Pushing the Limits: RF Field Control at High Loaded Q

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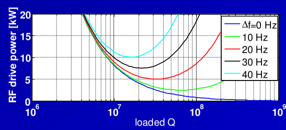
Abstract:
The superconducting cavities in an Energy-Recovery-Linac will be operated with a high loaded *Q* of several 10^7, possible up to 10^8. Not only has no prior control system ever stabilized the RF field in an elliptical linac cavity with such high loaded *Q*, but also highest field stability in amplitude and phase is required at this high loaded *Q*. Because of a resulting bandwidth of the cavity of only a few Hz, this presents a significant challenge: the field in the cavity is extremely sensitive to any perturbation of the cavity resonance frequency due to microphonics and Lorentz force detuning. To prove that the RF field in a high loaded *Q* cavity can be stabilized, and that Cornell's newly developed digital control system is able to achieve this, the system was connected to a high loaded *Q* cavity at the TJNAF IR-FEL. Excellent CW field stability - about $2\cdot10^{-4}$ rms in relative amplitude and 0.03 deg rms in phase - was achieved at a loaded *Q* of $2.1\cdot10^7$ and $1.2\cdot10^8$, setting a new record in high loaded *Q* operation of an elliptical linac cavity. Piezo tuner based cavity frequency control proved to be very effective in keeping the cavity on resonance and allowed reliably to ramp up to high gradients in less than 1 second.

Why high loaded 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 (> $5\cdot10^9$)!
- Optimal loaded Q is a function of the peak microphonics cavity detuning.
- Could operate cavity with less than 1 kW!
- Very low microphonic levels have been achieved: $6\sigma<10$ Hz (ELBE, TJNAF FEL)
- Optimal loaded Q is ≈ 10^8!

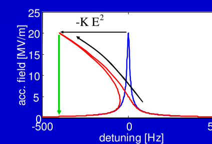


$$Q_{opt} = \frac{1}{2}\frac{f_0}{\Delta f} \qquad P_{g,\min} = \frac{V_{acc}^2}{2r/Q}\frac{\Delta f}{f}$$

High loaded Q challenges:

- Future ERLs require a very high RF field stability: σ_A/A < some 10^{-4}, $\sigma_\varphi < 0.1$ deg.
- But: The higher Q_L, the smaller the resonance bandwidth, and the more the field gets perturbed by cavity microphonics.
- During field ramp up, Lorentz-forces detune the cavity by many bandwidths. This needs to be compensated very accurately (piezo frequency tuner).
- Risk of ponderomotive instability.
- Good field and frequency stability is mandatory to stay at high fields.

⇒ State-of-the-art is cavity operation at a loaded Q of 1 to $3\cdot10^7$, not 10^8.



The test:

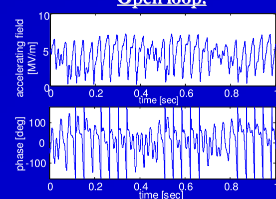
- Cornell's LLRF system has been designed to meet these high loaded Q challenges.
- Set up collaboration between Cornell and TJNAF to test Cornell's LLRF system at CEBAF and the FEL with high loaded Q cavities.
- TJNAF designed the RF reference system and the down-converter.

Digital Boards:

Results from CEBAF

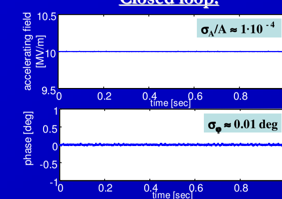
- Connected Cornell's RF control system to one of the CEBAF 5-cell cavities.
- This cavity is one of the most microphonically active cavities in CEBAF.
- Increased loaded Q to $4.2\cdot10^7$ (18 Hz cavity bandwidth).
- Run up to 4·100 μA = 400 μA total beam current.

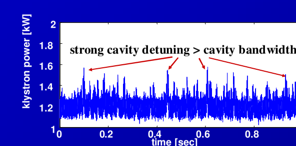
Open loop:



- Open loop: constant klystron power (amplitude and phase).
- Very strong microphonics (peak detuning > 1.5 · cavity bandwidth!).
- Open loop: ponderomotive instability.
- Closed loop: Very stable and reliable cavity operation (no trips over hours).

Closed loop:

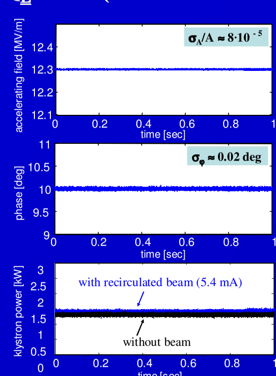




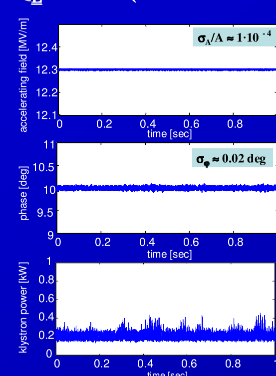
Results from the TJNAF FEL

- Connected Cornell's RF control system to one of the FEL 7-cell cavities.
- 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 fast frequency control

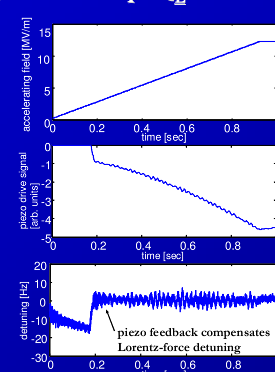
$Q_L=2\cdot10^7$ (75 Hz bandwidth)



$Q_L=1.2\cdot10^8$ (12 Hz bandwidth)



Field ramp: $Q_L=1.2\cdot10^8$



More at $Q_L=1.2\cdot10^8$