Runaway Effects in High Density Tokamak Discharges

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Introduction

Pellet injection is an effective way for tokamak plasma fuelling [1]. Periodic injection with the frequency of 1-10 Hz is planned for the ITER. However, the effects which occur during sequential injections are poorly understood, both experimentally and theoretically. The pellet ablation and toroidal acceleration enhancement was registered at the end of the injection series [2]. Conventional models [3, 4] tested by a number of single injection experiments cannot explain this effect. This paper considers the runaway avalanche stimulated by hydrogen pellet injection and its influence on pellet ablation and toroidal acceleration. The runaway avalanche is produced by close electron-electron collisions, in which thermal electrons acquire an energy higher than the threshold energy for runaway production.

Runaway avalanche stimulated by pellet injection

The classical runaway birth rate S due to the Dreicer mechanism is defined by the parameter $\varepsilon = E/E_{crit}$, where E is the toroidal electric field in the plasma and E_{crit} is the critical electric field [5]. After the beginning of injection, the plasma temperature T_e drops and the plasma density n_e rises. At the plasma conductivity $\sigma \sim T_e^{3/2}$ and $E \sim T_e^{-3/2}$, the Dreicer parameter $\varepsilon \sim n_e^{-1} T_e^{-1/2}$ drops after the injection start and the runaway generation via this mechanism decreases.

Another way of runaway breeding is an avalanche caused by close electron-electron collisions [6]. The avalanche may start if there are some runaways with the density n_r born during the initial stage of discharge. The maximal runaway energy W_{max} is usually limited to several tens of MeV. The cross section for a collision of relativistic and thermal electrons (with thermal velocity $v << c$) is given by $\frac{d\sigma}{dW_s} = \frac{e^4}{8\pi\varepsilon_0^2 m_e c^2 W_s^2}$, where W_s is the energy acquired by the thermal electron. The runaway density growth provided by such collisions can be expressed as $\frac{dn_r}{dt} = n_r n_e c \int_0^{W_{max}} \frac{d\sigma_s}{dW_s} P_r(W_s) dW_s$. Here $P_r(W_s)$ is the probability for an electron with energy W_s to become runaway. If $P_r(W_s)$ is a step function ($P_r(W_s) = 0$ at $W_s < W_c$ and $P_r(W_s) = 1$ at $W_s > W_{crit}$), the integration over the runaway energies with the critical energy $W_c = \frac{mV_c^2}{2}$, $V_c^2 = \frac{(2 + Z_{eff})\pi e^3 n_e \ln\Lambda}{mE}$ can give an estimate for the runaway avalanche rate [6]

$$\frac{dn_r}{dt} = \frac{n_r eEc}{2m_e c^2 \ln\Lambda(2 + Z_{eff})} = \frac{n_r}{t_0}, \qquad t_0 = \frac{2m_e c \ln\Lambda(2 + Z_{eff})}{eE} \tag{1}$$

This rate is proportional to the electric field. Since the pellet injection at constant plasma current causes a temperature drop and a subsequent electric field growth, the runaway avalanche is stimulated by pellet injections.

When the plasma density is high ($n_e \geq 10^{14}$ cm^{-3}), a relativistic correction must be taken into account for runaways. In the utmost relativistic case, for $\alpha < 1$ ($\alpha = \frac{E}{E_{crit}} \frac{T}{m_e c^2}$), all the runaways are decelerated [7]. However, for $\alpha > 1$ (but of the order of 1), runaways can be accelerated but then one should use a relativistic expression for the critical energy $W_c = \sqrt{p_c^2c^2 + m_e^2c^4}$, where p_c is a critical momentum, $p_c^2 = m_e^2V_c^2\left(1 - \frac{V_c^2}{c^2}\right)^{-1}$. The critical energy W_c can be expressed as

$$W_c = m_e c^2 \sqrt{\frac{1}{(\alpha - 1)} + 1}\ , \text{ where } \alpha = \frac{E}{E_{crit}}\frac{m_e c^2}{T} = 1.1\times 10^{21} \times \frac{E\ [V/m]}{n_e\,[m^{-3}]} \qquad (2)$$

Ignoring losses, one can estimate the avalanche rate, similar to (1):

$$\frac{dn_r}{dt} = \frac{n_r c n_e \pi e^4}{2m_e c^2 W_c} = \frac{n_r}{t_1}, \qquad t_1 = \frac{2m_e c^2 W_c}{c n_e \pi e^4} \qquad (3)$$

In a relativistic case, the critical energy (2) only slightly depends on the electric field and electron density. The main parameter for the birth rate is the plasma density and this is why pellet injections stimulate the avalanche.

