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On the measurement of the threshold electric field for runaway electron generation in the Frascati Tokamak Upgrade

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Experiments have been carried out to evaluate the threshold electric field for runaway generation during the flat-top phase of ohmic discharges in the Frascati Tokamak Upgrade tokamak. An investigation of the conditions for runaway electron generation and suppression has been performed for a wide range of plasma parameter values. The measured threshold electric field is found to be significantly larger ($\sim 2 - 5$ times) than predicted by the relativistic collisional theory of runaway generation, $E_R = n_e e^3 \ln \Lambda / 4\pi \epsilon_0^2 m_e c^2$, and can be explained to a great extent by an increase of the critical electric field due to the effect of the electron synchrotron radiation losses. These findings are consistent with the results of an ITPA joint experiment to study the onset, growth, and decay of relativistic runaway electrons [Granetz *et al.*, Phys. Plasmas **21**, 072506 (2014)]. Confirmation of these results for disruptions with high electric field might imply significantly lower requirements on electron densities for suppression and prevention of runaway formation in ITER. *Published by AIP Publishing.* [\[http://dx.doi.org/10.1063/1.4968839\]](http://dx.doi.org/10.1063/1.4968839)

I. INTRODUCTION

Runaway electrons (REs) represent a major threat in the operation of tokamaks, especially when generated during disruptions, and the understanding of the conditions that lead to their generation is important in the design of systems capable to mitigate and suppress them.

The runaway electron phenomenon in tokamaks is the result of the decrease of the Coulomb collision frequency with energy, $dp/dt \sim v^{-2}$ (p is the electron momentum) so that, for a given toroidal electric field in the device, it is always possible to find electrons with a large enough velocity for which the electric field force is larger than the collisional friction loss ($\sim v^{-2}$) and will be continuously accelerated, that is, they run away.¹ However, due to relativistic effects, the electron velocity cannot increase indefinitely when its momentum increases, but $v \rightarrow c$, so that for weak enough electric fields, below a critical or threshold electric field

$$E_R = \frac{n_e e^3 \ln \Lambda}{4\pi \epsilon_0^2 m_e c^2}, \quad (1)$$

absolutely no runaway electrons can be produced² as, if $E_{||} < E_R$, $v > c$ would be required for electron acceleration. Moreover, below such a threshold field E_R , all the existing runaway electrons are suppressed and become finally thermalized.

The critical electric field E_R , is not only a relevant parameter describing the runaway dynamics, but it also has important practical implications. Hence, runaway electron suppression during disruptions by densification using massive gas injection (MGI) or shattered pellet injection (SPI)

aims to reach the critical electron density above which runaway electron generation is prevented ($E_{||} < E_R$).³⁻⁵ However, in a large device like ITER, taking into account the present injection limits and the assimilation efficiency of the injected gas species (mainly Ar, Ne, He or D_2), it is still an open question if such a large density might actually be achieved. Moreover, for the case of argon or neon injection, because of the high cooling rate of these gases, the current quench time would be expected to fall below the eddy current limit, resulting in unacceptable forces on the ITER vessel and in-vessel components.⁴

Runaway suppression experiments by means of Electron Cyclotron Resonance Heating (ECRH) in the flat-top phase of Frascati Tokamak Upgrade (FTU) discharges⁶ found that the runaway electrons can be suppressed at electric fields substantially larger than those predicted by the relativistic collisional theory of runaway generation [Eq. (1)], and results from a recent ITPA joint experiment to study the onset, growth, and decay of the runaway electrons during quiescent, flat-top conditions in several devices⁷ also support evidence for a new threshold for runaway generation larger than the collisional threshold.² These findings suggest that there are other runaway electron loss mechanisms, in addition to collisions, that might be dominating the runaway dynamics in these experiments. On the other hand, this would imply that the required critical density for runaway mitigation might be significantly lower than expected on the basis of the relativistic collisional theory of runaway generation. Understanding the nature of such additional runaway loss mechanisms and whether this can be confirmed for disruption generated runaway electrons, remain open issues.

