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L.E. Zakharov, S. Putvinski, A.S. Kukushkin, R.A. Pitts,
M. Sugihara, S. Maruyama, S.V.Konovalov, and V.Lukash

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L.E.Zakharov
Princeton University, PPPL
Princeton NJ, USA
zakharov@pppl.gov

S.Putvinski, A.S.Kukushkin, R.A.Pitts, M.Sugihara, S.Maruyama
ITER Organization, St Paul Lez Durance, France
Sergei.Putvinski@iter.org
S.V.Konovalov, V.Lukash
RRC Kurchatov Institute, Moscow, RF

Abstract—**A new scheme for suppression of runaway electrons in ITER disruptions is proposed. It is based on maintaining the magnetic perturbations during the entire current quench phase by exciting kink modes using repetitive high pressure gas injection to the plasma edge. The total amount of gas injected is expected to be compatible with the ITER pumping system .**

Keywords: tokamak; disruption; runaway electrons; mitigation; gas injection

I. Introduction

Success of the ITER program depends critically on the development of robust and reliable techniques for disruption mitigation. The severity of disruption loads grows rapidly with machine size because of the increase of plasma temperature and volume to surface ratio. At the thermal quench (TQ), unmitigated disruptions in ITER will produce very large heat loads on plasma-facing components (PFC) and large electromagnetic forces on vacuum vessel (VV) and other in-vessel conducting structures such as blanket modules (BM), first wall (FW) panels and in-vessel coils. Runaway electrons (RE), if generated during the current quench (CQ) phase of disruptions, could be particularly damaging for the FW, resulting in a bulk melting of panels intercepting the RE beam. Lifetimes of certain PFCs are likely to be unacceptably short if the majority of ITER disruptions are not adequately mitigated, even in the case when a high level of disruption avoidance has been achieved. This mitigation must therefore be ensured by a carefully designed and tuned Disruption Mitigation System (DMS) with high reliability.

In common with the systems installed on several operating devices, the ITER DMS concept is based on injection of massive amounts of high Z noble gases such as Ne or Ar for re-radiation over the large FW surface of the otherwise highly peaked TQ energy loads. Projection of experimental results from today's tokamaks indicated that this challenging task is feasible. The estimated gas quantity required for suppression of energy loads in ITER is 0.5-2 kPa*m^3 for Ne and about half this amount for Ar. Such quantities are within the capability of ITER pumping system and will result in CQs with duration of 50-100 ms acceptable for the mechanical design of the VV and in-vessel components. To avoid local peaking of radiative power on the FW, the injection of high Z impurity should be distributed toroidally. First estimates indicate that at least 4 discrete toroidal locations will be required.

Experiments on ASDEX- Upgrade show that assimilation factor for the gas injector increases from typical 5-15% for standard DMS valves to about 50% for high pressure gas jets produced by in-vessel gas valve with high plenum pressure. The reduction of the gross amount of gas is very important for ITER which has a limited capability for pumping and tritium gas processing system. The maximum amounts of gases that can be injected by DMS without interruption in ITER operation are listed in table 1.

Gas for mitigation system	Required amount kPa*m^3	Pumping system limit kPa*m^3
D_2	500	100
He	500	40-50
Ne	100-200	200
Ar	100	100

Table 1. Maximum quantity of gas allowed in the VV during a disruption mitigation event.

The high density gases injected in the plasma during CQ might be used for de-confinement of the RE electrons as has been proposed in [1]. Indeed, collisional suppression of RE in ITER to the required maximum tolerable level of less than 2 MA would require massive gas injection which would not only result in operational interruptions due to the long down times required to evacuate the injected gas, but could also shorten CQ time below acceptable limit for forces on the VV and in-vessel components. A new RE suppression scheme which has been proposed based on RE de-confinement by means of sharp and dense repetitive gas jets promises significant (10 times) reduction of the required amount of gas and thus could be compatible with the ITER constraints. Experimental tests of this scheme are in progress on the Tore Supra, T-10, and ASDEX-Upgrade tokamaks.

Therefore, transition from standard DMS valves to the gas injection systems can improve overall performance of DMS. The present paper discusses possible applications of the high pressure gas jets for suppression of runaway electrons in ITER.

