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Plasma scenarios, equilibrium configurations and control in the design of FAST

G. Ramogida[a,*], G. Calabro[a], V. Cocilovo[a], F. Crisanti[a], A. Cucchiaro[a], M. Marinucci[a], A. Pizzuto[a], C. Rita[a], F. Zonca[a], R. Albanese[b], G. Artaserse[b], F. Maviglia[b], M. Mattei[b]

[a] *Associazione Euratom-ENEA sulla Fusione, Via Enrico Fermi 45, I-00044 Frascati, RM, Italy*
[b] *Associazione Euratom-ENEA-CREATE sulla Fusione, Via Claudio 21, I-80125 Napoli, Italy*

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ABSTRACT

The Fusion Advanced Studies Torus (FAST) conceptual study has been proposed [A. Pizzuto on behalf of the Italian Association, The Fusion Advanced Studies Torus (FAST): a proposal for an ITER Satellite facility in support of the development of fusion energy, in: Proceedings of 22nd IAEA Fusion Energy Conference, Geneva, Switzerland, October 13–18, 2008; Nucl. Fusion, submitted for publication] as possible European ITER Satellite facility with the aim of preparing ITER operation scenarios and helping DEMO design and R&D. Insights into ITER regimes of operation in deuterium plasmas can be obtained from investigations of non linear dynamics that are relevant for the understanding of alpha particle behaviours in burning plasmas by using fast ions accelerated by heating and current drive systems.

FAST equilibrium configurations have been designed in order to reproduce those of ITER with scaled plasma current, but still suitable to fulfil plasma conditions for studying burning plasma physics issues in an integrated framework. In this paper we report the plasma scenarios that can be studied on FAST, with emphasis on the aspect of its flexibility in terms of both performance and physics that can be investigated. All plasma equilibria satisfy the following constraints: (a) minimum distance of 3 energy e-folding length (assumed to be 1 cm on the equatorial plane) between plasma and first wall to avoid interaction between plasma and main chamber; (b) maximum current density in the poloidal field coils, transiently, up to around 30 MA/m^2. The discharge duration is always limited by the heating of the toroidal field coils that are inertially cooled by helium gas at 30 K. The location of the poloidal field coils has been optimized in order to: minimize the magnetic energy; produce enough magnetic flux (up to 35 Wb stored) for the formation and sustainment of each scenario; produce a good field null at the plasma break-down ($B_P/B_T < 2 \times 10^{-4}$ at low field, i.e. $B_T = 4$ T and $E_T = 2$ V/m for at least 40 ms).

Plasma position and shape control studies will also be presented. The optimization of the passive shell position slows the vertical stability growth time down to 100 ms.

1. Introduction

Fusion Advanced Studies Torus (FAST) has been proposed as a possible option for a European ITER Satellite facility [2], aimed at supporting the preparation of operation scenarios and the exploration of technologies relevant to DEMO physics and technology issues in a wider (dimensionless) parameter space than JT-60SA and with characteristic values closer to ITER.

FAST has been conceived to contribute drawing the maximum benefit from ITER before as well as in parallel with ITER exploitation in a time window lasting significantly longer than currently foreseen for any existing European devices and within reasonable financial constraints.

The R&D objectives in fusion physics, technology and engineering have been structured by the Fusion Facilities Review Panel in seven interrelated missions [2] along the path from ITER towards DEMO and further: FAST has been designed to address several different aspects of the first five of these interconnected objectives in a integral fashion. FAST will be able to explore Fast Particle physics issues (mission 1), to investigate general aspects of ITER relevant Plasma Operations (mission 2), to look into the physics of large heat loads on divertor plates (mission 3), to investigate Advanced Tokamak (AT) scenarios (mission 4) and to promote the validation of numerical simulation codes to predict ITER fusion and burning plasma performance (mission 5).

As the contribution to mission 1 objectives on burning plasma achievement in ITER, FAST will be able to investigate non linear dynamics that are relevant for the understanding of alpha particle behaviours in burning plasmas by using fast ions accelerated by heating and current drive systems, working with deuterium plasmas in a dimensionless parameter range closer to the ITER one

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* Corresponding author.
E-mail address: gramogid@frascati.enea.it (G. Ramogida).

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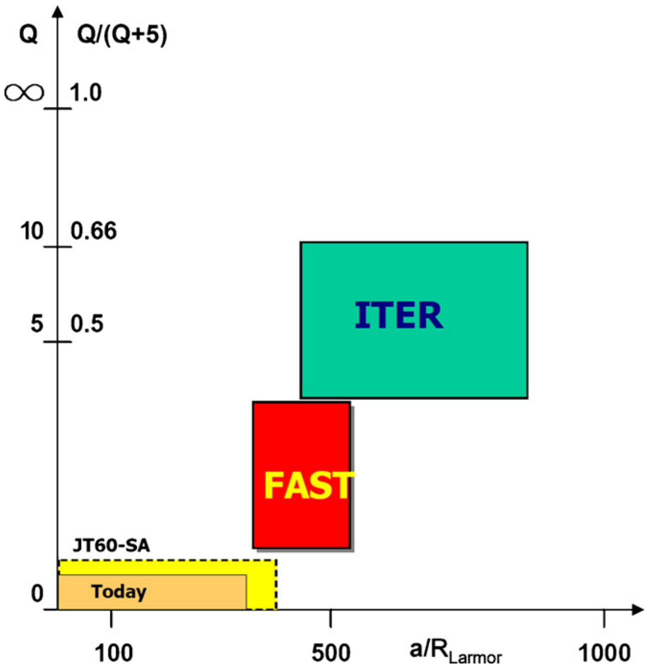

