HZB Helmholtz Zentrum Berlin
bERLinPro
BESSY VSR

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Microphonics control studies for high Q_L SRF Cavities

Module commissioning of the bERLinPro SRF Gun

MRCW18
Second Topical Workshop on Cryomodule Microphonics and Resonance Control
LLRF Workshop Series

Second Topical Workshop on Cryomodule Microphonics and Resonance Control, Brooklyn, NY

Systems under study

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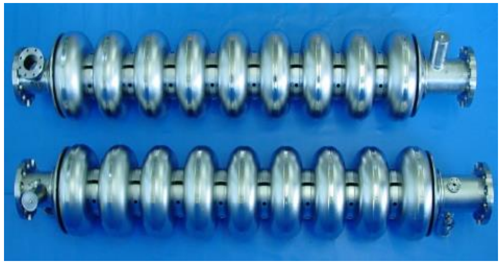
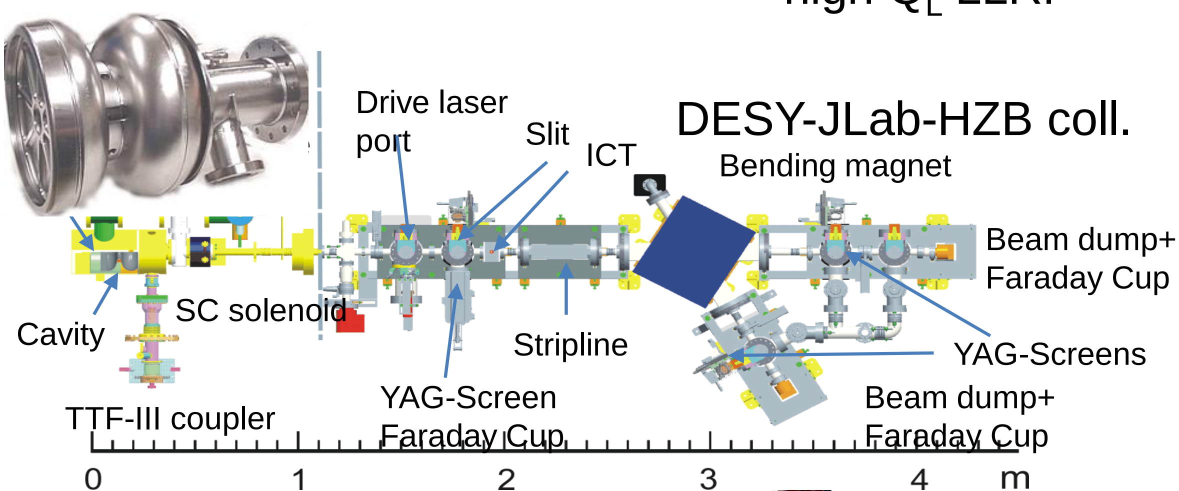
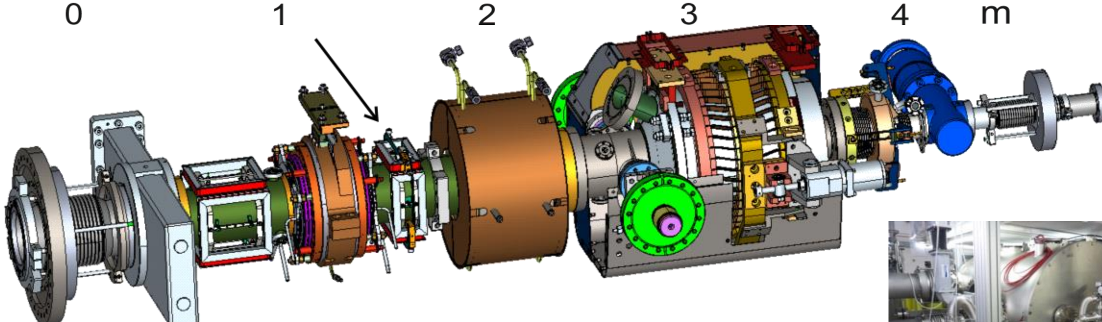


- CW modified TESLA cavity for BESSY-FEL (2005-2008)
  - Studied mainly at HTS (HoBiCaT)
  - Q_L from $5{\cdot}10^6$-$2{\cdot}10^8$, E_{acc}=8-22 MV/m
  - CW studies, heat load, microphonics compensation high Q_L LLRF



- Nb Pb lead cathode DESY gun (1.6 cell), 2011-2012
  - Studied with diagnostics beamline
  - E_0=12-25 MV/m
  - $Q_L=3{\cdot}10^6$-$1.5{\cdot}10^7$
  - $\Delta f/\Delta P$=100 Hz/mbar $\Delta f/\Delta E_0^2$=1 Hz/(MV/m)^2



bERLinPro ERL medium power SRF gun cavity cold string

- SRF Photoinjector (ERL), today
  - Studied with diagnostics beamline + cathode transfer
  - E_0=12-25 MV/m
  - QL=$1{\cdot}10^7$-$2.8{\cdot}10^7$
  - $\Delta f/\Delta P$=33 Hz/mbar $\Delta f/\Delta E_0^2$=3.4 Hz/(MV/m)^2

Microphonics: How does it appear?

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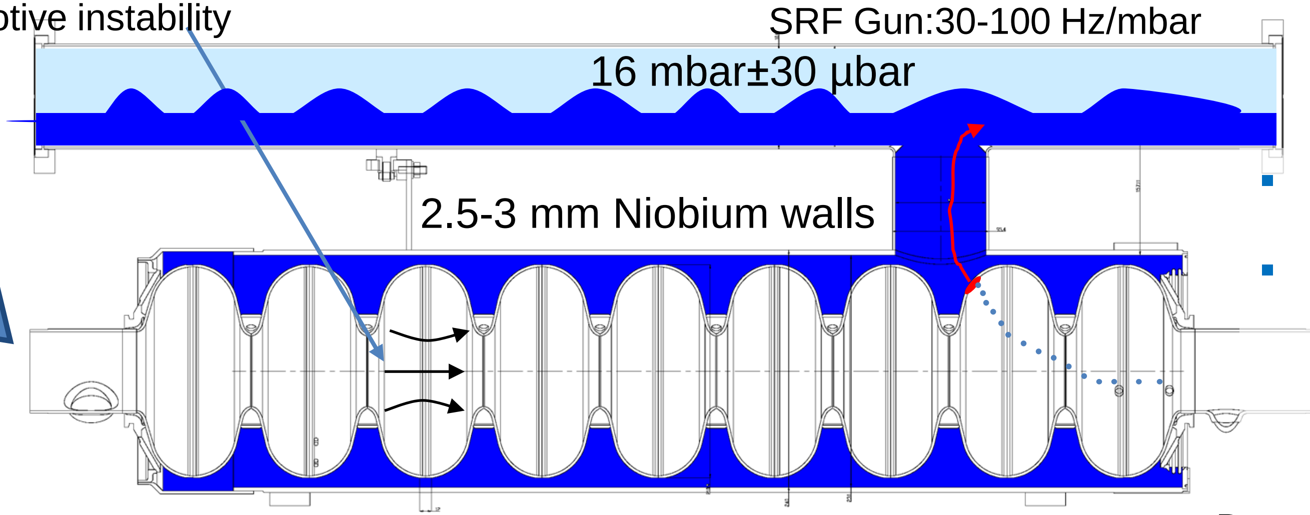
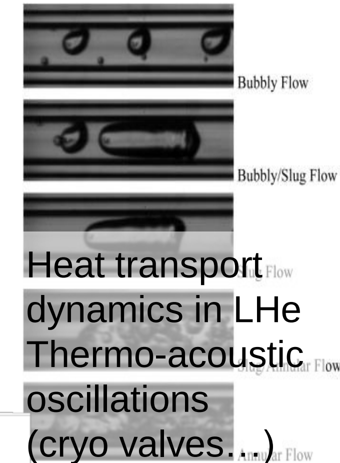
- Field amplitude variation:
  Dynamic Lorentz force, $\Delta f / \Delta E_{acc}^2 = 1\text{-}3 \text{Hz}/(\text{MV/m})^2$
  → Ponderomotive instability

- Helium pressure fluctuations
  $\Delta f / \Delta p$ = 50-60 Hz/mbar,
  SRF Gun:30-100 Hz/mbar





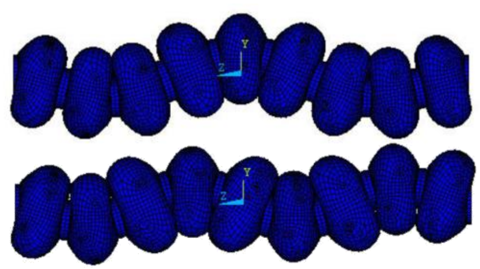
- Heat transport dynamics in LHe
- Thermo-acoustic oscillations (cryo valves…)

- Stochastic background noise

- Deterministic, narrow-band sources: Vacuum pumps

Mechanical oscillations of the Cavity: Microphonics

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



222 Hz
G. Bissofi
151 Hz

Lowest modes: Usually transverse

Is that the whole story?

G.P. Gelata et al. International Journal of Thermal Sciences Volume 58, August 2012, Pages 1-8

Microphonics: What do we see?

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- The cavity is the best sensor of mechanical excitation itself, true?
  → What deformation affects actually the RF mode (TM_{0yz} different than e.g. TM_{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_{010} π-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?

