Scenario Development for FAST in the View of ITER and DEMO

F. Crisanti 1), R. Albanese 2), F. Artaud 3), O. Asunta 4), B. Baiocchi 5,6), M. Baruzzo 7), V. Basiuk 3), A. Bierwage 8), R. Bilato 9), T. Bolzonella 7), M. Brambilla 9), G. Breyiannis 1)[1], S. Briguglio 1), G. Calabrò 1), A. Cardinali 1), G. Corrigan 10), A. Cucchiaro 1), C. Di Troia 1), D. Farina 5), L. Figini 5), G. Fogaccia 1), G. Giruzzi 3), G. Granucci 5), F. Imbeaux 3), T. Johnson 11), L. Lauro Taroni 12), G. Maddaluno 1), R. Maggiora 13), P. Mantica 5), M. Marinucci 1), D. Milanesio 13), V. Parail 10), V. Pericoli-Ridolfini 14), A. Pizzuto 1), S. Podda 1), G. Ramogida 1), A. Salmi 4), M. Santinelli 1), M. Schneider 3), A. Tuccillo 1), M. Valisa 7), R. Villari 1), B. Viola 2), G. Vlad 1), X. Wang 15), R. Zagórski 14), F. Zonca 1)

1) Associazione ENEA-Euratom sulla Fusione CP 65 - 00044-Frascati (Rome) Italy.
2) Assoc. Euratom/ENEA-CREATE, Univ. Napoli Federico II, Via Claudio 21, 80125 Napoli, Italy
3) Association Euratom-CEA, DRFC/CEA/Cadarache, 13108 St. Paul-lez-Durance, France
4) Association EURATOM-Tekes, Aalto University, Department of Applied Physics, Finland
5) Istituto di Fisica del Plasma, Euratom-ENEA-CNR Association, Milan, Italy
6) Università degli Studi di Milano,Dipartimento di Fisica, Milan, Italy
7) Consorzio RFX, EURATOM-ENEA Association, Corso Stati Uniti 4, 35127 Padova, Italy
8) Japan Atomic Energy Agency, Naka, Japan
9) Max-Planck-Institut fuer Plasmaphysik-Euratom Association, Garching, Germany
10) Euratom/CCFE Association, Culham Science Centre, Abingdon, OX14 3DB, UK
11) Association EURATOM-VR, Fusion Plasma Physics, EES, KTH, Stockholm, Sweden
12) New College, Oxford OX1 3BN, UK
13) Politecnico di Torino, Dipartimento di Elettronica, Torino, Italy
14) EFDA-CSU-Garching, Boltzmannstraße 2, D-85748 Garching bei München, Deutschland
15) Institute for Fusion Theory and Simulation, Zhejiang University, Hangzhou, PRC

E-mail contact of main author: Crisanti@frascati.enea.it

Abstract. The Fusion Advanced Studies Torus (FAST) aims at contributing to the exploitation of ITER and to tackle innovative DEMO technology. FAST has been designed to explore integrated scenarios studying: a) relevant plasma-wall interaction problems, with a large power load (P/R ~ 22) and full metallic wall; b) operational problems in regimes with relevant fusion parameters; c) non-linear dynamics of alpha particle in burning plasmas. Recently three new FAST scenarios have been developed. 1) FAST load assembly has been conceived to accommodate 10MW of NNBI plus 30MW of ICRH; this allows producing fast particle populations with different anisotropy and profile localization. 2) One of the FAST proposal critical points is the extensive use of ICRH power with first wall and divertor in full tungsten; a variant of the reference scenario has been studied, where 15 MW of ICRH have been replaced with 15MW of ECRH at 170 GHz. 3) Recent experimental results show the necessity of suitable magnetic shear and robust plasma rotation to operate with a reliable ITB. C-MOD experience shows the possibility of achieving ITB operations at high plasma density even without external momentum injection, due to intrinsic rotation. Based on such experimental results and recent developments in the theory of momentum transport, a significant and peaked rotation profile can be envisaged in FAST. In order to study the plasma wall interactions in conditions approaching those of ITER and DEMO, the edge behavior has been analyzed in great detail by means of the EDGE2D/ EIRENE codes. These investigations show the capability of FAST of operating with a large wall load (up to 18 MWm-2), while maintaining it within tolerable limits by working at very high density, with a radiative edge.

