Characterization of the Plasma Current Quench during disruptions in the ST Globus-M

A. V. Dudkovskaya[1], M. I. Patrov[2]

[1]St Petersburg State Polytechnical University, St Petersburg, Russian Federation

[2]Ioffe Institute, St Petersburg, Russian Federation

Abstract

Disruptions and their consequences pose basic design and plasma operation challenges for reactor-regime tokamaks in general and for ITER in particular. It is well-known that stable disruption-free operation in a tokamak system is limited with regard to maximum I_p, maximum n_e and maximum total normalized plasma pressure β_N by 3 basic *operational limits*:

- **current limit**: set by a requirement for $q_{95} \geq \sim 2$,
- **density limit**: the plasma density should not exceed the empirical *Greenwald density limit* $n_{GW}(10^{20}\ m^{-3}) = I(MA)/\pi a^2\ (m^2)$,
- **pressure limit**: normalized toroidal β should not exceed the *Troyon ideal MHD beta limit*.

The beta and density limits and energy confinement define the significant design and plasma performance of reactor tokamaks. The combination of these parameters determines the achievable fusion power, neutron wall loading and fusion power gain.

In contrast, disruptions arise from consequences of MHD instabilities and can determine the operational lifetime of specific components, especially those associated with particle exhaust and plasma power.

Since the consequences of disruptions shorten the operational lifetime of plasma-facing components, it is important to

- minimize both the number and severity of disruptions and
- mitigate the consequences of disruptions that cannot be avoided.

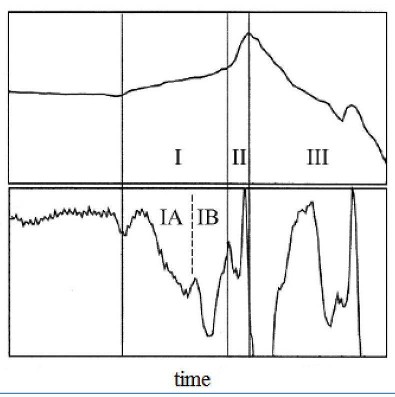
So it is necessary to find

- ways of reliable prediction of the disruptions and
- methods for 'fast shutdown' intervention which will make it possible to either avoid the occurrence of disruption or to soften the consequences of those disruptions which cannot be avoided.

Introduction

Major disruptions, often unanticipated loss of confinement, can be an unavoidable feature of tokamaks. Mechanisms for major disruption may be explained by **magnetic reconnection** of plasma areas with different helicity, which can occur during the development of *non-linear kink and tearing modes* ($m = 1/n = 1$, $m = 2/n = 1$).

An IRE (Internal Reconnection Event) is the most noticeable relaxation phenomenon, which is characterized by a collapse and a subsequent resilience of the pressure profile, the appearance of a positive spike in the toroidal plasma current trace and a large elongating distortion in the overall shape of the plasma. The IRE usually proceeds in 3 stages: *thermal quench* (TC), *current increase* and *current quench* (CQ).



A rapid loss of thermal energy – the thermal quench – which typically occurs in less than a msec, is followed by the current quench and the transfer of a large fraction of the current I_p to the surrounding conducting structures.

- **Vertical displacement events** (VDEs) are usually a consequence of a disruption (uncontrolled upward and downward motion of the plasma column that brings it in contact with the surrounding structures).

In addition to the possibly damaging heat loads it produces at the plasma vessel contact points, a VDE may lead to electromechanical stresses because of the currents it generates in plasma-facing structures. (If the poloidal currents in the vessel (halo currents) are toroidally uniform, their interaction with the toroidal field produces only a net vertical force on the vessel. If the toroidal distribution is nonuniform, then the resulting forces lead to a net torque.)

- Also it is necessary to take into account **runaway electrons**. RE can damage in-vessel component. RE are dangerous for the plasma facing components because of long range in FW materials and possible deep melting.

Many experimental and theoretical works have sought the point where disruption-free discharges are realizable or at least soft landing disruptions are achieved, but no reliable control technique has yet been developed mostly because of the complexity of disruptive processes, which could be device-dependent.

