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# Disruption and Runaway Electron Mitigation on ITER

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## I. Introduction

Disruptions represent one of the greatest potential limitations to establishing routine operation of ITER. The heat and electromagnetic (EM) loads during disruptions and vertical displacement events (VDEs), together with the runaway electrons (REs) appearing during the current quench phase, need to be reliably mitigated by significant factors. This paper presents our recent conclusions on the target values which an ITER disruption mitigation system must ensure and examines the physics basis of each of the currently proposed candidate methods.

## II. Assessment of impacts of disruptions and VDEs and mitigation target values

Energy load: the loads on the divertor targets during disruptions of typical ELMy H-modes are evaluated for the most severe expected condition [1] : stored energy at thermal quench (TQ) = 175 MJ, in-out divertor target loading asymmetry of 2:1, factor 5 expansion of pre-disruptive wetted area (≈3m$^2$), energy deposition rise time = 1.5 ms. Under these conditions, the wall loading measure ε becomes ≈388 MJ/m$^2$/s$^{0.5}$. Assuming a triangular time envelope for the transient loading, the critical value of ε for melting of tungsten is $\varepsilon_{melt}$ ≈48 MJ/m$^2$/s$^{0.5}$ so that for W divertor plates the disruption energy flux must be mitigated by a factor $\varepsilon/\varepsilon_{melt}$ ≈8. Energy loads at the TQ on the upper beryllium wall during VDEs (Fig. 1 a) are also evaluated for the expected most severe conditions [1], i.e., stored energy at TQ is ≈270 MJ, factor 3 expansion of the wetted area and energy deposition rise time = 1.5 ms. Since the first wall is shaped as shown in Fig. 1 b (to avoid large heat load on the leading edge

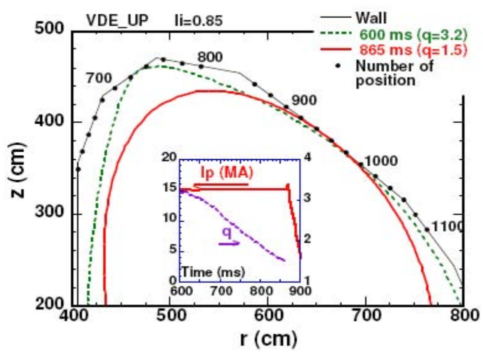


Fig. 1 a Equilibrium during VDE [2]

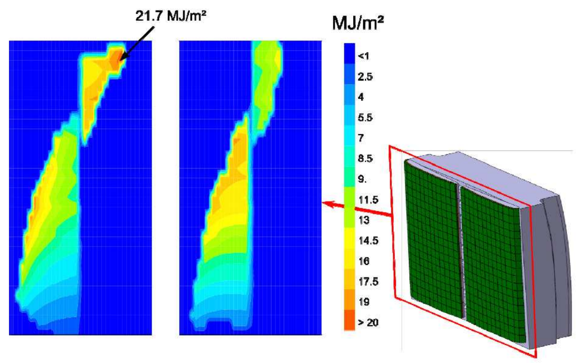


Fig. 1 b First wall shape and power load [3]

during ELMs due to alignment limitation), the energy load is localized on the wall and its peak value can reach ≈ 22 MJ/m$^2$ as shown in Fig. 1 b, which was calculated by following the

3D magnetic field line at the TQ [3]. This in turn gives $\varepsilon \approx 570$ MJ/m$^2$/s$^{0.5}$ and, given $\varepsilon_{melt} \approx 25$ MJ/m$^2$/s$^{0.5}$ for Be, the energy flux due to VDEs needs to be reduced by a factor $\varepsilon / \varepsilon_{melt} \approx 23$.

EM load due to halo current: the most critical EM load is the vertical force acting on the vacuum vessel (VV) due to halo current during downward VDEs, since the VV is a primary boundary of tritium confinement. The severity of the vertical force can be represented by $f \equiv TPF \times I_{halo}/I_P$, where TPF and $I_{halo}/I_P$ are the toroidal peaking factor and the total halo current fraction, respectively. The current design is based on the specification f=0.42 together with assumption that number of VDE events exceeding this value, N(0.42), is very rare (1-2 during the device lifetime). This latter assumption is imposed by the required time-consuming inspection, which degrades the operational efficiency significantly if the inspection is frequent. According to the present database for TPF and $I_{halo}/I_P$, N(0.42)≥20 is anticipated. To meet the requirement of a “rare event”, the design value of f must be increased to ≈0.64, which is very demanding for the design. It can be shown, however, that if mitigation system can reduce the halo current by a factor of 2 with mitigation success rate of ≈90%, N(0.42) can be below 2.

Runaway electrons: simple extrapolation of rather scarce data from JET [4] implies that the wetted area can be estimated as ≈0.3 m$^2$. Assuming a linear size scaling from JET to ITER, but also (as a worst case) that the expected deposition area in ITER could be similar to that observed in JET, the wetted area in ITER could be in the range 0.3-0.6 m$^2$. The beam energy of REs in ITER is estimated as ≈20 MJ, implying an expected energy density of ≈(35-70) MJ/m$^2$. For the upper beryllium wall, the penetration depth for REs with energy of 12.5 MeV and incident angle of (1-3)° is estimated at ≈(2.5-7.5) mm. The critical energy density for melting under this condition is expected to be ≈(6-14) MJ/m$^2$. From these simple arguments, more than a factor of 10 mitigation of the RE beam energy or current would be needed to avoid localized melting of the beryllium wall.

