

PAUL SCHERRER INSTITUT



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Experience with high power RF sources and RF conditioning

8th Hard X-ray FEL Collaboration Meeting

24 - 26 October 2016, Pohang, Korea

- Types of RF systems in SwissFEL
 - S-band
 - C-band
 - X-band

- Some first experiences

- Discussion topics:
 1. Humidity of transformer oil
 2. 'Strange' pulses from klystrons
 3. Experience with evacuation of transformer tank
 4. ...

Types of RF systems in SwissFEL

| | S-band | C-band | X-band |
|------------------|---|--|--|
| LLRF | Fully digital LLRF systems (presented at 2014 meeting) | | |
| Drive amplifiers | Solid-state: Microwave Amplifiers | Solid-state: Advantech | Currently TWT amplifier, plan to upgrade to solid- state eventually |
| Klystrons | Thales TH2100L | Toshiba E37212 | SLAC XL5 |
| Modulators | <i>Solid-state</i> ScandiNova K2 from test facility | <i>Solid-state</i> <i>Linacs 1&2:</i> Ampegon Type- μ <i>Linac 3:</i> ScandiNova M1071 | <i>Solid-state</i> ScandiNova K2 from test facility |
| Waveguides | SF_6 Mixture: MEGA, PSI, ... | <i>Vacuum</i> MHI-MS Loads: CML | <i>Vacuum</i> CERN, PSI, Nihon Koshuha |
| Structures | PSI RF gun 1-2 x RI 4m S-band | PSI BOC + 4 x PSI C-band | CERN-PSI-Elettra X-band (2x) |

bake-out

no bake-out

bake-out

S-band

- Re-use of Microwave Amps. amplifiers from injector test facility
- Initial stability: ~ 150 ppm
- Modified by PSI (group of C. Gough) in order to reach ~ 50 ppm

C-band

- Advantech won the tender
- Collaboration with PSI in order to achieve stability requirements
- Stability results of prototype: < 50 ppm, < 1 fs add. timing jitter

Sophisticated measurement system developed by C. Gough group to characterize amplifiers with ~ 10 ppm precision.

Solid-state modulators for C-band linac

Two prototypes were tested at PSI for evaluation of the series.

50 MW / 3 μ s RF, 370kV / 344A / <20 ppm voltage stability pulse to pulse @ 100 Hz

AMPECON

Type- μ modulator prot. for PSI C-band



- 13 modulators (Linac 1, Linac 2)
- Installation planned from Nov. 2016 – June 2017