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This paper reports on experiments designed to evaluate the threshold electric field for runaway generation for a wide range of plasma parameters during the flat-top of ohmic (OH) discharges in FTU,⁹ a circular cross-section tokamak (major radius $R_0 = 0.935$ m, minor radius $a = 0.3$ m) characterized by a high toroidal magnetic field (up to 8 T) and high plasma density (central line averaged density up to $\sim 3 \times 10^{20} \text{ m}^{-3}$). The critical conditions have been tested in two experimental scenarios: (1) runaway electron (RE) *onset* experiments, in which the density is decreased along the discharge until runaway electron generation occurs, and (2) runaway electron (RE) *suppression* of existing runaway electrons (created during a low density start-up) by gas injection. In Sec. II, the experimental setup will be described. The experiments carried out and the methodology used for the estimate of the critical field are presented in Sec. III, whereas the results are analyzed and discussed in Sec. IV. In consistency with previous studies,^{6,7} the measured threshold electric field is found to be substantially larger ($\sim 2 - 5$ times) than expected according to the purely collisional theory [Eq. (1)]. An investigation of the loss mechanisms which might explain these observations indicates that these results can be reasonably explained by an improved estimate of the threshold electric field, which includes not only the effect of the collisions but also the electron synchrotron radiation,⁶ always present, although in many cases additional energy losses still need to be invoked. An analysis of the runaway electron dynamics in these experiments allows to get a quantitative estimate of such additional losses, found to be consistent with runaway electron losses due to radial diffusion for previously reported levels of magnetic turbulence in FTU.⁸ Finally, the conclusions are summarized in Sec. V.

II. EXPERIMENTAL SETUP

The runaway electron measurements used in this work were performed using the following diagnostic systems: (a) BF_3 chambers; (b) NE213 organic liquid scintillator; (c) Gamma camera; (d) Runaway Electron Imaging and Spectrometry (REIS) system.

- (a) BF_3 chambers: Six absolutely calibrated BF_3 proportional counters (5 ms integration time), only sensitive to neutrons, placed in pairs on top of the cryostat¹⁰ to monitor the neutron yield.
- (b) NE213 organic liquid scintillator: 5 in. diameter $\times$ 5 in. thick, coupled to a Photo Multiplier Tube (PMT), sensitive both to neutrons and hard X-rays (HXR), operated in current mode (20 kHz sampling rate), placed without any collimation on the equatorial plane outside the cryostat and cross calibrated with the set of BF_3 neutron detectors in discharges with no runaway electrons.⁸ The NE213 detector is used to monitor the HXR emission due to the runaway electrons during the discharge.
- (c) Gamma camera:¹¹ it provides radially resolved measurements of HXR emitted perpendicularly to the magnetic field and produced by the runaway electrons through bremsstrahlung in the plasma. The detectors are NE213 liquid scintillators (2 in. diameter $\times$ 2 in.

thick) capable of n/γ discrimination, operated in count mode with a digital acquisition system (14-bit, 400 MSamples/s).¹² The system is sensitive to HXR with energy $> 100 \text{ keV}$ and time resolution, depending on the count rate, is down to $\sim 1 \text{ ms}$.

- (d) Runaway Electron Imaging and Spectrometry (REIS) system:¹³ A wide-angle optical system collects the runaway electron synchrotron radiation from two plasma cross sections corresponding to the RE backward and forward views, and transmits it to visible/infrared spectrometers through an incoherent bundle of fibres. The spectral range spans from 300 to 2100 nm.

III. MEASUREMENT OF THE CRITICAL ELECTRIC FIELD

The threshold electric field E_{thr} , was evaluated during the plasma current flat-top phase of deuterium ohmic discharges in two types of experiments: (1) RE onset and (2) RE suppression experiments (Fig. 1).

In the RE onset discharges (left Fig. 1), the electron density during the current ramp-up is set high enough to avoid runaway generation and then gradually decreased during the flat-top until the critical field value drops below the toroidal electric field and runaway electrons are generated. In contrast, during the RE suppression experiments (right Fig. 1), the threshold electric field is crossed in the opposite sense: the discharge starts at very low density, allowing runaway electron generation, and is followed by an increase of the density to a high enough value for runaway electron suppression, when the threshold field overcomes the accelerating electric field.

The critical time t_c , for RE onset/suppression is determined by comparison of the BF_3 neutron detector and the NE213 neutron/gamma scintillator signals (see Fig. 1). During deuterium discharges with negligible runaway population, a perfect overlapping of the BF_3 and NE213 signals occurs, while in the presence of runaways, the NE213 signal is contaminated by an excess of gamma-ray events and the NE213 scintillator signal no longer equals the BF_3 measurements.⁸ Hence, in the RE onset discharges, the scintillator signal overlaps with the BF_3 chambers signal during the pre-RE phase and begins to diverge at the time (t_c) that the runaway electrons are generated. The RE suppression experiments show a larger scintillator signal in the initial phase, indicating the presence of runaway electrons, while the two signals overlap at the time (t_c) when the runaway electron suppression occurs. Then, the threshold field is estimated as the value of the electric field at the critical time t_c , that is, at the time when the runaway signal appears (disappears) in the onset (suppression) experiments, $E_{thr} \sim V_{loop}(t_c)/2\pi R_0$.

