Edge Localized Mode and pedestal control using resonant magnetic perturbation coils

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Large transient heat and particle flux resulting from MHD instabilities (Type-I ELMs) are thought to driven by larger edge pressure gradients and currents in tokamak H-modes. Energy transients driven by Type-I ELMs are predicted to exceed the impulsive ablation limits of the divertor materials used in the ITER by about a factor of 20 and lead to sharply reduced divertor lifetimes. In DEMO these transients are expected to be at a factor of 5 larger than in ITER. Recently, a new technique using resonant magnetic perturbations (RMPs) has been developed that reliably eliminates Type-I ELMs at low pedestal collisionalities while maintaining a robust edge transport barrier with high pedestal temperatures. While this technique appears to have a straightforward scaling to burning plasmas in terms of the physics requirements, a significant level of effort is needed to develop the technology required to make this approach a viable candidate for ELM control in fusion power stations following ITER. RMP ELM control relies on the introduction of non-axisymmetric magnetic perturbations that are resonant on rational flux surfaces across the edge of the plasma, producing chaotic field lines due to island overlap and reducing the edge pressure gradient while avoiding resonances on low order rational surfaces that can destabilize core instabilities. In practical terms, this means that the RMP coil and its control system must be capable of following changes in the plasma shape, pressure profile and current profile using algorithms that are capable of matching the coil geometry with the range changes expected in the machine's operating parameters. This means that the coil geometry needs have sufficient flexibility to be able to properly mix of edge and core resonant harmonics in real time during startup and shutdown without generating large non-resonant fields that can cause core tearing and locked modes. Thus, an intelligent closed-loop feedback control system, driven by real time reconstructed equilibria data such as rtEFITs, is required in future devices where to occurrence of a single Type-I ELM could jeopardize the operation of the machine. In DIII-D the RMP coils are used to stabilize core MHD instabilities (resistive wall modes) and to correct field-errors. In ITER, the internal ELM control coils are designed to assist in maintaining vertical stability for avoiding off-normal events such as VDEs. These coils had to be fit into the existing ITER vacuum vessel design so it was not possible to implement a coil set with the same level of flexibility as will be possible in future machine where the design of the RMP coils and the vacuum vessel will be completely integrated to maximize the spectral flexibility of the coil system for changes in operating conditions. In ITER, each of the 27 coil segments will be controlled by it own power supply to allow for the possibility of changing the coil spectrum with changing plasma conditions e.g. during startup and shutdown as well as for various operating scenarios. On the other hand, it will not be possible to train the ELM control system in ITER since no large ELMs will be allowed in ITER even in the early operating phase of the machine. In this regard, we need a facility that can address the task of training an ELM control system for ITER and eventually DEMO. Although, some of this work can be done in DIII-D with the addition of the new RMP planned for 2011 but there are limitations on the coils that can be retrofit into the DIII-D vacuum vessel.

Internal coils, specifically designed for fusion power stations, will also have to deal with fast transients due to core MHD as well as a variety of non-axisymmetric magnetic perturbation sources such as magnetic materials in blanket modules, machine components and diagnostic systems. Developing optimized perturbation coil designs for ELM and pedestal control in burning plasma devices goes hand-in-hand with expanding our understanding of how magnetic perturbations affect the transport and stability of the pedestal plasma. This requires a strong coupling between existing and future experiments, theory and numerical modeling. In order to prepare for the best possible ELM and pedestal control in ITER and DEMO a wide array of international fusion program resources are required and more importantly a dedicated machine that is designed with a flexible RMP coil set that is completely integrated into the vacuum vessel design is an essential step for the development of this approach.

Issues to be addressed prior to DEMO

Since ELM control in a DEMO class fusion device is absolutely essential for the success of the facility, a high priority interim issue is to develop the necessary physics basis and control systems (including hardware and software) required to achieve the ELM control coil operating parameters that will be encountered during DEMO operations. An optimized DEMO RMP ELM control system will need to be capable of precisely controlling both the width and height of the pedestal plasma while eliminating ELMs. It will also need to be able to spread the steady-state flux across a wider region of the divertor target plates thus reducing the peak heat flux while maintaining a strongly radiating divertor plasma and sufficient particle exhaust rates for density control and fusion ash removal. Achieving this in DEMO will require a significant level of extrapolation using advanced numerical models that incorporate the latest theoretical and experimental understanding on pedestal transport and stability during resonant magnetic perturbations. It will also require intelligent feedback control algorithms with the spatial and temporal agility of fly-by-wire control systems used in modern avionics systems. While we expect to develop key elements of the physics and technology basis needed for DEMO using current and/or upgraded facilities as well as in ITER plasmas, an essential step needed for the validation of the control models requires an ability to accurately predict the full range of operating conditions that will be encountered in DEMO plasmas. These constraints imply that a burning plasmas facility is needed prior to the construction of DEMO, in which ELM control coils are an integral part of the machine and control system design. Such a facility provides an opportunity for the US fusion program to develop and validate critical systems needed for the success of the DEMO project and to test these systems over the range of operating conditions expected in DEMO.