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V. D. Shafranov and Tokamaks

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V. D. Shafranov was a key person in the fusion program. The paper presents the recollections of one of his close colleagues about Shafranov's impact on the early days of tokamak research.

1. Introduction

Academician Vitalii Dmitrievich Shafranov (figure 1) is one of the most revered pioneers in the world of controlled thermonuclear fusion. He began his career as a young graduate of the Moscow State University in 1952. For over 60 years he worked steadily and tirelessly, surmounting many obstacles that he encountered along the way. The work that he did on tokamaks includes many milestones, some of which he is remembered for, and others which are not credited to him. The first ITER prototype – the 'Tokamak with Non-round Section of the Plasma Loop' was the last breakthrough attributed to Shafranov.

My memories of Vitalii's first work in magnetic fusion (a subject into which I followed him 10 years later) are mostly based on first-hand accounts, for example (Ivanov 2012), as well as his own personal notes (Shafranov 2001) and of course his publications (Shafranov 1959, 1963, 1970; Leontovich & Shafranov 1961).

During his career he was in good company, his mentor was Leontovich, he was good friends with Braginsky and he worked closely with Kadomtsev. His director at the Division of Plasma Research of Kurchatov Institute was Artsimovich.

One of the first special tasks that was assigned to Shafranov was investigating the secret of ZETA. He took on that task together with Braginsky. To accomplish this, they had very little information to go on (mostly brief mentions in newspapers), for example 'that it was round'. After some deliberation they decided that ZETA was a tokamak. It was due to this that tokamaks gained a vital supporter in the form of head of the institute, Kurchatov (he previously favoured stellarators). Shafranov retained a great deal of respect and affection towards Braginsky throughout his whole life which I repeatedly witnessed.

Vitalii's first work 'The stability of a flexible conductor in a longitudinal magnetic field' was carried out together with Leontovich (Leontovich & Shafranov 1961) and referred to linear (or Z-) pinches, and only briefly mentioned the future tokamak. A much clearer 'consumer' result was achieved in Vitalii's next paper (Shafranov 1959)

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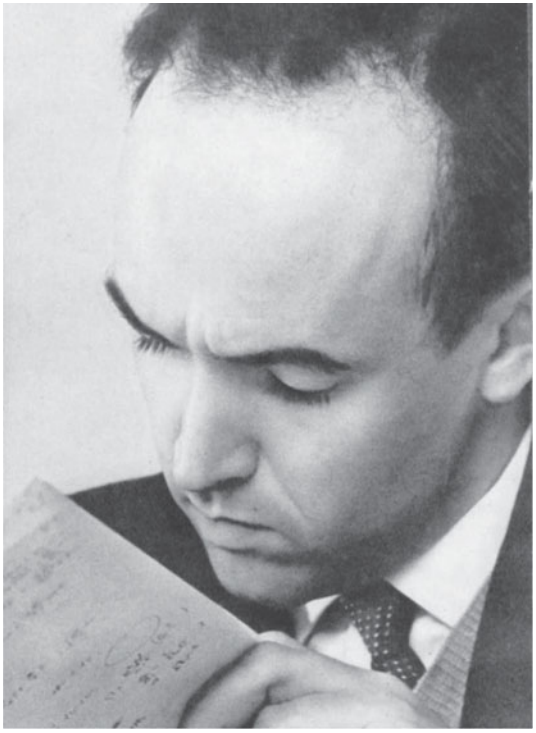

FIGURE 1. Shafranov in the 1960s.

(written in 1952, and openly published in 1958), where the stability criteria of a flexible conductor took on an almost modern form:

$$\frac{H_{ze}}{H_\varphi} > \frac{\lambda_m}{2\pi a}, \tag{1.1}$$

where H_{ze} is the longitudinal magnetic field, H_φ is the field due to the current, λ_m is the maximum length of the perturbation and a is the minor radius of the conductor. Substituting $\lambda_m = 2\pi R$ (the maximum length of the perturbation in a torus) into (1.1) gives the well-known Shafranov–Kruskal criterion, $q(a) > 1$. Later the $q(a) > 1$ criterion became the official designation for all tokamaks. It is also known as the macroscopic stability criterion. According to Artsimovich, it was expected that this formula should be known by every employee in the tokamak department (No. 44) of the Division of Plasma Research of the Kurchatov Institute.

Criterion (1.1) was derived by Vitalii under the assumption that the current flows along the surface of the plasma column. This assumption was relevant for linear pinches. It was not obvious to physicists at the time that this criterion also applied to quasi-state toroidal plasma discharges, where the current is distributed over the cross-section. Furthermore, the criterion leads to a low maximum allowable plasma current. One of Vitalii's colleagues, Ivanov stated that it was unfortunate that the fundamental macroscopic stability criterion (1.1), derived by Vitalii Shafranov at Golovin's request, was not appreciated initially; this was most likely because Golovin and Yavlinskii were busy constructing the new device, T-1, and also because Vitalii was very shy. Once, when they (Ivanov and Shafranov) were returning home from a rowing training session, Vitalii complained to Ivanov about this, and they decided to check this criterion experimentally on a linear pinch. At that time, both on a linear pinch and on the TMP (the first version of the tokamak with an 80 cm major-radius porcelain torus) there was a preference to work with currents of 200 kA and greater. This was based on Braginsky's estimations that in order to sustain a fusion type plasma, a current of at least 2 MA was required. This fact was widely accepted and was referred to as 'Braginsky's current'. According to Shafranov's criterion, under their experimental conditions, the plasma column should only have been stable under a current of below 50 kA. However, when the current in their experiment was reduced to 50 kA, signs of instability (such as fluctuations in Rogowski coils) disappeared. Initially this result was generally viewed with some scepticism. Furthermore, when they reported it to Artsimovich, he said: 'So what, you achieved a stable glow discharge. Who needs this? In our sources (ionic sources which were used in the separation of isotopes) it is always stable!' Vitalii and Ivanov were so disheartened by this that they did not show their results to neither Golovin nor Yavlinskii. Their experimental result was not published, and the TMP tokamak continued to operate at currents significantly higher than those allowed by the Shafranov stability criterion. The plasma was very turbulent and filled up the whole cross-section of the vacuum vessel. It was only towards the end of TMP that it was noticed that the plasma behaved differently during plasma current ramp-up, specifically before and after the plasma current reached the magnitudes specified by Shafranov's criterion. This was taken into account in the next machine, the T-1 (the first real tokamak made with a metallic vessel, which was built by Yavlinskii), the current was lowered in accordance with Shafranov's criterion, the plasma minor radius was restricted using a limiter and the plasma became more stable.

This criterion was thoroughly checked on the next tokamak T-2 (Dolgov-Savel'ev 1960; Dolgov-Savel'ev *et al.* 1960). When the Shafranov criterion was violated, the plasma boundary became turbulent. Plasma was also ejected onto the wall as if the plasma limiters were completely absent. More stable conditions with $q(a) > 1$ led to an improvement in plasma confinement, but not a radically different situation. The plasma electron temperature (which was determined via electrical conductivity) increased to 20–30 eV, which was a typical range for plasmas at that time. However, all the plasma waveforms from the tokamaks remained filled with high-frequency oscillations. This clearly pointed to the development of smaller scale plasma turbulence.

