RUNAWAY SNAKES IN TEXTOR-94

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1. Introduction

In TEXTOR-94, runaway electrons with energies up to 30 MeV are studied by detecting their synchrotron radiation. In earlier experiments [1], a runaway beam confined in an MHD island structure, rotating around the torus, has been made visible with this measurement method. The phenomenon was called ‘runaway snake’. In this paper, observations of such runaway snakes are presented. Several aspects of the drift orbit topology as well as the confinement of runaways are investigated.

2. Experiments

Because of the relativistic motion of runaway electrons in TEXTOR-94 (major radius R_0 = 1.75 m, minor radius a = 0.46 m), the synchrotron radiation is emitted in a narrow cone with a negligible opening angle, in direction of the instantaneous runaway velocity. The radiation is detected with an infrared (IR) camera (working range λ = 3 - 8μm), looking tangentially into the plasma in direction of electron approach and covering a full poloidal cross section. The camera scans one IR picture in ca. 16 ms (60 Hz, NTSC-TV standard).

When a (toroidally) rotating drift island containing runaways is observed by the scan-ning camera and the rotation frequency in the poloidal projection is larger than the picture frequency, multiple spot pictures are observed. Furthermore, the scanning nature of the camera used gives simultaneous information on space and time which allows an estimation of the rotation frequency by determining the time derivative of the rotated angle of the island in poloidal projection.

The shape of synchrotron radiation patterns depends on the helical structure of the runaway drift orbits and the finite pitch angle $\theta = v_\perp/v_\parallel$ resulting from the gyration of the runaways. In Fig. 1, a computer generated pattern is shown, calculated for nested runaway drift surfaces with radius r_{max} = 15 cm and θ = 0.08. The inclination α of the pattern is related to an average safety factor of the drift orbit surface $q_{\rm D}(r) \approx D/(R_{\rm o} \tan\alpha)$, where D is the distance to the detector. The width of the pattern perpendicular to the line of inclination is determined by θ.

In poloidal projection, a runaway drift island, in case of a n = 1 island only one closed tube, looks like only a part of a toroidal runaway shell. Because the island is rotating, it is scanned at

