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Recent results on disruptions mitigation with a new fast valve

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Introduction.

Mostly electromagnetic (EM) valves have been used for the injection of large amounts of impurity gas in experiments on disruptions mitigation. They are robust, fast (response and opening time of the order of the millisecond), can exert a large force in a short time and release a large amount of gas (of the order of one bar liter) at pressures up to 100 bars within a few milliseconds. However they have the disadvantage of employing a movable stem, made of ferromagnetic material, which can interact with the time varying magnetic field and move during the discharge. In order to avoid undesirable leakage or injection of gas, an EM valve is usually located a few meters (depending on the dimension of the tokamak) away from the plasma. The gas is then delivered to the plasma with a tube or let free to expand from a side port into the vessel. In both cases the gas arrives at the surface of the plasma with a time delay of several milliseconds - proportional to the square root of the specific mass of the gas used - and a low pressure, orders of magnitude smaller than the pressure in the gas reservoir. In ITER the long time delay of the gas traveling along a tube several meters long and the low initial delivery rate may undermine their use. For these reasons a new piezo-released valve, having the advantages of an EM valve (fast opening and high delivery rate) and being able to operate close to the plasma, was designed and built by the German company IGAM [1] in collaboration with IPP.

ASDEX Upgrade (AUG) went into operation in the Spring of 2007 after a shutdown, which lasted one year and led to a full tungsten machine. The valve was developed and installed in the tokamak during this period. In the first month of operation of AUG, the in-vessel valve has already been successfully used in a series of experiments, which have shown the improvement of the mitigation performance with respect to the previously used EM valves, located outside of the vessel [2]. The new valve allows the investigation of (1) the mitigation efficiency of localized versus distributed gas injection, (2) of mixtures of gases and (3) of high gas pressure. This paper reports results on issues (1) and (2).

The new in-vessel valve.

The in-vessel valve is a completely new development and satisfies very demanding functional requirements as a short opening time (of the order of 1 ms), a large orifice (14 mm of diameter) and practically no leakage ($< 10^{-9}$ mbarl/s). In addition the valve must maintain its full functionality and function under severe environmental conditions as high temperature (up to 150 ^{o}C during the baking of the vessel), strong magnetic field and high vacuum ($p < 10^{-7}$ mbar).

The valve is located on the low field side of the torus, at the midplane, 5 cm behind the limiting surface defined by the ICRH antenna and 10 cm from the plasma. It can operate with a pressure reservoir of 50 bar and inject up to 2 barl of gas within a few ms. It is the first valve of this type ever used close to the plasma on a tokamak.

The realization of the valve was preceded by the development of several concepts, the detailed FEM analysis of the most promising one, the careful choice of materials [3], the construction of a prototype and laboratory tests, the construction and test of the final valve. The valve, whose sectional view is shown in Fig. 1, consists of

1) a gas chamber, with a volume of 80 cm^3, reduced to 40 cm^3 for the present experiments;

2) a pneumatic piston, driven by pressurized air, used to exert pressure on

3) a movable stem, which closes the orifice of the valve;

4) four independent pairs of piezo-actuators, which expand under an applied voltage and hold the stem in the closed-valve position;

5) a disk spring package, which opens the valve - as soon as the piezo-actuators are discharged - by moving the stem away from the orifice.

The valve is water cooled, since it is going to be exposed to up to one MW/m^2 of power flux during 8-10 s. It is equipped with a remote controlled gas mixing system, which allows to mix two types of gas in a reservoir and fill the valve just before the discharge. A control unit monitors the charging currents of the piezo-actuators by comparing the actual values with reference ones, which are stored in a flash memory of the micro controller during a calibration procedure. In case of breakdown of one of the actuator couples, the control unit excludes it from operation. Two of the four couples of piezo-actuators are redundant to allow the operation of the valve in case of their partial failure. This security margin is dictated by the fact that the valve is mounted inside the vessel and cannot be accessed for maintenance during the whole experimental campaign (up to 10 months).

First experiments.

