C. R. Physique 20 (2019) 706–713

Contents lists available at ScienceDirect

Comptes Rendus Physique

www.sciencedirect.com

Science in the making 2: From 1940 to the early 1980s / *La science en mouvement 2 : de 1940 aux premières années 1980*

The birth of the research on the magnetic confinement for nuclear fusion

La naissance des recherches sur le confinement magnétique des plasmas de la fusion nucléaire

Guy Laval

198, rue Houdan, 92330 Sceaux, France

ARTICLE INFO

Article history:
Available online 21 May 2019

Keywords:
Plasmas
Confinement
Instability
Tearing
Transport
Fusion

Mots-clés :
Plasmas
Confinement
Instabilités
Déchirement
Transport
Fusion

ABSTRACT

At their very beginning, the researches on the magnetic confinement fusion had to face up plasma instabilities. Macroscopic plasma instabilities were the first ones to be identified and they were found to be very harmful for plasma confinement. During the first years after the Atoms for Peace Meeting in 1958, the main goals of experimental and theoretical researches dealt with their suppression or control. During this period, two special types of instabilities, the localized interchange modes and the tearing modes, were discovered. French physicists and the *Comptes rendus hebdomadaires des séances de l'Académie des sciences* have been steadily involved into this field. It generated a huge amount of works and, in spite of these efforts, they still remain an active research topic and maybe a matter of concern. However, the achieved progress allows most physicists to believe that these instabilities are not any more a real hurdle on the way to magnetic confinement fusion.

RÉSUMÉ

Dès leurs débuts, les recherches sur le confinement magnétique des plasmas de fusion se heurtèrent aux instabilités. Les instabilités macroscopiques se manifestèrent les premières et leur présence se révélait incompatible avec un confinement convenable du plasma. Parvenir à les supprimer où, au pire, à les contrôler guida l'essentiel des recherches expérimentales et théoriques sur la fusion pendant les premières années qui ont suivi la conférence *Atoms for Peace* en 1958. Dans cette exploration, deux catégories d'entre elles, les instabilités localisées et les instabilités de déchirement, ont tenu une place particulière en raison du rôle qu'y jouèrent les physiciens français et les *Comptes rendus hebdomadaires des séances de l'Académie des sciences*. Elles ont demandé un énorme travail et, malgré cet effort, elles constituent encore un sujet de réflexion et peut-être d'inquiétude, bien que

---

E-mail address: guy.laval@orange.fr.

https://doi.org/10.1016/j.crhy.2019.05.006

l’ensemble des progrès accomplis permettent à la plupart des physiciens de penser que ces instabilités ne mettent plus en péril la fusion par confinement magnétique.

---

1. Introduction

Between 1958 and 1965, a worldwide research program has been launched for mastering the confinement of hot plasmas. It was intended to evaluate the expectations of using controlled nuclear fusion reactions for energy production. Hot plasma physics was a rather new topic and had to be accepted by the physics community. The *Comptes rendus hebdomadaires des séances de l’Académie des sciences* were an important asset for the French researchers. The papers were published with a very short delay, while it took often long discussions to have access to the international journals. Unfortunately, they were written in French, and consequently did not attract many readers out of France. However, they provided a comforting safeguard.

2. The fusion power prospects in 1958

Even though the research on nuclear fusion started well before, 1958 is often considered as its year of birth as several crucial events occurred at this moment. Up to this date, the links between nuclear weapons and thermonuclear fusion lead to classify the results of experiments in USSR, USA, and UK. However, one of the most advanced devices, called ZETA (for Zero Energy Thermonuclear Assembly), was found to stay much farther from the expected goal than initially announced. The plasma temperature had been overestimated by misinterpreting measurements of neutron emissions and Doppler broadening of spectral lines. Instead of a high temperature allowing fusion reactions, these results showed that the plasma was unstable, moving with large velocities and generating strong electric fields. The plasma temperature was staying at too low levels for thermonuclear reactions.

The main effect of the instabilities was to reduce drastically the confinement time of the particle thermal energy. Consequently, these instabilities had to be suppressed or at least controlled. This program was expected to require many decades, maybe several centuries.

