HIGH PERFORMANCE ELM-FREE SEMI-DETACHED SCENARIO SUSTAINED AT HIGH-CURRENT IN JET DTE3

C. Giroud[1], D.B. King[1], I.S. Carvalho[2], D. L. Keeling[1], L. Frassinetti[3], R. A. Pitts[2], G. Pucella[4], S. Wiesen[5], A. Kappatou[6], N. Vianello[7], M. Wischmeier[6], F. Rimini[1], M. Baruzzo[4,7], M. Maslov[1], M. Sos[8], X. Litaudon[9], R. B. Henriques[1], K. Kirov[1], C. Perez von Thun[10], H. J. Sun[1], P. Dumortier[11], E. Lerche[11], P. Jacquet[1], M. Lennholm[1], J. Mitchell[1], A. Parrot[1], J. Bernardo[1], M. Zerbini[4], I. Coffey[1,12], K. Collie[1], J. Fontdecaba[13], N. Hawkes[1], Z. Huang[1], I. Jepu[1], D. Kos[1], K. Lawson[1], E. Litherland-Smith[1], A. Meigs[1], C. Olde[1], A. Patel[1], L. Piron[7,14], M. P. Poradzinski[1,10], Z. Stancar[1], D. Taylor[1], E. Alessi[15], I. Balboa[1], A. Boboc[1], S. Bakes[1], M. Brix[1], E. De la Cal[13], P. Carvalho[1], A. Chomiczewska[10], Z. Ghani[1], E. Giovannozzi[4], J. Foster[1], A. Huber[16], J. Karhunen[17], E. Kowalska-Strzeciwilk[10], K. Lawson[1], J. Maddock[1], J. Matthews[1], S. Menmuir[1], K. Mikszuta-Michalik[10], R. B. Morales-Bianchetti[1], E. Pawelec[18], G. Petravich[19], E. Pinto[13], D. Refy[19], I. Voldiner[13], G. Sergienko[16], S. Silburn[1], G. Stankunas[20], C. Silva[21], J. Svodoba[8], G. Szepesi[1], M. Tomes[8], B. Thomas[1], A. Tookey[1], Y. Zayachuk[1], N. Wendler[10], L. Xiang[1], F. Auriemma[7], I. Borodkina[8], D. Fajardo[6], A. Fil[9], S. Gabriellini[22], L. Garzotti[1], S. Henderson[1], Q. Hu[15], P. Innocente[7], I. Ivanova-Stanik[10], A. Jarvinen[17], H. Kumpulainen[16], C. Leoni[22], J. Lombardo[7], P. Mantica[15], A. Mariani[15], M. Marin[23], A.H. Neilsen[24], M. O.Mullane[1], O. Pan[6], V. Parail[1], I. Predebon[7], S. Saarelma[1], J. Seidl[8], A. Stagni[7], A. Thrysoe[24], M. Valovic[1], A. Widdowson[1], V.K. Zotta[22], JET Contributors* and the EUROfusion Tokamak Exploitation Team** .

