Investigation of Runaway Electron Eeam in EAST

Y. J. Shi 1), Z. Y. Chen 2), J. Fu 1), Y. Yang 1), J. H. Li 1), F. D. Wang 1), Y. Y. Li 1), W. Zhang 1), B. N. Wan 1), and EAST Team 1)

1)Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, Anhui, 230031, China
2) Institute of Nuclear Fusion, College of Electrical and Electronic Engineering, Huazhong University of Science and Technology, Wuhan, 430074, P.R.China

E-mail contact of main author: yjshi@ipp.ac.cn

Abstract: It is the first time to observe the synchrotron radiation emitted by runaway electrons with a visible CMOS camera in tokamak. Some information about runaway electron has been obtained in the EAST tokamak, which is the first full superconducting tokamak with non-circular cross-section in the world. Both the energy and pitch angle of runaway electrons have been derived from the measurement of synchrotron radiation. The synchrotron radiation of runaway electrons was observed in the center region in most cases. The normal synchrotron radiation pattern is ellipse with an inclination angle to the equator, which is consistent with the numerical calculation of runaway electron synchrotron radiation. In few cases, a stable shell shape of synchrotron radiation can be observed. The mechanism for the formation of the shell is unclear. Observations of a rapid changes in synchrotron spot and intensity are also presentd. In these rapid changing cases, the ECE signal has corresponding response, which are belonged to fast pitch angle scattering events (FPAS). The FPAS events can appear both in current flap-top phase or current decay phase.

1. Introuduction

Electrons in a tokamak with energies higher than some critical energy are continuously accelerated by the toroidal electric field, i.e., they run away [1-3]. The energy that a runaway electron reaches can be limited by the synchrotron radiation, the drift orbit shift, the flux swing, the magnetic fluctuations, the interaction with magnetic field ripple and waves [4-10]. Recently, bremsstrahlung radiation has been considered as mechanism to limit the maximum energy that runaway electrons can gained for high enough values of the effective charge and electron density [11, 12]. In large tokamaks, runaway electrons confined for a sufficiently long time can gain enough energy to cause serious damage to the first wall structures. The effect of runaway electrons when they impinge on the first wall is strongly dependent on the energy gained in the toroidal electric field. Therefore, it is of interest to investigate mechanisms that might help to control the energy that the runaway electrons can achieve. The energy limit of the runaway and the mechanisms for the energy limit have been predicted by some theories [4-9, 11-12].

In EAST, the runaway electron beams been observed with a visible CMOS camera. The experimental derived maximum energy of runaway electrons can reach 45 MeV. Two type of synchrotron radiation patterns of runaway beams have been observed in EAST. After the description of the experimental setup in section 2, the experimental results are presented in section 3. Finally, a summary is presented in section 4.

2. Experimental Setup

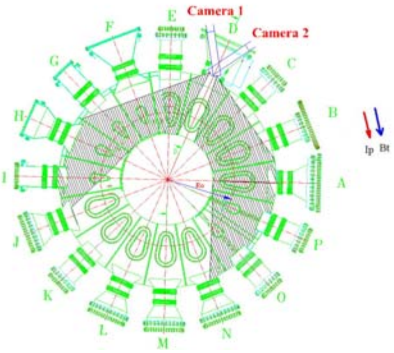

Fig.1. Experimental set up of the visible colour cameras *in EAST.*

EAST tokamak is the first non-circular full superconducting tokamak in the world, major radius R_0 = 1.75~1.85m, minor radius a = 0.4~0.5m [13,14]. In the initial experimental campaigns in 2006 and 2007, the first wall of EAST was made of full stainless steel with a Mo limiter, which was horizontally moveable on the low field side. A hydrogen plasma of plasma current I_p=100-500kA at toroidal magnetic field B_T = 2T had been achieved in EAST. Two visible color cameras were used to monitor discharge status and plasma shape. The CMOS sensor of the color camera was equipped with an additive color separation filter known as Bayer filter. The camera itself also was equipped with an IR cut filter. These color cameras can measure the light in the wavelength range 380 – 750 nm. The sampling frequency of the cameras is about 75 frames per second. One camera was positioned to view the plasma in toroidal direction toward electron approach; the other was positioned in the opposite direction (as seen in Fig.1). Runaway electrons have been firstly directly observed with an infrared camera in the TEXTOR tokamak [15-17]. Compared to infrared camera in TEXTOR, the background radiation from the wall will not be considered for the images measured with the visible color camera, which means more reliable and clear data can be obtained with it. Moreover, the camera in EAST can get the spectrum in one discharge.

