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Comparison of Runaway Electron Generation Parameters in Small, Medium-sized and Large Tokamaks – A Survey of Experiments in COMPASS, TCV, ASDEX-Upgrade and JET

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Abstract This report presents a survey of experiments on runaway electrons (RE) carried out recently in frames of EUROFusion Consortium in different tokamaks (COMPASS, ASDEX-Upgrade, TCV and JET). The effect of the increase of geometrical scale and physical parameters of plasma experiments on disruption generated RE has been studied. New data on RE generated at disruptions in COMPASS with carbon limiter and ASDEX-Upgrade with tungsten wall was collected and added to the database on RE in JET. Parameters of RE in COMPASS and ASDEX-Upgrade revealed increasing trends on toroidal magnetic fields and pre-disruption plasma currents and fit well into the JET database. In the second part of experiments the RE generation during flattop of discharges in COMPASS and TCV has been studied. MGI of Ne/Ar has been used to study the dissipative effect of MGI on parameters of RE. The secondary RE avalanching was detected and quantified for the first time in TCV after Ne injection in RE generating discharge. Kinetic instability driven by RE in TCV was identified.

Introduction Massive Gas Injection (MGI) is considered as the most developed candidate tool for design of the ITER Disruption Mitigation System (ITER-DMS) to suppress/avoid detrimental effects of disruptions and generation of runaway electrons (RE). Despite that MGI demonstrated the ability to mitigate a majority of severe processes at disruptions, a set of problems related to RE avoidance/suppression is still unresolved [1]. To overcome existing problems a detailed knowledge of RE generation physics and improved models for simulation of interaction of RE beams with large quantities of injected impure gases are required.

This report presents a survey of experiments on RE generation carried out in frames of EUROFusion Consortium program in JET with ITER-like wall (JET-ILW) and in small and medium-sized European tokamaks (MST): COMPASS, TCV and ASDEX-Upgrade [2-4]. In one group of experiments the parameters of RE generated in disruptions have been studied depending on the increase of device experimental parameters (geometrical scale and physical parameters: magnetic field (B_0), plasma current (I_{pla}), etc.). The RE data collected in ASDEX-Upgrade and COMPASS was included into database on RE from JET (with carbon wall (JET-C) and ITER-like wall (JET-ILW)) [5-7]. Another part of experiments was dedicated to the study of RE generation in steady-state discharge conditions. A scenario of RE generation during flattop stage of discharge in tokamaks constitutes the subject of a special attention due to the possibility to measure reliably plasma parameters during onset, growth and loss of relativistic RE. This scenario with low plasma density was developed and used in experiments on COMPASS and TCV. The RE generation dynamics was quantified using measured plasma parameters in frames of conventional theory of runaways. Obtained data was compared to the JET results [8].

Measurements of HXR and photo-neutrons were used to determine the RE energies during disruptions and during flattop. The neutron spectrometry diagnostic used on ASDEX-Upgrade has showed that maximal energy of RE in disruptions could achieve up to 10 MeV. In JET the HXR spectrometry has been used to study the energy of RE generated in disruptions and during steady state [9]. Measurements of HXR spectra revealed the generation of RE with maximal energies up to 7 MeV and mean energy ≈2.5 MeV during flattop. Similar or slightly higher mean energies, but with maximal energies up to 10-12 MeV were measured in disruptions. HXR bremsstrahlung radiated in very narrow forward radiation pattern with angular half-width $\theta \sim 1/\gamma_0$, (γ_0–relativistic parameter) was detected. Two narrow patterns with $\theta \sim 0.06 \div 0.1$ have been detected by vertical and horizontal JET HXR cameras in the vicinity of q=1 in JET [7]. One can see that measurements of HXR radiation patterns and the JET HXR spectroscopy data yield very close values of the RE energy. On TCV a photo-multiplier tube for Hard-X Rays (PMTX) allowed measuring HXR emissions of RE. It is placed outside the torus, in the hall of the machine. Due to the large production of energetic HXRs during the RE plateau stage the other HXR diagnostics (up to 20 and to 200 keV) saturate and only the PMTX camera could be used to detect the RE generation. One HXR detector on COMPASS with threshold energy above 50 keV is located outside the tokamak. The second HXR detector is shielded by 10 cm led box and placed on similar distance from the tokamak. This detector is capable to measure HXR with the lower energy threshold well above 500 keV. In RE dominated COMPASS discharges the synchrotron radiation from RE was directly measured by an infrared camera [10].

