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Real time plasma current and elongation control on TCV using ECRH actuators

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INTRODUCTION

- Real time control of ECRH systems is important for MHD control (sawteeth and NTMs) etc.
- Requires real time movable mirrors - TCV is uniquely placed to investigate this.
- Experiments to control the ECRH power & mirrors in real time.

THE TCV X2 ECRH SYSTEM

- 6 gyrotrons, 0.5MW each totalling 3MW X2 ECRH power
- flexible launcher system - 6 independent launchers
- independent, real time control of 2 power supplies (3 gyrotrons each)
- real time control of poloidal angle

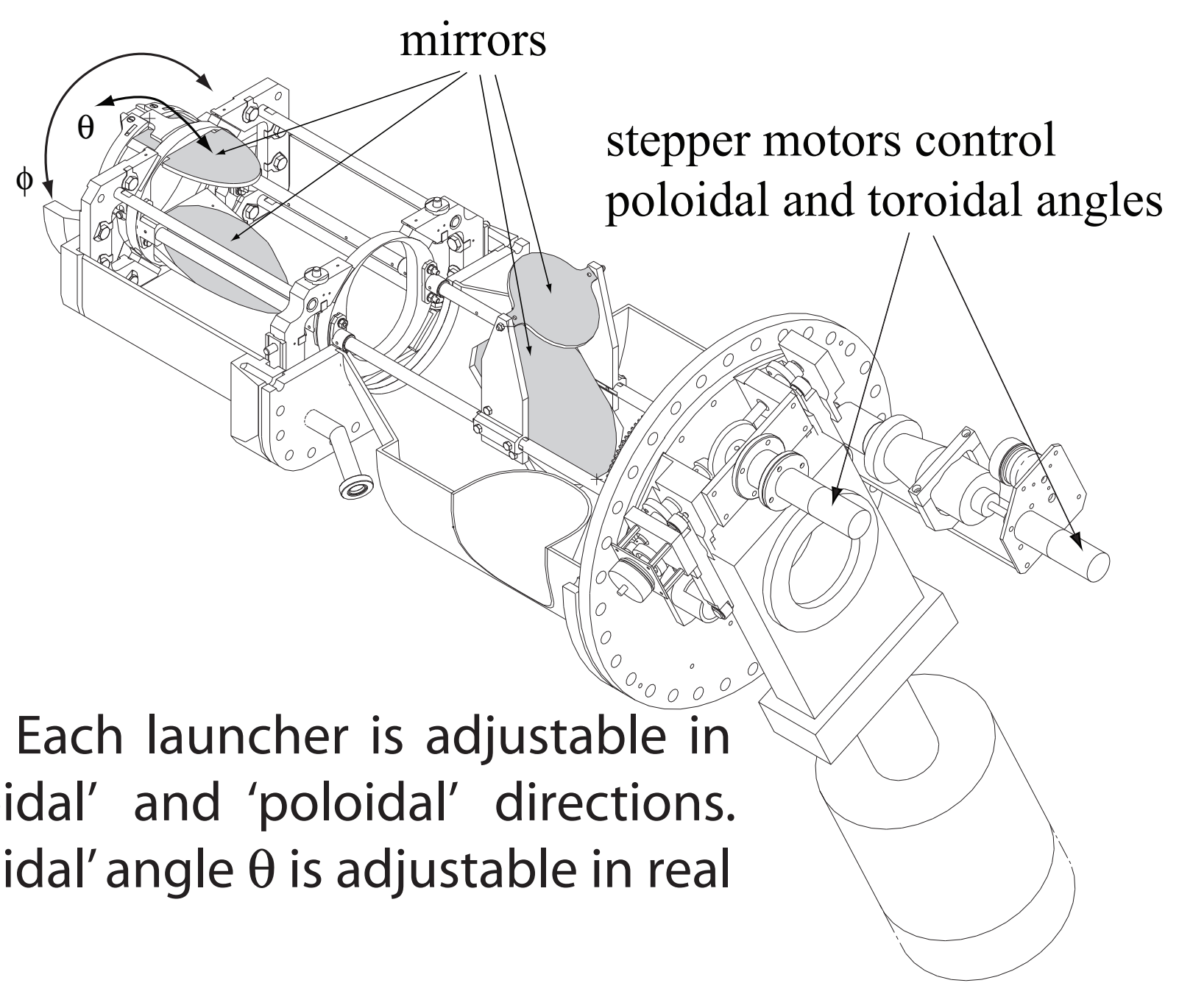


Figure 2. Each launcher is adjustable in the 'toroidal' and 'poloidal' directions. The 'poloidal' angle θ is adjustable in real time.

