Recovering Beam Charge Signals from Current Transformer Distortion Using Kalman Filtering

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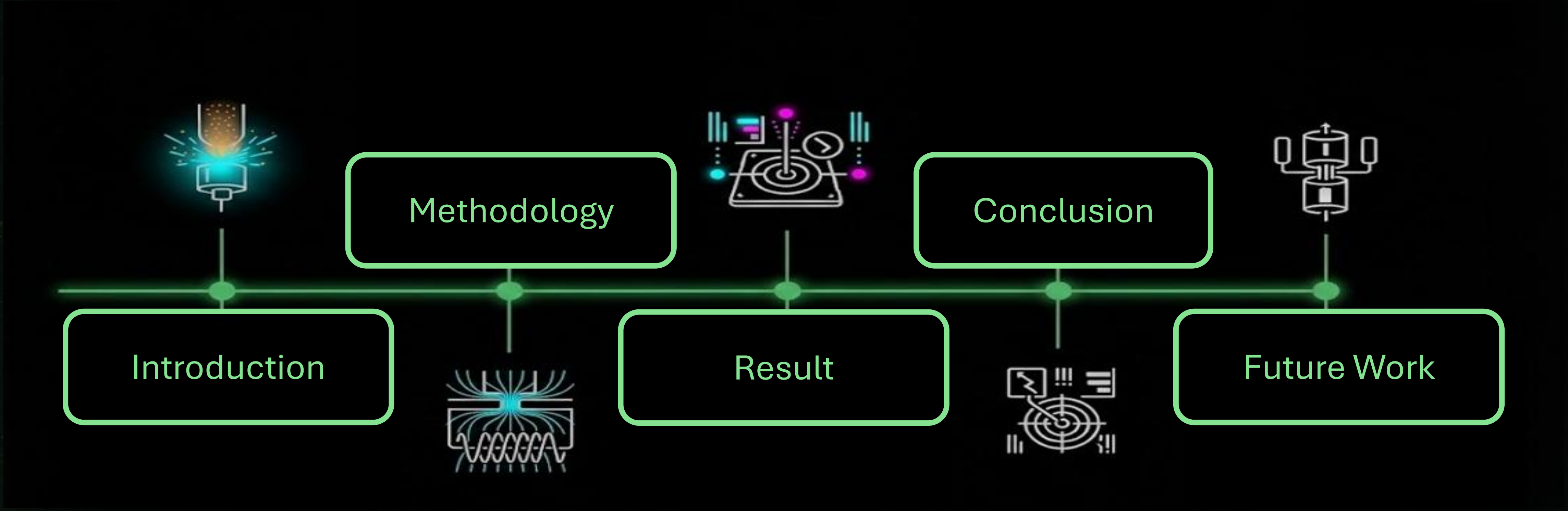
Outline



