Presentation of CW operations at CMTB

and for the European XFEL

Julien Branlard, for the LLRF team
Presentation of CW operations at CMTB
HZDR, 24.11.2015
CONTENT

➤ Why CW?

➤ XFEL as a CW machine

➤ Tests at CMTB
Why CW?
I. “So, what’s the big deal about CW… ?”

- Short Pulse (SP), Long Pulse (LP) and Continuous Wave (CW) operation

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>Bunch Rate (Nbunch/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.8</td>
<td>100k</td>
</tr>
<tr>
<td>10</td>
<td>50k</td>
</tr>
<tr>
<td>17.5</td>
<td>27k</td>
</tr>
</tbody>
</table>

![Graphs showing CW, LP, and pulsed operations with corresponding duty factors and bunch rates.](image-url)
I. “So, what’s the big deal about CW… ?”

Benefits of continuous wave (CW) operations

- Higher efficiency
- More flexible beam time structure
- Slower repetition rate lasers, cheaper/simpler detectors
- Lorentz force detuning and fill-transients no longer an issue

Benefits of long-pulse (LP) operations

- Still high duty factor (DF = 10-50%)
- Higher gradients than CW with same heat load
I. What are the technical and “practical” limitations?

1st limitation:

> Heat load at 2K (1.8K) should not exceed 20W per cryomodule

The main XFEL linac will be split in 7 cryogenic-strings (CS = 12 CM)

2 K, GRT
80 K, Return
8 K, Return

2.2 K forward
5 K forward
40 K forward

2-phase tube: 240 W (~20W/CM) is the estimated limit for one CS
I. What are the technical and “practical” limitations?

2\textsuperscript{nd} limitation:

> Heating of the HOM couplers must not cause quenching of the cavity

- TESLA cavity was designed for ca. 1% DF (1992)
- To make the cavity cheaper we put FP- and HOM couplers outside LHe vessel
- End groups (FP- and HOM couplers) are cooled by means of heat conduction

Courtesy: J. Sekutowicz, R&D towards high duty cycle sc linac operation, DESY-MAC, May 8th, 2014
I. What are the technical and “practical” limitations?

To reduce antennae heating, all XFEL cavities are equipped with high thermal conduction feedthroughs directly connected to the 2-phase tube with copper braids.

HOM feedthrough with cable, thermal connection and load

High thermal conduction HOM feedthroughs with sapphire windows

Courtesy: J. Sekutowicz, R&D towards high duty cycle sc linac operation, DESY-MAC, May 8th, 2014
I. What are the technical and “practical” limitations?

3rd limitation:

> CW operation increases the dynamic heat load

<table>
<thead>
<tr>
<th>T</th>
<th>Existing cryoplant Nominal operation</th>
<th>Upgraded cryoplant High DF operation (1.8K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Capacity</td>
<td>Heat Load (101 CM )</td>
</tr>
<tr>
<td>5-8 K</td>
<td>4000</td>
<td>3511</td>
</tr>
<tr>
<td>40-80 K</td>
<td>30000</td>
<td>15318</td>
</tr>
</tbody>
</table>

(*) with new injector section and additional 12 CM in the main linac

We will need to double the capacity of the present cryoplant
I. What are the technical and “practical” limitations?

4th limitation:

> Klystron are not CW-capable RF sources

- New RF-sources will be added to klystrons
- They should fit in the XFEL tunnel.
- Inductive Output Tubes (IOT)

  Currently seems to be best choice
  Very compact, which makes it superior to solid-state amplifiers
  Takes energy from the mains only when it generates RF-power
  → more efficient than klystron.

