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ABSTRACT
In this paper, we investigated plasma disruption i, produced populations of runaway electrons. We showed the time evaluation of plasma parameters (plasma current I_p , Loop Voltage V_{loop} , Power heating , Diamagnetic Loop, power spectrum density and Mirnov oscillations in a major disruption and compared results with a normal shot. We Showed, an increase in MHD Oscillations and loop voltage pick in pre-disruption stage, that also cause generating high energy runaway electrons.
Keywords: Plasma Disruption, Runaway Electrons, Mirnov coils, Diamagnetic loop

١. Introduction

The plasma disruption is a dramatic event in which the plasma confinement is suddenly destroyed. In a major disruption this is followed by a complete loss of current. Disruptions pose a serious problem for tokamak development. This is firstly because they limit the range of operation in current and density, and secondly because their occurrence leads to large mechanical stresses and to intense heat loads [١].
The plasma disruption is caused by strong stochastic magnetic field formed due to nonlinearity excited low-mode number magneto-hydro-dynamics (MHD) modes. It is hypothesized that the runaway electron beam is formed in the central plasma region confined by an intact magnetic surface due to the acceleration of electrons by the inductive toroidal electric field [٢].
It has been experimentally proved that the use of magnetic coils are essential for determining the MHD components, responsible for triggering the disruptive phenomenon in tokamaks.

In the tokamak concept the confinement of plasma is achieved by running a current through the plasma column. This plasma Current is generated by an inductive electric field in the toroidal direction. The precense of this electric field leads to the phenomenon of electron ‘runaway’ [Kno-٧٩]. This is an interesting physical aspect of the kinetic theory of plasma collisions between charged particles in the plasma are governed by the long-range, small-angle scattering Coulomb interaction. The characteristic feature of this interaction is the rapid decrease of momentum transfer with increasing particle energy. For electrons of sufficiently high energy the friction force due to collisions with the plasma particles does not compensate the externally induced electric force. Theses electrons are continuously accelerated and ‘runaway’ in phase space.
Electron runaway has been an intriguing theme for plasma physicists of both the theoretical and experimental persuasion, since the first publication in ١٩٤٩ by Giovannelli [Gio-٤٩]. Theories are able to describe the runaway phenomenon and resulting non-linear effects quite successfully. The runaway electrons are collisionally decoupled from the bulk plasma, due to the high relative velocities and associated small collision cross-section. In spite of this small collisional intraction there is still an interplay between the runaway and the bulk. The mutual influence between collective

plasma effects and the runaway electrons can give rise to the several instabilities[Mik-٤٧].

From an experimental viewpoint runaway electron studies are motivated by several arguments involving the diagnostic capablities and the effect of the runaway electrons on the plasma behaviour: - runaway electrons can be regarded as effectively collisionless which makes them a suitable probe for investing the non-collisional transport in a tokamak: - runaway electrons can affect the plasma behaviour since they can carry a substantial part of the plasma current. The possibly can improve the confinement of the plasma and their interaction with waves can transfer energy to the plasma. Furthermore, since the loss of high energetic runaway electrons can cause considerable damage to fusion machines, investigations into production, accelearation and loss processes of the runaway electrons is accelerated to energies high enough to penetrate the solid structure of the reactor [٣].

Plasma disruptions are a major concern for future tokamak operation because of their effects on wall components. A disruption is a sudden loss of the energy cofinement of the plasma. This loss is thought to be the result of the magnetic surfaces [Wes-٨٩]. The concurrent temperature drop leads to a rapid decay of the plasma current. A short digression upon the effects will show the severe damage the disruptive instability can bring about.

i) The sudden loss of energy confinement during a disruption implies that the total plasma kinetic energy is dumped on the wall components in a short time. Heat loads as high as ١٠ MJ/m٢ within ٠.١-١ ms are extrapolated for ITER from present day experiments [Whi-٩١]. Such energy fluxes will locally evaporate ١ cm of first wall material in about ١٠٠ disruptions, equivalent to several tens of kg per disruption. Moreover these power fluxes result in damage of wall components by cracking melting and fracture.

