EUROfusion

High Performance ITER-baseline discharges in deuterium with nitrogen and neon-seeding in the JET-ILW

Carine Giroud[1], S. Brezinsek[2], R. A. Pitts[3], I.S. Carvalho[4], A. Huber[3], E. Kaveeva[5], D. Keeling[1], J. Mailloux[1], V. Rozhansky[5], S. Aleiferis[1], B. Chapman[1], S. Henderson[1], L. Garzotti[1], E. Lerche[6], M. Marin[7], M. Maslov[1], M. Brix[1], P. Carvalho[4], I. Coffey[8], J.M. Fontdecaba[9], L. Horvath[1], I. Jepu[10], J. Karhunen[11], E. Litherland-Smith[1], A. Meigs[1], R.B. Morales[1], T. Pereira[4], D. Refy[12], Z. Stancar[13], M. Sertoli[1], S. Silburn[1], G. Szepesi[1], A. Thorman[1], M. Tomes[14,15], I.Veselova[5], B. Viola[1], S. Wiesen[2] and JET Contributors*

EUROfusion Consortium, JET, Culham Science Centre, Abingdon, OX14 3DB, UK

[1]Culham Centre for Fusion Energy, Culham Science Centre, Abingdon OX14 3DB, UK
[2]Forschungszentrum Jülich, Institut für Energie-und Klimaforschung - Plasmaphysik, 52425 Jülich, Germany
[3]ITER Organization, Route de Vinon-sur-Verdon, CS 90 046, 13067 St Paul Lez Durance Cedex, France
[4]Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisboa, Portugal
[5] Peter the Great St.Petersburg Polytechnic University, Polytechnicheskaya 29, 195251 St.Petersburg, Russia
[6] LPP-ERM-KMS, Association EUROFUSION-Belgian State, TEC partner, Brussels, Belgium
[7] DIFFER - Dutch Institute for Fundamental Energy Research, Eindhoven, The Netherlands
[8] Astrophysics Research Centre, School of Mathematics and Physics, Queen's University, Belfast, BT7 1NN
[9] Laboratorio Nacional Fusion. CIEMAT. Av Complutense 40. 28040 Madrid. Spain
[10] National Institute for Laser, Plasma and Radiation Physics, Magurele-Bucharest, Romania
[11] Aalto University, P.O.Box 14100, FIN-00076 Aalto, Finland
[12] Centre for Energy Research, 29-33 Konkoly Thege Miklós street 1121 Budapest, Hungary
[13] Jožef Stefan Institute, Ljubljana, Slovenia
[14] Institute of the Plasma Physics of the Czech Academy of Sciences, Prague, Czech Republic
[15] Department of Surface and Plasma Science, Faculty of Mathematics and Physics, Charles University, Czech republic

* See the author list of J. Mailloux et al to be published in Nucl. Fusion Special Issue: Overview and Summary Papers from the 28th Fusion Energy Conference (Nice, France, 10-15 May 2021)

Introduction

- ITER tritium plant is being designed to deal with both nitrogen (N) and neon (Ne) [1] but the use of N leads to the formation of tritium-containing ammonia → time-costly high temperature regeneration → reduction of plant duty cycle.
- On current devices with all-metal plasma-facing components, N generally provides the best performance with respect to a carbon dominated environment. [2,3,4]
- It would be beneficial for ITER to use Ne for divertor radiation
- New experiments at JET with a higher input power (30-33MW) have finally yielded a Ne-seeded scenario which behaves similarly to the high-performance seeded H-mode previously only achievable with N impurity.

Experimental details, performance of neon and nitrogen-seeded plasmas

- Stationary Type I ELMy H-modes have been obtained with Ip=2.5MA, B_T=2.7T, P_{RF}=5MW, with high triangularity (δ=0.4), with the same ITER-like divertor (VV) configuration with both inner and outer strike points on the vertical divertor target [2].

