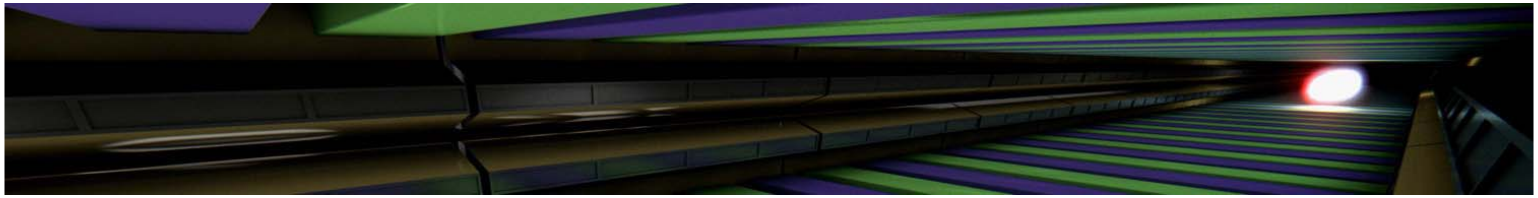

RF Heat Load Compensation for the European XFEL

J. Penning

with

M. Clausen, B. Schoeneburg, O. Korth

and additional material from

J. Eschke, T. Schnautz, M. Omet, J. Branlard

Deutsches Elektronen-Synchrotron (DESY), Hamburg, Germany

AHLC: Overview

- **The XFEL: Drilling down to our topic**
- Cold compressors: Powerful but sensitive
- Automatic Heat Load Compensation (AHLC)
  - How to compensate
  - How to calculate
  - Limitations of current approach
  - Implementation
  - Robustness issues
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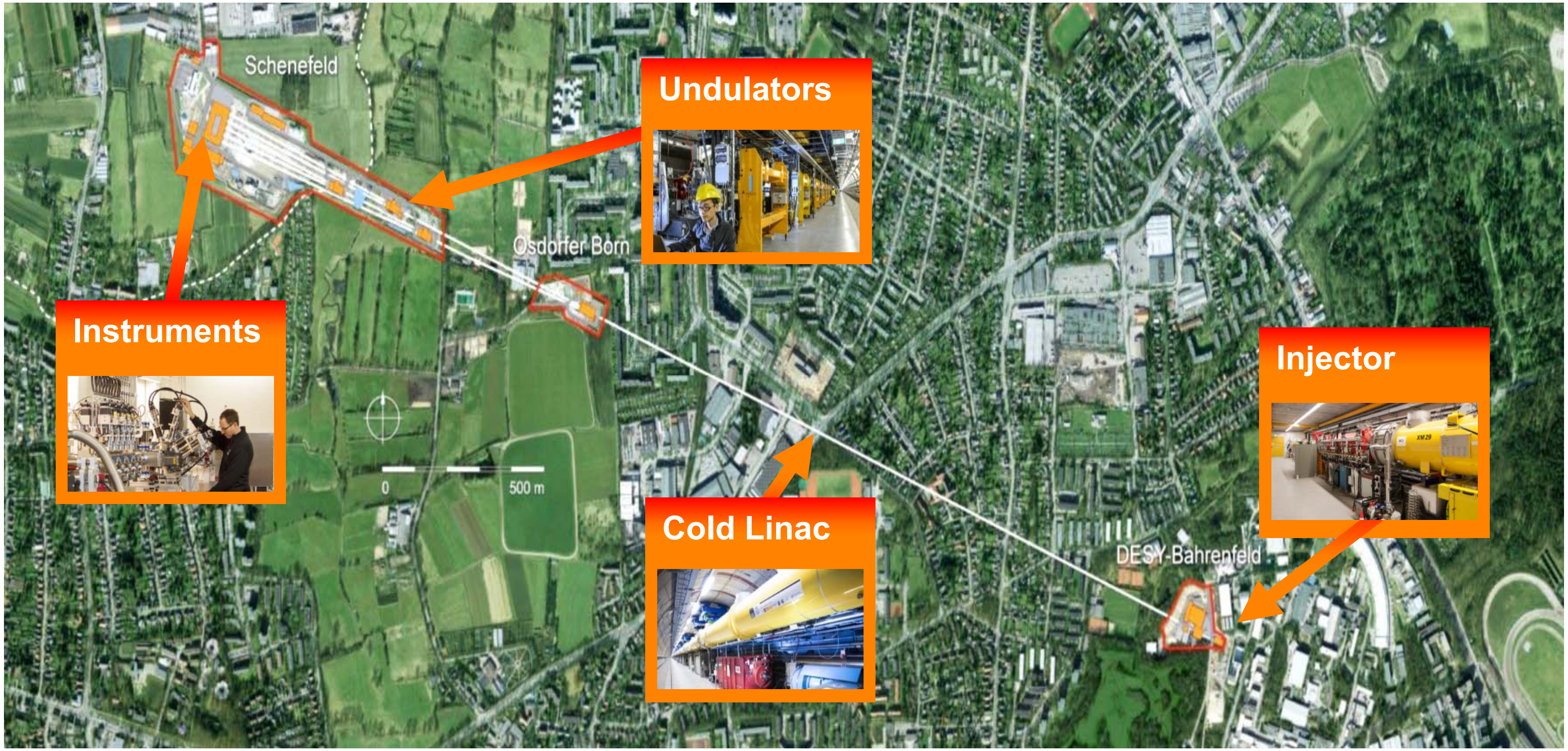
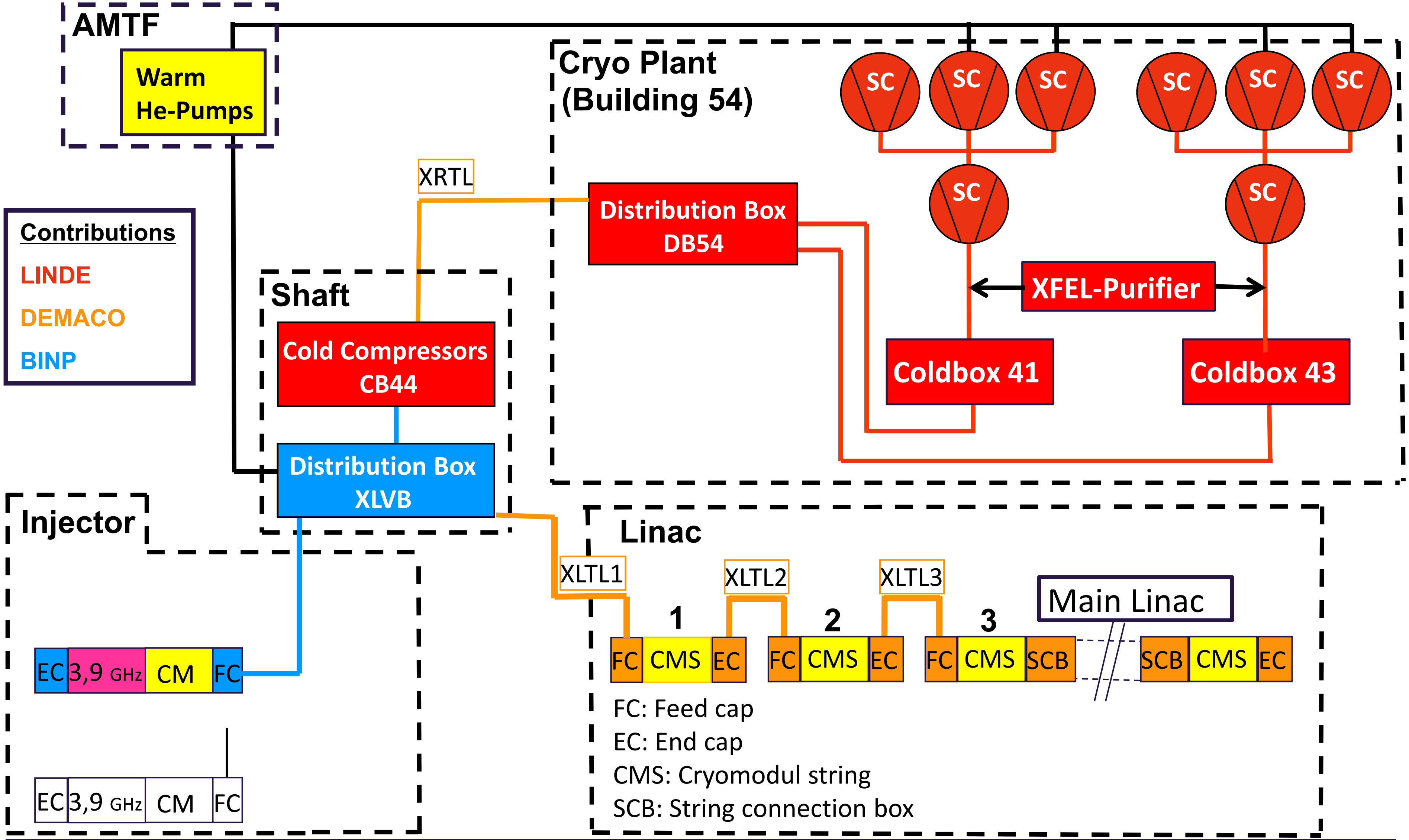
XFEL Overview

