REAL-TIME BEAM LOADING COMPENSATION FOR SINGLE SRF CAVITY LLRF REGULATION

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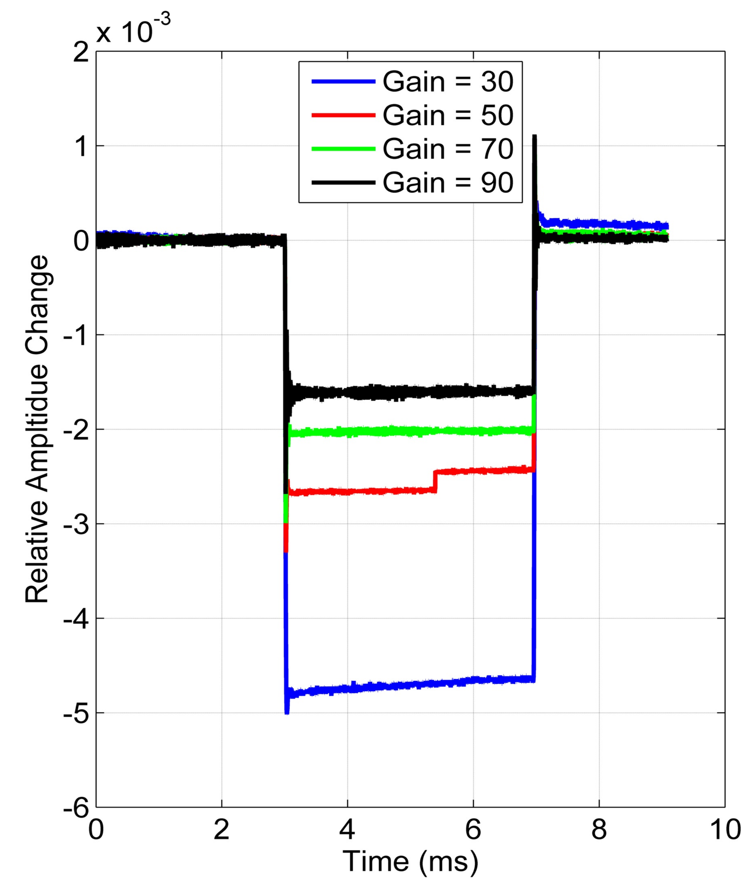
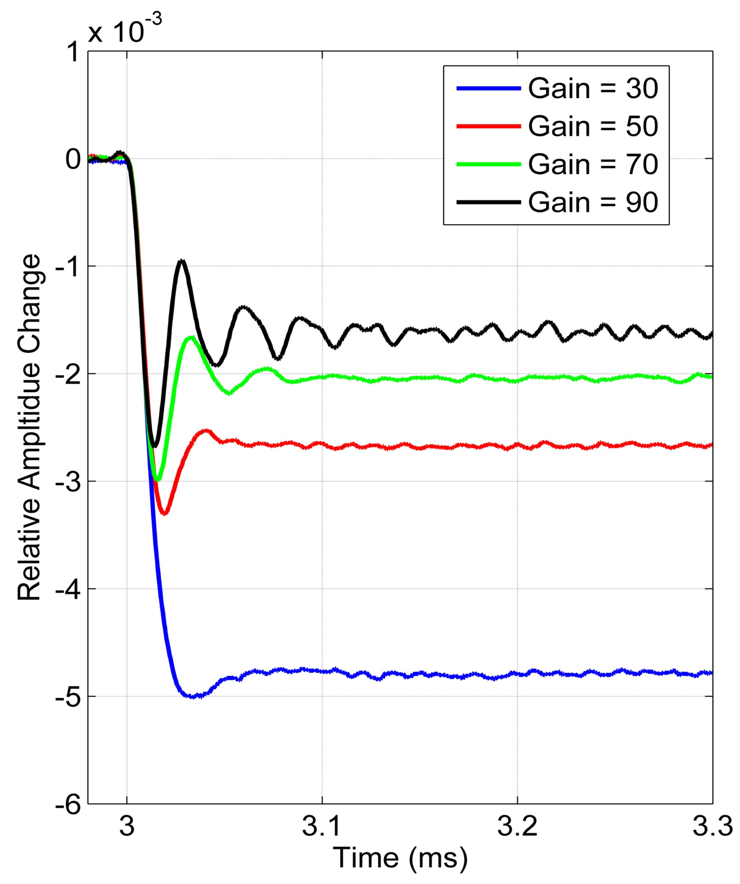
Abstract