The first MHD stable plasma was obtained on the TM-3 tokamak by Gorbunov and Razumova in 1962 (Gorbunov & Razumova 1964). This is the moment that the systematic study of real tokamak plasmas began.

During the next 40 years Vitalii Shafranov was responsible for three important developments related to tokamaks. Firstly, the theory of plasma equilibrium. Secondly, the theory of MHD stability in toroidal magnetic confinement systems. Finally, the D-shaped tokamak cross-section concept, jointly proposed with Lev Artsimovich.

2. Plasma equilibrium

Shafranov's equilibrium theory of plasma with a current in the conductive shell is the seminal theory on which the tokamak field is founded upon.

When the T-2 tokamak was operated under the $q(a) > 1$ condition, the plasma current waveform from the best pulses was found to have a two-hump shape. It was suspected that the cause of the unusual plasma current waveform was stray magnetic fields from the iron transformer core, which were transverse to the toroidal field.

Transverse stray magnetic fields have the effect of pushing the plasma column either up–down or inside–outside from its original position depending on the transverse field's direction. In order to mitigate against this behaviour, Sakharov suggested encasing the plasma column in a conductive shell. The shell anchored the plasma column vertically in the centre of the vessel, and maintained its equilibrium in the direction of the major radius.

At the request of Artsimovich, Vitalii took on the transverse balancing magnetic field problem and derived his second famous formula:

$$\varDelta_{\perp} = \frac{5b^2 B_{\perp}}{J_p}, \tag{2.1}$$

where $B_{\perp}$ is the transverse field, $\varDelta_{\perp}$ is the additional displacement of the plasma column with respect to the conductive shell centre, b is the conductive shell minor radius and J_p is the plasma current.

As can be seen from (2.1), during the initial stage of a tokamak pulse when J_p is small, even an insignificant $B_{\perp}$ compared to the toroidal magnetic field B_T is capable of shifting the plasma column away from the centre of the vacuum vessel towards the wall. The stray magnetic fields of the transformer current were measured in the T-2 tokamak. They were found to be sufficient to explain the formation of the two-humped current (Artsimovich & Kartashov 1963). This work had international repercussions; after this effect was observed on tokamaks, comparable effects were also found on stellarator-C with the toroidal current. This became the first specific topic of the subsequent long-term scientific collaboration between the Kurchatov Institute and Princeton Plasma Physics Laboratory (PPPL).

In 1961, Artsimovich instructed Yavlinskii who subsequently delegated the task to Mukhovatov, to construct a special tokamak (T-5) to study plasma equilibrium. T-5 had additional poloidal magnetic field coils. The poloidal coils were located in between the vacuum vessel and the copper shell, which allowed the position of the plasma column to be controlled during a discharge. Shafranov and Artsimovich became the mentors of this research.

Strelkov and I were also involved in the study of equilibrium. After Yavlinskii's sudden death (in a plane crash in the summer of 1962) Artsimovich entrusted Strelkov with bringing into operation the recently constructed tokamak T-3. At that moment in time, this was the largest tokamak in existence. As a freshly graduated specialist I was instructed to aid Strelkov in this work.

The difficulty with the T-3 tokamak stemmed from the fact that during its construction, stray magnetic fields were not seen as a big issue. It was assumed that as they were small compared to the toroidal fields, they would not interfere with the plasma. Meanwhile the toroidal fields in T-3 were planned to reach record values of 4 T (a significant magnitude, even by modern standards) in a magnetic field volume of up to 1 m^3. The electrical power for the machine was supplied by a powerful flywheel generator, which created an impulse lasting around 1 s.

It was found that when the magnitude of the toroidal field was raised to 1.5 T, the plasma breakdown was problematic and eventually could no longer be achieved. It was assumed that the reason for this was that, with the increase in magnitude of the toroidal field, the stray transverse magnetic field was also increasing due to manufacturing defects in the machine. Specifically this was most likely caused by the shifting of the toroidal coils due to mechanical forces during operations. If the stray magnetic field was of a magnitude of 10^{-4} T, then this would have had enough impact

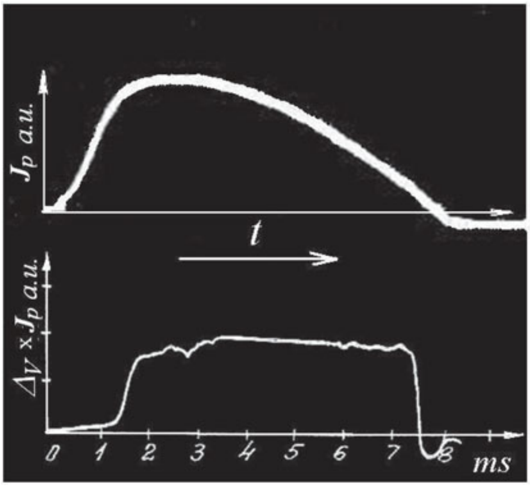

FIGURE 2. Waveforms of $J_p(t)$ and $\Delta_V J_p(t)$ for one of the T-3 pulses from the 1963 experimental campaign (Artsimovich *et al.* 1965).

to prevent breakdown. There was (and still is) no means of measuring such a small stray magnetic field, against the background of the large toroidal field.

A solution was found in an indirect fashion by using (2.1). The four poloidal magnetic B_p probes were installed in four poloidal locations, separated by 90° around the plasma column (Mirnov 1965). In order to measure the vertical (Δ_V) and horizontal (Δ_R) displacements of the plasma, a differential scheme was used. The difference in the poloidal magnetic field between each of the opposite pairs of probes has to be equal zero when the plasma is positioned in the centre of the vessel. The differential signal must also be proportional to the plasma shifts with respect to the central location. Thus, two pairs of probes made it possible to determine the position of the plasma column inside the vessel. Variants of this simple technique are still in use today on some tokamaks.

The typical plasma pulse duration on the T-3 tokamak was around 10 ms, whilst the integration time for the signals was around 50 ms. Due to this, the measurement system was not sensitive to the toroidal field. In the very first pulse, the $\Delta_V J_p$ signal (which should be proportional to $B_\perp$) produced an almost perfect rectangle on the oscilloscope (figure 2, Artsimovich, Mirnov & Strelkov 1965). The height of this did not depend on the amplitude of $J_p(t)$, but followed the value of $B_\perp \propto B_T$.

By carrying out the pulse at a relatively low B_T, we determined the ratio of the vertical to the horizontal components of $B_\perp$ which were produced by the toroidal coils. We then used the poloidal dipole magnetic coils to compensate for the stray fields throughout the whole range of B_T. As a result of this, the T-3 tokamak started operating at toroidal magnetic fields up to 3.5 T (Artsimovich *et al.* 1965).

