Berliner Elektronenspeicherring-Gesellschaft
für Synchrotronstrahlung m.b.H.

What is the optimal (=highest?) loaded *Q* for ERL linacs?

J. Knobloch, BESSY

Leibniz Gemeinschaft

Overview

- Review of the basics: Coupling to superconducting cavities
- Impact of the real world: Beam loading, microphonics
- Optimizing the cavity loading in the real world
  - RF Control
  - Microphonics
  - Beam loading
  - RF Processing
- Present “state-of-the-art”
- Open questions the must be resolved for the design of future ERLs
- At what loading can we realistically expect to operate?

Note:

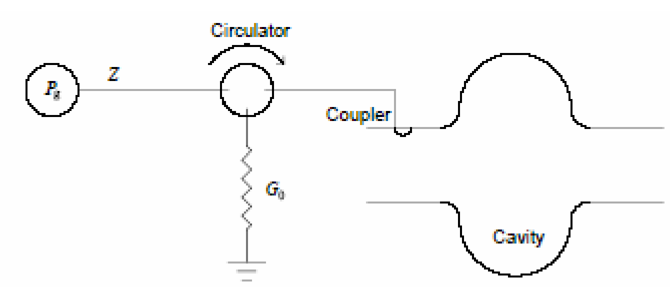
- Whenever examples are given,
  - will assume we are using 9-cell TESLA cavities operating at 1.3 GHz
  - 20 MV/cavity
  - 5 GeV total linac energy

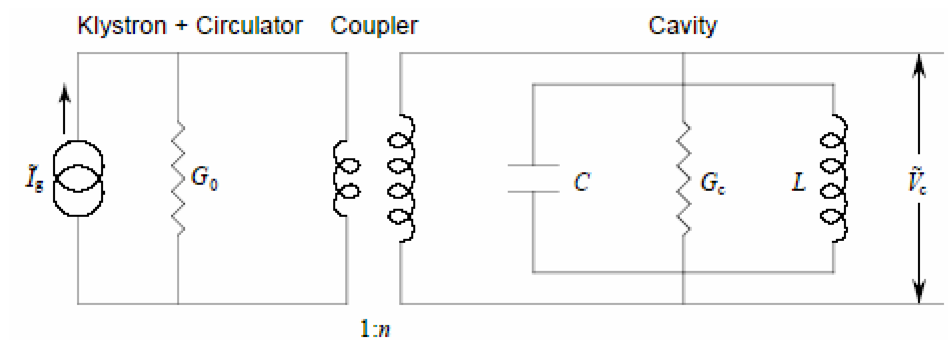
Input coupler connects the transmitter/transmission line to the cavity

- Transmission-line impedance in the 50 Ohm range
- Cavity shunt impedance R/Q x Q is in the 10^{12} Ohms/cell range

→ Strong mismatch between transmission line and cavity.

- A coupler serves as a “transformer” for impedance matching



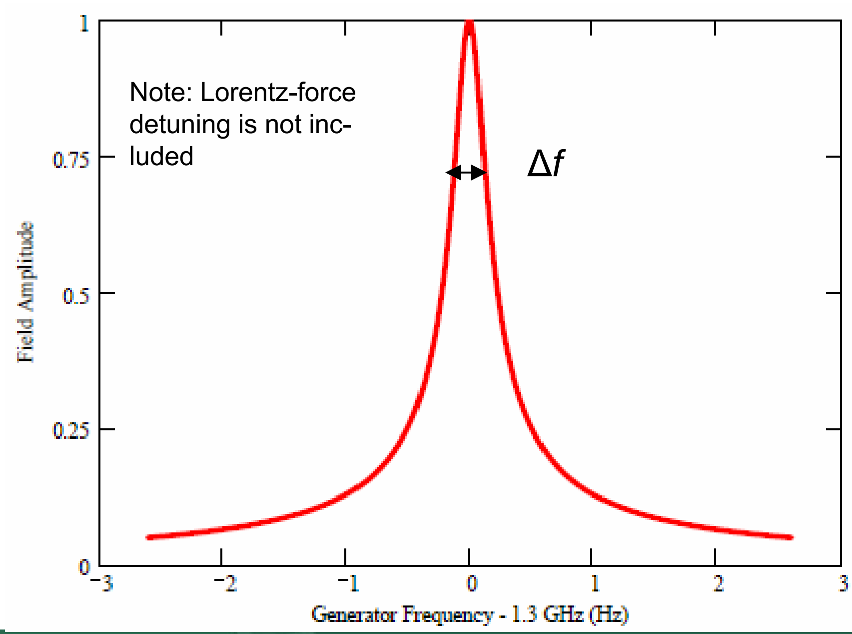


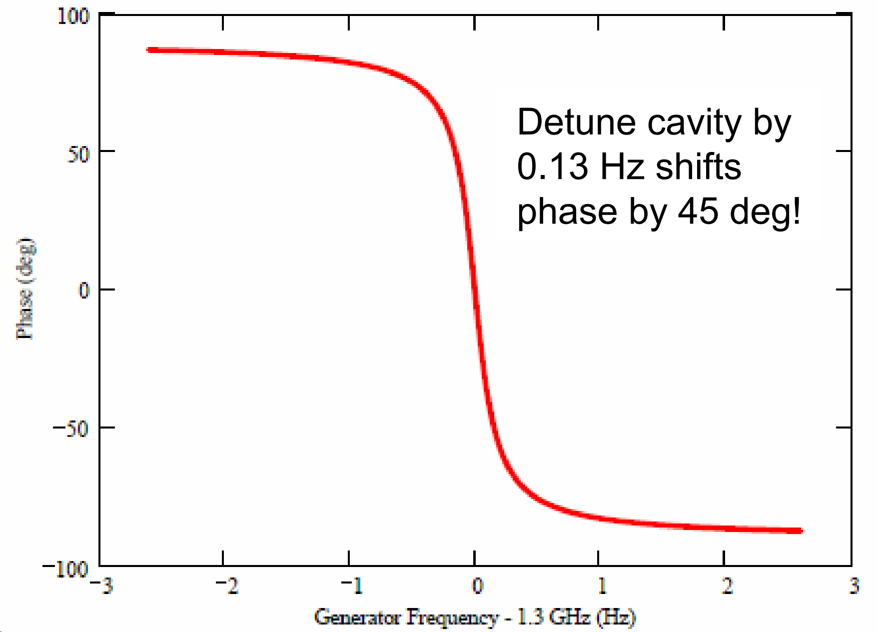
- External coupling factor is defined as ß = $P_e/P_c = Q_0/Q_{ext}$
- Match is given if $P_e = P_c$ or ß = 1

As with all oscillators, the cavity bandwidth is determined by the total losses

- Bandwidth of resonance = $\Delta f = f_0/Q_L$ FWHM ($Q_L = \omega U/P_{tot}$, $Q_0/2$)
- Δf = 0.26 Hz, at f_0 = 1.3 GHz and $Q_0 = 10^{10}$

  → need phase-lock loop to stay on resonance
- But in a linac, generator frequency must be fixed and can't follow the cavity → must stabilize the cavity field with generator power when cavity resonance drifts





Beam loading

- Beam loading = additional "loss mechanism" in the cavity
- $P_b = I_b V \cos\varphi$ → Total losses "in the cavity" are given by $P_{bc} = P_b + P_c$

→ matching condition changes. Now transmission line is matched to the cavity when $P_e = P_{bc}$

- Do the math to find for match (for heavy beam loading) $Q_e \approx \dfrac{V}{I_b \cos\varphi\, (R/Q)}$
- Example: For XFEL beam current = 10 mA, V = 20 MV
- → $Q_e = 1.9 \times 10^6$, Δf = 680 Hz
- Almost all power goes into the beam. P_b = 200 kW

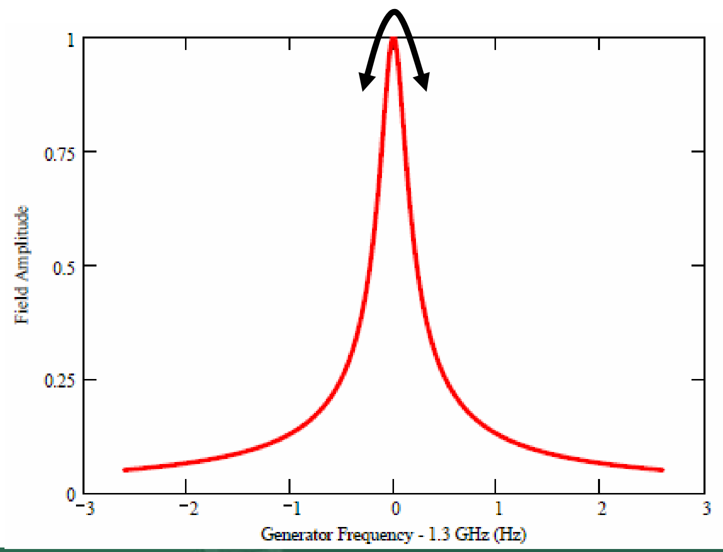
  → XFEL/TESLA klystron provides 220 kW/cavity

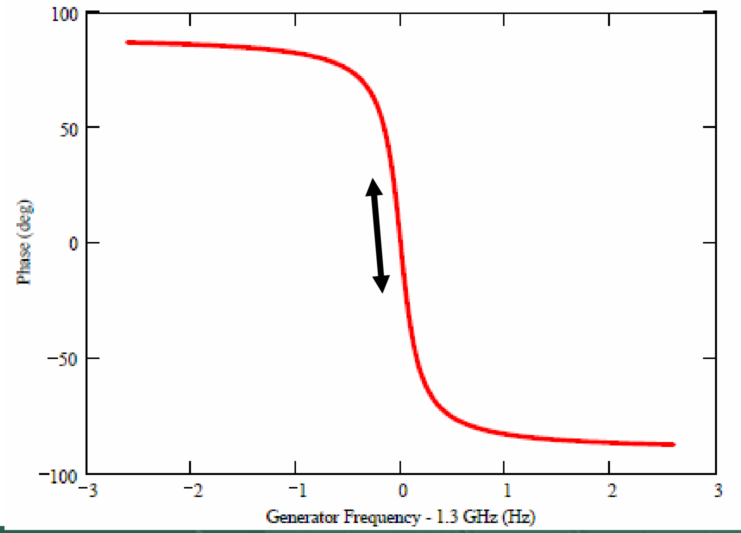
What happens when we shift the cavity frequency by δf?

- Klystron frequency is constant → amplitude decreases and phase changes
- **ψ =** atan(2 $\delta f/\Delta f$) ≈ **2 $\delta f/\Delta f$** → $V = V_0 \cos\psi \exp(i\psi)$
- To compensate, the klystron must provide additional power and change phase
- Required power to keep field constant

$$P_g(\Delta f, \delta f) := \frac{V_c^2 \cdot \Delta f}{4 \cdot RoQ \cdot f_0} \cdot \left[\left(1 + \frac{f_0}{\Delta f} \cdot \frac{RoQ \cdot I_b \cdot V_c}{V_c^2} \right)^2 + 4 \left(\frac{\delta f}{\Delta f} \right)^2 \right]$$

Beam loading   Detuning



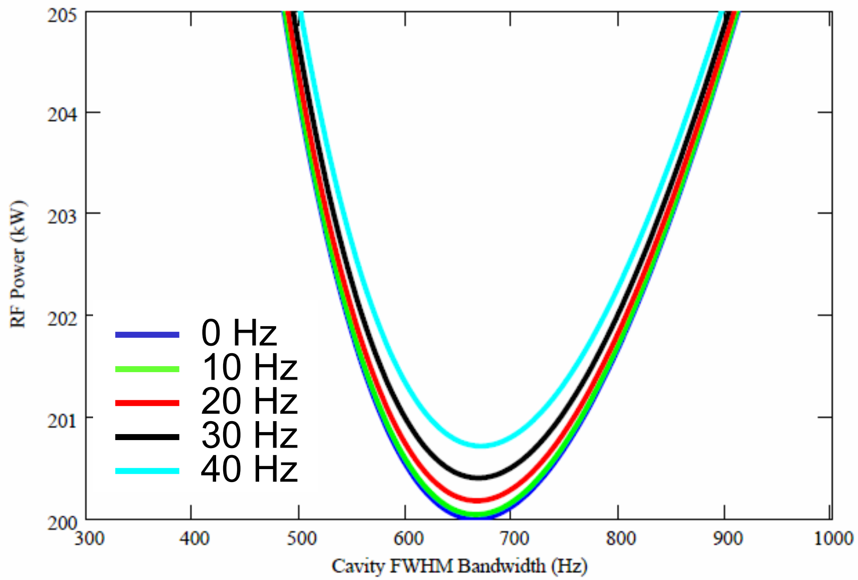


Measured microphonics

How much detuning can we expect in realistic modules?

