White paper

"Role of magnetic flux conservation, plasma surface current and TMHD in disruption simulations"

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MHD activity is a main trigger for disruption in tokamaks. Most of disruptions are related to the free boundary MHD modes, with many mechanisms associated with losing stability and triggering disruption dynamics. On the fast MHD scale (microseconds), the plasma and the wall react as ideal conducting structures. In such dynamics, magnetic flux conservation in the plasma and vacuum regions plays an important role. Accurate poloidal and toroidal magnetic flux conservation in the plasma and vacuum is not a trivial task because of the moving plasma-vacuum interface. A reliable algorithm providing exact flux conservation is based on the use of magnetic flux coordinates in the vacuum; which should be recalculated on each time step. This requires calculating a coherent solution to: two 3D elliptic problems for angle coordinates; one 3D elliptic problem for Coulomb gauge; and three 3D elliptic equations for the vector-potential itself on each time step in the vacuum region. This is the price for exact magnetic flux conservation. Flux conservation plays a key role in computing the corresponding plasma surface current, which we define as a jump of the tangential component of the magnetic field on the plasma-vacuum interface. In MHD simulations with a conducting wall, the plasma surface current will appear immediately after plasma starts moving away from equilibrium. During disruption, the kink mode quickly (within the thermal quench phase) grows and the plasma surface can touch the wall elements. The plasma surface current then is shared with the wall surface, drives the current in the wall bringing sideways force acting on the wall due to $\mathbf{j}_{\text{surface}}\text{x}\mathbf{B}$. This current is called Hiro current [8]. Driven by the kink mode, Hiro currents are always in the opposite direction to the plasma current. Its role in disruption physics has yet to be adequately addressed.

An accurate and robust built-in 3D electromagnetic solver, flux conservation vacuum algorithm, plasma surface current, and computation of Hiro current are the essential and innovative part of the recently developed Disruption Simulation Code (DSC-3D) [1,2,3,4]. The code solves the one fluid non-linear time-dependent 3D MHD model in a tokamak plasma surrounded by pure vacuum in the real geometry of the conducting tokamak vessel. DSC is a unique tool, utilizing the adaptive meshless technique on a 3D Cloud of Computational Points (CCP) with adaptation to the moving plasma boundary and accurate resolution of the plasma surface current. The code does not use poloidal or toroidal harmonics, and a corresponding adaptation of CCP can be provided in the radial, poloidal, and toroidal directions to resolve gas/pellets/plasma injectors that are strongly localized in space (spot-like). Many different boundary conditions ($\mathbf{v}_\perp \neq 0$, absorbing, etc.) on the plasma-touching wall elements can be applied. Another unique feature of DSC is that the code can work with two models: original MHD and Tokamak MHD (TMHD), when suppression on the fast magnetosonic scale is provided by neglecting the plasma inertia [1,3]. The code can switch between them as needed. Plasma inertia is responsible for the fastest magnetosonic and Alfven scales (typically less than microseconds) and plays no role on the much slower quasi equilibrium tens-of-millisecond scale, which is typical for disruption event. In a simple model of cylindrical plasma, it was demonstrated that the replacement of the inertia by a friction term did eliminate fast oscillations and did lead directly to plasma equilibrium. In the more complicated 3D case, such replacement also suppresses the fast scale and leads to slower quasi equilibrium evolution. The TMHD model allows jumping over the microseconds scale directly to the milliseconds disruption scale. Two additional versions of the code: DSC-2D (with helical symmetry) and DSC-1D (z-pinch plasma) were also developed. DSC(-3D,-2D,-1D) simulations have already demonstrated important aspects of plasma dynamics related to disruptions. The non-linear dynamics of the wall touching kink mode was simulated, with the identification of Lorentz force acting on the vessel tiles due to the plasma surface current [4]. Simulations were made for both fast ideal MHD regime until the saturation due to the excitation of Hiro currents, and the slower regime of the current quench due to resistive decay of the Hiro currents [3]. Suppression of fast magnetosonic oscillations by neglecting the plasma inertia was demonstrated and recently presented [5,1]. The non-linear dynamics of the VDE with self-consistent plasma surface current was modeled with DSC-3D [1].

We have proposed to develop a Disruption Prediction And Simulation Suite (DPASS) of computational tools to predict, model, and analyze disruption events. DPASS will use the DSC-3D as a core tool and will have modular structure. In addition to MHD, DPASS will eventually address such aspects of the disruption problem as: plasma edge dynamics, plasma-wall interaction, generation and losses of runaway electrons. DPASS will implement new understanding of disruptions [6] based on recent success in explaining toroidal asymmetry in magnetic measurements on the JET device [7], and the creation of the theory of the Wall Touching Kink Mode [8]. Two types of disruptions: Vertical Disruption Event and Non Vertical Disruptions will be addressed. New physics, related to the Hiro currents, will be also taken into account. Hiro currents are easily distinguishable: a) from the eddy currents in the wall which are much smaller in amplitude, excited by the perturbation of magnetic field, and are sensitive to gaps in the wall; and b) from halo currents [9] (driven in the same direction as the plasma current).

The development path for DPASS includes both a short term plan (first year – Phase I), and a long term plan (second and third year, Phase II). In the first year (Phase I), two modules will be developed, linked with DSC-3D and initial simulations will be conducted: the computational module will be for modeling the traditional (gas or pellet) Disruption Mitigation Scheme [10]; and the second computational module will be targeted to nanoparticle plasma jet injection as an innovative DMS [11].

Due to the nature of the runaway electrons (RE) [12], kinetic models are most suitable for simulation. There are a few kinetic codes [13,14,15,16], which describe the generation of the REs for specified parameters of the background plasmas. A module for linking one of these kinetic codes to DPASS will provide simulation of the plasma thermal energy and particle loss to the wall during thermal quench, and the dependence of RE generation on magnetic perturbations. From experimental observations it is known that losses of REs are also mostly defined by MHD instabilities. Injection of dense gas jets or large pellets can create additional electromagnetic perturbations which will affect the RE confinement. Self-consistent treatment of the RE dynamics with 3D MHD perturbations is needed to adequately describe RE confinement, loss, and wall loading. DSC-3D has a 3D electromagnetic solver to simulate the magnetic perturbations produced by external coils including the plasma effects on these perturbations. Evolution of the plasma during the current quench will be simulated by both MHD and TMHD models. DSC will be responsible for controlling the plasma stability during plasma evolution. By selecting the appropriate module, describing jet or pellet injection into the plasma, we get a tool to simulate different RE suppression schemes.

Being developed, DPASS will be an important step toward the simulation of disruptions and understanding opportunities for mitigation schemes.

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