It should be mentioned that there is an instrumental limit for the minimum amount of runaway electrons that can be detected, depending on the detector sensitivity. Thus, during the RE onset experiments, some runaway electrons might already exist in the plasma while the BF_3 and NE213 signals still coincide, and if so, the critical density (determined at t_c) would be underestimated and the measured E_{thr} (for a given density) would constitute an upper bound for the critical

FIG. 1. Time traces of the plasma current (I_p), loop voltage (V_{loop}), NE213 ($\gamma + n$) and BF_3 (n) signals, and line-averaged central density for representative discharges: RE onset (left) and RE suppression (right) experiments.

electric field. On the other hand, in the case of the RE suppression discharges, the critical electric field may be reached before the BF_3 and NE213 actually overlap, as once the critical density is achieved, some time is required until the REs are slowed down and suppressed, implying that, in this case, the critical density would be overestimated, and therefore the measured E_{thr} at a given density would constitute a lower bound for the actual threshold field. Thus, the combined use of the two separate methods, RE onset and suppression, gives the possibility to set, respectively, upper and lower limits for the critical field.

IV. DATA ANALYSIS AND DISCUSSION

A. Data analysis and comparison with the classical collisional theory

The database includes 56 deuterium discharges covering a wide range of plasma parameters ($B_t \sim 2 - 7.2$ T, $I_p \sim 0.35 - 0.9$ MA and $Z_{eff} \sim 1 - 13$). Fig. 2 shows the measured E_{thr} values as a function of the central line averaged density $\bar{n}_e$. Each point corresponds to a different discharge. The threshold field is in the range $\sim 0.1 - 0.4$ V/m and the critical (line averaged) density is typically $\sim 0.3 \times 10^{20} \text{ m}^{-3}$ for the RE onset experiments and $\sim (0.6 - 1.5) \times 10^{20} \text{ m}^{-3}$ for the suppression discharges, which is consistent with the discussion made at the end of the section above regarding the limitations of these methods for setting the threshold electric field and the critical density for runaway generation.

For a proper analysis of the parametric dependence of E_{thr} and its comparison with the theoretical predictions, it turns out to be adequate to use the local central electron density instead of the central line averaged electron density, as typically, during ohmic discharges in FTU, runaway electrons are mainly created in the central part of the plasma

column,⁸ which is corroborated by measurements of hard X-ray radial profiles (using the HXR radial profile monitor described in Sec. II) performed in the discharges of the present study. This is illustrated in Fig. 3 which shows the line-integrated HXR profiles at two different time slices during the generation of the runaway electrons for the RE onset discharge # 37714. The observed hard X-ray emission, due to in-plasma bremsstrahlung of the runaway electrons, shows a peaking in the plasma center.

Fig. 4 compares the measured threshold field in these experiments E_{thr} , with the critical field E_R , predicted by the relativistic collisional theory² using the local central electron density n_{e0} , $E_R \propto n_{e0}$ [Eq. (1)]. The electron density data are produced by a CO_2 scanning interferometer, and n_{e0} is determined through a radial inversion technique.¹⁴ The measured

FIG. 2. E_{thr} versus central line averaged density for the analyzed set of discharges.

FIG. 3. Line integrated hard X-ray profiles at $t = 0.6$ s and $t = 0.8$ s for FTU discharge #37714.

values of E_{thr} are typically in the range $E_{thr} \sim (2 - 5) \times E_R$, well above the values E_R , foreseen by the relativistic collisional theory suggesting that other runaway electron loss mechanisms, in addition to the classical collisional energy dissipation, are playing a role.

B. Synchrotron radiation losses

Although there are a number of loss mechanisms (electron radiation, drift orbit losses, turbulent transport, etc.) that could be proposed to explain the discrepancy between the measured E_{thr} and the Connor collisional threshold, the synchrotron radiation due to the electron motion on toroidal paths and to the gyromotion of the runaways, having a finite pitch angle as a result of the collisions with the plasma particles and impurity ions, is always present and its effect on the critical field for runaway generation, as that of the collisional energy losses, therefore, must always be considered.

FIG. 4. Comparison of E_{thr} for the RE onset/suppression experiments with the relativistic collisional theory E_R . Each point corresponds to a single discharge.