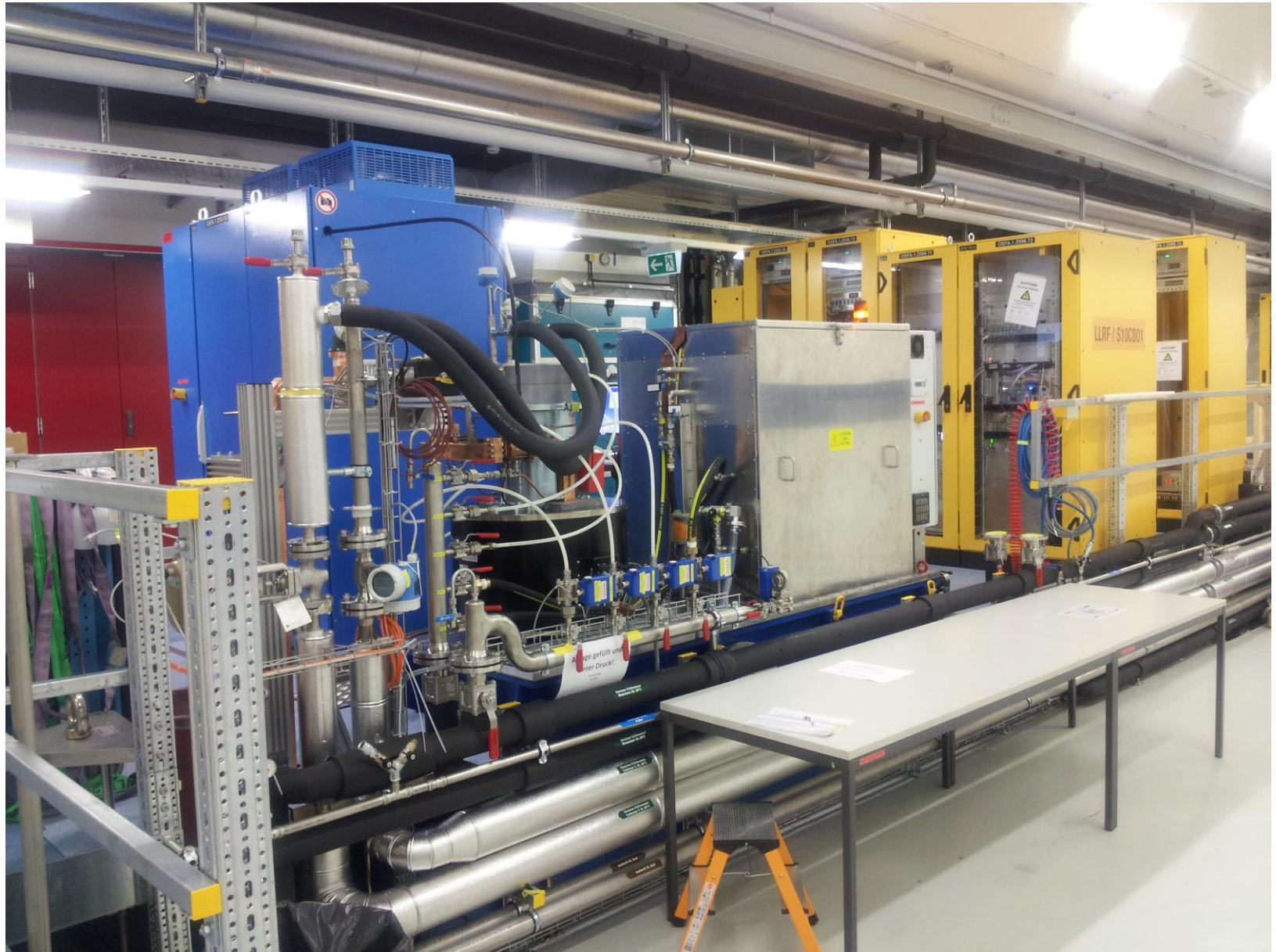
ScandiNova

K2-3 proto. for PSI C-band

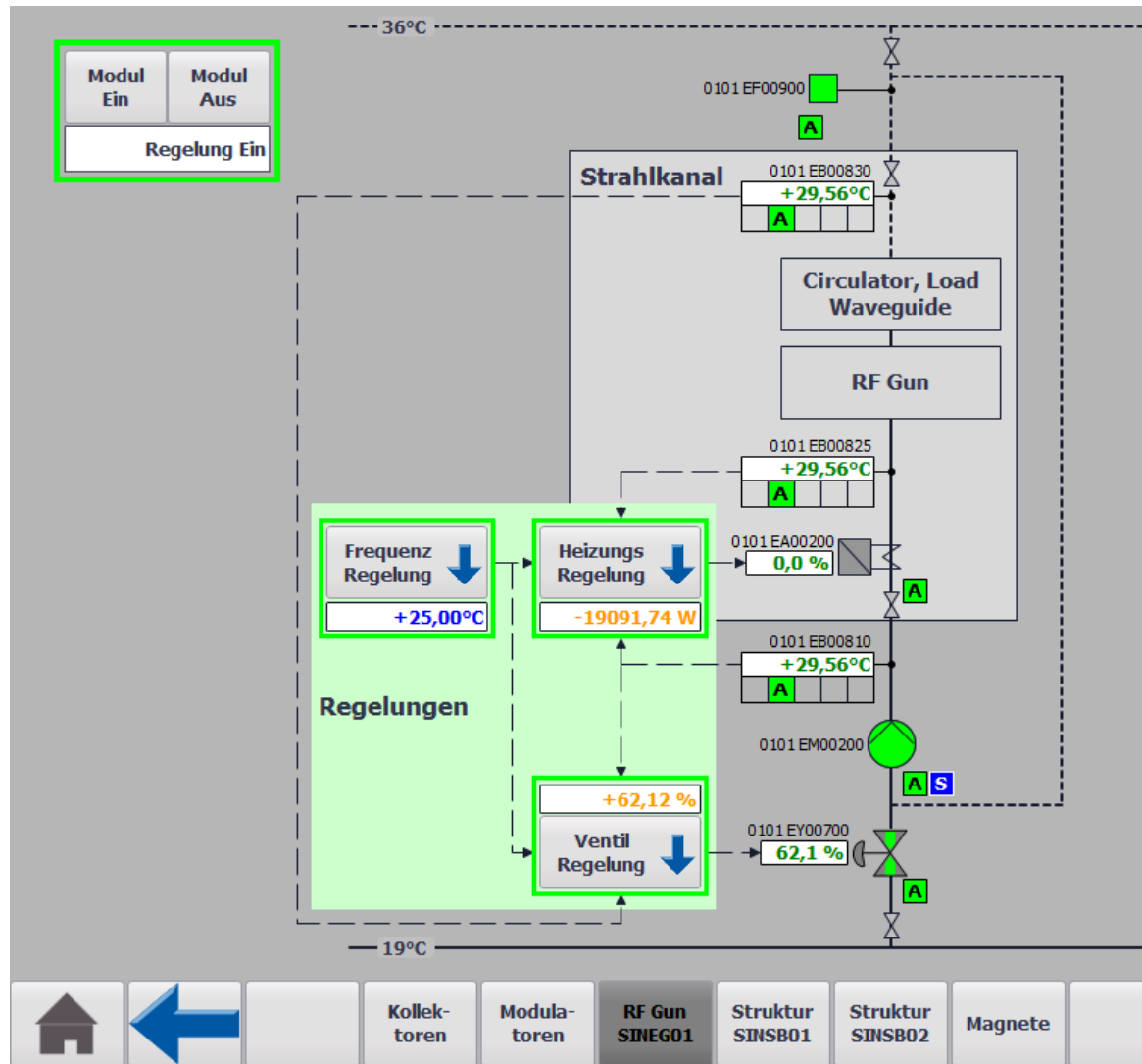


- 13 modulators (Linac 3)
- Installation planned from March 2016 – Sep. 2017

Power source of first C-band station (Ampegon prototype modulator)



Precision temperature control



Few mK stability by combination of 3 coupled feedback-loops, including an RF-based measurement

S10CB01: RF station expert RF station: Status State MPS DELAY Mode CONDITIONING ePic LLRF Help

Modulator State TRIGGER remote Cond. Tool ON **LLRF MPS DELAY** **Cooling** ILK State RF READY Mode Conditioning Timing Rate 100 Hz Klystron Out power 48 MW
last ILK Struct. 3 refl.: peak 24.10.2016 07:27:43.733 Event RF fire 1

Overview Modulator LLRF ILK Timing Temperatures Cooling **Conditioning Tool** **START** **STOP** **RESET** State: **ON** **RF Conditioning Tool S10CB01** HELP Detach

Power Setting RF Power Abs. Vac. Pressure Rel. Vac. Pressure Avg. Time betw. BD

89.19 % 47.57 MW 1.60e-08 mbar 65.6 % 838 s

Long Term Data Vacuum Channels Vacuum Control BDR **Power Control** Log Power Ramping Info

