EUROfusion

Integrated scenario development at JET for DT operation and ITER risk mitigation

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JET

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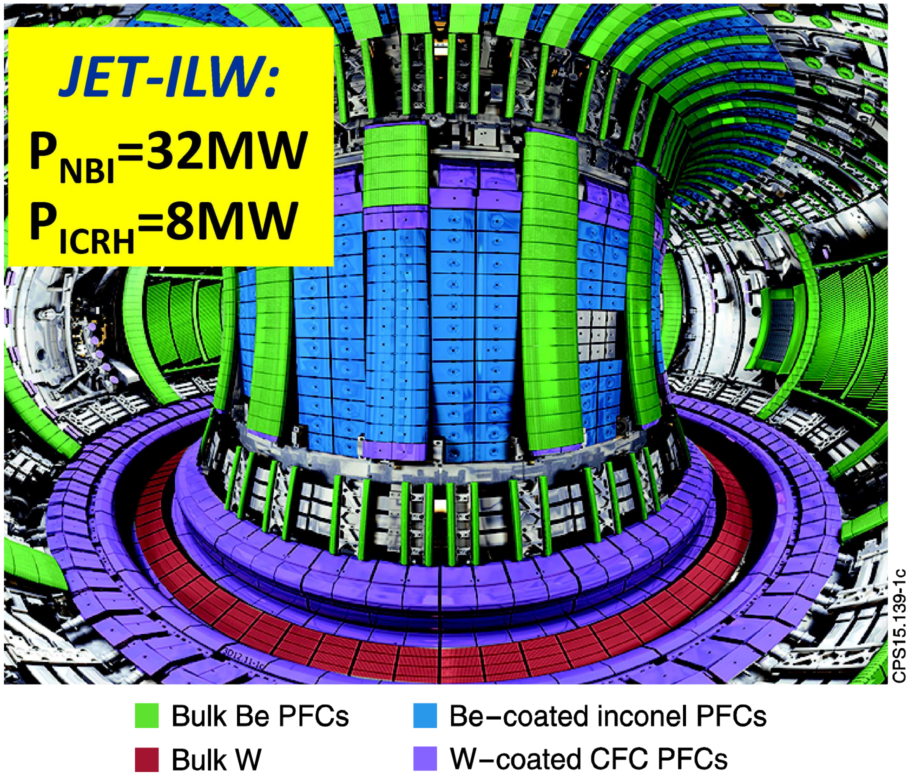
JET is designed for fusion power studies in support of ITER

DT scenarios with high enough alpha power production are essential to demonstrate that efficient electrical power generation is possible



[E. Joffrin NF2019] [J. Mailloux OV/1-2]

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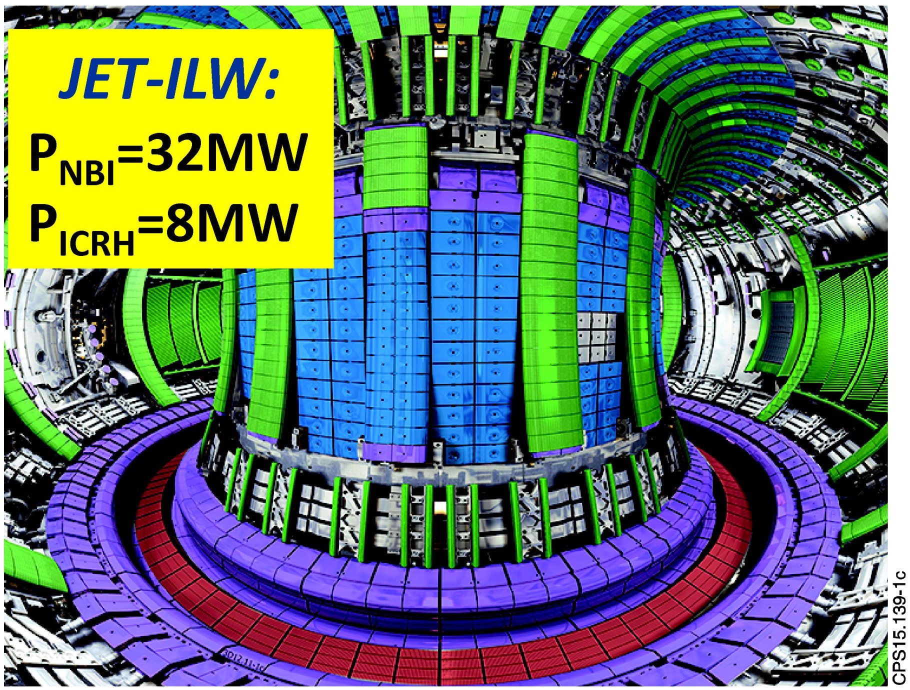