3. Experimental results

As indicted in above paragraph, the native purpose of the visible color cameras in EAST was not to detect runaway electron. But a bright spot in core plasma were often observed with the camera in EAST. The arguments that support this bright spot is the synchrotron radiation from runaway electron are as follow. Firstly, the bright spot was only observed in the direction of electron approach. It never appeared in the opposite direction. Secondly, the

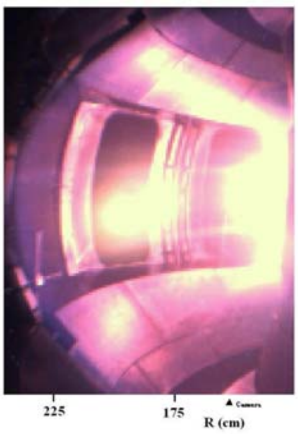

Fig.2. Typical synchrotron image obtained with the camera in a circular-configuration discharge

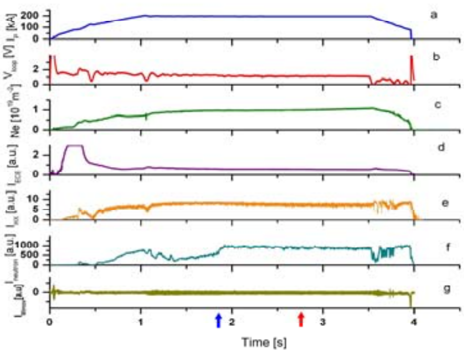

Fig.3. The waveforms of the discharge with synchrotron spot. a, the plasma current, b, loop voltage, c, the line average electron density, d, the electron temperature, e, the intensity of hard x-ray, f, the intensity of neutron, g, the Mirnov signal. The synchrotron spot observed with CMOS camera appeared from 1.8s. The picture in Figu. 2 was taken at 2.7*s.*

bright spots did not apparent earlier than about 1.5 second after the start of the discharge. This is the time needed for the runaway electrons to gain the energy necessary to radiate in

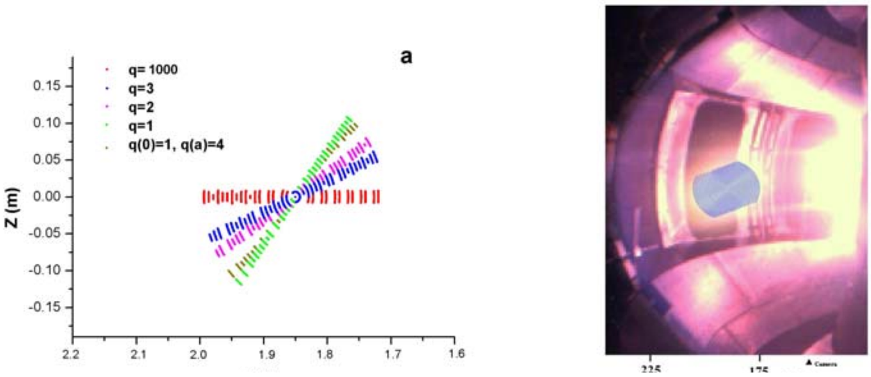

Fig.4. Numerical simulated shape of the synchrotron spot (poloidal projection) from 40MeV runaway beam with radius = 0.14 m in EAST. Left, The radiation pattern with different q and fixed pitch angle (θp = 0). q = 1000 means thereis no helical structure for the magnetic field. Right, the radiation pattern (bluecurves) with θp = 0.05, which is overlap into same image of figure2. A parabolic-like q profile is assumed (q (0) =2.8, q (a) =6.5).

