Multi-klystron operation experience XBox-3

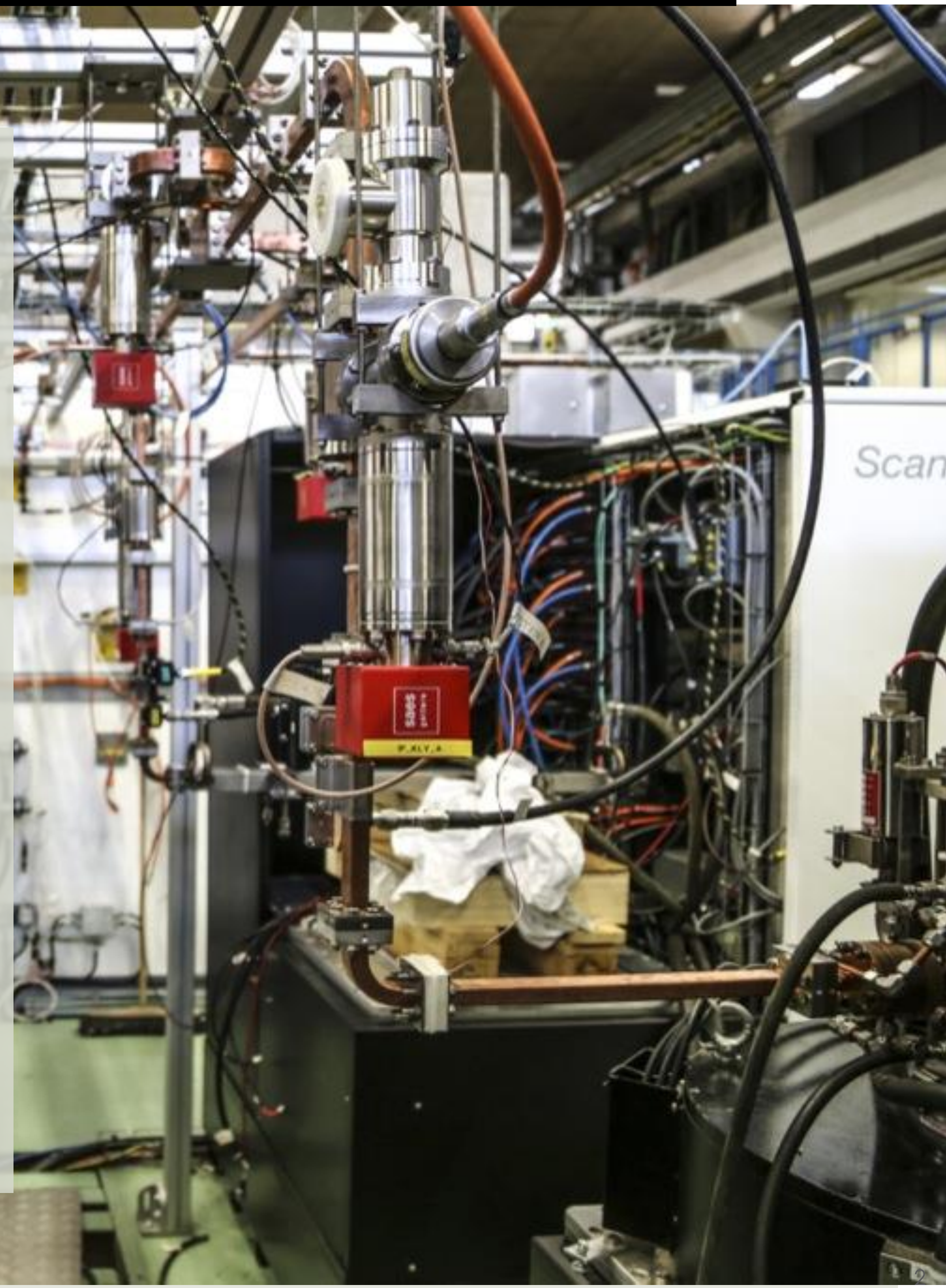
Matteo Volpi on behalf of XBox team

HG2017   15 of June 2017

THE UNIVERSITY OF MELBOURNE

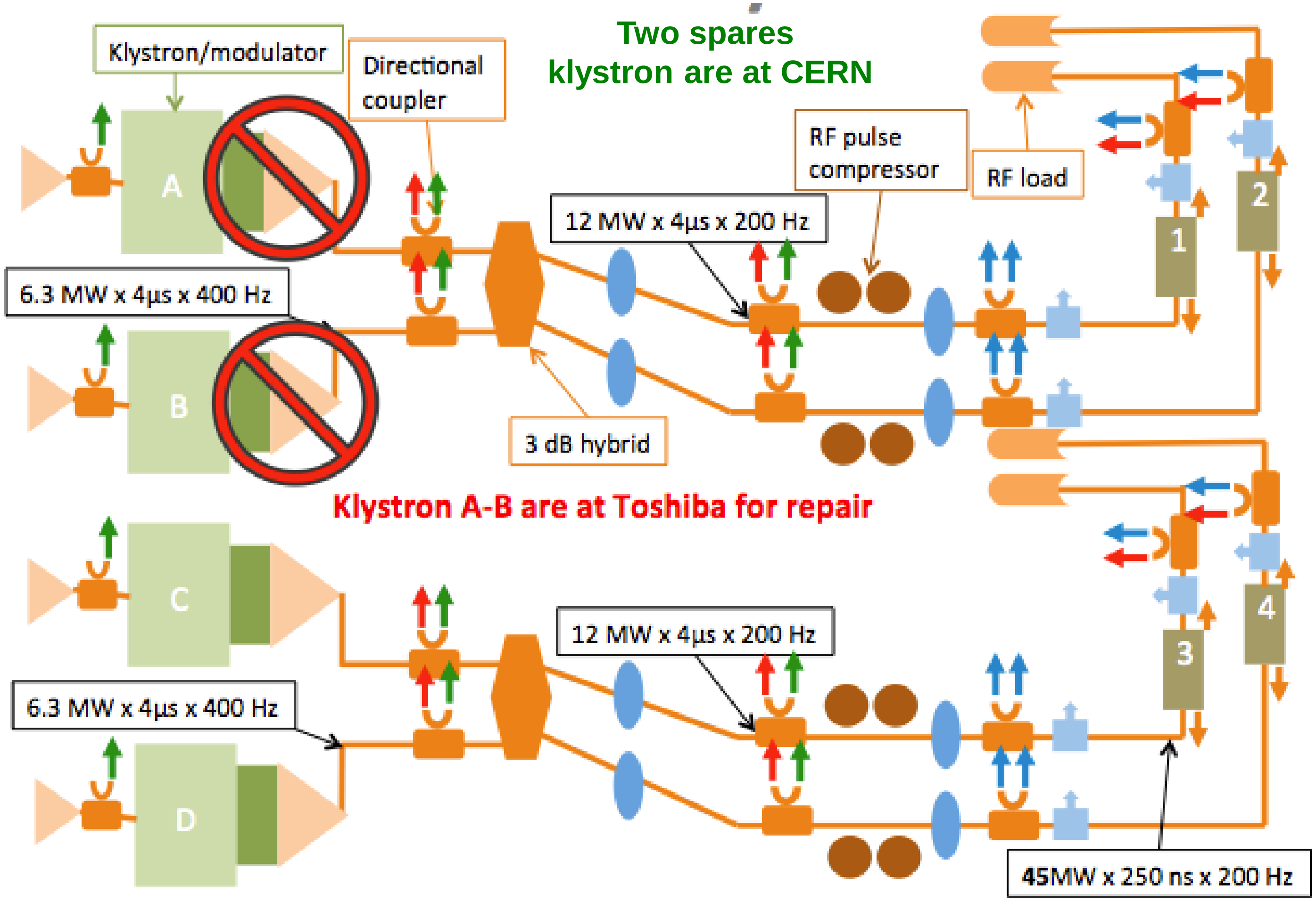
Outline

- Test stand specifications and layout
  - ≤ 250 ns pulse
  - ≤ 45 MW
  - ≤ 400 Hz pulse repetition rate
  - 4 test slots.
- Control systems
  - Power control: Pressure and BDR.
- Conditioning
  - Lines
  - Structures
- Conclusion

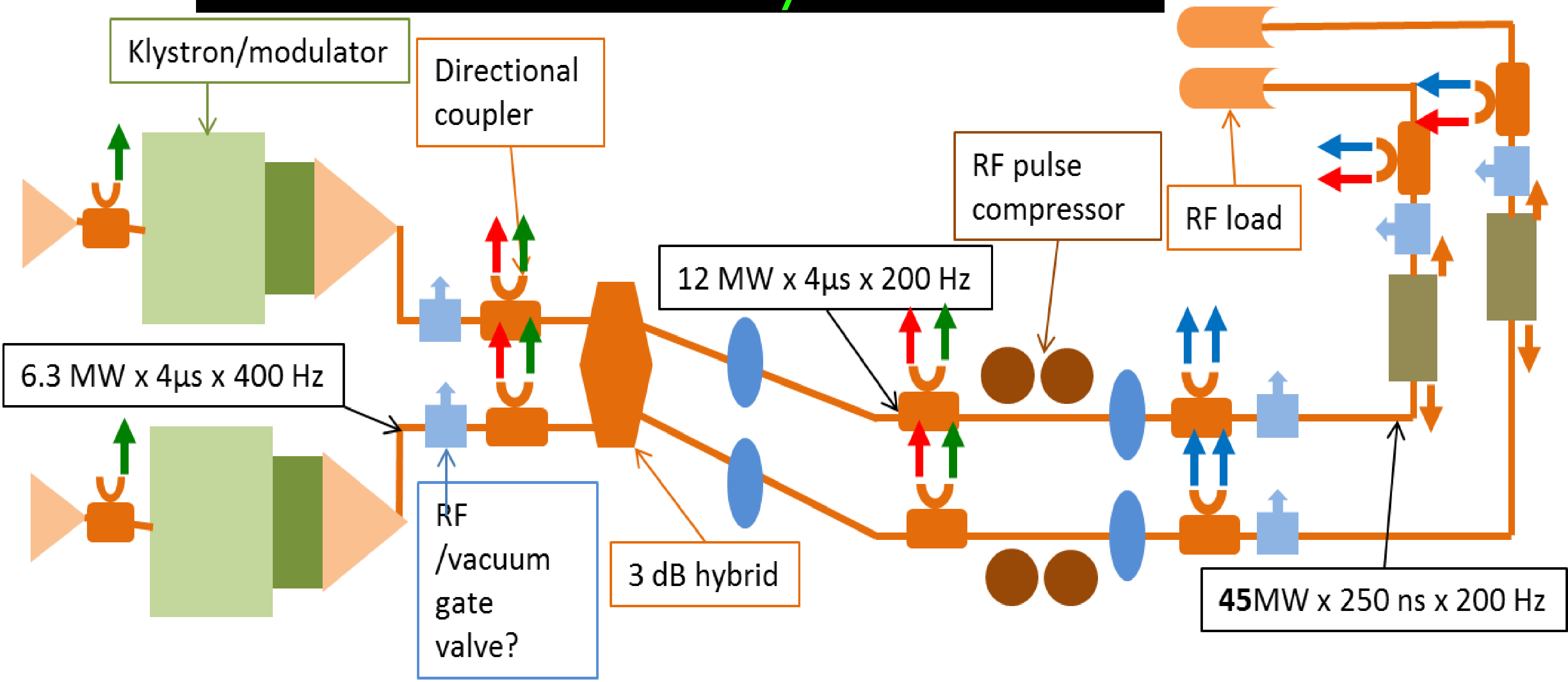


Xbox-3 status

4x Toshiba 6MW 5us klystron 4x Scandinova Modulators Nominal - Rep Rate 400Hz	Medium power tests (Xbox-3): 3D-printed Ti waveguide (UK) 3D-printed Ti waveguide (CERN) X-band RF valve (1)	On going tests (high power) C&D: TD24 R05 SIC N2 T24 PSI N1 X-band RF valve (1)



Xbox-3 Layout



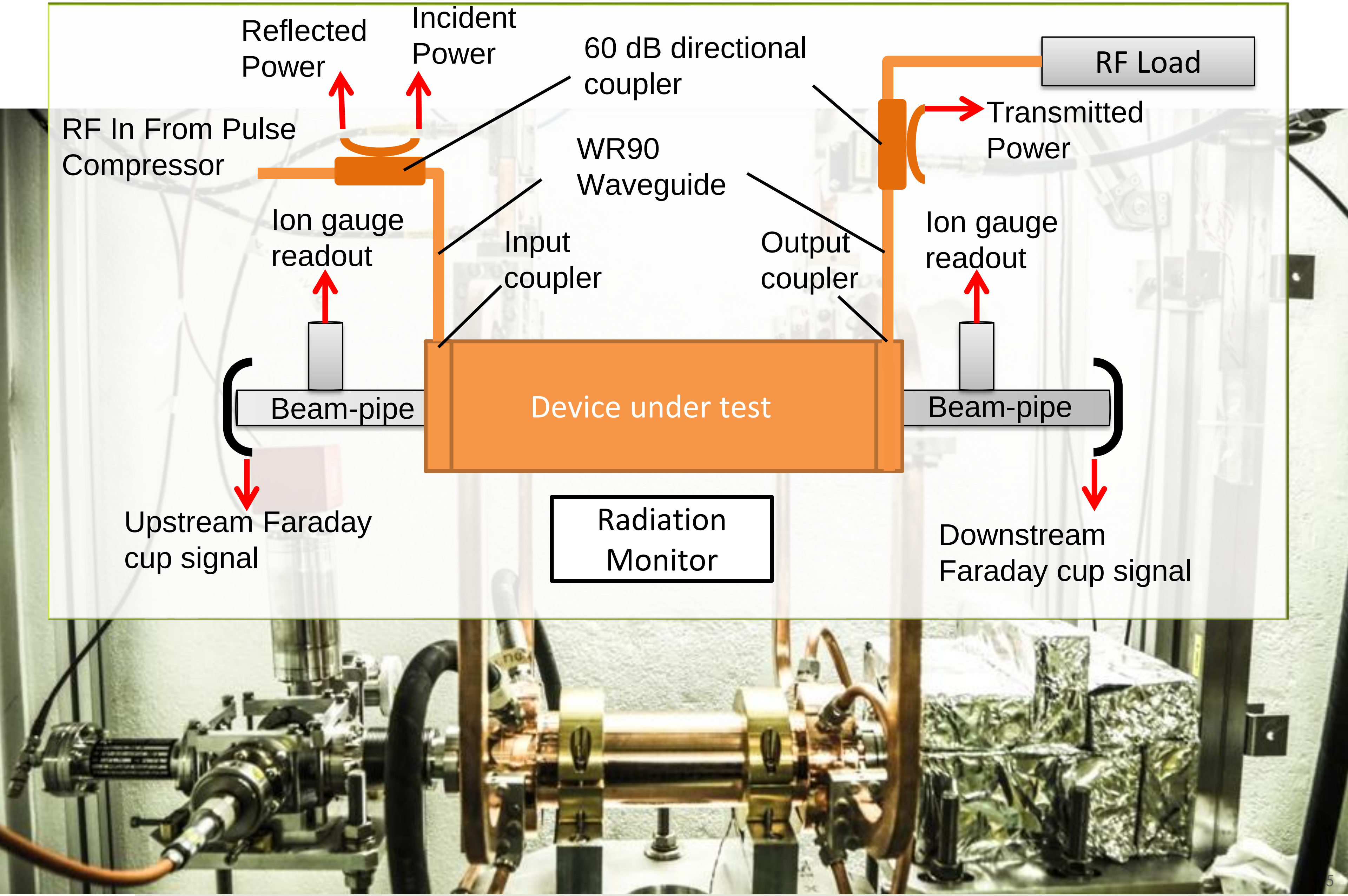
x4: 2 Faraday Cups (250MSPS ADCs) Used to interlock the system and are interesting for high gradient physics.

