high-V) Experiment

- 31.08 – 18.10.2020 → 7 weeks at low-V
- 19.10 – 22.11.2020 → 5 weeks at high-V *

* Although the high-V linac configuration was only really needed for 1 user week



- **Monitor**
  - SEU
  - LLRF system failures
  - Cavity quenches
  - Gradient limiters
  - Radiation



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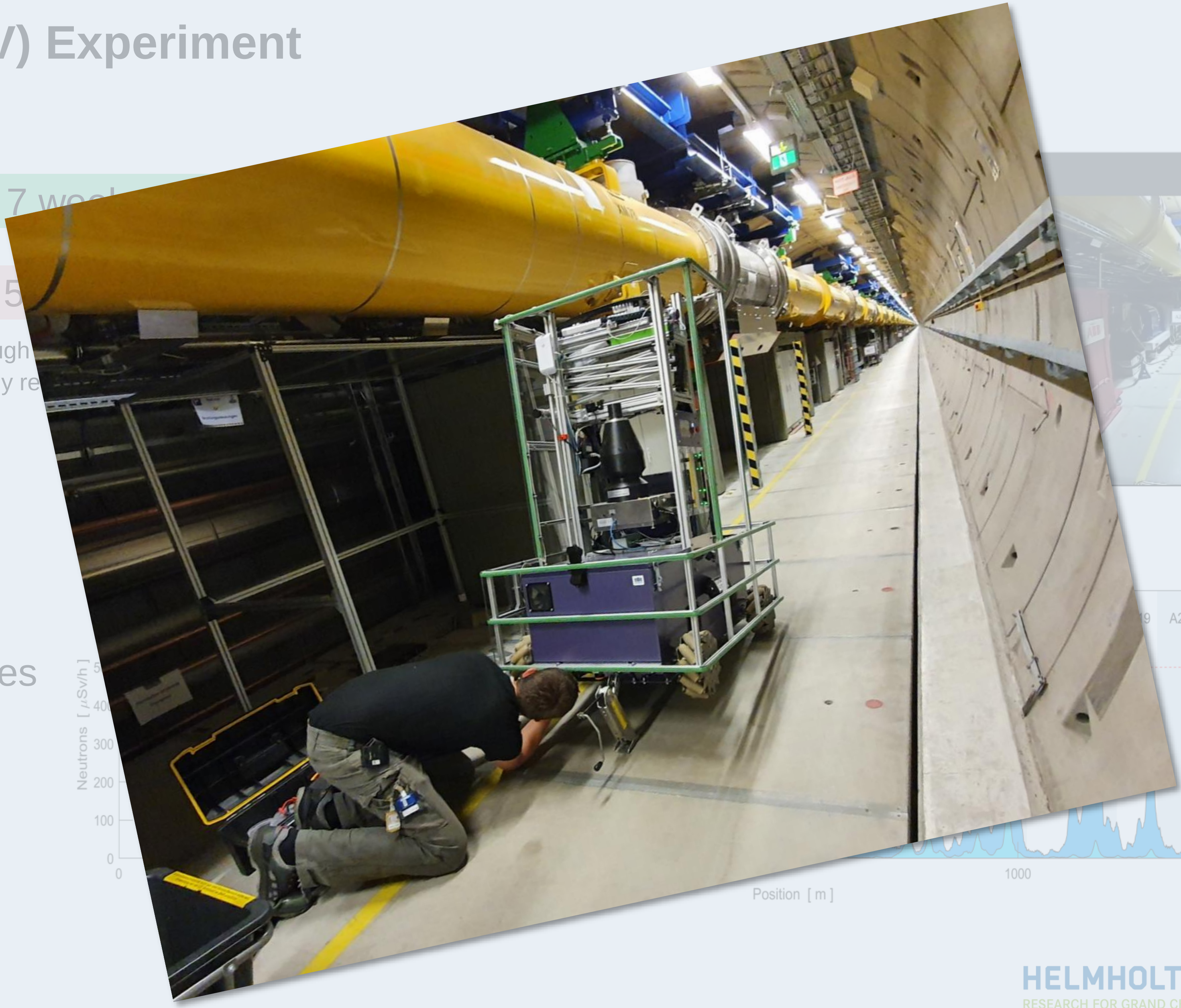