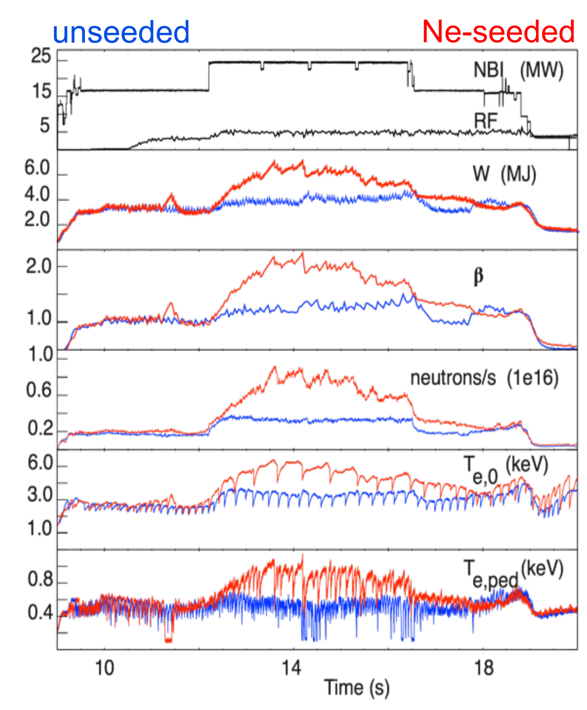


Fig.1: Time-trace of improved Ne-seeded plasma (96133,red) Γ_{Ne}=8x10[21] el.s-1 versus unseeded plasma (96139, blue) with same input power and D-gas rate.

P_{NBI}=25MW, Γ_D= 3x10^{22} el.s^{-1}
Γ_{Ne}=8x10^{21} el.s^{-1} (C_{Ne}=1%)
H_{98}: 0.60 → 0.86
β_N: 1.1 → 2.0
Te= 1.1 x Ti
f_{GW}: 0.82
Z_{eff} =2.0
f_{rad}: 0.76

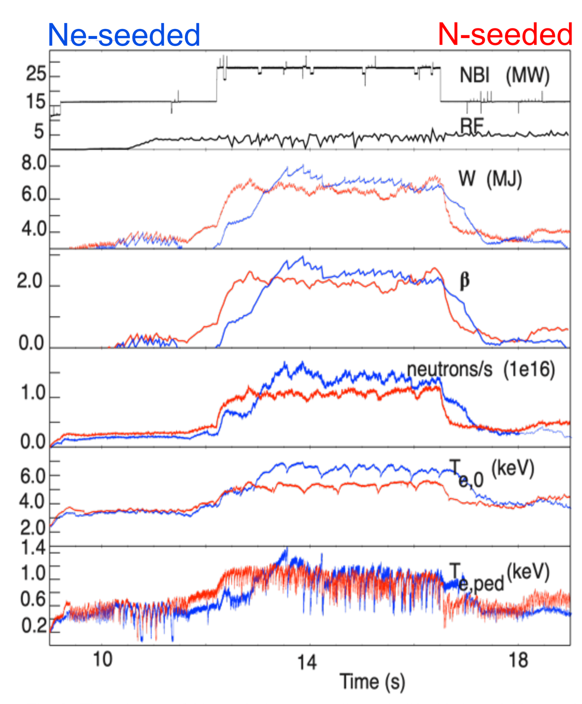


Fig 2: Time trace of N-seeded plasma (in red, #97125) and Ne-seeded plasma (in blue, #96915) with about 1% of impurity concentration at the pedestal top and D-gas (3.5x10^{22} el/s).

