A Combined Divertor and Bulk Plasma Density Control System

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A density control system capable of controlling gas introduction into JET in divertor experiments and using a variety of feedback signals is described. Combined feedback control using the bulk plasma density and ion saturation current from a Langmuir probe is demonstrated. Planned system upgrades are presented.

1. INTRODUCTION

A new torus gas introduction and control system has been implemented at JET. The system has been designed to control the plasma density in feedback mode using 10 gas introduction modules positioned around the vessel. Apart from using the bulk plasma density for feedback the system may also control some of the gas modules for feedback on other signals.

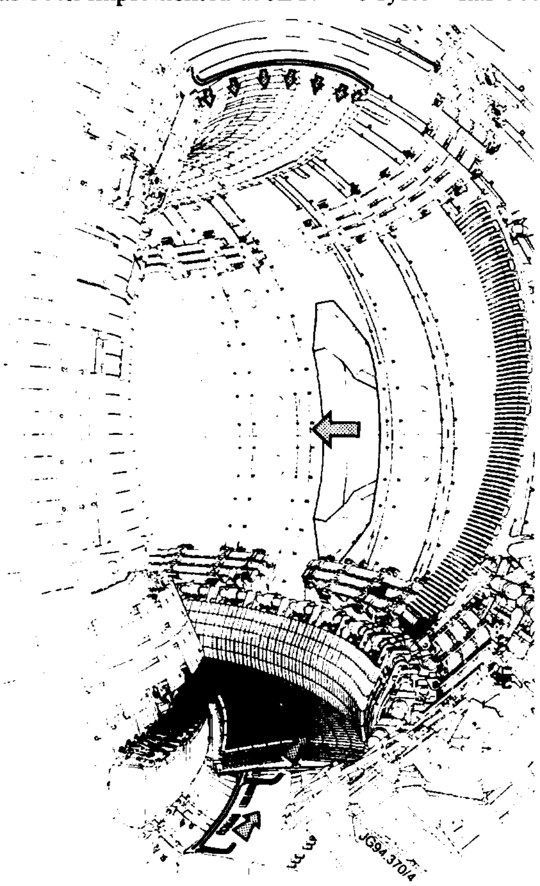

Fig 1. Layout of gas introduction inside torus. Four radial lines at top of torus, one of which is extended to LHCD launcher in midplane, two modules feeding through main horizontal port and four toroidal lines in divertor

2. EXPERIMENTAL SET-UP

A total of 10 gas introduction modules (GIMs) are installed on JET, two of them feeding in the torus midplane, four distributed around the top of the vessel and four modules distributed around the divertor area at the bottom of the torus (fig 1).

Modules in the bottom have distribution lines with pipework sized to ensure even distribution in toroidal direction in the new divertor. The modules at the top of the machine have radially extended

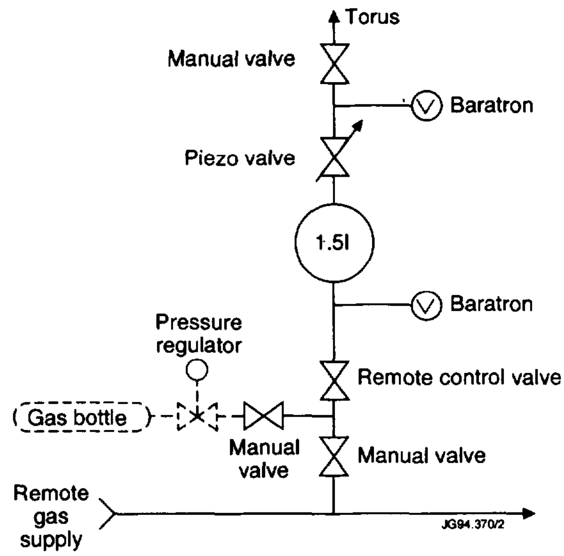

Fig 2. Schematic of a single gas introduction module

distribution lines. The distribution line for one of the top modules is extended to the torus midplane next to the LHCD antenna. The midplane modules are feeding the torus through a main horizontal port.

Each of the GIMs has a 1.5 l reservoir located close to the torus (fig 2). Between plasma pulses this reservoir is filled either from a remote gas supply system or from a local gas bottle. The local bottle option is normally used when operation with a special gas in a single module is required.

The four top modules share one remote supply line as do the four modules in the divertor area. Each of the remaining two modules in the midplane has its own remote supply line. The filling pressure for the remote supply lines can be remotely adjusted. During a plasma pulse the reservoirs are isolated from the supply systems (remote and local) and gas is fed to the torus through an analogue piezo valve. The pressure drop in the reservoir is used to calculate the gas flow after the pulse. A flow rate of 100 mbl/s from each GIM is achieved when operating with 500 - 600 mb deuterium. The gas flow response time at this flow rate is 150 - 200 ms. The maximum operating pressure is 1200 mb.