The runaway density growth starting from an initial value of n_r has been simulated using plasma temperature and density evolutions typical for experiments with sequential pellet injections (see Fig. 1 a), b)). Fig. 1 also shows the avalanche exponentiation time (c) and the runaway population (d). Dashed lines represent the case of constant plasma temperature and density (no injection), solid lines correspond to the temperature and density evolution in the case of multiple pellet injection. One can see that the exponentiation time drops from τ =2.5 s to about of τ = 1 s when the injections begin.

Runaway influence on pellet ablation and acceleration

Electrons with energy W much higher than the thermal energy T_e interact with pellets as follows [4]: for $W > W_{sthmin}$ = 10 keV they do not spend energy in the neutral shield surrounding the pellet, for $W > W_{sthmax}$ = 300 keV they do not spend energy in the neutral

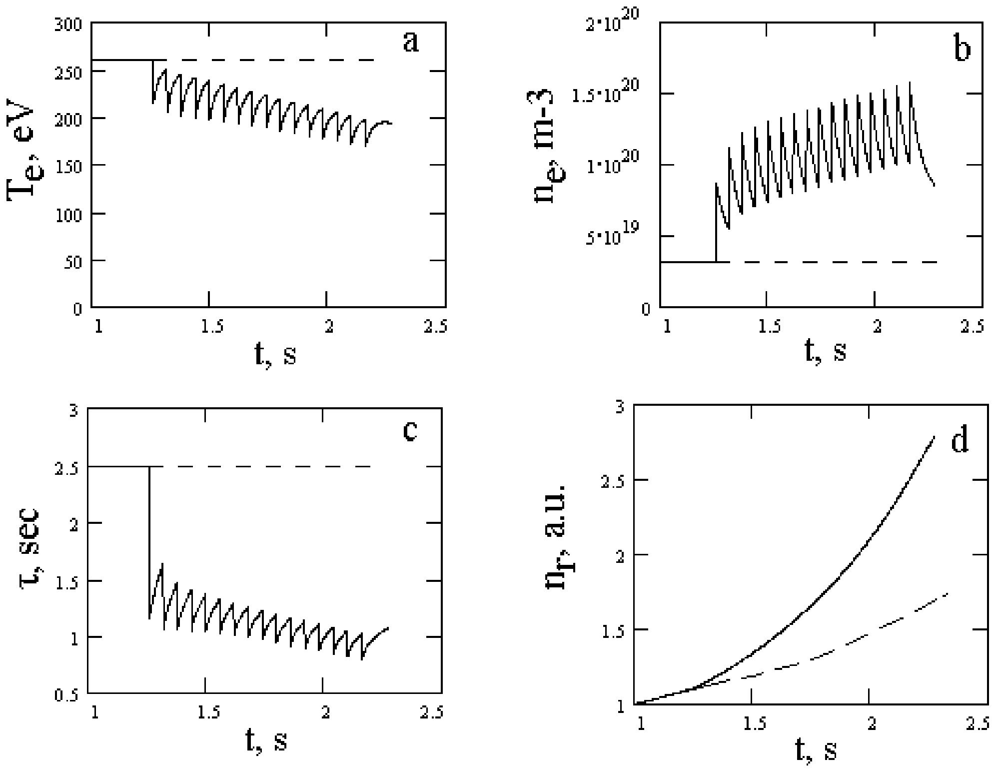

Fig. 1. Runaway avalanching with multiple pellet injection

shield and spend approximately 150 keV inside the pellet for the typical pellet diameter of 1.5 mm. These electrons do not cause anisotropic heating of the pellet, so that they do not stimulate additional pellet acceleration.

