EUROfusion

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High-performance ELM-free semi-detached scenario sustained at high-current in JET DTE3

Carine Giroud on behalf of the JET-ITER Baseline Team

Eurofusion Consortium and UKAEA, Culham Campus, Abingdon OX14 3QB

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JET

UK Atomic Energy Authority

Co-authors

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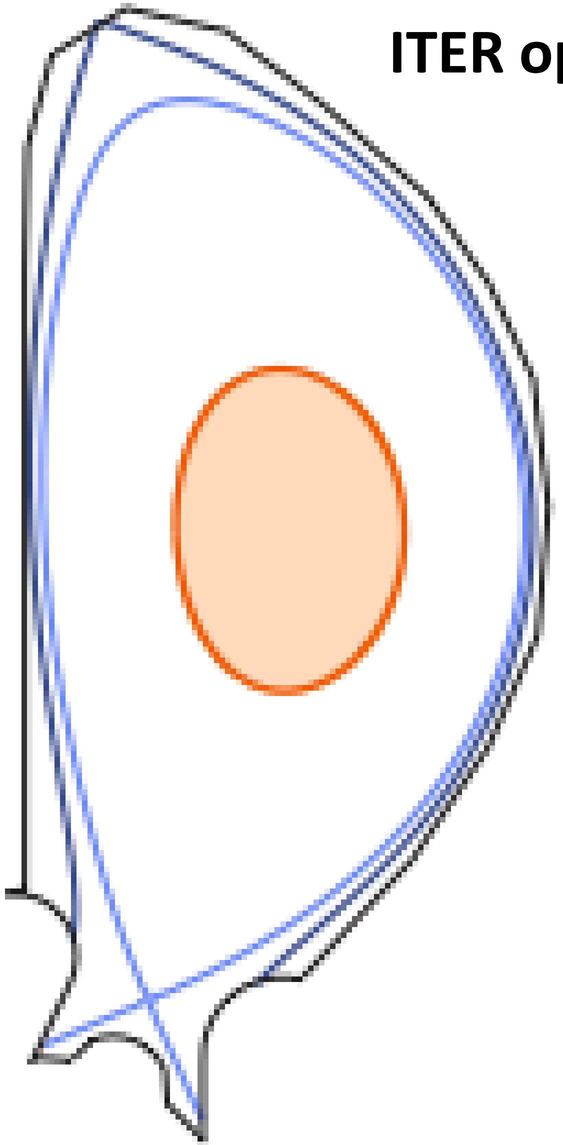
D.B. King[1], I.S. Carvalho[2], D. L. Keeling[1], L. Frassinetti[3], R. A. Pitts[2], G. Pucella[4], S. Wiesen[5], A. Kappatou[6], N. Vianello[7,16], M. Wischmeier[6], F. Rimini[1], M. Baruzzo[4,7], M. Maslov[1], M. Sos[8], X. Litaudon[9], R. B. Henriques[1], K. Kirov[1], C. Perez von Thun[10], H. J. Sun[1], P. Dumortier[11], E. Lerche[11], P. Jacquet[1], M. Lennholm[1], J. Mitchell[1], A. Parrott[1], J. Bernardo[1], M. Zerbini[4], I. Coffey[1,12], K. Collie[1], J. M.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], F. Eriksson[1], Z. Stancar[1], D. Taylor[1], E. Alessi[16], I. Balboa[1], A. Boboc[1], S. Bakes[1], M. Brix[1], E. De la Cal[13], P. Carvalho[1], A. Chomiczewska[10], J. Eriksson[15], Z. Ghani[1], E. Giovannozzi[4], J. Foster[1], A. Huber[17], J. Karhunen[18], 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], D. Moulton[1], M. Nocente[19], E. Pawelec[20], E. Pinto[13], D. Refy[21], P. Ryan[1], I. Voldiner[13], G. Sergienko[17], S. Silburn[1], G. Stankunas[22], C. Silva[23], 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[7,16], I. Borodkina[8], D. Fajardo[6], A. Fil[9], S. Gabriellini[1], L. Garzotti[1], S. Henderson[1], Q. Hu[16,19], P. Innocente[7], I. Ivanova-Stanik[10], A. Jarvinen[18], H. Kumpulainen[17], C. Leoni[24], J. Lombardo[7], P. Mantica[16], A. Mariani[16], M. Marin[26], A.H. Neilsen[27], H. Nystrom[3], M. O.Mullane[1], O. Pan[6], V. Parail[1], I. Predebon[7,16], S. Saarelma[1], J. Seidl[8], E.R. Solano[13], A. Stagni[7], A. Thrysoe[27], M. Valovic[1], A. Widdowson[1], V.K. Zotta[24], JET Contributors* and the EUROfusion Tokamak Exploitation Team** .

1 UK Atomic Energy Authority
2 iter
3 KTH Vetenskap och Konst
4 ENEA
5 DIFFER Dutch Institute for Fundamental Energy Research
6 Max Planck Institute for Plasma Physics
7 Consorzio RFX Ricerca Formazione Innovazione
8 IPP
9 cea
10 IFPiLM
11 ERM - KMS
13 Laboratorio Nacional de Fusión Ciemat
14 Università degli Studi di Padova
15 Uppsala Universitet
16 ISTP Istituto per la Scienza e Tecnologia dei Plasmi, Consiglio Nazionale delle Ricerche
17 Jülich Forschungszentrum
18 VTT
19 Università degli Studi di Milano Bicocca
20 UC
21 HUN REN Centre for Energy Research
22 Lietuvos Energetikos Institutas
23 ipfn Instituto de Plasmas e Fusão Nuclear
24 Sapienza Università di Roma
26 EPFL
27 DTU

Achieving an integrated scenario for ITER and future PP is complex



ITER operation at high fusion gain Q_{DT}=10 for 300-500s, 15MA, P_{SOL}≈100MW

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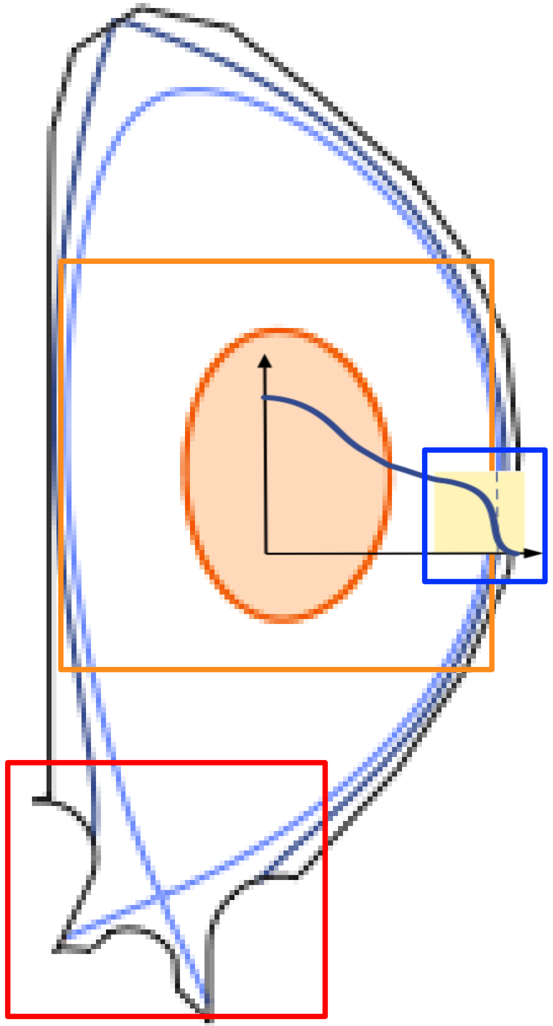

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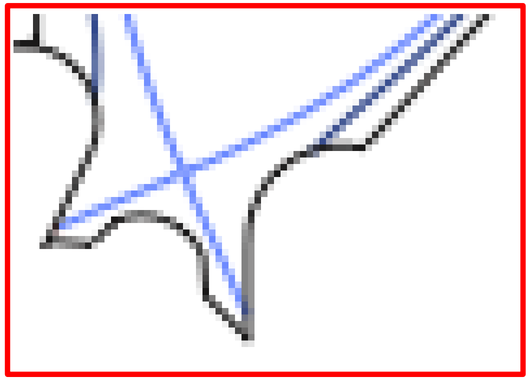
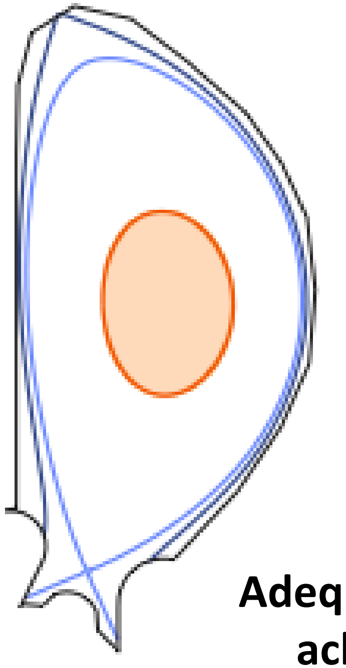
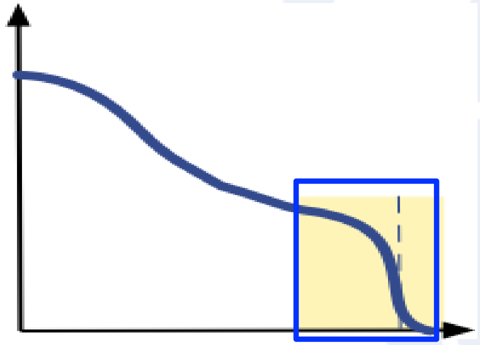
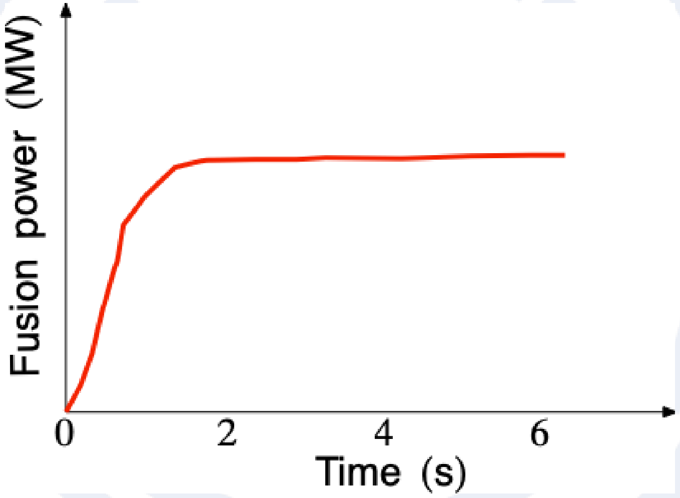








Maintain integrity of its PFCs:

- Stationary heat load < 10 $MW.m^{-2}$
- Use of extrinsic radiator, low-Z impurity (Ne)
- partial detached divertor state

Adequate plasma performance to achieve burning plasma goals

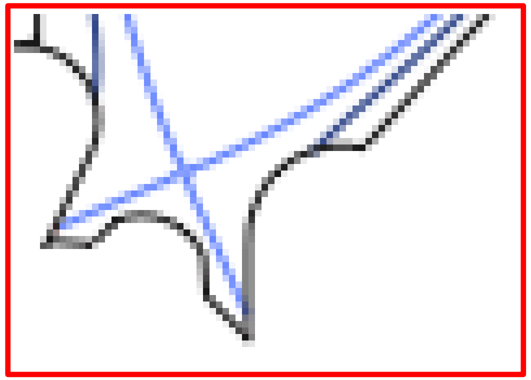
Achieving an integrated scenario for ITER and future PP is complex

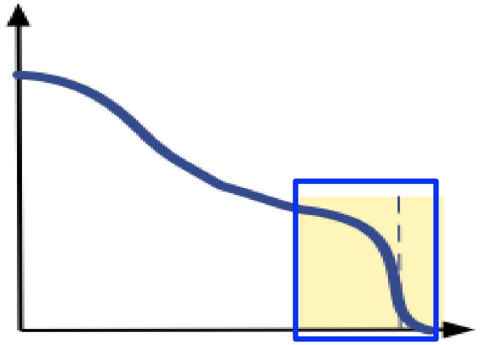
ITER operation at high fusion gain Q_{DT}=10 for 300-500s, 15MA, P_{SOL}≈100MW

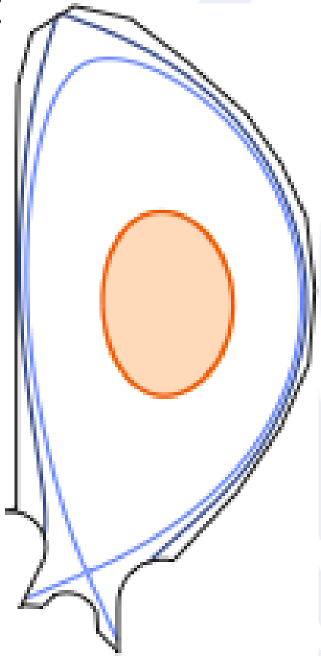
EXPECTATION

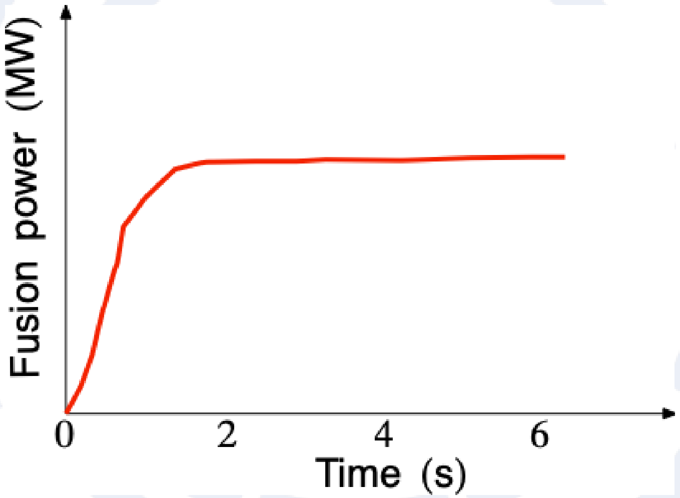
high divertor radiation cools pedestal

Detrimental cost to the energy confinement and fusion power









Achieving an integrated scenario for ITER and future PP is complex

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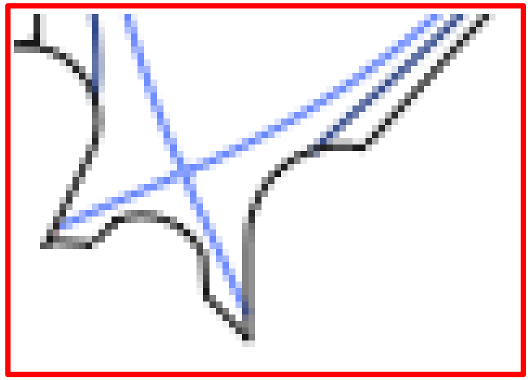
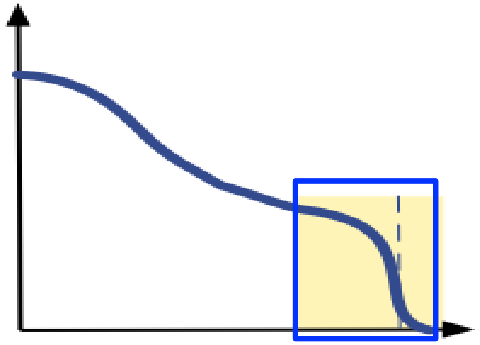
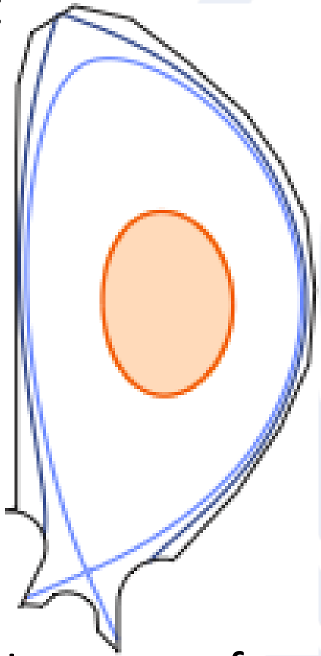
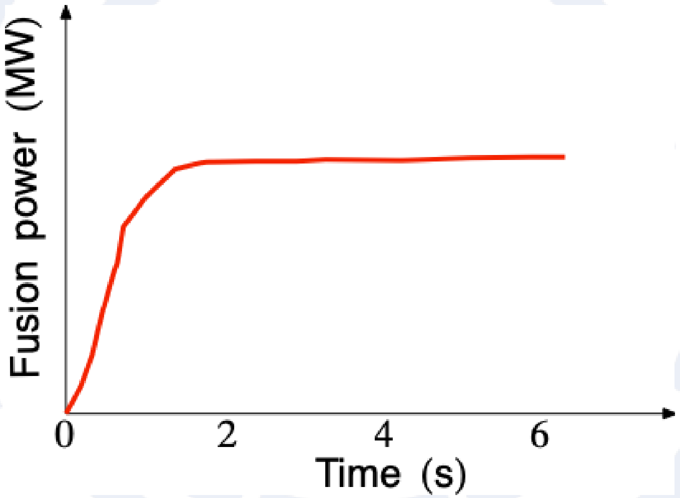