Fortunately, the canvas was not completely blank. As a matter of fact, classifying this research looked unnecessary. Then, all the results obtained on fusion in magnetically confined plasmas were disclosed during the 1958 Atoms for Peace Conference in Geneva. They were mostly concerned with pinches. Pinches were electric discharges in a gas-filled straight cylindrical tube, between two electrodes, at very large current intensity. It was expected that the attraction between the current filaments would violently pinch the discharge and compress the plasma to reach temperatures and densities needed for fusion reactions. The instabilities of the discharge lead to guide the discharge inside the tube with a longitudinal magnetic field generated by external solenoidal windings. Later, the electrodes were suppressed so that the discharge was contained into a toroidal vessel where the current was excited by induction. The largest device of that kind was ZETA [1].

It was thought that magnetohydrodynamics (MHD) was a valid tool to investigate the possible plasma equilibria and their stability. The MHD equations describe the behavior of a conducting perfect gas interacting with electromagnetic fields. The gas, namely the plasma, is supposed to obey a Navier–Stokes equation where the interaction between the plasma current and the magnetic field is considered by adding the Lorenz force to the pressure gradient in the momentum equation. An Ohm’s law relates the plasma current density and the electric field. It is usually written:

$$\mathbf{E} + \mathbf{V} \times \mathbf{B} = \eta \mathbf{J} \tag{1}$$

where **E** is the electric field, **V** the plasma velocity, **B** the magnetic field, **J** the current density and η is the plasma resistivity. Moreover, **E**, **B** and **J** are related by the Maxwell equations with the quasi-static approximation:

$$\begin{aligned} \mathbf{J} &= \nabla \times \mathbf{B} \\ \partial \mathbf{B}/\partial t &= -\nabla \times \mathbf{E} \end{aligned} \tag{2}$$

In fusion hot plasmas, the resistivity and the heat conductivity across magnetic lines are small so that the timescale of instabilities is much shorter than the diffusion timescales on the length scale of instabilities. It allows us to use the adiabatic perfect gas law as an equation of state and to neglect the resistivity in Eq. (1).

These approximations lead to the so-called ideal MHD equations:

$$\begin{aligned} \mathbf{J} &= \nabla \times \mathbf{B} \\ \partial \mathbf{B}/\partial t &= -\nabla \times \mathbf{E} \\ \mathbf{E} + \mathbf{V} \times \mathbf{B} &= 0 \end{aligned} \tag{3}$$

$$\rho\, \mathrm{d}\mathbf{V}/\mathrm{d}t = \mathbf{J} \times \mathbf{B} - \nabla p$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\frac{p}{\rho^{\gamma}} = 0$$

where ρ is the plasma density, p the plasma pressure and the last equation is the equation of state for adiabatic motions.

In Eq. (3), the electric field **E** is easily removed, yielding the relation:

$$\partial \mathbf{B}/\partial t = \nabla \times (\mathbf{V} \times \mathbf{B}) \tag{4}$$

From Eq. (4), it is easily shown that the magnetic flux through a closed curve moving with the fluid is conserved during the plasma motion. It is often called the frozen-in flux law. It may also be shown that if two point-like fluid elements are on the same field line at a given time, they will stay on the same field line for any time. These simple results constrain the plasma motion, as it will be seen.

The rather disappointing ZETA results pointed out the lack of knowledge concerning the equilibrium and stability of a toroidal plasma. The ideal MHD was then considered as the simplest model for a magnetically confined hot plasma, although still close enough to reality.

At the time of these studies, the confined plasma was supposed not to depend on time and to be motionless which implies $\mathbf{V} = 0$. With these assumptions, the plasma pressure and the magnetic field have to fulfill the equations:

$$\nabla p = \mathbf{J} \times \mathbf{B} \tag{5}$$

$$\nabla \times \mathbf{B} = \mathbf{J} \tag{6}$$

$$\nabla \times \mathbf{B} = 0 \tag{7}$$

In order to represent the plasma confinement, the isobaric surfaces are assumed to be nested tori, with a maximum pressure on a surface reduced to a closed line and often called the magnetic axis. As a matter of fact, according to Eq. (5), the magnetic field lines are wound on the isobaric surfaces. They are usually denominated magnetic surfaces. The pitch of this winding is an important parameter of the magnetic surface. It is measured in the following way. On a given magnetic surface, a magnetic line turns around the magnetic axis while moving along the toroidal surface. When the magnetic line has traveled N times around the torus, it has turned n times around the magnetic axis. The asymptotic limit of the ratio N/n is called the safety factor q. If q is rational, the field line is closed; if q is irrational, the field line is ergodic on the magnetic surface; in axially symmetrical configurations like in a tokamak, a strong current flows through the plasma torus. Then, the field lines look like helices encircling the magnetic axis. In this case, q may be easily smaller than one. In stellarators, the field is essentially generated by external windings, so that it is more difficult to obtain this winding of the magnetic lines. However, with complicated shapes of the magnets, q is finite, but usually larger than unity.