Hence, an additional pellet acceleration may be caused by electrons with energies of $10 < W < 150$ keV (suprathermal electrons). There are also suprathermal electrons born in close collisions of runaways with thermal electrons and having the energy lower than the critical energy. Thus, three electron groups can be distinguished: (1) thermal electrons with a Maxwellian energy distribution, (2) runaways which mostly have $W_{\max}$ of about several tens of MeV, (3) suprathermals with energies higher than thermal energy but lower than the critical energy W_c. Since runaways generate suprathermals, the growth of the runaway population causes a corresponding growth of the suprathermal population.

Estimate the runaway concentration necessary to double the pellet toroidal acceleration. Let us find the distribution function $f_{sth}(V)$ for the suprathermals at the given plasma temperature T_e, plasma density n_e, and runaway concentration n_r. The rate of suprathermal generation after a close runaway/thermal collision can be expressed similarly to the avalanching rate

$$I = n_r n_e v_r \frac{d\sigma_s}{dW_s}\frac{dW_{sth}}{dV} = n_r n_e c \frac{e^4}{2\pi\varepsilon_0^2 m_e^2 c^2 V^3} \tag{4}$$

Here, the velocity of a born suprathermal is between V and $V + dV$. Since we are interested in suprathermals with energy $W < W_{\text{sthmax}} = 150$ keV, we have used the non-relativistic expression for the energy $W_{\text{sth}}=(1/2)\text{m}_e V^2$.

The energy losses of suprathermals and their relaxation to the Maxwellian distribution are due to a large number of far suprathermal/thermal collisions with the effective frequency of

$$\nu_{sth}(V) = \frac{1}{3(\pi)^{3/2}}\frac{n_e e^4 \ln\Lambda}{\varepsilon_0^2 m_e^2 V^3}$$

Suprathermals are also accelerated by the electric field. But since their energies are lower than the critical energy $W_{\text{sth}} < W_{\text{sth max}} = 150$ keV $< W_c$, the electric field force is small compared with the friction force $F(V) = m_e V \nu_{sth}(V) >> eE$, so we can neglect the first one. For the sake of simplicity, we assume that all suprathermals move against the electric field and their velocities are uniformly distributed in this semi-sphere. The accurate analysis made by Besedin and Pankratov [8] shows that the just born electrons are moving tangentially to the electric field and then relax to the isotropic maxwellian distribution.

The kinetic equation for suprathermals can be written as follows

$$I(V) = -\frac{1}{V^2}\frac{d}{dV}\left(V^2 f_{sth}(V)\nu_{sth}(V)V\right) \tag{5}$$

Here, I is the suprathermal source (4). The right side of the equation is the difference between the incoming and outgoing electron flows in the velocity region between V and $V + dV$. Substituting (4) into (5), we get the equation for the suprathermal distribution function

$$\frac{df}{dV} = -\frac{3(\pi)^{1/2} n_r}{2c\ln\Lambda}\frac{1}{V} \tag{6}$$

By solving (6), we obtain logarithmically falling distribution:

$$f_{sth}(V) = \frac{3(\pi)^{1/2} n_r}{2c\ln\Lambda}\ln\left(\frac{V_c}{V}\right) \tag{7}$$

The integration constant was chosen to make the expression at the critical velocity vanish.

The density of the suprathermals with energies from $W_{\mathrm{sth\ min}}$ = 10 keV to $W_{\mathrm{sth\ max}}$ = 150 keV can be calculated as $n_{sth} = \int_{V\min}^{V\max} f_{sth} dV \approx n_r \frac{3(\pi)^{1/2}}{2\ln\Lambda}\frac{V_{\max}}{c} \approx \frac{n_r}{10}$. Fig. 2 shows the schematic plots of the distribution functions for the Maxwellian, suprathermal and runaway groups.