1. Introduction

It is presently widely accepted that a successful exploitation of ITER and a reliable as well as early design of DEMO needs a strong accompanying program. Within this roadmap, a key role should be played by the so-called “Satellite Experiments”: JT-60SA [1] and possibly FAST [2]. The two proposals are complementary, but with the capability of accessing

[1] ENEA GOTiT Fellow.

overlapping regions in the operation space; this may allow comparing scientific achievements and experimental results. The primary aim of FAST (Fusion Advanced Studies Torus) is studying integrated plasma scenario to the broadest possible extent. a) Plasma Wall problems that ITER will face, with an outlook on possible scenarios of relevance to DEMO; consequently a large power load is foreseen (P/R~22), with actively cooled divertor and First Wall (FW) in full tungsten; in addition the very high operational density ($<n_e>$ up to ~ $610^{20} m^{-3}$) will allow experiments with high density and radiative plasma edge (up to ~ 90%) even at low collisionality, as in ITER and unlike in other devices. b) ITER and DEMO will necessarily tackle severe operational problems, such as the presence of large ELMs (and the need of mitigating them), and the necessity of completely integrated plasma control tools; FAST will have very large ELMs (up to few MJ) and a complete set of systems to control the plasma operations in an integrated environment. c) Burning plasma stability and mutual feedbacks between thermal plasma and energetic particle populations are among the most interesting and unexplored physics aspects in view of ITER and, more importantly, DEMO. The possibility of performing ITER-relevant integrated experiments in satellites machines relies on the similarity argument based on the existence of three dimensionless parameters: ρ*, β and ν* [3]. In the original formulation and for fixed equilibrium geometry and profiles, the similarity argument corresponds to having one free quantity to choose among B (magnetic field), R (major radius), n (density) and T (temperature). One therefore can fix nR^2, $BR^{5/4}$ and $TR^{1/2}$ as "engineering quantities" for maintaining an identical set of ρ*, β and ν* with R free to vary [4]. However, already extending the similarity argument to the plasma edge, where atomic physics effects are expected to play an important role, challenges the description of plasmas in terms of ρ*, β and ν* only and suggests the introduction of T as a further "dimensionless" parameter; but doing so yields the apparent paradox that only the trivial solution exists, for which ITER relevant burning plasma physics issues can be addressed in ITER only [5]. This problem may be solved only relaxing the idea of maintaining identical ρ*, β, ν* while identifying crucial physics aspects that should be preserved. Consequently the target is to construct a "weak" similarity argument [2], which allows to suitably re-scale the ITER plasma parameters, while still addressing the relevant integrated physics. The use of (τ_{SD}/τ_E), instead of ν*, is more transparent in constructing our "weak" similarity argument, since $(\tau_{SD}/\tau_E) \approx (\beta_H/\beta)$, in conditions where the local power balance is dominated by fast ion heating. Similarly β should not be relaxed because this parameter regulates the relative frequency ordering between micro-scale turbulence and meso- and macro-scale fluctuations. Thus, on the basis of physics requirements, the "weak" similarity scaling is defined by fixing $\rho^* R^{\varepsilon}$ which does not break

Table 1: Operating scenarios

FAST	H-mode referente HMR	H-mode extreme HME	AT	Full NICD
I_p (MA)	6.5	8.0	3.5	2
q_{95}	3	2.6	5	5
B_T (T)	7.5	8.5	6	3.5
H_{98}	1	1	1.2	1.2
$<n_{20}>$ (m^{-3})	2	5	1.4	1
β_N	1.3	1.7	2.2	3.4
τ_E (s)	0.4	0.65	0.20	0.10
τ_{Res} (s)	5.5	5	3	2 ÷ 5
T_0 (keV)	13.0	9.0	12	7.5
Q	0.65	1.5	0.32	0.06
$t_{discharge}$ (s)	20	13	55	170
$t_{flat-top}$ (s)	13	2	45	160
I_{NI}/I_p (%)	15	15	60	>100
P_{ADD}(MW)	30	40	40	40