Introduction

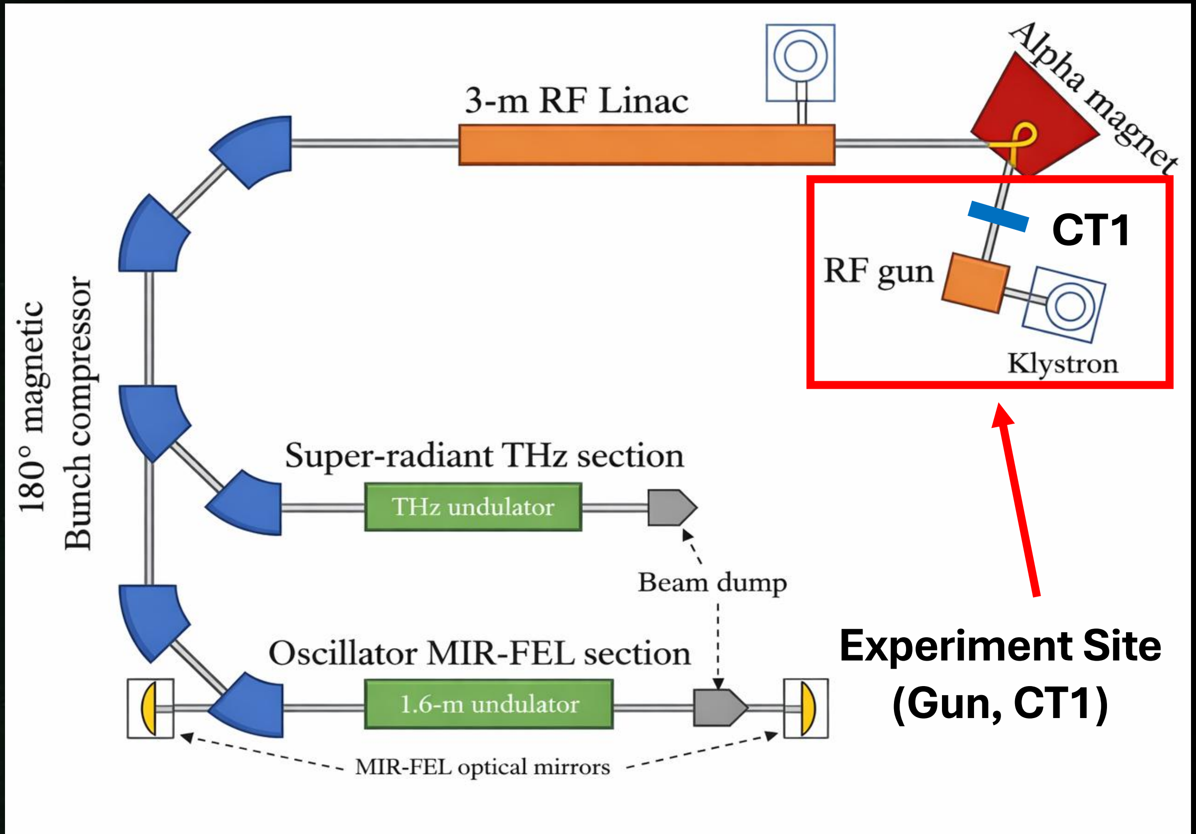


Figure1. Unscaled plant schematics

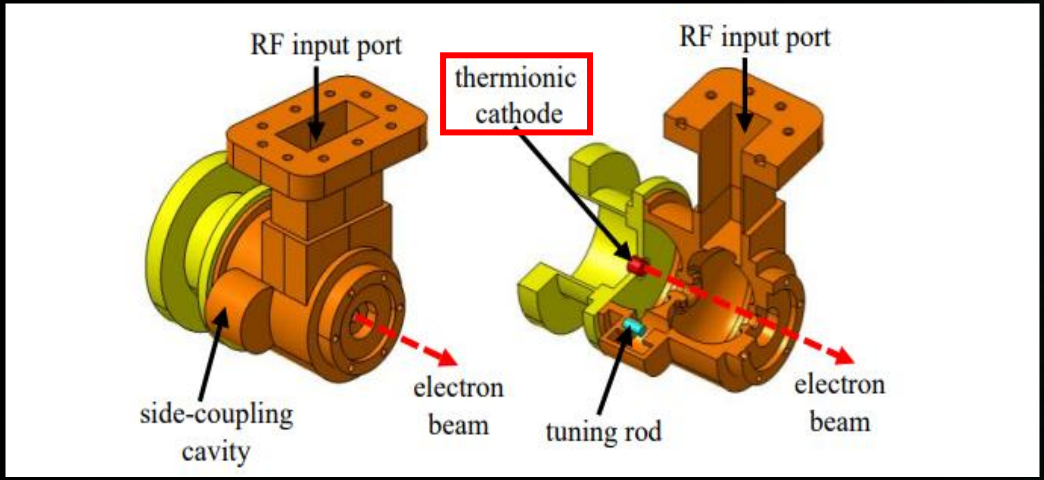


Figure2. RF Gun with Thermionic Cathode using Tungsten as electron Source

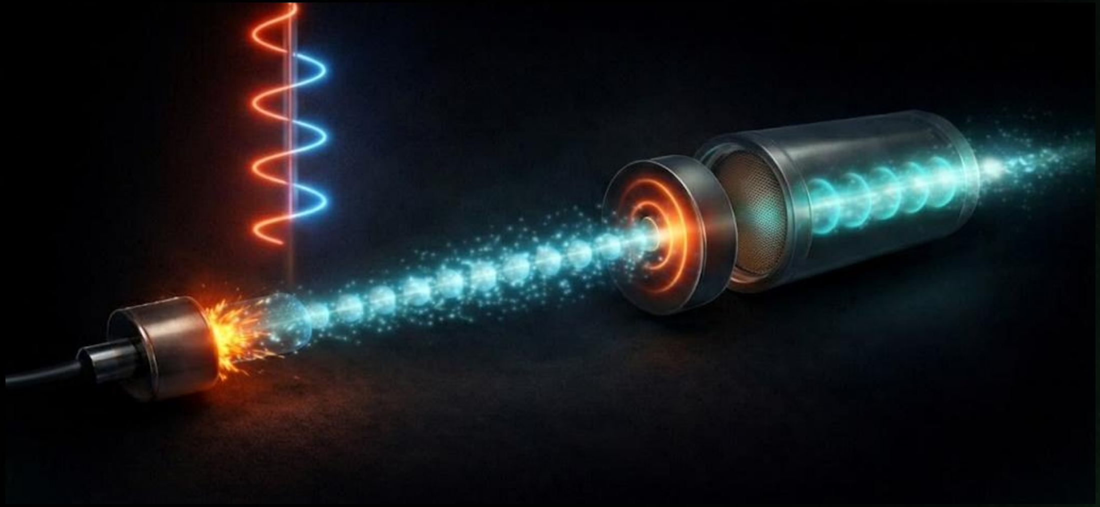


Figure3. Back-Bombardment Effect in Thermionic RF Gun

Introduction

Objective

Design and implement a closed-loop feedback control system to stabilize the beam charge in a thermionic RF gun by dynamically adjusting the filament voltage to compensate for thermal variations caused by back-bombardment and heat inertia, which are currently corrected manually. The system aims to provide a more stable beam charge, improving reliability and experimental performance.