II. Characterization of RE in ITER

Runaway electrons can be produced during CQ phase of plasma disruption in tokamaks due to the high loop voltage usually generated during this phase. They are often observed in present experiments during the CQ, especially on devices with high current and short τ_{CQ} with high loop voltage (see for example [2]). ITER will be the first tokamak where RE avalanche [3] will truly dominate RE generation. The large number of e-folds in ITER will mean that the process will be insensitive to the initial seed source of RE and it should thus be expected that every unmitigated plasma disruption in ITER at a significant plasma current ~15 MA will be accompanied by generation of 10-12 MA of RE current. The RE generation in ITER has been studied in detail theoretically and simulated numerically by a number of authors [4-7], confirming that ITER disruptions can readily produce RE currents of 10 MA or more.

The present range of the RE kinetic energy in ITER is bounded by kinetic energy of RE at the low end (10-20 MJ) and magnetic energy of RE current at the high end (~200 MJ) at I_{RE} = 10 MA if fraction of magnetic energy is transferred to their kinetic energy during their loss. In the worst case scenario when a large fraction of magnetic energy is transferred to the kinetic energy of RE the RE can cause deep melting of the FW panels. It has been shown recently that the transformation of up to 40% of magnetic energy during CQ has been observed in JET [8]. A transfer of up to 40% of magnetic energy to RE kinetic energy is presently assumed, restricting allowable REcurrents to ≤ 2 MA. The generation of RE during plasma disruptions must be suppressed in ITER.

III. High pressure gas jets for suppression of RE

It has been observed in experiments that RE are abruptly lost to the wall when safety factor at the plasma edge is reduced to less than 2 during plasma VDE and corresponding contraction of the plasma cross section and the current channel. Earlier [9], it was determined that the kink modes play a significant role in plasma disruptions. They can destroy the internal magnetic structure and confinement of energetic particles. It has been suggested to use high pressure gas jets to contract the current channel and cause secondary plasma disruptions during CQ. In order to determine how much jet has to shrink the current channel to make ideal MHD modes unstable we have carried out a simple stability analysis using cylindrical approximation. It has been assumed that jet creates very large resistivity at the plasma edge on its depth of penetration, r_{jet}. Current density at $r>r_{jet}$ is zero as well as plasma electrical conductivity and a skin current is generated at $r=r_{jet}$ to keep ψ = const at $r = r_{jet}$. Ideal wall is located at radius b = 1.3a and is included in stability analysis. Figure 1 shows evolution of current density and q-profile during propagation of the jet. Figure 2 shows growth rate of ideal modes, m=1, 2, and 3 as function of jet penetration radius. There is a stability window r/a = 0.7 – 0.82 where all three modes are stable. There is no stability window between m=1 and m=2 overlap. When jet will penetrate up to r = 0.7 a m=1 and m=2 become both unstable and shall likely result in major MHD event, destruction of magnetic surfaces, and rapid loss of seed runaway electrons.

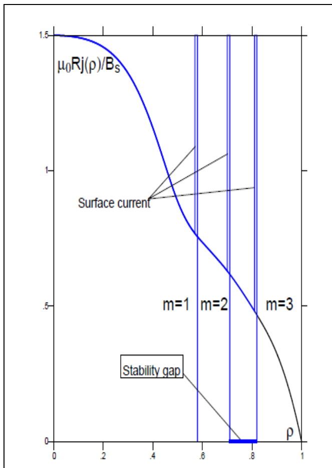


Figure 1. Normalized current density profile during propagation of the jet. ρ=r/a is normalized minor radius. Unstable modes are indicated by mode number.

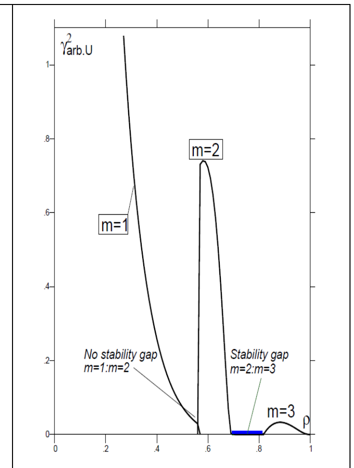


Figure 2. Growth rate of first three ideal MHD modes as function of jet penetration.

