ACTIVE BEAM CURRENT STABILIZATION IN THE CORNELL ERL PROTOTYPE INJECTOR

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Abstract

In order to operate the Cornell ERL prototype injector at beam currents beyond 10 mA, the beam current has to be highly stable. The reason is that fast beam current fluctuations generate transient effects in the DC gun voltage as well as in the fields of subsequent superconducting cavities, which can lead to excessive beam loss or to trips of subsystems. Therefore, a feedback scheme was developed which uses the signal of a beam current monitor as an input, and applies appropriate corrections to a Pockels cell installed within the laser path of the photo-injector laser. In this paper, high current results achieved with this feedback scheme are presented.

INTRODUCTION

Cornell is developing a high current, low emittance CW injector for the Cornell ERL project [1]. The injector is designed to ultimately deliver a beam current of up to 100 mA at a beam energy of 5.5 MeV. It is based on a DC gun, which is currently operated at voltages up to 350 keV, followed by a normal conducting bunching cavity, followed by five two-cell superconducting 1.3 GHz cavities, each capable of delivering 100 kW of power to the electron beam.

High beam currents cause a strong beam loading in both the DC gun and the cavities, and beam current changes lead to voltage variations in the gun as well as to voltage and phase variations in the subsequent cavities, which depending on their magnitude can trip these subsystems. Because the beam after the gun is not yet ultra-relativistic, gun voltage variations affect the beam arrival-time at the cavity locations, and the resulting variation in the beam phase can cause excessive beam loss. Voltage and phase variations in the cavities also cause beam loss, but at a reduced magnitude. A stable beam current is also important because bunch charge variations and the resulting beam induced voltage and phase changes lead to emittance growth.

Beam current variations in the injector are caused by variations of the laser power sent onto the photo-cathode, as well as by a degradation of the photo-cathode quantum-efficiency, which happens on a very slow time scale. The laser power variations can either originate directly from the laser system (see Fig. 1 for a schematic), or are generated by laser beam position jitter or a jitter of the transverse laser mode. In the latter case, the conversion to laser power fluctuations happens during the transverse shaping of the laser beam, which in our case is done with a pin-hole located after an approximately 20 m long laser transfer line.

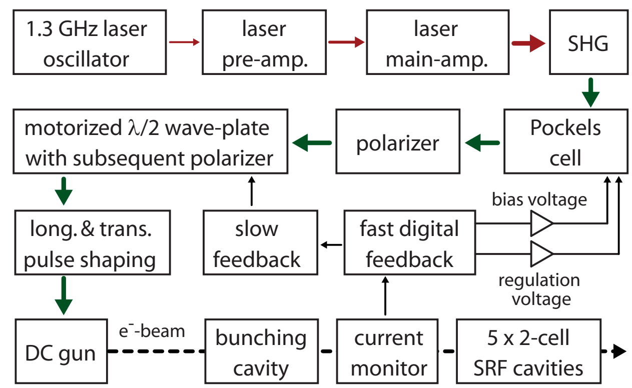

Figure 1: Schematic of the beam current feedback.

BEAM CURRENT FEEDBACK

We developed a feedback scheme, depicted in Fig. 1, to stabilize the beam current in the injector. It uses a beam current monitor as an input and acts on a Pockels cell with a subsequent polarizer, which is installed within the laser beam path to compensate for beam current variations.

Beam current monitor

Two different options for the current monitor are available. Both use the signal of a strip-line beam pick-up as an input, and two strip-line signals on opposing sides of the beam pipe are combined in order to minimize the dependence on the beam position. In the first option, a logarithmic detector is used to measure the power of the beam pick-up signal. This detector was used for the measurements presented in this paper. In a second detector option, the 1.3 GHz pick-up signal is down-mixed to a signal at an intermediate frequency of 12.5 MHz, and the amplitude of this signal is detected with an IQ-scheme. Option 1 provides a larger dynamic range, which is helpful when the injector is operated at very low beam currents ($\ll$1 mA). A disadvantage is a larger noise floor at higher beam currents, which is why we recently switched to detector option 2 during high current operation. The noise floor of detector option 2 is 6 μA (rms) in a 1 MHz bandwidth, which corresponds to a bunch charge resolution of around 5 fC (rms) for the 1.3 GHz electron bunches.

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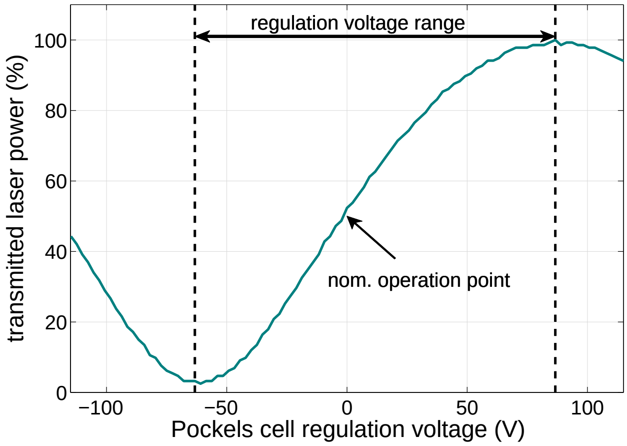

Figure 2: Transmitted laser power after the first polarizer in Fig. 1 for different regulation voltages applied to the Pockels cell.