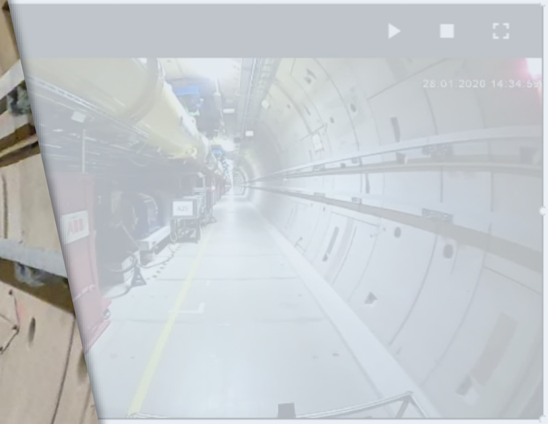

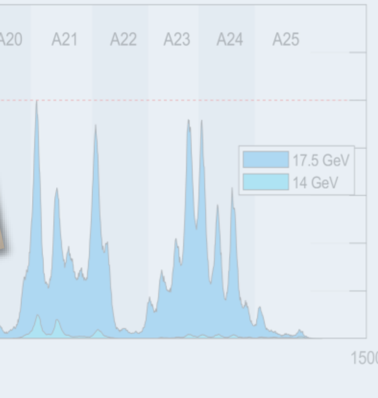

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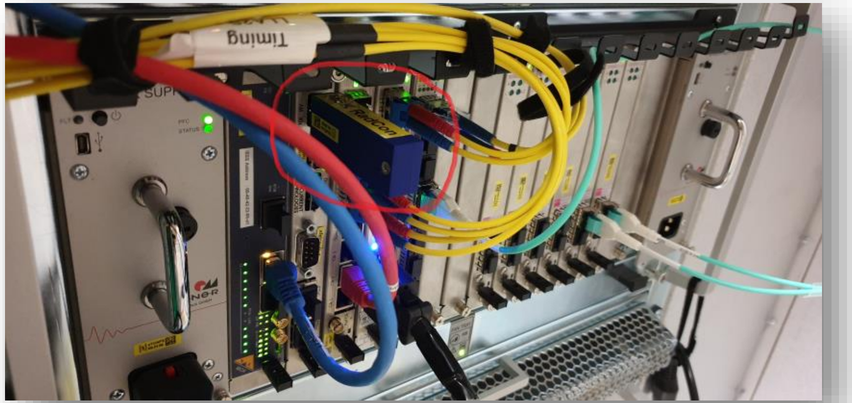
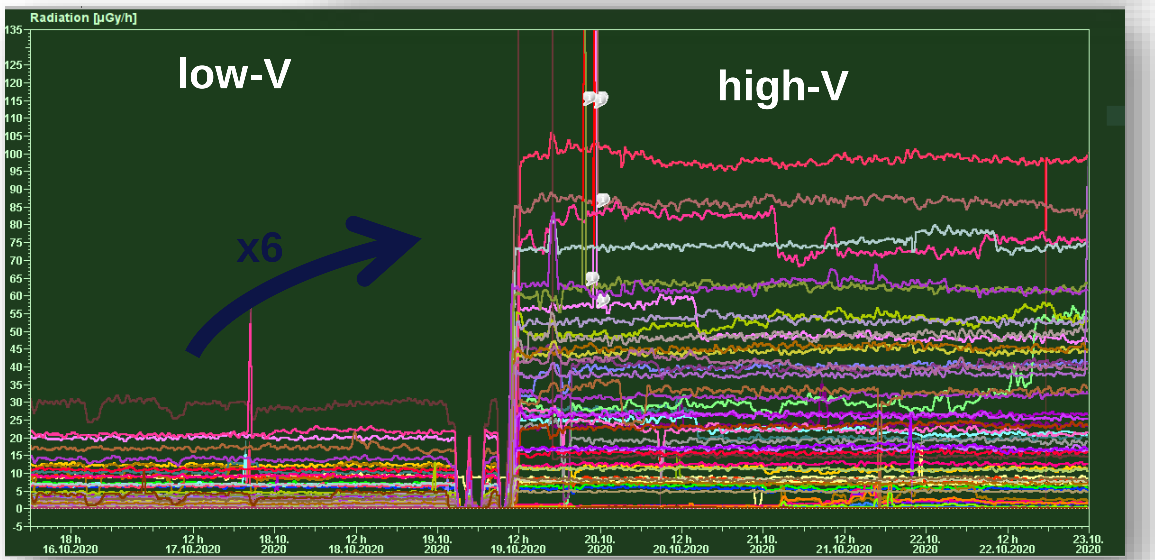
USB RadCons (inside racks)





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- **Monitor**
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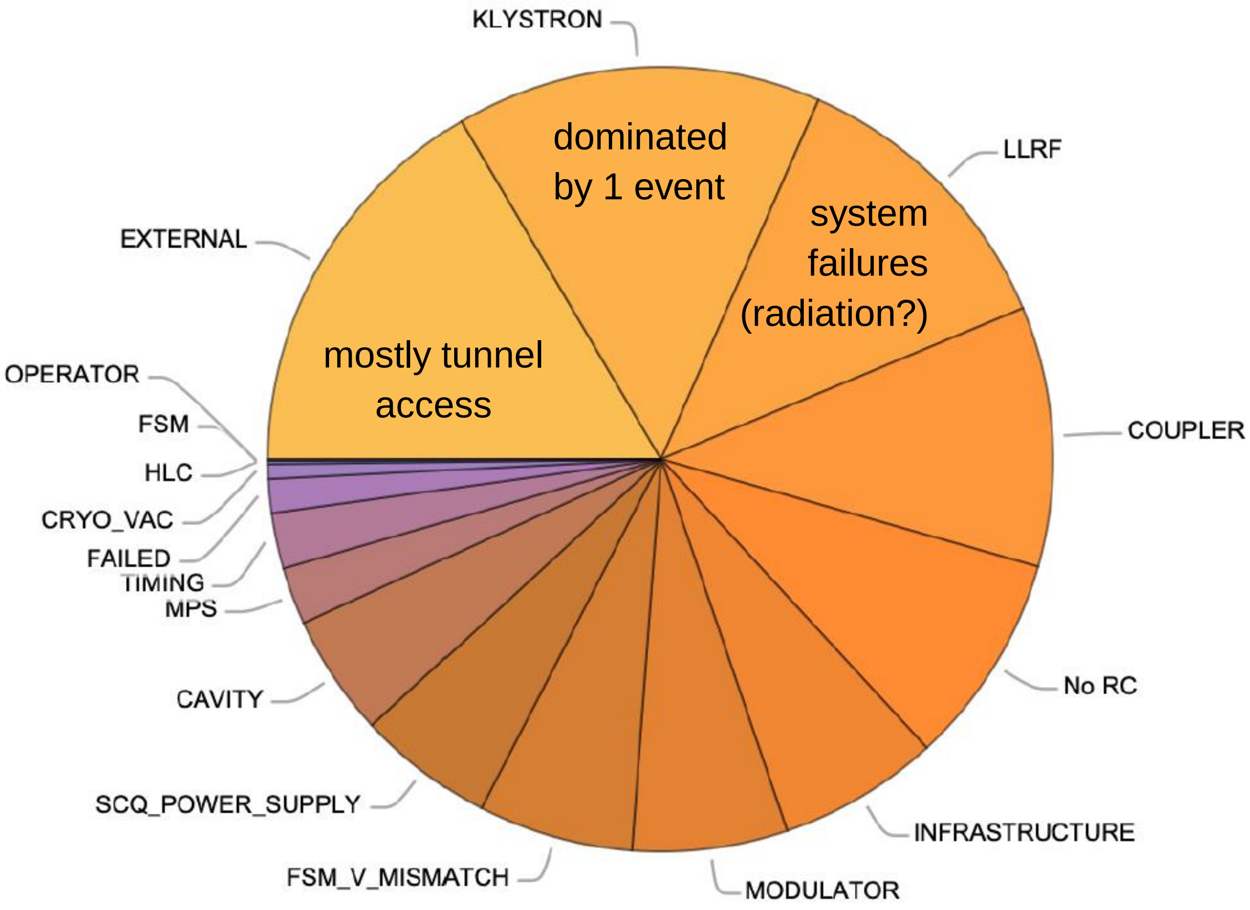
  - Radiation

