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# Real-Time Control of ELM and Sawtooth Frequencies: Similarities and Differences

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## **ABSTRACT**

ELMs and Sawteeth, located in different parts of the plasma, are similar from a control engineering point of view. Both manifest themselves through quiescent periods interrupted by periodic collapses. For both, large collapses, following long quiescent periods, have detrimental effects while short periods are associated with decreased confinement. It is of interest to implement control systems to maintain the collapse frequency in the desired range. Two control strategies can be considered. In pacing control, exemplified by pellet ELM triggering, the plasma is perturbed periodically at the desired frequency. Continuous control schemes, exemplified by ECRH or ICRH control of sawteeth, modify the underlying plasma parameters which determine the collapse frequency. Both pacing and continuous control techniques have been developed on JET, using pellet and gas injection for ELM frequency control and ICRH for sawtooth control. Avoidance of tungsten accumulation has become a major challenge following the installation of the all metal 'ITER like wall' on JET [1] and sawteeth and ELMs play an important role by expelling tungsten from the core and edge of the plasma respectively. Control of tungsten has therefore been added to divertor heat load reduction, NTM avoidance and helium ash removal as reasons for requiring ELM and sawtooth control [2]. JET experiments have, for the first time, established feedback control of the ELM frequency, via real time variation of the injected gas flow. Using this controller in conjunction with pellet injection allows the ELM frequency to be kept as required despite variations in pellet ELM triggering efficiency. JET Sawtooth control experiments have, for the first time, demonstrated that low field side ICRH, as foreseen for ITER, can shorten sawteeth lengthened by central fast ions. The development of ELM and sawtooth control could be key to achieve stable high performance JET discharges with minimal tungsten content. Integrated control of a range of mutually coupled plasma instabilities and properties, including ELMs and sawteeth will be required in future tokamaks and gaining such experience on current tokamaks is essential.

## **1. INTRODUCTION: CONTROL STRATEGY**

The intermittent nature of both ELMs and Sawteeth means that either pacing or continuous control strategies can be employed to control the burst frequency. In the case of pacing, the frequency of the bursts/collapses is controlled by periodically perturbing the plasma at the desired frequency. If the perturbation is sufficiently large, each perturbation will trigger either an ELM or a sawtooth crash. If the perturbation is applied a certain pre-programmed time after the detection of an ELM/Sawtooth crash and the perturbation is maintained or increased until the next ELM or Sawtooth crash is detected the reliability of the method can be significantly improved. In this case reliable detection of ELMs and Sawtooth crashes is required and, in this detection, the effect of the perturbation itself must not be misinterpreted as an ELM or a sawtooth crash. In continuous control the burst frequency is controlled by changing the underlying physics parameters responsible for the ELM or sawtooth period through continuous adjustment of actuator settings. If the plasma parameters are very stable throughout, it is possible that pre-programming the actuators can do the job but such

stability is not very likely, especially since the ELM and sawtooth periods are strongly affected by a number of unforeseeable perturbations. To implement a successful closed loop controller it is essential to have a reliable real time measurement of the ELM or Sawtooth period and other relevant underlying parameters. As opposed to most control problems the required precision with which the desired frequency is achieved is not very stringent. The most important role of the controller is to assure that the ELM or Sawtooth period does not exceed a certain maximum period as even one long interval between ELMs or sawteeth is likely to have detrimental effects.

Of the various control options described above sawtooth pacing have been demonstrated on TCV [3, 4], while ELM pacing has been achieved on JET and on various other machines [5, 6, 7, 8, 9, 10]. Open loop sawtooth control experiments on JET are reported in [11, 12], while continuous closed loop sawtooth period control have been demonstrated on Tore Supra [13], TCV [14] and JET [15]. The recent closed loop ELM frequency control experiments described in more detail below constitute the first demonstration of such a control scheme [16].

## **2. ACTUATORS FOR ELM CONTROL**

The choice of actuators depends on the control strategy and is obviously different for sawtooth and ELM control. ELM pacing has been demonstrated using either the injection of small pellets or the application of so-called ‘radial field kicks’. A radial field kick is a short duration, fast variation in the radial field. With the right duration and rate of change of the radial field, ELMs can be triggered with high reliability and with minimum impact on the general plasma performance [5, 6]. The radial field kick will, however, accelerate the plasma vertically increasing the risk of a Vertical Displacement Event (VDE) leading to a high force disruption. The added risk of causing VDE’s associated with radial field kicks means that such kicks are unlikely to be useful for ELM control in high current JET pulses and even less in high performance ITER plasmas.

