RF Heat Load Compensation for the European XFEL

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with

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and additional material from

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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
  - Summary
XFEL Cryogenic System

XFEL Overview

Injector

Cold Linac

Undulators

Instruments

Beijing, June, 2018
Jörg Penning
- Injector and 3 Linacs
- 9 Cryo-Strings
- 96 Cryo-Modules
- ~800 Cavities
- 32 cavities per RF station
- Design energy 17.5 GeV

![Diagram of XFEL Cryogenic System](image)
AHLC: Overview

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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

Coldboxes also want stable flow

What about this working point?
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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XFEL Cryogenic System

Sensors and Actuators

Flow

JT-Valve

Level

Heater
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.
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
  \[ E_{\text{fill}} = \int_0^{t_{\text{fill}}} P(t)\,dt \quad \text{with} \]
  \[ P(t) \sim U(t)^2 \quad \text{and} \]
  \[ U(t) \sim U \cdot (1 - e^{-\lambda t}) \]

- Solving yields
  \[ E_{\text{fill}} = P_{\text{forw}} \cdot t_{\text{fill}} \cdot 0.38 \]

\( \lambda \) is known from the tests
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.

\[ E_{\text{flat}} = P_{\text{forw}} \times t_{\text{flat}} \]
Detailed calculation: Decrease

- After switching off, the voltage decreases.
- The energy introduced to the cavity is
  \[ E_{\text{fall}} \sim \int_0^{\infty} U^2 \* e^{-\lambda t} \, dt \]
- This is equal to a square of fixed length \((t_{\text{fall}})\) by forward power.
- Solving yields
  \[ E_{\text{fall}} = P_{\text{forw}} \* t_{\text{fall}} \]
  \(t_{\text{fall}}\) being constant (~500 μs)

\(\lambda\) is known from the tests
Detailed calculation: Result

\[ P_{\text{diss}} \sim (E_{\text{fill}} + E_{\text{flat}} + E_{\text{fall}}) \times f_{\text{rep}} \times \text{Usage} \]

\[ = K \times P_{\text{forw}} \times (t_{\text{fill}} \times 0.38 + t_{\text{flat}} + t_{\text{fall}}) \times f_{\text{rep}} \times \text{Usage} \]

- **\( K \)** is an empiric factor of about \( 4 \times 10^{-7} \)
  - Pre-calculated from cavity tests
  - Refined after operating experience

- **\( P_{\text{forw}} \)** is the power as measured by the RF station which is distributed to 32 cavities each.

- **\( f_{\text{rep}} \)** is the repetition rate

- **\( \text{Usage} \)** Only active cavities are taken into account
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Simple approach
- Linear compensation only
- Treat all cavities the same

\[ P_{\text{diss}} = K \times P_{\text{forw}} \times (t_{\text{fill}} \times 0.38 + t_{\text{flat}} + t_{\text{fall}}) \times f_{\text{rep}} \times \text{Usage} \]
Quality vs. Energy shows non-linear behaviour
AHLC: Overview

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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
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
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
- Make use of two process controllers (IOCs)

Running AHLC

Running the linac
**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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From top: RF power, Level, He-Pressure, JT-Valve Readback, Flow, Heater Readback
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
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
Cryogenic 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)

<table>
<thead>
<tr>
<th>Cooling loop</th>
<th>unit</th>
<th>DESY calculated</th>
<th>DESY specification (calculated + safety margin)</th>
<th>Linde offer (guaranteed)</th>
<th>Linde offer (expected)</th>
<th>Test results CB 41 &amp; CB 43</th>
</tr>
</thead>
<tbody>
<tr>
<td>2K kW</td>
<td></td>
<td>1.46</td>
<td>1.9</td>
<td>1.9</td>
<td>2.01</td>
<td>&gt; 1.9</td>
</tr>
<tr>
<td>5K – 8K kW</td>
<td></td>
<td>2.4</td>
<td>3.6</td>
<td>3.6</td>
<td>3.95</td>
<td>4.0</td>
</tr>
<tr>
<td>40K – 80K kW</td>
<td>kW</td>
<td>16.0</td>
<td>24</td>
<td>24</td>
<td>26.12</td>
<td>25.9</td>
</tr>
</tbody>
</table>

**Conclusion:**
- Guarantee values for parallel coldbox operation have been exceeded!
**First cooldown:**

**XFEL Linac**

Cooldown with one coldbox

Start asymmetrical operation of two coldboxes to speed up cooldown

Recovery of cold return flows in cold boxes to enhance cryogenic capacity

Fast cooldown at temperatures below liquid nitrogen (no more thermal stress)
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
Bypass operation: Massflow compensation

Conclusion:
- CC-bypass operation delivers reasonable reactions on changes in 2K return flow
**XFEL Overview**

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

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**Focusing on the cold linac**