High-Voltage (high-V) Experiment

		Total	Low-V	High-V
Availability	%	97.9	**98.7**	**95.6**
Total operation time	days	125.2	90.4	34.8
Number of events	hrs	300	124	176
Total down time	hrs	64.7	**27.9**	**36.9**

		Total	Low-V	High-V
Trips	hrs	40.1	**13.5**	**26.6**
Linac off (access)	hrs	18.3	10.7	7.6
Ramp down	hrs	3.5	1.8	1.7
Development	hrs	1.9	0.8	0.8



High-Voltage (high-V) Experiment

Heat load

Effective (average) cavity Q_0 from measured dynamic load

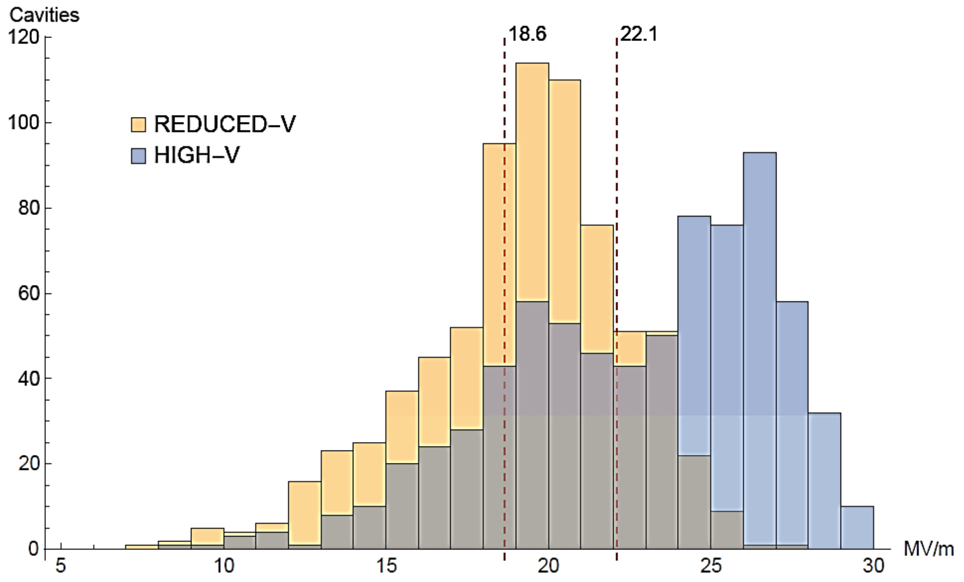
$$Q_{0,eff} \approx \frac{f_{rep}\left(t_{fill} + t_{flat}\right)}{(r/Q)\,P_{cryo}} \sum_{i=1}^{N_{cav}} \langle V_i^2 \rangle$$

where

$$\langle V_i^2 \rangle = \frac{1}{T_2 - T_1} \int_{T_1}^{T_2} V_i^2(t)\, dt$$

See talk from Rajinikumar Ramalingam:
“XFEL heat load measurements”
Tue. 19.01 WG1 session 2

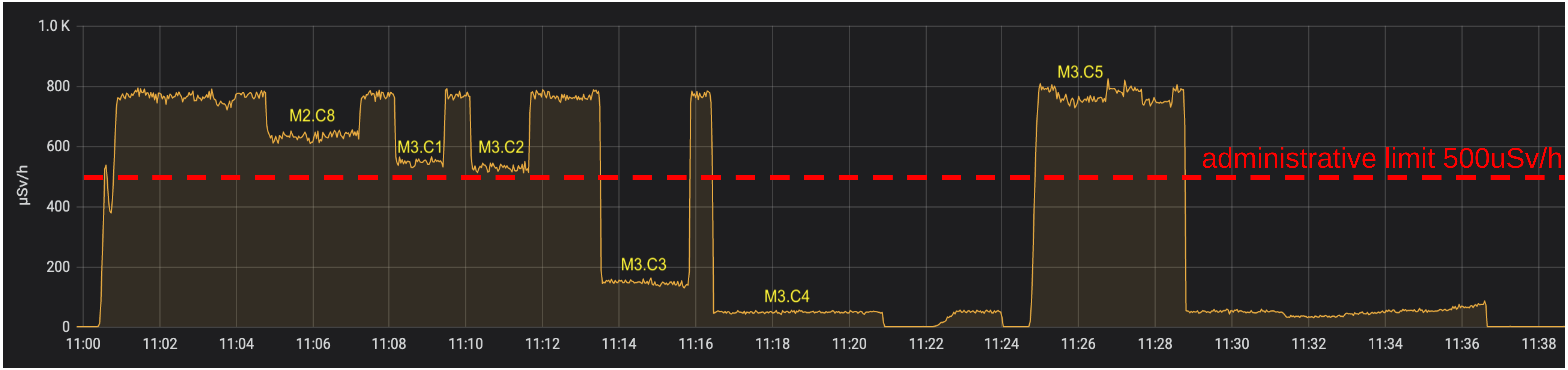
RF CONFIG	Time Frame	Average Dynamic Load (W)	Effective average Q_0
REDUCED-V	01.09—15.10.2020	400	1.04×10^{10}
HIGH-V	20.10—15.11.2020	600	0.98×10^{10}