P_{NBI}=28MW, Γ_D= 3.5x10^{22} el.s^{-1}
Γ_{Ne}=1.56x10^{22} el.s^{-1} (C_{Ne}=1%)
Γ_N=4.8x10^{22} el.s^{-1} (C_N=1%)

H_{98}	β_N	Te=	f_{GW}	Z_{eff}	f_{rad}	R_{nt} (x10^{16} n.s^{-1})
0.92	2.2	1.2xTi	0.75	2.6	0.78	1.4
0.83	2.0	Ti	0.86	1.6	0.75	1.0

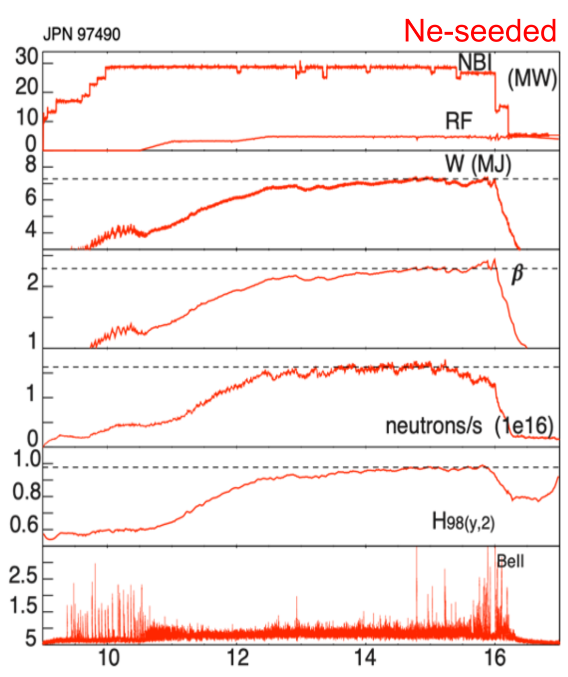
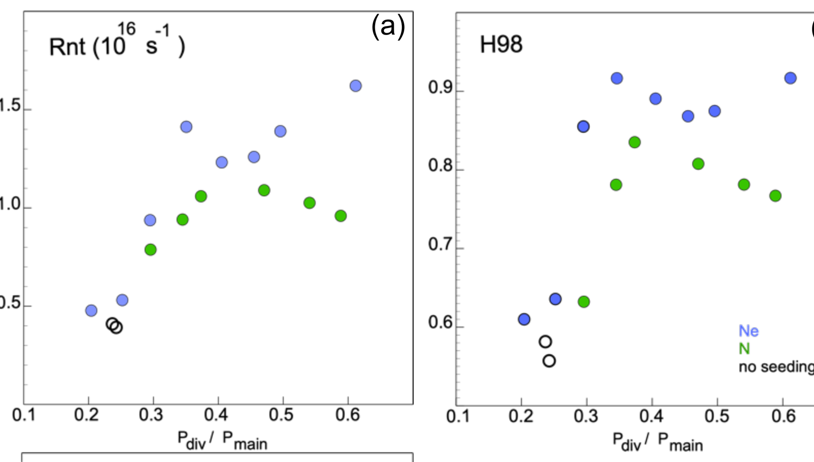


Fig. 3: Time trace of Ne-seeded plasma at highest radiative fraction with small/no ELM.

P_{NBI}=28MW, Γ_D= 3.5x10^{22} el.s^{-1}
Γ_{Ne}=2.2x10^{22} el.s^{-1}
H_{98}: 0.9 (corrected for fast particles)
β_N: 2.3
Te= 1.2 x Ti
f_{GW}: 0.68
Z_{eff} =2.7
f_{rad}: 0.80
R_{nt}= 1.6x10^{16} n.s-1
Small/no elms



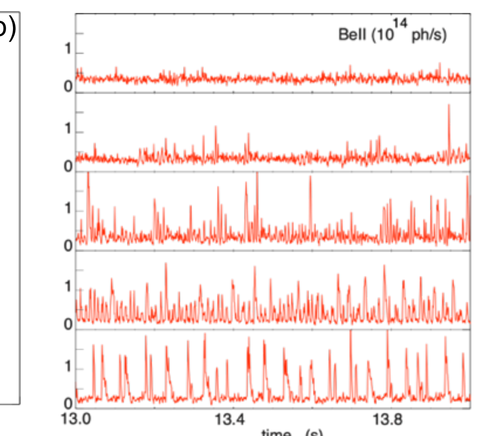


Fig 5: Time trace of Be^{1+} intensity in region close to the outer strike point for discharge with increasing Ne gas rate from bottom unseeded to top for the highest seeding of 2.2x10^{22} el.s^{-1}