These experiments produced the first documented evidence that tokamak plasmas, apart from in the early stage just after breakdown, happen to satisfy Shafranov's equilibrium conditions. Figure 2 shows that the $\Delta_V J_p$ rectangle forms from $\simeq$1 ms onwards after the breakdown. It was suggested that during the initial stage of the discharge, the plasma equilibrium is provided by the currents which flow through the plasma on to the vessel wall orthogonally to the toroidal magnetic field B_T. This was later confirmed by Mukhovatov and his colleagues on the T-5 tokamak (Mukhovatov

1966). Mukhovatov observed that, during the initial phase of the discharge, a current (of the scale of tens of amperes) flowed from the plasma to the limiter and the vacuum chamber. According to Shafranov's calculations, these currents could be responsible for the plasma equilibrium along the major radius (Shafranov 1966).

During this time, Shafranov derived a formula which linked the thermal and magnetic energy of the plasma column with its equilibrium position inside the vessel chamber (Shafranov 1963):

$$\varDelta_{R0} = \frac{b^2}{2R}\left[\ln\frac{b}{a} + \left(1 - \frac{a^2}{b^2}\right)\left(\beta_I + \frac{l_i}{2} - \frac{1}{2}\right)\right], \tag{2.2}$$

where R is major radius, a is plasma minor radius, $\beta_I \equiv (8\pi\langle p\rangle)/B_p^2$, $\langle p\rangle$ is average plasma pressure, B_p is the magnetic field of the plasma current at the plasma boundary and l_i is the internal plasma inductance (which is an indicator of the magnetic energy stored inside the plasma). Considering that the inner surface of the conductive shell is a magnetic surface, (2.2) represents a particular case of the famous Shafranov shift.

Using a couple of magnetic probes (Mirnov 1965), it is possible to measure the Shafranov shift of the plasma magnetic boundary, and then, by applying (2.2), the internal energy of the plasma can be deduced (Artsimovich *et al.* 1965).

To investigate the influence of B_Z field on the plasma displacement on the T-5 tokamak, Mukhovatov and I installed a couple of magnetic probes similar to those on T-3, but we found conflicting results. When, during the pulse, we applied an external vertical magnetic field B_Z (the value of which was calculated taking into account the screening by the conductive shell), the plasma shifted along the major radius in the expected direction. However, the degree of displacement was found to be approximately two times larger than what was expected from Shafranov's formula (2.1).

We turned to Shafranov for an explanation of this odd result. At first he did not understand us; he did not see a point in measuring the plasma radial displacement as a theory already existed for its location. We presented our work and thoughts on the matter. He pondered our problem, and to our great surprise could not suggest an explanation. At that point in time, theorists could generally immediately explain any experimental result which was put in front of them, thus it was very unusual that Shafranov could not. When we left him, he managed to find a positive element from the situation and said 'At least it shifts in the right direction!'.

Mukhovatov was responsible for finding the explanation to this problem. The conductive shell in the T-5 tokamak had a longitudinal slot at the top and bottom of the machine (the idea being that this would help stabilize the plasma column along the vertical Z axis), rather than in the equatorial plane (which would stabilize it in the horizontal direction). As a result of this, the shielding effect of the shell was weakened by a factor of 2, which meant that the calculated magnetic field, B_Z was underestimated. The physics concepts and experimental results on the plasma equilibrium in tokamaks with a conductive shell were subsequently summarised in Mukhovatov's and Shafranov's famous review (Mukhovatov & Shafranov 1971).

Shafranov's equilibrium theory of the plasma with a current in the conductive shell is the seminal theory on which the tokamak field is founded. Based on his theory, it was possible to evaluate the quality of plasma confinement in tokamaks, and develop an understanding of MHDs instabilities.

3. Confinement and MHD stability

The measurement of the plasma shift on the T-3 tokamak revealed that the total energy of the plasma increases continuously with time (Artsimovich *et al.* 1965). It was then unknown whether this was caused by an increase in $\beta_I(t)$ (2.2) (i.e. the plasma thermal energy), or due to an increase in magnetic energy $l_i(t)$ (which would be caused by a gradual peaking of the current density profile). Artsimovich proposed a radical solution to the dilemma, i.e. to measure the thermal energy of the plasma using the diamagnetic effect (the change in the toroidal magnetic flux in a cross-section of the plasma column). This method assumed that the plasma was in a state of equilibrium in the direction of the minor radius, which would be automatically true if the plasma column was in equilibrium in the major radius direction.

Razumova and I took on the task of measuring the plasma diamagnetism; she worked on the TM-2 tokamak, and I worked on the T-3 tokamak. It soon became evident that the task was harder than it first appeared. On the T-3 tokamak, the insignificant small diamagnetic signal was swamped by the noise from the flywheel generator which powered the toroidal solenoid. To mitigate against this, we had to install a large custom pulse LC filter. In total it took almost two years to resolve the issue of the noise.

Razumova did not have the same problem because the TM-2 tokamak which was powered by capacitor batteries. Therefore, she was the first to extract the diamagnetic signal (Razumova 1966). It was discovered that the diamagnetic thermal energy (W_{dia}) was significantly larger than was previously estimated, based on the measurements of conductivity with the assumption of pure hydrogen plasma (this was a normal practice in the 1956–1964 period).

On the eve of the 1965 Culham conference, the T-3 also managed to register its first reliable diamagnetic signal. The plasma energy of T-3 increased during the discharge in accordance with the time development of the plasma displacement $\Delta_{R0}(t)$ (Mirnov 1968). If the density measurements are included (in the 1960s Gorbunov was responsible for the density measurements on all tokamaks) then the average (over the plasma cross-section) electron plasma temperature reached 400–600 eV, which is 3–4 times higher than the electron temperature of the plasma obtained from the conductivity measurements. Similarly to the TM-2, in T-3 experiments a significant gap was seen between the measured and the calculated Bohm (anomalous diffusion as the result of turbulence) tokamak confinement time.

At the 1965 Culham conference, Artsimovich stated that the energy confinement time τ_E (equal to the ratio of the plasma energy to the input power) on tokamaks was three times higher than the Bohm confinement time. This was not accepted by the other attendees. On stellarator-C the measured energy confinement time was practically equal to the Bohm confinement time, this cast doubt on the prospects for closed systems in the field of fusion.

The next step was to find the relationship between τ_E and the basic parameters: the toroidal magnetic field B_T, the plasma density n_e and the discharge current J_p. The data from the T-3 tokamak was processed using a system of three equations: two Shafranov's plasma equilibrium equations for the major and minor radii directions and the energy balance equation for the plasma. The following values were measured: plasma current $J_p(t)$, loop voltage $V(t)$, the diamagnetic flux and the plasma shift in the major radius direction, $\Delta_{R0}(t)$ (Mirnov 1969; Gorbunov, Mirnov & Strelkov 1970). The unknowns were: the thermal energy of the plasma $\propto \beta_I$, the magnetic energy $\propto l_i$ and the input power P_{oh}, which was in fact related to the average electrical conductivity σ. The next step was to calculate the energy confinement time τ_E. In the winter of 1967, Gorbunov and I took on this task, working on the T-3 tokamak, having no idea of its scope and implications.