Machine	σ [Hz]	6σ [Hz]	Comments
CEBAF	2.5 (average)	15 (average)	significant fluctuation between cavities
ELBE	1 (average)	6 (average)	
SNS	1 to 6	6 to 36	significant fluctuation between cavities
TJNAF FEL	0.6 to 1.3	3.6 to 7.8	center cavities more quiet
TTF	2 to 7 (pulsed)	12 to 42 (pulsed)	significant fluctuation between cavities

- Peak values at TTF around 40 Hz
- Impact on RF system is negligible and optimal coupling unchanged

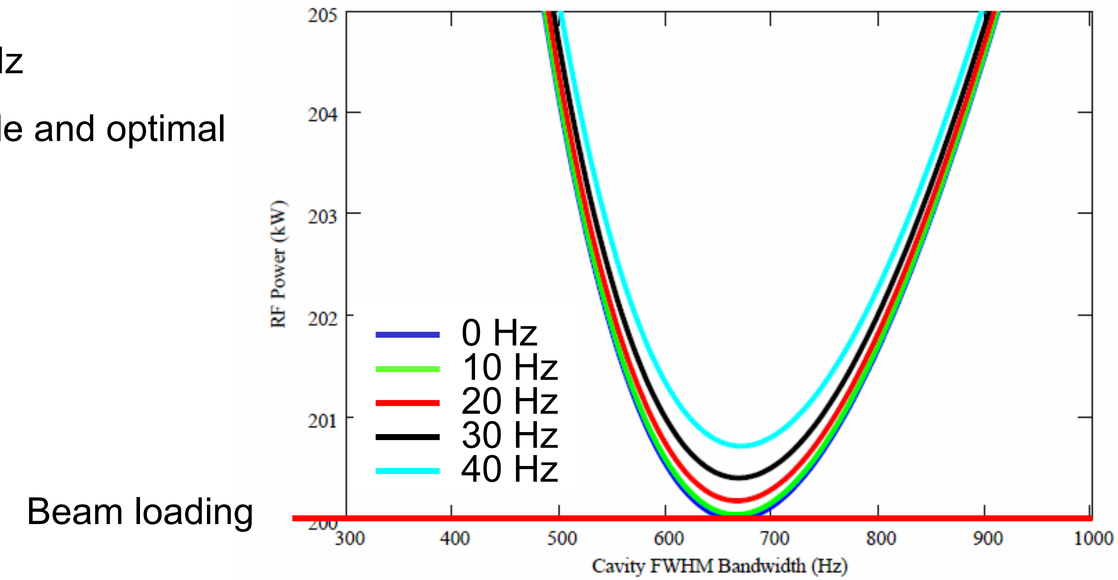


Measured microphonics

How much detuning can we expect in realistic modules?

Machine	σ [Hz]	6σ [Hz]	Comments
CEBAF	2.5 (average)	15 (average)	significant fluctuation between cavities
ELBE	1 (average)	6 (average)	
SNS	1 to 6	6 to 36	significant fluctuation between cavities
TJNAF FEL	0.6 to 1.3	3.6 to 7.8	center cavities more quiet
TTF	2 to 7 (pulsed)	12 to 42 (pulsed)	significant fluctuation between cavities

- Peak values at TTF around 40 Hz
- Impact on RF system is negligible and optimal coupling unchanged
- Why? Because $\delta f \ll \Delta f$



What stability levels can we expect out of our cavities?

- Assume we use a simple P-type controller with gain κ
- RMS detuning is of order σ_{mic} = 7 Hz
- Change in cavity phase due to detuning = $\delta\psi \approx 2\ \delta f/\Delta f$ = 1.2 deg
- Feedback reduces this to about $\delta\psi/(1 + \kappa)$ = **0.012 deg** for κ = 100
- Resultant energy jitter is given by $\sigma_E/E = \tan(\varphi_b) \times d\psi/(1+\kappa)$ = **3.7 x 10^{-5}** for φ_b = 10 deg
- Typically, require amplitude and phase stability in the range 0.02 to 0.1 deg and energy stability around 10^{-4} – 10^{-3}

→ Microphonics impact beam quality only little (because bandwidth is large)

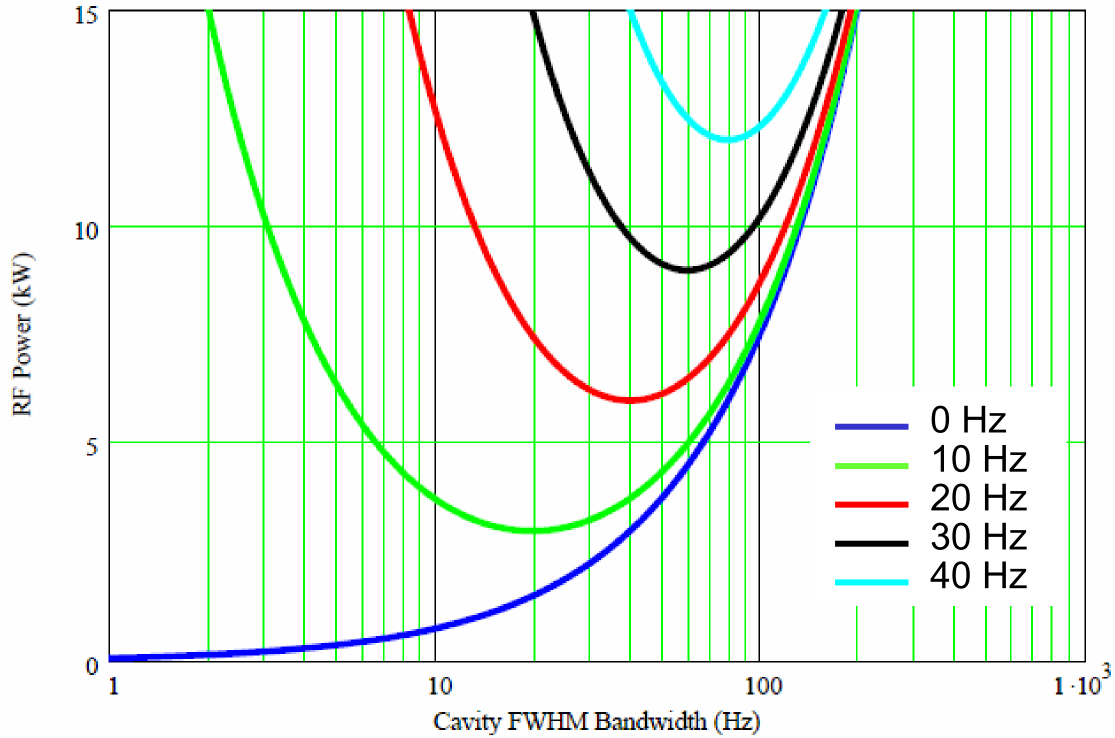
Cavities without beam loading

What happens when the beam loading is zero (ERL main linac)?

- If no microphonics present, match is given by $Q_L = Q_0/2$ and bandwidth < 1 Hz
- *But with microphonics things are very different!*
- Power requirement is given by $P_g = \dfrac{V^2\,\Delta f/f}{4\,(R/Q)}\,(1 + 4\,\delta f^2/\Delta f^2)$
- "Matching" condition
  $\Delta f_{opt} = 2\,\delta f_{mic}$
- Minimum power is given by:

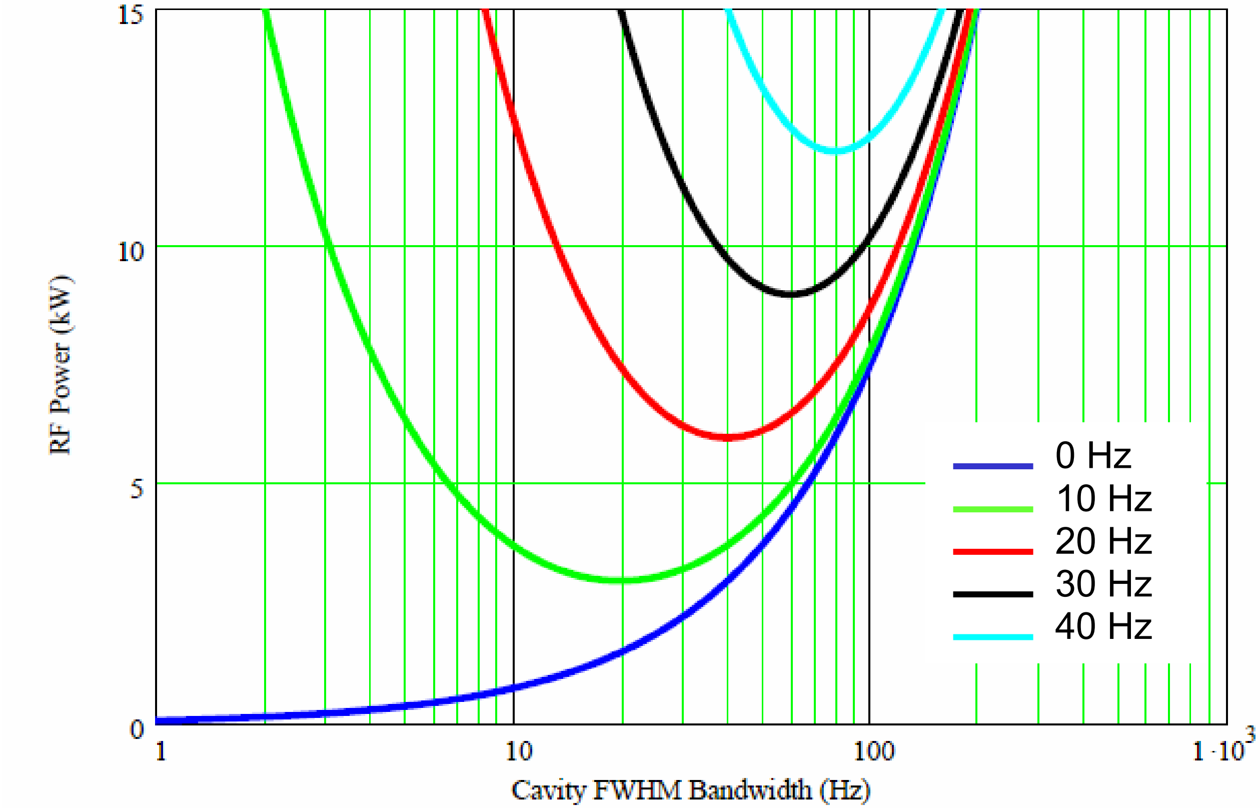
$$P_g = \frac{V^2\,\delta f/f}{(R/Q)}$$

- **THIS IS A BIG DEAL!**



Consequence: Wasted RF power

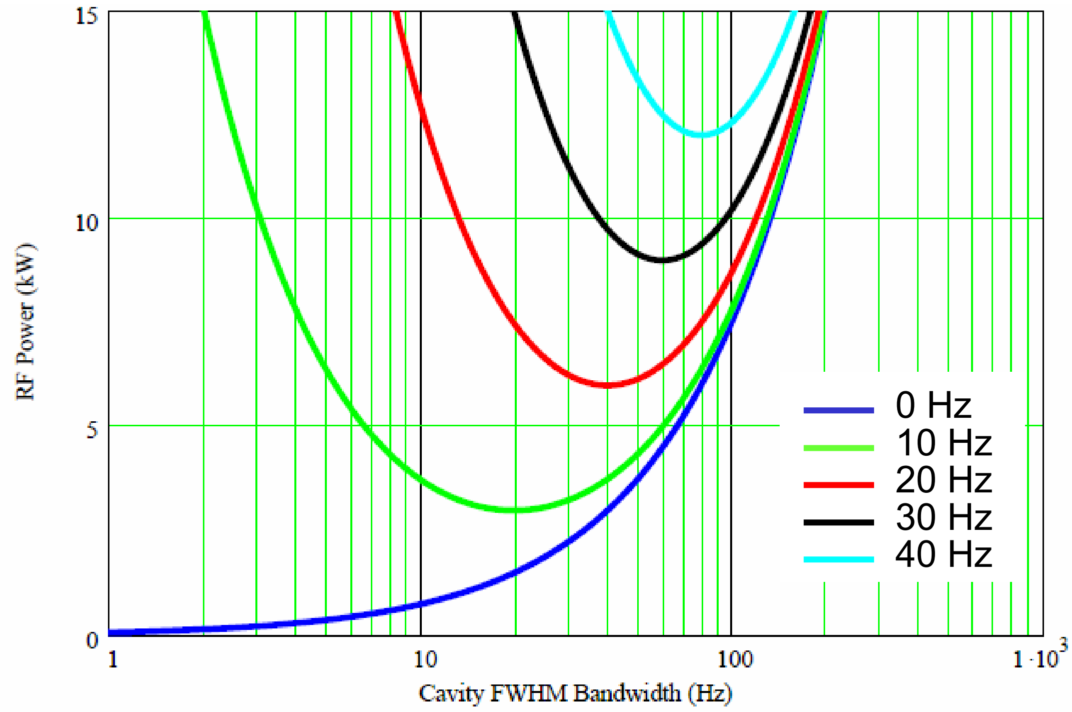
- If no microphonics present, power per cavity is around 30 W
- With 10 Hz RMS microphonics, power per cavity is 3 kW per cavity!
- That's of order 100x as much! But the whole point of an ERL is to save energy



Matching condition determined by microphonics

- Value of optimal coupling factor is determined by microphonics
- But a priori don't know what microphonics to expect, may also change with time

