Moderate beta baseline scenario in preparation to D-T operations at JET

V. K. Zotta[1], L. Garzotti[2], F. J. Casson[2], D. Frigione[3], R. Gatto[1], F. Koechl[2], E. Lerche[2], P. Lomas[2], C. Mazzotta[4], G. Pucella[4], F. Rimini[2], D. Van Eester[5] and JET Contributors*

[1] *Sapienza Università di Roma, Rome, Italy*
[2] *CCFE Culham Science Centre, Abingdon, UK*
[3] *Università di Tor Vergata, Rome, Italy*
[4] *ENEA C. R. Frascati, Frascati, Italy*
[5] *Laboratory of Plasma Physics LPP-ERK/KMS, Bruxelles, Belgium*
**See the author list of E. Joffrin et al.2019 Nucl. Fusion 59, 112021.*

1. INTRODUCTION In 2021, JET will operate with a D-T plasma mixture. To achieve high fusion power with a steady performance, two ELMy H-mode scenarios are under development: the baseline scenario, with low β_N where good confinement is achieved at high current and the hybrid scenario, at lower current and higher β_N, with a shaped current profile. Most of the extrapolations done for baseline plasmas used as reference one of the baseline most performing pulses with a $\beta_N \approx 2.2$ which is higher than usual in typical baseline pulses. In this work we present the results of the predictive simulations done with the JINTRAC suite of codes and the QuaLiKiZ transport model, using as reference a more conventional baseline with $q_{95} \approx 3$ and $\beta_N \approx 1.8$. The simulation settings and the transport model have been validated against the experimental results obtained in D-T plasma mixture during DTE1, when JET was equipped with a carbon wall, and against the experimental results obtained in D plasmas both with the C wall and the ITER-like wall (Be/W) installed in 2011. The extrapolations to D-T plasma mixture at high current show that 10 MW of fusion power are achievable in a wide range of experimental conditions, while 15 MW of fusion power could be approached only with full auxiliary power (40MW) in particularly pure plasmas.

2. VALIDATION OF THE REFERENCE DISCHARGE The baseline scenario used as reference in this work is the stationary phase of JPN 92376, it is an H-mode with a plasma current I_p = 3.0 MA, a toroidal magnetic field B_T = 2.8 T and an additional heating power around 26 MW, 22 MW from neutral beam injection (NBI) and 4.4 MW from ion cyclotron resonance heating (ICRH) in H minority scheme. The relevant plasma parameters averaged during the time window of interest are reported in Table 1. The integrated modelling of the reference pulse has been done with the JINTRAC suite of codes [1] using the JETTO transport solver [2] and the QuaLiKiZ transport model [3,4]. QuaLiKiZ (quasi linear gyro-kinetic code) is a first-principle transport model that can deal with the core transport of multiple hydrogenic species and, therefore, can be used in the extrapolations to D-T plasmas. In the simulations the evolution of the current density profile, of the electron density profile and of the ion and electron temperature profiles are predicted as well as the plasma rotation, while the evolution of the impurity density profiles is predicted using the SANCO impurity transport code [5]. The heating deposition profiles are computed using PENCIL for NBI [6] and PION for ICRH [7], and the synergy between them is taken into account in JINTRAC [8]. The equilibrium is calculated self-consistently with the evolution of the current density profile and the kinetic profiles with ESCO equilibrium solver [9].

Table 1: relevant experimental plasma parameters of the simulated JET pulses averaged in the time window of interest and used as reference for the extrapolations.