Field emitters

Example: A18.M3.C4

- **Procedure**
  - Park MARWIN at peak neutron radiation
  - Detune / retune cavities one at a time until field emitter is found
  - Detune found field emitter (immediate solution)

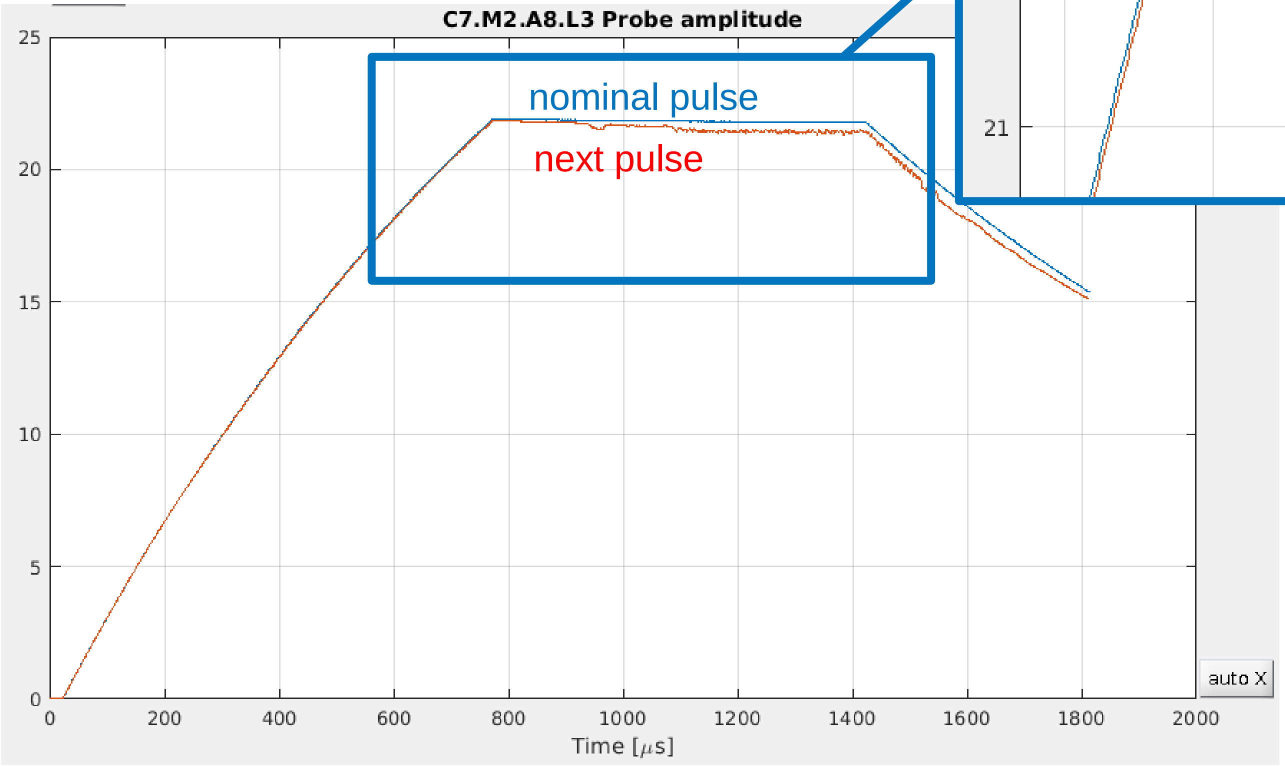


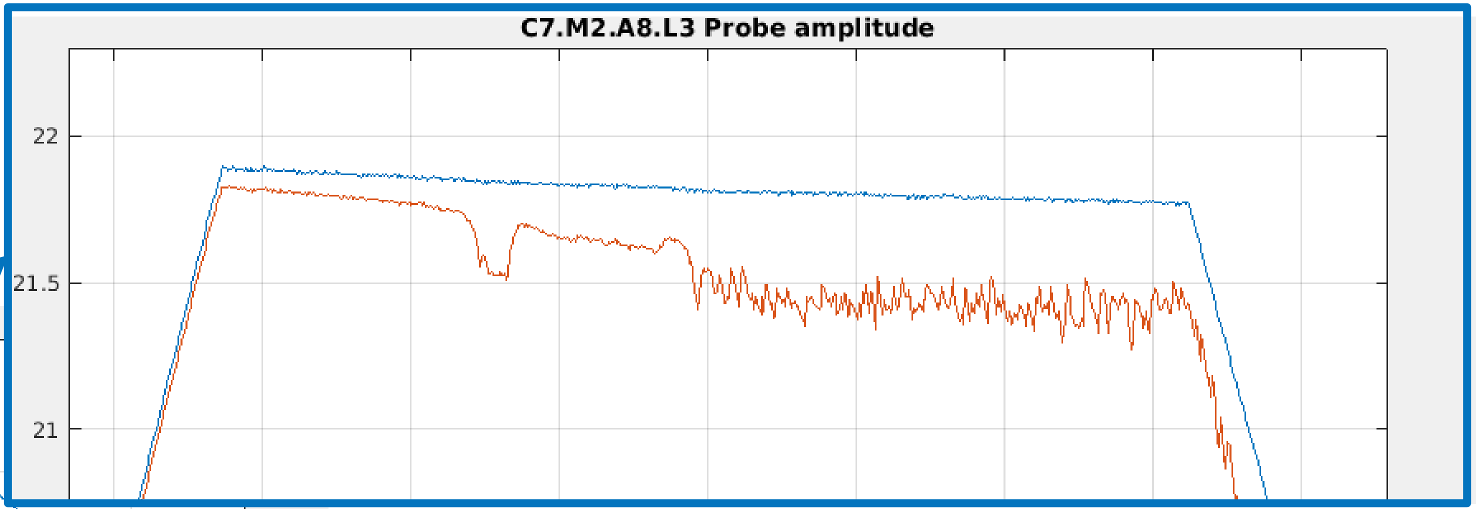
See talk from Nick Walker
“Experience with field emitters at EuXFEL”,
Wed. 20.01 WG1, session 4

Some trip examples

Multipacting ?

- **A8.M2.C7**
  - Start appearing above 20 MV/m
  - Seems to have cured by itself