Runaway Electrons Generated During Disruptions Disruption scenarios for RE generation in the ASDEX-Upgrade, COMPASS and TCV Tokamaks were developed on the basis of the JET limiter configuration scenario using Disruption Mitigation Valves (DMVs) for MGI (described in detail elsewhere [1,6,7]). Reliable RE generation in ASDEX-Upgrade and COMPASS was achieved when disruptions were triggered by injections of large amount of impure gases (Ar, Ne) during current ramp-up stages, while the disruptions with RE in JET were triggered by MGI during flattop stage.

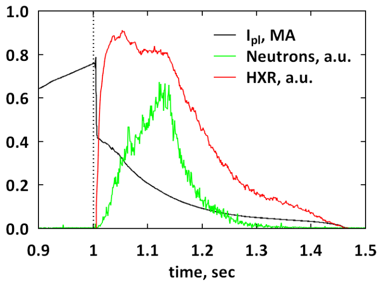

Figure 1. ASDEX-Upgrade discharge #32034: scenario for study RE generation at disruptions, disruption is triggered at t=1.0 s by MGI (dots).

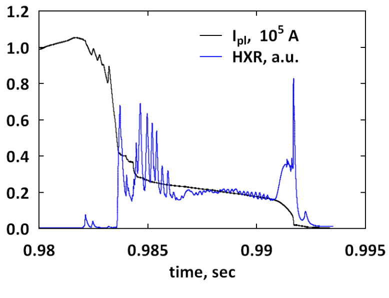

Figure 2. Typical RE plateau at disruption triggered by Ar injection in COMPASS discharge #10825.

The RE generation scenario in ASDEX-Upgrade is based on Ohmic L-mode inner limiter circular plasma discharges with I_{pl}=0.8 MA at B_T=2.4-2.5 T. The injection of 0.05-0.2 bar*l of Ar from piezoelectric in-vessel valve resulted in characteristic rise of MHD activity and disruptions. To optimize the RE generation at disruptions the low-density plasmas ($<n_e>\sim 2.5\text{-}3.6*10^{19}$ m^{-3}) were heated by 2-2.5 MW of ECRH applied for 0.1-0.2 sec immediately before Ar/Ne injections. Disruptions were well reproducible with typical thermal quench time t_{TQ} ~0.001 s. Generation of RE current plateaux with up to 0.4 MA and duration up to 0.4 sec have been observed (Figure 1). Disruptions in hydrogen plasmas resulted in comparable RE plateaux to those obtained in deuterium, while slightly lower RE currents were achieved in helium. Use of the second DMV (triggered on 70 ms after the first injection) allowed a study of dissipative effects of high-Z impurity gases on RE beams [2].

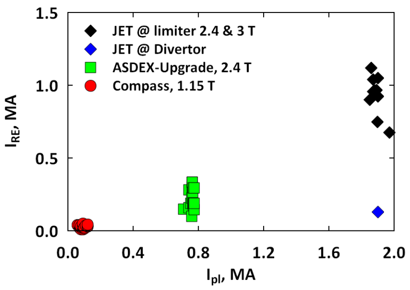

Figure 3. Disruption generated RE currents vs. plasma currents in small, medium-sized and large tokamaks

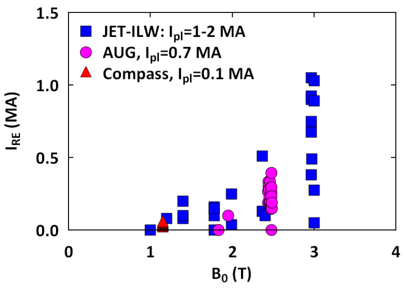

Figure 4. RE generation vs. toroidal magnetic fields in small, medium-sized and large tokamak