Due to the experiments on the T-3 tokamak, carried out at $q(a) > 3$, it was found that τ_E was not related to the magnitude of B_T. The energy confinement time τ_E increased linearly with the current J_p and increased with the plasma density n_e as n_e^α with $\alpha \simeq 0.5$. All of this contradicted the understanding of tokamak plasma physics at the time, which led to a widespread indignation and accusation in incompetence towards myself, as I was responsible for the magnetic measurements. This reaction by people was based on expectations that either $\tau_E \propto B_T^2$ (classical transport) or $\tau_E \propto B_T$ (Bohm scaling). The revolutionary neoclassical theory of transport processes developed by Galeev and Sagdeev which replaced B_T by B_J was published only in the following year (1968). Furthermore either a negative relationship between τ_E and n_e (classical transport) or no relationship at all (Bohm scaling) was expected, but not the positive relationship that was found.

During the 1968 IAEA conference at Novosibirsk, Artsimovich presented the empirical scaling of $\tau_E \propto a^2 B_J n_e^\alpha$, where $\alpha \simeq 1/3$ (Artsimovich *et al.* 1969). The a^2 factor in the final formula was introduced by Artsimovich himself because it could then describe the plasma confinement in both the T-3 and TM-2 tokamaks at the same time. It was later shown by Mukhovatov and Merezhkin that a^2 should be replaced with Ra (based on experiments on T-11), but it was not possible to capture this distinction by comparing T-3 and TM-2 data.

However Artsimovich did not like the positive dependence on electron density, n_e, which contradicted the classical transport model based on binary collisions which predicts $\tau_E \propto 1/n_e$. During discussions at the Dubna meeting on closed systems in 1969, he presented this questionable scaling as ‘Mirnov’s’. It was later shown (after the death of Artsimovich) that the increase of τ_E with the plasma density is explained by enhanced radial electron heat transport due to microscopic fluctuating magnetic islands (Kadomtsev–Callen ‘magnetic-flutter’ model, see Callen (1977)).

Harold Furth also did not like the new scaling because it led to pessimistic predictions for a tokamak power station (the size required would be too large). After the Dubna meeting, Furth called this scaling the ‘conservative Mirnov scaling’, I believe, thus highlighting his doubtfulness. When it was discovered that the new scaling almost perfectly predicted the plasma energy confinement time for the T-10, the Princeton Large Torus (PLT) people started referring to it in a more respectful manner as the ‘Mirnov scaling’. When the minor radius, a, was replaced with the major radius R, the scaling was renamed ‘Mirnov-like scaling’. It was later renamed once more to ‘GMS-scaling’ after the analysis method was described for the T-3 tokamak (Gorbunov *et al.* 1970).

GMS-scaling was found to be practically identical to the scaling developed for ITER 30 years later $\tau_{E,98} \simeq R^{1.7} a^{1.2} B_p p n_e^{0.4} P_H^{-0.6}$ (ITER Physics basis 1999), where P_H is the input power to the plasma. GMS-scaling was developed only for Ohmic heating regime, due to this it was not able to predict the dependence on P_H. The main tool used by us in developing GMS-scaling was the Shafranov plasma equilibrium theory and his three famous formulae. The participants in this work were awarded the State Prize of the USSR in 1971, see figure 3.

Artsimovich emphasized that the formula $\tau_E \propto a^2 B_p n_e^\alpha$ can only be used in steady-state conditions (Artsimovich *et al.* 1969), i.e. the scaling applied to the observed plateau of τ_E during a pulse. Meanwhile a dependence of τ_E on the shape of the plasma current waveform was observed on the T-3 tokamak. Specifically the secondary rise of the current led to a decrease in τ_E, whilst an increase in the current led to an increase in τ_E (Mirnov 1969).

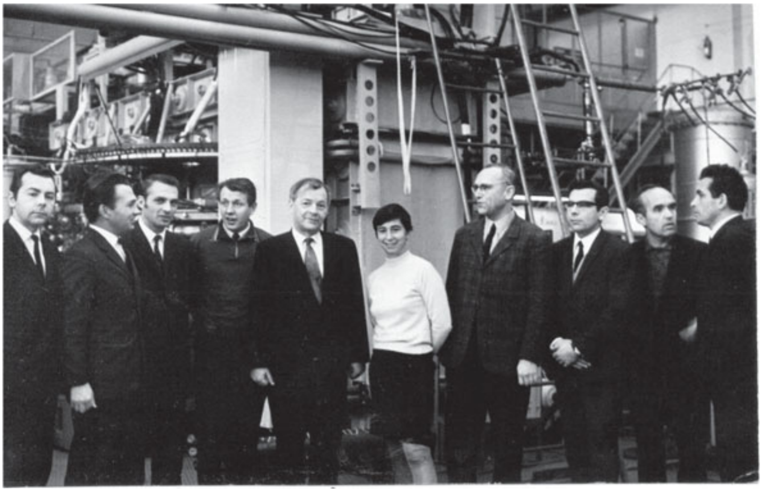

FIGURE 3. From left to right: Mirnov, Gorbunov, Us, Strelkov, Artsimovitch, Razumova, Spiridonov, Mukhovatov, Shafranov and Ivanov – awarded the State Prize of the USSR in 1971, in the front of T-4 tokamak.

This observation indicated that the plasma confinement depends on the distribution of the plasma current over the cross-section of the plasma or, in other words, on the magnitude of l_i. The current profile in turn defines the magnetic shear. Magnetic shear is the main obstacle to the development of MHD perturbations across the magnetic field. For instance, a uniform current distribution ($l_i = 0.5$) corresponds to no magnetic shear which allows a magnetic resonance perturbation to grow unhindered while 'pushing' aside the magnetic force lines.

During the pulse $\tau_e(t)$, $\beta_I(t)$, and $l_i(t)$ were calculated using the method described in Artsimovich *et al.* (1965). $\beta_I(t)$ and $l_i(t)$ were found to increase in magnitude along with an increase in the shift of the plasma throughout a pulse, i.e. the plasma confinement improved with the peaking of the current profile until reaching a plateau (steady-state conditions). The growth of $l_i(t)$ also means a growth in magnetic shear.

According to calculations, during the plasma current ramp up, the plasma current profile should remain flat. Therefore, during the phase of increasing current, the average magnetic sheer has to be small. During the quasi steady state of the pulse, the current diffused towards the hot central zone and the shear increased accordingly. The increase in magnetic shear is responsible for the increase in τ_E (Mirnov 1969). Today it is the common knowledge that for good shots β_I is proportional to l_i (ITER Physics basis 1999).

The next challenge was to find the relationship between τ_E and magnetic shear. During the plasma current ramp up, the oscillating bursts of poloidal magnetic field were observed (figure 4). They were recorded using Rogowski coils and magnetic probes (Mirnov 1969). The oscillation amplitude was found to be weakly dependent on $q(a)$. In addition, the oscillations were found to be caused by an increase in the rate of the current rise, in other words, a decrease in l_i. After discussing the experimental results with Shafranov and other colleagues we came to the conclusion that these oscillations were a manifestation of the tearing instability (Furth *et al.* 1973) (this conclusion was later shown not be completely correct). These experiments were described in Mirnov (1969), and the oscillations were later referred to as 'Mirnov's Oscillations'.