X6: Log detectors ~50MHz Bandwidth, 45dB dynamic range (250MSPS ADCs) Used for interlocking the system.

X6: FPGA IQ demodulation 400-MHz AC (228MSPS ADCs) Phase and amplitude needed for reliable line/phase switching.

x6:3 FPGA IQ demodulation 400-MHz AC (1600MSPS ADCs) Most interesting signals for BD physics.

Diagnostics of the DUTs



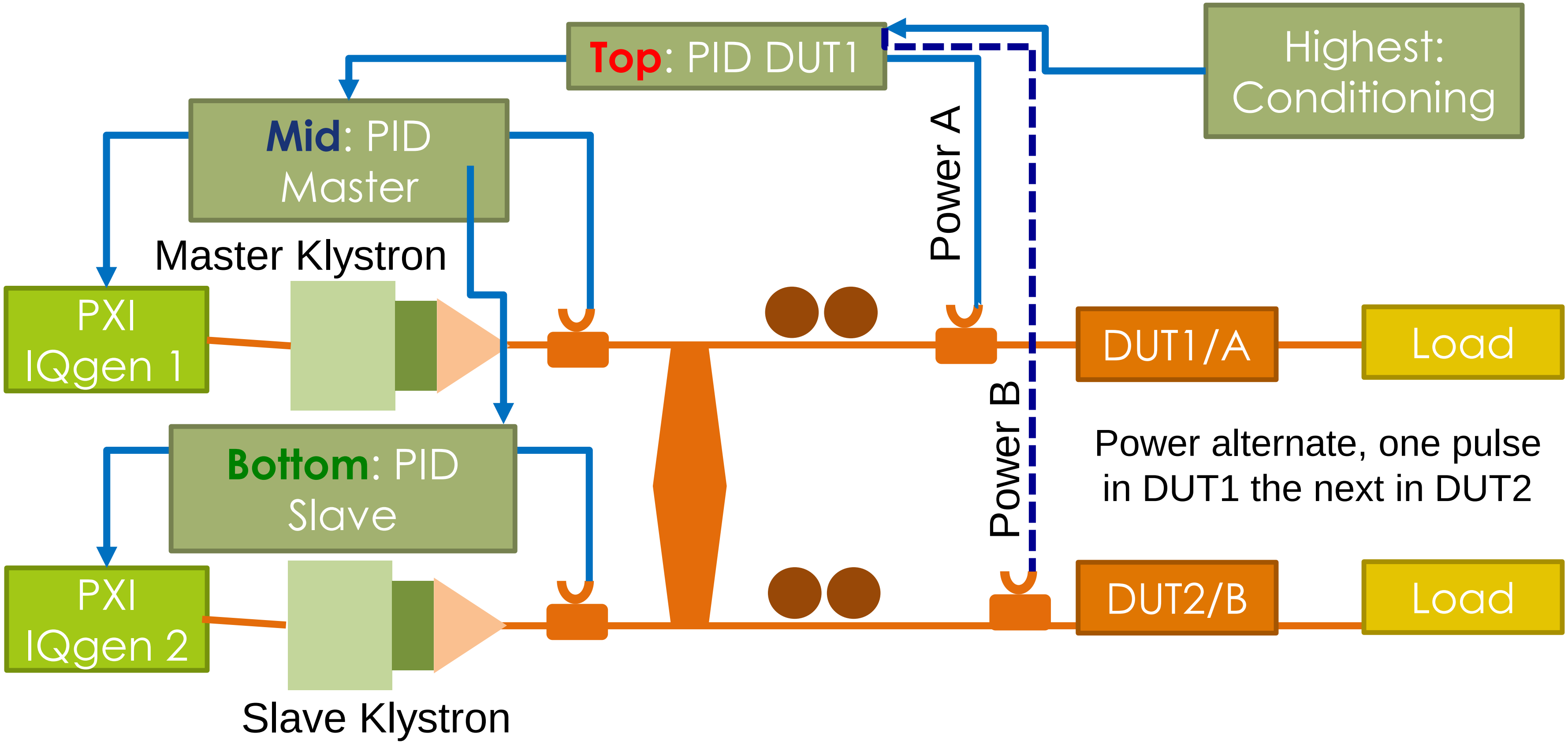
Safety, Interlocks and control Algorithms

- Main personal safety issue is **X-ray radiation during operation.**
  - Interlocks on the bunker door and klystron/modulator access doors stop modulator pulsing if opened.
  - Modulator interlocked is radiation levels are too high inside or outside of the bunker.

- Machine protection issue is from high **vacuum and reflected power to the klystron.**
  - Double interlocking of the vacuum; 10^{-5} mbar interlocks the modulator and 10^{-7} mbar interlocks the LLRF driver.
  - Reflected power is monitored by log detectors which stop the LLRF output if a certain level is reached.

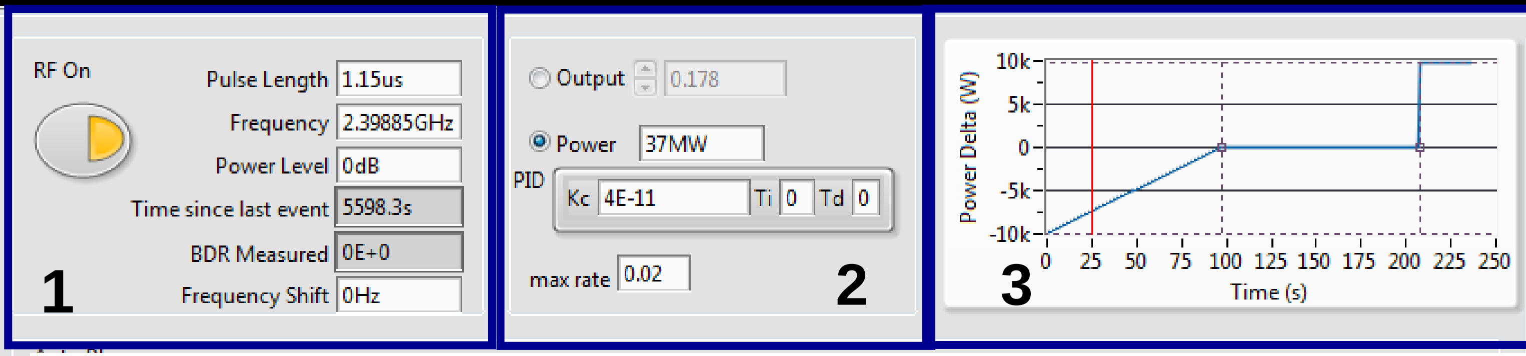
- Interlock hardware
  - **Modulator** control system is used for radiation and access interlocks.
  - **NI 6583 module** attached directly to an FPGA in the PXI crate is the main trigger and interlock module. This is used for all other interlocks; vacuum, RF, high temperatures, etc.

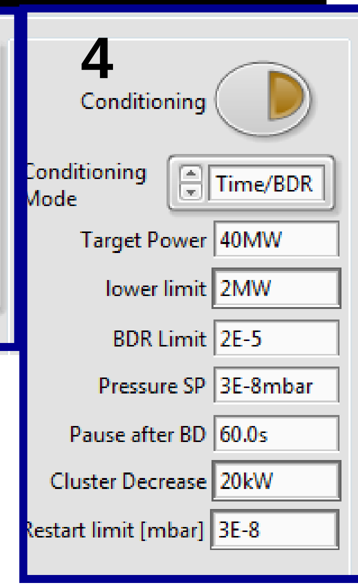
RF feedback algorithms: POWER



- **Top**: The DUT PID requests more/less power from the Master PID depending on the power level to the DUT.
- **Mid**: The Master PID requests more/less power from the PXI IQgen 1 card depending on the power level to the master.
- **Bottom**: The Slave PID tries to make the output power of the Slave klystron equal to the master klystron by controlling the power of PXI IQgen 2.

Conditioning control algorithm



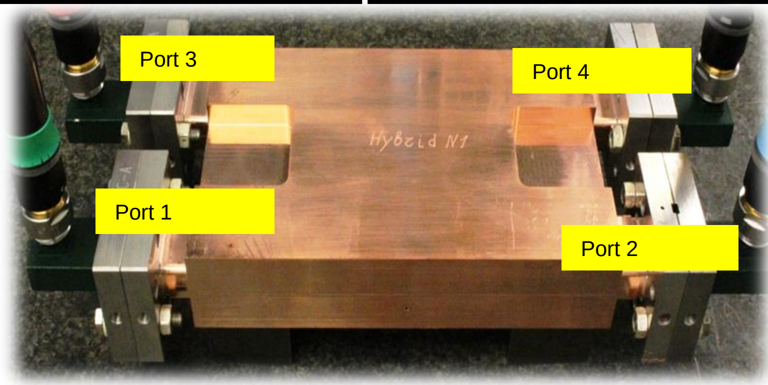


1. Pulse length and LLRF frequency are set:
2. Fast → pulse to pulse
   - PID loop on the incident power to the structure
3. Medium → seconds-minutes
   - increase power by 10kW every few minutes (**cycle loop**) if no BD
   - reduce power by 10kW if successive BDs too close in time
4. Slow → hours
   - **BDR measurement** performed across a moving window of approx. 1M pulses.
   - BDR measurement and stop power increase if it is too high

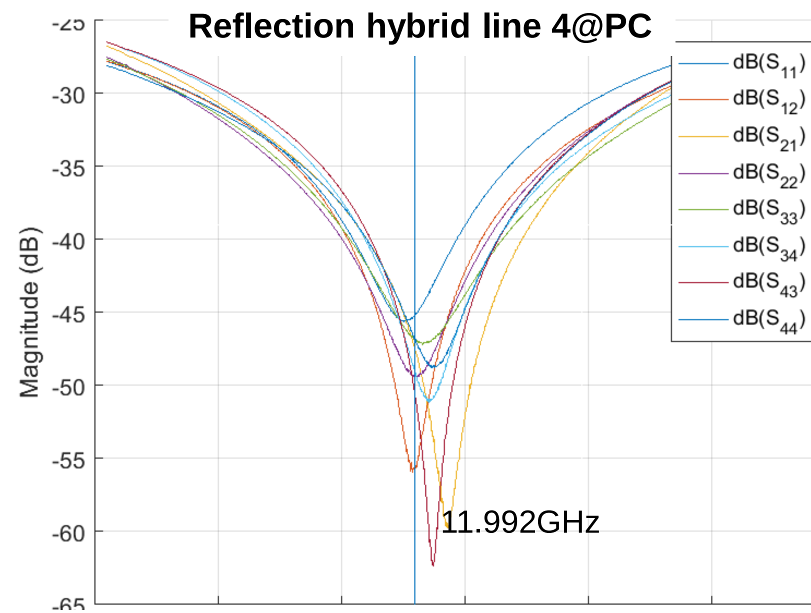
OR

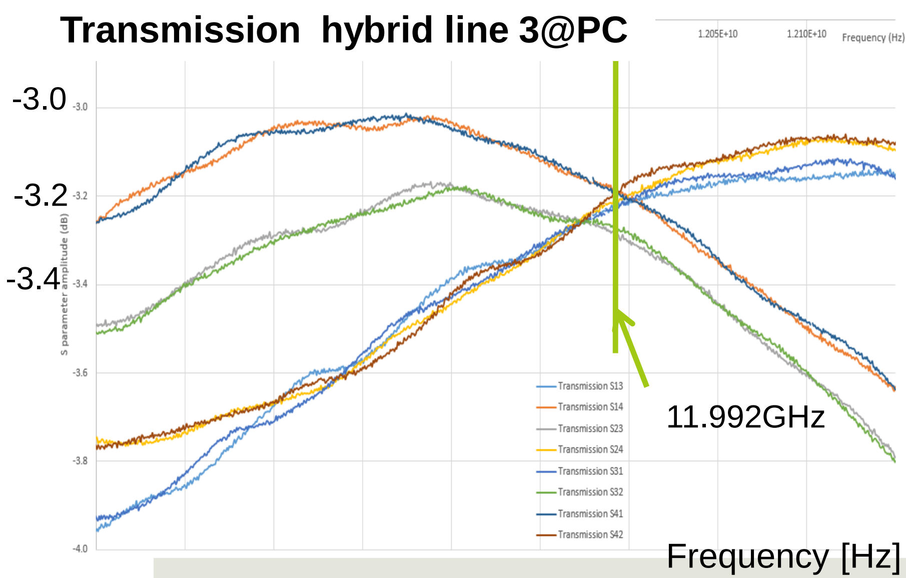
- Use PID loop using the system **pressure** as a process variable.
- Increase in pressure results in a reduction of power and vice versa.