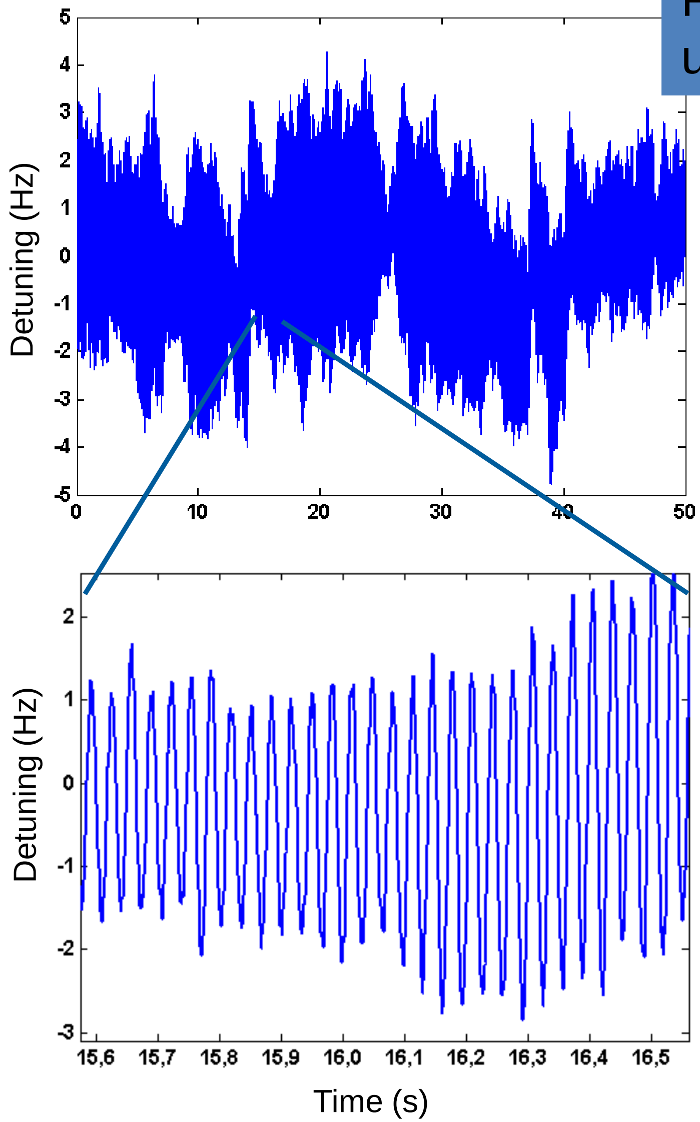
<u>Be aware of other contributions to appear in the signal:</u>

- Transient beam-loading (hopefully repetitive, but what about beam losses in recirculating machines?) ←→ 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)

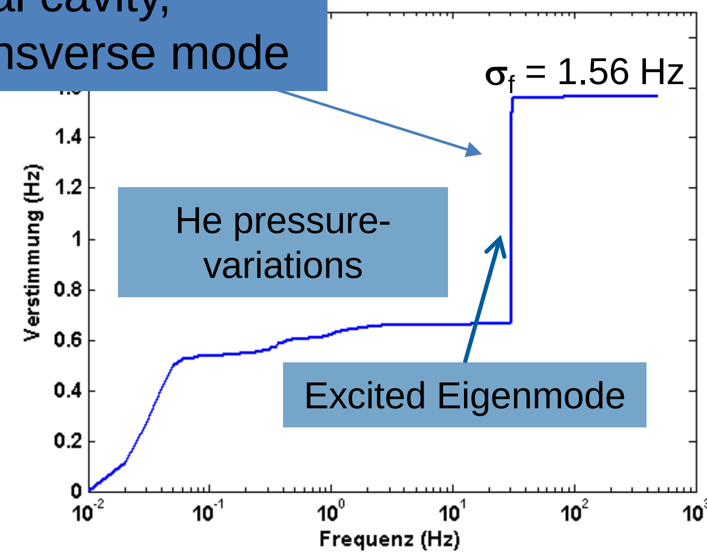
→ Some of them alter the measurement, some are real detuning, but eventually not tackled by tuners

Detuning characterization of a TESLA cavity, short-term

For elliptical cavity, usually transverse mode



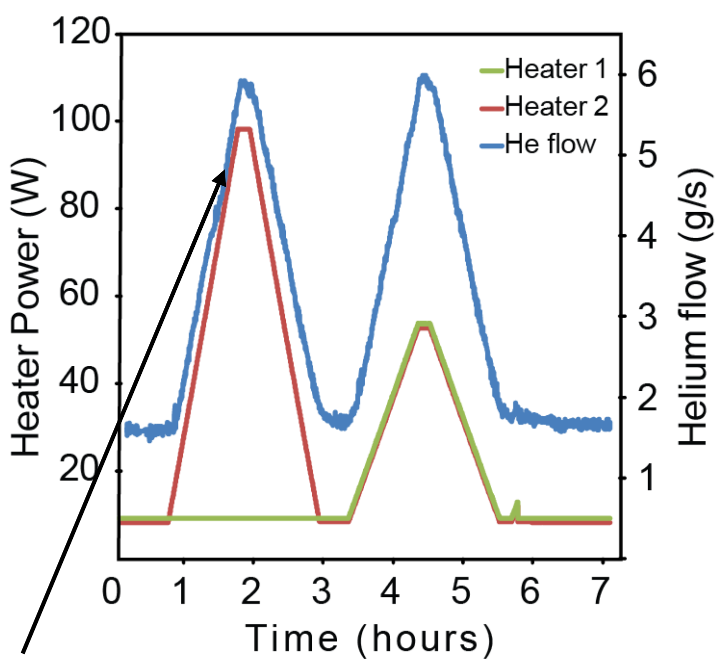
ΣFFT



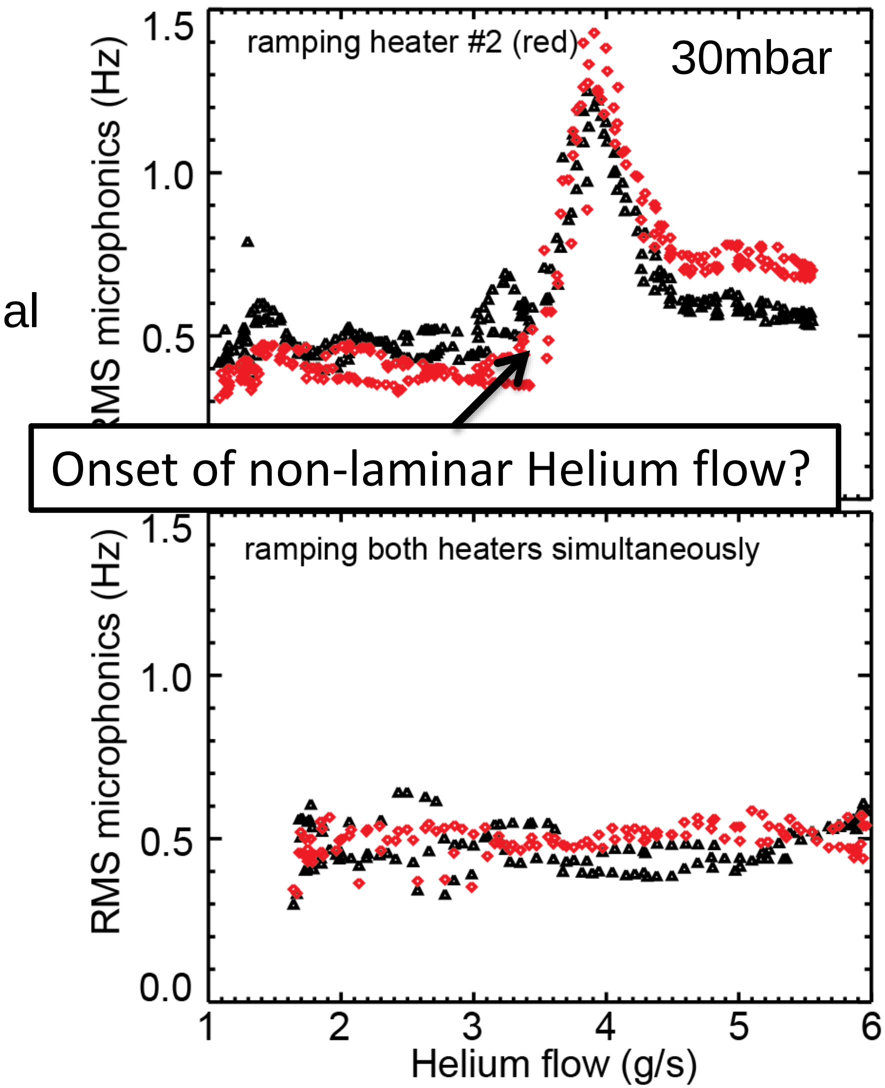
- HoBiCaT: σ_f = 1 - 5 Hz (rms)
  ←→ 2-13° phase error (Aim: 10^{-2} °)
  „open loop" „closed loop"
- He pressure variations: f_{mod} < 1 Hz
- Cavity specific: First mode at 20 - 50 Hz
- Spectrum can appear more populated
  → depends on cavity system

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



Chimney limit



Correlation of Helium pressure and detuning of cavity

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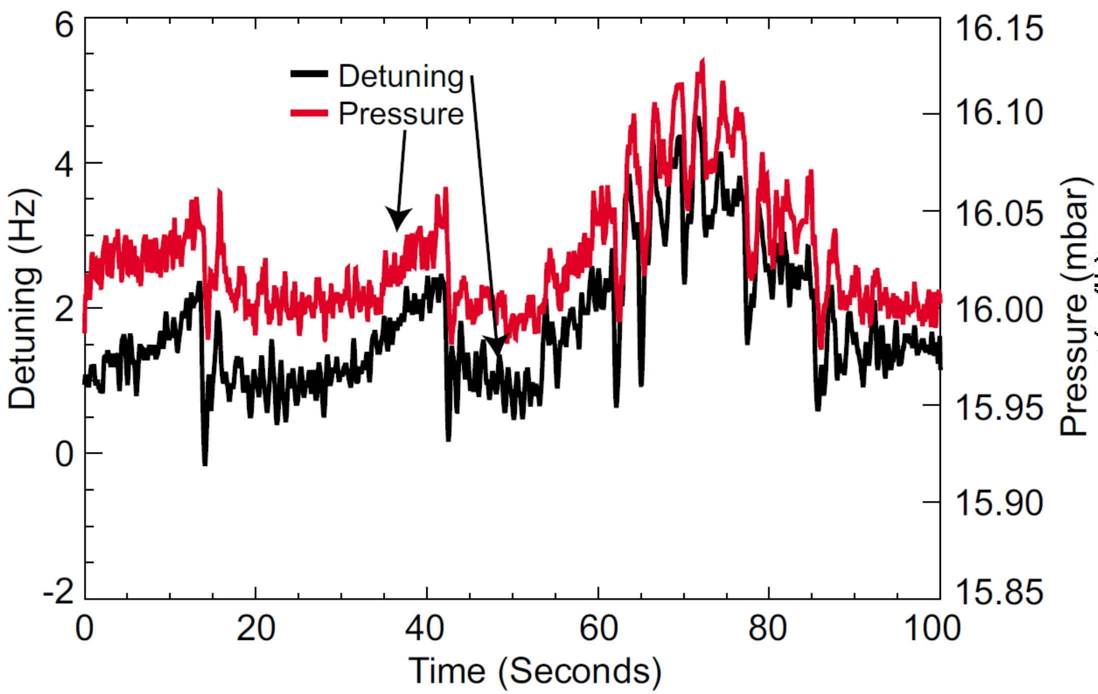