[1]UKAEA, Culham Campus, Abingdon OX14 3DB, UK; [2]ITER Organization, Route de Vinon-sur-Verdon, CS 90 046, 13067 St Paul Lez Durance Cedex, France; [3]Fusion Plasma Physics, EECS, KTH Royal Institute of Technology, SE-10044 Stockholm, Sweden; [4]Fusion and Nuclear Safety Department - ENEA C. R. Frascati - via E. Fermi 45, 00044 Frascati (Roma), Italy; [5]DIFFER - Dutch Institute for Fundamental Energy Research, De Zaale 20, 5612 AJ Eindhoven, Netherlands; [6]Max-Planck-Institut für Plasmaphysik, Garching, Germany; [7]Consorzio RFX, Corso Stati Uniti 4, Padova, 35127 Italy; [8]Institute of Plasma Physics of the CAS, Za Slovankou 1782/3, 182 00 Prague, Czech Republic; [9]CEA, IRFM, F-13108 Saint Paul Lez Durance, France; [10]Institute of Plasma Physics and Laser Microfusion, Hery 23 Street, 01-497 Warsaw, Poland; [11]Laboratory for Plasma Physics LPP-ERM/KMS, B-1000 Brussels, Belgium; [12]Astrophysics Research Centre, School of Mathematics and Physics, Queen's University, Belfast, BT7 1NN; [13]Laboratorio Nacional Fusión. CIEMAT. Av Complutense 40. 28040 Madrid. Spain; [14]Dipartimento di Fisica "G. Galilei", Università degli Studi di Padova, Padova, Italy; [15]Institute for Plasma Science and Technology, CNR, 20125 Milano, Italy; [16] Institute of Fusion Energy and Nuclear Waste Management–Plasma Physics, Forschungszentrum Jülich GmbH, Germany; [17]VTT Technical Research Centre of Finland, P.O. Box 1000, 02044 VTT, Finland; [18]Institute of Physics, University of Opole, Oleska 48, 45-052 Opole, Poland; [19]Centre for Energy Research, 29-33 Konkoly Thege Miklós street 1121 Budapest, Hungary; [20]Lithuanian Energy Institute, Laboratory of Nuclear Installation Safety, Breslaujos Str. 3, LT-44403 Kaunas, Lithuania; [21]Instituto de Plasmas e Fusao Nuclear, Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisboa, Portugal; [22]Sapienza University of Rome, Rome, Italy; [23]SPC, Swiss Plasma Center, Ecole Polytechnique Federale de Lausanne, Station 13, Lausanne 1015, Switzerland; [24]PPFE, DTU Physics, Technical University of Denmark, 2800 Kgs. Lyngby, Denmark; *See the author list of CF. Maggi et al., Nucl. Fusion 2024, 10.1088/1741-4326/ad3e16, **see the author list of E. Joffrin Nuclear Fusion 2024 10.1088/1741-4326/ad2be4

Recent advances in core-pedestal-exhaust integration at high plasma current in JET with tungsten (W) divertor and a beryllium (Be) first wall are vital in support of robust achievement of the ITER Q =10 baseline scenario and provide unique insights for the design of the next step D-T devices, including DEMO and STEP. A viable exhaust solution for a reactor-grade plasma must sustain a high radiative fraction (f_{rad}) - achieved through injection of extrinsic impurities - to dissipate the power flux in the scrape-off layer (SOL) and divertor regions which would otherwise lead to intolerable divertor target heat fluxes [1]. Simultaneously, a sufficiently hot pedestal must be maintained to ensure good energy confinement, above the H-mode power threshold, ideally without Edge Localised Modes (ELMs), but with particle control and minimising main chamber erosion from fast ions sputtering.

Over the past two years, dedicated "JET-ITER baseline" experiments have been performed in D and in D-T while approaching the core-edge-exhaust integration conditions required for ITER baseline plasmas. These plasmas are developed at high input power (P_{in} =30-35MW), with high plasma current (I_p=2.5-3.2MA) and with a magnetic configuration close to that of ITER: high triangularity (δ_u=0.36-0.4, δ_l=0.35), q_{95} =2.7-3.3, with a closed divertor with both strike points positioned on the vertical W divertor tiles (VV configuration, inertially cooled). Partial divertor detachment - an essential requirement for protecting the ITER divertor against high-heat flux under burning plasma conditions - is reached and sustained by injecting neon (Ne) (as foreseen on ITER) under feedforward conditions. Simultaneously, low pedestal collisionality is reached ($\nu^*_{e,ped}$~0.3-0.4), at ITER baseline normalised pressure values (β_N ~2.1), and with small/no ELMs ($\Delta T_{OuterTarget.max}$<20°C, W_{ELM}/W<0.3%). These experiments provide crucial data for physics-based extrapolation of JET results to ITER and beyond, helping to understand the access and sustainment conditions, operational domain and the complex interplay of the underlying physics governing core, pedestal and exhaust integration.