Parameters for HVPS Power Control Curve

HVPS Value for 0% Power: 1000 V
 HVPS Value for 100% Power: 2840 V
 HVPS nonlinearity factor: -1.01

Parameters for Drive Power Control Curve

Amp. Scale Value for 0% F: 0.58
 Amp. Scale Value for 100%: 0.63
 Amp. nonlinearity factor: -1.00

Power Control Mode

HVPS+RF HVPS ONLY RF ONLY

HVPS Control Curve

Amplitude Control Curve

RF-POWER [MW]

Peak Vacuum Pressure [mbar]

| | | | | | |
|------------------------|---|-----------------------|----------------|-----------------------------|---------------|
| Modulator State | STANDBY HVON TRIG | Conditioning SM State | RF ON | Target Pressure | 2.00e-08 mbar |
| Modulator HVPS Setting | 2738.6 V | Ramping Limit | BREAKDOWN RATE | ref. Press. at actual power | 2.44e-08 mbar |
| Modulator HVPS Monitor | 2708.5 V | BDR Power Limit | 89.190 % | Vacuum Ramp. Speed | 81.65 %/min |
| Klystron Voltage | -348.1 kV | LTR Power Limit | 89.570 % | LLRF Amplitude | 0.63 |
| Klystron Current | -303.3 A | Number of Breakdowns | 442 | | |
| Klystron Vacuum | 1.31e-11 mbar | RF Time since last BD | 58 s | | |
| Last Message: | 24.10.2016 07:27:48.733 RF ON: RF is on | | | | |

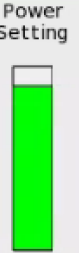
S10CB01: RF station expert
RF station: ■ Status State MPS DELAY
Mode CONDITIONING
ePic LLRF Help

Modulator State TRIGGER remote Cond. Tool ON
LLRF MPS DELAY
Cooling
ILK State RF READY Mode Conditioning
Timing Rate 100 Hz
Klystron Out power

Overview Modulator LLRF ILK Timing Temperatures Cooling **Conditioning Tool**
last ILK Struct. 3 refl.: peak 24.10.2016 07:27:43.733
Event RF fire 1
48 MW

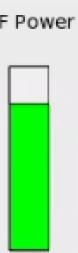
START **STOP** **RESET**
State: **ON**
RF Conditioning Tool S10CB01
HELP Detach

Power Setting




89.57 %

RF Power




47.82 MW

Abs. Vac. Pressure




1.60e-08 mbar

Rel. Vac. Pressure



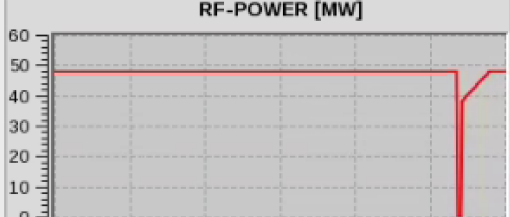
66.0 %

Avg. Time betw. BD

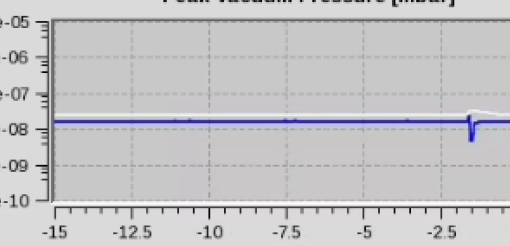



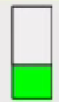

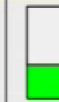


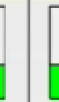
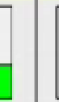








838 s

RF-POWER [MW]



Peak Vacuum Pressure [mbar]



| Long Term Data | | Vacuum Channels | | | | | Vacuum Control | | BDR | Power Control | | Log | Power Ramping | | Info |
|---|---|---|---|---|--|---|---|---|---|---|---|---|---|---|---|
| VMNC-A010 | VPIG-A050 | VPIG-A040 | VPIG-A030 | VPIG-A090 | VPIG-A020 | VPIG-A010 | VPNG-A010 | VPNG-A020 | VPNG-A030 | VPNG-A040 | VPNG-A050 | VPNG-A060 | VPNG-A070 | VPNG-A080 | KLYSTR |
| Relative Pressure | Relative Pressure | Relative Pressure | Relative Pressure | Relative Pressure | Relative Pressure | Relative Pressure | Relative Pressure | Relative Pressure | Relative Pressure | Relative Pressure | Relative Pressure | Relative Pressure | Relative Pressure | Relative Pressure | Relative Pressure |
| 6.7 % | 12.8 % | 12.8 % | 12.8 % | 66.0 % | 12.8 % | 12.8 % | 0.5 % | 0.0 % | 0.0 % | 0.0 % | 0.0 % | 1.4 % | 0.0 % | 1.4 % | 0.1 % |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Pressure [mbar] | Pressure [mbar] | Pressure [mbar] | Pressure [mbar] | Pressure [mbar] | Pressure [mbar] | Pressure [mbar] | Pressure [mbar] | Pressure [mbar] | Pressure [mbar] | Pressure [mbar] | Pressure [mbar] | Pressure [mbar] | Pressure [mbar] | Pressure [mbar] | Pressure [mbar] |
| 1.6e-09 | 3.1e-09 | 3.1e-09 | 3.1e-09 | 1.6e-08 | 3.1e-09 | 3.1e-09 | 1.2e-10 | 0.0e+00 | 0.0e+00 | 0.0e+00 | 0.0e+00 | 3.5e-10 | 0.0e+00 | 3.5e-10 | 1.3e-11 |
| Scaling Factor [%] | Scaling Factor [%] | Scaling Factor [%] | Scaling Factor [%] | Scaling Factor [%] | Scaling Factor [%] | Scaling Factor [%] | Scaling Factor [%] | Scaling Factor [%] | Scaling Factor [%] | Scaling Factor [%] | Scaling Factor [%] | Scaling Factor [%] | Scaling Factor [%] | Scaling Factor [%] | Scaling Factor [%] |
| +100 | +100 | +100 | +100 | +100 | +100 | +100 | +100 | +100 | +100 | +100 | +100 | +100 | +100 | +100 | +100 |
| Enable Channel | Enable Channel | Enable Channel | Enable Channel | Enable Channel | Enable Channel | Enable Channel | Enable Channel | Enable Channel | Enable Channel | Enable Channel | Enable Channel | Enable Channel | Enable Channel | Enable Channel | Enable Channel |
| <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> | <input checked="" type="checkbox"/> |