the spectral region of the camera. The first two arguments are the same as that in TEXTOR [6, 16]. Thirdly, the pattern and shape of the bright spot in EAST is very unusual. The shape of the bright spot in EAST is seriously inconsistent with the shape of magnetic surface. In the circular discharges of EAST, the bright spot is ellipse like (see Fig.2). Moreover, the ellipse bright spot inclines to the equatorial plane. Such incline ellipse shape is consistent with the characters of the synchrotron radiation from runaway electron in tokamak [19, 20]. The inclination angle of the synchrotron radiation spot is related with the current profile, which is a consequence of the helical structure of the runaway guiding centre orbit. In Ref. 20, the angle in the poloidal plane between equator and a line in the direction of the inclination is given by

$$\tan\beta \approx D/(q(r)R_0)$$

where D is the distance between the observed runaways and the detector and q(r) is the local safety factor. D is about 3 m in EAST. The waveforms of plasma parameters are shown in Figure 3. The plasma current is about 220 kA and the central line averaged density is about 1×10^{19} m^{-3}. Most cases with synchrotron radiation spot have observed in such parameters. The surface plasma loop voltage is about 1.2 V at flap-top phase. In this shot, the synchrotron spot observed with CMOS camera appeared from 1.8s. The picture in Figure 2 was taken at 2.7s in this shot. The detector for the HXR on EAST is not so sensitive to high energy x-rays. The HXR signal is mainly come from the thick bremsstrahlung radiation emitted by the outside lower energy runaway electrons. The neutron signal on EAST is mainly from photon-neutron emission, which is sensitive to high energy x-ray emitted by runaway electrons. It can be seen that the intensity of neutron increased from 1.5 s, which is an indirect evidence for high energy runaway electrons. The neutron signal stops to increase after 2s because the detector saturates. The pitch angle of the runaway electron also can be deduced from the extent of the synchrotron spot with numerical simulation [18]. The major radius R_0 is about 1.85m in runaway discharges. Fig. 4a shows a few examples of the numerical simulated synchrotron patterns. The calculated pattern with pitch angle θ_p =0.05 and q(0)=2.8 is consistent with for the EAST case in Fig.2.

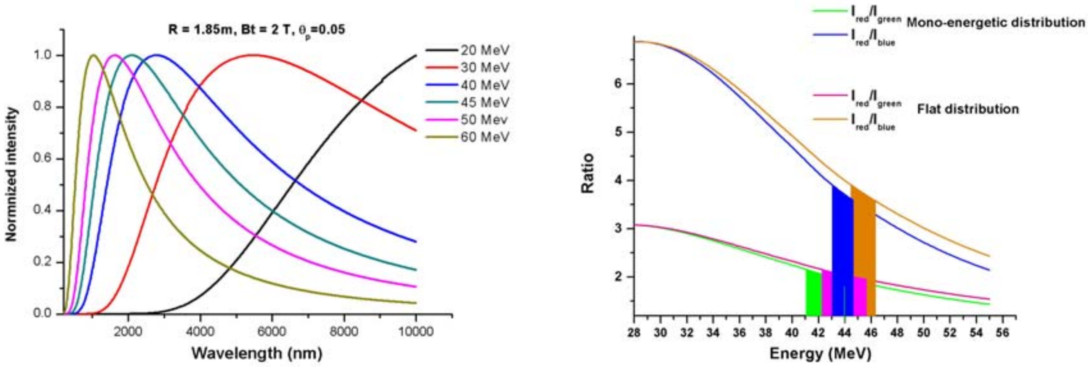

Fig.5. Left, The spectra of the synchrotron radiation. Right, The relation between the runaway energy and the ratios of the three color pixels. The shading bars are corresponded to the experimental data.

