About the probability of tokamak current drive (helicity injection) by inverted disruption.

S.V.Mirnov
TRINITI Troitsk Moscow Reg. 142 190 Russia
mirnov@triniti.ru

Abstract. The investigation of exterior MHD-activity during the major disruption in tokamak gives the important arguments for the benefit of force model of disruption grounded on the idea of radial separation a "positive" (coincident with direction of a main current) and "negative" (opposed directed) helical current perturbations. If this model is fair, there is a probability to inject in a plasma from its boundary the positive helical current perturbation under condition, if the poloidal number of them - m>q(a). The analysis shows, that in case of small magnetic shear in the central areas of plasma such injected perturbations can be achieved by magnetic reconnection in the center and hence to increase the main poloidal magnetic flux. If a magnetic shear in the center is not small enough, the injected helical perturbations should decrease it and in this quality could be used for the current profile monitoring in tokamak.

1. Introduction

All disruptions in tokamak are accompanied by ejection of the poloidal magnetic flux from a hot plasma region. This phenomenon manifests itself as short-term positive spikes of a total current Ip, or as negative spikes of the appropriate voltage Vp [1]. Scale of these phenomena oscillates from hardly noticeable (gongs) in case of internal disruptions up to events, which result in dissipative quench of total current. Obviously the opposite process – injection of a poloidal magnetic flux to plasma-should be accompanied by positive pulse Vp. Some example of a poloidal magnetic flux injection to plasma center can be observed at a stage of plasma current ramp up (Fig.1[2]). The dissipation of the current skin component owing to development m=3/n=1 tearing-mode is accompanied by current penetration into the plasma center. It is seen from the shift of a plasma column (owing to growth of internal inductance *li*), as well as from positive peak Vp (t). Is the periodic repetition of similar acts of magnetic flux injection possible? In direct way – definitely not, because the basis of such injection is a permanent growth of an inductor magnetic flux, enveloped by a plasma column magnetic axis. Its maximum value, as is known, is restricted. In usual conditions, when plasma electrical conductivity at the axis is high, any periodic modulations of the inductor flux will call proportional modulations of a complete current, or plasma column inductance. However in a tokamak plasma column can exist magnetic fluxes, which are not completely enveloped by a column axis, namely, magnetic fluxes of helical current perturbations fractionally closing around its helical axis. As is known, their primary energy reservoir is plasma column magnetic energy. Their origin is a reconnection of magnetic field lines as a result of helical instabilities development: ideal, dissipative or ballooning. During the reconnection along with magnetic energy a part of a common magnetic flux enveloped up to the toroidal axis should be transformed to helical current perturbations. Formally this loss of main poloidal flux is taken into account by decrease of internal inductance of a plasma column. An important feature of helical current perturbations is weak coupling of their internal magnetic fluxes to the main poloidal flux. The part of helical flux enveloped by a common magnetic axis we denote Φ_E, while the part enveloped by a common magnetic axis - Φ_{Im}. If the perturbations are localized near to the plasma boundary, Φ_E can be less than Φ_{Im}. From one side this feature allows us to explain several exterior peculiarities of disruptions [2,3]. From another side, it allows us to offer the idea of helical magnetic flux injection from plasma boundary to a hot zone to transform them further into a common magnetic flux. We call this process as inverted disruption [3]. Thus the following basic features concerning a nature of disruptions are used:

1. The disruption is an instability of helical current perturbations in the magnetic field of tokamak. As a result of their interaction the electromagnetic forces appear, which extend the current perturbation in radial direction [4, 5].
2. The radial displacement of helical current perturbation should be eliminated by means of enclosing of hot plasma. This stabilization can be weakened by magnetic reconnections [6], which arise due to anomalous dissipation of extra-currents generated in neutral layers.

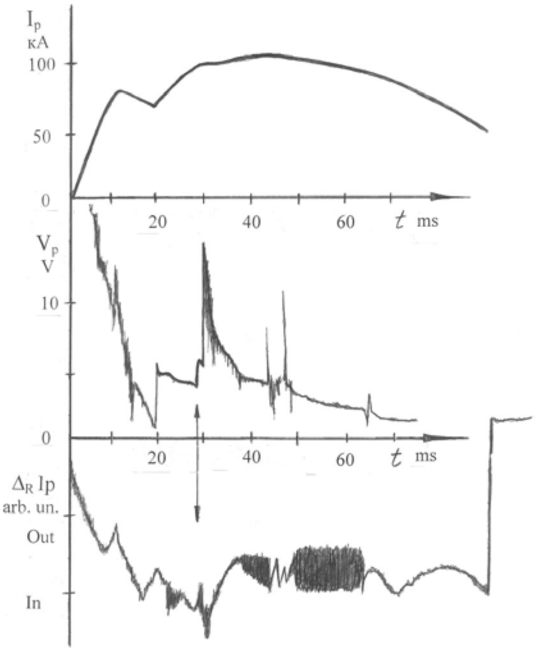

Fig.1 Wave forms of Jp,Vp,Shafranov shift -$\Delta_R(t)$ in process of secondary current ramp up.

