A SURVEY ON CONTROL-ORIENTED PLASMA PHYSICS IN TOKAMAK REACTORS

AITOR J. GARRIDO, IZASKUN GARRIDO, OSCAR BARAMBONES AND PATXI ALKORTA[†]
Dpto. de Ingeniería de Sistemas y Automática. EUITI de Bilbao/Eibar[†]. Pza. de la Casilla, 3. 48012. Bilbao
Universidad del País Vasco / University of the Basque Country
SPAIN

Abstract: - Nuclear fusion control, and specifically plasma control, represents one of the newest and more promising applications of Control Engineering, with increasing interest in the control community. In this paper it is made a control-oriented review of the state of the art of nuclear fusion techniques. For this purpose, a comprehensive description of the fusion process is provided, focusing in the most used fusion reactor topology - the tokamak- that will also be used at ITER. From this point of view, a description of the MHD equations of plasma is given, which are usually applied together with the transport equations for the design of simulators as DINA. Also, a review of the most used codes for plasma simulation is given, with the aim of providing a starting point for control engineers to derive their own code or choose the appropriate existing one to work on.

Key-Words: - Fusion Control; Plasma Physics; Tokamak Simulation; MHD.

1 Introduction

The control of plasma in fusion processes is an area of increasing interest, due to the relevance that new energy research is acquiring, involving ambitious international projects of great significance as the ITER (International Thermonuclear Experimental Reactor). This international research and development project aims to demonstrate the scientific and technical feasibility of fusion power. The partners in the project are the European Union, the People´s Republic of China, India, the Republic of Korea, the Russian Federation and the USA, and contemplates the construction of a tokamak reactor in France, [1].

In the last years, substantial effort and resources are currently being devoted into the development of a clean nuclear technology, which is based upon fusion processes. This effort materializes both in a large number of research papers published, specially in the field of Control Engineering applied to fusion processes, as well as the publication of special sections on the part of the IEEE Control Systems Magazine (see [2] and [3]), establishing an area of novel application for Control Theory after some timid efforts in the 50s and beginning of the 90s.

In spite of fossil, fission, hydroelectric, and renewable (wind, geothermal, solar, etc.) energies, the predictions on the world-wide energy consumption point towards an energy deficit due to the increment of the demand and the decrement of the energy resources derived from fossil fuels (see [4]). This is, together with the climate change effects, the main reason why it is necessary to obtain clean and alternative energy sources, [5].

In this sense, even when controlled fusion is extremely technologically challenging, a fusion-power reactor would offer significant advantages over existing energy sources. In particular, there exists sufficient fuel supply for several thousand years since the necessary hydrogen isotopes can be generated from water and abundantly available lithium, during the reaction cycle. Unlike fission, fusion would produce no air pollution or greenhouse gases during normal operation since the fusion reaction product is helium. In contrast to fission, a fusion reactor implies no risk of a nuclear accident since a nuclear meltdown with a large, uncontrolled release of energy cannot occur. Besides, most radioactive materials produced in a fusion reactor can be safely and easily disposed of within a few decades, in contrast to most fission by-products, which require special storage and handling for thousands of years.

A nuclear fusion is the process by which multiple nuclei join together to form a heavier nucleus. In order to force the nuclei to fuse it is necessary considerable energy, due to the positively charged protons. However, the fusion of light nuclei generally releases more energy than it takes to force them together. Under these conditions matter reaches the plasma state, in which ions coexist with free electrons. For this reason, the plasma results to be an excellent conductor which can be magnetically confined. The most common magnetic confinement structure is denominated tokamak, acronym of TO*roidalnaya* KA*mera i* MA*gnitnaya* K*atushka* that means toroidal camera with magnetic coils, which is also the design that will be used in ITER. The research for pacific uses of nuclear fusion using tokamaks began in the fifties in the former Soviet Union. This technology has nowadays reached the point in which the experimental tokamaks can produce almost as much energy as they consume. In this sense, the proposed ITER tokamak is desired to generate ten times as much energy as it consumes (see [2]).
The main problems to deal with in plasma control are current, position and shape control. Some of these problems have already been subject to thorough research, although it is still possible to improve the behaviour and robustness in the presence of nonlinearities. Other issues in plasma control still need further effort to reach the necessary levels of performance. As more sophisticated control methods are required in tokamaks, the fusion community has begun to recognize its benefits. This recognition, the increasing amount of experimental challenging problems, and the urgent need of control of the ITER tokamak, make the present time a really good moment to work in plasma control [6].