OPTIMUM

seed impurity would increase the divertor radiation

increase the pedestal pressure and temperature

Increase of confinement and fusion power

small ELM or ELM-free plasma desirable to minimize high-Z impurity source and achieve stationary conditions

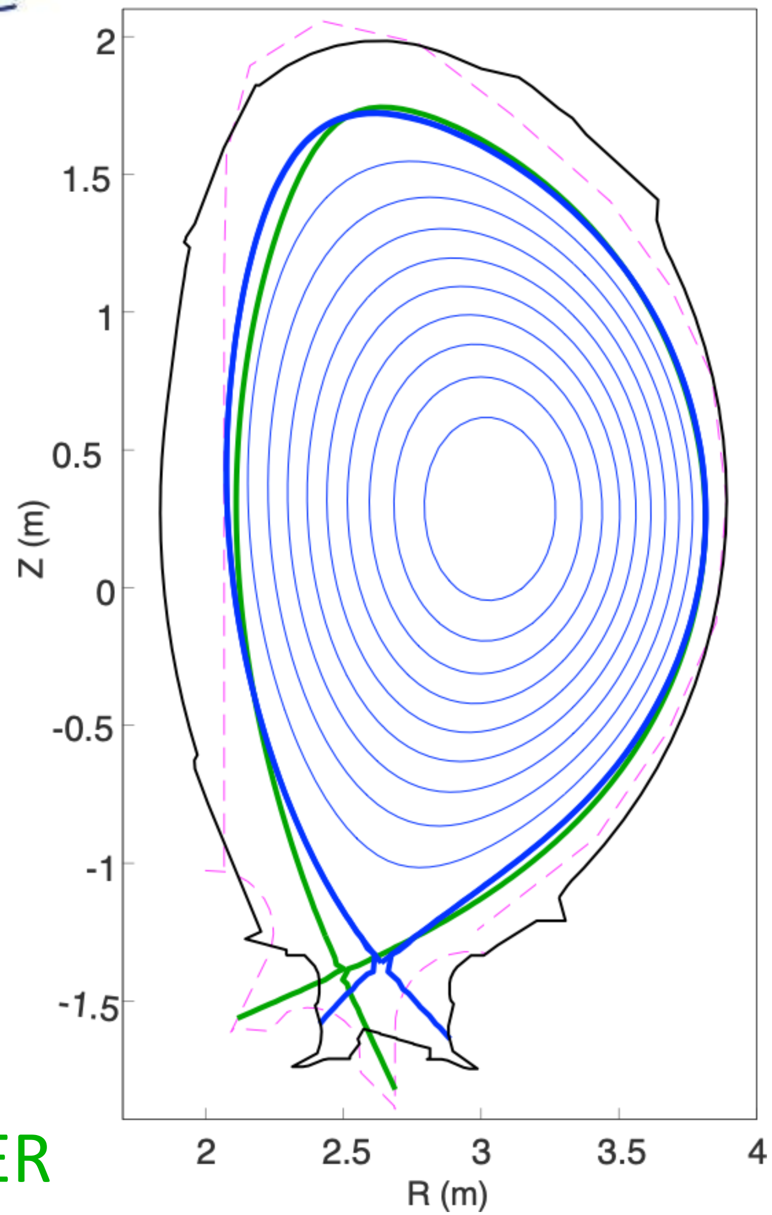
Outline of the talk

JET

- Neon-Seeded JET-ITER Baseline: Advancing Core-Edge integration for ITER
- Exploring Plasma Response and Operational Space with Neon Seeding Near the L-H Power Threshold
- Identifying the Underlying Physics Driving Performance

The JET ITER baseline scenario

JET



ITER

High-triangularity δ_{av}= 0.35-0.38

Divertor configuration closer to ITER divertor

Partial detachment with extrinsic impurity (Ne)

Investigate core-edge-SOL integration

Exhaust (imp) , Pedestal, Confinement, Stationarity

2.5MA to 3.2MA: q_{95}=2.7-3.3

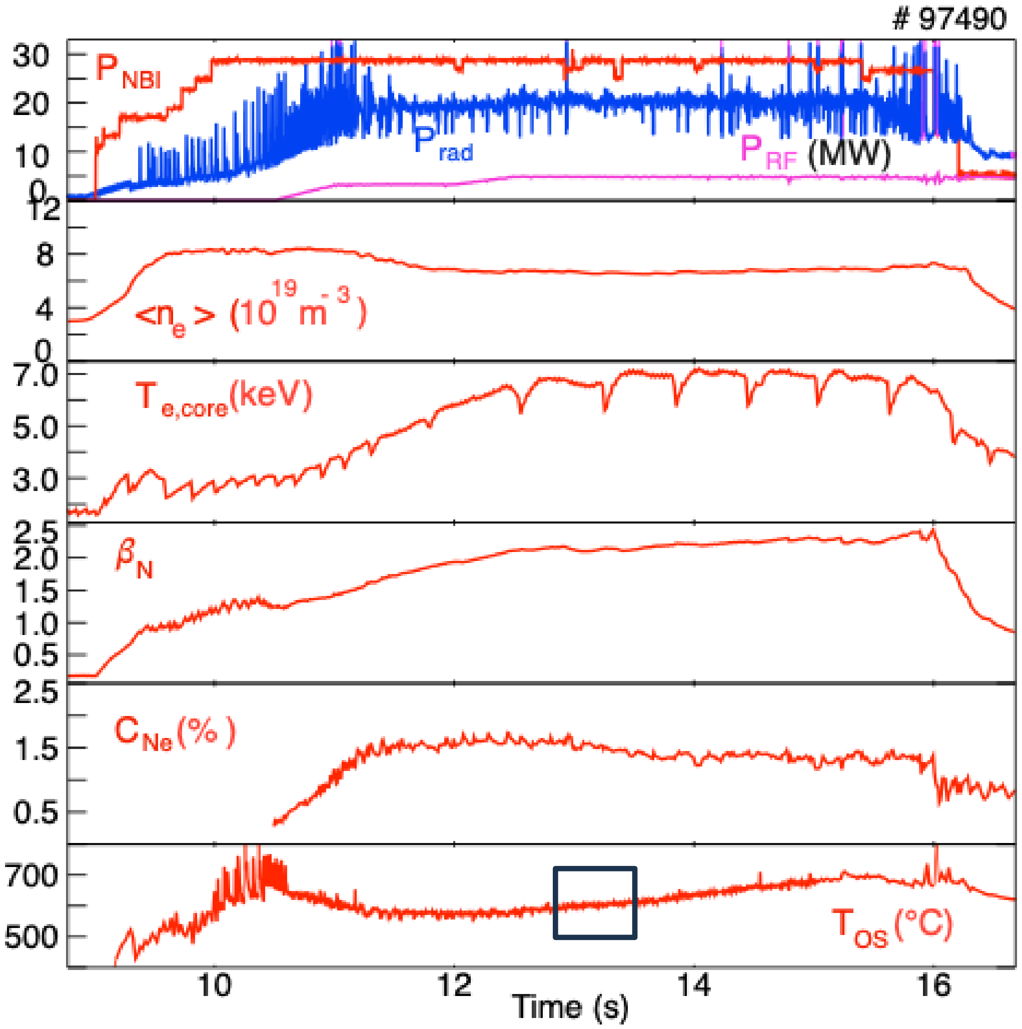
High power P_{nbi}=28-32MW P_{rf}=5MW

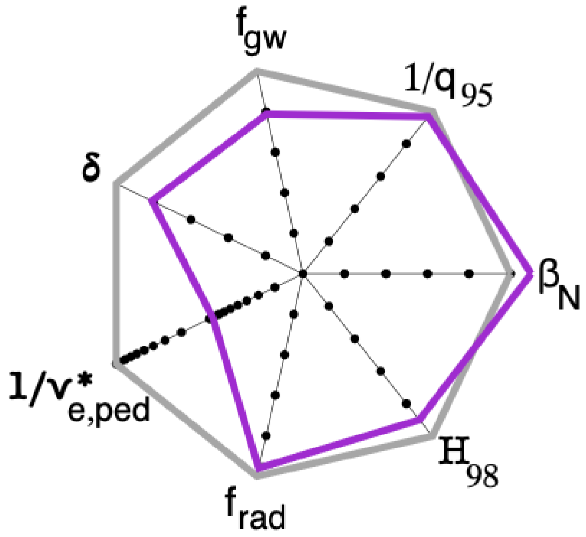
D-D and D-T

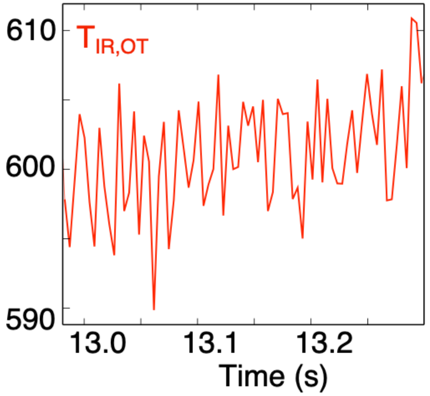
No detachment control scheme applied

First demonstration of integrated ELM-free high-performance Neon-seeded plasma at JET

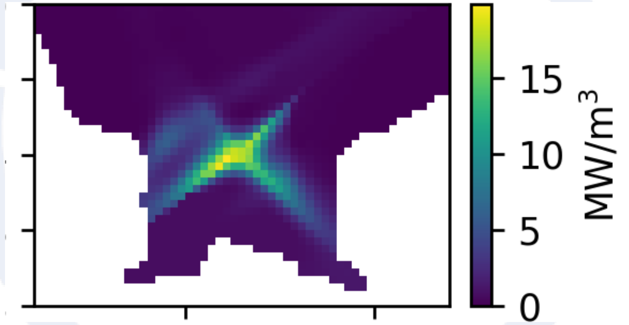
D-D operation 2.5MA/2.7T







ITER	#97490
$H_{98(y,2)}$=1	$H_{98(y,2)}$ =0.9
f_{GW}=0.85	f_{GW}=0.68
β_N=1.8	β_N=2.2
Z_{eff}=1.8	Z_{eff}=2.7
v^*_{ped} = 0.06	v^*_{ped} = 0.6
	$P_{sep}/P_{LH,Martin}$< 2



V Svoboda

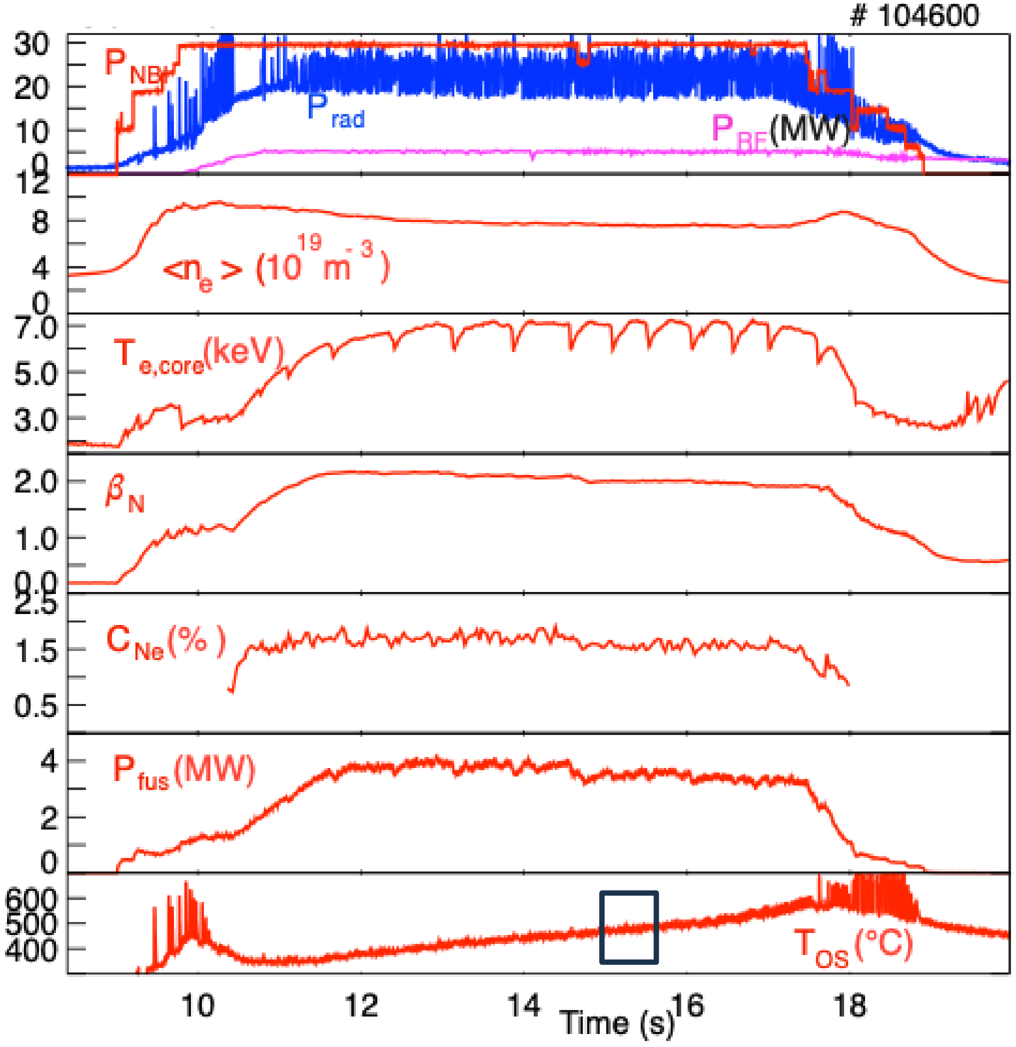
$T_{e,OT}$ < 5 eV

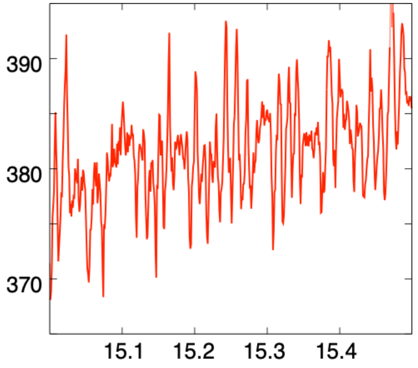
Transfer from D to D-T was straightforward.