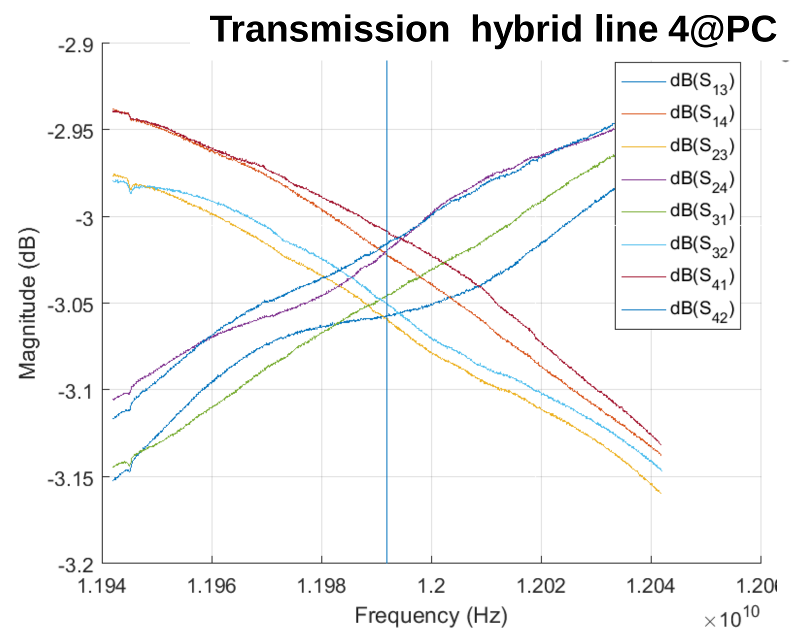
Hybrid



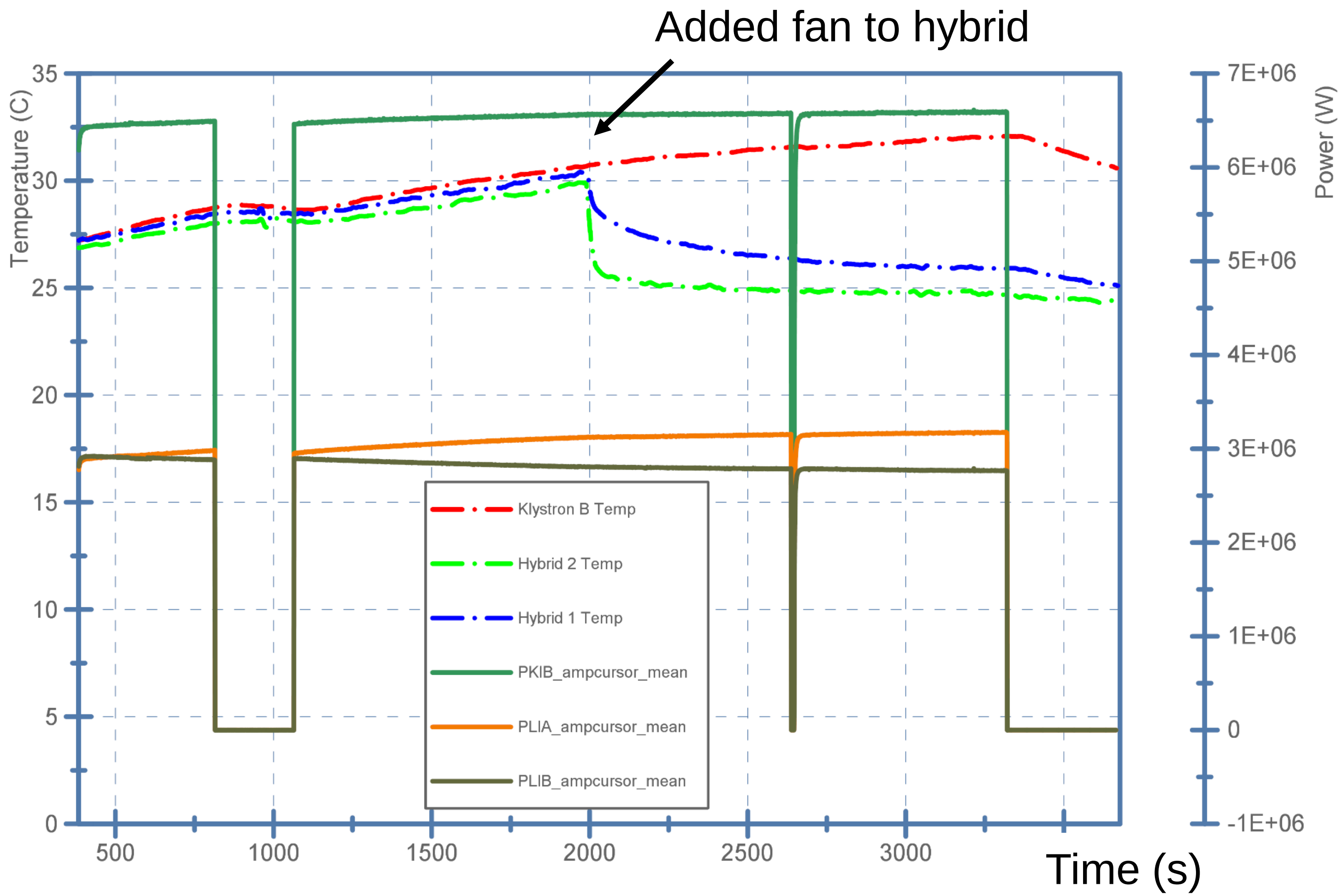
- From simulation
  - Reflection at the klystron is the line with the highest reflection plus 6dB.
  - The reflection depends on the difference phase between the two klystrons.







Hybrid split over time @ 400 Hz

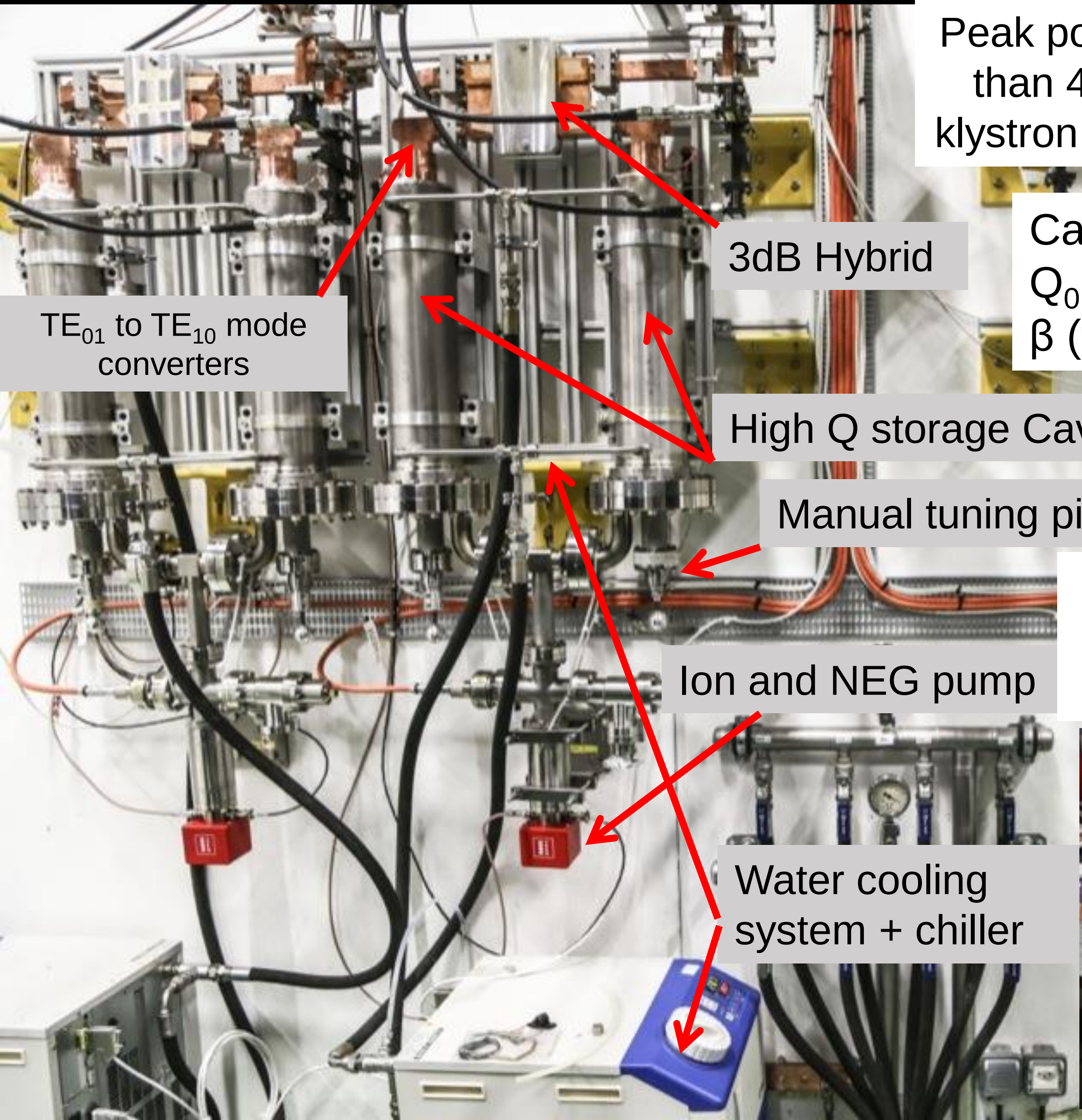


- Splitter depends on the temperature and repetition rate => fix with the bottom PID in klystron input power

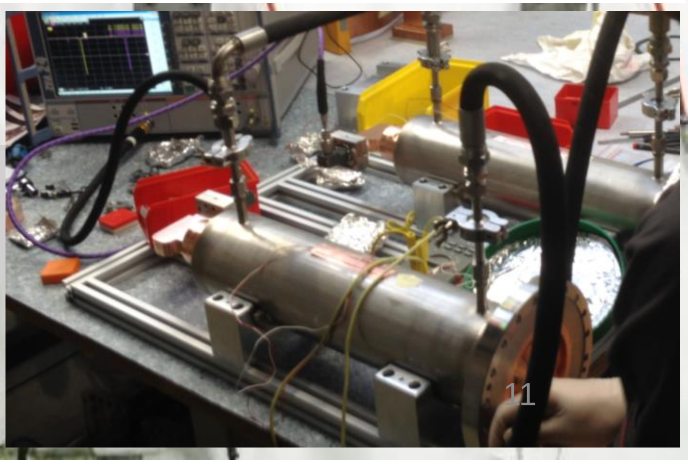
PC installed at Xbox-3

Peak power compression ratio of more than 4, when compressing the 3 μs klystron pulse to a 200 ns output pulse.

Cavity operating mode $H_{0,1,32}$,
Q_0 (expected) = $2x10^5$,
β (theoretical)=3.5



Third and fourth PCs tuned, ready
for installation in line 1 and 2.

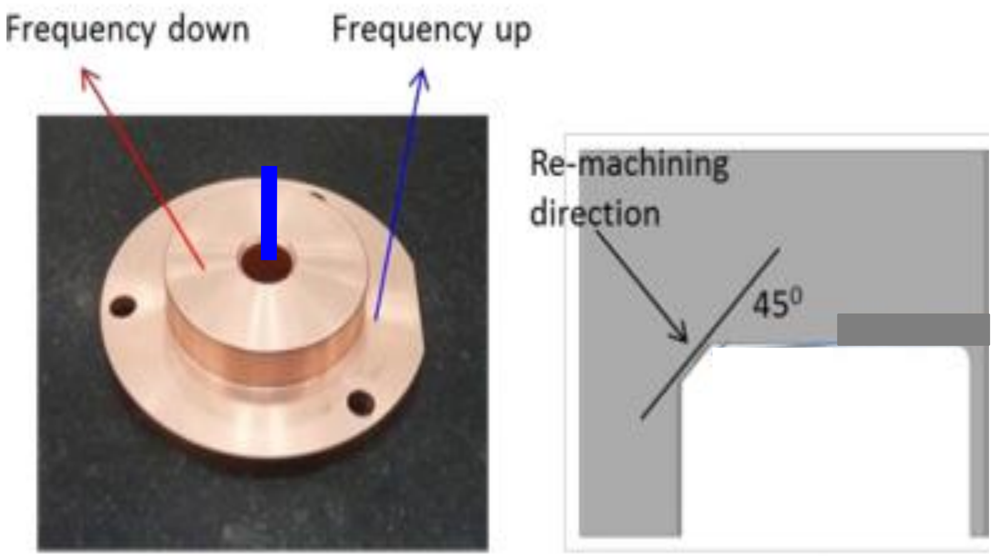


Pulse compressors tuning

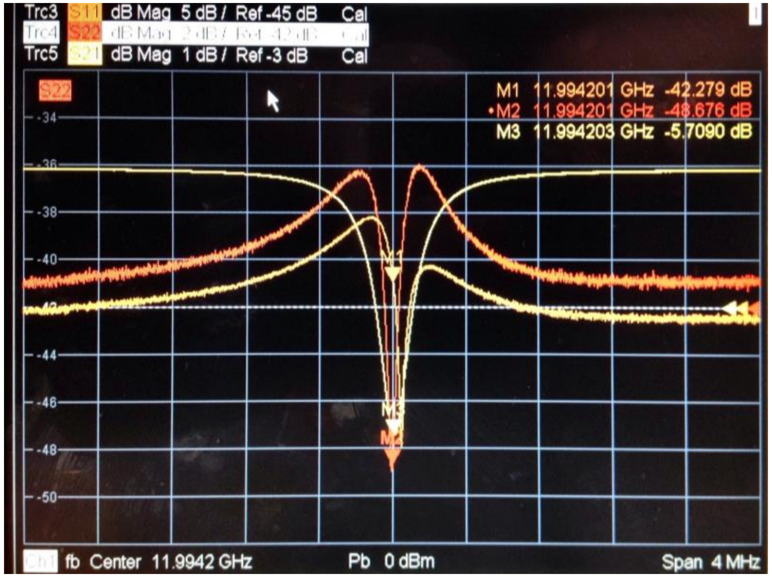
- The end of the cavity is a removable copper plate that can be machined

De-tuning plungers increase the mode frequency then the pulse compressor will be transparent

to the incoming RF pulse.