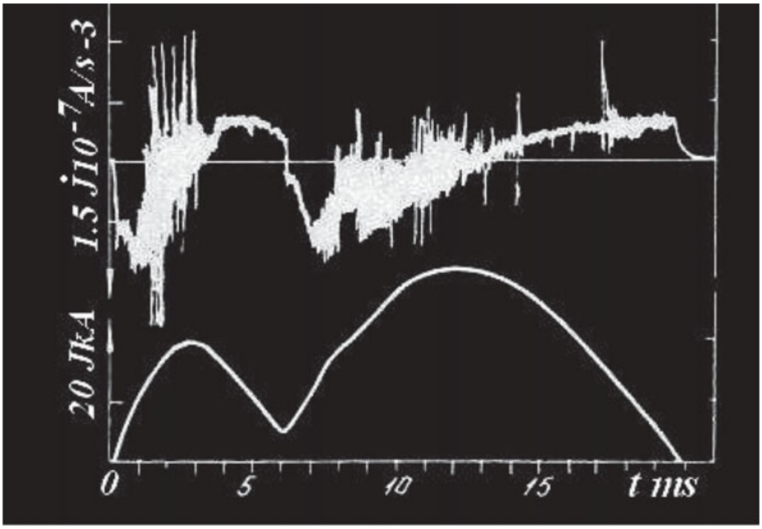

FIGURE 4. $J_p(t)$ and its derivative with double $J_p(t)$ ramp up waveform on the T-3 tokamak (Mirnov 1969).

One year later, Shafranov published his famous work on the topic of ideal MHD stability of the plasma boundary (‘external MHD stability’) (Shafranov 1970). This work produced one of the links between the stability of the boundary and the average magnetic shear. According to Shafranov (1970), while the shear is small ($l_i \simeq 0.5$), the plasma periphery is unstable with respect to all of the resonant kink perturbations. This is true if the $nq(a) = m$ condition is satisfied outside the plasma boundary, where m and n are the poloidal and toroidal mode numbers of the perturbation, respectively. Meanwhile, the deformation of the plasma boundary should have the nature of a travelling wave, which is what was observed. According to Shafranov’s theory, the kink surface instability is stabilized by the magnetic shear and by the conductive wall of the tokamak.

According to Shafranov’s estimates, the parabolic current distribution ($l_i \simeq 1$) is sufficient to stabilize all of the modes with $m \geqslant 3$, which was observed on all of the tokamaks at that time (T-3, TM-3, T-5). After this, it became clear that the process of increasing plasma current is controlled by two competing processes: the flattening of the current profile and the destabilization of the mode leading to the exacerbation of the peaking of the current profile. It was natural to assume that, with a reduction in the rate of increase of $J_p(t)$, windows of stability could be found amongst low $m = nq(a)$ modes. Our experiments with Semenov on T-3A in the summer of 1969 confirmed this assumption $m = 4$, $m = 3$, $m = 2$ were observed. Between these modes we observed windows of stability (figure 5) as predicted by Shafranov’s theory. In practice, this provided the opportunity to work in the stability window at $q(a) \simeq 2.5$ and accordingly with an enhanced plasma current.

Shafranov was very interested in the developments from T-3A. He asked if we were planning on reporting them at the conference at Dubna (a meeting on closed systems in 1969). We told him that we were planning on presenting the modest correlation found from the new diagnostic measurements. The program of the meeting was tightly packed with a number of exciting presentations, including the report of the famous joint British–Soviet experiment. As I explained to Shafranov, I thought that we had

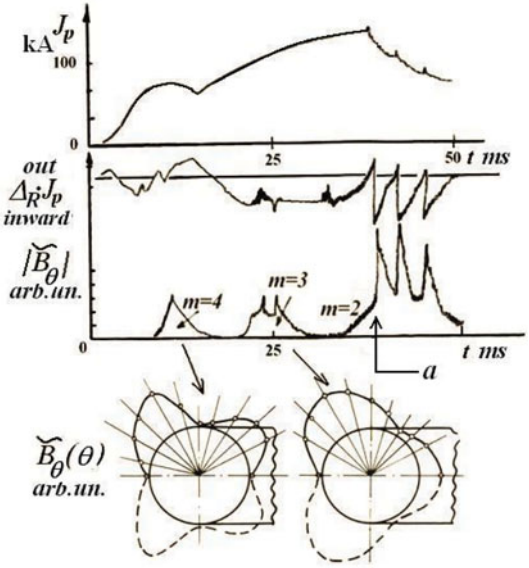

FIGURE 5. T-3A pulse with a continues plasma current ramp up: waveforms of plasma current $J_p(t)$, Shafranov shift of the plasma boundary $\Delta_R J_p(t)$, amplitude of poloidal magnetic perturbations $\tilde{B}_\theta(t)$. The mode structure for specific time points are presented at the bottom of the figure for modes $m = 4$ and $m = 3$, $n = 1$ (Mirnov & Semenov 1971).

little chance of getting onto the program with our diagnostic work. Kadomtsev was responsible for tokamaks on the program committee. Shafranov immediately took me to see him. Kadomtsev told us: 'There is nothing interesting here, what other type of perturbations could be found in tokamaks if not the kink type'. Shafranov's reaction to this was more than irritable. I never saw such a reaction from Shafranov either before this moment or afterwards, and I believe neither had Kadomtsev. He assured us that the report would be included in the program.

At that time Artsimovich's model dominated tokamaks. Intuition told Artsimovich that the existence of a strong resonance in the centre of $q(r) = 1$ could not go unpunished. He believed that the external MHD activity of the plasma was a secondary phenomenon, and therefore insignificant. No one could have predicted the development of the sawtooth instability near $q(r) = 1$, which limits the current density in the centre of the plasma.

Shafranov discovered the phenomenon of external MHD instability of the plasma in Shafranov (1970). In some cases, the peripheral instability activates the inner instability whilst in others, this is reversed. This duality can be seen most clearly in the dynamics of major disruptions.

Disruptions can be divided into minor and major disruptions. During minor disruptions, the current, J_p, varies only slightly, whilst during major disruptions, the current disintegrates completely. Our more recent studies (Mirnov *et al.* 2000) showed that in the case of minor disruptions, the impurities penetrated only into the peripheral zone of the plasma (as far as $\simeq a/2$) and the centre is not affected by them. During major disruptions, impurities from the periphery are drawn into the centre by the powerful convective instability, similar to an ideal kink mode such as Kadomtsev–Pogutse's 'vacuum bubbles' (Kadomtsev & Pogutse 1974). It seems that magnetic reconnection develops during disruptions, localized for the case of minor disruptions, and global for major disruptions.

For example figure 5 shows a typical minor disruption with growth of the $m=3$ instability and its stabilization. Major disruptions begin with the development of $m=2$ (arrow ‘a’ in figure 5), which is correlated with a thermal quench. The $m=2$ instability and thermal quench end with a short positive spike of the plasma current, indicating the loss of the plasma poloidal magnetic flux.

