Microphonics control studies for high $Q_L$ SRF Cavities

Module commissioning of the bERLinPro SRF Gun
Systems under study

- **CW modified TESLA cavity for BESSY-FEL (2005-2008)**
  - Studied mainly at HTS (HoBiCaT)
  - $Q_L$ from $5\cdot10^6$-$2\cdot10^8$, $E_{\text{acc}}=8$-$22$ MV/m
  - CW studies, heat load, microphonics compensation high $Q_L$ LLRF

- **Nb Pb lead cathode DESY gun (1.6 cell), 2011-2012**
  - Studied with diagnostics beamline
  - $E_0=12$-$25$ MV/m
  - $Q_L=3\cdot10^6$-$1.5\cdot10^7$
  - $\Delta f/\Delta P=100$ Hz/mbar
  - $\Delta f/\Delta E_0^2=1$ Hz/(MV/m)$^2$

- **SRF Photoinjector (ERL), today**
  - Studied with diagnostics beamline + cathode transfer
  - $E_0=12$-$25$ MV/m
  - $Q_L=1\cdot10^7$-$2.8\cdot10^7$
  - $\Delta f/\Delta P=33$ Hz/mbar
  - $\Delta f/\Delta E_0^2=3.4$ Hz/(MV/m)$^2$
Microphonics: How does it appear?

- Field amplitude variation:
  Dynamic Lorentz force, \( \Delta f / \Delta E_{acc}^2 = 1-3 \text{Hz}/(\text{MV/m})^2 \) → Ponderomotive instability

- Helium pressure fluctuations
  \( \Delta f / \Delta p = 50-60 \text{ Hz/mbar} \)
  SRF Gun: 30-100 Hz/mbar

- Deterministic, narrow-band sources:
  Vacuum pumps

- Stochastic background noise

- Mechanical oscillations of the Cavity: Microphonics

- Response of the Cavity-Helium vessel-Tuner system:
  Mechanical Eigenmodes

- Heat transport dynamics in LHe
  Thermo-acoustic oscillations (cryo valves...)

- 222 Hz
  G. Bissofi

- 151 Hz

- 16 mbar±30 µbar

- 2.5-3 mm Niobium walls

- Is that the whole story?

Volume 58, August 2012, Pages 1-8
Microphonics: What do we see?

• The cavity is the best sensor of mechanical excitation itself, true?
  ➔ What deformation affects actually the RF mode (TM\textsubscript{0yz} different than e.g. TM\textsubscript{1yz})?  

Cavity design: Cavity sensitivities

• Helium bath often main driver of microphonics, usually the static term $\Delta f/\Delta P$ can be measured or the cavity design optimized for
  ➔ What about dynamic response?

• Detuning is often obtained by comparing forward and transmitted (reflected) wave of the TM\textsubscript{010} $\pi$-mode (or FPC excited RF mode).
  ➔ We only see what affects the RF mode, not all oscillations, do we care?

  Cavity oscillations w.r.t. beam motion?

  ➔ Is this always what we consider microphonics (oscillations in acoustic regime)?
  ➔ Can we compensate every oscillation which affects the wanted cavity RF mode using tuner with e.g. piezos?

Be aware of other contributions to appear in the signal:

– Transient beam-loading (hopefully repetitive, but what about beam losses in recirculating machines?) $\leftrightarrow$ beam arrival jitter, synchrotron oscillations
– Multipacting in more special cavities (e.g. SRF gun, coaxial parts)
– Loop oscillates if stability criterion is not met
– Coaxial FPC: Oscillation of inner conductor (cooling media)
  ➔ Some of them alter the measurement, some are real detuning, but eventually not tackled by tuners
Detuning characterization of a TESLA cavity, short-term

For elliptical cavity, usually transverse mode

- HoBiCaT: $\sigma_f = 1 - 5$ Hz (rms)  
  $\leftrightarrow$ 2-13° phase error (Aim: $10^{-2}$°)  
  "open loop" "closed loop"

- He pressure variations: $f_{\text{mod}} < 1$ Hz

- Cavity specific: First mode at 20 - 50 Hz

- Spectrum can appear more populated  
  $\rightarrow$ depends on cavity system
Microphonics and thermal load on cavity tank

- Simultaneous 2 cavity operation (TESLA cavities)
- Heaters attached at each tank
- Monitor microphonics due to thermal load on cavities

Onset of non-laminar Helium flow?