ii) The fast variation in plasma position induces electric fields which produce currents crossing from plasma to wall components. These lead to enormous j×B forces. For ITER-like machines forces on the vacuum vessel structure of up to ١٠ MN are anticipated [Mer.٨٧]. Forces of similar strength on the vaccum vessel result from the sudden loss of the plasma pressure and the current decay, both producing a rearrangement of the toroidal magnetic field and inducing a current in the vaccum vessel [Wes-٨٩].

i) Finally, the increased electric field favors the production and acceleration of runaway electrons. Runaway currents as high as ١٠ MA and energies of ٥٠-٥٠٠ MeV are predicted for ITER. The Runaway danger is twofold. Firstly, the total energy in this runaway beam may exceed ١٠٠ MJ, which can be deposited very locally as a result of the outward drift or a position instability. Secondly, as a result of the high energy, the runaways can penetrate the first wall (a rough estimate of the electron range (S) in carbon yealds S=٠,٢٥ cm/MeV) and deposit their energy in the metal coolant channels of the plasma facing components. These might be damaged by melting with the possible consequence of coolant leakage into the vacuum vessel [Bol-٩٠].

ii) The Lifetime of a fusion reactor will be limited to only a few disruptions if the prognoses come true. Even for present day tokamaks major disruptions have led to destruction of wall components [Tak-٨٩, Dic-٨٨]. For this reason much effort is put in studies to understand, control and avoid disruptions.

Runaway electrons are only indirectely observed, by HXR radiation [Gil-٩٣], Neutron radiation [Jar-٨٨], activation or damage of wall material [Bar-٨١, Jar-٨٨] or the observation of a current plateau [Wes-٨٩]. This interpretation of these data and

extrapolations to a burning fusion reactor are a certain respects conflicting; - estimates of the runaway energy in ITER vary between ۵۰-۵۰۰ MeV [Rus-۹۳, Boi-۹۰] ; Russo and Campbell predict the runaway generation to occure predominently at the edge of the plasma [Rus-۹۳], whereas other studies assume central creation [Fle-۹۳] ; - runaway current up to ۵۰% of the plasma current has been measured at JET [Wes-۸۹,Gil-۹۳], whereas at DIII-D hardly any evidence of a runaway current is found [Rus-۹۳]; - the loss of these runaway electrons has been observed to occure suddenly or smoothly]Gil-۹۳].
The use of the synchrotron radiation diagnostic as applied on TEXTOR can contribute substantially to the measurements and understanding of runaway electrons during disruptions as this is the only technique to observe the runaway electrons directly. The energy, number and position of the runaway beam can be determined accurately, allowing more reliable extrapolation towards ITER [۳].

۱. Runaway generation mechanisms

At suprathermal speeds the dynamical friction force on an electron decreses with increasing velocity . The force from an electric field (e.g the electric field E induced in a tokamak disruption) therefore dominates over friction above a critical velocity $v_c = v_T\sqrt{E_D/2E}$, where v_T is the thermal velocity , $E_D = \nu m_e^2 c^3 / eT$ the Dreicer field, $\nu = n_e e^4 \ln\Lambda / 4\pi\varepsilon_0^2 m_e^2 c^3$, The relativistic electron collision frequency , n_e the electron density , T the electron temperature and $Ln\Lambda$ the coulomb logarithm . A runaway generation mechanism is a process which moves electrons into the runaway region $v > v_c$ of velocity space where they are accelerated to become highly energetic runaway electrons . The acceleration can only occure if E is greater than the critical electric field $E_C = m_e c\nu / e$, corresponding to a minimum in the friction force at relativistic velocities . In tokamaks with large current the dominant runaway generation mechanism is the avalanche , which is caused by close range collisions between existing runaways and thermal electrons . The avalanche is a secondary process , for which the necessary initial speed of runaways can be created by several different primary mechanisms . one such process is the Dreicer runaway mechanism , in which electrons diffuse into the runaway region due to a random walk in velocity space caused by long range collisions . In the following we will limit the discussion to the dreicer and the hot tail runaway electron mechanisms. Losses of runaways due to magnetic perturbations are important in disruptions , and the dependence of the fluctuation level $\delta B/B$ was investigated in . Here we for simplicity assume the unknown parameter $\delta B/B$ to be zero to study a worst case scenario without losses , an approach that might be more relevant for impurity injection scenarios than for natural disruptions .