The piezo valves are controlled by two CAMAC based microprocessors, one for the top and midplane modules and one for the divertor modules. The two microprocessors run identical software to control the opening of the piezo valves.

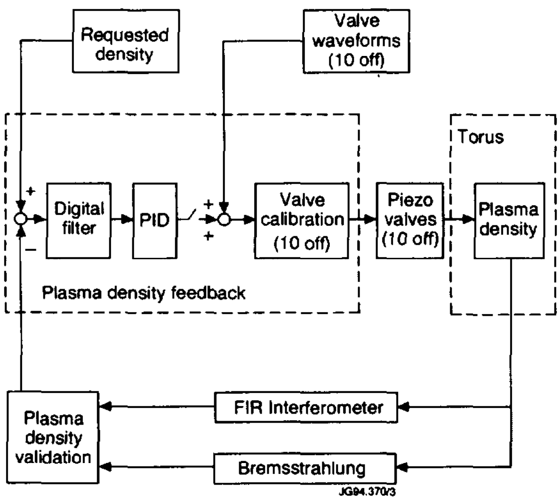

Fig 3. Schematic of feedback control system

For convenience each piezo valve may be controlled using three time windows and a waveform which specifies the percentage opening of the piezo valve. The three time windows specify the duration of a gas puff with fully open valve, the period when the waveform will be applied and time when feedback control of the valve should take place, respectively. During feedback control, the pre-set valve opening waveform is used for feed forward control. Many combinations of puff, pre-programmed and feedback time windows may be applied. A schematic of the control system is shown in fig 3.

The main signal used for feedback control of the gas system is the electron line density measured by the FIR interferometer. A weighted average of pre-selected interferometer channels is used to represent the bulk plasma density. In cases when the interferometer signal becomes invalid during a pulse, say due to a fringe jump, the system changes to use a horizontal and/or a vertical Bremsstrahlung signal. The density is derived from the Bremsstrahlung signal by taking the square root of the raw data and applying a calibration constant. The calibration constant is recalculated on every plasma pulse where the interferometer and Bremsstrahlung signals are available.

Other signals may also be used for feedback control of the gas modules. These include divertor tile temperature, divertor electron density as measured by microwave interferometry, a number of spectroscopic signals and FIR interferometry with a different channel selection and weighting to the bulk plasma measurement.

Each of the microprocessors may use only one of the above signals for feedback control. If the bulk plasma density is being used the corresponding gas modules are said to be in the primary loop and gas modules controlled by any other signal are in the secondary loop.

The primary loop is an essential part of normal plasma operation, whereas the secondary loop is of an experimental nature to try to control such parameters as divertor density, divertor tile temperature, LHCD coupling etc.

Feedback Control

The feedback control uses a transfer function of the following form

$$K_c\left(1+\frac{1}{s*T_I}\right)\left(\frac{1+s*T_D}{1+s*\frac{T_D}{\alpha}}\right)$$

Here K_C is the gain factor, T_I and T_D are integral and derivative time constants, respectively, and α is a limit for high frequency derivative roll-off, s is the Laplace transform variable. The particular transfer function was derived from earlier experiments on JET and was used in operation prior to the installation of the pumped divertor. The time constants and α are adjustable from pulse to pulse and for the primary loop a pre-programmed waveform is used for the gain. The error signal is digitally smoothed before the transfer function is applied. The output from the transfer function is then added to the pre-programmed waveform for each gas module which operates in feedback mode. The value which is in terms of 0 - 100 % opening of the piezo valve is finally translated into a voltage for the piezo valve. The calibration of valve opening vs. piezo driving voltage is highly non-linear and varies from valve to valve; the loop however remains stable under these conditions.

The secondary loop uses a similar scheme as outlined above for the primary loop, but with the following modifications. The gain used in the secondary loop is a constant, adjustable from pulse to pulse. The operation of the secondary loop is inhibited if the bulk plasma density exceeds a pre-set limit. This limit is independent of primary loop feedback operation. This is to avoid that the secondary loop would overfuel the main plasma. The error signals are updated on a 5 ms time scale; however, the feedback signal is only updated on a 100 ms time scale in order to match the general response time of the system and avoid instabilities. Dead times within the system are substantially lower than the time constants in the feedback loop and are thus of no concern.

3. OPERATIONAL EXPERIENCE

The primary density feedback loop has been operated since the restart of JET operations in early 1994. An example of the performance of main density control is show in fig 4.

The system currently suffers from the interferometer density measurements not being ideal. The interferometer channels which are currently being processed in real time all include the divertor plasma. This situation, however, is likely to change in the near future when the lateral interferometer channels have been commissioned.