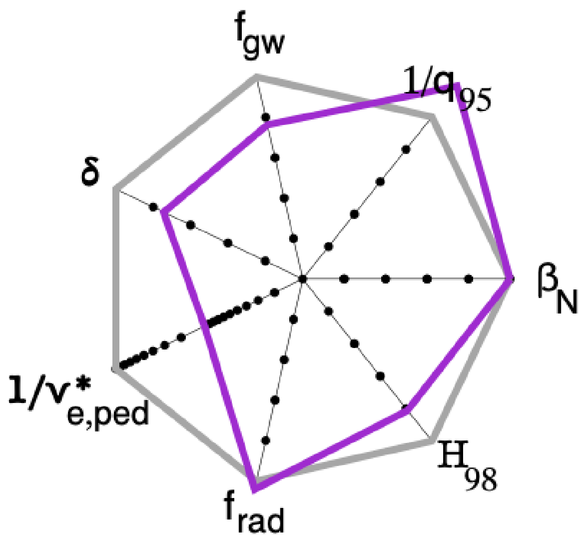
F_{rad} corrected to achieve energy balance

Successfully achieved in D-T at 3MA

D-T operation 3.0MA/2.9T

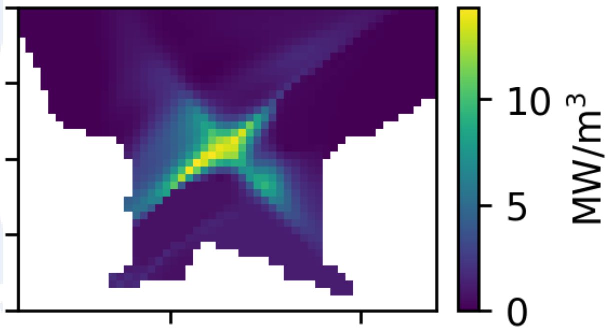






#104600

$H_{98(y,2)}$ =0.85
f_{GW}=0.68
β_N=2.0
Z_{eff}=3.2
$\nu^*_{e,ped}$ = 0.5



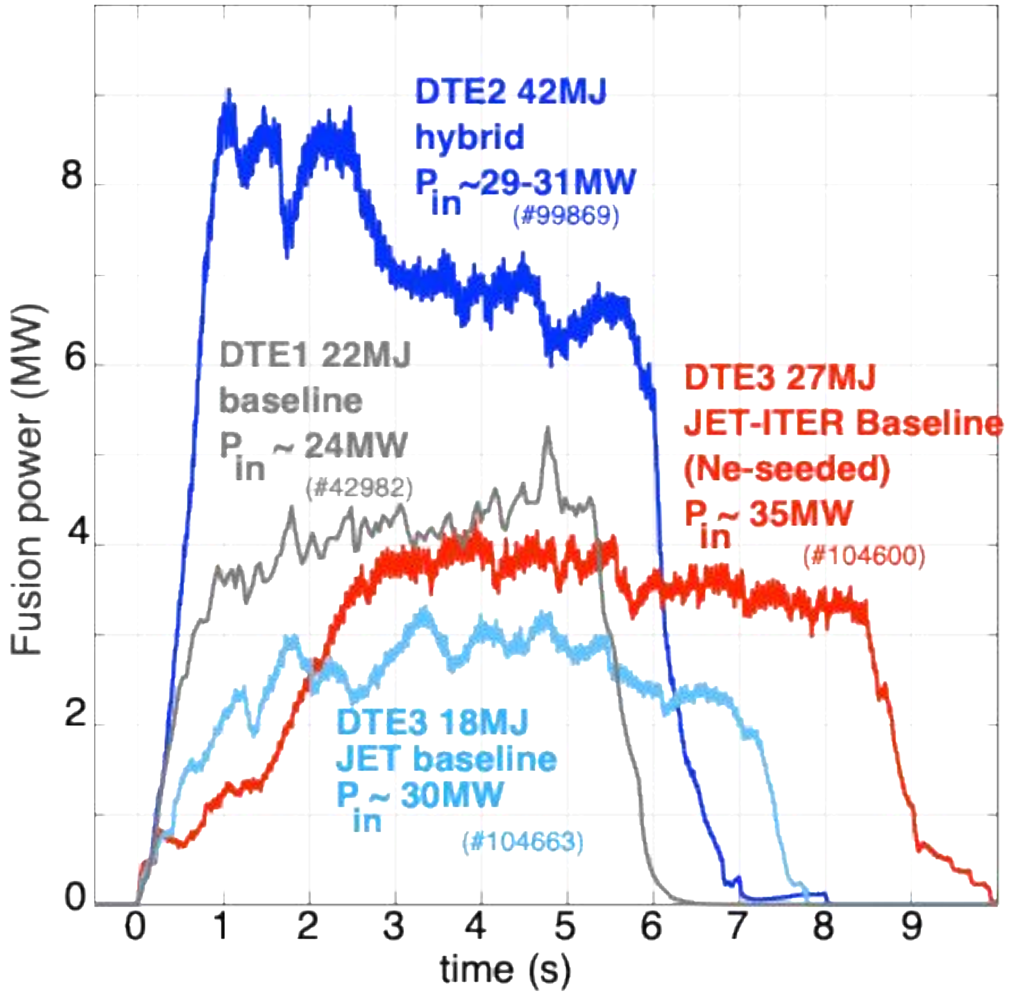
V Svoboda

$T_{e,OT}$ < 5 eV

Best performance DT-seeded plasmas and achieved very long pulse (7.4s NBI at 30MW) **P_{fus} = 4MW**

Stationary 3MA Ne-seeded plasma reaches P_{fusion} = 4MW

JET



- Stationary plasma with fusion energy 27MJ (DTE1 22MJ)
- No time allocated to improve performance
- D-NBI beam led to D-T mix $n_T/(n_D+n_T) <0.5$ *
- about 1/3 of neutron rate from thermal reaction

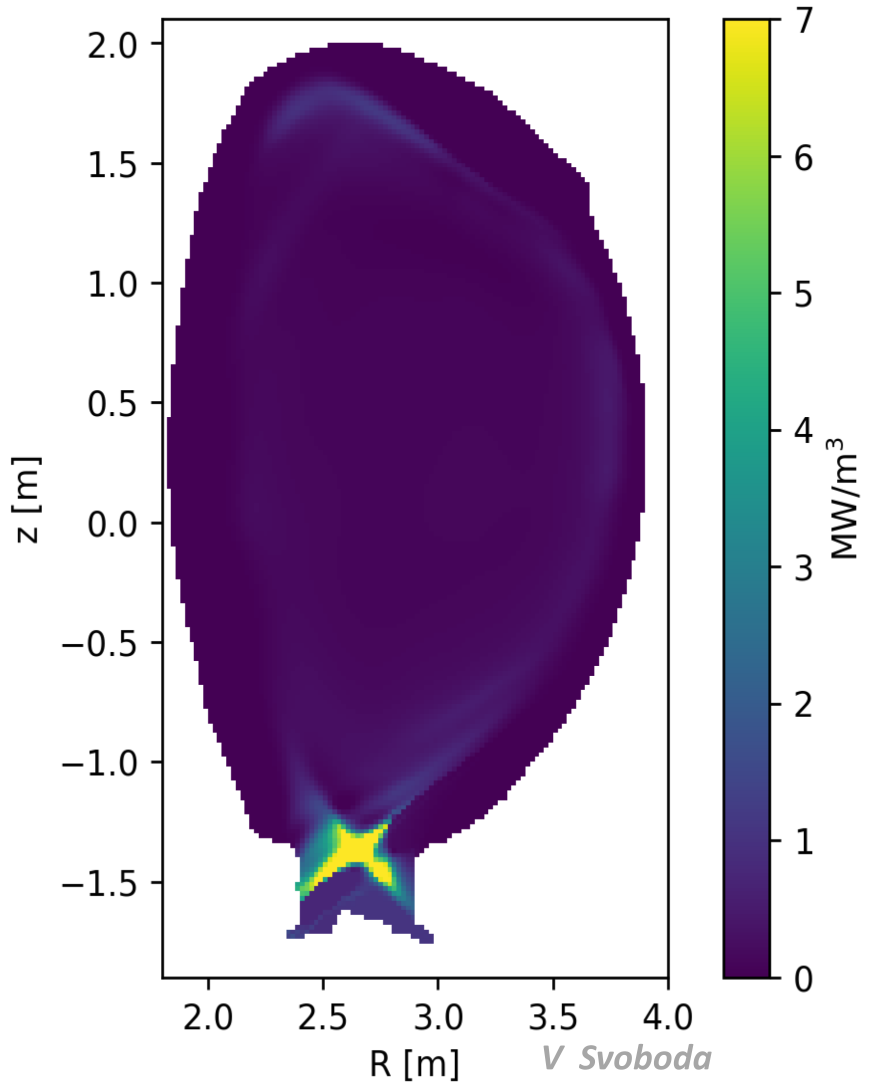
*Lombardo J. Nucl. Fusion 65 (2025) 096009

F.Auriemma, V. Zotta, S. Gabriellini, M. Poradzinski, J. Eriksson, M. Nocente

W content remains low in ELM-free JET-ITER baseline plasmas

JET

#104600. $C_W < 1e\text{-}4$



V Svoboda

- Ne impurities dominate W sputtering in D-D and D-T operation
- No W screening in pedestal.

D. Fajardo *et al* TH/8 EX/9

- Indication of excellent divertor screening due to main ion flow : first ER02.0 results

H. Kumpulainen *et al* TH/8 EX/9

Outline of the talk

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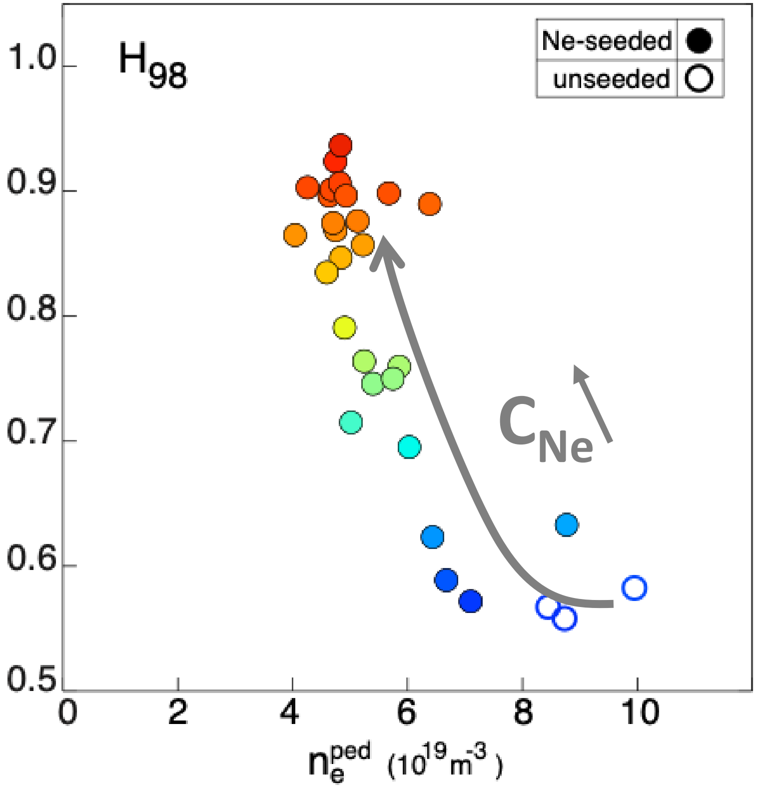
- Exploring Plasma Response and Operational Space with Neon Seeding Near the L-H Power Threshold
- Identifying the Underlying Physics Driving Performance

Confinement improves as Neon increased and $n_{e,ped}$ decreases

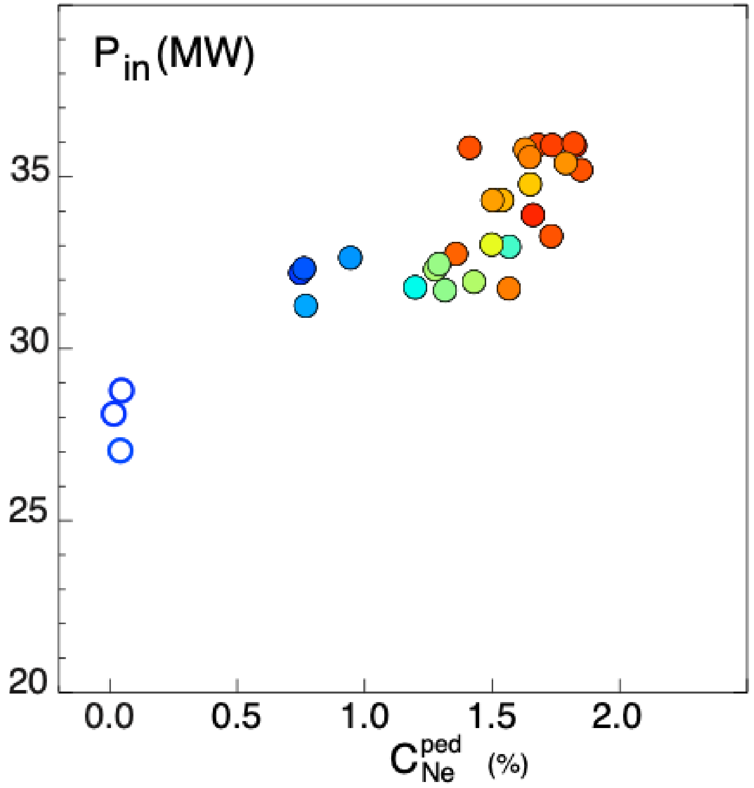
JET

2.5MA Γ_D=3.5-4.5x10^{22} el.s^{-1}

Same trend applies for neutron rate



Color of symbol related to H98 value



High performance plasmas are at high neon concentration (C_{Ne} > 1.3%) and high power

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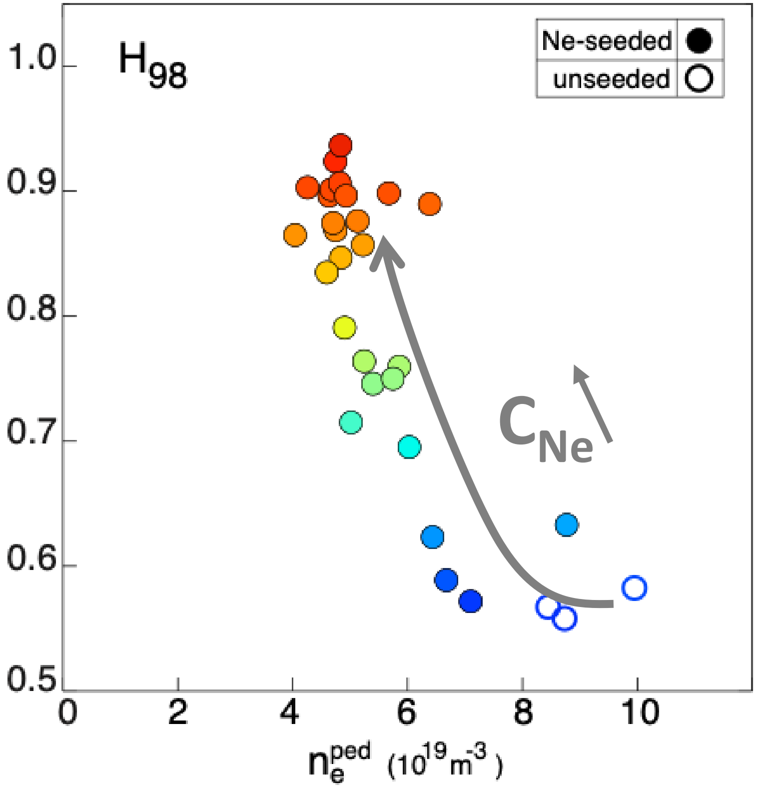