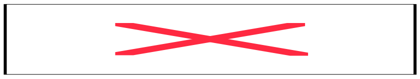
In conclusion, jet penetration length has to be large to reach up to q = 2 surface to trigger major MHD event due to shrinking of the current channel. In the above example the jet length has to be about 0.6 m. It will be shown below that the gas pressure must be sufficiently high to propagate across the CQ plasmas.

IV. Requirements for electrical resistivity of the gas jet

Electrical resistivity of the gas in the jet has to be very low to provide a fast contraction of the current channel. To estimate the required resistivity of the gas jet we shall use approximation of a straight cylinder. In the low pressure CQ plasmas the current density parallel to the magnetic field $\vec{j} = \vec{b}\, j_s(\vartheta, \varphi)$, where θ and φ are poloidal and toroidal angles. From div(j) = 0 one can get that on a magnetic surface

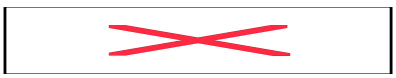
. (1)

At the same time j_s is a periodic function of θ and φ and can therefore be presented as



(2)

Comparing the last two equation one can conclude that only j_{00} and resonance harmonics with $m = nq$ shall remain in the Furrier expansion. On irrational magnetic surfaces there are no resonance harmonics and, hence, current density is constant, $j_s = j_{00} = Const$ and magnetic field is not perturbed in spite of the local perturbations of the plasma resistivity. Instead the jet results in perturbation in electrical potential as described by Ohms law:

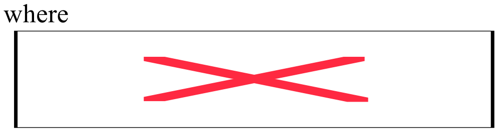


(3)

Here $E = Const$ is the inductive component of the electric field in the toroidal direction, Φ is the electric potential, and η is the plasma resistivity. It follows from the above equation by averaging it by q and j that

$$Eb_{*} = \eta_{00} j_{00} \quad (4)$$

where



(5)

Where D is jet diameter and Sside is area of the magnetic surface. To create a large change in electrical resistivity in the shadow of the jet the gas resistivity must be very high:

$$\eta_{jet} >> \eta_{pl} S_{side}/D^2 \quad (6)$$

In addition to the large perturbations of electrical potential the jet will also create magnetic perturbations and islands on rational magnetic surfaces. It can be shown that the size of the magnetic islands is comparable with the jet diameter. Therefore, a dense and not conductive gas jet in addition to the contraction of the current channel will result in large magnetic and electrical perturbations in the shadow of the jet.

Finally, we shall estimate what would be electrical conductivity of the jet generated by gas ionization by RE's. According to Eq. 3 the average plasma resistivity at the magnetic surface where jet is present is

$$<\eta> = \eta_p + \eta_{jet}(D^2/S_{side})) = \eta_p (1 + (n_e\tau_e/n_{e0}\tau_{e0})(D^2/S_{side})) \sim$$

$$\sim \eta_p (1 + 0.002 T_e^{3/2}(n_0/n_{e0})D^2/S_{side})) \quad (7)$$

where η_p is plasma resistivity, $\eta_{jet} = m_e/e^2 n_e \tau_{e0}$ is jet resistivity. I have assumed that $<v_e\sigma_{e0}> = 10^{-13}$ m^3/s (polarization scattering), $\ln(\Lambda) = 15$. To increase average resistivity where jet is present specific resistance of the gas in the jet has to be high

$$\eta_{jet} >> \eta_p S_{side}/D^2 \sim 1.5\ 10^4\ \eta_p \quad (8)$$

or degree ionization in the jet has to be small. At T = 10 eV

$$n_{e0}/n_0 < 4\ 10^{-6} \quad (9)$$

It has been shown in [10] that degree of ionization generated by RE in the gas is about 10^{-7} at current density of RE equal to the full current density 50 A/cm^2. At lower current density expected during repetitive puffs it is sufficiently lower which allows to neglect effect of RE on gas ionization. Other effects can also increase degree of ionization and electrical conductance. For example photo-ionization might contribute to the plasma density in the gas and has to be properly estimated.