Similar scenario for RE generation was used in COMPASS [3]: the circular plasma limited by carbon limiters from the high field side (HFS) and additional one from the low field side (LFS) for the vessel protection. Experimental magnetic field was B_0 = 1.15 T and plasma currents were I_{pl} = 80-140 kA. An average electron density $<n_e>$ was kept relatively low (0.8-2.2*10^{19} m^{-3}) in order to maximize the RE generation rate. RE generation at disruptions in COMPASS has been detected as characteristic current plateaux (Figure 2) with values up to 60 kA and hard X-rays (HXR) and photo-neutron bursts during plateaux.

The data on RE currents in tokamaks shows increasing trend with increase of plasma currents from small and medium sized devices toward JET (Figure 3). However, RE currents generated in COMPASS at B_0 =1.15 T and currents $I_{pl} \leq$ 120 kA were close to that JET data at B_0=1.2 T and $I_{pl} \leq$ 1.2 MA. As well, the MGI disruptions in ASDEX-Upgrade at I_{pl} ~0.8 MA and B_0 =2.4 T resulted in RE plateaux with values similar to obtained in JET with I_{pl} at least 2 times larger at B_0=2-2.4 T (Figure 4) [5-7].

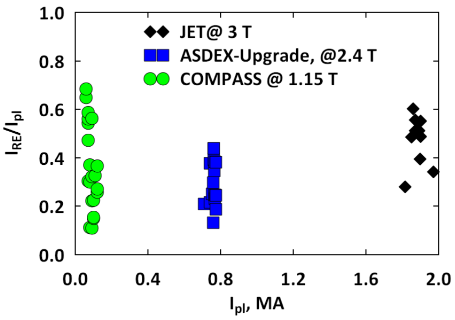

Figure 5. Conversion of plasma currents to RE currents in small, medium-sized and large tokamaks

Upper values of the conversion rate of plasma currents into RE currents in JET and ASDEX-Upgrade are close to 0.6, while in COMPASS the RE currents sometimes achieved up to 0.7 of pre-disruption values revealing apparent insensitivity of RE generation process to the physical parameters and geometrical sizes of experiments (Figure 5). However, the dependence on scale of experiments exists and it appears as one of the determining factors for the RE generation if to analyse the data on plasma current quench rates (CQ): $I_\gamma = \frac{1}{I_{pl}}\frac{dI_{pl}}{dt}$. The CQ is usual driver for generation of high $E_\parallel$ and RE generation. It could be used as a measure of the RE growth rate when HXR emission together with a measurable deviation from the exponential decay of resistive plasma current (or even RE plateaux) are observed [5], i.e. $\frac{1}{j_{RE}}\frac{dj_{RE}}{dt} = -\frac{1}{I_{pl}}\frac{dI_{pl}}{dt}$. Figure 6 presents evolution of CQ-rates for the data in Figure 5, thus demonstrating the influence of physical parameters and geometrical scales on RE generation. First of all, this influence is associated with increased variability of different plasma parameters such as the total plasma inductance, conductivity, plasma current decay time, variation of magnetic fluxes, etc. I.e. the probability of RE generation increases in the larger limits of spatial and temporal evolution of plasma parameters during disruptions.

Small and medium sized tokamaks revealed characteristics of RE in MGI disruptions similar to those in JET-C and JET-ILW. However, significant differences also have been found. In particular, the different evolution of the average densities of RE plateaux in JET and ASDEX-Upgrade has been found. The pre-disruptive average densities of plasma currents were:

$<j_{pl}>\approx 0.5$ MA/m^2 – in JET and $<j_{pl}>\approx 0.8$ MA/m^2 – in ASDEX-Upgrade (Figure 7). After disruptions the average current densities of RE plateaux in JET remained close to pre-disruption values. The average RE current density sometimes increased during the plateau slow decay achieving almost 2 times larger values at the time of plateau termination. Meanwhile, during ASDEX-Upgrade disruptions the runaway acceleration provided the average density of RE beams about 2-3 times lower relatively to pre-disruptive values and there were no indications on similar to JET increase of RE current density during plateau decay. Again, apparent contradiction between CQ rates and RE generation could be understood if to take into account that characteristic current decay time in JET is τ_{CQ}~8-12 ms, which is significantly larger than in ASDEX-Upgrade (τ_{CQ}~2-3 ms).