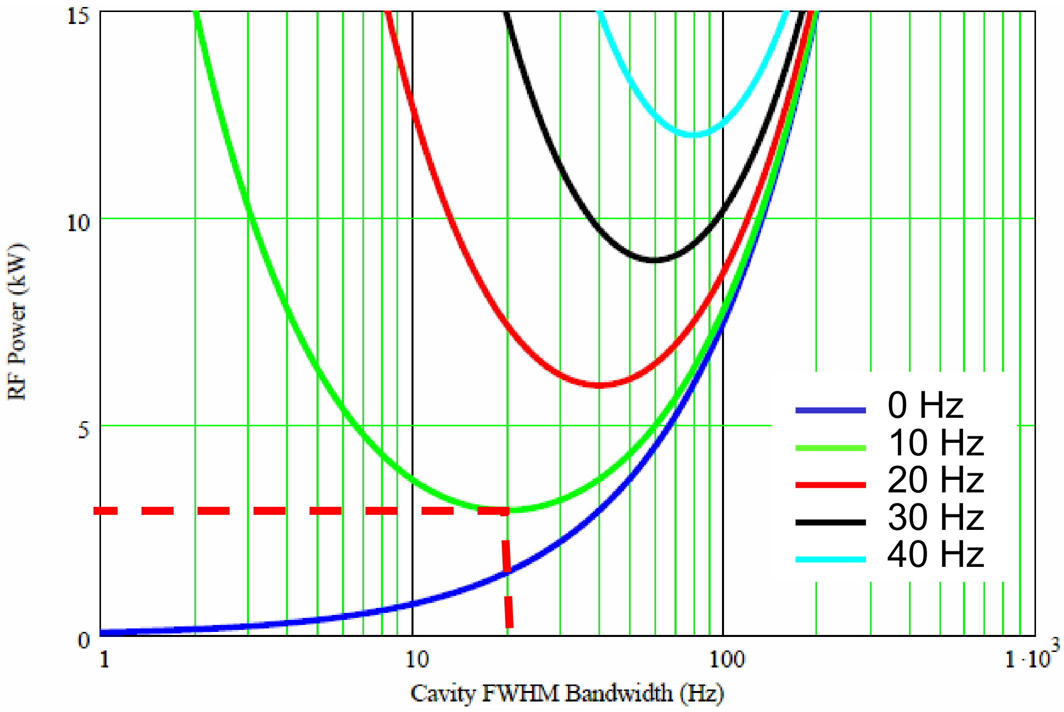
Machine	σ [Hz]	6σ [Hz]
CEBAF	2.5 (average)	15 (average)
ELBE	1 (average)	6 (average)
SNS	1 to 6	6 to 36
TJNAF FEL	0.6 to 1.3	3.6 to 7.8
TTF	2 to 7 (pulsed)	12 to 42 (pulsed)



Matching condition determined by microphonics

- Value of optimal coupling factor is determined by microphonics
- But a priori don’t know what microphonics to expect, may also change with time
- E.g., if microphonics double from 10 to 20 Hz, power increases from 3 kW …

Machine	σ [Hz]	6σ [Hz]
CEBAF	2.5 (average)	15 (average)
ELBE	1 (average)	6 (average)
SNS	1 to 6	6 to 36
TJNAF FEL	0.6 to 1.3	3.6 to 7.8
TTF	2 to 7 (pulsed)	12 to 42 (pulsed)

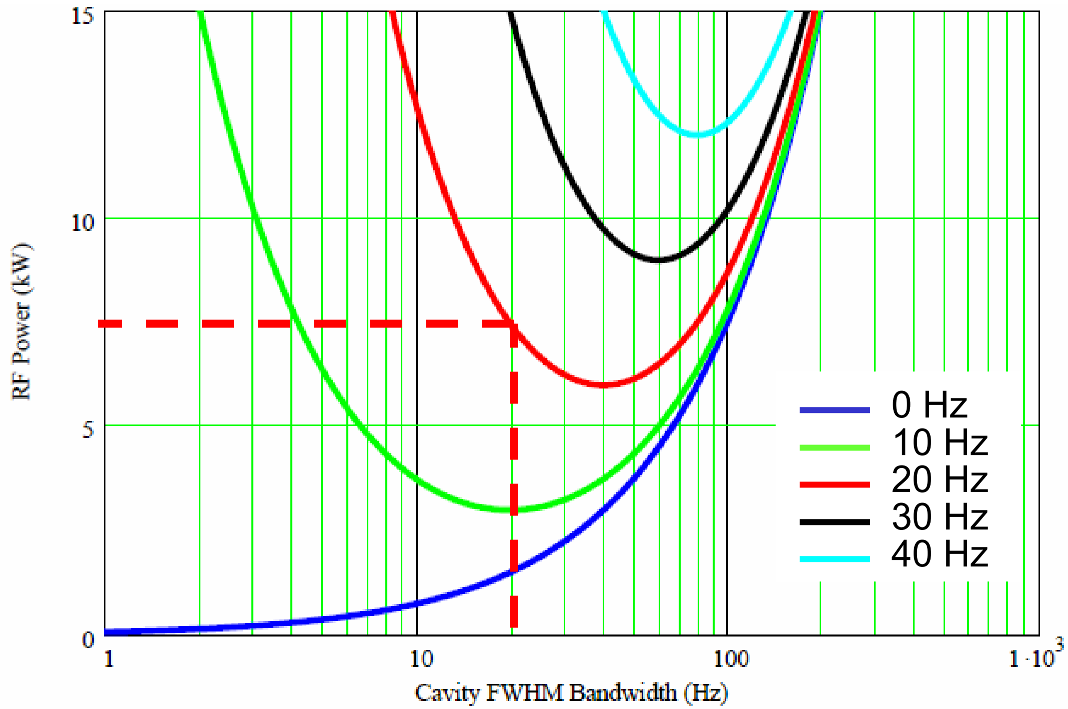


Consequences of Microphonics for ERL cavities

Matching condition determined by microphonics

- Value of optimal coupling factor is determined by microphonics
- But a priori don't know what microphonics to expect, may also change with time
- E.g., if microphonics double from 10 to 20 Hz, power increases from 3 to 7.5 kW!

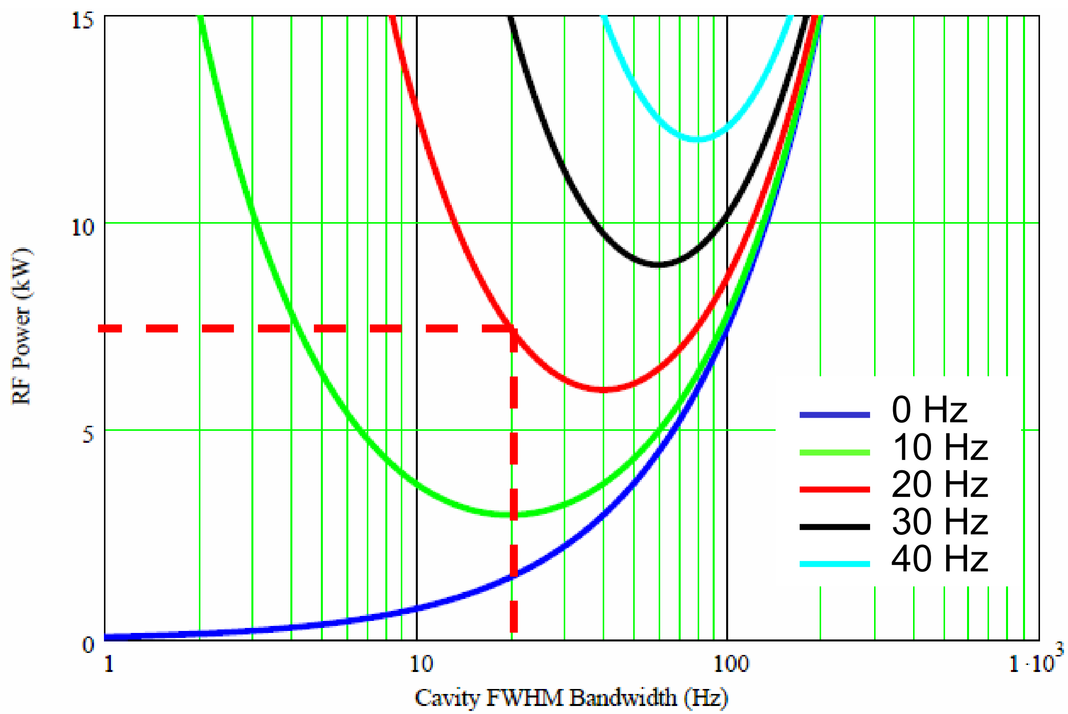
Machine	σ [Hz]	6σ [Hz]
CEBAF	2.5 (average)	15 (average)
ELBE	1 (average)	6 (average)
SNS	1 to 6	6 to 36
TJNAF FEL	0.6 to 1.3	3.6 to 7.8
TTF	2 to 7 (pulsed)	12 to 42 (pulsed)



Matching condition determined by microphonics

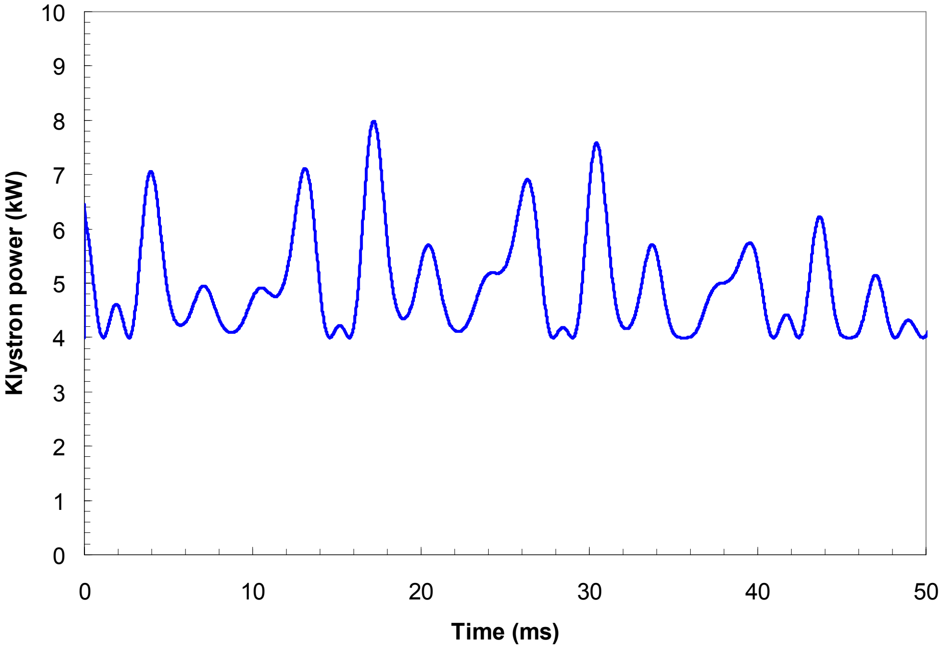
- Value of optimal coupling factor is determined by microphonics
- But a priori don't know what microphonics to expect, may also change with time
- E.g., if microphonics double from 10 to 20 Hz, power increases from 3 to 7.5 kW!
- PROBABLY ADJUSTABILITY OF COUPLING FACTOR WILL BE QUITE IMPORTANT TO OPTIMIZE CAVITY OPERATION

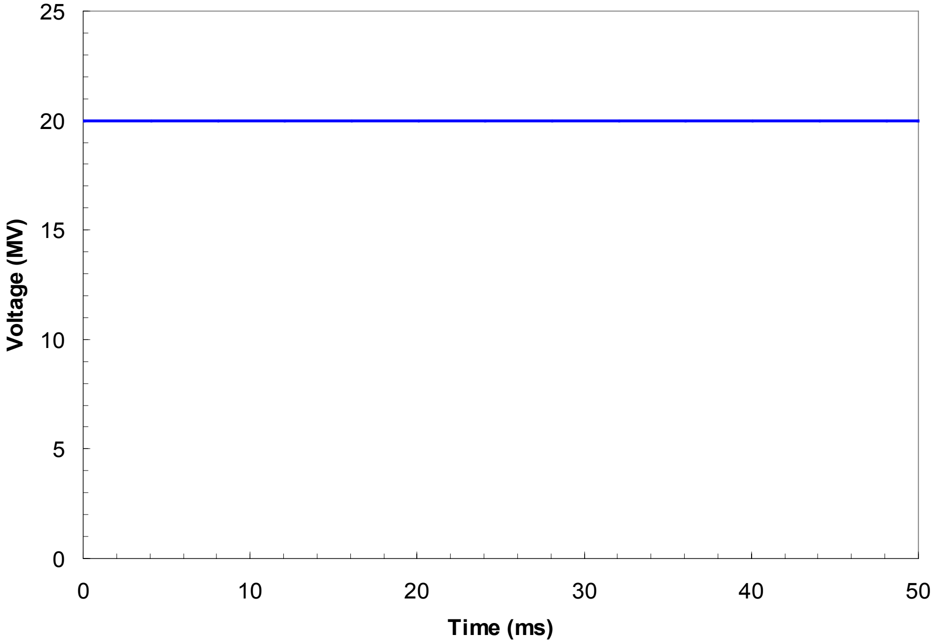
Machine	σ [Hz]	6σ [Hz]
CEBAF	2.5 (average)	15 (average)
ELBE	1 (average)	6 (average)
SNS	1 to 6	6 to 36
TJNAF FEL	0.6 to 1.3	3.6 to 7.8
TTF	2 to 7 (pulsed)	12 to 42 (pulsed)



RF System Layout (transmitter and coupler) determined by microphonics

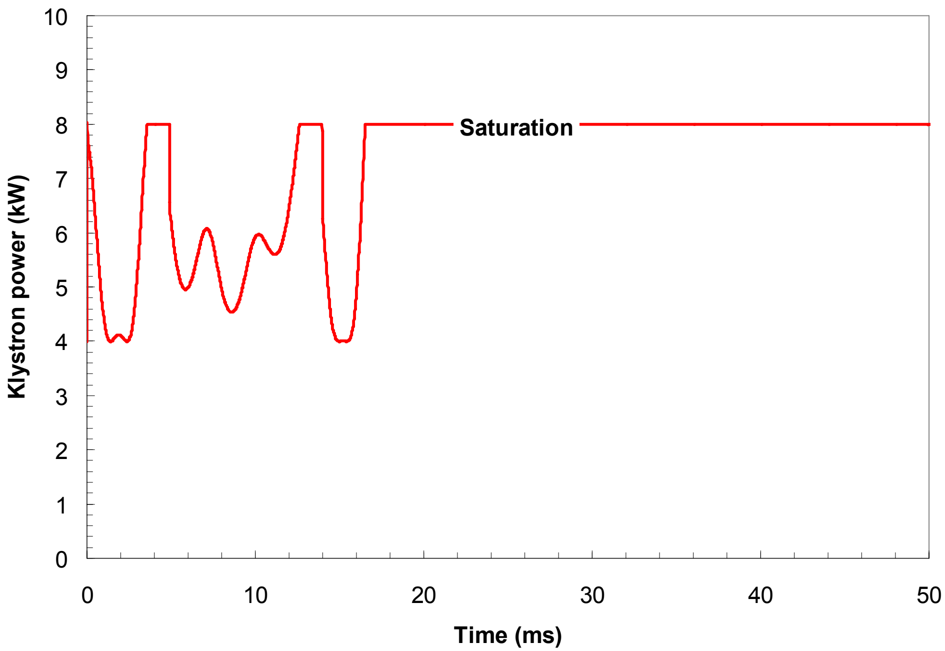
- To stabilize the cavity field we always need to have sufficient RF power available to compensate microphonics, otherwise cavity will likely trip (dangerous!)