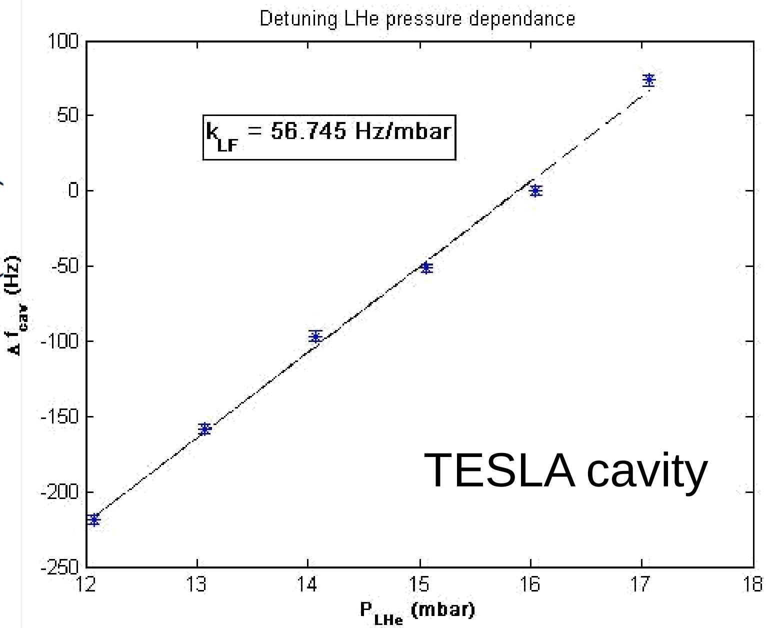

- Open loop measurement of cavity frequency and He pressure
- 50-60 Hz/mbar down to resolution limit of pressure meters (~1Hz)
- Evidence that main contribution of microphonics mediated through superfluid Helium

Longterm stability: Peak events→ how much, how often?

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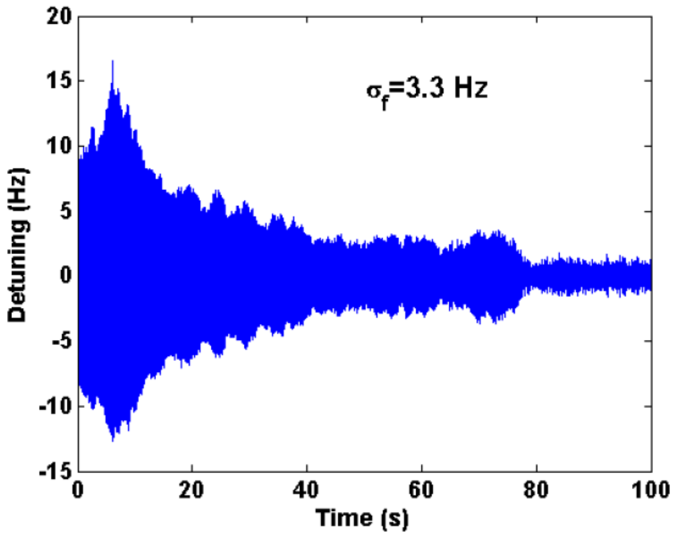
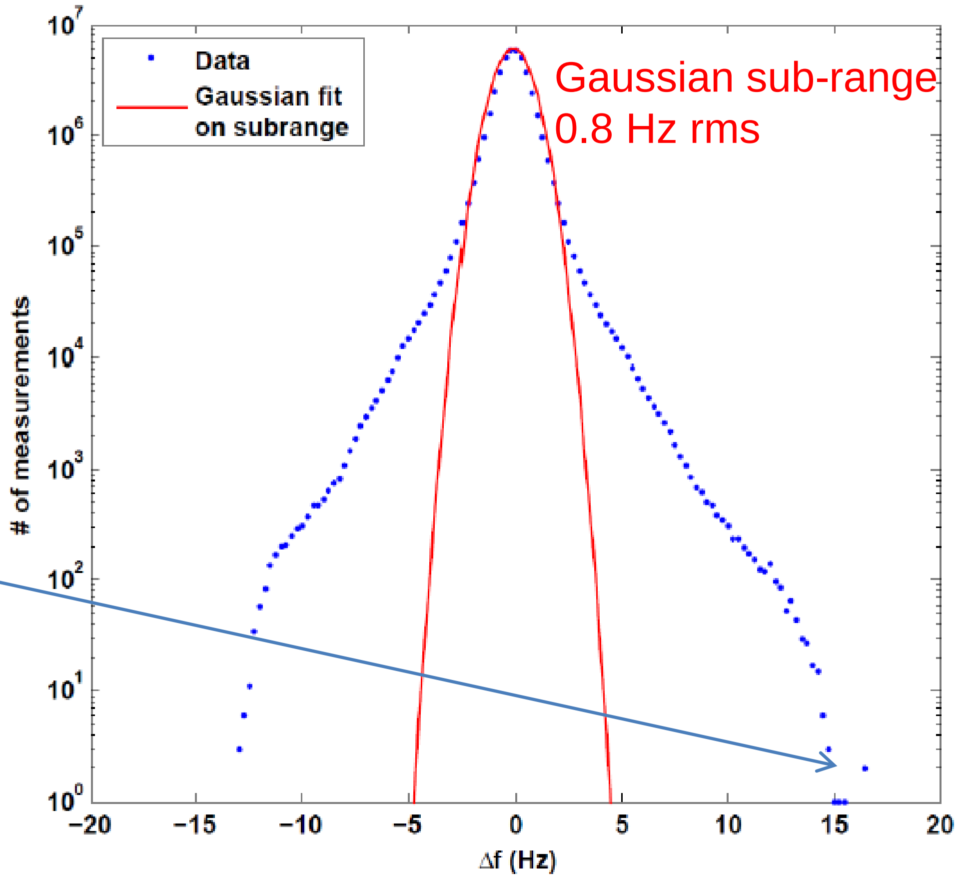
Microphonics recorded at HoBiCaT with TESLA cavity for 48 hours at E_{acc}=8MV/m

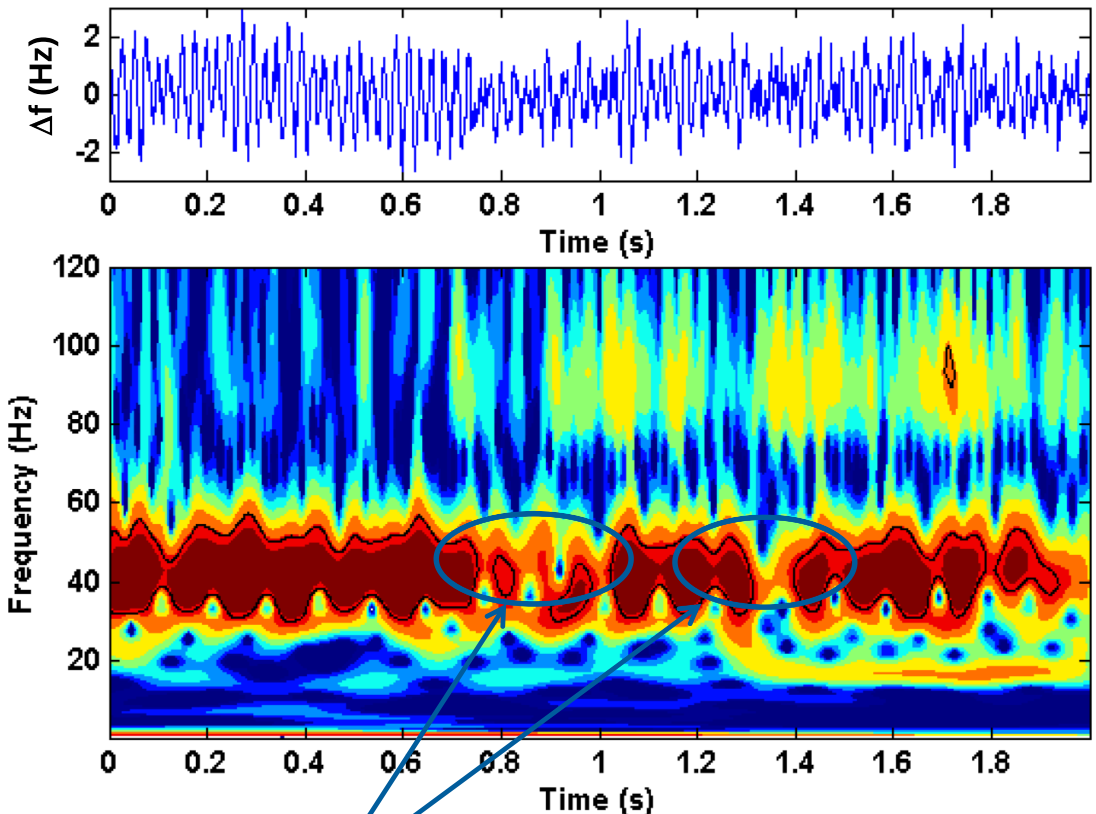
- RMS Values around 1-5 Hz ← Determines field stability and thermal loading of RF system (5 kW)
- Peak values extend out to 17 σ! ← Determines RF power installation (15 kW)
- Peak events occur 10-20 times a day! (This was partly improved by changes to the control settings of the under-press. pumps.)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

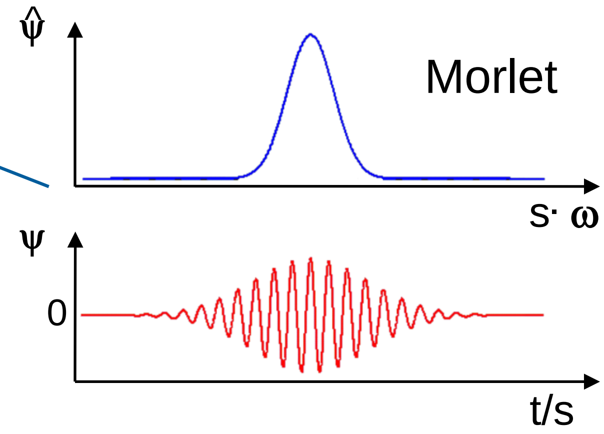




Excited 1st mech. resonance: Transverse mode

Time-frequency analysis by Wavelets





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

- Variation up to Δf =10 Hz on a ~100 ms time scale → Adaptive, „learning“ (dynamic) compensation mandatory
- Spectrum of He-pressure variations of stochastic nature → Need for classic feedback control