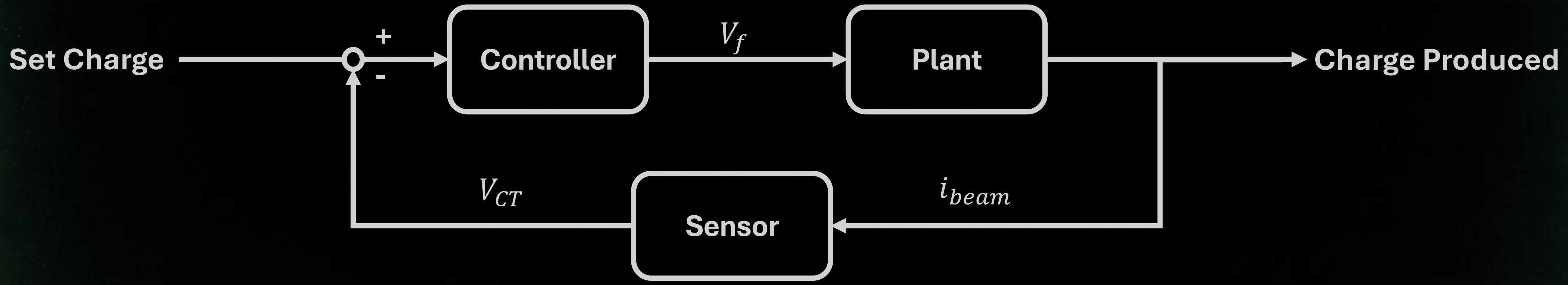


Figure4. Simplified system diagram of the designed feedback with the controller

Introduction (Current Transformer)

Principle

The pulsed electron beam (i_b) acts as a single-turn primary current, inducing a magnetic field concentrated by the core generates a secondary current (i_{CT}) in the windings, which is converted to a measurable voltage (V_{CT}) across the sensing resistor.

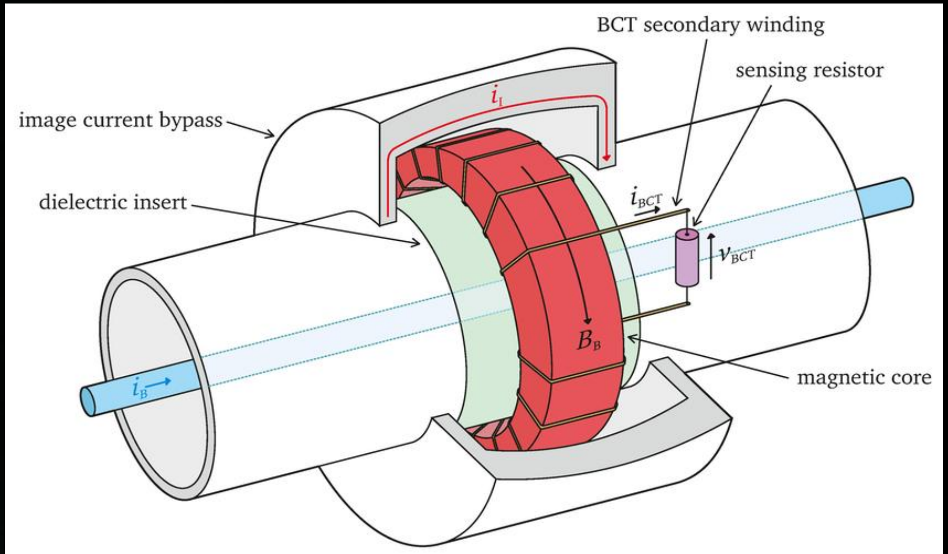


Figure5. Schematic of Current Transformer

Advantages

- ✓ **Non-Destructive Measurement**: The beam is not destroyed during monitoring.
- ✓ **Real-Time Monitoring**: provided a signal to be monitored in real time.
- ✓ **Integration**: Integrated outside the vacuum.