These simple remarks on MHD equilibria were necessary for introducing the instability issue.

3. The Mercier criterion

Already, in 1956, a pioneering work started the search for instabilities in tokamaks and the way to cure them. M.D. Kruskal, M. Schwarschild, and V.D. Shafranov [2,3] showed that the pinch instabilities could be stabilized by a guiding magnetic field provided that $q > 1$ at the plasma boundary. As a matter of fact, they did not study a toroidal discharge. They used a rough approximation by studying a cylindrical stabilized pinch with periodic boundary conditions for the perturbation of the equilibrium. The period in the longitudinal direction was considered as being equal to the magnetic axis length of the tokamak, i.e. 2πR, R being its radius. Moreover, it was assumed that the current was flowing only at the plasma boundary, generating an azimuthal field only out of the plasma column. However, this result stimulated the research for more precise realistic models.

Then, two years later, Bernstein, Frieman, Kruskal, and Kulsrud [4] published their energy principle for hydromagnetic stability problems. It stated that the linearized equations of ideal MHD in the vicinity of an equilibrium could be written under the form:

$$\rho_0 \ddot{\xi} = \hat{\boldsymbol{F}}(\xi) \tag{8}$$

where ρ_0 is the equilibrium plasma density, $\xi(\mathbf{r})$ is the displacement vector of fluid elements from their equilibrium position $\mathbf{r}$ and $\ddot{\xi}$ is their acceleration. The operator $\hat{\boldsymbol{F}}$ is a self-adjoint linear operator on $\xi(\mathbf{r})$. An inner product is introduced by setting:

$$(\xi_1, \xi_2) = \int \xi_1 \cdot \xi_2 \, \mathrm{d}v$$

where $\xi_1 \cdot \xi_2$ is an ordinary scalar product between the displacement vectors ξ_1 and ξ_2 and where the integral is taken over space. Setting $(\xi, \hat{\boldsymbol{F}}\xi) = \delta W$, the equilibrium is stable if and only if there is no displacement making δW negative. It means that the stability may be tested for a restricted class of displacements, providing then a necessary condition for stability.

C. Mercier used this property of the energy principle for studying the stability of toroidal plasmas with axial symmetry. He tested the equilibrium against displacements localized in the vicinity of a magnetic surface. He obtained a condition for instability [5], generalizing a criterion obtained by Suydam in 1958 for cylindrical plasmas. The paper was published in 1960 in *Nuclear Fusion*, but it was written in French.

In April 1961, C. Mercier [6] published a note in French in the *Comptes rendus hebdomadaires des séances de l'Académie des sciences*, in which he unveiled a necessary condition for the stability of toroidal plasmas without any symmetry. It could be applied to tokamak-like configurations and to stellarator as well, assuming that closed nested magnetic surfaces exist in this last case. A few months later, with M. Cotsaftis and again in French, C. Mercier published another paper in the *Comptes rendus hebdomadaires des séances de l'Académie des sciences* [7] where the Mercier criterion was computed on surfaces close to the magnetic axis. For toroidal plasmas with axial symmetry, the condition for instability coincides with the condition found by Kruskal and Shafranov, at the plasma edge, namely $q < 1$, but in this case, the condition has to be fulfilled in the vicinity of the magnetic axis. In order to keep $q > 1$ on the magnetic axis, it is necessary to control the current density profile. This is more difficult than to fulfill the Kruskal–Shafranov condition $q > 1$ at the edge, since this condition needs only a limitation of the total current.

The Mercier criterion has been constantly used for more than fifty years. As soon as a new toroidal configuration is considered, the first test of stability is carried out with the Mercier criterion. It explores only a restricted class of perturbations. Other instabilities can occur, but its simplicity is very convenient. It is worth noticing that the proof of the general Mercier criterion has never been published and that the French *Comptes rendus* deserve gratitude since without them the result of the derivation could not be found in the literature.

