Integrated Modeling of Runaway Electron Beam Formation in JA DEMO Post-Disruption Plasmas

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The runaway electron (RE) beam formation in JA DEMO is simulated using the integrated disruption code INDEX. It is shown that the gamma-ray flux is comparable with that of the published results for ITER and the Compton scattering of gamma rays governs an irreducible minimum of the RE seed (~ 0.01 - 0.1 A), which can lead to multi-mega-ampere RE beams in the absence of significant radial transport of REs.

Keywords: disruption, runaway electron, integrated modeling, DEMO, Compton scattering

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The mitigation of disruption loads is mandatory to ensure routine operation in reactor-grade mega-ampere tokamak devices. A particular concern is volumetric heating by runaway electrons (REs). The RE energy can be deposited deep inside the plasma-facing components, which could cause in-vacuum vessel loss of coolant accident (in-VV LOCA). However, the tungsten coating on the blanket first wall needs to be sufficiently thin for effective tritium breeding. In the present design of JA DEMO [1], the thickness of the tungsten coating is only about 0.5 mm, and an installation of the limiters, which is protruded toward the plasma compared to the blanket, are considered [2] to protect the blanket modules against both steady-state and transient loads. For establishing such a limiter concept, it is important to specify the RE loads. In this study, we implement the state-of-the-art RE model in the 1.5D integrated disruption simulator INDEX [3] and report the first evaluation of RE beam formation in JA DEMO.

In high-current reactor-grade tokamaks, RE production is considered to be not merely an occasional but inevitable event due to high amplification gain with secondary RE generation [4]. To evaluate the secondary RE source, we adopt a mean-particle model [5] to calculate the avalanche growth rate. Although the original implementation was based on the semi-classical formula for the Coulomb logarithm [5], we have newly implemented the Hesslow's Coulomb logarithm model that accounts for the screening effect with density functional theory calculation [6] for partially ionized impurities. To verify our implementation, the simulation results for the ITER-equivalent circular tokamak has been compared with the published results of the GO code [7], showing good agreement.

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While different mechanisms can bring seed electrons into the RE regime [4], we focus on the RE seed terms of tritium beta decay and the Compton scattering of gamma rays [8]. Although additional RE production due to the Dreicer and hot-tail mechanisms needs to be assessed separately, the above two mechanisms are considered as the lower limit of the RE seed in the reactor environment.

The RE seeds produced by Compton scattering are more difficult to be suppressed because of higher electron energies. Following the assessment in ITER [8], we assume that the gamma flux during disruptions is at a similar level to that during burning plasma conditions. Assuming the 1.5 GW fusion output and the neutron source of 5.33×10^{20} n/s, the energy spectrum of gamma fluxes from 0.01 MeV to 20 MeV has been evaluated using the MCNP code [9], as shown in Fig. 1 (a). The obtained total gamma-ray flux is 6.3×10^{17} /m^2/s. An insight obtained here is that despite high neutron fluence (/m^2) in JA DEMO, the gamma-ray flux (/m^2/s) is comparable to that of ITER (~ 10^{18} /m^2/s) [8], implying that the operational experience in the DT experiments in ITER can built

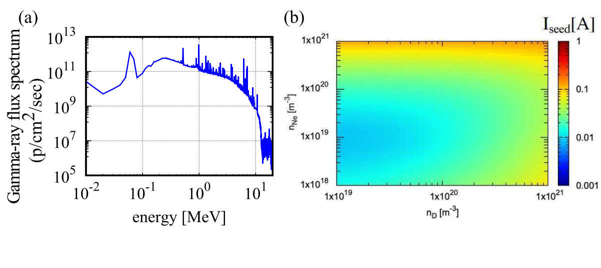

Fig. 1 (a) Energy spectrum of gamma-ray flux in 1.5 GW JA-DEMO and (b) the parameter scan of the seed current by Compton scattering of the gamma rays.

a basis for the RE avoidance and mitigation in JA DEMO. Figure 1 (b) shows the RE seed currents produced by the Compton scattering of gamma rays calculated over a wide range of neon and deuterium densities. When calculating the electron temperature in post-disruption plasmas from the volume-integrated power balance, we have obtained the RE seed current of approximately 0.01 - 0.1 A in the wide parameter range, where more RE seeds are obtained at higher densities because of the presence of more target electrons for Compton scattering. These seed currents are difficult to be eliminated, even assuming massive material injection, which may worsen the situation by introducing the target electrons with overfueling [7].