Limitation

- × **Signal Distortion**: Due to the finite secondary inductor(L) and resistor(R) the, CT cannot maintain DC level

Introduction (Current Transformer)

Pulse Distortion

1. A transformer requires a changing magnetic flux to induce a voltage.

2. Flat-top region: current increasingly diverts into the core's magnetizing inductance (L) instead of the resistor (R), causing the output to droop.

3. The stored magnetic energy dissipates as a negative recovery spike.

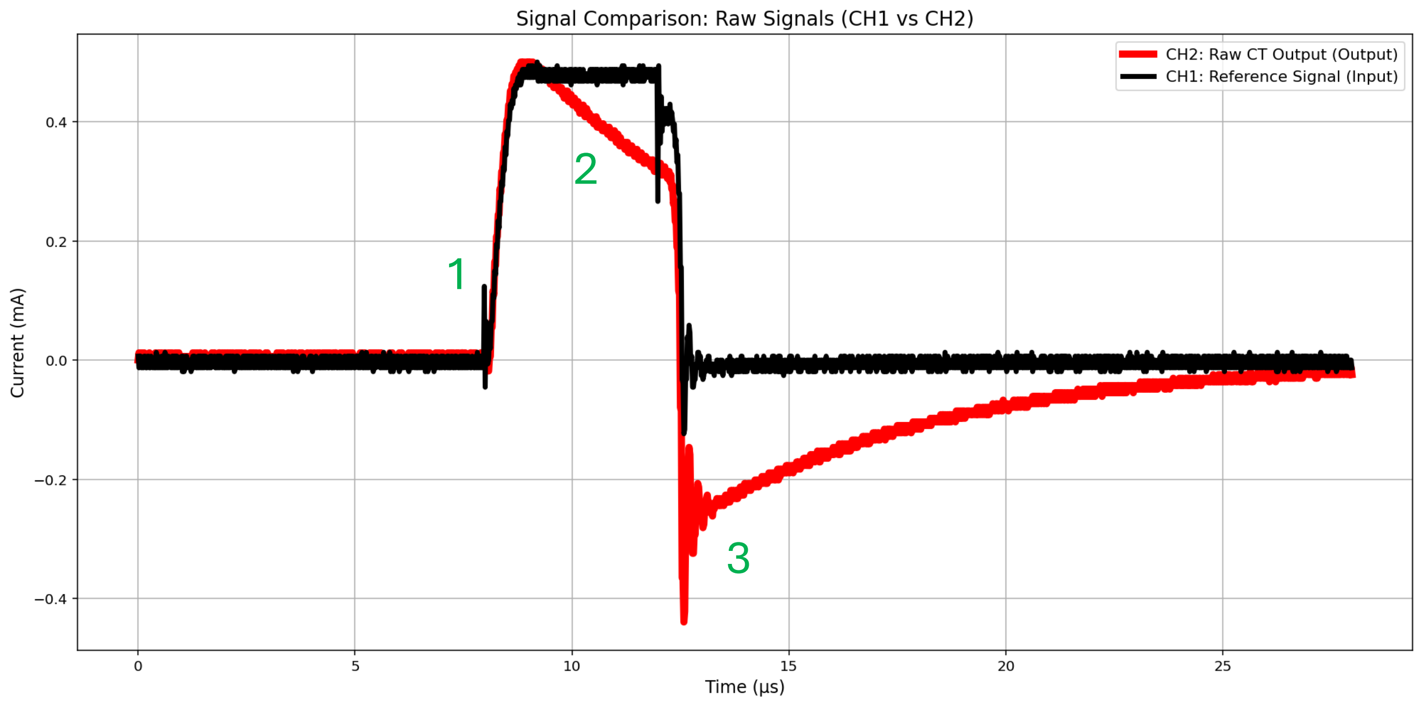


Figure6. Result from the square-wave signal compared with the signal from CT

Methodology (Plan)