4. The Rebut mode

In the early sixties, as seen above, the fusion researchers were struggling with the instabilities of pinches. They were due to the large current flowing through the plasma. Then, in Livermore, it was thought that the pinch stability could be improved by diverting a part of this current into a coaxial conducting rod situated inside the confinement tube and the tubular plasma. Called the hard-core pinch, it looked like having interesting properties. In particular, according the ideal MHD, the hardcore pinch was stable for a range of parameters. Experiments showed that better confinement was achieved, but that the plasma current intensity had to be kept at lower values than predicted by theory. The discharge was unstable for current intensities at which ideal MHD guaranteed stability.

In France, at Fontenay-aux-Roses, Rebut and Torossian were doing the same kind of experiment on a tubular pinch and reached the same conclusions. Rebut understood that ideal MHD was to blame for this discrepancy between theory and experiences. Without a better model, he was inspired by the theory of buckling where the beam buckling limit is computed by searching the compression threshold at which a distorted neighboring equilibrium exists [8]. Then only equilibrium equations are necessary.

Then, he noticed that the ideal MHD equations were not questioned for the equilibrium so that they could be used for a slightly perturbed equilibrium. The MHD equations for any stationary plasma may be written:

$$\begin{aligned} &\nabla p_0 = \mathbf{J}_0 \times \mathbf{B}_0 \\ &\mathbf{J}_0 = \nabla \times \mathbf{B}_0 \\ &\nabla \times \mathbf{B}_0 = 0 \end{aligned} \tag{9}$$

where p_0, $\mathbf{J}_0$, $\mathbf{B}_0$ are the plasma pressure, the current density and the magnetic field at equilibrium.

For the neighboring equilibrium they may be linearized yielding:

$$\begin{aligned} &\nabla p_1 = \mathbf{J}_0 \times \mathbf{B}_1 + \mathbf{J}_1 \times \mathbf{B}_0 \\ &\mathbf{J}_1 = \nabla \times \mathbf{B}_1 \\ &\nabla \times \mathbf{B}_1 = 0 \end{aligned} \tag{10}$$

where p_1, $\mathbf{J}_1$, $\mathbf{B}_1$ are perturbations of the plasma pressure, the current density and the magnetic field of the equilibrium and Eq. (10) are the linearized equilibrium equations they have to fulfill.

In order to fit the experiment, Rebut considered equilibria with cylindrical symmetry. In cylindrical r, θ, z coordinates, the magnetic surfaces were coaxial cylinders with constant r, the equilibrium magnetic field had only $B_\theta = B_{\theta_0}$ and $B_z = B_{z_0}$ components, depending only on r. The perturbed field $\mathbf{B}_1$ is assumed to be a superposition of elementary harmonic solutions $\mathbf{B}_1 = \mathbf{b}_1(r)\exp(\mathrm{i}m\theta + \mathrm{i}kz)$. From Eq. (10), the following relation is obtained:

$$p_1 = \mathrm{i}\,\frac{p_0' B_{1_r}}{F}$$

where

$$F = \frac{mB_{\theta_0}}{r} + kB_{z_0} \quad \text{and} \quad p_0' = \frac{\mathrm{d}p_0}{\mathrm{d}r}$$

In a tubular pinch, $p_0' = 0$ on a cylinder $r = r_0$. If m and k are chosen so that $F = 0$ for $r = r_0$, p_1 remains finite even if B_{1_r} does not vanish on this cylinder. P.-H. Rebut showed that such a perturbed equilibrium does exist for a particular set of parameters.

But the ideal MHD demands that the radial displacement ξ_r is linked to B_{1_r} by the relation $B_{1_r} = \mathrm{i}F\xi_r$, as it is easily shown by using the second and the third expressions of Eq. (3). Consequently, according to the ideal MHD, B_{1_r} should vanish for $r = r_0$. It suggests that the ideal MHD does not allow a transition from the initial cylindrical equilibrium to this neighboring helical equilibrium.