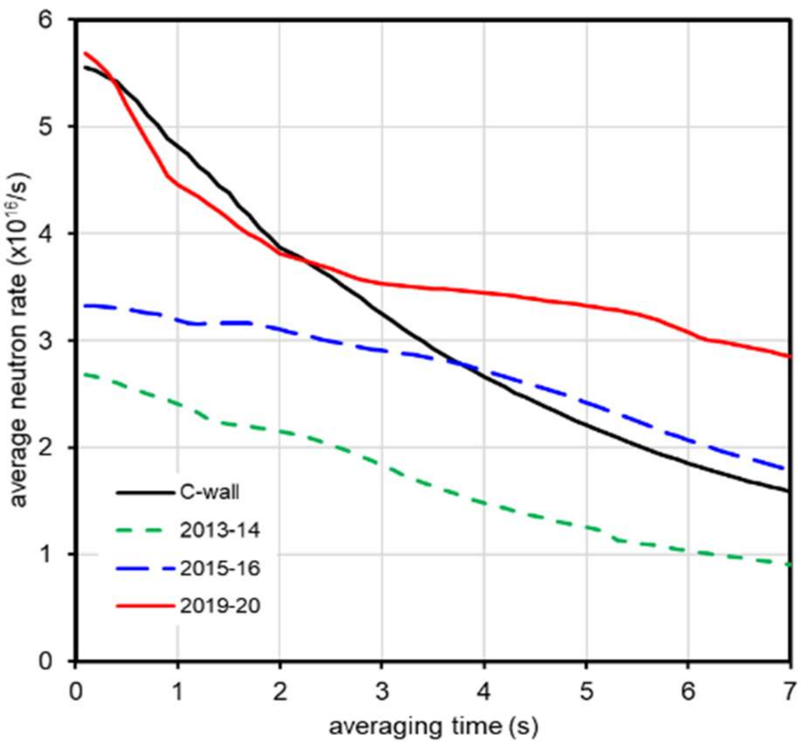
Bulk Be PFCs | Be−coated inconel PFCs
Bulk W | W−coated CFC PFCs

[E. Joffrin NF2019] [J. Mailloux OV/1-2]

- JET can provide unique information in **ITER relevant DT scenarios**
  - Core and edge confinement
  - Isotope effects
  - Impact of alpha particles
  - Techniques for power exhaust
  - Impurity sources and accumulation control in a metallic wall environment
  - RTCC techniques
  - PWI

2019-2020: significant improvement

JET has developed D scenarios for fusion power maximization in preparation of DTE2



During 2019-2020, D scenarios have significantly improved:

- High NBI (30MW) and ICRH power
- Low or absent high Z impurity accumulation
- High thermal confinement
- Improved stability and control
- Record peak and 5s average DD fusion