the relative wavelength ordering between micro-scale turbulence and meso- and macro-scale fluctuations, for (ρ^*_H/ρ^*) preservation is guaranteed by the condition that electron collisional heating fraction by the Fast Particles (FP) is the same as for fusion alphas in ITER. In FAST it has been chosen $\varepsilon=1/2$. By using $\varepsilon\leq1/3$ would yield the non-physical condition, where smaller devices would need to operate at higher temperature. Meanwhile, the choice $\varepsilon=1$, would yields the "weak" similarity scaling fitting some of present day machines, like JET, DIII-D and ASDEX Upgrade. A straightforward use of the "weak" similarity scaling [2] with $\varepsilon=1$ gives $T\propto R^{4/3}$, $I_p\propto R^{5/3}$, $B\propto R^{2/3}$, $n\propto R^0$, $P_{ADD}/R\propto R^{4/3}$; $\nu^*\propto R^{-5/3}$. Using this criterion, the reference ITER H-mode scenario (B_T=5.3T, I_p=15MA and T=20keV) can be studied with "equivalent" parameters by ASDEX Upgrade (R=1.65m) with B_T=2.2T, I_p=1.65MA, T=3.4keV and/or by JET (R=3.0m) with B_T=3.3T, I_p=4.5MA, T=7.6keV, the main difference between the two devices being in the achievable performance: Q=0.041 for ASDEX Upgrade and Q=0.32 for JET. In summary the choice of FAST, i.e. $\varepsilon=1/2$, is "heuristic" but reasonable [2], for it is the one which makes ρ^* *as close as possible to ITER* relevant values and implies $T\propto R^{1/3}$, $I_p\propto R^{2/3}$, $B\propto R^{-1/3}$, $P_{ADD}/R\propto R^{-1/6}$, $\nu^*\propto R^{-2/3}$ and $n\propto 1/R$.

When fixing FAST major radius R=1.82m (a=0.64m), the "weak" scaling implies T≅13keV, I_p≅6.8MA, B≅8T for FAST by similarity with the ITER H-mode scenario. These values are evidently close to those of the FAST H-mode reference scenario (HMR), which is reported in Table 1 together with the highest performances (HME), an Advanced Tokamak (AT) and the Full Non Inductive (NICD) scenarios. In this work, we present the latest progresses in the FAST scenarios development and the related studies. In particular three different scenarios and hypotheses are illustrated and discussed.

- The FAST load assembly has been conceived to accommodate 10MW of Negative Neutral Beam Injection (NNBI - 0.7÷1 MeV) on top of the 30MW of ICRH foreseen in the reference scenario [6,7]. This allows producing fast particle populations with different anisotropy and profile localization. Transport simulations performed with JETTO and CRONOS confirm zero dimensional estimates and demonstrate the possible achievement of an equivalent Q~1.5.
- One of the critical points of the FAST proposal is the extensive use of ICRH power with FW and divertor in full tungsten; ASDEX [8] latest experiments show evidence of plasma pollution as a consequence of the sputtering caused by the parallel electric field produced at the ICRH Antenna. Given that 15 MW of ICRH are sufficient for locally achieving ITER relevant values of β_{Hot} in the FAST H-mode reference scenario [2], while 30 MW of total additional power are needed to achieve the necessary bulk plasma performances, a variant of the reference scenario [2] has been studied, where 15 MW of ICRH have been replaced with 15MW of ECRH at 170 GHz.
- Recent experimental results [9] show the necessity of suitable magnetic shear and robust plasma rotation to operate with a reliable ITB. In FAST as well as in ITER, there is a small or null external momentum injection, raising doubts on the possibility of achieving ITB scenarios. However, C-MOD [10] experience shows the possibility of achieving ITB operations at high plasma density even without external momentum injection, exploiting the existence of an edge intrinsic rotation, carried into the core plasma by a significant momentum pinch. The integration of recent theoretical findings for momentum transport and numerical simulation has shown the possibility for FAST to have a relevant and peaked intrinsic plasma rotation. The use of NNBI providing a source of core torque provides an additional and sounder basis for achieving significant rotation profiles. The presence of a large bootstrap fraction (up to 60 ÷70%) and the use of 4MW of LHCD (driving up to 30÷40% of I_P) allows achieving full non-inductive current drive with plasma current I_p=2MA and toroidal magnetic field B_T=3T.