JET pulse number	92376	96482	42464	42982
Main ion species	D	D	D	D-T
Simulated time window [s]	9.6 – 10.7	10 – 12	14.4 – 16.4	15 – 17
B_T [T]	2.8	3.35	3.8	3.8
I_p [MA]	3.0	3.5	3.8	3.8
q_{95}	3.2	3.2	3.5	3.5
β_N [% / MA]	1.8	1.9	1.2	1.45
P_{NBI} [MW]	22	29	18	21.6
P_{ICRH} [MW]	4.4	4.3	0.5	2.0
n_{e0} [10^{19} m^{-3}]	7.8	9.4	8.5	7.8
$<n_e>$ [10^{19} m^{-3}]	5.8	6.1	5.6	5.8
T_{e0} [keV]	5.4	6.0	7.5	5.8
$<T_e>$ [keV]	2.8	2.5	4.5	3.3
T_{i0} [keV]	6.9	8.0	7.6	10.3
$<T_i>$ [keV]	3.0	3.8	3.7	4.9
W_{th} [MJ]	7.5	10.0	8.3	7.9
Neutron rate [10^{16} n/s]	1.65	3.0	1.33	168.8
Z_{eff}	1.9	1.8	2.3	2.8

The initial conditions of the simulation on the electron temperature and density profiles are taken form the measurements of the JET High Resolution Thompson Scattering (HRTS) [10], while the ion temperature profile and the toroidal rotation profile are taken from the beam charge exchange spectroscopy (CX) [11]. The boundary conditions are imposed at the separatrix which is assumed to be located at the position where $T_e = T_i = 100$ eV. The edge transport barrier (ETB) is modelled in order to match the experimental pedestal height and a thermal heat diffusivity is imposed in the pedestal region to reproduce the experimental pedestal temperature. The assumption of the thermal heat diffusivity in the ETB contains some uncertainty, which is reflected on the simulation uncertainty on the predicted confinement and, consequently, on the predicted performance, both in the validation and in the extrapolations at higher plasma current. The sensitivity to different impurity mixtures has been evaluated in the validation phase prescribing the experimental Z_{eff} and a single dominant impurity (Be or Ni) and afterwards prescribing an impurity mixture of Be, Ni and W with the concentrations estimated by considering several diagnostics as described in [12]. The predicted plasma profiles are compared to the experimental profiles of JPN 92376 averaged in the time window of interest in Fig.1. In Fig.2 the experimental time traces of Z_{eff}, P_{rad} and of the neutron rate are plotted against the predicted time traces for the simulation with the optimised settings.

The simulation shows a good agreement with the experimental measurements in the plasma profiles and in the time traces, approaching the experimental measurements in the simulated time window within the measurement uncertainties and the experimental fluctuations. Moreover, the predicted pedestal pressure is 8.5 MPa close to the experimental value of 8.7 MPa, showing that the first-principle model describes the core transport and the empirical modelling of the pedestal gives a realistic operational point.

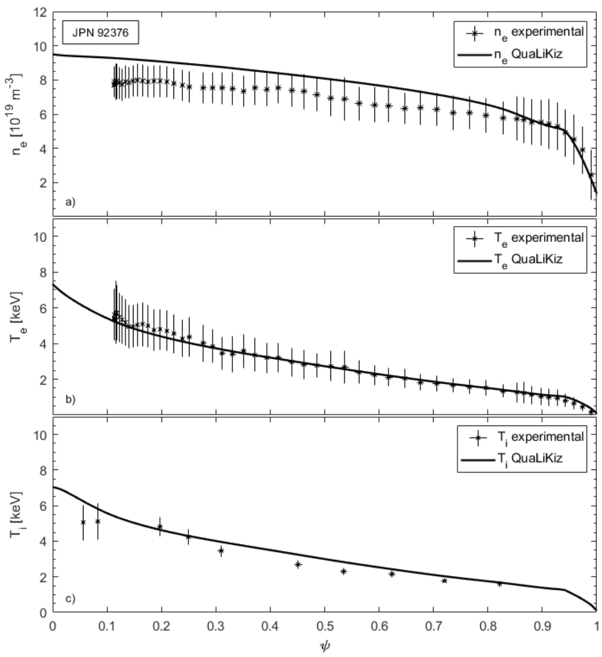

Figure 1: comparison between the experimental and the modelled electron density (a), electron temperature (b) and ion temperature (c) profiles of the JPN 92376.