Therefore, the conditions for RE generation in JET are sustained for a longer time since the growth of RE density is self-limited by decrease of electric field on CQ. At the sufficient decrease of electric fields the generation of new REs is ceased and the remaining plateau current is carried by RE. At other similar conditions the longer stage of RE generation in JET provided denser RE beams than in ASDEX-Upgrade from the early beginning of the plateau.

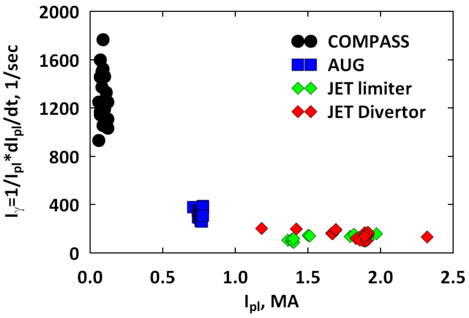

Figure 6. CQ rates in disruptions with RE generation in small medium-sized and large tokamaks

The increase of RE density during plateaux in MGI disruptions follows to slow inward beams motion, contraction of RE beam channels and presence of measurable but small time derivatives of RE currents (≤10 MA/sec, compare to ≈100-200 MA/sec at CQ [6]). In this case the current peeling effect during inward beam motion inevitably should result in decrease of existing magnetic flux and generation of additional electric field [11]. Note also, that in ASDEX-Upgrade the shorter gas travelling distance from in-vessel valve to plasma should result in faster gas penetration and more effective RE plateau dissipation. Unlike JET results [1], the ASDEX-Upgrade experiments have shown obvious dissipative effects of the secondary MGI of Ar/Ne on RE beams for both, far and close located injection valves [2].

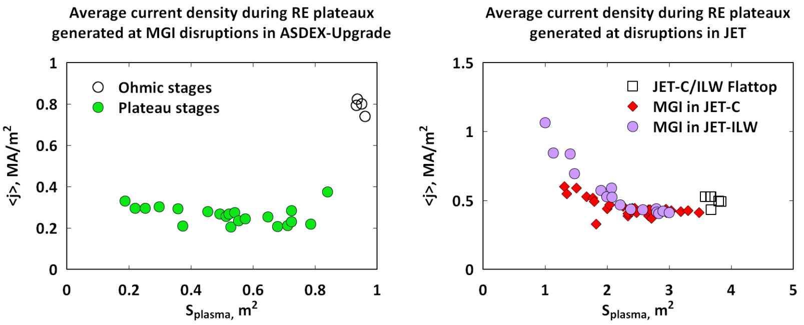

Figure 7. Comparison of average runaway current plateaux densities in ASDEX-Upgrade and JET (-C/-ILW) generated during disruptions triggered by MGI.

Runaway Generation Parameters during flattop stage in TCV, COMPASS and JET

Transient nature of disruptions does not allow reliable measurements of plasma parameters evolution. Modelling of RE generation is still very complicated task, since it requires an inclusion of many parameters, which are strongly varied during disruptions. Therefore, a scenario of RE generation on steady-sate stage of discharges in tokamaks constitutes a subject of special attention due to possibility to measure reliably plasma parameters during onset, growth and loss of relativistic RE. This steady-state scenario with low plasma density was used in the second group of experiments in COMPASS and TCV. Obtained data on RE generation dynamics was compared to the data measured during steady-state phase of the JET discharge JPN #86078 and reported in [7].