Motivated by one of the main targets of the FAST research program, i.e., the study of plasma wall interactions, in conditions approaching as much as possible the ITER and DEMO edge behaviour [11] has been analyzed in greater detail by using the EDGE2D/EIRENE codes.

2.1 NNBI Scenario.

A preliminary configuration for NNBI FAST injector has been produced with the criterion of being as close as possible to the present ITER design [12,13]. The considered beam energy ranges between 0.7 ÷ 1.0 MeV. The ITER NBI source geometry was used, but reducing at two the hyperbeamlets columns, each one with 5 rows. The injection is tangential, with an angle of 45° on the magnetic axis. The source retains the possibility of tilting slightly (0.797°) the vertical angle that, given the distance to the plasma and the compact size of the device, allows a very off-axis injection. A sensitivity of this NNBI configuration on the standard FAST H-mode scenario has been performed by using NEMO [14] and SPOT [15] codes, that calculate, respectively, the fast ions birth profiles starting from the cross sections of all of the ion generation processes and the thermalization with bulk plasma of test particles generates according of birth profile of the fast ions. Simulations have been performed, by varying the Beam energy (0.7÷1.0 MeV), the Beam Neutrals (H, D), the Beam divergency and the on-axis versus the off-axis deposition. Given the FAST high density, the shine through power is practically always null. The plasma shape, density and temperature profiles used were taken from a CRONOS [16] simulation of FAST H-mode standard scenario with 30MW of injected ICRH power, where heat diffusion equations were solved using Bohm/gyro-Bohm diffusivities with prescribed electron and ion densities. Eventually, the full FAST H-mode scenario has been simulated by using NEMO plus CRONOS. For this case 30 MW ICRH, coupled at ρ=0.25 were assumed, with the deposition profile calculated offline using the full wave code TORIC [17]; besides, 10 MW NNBI (D) at 1 MeV have been used with on-axis deposition. The NNBI system provides also some small momentum input with a central plasma rotation ~ 2 10^4 rad/s in the absence of edge intrinsic rotation, When included in a transport analysis this rotation can play an important role. In Fig. 1 the beam impact on temperature profiles can be seen, when replacing 10 MW ICRH with 10 MW NNBI. JETTO (with BgB model for the transport), coupled with ASCOT [18] and PION, has been used for the analysis, and the effect of rotation on thermal transport taken into account. In blue the ion temperature profiles are drawn and in red the electron ones. The solid lines represent the cases with only ICRH (and no intrinsic rotation), whilst the dashed lines indicate the cases with the 10MW NNBI. Ti and Te are pretty similar for the case with only ICRH, but are decoupled with the beams on. Moreover the two temperatures (mainly the ions) are larger when the 10 MWNNBI power replaces the ICRH. This effect is essentially due to the role played by the beam induced rotation. 10MW NNBI and 30MW ICRH have also been used [19] to simulate the HME FAST scenario with very high density (~ 5 10^{20}m^{-3}), by using different transport models and obtaining always a temperature of the order of 10 KeV at the

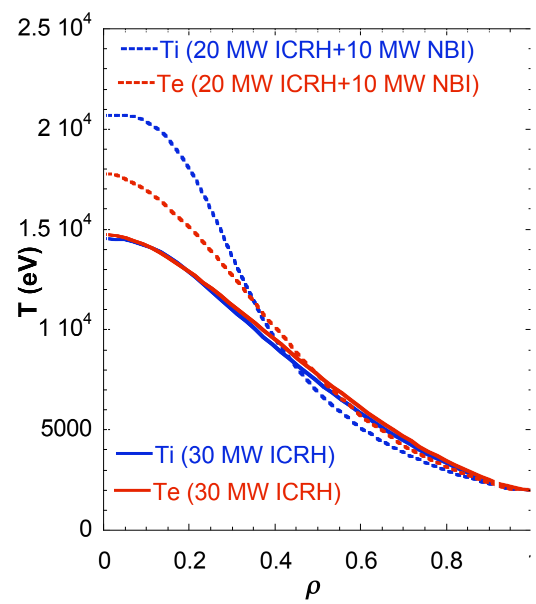

Fig. 1: *Electron (red) and ion temperature (blue) profiles, with only (solid) ICRH and with 10 MW NNBI (dashed) replacing*