Guided by the beam buckling theory, Rebut postulated that the existence of this helical equilibrium determined a transition from a stable pinch to an unstable one, even if the appropriate dynamical laws allowing the transition were not known. Then, he explained the experimental results by considering a family of tubular pinches with the total plasma current as a variable parameter. He found that a neighboring equilibrium with the right boundary conditions did exist for a given value of the total current. This result was supported by physical arguments, since this limiting current was identified as the condition for breaking the initial cylindrical configuration into several helical pinches.

Assuming that only one harmonic with given m and k was excited, the perturbed state is invariant by a helical transformation. Then, the magnetic surfaces are still integrable. Rebut showed that, in the perturbed equilibrium and the subsequent unstable evolution, the topology of magnetic field lines has been changed so that the frozen-in laws of ideal MHD were forbidding these modes.

However, this theory did not allow computing the growth rates of the instabilities.

5. The tearing mode

Puzzled by Rebut's theory and its successful explanation of experiments, H. Furth, J. Killeen, and M.N. Rosenbluth (FKR) [9] tackled the enigma by modifying Ohm's law and by solving the equations numerically. In order to get rid of the frozen-in law, they started from the resistive MHD equations obtained by setting $\mathbf{E} + \mathbf{V} \times \mathbf{B} = \eta \mathbf{J}$ instead of $\mathbf{E} + \mathbf{V} \times \mathbf{B} = 0$ in Eq. (3), where η is the plasma resistivity. The time scale τ of the magnetic flux diffusion should have been $\tau = \lambda^2/\eta$, where λ is a typical dimension of the perturbation. It was found to be much too long for explaining the experiments. However, the numerical and the analytical results showed that the right time scale is not the resistive diffusion time scale over a typical length of the perturbation, but rather the diffusion time over the size of a thin singular layer laying on the surface where $F = 0$ and where this magnetic surface is torn to allow the change of topology. It explains why this instability is known as the tearing mode.

In Rebut's theory, it was assumed that F vanishes on the maximum plasma pressure surface. FKR theory was concerned with the stability of flat sheet pinches instead of cylindrical ones as considered by Rebut, but it could be considered as an appropriate approximation of a thin hardcore pinch. FKR theory showed that the tearing mode was more ubiquitous than found with the neighboring equilibrium theory. It did not need that the maximum plasma pressure occurred at the radius where $F = 0$. It could be present in ordinary pinches where the plasma pressure was maximum at $r = 0$. This mode remains one of the main threats for ITER and for future fusion reactors, as it is essentially responsible for the disruptions that throw the plasma on the walls of the confinement vessel. Suppressing or controlling this instability is at the heart of a successful magnetic fusion research.

As regards the note published by Rebut in the *Comptes rendus* [10,11] on this topic, it had to wait until 1965 and it did not concern resistive instabilities. It dealt with the stability of the collisionless plasmas described by the Vlasov–Maxwell equation. As a matter of fact, the hardcore pinch was still considered as a promising magnetic configuration for the fusion program and a toroidal version was built in California. It was named the "Levitron", as the circular hardcore levitated inside a toroidal tubular pinch. The current instabilities seemed to be suppressed for a low-enough current inside the plasma, but other micro-instabilities with smaller wavelengths could be deleterious for the confinement time of the energy. These instabilities had to be described with the Vlasov–Maxwell equations. In two notes published in the *Comptes rendus*, Rebut discussed the micro-instabilities stabilization by the shear of magnetic lines. This shear may be very strong in a hardcore pinch and was an important asset of this configuration. Rebut's theoretical method was similar to the neighboring equilibria, but, to find the transition from instability to stability, he had to look for purely oscillating neighboring perturbations instead of stationary ones.

In his second paper in the *Comptes rendus* [11], Rebut mentioned that the tearing mode in a collisionless plasma could also be studied in this way, but he quoted another earlier article published in this journal [12], in which another technique was used to solve this issue. The FKR paper had shown that the resistivity was much more efficient than expected to allow tearing instabilities. However, since the resistivity decreases with temperatures like $T_\mathrm{e}^{-3/2}$, where T_e is the electronic temperature, in the very hot plasmas needed for fusion, the instability could become very slow or even other effects could stabilize the plasma.

