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 JLab IR-FEL. Excellent cw field stability - about 10^{-4} rms in relative amplitude and 0.02 deg rms in phase - was achieved at a loaded Q of $2.1 \cdot 10^7$ 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 high gradients in less than 1 second.

WHY HIGH LOADED Q_L?

Cornell University's Laboratory for Elementary-Particle Physics (LEPP) is exploring the potential of a light source based on an Energy-Recovery-Linac (ERL) [1]. ERLs, as many of the proposed FEL light sources, are machines with small (FEL case) on no (ERL case) beam loading in the RF cavities. While in the FELs the average beam current is small, in an ERL the beam loading from a high current accelerated beam is compensated by the anti-loading of the decelerated beam.

Optimal loaded Q_L

In the case of no beam loading, the optimal loaded quality factor Q_L is a function of the peak cavity detuning Δf during operation (f_0 is the fundamental mode cavity frequency):

$$Q_{L,\text{opt}} = \frac{1}{2} \frac{f_0}{\Delta f}. \qquad (1)$$

Note that running with this loaded Q will minimize the peak RF power required, i.e. will minimize the peak RF power to be installed. Figure 1 shows the required RF drive power as function of Q_L for different peak cavity detunings. The dramatic increase of RF power with cav-
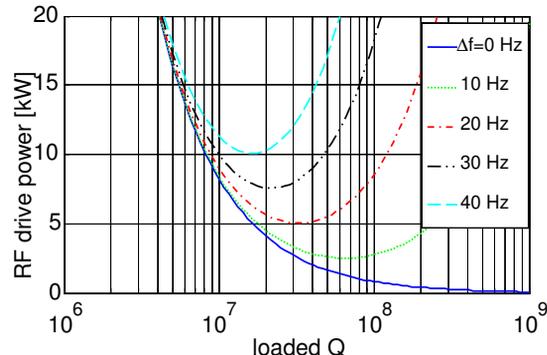

Figure 1: Peak RF drive power as function of Q_L (for a 1.3 GHz, 7-cell cavity at 20 MV/m accelerating gradient).

ity detuning is obvious from Figure 1. Fortunately, very low microphonic levels (peak detuning below 10 Hz) have been achieved in superconducting linac cavities (for example cavities in module 3 at the TJLab IR FEL and cavities at the ELBE light source). This would allow to operate the cavities in an ERL very efficiently at a loaded Q_L of several 10^7 up to 10^8. However, present state-of-the-art is operation at loaded Q_L of 1 to $3 \cdot 10^7$. For a multi-GeV ERL linac, going to a loaded Q_L of about 10^8 would result in very significant cost savings in both construction and operational costs.

High Q_L Challenges

Running RF cavities at high loaded Q_L of about 10^8 is challenging for the following reasons:

- Field startup: At a loaded Q_L of 10^8 the cavity bandwidth is only a few Hz, while the Lorentz-forces will detune the cavities by several hundred Hz during cavity filling. It is therefore essential to compensate for the Lorentz-force detuning very precisely during cavity turn-on.

- LLRF control: The small cavity bandwidth of a few Hz makes the RF field in the cavity extremely sensitive to any perturbation of the cavity resonance frequency due to microphonics or Lorentz force detuning. This challenge is amplified by the fact, that future ERL light sources will require very tight field stability in both amplitude and phase (few 10^{-4} in relative rms amplitude stability and well below $0.1°$ in rms phase stability). Fortunately, for higher frequency perturbations the increased field sensitivity is partly compen-

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sated by the increased low pass characteristic of the high Q_L cavity.

These challenges explain, why the highest loaded Q_L at which elliptical RF cavities in linacs are operated presently is limited to Q_L of 1 to $3 \cdot 10^7$. However, as discussed above, operating the cavities in an ERL at higher Q_L is highly desirable.

CORNELL'S DIGITAL RF CONTROL SYSTEM

At LEPP we have developed a new digital LLRF control system ([2, 3]) for the heavily beam loaded cavities in the CESR storage ring as well as for highest loaded Q_L cavities in ERLs. The new digital LLRF system is in successful operation at CESR since summer 2004 [4]. Great care has been taken to achieve the required flexibility of the system, as well as to meet the demands of high Q_L cavity operation. Among others, the system includes the following features: low noise field IQ detection; low latency field control; advanced cavity frequency control with feedback loop for the slow stepping-motor driven tuner and feedforward-feedback control for the fast piezo-driven frequency tuner; state-machine for start-up and trip-recovery.