So since complete avoidance of disruptions is not achieved, we should mitigate its damaging effects through better understanding of the various events that accompany them and investigating types of the instabilities, responsible for evolution of the IRE.

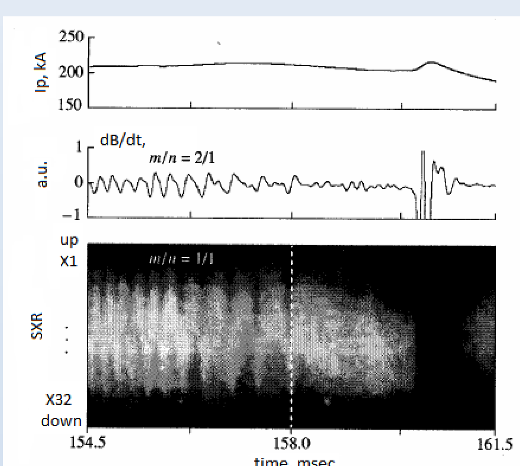
MHD Instabilities & Disruptions

About Spherical Tokamak Globus-M

- $I_p \leq 0.25\ MA$
- $B_T = 0.4\ T$, ($1\ T$ Globus-M2)
- $R = 0.36\ m$, $a = 0.24\ m$
- $R/a = 1.5$
- $k = (1.2 - 2.2)$
- $n_{e_{max}} \approx 2 \cdot 10^{20}\ m^{-3}$
- $T_{e_{max}} \approx 1.5\ keV$, $T_{i_{max}} \approx 0.9\ keV$
- $P_{NBI} < 1.2\ MW$

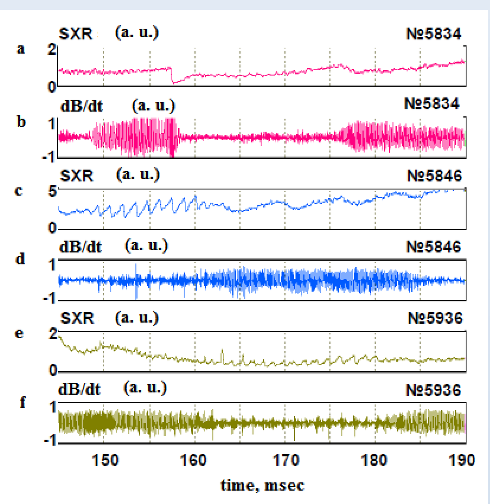
Plasma Instabilities

Snake instability $m/n = 1/1$



Current quench is caused by coupling between NTM 2/1 and *snake instability* 1/1.

Sawtooth oscillations and NTM 2/1



Interaction between sawtooth oscillations and neoclassical tearing mode 2/1.

Tearing Mode

Instabilities located at different radial locations can perturb rational surfaces throughout the plasma, which can result in NTM growth if the perturbation is big enough.

Possible triggers of NTMs:

- First of all, ***a sawtooth instability*** is an internal kink mode at the $q = 1$ surface that can periodically *crash*, throwing heat and particles out of the core and perturb other rational surfaces. This is a common cause of NTM growth and can be ameliorated, for example, by using localized current drive to increase the sawtooth frequency, which decreases the size of the crash and the likelihood of NTM growth.

2 main approaches to sawtooth control exist:

- In the first, one attempts to eliminate or avoid the sawtooth crash for the duration of the discharge by lengthening the sawtooth period (**stabilization**);
- while in the second, the goal is to increase the rate of the sawteeth (**destabilization**) to reduce the perturbation to the plasma at each individual crash.

However in some ST Globus-M experiments sawtooth oscillations have been observed not to trigger NTM seed island formation but tearing modes were suppressed by sawteeth.

- Another potential source of seed islands is the ***fishbone instability***, also related to the $q = 1$ surface but is driven unstable by energetic, trapped particles.

- ***Edge localized modes*** (***ELMs***) are periodic edge-plasma eruptions caused by the steep pedestal pressure gradient in H-mode, which can also create seed islands.