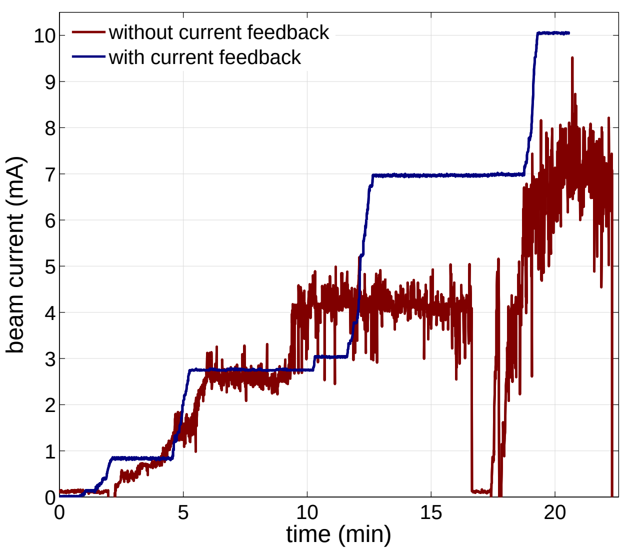

Figure 3: Ramping up of the beam current with and without the beam current feedback.

Regulation loop

The signal of the current monitor is digitized with an ADC clocked at 50 MHz and enters a digital PID control loop which is implemented in a Virtex-5 FPGA. The control loop incorporates the signals of two ADCs as inputs and two DACs as outputs, and it is capable of performing the feedback calculations at the full ADC clock rate (up to 125 MHz). The FPGA module (N.A.T. PRJ-NAMC-VIRTEX5-30) is installed in a μTCA crate, which allows for fast access of the control loop data via the control system DOOCS, which is integrated into our EPICS control system.

The first DAC signal of the controller is amplified by a ± 150 V amplifier with a bandwidth of 3 MHz and provides the regulation signal to the Pockels cell. The second DAC signal is amplified and provides a bias voltage to the Pockels cell, which is adjusted such that the regulation voltage can vary the laser power within a maximum range.

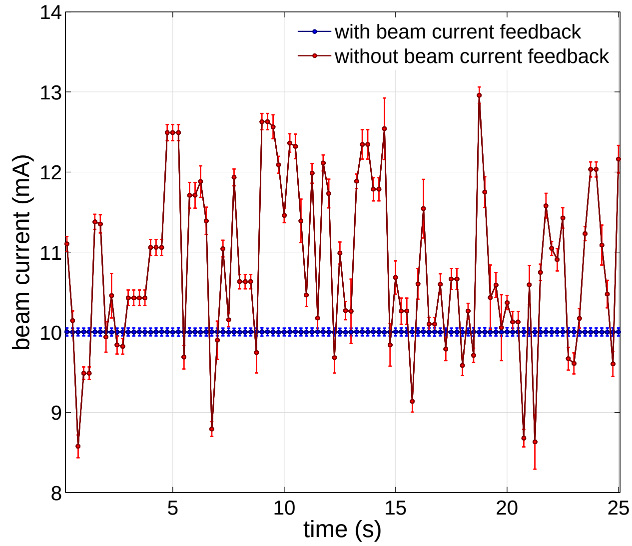

Figure 4: Slow beam current variations with and without the beam current feedback enabled. The error bars indicate the fluctuations occurring within a 15 ms long duration, measured within a bandwidth of 1 MHz.

Figure 2 shows the laser power after the Pockels cell polarizer as a function of the regulation voltage. As expected from Malus' law, the response curve is $\cos^2$-like. The limits of the regulation voltage are set to the maximum and minimum of this curve as indicated in the graph. The maximum extinction ratio with this Pockels cell is typically around 40:1.

After the Pockels cell and its polarizer, a motorized half wave-plate with an additional polarizer is installed, which is used to limit the total amount of laser power sent onto the photo-cathode. The angle of the wave-plate is controlled by a slow feedback loop, which ensures that the Pockels cell regulation voltage is close to the nominal operation point indicated in Fig. 2 at all times, independent of the beam current setpoint in the regulation.

Measurement results

Figure 3 shows the beam current while it is slowly ramped up. In order to have an independent out-of-loop measurement, the current reading from the gun power supply is displayed. When the beam current regulation is not active, significant current fluctuations are visible, which ultimately led to a trip. With activated feedback, the current fluctuations are significantly reduced.