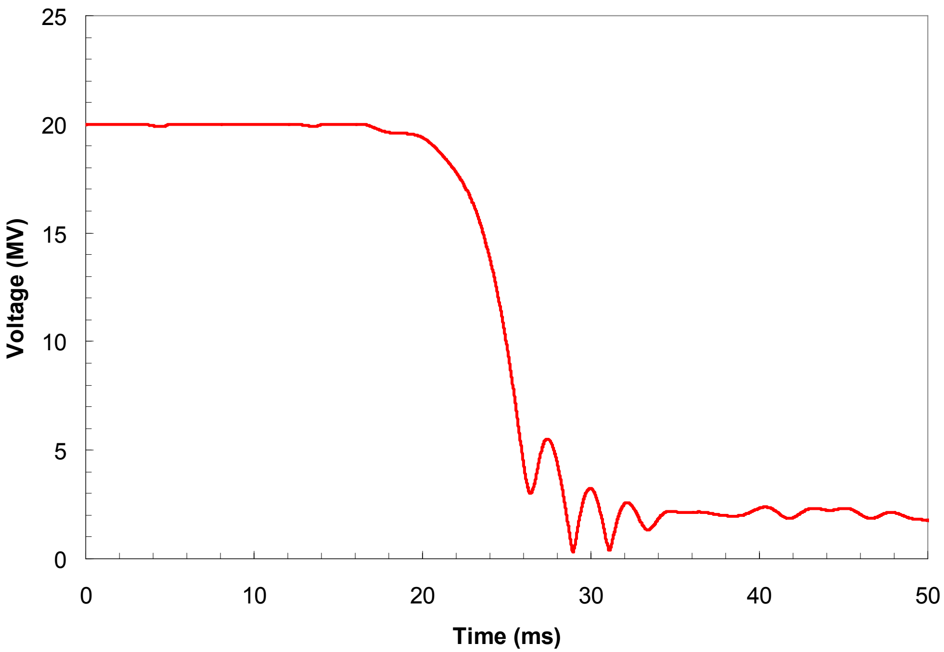




RF System Layout (transmitter and coupler) determined by microphonics

- To stabilize the cavity field we always need to have sufficient RF power available to compensate microphonics, otherwise cavity will likely trip (dangerous!)

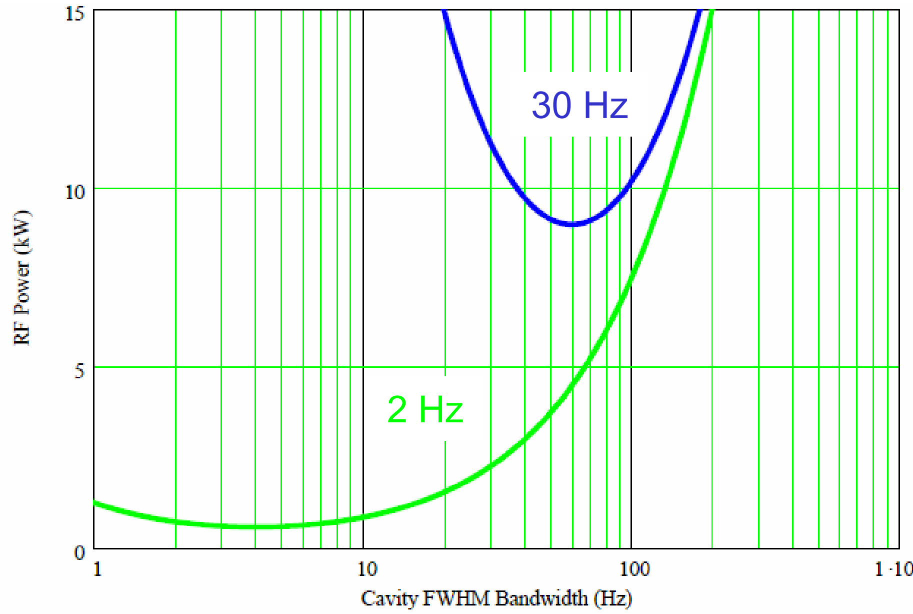




Consequences of Microphonics for ERL cavities

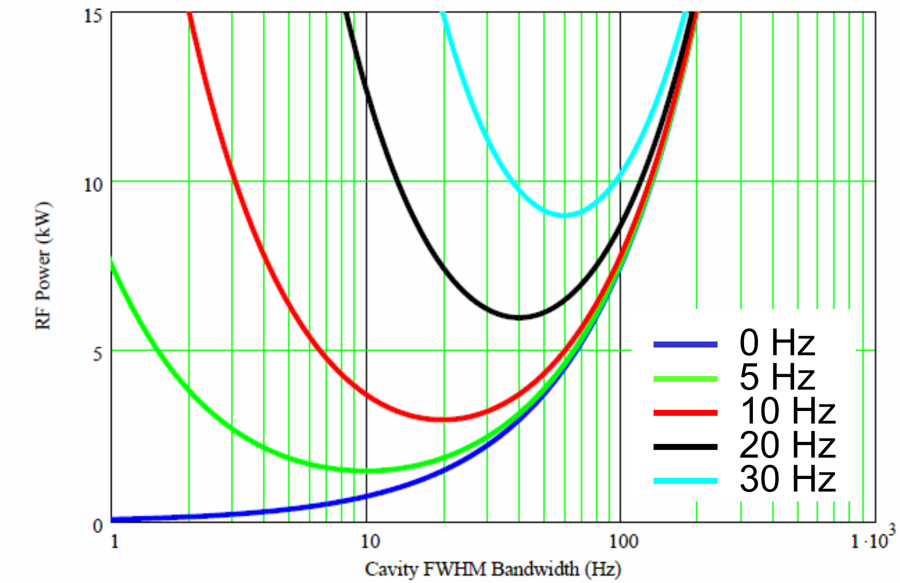
RF System Layout (transmitter and coupler) determined by microphonics

- To stabilize the cavity field we always need to have sufficient RF power available to compensate microphonics, otherwise cavity will likely trip (dangerous!)
- **Peak microphonics determine RF power installation**
  - → Capital investment and RF technology choice is driven by microphonics
- E.g., peak microphonics of 30 Hz.
  - → Best we can do is 9 kW per cavity
  - → Must use something like CPI klystron transmitter similar to CEBAF's at 140 k€/cavity (?)
- Let's dream and assume microphonics are only 2 Hz
  - → Best we can do is 650 W → solid-state amplifier
  - → much "nicer" RF system, easier maintained
  - → Cost is about 50 k€/cavity (for 1 kW)
- But must check if we can operate at this narrow bandwidth!



Cannot optimize coupling both for peak microphonics and average microphonics

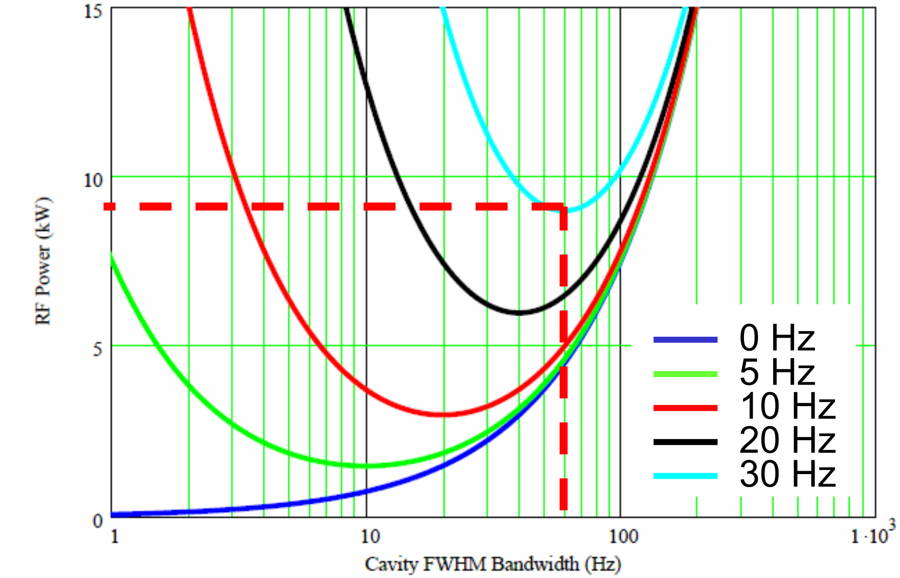
- E.g., Microphonics are 5 Hz RMS and 30 Hz peak
- Try to minimize installed RF power → optimize bandwidth for peak detuning (Δf = 60 Hz)



Consequences of Microphonics for ERL cavities

Cannot optimize coupling both for peak microphonics and average microphonics

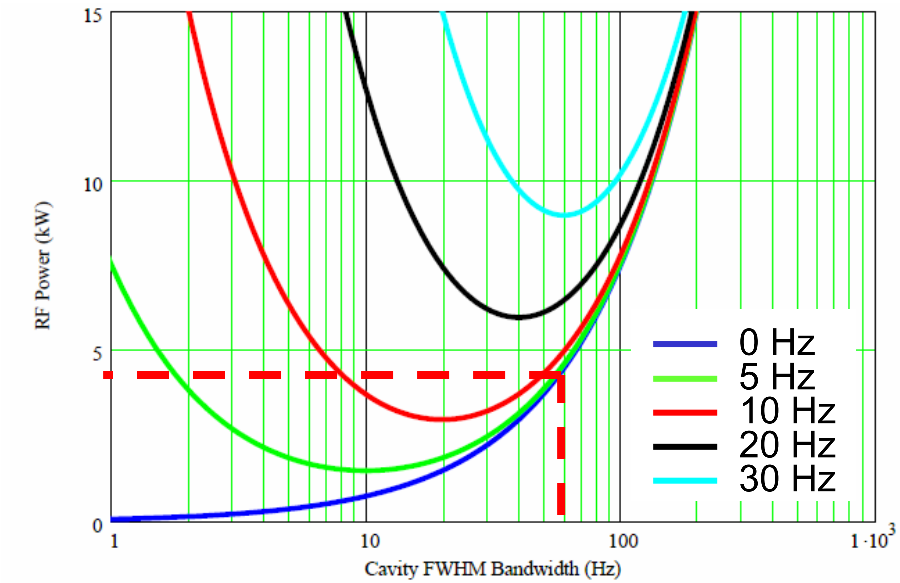
- E.g., Microphonics are 5 Hz RMS and 30 Hz peak
- Try to minimize installed RF power → optimize bandwidth for peak detuning (Δ*f* = 60 Hz)
- Peak RF power required is 9 kW