| | | | | | |
|---|-------------------|-----------------------|-----------|-----------------------------|---------------|
| Modulator State | STANDBY HVON TRIG | Conditioning SM State | RF ON | Target Pressure | 2.00e-08 mbar |
| Modulator HVPS Setting | 2742.3 V | Ramping Limit | LONG TERM | ref. Press. at actual power | 2.42e-08 mbar |
| Modulator HVPS Monitor | 2685.8 V | BDR Power Limit | 89.570 % | Vacuum Ramp. Speed | 75.91 %/min |
| Klystron Voltage | -348.8 kV | LTR Power Limit | 89.570 % | LLRF Amplitude | 0.63 |
| Klystron Current | -304.4 A | Number of Breakdowns | 442 | | |
| Klystron Vacuum | 1.33e-11 mbar | RF Time since last BD | 93 s | | |
| Last Message: 24.10.2016 07:27:48.733 RF ON: RF is on | | | | | |

S10CB01: RF station expert RF station: ■ Status State MPS DELAY Mode CONDITIONING ePic LLRF Help

Modulator State TRIGGER remote Cond. Tool ON **LLRF MPS DELAY** Cooling ILK State RF READY Mode Conditioning Timing Rate 100 Hz Klystron Out power 48 MW

last ILK Struct. 3 refl.: peak 24.10.2016 07:27:43.733 Event RF fire 1

Overview Modulator LLRF ILK Timing Temperatures Cooling **Conditioning Tool** HELP Detach

START **STOP** **RESET** State: **ON** **RF Conditioning Tool S10CB01**

Power Setting: 89.57 %

RF Power: 47.82 MW

Abs. Vac. Pressure: 1.60e-08 mbar

Rel. Vac. Pressure: 66.0 %

Avg. Time betw. BD: 838 s

RF-POWER [MW]

Peak Vacuum Pressure [mbar]

Parameters for Vacuum Control Algorithm

Target Press for Cond: 20 pbar

Ref. Press. Factor for 0A: 3.0

Max. Reference Press for: 51 pbar

Maximum Up Speed: 201 %/min

Pressure for Max. Up: 50 %

Vac. Ramping Nonlinearity: 4.9

Maximum Down Speed: 500 %/min

Pressure for Max. DOWN: 200 %

Reference Pressure vs. Power Setting

Ramping Speed vs. Relative Vac. Pressure

| | | | | | |
|---|-------------------|-----------------------|-----------|-----------------------------|---------------|
| Modulator State | STANDBY HVON TRIG | Conditioning SM State | RF ON | Target Pressure | 2.00e-08 mbar |
| Modulator HVPS Setting | 2742.3 V | Ramping Limit | LONG TERM | Ref. Press. at actual power | 2.42e-08 mbar |
| Modulator HVPS Monitor | 2680.1 V | BDR Power Limit | 89.570 % | Vacuum Ramp. Speed | 75.91 %/min |
| Klystron Voltage | -348.8 kV | LTR Power Limit | 89.570 % | LLRF Amplitude | 0.63 |
| Klystron Current | -304.5 A | Number of Breakdowns | 442 | | |
| Klystron Vacuum | 1.33e-11 mbar | RF Time since last BD | 130 s | | |
| Last Message: 24.10.2016 07:27:48.733 RF ON: RF is on | | | | | |

S10CB01: RF station expert RF station: ■ Status State MPS DELAY Mode CONDITIONING ePic LLRF Help

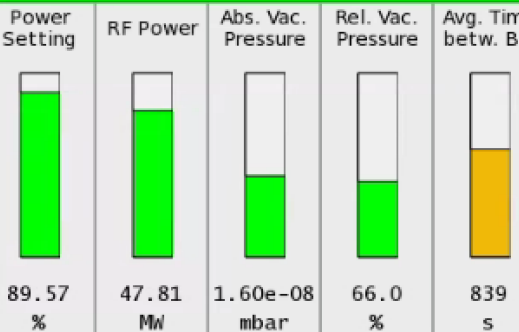
Modulator State TRIGGER remote Cond. Tool ON **LLRF** MPS DELAY **Cooling** ILK State RF READY Mode Conditioning Timing Rate 120 Hz Klystron Out power 48 MW

last ILK Struct. 3 refl.: peak 24.10.2016 07:27:43.733 Event RF fire 1

Overview Modulator LLRF ILK Timing Temperatures Cooling **Conditioning Tool**

START **STOP** **RESET** State: **ON** **RF Conditioning Tool S10CB01** HELP Detach

Power Setting **RF Power** **Abs. Vac. Pressure** **Rel. Vac. Pressure** **Avg. Time betw. BD**



89.57 % 47.81 MW 1.60e-08 mbar 66.0 % 839 s

Long Term Data Vacuum Channels Vacuum Control BDR Power Control Log **Power Ramping** Info