Coarse tuning   Fine tuning



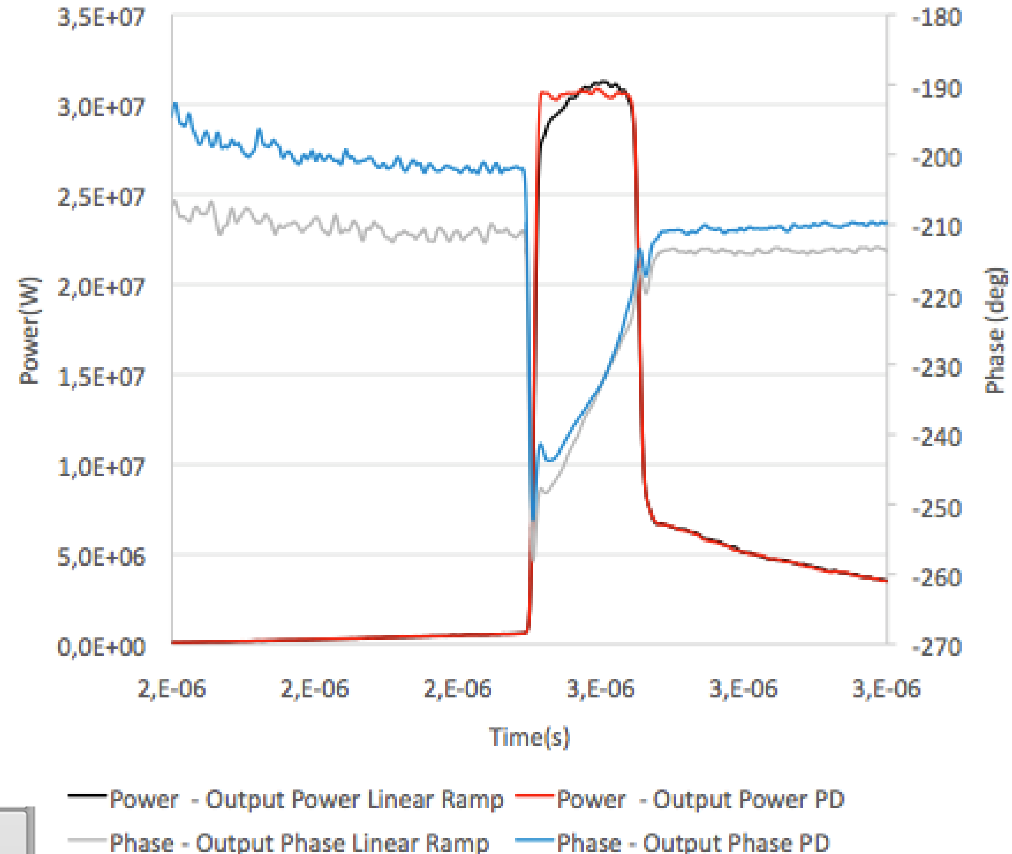
- The coarse tuning will impart a frequency variation of 20 MHz/mm, while the fine frequency tuning of the chamfer is 1.1 MHz/mm.

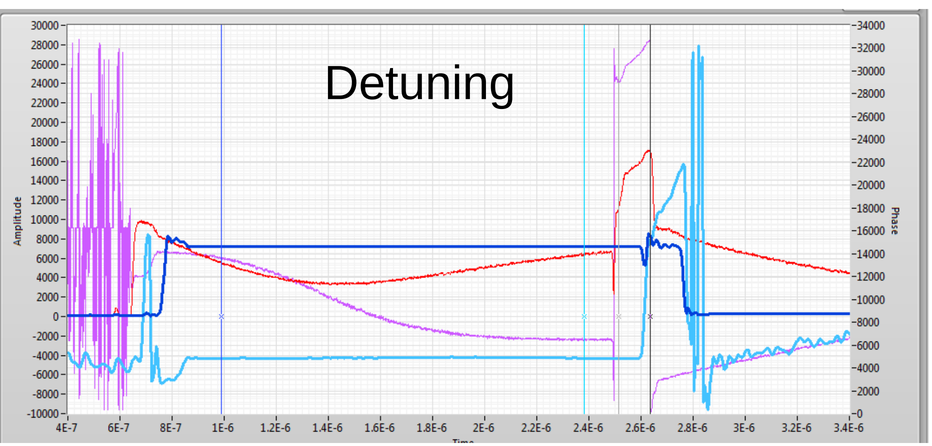
Pulse Compressor Pulse Flattening

The flat-top data is fitted with a 5th order polynomial.
The following feedback is applied.

$$\phi_{n+1} = \phi_n + g_p(A_{SP} - A_n) + g_d(dA_n/dt)$$

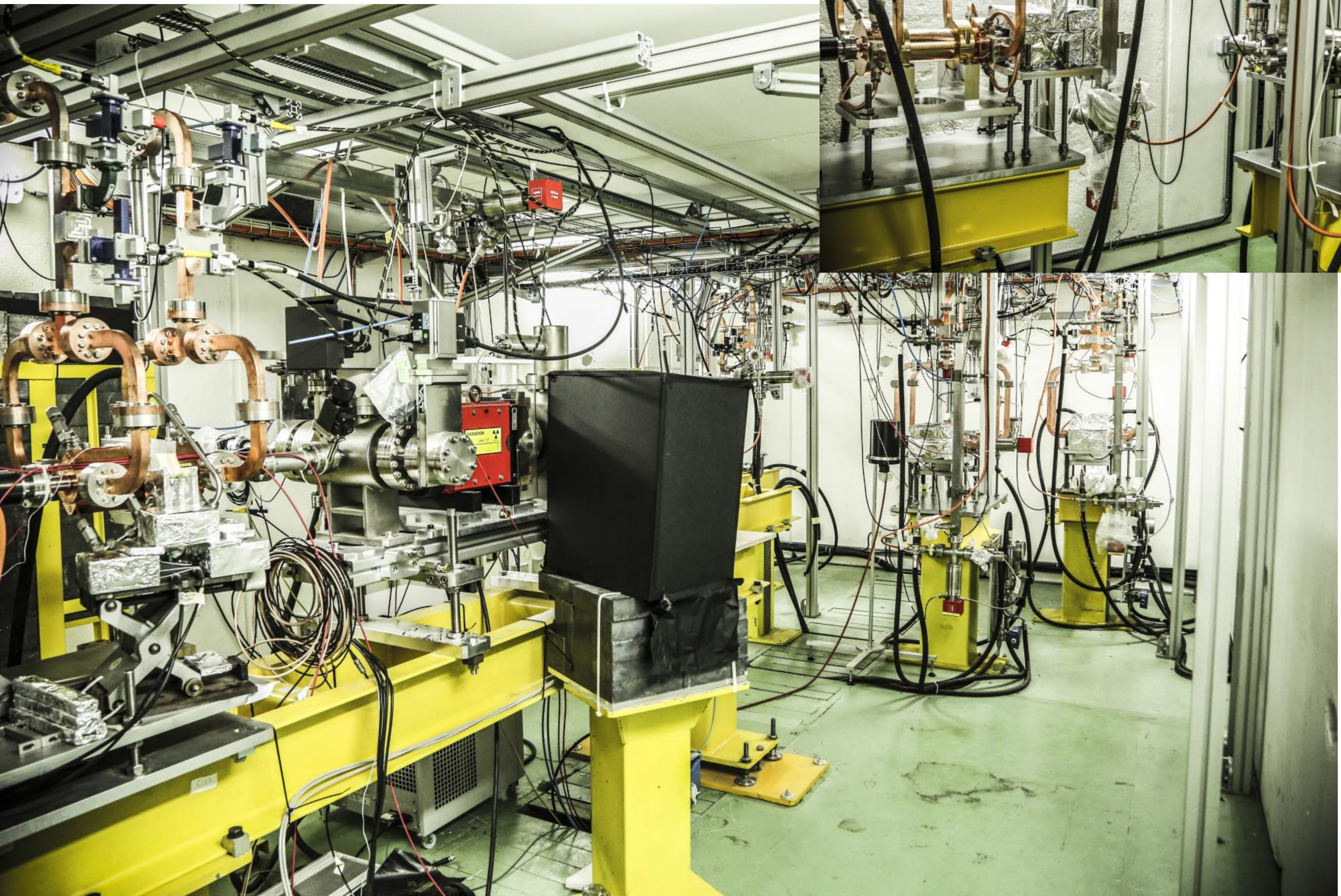
A_{SP}	amplitude set point
A_n	current amplitude
g_p	proportional feedback gain
g_n	differential feedback gain





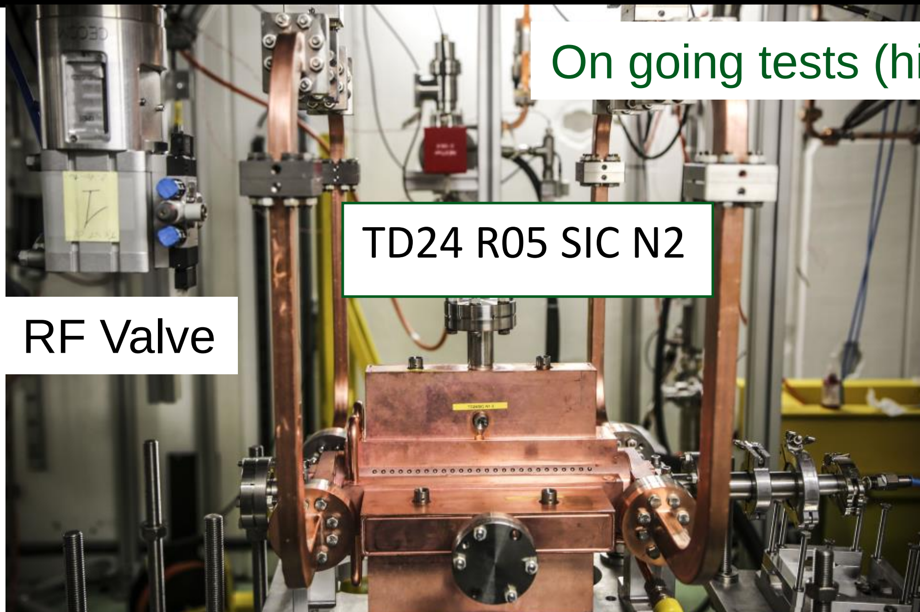
- Any change in the average RF power (such as RF power interruption due to an RF breakdown) caused the pulse compressor to cool and detune.
  - Temperature isolation
    - Frequency shift