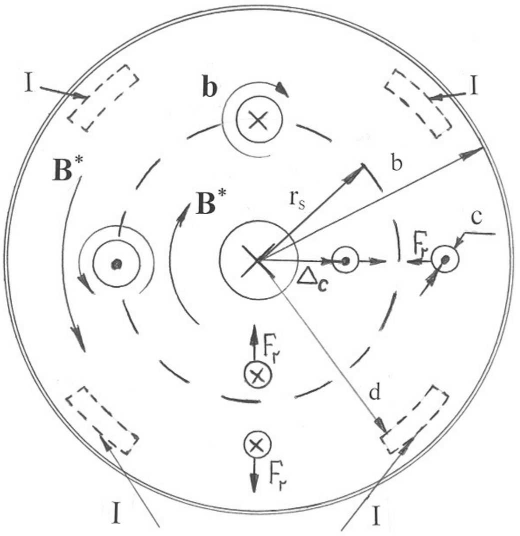

Fig.2. Scheme of radial forces origin.

2.Inverted disruption

In Fig.2 the scheme illustrating the origin of these forces is presented. Let the radius of the conducting chamber be b, and let the plasma current Ip flow from the observer. The dotted line ring is a resonance surface of radius r_s (assume q (r_s) =2). At the surface an appropriate current perturbation J_m is located as filaments of radius c and magnetic field **b**. In the neighborhood of r_s are figured $\mathbf{B}^*$-vector of an"additional" Kadomtsev-Pogutse magnetic field

$\mathbf{B}^* = B_p\,(dq/dr)\,(r/q)\,\delta r\,\mathbf{e}_\theta = B^*\mathbf{e}_\theta$ (1 [7]), which is the magnetic field, intersected by resonant helical current filament (m=2/n=1) during its displacement at the distance δr from r_s (we assume $dq/dr > 0$ everywhere). From Fig.2 it follows that the own magnetic field of current perturbations, **b,** increases the field $\mathbf{B}^*$ in the area of negative current modulation and decreases it in the area of positive modulation. Moreover, the helical current perturbation creates b_r- the resonant magnetic components intersecting a circle of radius r_s. Their adding means a break of the former resonance surface $q(r_s)$ =m/n as well as its reorganization with formation of conventional magnetic islands in the area of negative current modulation. In the area of positive current modulation an x-point geometry should be realized. Usually it is assumed, that a magnetic field of perturbation $b_\theta < B^*$. This condition, however, can be easily violated, if current perturbations are too high, or, if magnetic shear close to r_s is small. As soon as b_θ exceeds B^* one may expect a new magnetic reconnection with splitting of one x-point in two, elongated in r direction, and formation between them of a "positive" magnetic island [8] with an own magnetic flux closed around its helical axis. This bifurcation will occur if the current density of positive perturbation j_m exceeds the critical value:

$j_{cr} = \langle j\rangle_{rs} (dq/dr) (r/q) \big|_{r_s}$ (2), where $\langle j\rangle_{rs}$ is the average current density inside r_s.