2 Background on tokamak reactors

2.1 Principles of nuclear fusion

The basic principle of nuclear fusion is that when two light nuclei fuse into a heavier and more stable nucleus, the nuclear rearrangement results in a reduction in total mass and a consequent release of energy in the form of kinetic energy of the reaction products. The most promising method of supplying the energy is to heat the fuel up to a sufficiently high temperature so that the thermal velocities of the nuclei are high enough to fuse. This is the process that takes place continuously in the Sun and stars. In the core of the Sun at temperatures of 10-15 million degrees Celsius, hydrogen is converted to helium providing enough energy not to collapse due to gravitational forces, and sustaining life on Earth as a consequence. In order to reproduce this energy production process on Earth, different fusion reactions may be considered. The most suitable reaction occurs between the nuclei of deuterium and tritium, two heavy isotopes of hydrogen, which is illustrated in Fig. 1 and takes places as follows:

$$ {}_1^2D + {}_1^3T \rightarrow {}_2^4He + n + 17.6\ \mathrm{MeV} \quad (1) $$

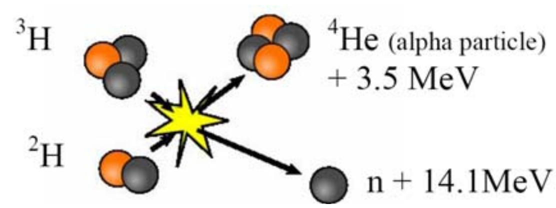

Fig. 1. Nuclear fusion reaction of Deuterium and Tritium

In order to achieve and maintain the reaction for a substantial period of time, temperatures of the order of $100 \cdot 10^6$ ºC (10^4[eV]) and a density of about 10^{20} m^{-3} are required. Under these conditions the fuel changes its state from gas to plasma, in which the electrons are separated from the atoms, becoming these atoms charged ions (see [7]).

2.2 Availability

Deuterium is a plentiful resource as it can be easily extracted from water but tritium does not occur naturally. It could, however, be manufactured from lithium using the neutrons released in the fusion reaction. In turn, lithium is abundant on Earth and known reserves would last for at least 1000 years.
As an example, 10g of deuterium which can be extracted from 500l of water and 15g of tritium produced from 30g of lithium would provide enough fusion fuel for the lifetime electricity needs of an average person in an industrialized country, [8].

2.3 Magnetic confinement: tokamak

Since plasma consists of two types of charged particles, ions and electrons, it may be contained within a region away from the vessel walls by the forces of magnetic fields on the charged particles in the gas. A magnetic field exerts a force on a moving charge, that readily spiral along the field lines diffusing slowly across them. An early attempt to build a magnetic confinement system was the stellarator, introduced by Lyman Spitzer in 1951. Essentially the stellarator consists of a torus that has been cut in half and then attached back together with straight crossover sections to form an 8-figure. In 1968 russian research on the toroidal tokamak was first presented in public, with results that far outstripped existing efforts from any competing design, magnetic or not, 9]. Since then, the majority of effort in magnetic confinement, including the future ITER reactor, has been based on the tokamak principle (see Fig. 2).

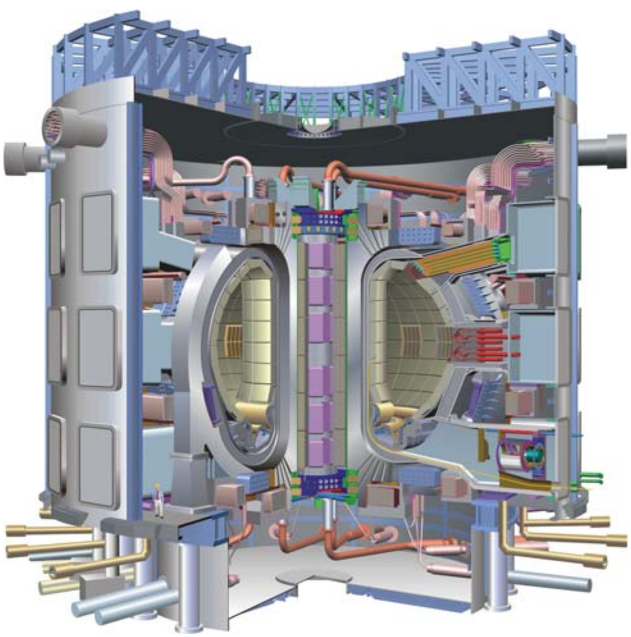

Fig. 2. ITER tokamak planned reactor (poloidal cut)