Thus, the classical collisional critical field E_R , should be replaced by a new threshold E_R^{rad} , including the effect of the collisions and the electron radiation. Indeed, the increase in the threshold electric field for runaway generation including these effects has been addressed several times in the past^{15–17} and has allowed to explain the observations made on runaway electron suppression during the flat-top phase of FTU ECRH heated discharges.⁶ Moreover, it was experimentally found that such a radiation threshold electric field constitutes an effective lower bound for the existence of runaway electrons in FTU.⁶

This effect is illustrated in Fig. 5, which shows the comparison between the measured E_{thr} and the critical field for runaway generation including the effects of radiation E_R^{rad} , for the onset/suppression experiments here reported. The radiation threshold E_R^{rad} , has been calculated following⁶

$$\frac{E_R^{rad}}{E_R} \simeq 1 + C(Z) F_{gy}^\alpha, \quad (2)$$

an empirical fitting to the numerically calculated E_R^{rad} using a test particle approach which takes into account the radiation associated with the electron motion on toroidal paths, as well as with the electron gyromotion,⁶ and that agrees well with the estimates based on the kinetic approximation.¹⁷ In this equation $F_{gy} = 2\epsilon_0 B_0^2 / 3n_e \ln \Lambda m_e$ is a dimensionless parameter describing the effects of radiation¹⁵ (see Sec. IV C), $\alpha = 0.45 \pm 0.03$, and $C(Z) \simeq 1.64 + 0.53 Z - 0.015 Z^2$,⁶ where Z is the ion charge which in plasmas with partially stripped impurity ions includes the effect of the scattering of the runaway electrons by the full nuclear and the electron-shielded ion charge of the impurity ions.^{18,19} For the analyzed experiments, for which the electron temperature in the plasma center (where the runaway electrons are mostly located) is of a few keV, the impurities are highly ionized and Z can be roughly approximated by the effective ion charge $Z \sim Z_{eff}$, deduced from visible bremsstrahlung measurements. As the runaway electrons are mainly located in the core region of the plasma, the local central electron density is used for the calculations.

FIG. 5. Comparison of E_{thr} for the RE onset/suppression experiments with the radiation threshold E_R^{rad} . Each point corresponds to a single discharge.

E_{thr} in Fig. 5 falls well within the range of critical fields predicted including the effect of electron synchrotron radiation losses $E_{thr} \sim (1.0 - 1.7) \times E_R^{rad}$. Furthermore, Eq. (2) for E_R^{rad} shows a dependence on the plasma parameters (n_e , B_0 and Z in contrast to the dependence on n_e alone for E_R) which seems to be consistent with the measurements. This is illustrated in Fig. 6 in which the measured $(E_{thr}/E_R^{rad} - 1)$ is plotted as a function of $C(Z) \cdot F_{gy}^\alpha$ [$C(Z)$, F_{gy} and α defined above] for the analyzed discharges. According to Eq. (2), $C(Z) \cdot F_{gy}^\alpha$ quantifies the deviation of E_R^{rad} from the collisional threshold and contains the dependences of E_R^{rad} on the plasma parameters [$C(Z) \cdot F_{gy}^\alpha \propto C(Z) \cdot B_0^\alpha/n_e^\alpha$, with $\alpha \sim 0.45$]. Fig. 6 suggests that the predictions of the synchrotron radiation theory provide a good agreement with the measurements not only as far as the magnitude of the threshold electric field is concerned, but also the dependence of E_R^{rad} on the plasma parameters [Eq. (2)] reasonably agrees with the experiment. The results shown in Figs. 5 and 6 also indicate that, although close, the measured E_{thr} is typically larger than E_R^{rad} [$\sim (1.0 - 1.7) \times E_R^{rad}$]. This behavior is not unexpected, since the radiation threshold (E_R^{rad}) sets a minimum electric field below which no runaways can exist when collisions and radiation losses are considered. However, the presence of other loss mechanisms (such as radial runaway losses due to magnetic fluctuations,²⁰ drift orbit losses, etc.) cannot be discarded, increasing even further the value of the threshold field for runaway generation, which is supported by a detailed analysis of the runaway electron dynamics in these experiments as will be shown in Sec. IV C.