Figure 5 indicates that the beginning of a major disruption is preceded by the development of the external activity $m=2$ activity. It was also necessary to add an indicator of the internal MHD activity. As a result of discussions and reflections with others (especially with Mukhovatov) I settled on the diagnosis of soft X-rays (SXR) in the range of 1–10 keV. The first detector used by us on the T-4 (following modification of the T-3A tokamak with $B_T=4.5$ T and $J_p=250$ kA) consisted of a simple organic scintillator and photomultiplier.

The scintillator was separated from the vacuum vessel by aluminium foil with a thickness of 20 μm. This was the most risky element of the experiment as a failure in the foil could destroy the tokamak vacuum pumps. In the first successful pulse we recorded a strong SXR signal corresponding to an electron temperature of 1.4 keV at the centre of the plasma. During these tests we unexpectedly discovered a new physical phenomenon, namely the accumulation of high Z-impurities (mostly tungsten on T-4) in the centre of the plasma (Vershkov & Mirnov 1974). The accumulation of the heavy impurities increased the intensity of SXR by approximately 100 times, pushing the signal above the background noise level up to 10 times.

Peripheral kink instabilities, $m=2$ and $m=3$, were noticed before major disruptions, whilst the centre did not manifest any sign of instability. Our work on this topic was presented by Shafranov at the IAEA conference in 1971 (Mirnov & Semenov 1971). In PPPL von Goeler and his colleagues began taking identical SXR measurements to investigate the internal MHD instabilities on the ST tokamak. As a result they discovered sawtooth oscillations near $q(r)=1$ (sawtooth activity), namely the kink perturbation $m/n=1/1$ (von Goeler, Stodiek & Sauthoff 1974), which was periodically interrupted by internal disruption. Initially, it was thought that the harmless effects of internal $m/n=1/1$ activity and our experiments on the T-4 appeared to completely eliminate the Artsimovich concept of major disruptions. However, it was discovered later on that our initial impression was not correct.

4. Major disruption in tokamaks as interference of internal (Kadomtsev) and external (Shafranov) MHD activity

According to Kadomtsev’s model (Kadomtsev 1975), internal disruptions should begin with the development of an ideal kink mode $m=1$, which is destabilized by the pressure gradient near $q(r_s)=1$ (Bussac *et al.* 1975). The development of this mode is interrupted by magnetic reconnection which forms a local magnetic island in the centre of the plasma, i.e. the instability is similar to a tearing mode.

Progress in SXR and electron cyclotron emission (ECE) diagnostics allowed experimenters to observe these processes in detail. In particular, it was possible to separate the ideal and tearing modes. The magnetic islands which are the characteristic signs of tearing mode appear on the $T_e(r)$ profiles as a flat area close to the singular magnetic surfaces in contrast with almost sinusoidal T_e oscillations during ideal kink development. In the course of minor disruptions, von Goeler observed the transition of the external $m=2$ ideal mode into a tearing mode near $q(r_s)=2$ on the ST

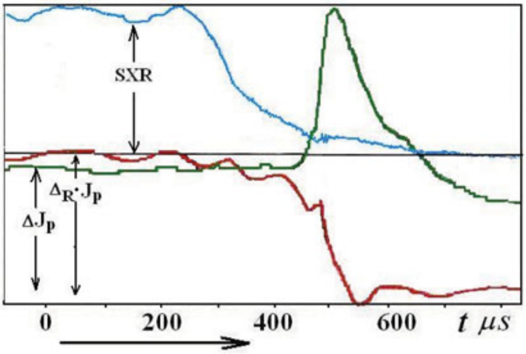

FIGURE 6. Example of a major disruption on the T-11M tokamak: SXR represents the centre MHD-activity, $\Delta_R J_p(t)$ reflects the evolution of the total plasma energy, $\Delta J_p(t)$ is the variation of the plasma current (Mirnov & Semenov 1977).

tokamak (von Goeler 1975). The external minor disruptions started with an ideal kink mode similar to Shafranov's surface wave, $m = 2$. Following this, during the magnetic reconnection, it transformed into a quasi-stationary tearing mode with the formation of a magnetic island. Thus the dynamics of external minor disruption are similar to Kadomtsev's model of internal disruption.

This sequence of events seems obvious – the development of magnetic islands supposedly reduces the gradient of the plasma pressure and the current density, thus, eliminating the underlying causes of MHD instabilities. Due to this, it makes sense to talk about the tearing mode as a stabilizing factor with respect to an ideal kink instability.

The dynamics of major disruptions was studied on the T-11M tokamak, where the plasma current was measured using a Rogowski coil which was mounted on the inner surface of the discharge chamber. It was found that the characteristic feature of a major disruption is a large (up to 10–20 % of J_p) current spike, which signifies a release of poloidal magnetic flux from the plasma. It can be seen from figure 6 that there is a sudden drop in SXR approximately 200 μs before the positive spike of the plasma current, i.e. the destruction of the central plasma, otherwise known as a fast thermal quench. The internal $m = 1$ mode was found during the thermal quench from experiments carried out on T-4 (with 2 horizontal and 2 vertical SXR channels) (Mirnov & Semenov 1977). It was found that the burst of the ideal $m = 1$ mode linked with the fast $m = 0$ SXR perturbation has a greater amplitude than the internal $m = 1$ mode during sawtooth activity.

Figure 7 shows a rendered view of $\tilde{B}_\theta$ for the case of a major disruption. The mode number m is determined as follows. At any time t, a vertical line is drawn on figure 7. Then the number of crossed lines of light and dark areas (relating to maximum and minimum values of B_p) is the mode number m. It can be seen that before and during the thermal quench, the oscillation is dominated by $m = 2$. The growth of this mode is interrupted by a short outburst of a small-scale magnetic fluctuation. This is followed by an $m = 3$ mode.

Bursts of high-frequency oscillations are common for all cases of magnetic reconnection observed in tokamaks. A change of the poloidal mode number from $m = 2$ to $m = 3$ during the development of a major disruption was first discovered

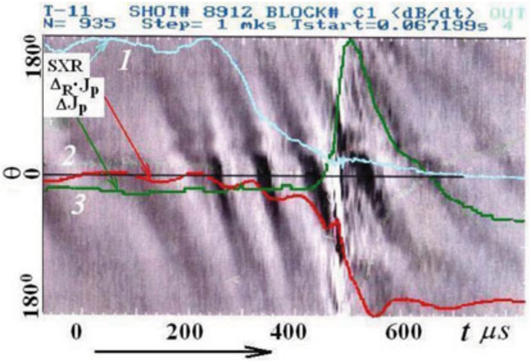

FIGURE 7. A rendered view of poloidal magnetic field perturbation $\tilde{B}_p(\theta, t)$ for the case of a major disruption on the T-11M tokamak (Semenov *et al.* 1995).

by Merezhkin on the T-6 tokamak (Merezhkin 1978), the accompanying magnetic reconnection was observed on the T-3A tokamak (Mirnov & Semenov 1971).