In the tokamak, the plasma is heated in the toroidal vessel and kept away from its walls by applying two combined magnetic fields: The *toroidal field*, around the torus, which is maintained by the *toroidal field coils* surrounding the vacuum vessel (see Fig. 3), providing the primary mechanism of confinement of the plasma particles. And a smaller *poloidal field* (about 10% of toroidal field), around the plasma cross section, that keeps the plasma away from the walls and contributes to maintain the plasma's shape and position. The poloidal field is induced both internally, by the current driven in the plasma, and externally, by the *outer poloidal field coils* that are positioned around the perimeter of the vessel (see Fig. 3). In turn, the main plasma current is induced in the plasma by the action of a large transformer (inductive current drive): A changing current in the primary winding formed by the *inner poloidal field coils* located around a large iron core induces a current in the plasma, which acts as the transformer secondary circuit.

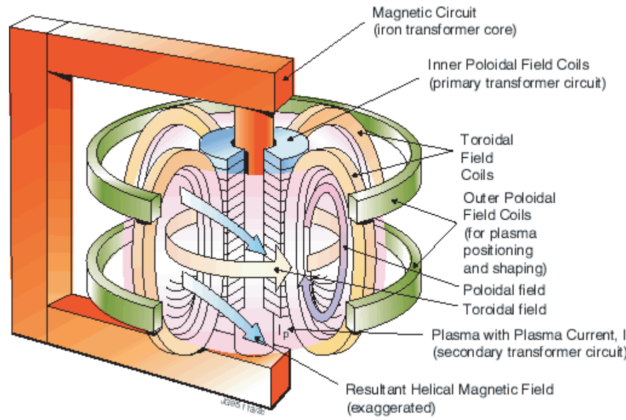

Fig. 3. Nuclear fusion reaction of Deuterium and Tritium

The combination of toroidal and poloidal field components, results in a helicoidal magnetic field that contains the plasma. Since in a magnetic field the particles spiral along the magnetic field lines, the electric current in the plasma flows approximately parallel to the magnetic field. Thus, the plasma current also has a toroidal and a poloidal current component, [10].

2.4 Plasma generating and heating procedures

In general, the following effects and methods are used to heat the plasma:

Ohmic Heating due to the Driven Current

Ohmic heating is the energy imparted by charged particles as they flow within the driven current and collide with other particles.

Neutral Beam Heating

Neutral-beam heating or injection involves the introduction of high-energy neutral atoms into the plasma. Beams of deuterium or tritium ions, accelerated using very high potentials are injected into the plasma. In order to allow the penetration in the confining magnetic field, the accelerated beams are neutralized. Once in the plasma, the atoms are immediately ionized and trapped by the magnetic field. The high-energy ions then transfer part of their energy to the plasma particles in repeated collisions, increasing the plasma temperature. The power available through this method is typically around 20MW.

Radio-Frequency Heating

As it has been indicated before, the plasma ions and electrons rotate around the toroidal vessel following the magnetic field lines of the tokamak. This fast ions rotation may be used to heat the plasma by means of radio waves that resonate with the ions frequency. These radio waves, in the radiofrequency range are injected in the tokamak increasing the energy of the ions and heating the plasma. This method can typically inject up to 20MW of heating power.

Current Driven by Microwaves

Similarly to radio-frequency heating and ions, but through a different mechanism, microwaves with a frequency of the order or GHz are used to accelerate the plasma electrons. The method known as Lower Hybrid Current Drive (LHCD) provides waves with a hybrid frequency that, although it possesses an inefficient heating effect, it can drive electric current thanks to the fact that it has an electric component parallel to magnetic field lines. The power provided by this method is around 10MW, and is one of the most used methods in the control of the plasma during the fusion process.