C. Runaway electron dynamics

Here, a detailed analysis of the runaway electron dynamics for the onset and suppression experiments is carried out. The runaway electron production, energy, and distribution function are calculated. Its comparison with the

FIG. 6. For FTU RE onset/suppression discharges: $(E_{thr}/E_R^{rad}) - 1$ versus $C(Z) F_{gy}^\alpha$ [$C(Z)$ and α defined in the text]. The full and dashed lines show the predicted radiation and collision threshold electric fields E_R^{rad} and E_R , respectively.

existing observations will provide a useful insight on the behavior of runaway electrons in these discharges allowing, in the case of the RE suppression experiments, to introduce a quantitative estimate of the magnitude of the additional losses that must be invoked to explain the deviations of E_{thr} from the critical field due to collisions and electron synchrotron radiation (E_R^{rad}).

Fig. 7 shows the results of simulations for the RE onset discharge # 37714 (left Fig. 1). The runaway production [trace (b) in left figure] has been calculated according to the Dreicer mechanism (due to electron diffusion in velocity space at the critical velocity) by the expression^{2,21}

$$\frac{dn_r}{dt} = n_e \nu_0 \lambda(\varepsilon), \quad (3)$$

where n_r is the runaway density, ν_0 is the collision frequency, and λ is the runaway birth parameter, mainly determined by the parameter $\varepsilon \equiv E_{||}/E_D$, with $E_D = e^3 n_e \ln \Lambda / (4\pi \varepsilon_0^2 k T_e)$. Although it is not possible to make an absolute comparison between the calculated Dreicer growth rate and the runaway diagnostics signals, runaway electron generation in FTU ohmic discharges is typically dominated by the Dreicer mechanism⁸ and the resulting time evolution of $\int (dn_r/dt)_{Dreicer}$ [trace (b) in Fig. 7] for the RE generation experiments is found to be usually consistent with the runaway measurements and the estimated critical times for runaway generation (BF₃ and NE213 traces). For the example shown in Fig. 7 ($E_{||} \sim 0.24$ V/m, $T_e \sim 3$ keV, $n_e \sim 3 \times 10^{19}$ m⁻³), the parameter $\varepsilon \equiv E_{||}/E_D \sim 0.05$ should lead to a sizeable Dreicer runaway production.²²

Nevertheless, secondary generation²³ cannot be discarded. According to this theory, runaway electrons are produced due to Coulomb collisions between existing runaway electrons and thermal electrons which, as a result, become runaways. The characteristic avalanching time τ_s , calculated using the approximation²⁴ is given by

$$\tau_s \approx \frac{4\pi \varepsilon_0^2 m_e^2 c^3}{e^4 n_e} \sqrt{\frac{3(5 + Z_{eff})}{\pi}} \left(\frac{E_{||}}{E_R} - 1 \right)^{-1}, \quad (4)$$

which, in the case of the discharge in Fig. 7, yields $\tau_s \sim 0.7$ s, so that the secondary generation mechanism could contribute somewhat to the formation of the runaway population during the late phase of the discharge, although the runaway losses via radial diffusion, with a characteristic diffusion time for FTU ohmic discharges $\tau_d \sim 0.4$ s,⁸ should prevent the exponential growth associated with the avalanche mechanism.

The runaway energy distribution function $f(E)$, has been estimated calculating the energy evolution of the generated runaway electrons by means of the simple test particle description of the runaway dynamics,¹⁵ including the electric field acceleration, collisions with the plasma particles, and deceleration due to synchrotron radiation losses

$$\frac{dq_{||}}{d\tau} = D - \gamma(1 + Z_{eff} + \gamma) \frac{q_{||}}{q^3} - \left(F_{gc} + F_{gy} \frac{q_{\perp}^2}{q^4} \right) \gamma^4 \left(\frac{v}{c} \right)^3 \frac{q_{||}}{q}, \quad (5)$$

FIG. 7. For the RE onset discharge #37714 ($I_p = 0.36$ MA; $B_t = 6$ T): Left: Time evolution of BF₃ and NE213 scintillator signals (a), estimated runaway production (b), and calculated maximum and average runaway energies (c). The estimated maximum energy from the central chord measurements of the hard X-ray profile monitor (open dots) is also shown for comparison; Right: Calculated runaway distribution function at 0.55, 0.85 and 1.25 s.