Fig. 1. FAST physics operational space in the ($Q/(Q+5)$, a/R_{Larmor}) plane. Since $Q/(Q+5) = N/N_c \propto T^{5/2}$ and T controls edge physics conditions as well as PWI [5,6], this Fig. emphasizes one of the fundamental aspects of burning plasma physics integration, which is the very original motivation of FAST.

than that of existing machines [1], as depicted in Fig. 1. Although the use of the Q factor to define the physics operational domain is questionable for a machine dedicated to operate with deuterium plasmas and not with a deuterium–tritium mixture, it has been emphasized in [3,4] that $\tau_{\mathrm{SD}}/\tau_{\mathrm{E}} \propto T^{5/2}/N$, with $N = nT\tau_{\mathrm{E}}$ and $\tau_{\mathrm{SD}}/\tau_{\mathrm{E}}$ the ratio of alpha particle (fast ions) collisional slowing down time to the energy confinement time. Thus, for fixed $\tau_{\mathrm{SD}}/\tau_{\mathrm{E}}$ in order to ensure similarity of $\beta_{\mathrm{fast}}/\beta$ ($\beta_{\mathrm{fast}}/\beta$ is the ratio of fast ion to thermal plasma kinetic energy densities) and of electron–ion equipartition, $N \propto T^{5/2}$ and it is reasonable to fix T when defining operation scenarios of a burning plasma relevant experiment since $Q/(Q+5) = N/N_c$ [3,4], with N_c the critical triple product at ignition. Meanwhile, fixing T corresponds to controlling edge physics conditions and plasma wall interactions (PWI) [5,6]. Thus, although the choice of the y-axis in Fig. 1 may be questionable and is not the most general one, it captures one of the fundamental aspects of burning plasma physics integration, which is the very original motivation of FAST. Meanwhile (see Section 4), the fact that FAST can operate with characteristic dimensionless (both thermal and fast) particle orbits similar to those of ITER ensures that FAST transport physics will indeed be relevant since it will reproduce micro- to meso-scale cross-couplings typical of burning plasma conditions [7–11] and the ratio between energy confinement time and electron–ion equipartition time will be comparable to that of ITER; thus, the access to the high performance regimes will occur at dominant and DEMO relevant electron heating.

FAST will be able to contribute, as other machines, to several aspects related to mission 2 issues on reliable operations: plasma and ELM control, assisted break-down development, assessment of the toroidal field ripple (TFR) effects, power coupling studies in a fast particles operational space closest to that of ITER.

The high magnetic field in FAST together with its compactness will make possible to obtain a very high power flux P/R, greater than ITER and approaching the DEMO target value, allowing FAST to test, in relevant conditions, technical approaches to mission 3 issues, related to first wall and divertor power handling, such as full-tungsten wall/divertor and liquid lithium divertor solutions.

Even if it is not a superconducting machine, FAST will be indeed capable to approach steady state conditions of interest for mission 4 objectives, thanks to its availability of heating and current drive power sufficient to access a full non inductive current drive scenario with high bootstrap current fraction.

The contribution of FAST to extend the validation of predictive codes to wider parameter regimes, as far as mission 5, will be also relevant, to fill the gap in operational space foreseen between ITER and JT-60SA. The various physics that can be addressed in FAST to verify and validate numerical codes and theoretical models are described in Refs. [7–12] and in the extended versions of Refs. [13,14].

2. The FAST machine

The requirement for plasma behaviour sufficiently close to ITER sets stringent constraints to FAST features that must be accomplished:

(1) plasma current, I_p, from 2 MA (corresponding to full non inductive current drive scenario) up to 8 MA (corresponding to maximized performance scenario);
(2) auxiliary heating systems able to accelerate the plasma ions to energies in the range 0.5–1 MeV;
(3) plasma major radius of about 1.8 m and minor radius around 0.65 m;
(4) pulse duration from 20 s for the reference H-mode scenario up to 160 s (~40 resistive times τ_{res}) for the longest Advanced Tokamak scenario at 3 MA/3.5 T.

These features have been satisfied in the current FAST design of a compact ($Ro = 1.82$ m, $a = 0.64$ m, triangularity $\delta = 0.4$) and cost-effective machine able to investigate, at the same time and in integrated way, non linear dynamics effects in the fast particle behaviours [1], plasma wall interaction under ITER relevant power load [13], ITER relevant operational issues and Advanced Tokamak regimes up to fully non inductive plasma current driven scenarios.

FAST load assembly is shown in Fig. 2: it consists of 18 toroidal field coils (TFC), a central solenoid (CS) vertically segmented in six coils to allow plasma shaping flexibility, manufacture easiness and efficient cooling, six external poloidal field coils, the vacuum vessel (VV) with its internal components and the mechanical support structure.

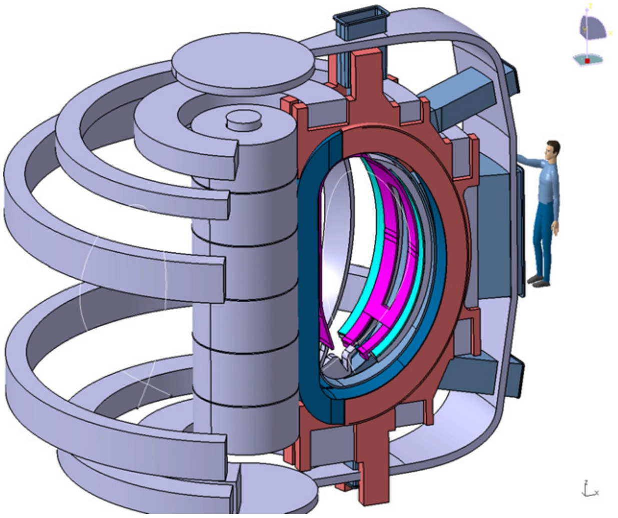

Fig. 2. The load assembly of FAST.