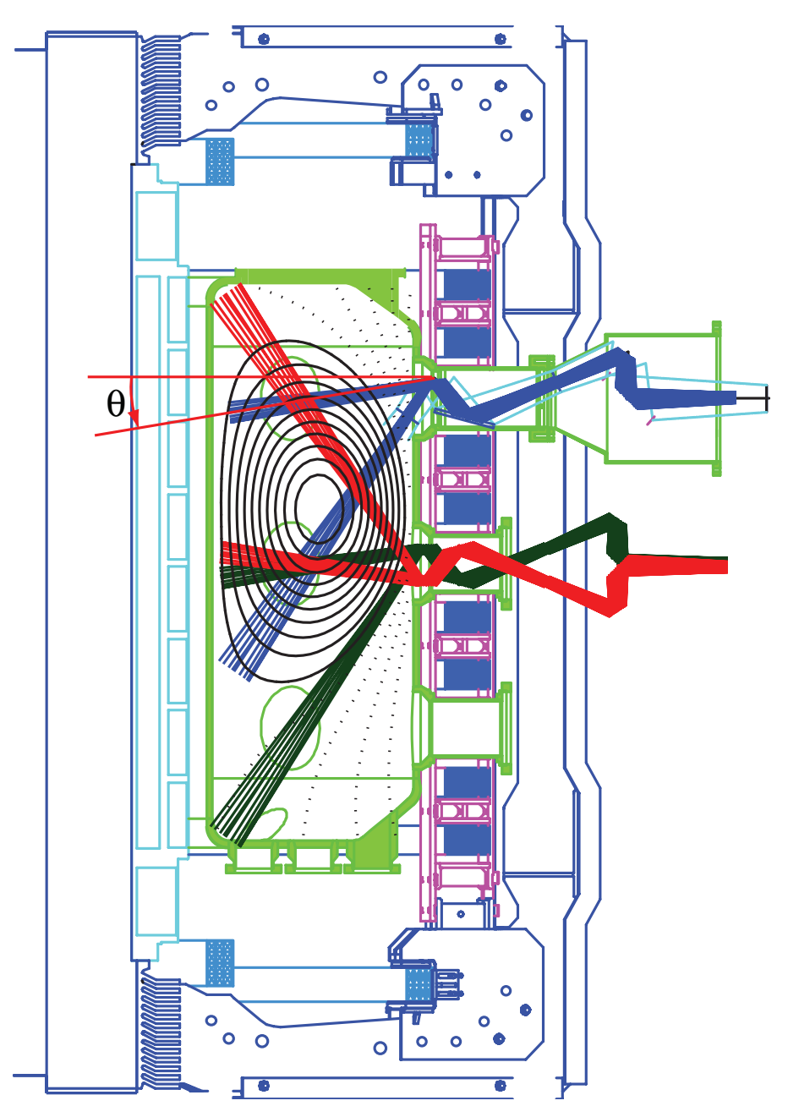