The experiments presented in this paper were aimed at the comparison between the mitigation performance (1) of the old and new valves and (2) of pure impurity gases and their mixtures with D_2. A series of similar discharges in H mode was shut down by massive gas injection. The valve was triggered at the end of the flattop, in plasmas with a toroidal current of 0.8 MA and $q_{95} = 5.7$. The plasma, heated by 5 MW of NBI power, had a target density of 6 10^{19} $1/m^3$, a thermal energy of about 0.3-0.35 MJ and a magnetic energy of 1 MJ.

The comparison between the old and the new valves was carried out between similar shots with the injection of 400 mbarl of gas (that is 10^{22} atoms of gas) within 5 ms. The striking differences between the shutdown induced by the new and the old valves are illustrated in Fig. 2. With the in-vessel valve

1) the delay time between trigger and start of the current quench is practically eliminated (Fig. 2(a)); the current decay induced by the new valve starts 1 ms after the trigger, that is as soon as the valve is open;

2) the rate of induced current decay is twice the one observed with the old valves (Fig. 2(a)). It is known that the faster the current decay of an elongated plasma is, the smaller is the vertical force on the vessel;

3) the fueling efficiency (in terms of increase of the electron density per number of injected atoms of gas) is higher and the rise of the plasma density starts as soon as the valve opens (Fig. 3); a large electron density is required for the suppression of the runaway already at the start of the current quench;

4) the maximum radiated power reaches the 0.5 GW and is a factor of two higher than with the old valve (no figure).

A second series of experiments was carried out to investigate the mitigation and fueling efficiency of mixtures of deuterium (D_2) and neon or argon. Mixtures of a low-Z and a high-Z gas are found to increase the density of the plasma more than the high-Z alone and be as efficient as high-Z injection in quenching the current in other tokamaks (see for example Ref. [4]).

This is not the case with the pressure and quantity of gas injected in the AUG experiments presented in this work. The time delay between the trigger and the start of the current quench increases with increasing percentage of D_2 in the mixture. The rate of thermal energy dissipation (Fig. 2(c)), the rate of the current quench and the radiated power increase with increasing concentration of neon or argon. The velocity of the cold front in the plasma, as measured by the SXR, is also sped up by increasing the percentage of high-Z gas in the mixture. The rise of the electron density is very fast and seems to be independent of the type of gas injected. Typically the increase of the electron inventory is 20 % of the number of injected gas atoms and takes place within 2 ms from the trigger. The density remains high during most of the current quench.

The reasons for the different observations between AUG and the other tokamaks have to be clarified by cross-machine comparison of the detailed measurements and of the experimental conditions.

Conclusions.

A new concept for a fast valve located in the vessel very close to the plasma was developed for ASDEX Upgrade. The in-vessel valve shows a better mitigation performance with respect to the older EM valve in terms of 1) extremely fast response of the plasma - the start of a fast current quench within 1 ms from the trigger -, 2) high cooling efficiency, which translate in a fast current quench, and 3) high fueling efficiency.

Experiments at higher reservoir pressure and higher plasma energy will be carried out to learn to scale the mitigation performance of the new valve to an ITER plasma. Simulations with EIRENE-SOLPS have begun to understand the complex processes of particle transport and energy dissipation, which seem to depend on the degree of localization of the gas injection.

References

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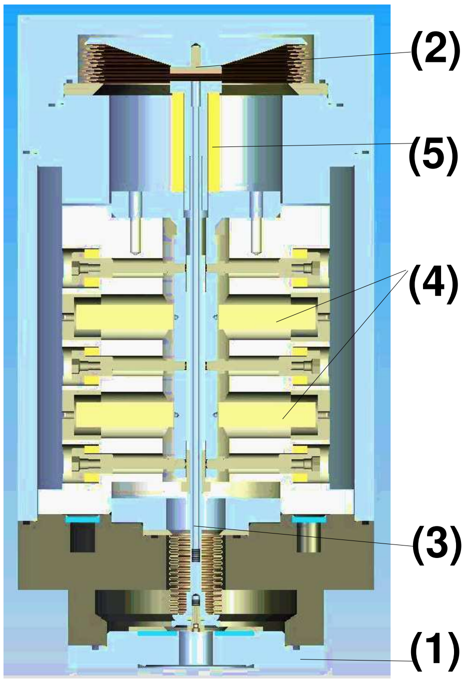

Fig. 1 Sectional view of the in-vessel valve showing (1) the gas chamber, (2) the pneumatic piston, (3) the stem, (4) the piezo-actuator and (5) the disk spring package.