The growth rate of avalanche is a fraction of the CQ time [3]. Therefore, several gas jets has to be injected to keep RE current below acceptable level of 2 MA. Numerical simulation with the DINA code shows that 5 or 6 injections are needed during CQ.

V. Propagation of the Dense Gas Jets

Plasma during CQ in ITER will be contaminated by high Z impurities injected pre-emptively for mitigation of the thermal energy loads on the plasma facing components. Plasma temperature and electron density shall be determined by energy balance between radiation of the impurities and Ohmic heating. At the required ~1 kPa*m3 of Ne the expected plasma parameters are: $T_e = 4$ eV, $n_e = 5\ 10^{20}$ m^{-3}, plasma pressure, p ~ 600 Pa, and loop voltage V = 1800 V. CQ time (linear) is about 70 ms. It should be noted that electron mean free path is less than 1 cm and electron heat conduction along the field lines is very slow.

For the sake of simplicity we shall consider 2D jet propagating across magnetic field as shown in Figure 3. We shall define jet boundary where degree of ionization is very small and, hence, electrical resistance of the gas is very large and gas can move freely across the magnetic field.

Figure 3. Red line represent boundary of the jet (ionization front). Details of the jet flow pattern in coordinate system moving with the front is shown in the left.

We shall consider propagation of a jet with gas pressure, p_0, higher then plasma pressure and lower then pressure of magnetic field.

$$p_{pl} << p_0 << B^2/2\mu_0 \qquad (10)$$

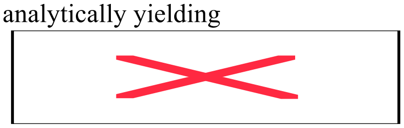
Therefore, we can assume that plasma can move only along the field lines. Obviously if

$$p_0\cos(\alpha) > p_{pl} \qquad (11)$$

then gas velocity at the edge of the jet will be close to gas sound velocity as in free expansion. For $p_0 >> p_{pl}$ as in the case of gas injection in CQ plasma the above equation is valid almost everywhere except very end of the jet nose. This area marked in figure 3 by dashed circle defines propagation velocity of the gas into the plasma. Here the front moves by cooling down and extinguishing plasma by recombination as would be when a solid object is moved into the plasma. One can use coordinate system moving with the front and assume that the front is flat ($\alpha<<1$). In this coordinate system plasma is moving towards the front with velocity u and gas with velocity V_0-u. The gas and plasma flow turns 90 degrees near the ionization front and continue to flow along the magnetic field. Because plasma flow rate, $n_{pl}u$, is much smaller then gas flow rate, n_0V_0, one can neglect its contribution to the flow pattern and assume that normal component of gas flow velocity is zero at the front. Heat exchange between plasma and gas occurs by heat conduction across the flow near y=0 similar to one that occurs in a boundary layer. To estimate heat exchange between gas and plasma one has to find solution for the gas flow. We assume that density in upcoming gas profile is uniform, n=const, and, hence, flow with div(V) = 0 will preserve n = const everywhere. Hence, an acceptable analytical solution of momentum balance equation for velocity field near x = y = 0 shall be $V_x = V'x$, $V_y = -V'y$, where V' is constant which is defined by total flow pattern $V' \sim (V_0\text{-u})/d$. With this flow pattern and constant gas density power balance equation can be written as follows:

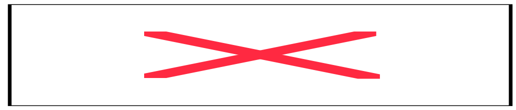
$$x\frac{\partial T}{\partial x} - y\frac{\partial T}{\partial y} = \frac{\chi}{V'}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \qquad (12)$$

The boundary conditions for temperature shall be dT/dx = 0 at y=0 and $dT/dy = q/n_0\chi$ at y=0, where q is heat flux from the plasma, $q = n_{pl}u(E_{iz}+ 3T)$. The above equation can be solved analytically yielding



(13)

Where Tiz ~1 eV is gas temperature at which the degree of ionization is significant (local thermal equilibrium is assumed). One should note that the cooling rate does not depend on coordinate ϕ or y along the front which means that the front shape remains flat. Now power balance on the front yields equation for the front velocity, u:



(14)

To estimate front velocity one has to define heat conductivity, c. As it has been mentioned earlier Re number in the high density jet is very high and jet is turbulent. We shall define heat conduction coefficient as follows:

$$\chi = \Delta V_0 \qquad (15)$$

where D is typical scale for turbulent pulsations. It can be estimated assuming that Re number on this scale is about critical one, $Re_{cr} \sim 1000$. Therefore,

$$\Delta/d \sim Re_{cr}/Re \qquad (16)$$

and $V_0 d/\chi \sim Re/Re_{cr}$.