The impacts and target values of mitigation are summarized in the table below.

| | Energy load on divertor target | Energy load on first wall | EM load due to halo currents | Runaway electrons |
|---|---|---|---|---|
| Target value of mitigation | 1/(5-10) | <1/10 (VDEs) | 1/(2-3) | < 1/10 |
| Impact when mitigation system is not installed | Life time: 20 disruptions | Life time: < 10 VDEs | Design must be done for criterion: $TPF^*I_{halo}/I_p \approx 0.64$ | Life time: < 4 REs |

**III. Assessment of physics basis of potential mitigation schemes**

Among the three major impacts of disruptions/VDEs, the physics mechanisms and effectiveness of mitigation of the energy load and the halo current via impurity injection are relatively well understood and demonstrated experimentally. Thus, impurity injection is likely to be a basic mitigation scheme. The most difficult aspect of mitigation is to avoid or suppress REs. A number of candidate techniques are being tested, or have been suggested, to achieve the required RE mitigation factors. The following methods are currently being examined as potentially feasible for application on ITER: (a) massive gas injection, (b) massive pellet injection, (c) massive beryllium injection, (d) moderate gas injection with pre-emptive application of resonant magnetic perturbations (RMP), (e) moderate gas injection in association with a second scheme to provide a gradual deposition of the RE energy. This last method requires control of the RE beam position (by external and internal coils). Potential schemes for gradual deposition of the REs are: moderate injection of high Z gas, the application of RMP fields leading to enhanced RE losses or reversed one-turn loop voltage. In the following, our assessment of the present physics basis for each scheme is summarized.

<u>(a), (b), (c) Massive material (gas or pellet) injection (MMI)</u>

• Many machines confirm that the target value of mitigation for EM loads due to halo current can be satisfied. However, mitigation for the energy loads is not yet sufficient, e.g., radiative energy loss at TQ reaches only up to 60 % of the pre-disruptive thermal energy in JET.

• In present experiments, the primary RE generation mechanism seems suppressed. This can be achieved with density, $n_e \approx 10^{21}\ m^{-3}$. If, in ITER, other generation mechanisms for seed RE, i.e., Compton scattering and tritium decay, are dominant, the avalanche mechanism will have to be suppressed by increasing the density up to the critical value $n_C$ ($\approx 5\times10^{22}\ m^{-3}$).

• Many machines observe light gas is better for RE suppression and higher assimilation.

• Possibly higher assimilation for the case of large pellet injection should be confirmed.

• Careful examination of current quench time needs to be undertaken when the electron density is increased up to the level of $n_C$ to suppress the avalanche process.

• Poloidal and toroidal asymmetry of radiation energy load due to MMI seems large especially during the initial phase (ASDEX-U, C-MOD). Further data are needed to identify the required number of injection ports to avoid localized melting of the first wall near by.

• The time period (between the start of edge cooling and the current quench), over which the necessary gas amount ($\approx 10^{26}$) is injected, must be longer than at least 5-10 ms in ITER ($\approx$5 ms for $\approx 10^{23}$ injection in present JET). Proper machine size dependence must be identified.

• A large number of particles cannot be injected in the core without causing MHD collapse by Be pellet (same for other MMI schemes), which will produce a large quantity of Be dust [5].

(d), (e) Moderate gas injection + RMP (pre-emptive), moderate gas injection + V & R position control + reversed one-turn loop voltage and/or heavy gas injection and/or RMP

- Reduction of the RE current and the RE plateau duration by application of RMP in a pre-emptive way has been demonstrated in TEXTOR, confirming previous JT-60U results. The required perturbed magnetic field is estimated as $b_r/B_T \approx 0.1\%$, but the scatter is still large.
- Suppression of already existing REs by applying RMP needs to be demonstrated. If it works well, this way of using RMP is more useful in ITER than using the pre-emptive approach.
- Soft termination of REs by reversed loop voltage and heavy gas injection has been demonstrated in Tore Supra, confirming previous JT-60U experiments. When combined with the position control this scheme could terminate REs without strong wall interaction.
- Recent experiments in Tore Supra and TEXTOR show that the radial position control of RE beams is feasible. Initial calculations for a simplified RE beam model in ITER (in which the plasma current is decreased to 10 MA from 15 MA and internal inductance increases from 0.5 to 3.0 within 20 ms) show that the vertical position control is possible with the present design limit for the voltage of the in-vessel VS coil power supply (1.7 kV) [6].

**IV. Assessment of candidate system and concluding remarks**

Based on these assessments, the following candidate schemes and their tentative specifications for disruption mitigation are currently being examined. At present, most

| Candidate | Tentative specification |
|---|---|
| (a) MGI | $D_2$ or He (500 kPa·m$^3$) or Ne (100 kPa·m$^3$) ; assimilation ≈0.2 |
| (b) MPI | $D_2$ (200 kPa·m$^3$) or Ne (40 kPa·m$^3$) ; assimilation ≈0.5 |
| (c) Be | Be (≈ 400 g ) ; assimilation ≈0.5 |
| (d) RMP pre-emptive | Ne (20 kPa·m$^3$) + $b_r/B_T \approx 10^{-3}$ |
| (e) Position control | Ne (20 kPa·m$^3$) + Kr, Xe ($2\times10^2$ Pa·m$^3$) and/or $b_r/B_T \approx 10^{-3}$ |

promising mitigation scheme seems to be MGI or MPI. The selection of gas species and its mass needs further physics input together with an engineering assessment of their impact on injection, pumping and gas processing systems, which is underway.

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**References;**

[1] A. Loarte et al., 20th FEC 2004.
[2] M. Sugihara et al., NF **47** (2007) 337.
[3] R. Mitteau, ITER_D_2MWRL2.
[4] M. Lehnen et al., JNM **390-391** (2009) 740.
[5] S. Putvinski, ITER_D_ 2MJPGH.
[6] A. Kavin, ITER_D_2NGJH5 .