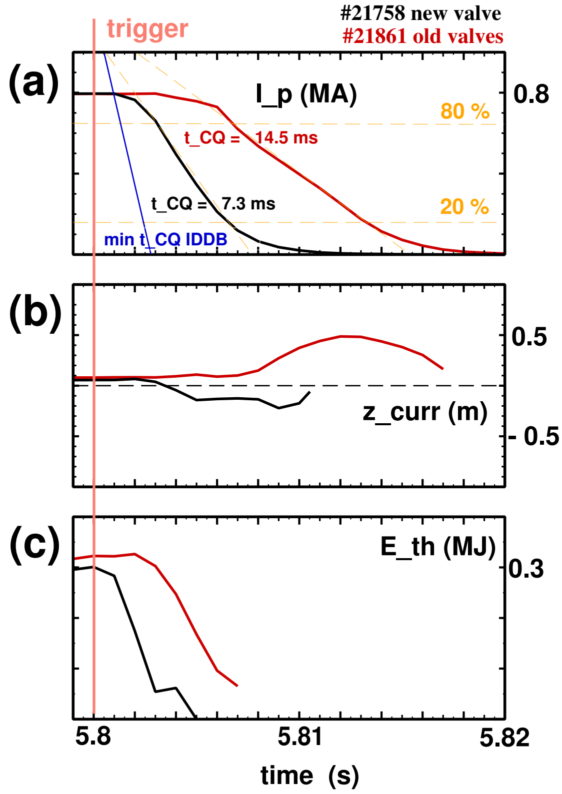

Fig. 2. Time traces of (a) the plasma current, (b) the plasma vertical position and (c) the thermal energy during the current quench caused by the new in-vessel valve (black) and by the older valve located outside of the vessel (red).

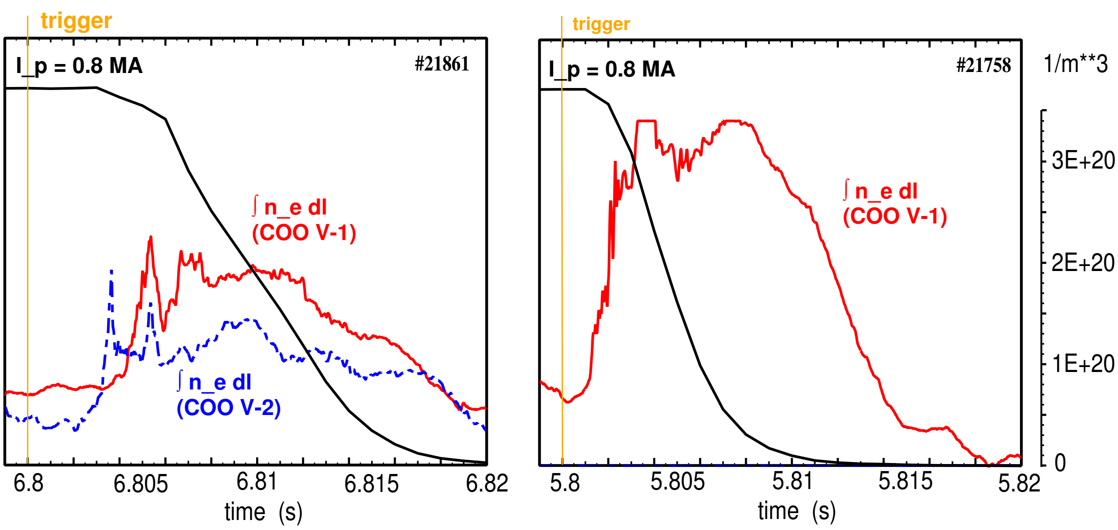

Fig. 3 Line integrated electron density measured by vertical cords of the CO_2 interferometer, viewing the plasma close to the core (V_1) and towards the edge (V_2) after massive gas injection with the older (left) and new (right) valves.