Injection of small pellets of frozen deuterium has proved to be efficient in triggering ELMs with good reliability as observed in a number of experiments [7, 8, 9]. In JET experiments the pellets do not arrive with very precise intervals into the plasma and the flight time of the pellets from the pellet injector to the plasma is so long that, when pellet frequencies in the 10-50Hz range are used, several pellets will be on their way through the pellet flight lines at the same time. As a consequence there is no way of affecting the time a pellet reaches the plasma depending on the timing of the last ELM. While Vertical field kicks do not affect the natural ELM frequency, the injection of pellets increase the edge pressure by modifying the natural ELM frequency in a similar way to gas injection as described below.

Continuous ELM control can use a variety of actuators. When operating in the ‘Type-I ELM’ operational space the ELM frequency increases both with heating power and with increased gas [17] [18]. If excessive gas is injected the ELMs change to high frequency ‘type-III ELMs’, where the frequency variation with gas injection becomes less clear. The current paper only considers the control of Type-I ELMs and hence the control schemes developed should avoid pushing the plasma into the Type-III regime. Though varying the heating power is very efficient in changing the ELM frequency,

the power is normally determined by other requirements and hence gas injection is a more relevant actuator for ELM frequency. Two characteristics of the way gas injection affects the ELM frequency are important for the development of a closed loop ELM frequency controller based on gas injection:

- i) The gas flows from the Gas Injection Modules (GIMs) to the vacuum vessel through fairly long pipes – leading to a significant delays (200–500ms for JET)
- ii) The reaction of the ELM frequency to a change in gas injection is highly non-linear.

Figure 1 shows an open loop step response experiment where the gas injection rate is changed abruptly from  $0.1 \times 10^{23}$  electrons/s to  $1.2 \times 10^{23}$  electrons/s, while Figure 2 shows the steady state ELM period (the inverse of the ELM frequency) as a function of the gas injection rate as found by repeating the experiment shown in figure 1 with a variety of gas injection rates.

Various other actuators can be used to affect the ELM frequency. One of the most promising of these is the application of non-axis-symmetric magnetic fields [19, 20]. To the knowledge of the authors no closed loop schemes have been developed for ELM control with non-axis-symmetric fields, though implementing such control certainly seems feasible. Finally, the injection of impurities strongly affects the ELM frequency. Whether impurity injection would be a good actuator for ELM control is questionable as such impurity injection is likely to be used to control other parameters, such as edge radiation, and it is therefore more likely that impurity injection will have to be treated as a disturbance by a closed loop ELM frequency controller.

### 3. ACTUATORS FOR SAWTOOTH CONTROL

For sawtooth control the main actuators are Electron and/or Ion Cyclotron Resonance Heating (ECRH / ICRH), which can be used either pulsed to achieve sawtooth pacing or continuously for open or closed loop continuous control. The sawtooth frequency is seen to depend critically on the radial location of ion and electron cyclotron resonances and hence continuous controllers vary this location by changing the ICRH frequency and/or the ECRH injection angle. The ability of precisely located ICRH to significantly affect the sawtooth period has been demonstrated in a number of JET experiments [11][12]. In most of these experiments the ICRH absorption was located on the High Field Side (HFS) of the plasma centre and in this case it was seen that:

- i) The ICRH waves had to be injected with a preferred toroidal propagation direction ( $N||$ ). This was achieved by operating the JET antennas with a specific phasing between the individual straps in the JET four strap antenna.
- ii) The ion cyclotron resonance position had to be located with great precision with respect to the  $q=1$  surface, where  $q$  is the safety factor.