plasma centre. Various minority concentrations (^{3}He 1-3%) have been used to do a parametric study of the beta of the supra-thermal population. β_H can reach values up to 3%, i.e. well in line with the needs for exciting meso-scale fluctuations with the same characteristics of those expected in various regimes of reactor relevant conditions. Moreover, the combination of ICRH+NNBI adds great flexibility to the experimental study of these phenomena, owing to the generation of fast ion populations with different velocity space anisotropy and radial profiles, and allowing to study the integrated transport processes of both thermal and supra-thermal plasma components. A recently extended version of the HMGC code [20] can be used to investigate the destabilization and saturation of fast ion driven Alfvénic modes in such experimental situation. The FAST extreme H-mode scenario is characterized by a dense spectrum of Alfvénic fluctuations with the same wavelength and frequency spectra that are expected in ITER (peaked at $15 < n < 25$)

2.2 ICRH + ECRH Scenario.

Several different core transport models have been used to simulate the FAST reference scenario [21,22], some of them based on first principle (Weiland [23] and GLF23 [24]) and some on semi-empirical models (mixed Bohm-gyroBohm (BgB) [25] and Critical Gradient Model (CGM) [26]). In these simulations the density profile has been assumed flat (as usually happens in the present H modes) and/or it has been assumed (or left to evolve) peaked, as scaled by the present database for the FAST low collisionality case and/or as obtained by using GLF23. The simulations have been carried out using the JETTO code [27]; for ICRH heating profiles we have either used the PION code [28] called self-consistently by JETTO or by TORIC that is run outside JETTO and requires a few iterations. The final result is that all models predict about the same electron temperature, but there is a larger range of variation in the Ti profiles. In particular a careful attention has been used to study the alternative scenario where only 15 MW ICRH are used together with 15MW ECRH at 170 GHz. The ECRH heating profiles have been provided by the GRAY code [29], that requires iterations with JETTO. In this scenario the ICRH has been reduced up to the minimum level sufficient to generate a $\beta_H \sim 1\%$. Since the ECRH resonance is at 6.1T, B_T =6.0T and Ip=5.5MA were used for this simulation; however, as a consequence of the Shafranov shift, the actual experiment could be planned at B_T =6.7T with a plasma current of around 6.0MA. In Fig. 2 the electrons and ions temperature, as predicted by using the different models, are shown for the case with only ICRH and for the case with ICRH+ECRH. In the latter case the electron temperature remains always larger than the ion temperature ($T_e(0) \sim 15$ KeV, $T_i(0) \sim 9$ KeV). Although the ECRH deposition has been spread out on a $\Delta\rho \sim 0.2$, the fact that $T_e > T_i$ that can be justified from the much larger input power density on the

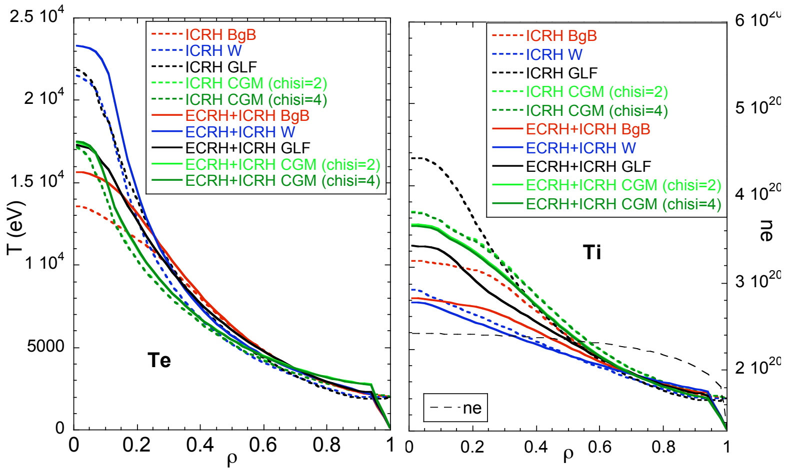

Fig. 2: Ion and electron temperature and density profiles shown for the case of ICRH +ECRH (full line) and full ICRH (dotted line). Red lines are for old BgB, blue for Weiland, black for GLF23 and green for CGM. The assigned density profile is shown with dashed line.

electrons when compared to the ions one. This causes a negative loop where higher T_e/T_i decreases the ITG threshold, with consequent colder ions and not significantly hotter electrons than the full ICRH case.