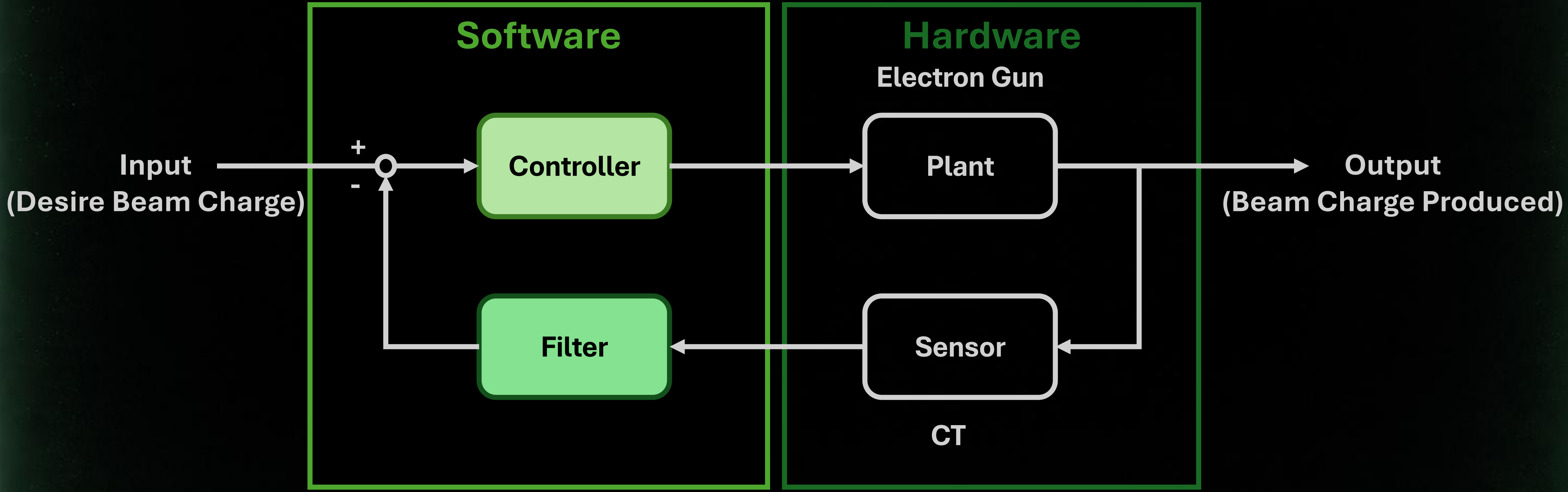


Figure7. Simplified system diagram of the designed feedback with the controller and signal filter integrated

Kalman Filter (State Estimator)

A Kalman Filter **estimates** the **internal (unobservable) state** of a dynamic system using **observable measurements** and the **system model**.