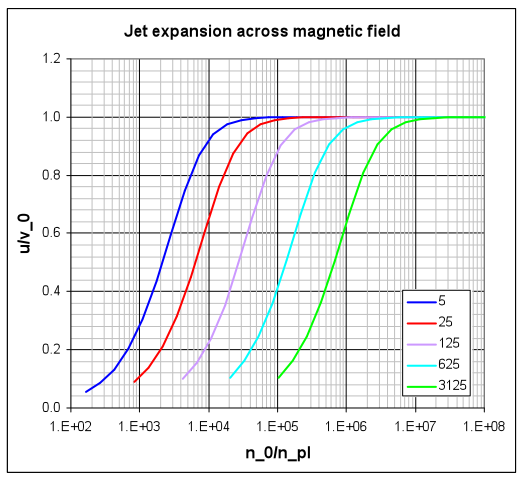


Figure 4. Normalized front velocity as function of normalized gas density. Other parameters are E_{iz} = 15 eV, T_{iz} = 1500 K, n_{pl}=1E20 m^{-3}.

Normalized velocity u/V_0 is shown in figure 4 as a function of normalized gas density n_0/n_{pl}. Different curves correspond to different plasma temperatures. As in figure 4 minimum density for each curve correspond $p_0 = p_{pl}$. One can see that ballistic regime $u \sim V_0$ can be achieved only at high gas density.

In conclusion high density neutral gas can propagate across magnetic field in the cold plasmas. To ensure ballistic regime $u \sim V_0$ in CQ plasmas with temperatures < 100 eV gas density has to be five orders of magnitude higher than the plasma density. In this case jet will propagate almost freely along as well as across the high magnetic field.

VI. GAS DELIVERY CONCEPTS FOR DMS

High pressure gas jet with a sharp front which is required for RE suppression can be produced by a fast valve located close to the plasma edge. It must be able to reliably operate at high magnetic field, neutron and gamma fluxes, and high power loads as expected in ITER. The materials of the valve must be able to withstand Tritium environment. Such a valve does not exist and must be developed.

Figure 5. Cartridge for DMS
1 – gas canister
2 – electrode
3 – exploding wire
4 – rupture disk

Two concepts have been proposed for ITER [63-64]. The report of ref. [63] describes a gas delivery system based on small cartridges equipped with rupture disks on the plasma side of the canister. Figure 5.1 illustrates the conceptual design of the gas cylinder, in which the rupture disk is opened by an exploding wire (3) detonated by running a current through the wire powered by a capacitor bank. Gas pressure in the plenum is about 100 bars and each cartridge contains between 1 and 10 kPa-m^3 depending on the application. The nozzle diameter is about 25 mm. A prototype of the gas cartridge with rupture disk has been tested in the laboratory at CEA/IRFM Cadarache. Once the DMS cartridges have been discharged, in a system for ITER, they would have to be reloaded and replaced. The expected frequency of plasma disruptions in ITER is one event every 10 pulses, implying that reloading would be required once or twice per operational day. A conceptual design for a reloading system based on pneumatic loading of cartridges has been proposed in [63]. A loading section of about 1 m length and a driving pressure of ~1 bar are sufficient to accelerate cartridges along a guide tube up to the standby position. Only small amounts of gas are required for the acceleration. The cartridge is returned back to the loading dock by the rocket force produced by the gas discharge during DMS action. Estimates and supporting calculations show that such a pneumatic loading system is feasible in ITER. One should note that if it were installed, it would not be the only pneumatically driven system on ITER. The neutron activation sample diagnostic is designed for pneumatic sample loading.