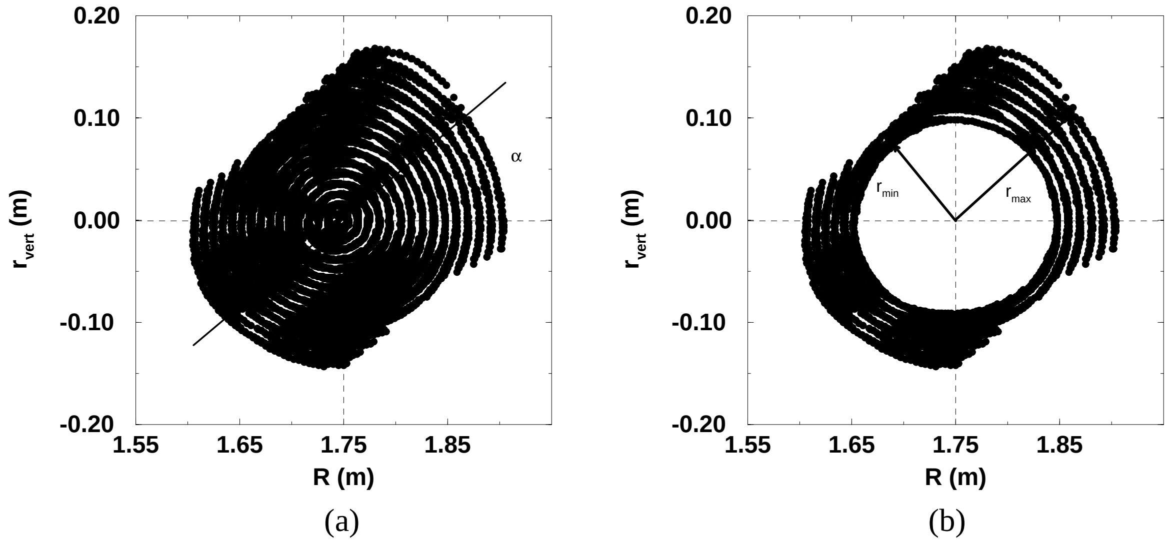


Figure 1: (a) Calculated synchrotron pattern of a 25 MeV runaway beam with r_{max} = 15 cm and θ = 0.08. Inclination is indicated. (b) Synchrotron pattern of a runaway shell with r_{min} = 10 cm and r_{max} = 15 cm. Same parameters as for case (a). A parabolic q profile is assumed, q_o = 0.88, I = 350 kA

changing positions and, therefore, an overlay of IR pictures during a snake should reconstruct the pattern coming from a runaway shell $r \in [r_{min}, r_{max}]$, also shown in Fig. 1.

3. Runaway snake observation

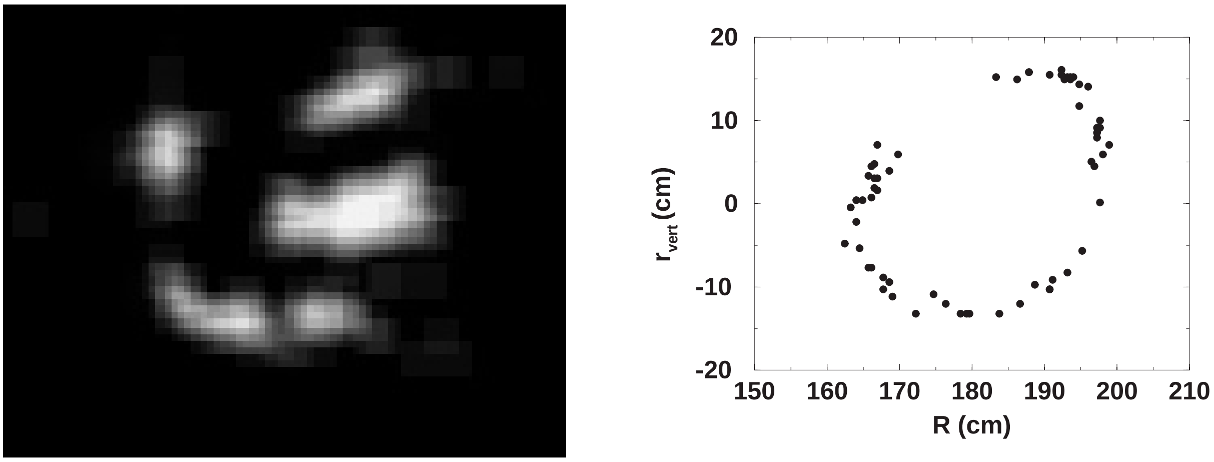
In a typical runaway discharge ($n_e < 1 \times 10^{19}$ m^{-3}, B = 2.2 T, $I_p =$ 350 kA, $V_{loop} \approx 1$ V), MHD mode activity is excited by pellet injection. The synchrotron radiation spot that had appeared at $t \approx 1$ s, vanished after the injection. After 1 s, synchrotron radiation reappeared in a rotating structure. Fig. 2 shows one IR picture of the snake as well as subsequent (calibrated) IR pictures plotted in the same figure, showing an inclined 'elliptical' pattern. The radius parallel to the line of inclination $r_{\|}$ is interpreted as r_{max}, the perpendicular radius $r_{\perp}$ as r_{min}. The difference is a lower limit of the size of the drift island. Results for this case: $r_{\|}$ = 18.5 $\pm$ 0.8 cm, $r_{\perp}$ = 14.4 $\pm$ 1.2 cm. The shift δ is estimated to be 5 $\pm$ 1 cm. The rotation frequency is in agreement with frequencies on density and magnetics signals of rotating MHD modes.