Consequences of Microphonics for ERL cavities

Cannot optimize coupling both for peak microphonics and average microphonics

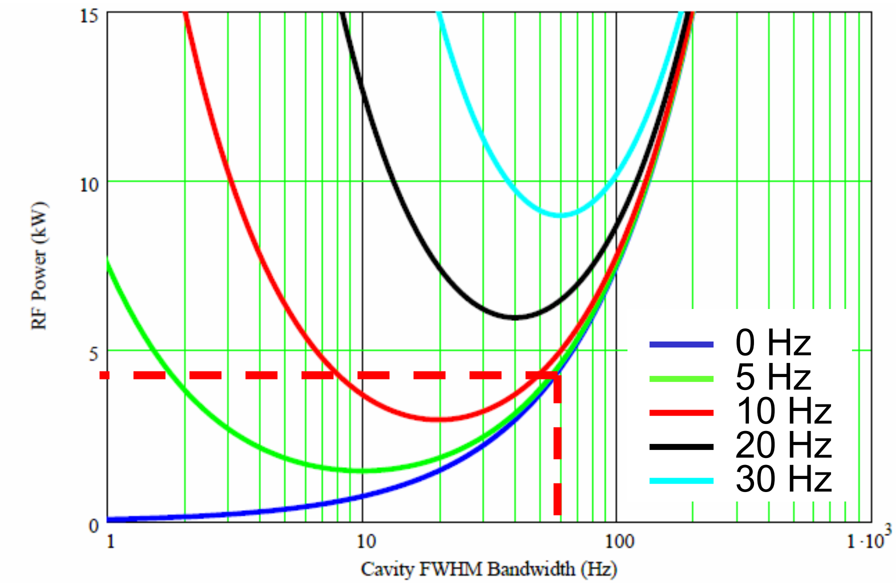
- E.g., Microphonics are 5 Hz RMS and 30 Hz peak
- Try to minimize installed RF power → optimize bandwidth for peak detuning (Δ*f* = 60 Hz)
- Peak RF power required is 9 kW
- Average RF power required per cavity is 4.6 kW (rather than 1.5 kW at optimal coupling)



Consequences of Microphonics for ERL cavities

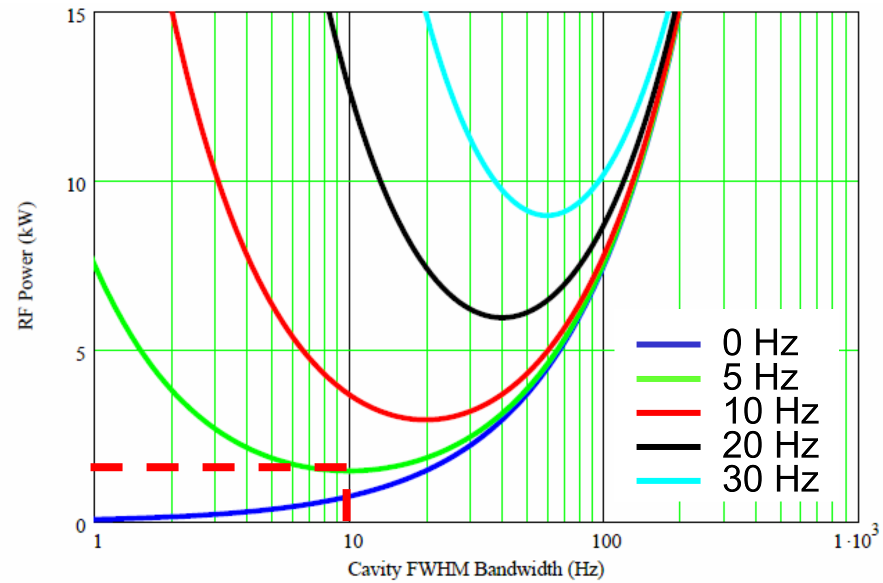
Cannot optimize coupling both for peak microphonics and average microphonics

- E.g., Microphonics are 5 Hz RMS and 30 Hz peak
- Try to minimize installed RF power → optimize bandwidth for peak detuning (Δf = 60 Hz)
- Peak RF power required is 9 kW
- Average RF power required per cavity is 4.6 kW (rather than 1.5 kW at optimal coupling)
- Thermal load on coupler/RF distribution system increases (e.g., TTF coupler can barely handle this SW power)
- Waste a factor 3 in wall-plug power
- But other way around is even worse



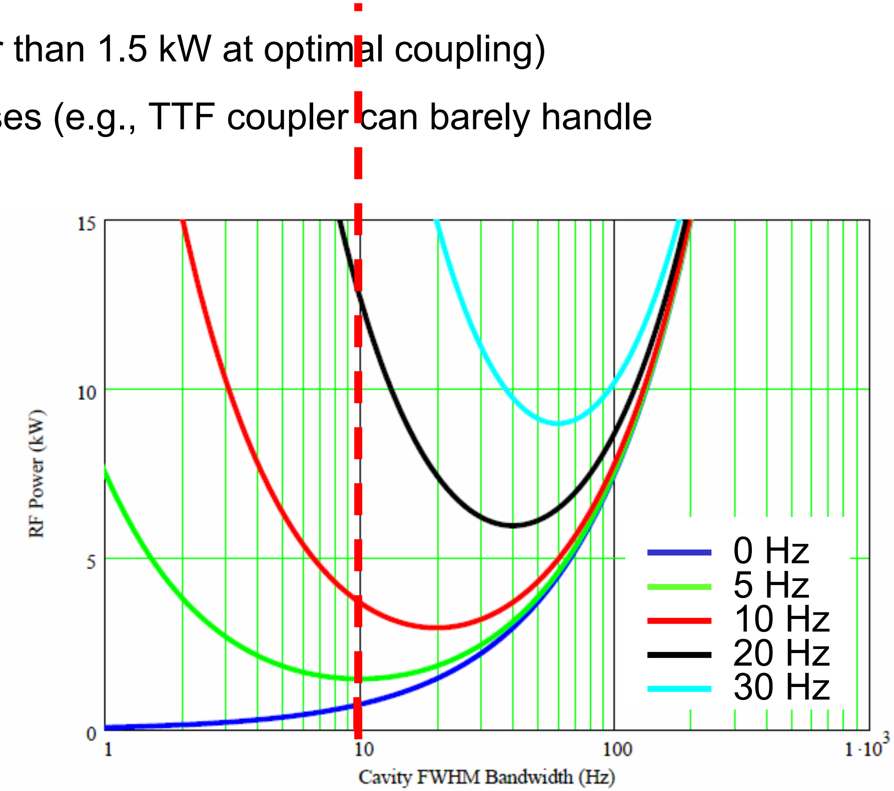
Cannot optimize coupling both for peak microphonics and average microphonics

- E.g., Microphonics are 5 Hz RMS and 30 Hz peak
- Try to minimize installed RF power → optimize bandwidth for peak detuning (Δf = 60 Hz)
- Peak RF power required is 9 kW
- Average RF power required per cavity is 4.6 kW (rather than 1.5 kW at optimal coupling)
- Thermal load on coupler/RF distribution system increases (e.g., TTF coupler can barely handle this SW power)
- Waste a factor 3 in wall-plug power
- But other way around is even worse
    - Optimize for RMS microphonics
    - CW load is 1.5 kW



Cannot optimize coupling both for peak microphonics and average microphonics

- E.g., Microphonics are 5 Hz RMS and 30 Hz peak
- Try to minimize installed RF power → optimize bandwidth for peak detuning (Δ*f* = 60 Hz)
- Peak RF power required is 9 kW
- Average RF power required per cavity is 4.6 kW (rather than 1.5 kW at optimal coupling)
- Thermal load on coupler/RF distribution system increases (e.g., TTF coupler can barely handle this SW power)
- Waste a factor 3 in wall-plug power
- But other way around is even worse
  - Optimize for RMS microphonics
  - CW load is 1.5 kW
  - Peak load is 28 kW!



Consequences of Microphonics for ERL cavities

RF Stability and beam quality are impacted

- Again, assume peak microphonics around 30 Hz, average mircophonics about 5 Hz.
- Bandwidth = 60 Hz
- 5 Hz RMS detuning results in a phase of nearly 10 deg.
- For RF feedback gain of 100, phase stability is about 0.1 deg

  → Probably not sufficient for most machines!
- What can we do? Increase the gain of the feedback to > 100
- Where is the limit?
  - Stability of the feedback loop. Latency has a big impact.

    → For 60 Hz BW and 5 μs latency, limit is about gain = 1400, for safety set maximum to 700
  - Pickup measurement: noise is multiplied by 2x feedback gain.

    →For N/S ratio at the 0.1% level, N/S noise level on klystron power is 100% if gain is 500

    →Question: How much noise do we have? How much klystron noise can we tolerate?

How much feedback gain do we need for phase stability at the optimal loading?

- Assume we have measured the RMS microphonics: σ_{mic}
- For how much peak microphonics should we budget the RF system?
  - Depends on how many trips/day we are willing to accept
  - Some papers quote $\delta f_{pk} = 6\ \sigma_{mic}$ to yield a few trips a day ← **is this OK, THIS MUST BE MEASURED!**
- Optimize the Q_L for the peak microphonics $\Delta f = 2 \cdot 6\ \sigma_{mic}$
- RMS phase error in the cavity will therefore be about $(2 \cdot \sigma_{mic})/(\Delta f \cdot [1 + \kappa]) = 9.6$ deg/$(1 + \kappa)$
  - If we need 0.02 deg phase stability then gain κ = 9.6 deg/0.02 deg = 475
- Measurement noise must therefore be significantly less then 0.1%.
  - Assume pickup probe has $Q_{ext} = 10^{12}$
  - Cavity field is 20 MV
  - → Probe power is 390 mW, equivalent voltage is 4.4 V (at 50 Ohm)
  - Assume noise is 1 mV
  - → Noise is around 0.02%
  - → Operation with gain around 500 should be fine

Optimizing the cavity bandwidth: ELBE Modules

Where do we stand today?

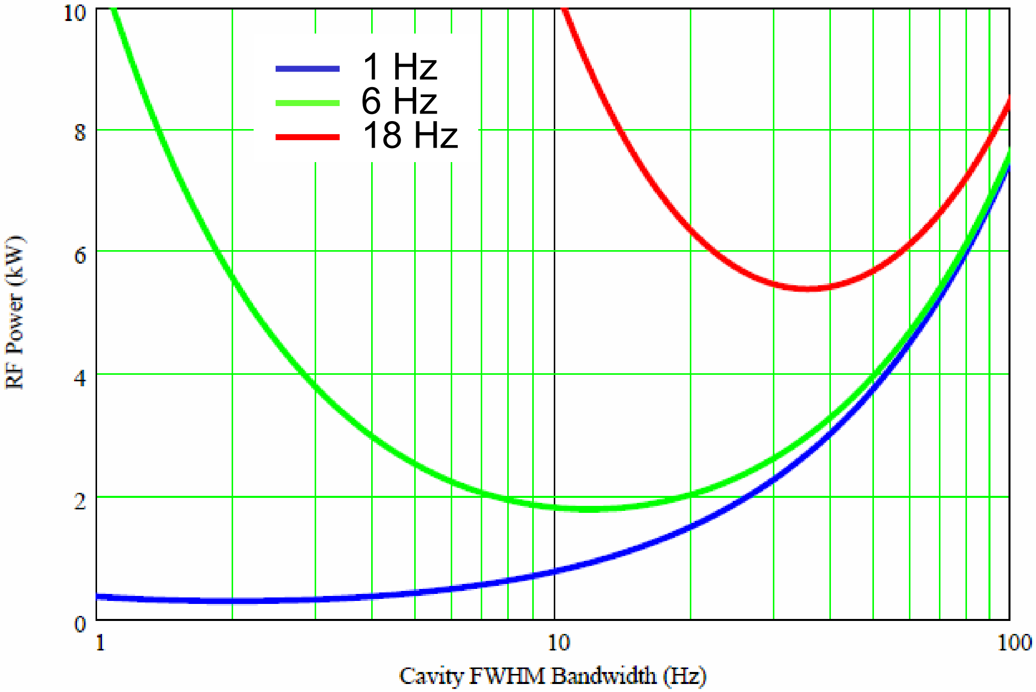
- Take ELBE modules as a “pretty good system”
- RMS microphonics = 1 Hz.

Machine	σ [Hz]	6σ [Hz]	Comments
CEBAF	2.5 (average)	15 (average)	significant fluctuation between cavities
ELBE	1 (average)	6 (average)	
SNS	1 to 6	6 to 36	significant fluctuation between cavities
TJNAF FEL	0.6 to 1.3	3.6 to 7.8	center cavities more quiet
TTF	2 to 7 (pulsed)	12 to 42 (pulsed)	significant fluctuation between cavities

Where do we stand today?

- Take ELBE modules as a "pretty good system"
- RMS microphonics = 1 Hz.
- What do we take as peak microphonics? Take 6 σ

Machine	σ [Hz]	6σ [Hz]
CEBAF	2.5 (average)	15 (average)
ELBE	1 (average)	6 (average)
SNS	1 to 6	6 to 36
TJNAF FEL	0.6 to 1.3	3.6 to 7.8
TTF	2 to 7 (pulsed)	12 to 42 (pulsed)

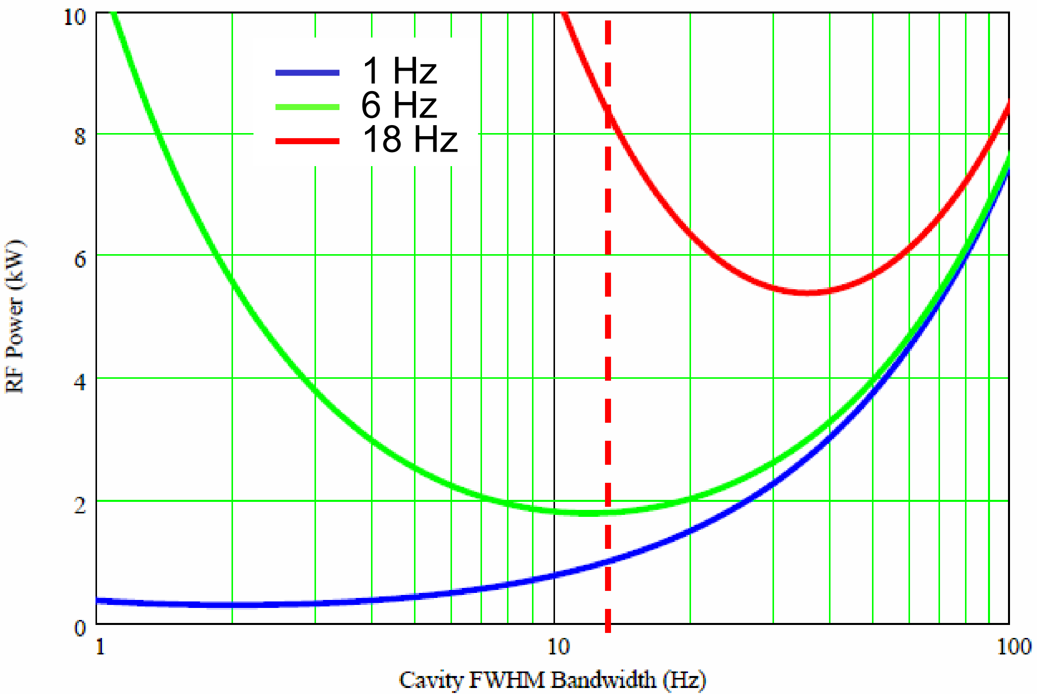


Where do we stand today?