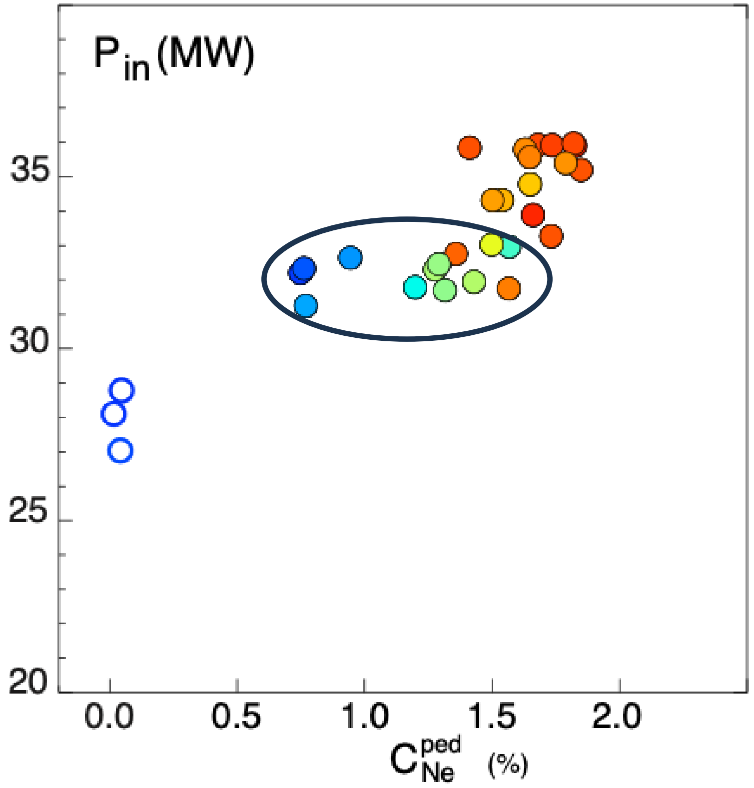

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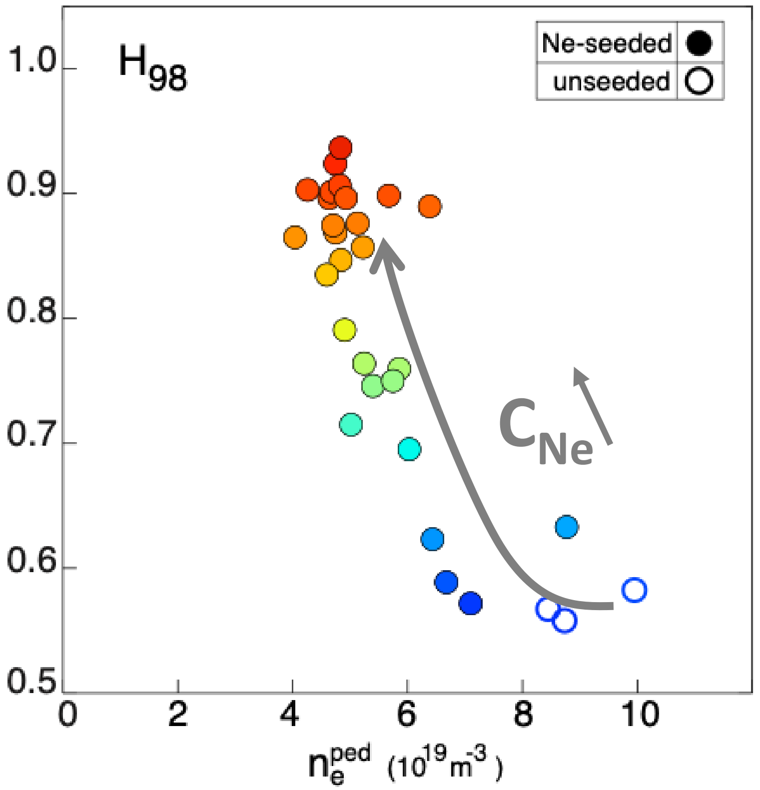

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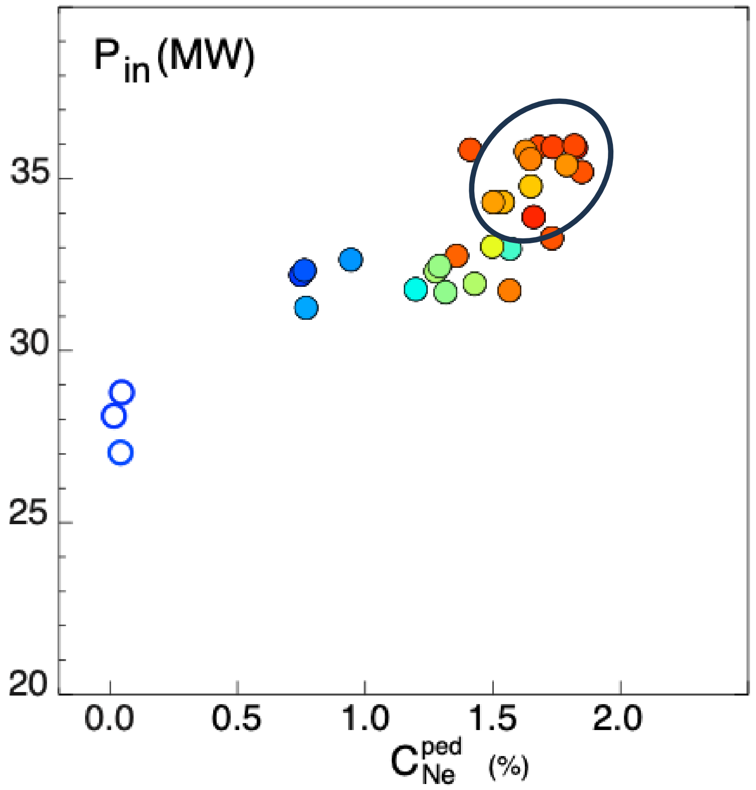

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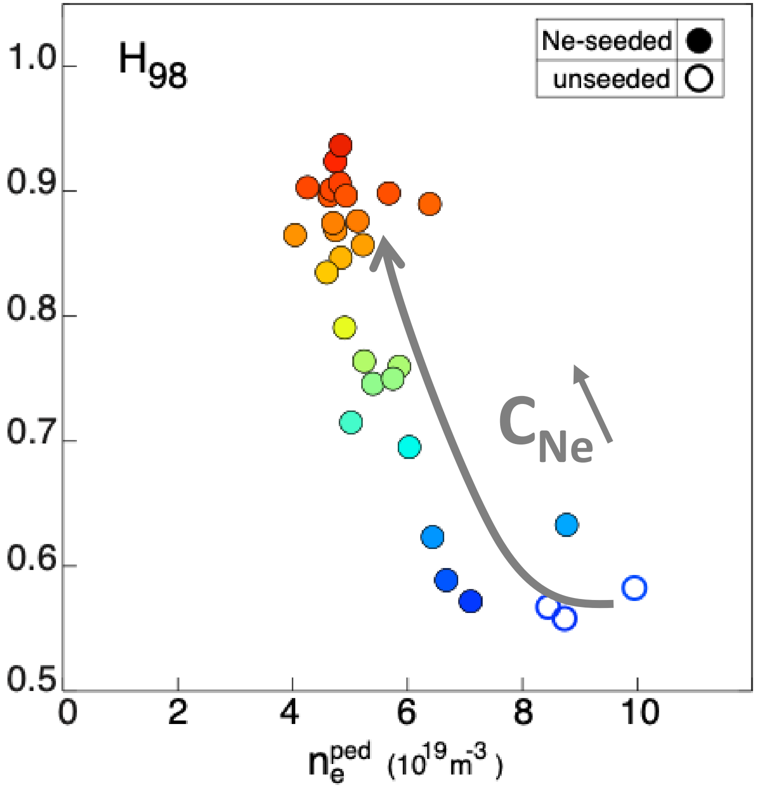

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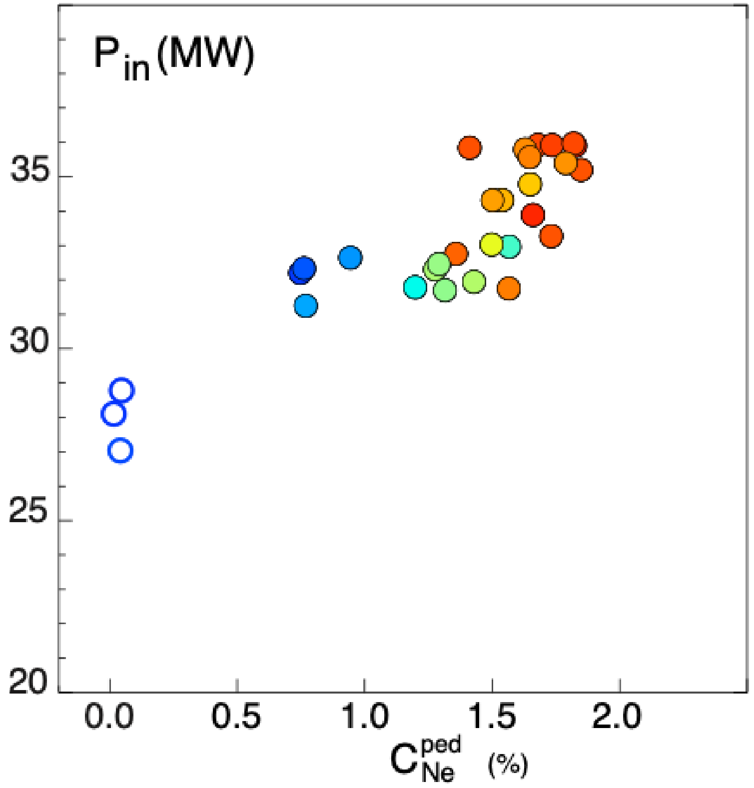
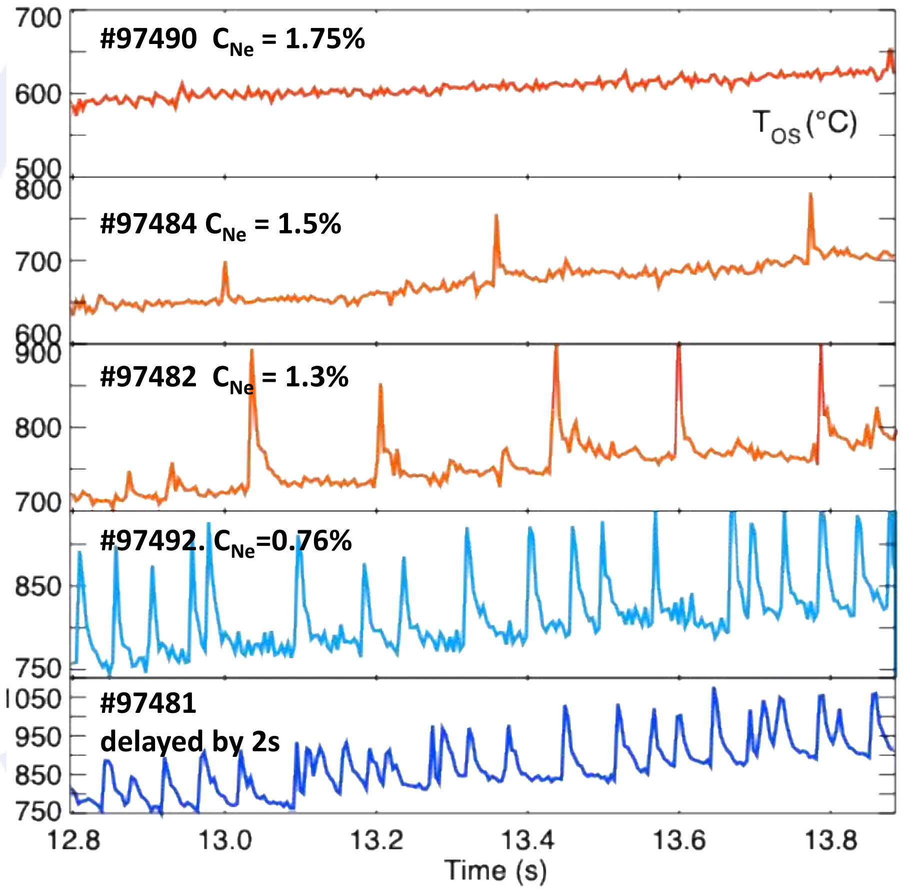


Reduction of ELMs as C_{Ne} increases



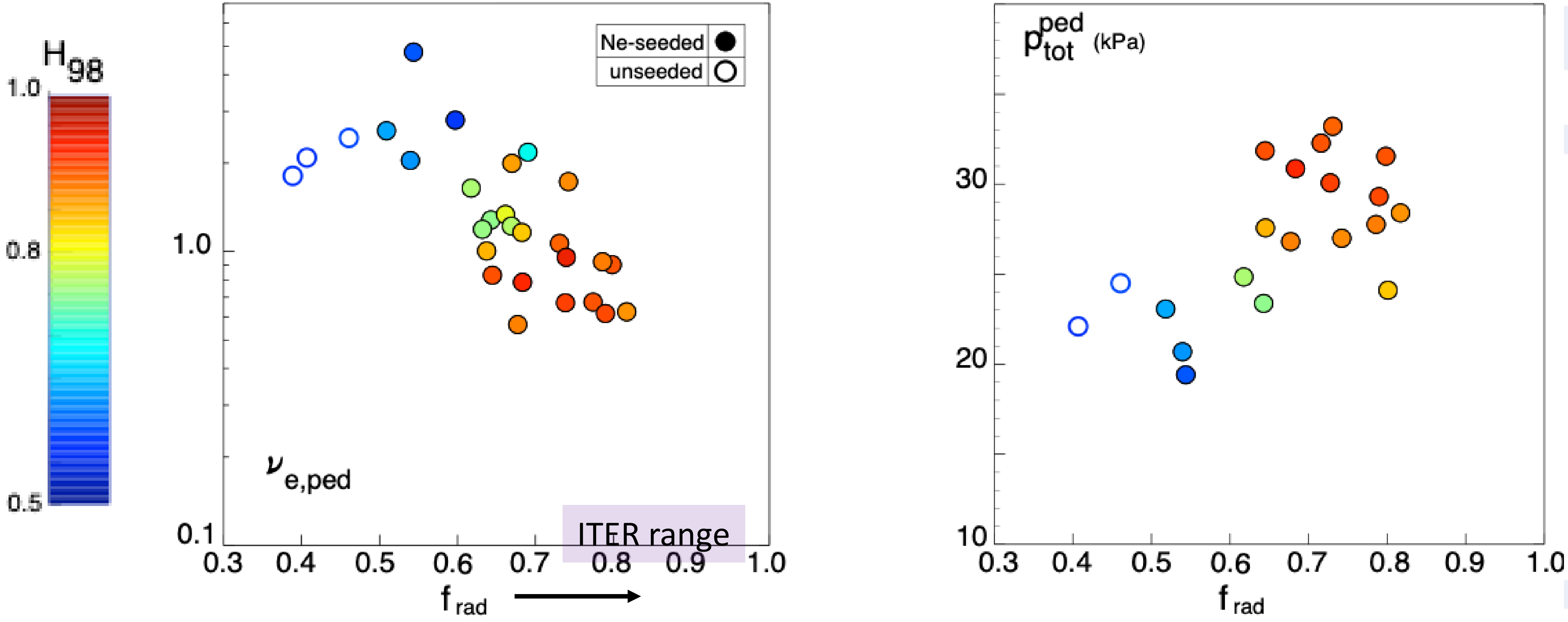
High performance plasmas are at high neon concentration (C_{Ne} > 1.3%) and high power

High-confinement correlates with pedestal pressure increase

JET

2.5MA Γ_D=3.5-4.5x10^{22} el.s^{-1}

$P_{sep}/P_{LH,Martin} \leq 2$



Partial detachment

Core density peaking insufficient, confinement improvement stems from increased pedestal pressure

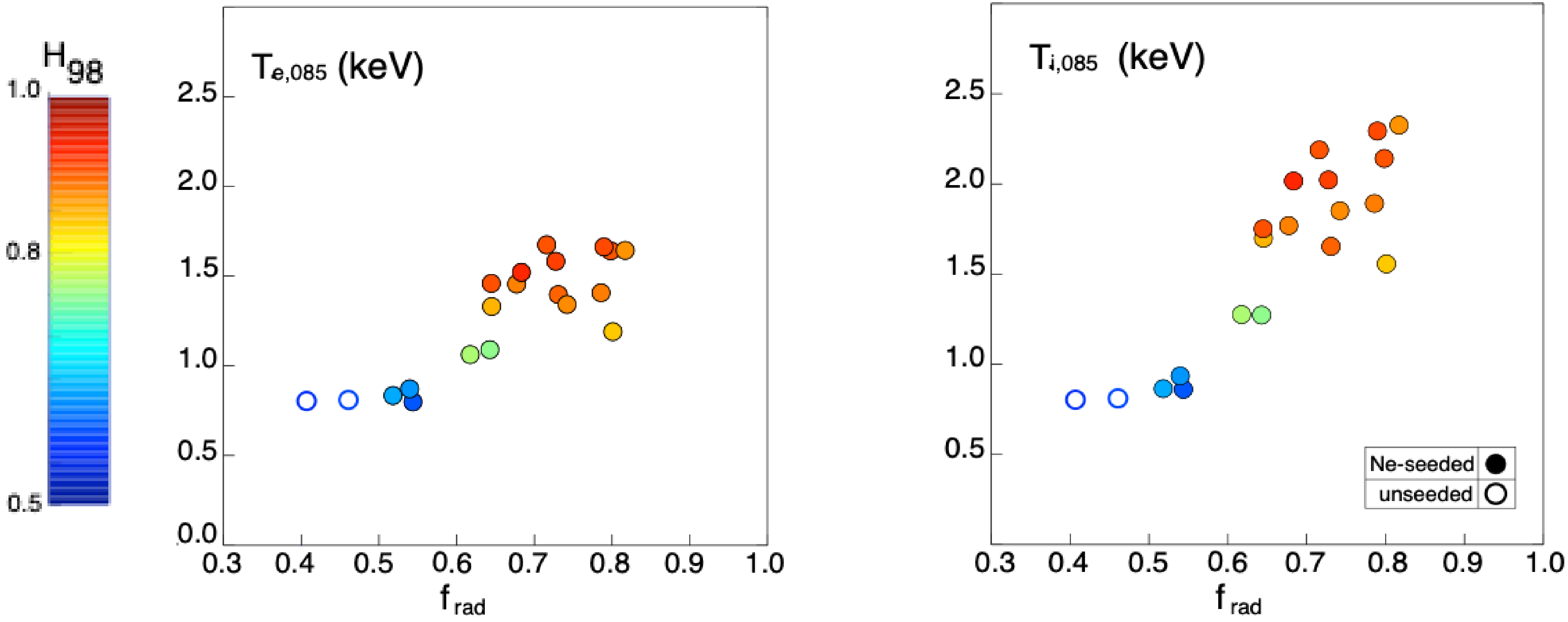
Supported by JINTRAC core integrated modelling with QuaLiKiZ and TGLF