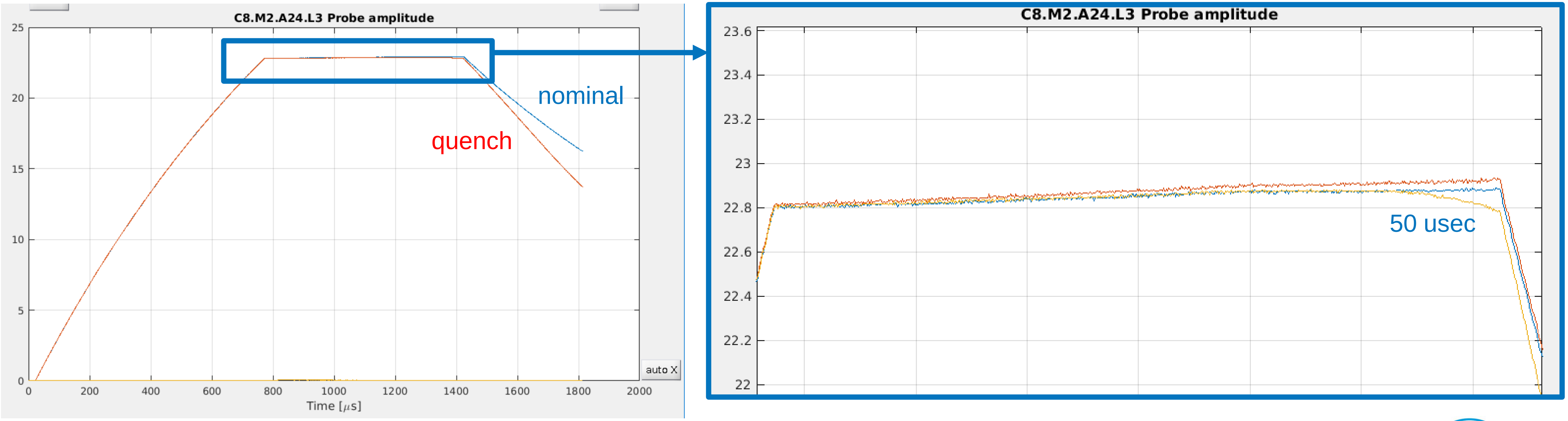




Some trip examples

Spontaneous quench

- **A8.M2.C8**
  - Isolated quench event
  - Quench occurred at 22.8 MV/m
  - Cavity power limited during cryomodule tests (i.e. > 31.5 MV/m)

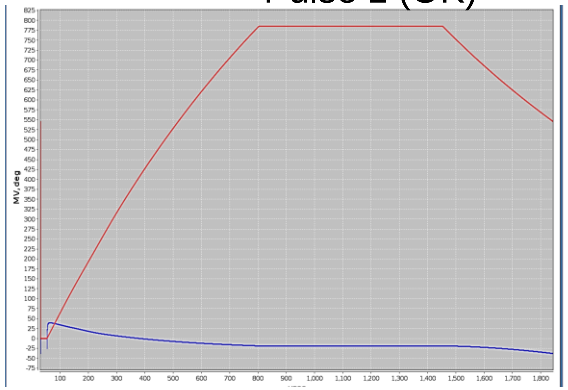


Some trip examples

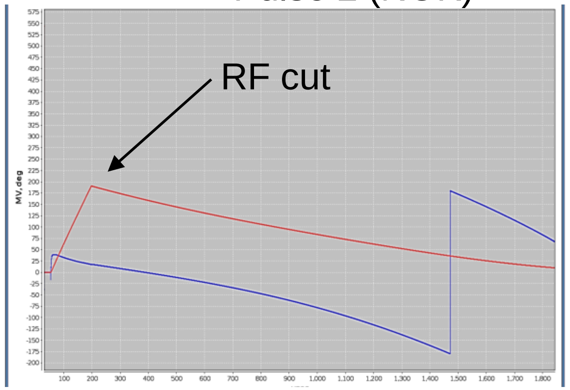
Klystron instability

- **A13**
  - KLM (high power signals monitoring)
  - Detected reflected activity at input of klystron
  - Stops RF drive within usec
  - Prevents rise of vacuum level in tube
  - Next pulse is OK