2.3 Steady State Scenario.

As shown in Table 1 the scenario NICD has, in principle, the unique capability to study a full non inductive regime at high β_N, with a reactor relevant FW in tungsten. However FAST will have only a small input of external momentum [12,22] (like ITER) and only in the framework of the NNBI scenarios. From recent experimental results it seems that the toroidal rotation plays a key role in achieving improved ion core confinement [9,30], not only through the well-known threshold up shift, but through a significant reduction of the ion stiffness. The rotation has been included in the simulations by modeling the momentum transport with physical assumptions consistent with recent theoretical developments [31]. Due to the inward pinch, core rotation in FAST can be driven by intrinsic rotation edge sources. Given the present lack of understanding and theory-based predictive capability on intrinsic rotation, we have assumed for FAST an edge rotation value ω_ϕ=30 krad/s, as provided by the scaling in [32]. Given the high values of intrinsic rotation measured in C-MOD, a high field compact machine conceptually similar to FAST, it may be still legitimate to assume an edge rotation value as predicted by the existing CMOD driven empirical scaling. The NICD scenario, with I_p=2MA, has been simulated [22], by using the BgB model, without including any torque source and by adding 4MW of LHCD at 5GHz ($n_{||}$=2.3). In Fig. 3 the obtained/used rotation profile is shown. An ion temperature profile with an ITB-like gradient, around ρ~0.5÷0.6, has been obtained with a reversed q profile (q_{min}~2). The ion and electron temperature are very close with T_{i0}~20KeV, T_{e0}~15KeV and with a density n_{e0}~2 10^{20} m^{-3}. These parameters have to be regarded as overestimated due to the simplistic assumptions of the BgB model.

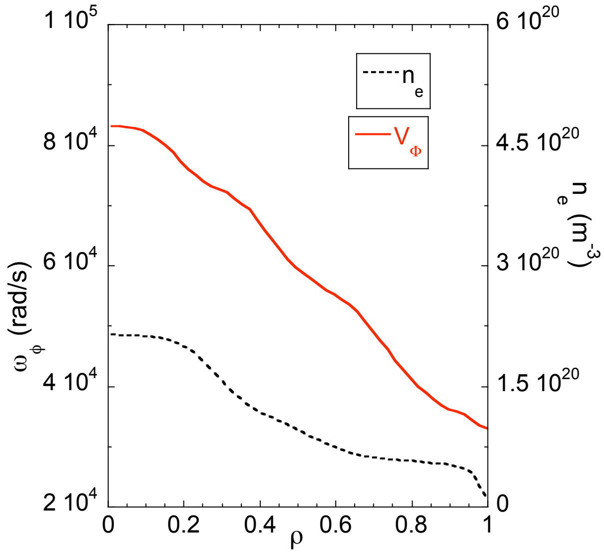

Fig. 3. Rotation profile for NICD scenario

3.0 Plasma-Wall Interaction.

In all the FAST scenarios the additional power is always ranging between 30 and 40 MW, giving a P/R up to 22, with a FW and a divertor in W. The code COREDIV [33], that couples the bulk transport with the SOL physics (1D in the bulk and 2D in the Scrape-Off Layer (SOL)), and where the sputtering and atomic physics are taken in account, has been used in a previous work [11] to have a first indication of the FAST plasma wall interaction problems. Although the most important physics aspect are included, this code has the drawback of not using at all the actual geometry of the FW and/or of the divertor, consequently all the important topological effects are not described and/or foreseen. However, some general (pessimistic) features could already be investigated. In particular it was clear that, at very high density ($\langle n \rangle \geq 2\ 10^{20} m^{-3}$), the power load on the divertor could be limited around 18 MW/m^{-2}, a figure compatible with FAST design where W monoblock tiles is planned to be used [2,7]. At lower density, and in particular for the Advanced Tokamak scenarios, a slight impurities seeding had to be foreseen, but, eventually, for all the planned scenarios an effective $Z_{eff} \leq 2$ was predicted in the bulk plasma. The use of the EDGE2D-EIRENE [34] code has allowed to introduce the real geometry of the FW and of the divertor and to study the topological effects [35]. In order to isolate the different aspects of the problem, we have started the analysis on the reference scenario without including any impurity at all. A large variation of the striking angles (from around 30° down to less than of 10°, separately for the inner and for the outer strike point), and of the closeness of the final divertor corners has been tested. The effect of the location and of the efficiency of some conceptual pumping has been investigated, too. So far, this analysis has been performed only for the reference scenario, but it has to bear in mind that the same plasma shape is foreseen for all the FAST scenarios. As predicted by