C. Leoni, V. Zotta, Q. Hu, M. Marin

Pedestal pressure increases due to plasma temperature

JET

2.5MA Γ_D=3.5-4.5x10^{22} el.s^{-1}

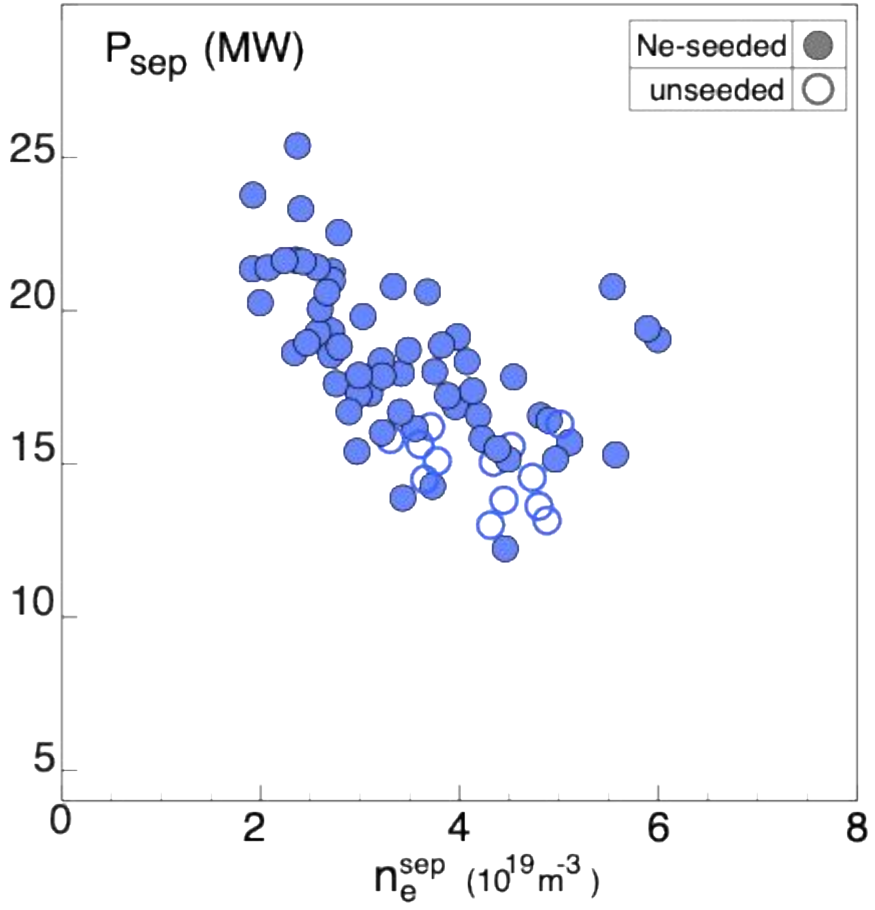


Increase of pedestal T_i/T_e from 1 to 1.5 as C_{Ne} increased

Pedestal pressure widens and pedestal density gradient lowers

Access to ELM-free high-performance regime

2.5MA all gas-rate (Γ_D=1.5-6.0 x10^{22} el.s^{-1})
D-D operation



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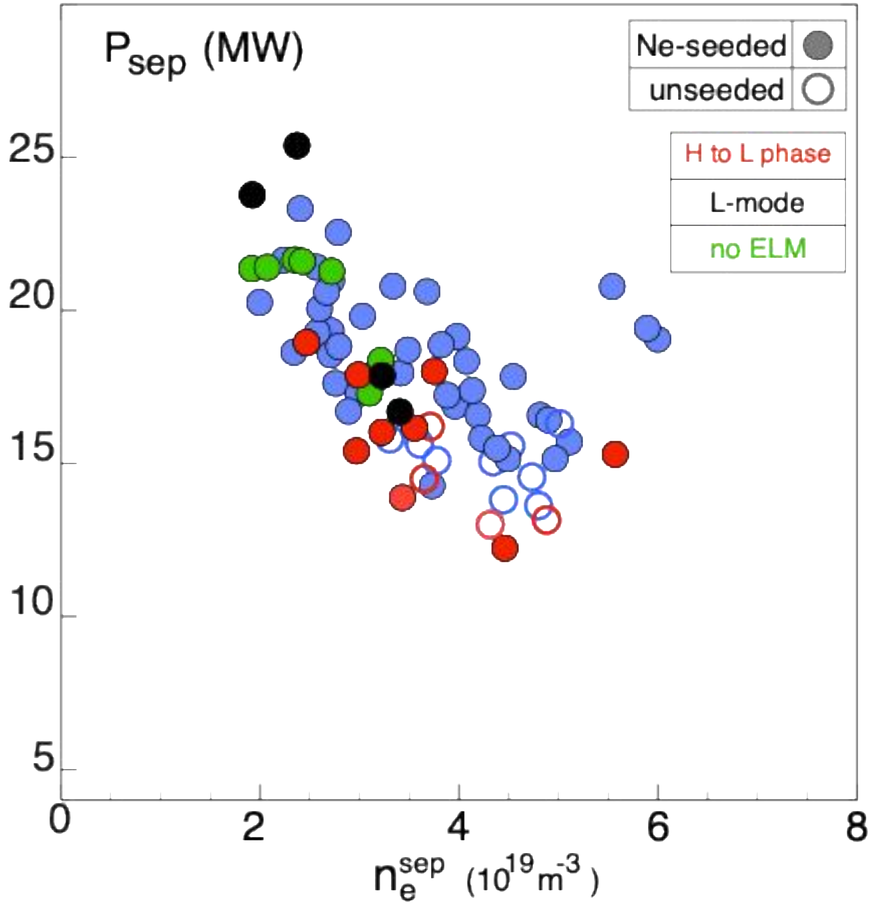

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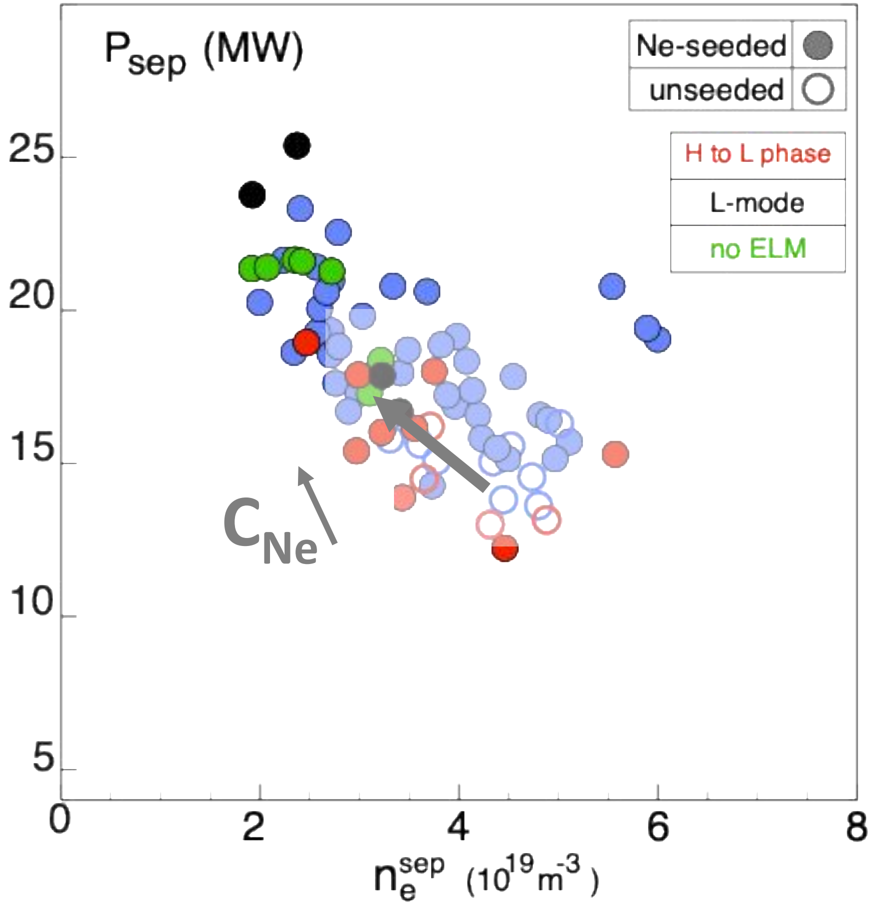

- From unseeded, P_{sep} needs to be high enough to avoid hard H to L-transition

Access to ELM-free high-performance regime

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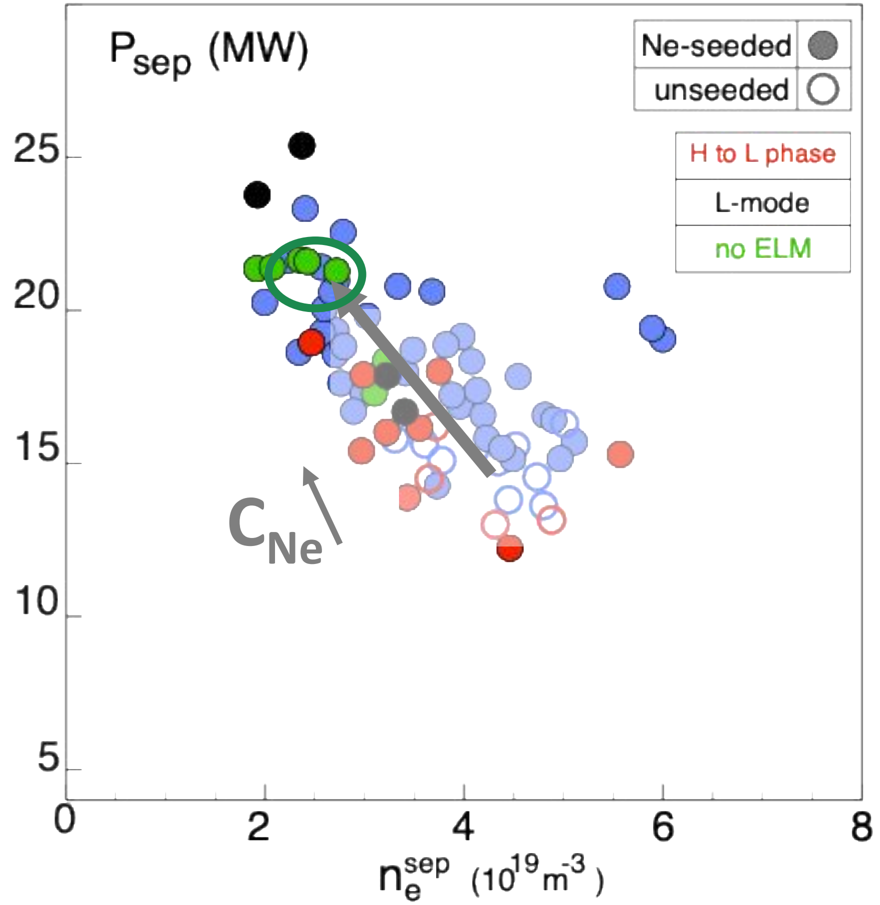

- From unseeded, P_{sep} needs to be high enough to avoid hard H to L-transition
- No-ELM domain exists at low $n_{e,sep}$= 2-3 x10^{19} m^{-3}

Access to ELM-free high-performance regime P_{sep}/P_{LH} ≥1.25

JET

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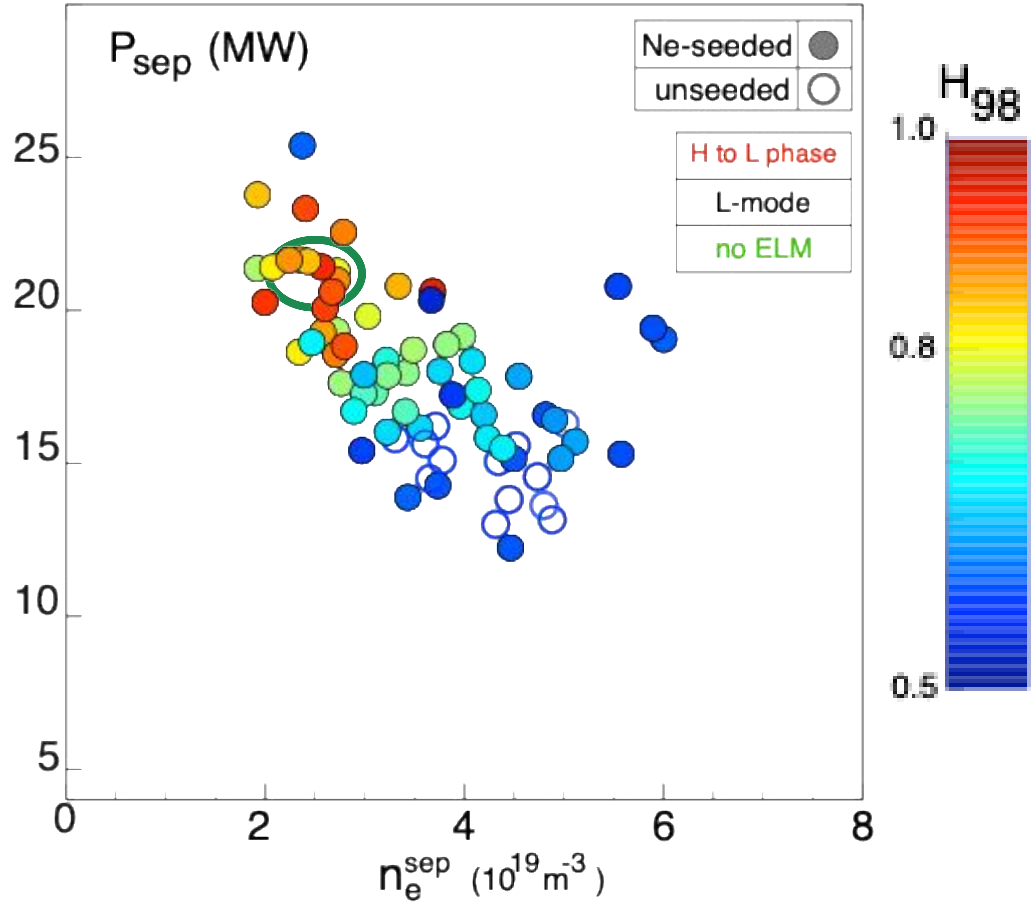
D-D operation

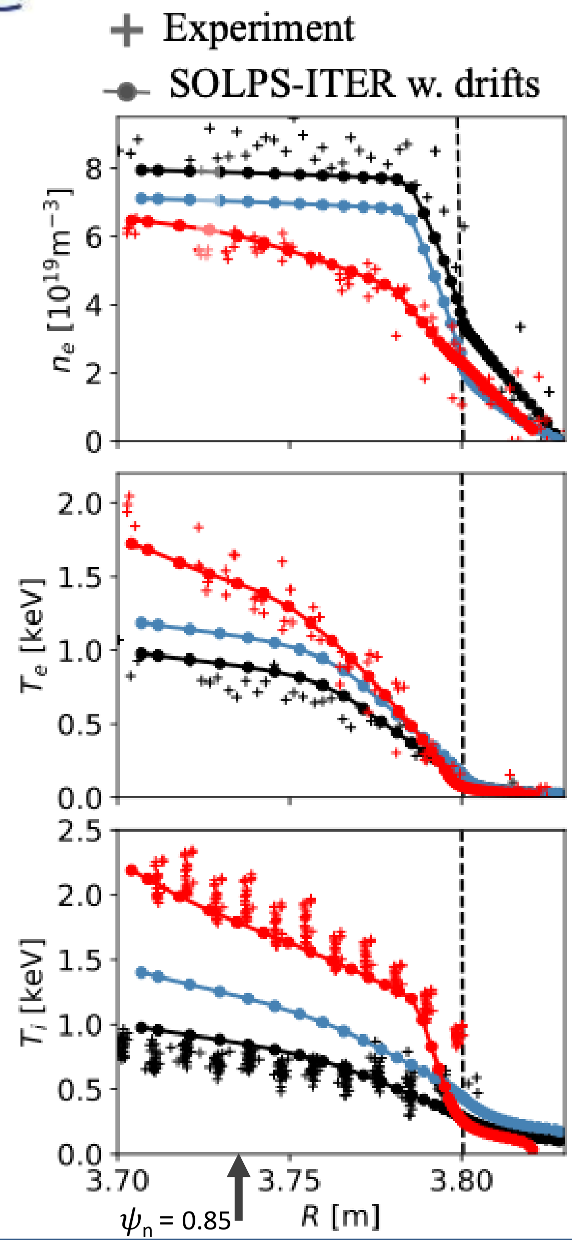


- From unseeded, P_{sep} needs to be high enough to avoid hard H to L-transition
- No-ELM domain exists at low $n_{e,sep}$= 2-3 x10^{19} m^{-3}
- No-ELM domain at high confinement is at:
  - low $n_{e,sep}$= 2-2.5x10^{19} m^{-3}
  - P_{sep}/P_{LH} ≥1.25 (high C_{Ne} and enough power)
- 20% reduction in P_{LH} threshold in D-T opens access to high-performance 3MA plasmas

Outline of the talk

- Neon-Seeded JET-ITER Baseline: Advancing Core-Edge integration for ITER
- Exploring Plasma Response and Operational Space with Neon Seeding Near the L-H Power Threshold
- Identifying the Underlying Physics Driving Performance
  - What mechanisms reduce the ELM size ?
  - Why does the density decrease with neon seeding ?
  - How can we achieve density control without ELM ?