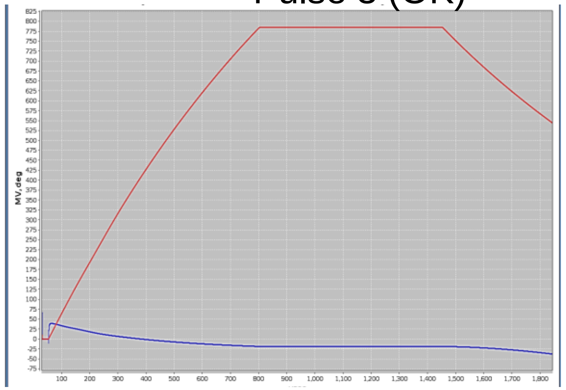
Pulse 1 (OK)

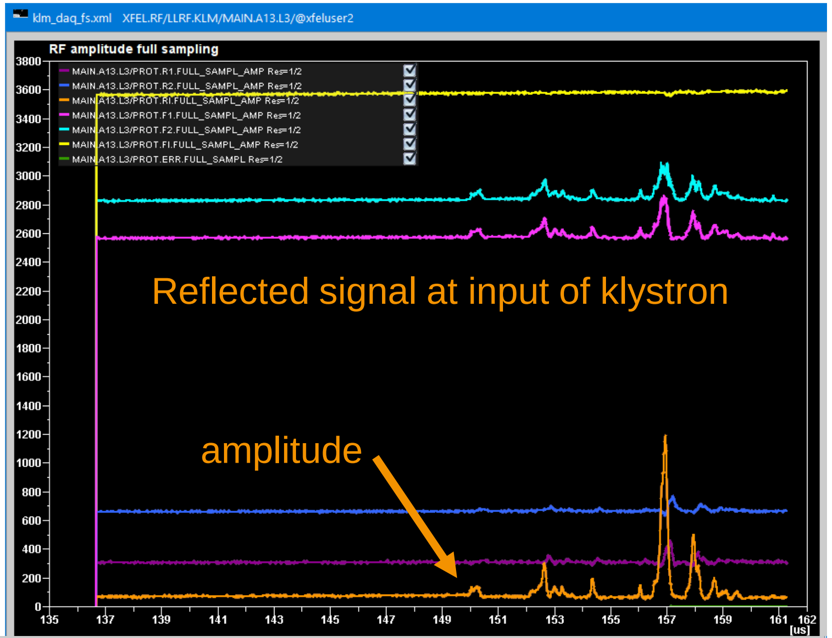


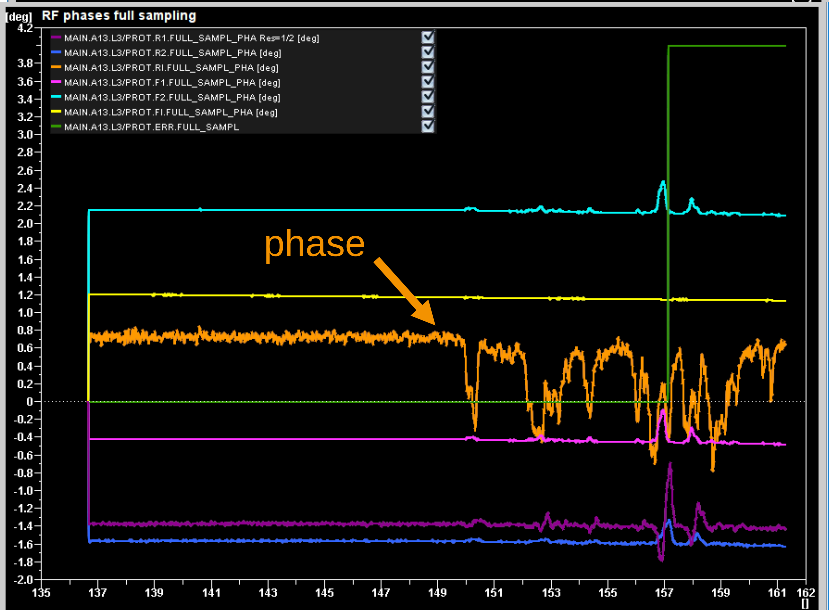
Pulse 2 (NOK)



Pulse 3 (OK)