In the rapid thermal quench phase $(\tau_{TQ} \sim 1ms)$ of a disruption the electron velocity distribution is not in a steady state which is assumed in the derivation of the Dreicer runaway rate . At hight velocities the collision frequency is lower than the cooling rate , so in an initial transient phase high energy electrons do not have time to thermalize . They are left as a hot tail , while the low energy bulk of the distribution function cools down , following a maxwellian with a decreasing temperature *T(t)* . If the cooling is rapid compared with the collision frequency at the runaway threshold velocity , then the hot tail makes the number of electrons in the runaway region higher than what it would be for a maxwellian with temperature *T(t)*. Many more runaways are therefore produced than given by the Dreicer rate . Hot tail runaway generation also differs from Dreicer generation because it is limited in time to the cooling phase , wherease Dreicer generation continues as long as the electric field is high .
The analytic work considers thermal quench types where the cooling is caused by an inflow of impurities , e.g . wall material or injected pellets . This mainly cools down the thermal electrons through excitation and ionization processes, whereas the suprathermal electrons show down due to collisions with the thermal electrons . The number of runaways is approximated by first sloving the kinetic equation to determine the evolution of the

distribution function f without the influence of the electric field . The obtained velocity distribution is then integrated over the runaway region set up by the electric field . the kinetic equation is

$$\frac{\partial f}{\partial t}=\frac{vc^3}{v^2}\frac{\partial}{\partial v}2G(\frac{v}{v_T})(\frac{v^2}{v_T^2}f+\frac{v}{2}\frac{\partial f}{\partial v})$$

(١)

Where $G(x)$ is the Chandrasekhar function, $v_T(t)$ is the thermal speed and the temperature $T(t)$ is a specified function of time .

The runaway generation depends sensitively on the final temperature and on the cooling history $T(t)$. In the special case $T(t)=T_0(1-t/t_{pow})^{2/3}$, for which $\delta\equiv(v_T^3/2vc^3)d\ln T/dt$ is costant , the distribution at low temperatures approach a self-similar solution in the variable $x=v/v_T$. Integrating the solution over the runaway region gives the runaway population density estimate

(٢)

$$\frac{n_{run}}{n_e}\approx\frac{\delta^{-2/3}}{\sqrt{3\pi}}\exp\left(-\frac{3}{5}\delta^{-2/3}\right)\left[2\ln\left(\frac{\delta x_t^3-1}{\delta x_c^3-1}\right)-3\left(\frac{1-x_c^2}{1-x_t^2}\right)\right]+\frac{2\delta^{1/3}}{\sqrt{\pi}}\exp(\delta^{-2/3}).$$

Which holds when $\delta^{-1/3}<x_c<x_t$, where $x=v_{c0}T^{1/4}/v_{T0}T_0^{1/4}$ and $x_t^2=\delta^{-2/3}T_0/T$.

In the case of an exponential-like temperature decay $T=T_{final}+(T_0-T_{final})\exp(-t/t_{\exp})$, an approximate solution using velocity moments of the kinetic equation yields the runaway density

$$\frac{n_{run}}{n_e}=\frac{4}{\sqrt{\pi}}\int_{u_c}^{\infty}\left(1-\frac{(u_c^3-3\tau)^{2/3}}{(u^3-3\tau)^{2/3}}\right)e^{-u^2}u^2du,$$

(٣)

Where $u^3=v^3/v_{T0}^3+3\tau$ and $\tau(t)$ can be calculated by sloving a first order ordinary differential equation , which for larg t gives the approximate result $\tau(t)\approx(t-t_{\exp})vc^3/v_{T0}^3$ [٤] .