$$\dot{x}(t) = Ax(t) + Bu(t)$$
$$y(t) = Cx(t) + Du(t)$$

$A = System\ Dynamic\ Matix$

$B = Input\ Scaling\ Matrix$

$C = Output\ Scaling\ Matrix$

$D = Input\ Feedthrought\ Matrix$

$x(t) = State\ Vector$

$\dot{x}(t) = \frac{dx(t)}{dt}$

$u(t) = Input\ Vector$

Kalman Filter Block Diagram

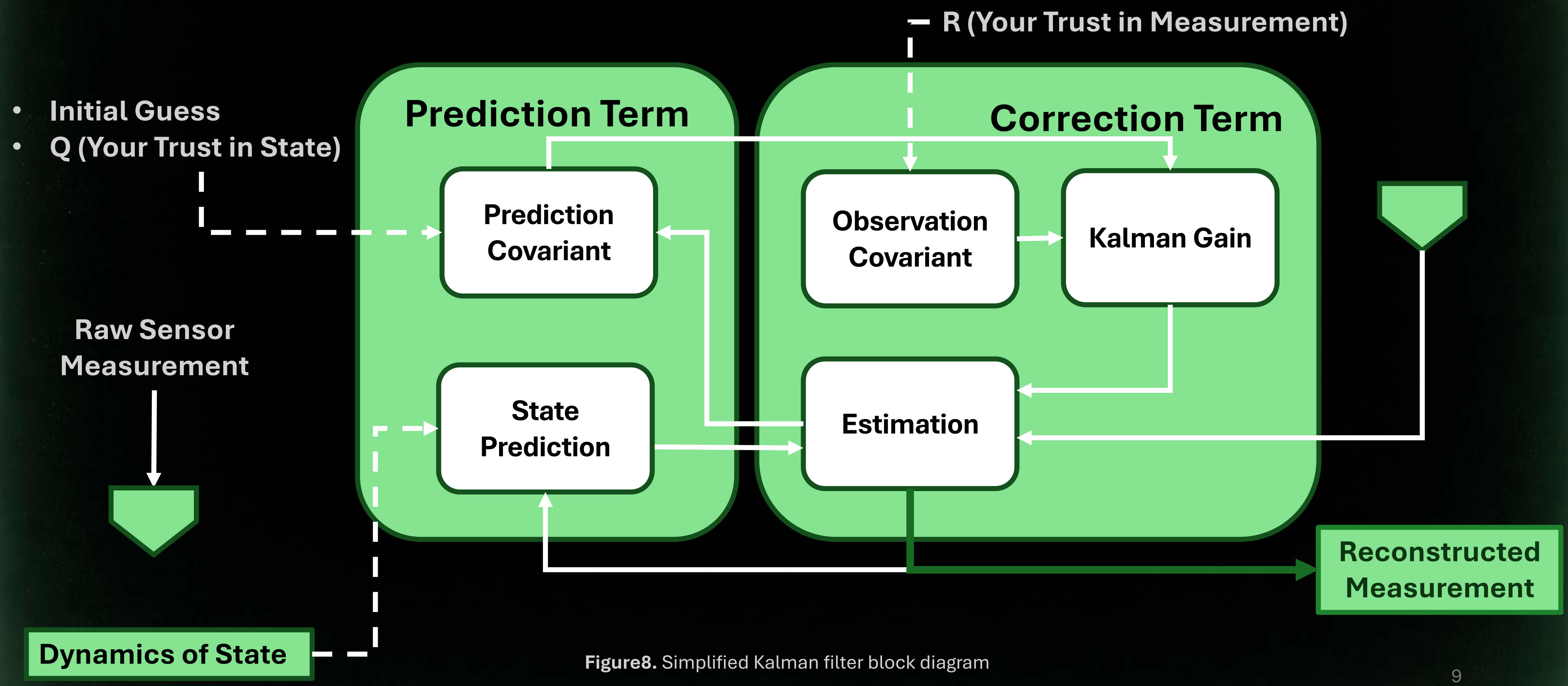
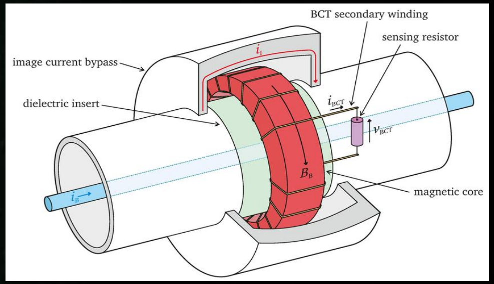


Figure8. Simplified Kalman filter block diagram

Dynamic System



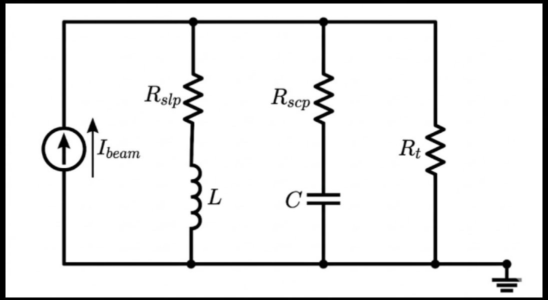
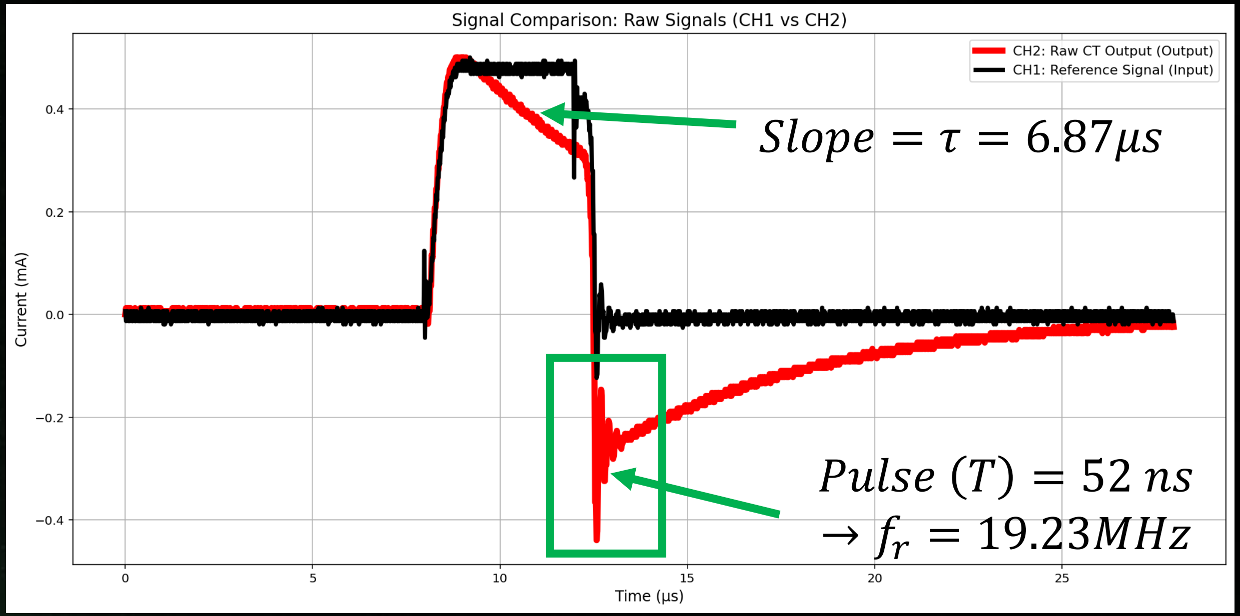