Tuner qualification

Tested 3(4) different tuner systems



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

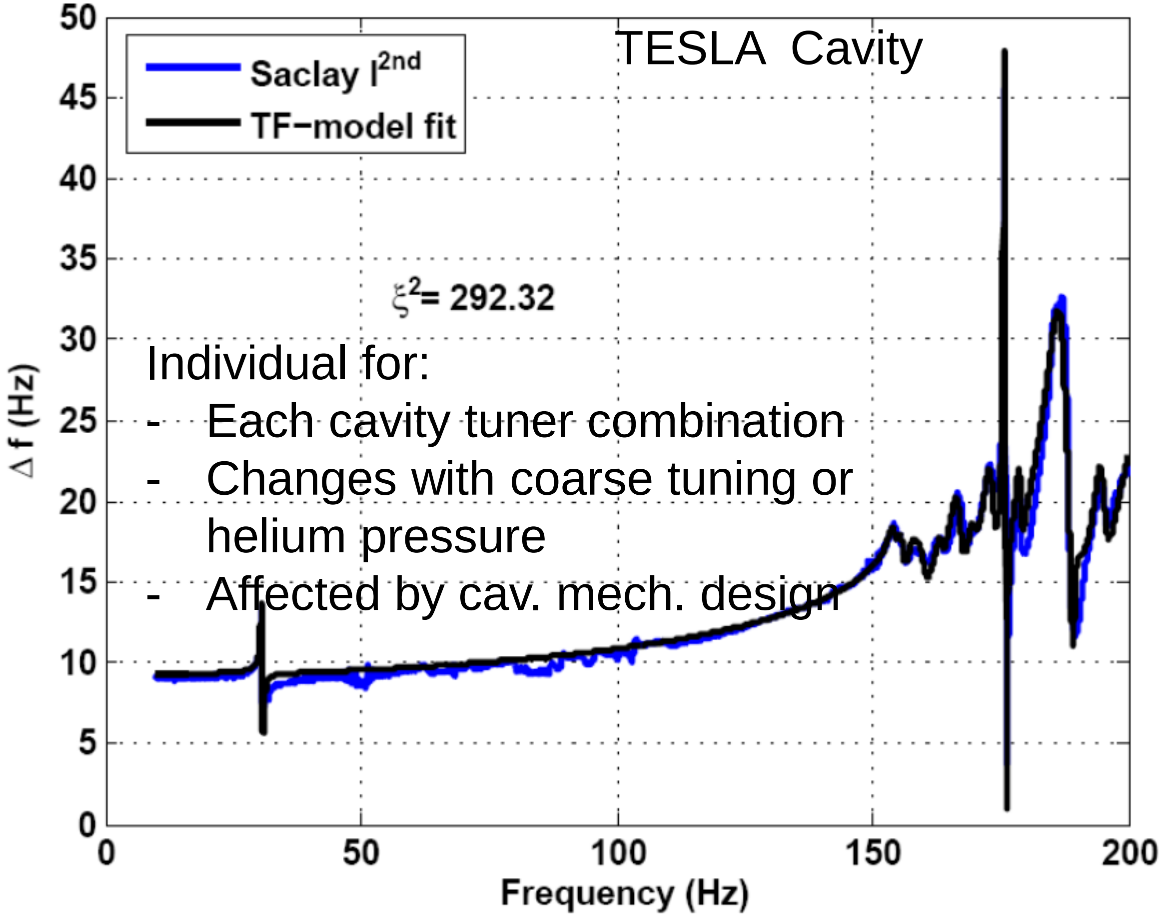
→ Important for CW piezo based detuning control

* 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

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

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



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

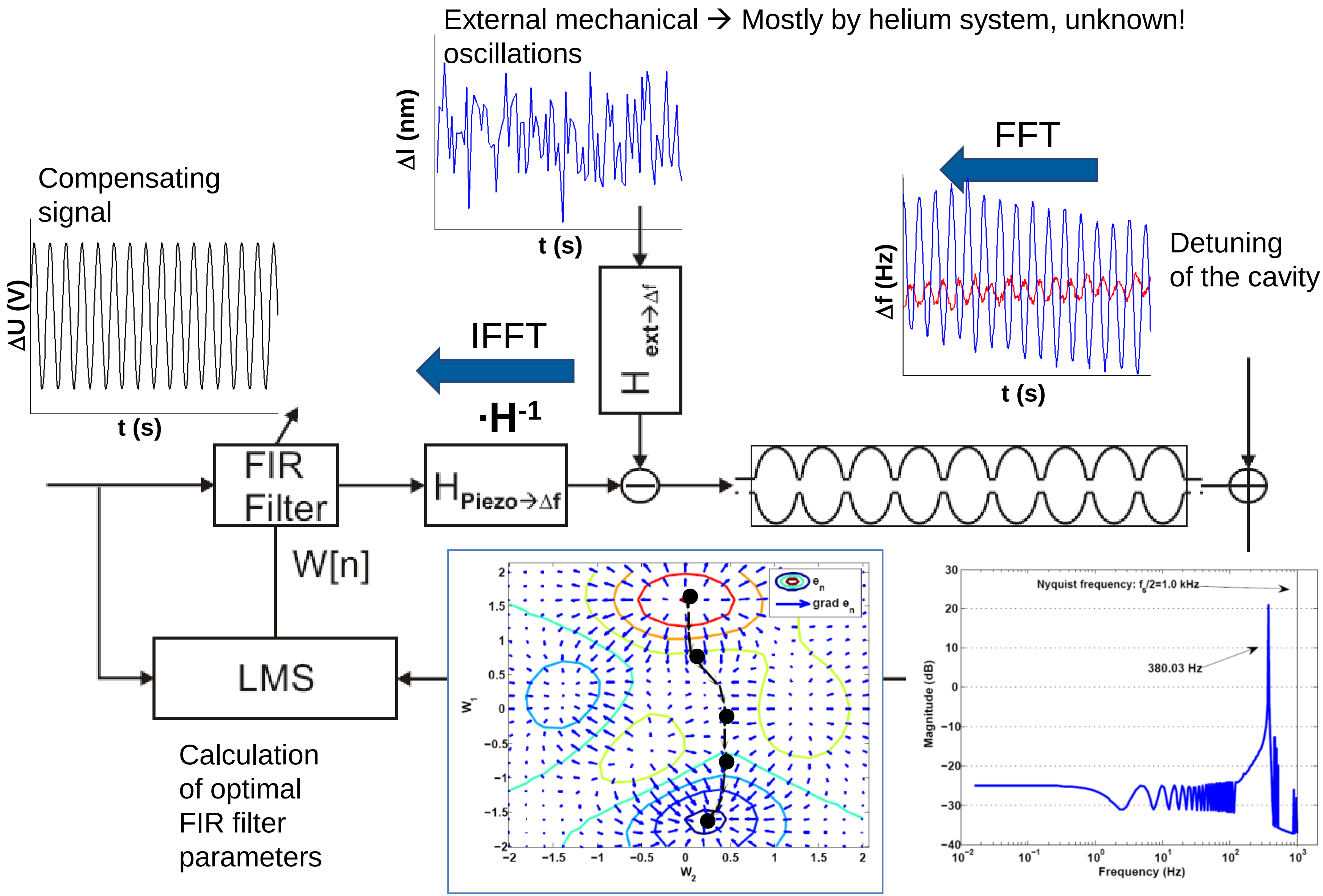
← Relevant for tuning →

But: Only LF and piezo transfer functions accesible in operation!

- 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

A tested scheme: Least-mean-square based adaptive feedforward



A. Neumann et al, Phys. Rev. ST Accel. Beams 13, 082001

Piezo based compensation results

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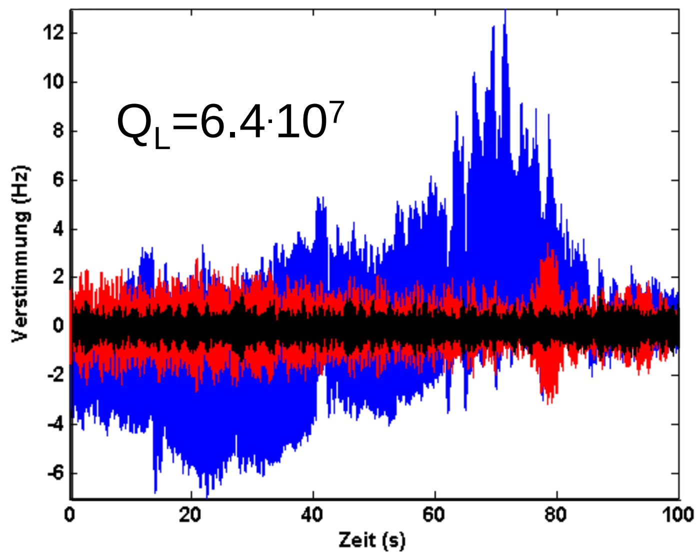


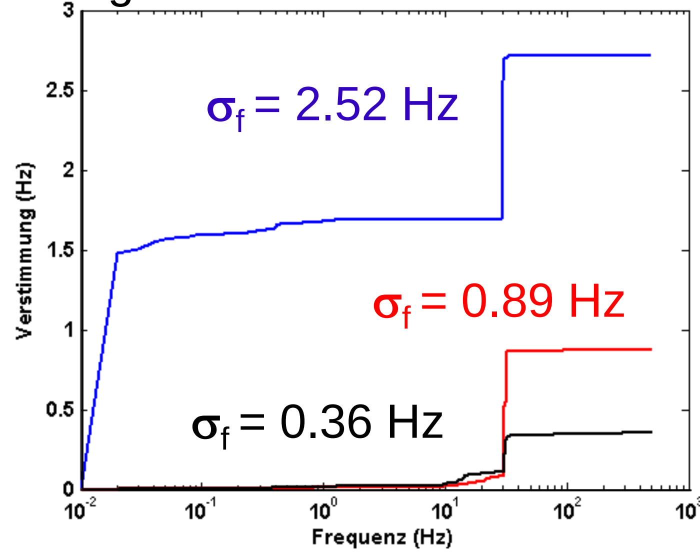
ΣFFT

Open loop

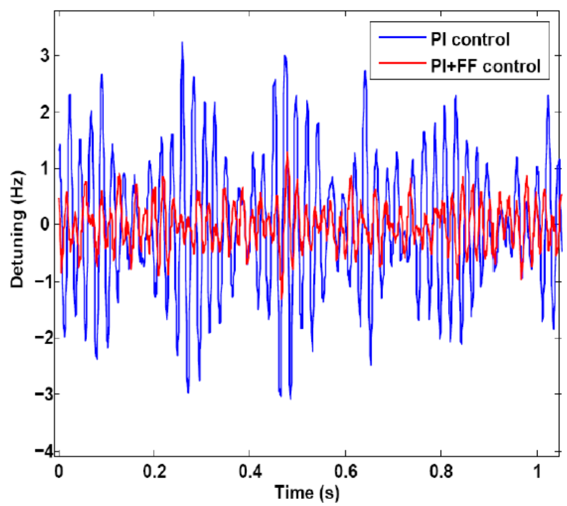
Feedback only

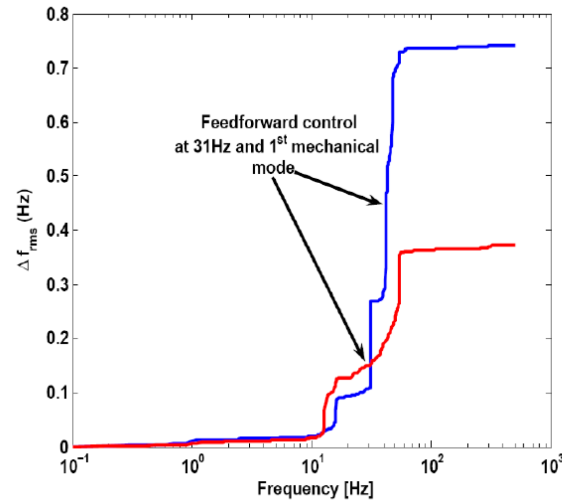
Feedback and Feed-forward

Single-resonance control:



14 deg phase mod. down to 2 deg → sub-promille stability in theory possible





Multi-resonance control:

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

Resonances: Control voltage of mV regime required before amplifier

LLRF studies with U Cornell: Limits of Q_L

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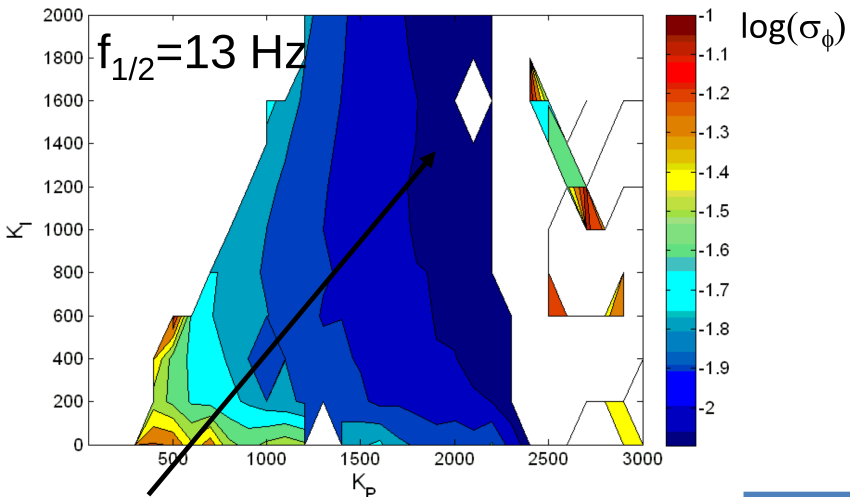
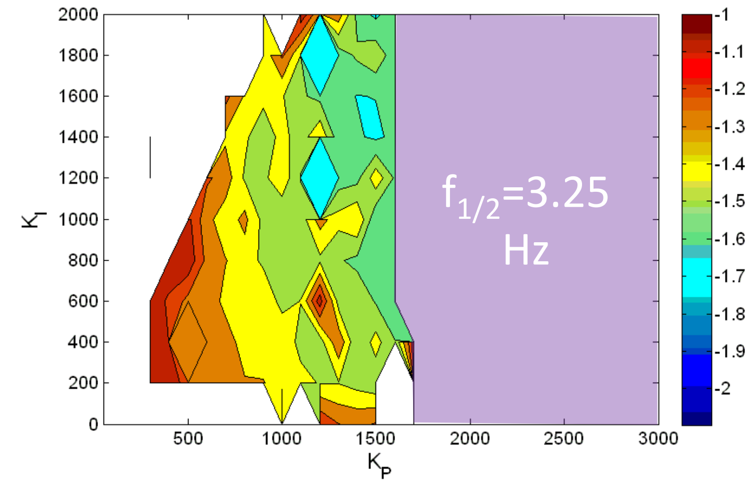
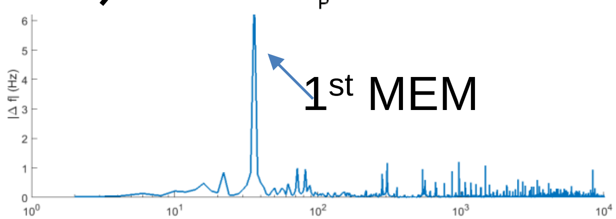
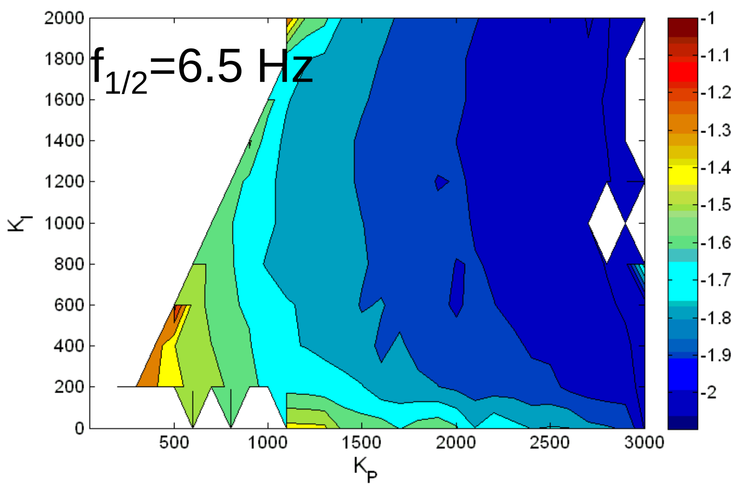








Q_L	σ_ϕ (deg.)
$5 \cdot 10^7$	0.008°
$1 \cdot 10^8$	0.0093°
$2 \cdot 10^8$	0.0236°

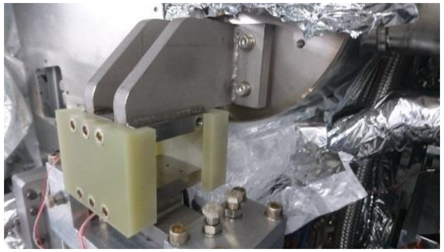
9 cell TESLA cavity
E_{acc}= 10-12 MV/m
T_{bath}= 1.8 K
PI piezo loop
8/9-π filter optimized
σ_f = 5-10 Hz,
Δf_{peak}= 15-25 Hz

LF detuning → IOT beam instable

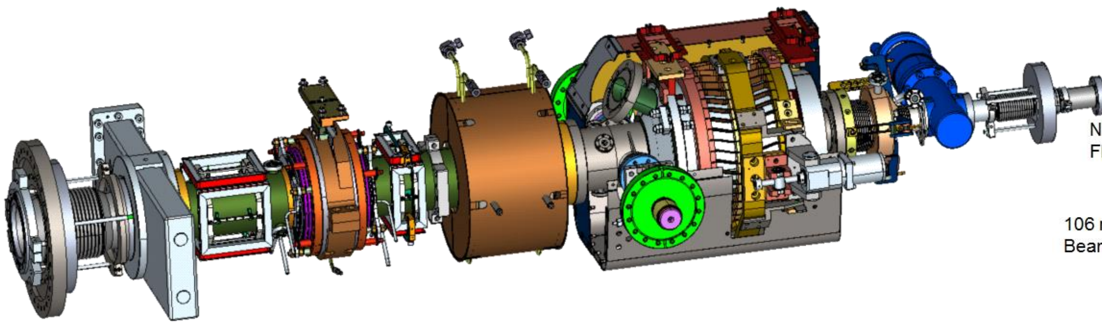
Cavity field trip

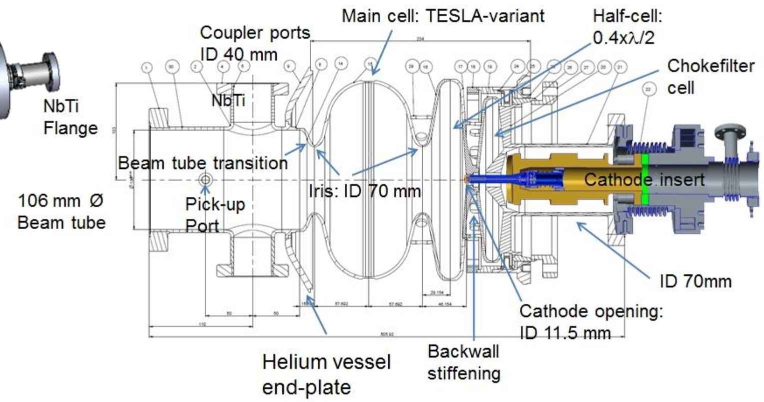
Areas with σ_ϕ>0.1 were blanked out

SRF Gun for bERLinPro: Stability issues



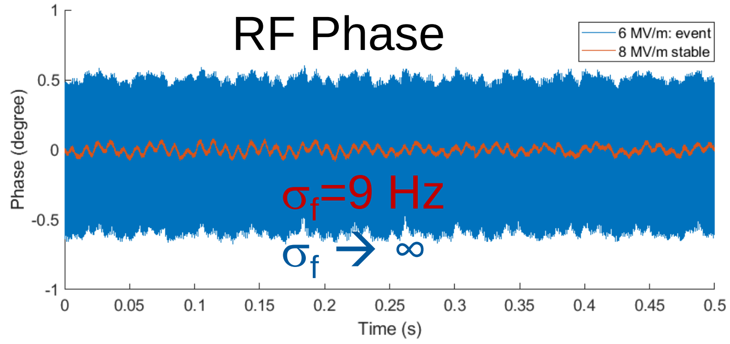
- Thermal short → high static losses (20 W)
  trial to cool via filling line, no phase separator,
  thus flash gas lead to bubble formation beating the cavity
  up to 3 kHz (PLL-mode)!

