# *Pushing $Q_L$*

*Matthias Liepe*

**Outline:**

- **Why?**
- **What's the problem? Challenges…**
- **State-of-the-Art**
- **Outlook**

# *Why do we want a high $Q_L$?*

**ERL:** ⇒ **No effective beam loading in main linac!**

**(accelerated and decelerated beam compensate each other)**

⇒ **Only wall losses: some Watts**

⇒ **Matched external Q is very high (> $5 \cdot 10^9$)!**

⇒ **Could operate cavity with less than 1 kW!**

**But: State-of-the-art is cavity operation at or below $Q_L = 2 \cdot 10^7$…**

**Why?**

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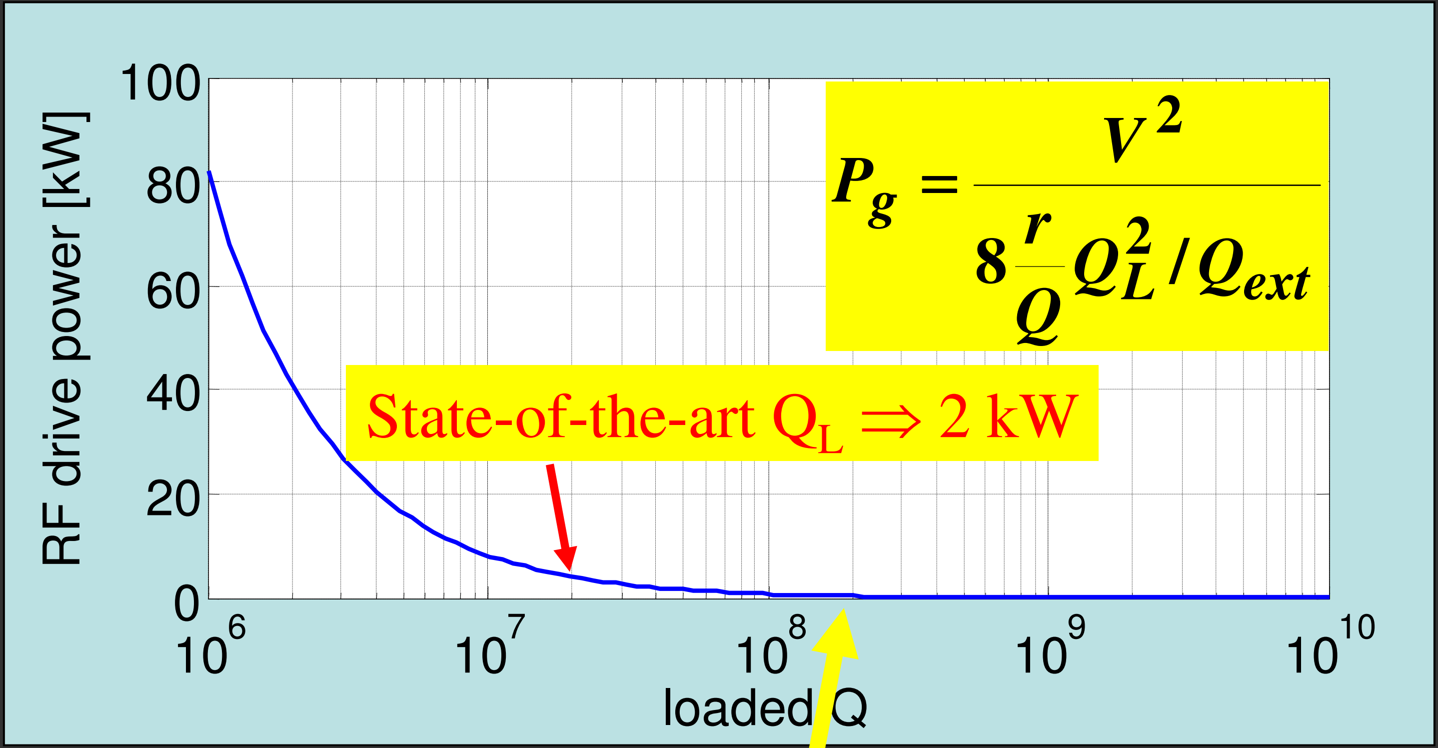
# Why do we want a high $Q_L$?

**Example: RF drive power for 7-cell Cornell ERL cavity at 20 MV/m**




$$P_g = \frac{V^2}{8\frac{r}{Q}Q_L^2/Q_{ext}}$$

**⇒ Want $Q_L > 10^8$! ⇒ 200 W**

# What's the problem?

## *if only we could run at high $Q_L$… Challenges:*

- **Microphonics**: The optimal $Q_L$ is a function of the peak microphonics detuning!
- **RF field stability**: RF control and high field stability gets harder at high $Q_L$
- **Start up**: Lorentz-Force will detune cavity by many bandwidths during field ramp up

