EUROFUSION CP(15)05/89

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(22nd June 2015 – 26th June 2015)
Lisbon, Portugal

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Introduction. Runaway electron (RE) experiments are an important part of the ongoing ITER-relevant studies on COMPASS, as the REs could severely damage the plasma facing components in the future fusion reactors. The electron is said to “run away” (in the velocity space), when the collisional drag force F_{coll} acting on it becomes smaller than the accelerating force F_{acc} due to the toroidal electric field E_{tor}. This net accelerating force comes from the fact that the F_{coll} decreases with approximately quadratic dependence on the velocity. The theory made by Dreicer [1, 2] defines a critical velocity v_c above which one an electron diffusing in the velocity space becomes the RE (*primary/Dreicer* mechanism). Beside diffusing, a thermal electron can escape to the runaway region if it collides with the primary generated RE and both the electrons remain in the runaway region (*secondary/avalanche* mechanism).

A relativistic accelerated charged particle in the presence of the magnetic field emits Synchrotron Radiation (SR). As SR is emitted preferentially in the direction parallel to the RE motion (the so-called headlight effect) it should be observed from a tangential view. Consequently, the SR offers a valuable opportunity for measuring parameters of the confined high-energy REs directly from the plasma core.

In this paper it is demonstrated that the relative intensity of the infrared (IR) radiation is correlated with the critical energy W_c for production of REs. Furthermore, analysis of the first direct observation of the RE beam in the COMPASS tokamak with the calibrated camera is presented.

Experimental Setup. The COMPASS tokamak [3] is a experimental fusion device with major radius $R_0 = 0.56\,\mathrm{m}$ and minor radius $a = 0.23\,\mathrm{m}$. Toroidal magnetic field B_{tor} was 1.15 T for all discharges reported in this paper, the typical pulse length is 0.4 s, although the low current circular discharge dominated by REs can last approximately 1 s. Furthermore, the SR was successfully measured at the low line-averaged density discharges ($\bar{n}_e \leq 2.5 \times 10^{19}\,\mathrm{m}^{-3}$) for the wide range of the plasma current values $100 - 250\,\mathrm{kA}$.

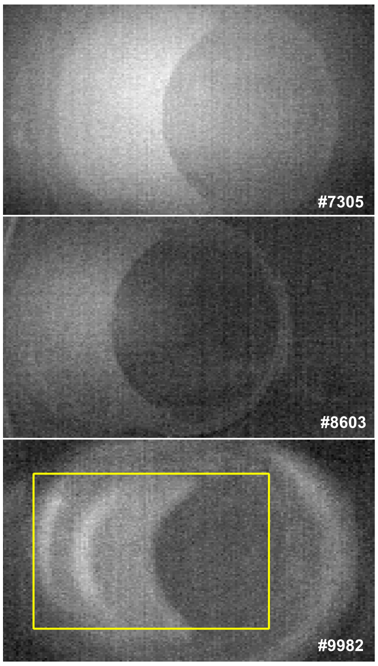

Figure 1: Different observations from the first (top) to the third (bottom) campaign. The moon-like shape is the carbon neutral beam injector dump. A yellow rectangle is the analysed area from Fig. 3.

The SR falls in the mid-wavelength IR region for the REs generated in the COMPASS tokamak, therefore the bolometric IR camera with the wavelength range $7.5 - 13\,\mu\mathrm{m}$ was used. During these experiments, the IR camera was installed at a mid-plane tangential port. The diameter of the observed area of the plasma cross-section varied between the RE campaigns: 14.9, 16.9 and 15.5 cm for the first, the second and the third campaign, respectively. Fig. 1 shows the resulting differences in the observed picture.