Chimney limit
Correlation of Helium pressure and detuning of cavity

- Open loop measurement of cavity frequency and He pressure
- 50-60 Hz/mbar down to resolution limit of pressure meters (~1Hz)
- Evidence that main contribution of microphonics mediated through superfluid Helium
Long-term stability: Peak events → how much, how often?

Microphonics recorded at HoBiCaT with TESLA cavity for 48 hours at $E_{\text{acc}}=8\text{MV/m}$

- RMS Values around 1-5 Hz ← Determines field stability and thermal loading of RF system (5 kW)
- Peak values extend out to 17 σ! ← Determines RF power installation (15 kW)
- Peak events occur 10-20 times a day!
  (This was partly improved by changes to the control settings of the under-press. pumps.)
- Expected field stability: 0.02 - 0.1°
- For “comfort“ want to reduce the microphonics

Excited 1st mech. resonance: Transverse mode
Time-frequency analysis by Wavelets

- Variation up to $\Delta f = 10$ Hz on a $\sim 100$ ms time scale
- Spectrum of He-pressure variations of stochastic nature

- Adaptive, „learning“ (dynamic) compensation mandatory
- Need for classic feedback control

$W_n(s) = \sum_{n'=0}^{N-1} x_{n'} \Psi^* \left[ \frac{(n' - n)\delta t}{s} \right]$
Tuner qualification

Tested 3(4) different tuner systems

<table>
<thead>
<tr>
<th></th>
<th>Saclay I*</th>
<th>Saclay II</th>
<th>INFN Blade**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mech. principle</td>
<td>1-lever+flexures</td>
<td>2-levers+flexures</td>
<td>Knee-lever+blades</td>
</tr>
<tr>
<td>Tuning resolution</td>
<td>0.176Hz/step</td>
<td>0.09 Hz/step</td>
<td>2.6 Hz/step</td>
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<tr>
<td>Drive</td>
<td>Phytron / HD 1:88</td>
<td>Phytron / HD 1:88</td>
<td>Sanyo / PG 1:100</td>
</tr>
<tr>
<td>Max remanence</td>
<td>30 Hz</td>
<td>55 Hz</td>
<td>380 Hz</td>
</tr>
<tr>
<td>Coarse tuning range</td>
<td>750 kHz</td>
<td>500 kHz</td>
<td>720 kHz</td>
</tr>
<tr>
<td>Coercitive steps</td>
<td>180 (no backlash)</td>
<td>350-500 (backlash)</td>
<td>100 (backlash)</td>
</tr>
<tr>
<td>Used piezo type</td>
<td>HV (0-1000V)</td>
<td>LV (-10-150V)</td>
<td>LV (0-200V)</td>
</tr>
<tr>
<td>Piezo tuning range</td>
<td>750 Hz</td>
<td>1420 Hz</td>
<td>800 Hz</td>
</tr>
<tr>
<td>Group delay ($d\phi/d\omega$)</td>
<td>290 µs</td>
<td>150 µs</td>
<td>650 µs (138 µs)***</td>
</tr>
<tr>
<td>Lowest resonance</td>
<td>40 Hz</td>
<td>40 Hz (double)</td>
<td>35 Hz</td>
</tr>
</tbody>
</table>

→ Important for CW piezo based detuning control

* Increased stiffness of piezo holder frame
** Several versions exist
*** 138 µs for 1.4 cell SRF gun with Cornell blade tuner
Model based controller: Fit of the system

\[ \Delta \dot{\omega}_{cav,k}(t) + 2\xi \omega_{m,k} \cdot \Delta \omega_{cav,k}(t) + \omega_{m,k}^2 \cdot \Delta \omega_{cav,k} = \pm k_{p,k} 2\pi \omega_{m,k}^2 V_{Piezo}(t) \]

\[ \Delta \omega_{cav}(t) = \sum_k \Delta \omega_{cav,k}(t) \]

- Fit: Parallel acting 2nd order systems
- Evaluate response of higher modes at lower frequencies
- >20 modes needed for fit
- Systems complexity complicates use of model based feedbacks (e.g. Kalman filter)