Courtesy: J. Sekutowicz, R&D towards high duty cycle linac operation, DESY-MAC, May 8th, 2014
I. Inductive Output Tube (IOT) prototypes from CPI

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Spec</th>
<th>Measured (1\text{st} prototype)</th>
<th>Measured (2\text{nd} prototype)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output P</td>
<td>[kW]</td>
<td>120</td>
<td>85</td>
<td>105</td>
</tr>
<tr>
<td>Gain</td>
<td>[dB]</td>
<td>&gt;22</td>
<td>22.3</td>
<td>22.7</td>
</tr>
<tr>
<td>Efficiency</td>
<td>[%]</td>
<td>&gt;60</td>
<td>54</td>
<td>63</td>
</tr>
</tbody>
</table>

- The IOT amplifier is superior to cw klystrons for the lp mode operation (IOT is a grid tube)
- The tube is very compact and can be installed in the tunnel
- The 2\text{nd} prototype demonstrated performance very close to specifications
- Both prototypes are used to test CMs in cw/lp modes (many operation hours since 2011)

H x W x D = 1.3m x 0.6m x 0.4m
I. R&D programs towards CW operation

Project Oriented Funding (POF3)
- Program Matter and Technologies
- ST1: Superconducting science and technology
- ST3: \textit{ps and fs} electron and photon beams
- 5 year financed program
XFEL as a CW machine
II. The European XFEL

The European X-ray Free Electron Laser

- 17.5 GeV light source, Hamburg, Germany
- TESLA superconducting 1.3GHz RF cavities
- 1.4 msec pulses at 10 Hz
- e-beam 1.35 mA nom. - 4.5 mA max
- 2016: construction / commissioning
- 2017: first user operation

source: http://www.xfel.eu
II. The European XFEL LLRF system

> LLRF: DESY in-kind

- 26 RF stations (808 cavities, 101 cryomodules)
- MicroTCA.4 LLRF system, master / slave
- Vector sum (32 cavities) RF control
- 2 piezo per cavities (1kHz tuning)
- Motorized cavity tuners
- Motorized $Q_L$, one-time fixed power ratios

**RF parameters:**
- Pulse length 1.4msec (750 + 650 usec)
- $Q_L = 4.6e6$ ($\frac{1}{2}$ bw = 140 Hz)
- 10 Hz rep. rate
- $\Delta A/A = 0.01\%$  $\Delta \Phi = 0.01$ deg.
II. Making the XFEL CW

1. Replace the first 17 CMs (Inj, L1, L2) with CMs capable of higher heat load
2. Add IOT as alternative power sources to the existing waveguide system
3. Double the cryoplant 2.5 kW \(\rightarrow\) 5 kW
4. Replace the normal conducting RF gun with a SC CW gun
## II. Target XFEL accelerator parameters for cw/lp modes

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Injector Section (INJ + L1 + L2) up to 2GeV</strong></td>
<td></td>
</tr>
<tr>
<td>$Q_0$ at 1.8K of cavities in INJ / L1 / L2</td>
<td>$[10^{10}]$</td>
</tr>
<tr>
<td>1.8K dynamic load per CM in INJ / L1 / L2</td>
<td>[W]</td>
</tr>
<tr>
<td>$E_{acc}$ for cw mode in linacs INJ / L1 / L2</td>
<td>[MV/m]</td>
</tr>
<tr>
<td><strong>Main Linac (L3)</strong></td>
<td></td>
</tr>
<tr>
<td>Number of CMs</td>
<td>-</td>
</tr>
<tr>
<td>1.8K dynamic/static load per CM</td>
<td>[W]</td>
</tr>
<tr>
<td>$Q_0$ of cavities</td>
<td>$[10^{10}]$</td>
</tr>
<tr>
<td>Maximum $E_{acc}$ for cw mode</td>
<td>[MV/m]</td>
</tr>
<tr>
<td>$Q_{load}$ of input coupler</td>
<td>$[10^7]$</td>
</tr>
<tr>
<td>Max. mean RF-power $P$ per cavity</td>
<td>[kW]</td>
</tr>
<tr>
<td>Max. peak RF-power $P$ per cavity</td>
<td>[kW]</td>
</tr>
<tr>
<td><strong>Beam</strong></td>
<td></td>
</tr>
<tr>
<td>Charge per bunch</td>
<td>[nC]</td>
</tr>
<tr>
<td>Time between subsequent bunches</td>
<td>[µs]</td>
</tr>
<tr>
<td>Energy (cw mode)</td>
<td>[GeV]</td>
</tr>
<tr>
<td>$I_{beam}$</td>
<td>[mA]</td>
</tr>
<tr>
<td><strong>Cryogenic Plant</strong></td>
<td></td>
</tr>
<tr>
<td>1.8K capacity including 50% margin</td>
<td>[kW]</td>
</tr>
</tbody>
</table>
Tests at CMTB
III. CW and LP tests at CMTB