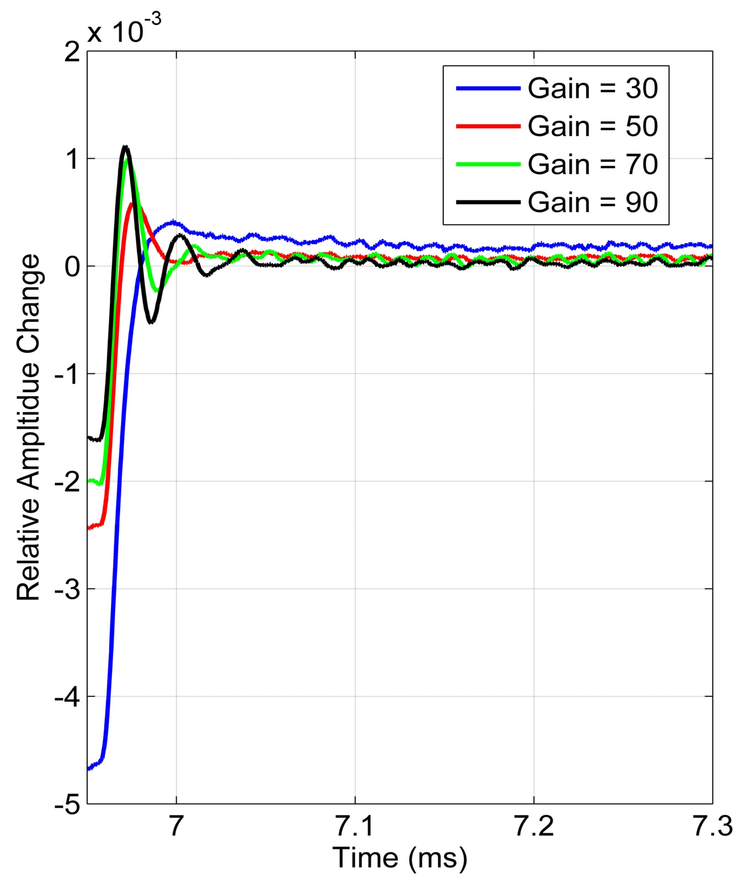
Stable and reproducible generation of a photon beam at Free Electron Lasers (FELs) necessitates a low energy spread of the electron beam. A low level radio frequency (LLRF) control system stabilizes the RF field inside accelerating modules. An electron beam passing through the cavity induces a voltage proportional to the charge and the cavity shunt impedance. The feedback loop tries to compensate for the perturbation after the accelerating gradient drops. The delay and high gain result in an overshoot or oscillations during transients. A feed forward signal can be applied to act on the plant simultaneously with the RF feedback. It can be generated off-line, based on system characteristics and beam parameters or on-line using information obtained from the beam diagnostic systems. In the latter scheme fluctuations of the beam current are accounted for in real-time using an open-loop (feedforward) controller. The bunch charge detection scheme and its implementation is described. This paper describes results of the tests performed on the ELBE (Electron Linac for beams with high Brilliance and low Emittance) radiation source at the HZDR (Helmholtz-Zentrum Dresden-Rossendorf) facility using a MTCA.4-based LLRF control system.

Beam loading

An electron beam passing through the cavity induces a voltage proportional to the charge and the cavity shunt impedance. For an SRF cavity with a high loaded quality factor (QL) compensation of the beam loading may require providing more RF power than is required to sustain the field gradient in the cavity, making it a major source of distortion of the RF field
The feedback loop compensates the perturbation only after the accelerating gradient drops. The loop delay and high gain result in an overshoot or even oscillations during transients.
Waveforms from a MTCA.4-based digital LLRF system using only a PI feedback controller are shown.