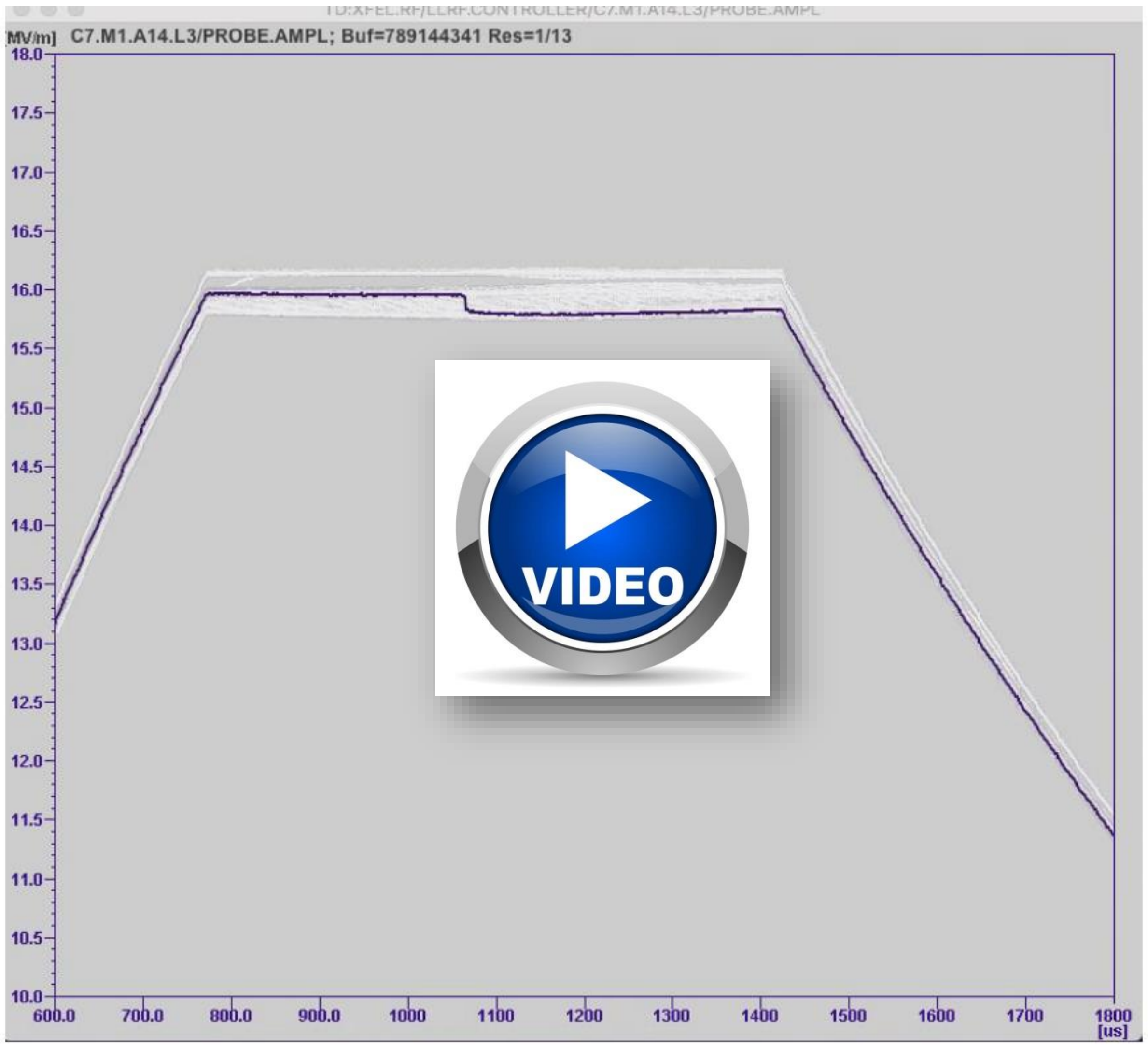




Some trip example

Piezo induced disturbance

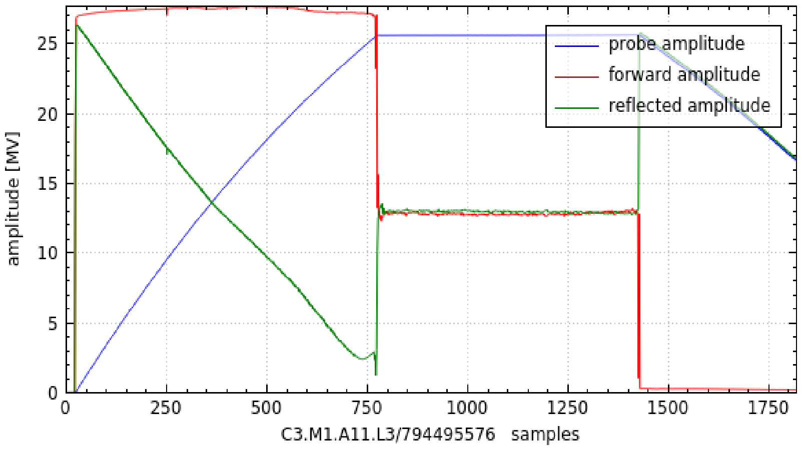
- **A14.M1.C7**
  - Faulty LFD compensation
  - Likely corrupted firmware (SEU)
  - Recovered with an FPGA power cycle