$$\frac{dq}{d\tau} = D \frac{q_{\parallel}}{q} - \frac{\gamma^2}{q^2} - \left(F_{gc} + F_{gy} \frac{q_{\perp}^2}{q^4} \right) \gamma^4 \left(\frac{v}{c} \right)^3, \quad (6)$$

where $q_{\parallel}$, $q_{\perp}$ and q are the parallel, perpendicular, and total electron momenta normalized to $m_e c$, v is the electron velocity and γ is the relativistic gamma factor [electron kinetic energy, $E = (\gamma - 1) m_e c^2$]; $\tau = \nu_r t$, with $\nu_r = n_e e^4 \ln \Lambda / 4 \pi \epsilon_0^2 m_e^2 c^3$; $D = E_{\parallel} / E_R$ is the normalized electric field and F_{gc} , F_{gy} describe the two contributions to the radiation losses coming from the guiding center motion and the electron gyromotion, respectively: $F_{gc} = F_{gy} (m_e c / e B_0 R_0)^2$, $F_{gy} = 2 \epsilon_0 B_0^2 / 3 n_e \ln \Lambda m_e$.

The first term in these equations corresponds to the acceleration due to the toroidal electric field, and the second term includes the effect of the collisions with the plasma particles.²⁵ The third term describes the synchrotron radiation losses.¹⁵

At each time step, the runaway electrons are assumed to be generated at the lowest energy $\gamma_0 > \gamma_c$ (γ_c : critical energy for runaway generation), and then the runaway distribution function at time t is formally given by

$$f(\gamma, t) = \int_0^t \frac{dn_r}{dt'} (\gamma_0, t') dt', \quad (7)$$

where $t=0$ denotes the start of the runaway generation process and the integration is carried out over the times t' , for which an electron generated with energy γ_0 , would have gained, according to the test particle equations, an energy γ at time t . The resulting distribution function at three different times during the discharge is plotted in right Fig. 7. The distribution function is broad, extending up to the maximum runaway energy at each time step, and showing a trend along the discharge to accumulate close to the limiting energy ~ 3 MeV.

Trace (c) in left Fig. 7 shows the time evolution of the calculated maximum electron energy E_{max} , and the average runaway energy

$$E_{av} = \frac{\int_{\gamma_0}^{\gamma_{max}} (\gamma - 1) m_e c^2 f(\gamma) d\gamma}{\int_{\gamma_0}^{\gamma_{max}} f(\gamma) d\gamma}, \quad (8)$$

[$E_{max} = (\gamma_{max} - 1) m_e c^2$].

Initially, E_{max} is noticeably larger than E_{av} , and later in the discharge, once the electrons start to accumulate close to the limiting energy, E_{max} and E_{av} get closer. The maximum measured gamma energy determined from the end points of the gamma ray spectra for the central chord of the gamma camera is also shown as function of time in trace (c) in the figure and can be assumed to describe the time evolution of the maximum runaway energy. Despite the large uncertainties, to a great extent associated to the relatively low number of gamma counts (particularly for the earlier times in the discharge) which prevent from getting more accurate estimates, the measurements seem to be consistent with the calculations.

A second example of a RE onset discharge is illustrated in Fig. 8. In this case, the simulations suggest a large electron energy increase (up to $\sim 30 - 40$ MeV) during the RE generation phase, which is supported by measurements of the REIS system. Hence, Fig. 9 shows the measured synchrotron radiation spectra at three different times during the discharge (1.3, 1.4 and 1.5 s). The spectra are fitted (black solid lines) using formula (1) from Ref. 26 for the power radiated by the electron. Although the entire distribution function should be used for an accurate calculation of the synchrotron radiation spectra, for the aim of a simple estimate of the maximum electron energy, as it has been done in the past in several studies,²⁷ the synchrotron emission from a single electron is used as an approximation, using a specific value of the momentum and pitch-angle identified as the maximum momentum and pitch-angle of the runaway electrons. The electron pitch angle ($\theta \sim 0.1$ rad) is obtained from the test particle simulations of the runaway dynamics and the maximum electron energy is given by the values best fitting the spectra (see inset in Fig. 9) which are found to be consistent with the predictions of the simulations based on the test

FIG. 8. For the RE onset discharge # 39469 ($I_p = 0.37$ MA; $B_t = 3.7$ T): Left: Time evolution of BF₃ and NE213 scintillator signals (a), estimated runaway production (b), and calculated maximum and average runaway energies (c); Right: Calculated runaway distribution function at 0.8, 1.0 and 1.4 s.

particle model (energy $\sim 30 - 40$ MeV). The large energy reached by the electrons in this discharge in comparison with # 37714 (~ 3 MeV) is due to the larger accelerating electric field (~ 0.4 V/m vs. ~ 0.25 V/m for # 37714) and to the lower synchrotron radiation losses as a result of the smaller magnetic field (3.7 T vs. 6 T, respectively), and a lower (nearly half) Z which reduces the collisionality, and hence, the electron pitch angle and the synchrotron radiation associated with the electron gyromotion.