The baseline scenario for RE studies in TCV is: L-mode, inner wall limited Ohmic discharges at B_0 = 1.43 T, with I_{pl} = 200 kA and $<n_e> \leq 3*10^{19}$ m^{-3}. Conditions for measurable RE generation during flattop were achieved by controlled plasma density ramp-down (Figure 8). RE in COMPASS are normally produced during the current ramp-up phase providing measurable seed RE population detected using HXR diagnostics. The baseline scenario for RE in COMPASS is: $B_0 = 1.15$ T, $I_{pl} = 90$-150 kA, $<n_e> \leq 3*10^{19}$ m^{-3}, Ohmic, L-mode, inner wall limited. Using different fuelling scenarios the RE populations could be controlled allowing studies on RE confinement and loss during flattop [3] (Figure 9).

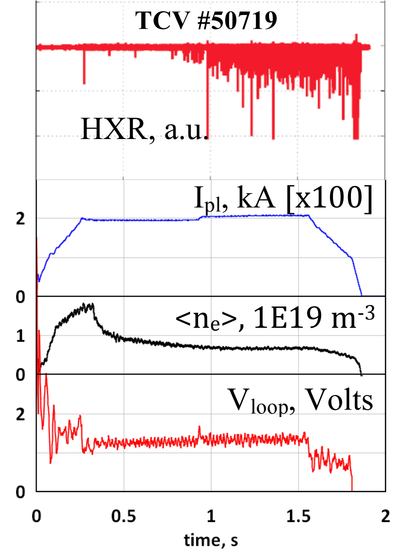

Figure 8. RE generation scenario in flattop stage in TCV discharge #50719

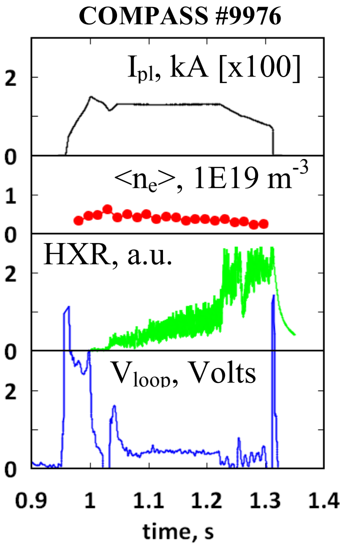

Figure 9. Main parameters in RE generating discharge in COMPASS

Similarly to JET data, plasma parameters in COMPASS and TCV have been numerically processed in order to minimize the effect of the data large scattering (filtering noise, etc.) onto results of numerical evaluation of runaway dynamics. All measured parameters were used in simulation of runaway generation in radially averaged model with the aid of iterative method [12]. In this modelling the effective ion charge value (Z_{eff}) was used as iterative parameter and calculated using the equation of plasma electro-conductivity on the basis of measured plasma current, loop voltage (V_{loop}), electron temperature (T_e) and density $<n_e>$. Analysis of low-density discharges in COMPASS, TCV and JET [7] has shown that primary (Dreicer) process is dominating in RE generation. This conclusion follows from the numerical simulation of the RE generation dynamics. In low plasma densities the mean velocity of plasma currents could increase up to $u_0 \equiv \frac{<j_{pl}>}{e<n_e>} \cong$ 1.0E6 m/sec in COMPASS, ≅ 4.0E6 m/sec in TCV and up to ≅ 3E6 m/s in JET. One can see that achieved asymmetry of electron distribution function (EDF) at corresponding streaming parameter $\xi^* \equiv \frac{u_0}{v_{Te}} \cong 0.1$ should result in increase of the number of electrons (up to 10%) moving in a velocity space close to and above the critical runaway velocity $v_{CR} = \sqrt{\frac{e^3 n_e \, ln\Lambda \, (2+Z_{eff})}{4\pi\varepsilon_0^2 m_e E_0}}$. This velocity is determined by the balancing between the electron acceleration in external electric fields (E_0) and the dissipative drag, i.e. when electrons achieve $v_e > v_{CR}$, they become runaway. Corresponding critical threshold in kinetic energy for runaway is: $W_{CR} \equiv \frac{m_e v_{CR}^2}{2} = \frac{e^3 n_e \, ln\Lambda \, (2+Z_{eff})}{8\pi\varepsilon_0^2 E_0}$. This threshold is only a parameter, which is valid for characterization of both main mechanisms responsible for RE generation – primary and avalanching. In COMPASS, TCV and JET the critical energy (W_{CR}) varied between 5-10 keV and 150-220 keV depending on measured electric fields. In terms of electric fields one can formulate that the runaway generation will develop if applied electric field E_0 will exceed a certain critical value (E_{CR}) determined by the balancing between energy gain and dissipation. For electron populations with thermal velocities: $v_{Te} = \sqrt{k\,T_e/2m_e} \ll c$ (non-relativistic energies), the runaway critical field is: $E_{CR} \equiv E_{DR} = \frac{e^3 n_e \, ln\Lambda \, (2+Z_{eff})}{4\pi\varepsilon_0^2 m_e v_{Te}^2}$. This field ($E_{DR}$) characterizes the primary (Dreicer) runaway generation process. If $E_0 \geq E_{DR}$ all plasma thermal electrons will runaway. For typical plasma parameters in tokamaks: $E_0 \ll E_{DR}$, so that only an exponentially small population of the electrons from the tail of EDF will experience collisionless acceleration with usual generation rate: $\lambda_R = C(Z_{eff}) \cdot n_e \nu_{ee} \varepsilon^{-\frac{3(Z_{eff}+1)}{16}} \cdot \exp\left(-\frac{0.25}{\varepsilon} - \sqrt{\frac{Z_{eff}+1}{\varepsilon}}\right)$, where $\varepsilon = E_0/E_{DR}$. Primary rate will increase with decrease of plasma density and increase of T_e and mean plasma current velocity. To study the RE generation dynamics on the basis of measured plasma parameters an equation for the radially averaged RE density (n_{RE}) evolution was used:

$$\frac{dn_{RE}}{dt} = \lambda_R + \frac{n_{RE}}{t_0} - \frac{n_{RE}}{\tau_{conf}} \qquad (1)$$

A perfect RE confinement is assumed, because, during the times of interest in these experiments an attainable maximum of kinetic energy was much higher than possible RE energy gain. The first term (λ_R) is described above. The evolution of RE density due to secondary avalanching [13] is characterized by the second term. Secondary avalanching growth rate is $\gamma_{AV} = 1/t_0$, t_0 is characteristic avalanching time. In [14] the avalanching time was derived in assumption that there are seed RE with high energies and accelerating electric field is much larger than critical one as it happens during disruptions: $t_0 = \frac{\sqrt{12}\, ln\Lambda\, m_e c\, (2+Z_{eff})}{9eE_0}$. More generally, the parameter t_0 is depending not only on E_0, but also on the critical field determined by drag force acting on relativistic electrons. In [15] the critical field for relativistic electrons was derived: $E_R = \frac{e^3 n_e\, ln\Lambda}{4\pi\varepsilon_0^2 m_e c^2}$. The effect of impurity ions ($Z_{eff} > 1$) on runaway process has been also investigated in [15]. It was shown that relativistic effects significantly modify the dynamics of runaway process. The critical field derived in [15] was subsequently used in [16] as a threshold field for avalanching process, i.e. $E_{CR\_AV} = E_R$, here E_{CR_AV} - critical field for avalanching. Most frequently, the avalanching time t_0 is calculated using the interpolation formula, which was derived on the basis of analytical solution of the bounce-averaged gyro-kinetic relativistic Fokker-Planck equation in different limits [16]. In approximation of large electric fields the avalanching growth could be calculated from:

$$t_0 \cong \frac{4\pi\varepsilon_0^2 m_e^2 c^3}{e^4 n_e(\alpha-1)}\sqrt{\frac{3}{\pi\varphi}(Z_{eff}+5)} \qquad (2)$$