Results. Even though the observed area was relatively large for monitoring of the plasma core in comparison to a, it seems that almost all of the recorded intensity is rather a reflection of SR from the vessel than a direct SR from the visible plasma volume. Nevertheless, it is possible to analyse the dependence of the relative synchrotron intensity as function of the critical energy W_c. Following the Dreicer runaway theory, the critical energy is given as [4]:

$$W_c = \frac{e^3 \ln\Lambda}{4\pi\varepsilon_0^2}\frac{n_e}{E_{tor}}\sqrt{2+Z_{eff}}, \qquad (1)$$

where Z_{eff} is the effective ion charge and $\ln\Lambda$ is the Coulomb logarithm. For the calculation given here Z_{eff} is assumed to be constant and set to $Z_{eff} = 2$, therefore W_c is proportional to the ratio between the electron density n_e and the loop voltage V_{loop}, which are both measured quantities. In Fig. 2 the maximum of the relative intensity from the IR camera signal is plotted as a function of the averaged W_c during the first 240 ms of the discharge. One can see that different set-ups have different maxima, but in general a margin around $\sim 40\,\mathrm{keV}$ could be distinguished.

There are two main reasons why almost all discharges with the observation of the SR come from the reflection. First, the observed field of view is slightly farther from the region where the high-energy REs are presumably generated [5]. Moreover, even if the RE beam reaches proper radial position for the direct observation of the SR, the IR camera almost regularly disconnects. This is probably because the radiation is so strong that it saturates the camera's electronics. The cases when the camera disconnects are separately grouped and plotted on Fig. 2 and one can see that they occur only when $W_c < 37\,\mathrm{keV}$.

The evolution of the RE beam for the discharge #9814 is showed in Fig 3. The SYnchrotron spectra from RUnaway Particles (SYRUP) code [6] is used for the theoretical estimation of the

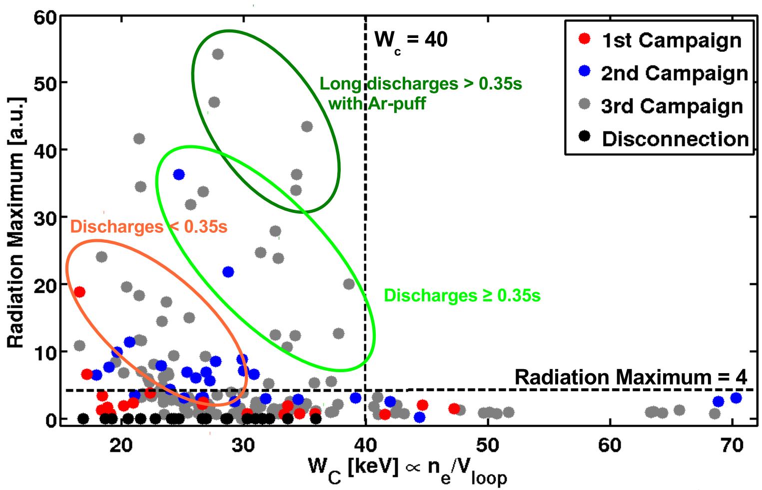

Figure 2: The relative intensity measured by the IR camera as a function of the averaged W_c during the first 240 ms of the discharge. Discharges are grouped by the campaigns, while discharges when the IR camera disconnects during all campaigns are grouped separately.

synchrotron spectral power density $dP/d\lambda$ per RE. The SYRUP requires the maximum RE energy W_{max} and the pitch angle $\theta = \arctan\left(v_\perp/v_{||}\right)$ as inputs. The latter one can be measured from Fig. 3 [7], while W_{max} has been calculated using the 0D-model from [8] that takes into account a power gain by the electric field P_E and a power loss by the SR P_{synch} for the highly relativistic electrons:

$$\frac{dW_{max}}{dt} = P_E - P_{synch}, \quad P_E = ecE_{tor} = \frac{ecV_{loop}}{2\pi R}, \quad P_{synch} = \frac{2m_e c^3 r_e \gamma^4}{3R_C^2} \tag{2}$$

where r_e is the classical electron radius and R_C is the curvature radius of the RE. The plasma parameters are necessary for the quasi-steady-state RE distribution function calculation implemented in SYRUP. For purpose of this paper, the necessary plasma parameters are taken to be constant: $\bar{n}_e = 1.6 \pm 0.2 \times 10^{19}\,\mathrm{m}^{-3}$, $T_e = 530 \pm 60\,\mathrm{eV}$, $Z_{eff} = 2$ and $E_{tor} = 0.33 \pm 0.04\,\mathrm{V/m}$. Furthermore, the calculation from Eq. 2 gives rising W_{max} from 20 to 30 MeV at time when the SR was observed (Fig. 3).