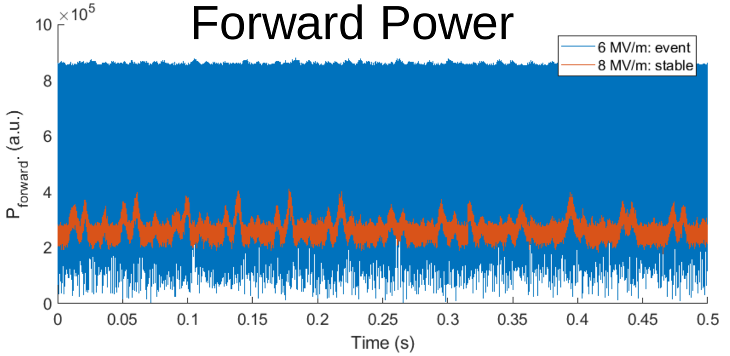


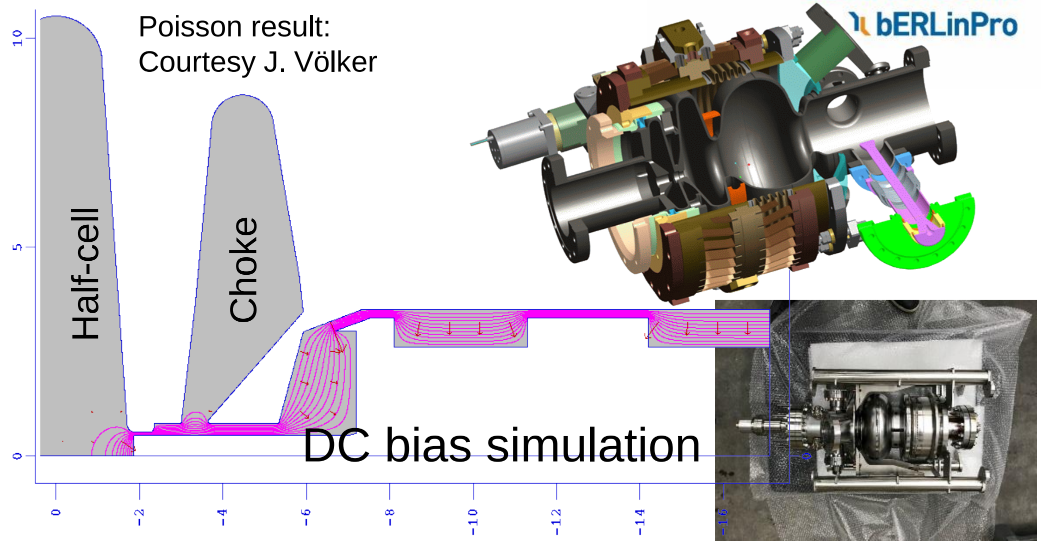


- SRF gun cavities have high sensitivity to Lorentz force, up to 3 kHz tuning for target field required, higher probability of ponderomotive instabilities
- Several cooling media attached to cavity and ancillaries:
  Cooling of normal conducting cathode via 80K helium gas
  → Vibration of cathode? Would act as a plunger modulating the TM_{010}-π mode (depending on cathode position)
- 80 K cooling of HOM absorber….

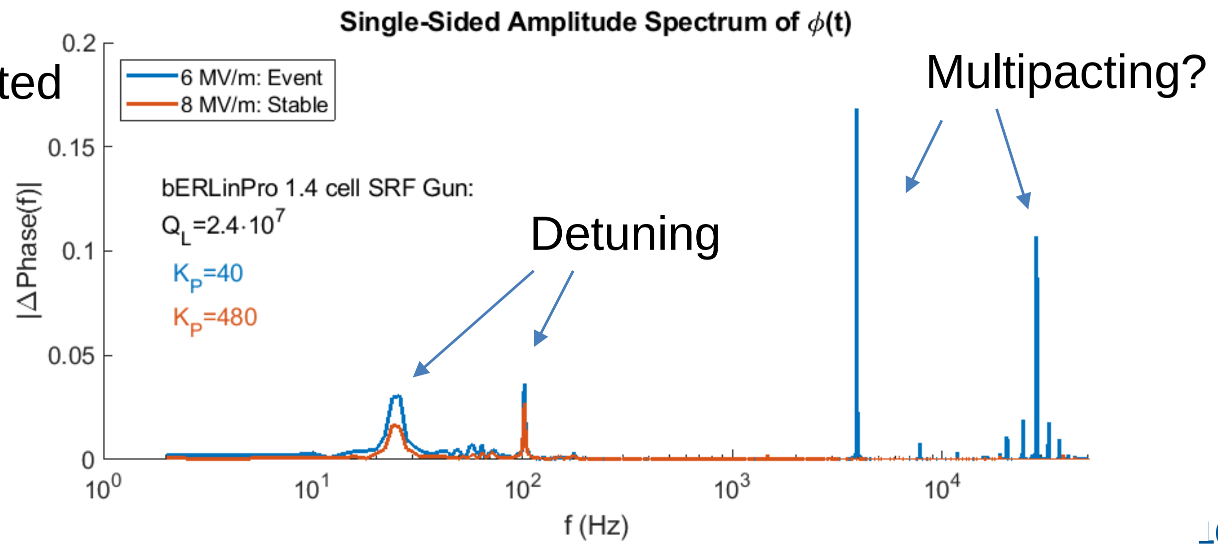
Some example during SRF gun operation





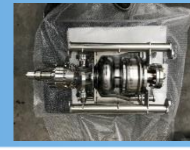


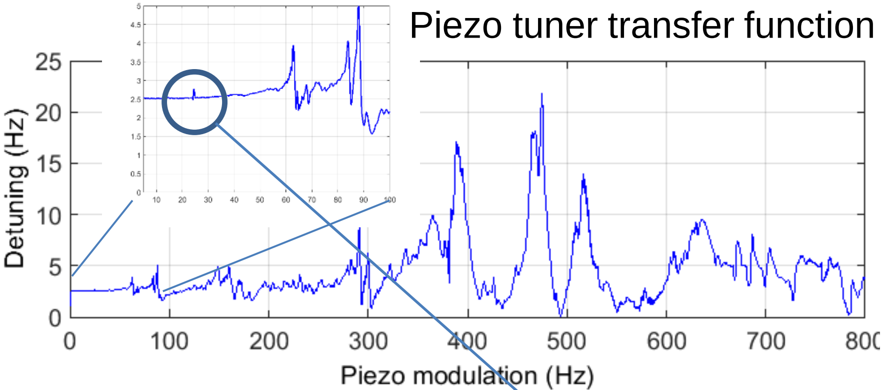
No direct correlation to loop gain!

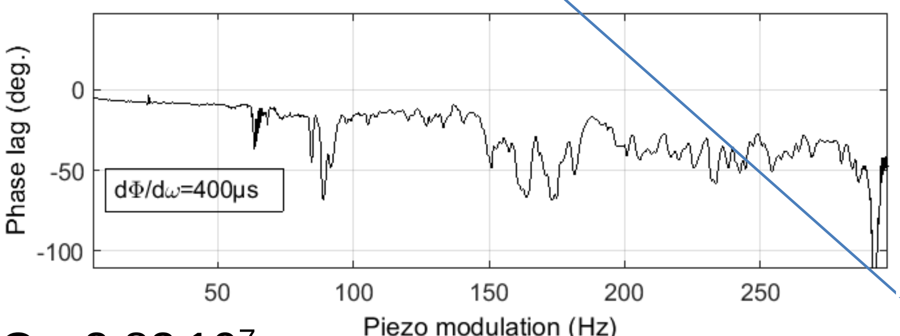


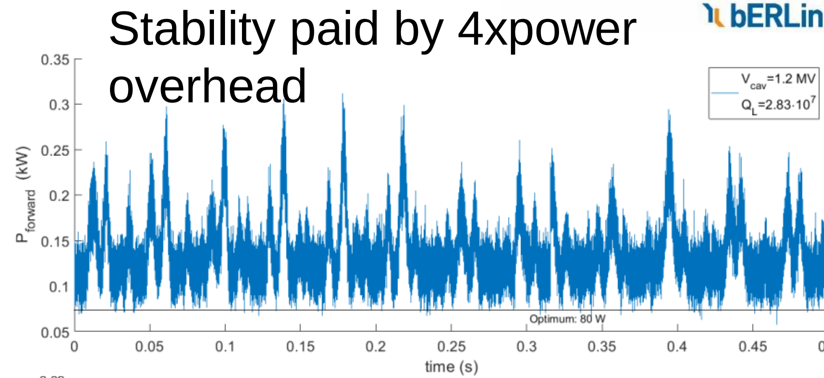
- This instability was affected by DC bias voltage in cathode channel
- This is used to mitigate Multipacting
- Strong correlation with vacuum activity
- Piezo in lowpass PI loop