٢. Experimental Set-Up

The IR-T١ tokamak is a small size tokamak, with large aspect ratio, low beta, circular cross section, which has two stainless steel grounded fully poloidal limiters. The average pressure before discharge was in the range ٢.٥ – ٢.٩ ×١٠

Table ١: Main Parameters of IR-T١ Tokamak [٨]

Parameters	Value
Major Radious	٤٥ cm
Minor Radious	١٢.٥ cm
Toroidal Field	< ١.٠ T
Plasma Current	< ٤٠ kA
Discharge Duration	< ٣٥ ms
Electron Density	٠.٧-١.٥×١٠^{١٣} cm^{-٣}

The magnetic coil system is composed of ١٢ Mirnov coils, installed around one circular cross section inside the vacuum vessel of the tokamak , as shown in Fig ١.

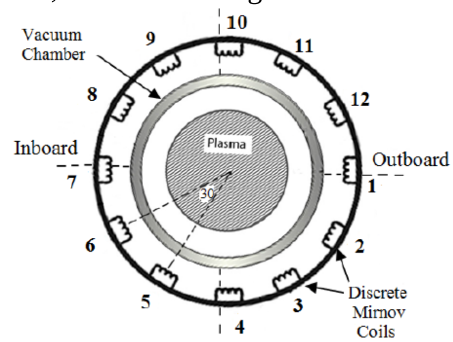


Fig ١: Position of poloidally array of ١٢ Mirnov coils [٥].

٣. Experimental Results

Analysis of a disruptive discharge

The experimental magnetic signals picked up by the Mirnov coils, however, show typical Mirnov oscillations, with frequencies in the range of ١٠ KHZ to ١٥ KHZ.

Fig ٢. shows the experimental signals of a discharge (Plasma Current, Loop Voltage, Heating Power.

Power spectral density

Power spectral density function (PSD) shows the strength of the variations (energy) as a function of frequency. In other words, it shows at which frequencies variations are strong and at which frequencies variations are weak. The unit of PSD is energy per frequency (width) and we can obtain energy whitin a specific freqency range by integrating PSD within that frequency range. Computation of PSD is done directly by the Method FFT. PSD is a very useful tool to identify oscillatory signals in time series data, and also discribes how the energy or power of a signal is distributed with frequency . If $f(t)$ is a finite energy (square integral) signal, the spectral density of the signal continuous of the signal :

$$\Phi(\omega) = \left| \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} f(t)\, e^{-i\omega t} dt \right|^2 = \frac{(F(\omega)F^*(\omega))}{2\pi}$$

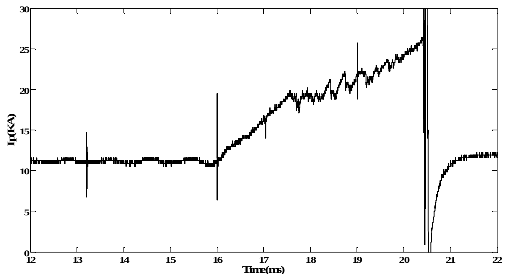
F(ω) is the signal continuous Fourier transforms of $f(t)$ and is F*(ω) complex conjugate. If the signal is discrete with values f_n , over an infinite number of elements, we still have an energy spectral density:

$$\Phi(\omega) = \left| \frac{1}{\sqrt{2\pi}} \sum_{-\infty}^{+\infty} f_n\, e^{-i\omega t} dt \right|^2 = \frac{(F(\omega)F^*(\omega))}{2\pi},$$

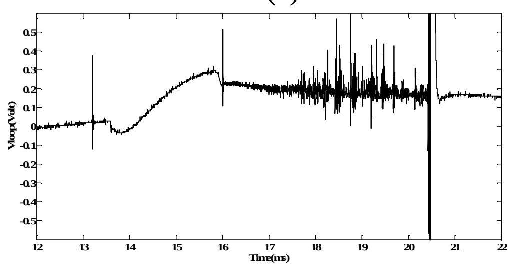
Where is the discrete-time Fourier transform of f_n . Power can be the actual physical power, or more often, for convenience with abstract signals, can be defined as the squared value of the signal. This instantatanous power is then given by : $p(t)= s(t)^{٢}$ for a signal $s(t)$ [٥].

