CW operation of XFEL cryomodule – field regulation performance study for high QI resonators

Agenda

1. CW and LPO operation motivation,
2. LLRF system setup,
3. Module under test,
4. Challenges,
5. Moderate and high gradient operation studies,
6. Results,
7. Summary and future plans.
**Motivation for high DF studies**

- upgrade of the FLASH and XFEL,
- relaxed beam patterns for dedicated experiments,
- duty factor increase (limitation comes from the input coupler design – max 2kW of power)

**Possible costs drivers for SP -> CW:**
- New (dedicated) RF gun,
- Adaptation (extension) of the cryo-plant capacity,
- LLRF system adaptation,
- Dedicated RF power source (for CW mode) – IOT prototype under test.
CMTB – CW/LPO teststand

- Tests of XFEL cryomodule have been performed in DESY at Cryo Module Test Bench (CMTB),
- CMTB is single 8 cavities cryomodule test stand,
- It is equipped with fully functional cryogenics and high power system suitable for short pulse and CW (LPO) operation
CW - LLRF system setup

- MTCA.4 based LLRF system,
- Hardware setup similar to the XFEL configuration (single module operation),
- PZ16M for the piezo control,
- System can be switched from SP to CW operation with dedicated firmware/server configuration
CW operation of XFEL cryomodule – field regulation performance study for high Ql resonators

Barcelona, 19-10-2017
Wojtek Cichalewski et. al,
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**CW - LLRF system setup**

- **RF field regulation loop:**
  - P and MIMO controller,
  - similar to short pulse with 4,5MHz feedback sampling,

- **Cavity frequency regulation:**
  - DC offset,
  - PI controller (mainly I component used) for low freq (<10Hz) regulation,
  - ANC based solution for persistent microphonics effects reduction
Piezo based microphonics effect suppression

Active Noise Canceller

- adaptive algorithm
- Least Mean Squares
- implemented in the FPGA
- no system identification required

Courtesy R. Rybaniec

Rybaniec Radosław, Przygoda Konrad, Cichalewski Wojciech [et all.]: FPGA based RF and piezo controllers for SRF cavities in CW mode, w: IEEE Transactions on Nuclear Science, IEEE Nuclear and Plasma Sciences Society, vol. 64, nr 6, 2017, ss. 1382-1388, DOI:10.1109/TNS.2017.2687981

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XFEL module under test

 XFEL module ID: XM-3

Module XM-3 on CMTB
6.03.2017

Cavities Field Emission
E_{ACC} [MV/m]

Module XM-3 CMTB:
FE start
X>10^{-mGy/min}
max.gradient
cavity

Cavities Field Emission
6.03.2017

0 5 10 15 20 25 30 35 40

Courtesy D. Kostin

AC114 AC156 AC146 AC154 AC157 AC158 AC151 AC152

0 5 10 15 20 25 30 35 40

Challenges

1. High QI $\rightarrow$ narrow bandwidth,
2. Microphonics,
3. Ponderomotive instabilities effect,
4. FPC heating $\rightarrow$ QI change (drop),
5. IOT nonlinearities,
6. Cavities HP signals cross-talk and reflections.
High Loaded Quality factor

- FPC are designed to operate with input power up to 2 kW (pulse operation – range of 400kW),
- to increase Eacc for the same power – Q external needs to be adjusted,

<table>
<thead>
<tr>
<th></th>
<th>FLASH</th>
<th>XFEL</th>
<th>CW</th>
<th>CW Max ?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ql value</td>
<td>3e6</td>
<td>4,6e6</td>
<td>2e7</td>
<td>5e7</td>
</tr>
<tr>
<td>Half BW (Hz)</td>
<td>216</td>
<td>142</td>
<td>32,5</td>
<td>13</td>
</tr>
<tr>
<td>Input power [kW]</td>
<td>32,6</td>
<td>21,2</td>
<td>5</td>
<td>1,95</td>
</tr>
</tbody>
</table>

(for Eacc = 20MV/m, tuned)

- In order to achieve high operation gradient Q external needs to be increased high,
- Bandwith becomes really narrow – cavity is more prone to the microphonics,
- Other option (not discussed here) is a Long Pulse Operation (reduce DF to be on the safe side with FPC power limit)…..
Microphonics

Microphonics main sources
- Vacuum pumps,
- Helium pressure fluctuation,

Main frequencies visible on the cavity field
- 31 Hz
- 49 Hz

Microphonics detuning implies more RF power for compensation

Courtesy R. Rybaniec
Cavity gradient change in function of the detuning shows hysteresis effect

- In case of the Vector Sum control – detuning (and field drop) of single cavity will affect others.
- Initial pretuning of the cavity have to take into account this issue.
Couplers thermal expansion effect

- Cavity operation with input power above 3kW leads to the FPC heating,
- Temperature increase results in the Ql change.