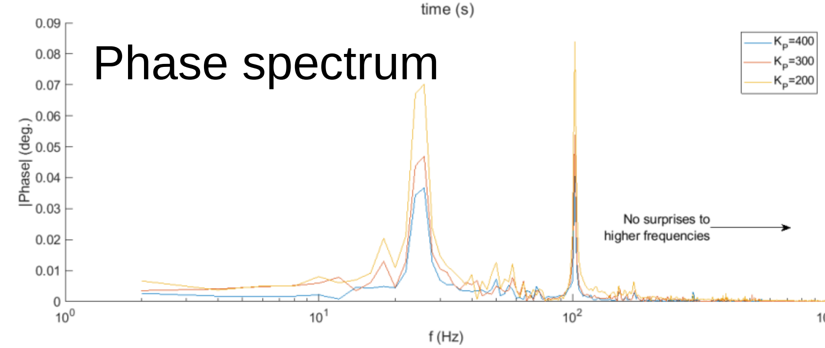
SRF gun cavity LLRF operation











$Q_L = 2.83 \cdot 10^7$

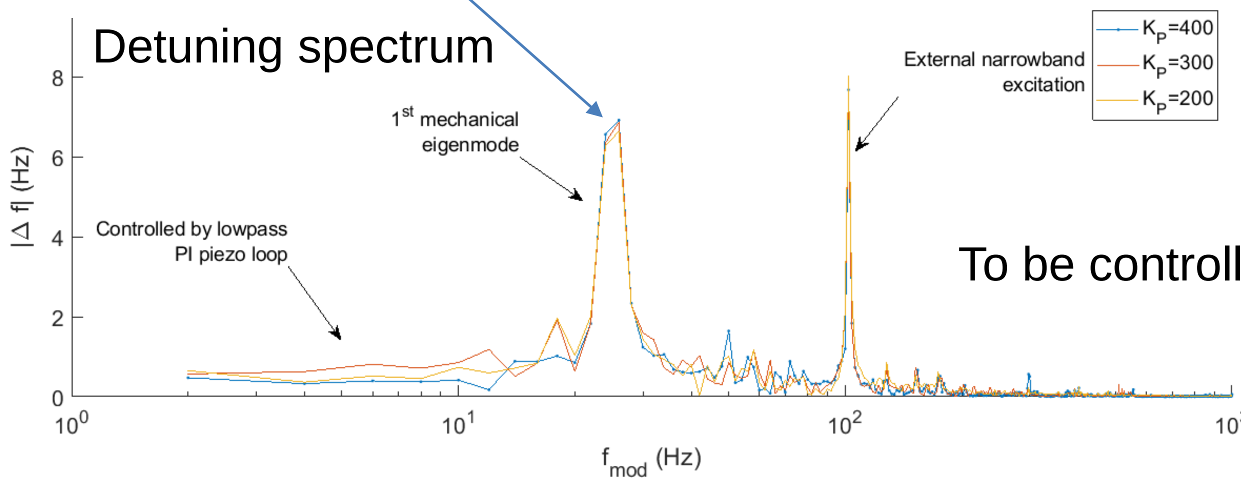
$\Delta f_{peak} = 20$ Hz

$\sigma_f = 9.8$ Hz

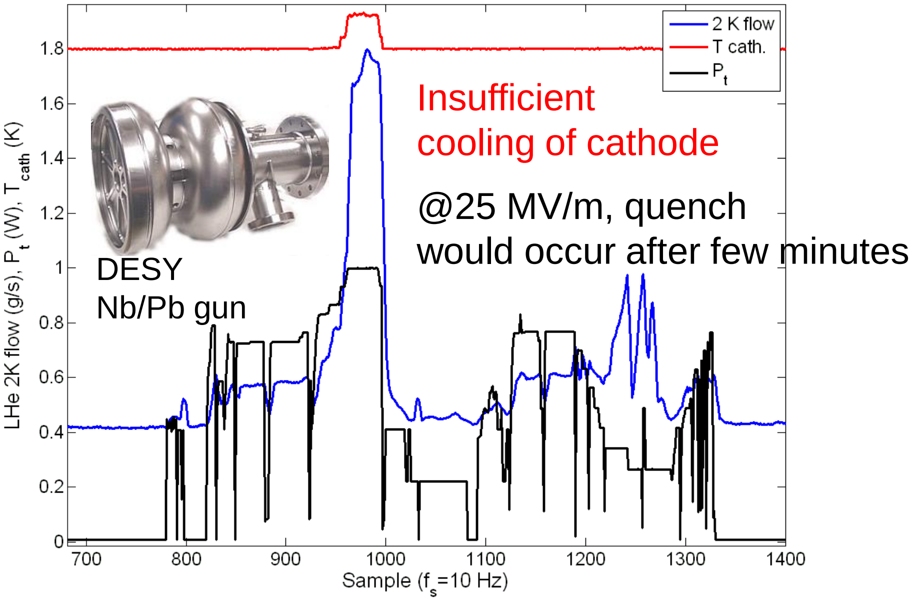
→

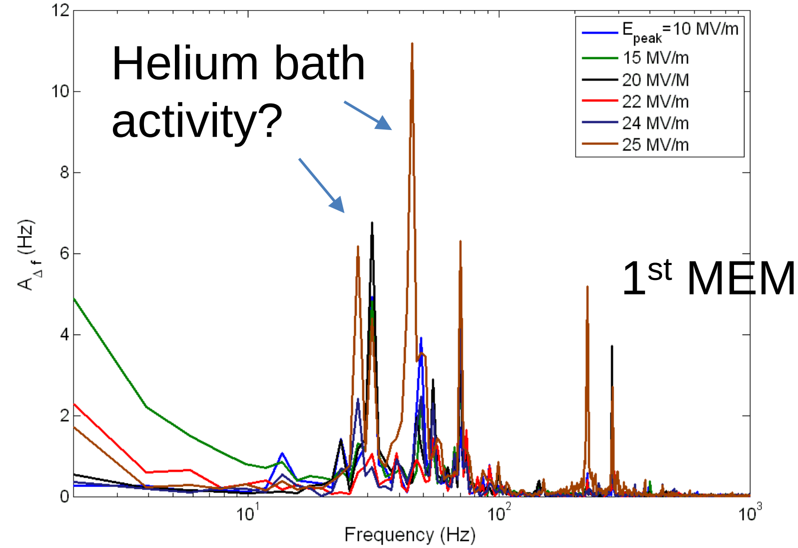
$\sigma_\phi = 0.03$ deg.

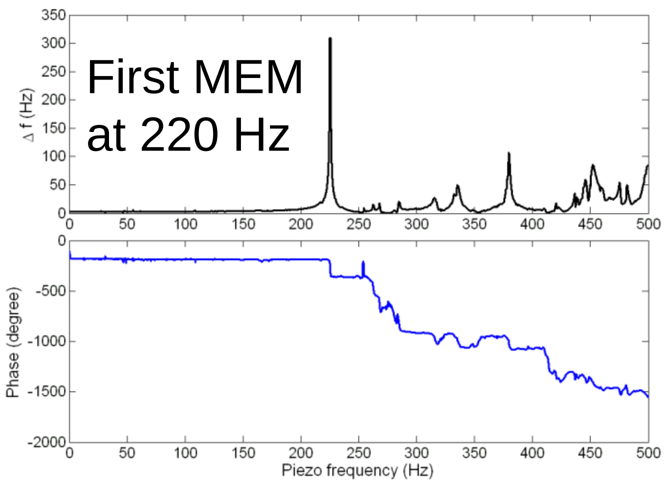
$\sigma_A / A = 1.5 \cdot 10^{-4}$

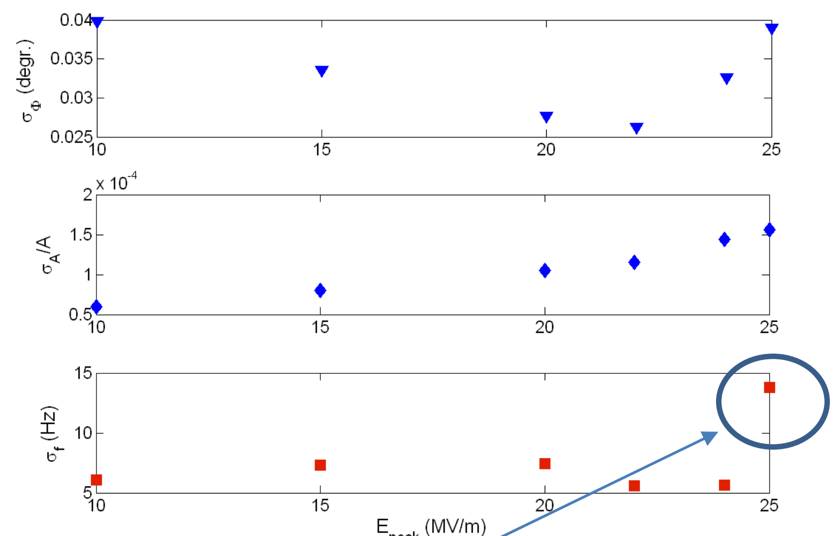


SRF gun cavity LLRF operation: Limits









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

Message to be delivered

- Low beam-loaded high Q_L operated multi-cell SRF elliptical cavities can be operate up to Q_L of $2{\cdot}10^8$ with stability below 0.02°
  → For better stability $5\text{-}7{\cdot}10^7$
- 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 →

- 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?

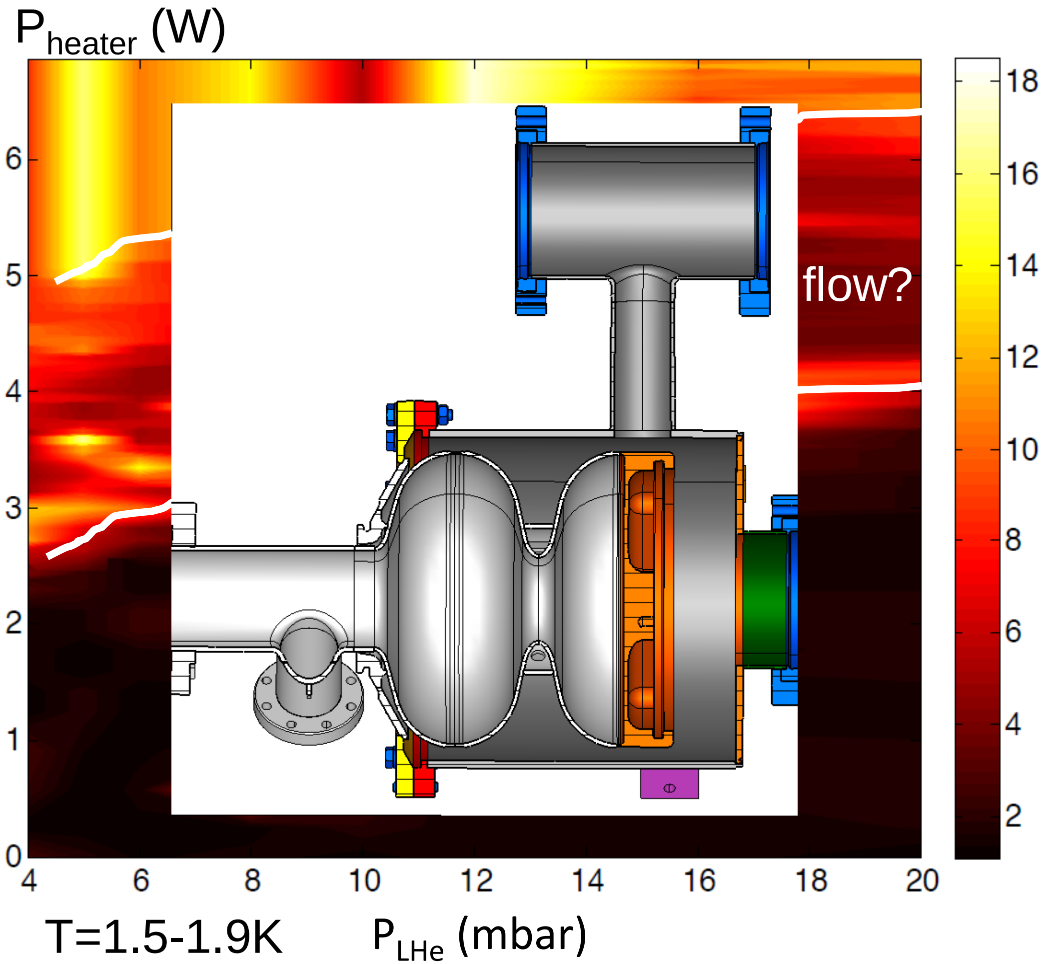
Thanks to all collaborators and partners of the past, present and future projects and co-workers at HZB:

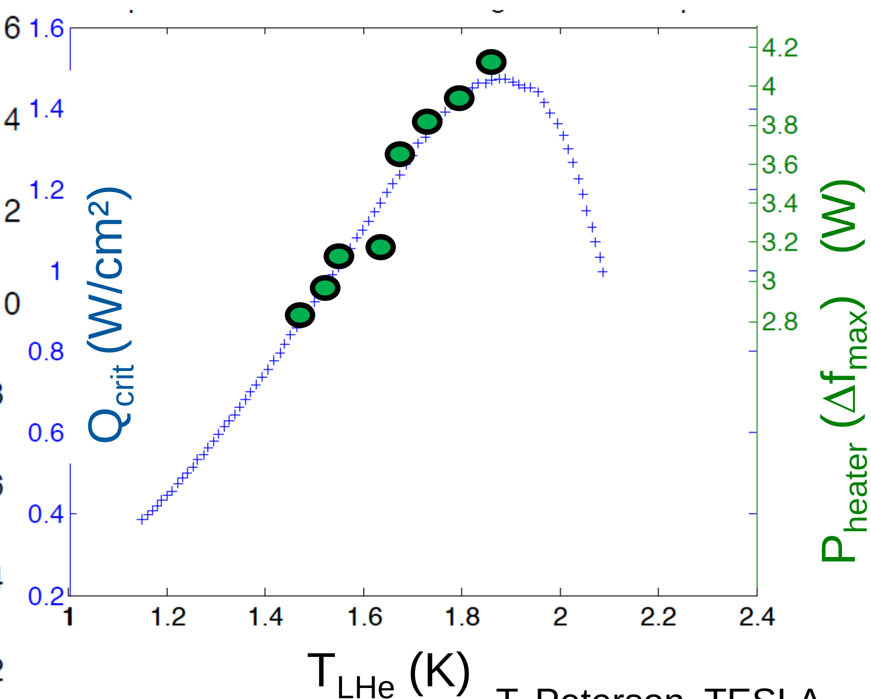
Further readings:

- A. Neumann, W. Anders, O. Kugeler, J. Knobloch (2010). "Analysis and active compensation of microphonics in continuous wave narrow-bandwidth superconducting cavities", Phys. Rev. ST Accel. Beams 13, 082001.
- O. Kugeler, A. Neumann, W. Anders, J. Knobloch (2010). "Adapting TESLA technology for future cw light sources using HoBiCaT", Rev. Sci. Inst. 81 (7).
- 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?



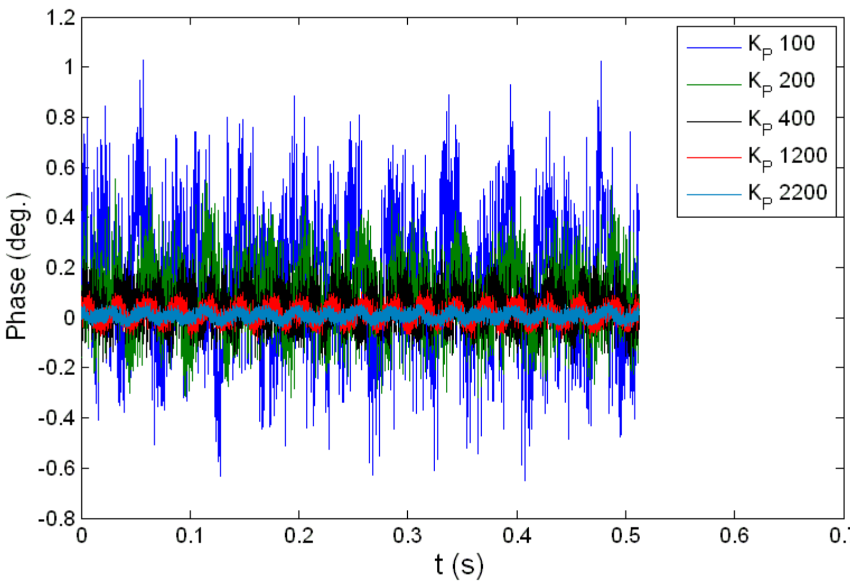


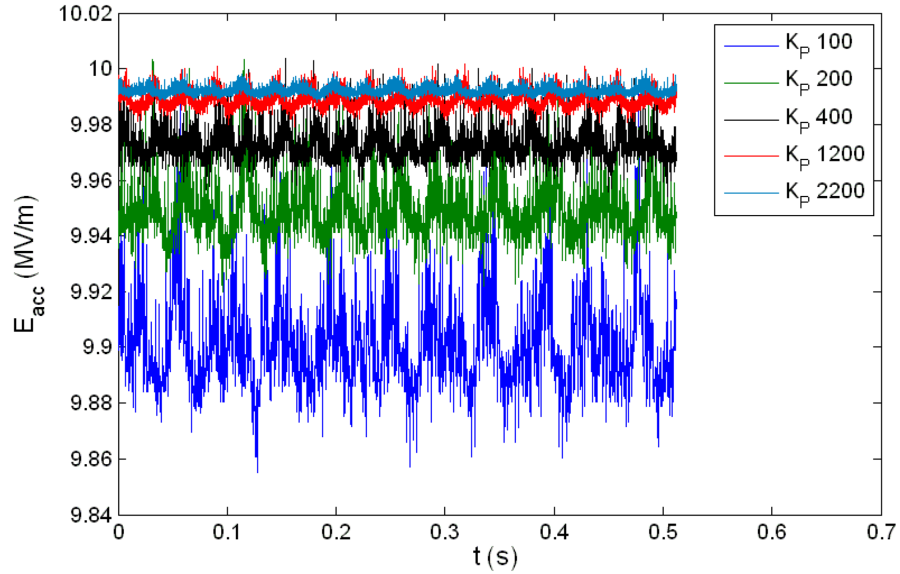
T. Peterson, TESLA-Report 1994-18

Cavity driven by LLRF at E_0=15 MV/m
Piezo compensation in PI loop mode
with low-pass filtering, Q_L=1.4·10^7

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

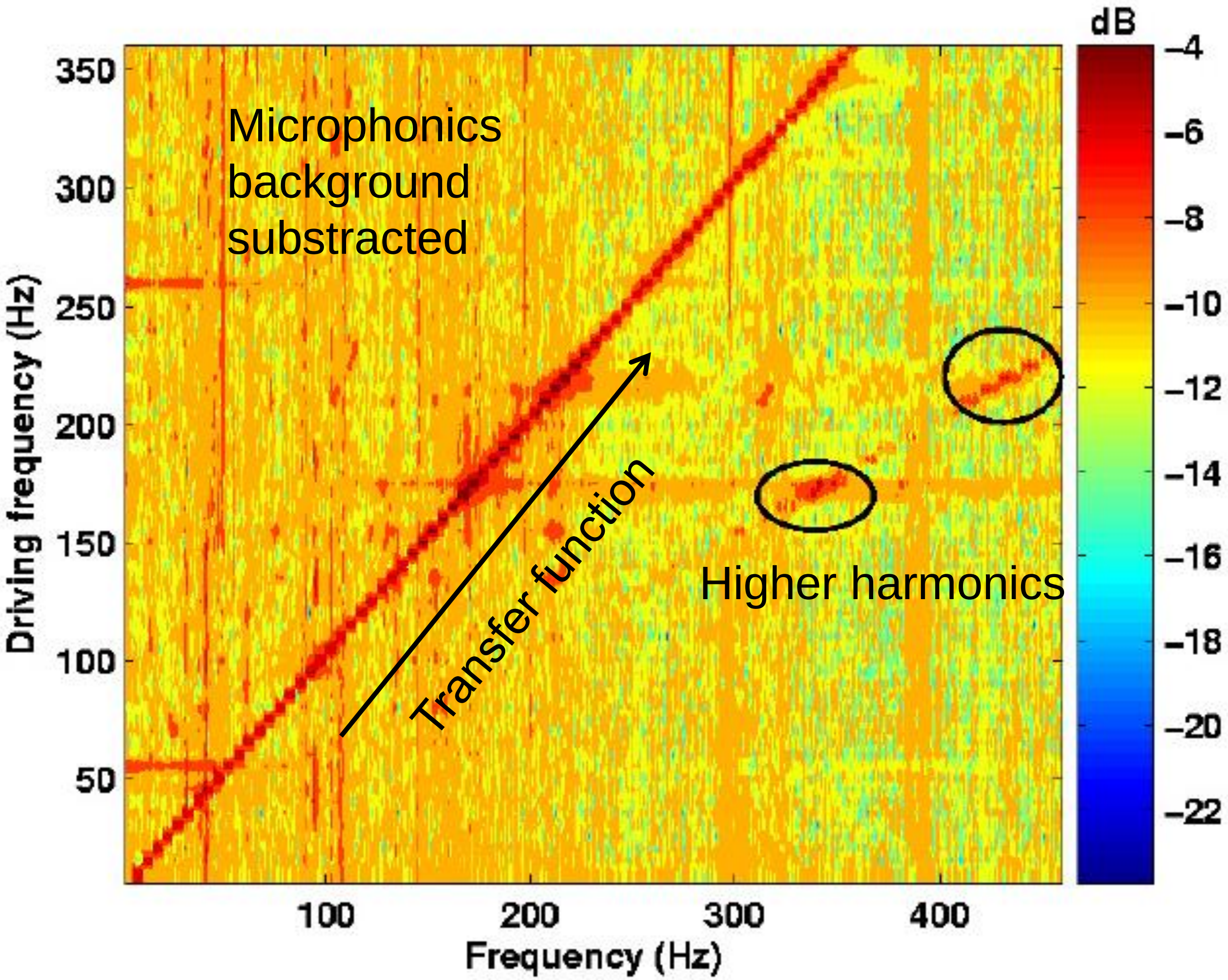
LLRF studies: Summary





Q_L	σ_f (Hz)	σ_ϕ (deg)	σ_A/A	P_f (kW)
$5\cdot10^7$	9.5	0.008	$1\cdot10^{-4}$	1.106
$1\cdot10^8$	7.9	0.009	$2\cdot10^{-4}$	0.595
$2\cdot10^8$	4.2	0.024	$3\cdot10^{-4}$	0.324

Tuner dynamics: Higher order response?

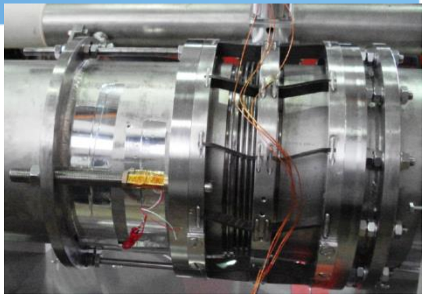


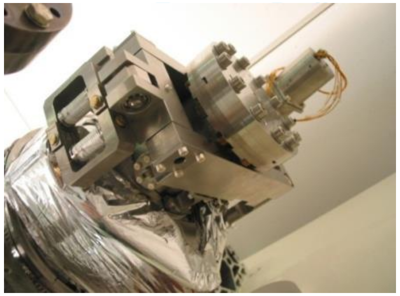
Here complete detuning spectrum taken at a given excitation frequency

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

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)

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 1st mechanical eigenmode sets in