Having determined the pitch angle from the spot shape, the energy of runaway electron also can be estimated from the synchrotron spectrum. The energy distribution function of runaway electron is unknown. Two extreme cases can be considered: a mono-energetic and a flat-distribution, corresponding to either a limited time of runaway generation for instance during start-up or a continuous generation, respectively. The calculation method of synchrotron radiation spectra is the same as Refs 6 and 18. The oscillations of curvature radius of runaway electrons are not taken into consideration in this paper. More detail analysis of synchrotron radiation spectra can been see in Refs. 21. Several spectra of the synchrotron radiation are shown in figure 5a. As indicated in Refs.6 and 18, the most of the radiation is emitted by the highest energetic runaways. The determination of the energy is not sensitive to the exact shape of the distribution. There three kinds of pixels in the color camera: red, green, and blue. Having determined the synchrotron radiation spectra and the distribution of runways, the relation between the energy and the intensity ration of the three pixels can be obtained. The relation between the energy and the intensity ratio of the three pixels is shown in figure 5b. At current flat-top phase, the intensity ratio between red and green pixel is 2.05±0.1. At the same time, the intensity ratio between red and blue pixel is 3.74±0.15. The energy of the runaway electron deduced from the intensity ratio between pixels is 41.1~44.6 MeV for mono-energetic distribution and 42.3~46.3 MeV for flat distribution. To keep a runaway electron be confined within the plasma, the the orbit shift of runaways must be smaller than the minor radius *a*. The maximum energy of runaway electron limited by orbit shift for EAST runaway cases is approximately 47 MeV. The maximum energy of runaway electron (E_{lim}) limited by the synchrotron radiation losses can be calculated by the test particle dynamic equations [7]. Recently, bremsstrahlung radiation has been considered as mechanism to limit the maximum energy that runaway electrons can be gained [11, 12]. According the carefully analysis in Ref.12, the bremsstrahlung radiation is important for the plasma with high enough values of the effective charge and electron density. For EAST plasma in this paper, both the Z_{eff} and the density are too low. The bremsstrahlung radiation can be neglected for EAST cases. Here, we use the same method and equations as in Ref.7 to calculate the energy limit of runaway electron for the EAST cases. The centre electron density $n_e(0)$, electron temperature $T_e(0)$, toroidal electron field $E_{//}(0)$, and the effective ion charge Z_{eff} are necessary parameter in the equations of Ref.7. For the EAST discharges with synchrotron radiation spot, these

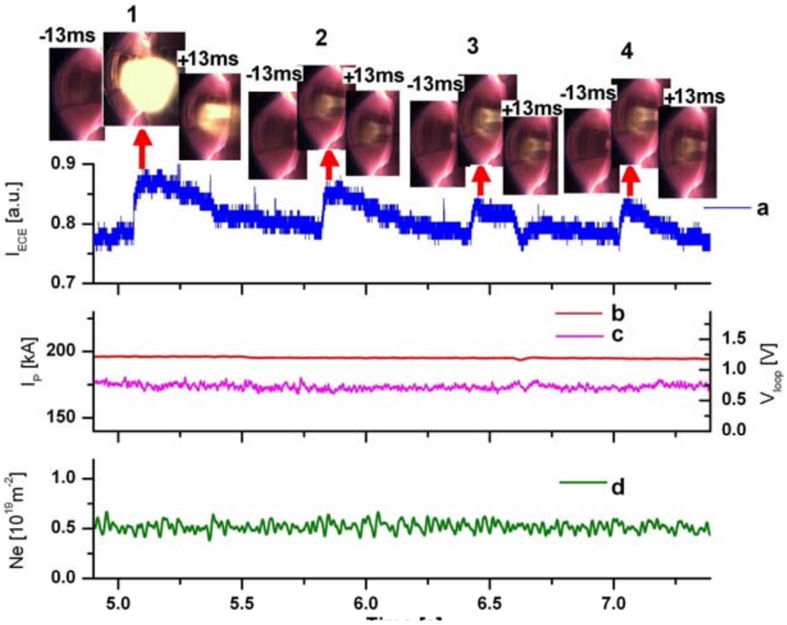

Fig.6. Top,pictures of CMOS camare clear show the FPASs.Four continuous FPAS events have occurent in about 3s. Bottom, the waveforms of other signals. a, the ECE intensity, b,the plasma current, c, loop

