Pushing the Limits: RF Field Control at High Loaded Q

M. Liepe, S. Belomestnykh, J. Dobbins, R. Kaplan, C. Strohman, B. Stuhl, LEPP, Cornell University
C. Hovater, T. Plawski, TJNAF

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 tipping. 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 FEL. Excellent CW field stability - about \( 2 \cdot 10^{-15} \) in amplitude and phase - was achieved at a loaded \( Q \) of \( 2.1 \cdot 10^9 \) and \( 1.2 \cdot 10^8 \), 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 higher fields in less than 1 second.

Why high loaded \( Q \)?
- No effective beam loading in main linac (accelerated and decelerated beam components cancel each other)
- Only wall losses give \( Q \)
- Matched external \( Q \) is very high (> \( 5 \cdot 10^5 \))
- Optimal loaded \( Q \) is a function of the peak microphonics cavity detuning.
- Could operate cavity with less than 1 A!
- Very low microphonics levels have been achieved (\( >10 \) Hz (ELBE, TJNAF FEL))
- Optimal loaded \( Q \) is \( >10^5 \)

Results from CEBAF
- Connected Cornell’s RF control system to one of the CEBAF 7-cell cavities.
- This cavity is one of the most microphonically active cavities in CEBAF.
- Increased and loaded \( Q \) to \( 4.2 \cdot 10^9 \) (18 Hz cavity bandwidth).
- Run up to \( 4 \cdot 100 \mu A \) = \( 400 \mu A \) total beam current.

Open loop:
- Open loop: constant klystron power (amplitude and phase).
- Very strong microphonics (peak detuning \( \Delta f =5 \) cavity bandwidth).
- Open loop: ponderomotive instability.

Closed loop:
- Closed loop: Very stable and reliable cavity operation (no trips or beam losses).
- Stepping motor feedback for frequency control.
- Piezo tuner feedback for fast frequency control.
- Had the following control loops active:
  - PI loops for cavity field (load Q component)
  - Stepping motor feedback for frequency control
  - Piezo tuner feedback for fast frequency control

High loaded \( Q \) challenges:
- Future ERLs require a very high RF field stability \( \Delta f / A < 10^{-15} \), \( Q > 10^6 \)
- But the higher \( Q \), the smaller the resonance bandwidth, and the more the field gets disturbed by cavity microphonics.
- During field ramp up, Lorentz forces detune the cavity by many bandwidths. This needs to be compensated very accurately (picosecond range).
- Risk of ponderomotive instability.
- Good field and frequency stability is mandatory to stay at high fields.

More at \( Q > 2 \cdot 10^6 \)
- \( 5.5 \) mA beam takes 47 kW of RF power! and recovers 47 kW of RF power.
- Operated cavity at \( Q =2 \cdot 10^9 \) (75 Hz bandwidth).
- Operated cavity at \( Q =1.2 \cdot 10^8 \) (12 Hz bandwidth).
- Field ramp: \( Q = 1.2 \cdot 10^9 \)

The text:
- 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.