The derivative $dP/d\lambda$ obtained from SYRUP should first be converted to an integral, measurable value such as brightness B [8]:

$$B(\lambda, \theta, W_{max}) = \frac{dP}{d\lambda}\frac{2R}{\pi\theta} n_{re}^{synch}, \tag{3}$$

where n_{re}^{synch} is the density of the observed REs. To get the comparable theoretical estimation

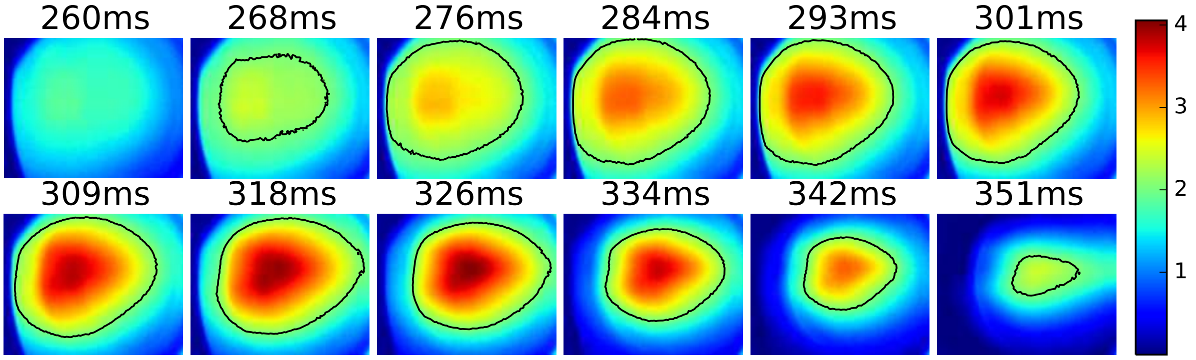

Figure 3: Time evolution of the RE beam observed with the IR camera (the color scale is in W sr^{-1} m^{-2}). The black line represents 50% of the maximum intensity, which is taken as the margin of the RE beam. Note that in order to obtain this evolution, the radiation level as observed at 227 ms (the background thermal radiation) is subtracted from all the frames.

with the IR camera measurement, the brightness B can be integrated over the camera wavelengths:

$$S(\theta, W_{max}) = \int B(\lambda, \theta, W_{max}) T(\lambda) \mathrm{d}\lambda, \tag{4}$$

where $T(\lambda)$ is a transparency of the optical path between the plasma and the IR camera. The pitch angle θ in the IR camera measurements varied from 0.15 to 0.30 rad, which leads to the corresponding RE density n_{re}^{synch} values $0.65 - 1.7 \times 10^{15}\,\mathrm{m}^{-3}$. Note that this evaluated n_{re}^{synch} gives only density of the high-energetic REs contributing to the SR.

Discussion. A method of extracting the relevant information from the reflected SR using an appropriate analysis is presented. From here the threshold of the critical energy $W_c = 40\,\mathrm{keV}$ during the discharge can be estimated. Note that the W_c value is a dynamic quantity and that the value given is its average over the time range. Additionally, longer discharges have more intense synchrotron radiation, as expected due to the longer acceleration time.

One should note that SYRUP could be used to estimate the W_{max} provided that the n_{re}^{synch} is known, however calculation of n_{re} is a demanding task by itself, which is out of the scope of this paper. Nevertheless, for the future work usage of the code name CODE [9] as an efficient numerical tool for approximation of the RE distribution function is planned for the W_{max} estimation based on the observed SR.

Acknowledgment. This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. Next to thank is the project MSMT #LM2011021 from which the COMPASS operation is supported. Then, the authors would like to acknowledge work of the WP14-MST2-9 research project team. The “Joint Doctoral Programme in Nuclear Fusion Science and Engineering” is acknowledged by the first author for supporting the studies.

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