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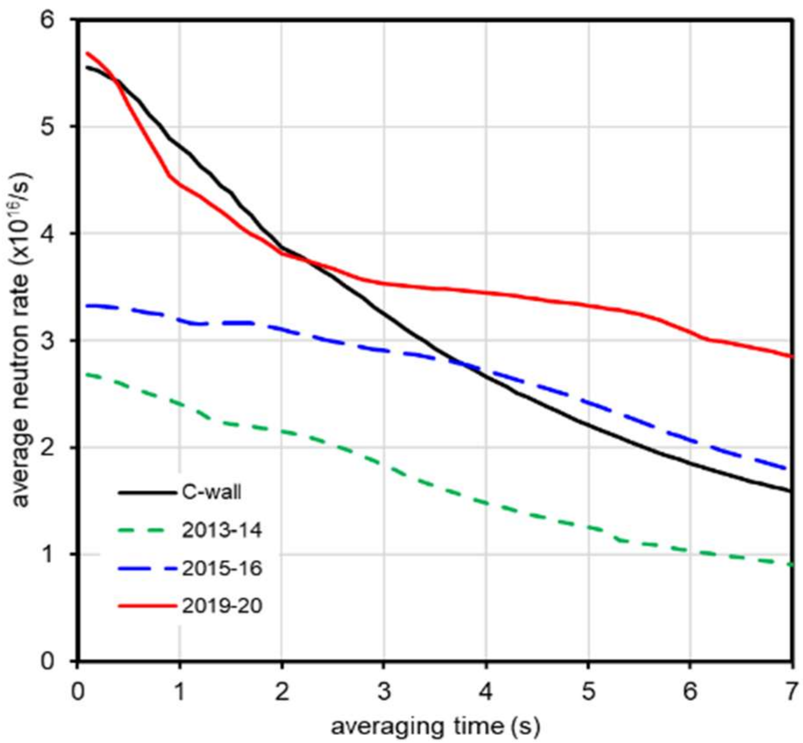

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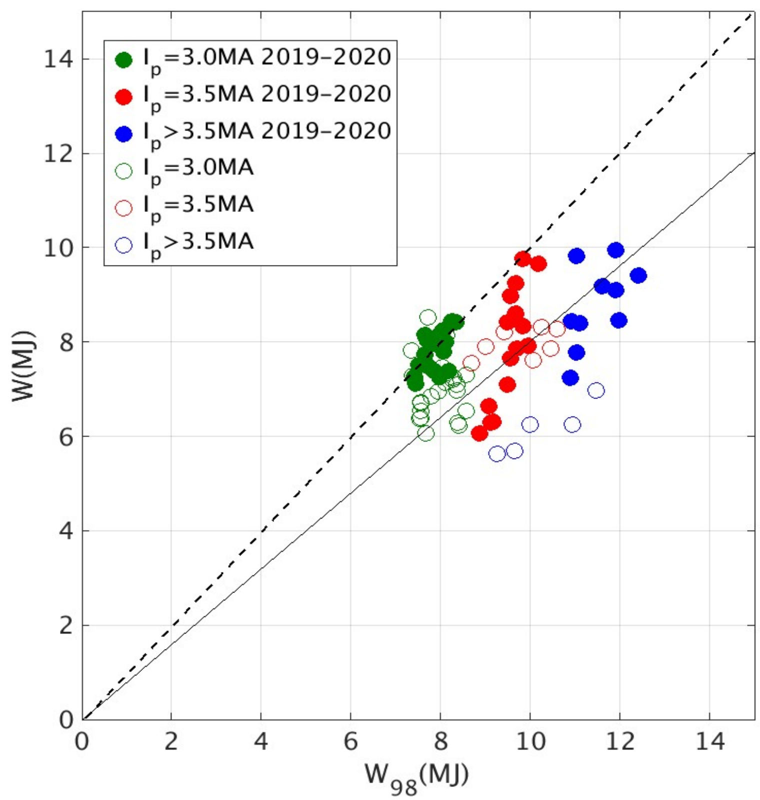
Results obtained in a wide operational space→ Confidence on ITER extrapolabitlity

Outline

- Develop D-T scenarios: baseline
- Develop D-T scenarios: hybrid
- Predict first: towards DT predictions
- Conclusions