The heat flux of suprathermals is $Q_{sth} = \int_{V\min}^{V\max} \frac{m_e V^2}{2} V f_{sth} dV \approx n_r \frac{3(\pi)^{1/2}}{2c\ln\Lambda}\frac{m_e}{2}\frac{V_{\max}^4}{4}$ The additional ablation rate due to suprathermals can be estimated as $\frac{dN_{sth}}{dt} = \frac{Q_{sth} 2\pi r_p^2}{\lambda_m / 2}$. Here, $\lambda_m = 15.2\times10^{-3}$ eV/molecule is the deuterium sublimation energy, $2\pi r_p^2$ is a half of the pellet surface collecting suprathermals. Additional toroidal acceleration of a pellet can be estimated using the pellet jet equation [4]

$$M(t)\left(\frac{dv_z}{dt}\right) = \langle\cos^2\theta\rangle U m_i \frac{dN_{sth}}{dt}$$

where *M(t)* is the pellet mass, dv_z/dt - toroidal acceleration, $<cos^2\theta>=1/2$ (θ is the angle between the ablated atom velocities and the toroidal direction), $U \approx 10^6$ cm/s is the atom velocity estimated as gas sonic velocity.

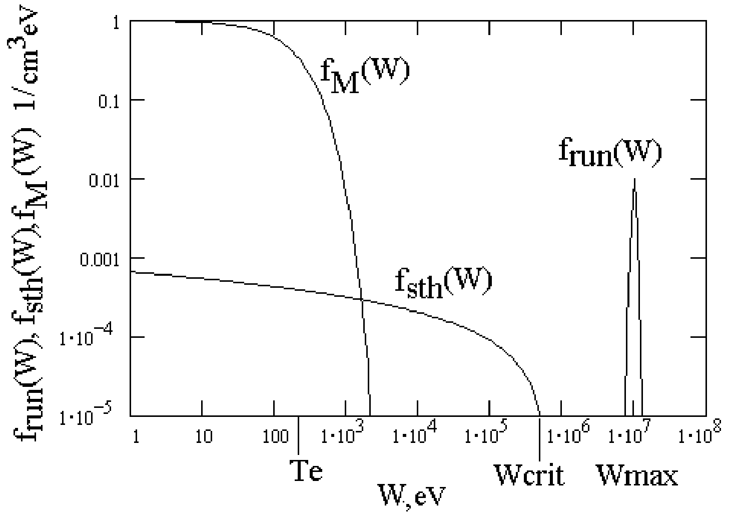

Fig. 2. Distribution functions: maxwellian, suprathermal, runaway. T_e *= 200 eV,* $n_e = 10^{14}$ *cm*$^{-3}$*,* $n_r = 3\times10^8$ *cm*$^{-3}$*.*

The runaway density necessary to produce a substantial additional pellet acceleration is low. For example, it is sufficient to have 3×10^8 cm^{-3} of runaways in the region of several centimeters of the minor radius to double the experimental pellet acceleration.

To describe the observed effect in terms of conventional models, one should assume that the current density exceeds **by the factor of 6** and the plasma temperature exceeds by 30% the respective experimental values.

Summary

It is shown that the multiple hydrogen pellet injection provides the condition necessary for enhanced runaway avalanching. At a moderate plasma density, pellets cause a temperature drop and a subsequent electrical field rise, which stimulates the avalanching. When the density is high so that the runaway threshold is relativistic, the pellets also stimulate avalanching due to the plasma density enhancement.

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REFERENCES

[1] Milora, S.L., Houlberg, W.A., Lenguel, L.L., et al., Nucl. Fusion **35** (1995) 657.
[2] Lang, P.T., Alexander,M., Büchl, K., et al., Europhys. Conf. Abstr. **Vol. 18 B**, Part 1 (1994) 306.
[3] Parks, P.B., Turnbull, R.J., Phys. Fluids, **21**1(978) 1945.
[4] Kuteev, B.V., Nucl. Fusion **35** (1995) 431.
[5] Dreicer, H., Phys. Rev. **115(2)** (1959) 238.
[6] Jayakumar, R., Fleischmann, H.H., Zweben, S.J., Phys. Let. **A 172** (1993) 447.
[7] Connor, J.W., Hastie, R.J., Nucl. Fusion **15** (1975) 415.
[8] Besedin, N.T., Pankratov, I.M., Nucl. Fusion **26** (1986) 807.