Figures 2 and 3 show the simulation result obtained from the INDEX code, assuming that the current quench (CQ) starts with the nominal I_p value of $I_0 = 12.3$ MA and the initial bulk densities of $n_{D,0} = n_{T,0} = 0.57 \times 10^{20}$ /m^3. In the simulation, an artificial heat sink is applied to mimic the loss of thermal energy and the resultant β_p collapses, and the neon density increase up to $n_{Ne} = 1 \times 10^{20}$ /m^3 is prescribed, where the impurity source is assumed to be radially uniform. Figure 2 show that the RE seed current of about 0.1 A is produced at the beginning of the CQ, and the RE current I_{re} increases exponentially up to 7 MA – more than a half of the pre-disruption current. Figure 3 (a) shows the vertical displacement of the RE beam. After the RE current becomes comparable to the total plasma current, $I_{tot}(= I_{ohm} + I_{re})$, the plasma moves upward and touches the first wall ($t \sim 170$ ms). Going upward, the plasma volume shrinks and the safety factor at the edge q_a gradually decreases, as shown in Fig. 3 (b). Note that after $t > 250$ ms, q_a becomes lower than 2 and the large kink instability can be driven. Figure 3 (c) shows the RE current density in the poloidal cross section. The 2D cross section of the blanket modules (at $\phi = 5$ deg., containing the hemisphere structures), the limiter (straight blocks), and the initial separatrix are also plotted. As shown here, the RE beam is scraped off by the limiter in this calculation. Figure 3 (d) shows that the maximum total energy of the RE beam W_{re} [8] is about 100 MJ, and the energy scraped off from the RE beam W_{scl} owing to the vertical displacement is deposited (~ 100 MJ) on the limiter surface.

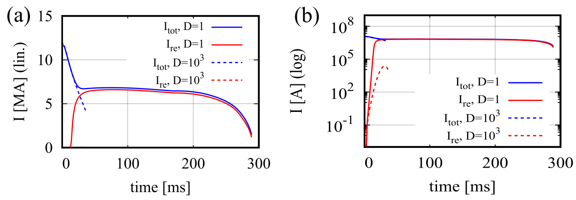

Fig. 2 Plasma total current and RE current (a) on a linear scale and (b) on a logarithmic scale. The solid curves represent the results for $D_{re} = 1$ m^2/s, and the dashed ones represent the results for $D_{re} = 10^3$ m^2/s.

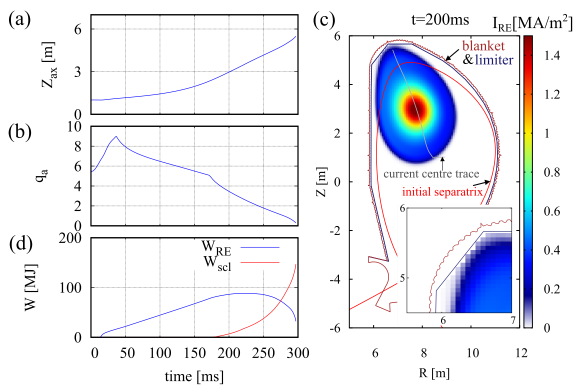

Fig. 3 (a) Vertical displacement of the plasma current center, (b) safety factor at the plasma edge, (c) RE current density in the poloidal cross-section at $t = 200$ ms and its enlarged view, and (d) energy stored in REs and RE energy scraped by the first wall. ($D_{re} = 1$ m^2/s)

The simulation performed here is not meant to demonstrate any mitigation scenarios but to illustrate a possible scenario of the RE beam formation, which can be used to assess the machine integrity against the RE wall impact for safety [10]. In fact, the RE current plateau values depend on the choice of the radial transport coefficient D_{re}. The result of the sensitivity to D_{re} is also shown in Fig. 2, where $D_{re} = 1$ m^2/s (solid) and $D_{re} = 10^3$ m^2/s (dashed). For $D_{re} = 10^3$ m^2/s, a significant decrease in the RE current is observed, which corresponds to $\delta B/B \sim 10^{-3}$ [11]. A recent ITER simulation showed that the diffusion coefficient reach the order of 10^3 - 10^5 m^2/s in the early CQ when the magnetic field becomes stochastic [12]. The RE current plateau level depends on when and to what radial extent the magnetic surfaces reform. Motivated by that the RE generation can be suppressed when the open magnetic fields are maintained [13], the avoidance strategy using passive applied 3D magnetic fields has recently been studied [14]. The results of this study has pointed out that the evaluation of RE orbit loss for realistic 3D magnetic field (both kink and applied ones) is also an important research area for future studies towards JA DEMO.

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