On ITER only Low Field Side (LFS) ICRH will be available for sawtooth control and the efficiency of this scheme remained uncertain. Recent theoretical advances showing that ICRH affect the sawteeth mainly via a fast ion effects and less through changing the local shear at the  $q = 1$  surface, indicate that LFS ICRH should be able to shorten sawteeth [12]. To test this theory recent sawtooth

control experiments on JET have been using Hydrogen minority ICRH deposited near  $q = 1$  on the low field side, with the hydrogen concentration kept low (2-4%) in order to increase the energy of the fast ions. These experiments, discussed in the following, have demonstrated that low field side ICRH can be used for sawtooth control, shortening sawteeth lengthened by central fast Neutral Beam Injection (NBI) ions. Moreover, these experiments have demonstrated, for the first time, that current drive phasing of the antennae is not needed in order to shorten the sawteeth in contrast with what has been concluded in the past when high field side ICRH was considered. Figure 3 shows a case where sawteeth, lengthened by  $\sim 2.5$  MW of NBI power, are shortened by the application of 1.5 MW ICRH with symmetric, non-current drive phasing. In this discharge, the toroidal field and plasma current were swept resulting in the ICRH resonance location moving slowly from off axis towards the plasma axis. The result of sweeping field and current together is that the location of the  $q = 1$  surface stays constant while the Ion Cyclotron resonance location scans from outside to inside the  $q = 1$  surface as illustrated in the 3rd trace of the figure. The figure shows that short sawteeth are achieved when the ICRH resonance position is near the  $q = 1$  surface. It is noteworthy that the sawteeth transit abruptly between long and short periods in a behaviour very similar to observation using ECRH on Tore Supra [13]. The experiment was repeated with different antenna phasings and figure 4 shows the sawtooth period plotted as a function of the ICRH resonance position relative to the  $q = 1$  radius, as determined from the sawtooth inversion radius, for three pulses similar to the one in figure 3. The antenna phasings in these three discharges resulted in i) symmetric  $N_{\parallel}$  (dipole), ii) co-current propagating waves (+90) and iii) counter current propagating waves (-90) respectively, showing that sawtooth destabilisation was achieved in all three cases. Subsequent stability calculations for the three discharges, shown in the bottom box in figure 4, have confirmed that ideal kink mode potential energy functional  $\delta W$  is driven negative when the ICRH resonance is located near the  $q = 1$  surface, confirming that sawtooth destabilisation would be expected in all three cases[21]. An additional observation from these experiments and stability calculations is that the radial range of ICRH deposition locations resulting in sawtooth destabilisation is significantly wider for LFS ICRH than for HFS ICRH. This destabilisation region does, however remain fairly narrow – in the range of 10cm – and hence reliable sawtooth destabilisation is likely to require real time control of ICRH resonance position. Furthermore this region seem to become narrower with increase NBI power.

The preferable way to change the ICRH resonance position is through variation of the ICRH frequency as this does not affect the general plasma equilibrium. Real time RF frequency variation was developed on JET leading to the demonstration on closed loop sawtooth period control as described in [15]. The main difficulty of the control scheme used in these experiments was the limited power available due to the difficulty in maintaining good matching between the RF generator and the RF transmission line-antenna-plasma ensemble during RF frequency variation. An internal matching system responded to the mismatch created by the frequency variation by moving large transmission line components called trombones. As this trombone movement is much slower than

the available rate of change of the RF frequency, a mismatch always persisted during the frequency change. Recent developments on JET have allowed the frequency to be controlled by moving the trombones directly and letting the internal matching system change the frequency to maintain match. This control scheme has allowed good matching to be maintained throughout the frequency variation, thereby increasing the RF power which can be coupled to the plasma during such RF variation. The main limitations for the use of real time RF frequency remain:

- i) The very limited range of variation of the RF frequency which, on JET, allows the Ion Cyclotron resonance to be moved by only 5–10cm. If this method has to be implemented on ITER the range of variation needs to be significantly increased.
- ii) The slow trombone speed which results in a full frequency range sweep taking ~10s. This slow response is likely to be irrelevant on ITER where the required sawtooth period is expected to be measured in tens of seconds.

The sharp transitions between long and short sawteeth seen in figure 3, make it likely that the available RF frequency variation, though small, should be sufficient to allow reasonably responsive feedback control of the sawtooth period. This may however mean that a more intelligent controller similar to the one implemented on Tore Supra [13] has to be implemented.