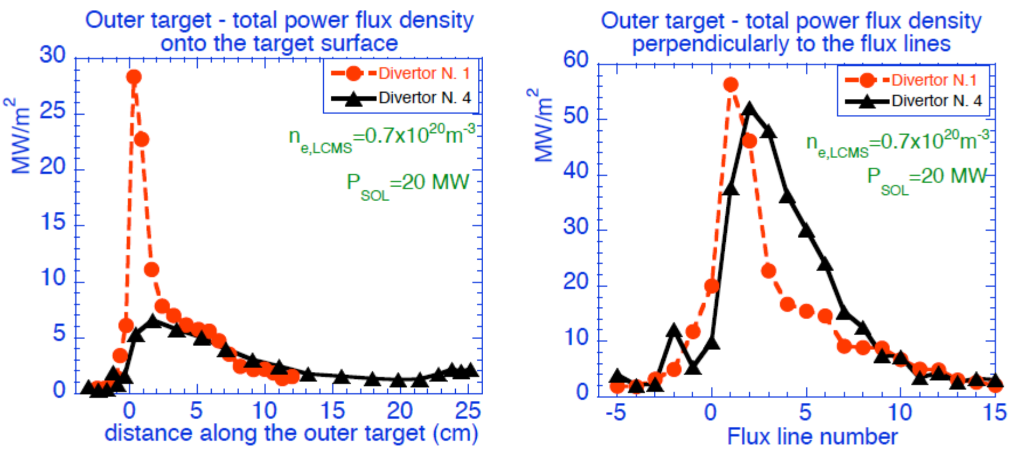

Fig. 4: a) Total Power Load on the outer for divertor shape 1 (strike point angle ~30°) and divertor shape 4 (strike point angle ~10°); b) Total power flowing along the tubes flux for the two cases of a).

COREDIV, 20 MW (~30% of bulk plasma radiation) have been assumed to flow through the Last Close Magnetic Surface (LCMS); again, by using COREDIV it was predicted a density $n_{e\_LCMS} \sim 0.7\ 10^{20} m^{-3}$ on LCMS. A density scan between 0.7 and 1.2 $10^{20} m^{-3}$, on the LCMS, has been performed for all the studied divertor geometries. By increasing the density, the power on the divertor plates more than halves, where the “saved” power partially flows to the wall and partially is radiated by atomic processes. Looking at the neutral density profiles and dynamics, there is a clear indication of the tendency to a power detachment at the highest densities. In Fig. 4a-b the power deposition profile is shown, along the outer divertor plates (a) and along the flux tubes (b), for the two extremes cases with a strike point angle of ~30° (divertor 1) and of ~10° (divertor 4). The two divertors present differences also for the pumps location and for the closeness of the divertor corner: much more close for divertor 4. A pretty large difference (Fig. 4a) in the power load on the divertor tiles (from ~ $20 MWm^{-2}$ to ~ 4 MWm^{-2}) it is registered for the two cases; since the geometrical effect should be only of the order of a factor ~ 2.8, the rest of the gain must be due to something different. From Fig. 4b it can be noticed that the power flowing along the flux tubes is broader for divertor 4; this effects is due to the increase of the neutral density in the region in front of the strike point; consequently, the radiation due to the atomic processes takes in account of the rest of the saving in the power flowing on the tiles. The obvious conclusion is that with an opportune design of the divertor (strike point angle between 15 and 20 and sufficient closure of the corners) no problem should be foreseen when working with FAST at high density. The behaviour of the power with the density at the LCMS suggests, instead, that for all the AT scenarios (with n_{LCMS}~0.3 $10^{20}m^{-3}$) an impurity seeding will be necessary [11].

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