To avoid damage to the plasma facing components, future tokamaks will have to avoid ELMs or find ways of minimizing their size, which should reduce the chance of creating seed islands bigger than threshold width.

- ***Triggerless or spontaneous NTMs***, which grow, apparently without a seed island, from an unknown small size below the background noise level.

Explanations for the growth of such NTMs include coupling between an *(m - 1)/n* mode and the *q = m/n* surface [1], proximity to a plasma beta limit [2] or a removal of the threshold by a coupling to resistive wall modes [3].

The stability of NTM is given by a sum of various contributions, included in *the modified Rutherford equation (MRE)*:

$$\frac{\tau_r}{r_S}\frac{dW}{dt} = r_S\Delta' - a_{nl}W + \Delta_{bs}(W) + \Delta_{GGJ}(W) + \Delta_{pol}(W) + \Delta_{ECCD} =$$

$$= r_S\Delta' - a_{nl}W + a_{bs}r_S\beta_p\frac{W}{W^2 + W_d{}^2} + \frac{a_{GGJ}r_S\beta_p}{\sqrt{W^2 + 0.65W_d{}^2}} + a_{pol}r_S\beta_p\frac{W}{\sqrt{W^4 + \rho_{b,i}{}^4}} + \Delta_{ECCD}$$

W is the width of a magnetic island occurring at a radius r_S and τ_r is the local resistive diffusion time. $\Delta' = \frac{1}{\delta B_r}\left[\frac{d\delta B_r}{dr}(r_S + \varepsilon) - \frac{d\delta B_r}{dr}(r_S - \varepsilon)\right]$ describes *classical tearing mode*, $\Delta' > 0$ gives island growth; the magnetic energy change due to the presence of a tearing mode is proportional to $-\Delta'$, which again indicates that $\Delta' > 0$ makes the tearing mode unstable [4]. Δ' is considered to be constant, giving rise to linear growth or decay in time.

Δ_{bs} is the bootstrap drive term:

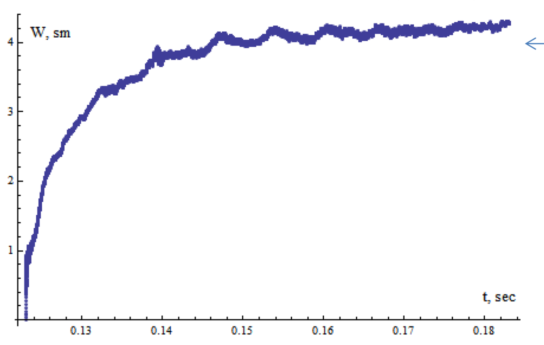
A tearing mode consists of a helical magnetic island with its own internal flux surfaces. This provides a route for transport of heat and particles along field lines from one side of the island to the other. This fast parallel transport serves to flatten the pressure profile across the island. This produces a helical hole in the pressure gradient dependent bootstrap current at the island O-point, providing a neoclassical drive for tearing mode growth. Δ_{bs} describes the bootstrap current perturbation.

Δ_{GGJ} and Δ_{pol} are the stabilizing curvature and polarization terms, respectively. The effect of current drive represented by Δ_{ECCD}. $\Delta_{nl} = -a_{nl}W$ is the non-linear contribution from the current profile.

The modified Rutherford equation

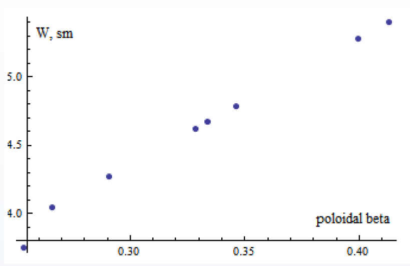
β_p dependence

A feature of the MRE is that Δ_{bs}, Δ_{GGJ} and $\Delta_{pol} \propto \beta_p$.



Measured island width W from Mirnov coil signals during island onset and growth for discharge 5926.