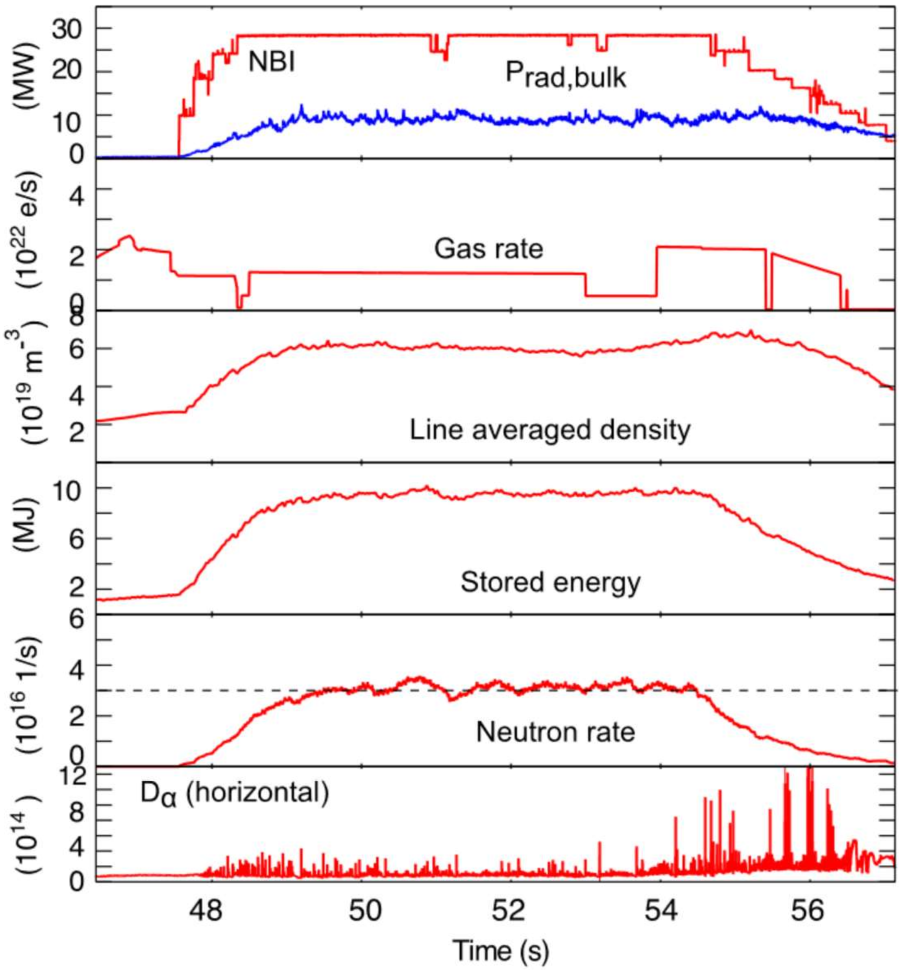
Baseline scenario: improved performance in 2019-2020



- Baseline scenario at JET is characterized:
  - high toroidal current $I_p \geq 3.0$MA
  - $q_{95} \sim 3$
  - $\beta_p < 1$ and $\beta_N \sim 2$
- Improvement of confinement during 2019-2020 campaigns [L. Garzotti NF2018]
- $H_{98}(y,2) \geq 1$ at $3.0\text{MA} \leq I_p \leq 3.5\text{MA}$
- Significant improvement at $I_p > 3.5$MA but not fully optimized yet

Stationary Scenarios for the DT phase achieved: baseline route

Baseline: 3 MA/2.8 T (q_{95}=3.1)



- $H_{98}(y,2)$ = 1.05, β_N = 2.2, β_p = 0.9, f_{GLD}~ 0.7
- Improvement wrt Type-I ELMs plasmas
  - Reduced gas puff + Pellets (45Hz): high confinement
  - Inclusion of small Ne quantities provides stability [C. Giroud IFE/P4-12]
- Long phases with high frequency (200-400Hz) small ELMs
- Core radiated power stable
- Divertor in 'attached' conditions