BEAM TESTS AT HIGH Q_L

To explore the performance of Cornell's digital LLRF system with high Q_L cavities, a collaboration between LEPP and Jefferson Lab has been set up. Jefferson Lab provided the infrastructure for testing the LLRF system, and built a low noise RF synthesizer and down converter for TJLab's 1.5 GHz cavities. Over a period of two weeks, we were able to study in detail the operation of highest Q_L cavities at CEBAF and the TJLab IR FEL.

Test at CEBAF

Within two hours, Cornell's digital LLRF system was connected to one of the CEBAF cavities (SL20-2), and subsequently operated with full CEBAF beam for several hours. The loaded Q_L of the cavity was increased to $4 \cdot 10^7$. The measured open and closed loop field stability is shown in Figure 2. Open loop the field is heavily perturbed by microphonics; SL20 is one of the most microphonically active cryomodules in CEBAF. After closing the digital feedback loops the measured rms amplitude and phase field stability was 10^{-4} and $0.02°$ respectively (the phase is measured against the CEBAF reference, which is also used as input to the LLRF system). Even with peak detunings beyond the cavity bandwidth the cavity operation proved to be very reliable.

Test at the TJLab IR FEL

In the second test at Jefferson Lab, the system was connected to a high loaded Q 7-cell cavity at the TJLab IR-FEL
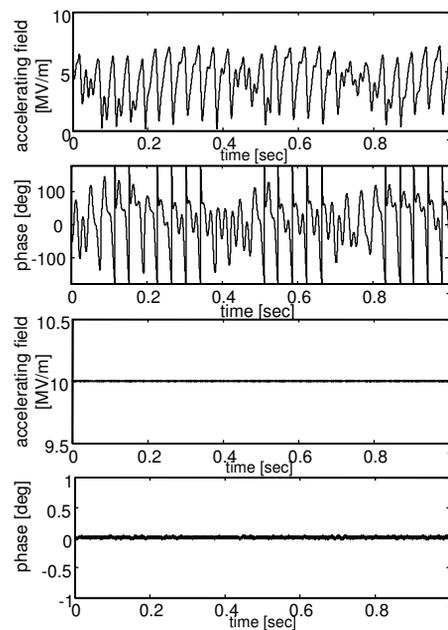

Figure 2: Measured amplitude and phase vs. time for the cavity SL20-2 in CEBAF. Top two graphs: Open loop response. Lower to graphs: Closed loop stability.
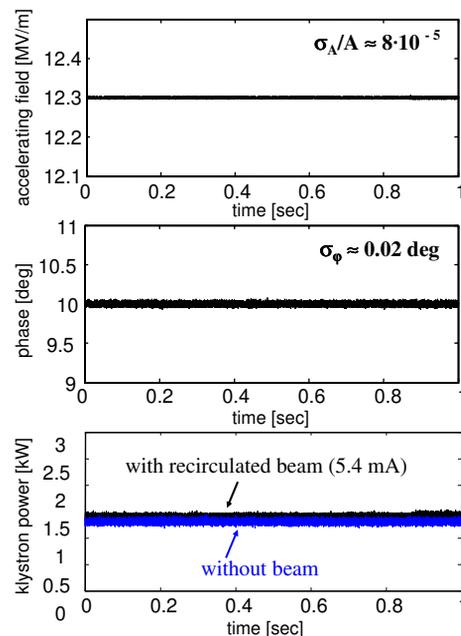

Figure 3: Upper two graphs: Measured field amplitude and phase with 5.4 mA beam current at a $Q_L = 2 \cdot 10^7$. Lower graph: RF drive power without and with recirculated beam.