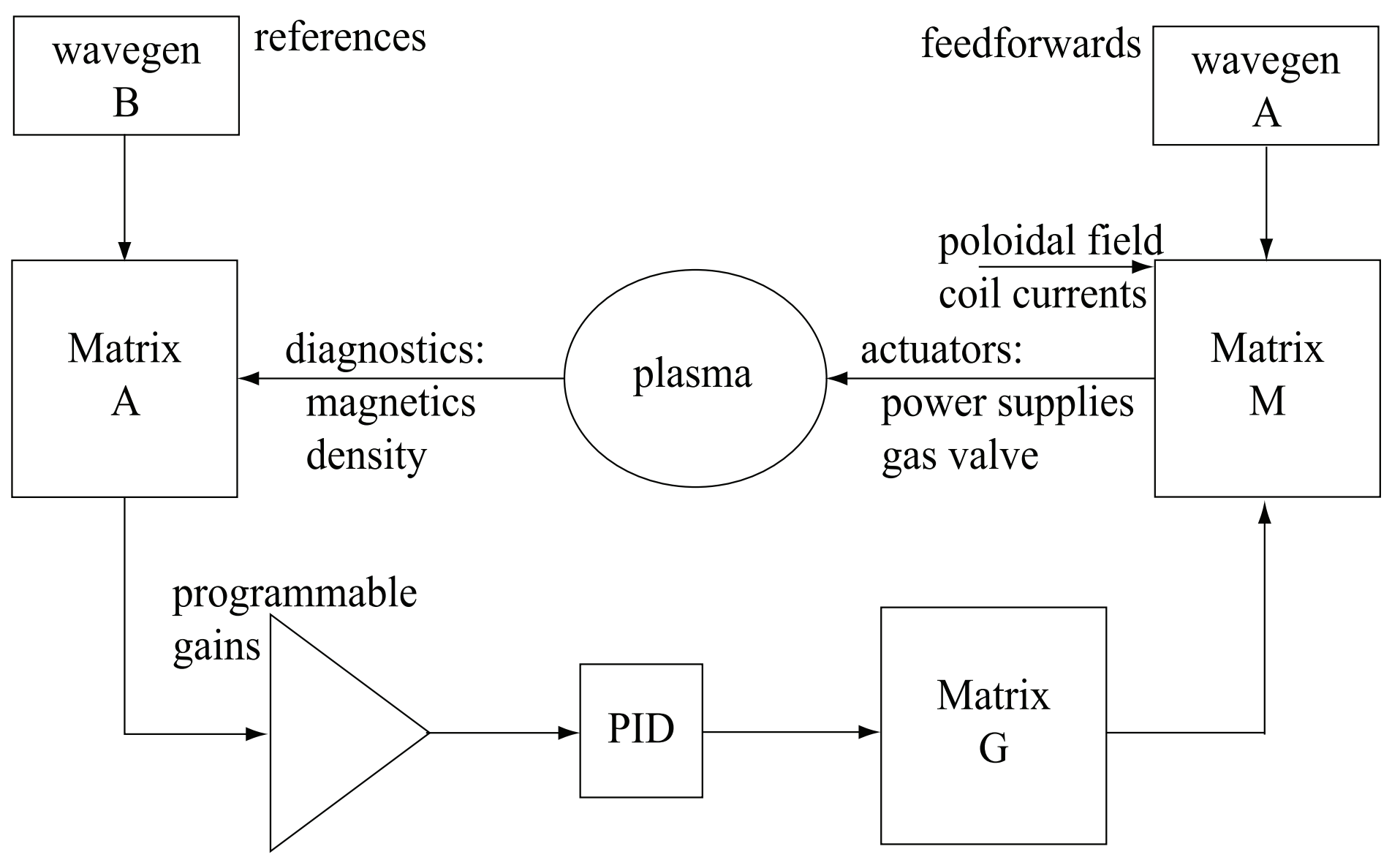