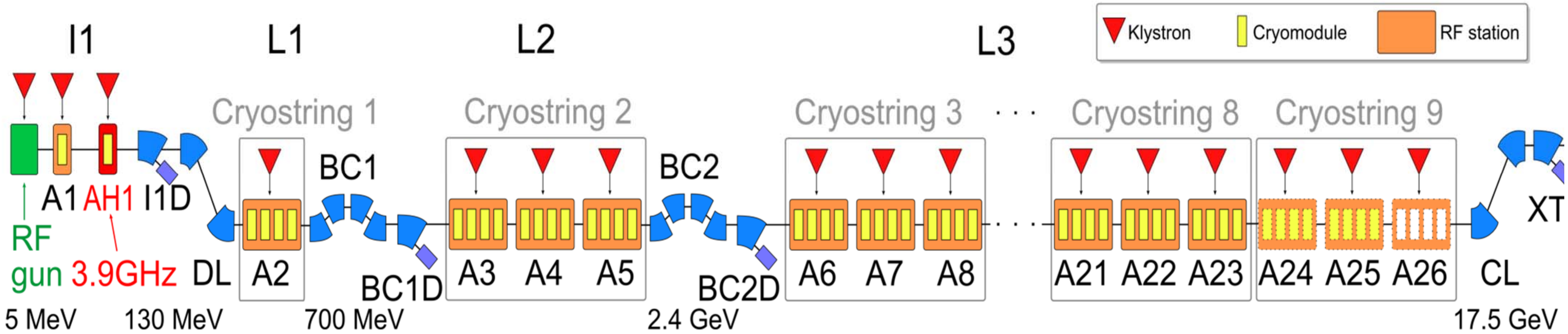


XFEL cryo plant
Overview



Focusing on the cryo installation

- Injector and 3 Linacs
- 9 Cryo-Strings
- 96 Cryo-Modules
- ~800 Cavities
- 32 cavities per RF station
- Design energy 17.5 GeV



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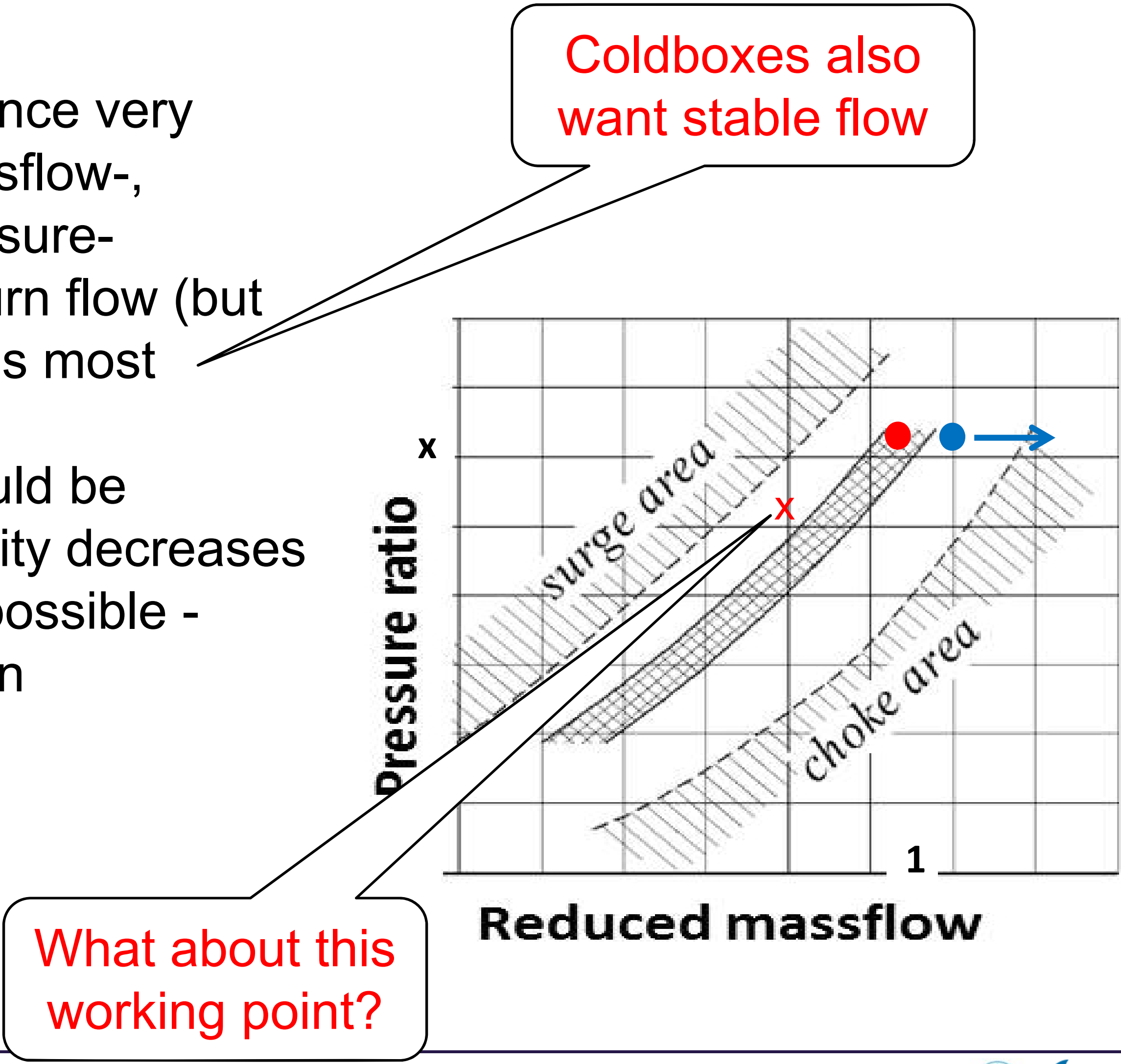
Cold compressors
General challenges (repeated)

- Cold compressors are turbomachines and hence very sensitive towards massflow-, temperature- and pressure-changes in the 2K-return flow (but the massflow-stability is most important)
- Choke operation: Should be avoided as cryo capacity decreases
- Surge operation: Not possible - breakdown of operation



Cold compressors

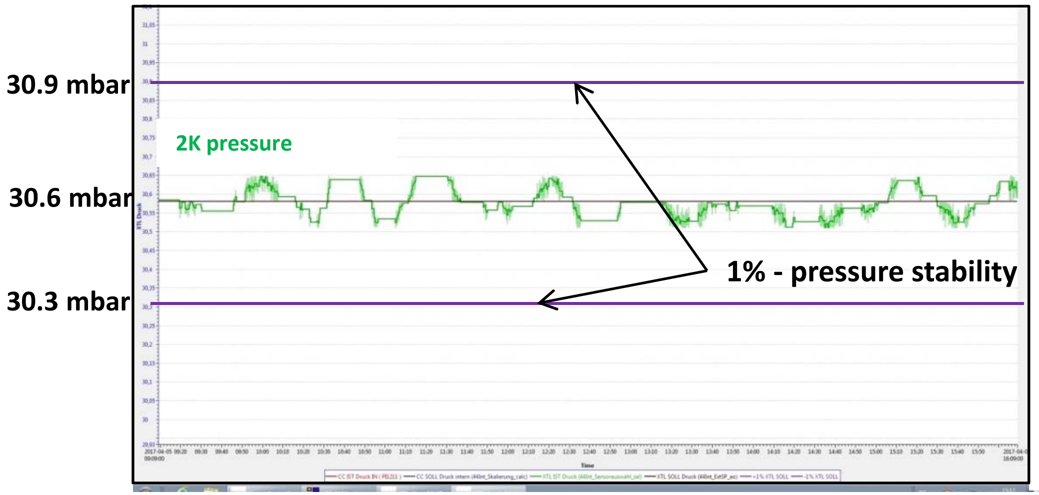
Operational experiences – 2K pressure stability (repeated)

Cold compressors: 2K Pressure stability

- **Specified pressure stability: 1% (31 mbar +/- 0.3 mbar)**
- **Cascaded regulation for pressure adjustment in 2K circuit is used (DESY)**
- **Automatic heat load compensation (DESY): Changes in the 2K return flow - caused by dynamic RF operation - are determined automatically and compensation takes place in the linac by automatic heating in the 2K liquid helium**