The advantages of this scheme are the absence of moving parts that must be energized during triggering of the gas discharge and reliable UHV sealing of the gas. The main issues for this system are relative complexity of the loading system and the need for a large number of gas cylinders which will be activated during day-long neutron irradiation exposures. Neutron activation estimates show that the cylinder will "cool down" to hands-on levels about 1 month after removal, allowing refurbishment. Bearing in mind that a single DMS shot will use up to 10 gas cartridges (4 for TQ mitigation and 5-6 for RE suppression), about 10 cartridges will need to be refurbished per day and 300 used cartridges will require storage for activation levels to fall. If the same quantity of charged cartridges will be stored in the magazine of the loading system, around 600 cartridges must be in circulation. In addition, the delivery system will likely need remote handling servicing capability in the port cell.

Gas plenum

Figure 6. Conceptual design of the flush valve.

A second possibility for rapid gas delivery is based on a fast valve located in close proximity to the plasma surface (behind the water cooled FW of the port plug). One of the principle difficulties faced in the development of such hardware is the large force acting on the valve flap at high pressure in the plenum (100 at) and the relatively large nozzle diameter required to create the high pressure gas jet.

The gross pressure force compressing the flap is ~3000 N at the gas pressure of 100 bar, making it difficult to design the actuator. In the concept shown in Fig. 6, this problem is solved by implementing a bellow at lower pressure, allowing the surface area of the flap where the high pressure is applied to be reduced and thus to reduce the force needed to open the valve. The diameter of the bellow relative to the nozzle diameter must be chosen to ensure that the net pressure force on the flap changes sign when the flap is only slightly open and gas streams through the gap. Under these conditions, the actuator only needs to open the gap slightly, at which point pressure in the nozzle will force the flap fully open. This force reduction technique allows the mass of the moving components, and thus the valve opening time, to be reduced.

The valve can be closed by pumping gas inside the bellow, expanding the latter and forcing the valve shut. Once the plenum has been filled with the mitigation gas, the bellow is evacuated to reduce the pressure used to drive its expansion. Similar concept of DMS valve has been used on TEXTOR and JET [13,14]. The typical dimensions of such a valve can be roughly estimated from Fig. 6, noting that the suggested nozzle ID = 25 mm.

On ITER, a valve of the design proposed in Fig. 6 needs an actuator capable of functioning in magnetic fields of up to 4 T.

A suitable actuator concept, dr iven by eddy currents has been suggested and successfully applied on both TEXTOR and ASDEX -Upgrade [13,14]. On ITER, if neutron fluxes would be problematic, the actuator could be removed behind the blanket shield modules in the port plugs and connected to the flap by a strong rod or cable. Estimates show that a rod of 1 m in length could be used without slowing the valve opening time due to inertial forces acting on the rod. Opening times of ~1 ms should be possible.

A potential issue for any valve concept is the provision of reliable sealing consistent with the UHV environment of the VV and able to withstand 10^3 opening and closing cycles. Additional R&D and tests are obviously required to evaluate the feasibility of a flush valve for ITER. Without the benefit of a full design, both the cartridge system and the flush valve appear to be compact enough to be installed in the port plugs and can share space with diagnostics or other systems.

VII. SUMMARY AND CONCLUSIONS

High pressure gas jets can have several advantages in comparison with traditional low pressure Massive Gas Injection (MGI) schemes. As shown in experiments they can significantly increase assimilation factor for the injected gas which is very important for ITER DMS. They can significantly reduce DMS reaction time and thus can exploit different scenarios for MGI. With fast gas jets with propagation time of several milliseconds DMS will have flexibilities for tailoring time dependent gas injection including consequitive injection of different gases as well as injection of gas in CQ. An example is repetitive gas injection for suppression of RE during CQ of disruption described in the previous sections.

It has been shown by the above estimates that physics of propagation of high pressure gas jet is very complex and the accurate estimates require much more sophisticated tools which yet to be developed. Processes in the cold CQ plasmas could be very different and standard tokamak approximations such as constant plasma parameters on the magnetic surfaces might not be applicable to those plasmas.

More experimental and theoretical work is needed for better characterization of CQ plasma as well as propagation of the high density gas jets.

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Information Services
Princeton Plasma Physics Laboratory
P.O. Box 451
Princeton, NJ 08543

Phone: 609-243-2245
Fax: 609-243-2751
e-mail: pppl_info@pppl.gov
Internet Address: http://www.pppl.gov