Transfer function as look-up table or Kalman approach tested with cavity simulator
See talk A. Ushakov

Fit for:
- Each cavity tuner combination
- Changes with coarse tuning or helium pressure
- Affected by cav. mech. design

Individual for:

\[ \chi^2 = 292.32 \]

Relevant for tuning

But: Only LF and piezo transfer functions accessible in operation!
A tested scheme: Least-mean-square based adaptive feedforward

Compensating signal

\[ \Delta U(V) \]

\[ t(s) \]

External mechanical → Mostly by helium system, unknown!
oscillations

\[ \Delta l(nm) \]

\[ t(s) \]

FFT

Detuning of the cavity

\[ \Delta f(Hz) \]

\[ t(s) \]

\[ \cdot H^{-1} \]

FIR Filter

Calculation of optimal FIR filter parameters

\[ W[n] \]

LMS

A. Neumann et al, Phys. Rev. ST Accel. Beams 13, 082001
Piezo based compensation results

**Piezo resolution seems to limit control of neighboring modes → transfer of energy**

**Multi-resonance control:**

Piezo resolution seems to limit control of neighboring modes → transfer of energy

**Resonances:** Control voltage of mV regime required before amplifier

**Single-resonance control:**

- $\sigma_f = 2.52$ Hz
- $\sigma_f = 0.89$ Hz
- $\sigma_f = 0.36$ Hz

**Open loop**

- $s_f = 2.52$ Hz
- Feedback only
  - $s_f = 0.89$ Hz
- Feedback and Feedforward
  - $s_f = 0.36$ Hz

**Results:**

- $Q_L = 6.4 \times 10^7$
LLRF studies with U Cornell: Limits of $Q_L$

9 cell TESLA cavity
$E_{acc} = 10-12$ MV/m
$T_{bath} = 1.8$ K
PI piezo loop
8/9-$\pi$ filter optimized
$\sigma_f = 5-10$ Hz,
$\Delta f_{peak} = 15-25$ Hz

$Q_L$ | $\sigma_\phi$ (deg.)
--- | ---
$5 \cdot 10^7$ | 0.008°
$1 \cdot 10^8$ | 0.0093°
$2 \cdot 10^8$ | 0.0236°

$1^{st}$ MEM

$f_{1/2} = 13$ Hz

$\log(\sigma_\phi)$

$Cavity$ $field$ $trip$

Areas with $\sigma_\phi > 0.1$ were blanked out

$LF$ $detuning \rightarrow IOT$ beam instable
SRF Gun for bERLinPro: Stability issues

- Thermal short $\rightarrow$ high static losses (20 W) trial to cool via filling line, no phase separator, thus flash gas lead to bubble formation beating the cavity up to 3 kHz (PLL-mode)!

- SRF gun cavities have high sensitivity to Lorentz force, up to 3 kHz tuning for target field required, higher probability of ponderomotive instabilities

- Several cooling media attached to cavity and ancillaries:
  - Cooling of normal conducting cathode via 80K helium gas $\rightarrow$ Vibration of cathode? Would act as a plunger modulating the TM_{010}-$\pi$ mode (depending on cathode position)
  - 80 K cooling of HOM absorber....
Some example during SRF gun operation

- This instability was affected by DC bias voltage in cathode channel
- This is used to mitigate Multipacting
- Strong correlation with vacuum activity
- Piezo in lowpass PI loop

RF Phase

$$\sigma_f = 9 \text{ Hz}$$

Forward Power

No direct correlation to loop gain!

Poisson result: Courtesy J. Völker

DC bias simulation

Single-Sided Amplitude Spectrum of $$\phi(t)$$
**SRF gun cavity LLRF operation**

**Piezo tuner transfer function**

- $Q_L = 2.83 \cdot 10^7$
- $\Delta f_{\text{peak}} = 20 \text{ Hz}$
- $\sigma_f = 9.8 \text{ Hz}$
- $\sigma_\phi = 0.03 \text{ deg}$
- $\sigma_A / A = 1.5 \cdot 10^{-4}$

**Stability paid by 4xpower overhead**

**Phase spectrum**

**Detuning spectrum**

- Controlled by lowpass PI piezo loop
- 1st mechanical eigenmode
- External narrowband excitation

To be controlled!
SRF gun cavity LLRF operation: Limits

Insufficient cooling of cathode

@25 MV/m, quench would occur after few minutes

DESY Nb/Pb gun

A lot of power dissipated in LHe bath → effect on microphonics?

