# <u>Disruptions – Research Needs</u>

*R J Buttery, Feb 2009.*

EURATOM/UKAEA Fusion, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK.

The issue of tokamak disruptions is a crucial one for ITER and DEMO, and a subject that is not being sufficiently addressed in current research programmes. ITER must operate with low levels of disruptivity, and any disruptions that do occur should be mitigated with respect to heat loads, vessel forces and runaway beams, in order to avoid excessive device wear. For DEMO, however, the issue is much more challenging – disruptions in DEMO must be virtually eliminated, and any events that do occur must be strongly mitigated and/or recovered. This required level of operating efficiency is almost the opposite of most tokamaks' present operating approach, where disruptions are often tolerated or even routine.

There is a crucial opportunity using the <u>present generation</u> of devices to get at disruption physics and develop management strategies at a scale where they can be studied effectively, benefiting from the excellent configuration and diagnosis capabilities available, while accessing events that are relatively modest in size with low risk of device damage (which in any case is easier to recover from). The issues cut across all paths for magnetic fusion power, because plasma terminations can occur for a wide range of causes – both technical and physics, and so disruption management, mitigation and recovery schemes will always be required.

*Progress needs to be made on four main fronts:*

- Safe terminations systems such as Massive Gas Injection (MGI) – excellent pioneering work by the US here needs to be reinforced to extend and test capabilities with MGI, and consider other novel techniques or combined mitigation approaches (jets, pellets, RMPs, influence of impurities) – this requires experiment time and staff resources.

- Machine developments are important to get at the underlying physics and understand extrapolability (eg diagnostics), develop better control and response strategies, include new tools (eg RMPs), and further develop safe termination systems. On the first issue, key diagnostics are needed to interpret the process – for example to measure runaway spectra and localised losses, or to understand the role of impurities in disruptions

- Code work – promising codes need to be further supported: modelling the various aspects of disruption physics in realistic geometry, for example realistic vessel models which account for halo currents and forces in 3d MHD processes; integrating codes for example to combine prediction of MGI effects with prediction of runaway onset.

- Development of routine disruption avoidance and mitigation using techniques, ranging from simple lock mode detectors to sophisticated prediction tools based on real time modelling or active sensing, and with actions such as 'soft landing' ramp-downs (sequence of gas, power, Ip, error field, etc.), rotation or peaking control using additional heating. This may require modest machine development (eg control systems), but more importantly, a direct operational focus to understand how to develop routinely safe operation, together with staff resources and some dedicated machine time. The goal here is to avoid most events or land the plasma safely in off-normal conditions, so that the tasks for the more challenging mitigation systems is greatly reduced.

*There are several underlying physics aspects to the disruption process which need to be addressed somewhat separately. Here we can consider the particular research priorities and resource needs:*

<u>Vertical Displacement Event (VDE), halo currents, and vessel forces.</u>
Work needed here combines a pragmatic measurement and empirical extrapolation, with modelling to understand trends and make hard predictions. Thus databases need to be developed and populated, particularly bolstering efforts of the ITPA. In some cases, relevant sensors (force, halo) need to be installed, with experiments run; halo current widths and sideways forces are key issues to address. Code work needs to be well supported to: allow plasma shape reconstruction in the presence of halo currents, benchmark 2d VDE and halo models, develop 3d plasma distortion models (eg kinks), predict halo current flows, and include/interface to codes with self consistent 3d vessel responses in order to calculate forces.

<u>Runaway Electrons</u>
Turning first to threshold issues, work needs to focus on primary and secondary runaway generation mechanisms, with realistic geometry codes, extending these to also analyse the action of potential mitigators (gas, RMP, etc.). Experiments are important to test threshold levels and scalings, with some novel regime development to foster the right conditions for runaway onset. A key aspect is understanding the MGI role, where folding the profile evolution under MGI (see below) into runaway generation codes is important, as well experimentally resolving how MGI impacts runaway generation and current quench. Measuring the runaway energy spectrum is an important test of the models.

The work also needs to study the non-linear regime, exploring how the runaway beam evolves, how much heat will be deposited, prospects for mitigation once formed (eg RMPs, more MGI, pellets, etc.), and how the beam is affected by plasma motions, including VDEs and other MHD (eg kinks, tearing). This requires more measurements of runaway behaviour and so a focus on generating runaway regimes (possibly more tools to be installed to facilitate right conditions) and getting the right diagnostics to observe behaviour (eg IR, energy spectrum, and diagnosing the beam trajectory). This might be extended to attempts to control a runaway beam (some hardware and control development implied). On the code side the work will be extensive, to model a runaway beam in 2d and 3d, and understand its dynamics – eg based on interfaces of 2d runaway codes to 3d gas jet dynamics codes. Runaway beam stability is also an issue.

<u>Action of MGI and other safe termination systems; interaction with wall</u>
MGI appears to represent a potentially highly effective tool for disruption force mitigation, and possibly the thermal quench. It may also be an important tool for runaways, but MGI levels may need to be substantially higher to prevent secondary runaway generation. However data remains sparse on these issues, and in any case much further experimental work is needed to extend MGI tests and systems (eg more gas, role of different gas and injection locations, etc.), extend the range of regimes in which it is tested, and understand the effects on other aspects of the disruption – especially the current quench, which may further influence runaway thresholds. It

seems likely that consideration may also need to be given to combined application of MGI with other techniques (eg RMP, or even VDE) to help avoid the runaway beam. Similarly further techniques (eg liquid jets, pellets, impurity roles, etc.) should be considered and tested as alternate safe termination systems.

Modelling all of these aspects is vital to understanding the action and applicability of the mitigation scheme. There is good work underway/possible with codes like NIMRAD, SOLPS, or KPRAD, so focus here must be on folding in all the runaway (and if needed halo) physics, and comparing with experimental signatures to confirm processes. Work might need to be extended to 3d MHD simulations in the longer term, as the plasma becomes unstable and starts to kink.

*This work naturally combines with understanding the quench process more generally, and the role of the wall / impurities, thus sharing many of the modelling approaches with below:*

Thermal Quench and Interaction with the wall

The wall plays a crucial role, both setting the requirements for mitigation (eg tolerable heat loads), and interacting in the process through the influx of impurities. Ongoing experimental work is needed to understand wall erosion. This might include testing particular components and materials, not least to understand their mutual interaction with the plasma. ***Improved diagnosis of impurity influx and its role in the disruption process is a key issues to explore*** to understand the progression of the disruption process. Basic fast diagnosis of thermal loads is also important – and it is worth considering diagnostic sharing here (eg IR cameras) as well as new diagnostics where needed. All these elements are partnered with strong code interpretation efforts to understand the impact at the wall, which includes similar approaches to those described in the MGI section, plus additional modelling of the wall materials themselves.

Common issues

An important strategic need in modelling all of the above processes is the ability to evolve and reconstruct the plasma evolution as the disruption process evolved (perhaps if only in a 2d sense) in order to provide profiles and structure to the relevant codes predicting runaway generation, halo currents, etc. This needs to be able to reconstruct experimental situations beyond capabilities of the usual EFIT-like codes.

The other recurring theme is the need for databases to look at cross machine trends and identify outliers (and their causes) – here the effort to support an ITPA database may need augmenting, with the database extending to further issues (not just VDEs and halos); the US is well positioned to assist with this role.

***In summary***, disruptions represent a crucial issue for fusion power, and one that needs to be addressed more in current programmes. However, fortunately, many of the tools and technologies to study this already exist and it is a question of applying them with relatively modest experiment improvements, but a much greater focus of staff and experiment resources. This needs to be partnered with much more challenging developments on the numerical interpretation side.

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