Bunker view



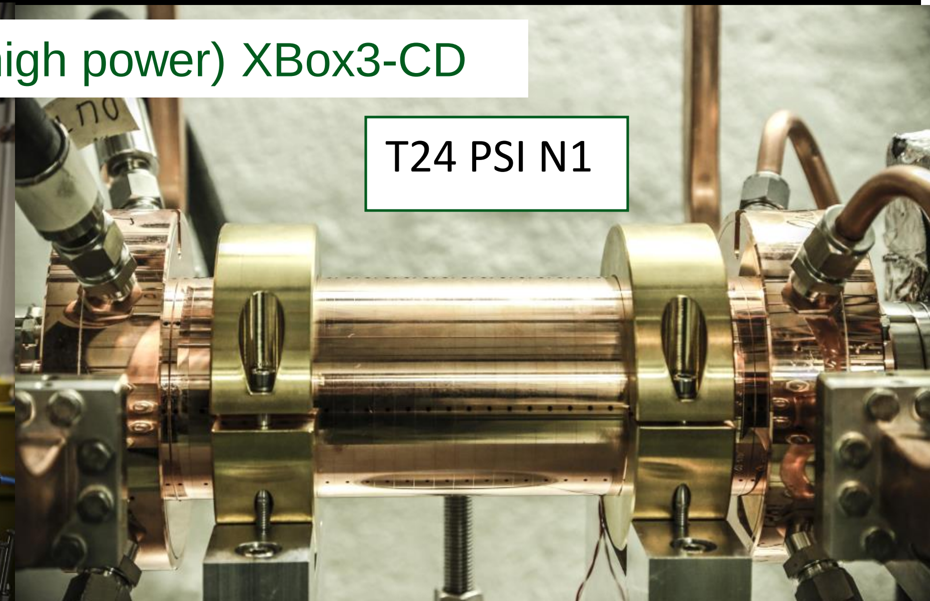
Xbox-3 Tests

On going tests (high power) XBox3-CD



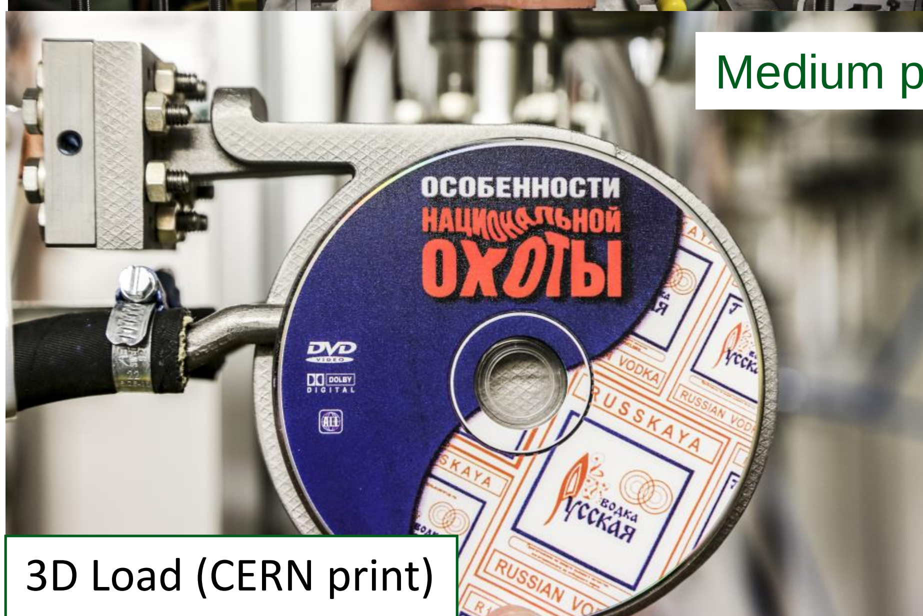
RF Valve

TD24 R05 SIC N2

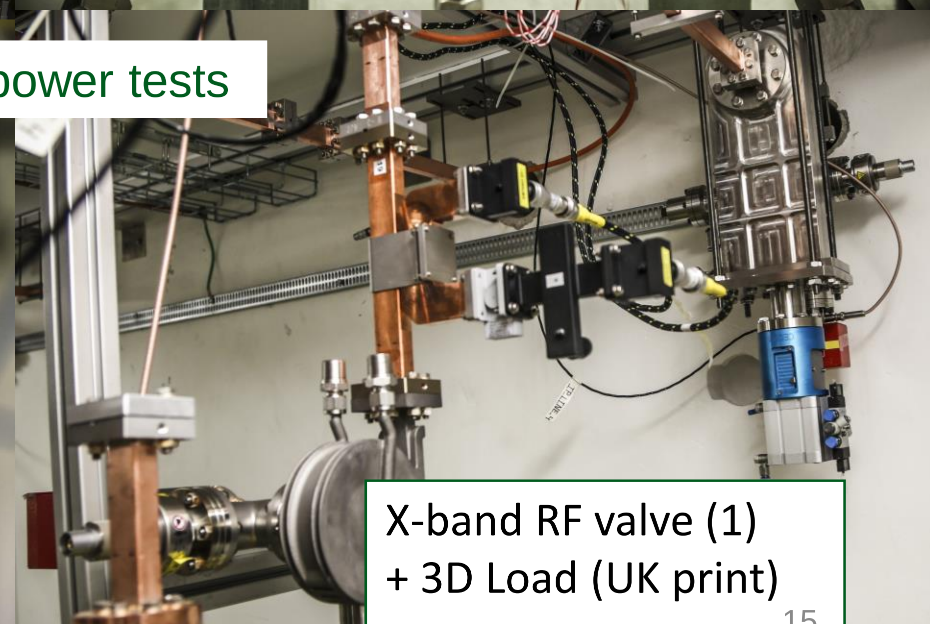


T24 PSI N1

Medium power tests



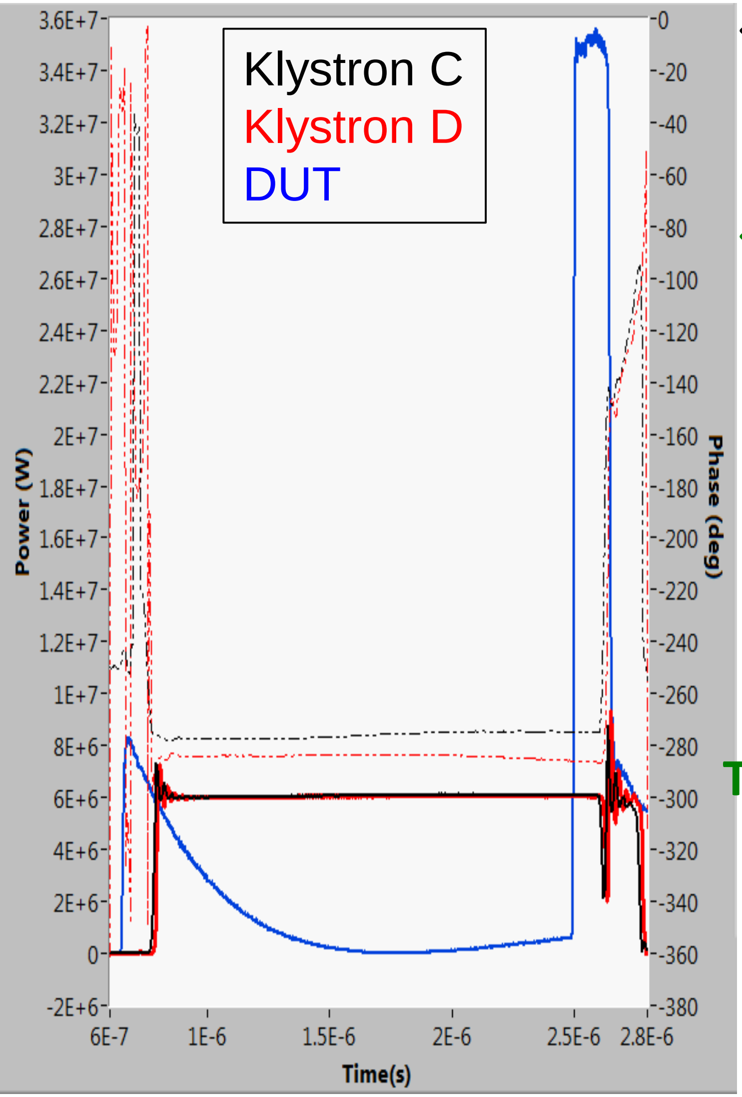
3D Load (CERN print)



X-band RF valve (1)
+ 3D Load (UK print)

Line conditioning

Pulses in line C and D

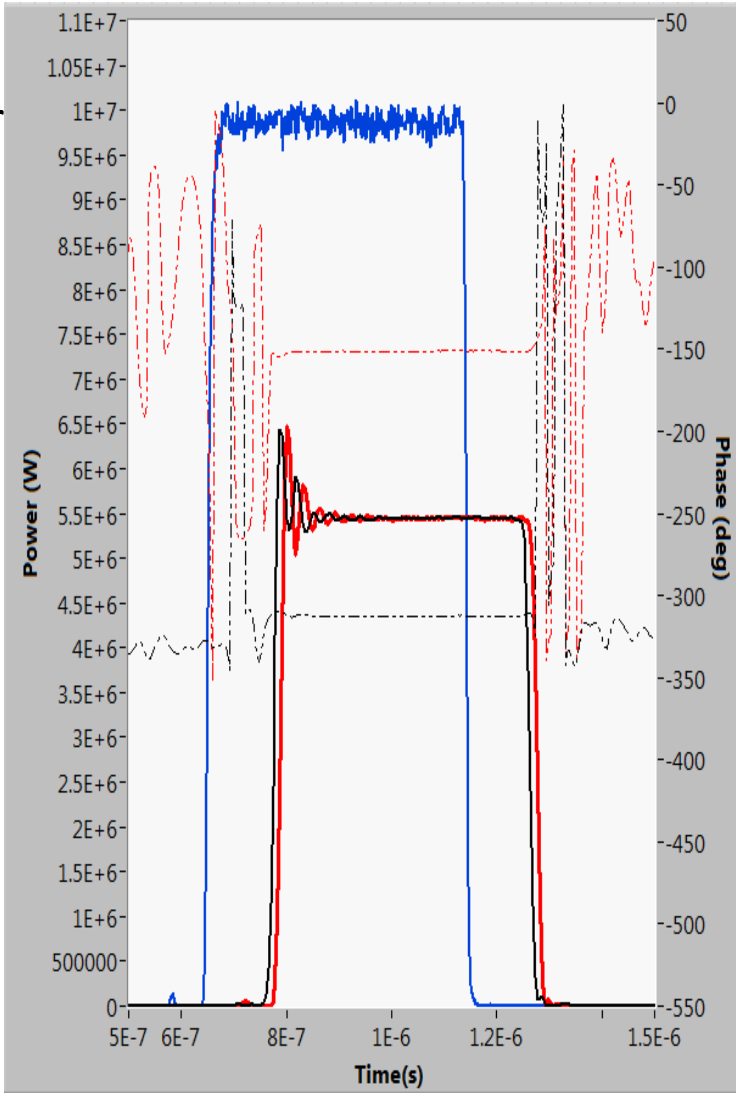


←Line C with pulse compressor so we can achieve higher power levels.

←**The output phase difference from the klystrons is small ≈0°.**

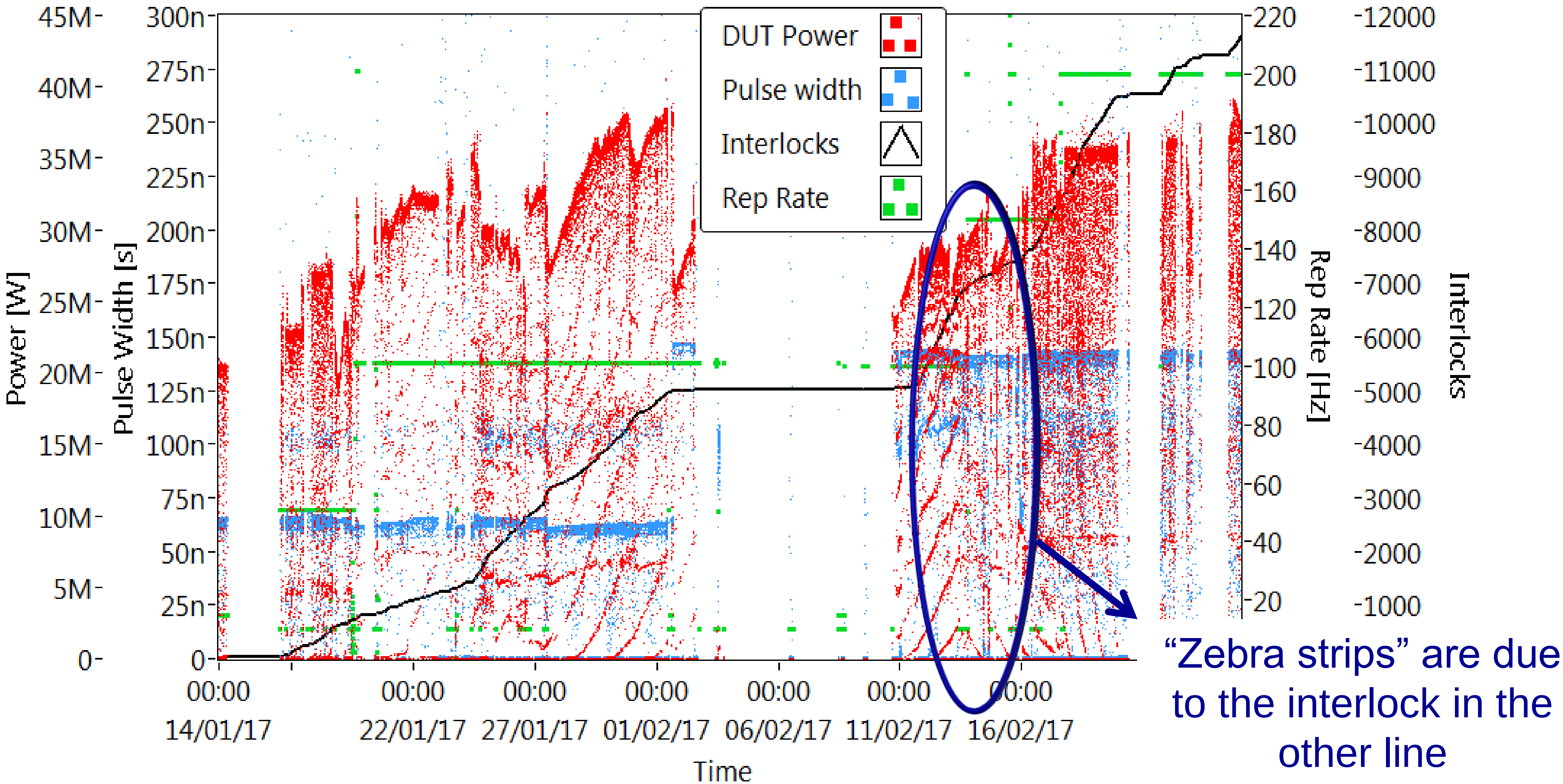
Early line D without pulse compressor; Lower power levels. →

The output phase difference from the klystrons is ≈180°. →



NOTE: Both of these pulses happened just 5 ms apart.

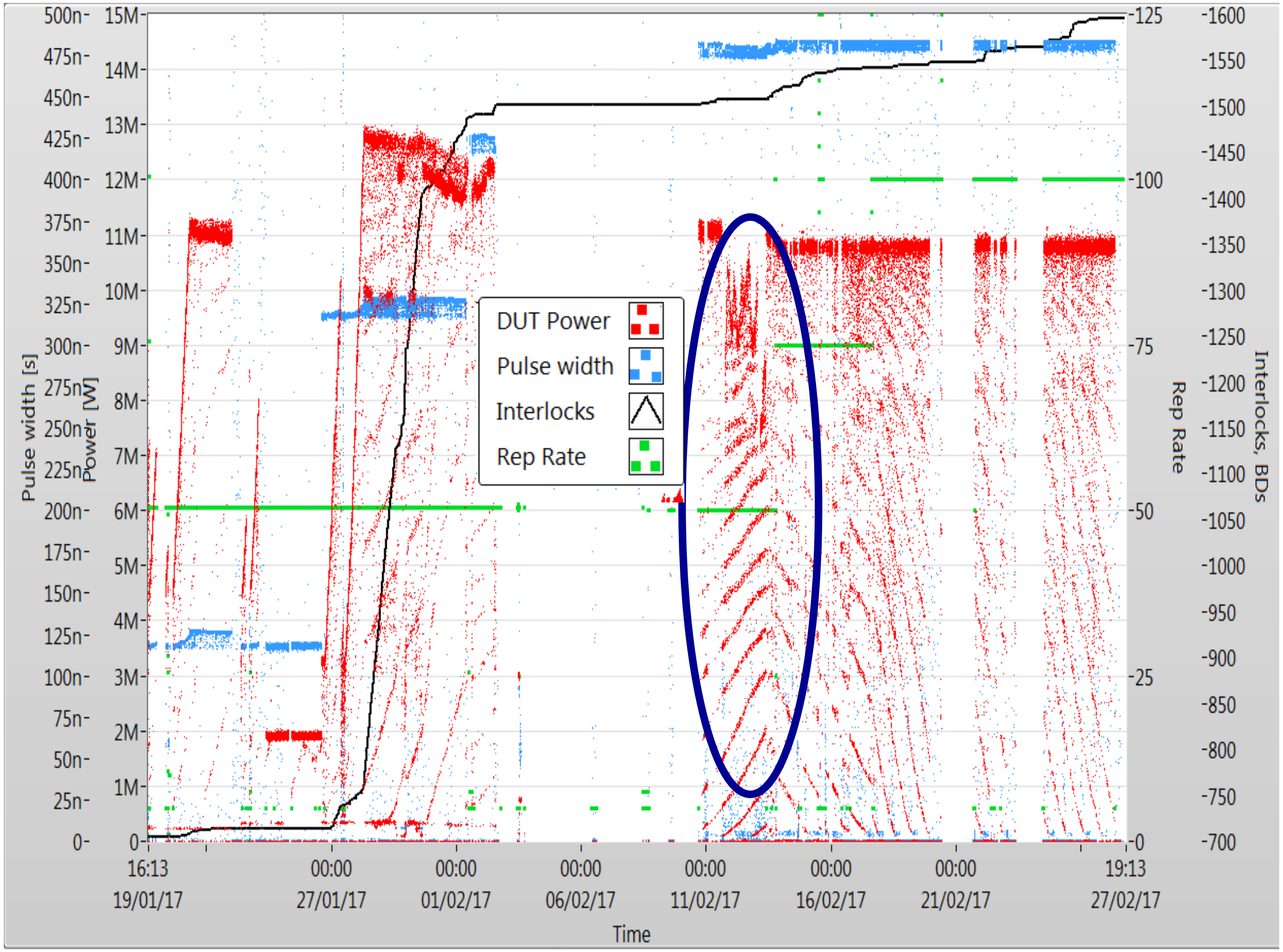
Conditioning plots: Line 3 with PC



- Conditioning history for line 3 with pulse compressor (PC).
  - Main source of BDs/interlocks are the pulse compressor and the load.
- Started at 25Hz and 60ns pulse width. Later increased to 100Hz and 140ns pulse width.
  - Final power reached ~40MW @ 140 ns.