First MEM at 220 Hz

Helium bath activity?

1st MEM
Message to be delivered

- Low beam-loaded high $Q_L$ operated multi-cell SRF elliptical cavities can be operate up to $Q_L$ of $2 \times 10^8$ with stability below $0.02^\circ$
  $\rightarrow$ For better stability $5-7 \times 10^7$
- Microphonics compensation can gain an order of magnitude and thus lower thermal load via FPC
- Major contributions bia excited mechanical eigenmode, often lowest transverse mode
- Excitation most probably transferred via helium system

- Special cavities like SRF guns demand for higher level of tuning control as they are more susceptible by design (half-cell)
- Operation at high losses or close to quench limit will open up new surprises, higher level of microphonics

Future studies $\rightarrow$

- Apply Kalman (A. Ushakov) and LMS feedforward control to SRF cavities as SRF gun, Booster 2-cell and Linac multi-cell
- Develop tuning strategies and firmware for high current and transient beam-loading cases (see talk P. Echevarria)
Questions?

Thanks to all collaborators and partners of the past, present and future projects and co-workers at HZB:

Further readings:
• A. Ushakov, P. Echevarria, A. Neumann Developing Kalman Filter Based Detuning Control with a Digital SRF CW Cavity Simulator Proc. of IPAC 2018, Vancouver, Canada, WEPAK012
Back-up slides down here
CW operation: A electro-magnetic-mechanical-thermo-acoustic coupled problem?

Cavity driven by LLRF at $E_0=15$ MV/m
Piezo compensation in PI loop mode with low-pass filtering, $Q_L=1.4\times10^7$

Additional power dissipated in $L_{\text{He}}$ bath by heater (few cm²) within liquid
Microphonics recorded while heater is powered

$P_{\text{heater}}$ (W) $\Delta f$ (Hz) rms

$T=1.5-1.9$K $P_{\text{LHe}}$ (mbar)

$Q_{\text{crit}}$ (W/cm²) $P_{\text{heater}}$ ($\Delta f_{\text{max}}$) (W)

T. Peterson, TESLA-Report 1994-18
LLRF studies: Summary

<table>
<thead>
<tr>
<th>$Q_L$</th>
<th>$\sigma_f$ (Hz)</th>
<th>$\sigma_\phi$ (deg)</th>
<th>$\sigma_A/A$</th>
<th>$P_f$ (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$5 \cdot 10^7$</td>
<td>9.5</td>
<td>0.008</td>
<td>$1 \cdot 10^{-4}$</td>
<td>1.106</td>
</tr>
<tr>
<td>$1 \cdot 10^8$</td>
<td>7.9</td>
<td>0.009</td>
<td>$2 \cdot 10^{-4}$</td>
<td>0.595</td>
</tr>
<tr>
<td>$2 \cdot 10^8$</td>
<td>4.2</td>
<td>0.024</td>
<td>$3 \cdot 10^{-4}$</td>
<td>0.324</td>
</tr>
</tbody>
</table>
Tuner dynamics: Higher order response?

Measured with first version of piezo frame (2005-2006)
Higher harmonic content most probably by piezo amplifier (even within drive signal?)
Measured at high excitation amplitudes (above 20 Hz)

Here complete detuning spectrum taken at a given excitation frequency

Usually transfer functions taken with lock-in amplifier to reduce noise content (Stanford Research, SR850)
Detuning spectrum versus bandwidth

For two different tuning schemes (Saclay I and INFN Blade) open loop measurements of microphonics vs. $Q_L$ were performed.

Both tuners showed to have different transfer functions and thus detuning spectra on the same cavity type!

\[
Q_{L,Saclay} = 3 \cdot 10^7 - 4 \cdot 10^8 \\
Q_{L,Blade} = 7 \cdot 10^5 - 2 \cdot 10^7
\]

Blade: Mechanical eigenmode at 300 Hz, vacuum pump freq.

Saclay: Excitation of 1\textsuperscript{st} mechanical eigenmode sets in