Parameters for BDR limitation

Power Reduction after Bre 20 %

Ramping Speed after Recov 20 %/min

Power at last breakdown 89.57 %

Actual BDR power limit 89.57 %

Parameters for long term ramping

Start Power for Long Term 7 %

Target Power for Long Term 90 %

Long Term Ramping Speed 1 %/h

Power Setting



89.57 %

Manual DOWN

LTR Power Limit



89.57 %

Manual DOWN Restart

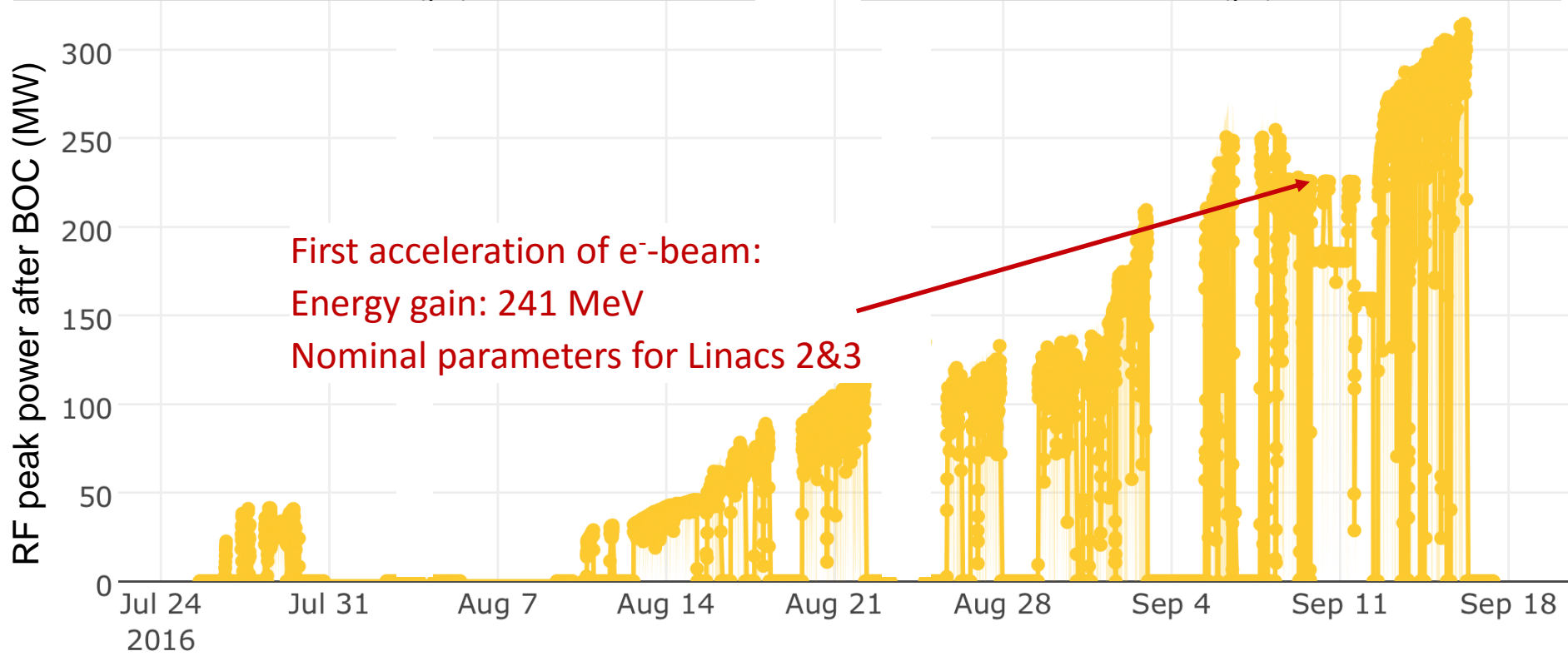
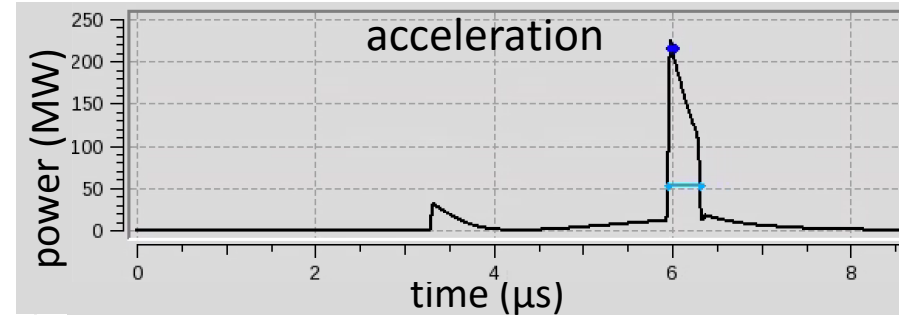
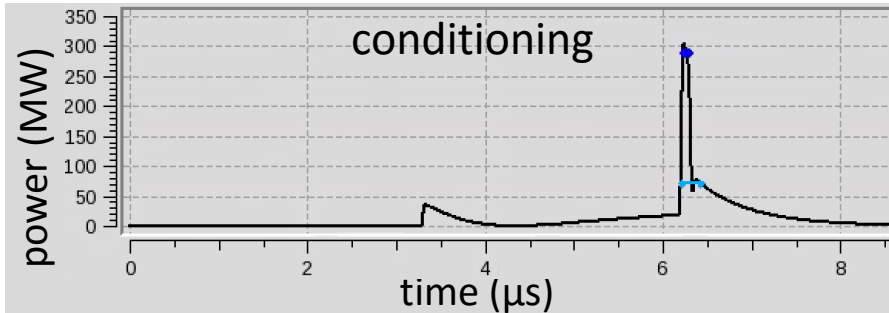
RF-POWER [MW]



Peak Vacuum Pressure [mbar]