In the earlier *Comptes rendus* article he quoted, the stability of a sheet pinch was studied with the Vlasov–Maxwell equations. As these equations were expected to be more difficult to solve than the MHD equations, the computations were restricted to the simplest case: the sheet pinch for which an exact solution of the Vlasov–Maxwell equations was known. Thus, the so-called Harris model amounts to suppose a plane of current with current density $J_y(x)$, allowing the variation of a magnetic field $B_z(x)$ from $-B_0$ at $z = -\infty$ to B_0 at $z = +\infty$, in order to balance the plasma pressure, which is maximum at $x = 0$ and decreases exponentially with $\|x\| \to \infty$.

Using the full Vlasov–Maxwell equations, it was found that the Rebut tearing mode was destabilized by Landau damping. It showed that, in spite of the absence of thermodynamic dissipative processes in the collisionless sheet pinch, the Landau damping could be a substitute for resistivity for tearing the magnetic surfaces and for reconnecting the field lines across the sheet. Such behaviors are commonly called kinetic effects. It looked rather surprising that the detailed behavior at a microscopic scale was needed to describe the evolution of a large-scale macroscopic perturbation.

The sheet pinch was not a very good model for a tubular pinch. In the sheet pinch, there was only one non-zero magnetic field component and this magnetic field was vanishing at the middle of the sheet. In the hardcore pinch, the field lines were wound on cylindrical magnetic surfaces and, most of the time, **B** did not vanish anywhere. Then, the sheet pinch analysis was extended to cylindrical geometries and the results were presented at an AIEA meeting in September 1965 by René Pellat [13]. At the end of his talk, a question from the audience could be interpreted as a claim of anteriority right. René Pellat answered by quoting the *Comptes rendus* paper on the sheet pinch instability. Once more, the *Comptes rendus* were the only existing proof of anteriority.

It was quickly realized that collisionless tearing modes could also be unstable in usual pinches and tokamaks. The instability growth rate was readily worked out [14] in order to determine the residual level of instability in a hot fusion plasma. Solutions were also obtained for intermediate regimes where modified fluid theories allowed one to go beyond resistive MHD. Today, in numerical models, kinetic effects are added to the fluid equations in order to catch their most important consequences for large tokamaks like ITER.

6. The tokamak era

At the beginning of the 1970s, the tokamaks having provided the most advanced results towards fusion, they were chosen as the best magnetic confinement machines, and a worldwide experimental and theoretical program started to approach the fusion conditions. Tokamaks were toroidal pinches stabilized by a strong toroidal field generated by external coils. The main drawback of the configuration was an uncontrollable end of the discharge with a disruption of the plasma current. The Kruskal–Shafranov condition for stability being satisfied, the origin of the disruption was to be searched out of the ideal MHD.

The tearing mode offered an explanation. First, it was shown that the exponential mode growth stopped when the region with a modified field topology reached the width of the thin singular resistive layer. Then the growth becomes algebraic like t^2 [15,16]. The agreement with experiment was good for mode $m = 2$, which was thought to be mainly responsible for disruptions [17].

Once the disruption origin has been identified, saw-teeth-like X-ray emissions showed that the plasma temperature was oscillating in a narrow region surrounding the magnetic axis. For a cylindrical model of the tokamak, M.N. Rosenbluth et al. [18] found that, in cylindrical pinch, an ideal MHD $m = 1$ instability could occur whenever q was less than one on the pinch axis. The instability condition for the toroidal geometry was computed later and showed that it did not coincide with the Mercier criterion [19]. In particular, the mode could be stable even if q was less than one on the magnetic axis, for low-enough pressure [20]. However, the growth rates looked too small to explain the saw-tooth X-ray emissions.

Resistive MHD answered the question [21]: a tearing $m = 1$ mode could be unstable, with growth rates explaining the observations, even when ideal MHD modes were stable. Then, in a way somewhat similar to what happened for $m = 2$ modes, the collisionless growth rate was computed as well as its behavior for intermediate collisionality.

7. Microtearing

Experimental data showed that, in tokamaks, the energy and particle transport to the walls could not be explained by classical collisions between plasma particles. Micro-instabilities were obvious candidates. These instabilities lead to field fluctuations with amplitudes and correlation length much larger than spontaneous thermal fluctuations. In most experiments, the plasma energy density was much smaller than the magnetic energy density. Naturally, the electrostatic instabilities looked better suited to explain the fast energy diffusion, since electric fields allow particle motions across the confinement magnetic field. Today, it is usually agreed that such an instability, linked to the ion temperature gradient [22], explains the energy confinement time and the temperature profiles in the most advanced tokamaks.