Key results and findings are particularly encouraging for ITER and may be summarised as follows:

- For the first time, a Ne-seeded integrated scenario at 3MA in D-T with partially detached divertor has been achieved in stationary conditions for up to 6.5s (29 x τ_E), with fusion power of 4MW and without ELMs (JPN #104600, 3MA, q_{95}=2.7, P_{in}=34MW, $H_{98(y,2)}$ = 0.85, f_{gw}=0.75, β_N ~2.1, $\nu^*_{e,ped}$~0.5, no ELMs, see Fig. 1a-b).
- JET-ITER baseline plasmas with high Ne content is sustained over multiple confinement times without the need for active detachment control thanks to low W content in the confined plasma and an effective particle control (with or without ELMs) in both D-D and D-T.
- Minimal adaptation of the D-D JET-ITER baseline scenario was required to reproduce the main results in D-T, with similarly high f_{rad} and high performance achieved with and without ELMs (JPN #104614, 2.5MA, q_{95}=3.3, P_{in}=32.5MW, $H_{98(y,2)}$ = 0.9, f_{gw}=0.74, β_N ~2.1, $\nu^*_{e,ped}$~0.6, no ELMs).
- In D-D and D-T, increasing Ne seeding reduces the pedestal electron density gradient, enabling a gradual and smooth transition to high confinement ($H_{98(y,2)}$ > 0.85, f_{rad}>0.8) and ELM-free regime, provided the input power is sufficiently high P_{sep}/P_{LH} > 1.25.

High-performance core-edge integrated scenario at high plasma current - The Ne-seeded JET-ITER baseline in D and D-T at 2.5MA is a robust scenario that can operate at proximity to partial divertor detachment, and achieve high-confinement (H_{98}>0.85-1.0) with pedestal temperature up to $T_{e,ped}$=1-1.1keV ($T_{i,ped}$=1.33-1.9keV) and central electron temperatures $T_{e,0}$=6.5-7keV ($T_{i,0}$=7.5-8.5keV) with a pedestal density of $n_{e,ped}$~ 4-5x10^{19} m^{-3} ($\nu^*_{e,ped}$~0.3-0.7), f_{GW} ~0.7-0.8, with small or no ELMs, confirming initial results obtained in D [2] (see Fig, 1cde). At higher currents, high confinement for the 3MA (q_{95}=2.7) Ne-seeded JET-ITER baseline is only accessible in D-T [3,4], not in D; whereas at 3.2MA (q_{95}=3.3), H-mode could not be sustained with Ne-seeding in D nor D-T [5]. In these highly fuelled plasmas, Ne-seeding provides a route to low pedestal collisionality and improved confinement, via an improved pedestal pressure compared to the unseeded plasmas; the core ITG stabilisation via increased dilution was not identified as a key player [6]. As the Ne content is increased, above $C_{Ne,ped}$ of 1% and at high enough input power (P_{in}>30MW), the pedestal widens, increases in temperature and pressure and the pedestal density gradient ($\nabla n_{e,ped}$) lowers. Simultaneously, the core electron density profile peaks and the ion and electron temperatures decouple (T_i/T_e=1.2). Two factors are being investigated to explain the decrease in $n_{e,ped}$: radiative dissipation in the divertor volume which decreases the power available for ionisation of neutrals recycled at the targets, reducing the upstream separatrix density; change of transport in the pedestal modifying the pedestal density gradients and pedestal width with Ne-seeding. Gyro-Kinetic simulations have shown that the transport due to electron scale turbulence is increased, with the ion heat flux governed by neoclassical transport. At present, a turbulent particle flux compatible with a reduction of electron density has not been identified. Encouraging first JINTRAC-COCONUT modelling with the increased ETG transport with Ne-seeding can reproduce the normalised pedestal gradient (α_{max}) compatible with small ELMs. Individual contributions of the physics puzzle are currently being investigated in view of making a first start towards an integrated picture via full JINTRAC-COCONUT modelling.