#### **4. REAL TIME ELM AND SAWTOOTH PERIOD MEASUREMENT**

Real time determination of ELM and Sawtooth frequencies is a requirement for closed loop control. Though the diagnostic measurements used for this determination are different in the two cases, the algorithms determining the frequency are similar. For the JET real time ELM frequency determination the choice of the appropriate diagnostic signal was key, in order to detect ELMs but no other perturbations. It was particularly important to avoid mistaking perturbations associated with pellets and kicks for ELMs. The bolometer measurement of the total radiated power, though it reacts much slower than the signals traditionally used to look at ELMs, proved ideal for robust real time ELM frequency determination. The small delay of a few milliseconds incurred by using this signal is of no consequence given the slow response of the gas injection actuator. The algorithm used for real time ELM detection looks for a rapid increase followed by a rapid decrease in the total radiated power [16]. Having developed an algorithm to detect ELMs in real time the derivation of a continuous ELM period signal follows along the same lines as the real time sawtooth period determination described in [15], with the instantaneous ELM/sawtooth period defined as the maximum between the time elapsed since the latest ELM/sawtooth crash and the interval between two most recent ELMs/Sawtooth crashes. This gives the controller information about any increase in the period without waiting for the subsequent ELM/sawtooth crash to occur. For the ELM controller the ELM frequency is found as the inverse of the period is used in the controller. The real time ELM frequency can be seen in figure 1 together with a simulated ELM frequency signal used for tuning of the closed loop controller.

## 5. CLOSED LOOP CONTROL

Though showing many similarities, the control algorithms for the Sawtooth and ELM control, as performed at JET are rather different due to the significant difference in the actuators and in both the dynamics and linearity of the plasma response.

The closed loop sawtooth controller originally described in [15] has been updated, as shown in figure 5, to accommodate the improved ICRH frequency control described above. Limited experimental time has prevented this newly developed RF frequency control scheme from being employed for closed loop sawtooth period control.

For the ELM controller, shown in figure 6, which was developed in 2013, the choice was made to control a ‘linearized’ ELM frequency with the linearization derived by translating the curve in figure 2 to show ELM frequency rather than ELM period and then inverting the resulting curve. The linearization assures that the loop gain, and thereby the controller response, remains constant even for significant changes in the required and measured ELM frequencies. The ELM controller has been operated frequently over the last year, demonstrating closed loop control of the ELM frequency, via real time variation of the injected gas flow for the first time [16]. Figure 7 shows an example of a discharge where the controller was active. In this pulse the plasma configuration was changed at 12s leading to a reduction in the ELM frequency. The controller responded to this disturbance, recovering the requested frequency in less than 1s. The controller has been challenged further by using it in conjunction with pellet ELM pacing. In these cases the aim of the experiment was to maintain a sufficiently high ELM frequency with as little injected gas as possible, relying on the injected pellets to maintain the ELM frequency. The role of the controller was to act as a ‘safety net’ preventing the ELM frequency from dropping below the minimum value for too long. In these experiments, the pellet triggering of ELMs is seen as a perturbation to which the controller responds by reducing the gas flow. Figure 8 shows an example where the gas flow is reduced to zero for a short while the ELM frequency is maintained purely by pellet injection. When the pellet ELM triggering faltered around 11–12s, the controller recovered the ELM frequency by increasing the gas flow again. The controller subsequently reduced the gas flow when the pellet performance improved. When the pellets stopped completely, as programmed, at 14s the controller tried to maintain the ELM frequency by increasing the gas flow to its maximum value, though this was not sufficient to achieve the requested frequency. The ELM frequency controller has proved especially useful in experiments where it is desirable to maintain a low, but not too low, ELM frequency.

## CONCLUSIONS

Control schemes using gas and pellets for ELM control and ICRH for sawtooth control, could be key to allow more stable high performance JET discharges with minimal tungsten content. In ITER and ideally also on JET, these control schemes have to be run together with impurity injection and ELM coil controllers in an integrated control system. Integration of a variety of controllers to control a range of mutually coupled plasma instabilities and properties will be required for the operation of future tokamaks. Gaining such experience on JET and other current tokamaks is essential for future ITER operation.

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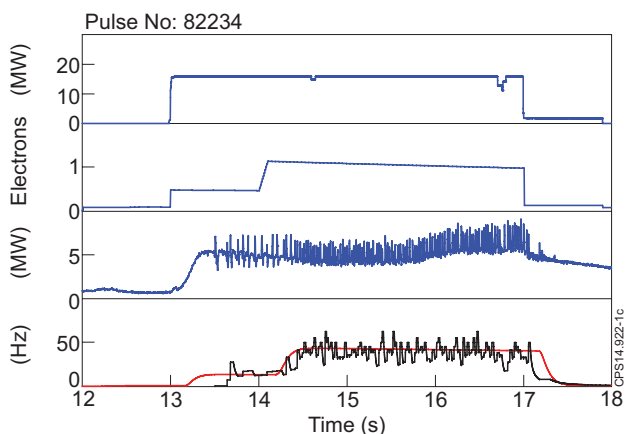


Figure 1: Open loop ELM frequency response to a step in gas injection rate. The red trace in the bottom box shows a simulation of the ELM frequency used for tuning of the closed loop.