However, a doubt has often been cast regarding the relevance of this instability for electron transport. For a long time, the anomalous transport concerned mainly the electrons. Then it was noticed that, if instabilities could destroy the magnetic surfaces, the electrons would diffuse easily to the walls, increasing the electrons' thermal conductivity. It is suspected that such a process is taking place during disruptions. It was then found that micro-tearing modes, with short wavelength, could be unstable [23]. These modes are similar to $m = 2$ tearing modes, but with large azimuthal number m and toroidal number n such that $q = m/n$ where the magnetic surface tearing occurs. The instability is driven by the electron temperature gradient, provided that the plasma energy density remains larger than the energy density of the field generated by the plasma current. It is usually thought that such anomalous transport is relevant for fat torus with low aspect ratio as well as for tokamaks with high plasma pressure.

In 1988, Rebut et al. [24] suggested that all anomalous transport phenomena in tokamaks could be explained by assuming that the magnetic field lines are braided by the micro-tearing modes, instead of being neatly combed, as assumed in usual theories. Then, by using heuristic and dimensional arguments, they obtained electron and ion thermal conductivity, which provided satisfactory simulations of experimental results.

More recently [25], in 2007, by using existing theory of micro-tearing modes, the electron thermal conductivity across the magnetic lines was computed without any adjustable parameter and compared with the results of a spherical tokamak (NSTX). The agreement is good for the region where there is a steep electron temperature gradient. This success could be explained by the low aspect ratio of the machine and by the locally large ratio of the plasma energy density to the magnetic energy density.

Then the question was raised: could these micro-tearing modes be responsible for at least a part of the anomalous transport in JET or ITER? In the meantime, a reliable numerical simulation technique became available. It used the so-called gyrokinetic equations, allowing one to study perturbations at the ion Larmor radius scale, together with kinetic effects. Such simulations had been widely used for studying the anomalous transport linked to electrostatic turbulence, which was supposedly the dominant mechanism in large tokamaks. The simulation of the electromagnetic turbulence showed that it plays an important role in machines with high plasma pressure, like NSTX, but it also showed that it could explain a non-negligible part of the thermal electron transport, even in the future ITER [26–28].

8. Conclusion

The fusion research has given rise to other scientific topics that were born in the 1950s and are still living, but maybe none of them remains a kind of fuzzy threat to day. The electromagnetic turbulence has survived all the evolutions of the magnetic confinement. Disruptions may be controlled, but it seems impossible to avoid them completely. The micro-tearing modes raise fundamental questions for which there is not yet a definitive answer. In particular, it questions the usual assumption of nested magnetic surfaces with magnetic braiding, as pointed out by P.-H. Rebut [29].

Of course, it must be added that the present knowledge in fusion sciences has allowed the design of the ITER experiment through a much broader work in theory, experiments and technology.

Acknowledgements

The reviewers, the editors of this dossier, and P.-H. Rebut are thanked for their useful advices.

References

[1] R.S. Pease, Experiments on the problem of controlled thermonuclear reactions, Nature 196 (1962) 4861.

[2] V.D. Shafranov, The stability of a cylindrical gaseous conductor in a magnetic field, Soviet J. At. Energy 1 (1956) 709–713.

[3] M.D. Kruskal, M. Schwarzschild, Some instabilities of a completely ionized plasma, Proc. R. Soc. A 223 (1954) 348.

[4] I.B. Bernstein, E.A. Frieman, M.D. Kruskal, R.M. Kulsrud, An energy principle for hydromagnetic stability problems, Proc. R. Soc. Lond. Ser. A, Math. Phys. Sci. 244 (1958) 17–40.

[5] C. Mercier, Un critère nécessaire de stabilité hydromagnétique pour un plasma en symétrie de révolution, Nucl. Fusion 1 (1960) 47–53.

[6] C. Mercier, Critère nécessaire de stabilité pour un système toroïdal hydromagnétique en pression scalaire, C. r. hebd. séances Acad. sci. 252 (1961) 1577.

[7] C. Mercier, M. Cotsaftis, Equilibre et stabilité pour les systèmes toroïdaux hydromagnétiques en pression scalaire au voisinage d'un axe magnétique, C. r. hebd. séances Acad. sci. 252 (1961) 2203.