Figure 1. Diagram of the TCV X2 ECRH system showing the available poloidal angle ranges.

Figure 3. The TCV controller is based upon matrix operations on signals and a PID controller.



Matrix A: calculates observables eg plasma current

Matrix G: calculates the actuator signal eg coil voltage.

Matrix M: corrects coil mutual inductance and resistivity.

- The matrix coefficients may be changed several times during a shot at pre-defined times.
- Replace the coil control loops with ECRH actuators - power and mirror position and place coils in controllers internal to their power supplies
- design the matrix M coefficients to limit the gyrotron power when the input is saturated at ~+/-10V.

PLASMA CURRENT CONTROL

- Fully non-inductive ECCD plasmas
- Ohmic transformer coils set to constant current during ECRH phase to guarantee zero loop voltage.
- controlling 200kW to 450kW per gyrotron
- totalling 1.2MW to 2.7MW
- real time plasma current signal generated, as usual, in the A matrix.
- use Proportional and Integral terms in the PID controller
- able to control +/- 30kA

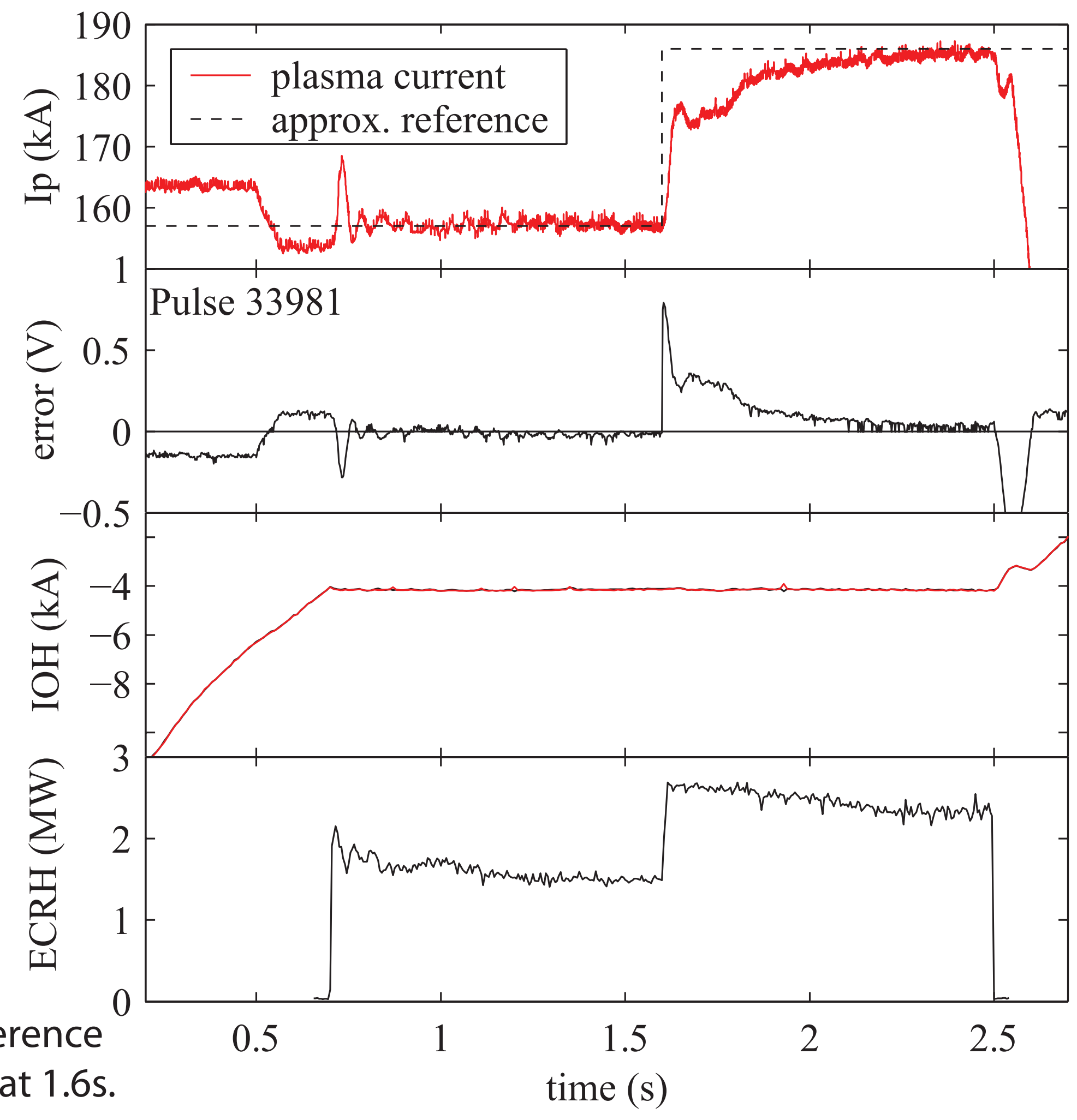


Figure 4. Controlling the plasma current. Reference current signal with a step from 160kA to 180kA at 1.6s.

PLASMA ELONGATION CONTROL

- In constant shaping (quadrupole) field, plasma elongation (κ) is a function of the current profile.
- heat off axis (ρ ~ 0.7), flatten current profile and elongate the plasma [2].
- No real time equilibrium reconstruction code on TCV.
- derive $\kappa_{realtime}$ signal based on the sum of fluxes at pre-defined points along the expected plasma boundary:

$$\kappa_{realtime} = \psi_{up} + \psi_{down} - \psi_{left} - \psi_{right}$$

- The fluxes are calculated from a simple finite element model of the plasma as 6 current filaments, [3]:

$$\psi_j = G_{ij} J_i$$

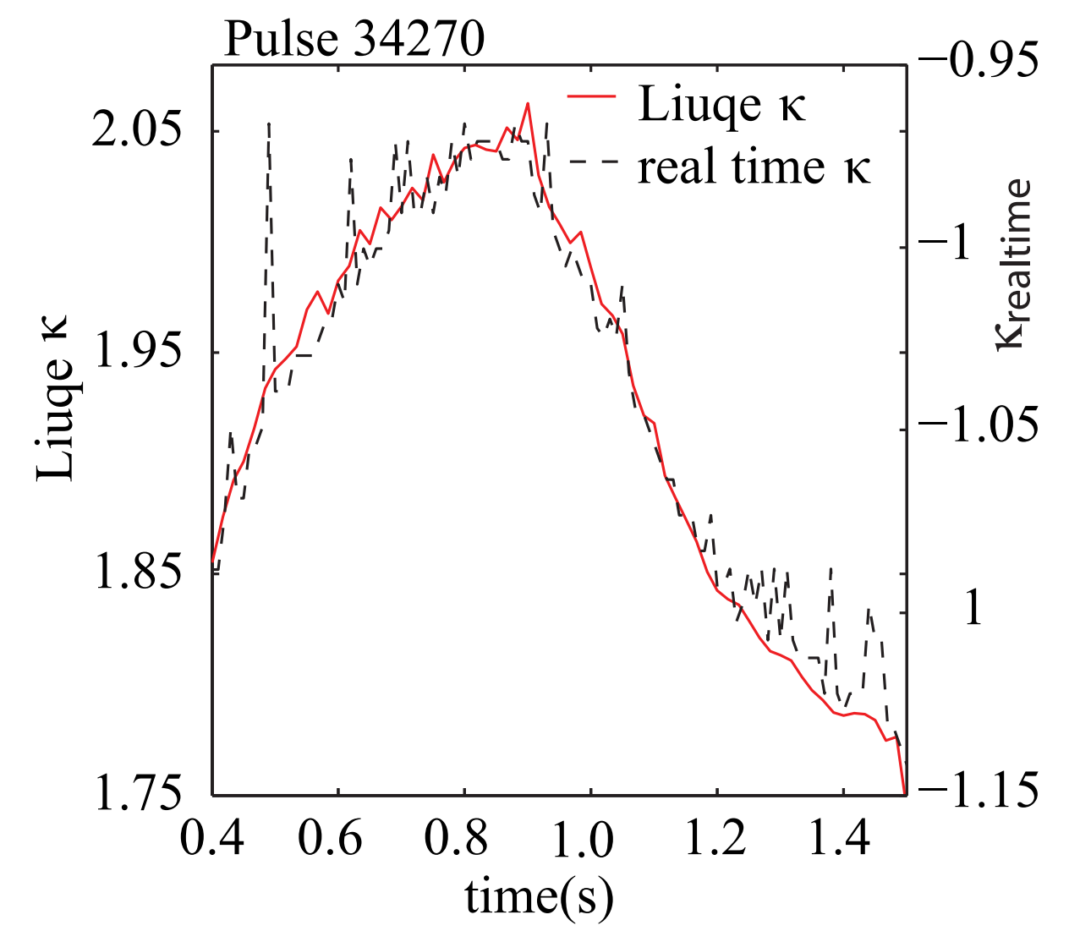


Figure 5: Comparison of our real time elongation signal and the LIUQE reconstructed signal

- The current in each filament (J_i) is derived from linear combinations of the flux (μ_k) at a network of poloidal field detection coils:

$$\mu_k = F_{ik} J_i$$

rearranging $\psi_j = G_{ij}\left(F_{ik}^{-1}\mu_k\right)$

- The fluxes are now a linear combination of magnetics signals, the coefficients of which are entered into the A matrix to generate $\kappa_{realtime}$