and tested with beam operation (up to 5 mA) in energy-recovery mode. At an initial loaded Q_L of $2 \cdot 10^7$ excellent field stability was achieved with 5 mA beam current in energy recovery mode; see Figure 3. No dependence of the field stability on beam current (0 to 5.5 mA) and off-crest angle (between $-40°$ and $+40°$) was found.
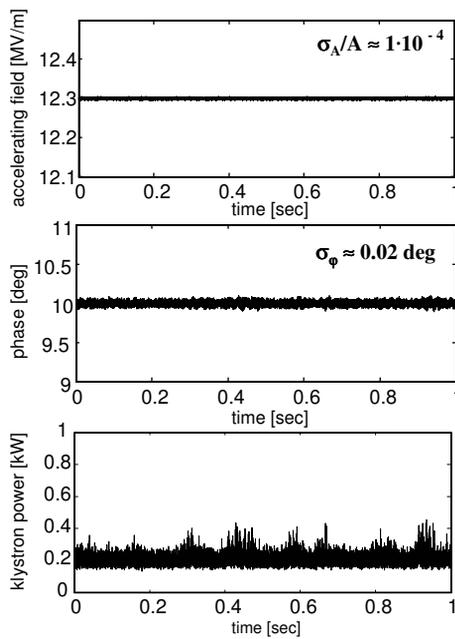
Figure 4: Upper two graphs: Measured field amplitude and phase with 5 mA beam current at a $Q_L = 1.2 \cdot 10^8$. Lower graph: RF drive power at the same time period.
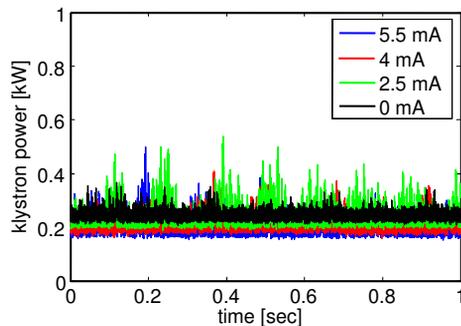

Figure 5: Measured RF drive power during the operation of a ERL cavity ($Q_L = 1.2 \cdot 10^8$) at 12.3 MV/m with different beam currents in energy-recovery mode.

Motivated by this success, we increased the loaded Q_L of the cavity to about $1.2 \cdot 10^8$ and repeated all previous tests. In summary, no change in field stability was seen (see Figure 4); only this time it took significant less RF power to drive the cavity (compare Figure 3 and Figure 4). Again, no major change in measured field stability was found when changing the beam current or going off-crest within aforementioned boundaries. Figure 5 shows that the RF drive power is indeed independent of beam current, as it should be in an ERL, with power peaks of about 500 W for operation at a gradient of 12.3 MV/m. At this high loaded Q_L the cavity operated very reliably over several hours with and without beam. No cavity trips occurred during this time.

Piezo tuner based cavity frequency control proved to be very effective in keeping the cavity on resonance during
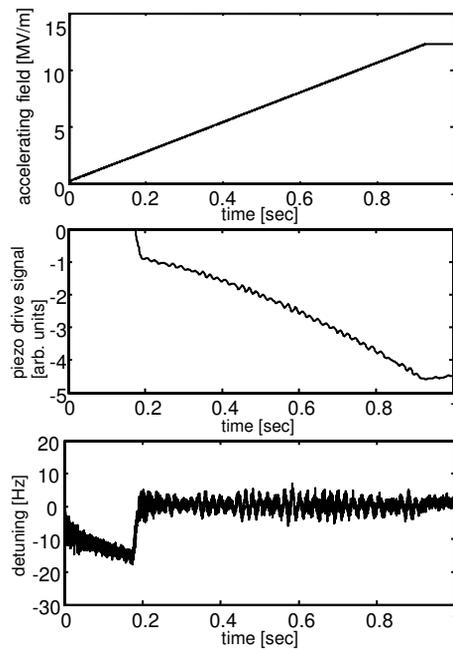

Figure 6: Top: Cavity filling at $Q_L = 1.2 \cdot 10^8$. Middle: Piezo drive signal during the same time period. Bottom: Cavity detuning during the same time period.

cavity filling. The Lorentz-force detuning of the cavity is compensated by the piezo tuner, and thereby allows reliably to ramp up to high gradients in less than 1 second even at $Q_L = 1.2 \cdot 10^8$; see Figure 6. This is desirable for fast trip recovery in a large ERL.

OUTLOOK

We successfully demonstrated highest loaded Q_L cavity operation in a real machine environment with very tight field stability. Nevertheless, we believe that further improvements are even possible. Presently we are working on a generation *II* of Cornell's digital LLRF system, which will be used in the Cornell ERL prototype [5].

ACKNOWLEDGMENTS

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