> Cryomodule Test Bench (CMTB)

Test CM in pulsed mode (FLASH + XFEL pre-series)
Backup for Accelerating Module Test Facility (AMTF)

MicroTCA LLRF system for VS operation (XFEL-like)

- 12 slot crate (9U)
- NAT MCH
- Concurrent CPU
- Wiener 1kW uPM
- Struck ADC + DWC
- Vadatech TCK7 + DESY VM2
- + 19” XFEL 16ch piezo driver

MicroTCA LLRF system for single cavity regulation

- 12 slot crate (9U)
- NAT MCH
- Concurrent CPU
- Wiener 1kW uPM
- Struck ADC + DWC-VM
- EicSys FMC20 + PZT4
- + 19” supporting modules

See talk from Konrad Przygoda (Wed. AM)
See talk from Igor Rutkowski (Wed. AM)
See talk from Christian Schmidt (Wed. AM)
III. LLRF development for CW operations

- Vector-sum RF feedback
- Individual piezo feedback

RF FB with active noise cancellation + Piezo feedback

See talk from Radek Rybaniec (Wed. AM)
III. Optimize the cavity bandwidth

\[
\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_{\text{ext}}}
\]

- \( Q_L \): Cavity loaded quality factor
- \( Q_0 \): Cavity unloaded quality factor
- \( Q_{\text{ext}} \): Cavity external quality factor

With higher \( Q_L \), less power is required to achieve same gradient.

\( V_{\text{CAV}} = 12 \text{ MV/m} \)
\( R/Q = 1040 \Omega \)

\[
V_{\text{CAV}} = \sqrt{\frac{4P_K R}{Q L}}
\]

\( P_K = 92 \text{ kW} \)
\( P_K = 18 \text{ kW} \)

Increasing \( Q_L \) decreases the cavity bandwidth, making it more sensitive to microphonics.
III. LLRF system development for CW/LP operation

Ponderomotive instabilities

Cavity detuning as a function of piezo DC bias for different operating points

Amplitude stability: standard dev. $4 \times 10^{-4}$
Better than spec

Phase stability: standard dev. 0.3°
Far from spec.

See talk from Wojtek Cichalewski (Wed. AM)
III. Benefits of operating at 1.8K

- RF heats up cavity walls $\rightarrow$ dynamic heat losses
- Surface resistivity ($R_S$) decreases \textbf{exponentially} with temperature ($T$)

$$R_S = A_s \omega^2 \exp\left(-\frac{\Delta(0)}{k_B T}\right) \ *

- Operations at 1.8K instead of 2K
  > $Q_0$ increases by factor of 2
  > Heat load ($HL$) decreases by factor of 2
  > Proportional to duty factor (DF)
  > Gradients can be increased by 40%

* Reference: “RF superconductivity for accelerator”, Padamsee, Knobloch, Hays

Higher gradient for same heat loss
III. Benefits of operating at 1.8K

\[ E_{\text{acc}} = 7.0 \text{ MV/m} \]
\[ DHL = 13.5 \text{ W} \]
\[ Q_0 \sim 3.1 \times 10^{10} \]

\[ E_{\text{acc}} = 9.5 \text{ MV/m} \]
\[ DHL = 16.1 \text{ W} \]

\[ Q_0 \uparrow \text{ by 52\%} \]

\[ E_{\text{acc}} = 7.0 \text{ MV/m} \]
\[ DHL = 8.9 \text{ W} \]
\[ Q_0 \sim 4.7 \times 10^{10} \]

Courtesy J. Sekutowicz
III. Experiments with pre-series CMs at 1.8 and 2K

In 2011 we installed the 1\textsuperscript{st} IOT prototype in CMTB 5 pre-series and 1 series cryomodules in cw/lp mode tested