[8] P.-H. Rebut, Instabilités non magnetohydrodynamiques dans les plasmas à densité de courant élevée, Plasma Phys. (J. Nucl. Energy Part C) 4 (1962) 159.

[9] H.P. Furth, J. Killeen, M.N. Rosenbluth, Finite resistivity instabilities of a sheet pinch, Phys. Fluids 6 (1963) 459.

[10] P.-H. Rebut, Instabilités quasi-électrostatiques créées par les courants dans un plasma inhomogène chaud et cylindrique, C. r. hebd. séances Acad. sci. 260 (1965) 1882.

[11] P.-H. Rebut, Caractères généraux des instabilités d'un plasma inhomogène chaud en géométrie cylindrique et tenseur de conductivité, C. r. hebd. séances Acad. sci. 260 (1965) 2150.

[12] G. Laval, R. Pellat, Méthode d'étude de la stabilité de certaines solutions de l'équation de Vlasov, C. r. hebd. séances Acad. sci. 259 (1964) 1706.

[13] R. Pellat, G. Laval, M. Vuillemin, in: Plasma Physics and Contr. Nucl. Fusion Research 1965, vol. II, IEAEA, Vienna, 1966, p. 259.

[14] J.F. Drake, Y.C. Lee, Kinetic theory of tearing instabilities, Phys. Fluids 20 (1977) 1341.

[15] P.H. Rutherford, Non-linear growth of the tearing mode, Phys. Fluids 16 (1973) 1903–1908.

[16] D.F. Escande, M. Ottaviani, Simple and rigorous solution for the nonlinear tearing mode, Phys. Lett. A 323 (2004) 278–284.

[17] B.V. Waddell, B. Carreras, H.R. Hicks, J.A. Holmes, D.K. Lee, Mechanism for major disruptions in tokamaks, Phys. Rev. Lett. 41 (1978) 1386.

[18] M.N. Rosenbluth, R.Y. Dagazian, P.H. Rutherford, Nonlinear properties of the internal $m = 1$ kink instability in the cylindrical tokamak, Phys. Fluids 16 (1973) 1894.

[19] H. Lutjens, A. Bondeson, G. Vlad, Ideal MHD stability of internal kinks in circular and shaped tokamaks, Nucl. Fusion 32 (1992) 1625.

[20] M.N. Bussac, R. Pellat, D. Edery, J.L. Soule, Internal kink modes in toroidal plasmas with circular cross sections, Phys. Rev. Lett. 35 (1975) 1638.

[21] B. Coppi, R. Galvão, R. Pellat, M. Rosenbluth, P. Rutherford, Resistive internal kink modes, Fiz. Plazmy 2 (1976) 961–966.

[22] J.F. Drake, N.T. Gladd, C.S. Liu, C.L. Chang, Microtearing modes and anomalous transport in tokamaks, Phys. Rev. Lett. 44 (1980) 994.

[23] B. Coppi, M.N. Rosenbluth, R.Z. Sagdeev, Instabilities due to temperature gradients in complex magnetic field configurations, Phys. Fluids 10 (1967) 582.

[24] P.-H. Rebut, P.P. Lallia, M.L. Watkins, The critical temperature gradient model of plasma transport: applications to JET and future tokamaks, in: Proc. 12th International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Nice, France, 12–19 October 1988, in: Nuclear Fusion, Suppl., vol. 2, International Atomic Energy Agency, Vienna, 1989, pp. 191–200.

[25] K.L. Wong, et al., Microtearing instabilities and electron transport in the NSTX spherical tokamak, Phys. Rev. Lett. 99 (2007) 135003.

[26] M.C. Firpo, Microtearing turbulence: magnetic braiding and disruption limit, Phys. Plasmas 22 (2015) 122511.

[27] T. Rafiq, et al., Microtearing modes in tokamak discharges, Phys. Plasmas 23 (2016) 062507.

[28] H. Doerk, et al., Gyrokinetic prediction of microtearing turbulence in standard tokamaks, Phys. Plasmas 19 (2012) 055907.

[29] P.-H. Rebut, The Joint European Torus (JET), Eur. Phys. J. H 43 (2018) 476–492.