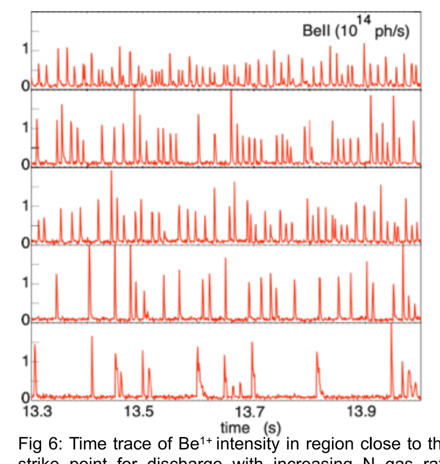


Fig 6: Time trace of Be^{1+} intensity in region close to the outer strike point for discharge with increasing N gas rate from bottom 3.6x10^{22} el.s^{-1} to top for the highest seeding of 8.3x10^{22} el.s^{-1}

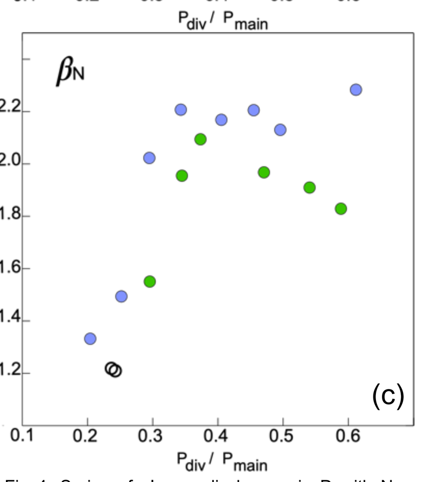


Fig 4: Series of plasma discharges in D with Ne (filled blue) and N (filled green) seeded and unseeded (open black) plasmas. Each symbol represent a discharge. a) averaged neutron rate b) normalized confinement c) normalized pressure