- Take ELBE modules as a “pretty good system”
- RMS microphonics = 1 Hz.
- What do we take as peak microphonics? Take 6 σ
- At 6 Hz, optimal cavity bandwidth = 12 Hz, or $Q_L = 1.1 \times 10^8$

Machine	σ [Hz]	6σ [Hz]
CEBAF	2.5 (average)	15 (average)
ELBE	1 (average)	6 (average)
SNS	1 to 6	6 to 36
TJNAF FEL	0.6 to 1.3	3.6 to 7.8
TTF	2 to 7 (pulsed)	12 to 42 (pulsed)

$Q_L = 1.1 \times 10^8$



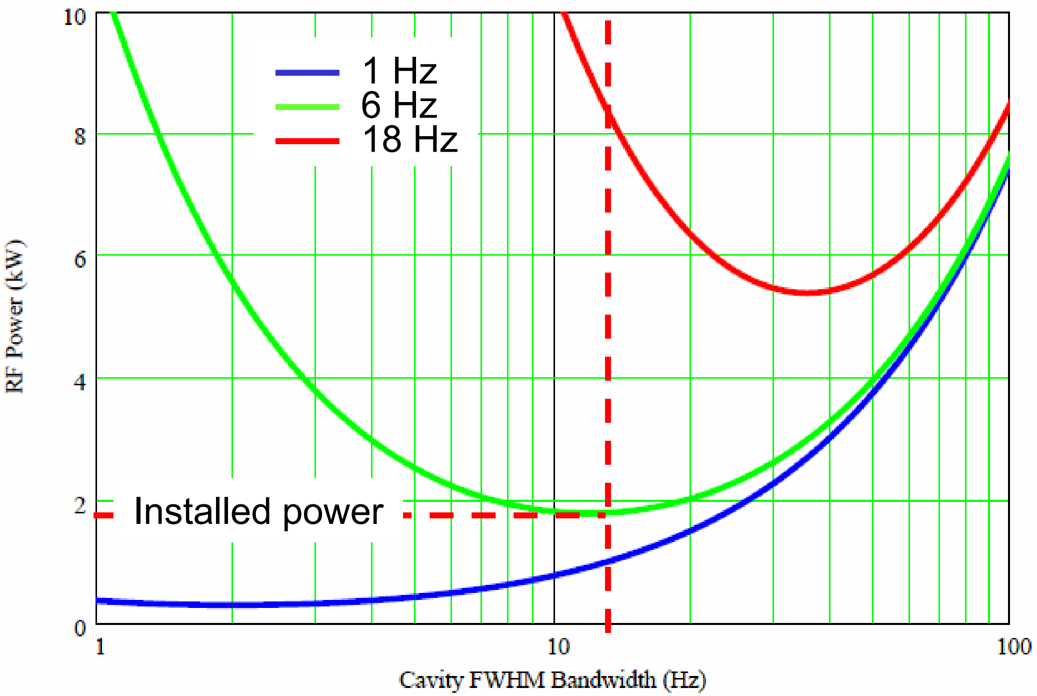
Optimizing the cavity bandwidth: ELBE Modules

Where do we stand today?

- Take ELBE modules as a “pretty good system”
- RMS microphonics = 1 Hz.
- What do we take as peak microphonics? Take 6 σ
- At 6 Hz, optimal cavity bandwidth = 12 Hz, or $Q_L = 1.1 \times 10^8$
- Installed RF power > 1.8 kW

Machine	σ [Hz]	6σ [Hz]
CEBAF	2.5 (average)	15 (average)
ELBE	1 (average)	6 (average)
SNS	1 to 6	6 to 36
TJNAF FEL	0.6 to 1.3	3.6 to 7.8
TTF	2 to 7 (pulsed)	12 to 42 (pulsed)

$Q_L = 1.1 \times 10^8$

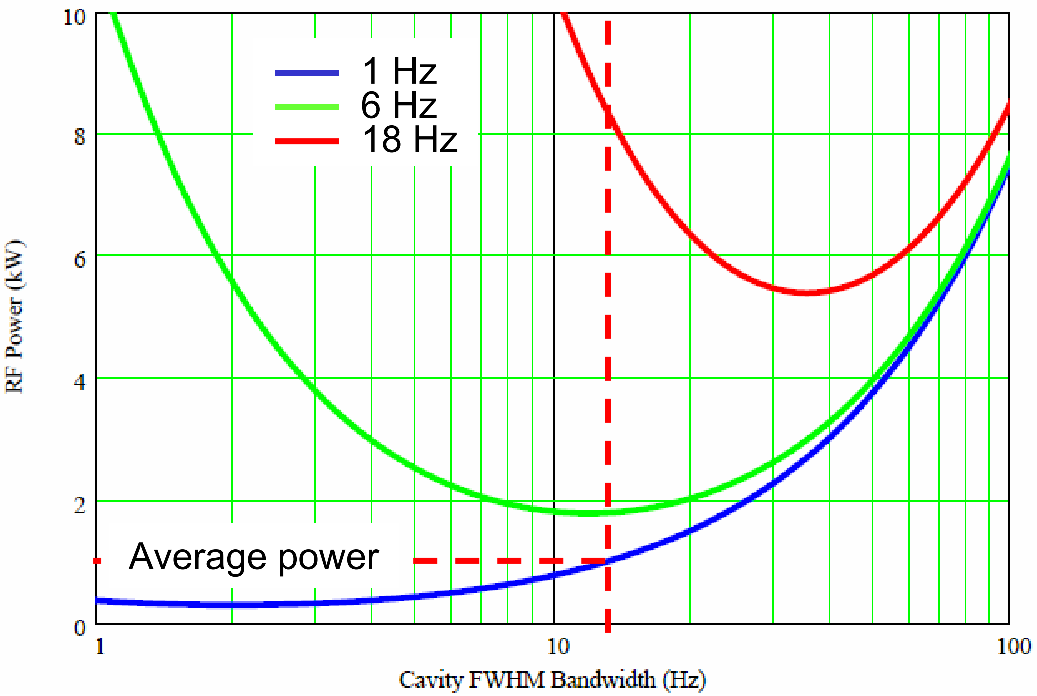


Where do we stand today?

- Take ELBE modules as a “pretty good system”
- RMS microphonics = 1 Hz.
- What do we take as peak microphonics? Take 6 σ
- At 6 Hz, optimal cavity bandwidth = 12 Hz, or $Q_L = 1.1 \times 10^8$
- Installed RF power > 1.8 kW
- Average RF power = 930 W (OK)

Machine	σ [Hz]	6σ [Hz]
CEBAF	2.5 (average)	15 (average)
ELBE	1 (average)	6 (average)
SNS	1 to 6	6 to 36
TJNAF FEL	0.6 to 1.3	3.6 to 7.8
TTF	2 to 7 (pulsed)	12 to 42 (pulsed)

$Q_L = 1.1 \times 10^8$

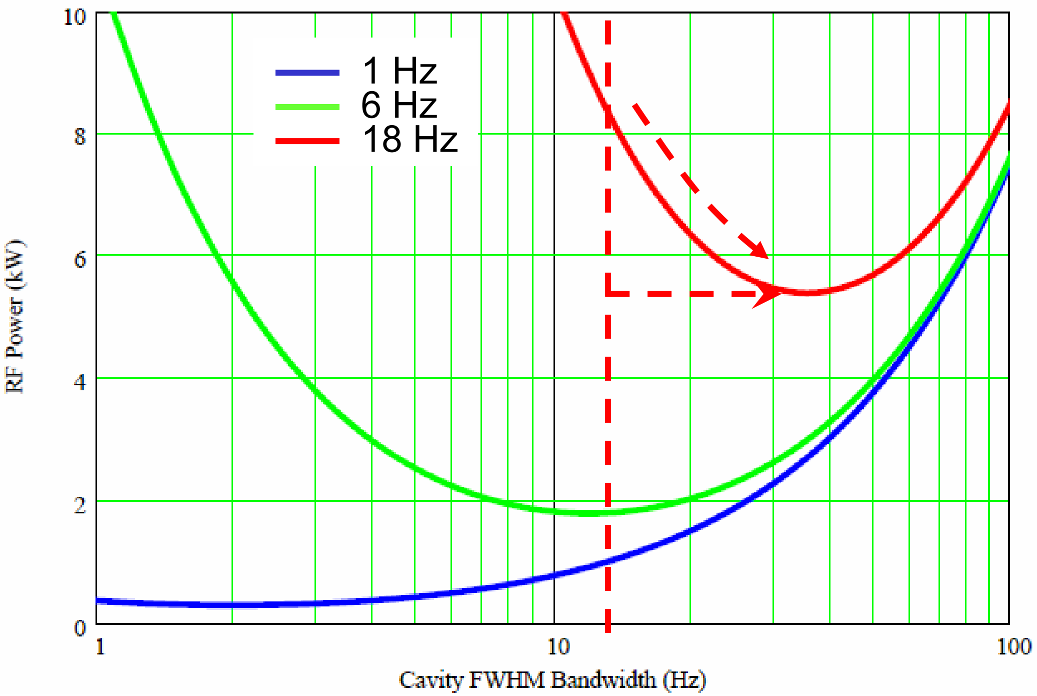


Where do we stand today?

- Take ELBE modules as a "pretty good system"
- RMS microphonics = 1 Hz.
- What do we take as peak microphonics? Take 6 σ
- At 6 Hz, optimal cavity bandwidth = 12 Hz, or $Q_L = 1.1 \times 10^8$
- Installed RF power > 1.8 kW
- Average RF power = 930 W (OK)
- For safety, should perhaps allow for a factor 3 more microphonics = 18 Hz peak
- Then require 5.4 kW, *provided the coupler can be adjusted*

Machine	σ [Hz]	6σ [Hz]
CEBAF	2.5 (average)	15 (average)
ELBE	1 (average)	6 (average)
SNS	1 to 6	6 to 36
TJNAF FEL	0.6 to 1.3	3.6 to 7.8
TTF	2 to 7 (pulsed)	12 to 42 (pulsed)