Experiments have also been done, where the four divertor gas modules have been controlled in parallel in feedback mode by the secondary loop using the ion saturation current from a divertor Langmuir probe for feedback, fig 5. In these experiments the primary loop controlling the bulk plasma density was running from 0.8 to 12 s and the secondary loop from 14.5 to 24 s. It can be observed that due to high out-gassing the primary loop is only feeding the plasma during the first few seconds of the discharge, the plasma density exceeding the requested waveform. The feed forward waveform for the main gas valve requested 20 % opening of the piezo valve. At 12 s the pre-programmed gas waveform is applied to the divertor GIMs followed at 14.5 s by application of

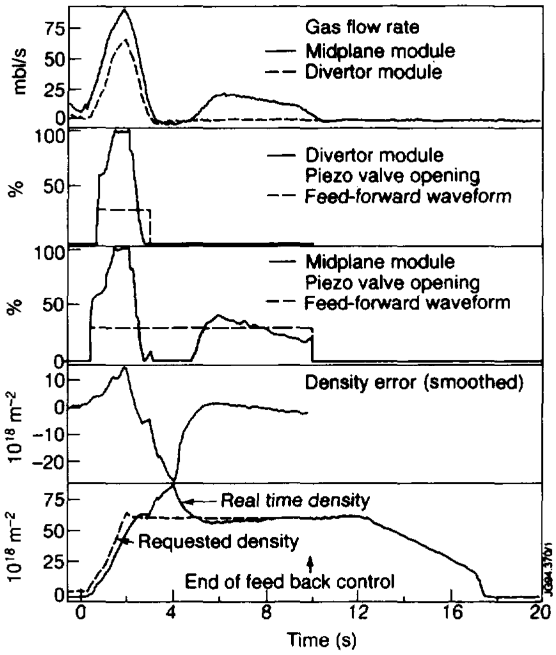

Fig 4. Gas system data for pulse 30786. Midplane module timing: puff 80 ms @ -0.4 s and feedback 0.5 - 10 s. Divertor module timing: feedback 0.8 - 3.0 s. Feed forward waveform at 30 % opening for both modules.

the feedback term. The feedback term has been operationally limited to adjust the pre-programmed waveform by maximum ± 20 % valve opening, and due to the large error signal this limit is in effect until 20.2 s at which time the feedback system is starting to control properly and maintaining the requested waveform.

The purpose of the experiments which formed the basis for the results in fig 5 was to control the detachment of the divertor plasma from the divertor tiles. The result of these experiments will be reported elsewhere.

4. SYSTEM UPGRADE

The present implementation of the density control system is very tight in memory space and imposes restrictions in the operational use of the system. In order to get rid of these constraints work is in progress to move the implementation from being CAMAC based to residing in VME.

The new VME implementation will allows us to select any combination of gas modules to be controlled by the primary and secondary feedback loops.

When the new centrifuge pellet injector becomes available, this will also be interfaced with the density feedback system. The centrifuge pellet injector will be capable of injecting deuterium pellets of cubic length 2 and 3 mm at a variable rate up to 40 pellets/s corresponding to a fuelling rate of 1000 mbl/s for up to 60 s. The centrifuge control system is designed to accept an analogue fuelling rate and launch pellets accordingly. The density feedback system will be modified to include a further feedback loop to cater for the centrifuge injection. It will be possible select either the bulk plasma density or any of the secondary loop signals for feedback control of the centrifuge pellet injection. The new transfer function is expected to have different characteristics due to the different fuelling physics.

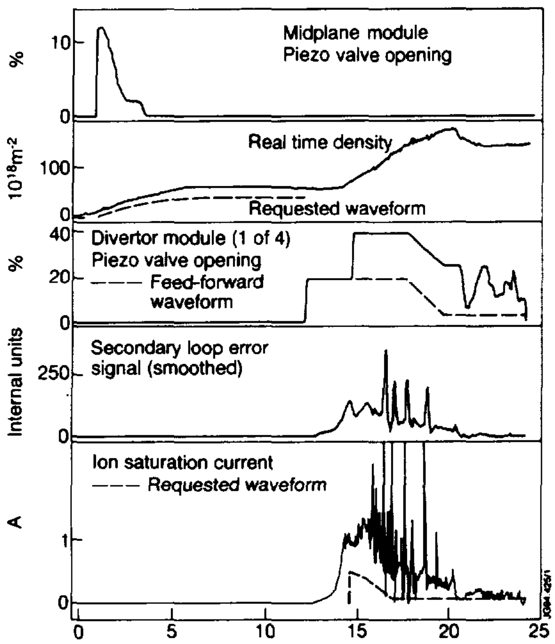

Fig 5. Operation of primary and secondary loop for pulse 31204. Midplane module timing: puff 60 ms @ -0.5 s and feedback 0.8 - 12 s. Divertor module timing: feedback 14.5 - 24 s.

5. CONCLUSIONS

The density control system is working as one of the key elements in JET operations. The successful operation of the secondary loop for control of the divertor gas modules has been demonstrated.

An upgraded version of the control system which will eventually include pellet fuelling is under development