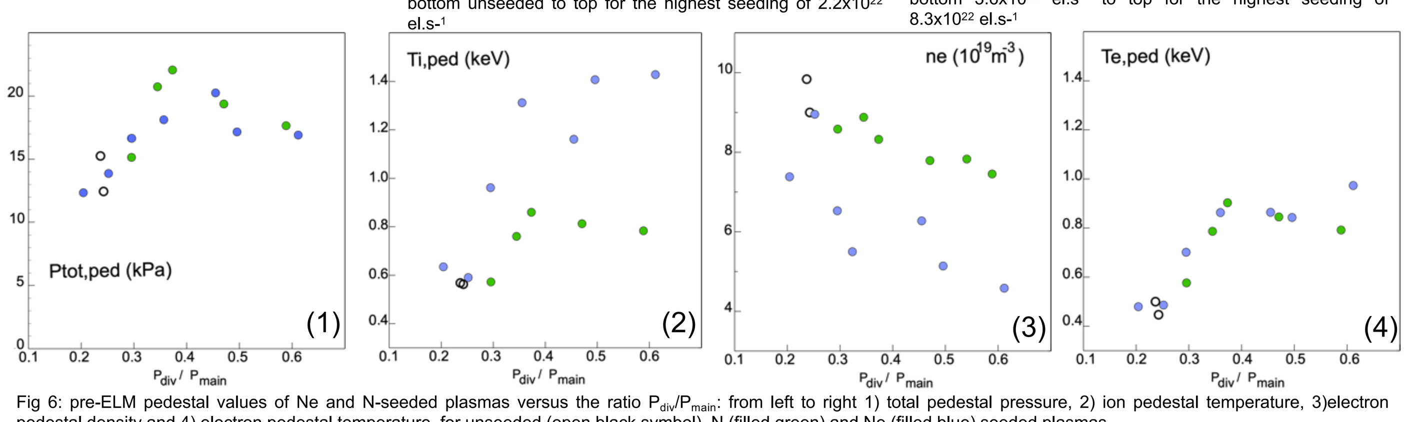


Fig 6: pre-ELM pedestal values of Ne and N-seeded plasmas versus the ratio P_{div}/P_{main}: from left to right 1) total pedestal pressure, 2) ion pedestal temperature, 3)electron pedestal density and 4) electron pedestal temperature, for unseeded (open black symbol), N (filled green) and Ne (filled blue) seeded plasmas.

- Unexpectedly, over the range of applied impurity-seeding rate, the neon-seeded plasmas have the highest neutron rates, H_{98} and β_N values and energy confinement time (Fig 4), in comparison to N-seeded plasmas.
- The ELMs are very different between Ne and N-seeded plasmas (Fig. 5 and 6) as the impurity seeding rate increases.
- At the highest Ne-seeding rate of 2.2x10^{22} el.s^{-1}, stationary plasmas are obtained with small ELMs/no ELM regime and impressive plasma performance, see Fig. 3.

- Pedestal behaviour is different for Ne and N-seeded plasmas:
  - Similar total pedestal pressure can be maintained (Fig.6)
  - Ne-seeded plasmas have a higher pedestal T_i and lower pedestal electron density than N-seeded plasmas, but similar pedestal T_e. (Fig 6)

Core modelling and improvement of confinement

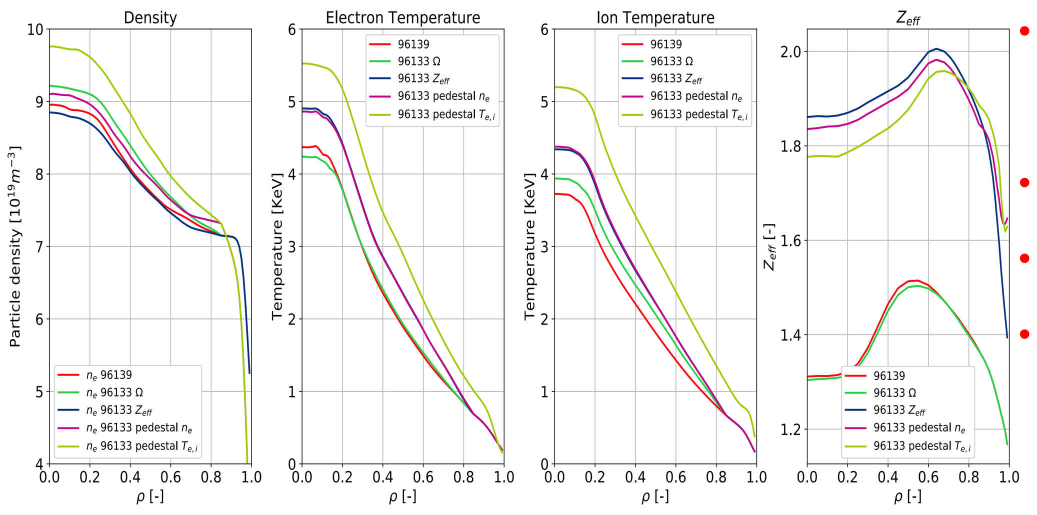


Fig. 7:Results from QualiKiz modelling with step-by-step change from unseeded discharge to Ne-seeded discharge. Unseeded discharge (#96139, in red), with rotation profile from #96133 (in dark green), with impurity composition of #96133 (in blue), with the electron density boundary value of #96133 (in purple), with the electron and ion temperature boundary of #96133 (in light green) [5].