Self Heating of Plasma

As explained before, once the fusion reactor fuel has reached the appropriate temperature and pressure, deuterium and tritium begin to fuse generating helium nuclei (alpha-particles), neutrons and energy. This energy produced continues heating the plasma and keeps the fusion reaction going on. In particular, this self-heating condition is known as *ignition*.

3 General equations of plasma

3.1 Equations of MHD equations

Magnetohydrodynamics (MHD) describes the dynamics of electrically conducting fluids. The MHD equations are given by, on the one hand the Maxwell equations jointly with Ohm's law due to electromagnetic nature of plasma, an on the other hand, the flow equation jointly with the mass conservation continuity equation due to the flow nature of plasma:

MHD equations

Maxwell equations:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \qquad \text{Faraday's law}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j} + \mu_0 \varepsilon_0 \mathbf{j} \frac{\partial \mathbf{E}}{\partial t} \qquad \text{Ampere's law}$$

$$\nabla \cdot \mathbf{E} = -\frac{\rho}{\varepsilon_0} \qquad \text{Gauss's law}$$

$$\nabla \cdot \mathbf{B} = 0 \qquad (2)$$

Ohm's law:

$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = \frac{\mathbf{j}}{\sigma}$$

Flow Equation:

$$\rho_m \frac{\partial \mathbf{v}}{\partial t} = \mathbf{j} \times \mathbf{B} - \nabla p$$

Continuity equation:

$$\frac{\partial \rho_m}{\partial t} + \nabla \cdot (\rho_m \mathbf{v}) = 0$$

where ρ_m is the mass density, ρ is the charge density, $\mathbf{v}$ is the plasma velocity, $\mathbf{j}$ is the current density, p is the plasma pressure, and $\mathbf{E}$ the electric field and $\mathbf{B}$ the magnetic field.

3.2 Tokamak equilibrium

Due to the quasi-static approximation, $\rho \approx 0$ can be considered for Gauss's law and the second right term of Ampere's law representing the displacement current may be neglected. Besides, under magnetohydrodynamic equilibrium conditions it is assumed that plasma velocity is zero and it is considered ideal MHD. This implies that the mass density and the magnetic field remain stationary: $\frac{\partial \rho_m}{\partial t} = 0$; $\frac{\partial \mathbf{B}}{\partial t} = 0$, and that the Lorentz force due to the interaction between current and magnetic field compensates the tendency to expand of the plasma due to its kinetic pressure:

$$\nabla p = \mathbf{j} \times \mathbf{B} \qquad (3)$$

This expression (3), jointly with the magnetic field Gauss's law and the simplified Ampere's law $\nabla \times \mathbf{B} = \mu_0 \mathbf{j}$, composes the ideal MHD equations for tokamak equilibrium conditions (see [9]).

3.3 Grad-Shafranov equation

The ideal MHD equations for tokamak equilibrium conditions can be expressed as a nonlinear elliptic partial differential equation obtained from the reduction of the ideal MHD equations given above to two dimensions (R, z). For this purpose, it is considered that any variation with respect to ϕ is zero; $\frac{\partial}{\partial \phi} = 0$, accordingly with the axisymmetric geometry of the toroidal vessel (see Fig. 4).

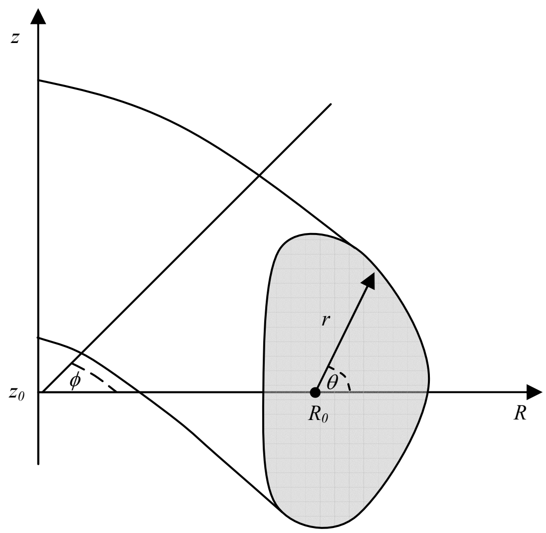

Fig. 4. Cylindrical coordinates (R, φ, z) for the plasma and polar coordinates (r, θ) of the poloidal section referred to the magnetic axis (R_0, z_0)