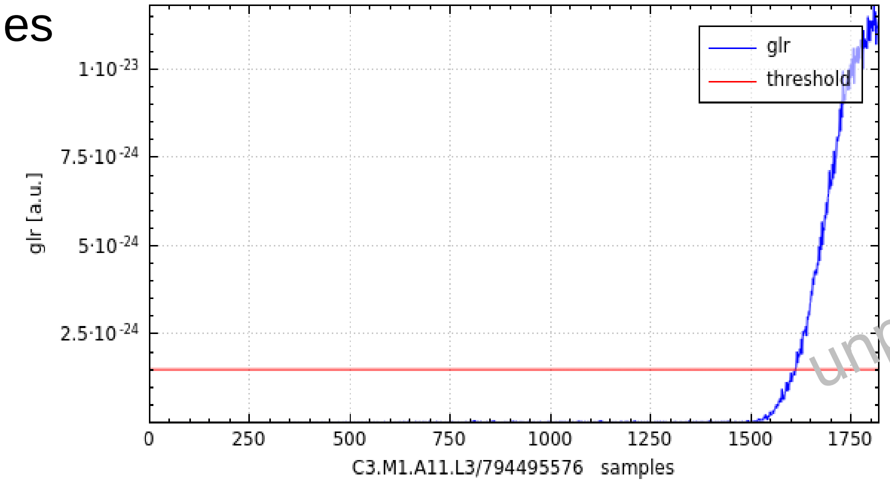


Outlook

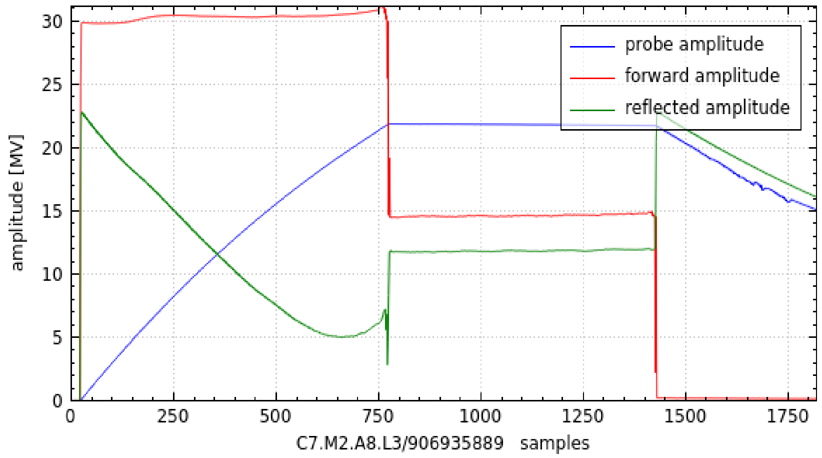
- Going CW
  - …
- Machine learning
  - …
- **“Big data” analysis**
  - Model-based techniques
  - General likelihood of anomaly calculated
  - Goal is “smarter” online fault classification

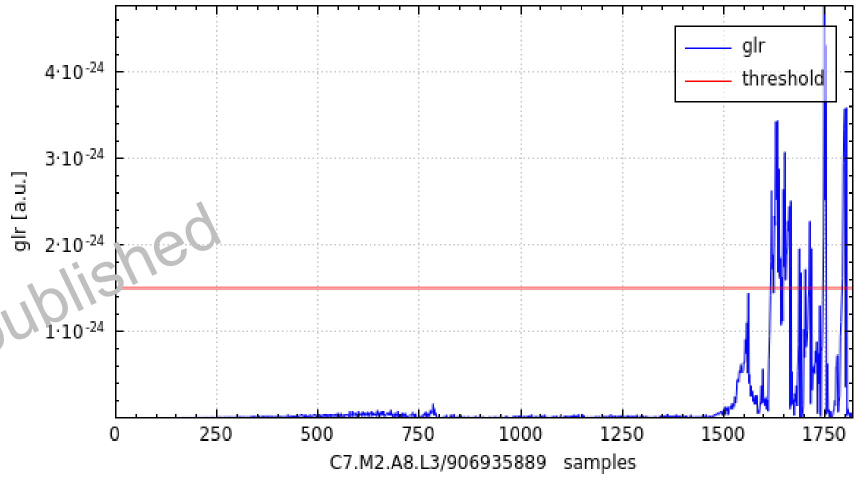
Quench





Multipacting ?

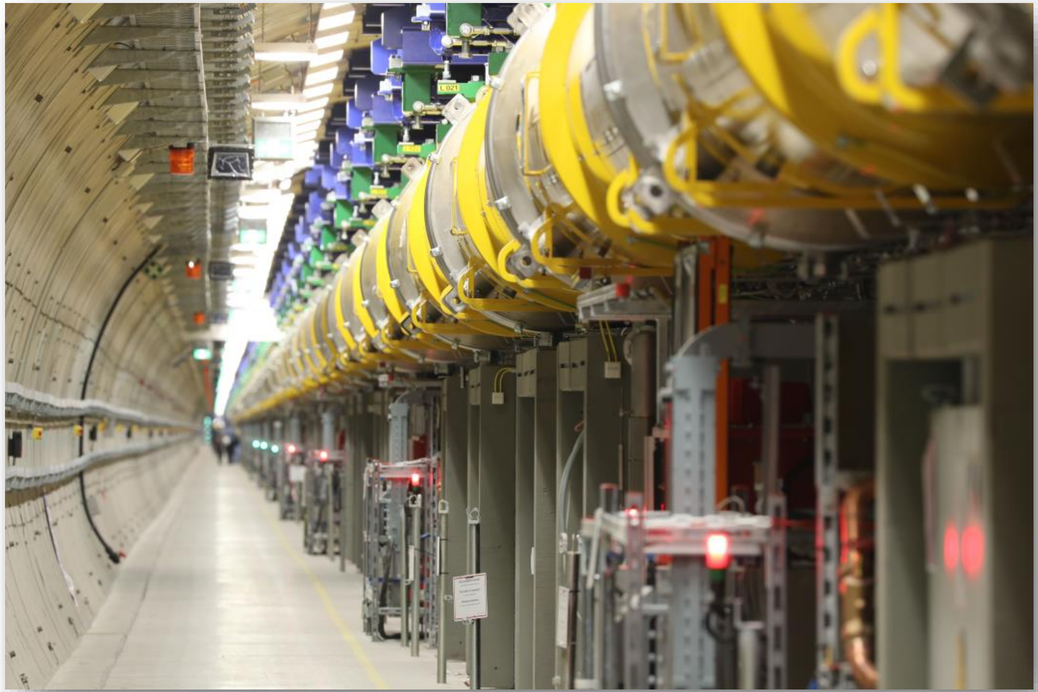




Courtesy Annika Eichler

Thank you for your attention!

Special thanks to Nick Walker



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