- QuaLiKiz simulation with j, T_e, T_i , n_e, n_i are predicted; impurity density and rotation are imposed. Boundary conditions taken at rho=0.85
- Both seeded and unseeded discharges, (from Fig1) are well reproduced as well as Rnt.
- ITG dominated at lower $k_\theta\rho_s$ (<1), while ETG weakly unstable for $k_\theta\rho_s \gtrsim 3$.
- Components leading to the origin of the improvement are identified by starting from the unseeded simulation and adding step-by-step
  - Rotation profile from Ne-seeded plasma
  - Ne impurity content
  - The pedestal electron density at rho=0.85
  - Pedestal electron and ion temperature

- ExB shear, impurity content ad high ratio T_i/T_e, each plays a role in improving the core confinement and neutron rate but together comparable to the role of the pedestal. Similar simulations with N-seeding are on-going.

Pedestal stability, structure, first gyrokinetic analysis

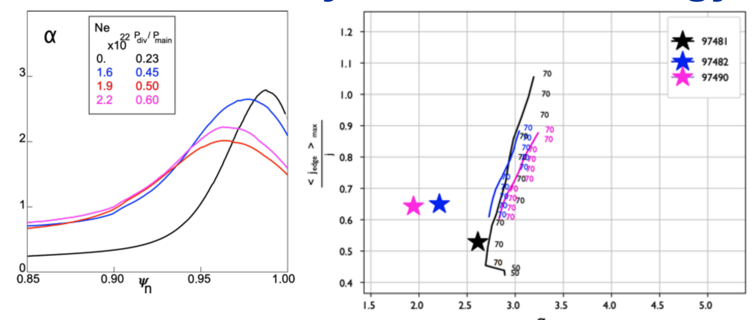


Fig. 8: normalised pressure gradient for Ne-seeded plasmas (left) and j-α stability diagram (right). Left graph. Legends show the Ne-gas rate and value of P_{div}/P_{main}.

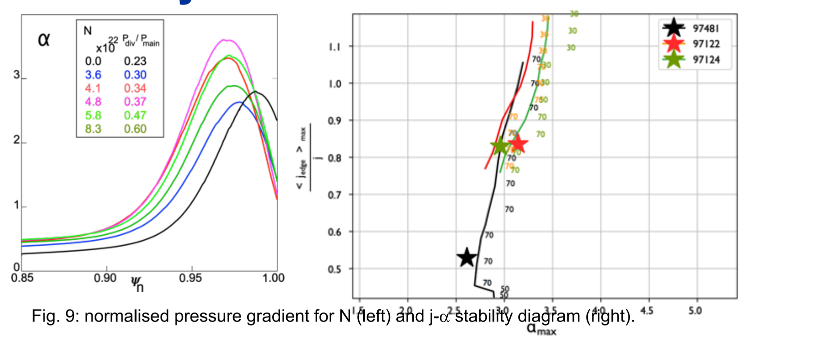


Fig. 9: normalised pressure gradient for N (left) and j-α stability diagram (right).

- For both Ne and N-seeded plasmas, an increase in pedestal width is observed (mostly due to the Te width)
- For N, the OP is close to the Peeling-Ballooning boundary and in the ballooning region of the j-α diagram.
- For Ne, α_{max} decreases with increasing Ne-gas rate. For moderate Ne-gas rate (1.6x10^{22} el.s^{-1}), OP is within 20% of the PB stability boundary, but above this Ne-gas rate, the OP moves further away from the PB boundary.