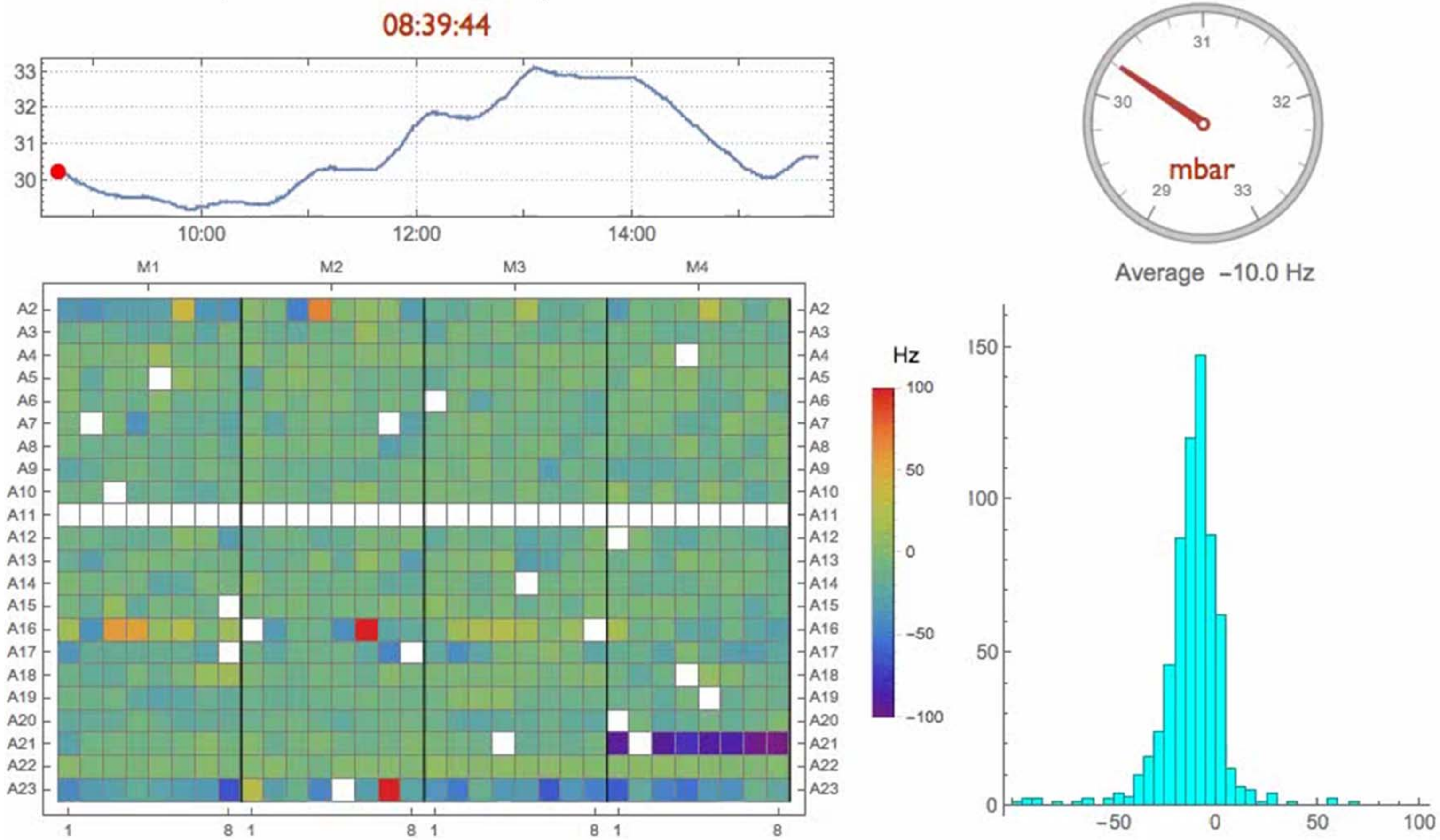
Conclusion:

- **Cold compressors deliver a pressure stability better than 0.3%, which is much better than internally specified.**
- **Heat load changes –caused by dyn. RF operation- can be compensated perfectly well by AHLC**



Excursion: Importance of pressure stability

- Cavity Detuning vs. He-Pressure
- Study by Julien Branlard
- Will be presented in September at Linear Accelerator Conference



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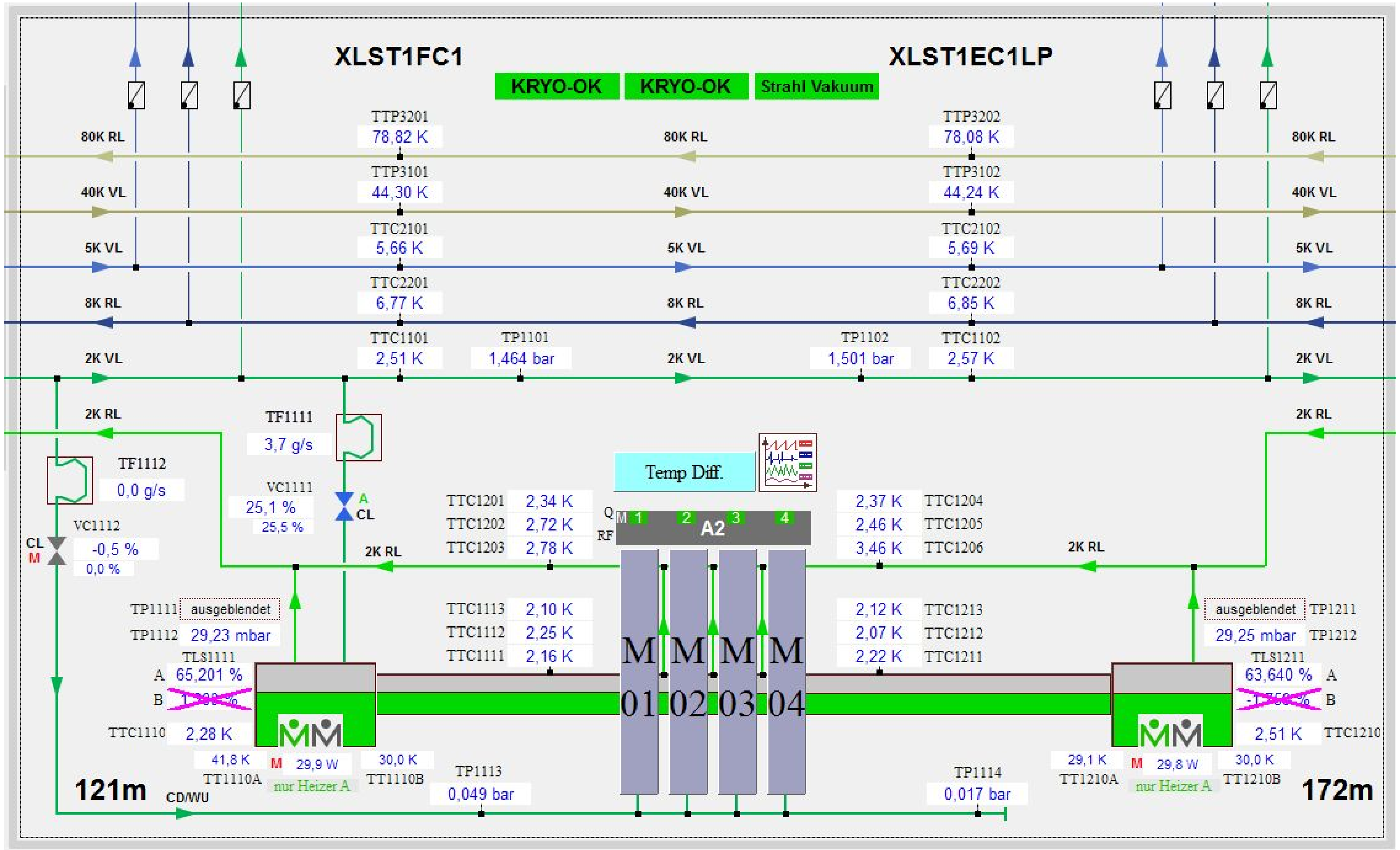
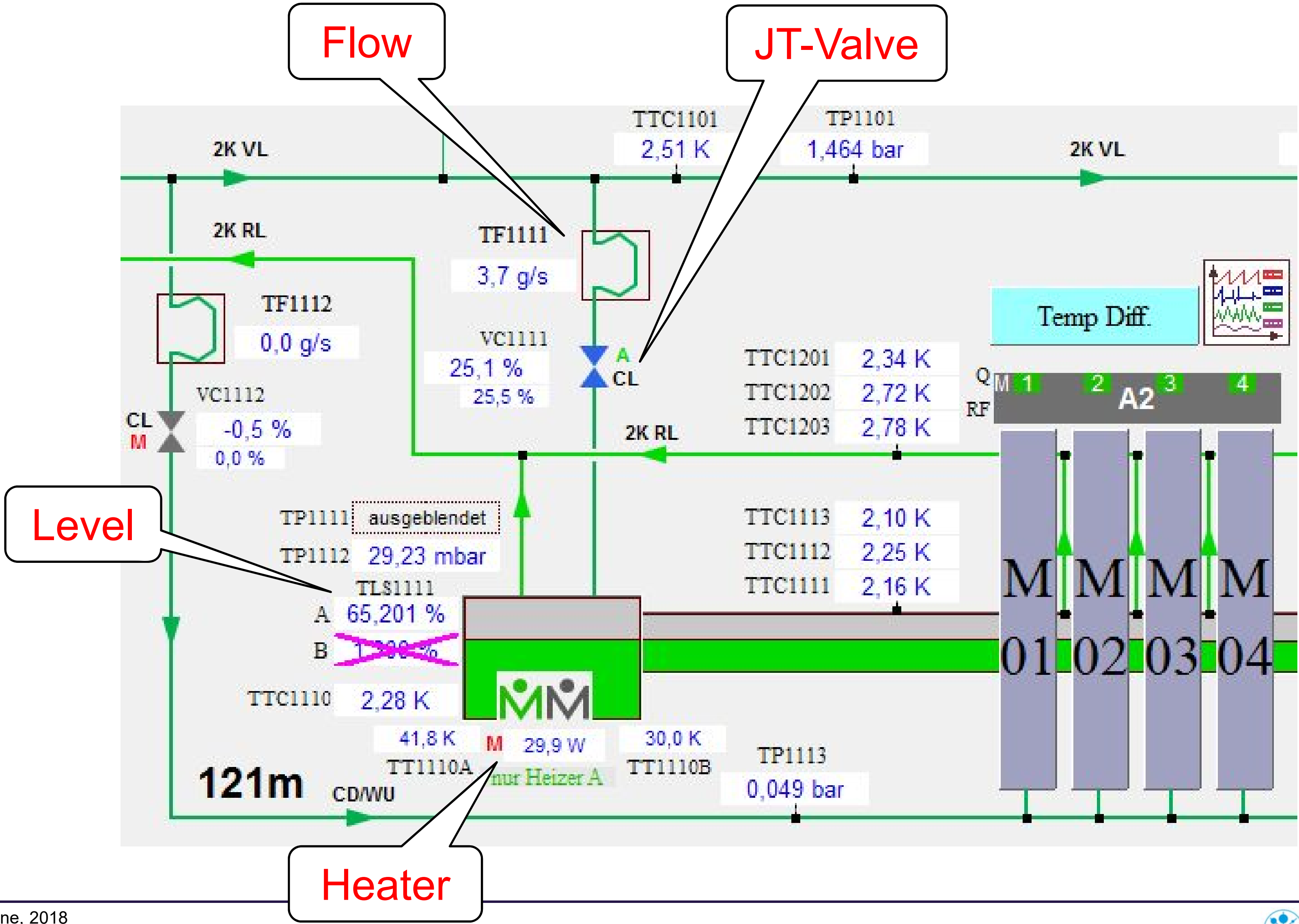
European XFEL