Here, $\varphi = (1 + 1.46\sqrt{r/R_0} + 1.72 \cdot r/R_0)^{-1}$, $\alpha = E_0/E_{CR\_AV}$. In fact, the growth rates calculated using both formulas [14,16] are very similar at the presence of relativistic RE and very large electric fields that usually measured during disruptions ($E_0 >> E_{CR\_AV}$). According to (eq. (2)), the growth rate should vanish if $E_0 \le E_{CR\_AV}$, and, therefore, below E_{CR_AV} (or E_R) no runaway generation will occur [17]. However, the condition $E_0 > E_{CR\_AV}$ considered to be sufficient for generation/avalanching of RE [17] does not signify that these processes should inevitably occur. In particular, low-density regimes in COMPASS, TCV and JET [7] enabled an enhanced generation of primary RE due to low critical energies despite that this process itself required significantly larger fields than E_R. However, at very low background electron density the close distance collisions do not enable the avalanching, i.e. growth rate itself is still small $\gamma_{AV} = 1/t_0 < 1$. Condition for avalanching requires substantially larger plasma densities and very high energies of seed RE electrons. First avalanching signatures have been detected in TEXTOR RE experiments [18], in which the interaction of RE population with injected Ne and/or Ar has been studied.

The interaction of RE with injected Ar and Ne has been tested in COMPASS, TCV to mock-up the JET RE suppression experiments [1]. Two types of evolution of RE discharges (besides disruptions [2]) were detected. A strong difference between COMPASS/TCV and JET-ILW results [1, 5-7] was found. Ar injection in COMPASS and TCV resulted in slow decay of RE currents. Current time derivatives (dI_{pl}/dt) were varied between 1 and 10 MA/sec and increased with increase of injected Ar quantity. Similar effect was observed also in #52711 and #52712. Discharges were carried out with controlled plasma density ramp-down to get the

RE generation. Plasma density decrease from t ≈ 0.35 s to t=0.45 s, subsequent decrease of V_{loop} from ≈0.85 V to ≈0.56 V and appearance of HXR signal are appropriate indications for RE generation conditions (stage is marked in light blue). The Thomson scattering measurements of T_e allow calculation of critical runaway parameters. Quantification of RE process has been carried out in frames of conventional theory of runaways using equation (1) for n_{RE} and equation: $\sigma_{pl}(t)E_0(t) = j_{OH}(t) - j_{RE}(t)$, where $E_0 = V_{loop}/2\pi R_0$ and $\sigma_{pl}(t)$ is a plasma conductivity [19]. It was shown that Dreicer generation yields up to n_{RE}~6x10^{15}m^{-3} thus providing RE current density up to 300 kA/m^2 and RE population in total current is ~60 kA. An avalanching during this time was negligibly small due to low critical runaway energy and low frequency of close distance collisions. However, the avalanching growth becomes significant immediately after Ne injection at t=0.47 sec. Density increases up to ~5.2*10^{18} m^{-3} during less than 10 msec. At the same time the drastic increase of PMTX (HXR) signal (more than 10 times) was observed (Figure 10). Moreover, intense HXR bursts were measured with amplitude about 100 times larger. Apparent expectations that Ne injection will disrupt discharge or somehow will reveal the strong dissipative effect onto RE population were not satisfied. Dissipative effect of Ne injection in these discharges was observed only partly. Namely, it caused the complete thermal collapse. Following T_e collapse the V_{loop} signal revealed transient but measurable increase. After that, the V_{loop} experienced obvious 2-times decrease despite low T_e and high plasma resistance. Time resolved analysis of this stage has shown that simultaneous fast increase of density and fast plasma cooling resulted in short time but large change of parameters in formula for avalanching time t_0 (formula (2)). During flattop stage the avalanche growth rate was well below 1. Fast increase of density and resistive electric fields resulted in increase of avalanching growth rate well above 10. After transition measured obvious V_{loop} decrease indicated self-limiting of avalanching. Note, TEXTOR study did not reveal significant changes in V_{loop} and only HXR and infrared emissions were used to characterise avalanching [18]. Evaluation of RE avalanching growth rate and calculation of RE density (with eq. (1)) show that after transition RE can carry up to 150 kA in a total plasma current in discharge #52716. This discharge was lasting till to 1.581 sec when it was terminated by disruptive-like event following the loss of half of the total plasma current and intense burst of HXR emission (Figure 11). A loss of the remaining fraction of the plasma current did not indicate any signature of the presence of any fraction of energetic electrons.