We obtained the PSD using FFT analysis on a Mirnov coils data tath shown in the fig ٨.

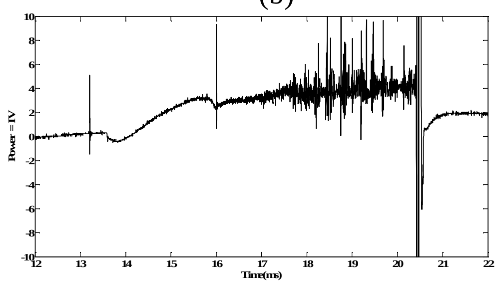
Plasma evaluations during a Disruption of IR-T۱ :



(a)



(b)



(c)

Fig ۲: (a) Plasma current, (b)Loop voltage,(c)Heating power in a plasmaDisruption

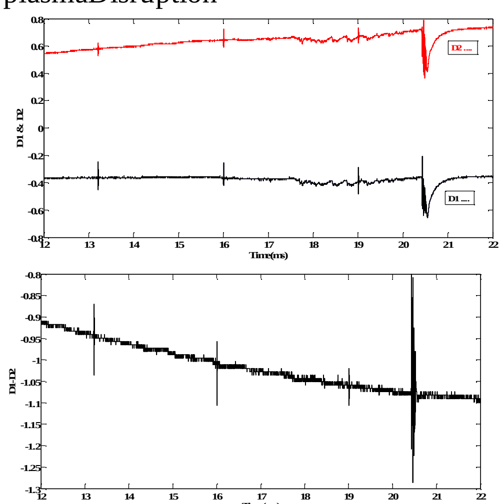


Fig ۳: Time evaluation of Diamagnetic Loop in IR-T۱.D۱,D۲

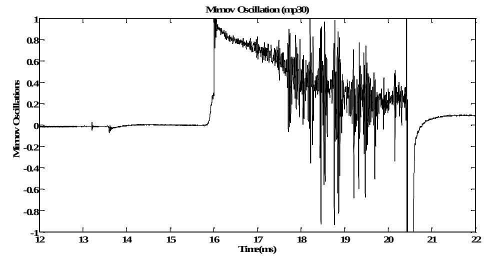
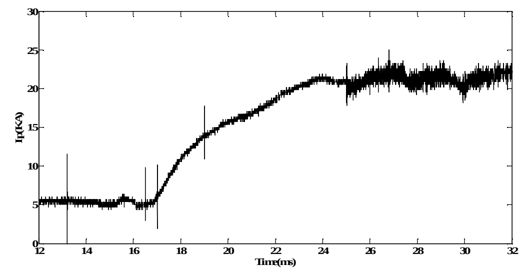


Fig ٤: Time evaluation of Mirnov Oscillation in IR-T۱ Tokamak in Disruption.

Plasma evaluations in a Normal Shot of IR-T۱



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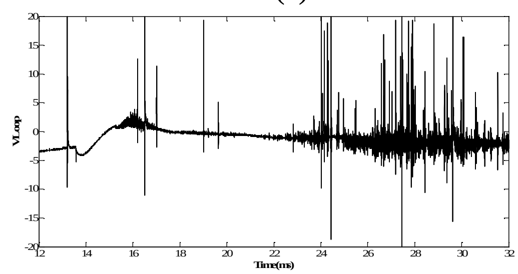
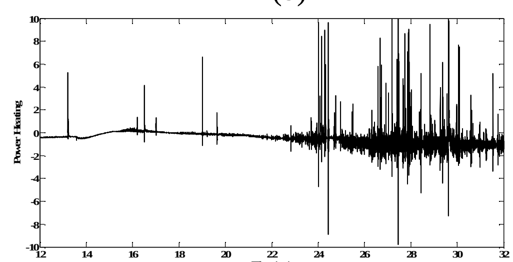
(a)