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![FPC temp change (80K side) vs time](image)

- CW operation, close loop, $E_{acc_{avg}} = 14.4 \text{ MV/m}$, $Ql_{avg} \sim 1.5e7$, $dA/A = 0.007\%$, $dP = 0.008 \text{ deg}$

![Ql vs FPC temp](image)
Couplers thermal expansion effect

- In close loop VS operation the QI change is being compensated by the input power increase.

- The increase of the IOT power results also in the phase shift (due to nonlinearity) this can impact the detuning estimation and then piezo feedbacks,

- Even tough the conditions are changing the VS regulation is better than XFEL spec.
IOT nonlinearities

IOT prototype (by CPI) is being used for cavities supply during CW/LPO study.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Specification</th>
<th>Prototype I 2009</th>
<th>Prototype II 2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>F [MHz]</td>
<td>1300</td>
<td>1300</td>
<td>1300</td>
</tr>
<tr>
<td>cw P_out [kW]</td>
<td>120</td>
<td>85</td>
<td>105</td>
</tr>
<tr>
<td>Gain [dB]</td>
<td>&gt;22</td>
<td>22.3</td>
<td>22.7</td>
</tr>
<tr>
<td>Efficiency [%]</td>
<td>&gt;60</td>
<td>54</td>
<td>63</td>
</tr>
<tr>
<td>V_{beam} [kV]</td>
<td>47–49</td>
<td>47–49</td>
<td>47–49</td>
</tr>
</tbody>
</table>

- Gain increase can cause sudden IOT output power jump during close to open loop transition,
- Phase shift at the output of the IOT can influence cavity detuning estimation -> limit performance of the piezo feedbacks.
**CW - LLRF system setup**

- **RF field regulation loop:**
  - P and MIMO controller,
  - similar to SP with 4.5MHz feedback sampling,
- **Cavity frequency regulation:**
  - DC offset,
  - PI controller (mainly I component used) for low freq (<10Hz) regulation,
  - ANC based solution for persistent microphonics effects reduction
**Ql ~1.5e7 operation**

Close loop CW operation:
- Proportional RF feedback,
- Piezo I controller
- ANC filters for some resonators (mainly 31Hz & 49 Hz),
- "cold couplers" Ql readout:

- Achieved performance:
  
  $dA/A = 0.007\%$ (XFEL sp. 0.01%)  
  $dP = 0.008$ deg (XFEL sp. 0.01)

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**Continuous Wave and Long Pulse Operation @ CMTB**

**Amplitude Spectrum**

- **31 Hz**
- **49 Hz**

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## Cavities Q_l adjustment

<table>
<thead>
<tr>
<th>Cav</th>
<th>Q_l</th>
<th>P_fwd [W]</th>
<th>E_acc [V/m]</th>
<th>Q_l</th>
<th>P_fwd [W]</th>
<th>E_acc [V/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.80E+07</td>
<td>8.72E+02</td>
<td>1.00E+07</td>
<td>1.53E+07</td>
<td>1.60E+03</td>
<td>1.00E+07</td>
</tr>
<tr>
<td>2</td>
<td>1.95E+07</td>
<td>1.25E+03</td>
<td>1.00E+07</td>
<td>1.59E+07</td>
<td>1.54E+03</td>
<td>1.00E+07</td>
</tr>
<tr>
<td>3</td>
<td>2.16E+07</td>
<td>1.13E+03</td>
<td>1.00E+07</td>
<td>1.59E+07</td>
<td>1.54E+03</td>
<td>1.00E+07</td>
</tr>
<tr>
<td>4</td>
<td>2.00E+07</td>
<td>1.22E+03</td>
<td>1.00E+07</td>
<td>1.51E+07</td>
<td>1.62E+03</td>
<td>1.00E+07</td>
</tr>
<tr>
<td>5</td>
<td>1.90E+07</td>
<td>1.28E+03</td>
<td>1.00E+07</td>
<td>1.60E+07</td>
<td>1.53E+03</td>
<td>1.00E+07</td>
</tr>
<tr>
<td>6</td>
<td>1.80E+07</td>
<td>1.36E+03</td>
<td>1.00E+07</td>
<td>1.57E+07</td>
<td>1.56E+03</td>
<td>1.00E+07</td>
</tr>
<tr>
<td>7</td>
<td>1.70E+07</td>
<td>1.44E+03</td>
<td>1.00E+07</td>
<td>1.49E+07</td>
<td>1.64E+03</td>
<td>1.00E+07</td>
</tr>
<tr>
<td>8</td>
<td>1.78E+07</td>
<td>1.37E+03</td>
<td>1.00E+07</td>
<td>1.52E+07</td>
<td>1.61E+03</td>
<td>1.00E+07</td>
</tr>
</tbody>
</table>