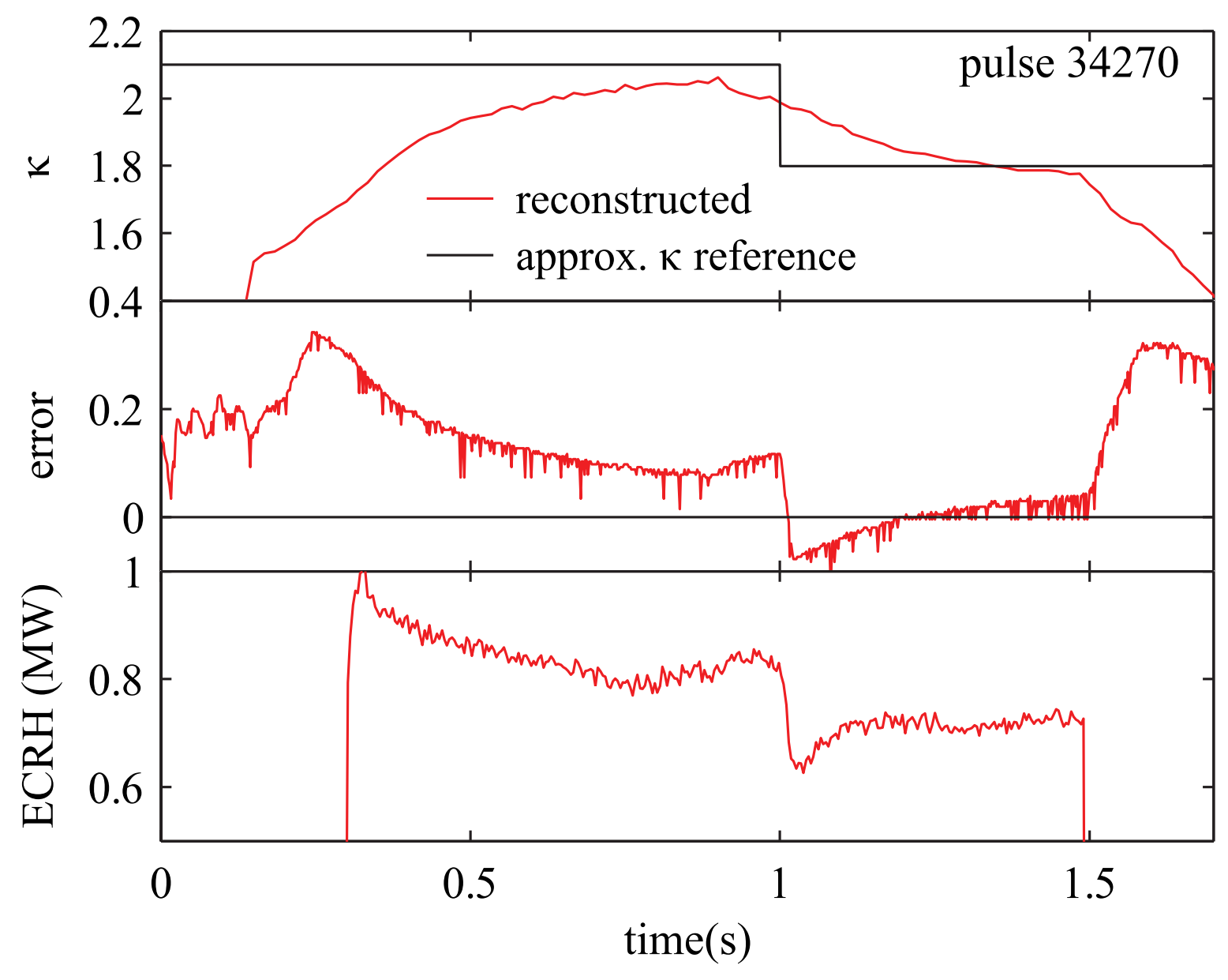


Figure 6. Controlling the elongation in real time. Here we use a reference elongation with a step-down at 1.0s.

- Proportional control only this pulse.
- ECRH power decreases at 1.0s and elongation responds as expected.
- Step-up elongation reference experiments showed a poor response to the step as the plasma density rapidly decreases during ECRH phase, decreasing the absorption efficiency.

ECRH DEPOSITION TRACKING CONTROL

- at constant mirror angle, the ECRH deposition becomes more centralised as the plasma elongates.
- implement real time control of the mirror angle to maintain the ECRH deposition at constant radius
- From the geometry of the plasma-mirror system, first find the linear relation between the elongation and the required mirror position.
- Insert the coefficients of this relation into the controller, as proportional terms and feedforwards/references - see figure for details.