# *What's the problem? Microphonics*

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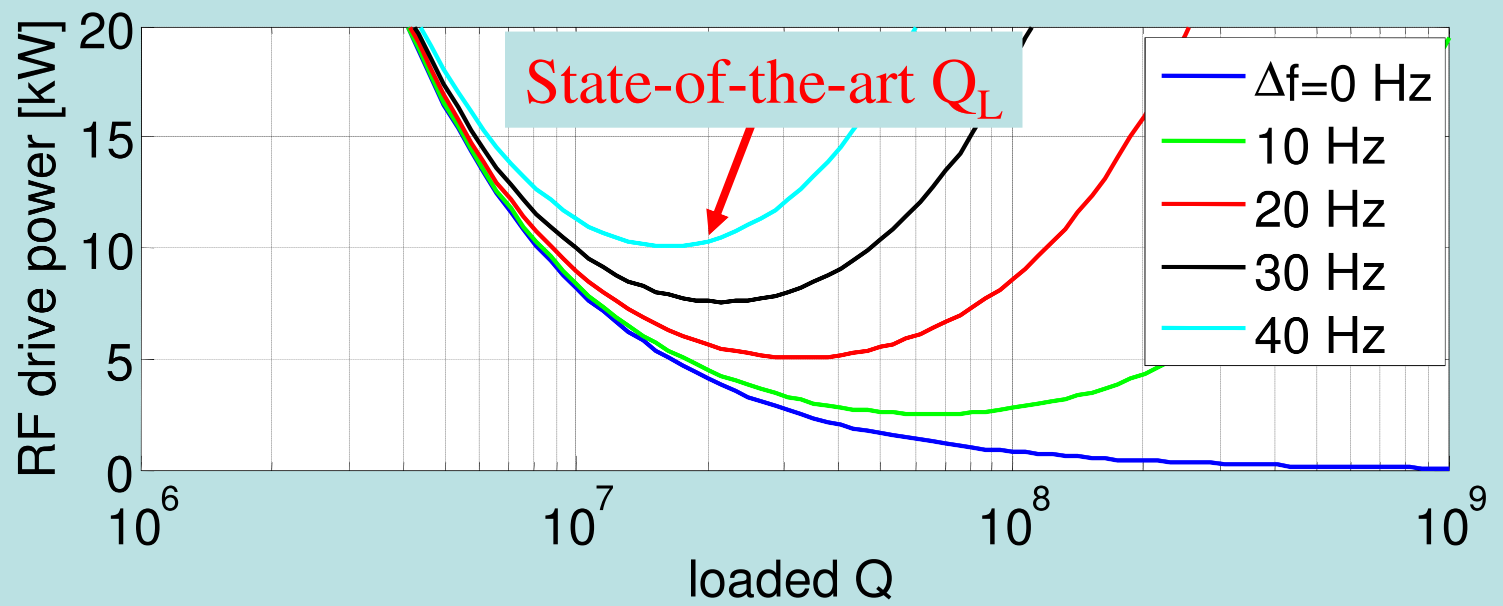
**The optimal $Q_L$ is a function of the peak microphonics detuning!**




$$P_g = \frac{V^2}{8\frac{r}{Q}Q_L}\left(1+\left(\frac{\Delta f}{f_{1/2}}\right)^2\right)$$

$$Q_{opt} = \frac{1}{2}\frac{f_0}{\Delta f}$$

$$P_{g,\min} = \frac{V_{acc}^2}{2r/Q}\frac{\Delta f}{f}$$

# *What's the problem?*
## *Field Stability/RF Control*

**Future ERLs require a very high RF field stability:**

$$\sigma_A/A < \text{some } 10^{-4}\ ,\ \sigma_\varphi < 0.1 \text{ deg.}$$

**But: The higher $Q_L$, the smaller the resonance bandwidth, and the more the field gets perturbed by cavity detuning (microphonics)!**

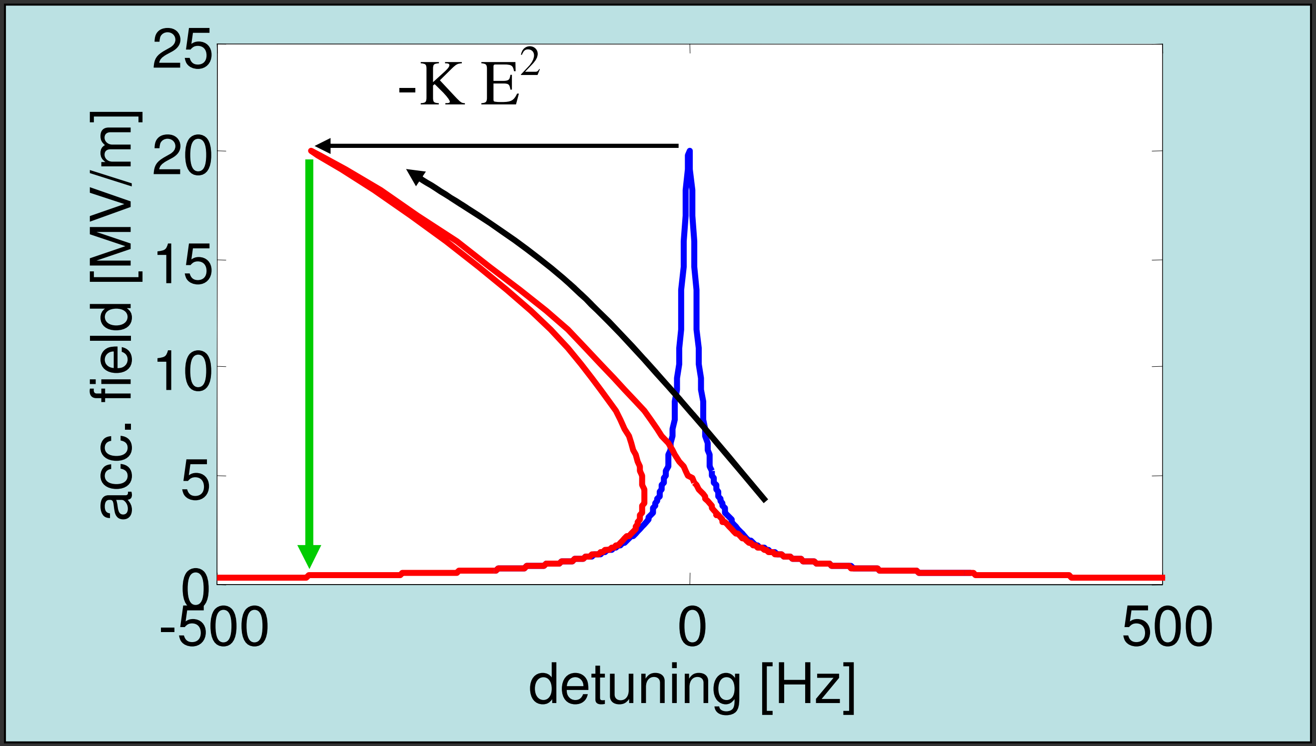
**$\Rightarrow$Needs advanced rf control system, which can deal with large amplitude and phase field perturbations.**