Conditioning of first C-band module



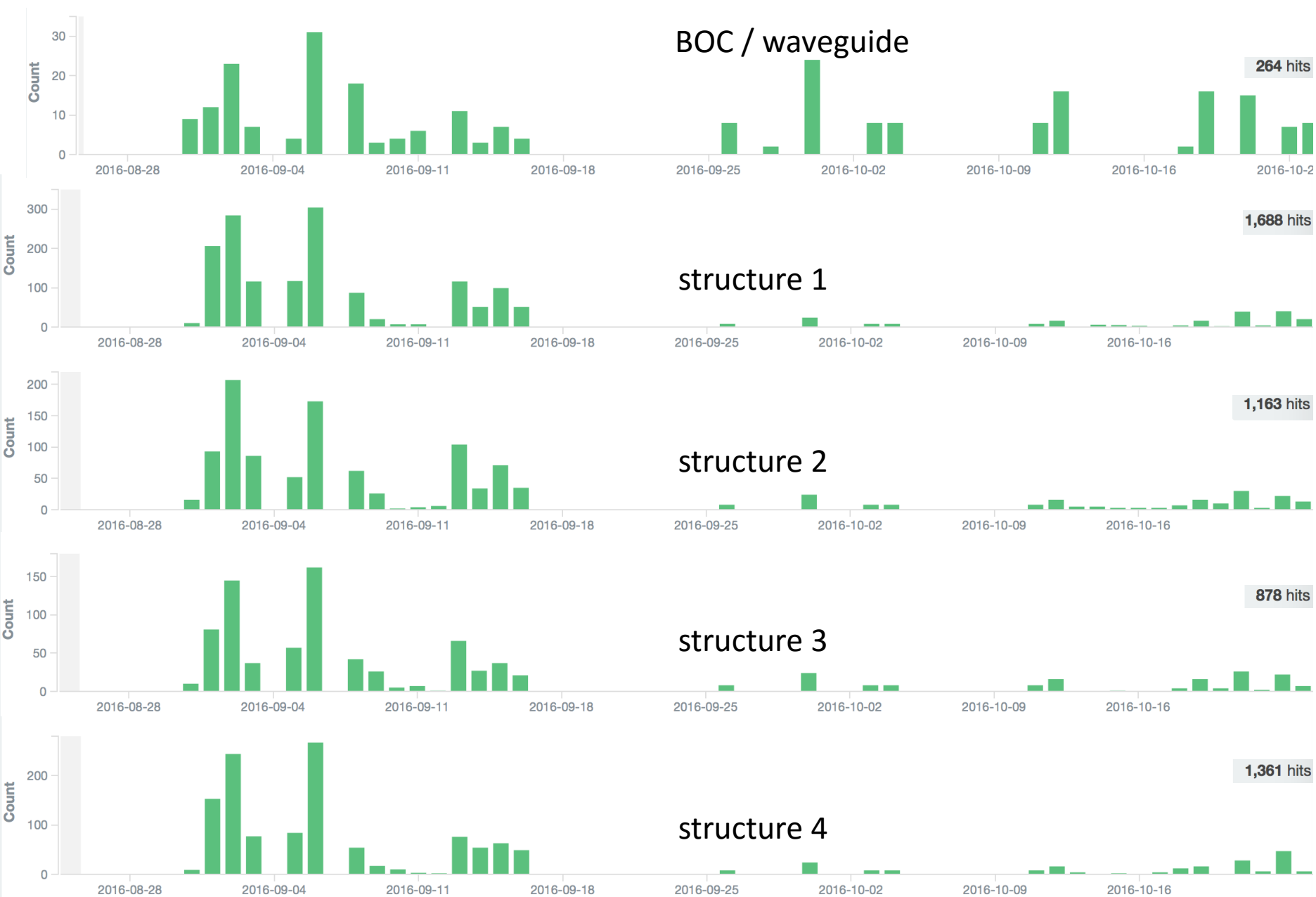
First acceleration of e⁻-beam:
 Energy gain: 241 MeV
 Nominal parameters for Linacs 2&3

Module conditioning:

Reached almost maximum available RF power
 (50 MW, 3 μs, full compression)



Break-down statistics during conditioning: First C-band module



S-band klystrons (Thales TH2100L):

Long-term experience only from test facility (SITF)

Many gun arcs in 10 Hz operation at SITF, little experience at 100 Hz

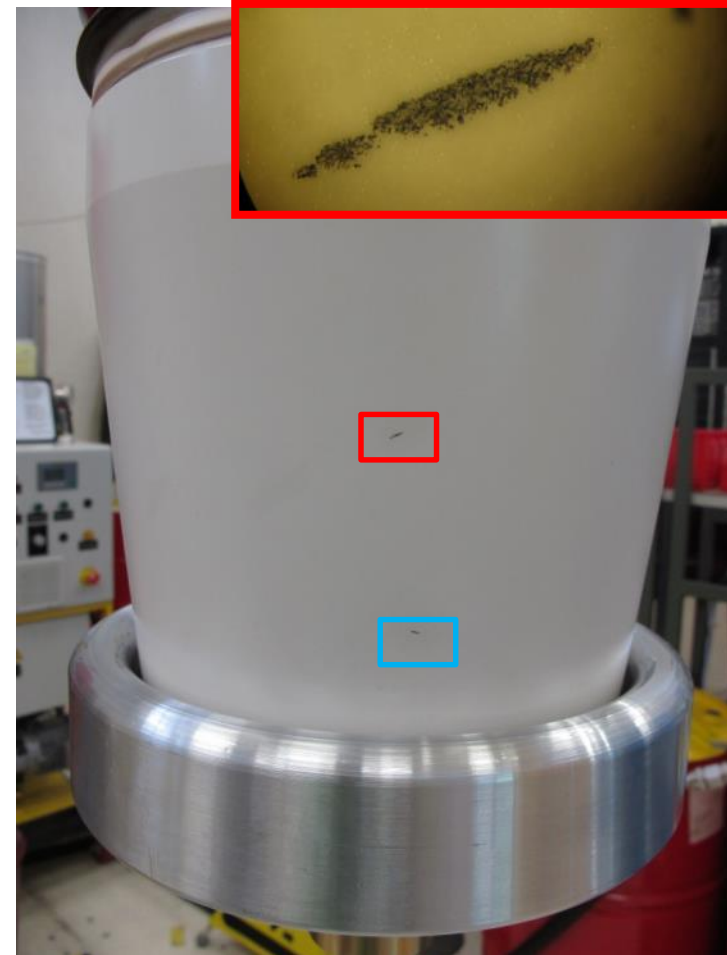
Two klystrons with high body losses, 100 Hz operation critical with these klystrons

Poor lifetime record in SITF -> potential risk for operation of SwissFEL

C-band klystrons (Toshiba E37212):

Overall very good experience, but...