When $dW/dt = 0$, island width saturates: $W_{sat} \approx r_S\beta_p\frac{a_{bs}+a_{GGJ}}{-\Delta'}$. Dependence $W_{sat} \propto \beta_p$ has enables a series of *beta ramp-down discharges*. It let investigate the balance of stabilizing and destabilizing terms for different sized islands in the MRE. W evolution includes three phases: growth, saturation and decay. The growth and saturation phases are spontaneous, but the decay is usually connected with a reduction in β_p via a reduction in the applied heat power. So the decay phase is more controllable and can let observe small island physics.



Magnetic island width W_{sat} is approximately proportional to β_p.

Tearing mode is defined as classical if Δ' is the dominant term and neoclassical if Δ_{bs} is the dominant term. Also it is possible that the balance of these terms may change during the existence time of an NTM.

In Globus-M experiments it was investigated that NTM occurs since $\beta_p \sim 0.25$.

Calculation of the magnetic island width from Mirnov coil data and comparison with a model

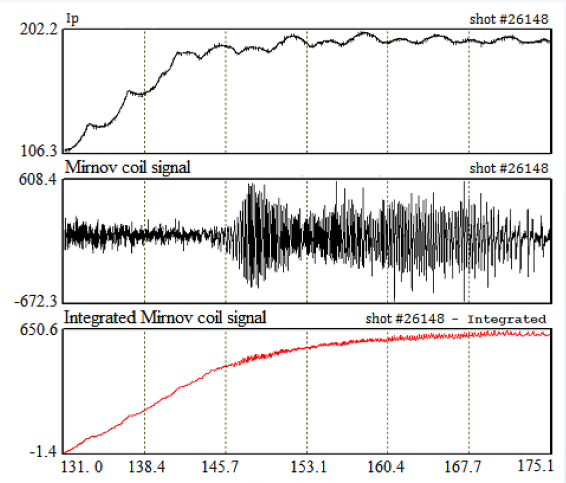
$$W = 4r\sqrt{\frac{B_{mn}}{mB_\theta}\left|\frac{q}{rq'}\right|}$$

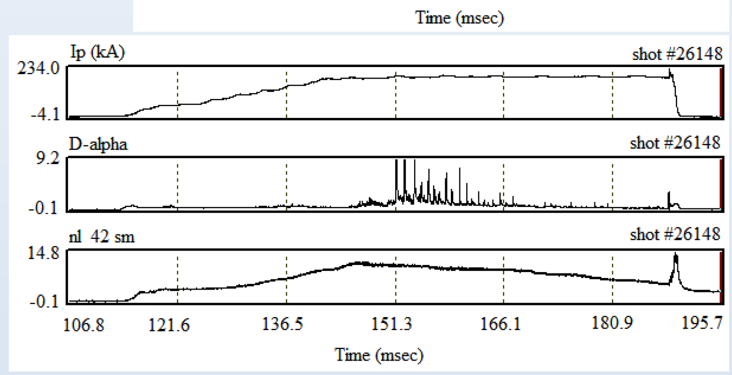
Mirnov coil signal $V = sw \cdot \frac{d\delta B_p}{dt}$, $\delta B_p \approx 1.5\delta B_r$, $sw \approx 63sm^2$ ($h = 16\ mm$, $d = 8.5\ mm$)

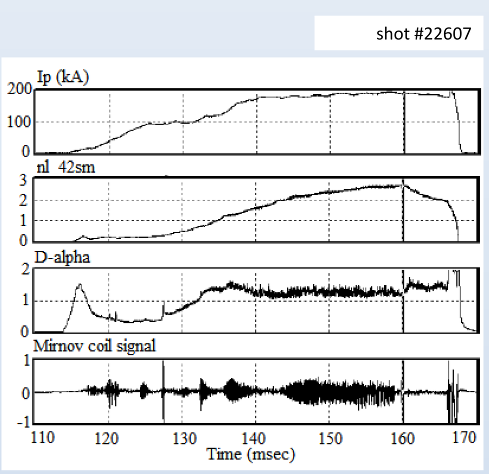
Discharges 26148 and 22607 are presented as an example, in which a spontaneous NTM is destabilized and IRE occurs. An NTM starts to grow, saturates, locks and then terminates the plasma.