The new islands differ from conventional magnetic islands by positive current modulation and characteristic elongation in r direction (in contrast with usual, elongated in θ direction). The conventional magnetic islands can be steady close to r_s. As one can see from Fig.2 any displacement of r further than r_s will cause returning force $\mathbf{J_m}$ x $\mathbf{B}^*$. In contrary positive magnetic islands should be unstable at r. It is seen from Fig.2, that any displacement of positive current filament from r_s to r will cause a radial force $\mathbf{J_m}$ x $\mathbf{B}^*$ increasing an initial displacement. As it was shown in [5], this instability can only be avoided by means of negative currents induced in exterior layers of hot plasma. They should iterate helical structure of a positive island, that is, they should be inclined with respect to magnetic field lines. But for this purpose the formation of the appropriate gradients of plasma pressure is necessary. These gradients in turn can collapse affected by different instabilities: tearing or ballooning modes, for example. The displacement of a positive magnetic island out to the area of higher magnetic shear, where the condition (2) is violated, should result in reconnection with a field $\mathbf{B}^*$. As a result a reduction of the magnetic flux of a field $\mathbf{B}^*$ in the area of magnetic reconnection outside from r_s should occur. This means flattening of the main current distribution and loss of magnetic shear away from r_s. Thus the area affected by destruction of a positive magnetic island should essentially exceed an initial zone close to r_s, as it is observed during fast thermal quench usually preceding the major disruption. The most important feature of force disruption model is spatial separation on r of the positive and negative helical current perturbations. Such separation should cause additional poloidal magnetic flux in the separation zone. In particular, during displacement of positive perturbations outside the negative perturbations should stay or move inside, following r_s. As a result a negative magnetic flux should occur between the plasma center and the edge. To compensate it the positive extra-current should be induced at the plasma center. The existence of such currents during major disruption was predicted on the base of magnetic measurements [2]. At last, the direct observation on spatial separation of the positive and negative current perturbations was made in measurement of exterior MHD-activity [3]. But, if such model is valid, it permits the reverse process. Namely, positive current perturbation of the number m (Fig. 2) appearing inside a resonance surface $q(r_s)=m$, should move towards the center. The probable stages of such displacement (I-IV) are presented in a Fig. 3. Its necessary condition should be: $q(r) < m$ in all area of perturbation displacement. The vanishing of an extra-current owing to an abnormal dissipation means the fast magnetic reconnection and penetration of the injected magnetic flux (Fig. 3 IV) into the center. It is possible, that the events shown in the Fig. 1 can be explicated by this scheme. It is obvious, that flux injection, presented in Fig. 3 (I-III) is only possible under condition, that the magnetic flux of a field $\mathbf{B}^*$ in the center is small in comparison with the injected magnetic flux. Moreover, the condition of helicity conservation requires reduction of a current J_m of injected positive current perturbation during its displacement to the center. Penetration of the injected current perturbation up to the radius r from initial a is only possible under the following condition:

$2\pi Rm \{0{,}2J_m \ln b/a + \Phi_{Im}\} > B_T\, \pi(a^2-r^2)\, (m/\langle q\rangle_{ar}-1) + \Phi^*$ (3),

where $\langle q\rangle_{ar}$ is the mean value q(r) between r and a. From (3) it is seen, that penetration of the injected flux into the center may only occur in the narrow area $\langle q\rangle_{ar}$ close to m. Probably, this is the reason that the injection of a poloidal magnetic flux to the center by means of the inverted disruption is not observed usual in experiments. A case presented on Fig.1 may be an exception. Here the configuration with small magnetic shear and injection of helical magnetic perturbation m=3/n=1 was realized simultaneously. What will occur, if the condition (3) is not fulfilled? It would be possible to expect an effect similar to that realized during the fast thermal quench. Namely, as a result of magnetic reconnection of **b** and $\mathbf{B}^*$ fields the Φ^* flux decrease in a reconnection zone and increase outside of it. That means the reduction of a current density j(r) inside the reconnection zone and increase outside of it (Fig.4, I-III). The consequent injection pulses of helical magnetic fluxes Φ_{Im} should reinforce effect. Thus, it is possible to expect that under the pulses of sufficient intensity and sequence the effective flattening of the j(r) profile will take place at the center. After the fulfillment of condition (3), the «break» of current perturbation to the center similarly to Fig.3 becomes possible. As a result it is possible to expect, that under sufficient power and periodicity of such injection some quasi-stationary flat profile j(r) will be established, similar to that currently used in so-called «optimized shear regimes» with small magnetic shear at the center of plasma column. The ohmic losses at the center, according to the supposed scheme, should be compensated by «break» of helical flux to the center, and compensation an overheat of the plasma center to be ensured by reconnection of the injected magnetic fluxes in peripheral areas of a plasma column. How is it possible to realize the periodic injection helical current perturbations to tokamak?

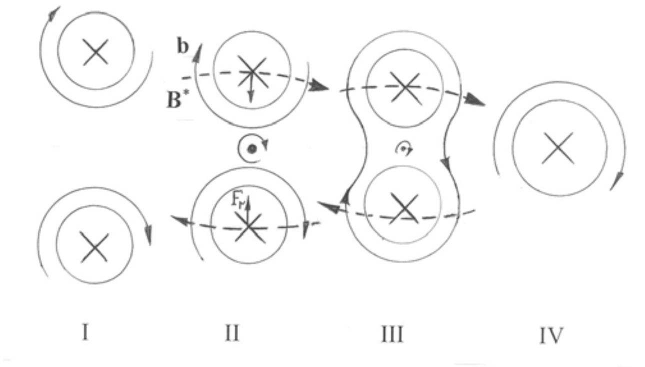

Fig.3 Scheme of the magnetic flux injection to the center

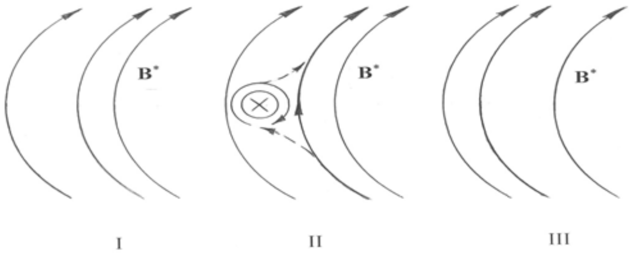

Fig.4 Scheme of reconnection of added helical and main poloidal magnetic fluxes.