The RE suppression experiment is presented in Fig. 10. The runaway electrons are generated in the beginning of the discharge (due to the large electric field and low density, as shown in Fig. 1) and the runaway production stops soon during the current ramp-up at ~ 0.15 s [trace (b) in left figure], when $E_{\parallel}$ decreases and the density increases. Initially, the runaway energy rises up to ~ 4 MeV [trace (c)] and decreases later on along the discharge, when the density increases until

the runaway electrons are suppressed. As the runaway production stops early in the discharge (~ 0.15 s), the distribution function rapidly evolves towards a mono-energetic beam (right pictures) with an average energy equal to the maximum runaway energy [left Fig. 10(c)]. As discussed in Sec. IV A, for a substantial number of discharges, the collisions and the electron radiation cannot account for all the runaway losses (typically $E_{thr} > E_R^{rad}$) suggesting that additional energy dissipation mechanisms should be playing a role. Indeed, in the simulations shown in Fig. 10, a loss term $-\vec{q}/\tau_d$ ($\tau_d \sim 0.14$ s in the figure) must be included in the test particle equations in addition to the collisional and radiation losses for consistency with the inferred runaway suppression from the BF₃/NE213 signals [trace (a) in left figure]. If no additional RE losses were considered ($\tau_d \rightarrow \infty$; red line in the figure), runaway electrons would not be suppressed and at ~ 0.8 s the runaway electron energy would still be ~ 3 MeV. As in Fig. 7, the open dots in trace (c) indicate the estimates of the maximum electron energy from the central line of sight of the hard X-ray profile monitor. The measurements agree reasonably well with the simulations up to ~ 0.4 s. The last experimental point (at 0.7 s) has a large error bar (the number of counts is very low), but compatible with the zero energy (i.e., runaway suppression) expected by the overlap of the BF₃ and NE213 time traces.

The empirical dissipation time τ_d , constitutes a quantitative measurement of the unknown energy loss mechanisms which should be taken into account in addition to the collisions and the electron synchrotron radiation to explain the observed runaway suppression in these experiments. The estimated values of τ_d for the set of analyzed discharges typically lie in the range $\sim 0.05 - 0.3$ s.

Among the mechanisms which could be proposed to explain these additional losses, quantified by means of τ_d , the radial diffusion of the runaway electrons, mainly due to magnetic fluctuations, has been often assumed to account for the observed anomalous runaway losses in many devices,^{28,29} which indeed might increase the value of the threshold electric field for runaway generation.^{20,30} There is no direct evidence for such a magnetic turbulence in these

FIG. 9. Synchrotron radiation spectra for the RE onset discharge # 39469 at 1.3, 1.4 and 1.5 s. Best fittings to the spectra (black solid lines) and the parameters used (electron energy and pitch angle; see inset in the figure) are also shown.

FIG. 10. For the RE suppression discharge #37405 ($I_p = 0.52$ MA; $B_t = 6$ T): Left: (a) Time evolution of BF₃ and NE213 scintillator signals, (b) estimated runaway production, and (c) calculated maximum and average runaway energies including additional energy losses ($\tau_d = 0.14$ s; black lines). The red line indicates the predicted runaway energy assuming no additional loss mechanisms ($\tau_d \rightarrow \infty$) for which no runaway suppression would be predicted. The estimated maximum energy from the central chord measurements of the hard X-ray profile monitor (open dots) is also shown for comparison; Right: Calculated runaway distribution function at 0.24, 0.44 and 0.64 s.