# What's the problem?

## Start-up: Lorentz-Force Detuning

- During field ramp up, Lorentz-forces detune the cavity by many bandwidths.
- This needs to be compensated very accurately (piezo frequency tuner).
- Once up there, good field and frequency stability is mandatory to stay there.

Example: At 20 MV/m: $\Delta f$=400 Hz, $f_{1/2}$ = 6.5 Hz at $Q_L = 10^8$



# Where are we today?
## State of the Art (I)

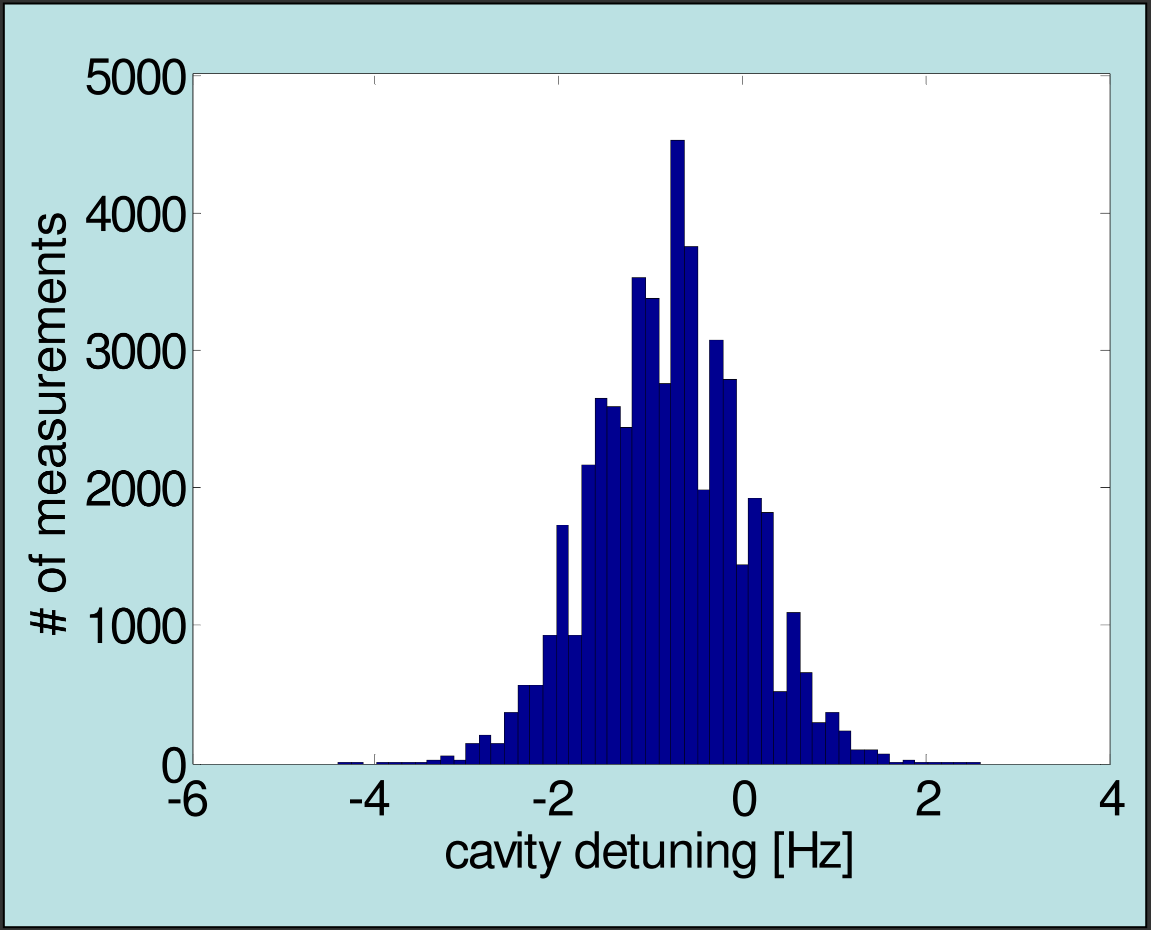
**JLAB FEL:**

**The cavities in the new cryomodule show very low microphonics:**

**rms ≈ 1 Hz**

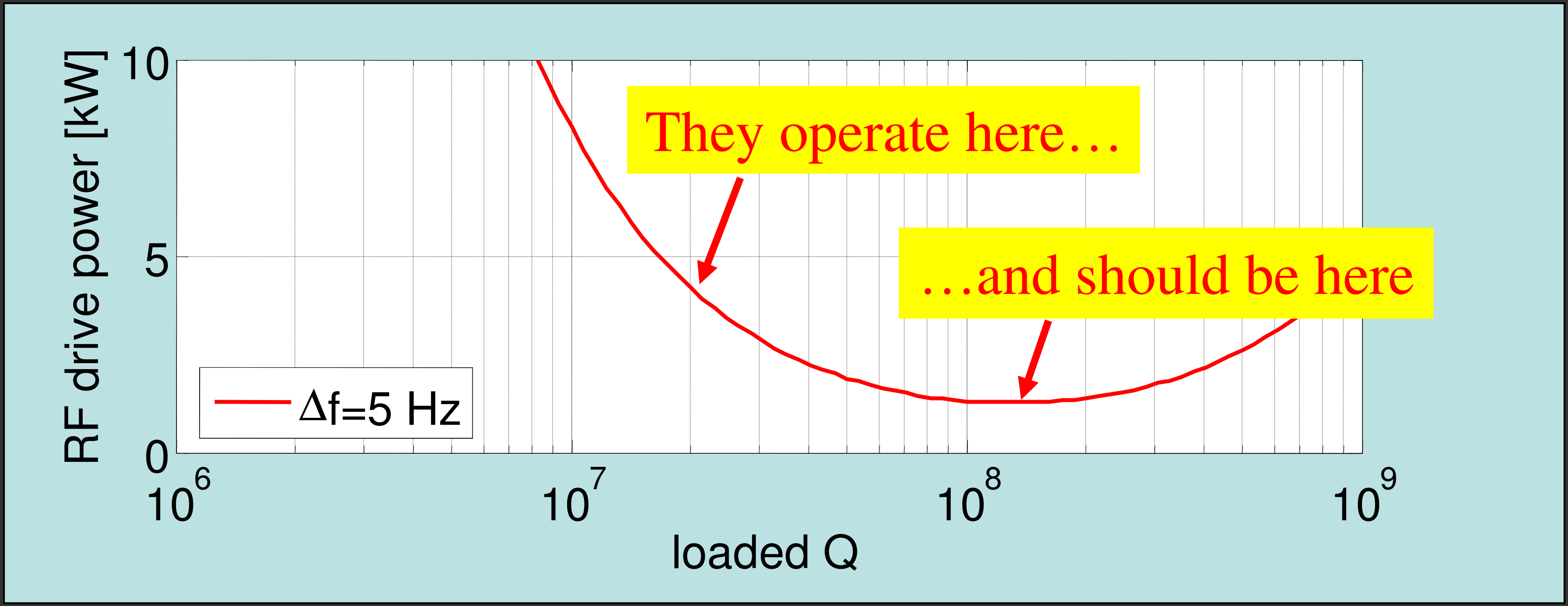
**peak detuning := 6 σ ≈ 6 Hz**

**Similar values have been obtained at the ELBE radiation source (see microphonics talk).**



# *Where are we today?*
## *State of the Art (II)*

**JLAB FEL:**




**⇒ A good mechanical design results in very low microphonics levels, and would allow to run at a $Q_L \approx 10^8$!**

# *Where are we today?*
## *State of the Art (III)*

**JLAB FEL: Why don't they operate above $Q_L=2\cdot10^7$?**

- **Classic amplitude and phase controller can not deal with large phase perturbations. However, at high loaded Q, microphonics is of the order of the cavity bandwidth. This results in large phase perturbations…**
- **Fast and precise frequency control is essential for cavity start-up and high field operation with high $Q_L$.**