Power load reduction, radiation and SOLPS-ITER benchmark for ITER

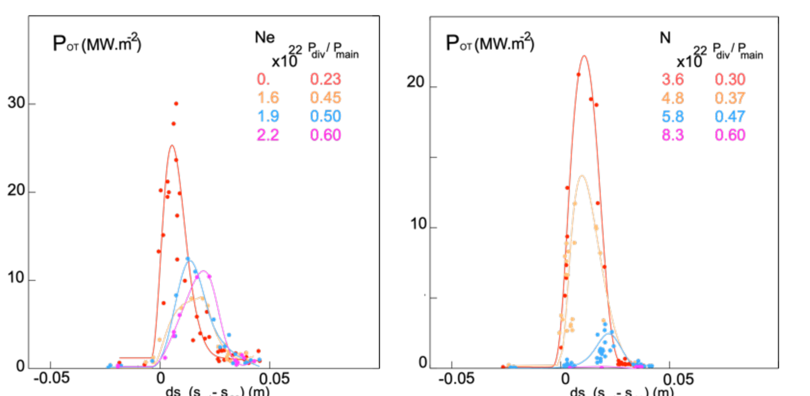


Fig.10: Power flux at outer target determined from Langmuir probes for increasing impurity seeding in Neon (left) and N (right). Seeding gas-rate and value of ratio P_{div}/P_{main} indicated on the graph.

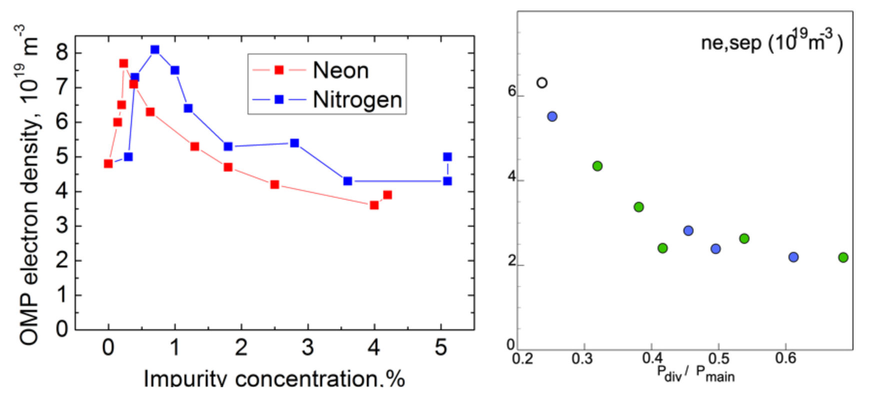


Fig 11: SOLPS-ITER separatrix density with increased impurity concentration at separatrix (left) for Ne and N-seeded plasmas. (Right) Measured separatrix density with increased ratio Pdiv/Pmain proxy for increased radiation of Ne (blue) and N(green) seeded plasmas.

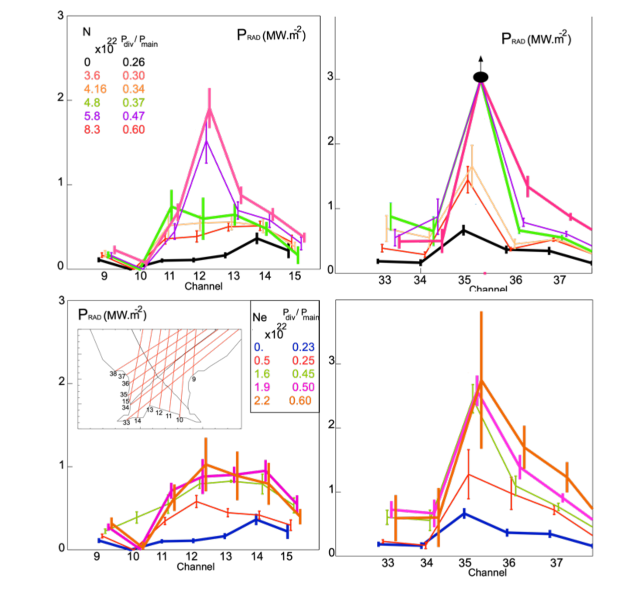


Fig 12: Measured vertical (left) and horizontal (right) divertor bolometry channels for N (top) and Ne (bottom) with contribution from core removed. Note the horizontal channel 35 became saturated for N (highlighted with black blob).