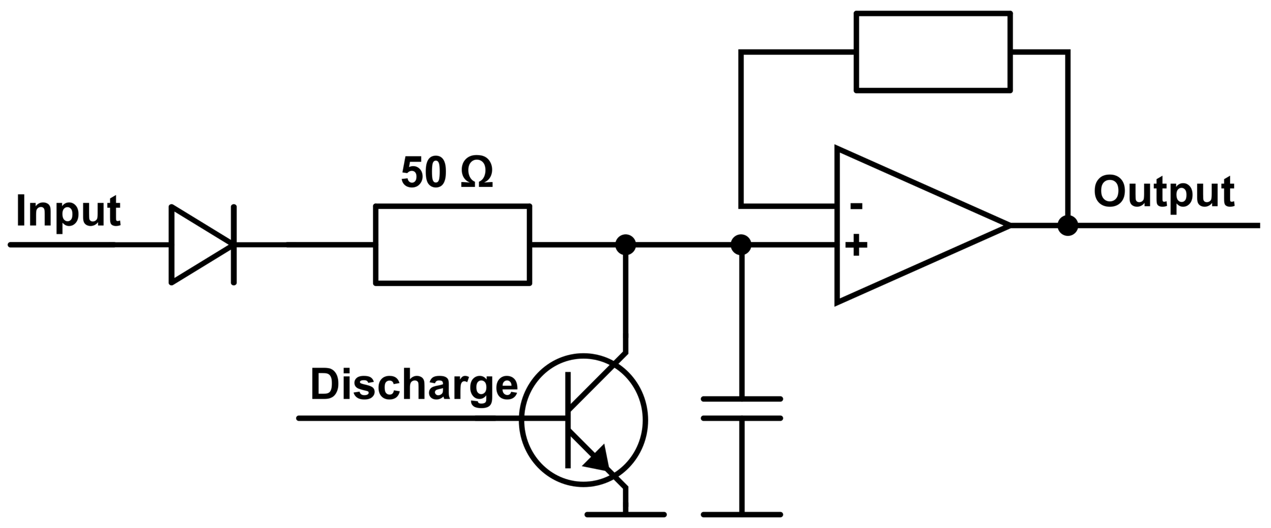






Detection hardware

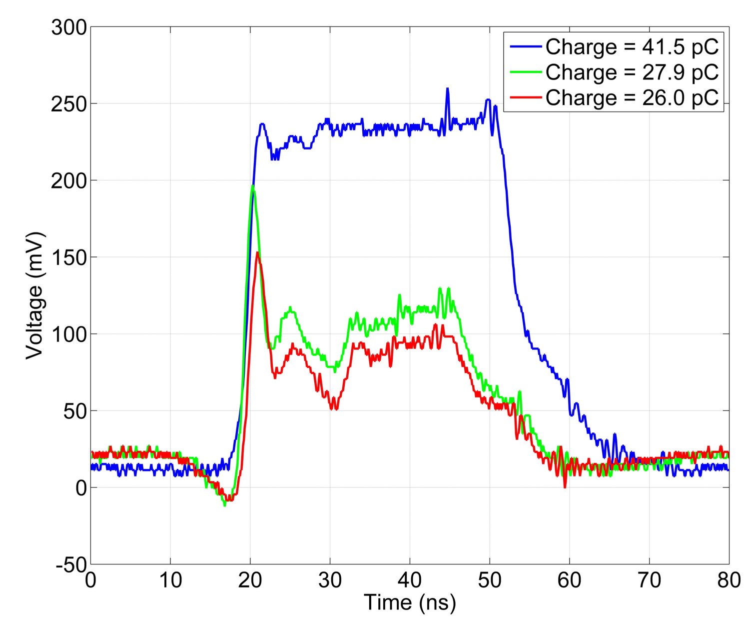
The bunch charge can be detected using various instruments. For real-time operation a non-destructive scheme is necessary. At ELBE facility an Integrating Current Transformer (ICT) is used. The signal at the output of the ICT is broadband and has low amplitude, resulting in low SNR. A high gain, wideband amplifier is used to condition the signal.
Very short rise and fall times make direct sampling of the signal impractical. For beam-loading compensation only the information about signal's amplitude is necessary. A peak hold detector with a reset circuit can be used to sample the amplitude. The precise timing information is lost, but requirements for an analog-to-digital converter (such as bandwidth, maximum sampling speed, and aperture jitter) are lessened. The block diagram of the circuit used in this project is shown.