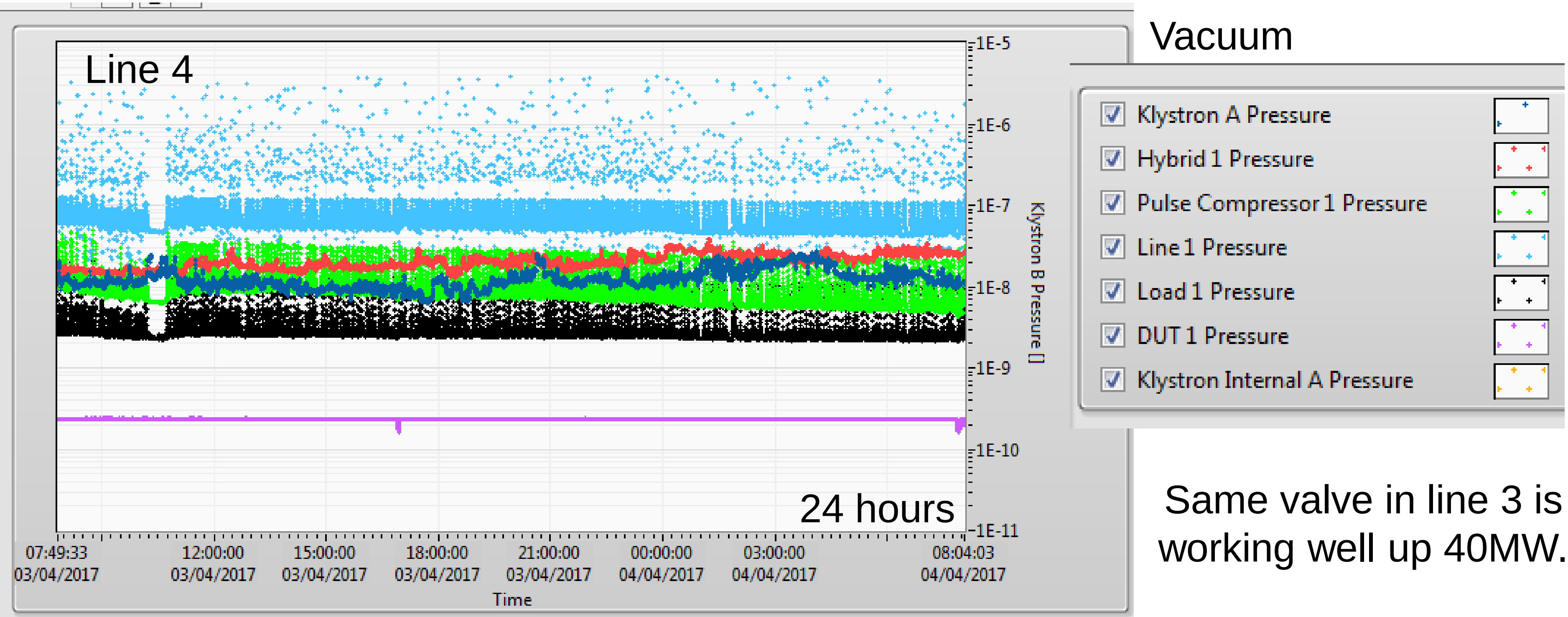
Conditioning plots: Line 4 no PC

- Conditioning history for line 4 without PC.
- After initial conditioning period there were few interlocks.
- Started at 25Hz and 120ns pulse width.
- Later increased to 100Hz and 480ns pulse width.
- Final power reached ~11MW @ 480 ns

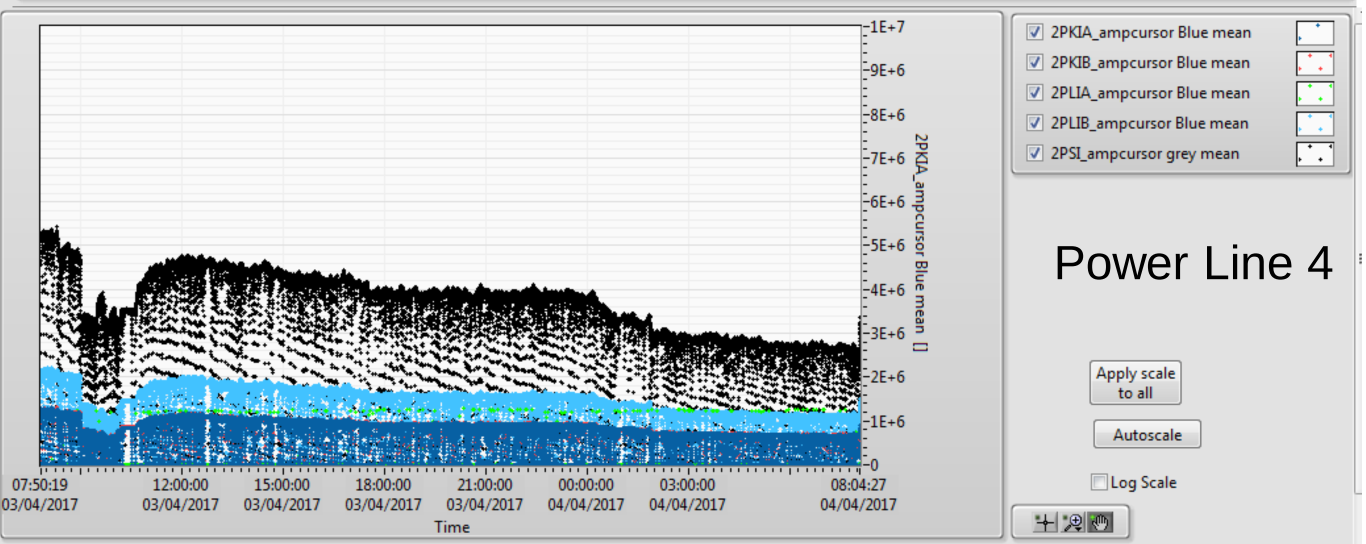


- We restart the conditioning after install the PC => unfortunately we can't reach more than ~7MW due to the RF valve vacuum activity

RF valve conditioning in Line 4

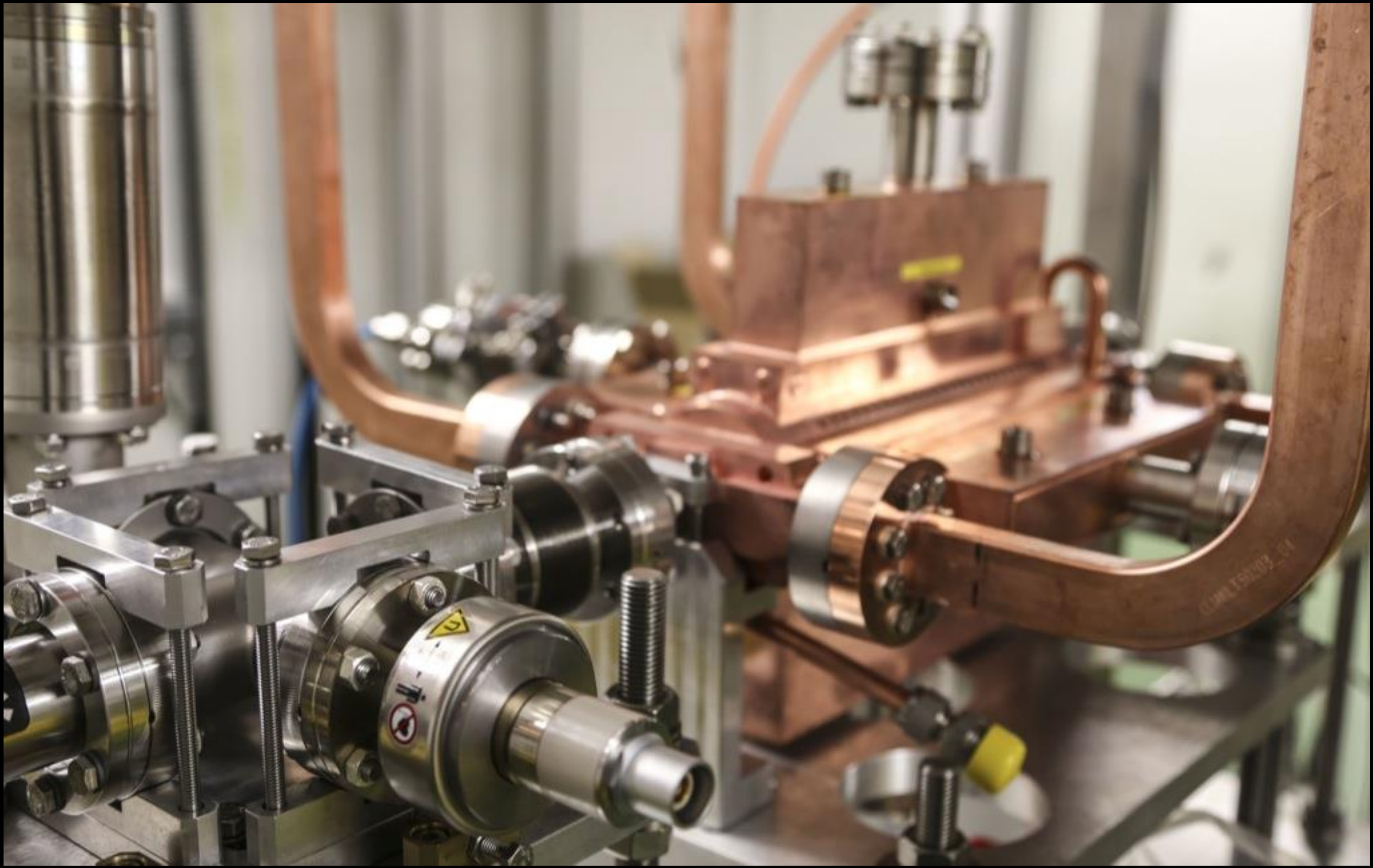


Same valve in line 3 is working well up 40MW.