Is the decrease of $n_{e,sep}$ & $n_{e,ped}$ with Neon due to SOL and divertor?



Case 1: unseeded

Case 2 : C_{Ne} = 1.6 %

Case 3: Transport of unseeded + Γ_{ne} (as in case 2)

From unseeded, with no change of transport assumption in divertor, SOL or pedestal, adding Γ_{Ne} as in exp:

- $n_{e,sep}$ drop from **3.8** to 2.6x10^{19} m^{-3} as in exp. (drop S_0)
- $n_{e,ped}$ drops by 10% instead of a 30% seen exp.

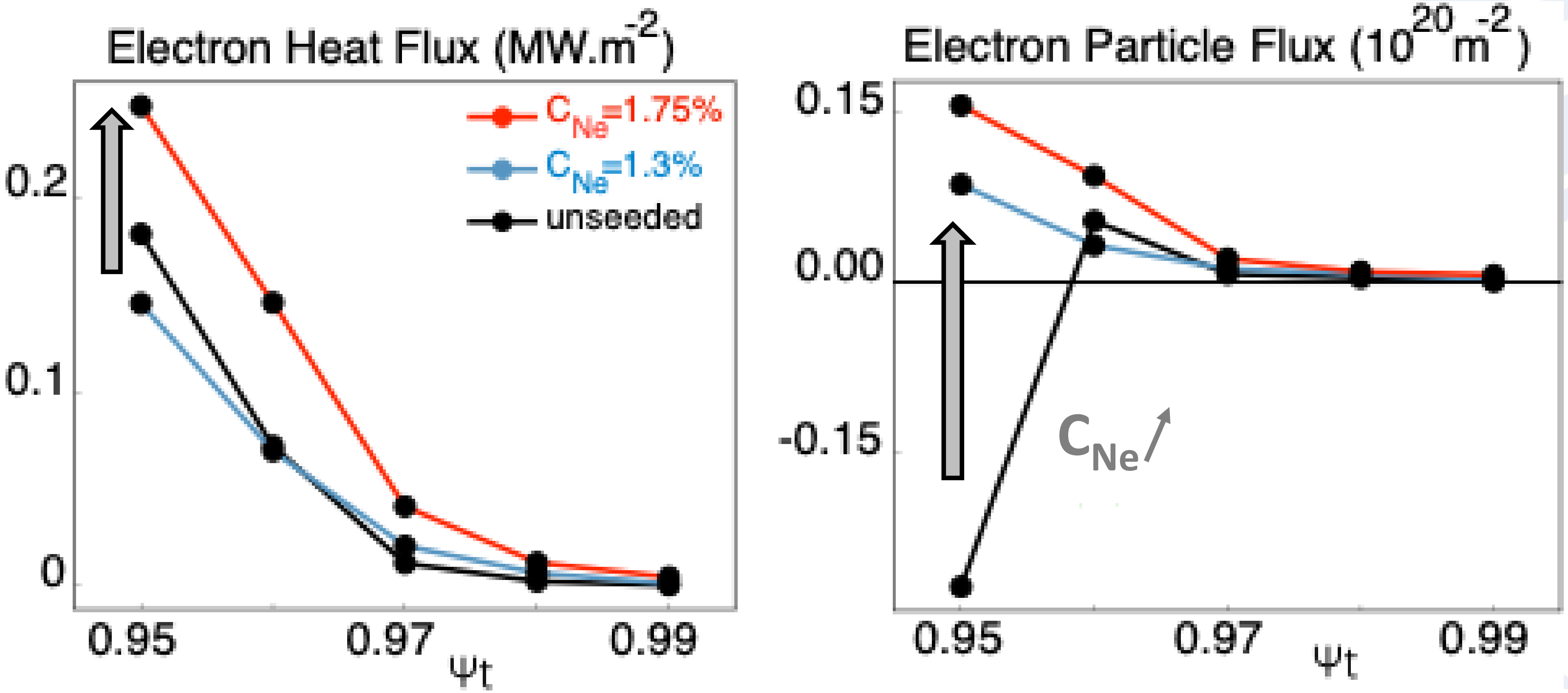
➔ Pedestal transport must change (in addition to $n_{e,sep}$) to account for $n_{e,ped}$ decrease

Similar results from SOLEDGE, EDGE2D-EIRENE

O Pan, P. Innocente, A. Jarvinen

ETG turbulent transport dominant in Ne-seeded pedestal, with particle flux reversal from unseeded to Ne-seeded

JET



(GENE, local, with 3 particle species)

- **Total heat transport increases at high C_{Ne} :** increased T_i/T_e destabilises ETG modes and stabilises ITG modes
- **Possible particle flux reversal from unseeded to seeded :** low T_i/T_e at low seeding
  - inward particle flux at the pedestal top due to low wavenumber turbulence
  - compatible with higher pedestal density

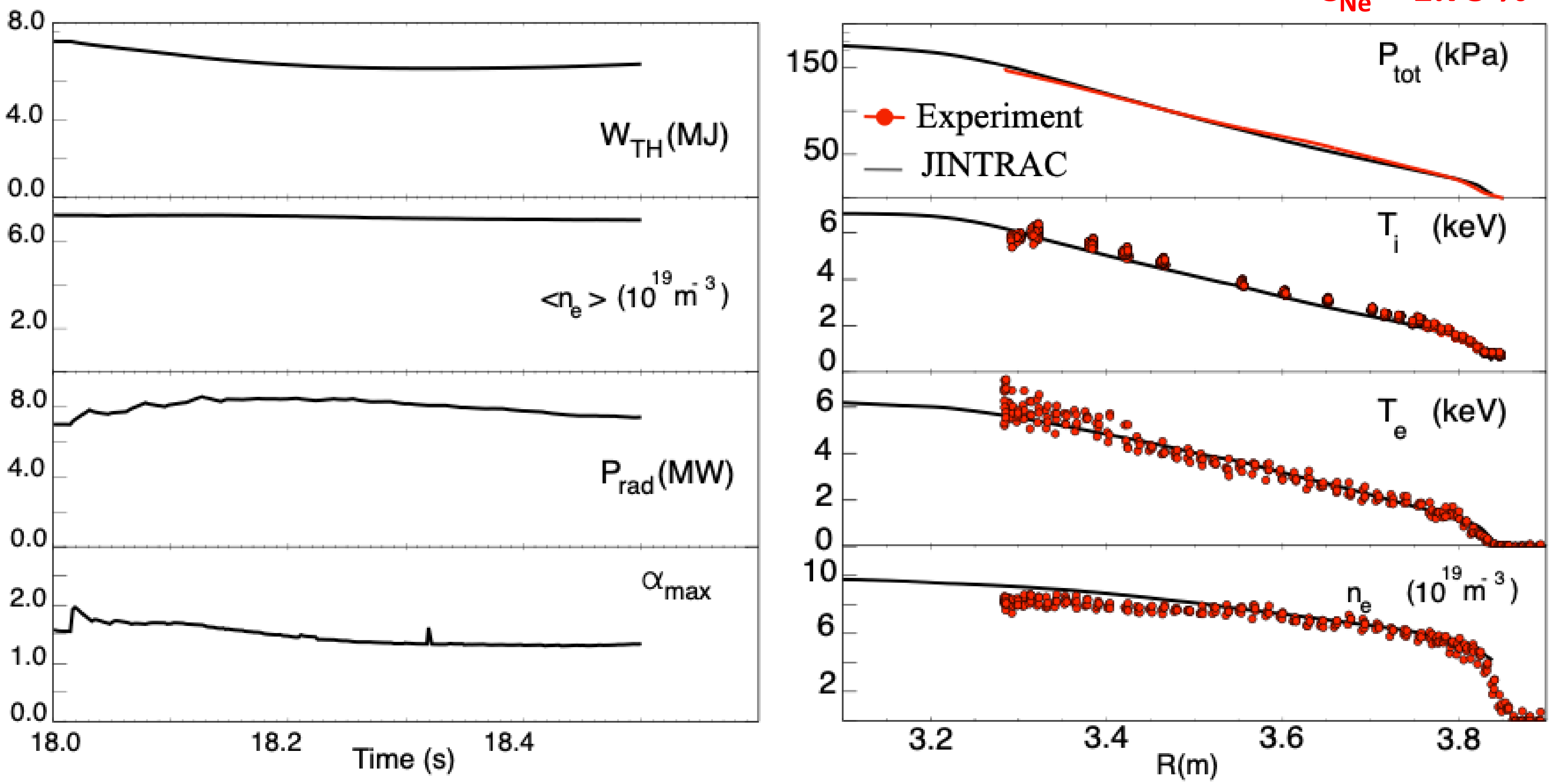
Local and global simulations in process to quantify the latter point

I. Predebon, A. Mariani, M. Marin, M. Dicorato

Integrated modeling used to test understanding of key experimental results : profile and time evolution

JET

C_{Ne} = 1.75 %



JINTRAC-COCONUT

- Standard EDGE2D-EIRENE settings
- QuaLiKiZ for anomalous transport core and pedestal (ETG transport coeff ~ GENE)

- Stationary conditions can be obtained with wider pedestal (as in exp.)
- Compatible with ELM-free conditions and high performance

V. Parail, M. Marin, F. Eriksson

Conclusion

JET

- Stationary, ELM-free, high-performance neon-seeded plasma achieved at 3MA in D-T, near the L-H power threshold with partially detached divertor conditions

- Access conditions identified at $n_{e,sep}$ about $2x10^{19}$ m^{-3}, $P_{sep}/P_{LH} \geq 1.25$ as seen at medium and high current, in D-D and D-T operation.

- Adding Neon:
  - Improves the plasma performance via primarily an improved pedestal
  - Reduces the separatrix and pedestal density, via modified pedestal transport possibly linked to a particle flux reversal.

- Unique scenario fulfilling major ITER requirements – underlying physics must be disentangled to enable reliable extrapolation to ITER operation.

Contributions at IAEA on JET-ITER baseline

JET

Day	Session	Name	Title
Wednesday @ 14:00	3141 Poster 2	**H.J Sun**	**Impact of the Plasma Boundary on Machine Operation, and the Risk Mitigation Strategy on JET**
Friday @16:10	2857 Oral	**D. Fajardo**	**Theory-based integrated modelling of tungsten transport: validation in present-day tokamaks and predictions for ITER**
Saturday @08:30	3486 Poster 7	D. Fajardo	Theory-based integrated modelling of tungsten transport: validation in present-day tokamaks and predictions for ITER
Friday @16:50	2761 Oral	**H. Kumpulainen**	**Simulation of tungsten erosion and edge-to-core transport in neon-seeded JET plasmas**
Saturday @08:30	3485 Poster 7	H. Kumpulainen	Simulation of tungsten erosion and edge-to-core transport in neon-seeded JET plasmas

JET-ITER baseline contributions so far

JET

Person	conference	Title
C. Giroud	PSI 2024	**High-current Neon-seeded ITER baseline scenario in JET D and D-T**
I. Carvalho	EPS 2024	**Neon-seeded ITER baseline scenario experiments in JET D and D-T plasmas**
E. Alessi	EPS 2025	**Impact of light impurities injection on n=1 core MHD activity at JET**
C. Leoni	EPS 2025	**Effect of neon seeding on density profiles and particle sources in the Integrated scenario at the Joint European Torus**
V. Zotta	EPS 2025	**The ITER baseline scenario on JET in D-T with Neon seeding**
E. Litherland-Smith	EPS 2025	**High and medium Z impurity concentration determination with InDiCA in JET**
M. Marin	TTF 2025	**Modelling impurity-seeded plasmas at JET**
I. Ivanova-Stanick	Plasma 2025	**Integrated numerical analysis of the neon seeded JET-ITER baseline scenario in deuterium plasmas**

See the 3MA DT JET-ITER baseline plasma on Youtube

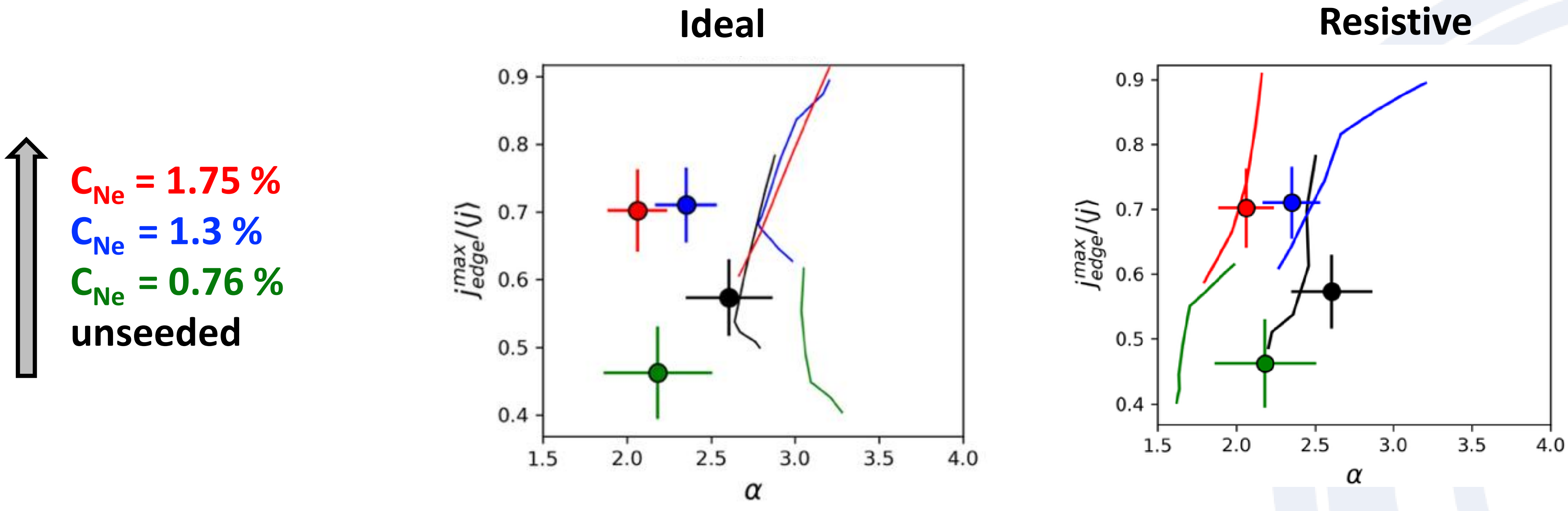
JET

Click here

JET

Back-up slides

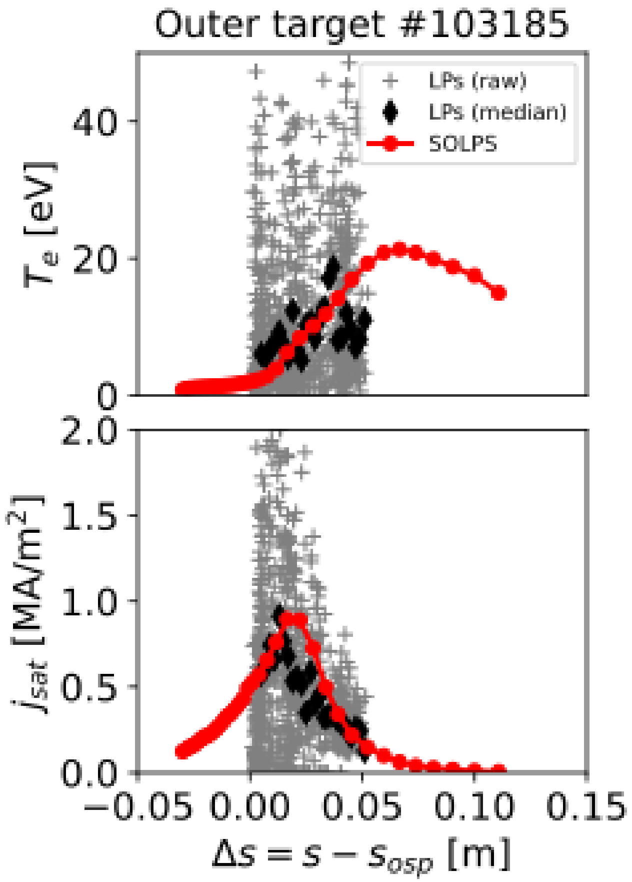
Pedestal experimental point close to resistive stability boundary