Flowdiagram of Linac 1



DESY HELMHOLTZ ASSOCIATION

Sensors and Actuators



Controls for the Linac: JT-Valve

- During Cooldown
  - the JT-Valve was controlled by the flow sensor
  - the main concern was stable operation of the coldboxes
- During stable operation
  - the JT-Valve is controlled by the **level sensor**.
  - the main concern now is the level of the He-bath for the cavities and the magnets.

Controls for the Linac: Heaters

- The Heaters allow for a steady power dissipation which can be ***reduced*** when the RF is applied to the cavities.
- The Heaters are set to ***some value*** which is higher than the expected power introduced by RF.
- ***Some value*** is based on experience from the cavity tests and fine tuned by the operators.
- The ***reduction*** of the Heater power is calculated automatically from RF operational data.

AHLC comes into play

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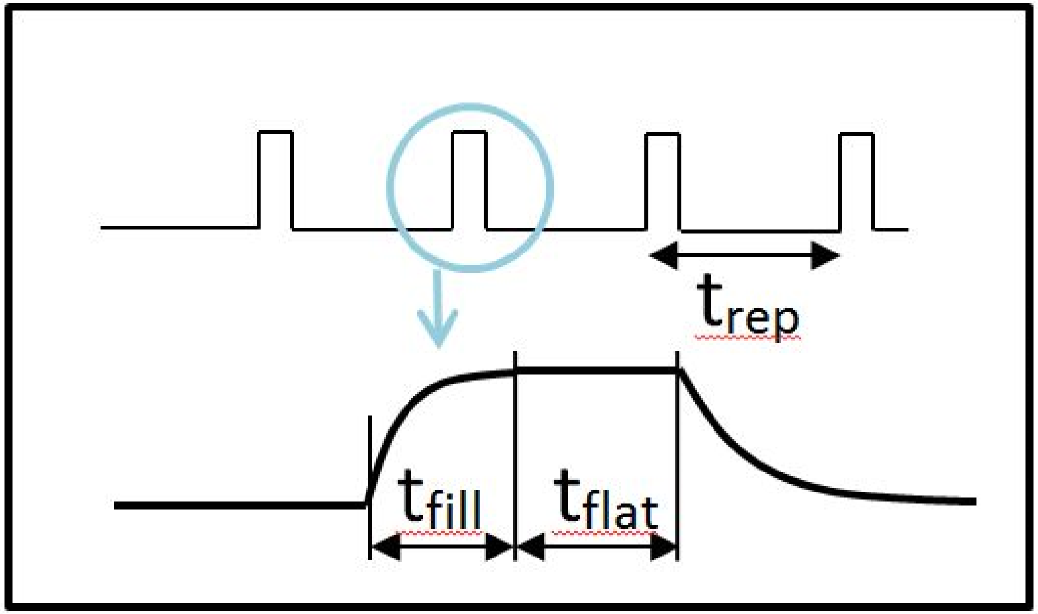
RF pulse structure

- RF pulses have a certain repetition rate
- Each pulse has a structure
  - Filling until a certain power is reached
  - Stay flat at that power
  - Switch off and let decrease



Detailed calculation: Filling

- Filling is achieved with a constant voltage, it is clipped when the desired power has been reached.
- The Energy introduced to the cavity is

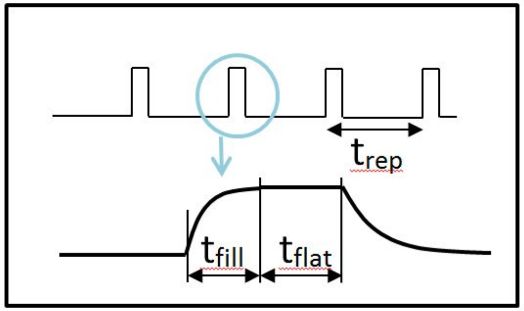
$$E_{fill} = \int_0^{t_{fill}} P(t)dt \quad \text{with}$$

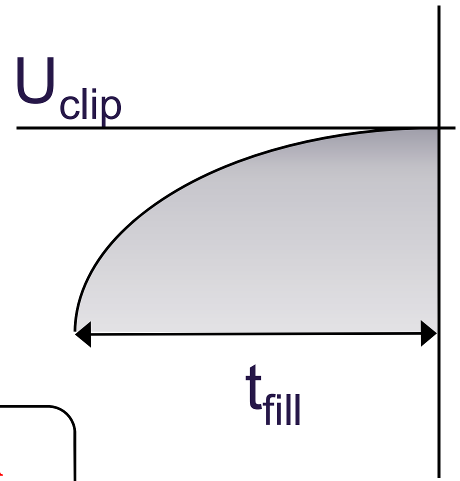
$$P(t) \sim U(t)^2 \quad \text{and}$$

$$U(t) \sim U * (1 - e^{-\lambda t})$$

- Solving yields

$$E_{fill} = P_{forw} * t_{fill} * 0.38$$

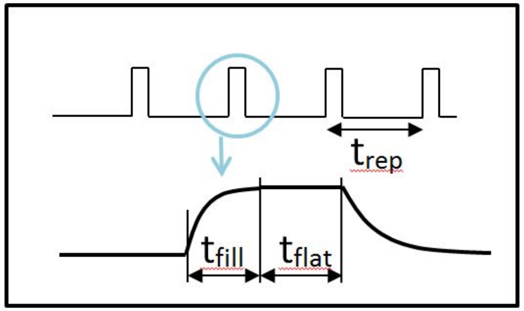




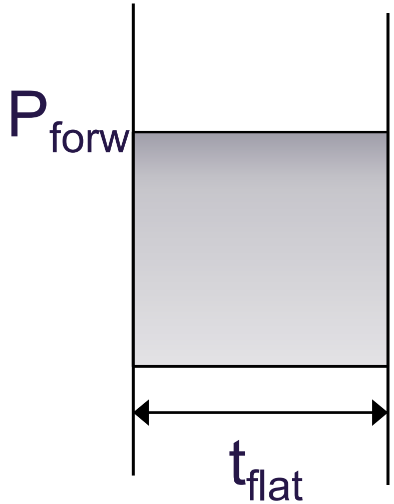
λ is known from the tests

Detailed calculation: Flat top

- During the flat top the voltage is kept at the clipped level.
- The dissipated energy is only dependent on the time and the forward power applied.