Figure9. Equivalent of Current Transformer



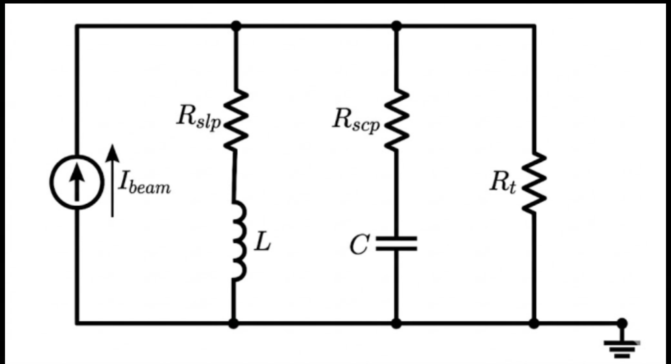
$$L = Rx\tau = 25\ x\ 6.87x10^{-6} = 170\mu H$$

$$C = \frac{1}{4\pi^2 f_r^2 L} = \frac{1}{4\pi^2(19.23x10^6)^2 175x10^{-6}} = 0.39pF$$

$$R_{scp} = \frac{tan\delta}{2\pi f_r C} = \frac{5x10^{-9}}{2\pi(19.23x10^6 x0.39x10^{-12})} = 1.05\Omega$$

$$R_{slp} = l\ xN\ x\ R' = (11)(10)(0.066) = 0.07\Omega$$

Dynamic System



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Kirchhoff Voltage Law

$$x(t) = \begin{bmatrix} v_{csp} \\ i_L \\ i_{beam} \end{bmatrix}$$

$$\dot{x} = Ax(t) + Bu(t)$$
$$y = Cx(t) + Du(t)$$

$$A = \begin{bmatrix} -\left(\frac{R_{eff}}{C_{sp}R_T}\right) & -\left(\frac{R_{eff}}{C_{sp}}\right) & \left(\frac{R_{eff}}{C_{sp}}\right) \\ \left(\frac{R_{eff}}{L_s}\right) & -\left(\frac{R_{eff}R_{scp} + R_{slp}}{L_s}\right) & \left(\frac{R_{eff}R_{scp}}{L_s}\right) \\ 0 & 0 & 0 \end{bmatrix}$$

$$C = [R_{eff} \quad (R_{eff} - 1)R_T \quad (1 - R_{eff})R_T]$$

Result (Kalman Estimation)