# Where are we today?
# Cornell RF control hardware

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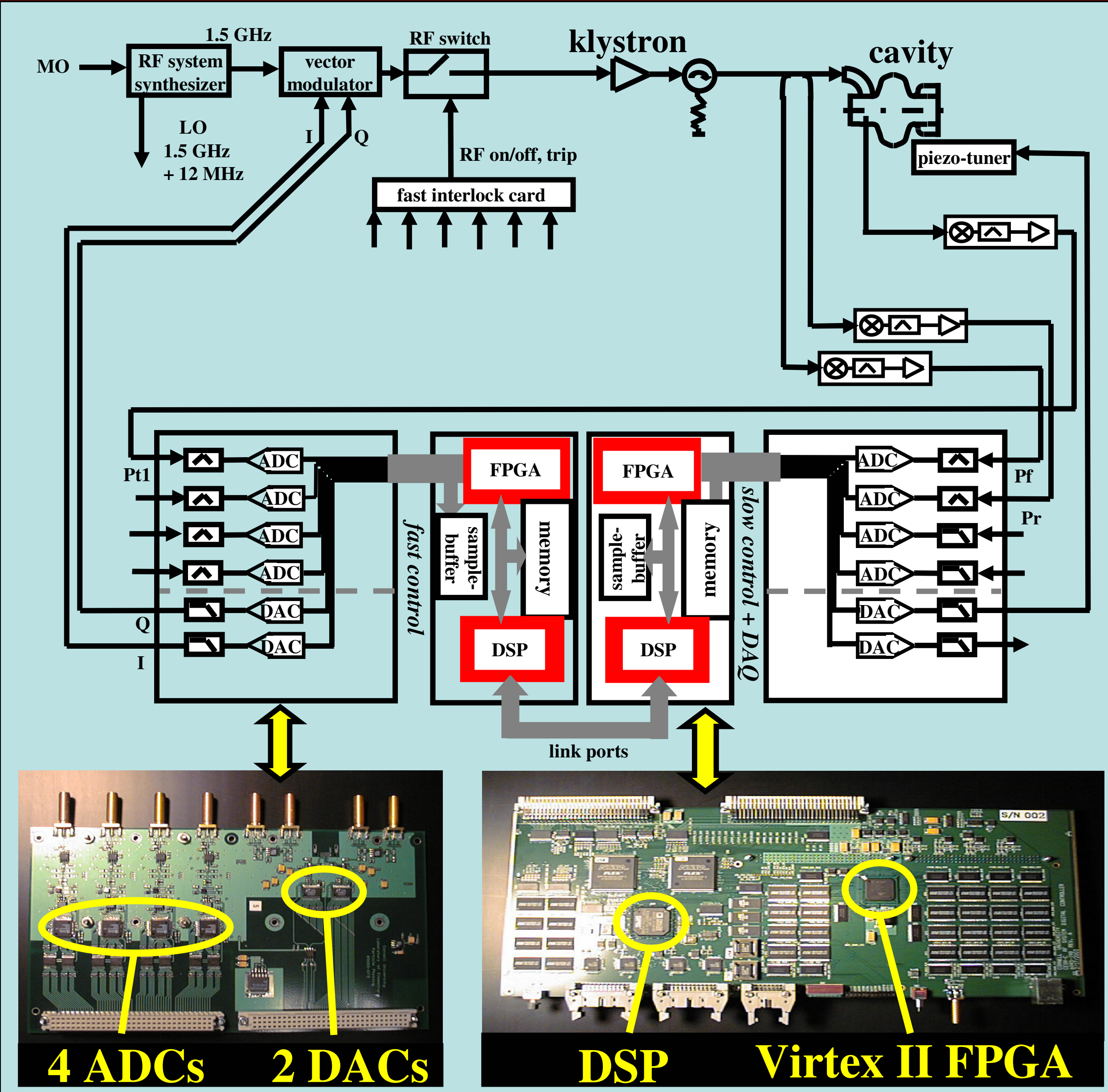
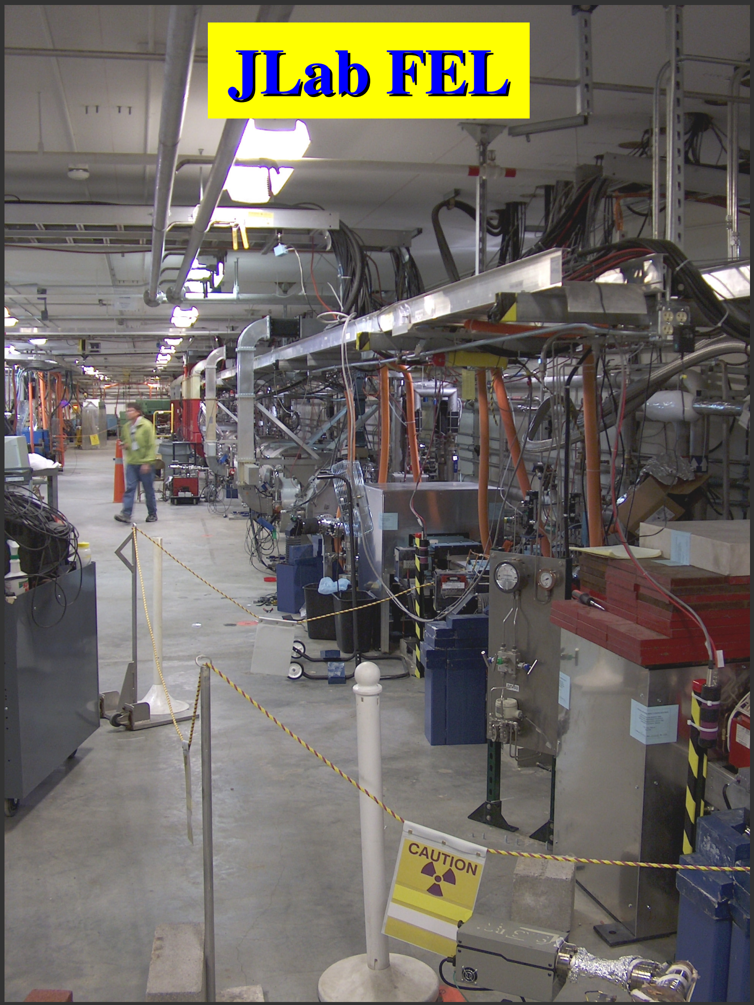