experiments, but measurements of the radial runaway diffusion coefficient in FTU ohmic discharges have provided estimates of the level $\tilde{b} \equiv \tilde{B}_r/B_0$ of the radial magnetic turbulence $\sim 10^{-5}$.⁸ Indeed, if it is assumed that the energy dissipation time τ_d in these experiments is determined by the radial loss of the runaway electrons, a runaway diffusion coefficient $D_r \sim a^2/5.8\tau_d$,²⁰ can be deduced, yielding $D_r \sim (0.05 - 0.3) \text{ m}^2/\text{s}$, which is in consistency with previous measurements made in FTU⁸ as well as in other tokamaks.^{28,29} From D_r , a simple estimate of $\tilde{b}$ can be obtained using the theoretical prediction for the diffusion coefficient $D_r \approx \pi q R_0 \tilde{b}^2 v_{||}$,³¹ where q is the safety factor and $v_{||}$ is the runaway velocity parallel to the toroidal magnetic field, yielding $\tilde{b} \sim 10^{-5}$, also consistent with the values previously reported in FTU ohmic discharges.⁸ The large drift displacement of the runaway electrons when their energy increases can decouple them from the field lines and so reduce their sensitivity to the magnetic turbulence^{32,33} and the resulting radial diffusion losses. The corrections to D_r due to drift orbit averaging depend on the relation between the runaway drift displacement and the radial correlation length of the turbulence. The runaway drift can be estimated by $d_r \approx m_e \gamma v_{||} q / e B_0$ which, assuming a typical runaway energy for the discharges for which τ_d was determined ~ 3 MeV (Fig. 10), would lead to $d_r \sim 2$ mm. On the other hand, the correlation length σ of the turbulence can be approximated by $1/m$, where m , the poloidal number of the fluctuations, is given roughly by $m \approx a/\rho_i$ (ρ_i is the ion Larmor radius) which, for the discharges considered ($T_i \sim T_e \sim 1 - 3$ keV) would yield $\sigma \sim 3 - 4$ mm. Hence, the runaway drift orbit displacement would be of the order or smaller than the radial correlation length of the turbulence, and large corrections due to drift orbit averaging effects should not be expected.

In summary, the estimated level of the magnetic fluctuations required to account for τ_d in these experiments (and so for the increase of E_{thr} over E_R^{rad}) would be consistent with the estimated values of $\tilde{b}$ inferred from the measured runaway radial diffusion coefficient in FTU ohmic discharges.⁸ On the other hand, losses associated with the outward drift of

the electron orbit when its energy increases do not seem to play a significant role in most cases. As discussed above, the magnitude of the runaway drift is typically only of a few mm and most of the runaway electrons are located in the central region of the plasma in these experiments. Nevertheless, other loss mechanisms (such as, for example, kinetic instabilities) cannot be completely discarded.

V. CONCLUSIONS

Dedicated experiments on RE onset and suppression have been carried out in the FTU tokamak in order to determine the threshold electric field for runaway generation during the flat-top phase of ohmic discharges.

More precisely, taking into account the sensitivity of the runaway detectors and the limitations of the methodology employed, the use of the two separate methods allows to provide upper (RE onset) and lower (RE generation) limits for the threshold field E_{thr} . It is found that the critical field for runaway generation measured in FTU is $\sim 2 - 5$ times larger than expected according to the relativistic collisional theory.² These results are in agreement with a recent ITPA joint experiment carried out in several tokamaks⁷ and suggest that other runaway electron energy loss mechanisms, in addition to collisions, should be playing a role and explain the differences with the classical theory. Indeed, the results found for E_{thr} reasonably agree with an improved threshold electric field for runaway electron generation E_R^{rad} , which includes the effect of the losses always present due to the collisions and the electron synchrotron radiation,¹⁵⁻¹⁷ $E_{thr} \sim (1.0 - 1.7) \times E_R^{rad}$, confirming earlier results from FTU RE suppression experiments by means of electron cyclotron resonance heating.⁶ Moreover, not only the measured E_{thr} is closer to E_R^{rad} but the predicted dependence of the new threshold electric field on the plasma parameters also matches reasonably well with the experimental data.

Nevertheless, even taking into account the electron synchrotron radiation, the measured threshold field E_{thr} , although close, is often found to be larger than E_R^{rad} and simulations of the runaway energy dynamics (runaway energy

and distribution function) during the RE suppression experiments confirm that additional losses should be considered in order to reproduce the observed runaway suppression. The simulations indicate that the characteristic dissipation time τ_d , describing the unknown additional losses is in the range $\sim 0.05 - 0.3$ s and that, if these are assumed to be due to anomalous radial losses driven by the underlying magnetic turbulence, the radial diffusion coefficient describing the radial runaway transport should be $D_r \sim (0.05 - 0.3) \text{ m}^2/\text{s}$ and the corresponding radial magnetic fluctuation level $\tilde{b} \sim 10^{-5}$, consistent with values previously reported in the core region of FTU ohmic discharges,⁸ although it cannot be completely discarded that other loss mechanisms (such as, for example, kinetic instabilities) might be playing a role.

These experiments, together with those performed within the ITPA joint experiment on low density flat-top runaway electron discharges,⁷ would imply that the required critical density for runaway mitigation might be noticeably lower than expected on the basis of the relativistic collisional theory of runaway generation, and it is still an open issue if these results can be confirmed for disruption generated runaway electrons.

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