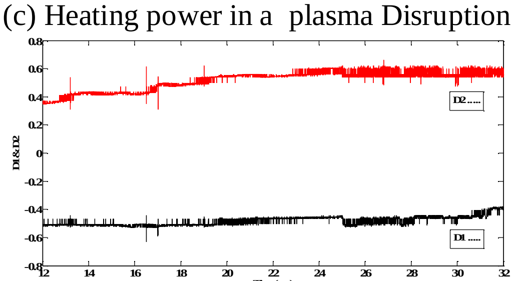


(b)



(c)

Fig ٥: (a) Plasma current, (b) Loop voltage, (c) Heating power in a plasma Disruption



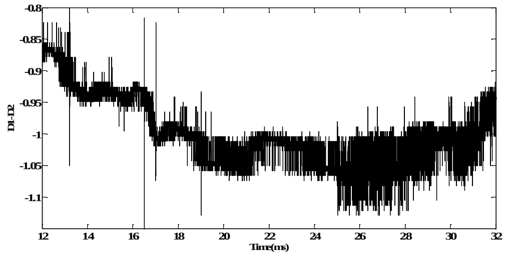


Fig ٦: Time evaluation of Diamagnetic Loop in IR-T١.D١ , D٢.

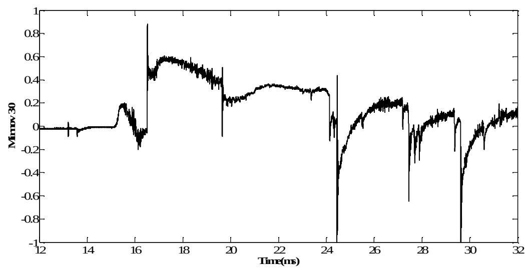


Fig ٧: Time evaluation of Mirnov Oscillation in IR-T١ Tokamak in Normal Shot..

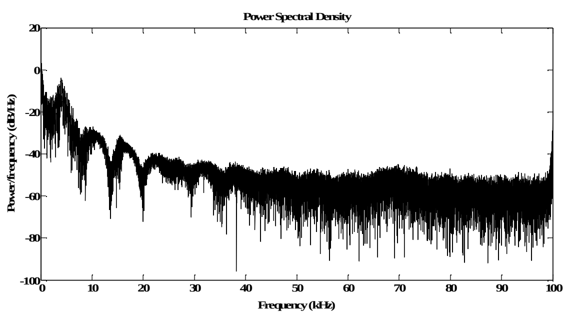


Fig ٨ : Power spectrum density of Mirnov Oscillation of IR-T١ Tokamak in a Disruption.

٤. Conclusion

Some disruption parameters were analized and measured in this article . We showed the time evaluation of plasma current I_p, Loop Voltage V_{loop} , Power heating , Diamagnetic Loop, power spectrum density and Mirnov oscillations in a major disruption and compared results with a normal shot. We Showed, an increase in MHD Oscillations and loop voltage pick in pre disruption stage, that also generated high energy runaway electrons.

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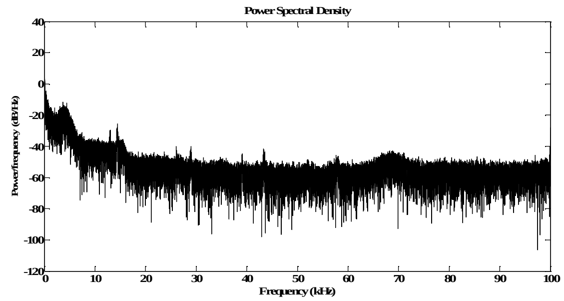

Fig ٩ : Power spectrum density of Mirnov Oscillation of IR-T١ Tokamak in a Normal shot.

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