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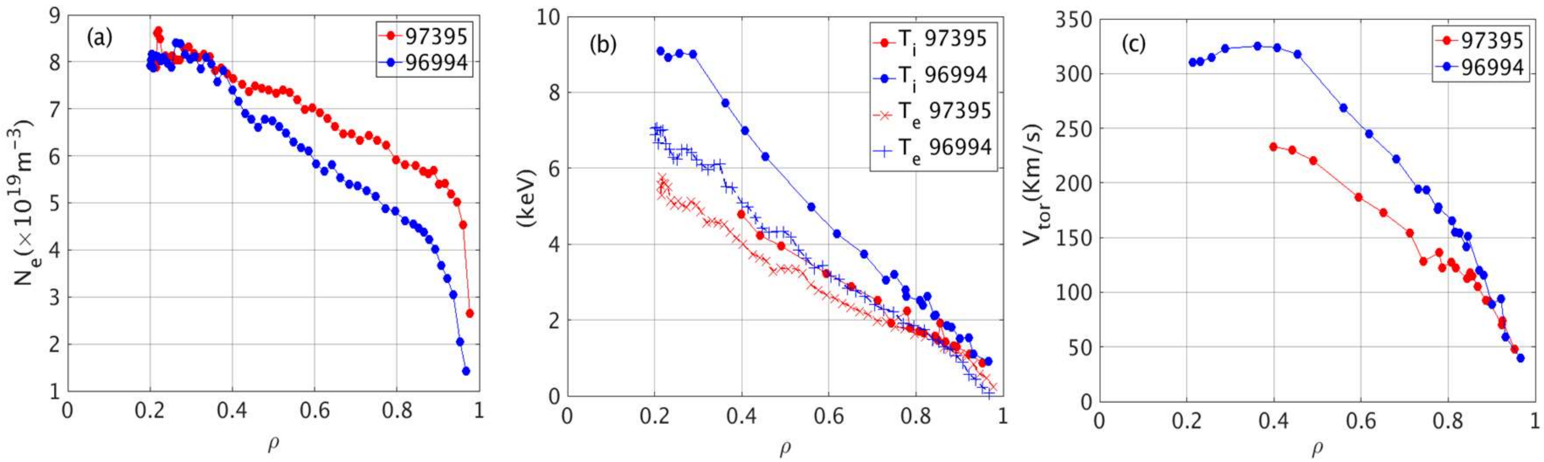
Differences between small and Type-I ELMs plasmas at same input power

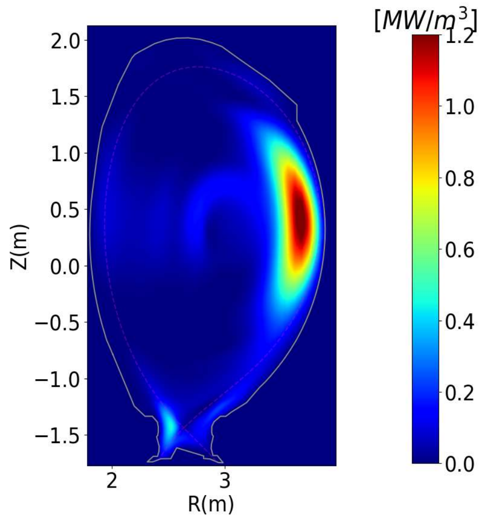
Type-I ELM only gas   Small ELM gas+pellets+Ne



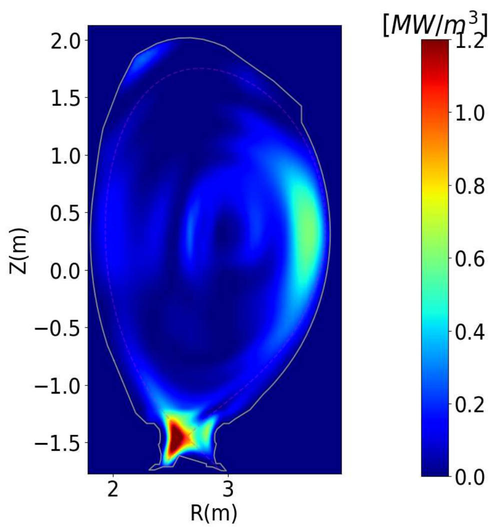
- Compared to type-I ELMs, small ELMs pulses are characterized by:
  - Higher density peaking
  - Wider pedestal at the same pedestal top pressure
  - $T_i/T_e>1$ including the pedestal top
  - Higher rotation and rotation shear [H-T Kim NF 2018]
  - Higher DD neutron rate