$$E_{flat} = P_{forw} * t_{flat}$$



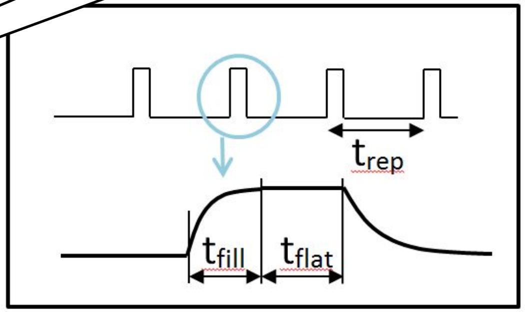
Detailed calculation: Decrease

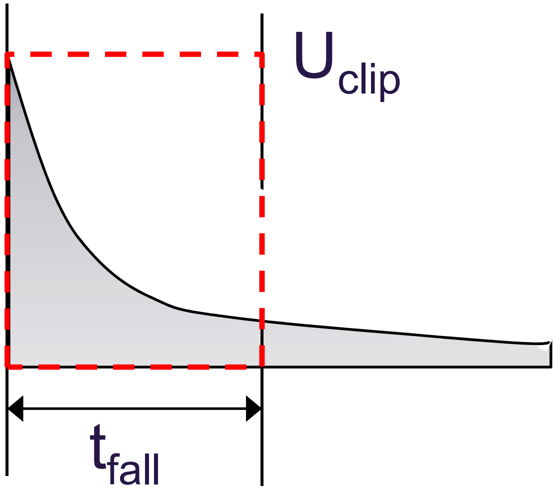
λ is known from the tests

- After switching off, the voltage decreases.
- The energy introduced to the cavity is $E_{fall} \sim \int_0^\infty U^2 * e^{-\lambda t} dt$
- This is equal to a square of fixed length (t_{fall}) by forward power.
- Solving yields

  $E_{fall} = P_{forw} * t_{fall}$

  t_{fall} being constant (~500 μs)





Detailed calculation: Result

$$P_{diss} \sim (E_{fill} + E_{flat} + E_{fall}) * f_{rep} * Usage$$

$$= K * P_{forw} * (t_{fill} * 0.38 + t_{flat} + t_{fall}) * f_{rep} * Usage$$

- ***K*** is an empiric factor of about $4 * 10^{-7}$
  Pre-calculated from cavity tests
  Refined after operating experience
- ***P_{forw}*** is the power as measured by the RF station which is distributed to 32 cavities each.
- ***f_{rep}*** is the repetition rate
- ***Usage*** Only active cavities are taken into account

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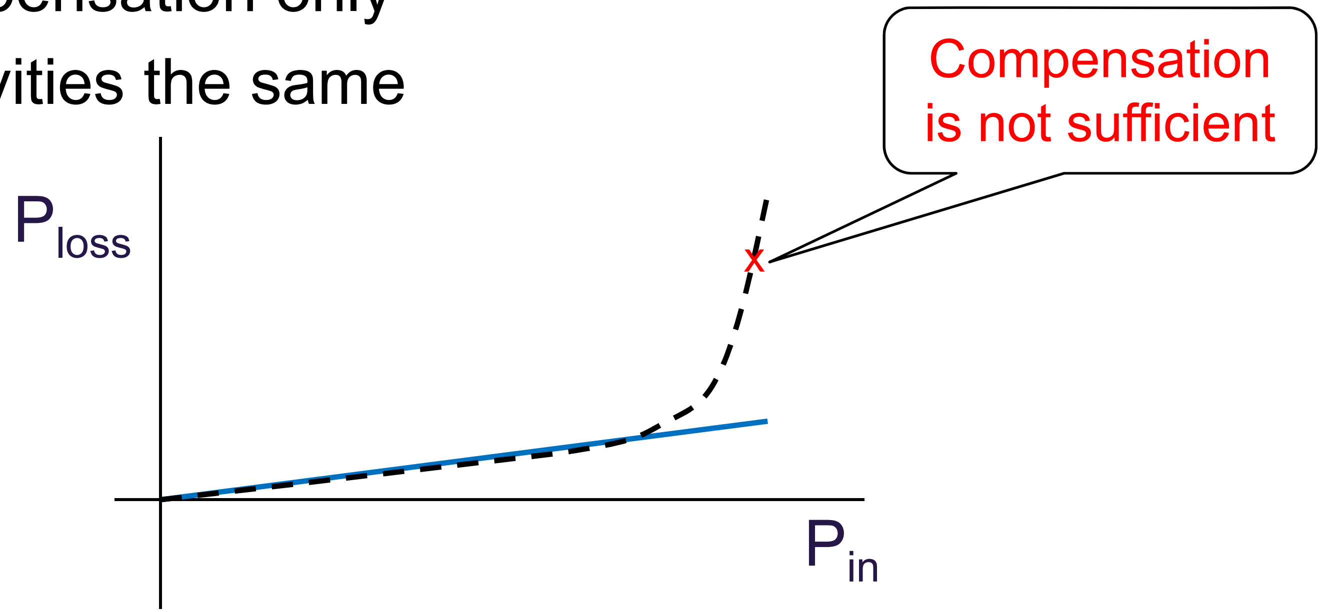
AHLC Calculation

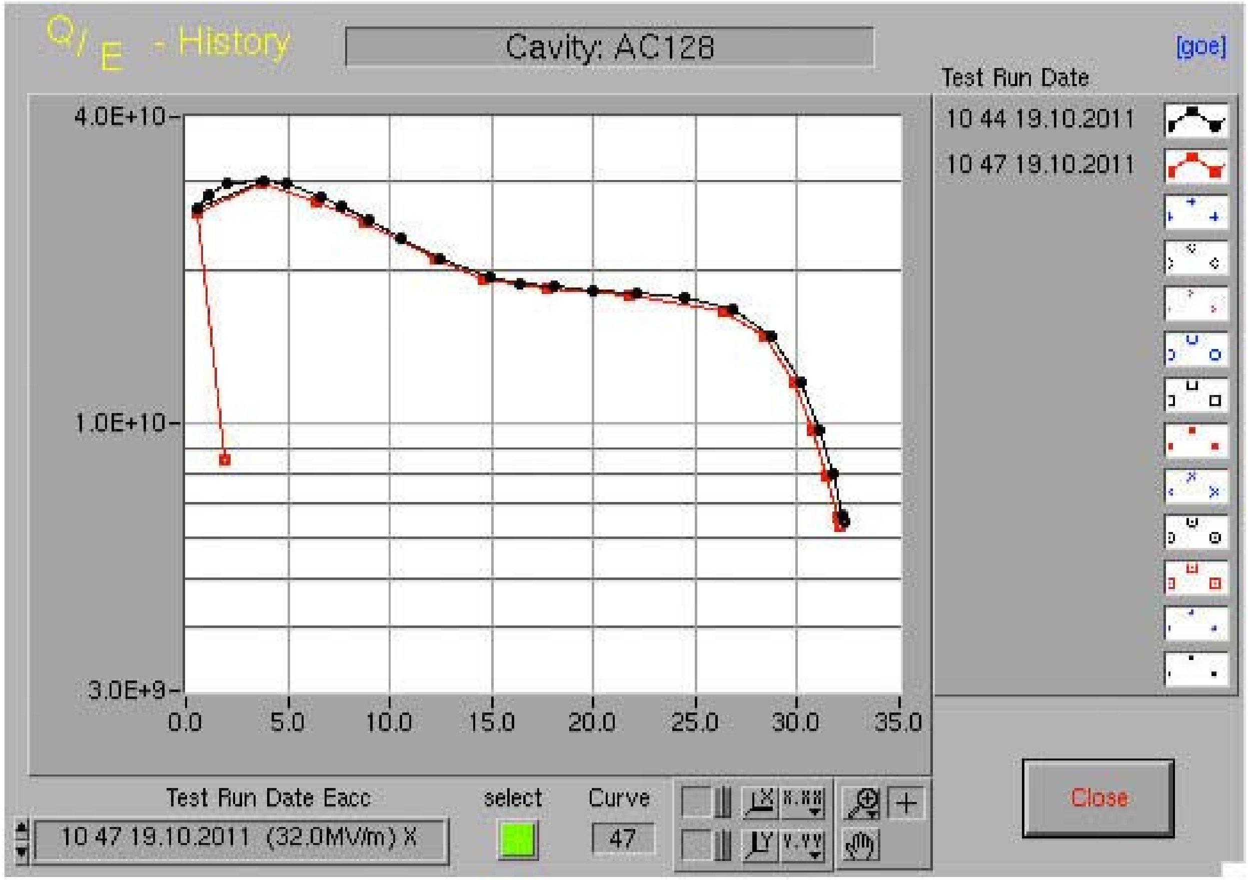
- Simple approach
  - Linear compensation only
  - Treat all cavities the same



$$P_{diss} = K * P_{forw} * (t_{fill} * 0.38 + t_{flat} + t_{fall}) * f_{rep} * Usage$$

AHLC Linear Approach

- Quality vs. Energy shows non-linear behaviour



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AHLC Putting into operation

- Try the most simple thing first
- Be able to modify the crucial part while maintaining operation
  - AHLC runs outside the process controller of the linac
  - Software updates to AHLC during normal operation of the linac are possible
  - AHLC could be enhanced significantly without overloading the process controller of the linac

Domain related robustness 1

- Rate-of-change (1W/s) helps survive
  - intermittent communication breakdowns
  - calculation errors
- Careful selection of manual setpoint for the heaters
  - Keep JT-valves always a bit open
  - Keep heaters always a bit on
  - That ensures a bit of control range always

