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Study of runaway electron dynamics at the ASDEX Upgrade tokamak during impurity injection using fast gamma-ray spectrometry

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To study the runaway electron (RE) dynamics during plasma discharge, as well as to develop scenarios for disruption mitigation, a gamma-spectrometric system has been developed and commissioned at the ASDEX Upgrade tokamak (AUG). The diagnostic system consists of two scintillation gamma-ray spectrometers based on the fast LaBr3(Ce) crystals. These spectrometers observe the AUG tokamak chamber quasi-radially at the equatorial plane [1, 2]. Both spectrometers are equipped with modern data acquisition systems based on fast digitizers recording detector signals with an ultra-high sampling rate (up to 400 MHz). The fast digital processing of the recorded waveforms from the detector allows obtaining the Hard X-Ray (HXR) energy spectrum at any given time of the discharge under investigation. In order to carry out the pulse-height analysis under conditions of high detector load and many piled-up events, up-to-date digital signal processing algorithms are used. Dynamics of REs has been studied using this diagnostic and reported in this paper.

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The measurements were carried out in the regimes of RE beam generation by injection of argon or krypton gas into a deuterium plasma. In the interaction of a developed RE beam with a heavy gas target, powerful bremsstrahlung flux is induced, reaching energy close to 20 MeV. The electron energy distributions were reconstructed from the measured HXR spectra by deconvolution methods [3, 4]. For this purpose, the detector response functions for monoenergetic gamma radiation in the range 0.1–30 MeV with a step of 0.1 MeV were calculated using the MCNP code. Bremsstrahlung generation functions caused by the interaction of accelerated electrons with a gaseous target were simulated as well corresponding to the detector viewing geometry. An analysis is carried out of the evolution of the maximum RE energy (Emax) derived by reconstructing RE distribution functions (REDF) from the measured HXR spectra with DeGaSum deconvolution code [4]. The experimentally obtained maximum RE energies at different stages of the discharge were compared with the results of test particle simulations that include the effect of toroidal electric field, plasma collisional drag force, synchrotron deceleration force. Figure 1 shows the main signals of AUG discharges # #34084 and 34183. During the discharge #34183 a series of deuterium pellets was injected after the argon puff. Figure 1e represents the evolution of the maximum RE energies reconstructed from HXR measurements in comparison with the results of test particle calculations. It was observed that the electrons attain their maximum energies in 50-100 ms after the gas injection. Then it gradually decreases due to the drop in loop voltage, energy loss due to synchrotron radiation emission and collisions dissipation of energy with the background plasma. The test particle simulation suggests that the Emax calculated by DeGaSum code matches reasonably well with the simulated energy evolution of REs created in the initial phase of the current quench. The decreases in RE-energy after the massive gas-injection (MGI) may be attributed to collision dissipation of the RE energy with plasma and that also leads to pitch angle scattering of REs, the increase in the RE pitch angle again enhances the synchrotron radiation losses that combined effect results in decreases of the Emax. These results are confirmed and supported by the test particle simulations.

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Furthermore, HXR measurements at the discharge with a multiple deuterium pellet injection (PI) allowed observing the effects of plasma cooling and argon ion recombination after PI. In Fig.2 red dots show the runway current restored with the DeGaSum code from the measured HXR spectra. This result shows the diagnostic measurements can also aid to reconstruct RE-current evolution during disruption mitigation scenarios and reported herein for the first time. The green line shows the estimated argon atomic density in the place of

the RE beam localization. This argon concentration is needed to explain the observed RE current. Analysis of REDFs has shown that after PI the runaway beam interacts mainly with the neutral gas target, which concentration significantly exceeds the electron density. During the discharge with pellet injections, Emax of REs was by 3-5 MeV lower than for the discharge with an application of MGI only (see Fig 1e).
The experiments and diagnostic signal analysis along with simulations demonstrated the ability of gamma-ray spectrometry to provide the most important RE parameters, such as maximum RE energy and current that is the measurement requirement for ITER [5]. Measurements at AUG make it possible to test equipment and RE diagnostic techniques to use them at ITER and new generation tokamaks.
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Country or International Organization

Russia

Affiliation

Ioffe Institute

Authors: SHEVELEV, Alexander (Ioffe Institute); KHILKEVITCH, Evgeny (Ioffe Institute); ILIASOVA, Margarita (Ioffe Institute); NOCENTE, Massimo (Dipartimento di Fisica, Università di Milano-Bicocca; Institute for Plasma Physics and Technology, National Research Council, Milan, Italy); PAUTASSO, Gabriella (Max Planck Institute for Plasma Physics); PAPP, Gergely (Max Planck Institute for Plasma Physics); DAL MOLIN, Andrea (Dipartimento di Fisica "G. Occhialini", Università di Milano-Bicocca, Milan, Italy); PANDYA, Santosh P. (Institute for Plasma Research); PLYUSNIN, Vladislav V (Instituto de Plasmas e Fusão Nuclear, Associação EURATOM-IST, Instituto Superior Tecnico); GIACOMELLI, Luca (Institute for Plasma Physics and Technology, National Research Council, Milan, Italy); GORINI, Giuseppe (Dipartimento di Fisica "G. Occhialini", Università di Milano-Bicocca; Institute for Plasma Physics and Technology, National Research Council, Milan, Italy); PANONTIN, Enrico (2Dipartimento di Fisica "G. Occhialini", Università di Milano-Bicocca, Milan, Italy); RIGAMONTI, Davide (Institute for Plasma Physics and Technology, National Research Council, Milan, Italy); TARDINI, Giovanni (Max Planck Institute for Plasma Physics); TARDOCCHI, Marco (Institute for Plasma Physics and Technology, National Research Council, Milan, Italy); BOGDANOV, Alexander (Ioffe Institute); CHUGUNOV, Igor (Ioffe Institute); DOINIKOV, Dmitri (Ioffe Institute); NAIDENOV, Victor (Ioffe Institute); POLUNOVSKY, Igor (Ioffe Institute); ASDEX UPGRADE TEAM (Max-Planck-Institute für Plasmaphysik, Boltzmannstr 2, D-85748 Garching bei München, Germany); EUROFUSION MST1 TEAM

Presenter: SHEVELEV, Alexander (Ioffe Institute)

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