parameters are: $T_e(0)$ = 0.5~0.7 keV, $n_e(0) = 1.3\times10^{19}m^{-3}$, Z_{eff}=2~3 . $E_{//}(0)$ can not be directly measured in EAST. With the known parameters ($T_e(0)$, Z_{eff}, and q(0)), $E_{//}(0)$ can be deduce from the resistivity equation of plasma[22]. Normally, $E_{//}(0)$ is no more than the surface electron field, which is 0.11 V/m in EAST runaway cases. For Te(0)=0.5 keV, we get E_{lim} = 47~49 MeV, $E_{//}(0)$=0.08~0.11 V/m, and θ_p = 0.06~0.07, which is very near the experimental values. For T(0)=0.7 keV, we get E_{lim} = 21~32 MeV, $E_{//}(0)$=0.05~0.07 V/m and θ_p = 0.10~0.13, which is inconsistent with the experimental observations.

The pitch angle scattering events (FPAS) are also clearly observed with the CMOS camare on EAST. FPAS are mainly reported on TEXTOR[6]. On EAST, the FPAS can appear both in flop-top phase and in current and density decay phase, which is different from TEXTOR. Fig.6 shows the typical FPAS in flop-top phase. Except ECE signal, no obviously fast changes in density, loop voltage, MHD etc are found when FPAS appear. Three consecutive frames of the CMOS camare are shown for each FPAS in Fig.6. The picture of FPAS differs from the previous frames by drastic change in spot width and intensity. On the subsequent frame the spot width and intensity decreased, but is still far high than that before FPAS. The transient time scale is about 0.1~0.2 ms, which can be obtained from the ECE signal and is very close to the TEXTOR cases. The intensity synchrotron radiation in first FPAS is much stronger than the subsequent three FPAS. The intensity increase of the ECE signal has the same performance. The decay time for FPAS is about 700 ms for the cases in fig.6, which is about 140 ms for FPAS in a current and density decay phase.

In EAST, the normal synchrotron radiation pattern is ellipse with an inclination angle to the equator. In few cases, a stable shell shape of synchrotron radiation also can be observed (see fig.7). The runaway snakes in TEXTOR have been reported in Refs.19 and 21. In Refs.19 and 21, a narrow runaway beam can be formed after the pellet injection and confined in an island structure. The toroidal rotation frequency of the runaway electrons is much higher than the rotation frequency of the island structure, so that the runaway electrons beams effectively

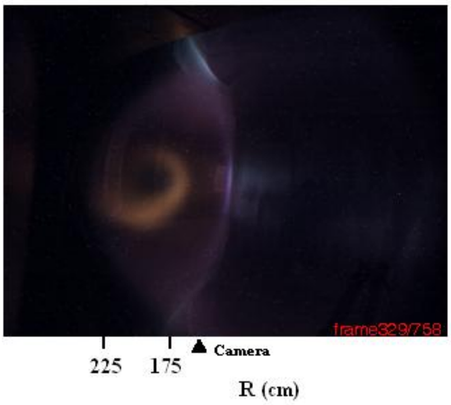

Fig.7. The shell image of the synchrotron radiation in

form a toroidal tube, i.e. runaway snake. The typical synchrotron radiation pattern of runaway snakes in TEXTOR is discrete stripe-like spots located around q=1 or q=2 surface, which is never observed in EAST. The signal of Mirnov coils shows that there is no obvious MHD activity during the discharges with shell pattern. But, generally, the magnetic island in core plasma is very difficult to be detected with the Mirnov coils. Only in one case, the position of the shell is located around q=1 surface in a discharge with sawtooth. The relation between the formation of the shell in EAST and the magnetic island is unclear. This shell is perfectly stable and stays at the same position for several seconds, which is an indication of the very low diffusion rate of the runaway electrons. It also can be seen that the intensity of the synchrotron shell in high field side (HFS) is far strong than that in low field side (LFS). Normally, the size of magnetic island will become larger in low field side. But size difference of magnetic island is a questionable mechanism for this phenomenon except the size of magnetic island in lower field side is ten times as that in high field side, which is impossible for the magnetic island in core plasma.The underlying mechnism is not clear.