Domain related robustness 2

- What happens when cavities are driven in the non-linear range?
  - AHLC cannot handle this
  - Usually happens on announcement from RF group
  - Maximum Gradient Task Force tries to push the limits
  - One RF station at a time
  - Supported by an operator

Quenches switch off RF

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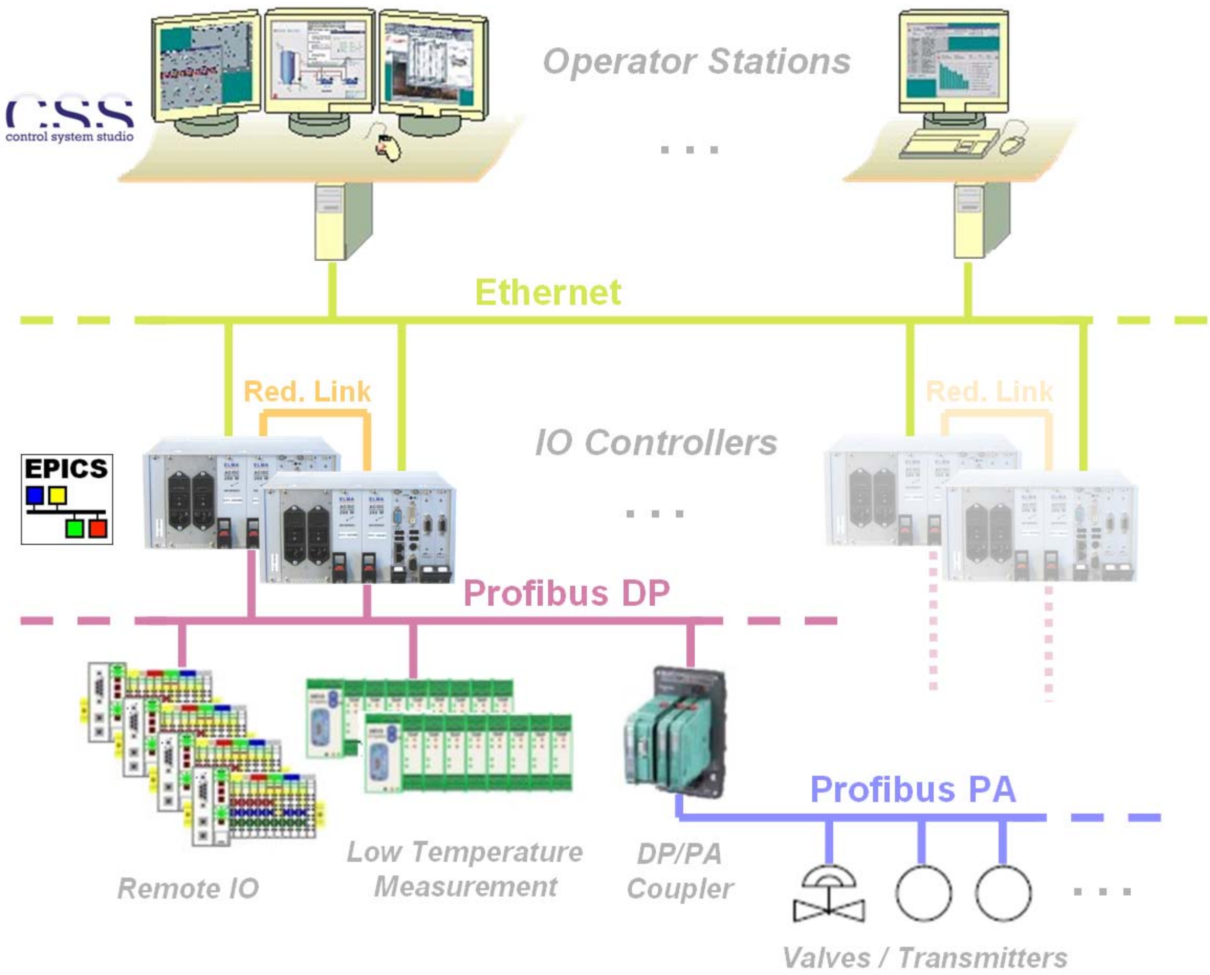
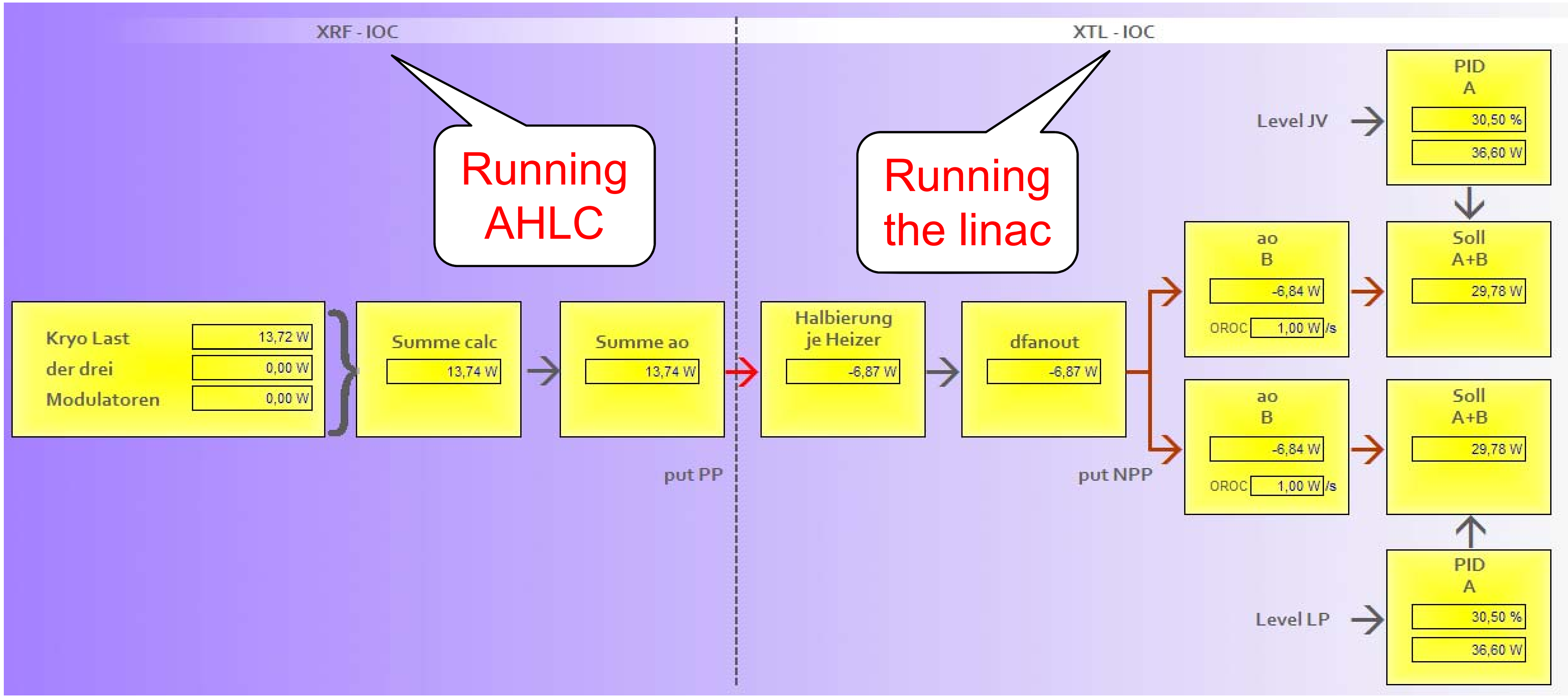
Architecture of Control System



- Operators Workplace
- IP-Network
- Process Control Hardware
- Fieldbus-Network
- Sensors / Actuators

Separation of concerns

- Make use of two process controllers (IOCs)



Technical robustness

- What happens if RF data cannot be retrieved?
  - Communication channels announce alarms so operators will notice
  - Current values freeze
- What happens if AHLC-process controller stops or is updated?
  - There will be no more updates via the process border
  - So the current values will be kept in the linacs process controller
  - The operator will be noticed because the AHLC-process controller failed