$Q_L = 1.1 \times 10^8$

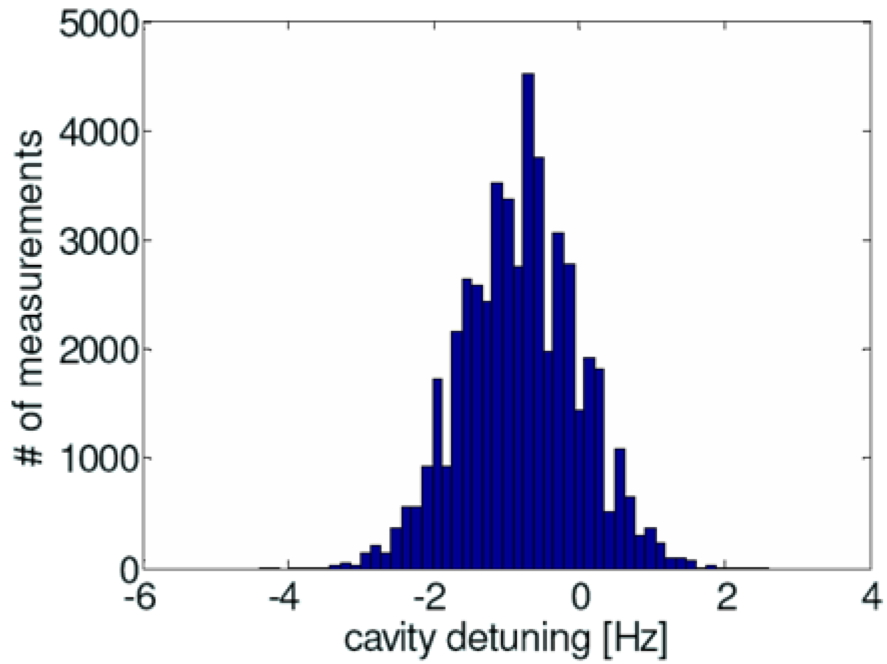


Can one control the RF Field? Measurements at JLAB FEL-ERL

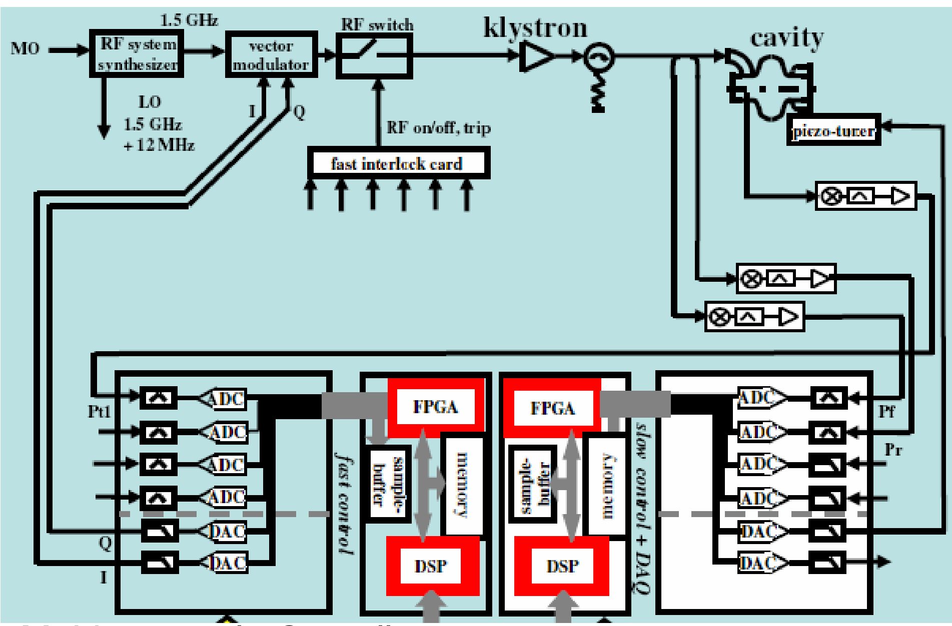
- Attempted RF control with Cornell digital control system at JLAB FEL with 5 mA (ERL)
- $Q_L = 1.2 \times 10^8 \rightarrow \Delta f = 12.5$ Hz, matched to peak microphonics
- Impressive results were achieved with amplitude and phase stability!!

Peak microphonics 6 Hz

RMS microphonics 1 Hz



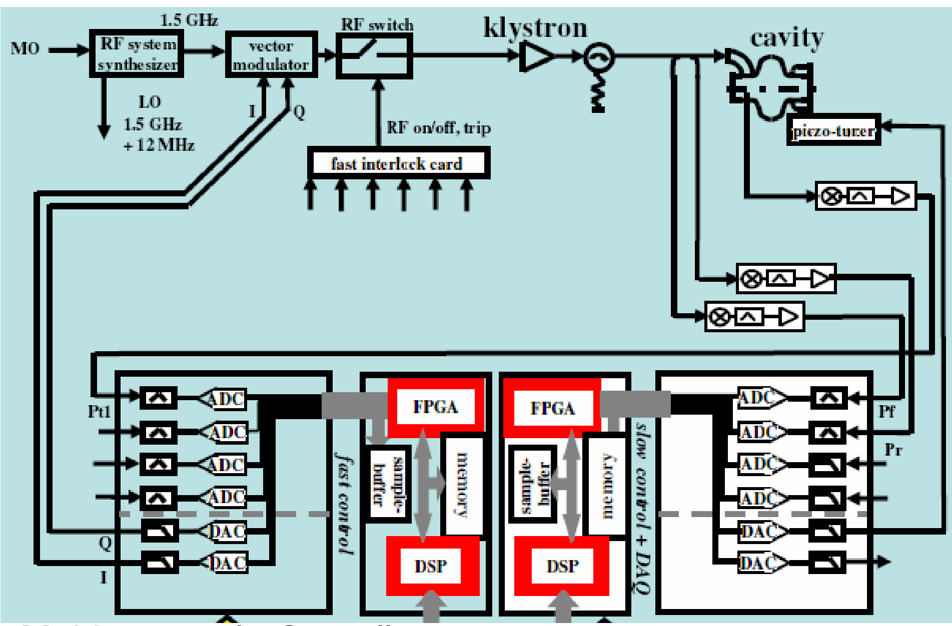
M. Liepe et al., Cornell



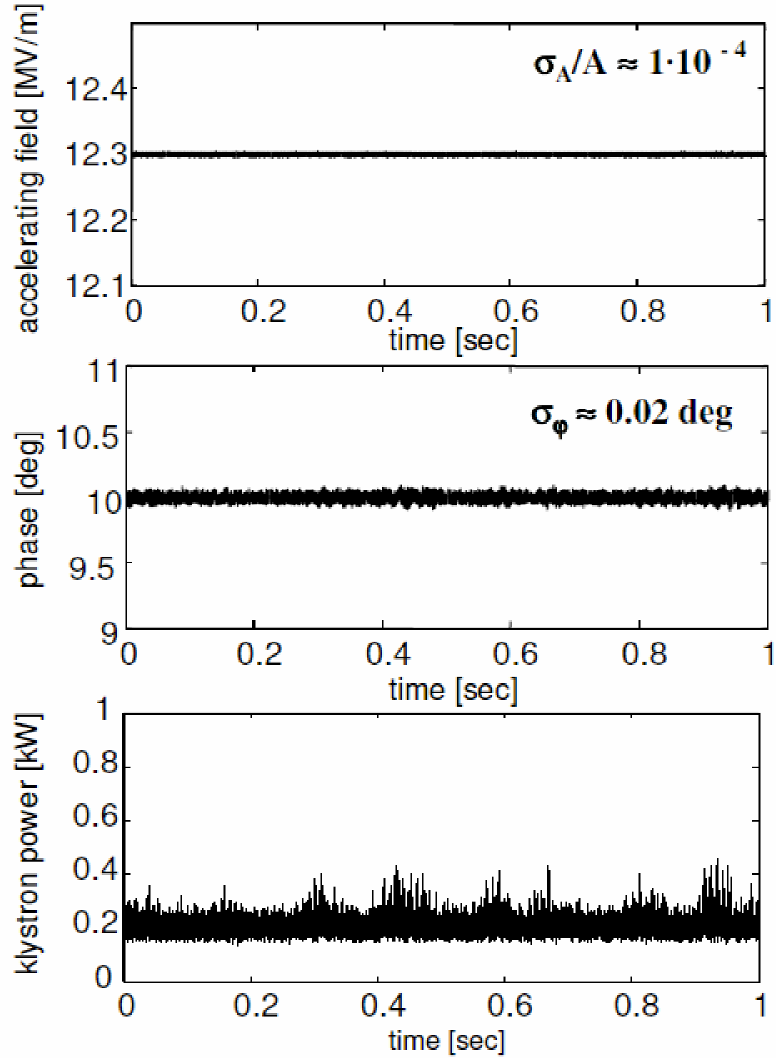
M. Liepe et al., Cornell

Can one control the RF Field? Measurements at JLAB FEL-ERL

- Attempted RF control with Cornell digital control system at JLAB FEL with 5 mA (ERL)
- $Q_L = 1.2 \times 10^8 \rightarrow \Delta f = 12.5$ Hz, matched to peak microphonics
- Impressive results were achieved with amplitude and phase stability!!
- Gain up to 600, limited by measurement noise

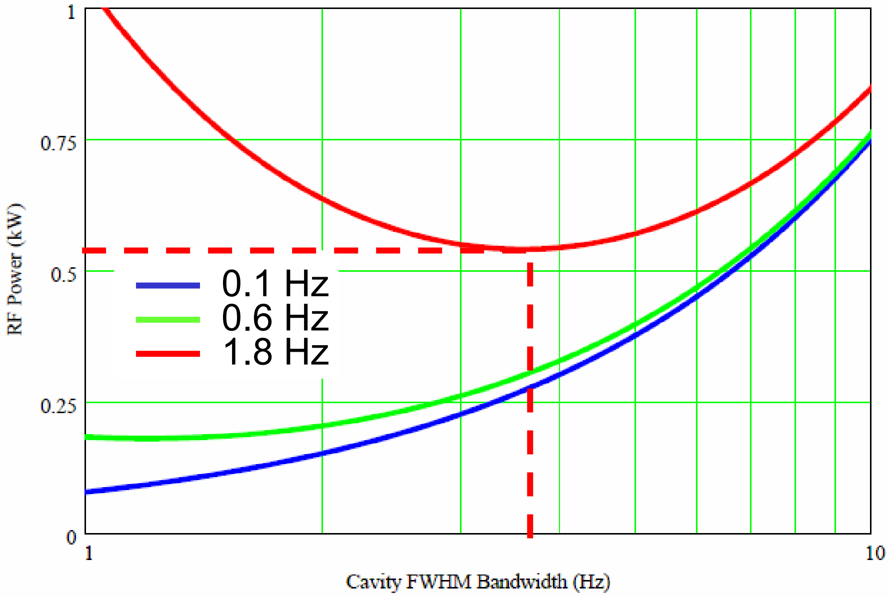


M. Liepe et al., Cornell



If we could dream, what bandwidth would we choose?

- We saw that the microphonics impact the layout/cost of the RF system significantly
- Scaling to 20 MV for TESLA cavities we still need about 5 kW of RF power (for safety, 18 Hz microphonics)
- This implies the use of klystron or IOT transmitters
- Very expensive → RF system is a cost driver
- Can get into the range of solid state amplifiers if microphonics can be reduced by a factor of 10
- Δf = around 3.6 Hz, Q_L = mid 10^8



Until now we assumed that there is no beam

- This is not the case, only that the beam is compensated for by the recirculating beam
- But what happens when the compensation is not perfect?
- For example
  - Current (amplitude or phase) out of the gun varies
  - Beam phase of recirculated current varies, e.g., due to rf stability issues in the cavities combined with dispersive segments
- Uncompensated beam induces a voltage in the cavity
- The higher the loaded *Q*, the greater this voltage
- For example
  - Reinjection phase is off by only 0.02 deg = 0.35 mrad = 43 fs!
  - Uncompensated current is 0.175 mrad x 100 mA = 35 µA
- If the bandwidth is very narrow, e.g., Δf = 2.6 Hz : $V_b = R/Q \times Q_L \times I$ = 18 MV at 90 deg to generator voltage!
- This is nearly the operating cavity voltage! Cavity phase is now nearly 45 deg → Q_L = 5E8 does not appear feasible
- Even when Q_L = 1E8, beam induced voltage would be 3.6 MV, which may prove limiting
- Beam stability issues will therefore play an important role in determining the optimal Q_L

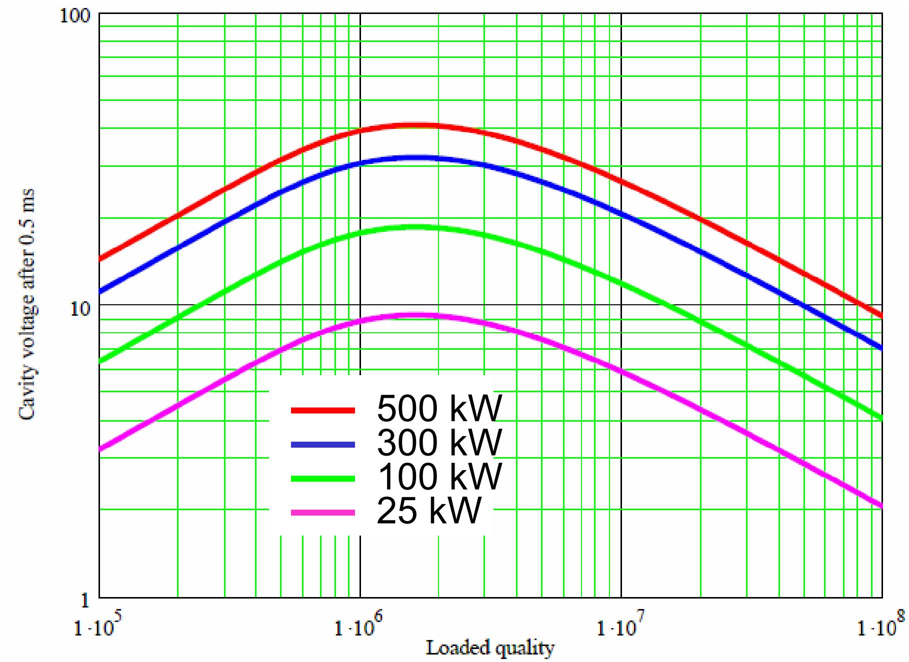
RF Conditioning

For light sources we need reliability → Possibility to RF condition is very desirable

- To condition field emitters, need to raise field quickly to high levels before a quench sets in
- Quench times are on the order of ms → Conditioning pulses must therefore be < 1 ms (say 0.5 ms)
- This is "incompatible" with the long time constants of narrow bandwidth ERL cavities

→ Another reason to use adjustable coupling

- Voltage versus time: $V(t, P_f, Q_L) := 2 \cdot \sqrt{\frac{R}{Q} \cdot Q_L \cdot P_f} \cdot \left(1 - \exp\left(\frac{-t \cdot \omega_0}{2Q_L}\right)\right)$