Runaway snakes can usually be identified as an m = 1, n = 1 phenomenon. There is, however, one observation of two runaway snakes that lived in the same discharge, at different radii. The outermost of these was identified as an m = 2, n = 1 snake, the inner one as an m = 2, n = 1 snake. This phenomenon occurred after the plasma was pushed to the inner wall.

4. Discussion

4.1. Drift surface parameters

In the 'classical' view, drift surfaces and magnetic surfaces with equal q have equal radius. The drift surfaces are shifted from the magnetic surfaces dependent on their energy with $\delta =$



(a) (b)

Figure 2: (a) one multiple spot IR picture of a snake (thermal background subtracted) and (b) an overlay of subsequent calibrated IR pictures. In the upper left corner the camera view was obscured by other diagnostics.

$q_{\rm D}\gamma m_e c/eB$ (where γ is the relativistic factor, c is speed of light, m_e and e are electron mass and charge respectively). Although the runaways reach relativistic energies in TEXTOR-94, the relativistic effects on drift surface radius and shift [2] are beyond the experimental accuracy. Due to the low densities in the typical runaway discharges, the exact q profile could not be measured. For the presented example, with q = 3.8, the radius of the q = 1 magnetic surface can be estimated by a/q_a = 12.1 cm. This number must be compared with the experimentally determined value ($r_{max} + r_{min}$)/2 = 16.5 $\pm$ 1.0 cm. Due to the presence of large magnetic islands and due to current carried by the runaways, the current density profile is probably rather peaked, which would mean that the q = 1 surface radius lies further out and matches the data better. The inclination of the pattern for a q = 1 surface is ϑ = 44$\pm$ 3, which is in agreement with the inclination of the measured pattern. From the measured shift and taking $q_{\rm D} \equiv q$ = 1, a runaway energy of W_r = 33 $\pm$ 7 is derived. The pitch angle is found to be 0.1 by comparison of the measured pattern with a calculated pattern, which is in agreement with earlier experimental estimates [3].

4.2. Confinement

After the pellet injection, synchrotron radiation disappeared, which is interpreted as a rapid loss of runaways due to strong ergodization of the magnetic field. The time it takes for the signal to disappear varies strongly from discharge to discharge. Transport coefficients of $D \approx$ 1 - 300 m^2s^{-1} are estimated. A fraction of the runaway population survives the ergodization period, confined in a remnant of an island. From the spread of the runaway snake with time, the radial runaway diffusion coefficient inside the snake is estimated at $D_r \approx$ 0.01 m^2s^{-1}. For comparison, classical, collision induced transport would be of the order of 0.001 m^2s^{-1}. In unperturbed Ohmic runaway discharges is found $D_r < 0.01$ m^2s^{-1} [4]. Thermal transport in Ohmic discharges is typically of the order $\chi_e \approx 1$ m^2s^{-1}.

The orbit shift is of the same order as the minimal width of the drift island $\Delta w = r_{max} - r_{min}$.This implies that the drift island lies, at least partly, outside the corresponding magnetic island. Runaways are confined in the drift island where locally the magnetic structure is of a stochastic nature.

5. Conclusion

Observations have been made of runaway drift islands at the $q_D = 1$ and $q_D = 2$ drift surface by synchrotron radiation measurement. Drift surface radius, pattern inclination, runaway energy and pitch angle are all consistent. Conditions for a snake observation are: low electron density to have typical runaway discharges, MHD activity and initial loss of runaways so that only those confined in a drift island remain visible. Drift islands are shifted from the corresponding magnetic islands into regions of perturbed magnetic surfaces. Nevertheless, confinement of runaway electrons within islands is of same order of magnitude as in normal Ohmic runaway discharges. Since electrostatic turbulence should have a negligible effect on these high energy runaways, their transport is expected to be dominated by magnetic turbulence. This is compatible with the fact that their confinement in Ohmic plasmas is much better than thermal confinement provided some good surfaces exist [5]. The excellent confinement inside a drift island is fully consistent with magnetic turbulence as the main cause of runaway transport.

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