<table>
<thead>
<tr>
<th>Date of the 1\textsuperscript{st} test</th>
<th>Cryomodule</th>
<th>Nb Material</th>
<th>HOM outputs Old / New</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 2011</td>
<td>PXFEL2_1</td>
<td>8 cavities Fine Grain</td>
<td>6 / 2</td>
<td>Heating of end-groups</td>
</tr>
<tr>
<td>Apr. 2012</td>
<td>PXFEL2_2</td>
<td>8 cavities Fine Grain</td>
<td>5 / 3</td>
<td>Heating of end-groups</td>
</tr>
<tr>
<td>June 2012</td>
<td>PXFEL3_1</td>
<td>8 cavities Fine Grain</td>
<td>5 / 3</td>
<td>Heating of end-groups</td>
</tr>
<tr>
<td>May 2013</td>
<td>PXFEL2_3</td>
<td>8 cavities Fine Grain</td>
<td>6 / 2</td>
<td>Heating of end-groups</td>
</tr>
<tr>
<td>Sep. 2013</td>
<td>XM-3</td>
<td>7 LG + 1FG</td>
<td>0 / 8</td>
<td>No heating of end-groups</td>
</tr>
<tr>
<td>May 2015</td>
<td>XM4</td>
<td>8 cavities Fine Grain</td>
<td>0 / 8</td>
<td></td>
</tr>
</tbody>
</table>

Courtesy J. Sekutowicz
III. CMTB Tests at 2K

Several stable cw runs at 2K under various conditions (3M means 3 various methods used used to determined Eacc)

Courtesv J. Sekutowicz
III. CMTB Tests at 1.8K

- Demonstrated Qo at 1.8K is significantly higher than the target Qo.
- Investigated impact of cooling rate on Qo.

Graph showing Qo vs. Eacc [MV/m] with data points for 23.06.15, 3M, 1.8K and 24.06.15, 3M, 1.8K.

Target Qo.
New HOM coupler with additional inductance and pulled back output antenna provides better heat dissipation and 50% less magnetic field.

- 3rd inductance
- Output antenna "hidden" inside output tube
- Two inductances

H = 0.022 A/m
H = 0.045 A/m

Courtesy D. Kostin
III. Superconducting electron gun

- Indium gasket
- Nb plug
- Pb coated tip
- sc cathode
- Nb cavity

![Diagram of superconducting electron gun](image)

### Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cathode</td>
<td>Pb</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>pC</td>
</tr>
<tr>
<td>Bunch length</td>
<td>ps</td>
</tr>
<tr>
<td>Bunch rep. rate</td>
<td>kHz</td>
</tr>
<tr>
<td>Energy</td>
<td>MeV</td>
</tr>
<tr>
<td>Beam current</td>
<td>µA</td>
</tr>
<tr>
<td>QE</td>
<td>%</td>
</tr>
<tr>
<td>Max. E on cathode</td>
<td>MV/m</td>
</tr>
<tr>
<td>Eγ on cathode</td>
<td>µJ</td>
</tr>
<tr>
<td>Laser P at cathode</td>
<td>W</td>
</tr>
</tbody>
</table>

- Bunch charge: 100-300 pC
- Bunch length: 3 ps
- Bunch rep. rate: 100-33 kHz
- Energy: 3.7 MeV
- Beam current: 10 µA
- QE: 0.015@260nm
- Max. E on cathode: 40 MV/m
- Eγ on cathode: 2.4-7.2 µJ
- Laser P at cathode: 0.24 W

![Graph of E_{cath} vs Qo](image)
Summary

- Benefits and limitations of CW operations
- “Roadmap” to a CW XFEL
- CMTB R&D towards CW operations, we have demonstrated:
  - Gradients needed in XFEL for beam energies of 7.9 GeV (CW) and 14 GeV (LP)
  - That new HOM output lines diminish additional heating of end-groups
  - RF-source (IOT) suitable for cw/lp operation
  - Benefit of operation at 1.8 K
  - Benefit of using large grain material
- Plan to test several serial XFEL cryomodules to determine more precisely relation $E_{\text{acc}}$ versus $DF$
- Further improvement of the LLRF system to meet the stability requirements
Acknowledgments to all involved with the CW tests:

Acknowledgments to Jacek Sekutowicz for his help and his material

Thank you for your attention !