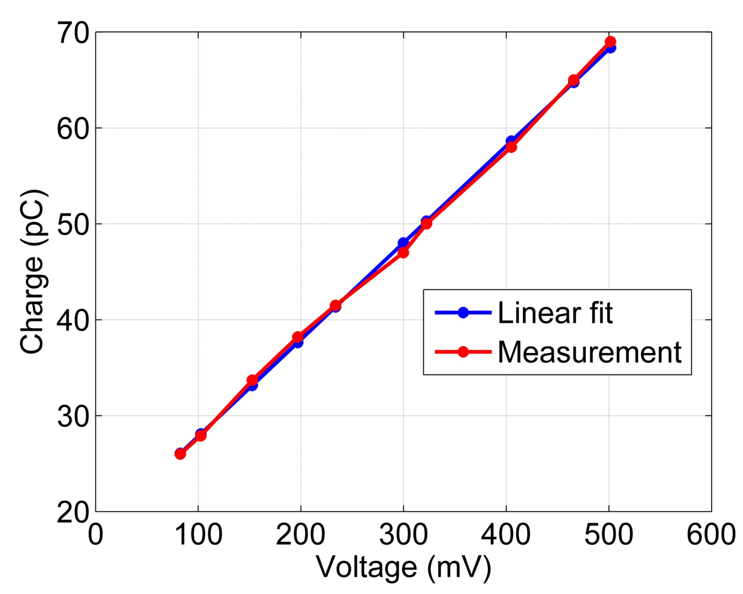


The input signal charges a capacitor through a fast Schottky diode and a series 50 Ohm resistor which provides matching during signal transients. The voltage in the capacitor is buffered using a low input bias current operational amplifier. A fast bipolar junction transistor discharges the capacitor after the peak value is sampled. The discharge signal is synthesized from the accelerator's reference signal and shifted by appropriate number of cycles.

Verification

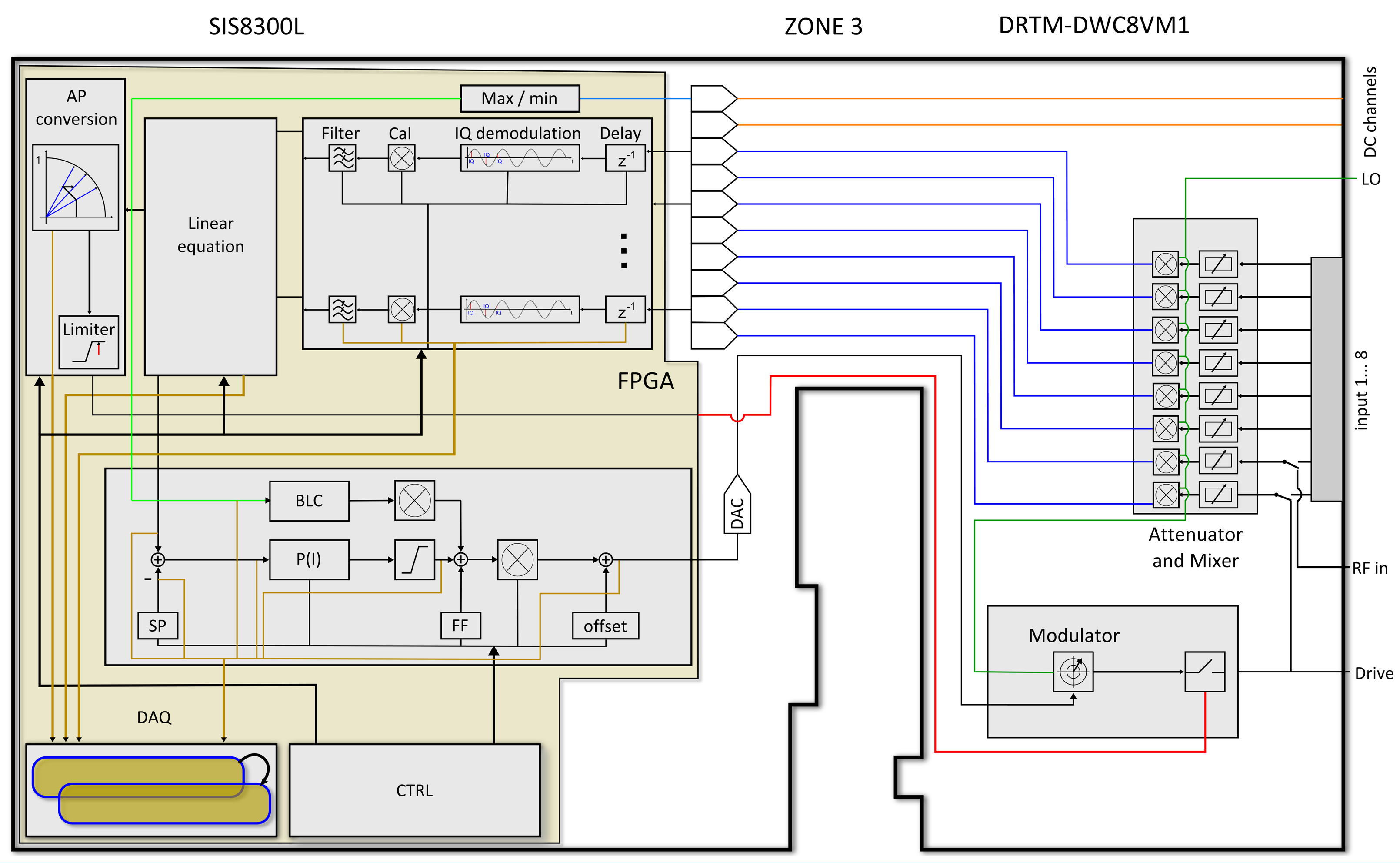
Waveforms of the peak detector's output signal sampled by a high-speed real-time oscilloscope for various bunch charges are presented. The transfer function of the system (voltage -> bunch charge) was characterized by relating the mean value of the signal (in time period 35 to 45 ns) to the known bunch charge using linear regression. The estimated model equals
$Q = 0.1044$ pC/mV * (V + 158.13) mV
The charged (Q) is lineary proportional to the measured voltage (V) with a roughly 158 mV offset. The maximum estimation error is 0.73 pC and mean absolute estimation error is 0.41 pC. The measurements prove the detection susbsystem can be considered linear.