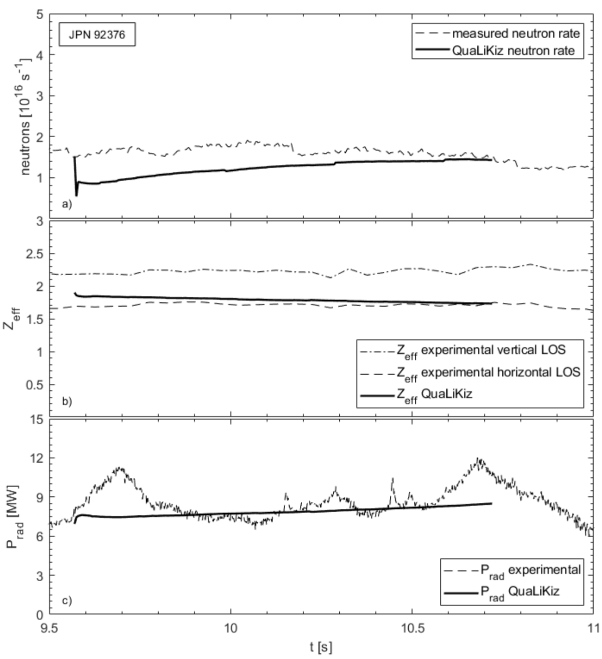

Figure 2: comparison between experimental and modelled neutron rate (a), Z_{eff} (b) and bulk radiative power (c) for JPN 92376.

In order to test the extrapolation capability, different simulations have been done starting from the simulation settings found for reproducing JPN 92376; a blind prediction has been done at constant Greenwald fraction on JPN 96482, adjusting the available heating power to the experimental heating power of JPN 96482. It can be seen that the blind simulation reproduces very well a JET discharge at higher current with the assumptions done on the pedestal in terms of scaled pedestal density and imposed thermal heat diffusivity. In addition, the DTE1 pulses JPN 42464 and JPN 42982 have been reproduced with the same methodology applied for reproducing JPN 92376, other details on these pulses can be found in [13,14]. The simulation results are shown and discussed in [15].

3. D-T EXTRAPOLATIONS The D-T extrapolations at higher current have been performed keeping constant the Greenwald fraction and using the optimised simulation settings found for reproducing the reference pulse. The results of the predicted fusion power at higher current and higher toroidal field (up to 3.7 T for I_p = 4.2 MA and 4.5 MA) are shown in Fig. 3; In this first group of simulations we assumed an available additional heating power of 40 MW (34 MW of NBI and 6 MW of ICRH in H minority scheme) [16].

We have investigated the sensitivity to the impurity mixture considering Be and Ni as dominant impurities and keeping constant the Z_{eff}. Afterward, we imposed a more realistic impurity mixture of Be, Ni and W keeping constant the Z_{eff} and the P_{rad}/P_{aux} value to the experimental value of the reference JPN 92376. Each point in the figures is constructed with three extrapolations where the thermal heat diffusivity at the ETB is varied by ±25% producing the error bars.

In Fig. 4 we have also investigated the sensitivity to the available additional heating power which has been gradually decreased from 40 MW to 38 MW (32 MW of NBI and 6 MW of ICRH), to 36 MW (32 MW of NBI and 4 MW of ICRH) and to 33 MW (29 MW of NBI and 4 MW of ICRH).

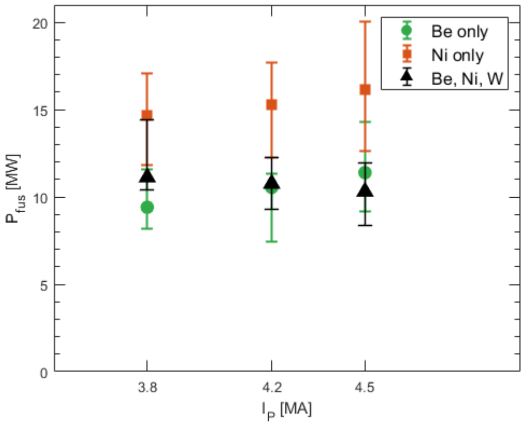

Figure 3: predicted fusion power in dependence of the plasma current at full additional power 40 MW. The error bars correspond to different assumptions on the thermal heat diffusivity in the ETB [$\chi_{ped} \pm 25\%$].