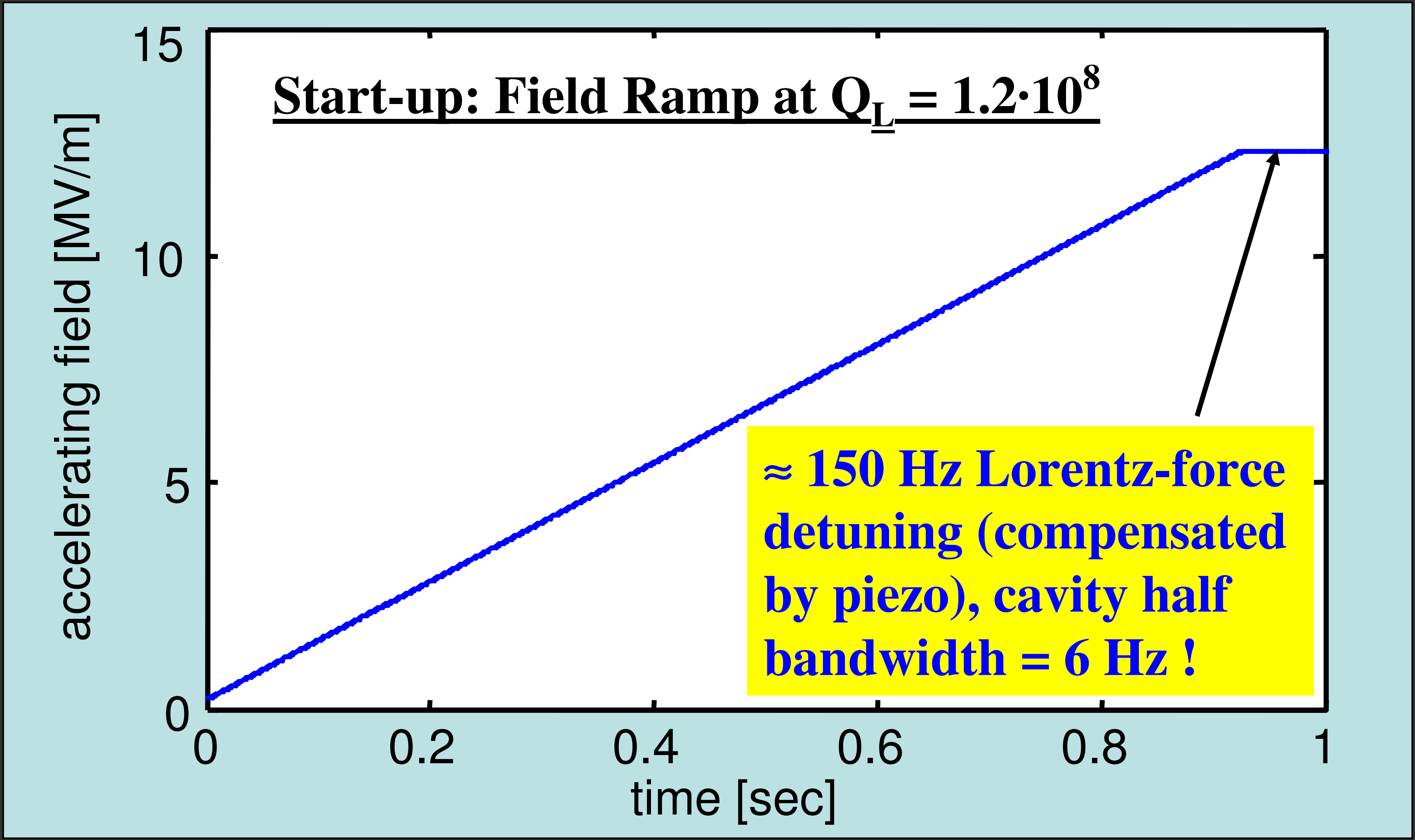

- *very low delay in the control loop*
- *Field Programmable Gate Array (FPGA) design combines the speed of an analog system and the flexibility of a digital system*
- *high computation power allows advanced control algorithms*
- *all boards have been designed in house*