4. Summary

It is the first time to observe the runaway electron beams with a visible camera in EAST tokomak. Very clear synchrotron radiation images from runaway electron beams have been obtained in EAST tokamak. Both the pitch angle and energy limit of runaway electrons can be derived from the measurement of synchrotron radiation. The experimental pitch angle and energy limit are 0.05 and 41 MeV~46 MeV. The experimental results are partly consistent with the test particle dynamics numerical simulation. The FPAS events have been observered both in current and density flap-top phase or current and density decay phase. A stable shell shape of synchrotron radiation can be observed in few cases. The mechanism for the formation of this shell is unclear.

References

[1] Dreicer, H., “Electron and ion runaway in a fully ionized gas”, Phys. Rev. **115** (1959) 238
[2] Cohen, R. H., “Runaway eletrons in an impure plasma”, Phys. Fluids **19** (1976) 239
[3] Knoepfel, H., et al., “Runaway electrons in toroidal discharges ”, Nucl. Fusion **19** (1979) 785
[4] Wiley, J. C., et al., W., “Simulations of the runway electron distributions”, Phys. Fluids

23 (1980) 2193
[5] Fuchs, V., et al., "Velocity-space structure of runaway electrons", Phys. Fluids **29** (1986) 2931
[6] Jaspers, R., Relativistic runaway electrons in tokamak plasmas, PhD Thesis Technische Universiteit, Eindhoven (1995), and http://alexandria.tue.nl/extra3/proefschrift/PRF11A/9405635.pdf
[7] Martin-Solis, J. R., et al., "Energy limits on runaway electrons in tokamak plasma", Phys. Plasmas **6** (1999) 238
[8] Martin-Solis, J. R., et al., "Effect of magnetic and electrostatic fluctuations on the runaway electron dynamics in tokamak plasmas", Phys. Plasmas **6** (1999) 3925
[9] Martin-Solis, J. R., et al., "Interaction of runaway electrons with lower hybrid waves via anomalous Doppler broadening", Phys. Plasmas **9** (2002) 1667
[10] Chen, Z. Y. et al., "Energy limit of runaway electrons in the HT-7 tokamak", Physics Letters *A* **351** (2006) 413
[11] Bakhtiari, M., et al., "Momentum-space study of the effect of bremsstrahlung radiation on the energy of runaway electron in tokamaks ", Phys. Plasmas **12** (2005) 102503
[12] Fernandez-Gomez, I., et al., "Determination of the parametric region in which runaway electron losses are dominated by bremsstrahlung radiation in tokamaks", Phys. Plasmas **14** (2007) 072503
[13] Wan, Y. X., et al. "Overview progress and future plan of EAST project", in Fusion Energy 2006 (Proc. 21st Int. Conf. Chengdu, 2006) (Vienna: IAEA) CD-ROM file OV/1-1 and http://www-naweb.iaea.org/napc/physic/FEC/FEC2006/html/node8.htm
[14] Wan, B. N., et al., "Recent experiments in the EAST and HT-7 superconducting tokamaks", *Nucl. Fusion* **49** (2009) 104011
[15] Finken, K. H., et al. "Observation of Infrared Synchrotron Radiation from Tokamak Runaway Electrons in TEXTOR", Nucl. Fusion **30** (1990) 859
[16] Jaspers, R., et al. "Experimental Investigation of Runaway Electron Generation in TEXTOR", Nucl. Fusion **33** (1993) 1775
[17] Jaspers, R., et al. "Islands of Runaway Electrons in the TEXTOR Tokamak and Relation to Transport in a Stochastic Field", Phys. Rev. Lett. **72** (1994) 4093
[18] Entrop, I., Confinement of relativistic runaway electrons in tokamak plasmas (1999), PhD Thesis, Technische Universiteit, Eindhoven, and http://alexandria.tue.nl/extra2/9903850.pdf
[19] Entrop, I., et al. "Runaway snakes in TEXTOR-94", Plasma Phys. Control. Fusion **41** (1999) 337
[20] Pankratov, I. M. "Analysis of the synchrotron radiation emitted by runaway electrons", Plasma Physics Reports **22** 5(1996) 535
[21] Pankratov, I. M. "Analysis of the synchrotron radiation spectra of runaway electrons", Plasma Physics Reports **25** (1999) 145
[22] Wesson, J, Tokamaks, Oxford Univ. Press, Oxford (2004)