**Sum** | **9.92E+03** | **Before** | **1.26E+04** |

Expected input pwr diff. 2.69E+03 21%
Results medium gradient ~15MV/m

Configuration:
- Proportional RF feedback,
- Piezo I controller
- ANC filters for some resonators

<table>
<thead>
<tr>
<th>Cav</th>
<th>Eacc [MV/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>17.80</td>
</tr>
<tr>
<td>2</td>
<td>14.39</td>
</tr>
<tr>
<td>3</td>
<td>14.07</td>
</tr>
<tr>
<td>4</td>
<td>16.08</td>
</tr>
<tr>
<td>5</td>
<td>14.35</td>
</tr>
<tr>
<td>6</td>
<td>13.03</td>
</tr>
<tr>
<td>7</td>
<td>14.92</td>
</tr>
<tr>
<td>8</td>
<td>12.76</td>
</tr>
</tbody>
</table>

dA/A = 0.007% (XFEL sp. 0.01%)
dP = 0.008 deg (XFEL sp. 0.01)

Amplitude stability during studies
Phase stability during studies
Results for high gradient ~18MV/m (avg)

Controllers configuration:
- Proportional RF feedback,
- Piezo I controller
- ANC filters for some resonators

<table>
<thead>
<tr>
<th>Cav</th>
<th>Gradient [MV/m]</th>
<th>dA/A [%]</th>
<th>dP [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22.20</td>
<td>0.067</td>
<td>0.65</td>
</tr>
<tr>
<td>2</td>
<td>17.80</td>
<td>0.137</td>
<td>0.75</td>
</tr>
<tr>
<td>3</td>
<td>17.09</td>
<td>0.097</td>
<td>0.72</td>
</tr>
<tr>
<td>4</td>
<td>19.68</td>
<td>0.137</td>
<td>1.02</td>
</tr>
<tr>
<td>5</td>
<td>17.35</td>
<td>0.059</td>
<td>0.69</td>
</tr>
<tr>
<td>6</td>
<td>15.70</td>
<td>0.062</td>
<td>0.85</td>
</tr>
<tr>
<td>7</td>
<td>18.40</td>
<td>0.205</td>
<td>1.13</td>
</tr>
<tr>
<td>8</td>
<td>15.07</td>
<td>0.068</td>
<td>0.33</td>
</tr>
</tbody>
</table>

dA/A = 0.011%
dP = 0.010 deg

- Individual cavities performance exceeds field regulation thresholds,
- VS control does not focus on the individual cavity regulation
Single cavity operation

- VS is not optimal for single cavity control,
- Try to operate single cavity to verify the regulation performance

Cavity 1 and cavity 3 have been chosen – highest Ql (lowest input power needed)
Single cavity operation – cavity 3

Cavity data:
ID: AC146
Quench level: 40.5 MV/m
Radiation FE start level: ~30 MV/m,
Main microphonics freq.: 31, 49 Hz

Gradient: 18 MV/m
- RF feedback ON, proportional gain of 8,
- Piezo Integral Feedback ON,
- ANC OFF
Achieved VS regulation accuracy:
\[ \frac{dA}{A} = 0.015\% \quad \frac{dP}{P} = 0.017 \text{ deg} \]
Single cavity operation – cavity 3

Gradient: 22 MV/m
- RF feedback ON, proportional gain of 12,
- Piezo Integral Feedback ON,
- ANC ON (31Hz & 49Hz),
Achieved VS regulation accuracy:
\[ \frac{dA}{A} = 0.018\% \quad \frac{dP}{P} = 0.016 \text{ deg} \]

Gradient: 23.5 MV/m
- RF feedback ON, proportional gain of 9,
- Piezo Integral Feedback ON,
- ANC ON (31Hz & 49Hz),
Achieved VS regulation accuracy:
\[ \frac{dA}{A} = 0.019\% \quad \frac{dP}{P} = 0.014 \text{ deg} \]

- tested up to the ~23.5 MV/m level,
- quench level not reached (40MV/m),
- High input power needed to achieve higher Eacc (Ql 2.2e7) – fast FPC temp increase,
- during gradient increase – strong oscillations of ~168Hz observed (cavity mechanical mode),
- power distribution for the single cavity operation can/should be optimized,
Summary and future plans

1. CW operation in close loop is possible with current setup with grad up to 18 MV/m (average),

2. Module operation for average grad of 15 MV/m with fulfilled XFEL specs.,

3. Higher cavities QI will reduce required input power and it is still not a challenge for precise field regulation.
Future plans

1. QI increase by modifying fundamental power couplers – planned late 2017,
2. Possible QI range – up to 5e7,
3. Long Pulse operation study,
4. Optimization of the cavity in resonance filling (for LPO)
5. Max Eacc / max DF study.
Thank You