# Where are we today?
## Cornell RF control test (I)

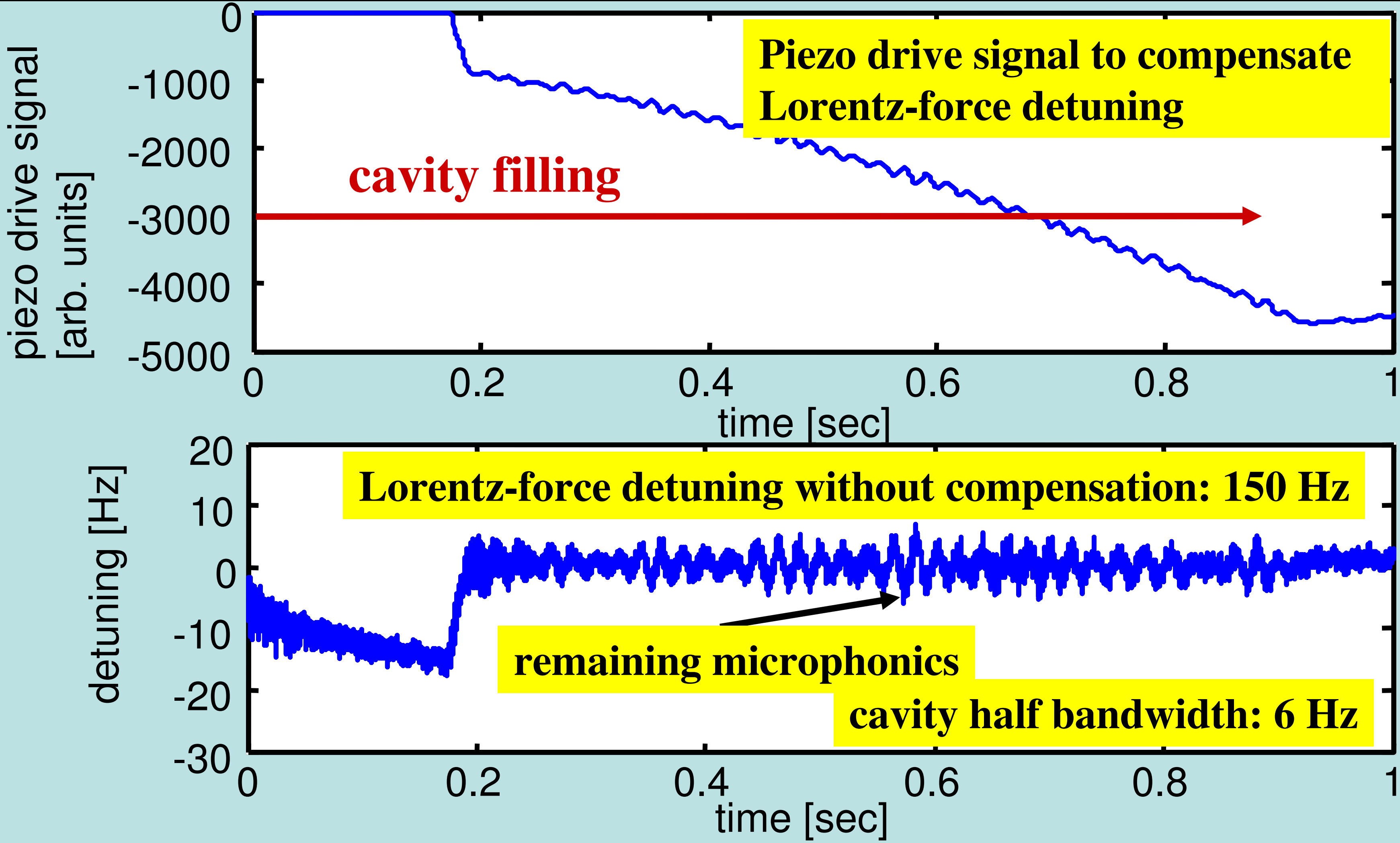



- Operated cavity at $Q_L=2\cdot10^7$ with 5 mA energy recovered beam.
- Operated cavity at $Q_L=1.2\cdot10^8$ with 5 mA energy recovered beam.
- Had the following control loops active:
  - PI loops for cavity field (I and Q component)
  - Stepping motor feedback for frequency control
  - Piezo tuner feedback for frequency control

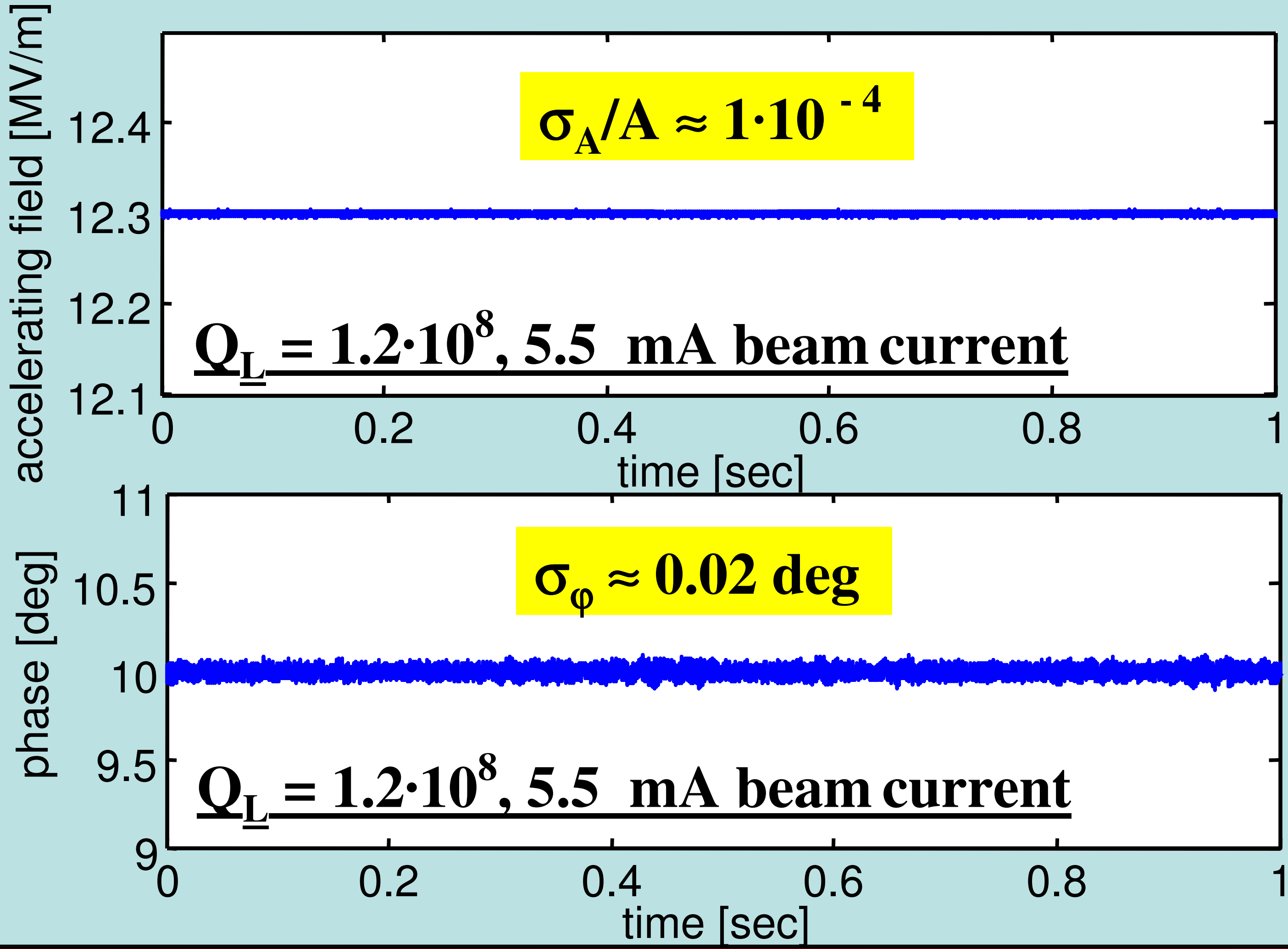
# Where are we today?
## Cornell RF control test (II)