Figure 7 shows the small oscillations in $\Delta RJ_p(t)$ and in SXR signals which occur immediately prior to thermal quench. These oscillations have the same frequency as the $B_p(t)$ oscillations. The $\Delta RJ_p(t)$ and $B_p(t)$ oscillations have the $m = 2$ structure, whilst the SXR oscillations have the appearance of an $m = 1$ mode. Thus, immediately prior to a major disruption, the internal and external modes are in resonance. The resonance occurs only after the amplitude of the external mode $m = 2$ exceeds a certain limit. In summary, it can be concluded that once peripheral instability achieves a critical amplitude, it proceeds to destabilise the plasma core. As a result, the $m = 1$ mode of the second kind grows and leads to a major disruption.

There are at least two mechanisms which can be responsible for the internal $m = 1$ mode of the second type. The first mechanism is the cooling of the peripheral plasma as a result of a minor disruption (mode $m = 2$, or $m = 3$ changing into $m = 2$). The resulting impurities from the minor disruption are able to penetrate into the plasma, approximately half way into the minor radius (Semenov *et al.* 2003). The cooling of the periphery caused by these impurities leads to the diffusion of the current into the centre, creating the conditions necessary for the development of the $m = 1$ mode of the second type and a thermal quench, e.g. TFTR (Fredrickson *et al.* 1995). The second mechanism is the internal $m = 1$ mode induced by an external $m = 2$ instability which is capable of suppressing the sawtooth activity. The current density in the centre begins to gradually grow until it exceeds a certain level, at which point a thermal quench occurs. This mechanism occurs in the cases shown in figures 6 and 7.

Sometimes, the thermal quench does not end with a major disruption, which allows the scale of the destruction of the central plasma zone to be estimated. It was found that the entire centre is destroyed up to $q(r_s) = 2$. The most probable explanation of this type of $m = 1$ perturbation is its nonlinear state, the so called 'positive magnetic island' (Mirnov 1998; Mirnov *et al.* 1998). The reason for the nonlinear state is most likely due to the pressure-driven ideal kink mode as in sawtooth activity, but a higher amplitude, some kind of 'overheated water effect'. A critical parameter for the occurrence of such $m = 1$ mode is the level of resonant magnetic perturbations that may be induced in the region $q(r_s) = 1$ during development of the ideal kink instability of the plasma centre.

The dimensionless parameter characterizing the amplitude of kink perturbations is the ratio of the local magnetic field disturbances $\tilde{B}_\theta$ to the magnetic shear field, $B_p(\mathrm{d}\ \ln\ q/\mathrm{d}r)\delta r$, where θ is the poloidal angle and δr is the deviation from the magnetic resonance surface (Kadomtsev & Pogutse 1974).

The sources of the magnetic perturbations that cause the formation of magnetic islands can be presented in the form of alternating negative and positive resonant current filaments in accordance with real current perturbations on the resonant magnetic surface. The filament currents must satisfy the poloidal flux conservation condition on any magnetic surface. If $\tilde{B}_\theta$ caused by them is small compared to the shear field, conventional magnetic islands are formed, where the O-points (negative islands) with improved plasma confinement alternate with the X-points with bad plasma confinement. The O-points have bulging-out surfaces and carry a negative current, opposite to J_p. For X-points, the bulging-in surfaces carry a positive current perturbation, which should quickly disappear. That is the case of conventional tearing mode.

It was observed on the MAST tokamak that during the course of a thermal quench, the SXR signal degrades (Helander *et al.* 2002), which meant that the current in the centre of the plasma is flattened, and accordingly the magnetic shear is reduced. This was expected for the convective transport of plasma. According to Shafranov (Shafranov 1970), the loss of magnetic shear in the central zone of the plasma should lead to the destabilization of the external modes. Figure 7 shows how, in response to the thermal quench, a sharp rise in magnetic activity is observed at the periphery; initially this is $m=2$, then a magnetic reconnection and the burst of the mode $m=3$. All this is a reaction to the flattening of the current profile. The short positive spike of plasma current is the response of the electromagnetic circuit of the plasma due to the loss of the poloidal magnetic flux. If the current sensors, Rogowski coil or pick-up coils, are installed on the outside of the vacuum vessel this change in current is shielded by a negative current flowing in the vessel. The negative current which flows along the vessel manifests itself as a negative impulse on the external toroidal full flux loop.

A fundamentally different situation arises if $\tilde{B}_\theta$ exceeds the shear field, i.e. the filament current density exceeds some threshold, $B_p(\mathrm{d}\ln q/\mathrm{d}r)/0.2\pi$. In this case, the topology of the magnetic islands can be represented in the form of alternating negative and positive islands, i.e. O-points. Furthermore, the positive islands are replaced by X-points (Mirnov 1998), see figure 8 (Mirnov *et al.* 1998). However the positive islands, unlike the negative ones, are unstable in the r-direction therefore they must move into the $q(r)>1$ region. The plasma temperature in the positive islands can increase before the magnetic reconnection occurs. Long-lived zones in the form of $m/n=1/1$ were sometimes observed using SXR diagnostics during pulses with low magnetic shear (Semenov *et al.* 2003). It is thought that the $m=1$ perturbation in the form of positive magnetic islands can be responsible for a fast thermal quench. The required condition for the formation of this type of $m=1$ mode is a high current density in the centre of the plasma. There are two results of the formation of this mode, firstly the magnetic shear in the centre of the plasma out to $q(r_s)>1$ (3/2 or 2) drops almost to zero, and secondly kink perturbations develop in the plasma periphery. This sequence of events corresponds to Artsimovich's heuristic models.

Thus a major disruption contains an odd mixture of external (Shafranov's) and internal (Kadomtsev's) MHD activity. Figure 9 shows a simplified scheme of the main process which take place during a major disruption (Mirnov 2001). Internal and external MHD instabilities can exist independently of one another as long as they

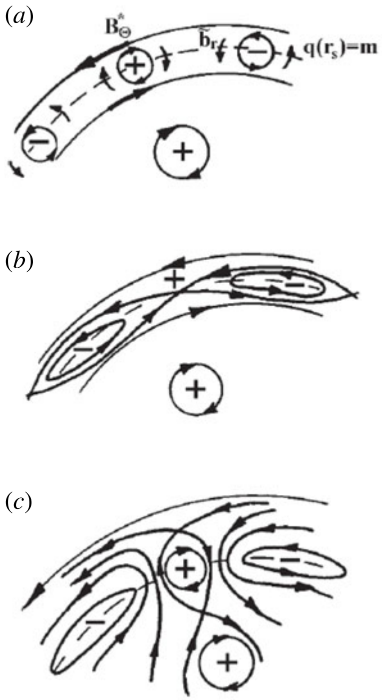

FIGURE 8. (*a*) Filament model, (*b*) linear and (*c*) nonlinear scenarios of the formation of magnetic islands (Mirnov *et al.* 1998).

have a relatively low intensity. Growth of the mode amplitude leads to the coupling of the modes, which ends with magnetic reconnection, i.e. disruptions. The main factor which induces both types of ideal MHD activity is a high pressure gradient occurring either in the central zone or in the plasma periphery. The periphery is therefore more susceptible than the centre to MHD activity. The main destabilizing causes of peripheral instabilities are RWM mode and the cooling of the plasma boundary due to impurities from the wall.