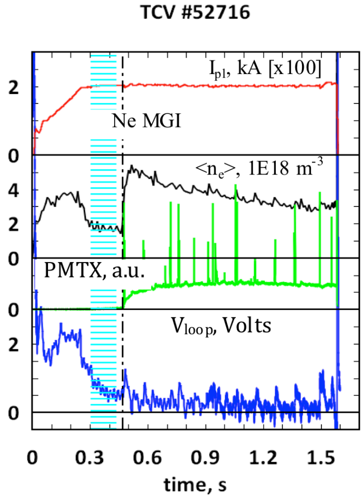

Figure 10. Signatures of RE avalanche and kinetic instability driven by RE in TCV.

Simultaneously to detection of avalanching in pulses #52711-#52712-#52716 the events characterizing the kinetic instability driven by RE have been observed. Usually it is identified when characteristic positive/negative spikes in V_{loop} signals, huge bursts in HXR, etc. are detected. These events were detected in RE discharges in TCV. The magnetized Langmuir oscillations in plasma could be generated if the certain conditions on runaway beam velocity and density are satisfied: $V_{beam} > 3V_{cr}{}^*(\omega_{ce}/\omega_{pe})^{3/2}$, where $V_{cr}=V_{Te}\alpha^{-1/2}$ ($\alpha=E_0/E_{DR}$); and $\nu_{eff} > \nu_e$, where $\nu_e=2.91{*}10^{-6}\ln\Lambda{*}n_e Z_{eff}T_e^{-3/2}$ and ν_{eff} is the effective collision frequency, which characterizes the enhancement of collisions due to electrostatic oscillations: $\nu_{eff}\approx\pi^{1/2}\omega_{pe}(\omega_{pe}/\omega_{ce})K(Zeff){*}\ \alpha^{-3(Z+1)/16-1.5}\exp\{-1/4\alpha-((Z+1)/\ \alpha)^{1/2}\}$. Analysis of parameters of

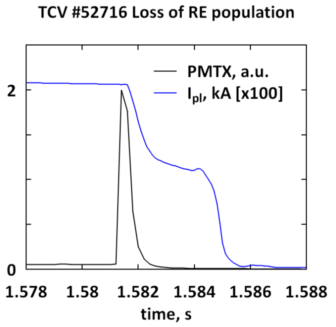

Figure 11. Termination of TCV discharge #52716

TCV discharges shows that this instability could be effectively excited resulting in intense scattering of energetic electrons. These instability events caused observed transient evolution of V_{loop} and intense bursts of PMTX signal. This data will be studied more in detail to provide the information on possible methods for destabilization of RE beams in tokamaks.

Summary

1). Experiments on disruption generated RE have been carried out in small, medium-sized and large tokamaks – COMPASS, TCV, ASDEX-Upgrade and JET. Small and medium sized tokamaks revealed wide range of possibilities for efficient study of RE generated at disruptions and during flattop of discharges. Disruption scenarios with MGI developed at JET were used in and allowed a study of RE generation at disruptions in COMPASS, TCV and ASDEX-Upgrade. RE generation parameters revealed similar trends to that obtained in JET-C and JET-ILW. It is shown that the probability of RE generation increases with increase of limits for spatial and temporal variations of plasma parameters during disruptions.

2) RE generation process was studied during flattop stages of COMPASS and TCV discharges. In low-density discharges the primary (Dreicer) mechanism is the main source for RE generation. Low frequencies of close distance collisions and low critical runaway energies are constraining the RE avalanching, which should be effective with increase of plasma density.

3) RE secondary avalanching was identified and evaluated for the first time in TCV in RE generating discharges after Ne injection. It was found that RE current fraction created via avalanching process could achieve half of the total plasma current in TCV, while the low temperature bulk electron population could carry the other part of current.

4) The evidence for kinetic instability (characteristic HXR bursts) has been observed in dominating RE discharges in TCV after avalanching. Parameter space for instability is still under analysis.

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