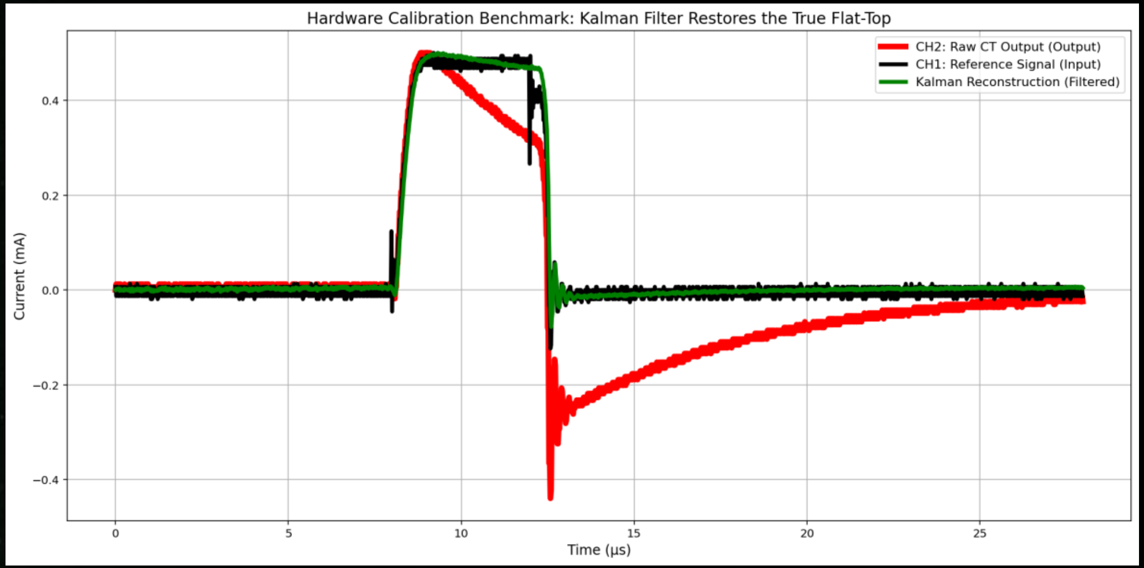

Figure10. Result of signal reconstruction using the Kalman filter as state estimation on the reference square wave

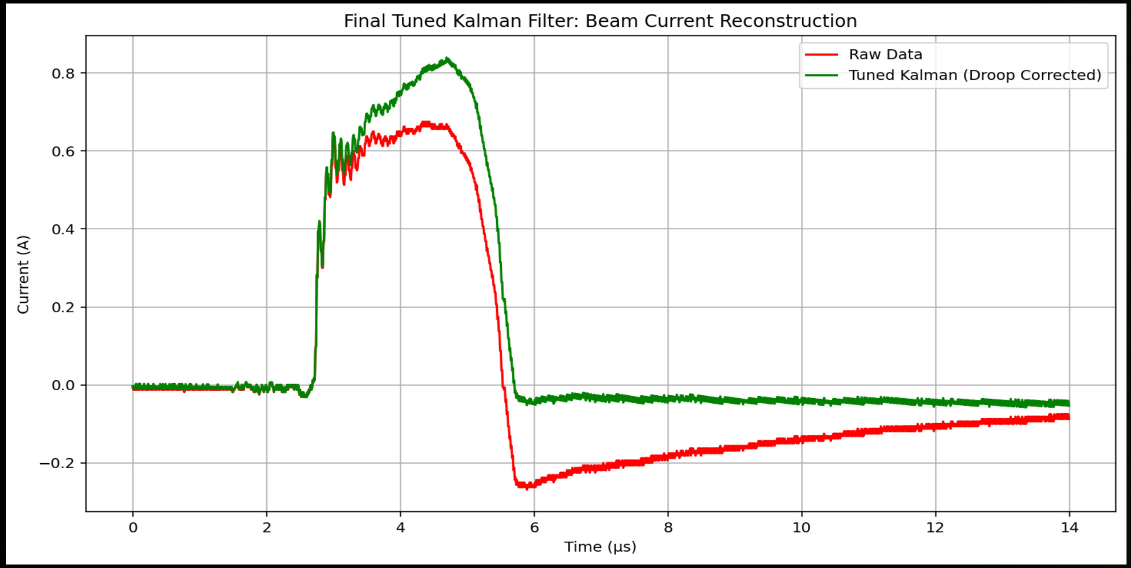

Figure11. Result of signal reconstruction using the Kalman filter as state estimation on operational data of the electron beam

Conclusion

- A Kalman estimator can reconstruct the original pulse shape from a distorted signal and accurately recover the reference square-wave waveform.
- While the filter produces a realistic waveform from real electron-beam data, the result should be treated as an approximation until the true beam pulse shape can be independently verified.

Future Work

- Refine the state-space model parameters and Kalman filter tuning parameters
- Validate the filter against additional reference signal shapes, not just the square wave
- Independently characterize the true beam pulse profile to confirm the real-beam reconstruction

Reference

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Thank you