Baseline plasmas: Impurity accumulation avoided

96731 with pellets without Ne



96994 with pellets with Ne



- In previous campaigns:
  - High confinement plasmas increase W neoclassical inward pinch→ core W accumulation [F J Casson PPCF 2014, NF 2020]
- In new campaigns:
  - Radiated power located in the low field side for baseline discharges at high confinement
- Ne shifts radiation blob to the divertor region

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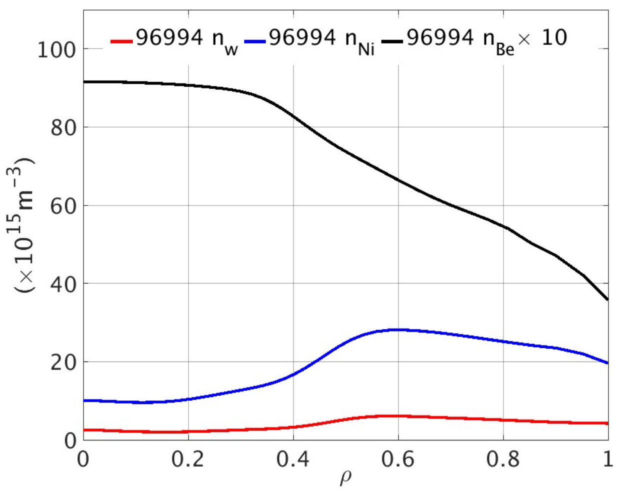
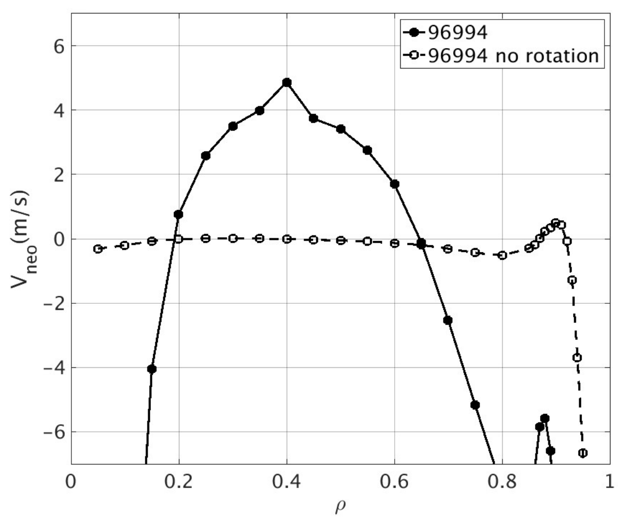
Baseline plasmas: Impurity accumulation avoided

Impurity densities



W Neoclassical pinch (NEO*)



- In previous campaigns:
  - High confinement plasmas increase W neoclassical inward pinch→ core W accumulation [F J Casson PPCF 2014, NF 2020]
- In new campaigns:
  - Radiated power located in the low field side for baseline discharges at high confinement
- Ne shifts radiation blob to the divertor region
- Ni, W density profile is hollow: blocked in the outer plasma
- Neoclassical W convection outward due to strong rotation [J. Garcia submitted to PRL]