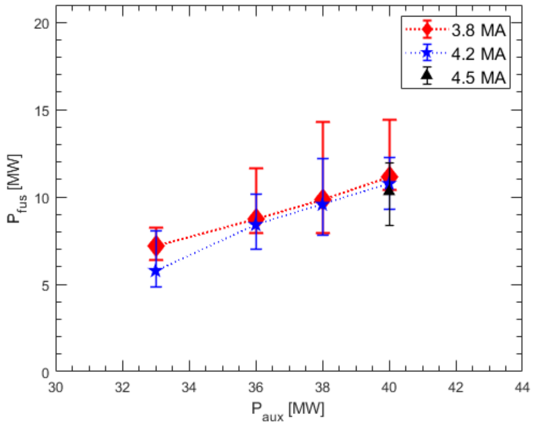

Figure 4: predicted fusion power in dependence of the available additional heating with Be, Ni and W impurity mixture**.** The error bars correspond to different assumptions on the thermal heat diffusivity in the ETB [$\chi_{ped} \pm 25\%$].

4. CONCLUSIONS In this work we have presented the extrapolations to D-T plasma mixture of a moderate β_N baseline scenario. The JETTO-QuaLiKiZ-SANCO simulations have shown a good prediction capability on the JET pulses used as benchmark. The extrapolation capability at higher current and higher toroidal magnetic field has been tested reproducing with a blind prediction the pure D discharge JPN 96482. The D-T fusion power predictions show the possibility of achieving 10 MW of fusion power under a wide range of assumption with an available additional heating power around or above 38 MW. With this scenario 15 MW of fusion power could be approachable only at full auxiliary power and for particularly pure plasmas.

Acknowledgments This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No.633053 and from the RCUK Energy Programme (grant number EP/P012450/1). To obtain further information on the data and models underlying this paper please contact PublicationsManager@ukaea.uk. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References:

[1] Romanelli M. et al 2014 Plasma and Fusion Research **9** 3403023
[2] Cenacchi G and Taroni A 1988 JETTO: a free boundary plasma transport code ENEA Report RT/TIB/88/5
[3] Bourdelle C. et al 2016 Plasma Phys. Control. Fusion **58** 014036
[4] Citrin J. et al 2017 Plasma Phys. Control. Fusion **59** 064010
[5] Lauro Taroni L. 1994 Proc. 21st EPS Conference on Controlled Fusion and Plasma Physics ECA **vol. 18B**, part I, p. 102
[6] Challis C. D. et al 1989 Nucl. Fusion **29** 563
[7] Eriksson L.-G., Hellsten T. and Willén U. 1993 Nucl. Fusion **33** 1037
[8] Gallart D. et al 2018 Nucl. Fusion **58** 106037
[9] Cenacchi G. and Rulli M. 1988 Upgrading of an equilibrium transport code for a multispecies free-boundary plasma, ENEA Report RTI/TIB/88/5
[10] Pasqualotto R. et al 2004 Rev. Sci. Intrum. **75** 3891
[11] Hawkes N. C. et al 2018 Rev. Sci. Intrum. **89** 10D113
[12] Sertoli M. et al 2019 J. Plasma Phys. **85** 905850504
[13] Horton L. D. et al 1999 Nucl. Fusion **39** 993
[14] Hyun-Tae Kim et al 2020 Nucl.Fusion **60** 066003
[15] V. K. Zotta, L. Garzotti et al "*Fusion power prediction for β_N = 1.8 baseline scenario in preparation to D-T operations at JET*" to be submitted to Nuclear Fusion.
[16] Garzotti L. et al 2019 Nucl. Fusion **59** 076037