For example, in discharge 22607 Mirnov coil data demonstrates the existence of the rotating MHD mode 2/1. Then MHD mode's rotation frequency reduces (coil signal equals zero at 158 msec). Then locked mode rises and leads to current quench at around 166 msec.

These discharges provide NTM evolution at a range of W, which can be studied using the MRE. Also other instabilities may interrupt or modify evolution of the NTM.

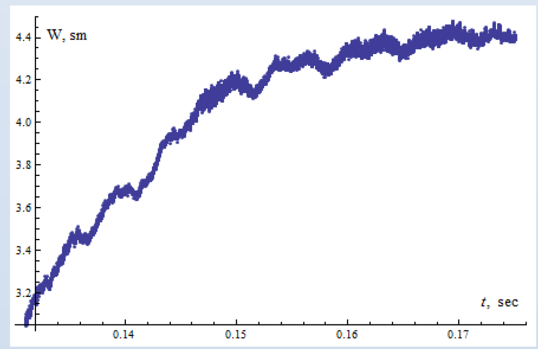




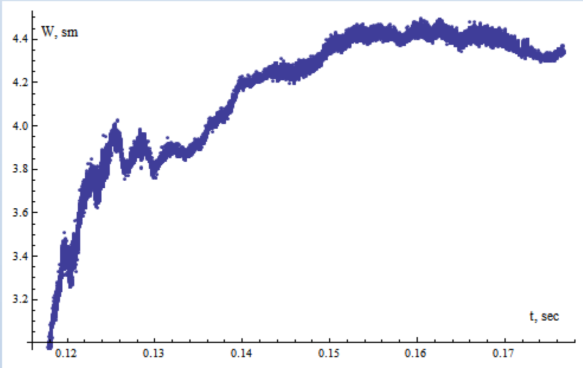


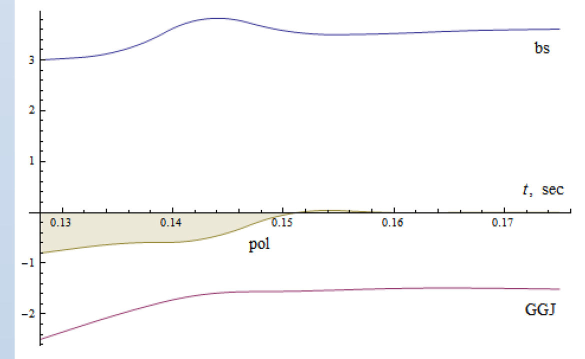
Time evolution for discharge #22607. The locking is seen as a drop in the amplitude of the Mirnov coil signal since the rotation slows, giving a reduced dB/dt.

Measured island width W from Mirnov coil data for discharge with NTM 26148

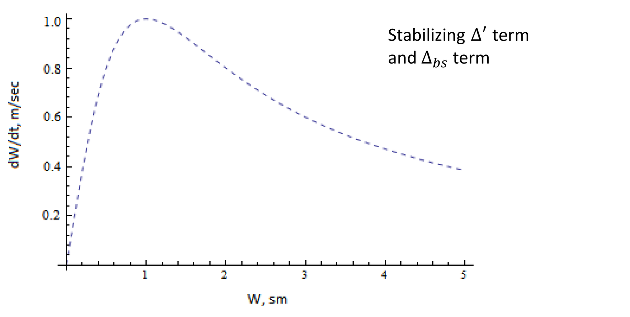


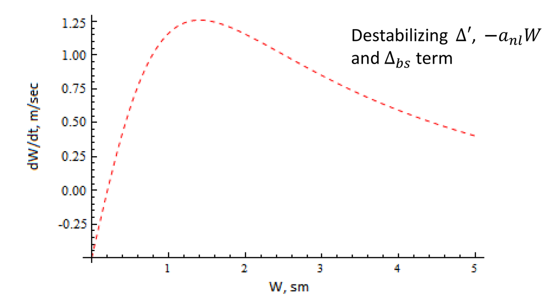
Island width W and time evolution of contributions to the MRE for discharge 22684:

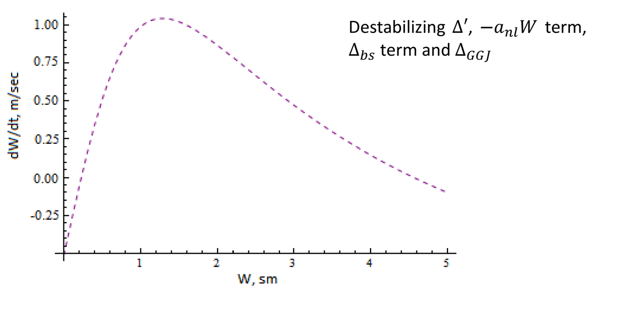


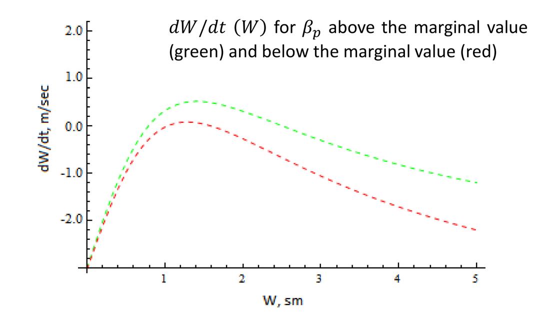


The modified Rutherford equation





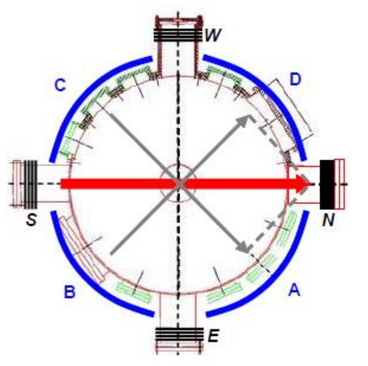




It is of interest to study effects of each of the terms in the MRE.

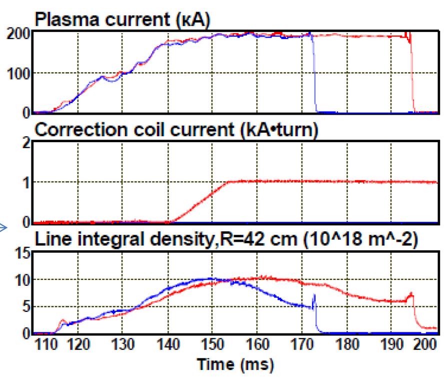
Error fields

The effect of axial asymmetric error fields in inducing locked modes in ST Globus-M also should be taken into account. The error fields occur due to toroidal and poloidal field coil imperfection. Error field locked modes arise from the braking torque applied to the plasma from a static error field, which can bring the rotating plasma to rest and allow islands to form [4]. A set of error field correction coils has been installed on Globus-M to minimize the effect of locked modes. The set consist of four coils arranged symmetrically outside of the vacuum vessel, with each coil spanning 67.5° toroidally.



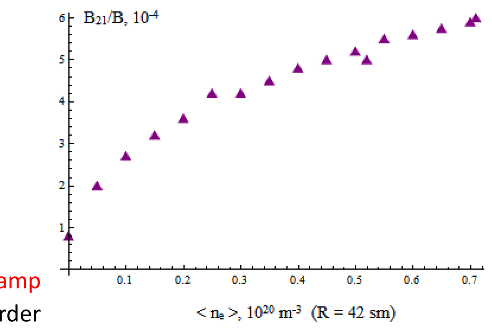
Globus-M top view with resulting magnetic field (→) produced by two pairs of error field correction coils (A, C) and (B, D).

OH shots with (#22632) and without (#22633) error field correction coils.



An empirical scaling for the *error field threshold* δB: $\delta B/B \propto n^{\alpha_n} \cdot B_T{}^{\alpha_B} \cdot q_{95}{}^{\alpha_q} \cdot R^{\alpha_R}$ (above which locked modes are induced).