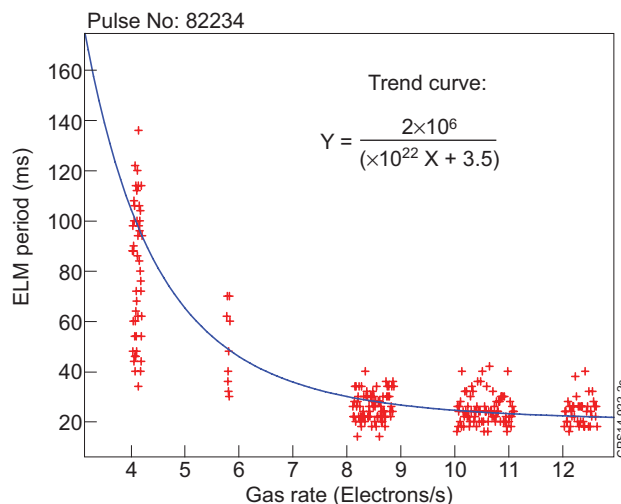


Figure 2: Steady state ELM period as a function of the gas injection rate.

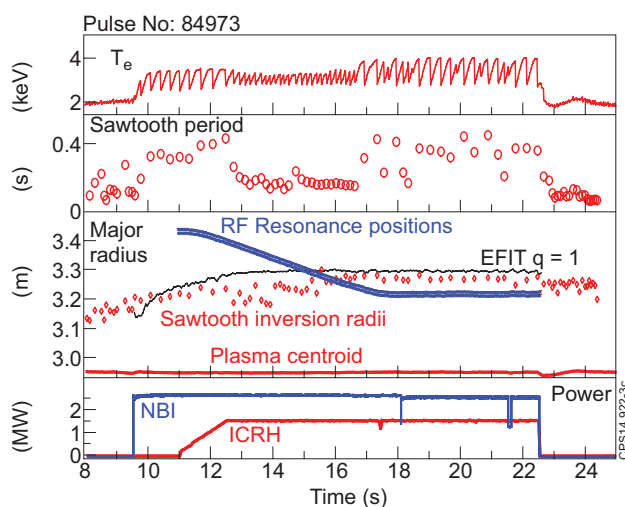


Figure 3: Low Field side minority ICRH in Dipole phasing, shortens sawteeth when the resonance is located near the  $q = 1$  surface. Hydrogen Concentration: 2–4%.

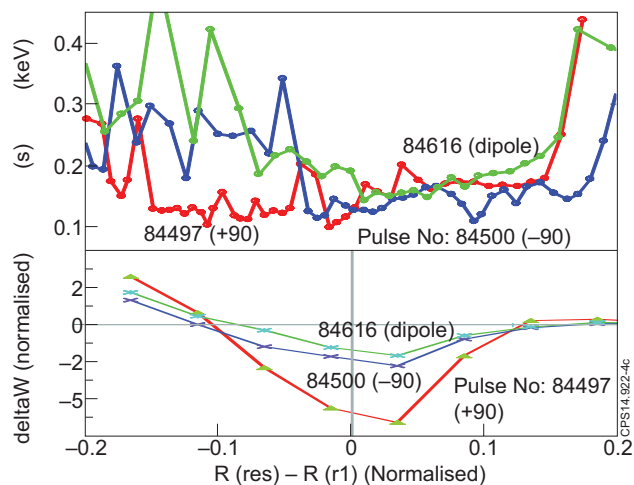


Figure 4: Sawtooth period as a function of the distance between the ICRH resonance and the LFS sawtooth inversion radius. The bottom traces show the calculated ideal kink mode potential energy functional.