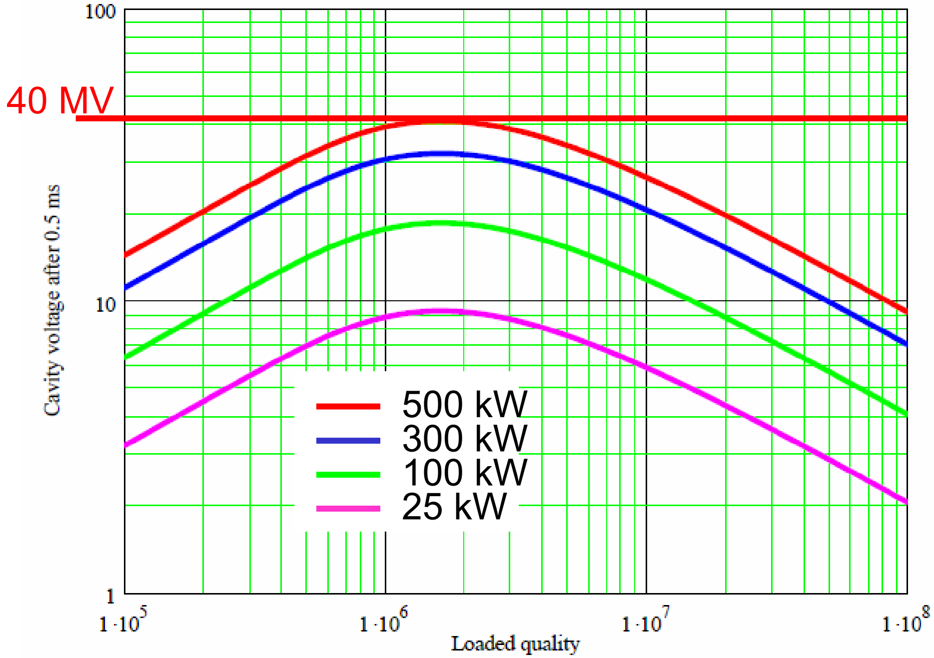


For light sources we need reliability → Possibility to RF condition is very desirable

- To condition field emitters, need to raise field quickly to high levels before a quench sets in
- Quench times are on the order of ms → Conditioning pulses must therefore be < 1 ms (say 0.5 ms)
- This is "incompatible" with the long time constants of narrow bandwidth ERL cavities

→ Another reason to use adjustable coupling

- Voltage versus time: $V(t,P_f,Q_L) := 2\cdot\sqrt{\frac{R}{Q}\cdot Q_L\cdot P_f}\cdot\left(1-\exp\left(\frac{-t\cdot\omega_0}{2Q_L}\right)\right)$
- For FE-free cavity must pulse to 2 x V_c = 40 MV

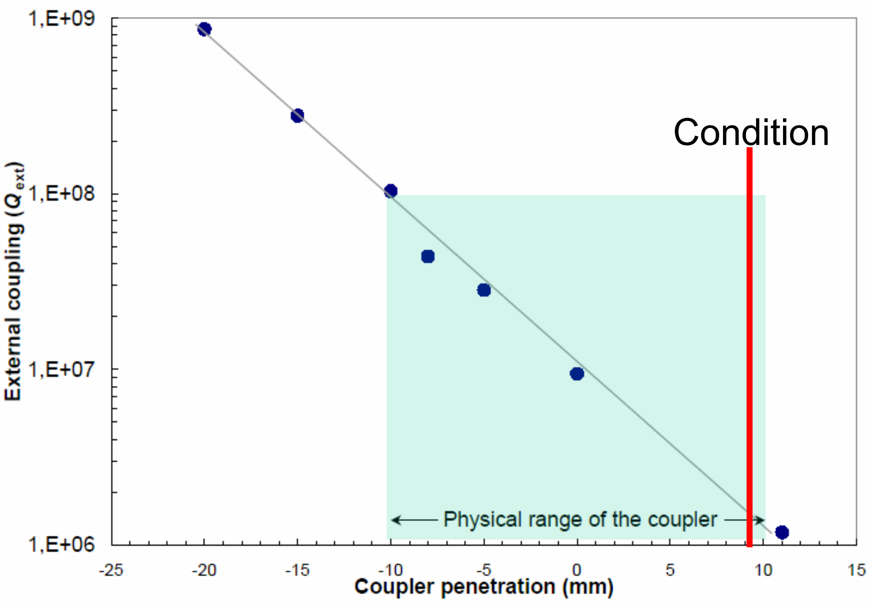


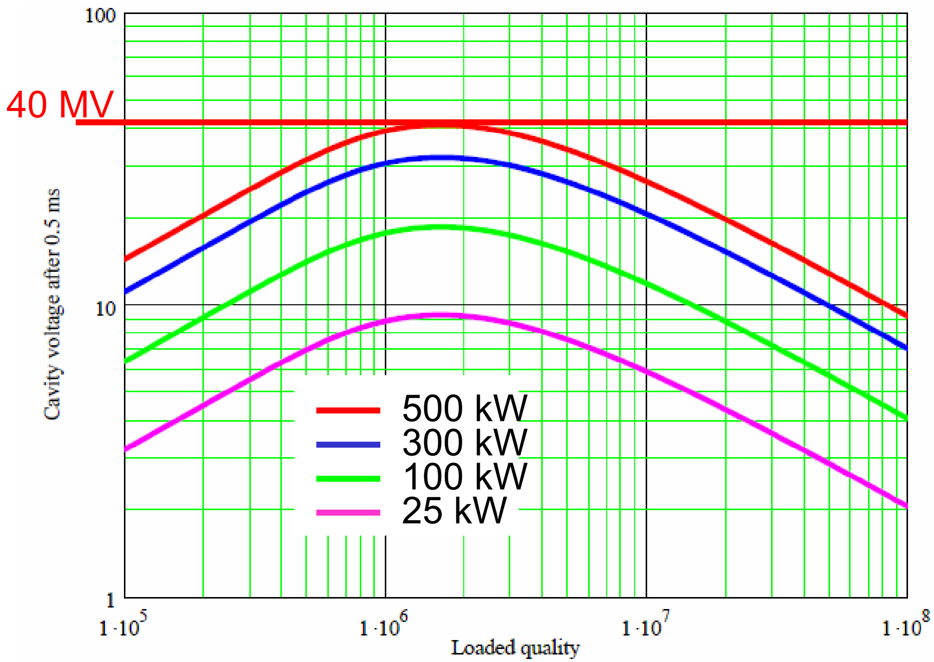
For light sources we need reliability → Possibility to RF condition is very desirable

- To condition field emitters, need to raise field quickly to high levels before a quench sets in
- Quench times are on the order of ms → Conditioning pulses must therefore be < 1 ms (say 0.5 ms)
- This is "incompatible" with the long time constants of narrow bandwidth ERL cavities

→ Another reason to use adjustable coupling

- Voltage versus time: $V(t, P_f, Q_L) := 2 \cdot \sqrt{\frac{R}{Q} \cdot Q_L \cdot P_f} \cdot \left(1 - \exp\left(\frac{-t \cdot \omega_0}{2 Q_L}\right)\right)$
- For FE-free cavity must pulse to 2 x V_c = 40 MV





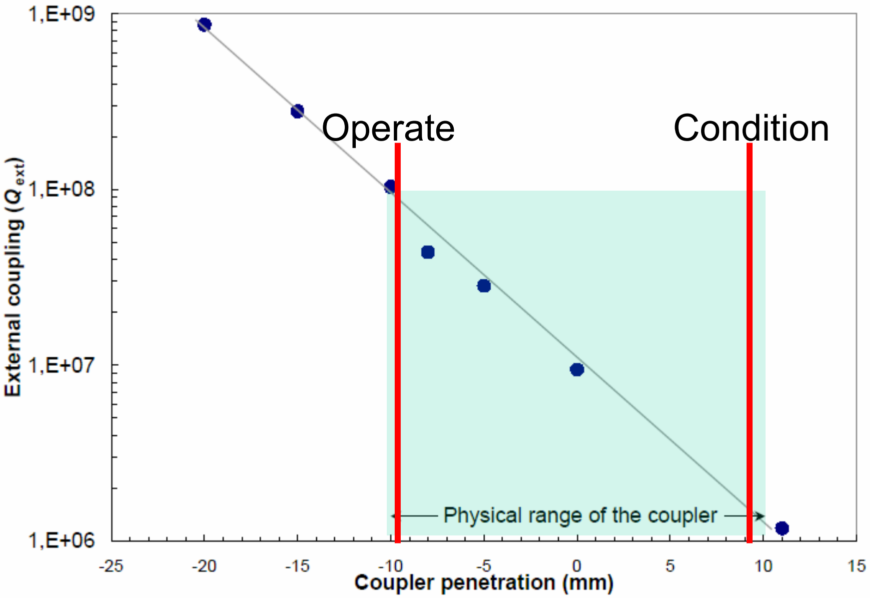
For light sources we need reliability → Possibility to RF condition is very desirable

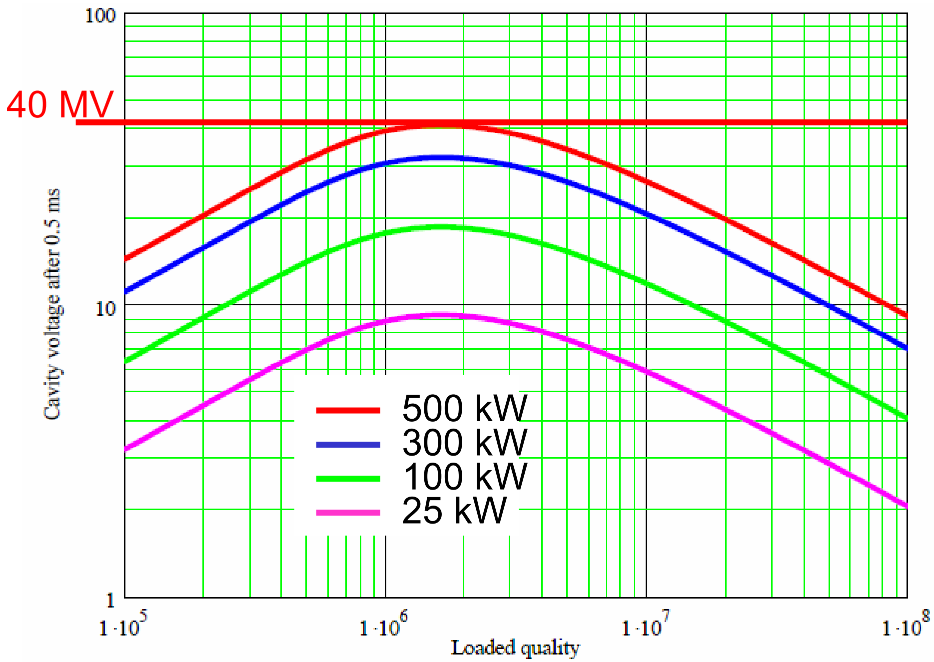
- To condition field emitters, need to raise field quickly to high levels before a quench sets in
- Quench times are on the order of ms → Conditioning pulses must therefore be < 1 ms (say 0.5 ms)
- This is “incompatible” with the long time constants of narrow bandwidth ERL cavities

→ Another reason to use adjustable coupling

- Voltage versus time: $V(t, P_f, Q_L) := 2 \cdot \sqrt{\frac{R}{Q} \cdot Q_L \cdot P_f} \cdot \left(1 - \exp\left(\frac{-t \cdot \omega_0}{2 Q_L}\right)\right)$
- For FE-free cavity must pulse to 2 x V_c = 40 MV

→ With TTF coupler cannot use Q_L > about 10^8





Resumé & Open Questions

Aspects that must be investigated whether high Q_L operation is possible:

- How far can one reduce the microphonic detuning? For around $Q_L = 10^8$-10^9 require *peak* detuning between 1 and 10 Hz.
  - → Investigate low-microphonic modules
  - → Given measured RMS microphonics, what peak levels must we design for?
  - → Stabilize the helium system down to the 0.01 mbar levels!
  - → Use microphonic compensation. This is in its infancy, but promising.
- What spread in microphonics should one expect
  - Must allow for a safety factor when dimensioning RF system
  - At present, factors of 3 in microphonics are not unreasonable
  - Installed RF power must be greater by factor of 3 + coupler adjustability
- Can the RF field be stabilized down to the 0.01-0.02 deg and 10^{-4} level?
  - → Requires a high-gain system (500)
  - → Cornell/JLAB measurements demonstrated this can be done at $Q_L = 1.2 \times 10^8$ with a "quiet" module
  - → Coupling optimized for $\delta f_{pk} = 6\ \sigma_{mic}$

3 Hz peak microphonics?
→ $Q_L < 2E8$

→ Even if $Q_L = 1E8$, some cavities will need to run at $Q_L = 3E7$. RF system must be designed for this

→ $Q_L = 1.2E8$ demonstrated
Even higher values may be possible provided low microphonics and low pickup noise

Resume & Open Questions ctd

Aspects that must be investigated whether high Q_L operation is possible:

→ Q_L < 1E8?

- How much uncompensated beam current can one expect in 100 mA ERLs?

→ changes in beam loading may prove to limit the Q_L. Even $Q_L = 10^8$ may be tough, but more measurements are needed

- How important is it to RF process the cavities?
  - For light sources this may be a big reliability issue
  - For RF processing require Q_L values around 10^6
  - Coupling ranges of x 100 will be tough to achieve → Maximum Q_L would be 10^8

→ Q_L < 1E8

→ Given present status, Q_L values much above 10^8 do not appear feasible (??). Possibly one will have to stay below this.