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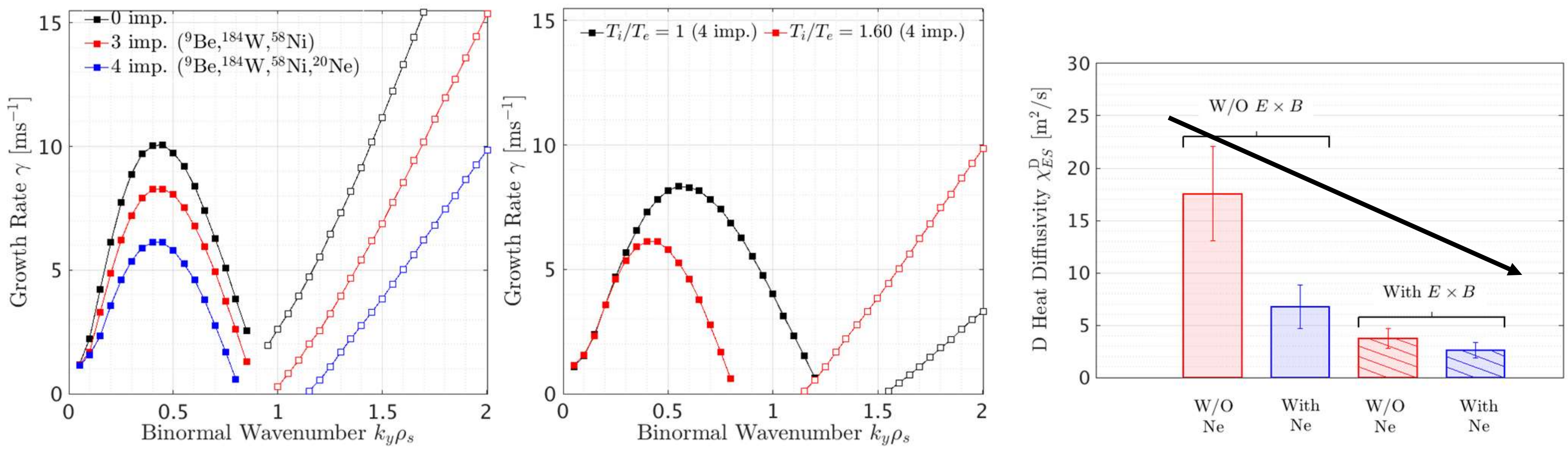
*[E. Belli PPCF 2008]

Three mechanisms for improved core confinement

Baseline @ ρ=0.8



- Gyrokinetic simulations performed with the GENE code [F. Jenko POP 2000]
- Ion heat transport reduction by:
  - Edge impurity concentration dilution (including Ne)
  - T_i/T_e~1.6 starting at the pedestal top
  - Strong edge ExB shearing

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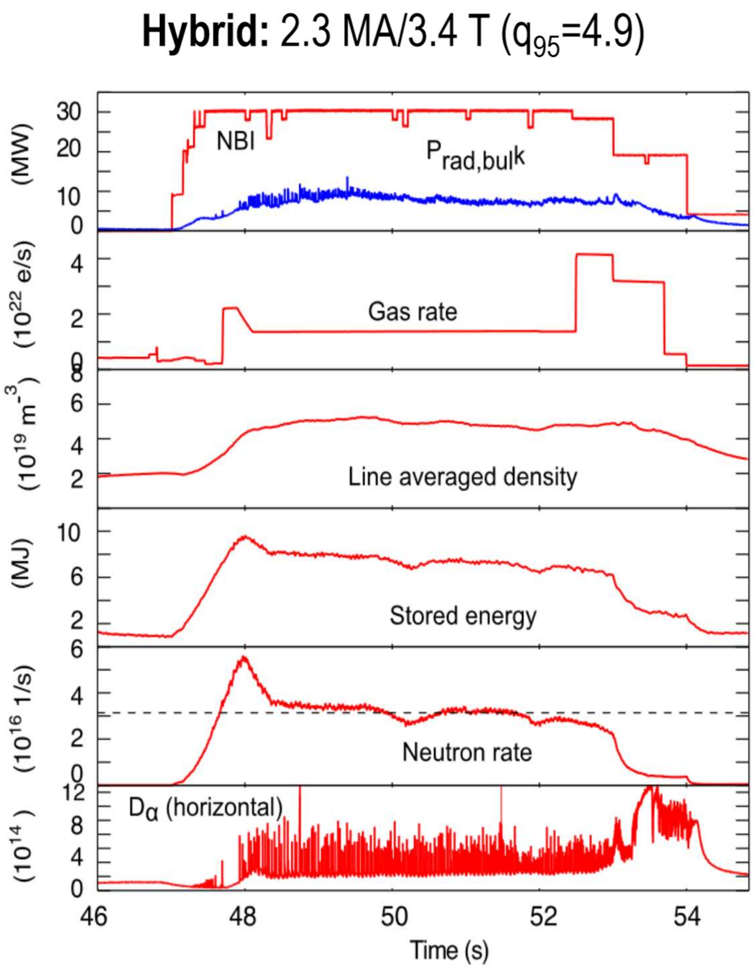
Stationary Scenarios for the DT phase achieved: hybrid route