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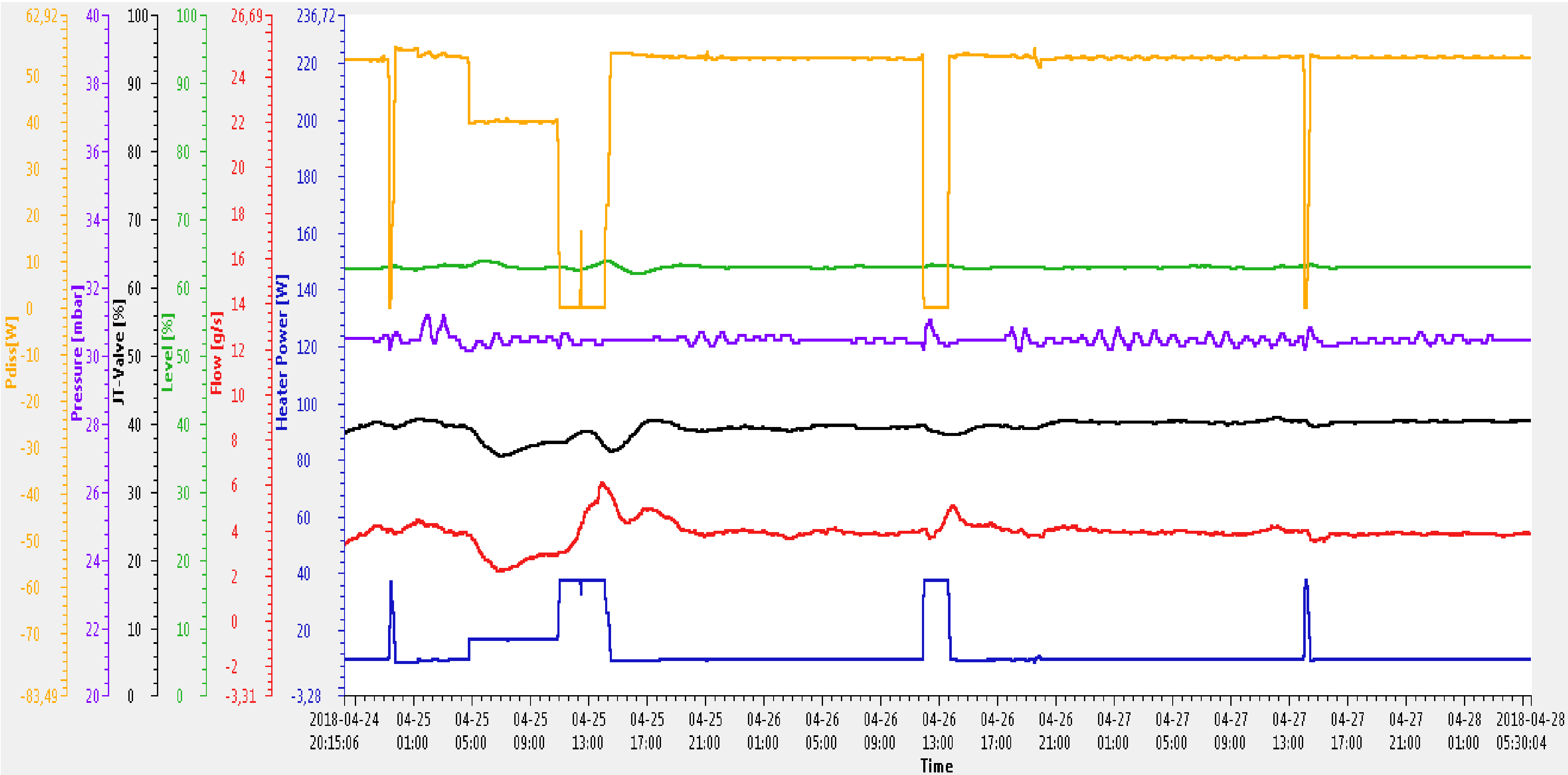
AHLC in action

- From top: RF power, Level, He-Pressure, JT-Valve Readback, Flow, Heater Readback



AHLC Next Steps

- If MGTF recommends operation near the non-linear range
  - We will make an approximation
  - The first step might take individual cavities into account
  - We can update AHLC any time

Summary

- AHLC tries to keep the flow of each cryo string stable
  - It calculates the heat introduced by RF operation from RF live data
  - By reducing the (manually preset) heater power the dissipated heat stays the same
  - Currently only the linear losses can be compensated, near quenching the compensation falls short
  - For ease of implementation all cavities are treated the same
  - The implementation handles communication breakdown and allows for live updates

Thank you for your attention

Additional slides

XFEL cryo plant
Cryo capacity

Croygenic plant-capacity: Performance requirements vs. performance results:

1. **Parallel coldbox operation: CB41 and CB43 with cold compressors (CB44)**
2. Single coldbox operation: CB41 or CB43 with cold compressors (CB44)

Cooling loop	unit	DESY calculated	DESY specification (calculated + safety margin)	Linde offer (guaranteed)	Linde offer (expected)	Test results CB 41 & CB 43
2K	kW	1.46	1.9	1.9	2.01	> 1.9
5K – 8K	kW	2.4	3.6	3.6	3.95	4.0
40K – 80K	kW	16.0	24	24	26.12	25.9

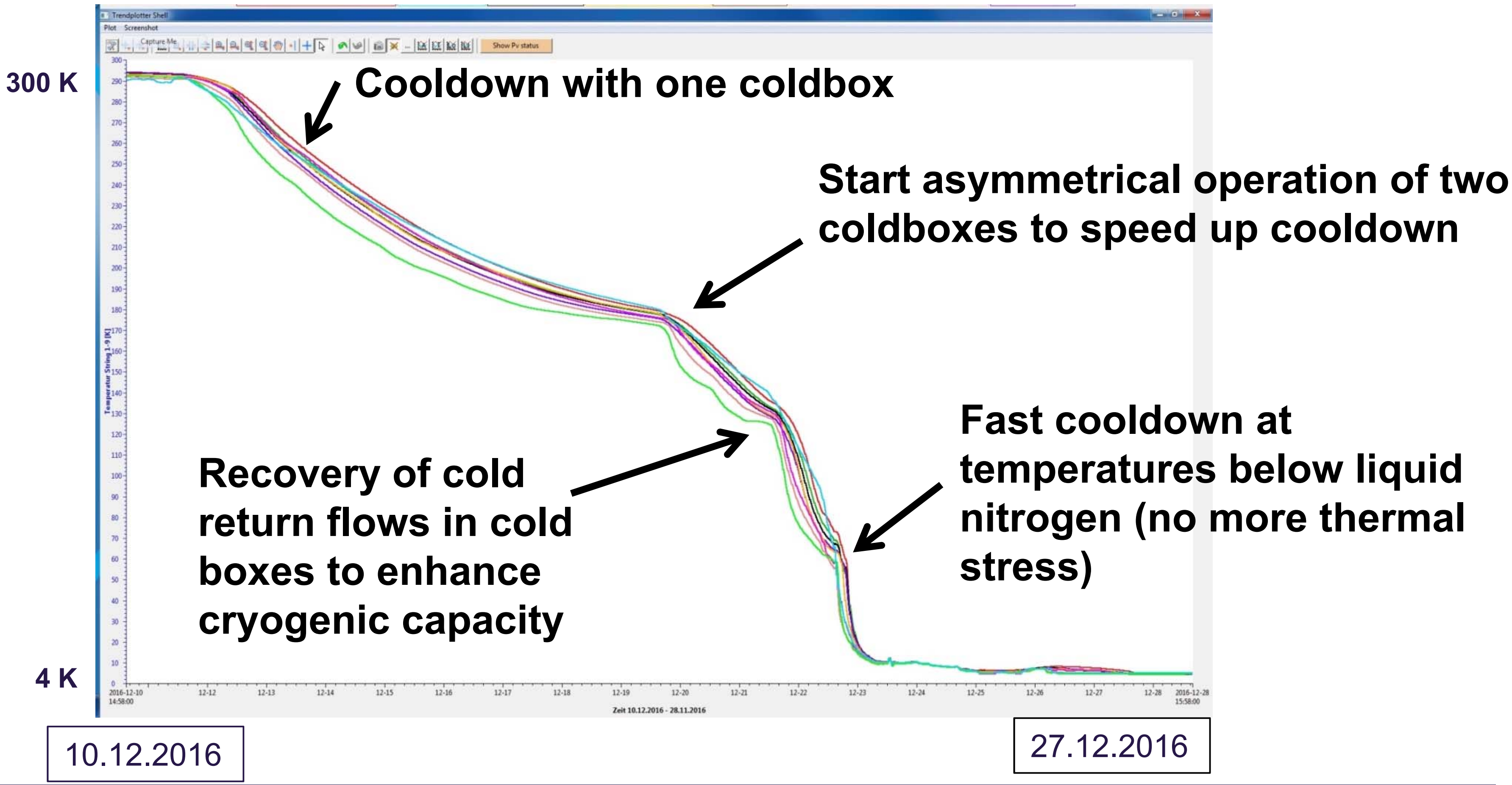
Conclusion:

- **Guarantee values for parallel coldbox operation have been exceeded!**

XFEL: First cooldown
Linac

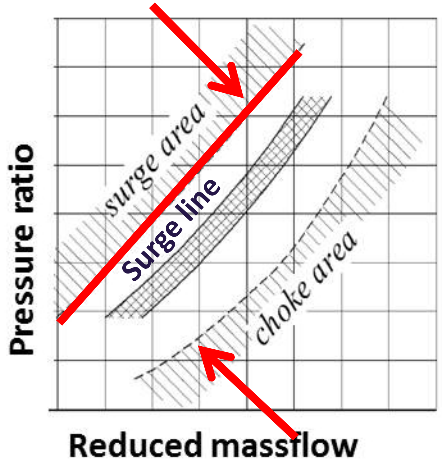
First cooldown:

XFEL Linac



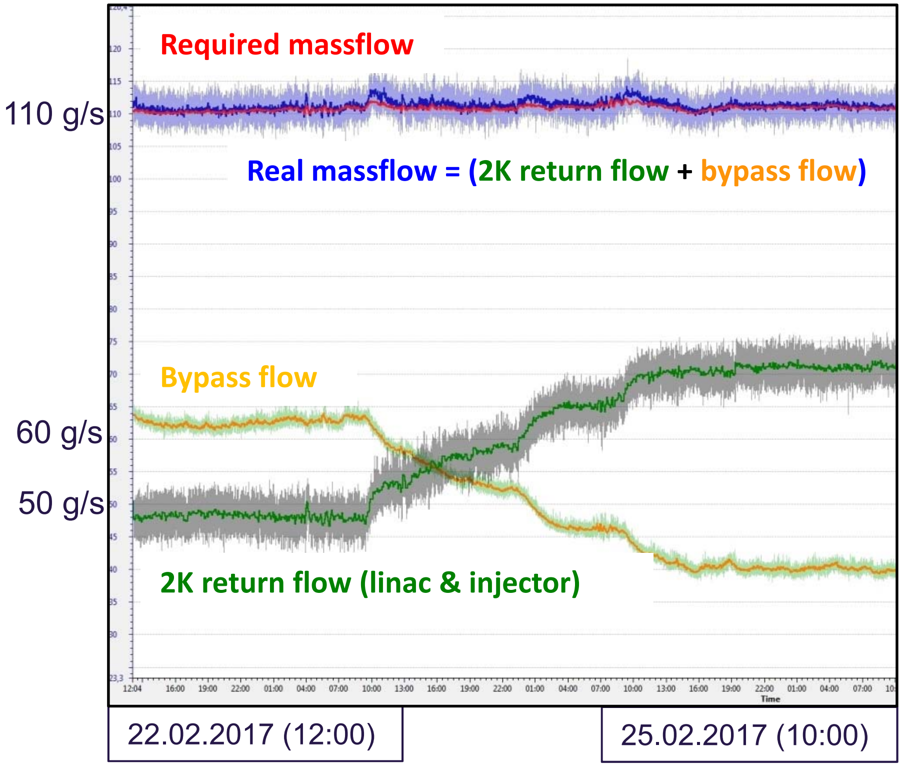
Cold compressors: Operational challenges:

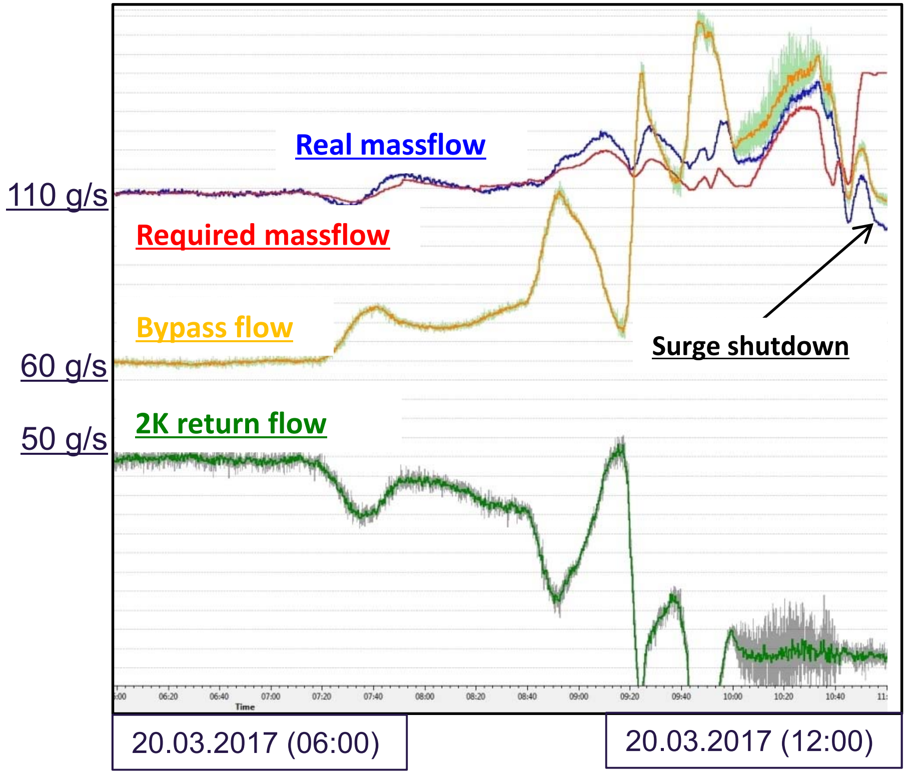
- Cold compressors are turbomachines and hence very sensitive towards massflow-, temperature- and pressure- changes in the 2K-return flow (but the massflow-stability is most important)
- Choke operation: Should be avoided as cryo capacity decreases
- Surge operation: Not possible - breakdown of operation



Cold compressors
Operational experiences - bypass operation

Bypass operation: Massflow compensation



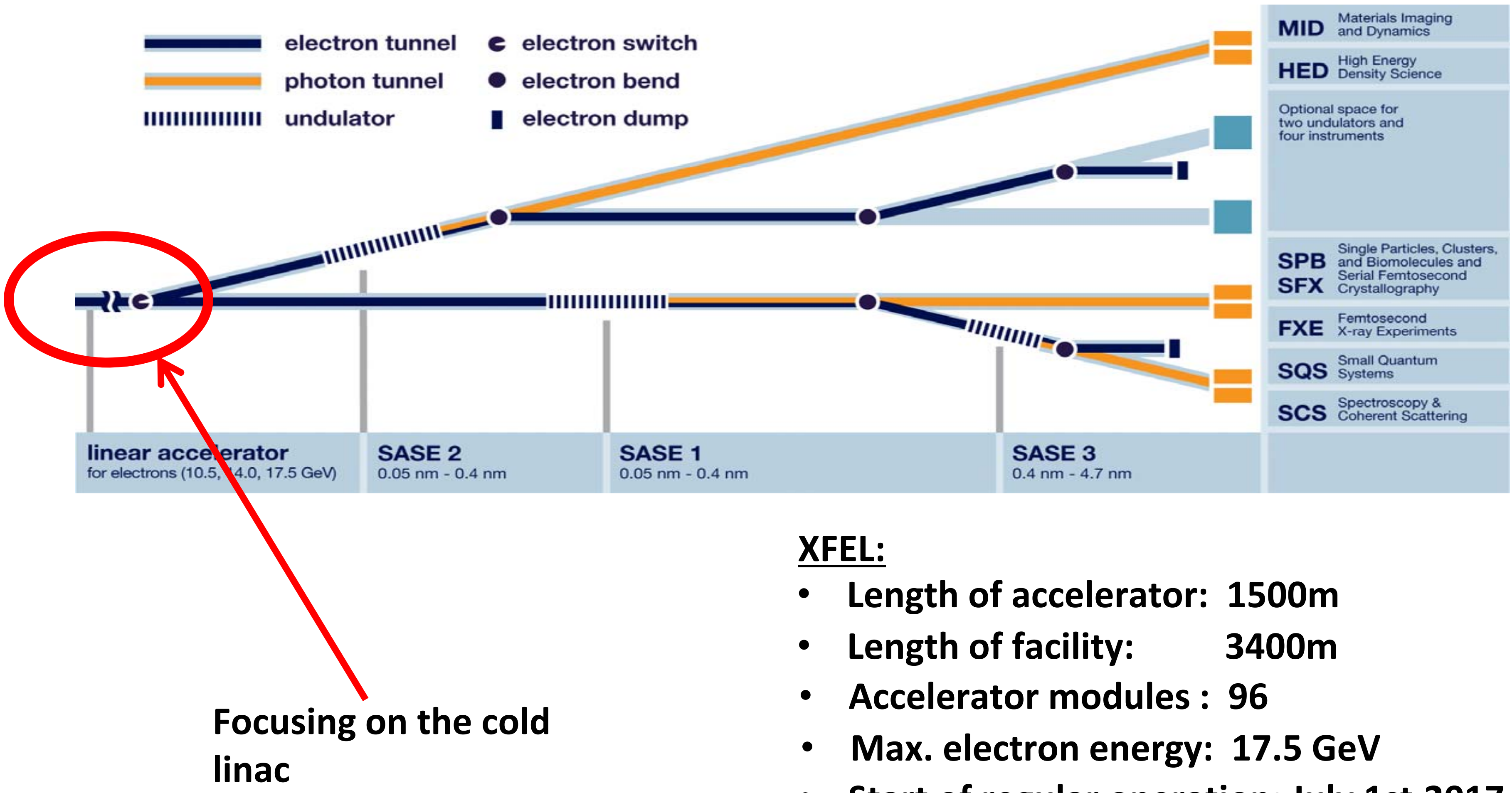


Conclusion:

- **CC-bypass operation delivers reasonable reactions on changes in 2K return flow**

European XFEL

XFEL Overview



XFEL:

- **Length of accelerator: 1500m**
- **Length of facility: 3400m**
- **Accelerator modules : 96**
- **Max. electron energy: 17.5 GeV**
- **Start of regular operation: July 1st,2017**