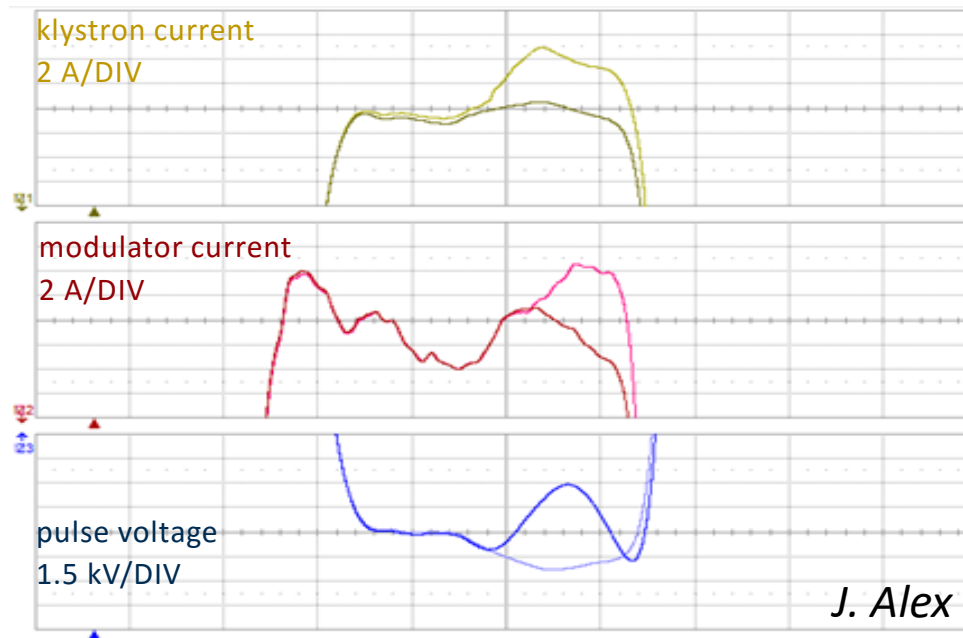
- Lost one tube in test stand
 - Crater on gun ceramics
- Exact cause unclear, candidates are:
 - Air bubbles in oil
 - Oil humidity too high?
 - 'Strange pulses'



C-band klystrons (Toshiba E37212): 'Strange pulses'

From time to time (rate can vary a lot), we observe 'strange pulses'

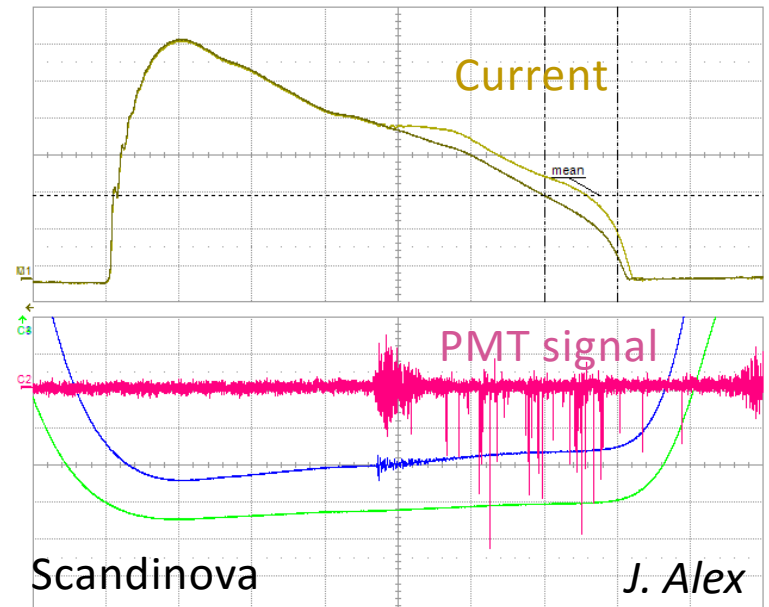
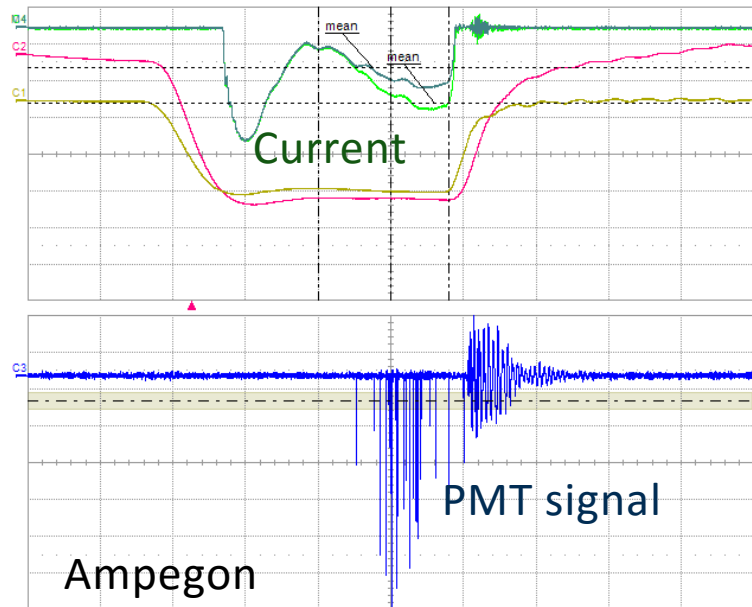
- During the pulse the klystron current increases up to 1%