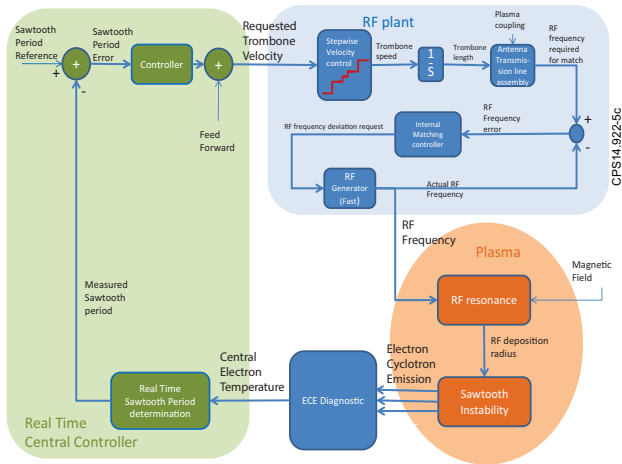


Figure 5: Sawtooth period feedback control Diagram.

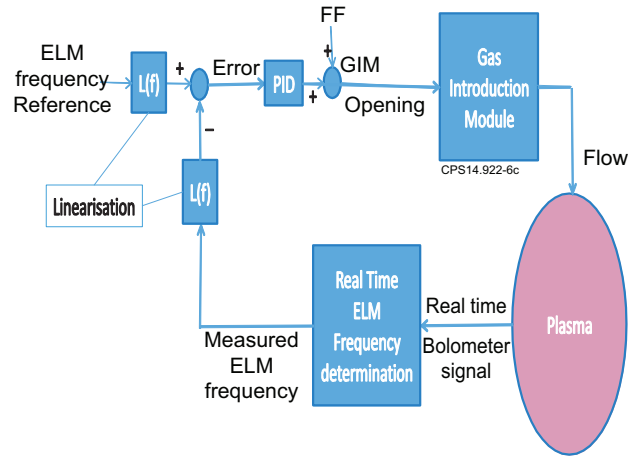


Figure 6: ELM frequency feedback control block Diagram.

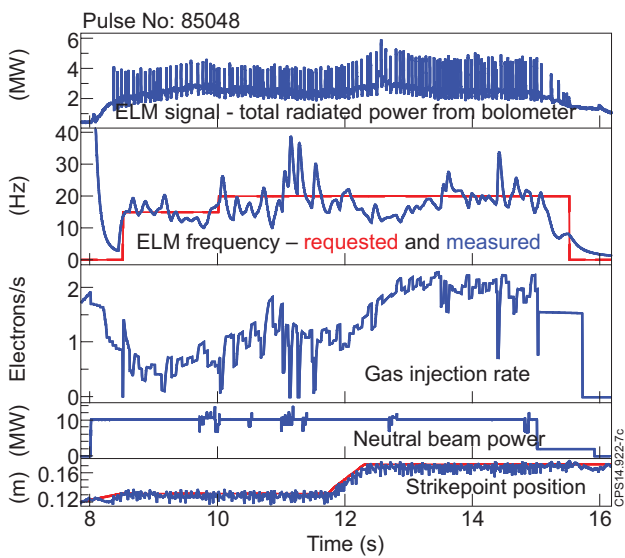


Figure 7: ELM frequency controller response to a step in request and to a change in strike point position.

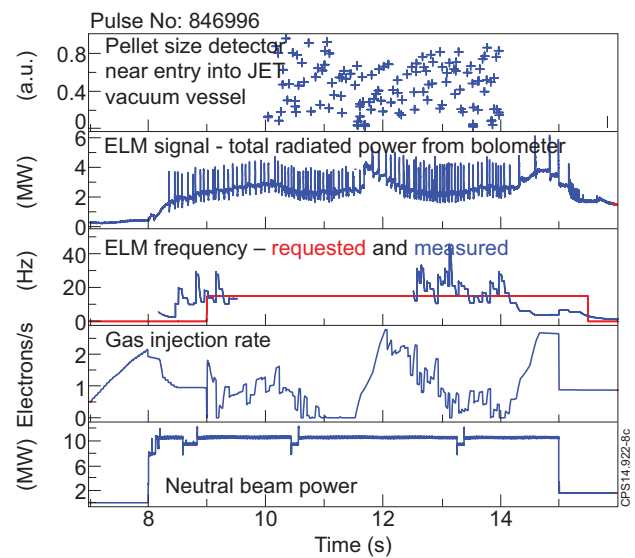


Figure 8: ELM frequency feedback control in conjunction with pellet injection.