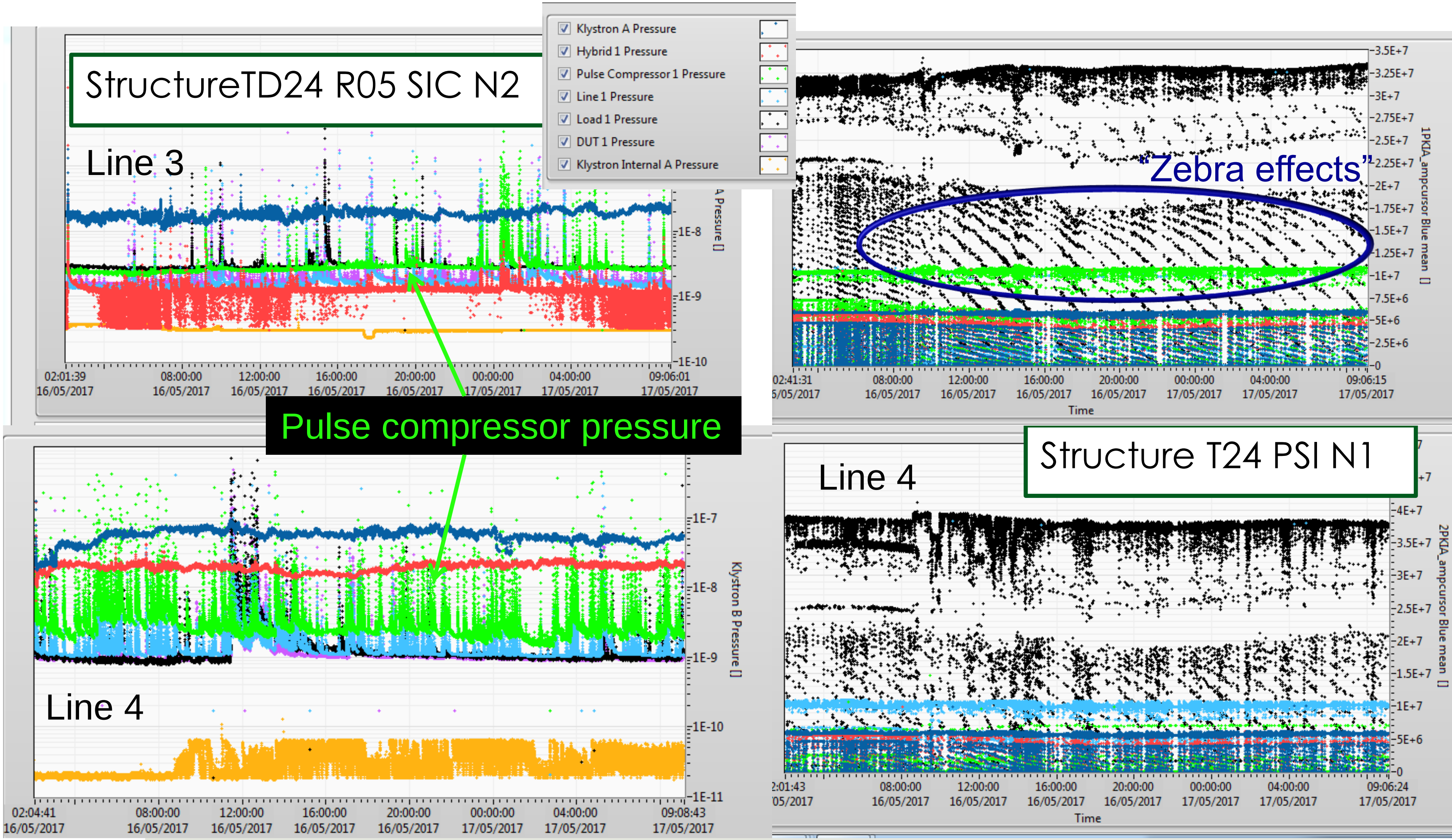
Power Line 4

Structure conditioning

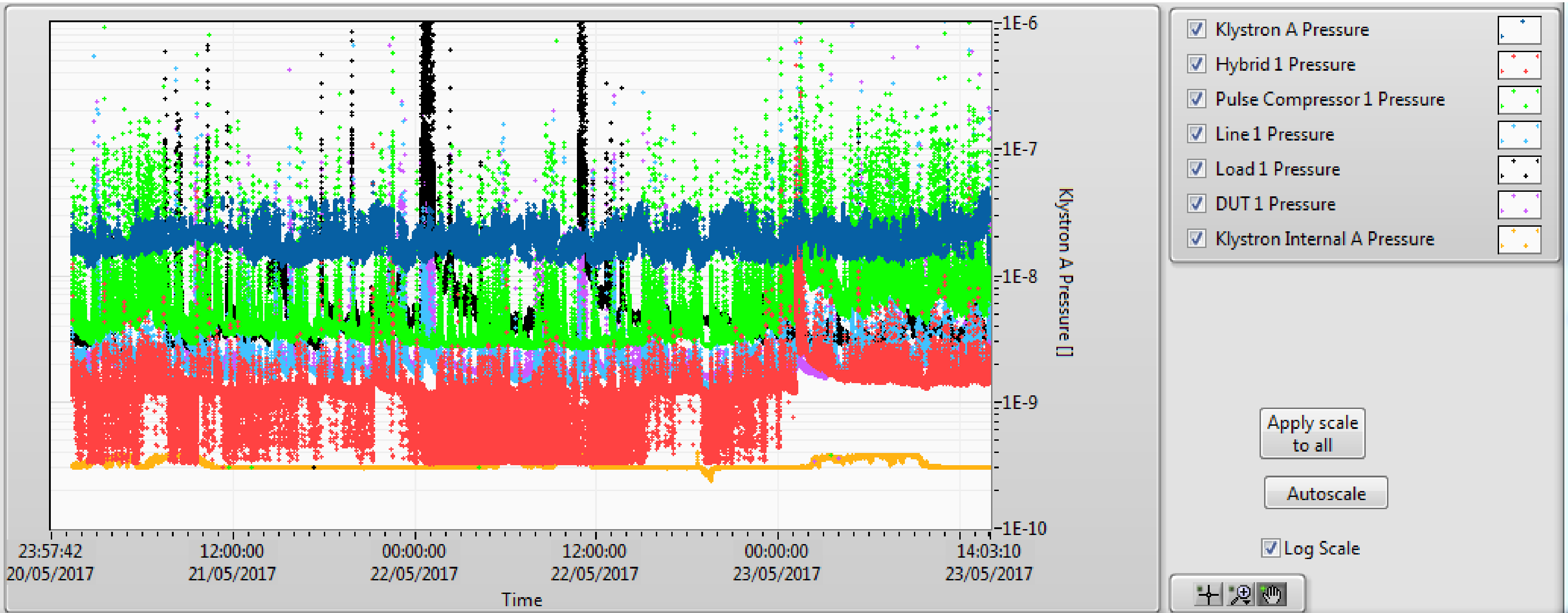


Vacuum activity

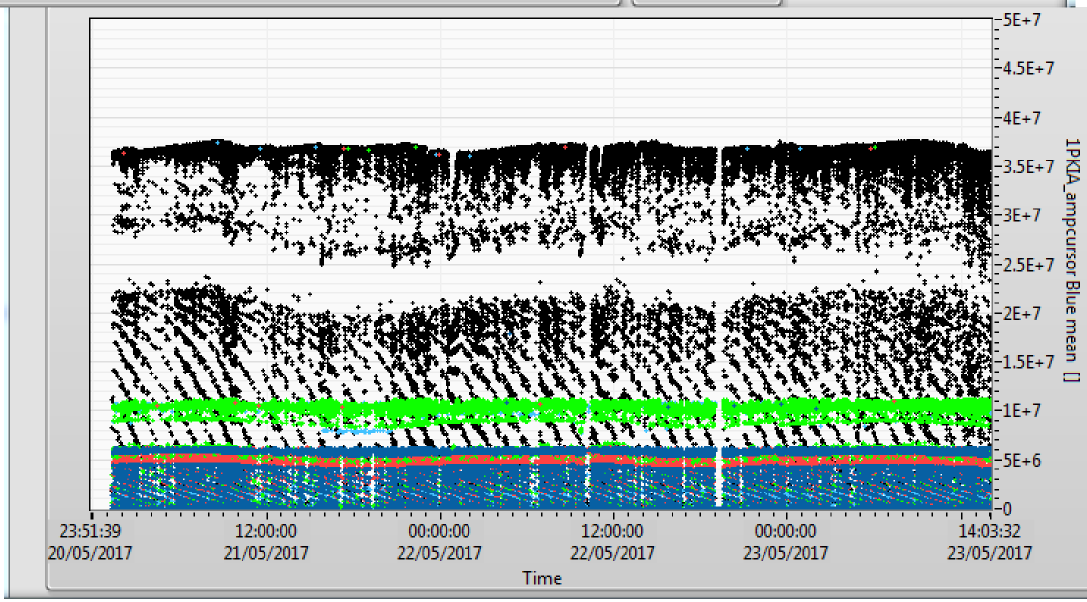
- Line 4 was not conditioned with the PC => high vacuum activity that affected line 3 as well
  - PC reflection included in the conditioning of the structure in line 4



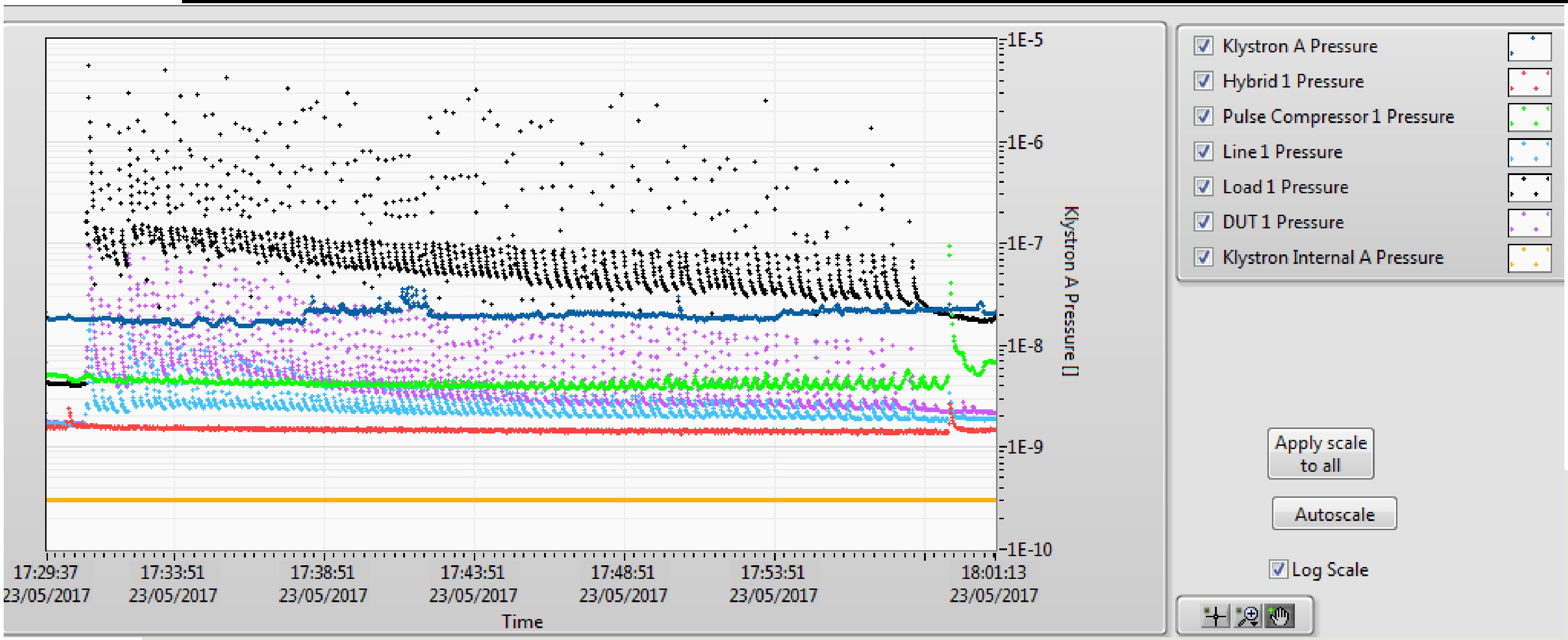
Vacuum activity line 3 @ high power



- At high power (~40MW) we start to observe vacuum activity in the PC
  - We also have a periodical activity in the load



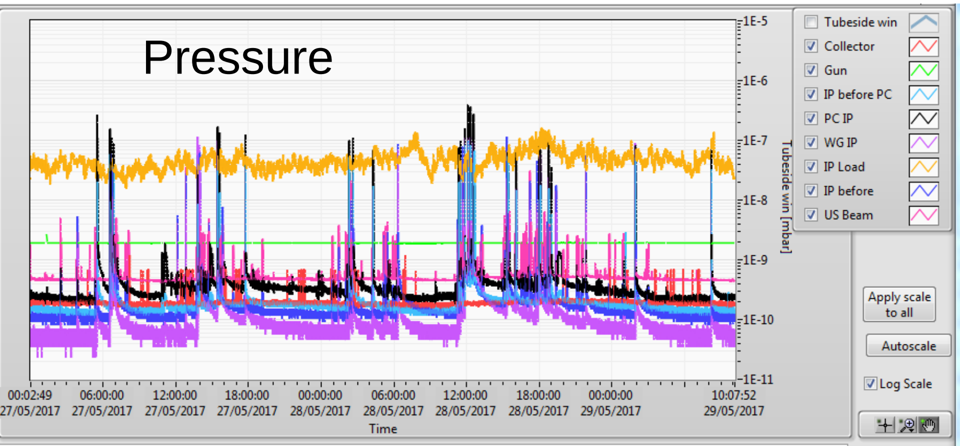
Load vacuum activity in line 3

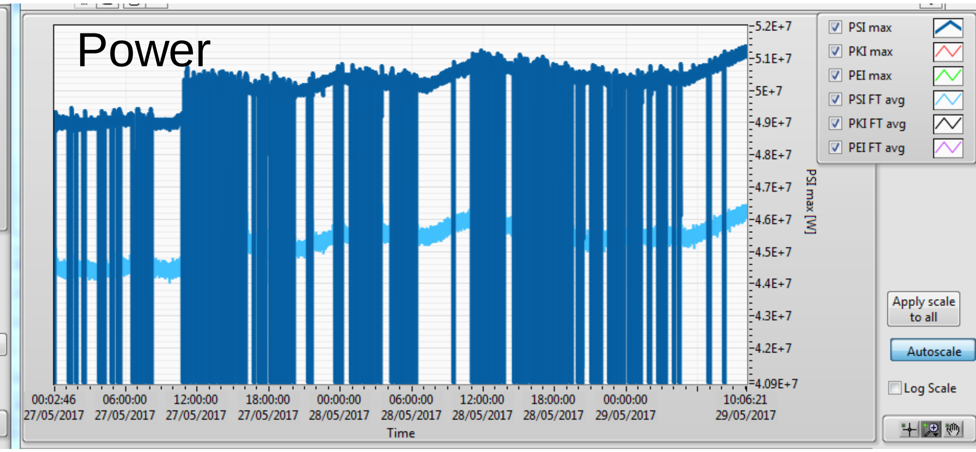


- Few times per day we observe half hour of vacuum activity in the load
  - Reconditioned the NEG pump
  - Under investigation pump and controller

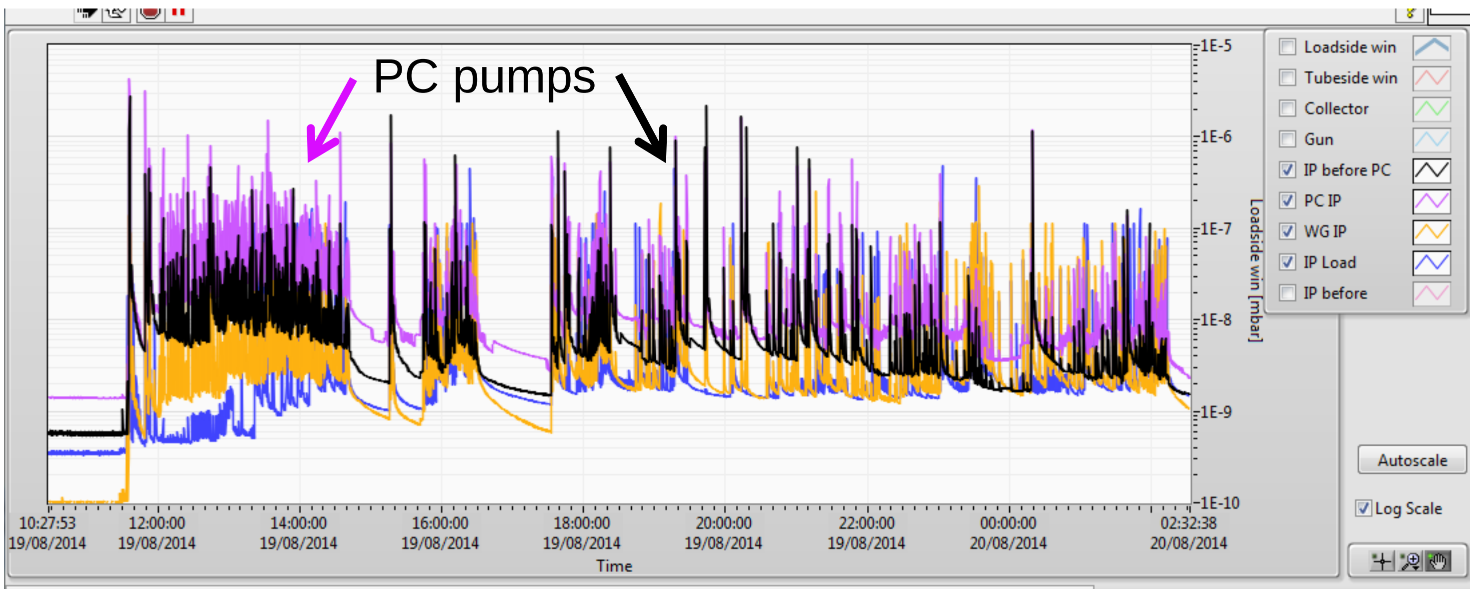
PC vacuum activity in XBox2

2017- 55MW TD26CC-N3 structure => line conditioned up to 60MW (no vacuum activity except during BD)