Avoiding peripheral instabilities is the main task for experimenters. This is achieved by (i) reducing the local thermal stresses on the wall, (ii) using the first conductive wall as a MHD stabiliser, (iii) control of the magnetic shear in the central regions, (iv) fragmentation of the large scale $m = 1$ perturbations in the centre, and (v) working inside the stability windows. The stabilising properties of the first resistive wall depend on the speed of rotation of the magnetic perturbations. Rotation counteracts the intrinsic error fields, which are caused by imperfections in the machine. Compensating for the error fields is a crucial challenge for experimenters who are attempting to avoid the development of a major disruption.

The first researchers to develop the theoretical foundations for internal MHD activity were Kadomtsev, Pogutse and their successors. Whilst the theoretical foundations of external MHD activity were laid down by Shafranov, and his protégés (Zakharov (Zakharov 1981), Yurchenko (Shafranov & Yurchenko 1967), Putvinskii and others).

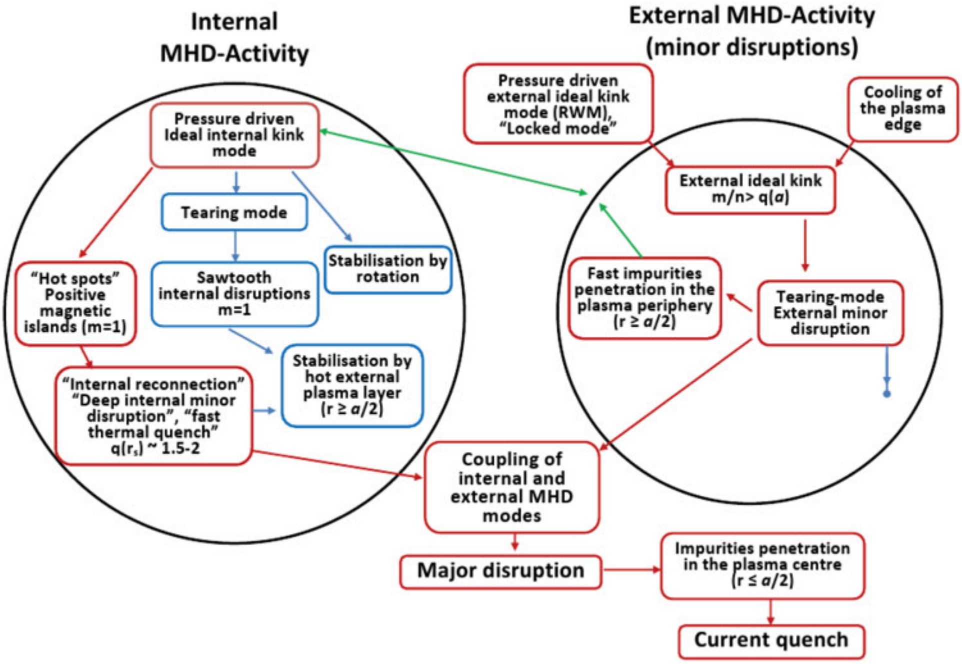

FIGURE 9. A simplified schematic diagram of the main process/events during a major disruption.

5. Later developments in tokamak design

Shafranov's work during the sixties was closely followed by the head of the Division of Plasma Research of the Kurchatov Institute, Artsimovich. In some cases, Artsimovich did not limit himself to general guidance but plunged into the work, developing new ideas with all his enthusiasm and energy. A good example of this is his final work with Shafranov 'Tokamak with non-round section of plasma loop' (Artsimovich & Shafranov 1972), which opened a new page in the development of tokamaks – the world of elongated vertical magnetic configurations with a poloidal divertor.

Their work ended with the prophetic words: 'The foregoing configuration of the plasma-loop cross section in the form of a segment makes it possible to solve one more problem of importance to the thermal insulation of the plasma. We have in mind here the creation of a natural limiting diaphragm. The point is that to produce a plasma column with a non-round cross section it is necessary to have external currents oriented relative to the current in the plasma in the manner shown schematically in figures 1 and 2 of Artsimovich & Shafranov (1972) (see figure 10). Between the plasma and conductors, in which the current flow in the same direction as in plasma loop, there is a hyperbolic point determining the position of the separatrix of the system of closed toroidal magnetic surfaces'.

A widely known aphorism of Artsimovich is: 'As head of department, I am in-between the theoreticians and the experimentalists. I point out the experiments which are worthy of explanations to the theoreticians, meanwhile I show the experimenters the theories that they can use to explain their results'. From the moment of Artsimovich's death, I noticed that Shafranov began to gradually shift

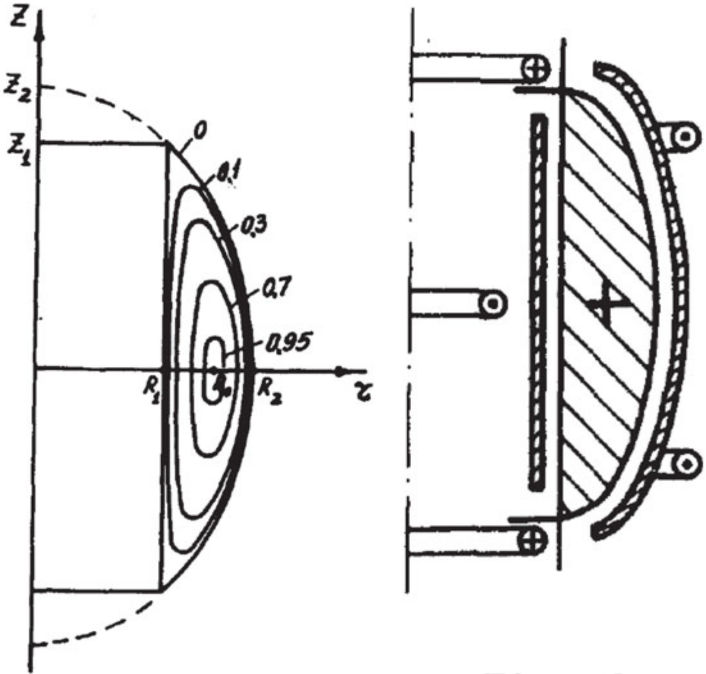

Fig. 1 Fig. 2

FIGURE 10. ITER-like magnetic configuration proposed by Artsimovich and Shafranov in 1972 (Artsimovich & Shafranov 1972).

towards topics concerning geometries of stellarators. His last publication on tokamaks was ‘Review of the current state of work on tokamaks in the USSR’ (Mirnov *et al.* 1976) (his co-authors only played the role of consultants in the paper). In modern tokamaks with poloidal divertors, proposed by Shafranov and Artsimovich in 1970, the plasma–wall interaction emerged as a major topic but was outside of his academic interests. He has focused on stellarators whose idea he admired.

A life in research is an attempt to push back the boundaries of the unknown, and shine a light onto previously unseen knowledge. Shafranov achieved this, and his accomplishments will forever remain with humanity. This task has now been passed onto new people.

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