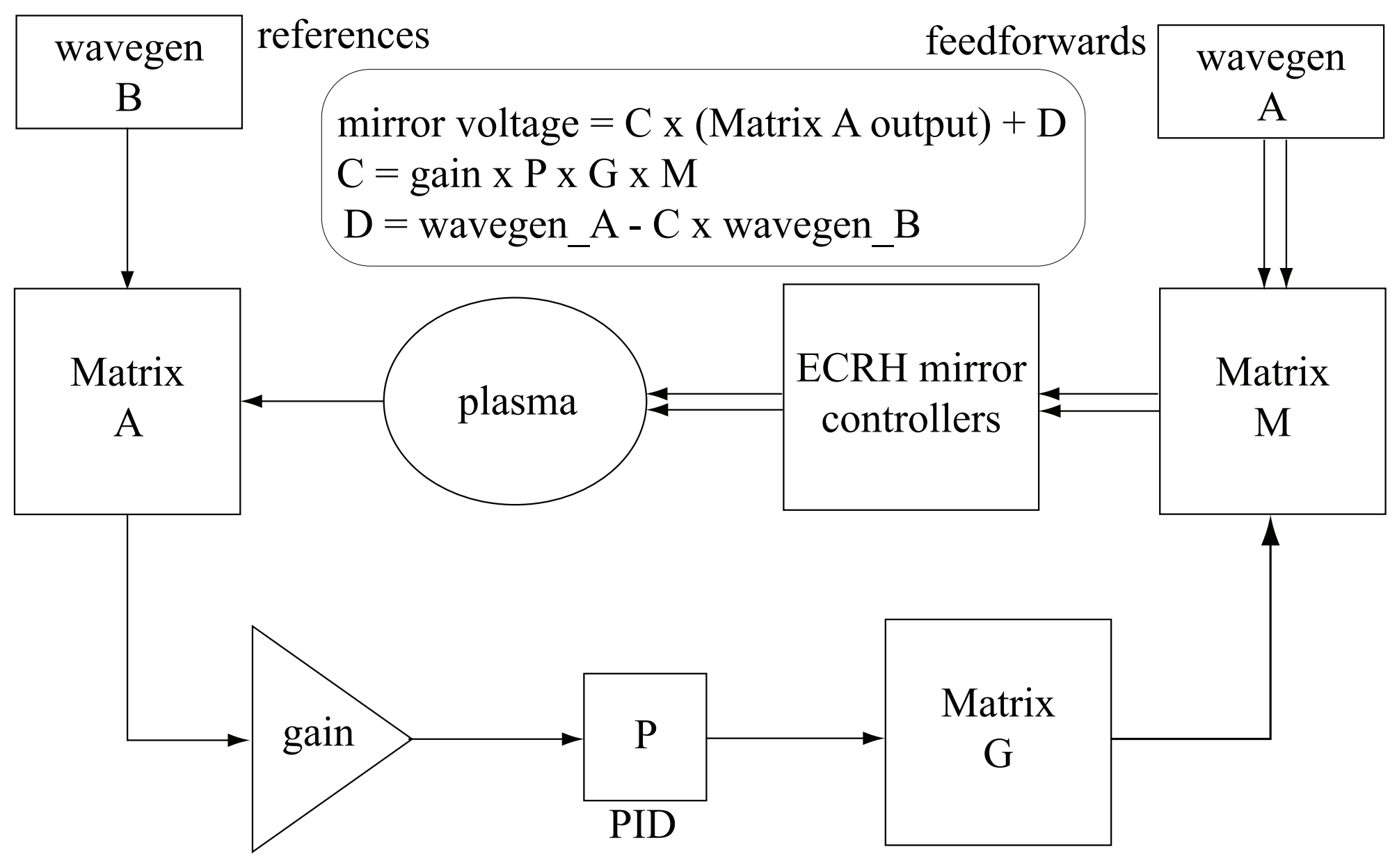


Figure 7. Programming the TCV controller for deposition tracking

Mirror motor voltage required to maintain the ECRH absorption at constant ρ, as a function of the elongation:

$$V_{mirror} = C\kappa_{realtime} + D$$

The coefficients *C* and *D* are constructed from the matrices, gains and signals in the controller:

$$C = PGM$$

$$D = wave_A - (PGM)wave_B$$

DEPOSITION TRACKING AND ELONGATION CONTROL RESULTS

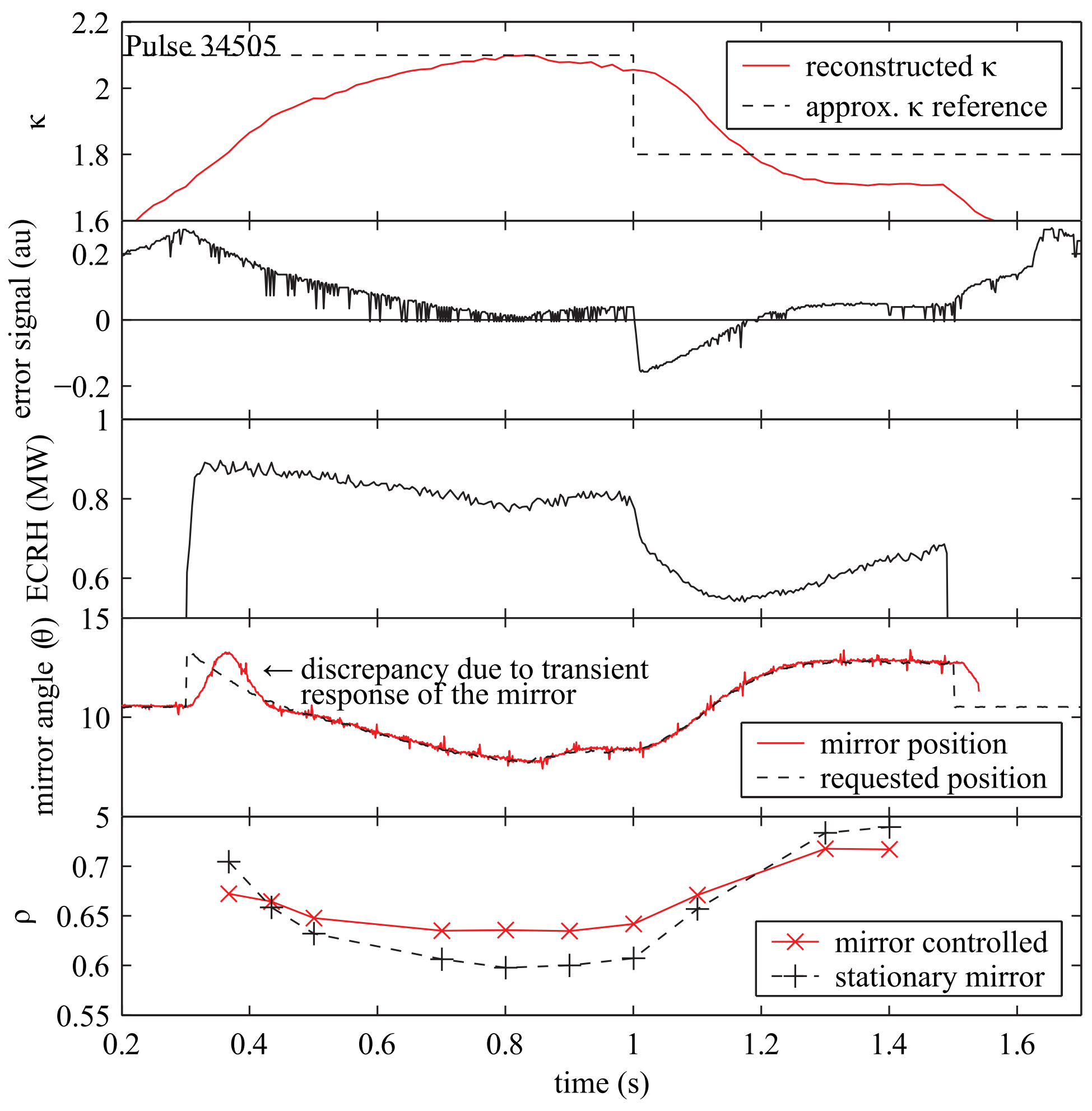


Figure 8. Results of the elongation control experiments.

- controlling the elongation and the deposition location in this pulse
- plasma elongates
- control system maintains the deposition on ρ ~ 0.65 surface.
- At step down in the elongation reference, ECRH power is reduced and elongation decreases.
- some drift in the deposition location as the elongation decreases, possibly due to non-linearity inherent in our $\kappa_{realtime}$ approximation.

FUTURE DIGITAL CONTROL ON TCV

- currently installing a mutli-DSP controller to replace the PID and G matrices. [4].
- will provide more channels for feedback control and the ability to utilise much more powerful algorithms.
- initial experiments will aim to replace the current analogue X3 mirror real time controller which moves the X3 top launch mirror to the position which maximises X3 ECRH absorption [5].
- other possible feedback loops include sawteeth, NTMs, ITBs etc.
- An example sawtooth control algorithm: Scan the X2 mirrors and calculate the sawtooth frequency at each position. Move the mirror to the position which maximises the frequency.
- Later, use other diagnostics (e.g. SXR, ECE) to find the rough location of the inversion radius to reduce the scan-and-test time.

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