Another comparison of these two cases is shown in Fig. 4 for an average beam current of 10 mA, measured with the beam current monitor. The rms current fluctuations over this 25 s long duration are 9.5% without the feedback and 0.5% with enabled regulation loop. The error bars in this plot indicate the beam current fluctuations occuring within

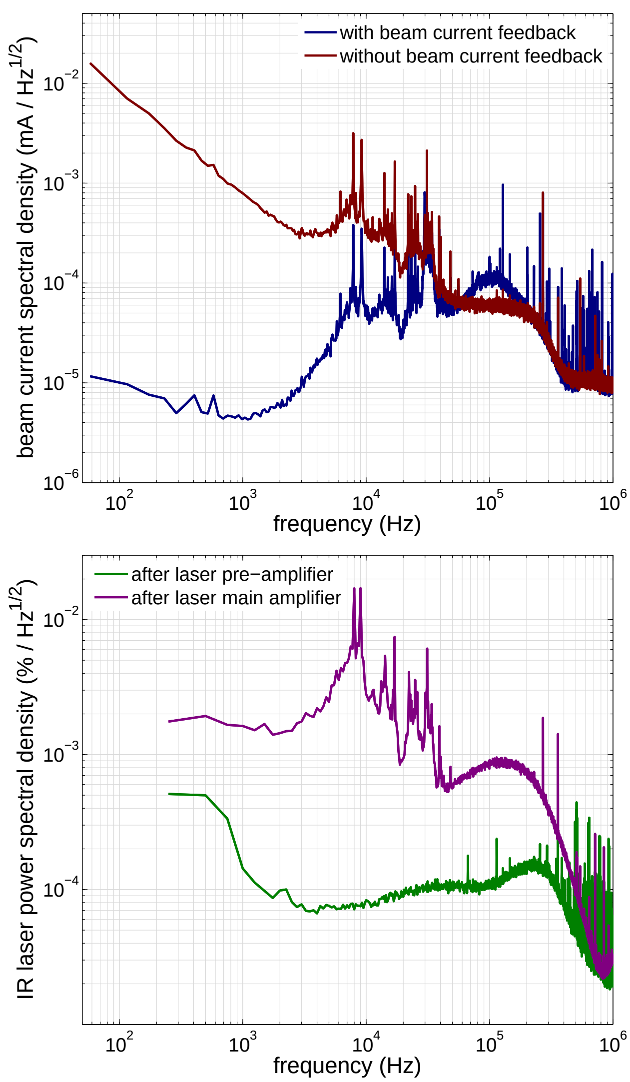

Figure 5: Top: Spectral density of the electron beam current with and without the beam current feedback enabled. Bottom: relative intensity noise of the infrared laser beam after the laser pre-amplifier and after the main amplifier.

a 15 ms long duration, which shows that most of the current fluctuations happen on a longer time scale.

The top plot in Fig. 5 shows the spectral density of the beam current for both feedback states. In addition to the expected increase of the fluctuations at low frequencies, there is a pronounced region between around 5 kHz and 50 kHz with strongly increased noise contributions. In these first studies, we used a regulation bandwidth of the current feedback of around 30 kHz, which suppressed these noise contributions only partly. The integrated noise in the 15 ms long time interval is 1.4% without the regulation and 0.5% with activated feedback. As a reference, the noise floor of the current detector option 2 is around 0.06% at a beam current of 10 mA, which will still allow for significant stability improvements.

We investigated the origin of the noise contributions between 5 kHz and 50 kHz. The bottom graph in Fig. 5 shows the relative laser intensity noise after the laser pre-amplifier and after the main-amplifier. This shows that the observed large noise contributions are caused by pump current fluctuations of the laser main amplifier, a 270 W diode laser from Laserline. We are in the process of implementing an additional feedback loop to stabilize the laser amplifier, which will be available for the next high current operation of the injector.

Operation in pulsed mode

In addition to the CW operation mode, the injector can also be operated in a pulsed mode in which bunch trains with durations between 80 ns and 10 μs are generated with a repetition rate of up to 10 kHz, using an additional Pockels cell in the laser path which is not shown in Fig.1. The beam current feedback also is capable of operating in this pulsed mode. The digital controller receives a trigger signal for every bunch train, and corrections to the Pockels cell voltage are only applied within the bunch train and not during the gap between bunch trains. This will be very helpful for many future studies which take place in the pulsed operation mode, such as measurements and optimizations of the beam emittance.

Beam protection

In case of a major trip of a subsystem in the injector, the gun voltage is shut down and the laser shutter closed. Due to the time delay it takes for the laser shutter to close after a gun trip, many additional electron bunches are generated, which then get accelerated by the decaying voltage in the gun. This causes excessive beam loss in the gun region, and often after such an event the cathode is damaged. We therefore implemented a fast shutdown using the beam current feedback, which in case of an interlock switches off the laser power within 1 μs to protect the cathode from getting damaged.

SUMMARY AND OUTLOOK

We implemented a beam current feedback to stabilize the operation of our high current prototype injector. We were able to reduce beam current fluctuations by a factor of 20 and achieved a beam current stability of 0.5%. The achievable current stability was mainly limited by instabilities in the laser main amplifier, and with an additional stabilization of the laser amplifier and the switch to a higher resolution current monitor, an even better beam current stability can be expected soon.

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REFERENCES

[1] G. H. Hoffstaetter, S. Gruner, and M. Tigner, *eds.*, Cornell ERL Project Definition Design Report, 2011, `erl.chess.cornell.edu/PDDR`.