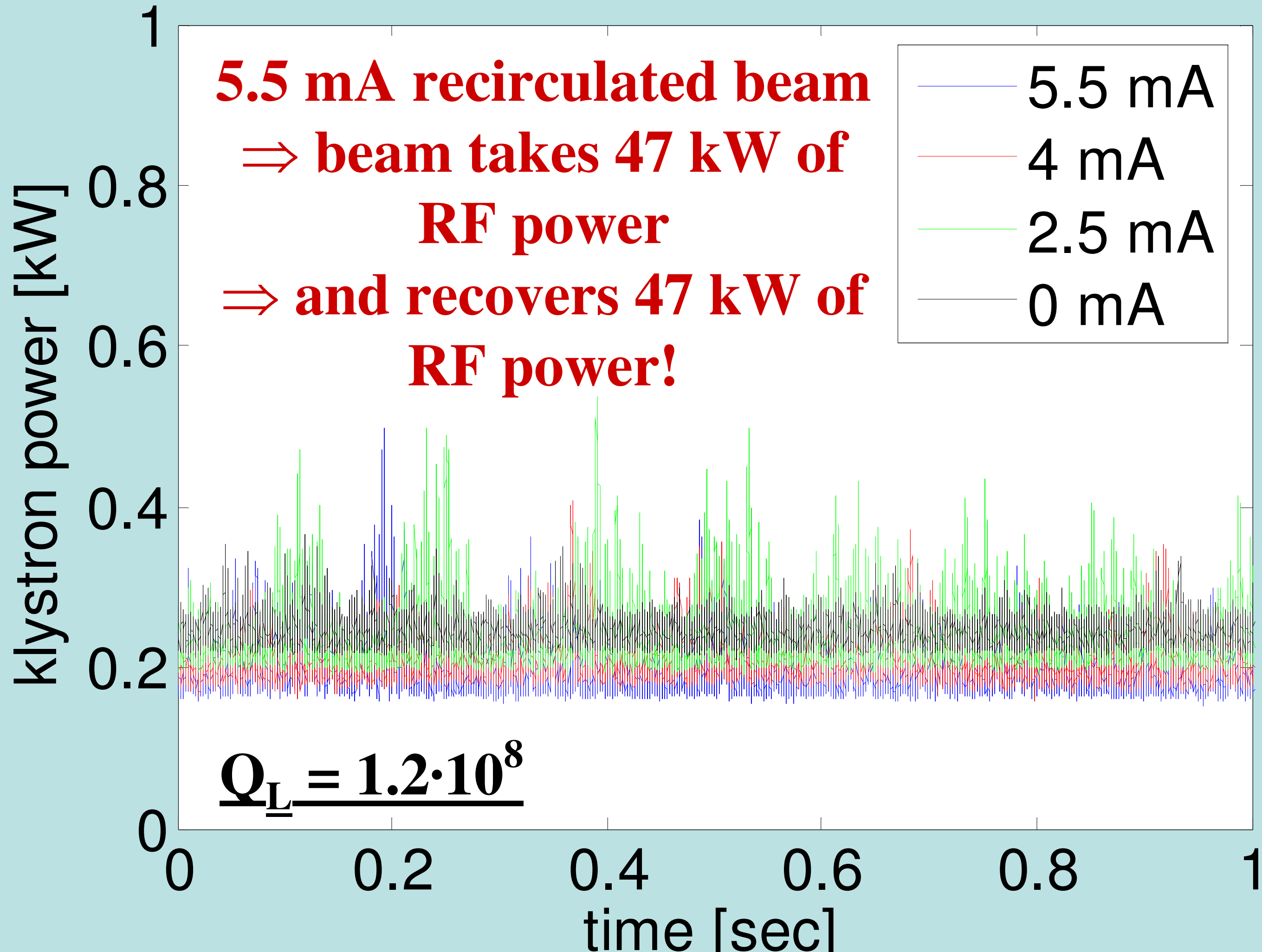
# Where are we today?
## Cornell RF control test (III)



# *Where are we today?*
## *Cornell RF control test (IV)*



# *Where are we today?*
## *Cornell RF control test (V)*



# *Outlook*
## *What does this mean?*

**Can one operate at $Q_L \approx 10^8$ ?**

- **Microphonics level can be made low enough (with good mechanical design). This has been demonstrated at the JLAB FEL and the ELBE radiation source.**
- **RF control can handle $Q_L \approx 10^8$! Cornell RF control test.**
- **Open question: How well does the beam loading compensation work at high currents?**
- **Conclusion: < 10 mA ERLs can use $Q_L \approx 10^8$. Low average current FELs can use $Q_L \approx 10^8$. High current ERLs:**

**Stay tuned!**