Understanding the reasons for the reduction of W concentration as performance and Ne increases – In this scenario, the high confinement plasmas with a hot core and hot pedestal have a lower W content in the confined plasma region compared to their unseeded counterparts. Unsurprisingly, with a partially detached divertor and no ELMs, the W erosion is negligible, leading to a core W content reduction (C_W<0.6x10^{-5}). When ELMs are still present, W is mostly eroded in the intra-ELM phases by Ne impurity ions with a gross W erosion higher than for unseeded plasmas; Some improved W screening is occurring either in the SOL – where a balance between the temperature gradient force, friction force, prompt W redeposition, and the divertor target sheath electric field determines W transport – or in the pedestal, where a large ion temperature gradient combined with a low-density gradient reverses the neoclassical convection outward, reducing W content across the pedestal. The seeded JET-ITER baseline scenarios did not suffer from an enhanced W content when transferring the scenario from D to DT at 2.5MA, since Ne impurities dominate W sputtering in both cases.

ELM-free operational domain in the JET-ITER baseline regime – As Ne content increases and the ELMs reduce in size and eventually disappear, the operational point calculated for the pedestal MHD stability, initially close to the ideal ballooning boundary at low seeding, moves away from the boundary; the decrease of α_{max} can be explained with resistive MHD. From the dataset obtained, the conditions to reach high confinement with no ELM are a high enough power, P_{sep}/P_{LH}≥1.25, and a separatrix density $n_{e,sep}$ ~2x$10^{19}$$m^{-3}$. When the plasma enters this regime and the Ne content is further increased, a smooth H-L transition with no hard re-attachment is observed. If P_{sep}/P_{LH} is too low, the hard transition from H-L prevents access to the high confinement and no ELMs regime. It is the lower power threshold P_{LH} in D-T [7] than in D that give access to this regime at 3MA in D-T with the available P_{in} in JET. **References:** [1] PittsNME2019 [2] C. Giroud IAEA 2021; [3]Giroud PSI 2024 [4] I.S.Carvalho EPS 2024 [5] D. Fajardo this conference; [6] Marin NF 2023; [7] Solano NF 2023

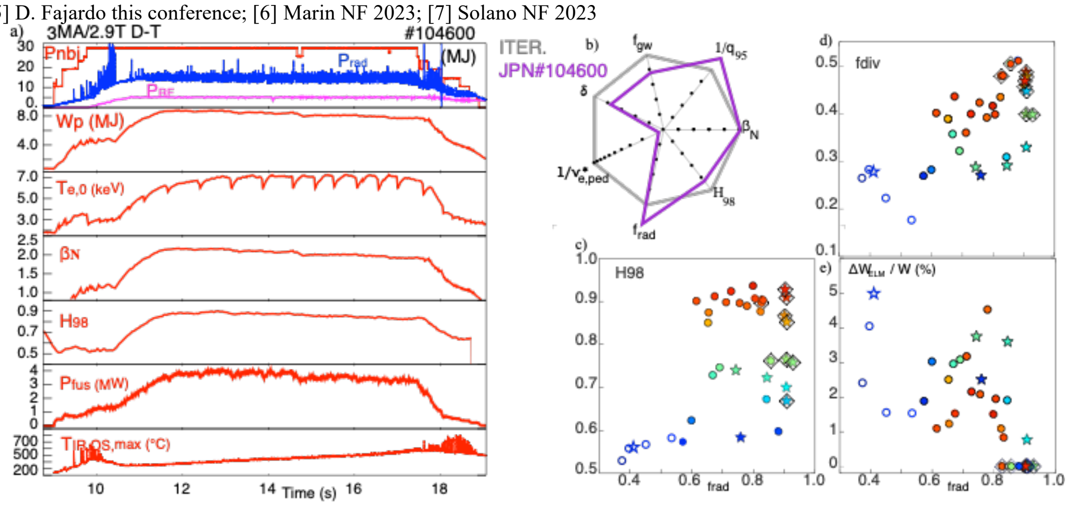

Fig. 1: For JPN #104600 a) time traces, b) Key parameters (purple) normalised to those of ITER (grey). c-e) 2.5MA/2.9T plasmas in D (circle) and DT (star) (open and filled symbols corresponds to unseeded and seeded plasma respectively) versus f_{rad} c) $H_{98}(y,2)$ d) fraction of divertor radiation f_{div} (P_{rad} just below the X-point to total radiation within edge boundary region (dR≥-12cm)), e) ELM size in terms of energy loss. Diamond symbols indicate no-ELM plasma. Colours is associated to $H_{98}(y,2)$ value.