In this way, the poloidal flux function (Ψ) can be expressed as (see [7], [9] and [11]):

$$\Delta^* \Psi = -\mu_0 R^2 \frac{dp(\Psi)}{d\Psi} - F(\Psi)\frac{dF(\Psi)}{d\Psi}, \qquad (4)$$

known as Grad-Shafranov equation, where Δ^* represents the elliptic operator:

$$\Delta^* = R\frac{\partial}{dR}\left(\frac{1}{R}\frac{\partial}{dR}\right) + \frac{\partial^2}{dz^2} \qquad (5)$$

and where the toroidal flux function F(Ψ) and the pressure function p(Ψ) are solely dependent of the poloidal flux function.

Grad-Shafranov equation is usually solved numerically using the set of transport equations considered which define the time evolution of the plasma in the tokamak (see [12] and [13]). The iterative calculation procedure philosophy is as follows: For the first equilibrium calculation, initial profiles of functions Ψ, *p* and *F* are used, it is computed its time evolution using the transport equations which use in turn the results of the equilibrium calculation, and then a new equilibrium can be calculated. This scheme is performed by the nonlinear code DINA (see [14] and [15]).

4 Control-oriented tokamak plasma simulation codes

In order to model the combined plasma, vessel and poloidal field coil system, many approaches have been tried. From initial linear models [16] which considered the plasma as a filament or a non-deformable plasma [17, 18], to DINA, a nonlinear free boundary resistive MHD and transport-modeling plasma simulation code, [15]. On the one hand, it may be considered several nonlinear codes with nonlinear models as PET, ASTRA, TSC, EFIT, PROTEUS, CREATE or the aforesaid DINA, which are useful to perform simulations including nonlinear behaviours as, for example, large amplitude non-linearities (e.g. large vertical position displacement) or non-time-invariant nonlinearities, but that in turn, possess a quite complicated structure which generally makes them unsuitable for controller design purposes. And, on the other hand, it may be considered linear models as RZIP, an enhanced rigid current displacement model considering changes to the plasma current and to its radial position (see [19], [20] and [21]) or CREATE-L which considers the plasma deformation by conserving an equilibrium of the plasma current distribution (see [22, 23]).

5 Conclusion

In this paper a control-oriented review of nuclear fusion technology has been given. Thus, a description of the fusion process has been provided, with especial emphasis on tokamak-type reactors. Focused on this topology, the plasma MHD equations used jointly with the transport equations in tokamak simulators have been derived. Finally, a review of the most used plasma simulation codes in tokamaks has been provided.

Acknowledgements

The authors are very grateful to the Basque Government by the support of this work through the research project S-PE06UN10. They are also grateful to UPV/EHU and MEC by its partial support through project EHU 06/88 and projects DPI2006-01677 and DPI2006-00714, respectively.

References:

[1] ITER Web site. *http://www.iter.org/*.

[2] A. Pironti and M.L. Walker. Control of Tokamak Plasmas (Introduction to the Special Section on Control of Fusion – Various authors). *IEEE Control Systems Magazine*, vol. 25, no. 5, pp. 24-29, Oct. 2005.

[3] A. Pironti and M.L. Walker. Control of Tokamak Plasmas Part II (Introduction to the Special Section on Control of Fusion: Part II – Various authors). *IEEE Control Systems Magazine*, vol. 26, no. 2, pp. 30-31, Apr. 2006.

[4] Global energy scenarios to 2050 and beyond. *http://www.worldenergy.org/wec-geis/edc/scenario.asp.*

[5] P.B. Weisz, Basic choices and constraints on long-term energy supplies. *Phys. Today*, vol. 57, pp. 47, Jul. 2004.