Probably the simplest way of such injection will be to induce helical currents in a plasma column by means of helical winding located in a limiter shadow. Let us show, for example, one scheme of such injection, if q(r) close to the plasma boundary is slightly below 4.The provisional scheme of an arrangement of such winding m=4/n=1 is presented by a dotted line (I) in Fig. 2. Let's consider for simplicity, that the chamber wall represents an ideally conducting shell of radius b, the special winding with helical geometry m=4/n=1 is displaced from the chamber at the small distance δr=0,2b and positioned at r=d, were q(d)=4. Let q(r)<4 in all other area of a plasma column. It can be shown, that significant part (0.3-0.4) of a helical flux Φ_{Im0}, created by such winding, can be frozen in peripheral region of a plasma column. If to tear a current J_{m0}, in plasma will be induced: a positive current Ip (symmetric part of current perturbation), current of positive helical perturbations I_m+, and negative I_m-. The helical currents of different polarity are in different conditions in relation to forces produced by tokamak magnetic field. The positive perturbations should be pulled to the center, and the negative - outside, towards the helical winding (inductor). Obviously, the outside displacement towards the inductor will be accompanied by cooling of the appropriate plasma, and enhanced dissipation of negative helical current. In contrast, the positive helical perturbations will move to the hot plasma region and should damp much more slowly. It should create a potential opportunity for magnetic reconnection and reorganization of current distribution.To repeat the injection pulse it is required to increase the current I_{m0} again. That should induce in plasma a negative current ΔIp and, accordingly, J_m^- and J_m^+. And again the positive current will appear in hot plasma, and negative - in cold, near to the inductor, that should promote them preferential resistive dissipation. The principal feature of helical current perturbations is that their magnetic fluxes are weakly coupled with the main poloidal magnetic flux and could be dissipated without significant consequences for the main plasma column. It allows to hope that preferential unipolar injection in a plasma column of the positive helical current perturbations with m>q(a) in periodic mode of operations will take place. Note that the induction coil could basically be replaced by a discharge between special limiters, playing a role of electrodes, in a shadow of basic limiter.

2. Conclusion

In what cases the offered helicity injection can find practical application? Its basic negative quality - necessity of plasma turbulization for transformation of a helical to main magnetic flux is incompatible with high performance of the plasma. However it can be useful for current profile control in the regime of small magnetic shear maintenance in the center to support the optimized tokamak regimes. However all our considerations were made in the framework of some idealized scheme, not supposing, that the induced helical perturbations can lead to destabilization of plasma column. But such effects are possible. First of all, the additional helical perturbation near the plasma boundary can generate a locked mode with all its negative consequences. Secondly, the injected perturbation m=4 might be reconnected to m=3 close q (r_s)=3. In this situation the minor exterior disruption will be possible. These questions can be answered only by experiment. In all cases the active injection the helical current perturbations to plasma would expand our knowledge of the major disruption origin.

References

[1] GORBUNOV , E.P., RAZUMOVA , K.A. Atomnaya Energiya **15** (1963) 363.

[2] MIRNOV, S.V., SEMENOV, I.B. Proc. 6th IAEA Conf. on Plasma Phys.&Contr. Fus. Res. 1 (1976) 291 and Proc. 8EPS Conf. on Contr. Fus.& Plasma Phys**.** **1** (1977) 45. [3] MIRNOV, S.V. Proc. 28EPS Conf. on Contr. Fus.& Plasma Phys. **ECA 25A** (2001) P4.037 p1473

[4] KADOMTSEV, B.B., Voprosi teorii plasmy (Rus) M.Gosatomisdat **2** (1964) p165.

[5] ZAKHAROV, L.E. Fizika Plasmy (Rus) **7** (1981) 18.

[6] KADOMTSEV B.B. Fizika Plasmy (Rus.) **1** (1975) 710.

[7] KADOMTSEV, B.B., POGUTSE, O.P., Zh. Eksp. Teor. Fiz. **65** (1973) 575

[8] MIRNOV, S.V., Fizika Plasmy (Rus) **24** (1998) 813. Plasma Phys. Rep. **24** (1998) 875.