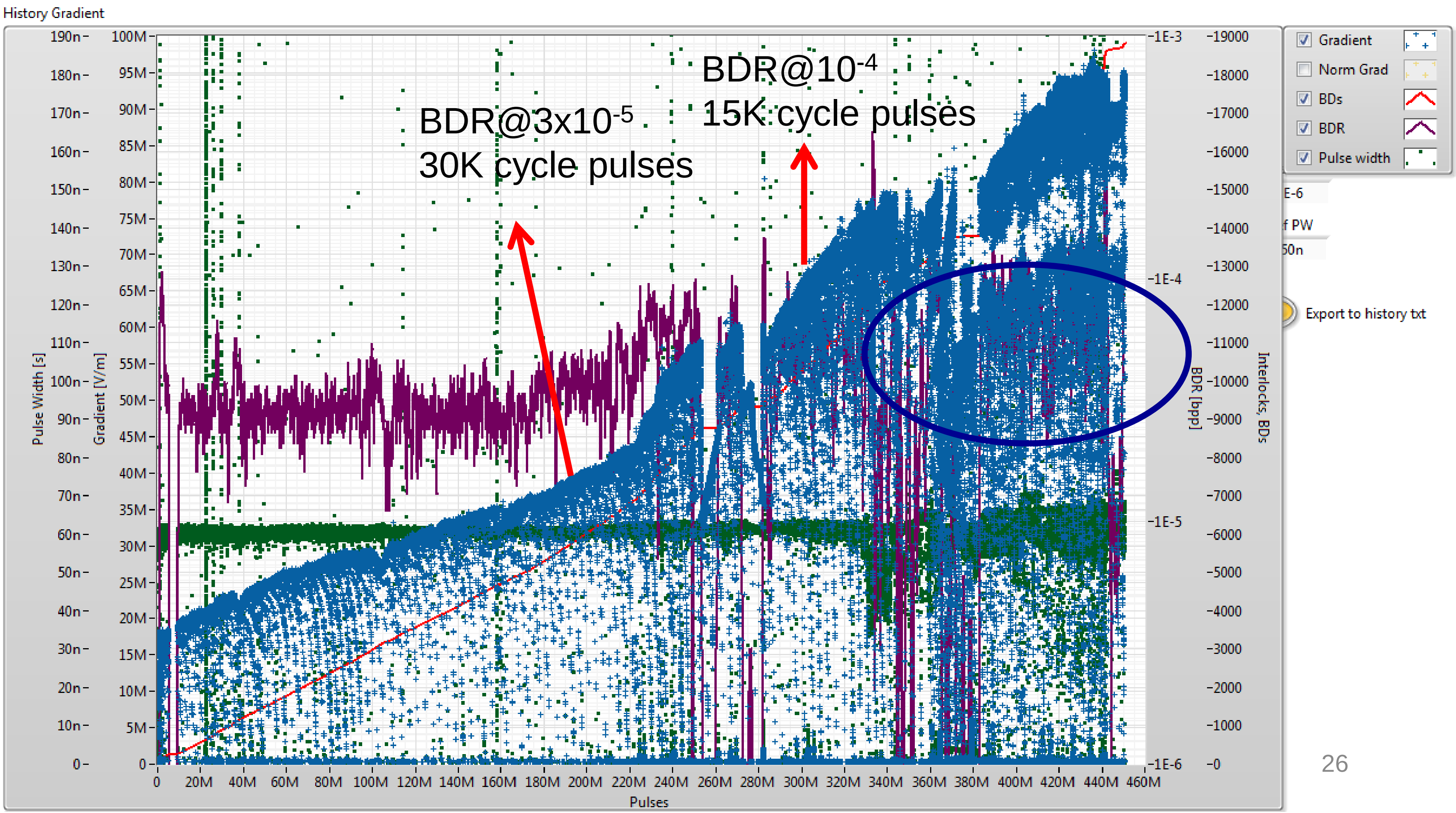
Line conditioning @ 25MW August 2014 => same PC vacuum activity as in XBox3



TD24 R05 SIC N2 (Xbox-3 CD Line 3)

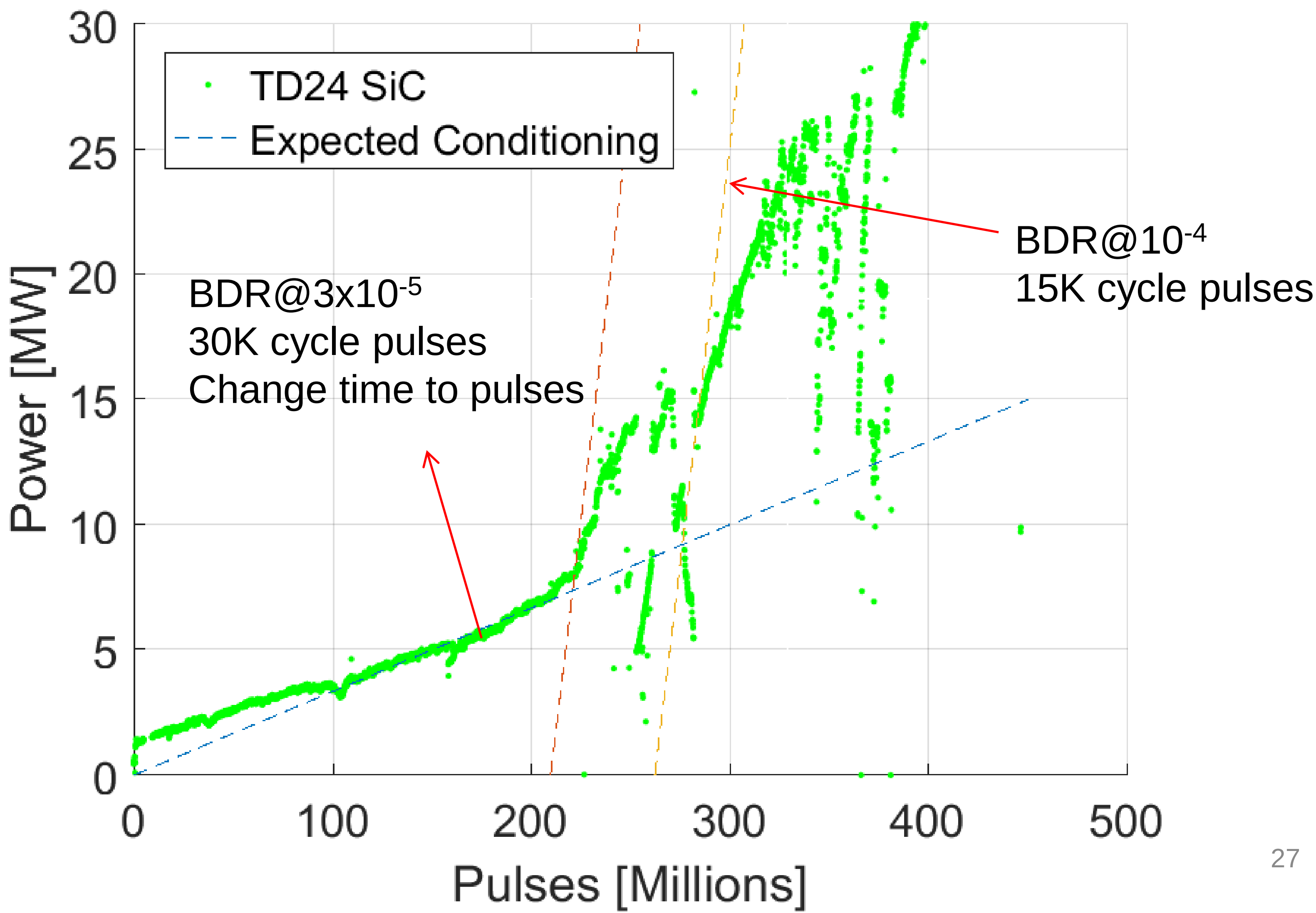
Reasons of slow conditioning are BDR set at 3×10^{-5} and cycle loop 30k pulses. Gradient (NOT Scaled) ~95MV/m

~12 M pulses per day.
~month of conditioning
Flat top pulse width 60ns.



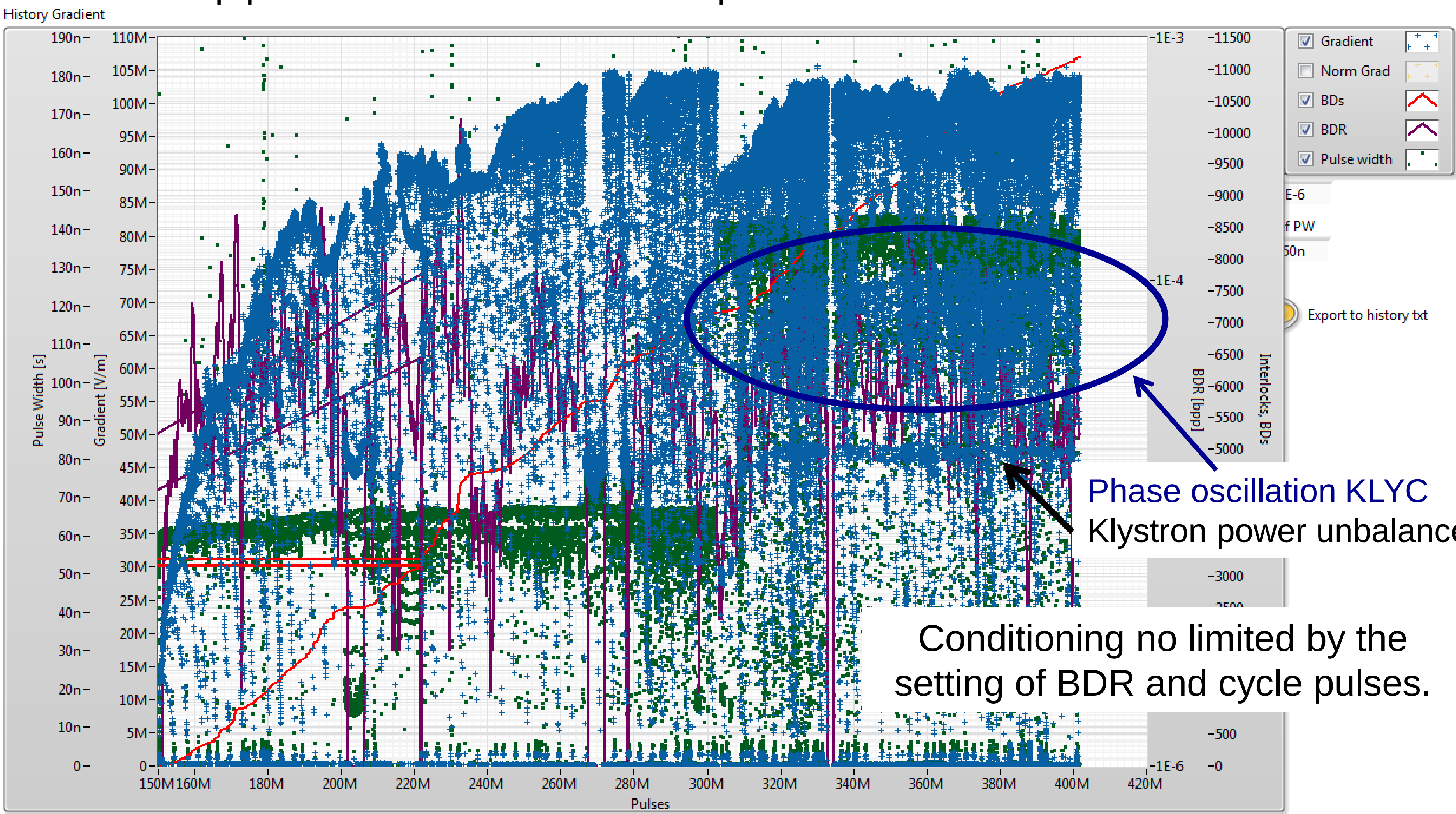
TD24 R05 SIC N2 (Xbox-3 CD Line 3)

The conditioning of the first 200M pulses was limited by the setting of BDR and cycle pulses.



T24 PSI N1 (XBox3-CD Line 4)

In 12 days of conditioning we reach 42MW.
Run at 300Hz (150Hz each line) => fast conditioning
That correspond to a gradient of ~110MV/m (NOT Scaled)
Flat top pulse width 60ns until 300M pulses then we move to 150ns



Conclusion

- First time that we condition two lines/structures at the same time
  - Klystron power feedback algorithm works well => stable power
  - The phase also is stable we don't observe shifts due to the change of temperature. Dedicated feedback algorithm not used yet.
- As expected the conditioning of the structures is faster at high repetition rate.
  - With a proper BDR and cycle loop the structure conditioning is in agreement with the previous structures already tested at 50Hz.
- Both spare klystrons at CERN.
  - Finish installation and start running Xbox3A&B (July).
  - Third and fourth PCs already tuned and they will be install soon.

Extra slides

Hybrid Split changing rep rate