[6] G. Ambrosino and R. Albanese. Magnetic control of plasma current, position, and shape in tokamaks. *IEEE Control Syst. Mag.*, vol. 25, no. 5, pp. 76–92, Oct. 2005

[7] J-Y. Favez, Ph. Mullhaupt, B. Srinivasan and D. Bonvin. A globally stabilising controller under saturated input for linear planar systems with one unstable pole. *American Control Conference 2004*, Boston, USA, 2004.

[8] J-Y. Favez, J.B. Lister, Ph. Mullhaupt, B. Srinivasan and F. Villone. Improving tokamak vertical position control in the presence of power supply voltage saturation. *30th EPS Conference on* Plasma Physics and Controlled Fusion, St Petersbourg, Russia, 2003.

[9] J. Wesson. Tokamaks, 3rd ed. Clarendon Press-Oxford, UK, 2004.

[10] J-Y. Favez, R.R. Khayrutdinov, J.B. Lister and V.E. Lukash. Comparing TCV experimental VDE responses with DINA code simulations. *Plasma Phys. Control. Fusion*, vol. 44, no. 2, pp. 171-193, Feb. 2002.

[11] G. Ambrosino and R. Albanese. Magnetic control of plasma current, position, and shape in tokamaks. *IEEE Control Syst. Mag.*, vol. 25, no. 5, pp. 76-92, Oct. 2005.

[12] S.I. Braginskii. Transport Processes in a Plasma. *Reviews of Plasma Physics*, vol. 1, pp. 205-311, 1965.

[13] R.R. Khayrutdinov and V.E. Lukash. Studies of Plasma Equilibrium and Transport in a Tokamak Fusion Device with the Inverse-Variable Technique. *Journal of Computational Physics*, vol. 109, no. 2, pp.193-201, 1993.

[14] L.E. Zakharov and V.D. Shafranov. Equilibrium of Current-Carrying Plasmas in Toroidal Configurations. *Reviews of Plasma Physics*, vol. 11, pp. 153-302, 1986.

[15] R.R. Khayrutdinov, J.B. Lister, V.E. Lukash, and J.P. Wainwright. Comparing DINA code simulations with TCV experimental plasma equilibrium responses. *Plasma Physics and Controlled Fusion*, vol. 43, no. 3, pp. 321-342, 2001.

[16] E. Bertolini, P.L. Mondino, and P. Noll. The JET magnet power supplies and plasma control systems. *Fusion Technology*, vol. 11, no. 1, pp. 71-119, 1987.

[17] E.A. Lazarus, J.B. Lister, and G.H. Neilson. Control of the Vertical Instability in Tokamaks. *Nuclear Fusion*, vol. 30, no. 1, pp: 111-141, 1990.

[18] J.B. Lister, E.A. Lazarus, A.G. Kellman, J.-M. Moret, J.R. Ferron, F.J. Helton, L.L. Lao, J.A. Leuer, E.J. Strait, T.S. Taylor, and Turnbull A.D. Experimental Study of the Vertical Stability of High Decay Index Plasmas in the DIII-D Tokamak. *Nuclear Fusion*, vol. 30, no. 11, pp. 2349-2366, 1990.

[19] A.S. Sharma, D.J.N. Limebeer, I. Jaimoukha, J.B. Lister. Modelling and Control of TCV. *IEEE Transactions on Control Systems Technology*, vol. 13, no. 3, 2005.

[20] J.B. Lister, A. Sharma, D.J.N. Limebeer, Y. Nakamura, J.P. Wainwright, and R. Yoshino. Plasma equilibrium response modelling and validation on JT-60U. *Nuclear Fusion*, vol. 42, no. 6, pp. 708-724, 2002.

[21] A. Coutlis, I. Bandyopadhyay, J.B. Lister, P. Vyas, R. Albanese, D.J.N. Limebeer, F. Villone, and J.P. Wainwright. Measurement of the open loop plasma equilibrium response in TCV. *Nuclear Fusion*, vol. 39, no. 5, pp. 663-684.

[22] A. Kavin. ITER-FEAT linear models description. In ITER NAKA JWS, no 1, Naka, Japan, 10 July 2000.

[23] P. Vyas, F. Villone, J.B. Lister, and R. Albanese. The separatrix response of diverted TCV plasmas compared with the predictions of the CREATE-L model. Nuclear Fusion, vol. 38, no. 7, pp. 1043-1053, 1998.