- Mix of small ELM-like events and large ELMs, both disappear at high C_{Ne}
- Pedestals are either unstable to resistive MHD modes or within the uncertainty of the resistive stability boundary

H. Nystrom. M. Sos

Additional information : SOLPS-ITER modelling

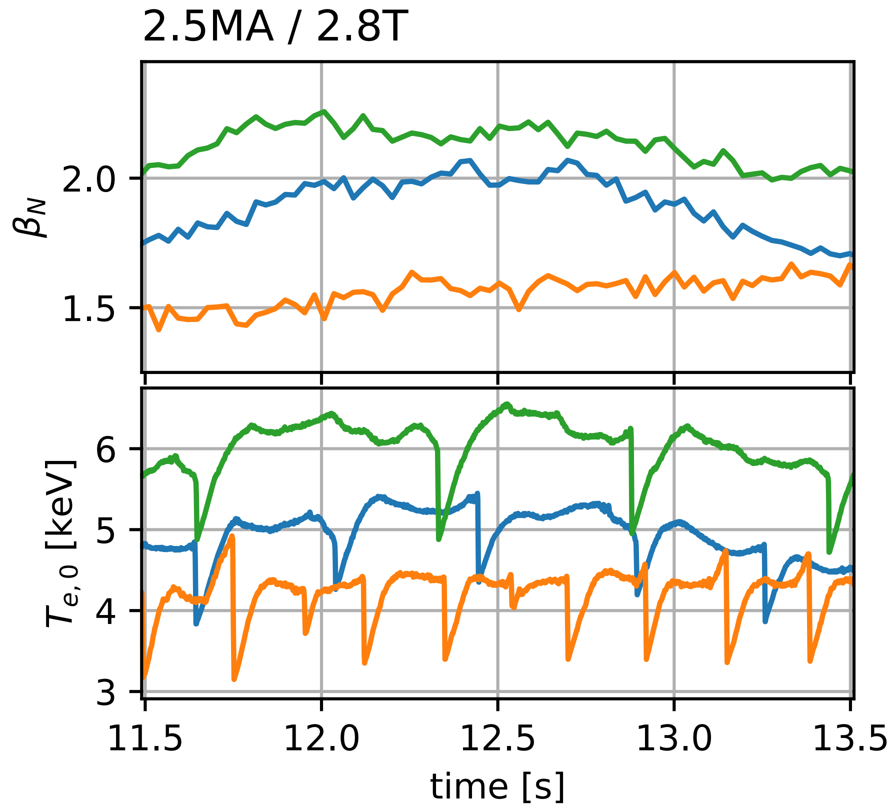


	$S_{D+,core}$	$S_{D+,total}$	P_{rad}
103398	1.1e22	1.06e24	5.7MW
103398 $\Phi_{Ne} = 1.6e21$	5.49e21	6.25e23	14.4MW

Characteristics of core MHD in Ne-seeded plasmas

JET

Sawteeth



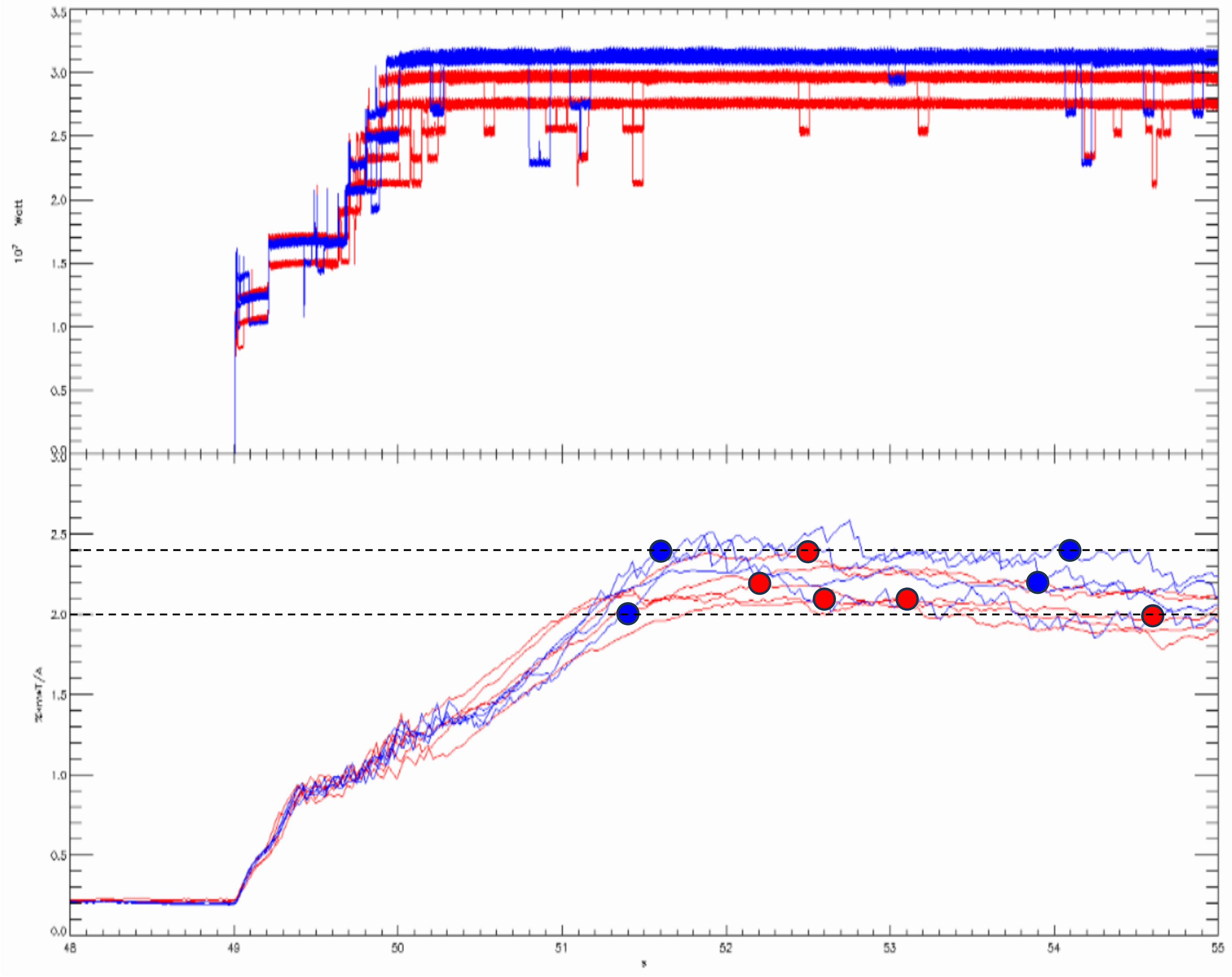
Improvement on confinement obtained with Ne-seeding is correlated with increase of $T_{e,0}$

→ lengthening of the ST period, and increasing the ST inversion radius

Neoclassical Tearing Modes

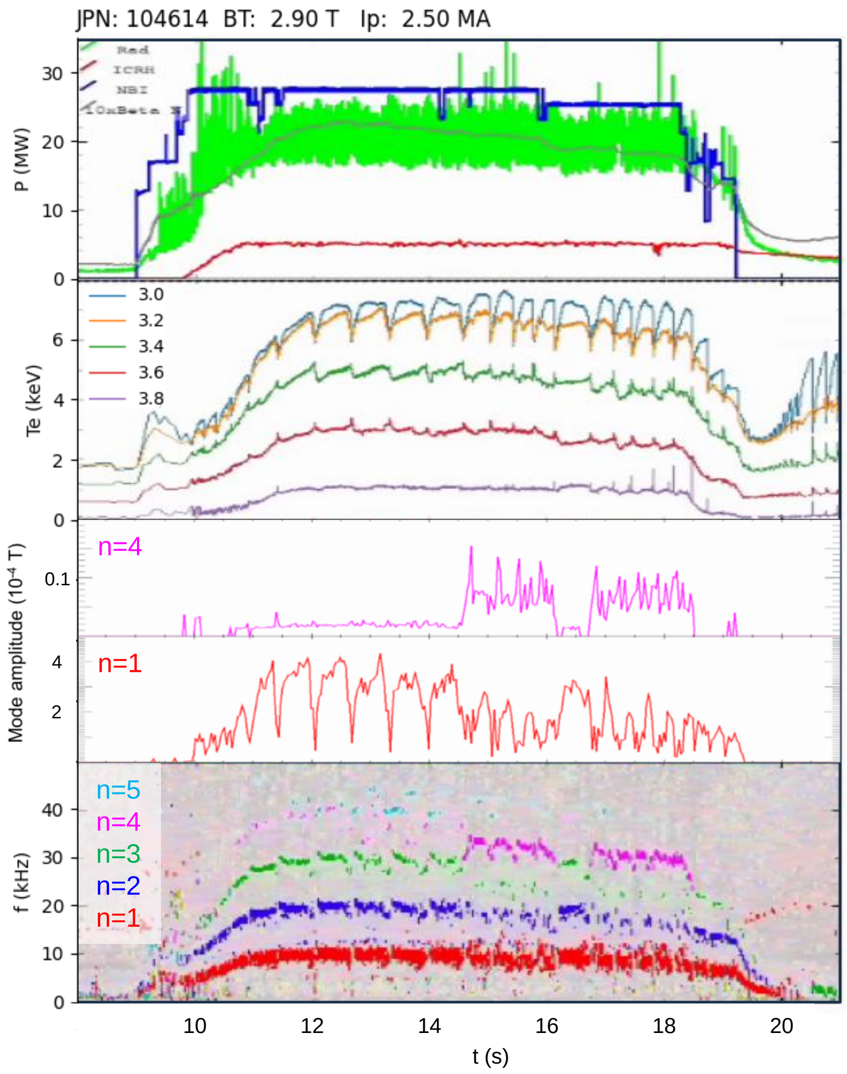
- ✓ Only **high-n NTM** (n = 4, 5, 6) in pulses with optimized H-mode access phase and Neon injection.
- ✓ **n=4** NTM not strongly affecting plasma performance (< 5 %) but decreasing the amplitude of the inter-sawtooth **1/1** mode and the sawtooth period.
- ✓ **n=3** NTM in pulse with too fast Neon injection and β_N increase.
- ✓ **n=2** NTM in pulses with long-period 1st sawtooth in the H-mode access phase.

β_N threshold for n=4 destabilization



DT	D
104553	105616
104555	105617
104601	105622
104614	105624
104620	

Neoclassical Tearing Modes



- ✓ Only **high-n NTM** (n = 4, 5, 6) in pulses with optimized H-mode access phase and Neon injection.
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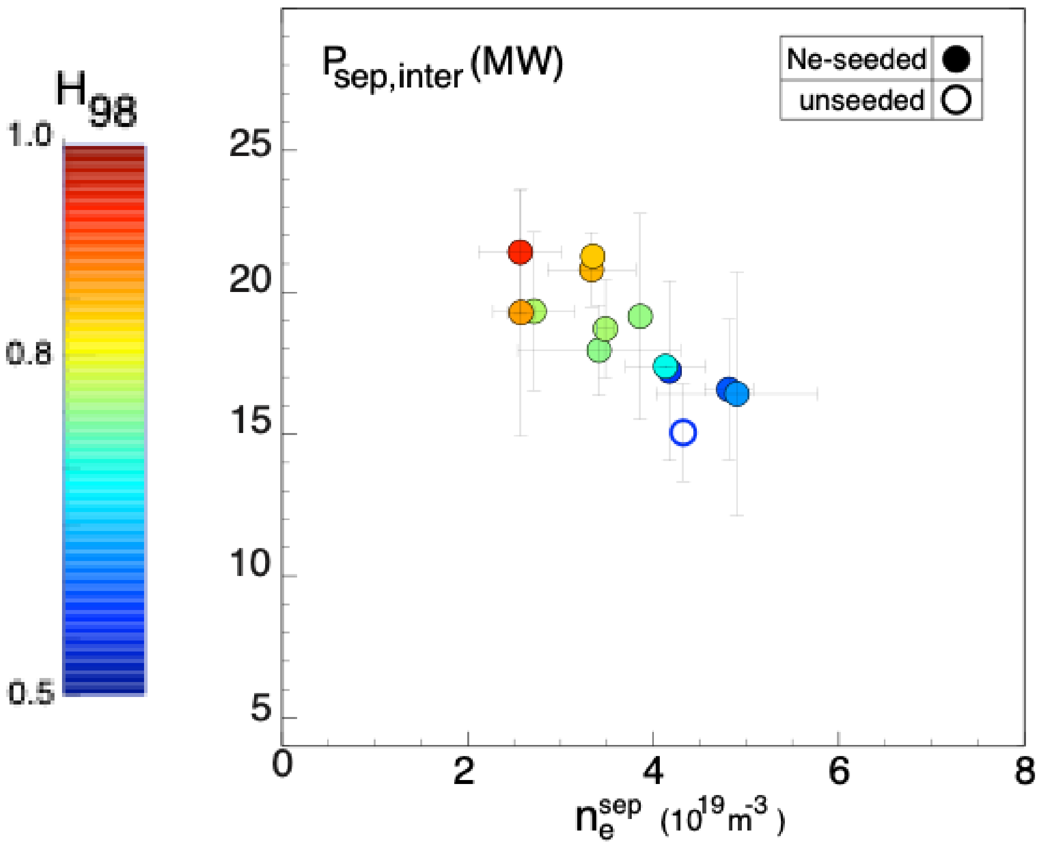
- ✓ **n=3** NTM in pulse with too fast Neon injection and β_N increase.
- ✓ **n=2** NTM in pulses with long-period 1^{st} sawtooth in the H-mode access phase.