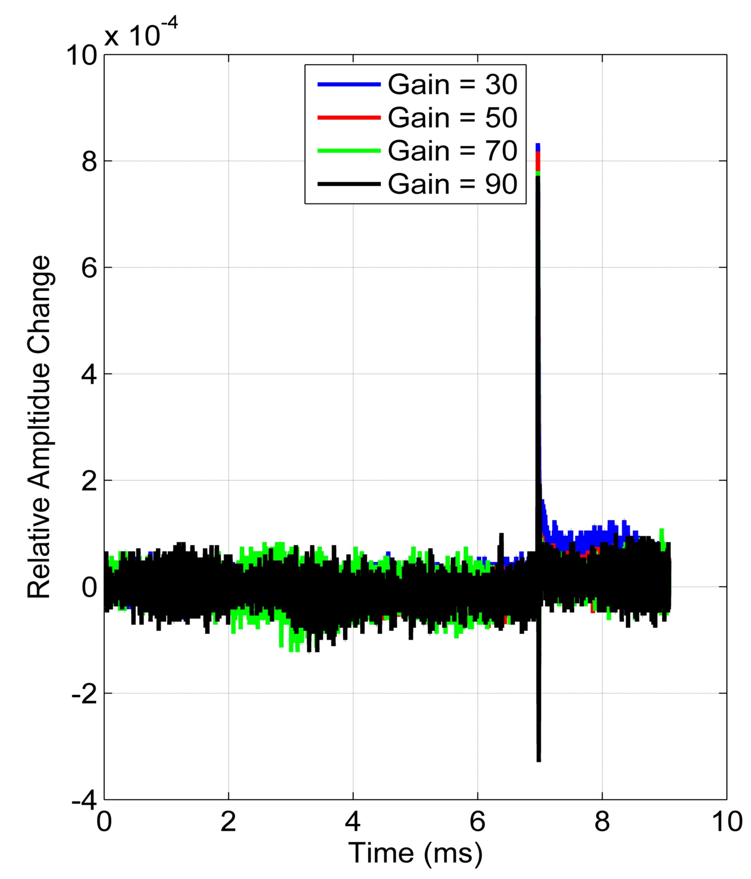
Controller algorithm

The digitizer module's FPGA runs a real-time controller algorithm. Based on the complex signal from cavities probe with respect to a setpoint, an error signal (measured value compared to the set point) is calculated and fed to the PI controller. The controller's output is added to feedforward tables and offset compensation scalars.
Raw ADC samples of the bunch charge detector output signal are feed into a block detecting the maximum and minimum values. The amplitude (difference between max and min values) is multiplied by a gain coefficient. The next step is the rotation on the IQ plane. This signal is combined with feedforward and feedback signals before the output rotation.



Results

Measurements of a MTCA.4-based digital LLRF system using a PI feedback controller and the real-time beam loading compensation (BLC) are shown. Gain factor and rotation angle were chosen experimentally.
The system response to beam rise is smooth, with no visible distortions. After the beam disappears, the RF field oscillates starting with the inital spike independent of the PI controller gain. The addition of the real-time BLC to the LLRF system improves the system response to beam transients.



Future developments

- Hardware development (offset reduction by using different type of peak detector)
- Automation routines

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