	α_n	α_B	α_q
JET	0.94	-1.2	-0.05 (1.65)
DIII-D	0.99	-0.97	0.83
MAST	1.1	-0.7	1.3
COMPASS-D	1.0	-2.9	1.6
Globus-M	0.4	—	1.7

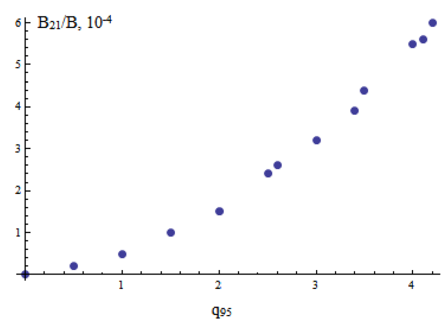


Analogous empirical scaling was obtained for ramp up and ramp down rates of the IRE current spike $\propto I_p{}^{-1.3} \cdot \langle n_e \rangle^{0.4}$ [5]. Also in order to characterize the plasma current quench *the time of the disruption* τ_{cq} was determined.

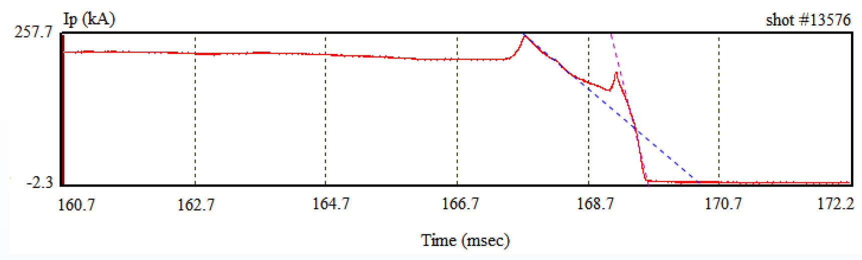
For these purpose wide Globus-M discharge database was analyzed. The plasma current waveform I_p may have a number of drops and spikes at the end of the discharge, so the final large current quench can be found (ignoring earlier, slower decay phases) and dI_p/dt can be determined after the final spike:

γ_{cq_decr} – the slope of the line, which approximate plasma current function I_p after the final current spike;

$\gamma_{cq\_bestfit}$ – the slope of the best fit line (with account taken of all current spikes).



During IRE when the current spike occurs, plasma current function also can be approximated by linear function with the slope γ_{cq_incr}.



Conclusions

- Complete avoidance of disruptions has not been achieved yet, so mitigation of its damaging effects through better understanding of the events that accompany them and investigating instabilities, responsible for evolution of the IRE, should be the primary goal.
- The IRE accompanies almost every spherical tokamak disruption, but experimental data about the IRE seems to be not sufficient. Nowadays a few theories of the internal reconnection exist. One of them is a well-known Hayashi theoretical model [6], which assumed non-linear coupling of low n modes. This disruption scenario was observed and consists in coupling of impurity associated snake and 2/1 tearing mode.
- The behavior of MHD modes was investigated in Globus-M experiments during reconnection events using combined analysis of SXR data and Mirnov magnetic probe signals.
- NTMs (common mode number 2/1) occur regularly on Globus-M and often cause plasma disruptions if they lock to the vessel wall. The modes occur above a critical β_N when an MHD perturbation (such as a sawtooth, fishbone, ELMs, error fields) triggers a seed island with large enough size. They degrade confinement and may lead to disruptions. Present studies have been focused more on the catastrophic 2/1 mode. Evolution of the NTM is described by the MRE and it is of interest to outline the results from fitting of the MRE to the observed NTM evolution in one of these discharges.
- In order to characterize the plasma current quench scaling for ramp up and ramp down rates of the current spike was obtained. It was found similar with analogous locked mode dependences. As a result of this analysis some statements of the instabilities evolving just before the IRE on ST Globus-M have been suggested.

References

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Contact Information

Dudkovskaya.alexandra@yandex.ru

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