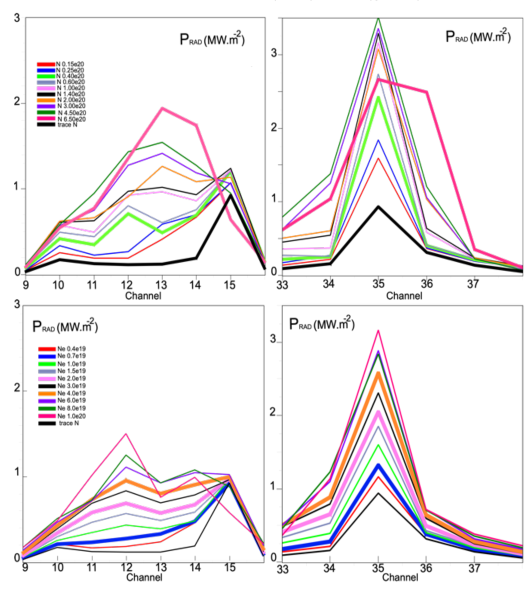


Fig 13: SOLPS-ITER vertical (left) and horizontal (right) divertor bolometry channels simulated data for N (top) and Ne (bottom)

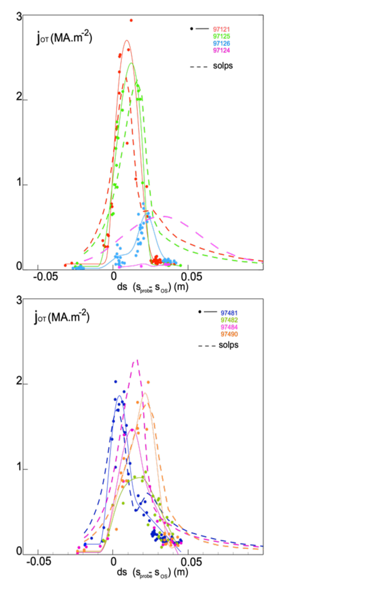


Fig 14: Measured saturation current at outer target for N (left) and Ne-seeded (right|) discharges (filled symbol-data, full line fit) and best match with SOLPS-ITER run (dashed line). Same color as used in Fig 12. and 13.

- N-seeding can lead to fully detached plasmas in inter-ELM period, whereas Ne-seeding only reduce the power load in the SP region so far (Fig10).
- N-radiation is more localised in the separatrix region than Ne (Fig.12)
- Benchmark with SOLPS-ITER of N and Ne-seeded plasmas on-going but already fairly good reproduction of radiation pattern, and saturation current (Fig 13 and 14) [6,7].
- Separatrix density decreases for both Ne and N as impurity content is increased in experiment, also observed in SOLPS-ITER (Fig. 11)

Conclusion

- JET has demonstrated for the first time that Ne-seeded plasmas are compatible with high-performance and can achieve higher normalized confinement and neutron rate than equivalent N-seeding plasmas.
- The decrease of electron pedestal density and rise in pedestal ion temperature is key in this improvement but improved core confinement also play a role via the increased ExB shearing rate, impurity content and higher ratio of T_i/T_e.
- Reduction of heat load is observed at the strike-point with neon; Full detachment obtained with N-seeding.
- ITER benchmark activities with SOLPS-ITER on Ne and N-seeded JET plasmas are underway [6,7].

References: [1] R.A. Pitts et al, Nuclear Materials and Energy 20 (2019) 100696 [2] C. Giroud et al., Plasma Phys. Control. Fusion 57 (2017) 035004 [3] C.Giroud EX/P5-25 IAEA 2014 [4] M. Bernert et al. Nuclear Materials and Energy 26 (2021) 100870 [5] M. Marin paper in [6] E. Kaveeva et al, PSI 2021 [7] V. Rozhansky IAEA 2021.

JET CCFE CULHAM CENTRE FOR FUSION ENERGY iter POLYTECH Peter the Great St.Petersburg Polytechnic University JÜLICH Forschungszentrum

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. The views and opinions expressed herein do not necessarily reflect those of the European Commission.