„Strange‘ pulse waveform
(zoom into flat-top)

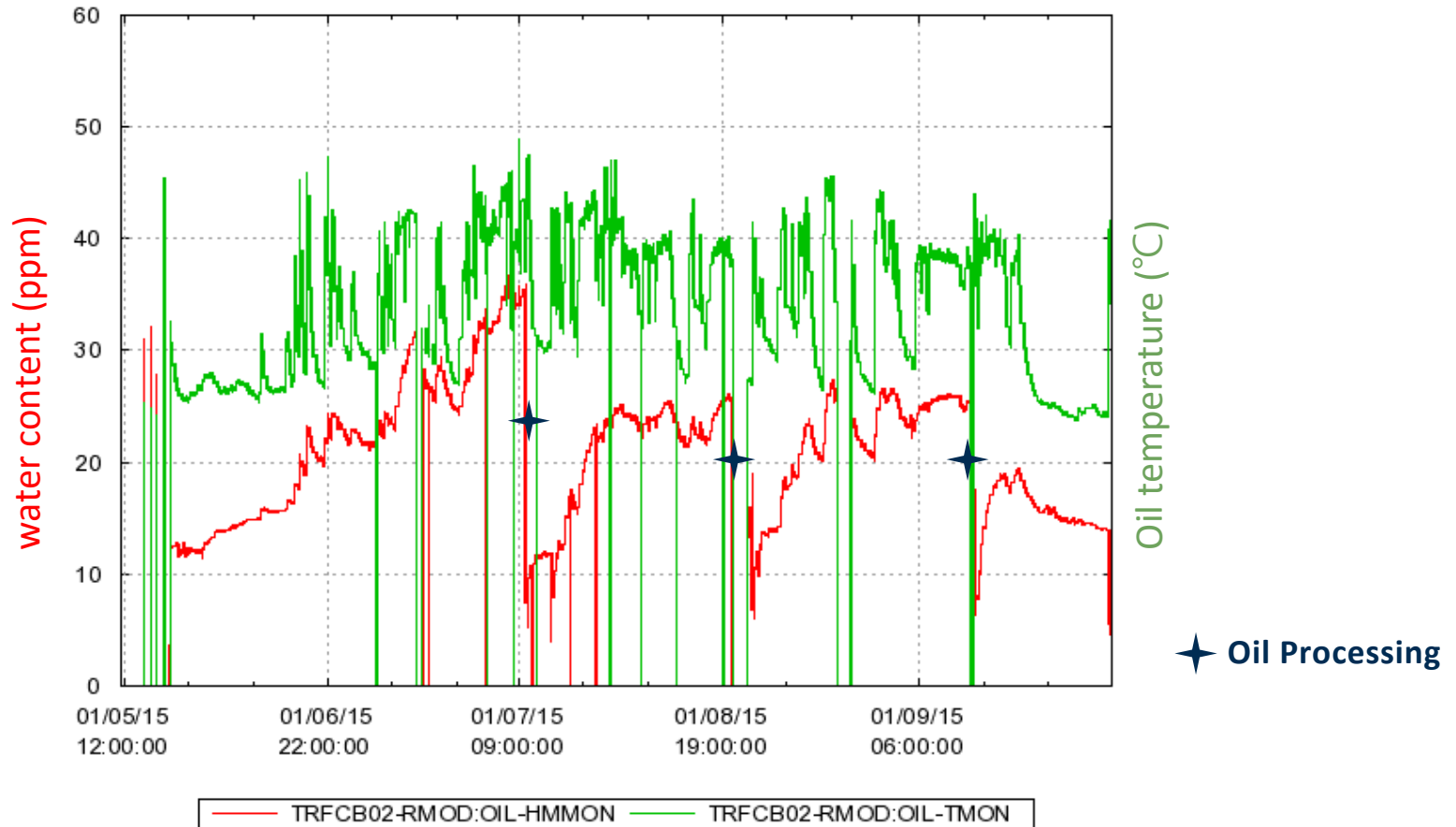
C-band klystrons (Toshiba E37212): 'Strange pulses'

- We see these pulses with both modulator types
- We see light with a photo-multiplier tube when these pulses appear
- Unclear, if strange pulses are dangerous to the klystron
- We experienced very high rate (1/4000) of strange pulses prior to klystron failure



Humidity of transformer oil in modulators

- In one of the modulator types, we saw a quick increase of the oil humidity during operation
- Rate of increase correlates with oil temperature



Humidity of transformer oil in modulators

- In one of the modulator types, we saw a quick increase of the oil humidity during operation
- Rate of increase correlates with oil temperature
- Around 2-3 g of water are added into the system per day during operation

PSI evaluated possible sources. Water seems to come out of isolation paper and other plastic material in the transformer.

- Around 500 g of water can be stored in the transformer when assembled at 50% relative humidity
- Tested: oil could be dried using a N₂ flow over the oil surface
- Tested: oil could be dried using a room air flow over the oil surface

Chemical equilibrium between humidity in air cover layer, oil, and plastic material in transformer

- **Need a way to dry the transformers / oil during operation**

Actions by PSI

- Oil tanks of C-band modulators (both from Ampegon and ScandiNova) allow for an evacuation
 - Air bubbles in the oil can be removed
 - Can help drying the transformers?
- Oil drying system is added to modulator(s)
 - Allows operation when transformer is not yet dry

Experience at your facilities?