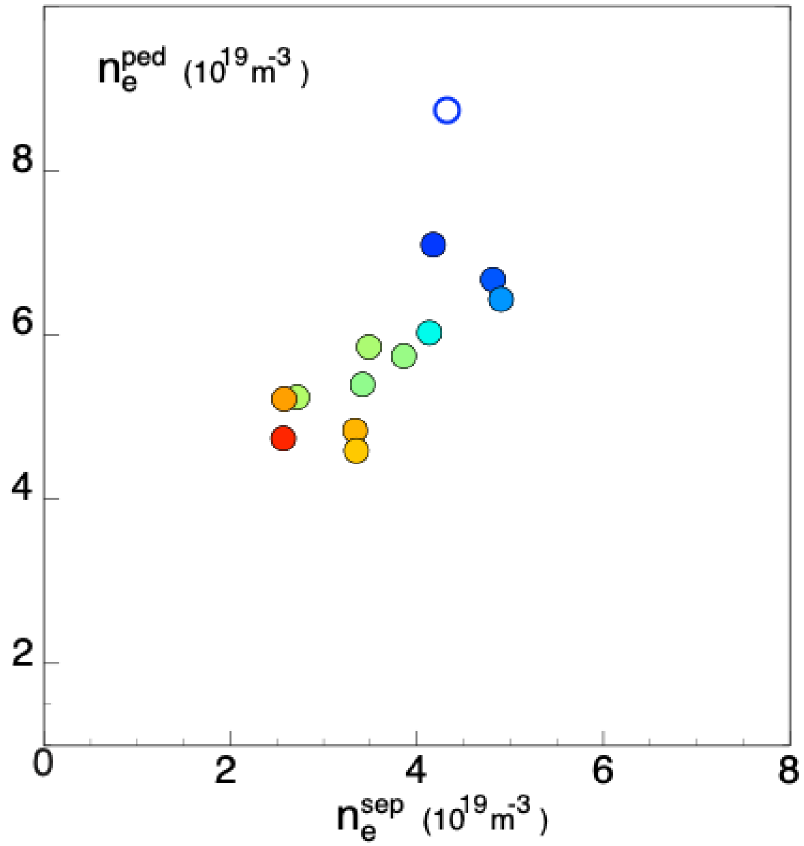
As C_{Ne} is increased, $n_{e,ped}$ and $n_{e,sep}$ decrease , $P_{sep,inter}$ increases

JET

2.5MA Γ_D=3.5-4.5x10^{22} el.s^{-1} subset

$n_{e,sep}$ determined by power balance
Psep,inter=P_{in} – $P_{rad,core}$ – dw/dt

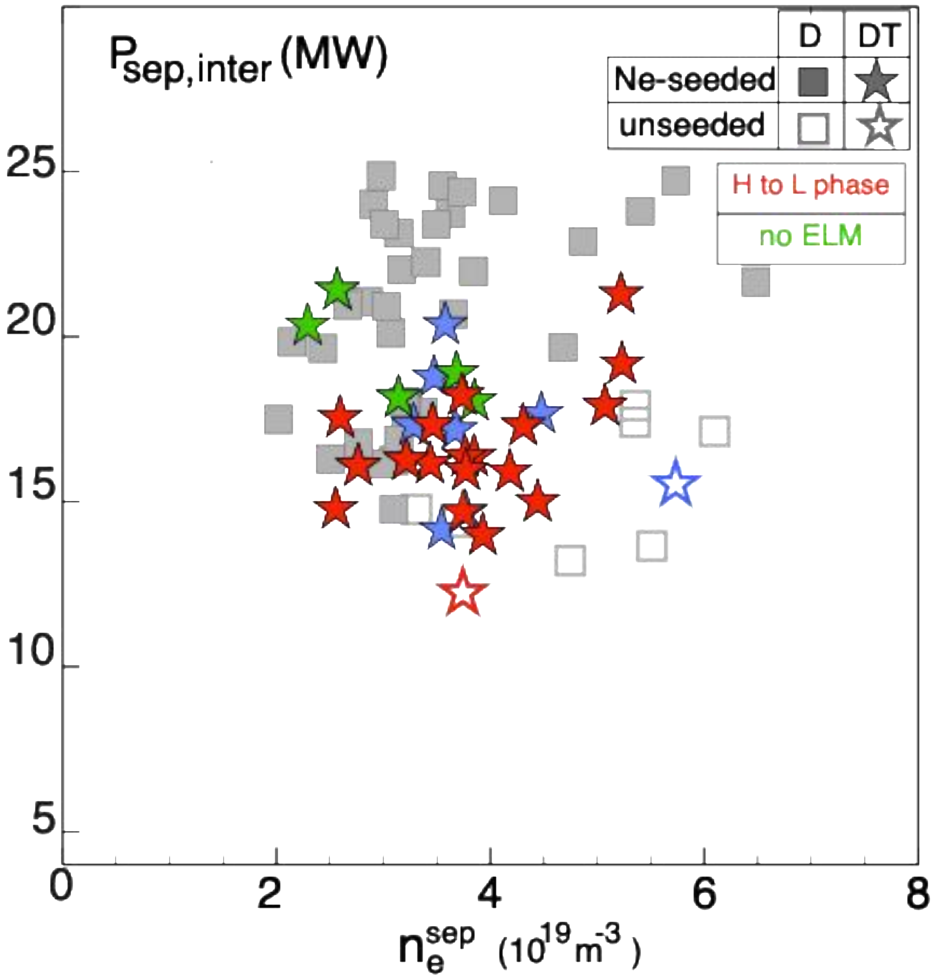




Operational space of JET-ITER baseline at 3.0MA

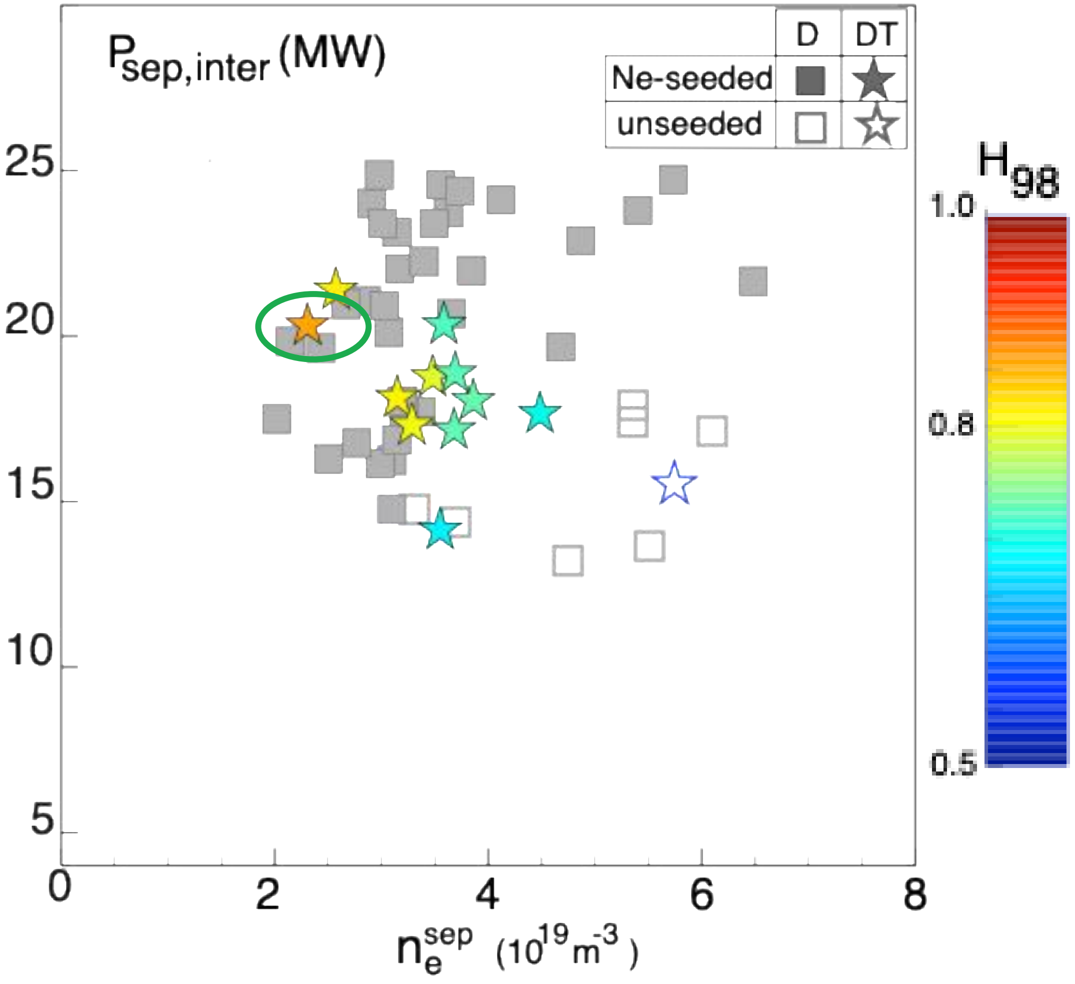
JET

3.0 MA all gas-rate (Γ_D=1.5-6.0 x10^{22} el.s^{-1})



Operational space of JET-ITER baseline at 3.0MA

3.0 MA all gas-rate (Γ_D=1.5-6.0 x10^{22} el.s^{-1})

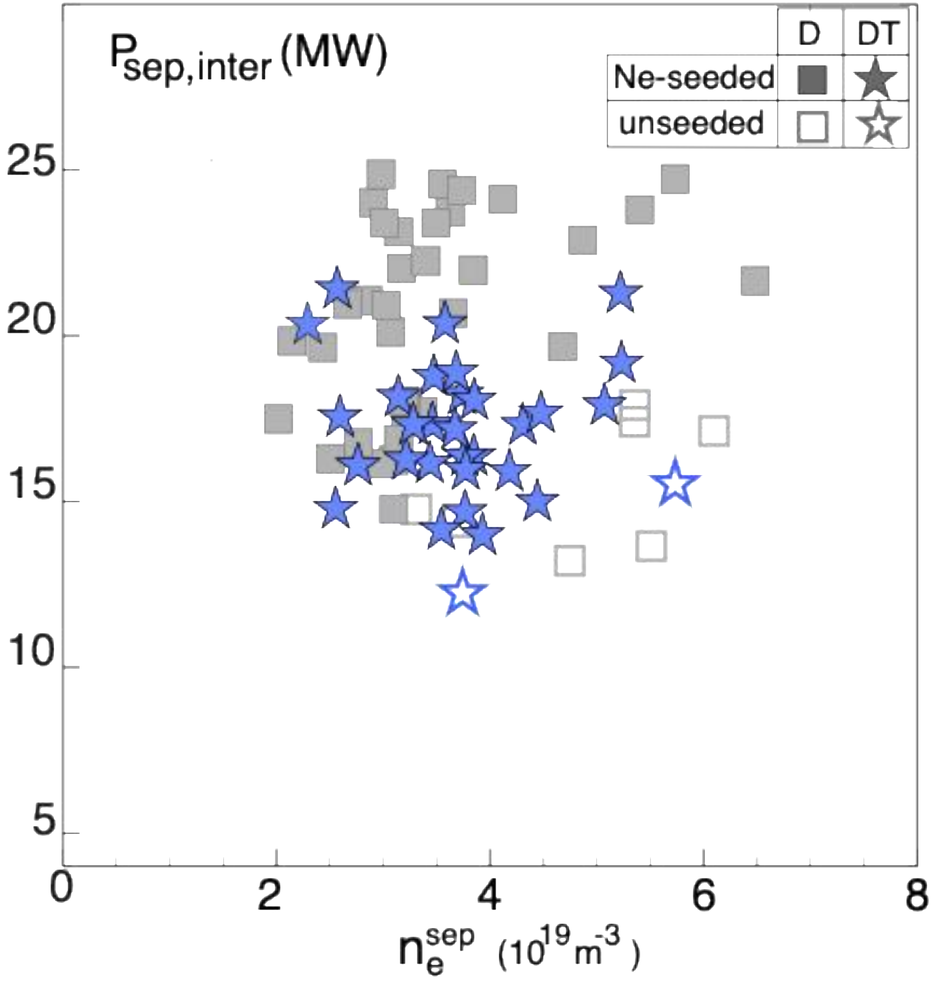


- No-ELM plasma exists at low $n_{e,sep}$= 2-3 x10^{19} m^{-3}
- Accessible if $P_{sep}/P_{LH} \gtrsim 1.25$

Operational space of JET-ITER baseline at 3.0MA

JET

3.0 MA all gas-rate (Γ_D=1.5-6.0 x10^{22} el.s^{-1})

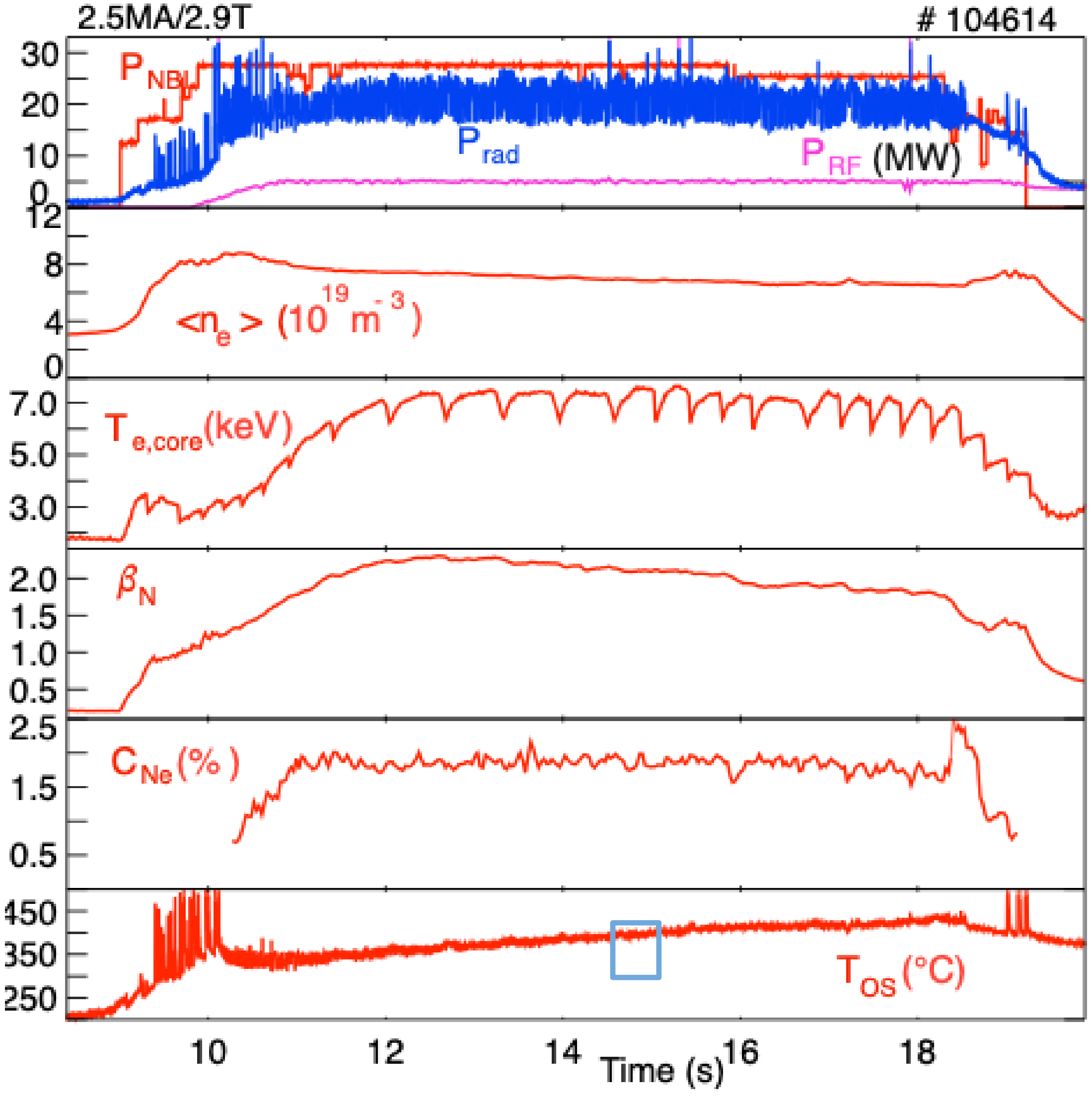


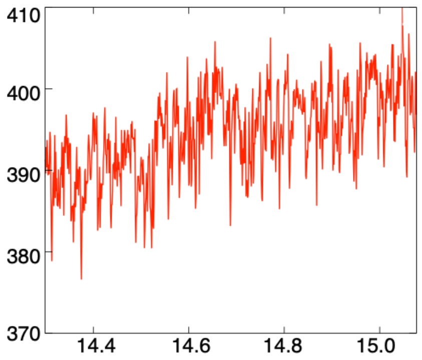
Demonstrated scenario is compatible with D-T operation with high-performance and no-ELM

JET

#104614

$P_{sep}/P_{LH} < 2$
$H_{98(y,2)} = 0.9$
$\beta_N = 2.2$





- Similar behaviour in D-T as in D
- Transfer from D to D-T was fairly straight forward.

→ Similar observations at higher current 3MA and 3.2MA

→ Change from D to D-T was beneficial at 3MA