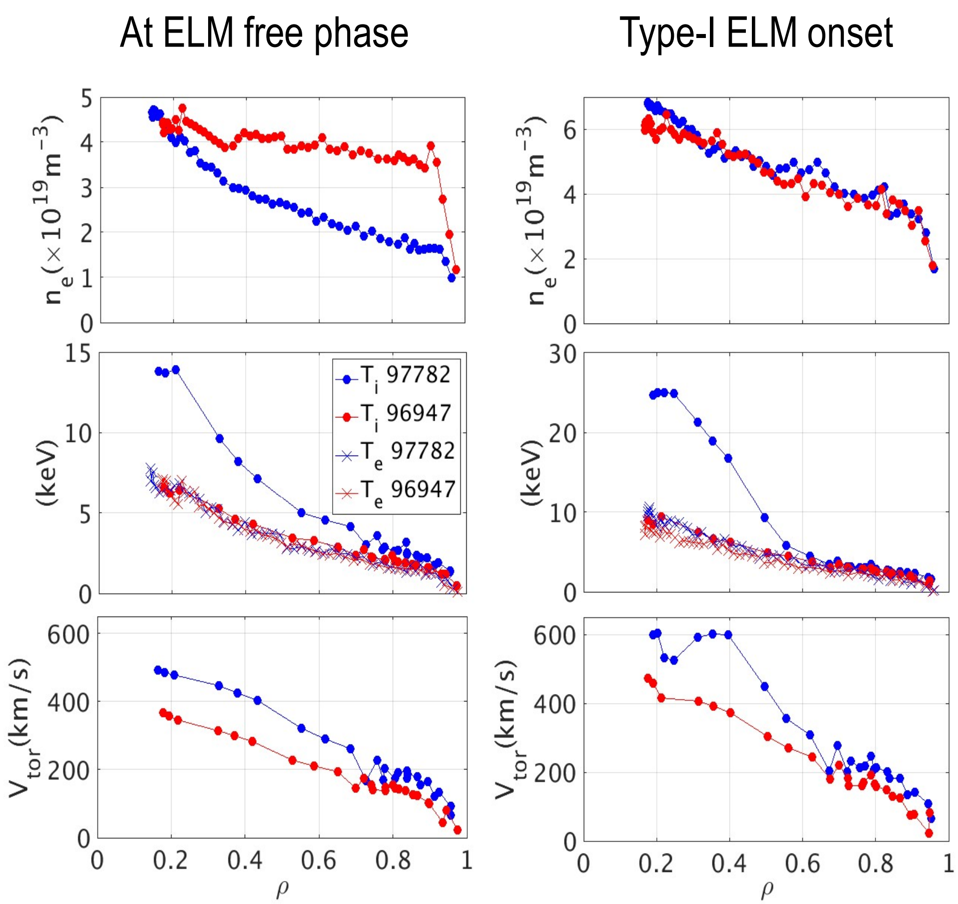


- **Hybrid scenario at JET is characterized:**
  - 2.2MA≤ I_p≤2.5MA, Bt=3.4T
  - 4.5≤q_{95}≤5.0
  - β_p≥1 and β_N~2
  - Type-I ELMs
- Strong increase of stability and duration in 2019-2020
- Core radiated power stable
- Record peak and average neutron rate at JET
- New entry to H-mode: initial ELM free phase
- Disruption rate reduced to ~5-9% with RTCC techniques

Strong impact of new H-mode entry

Former gas fuelled H-mode entry

New low gas ELM free entry

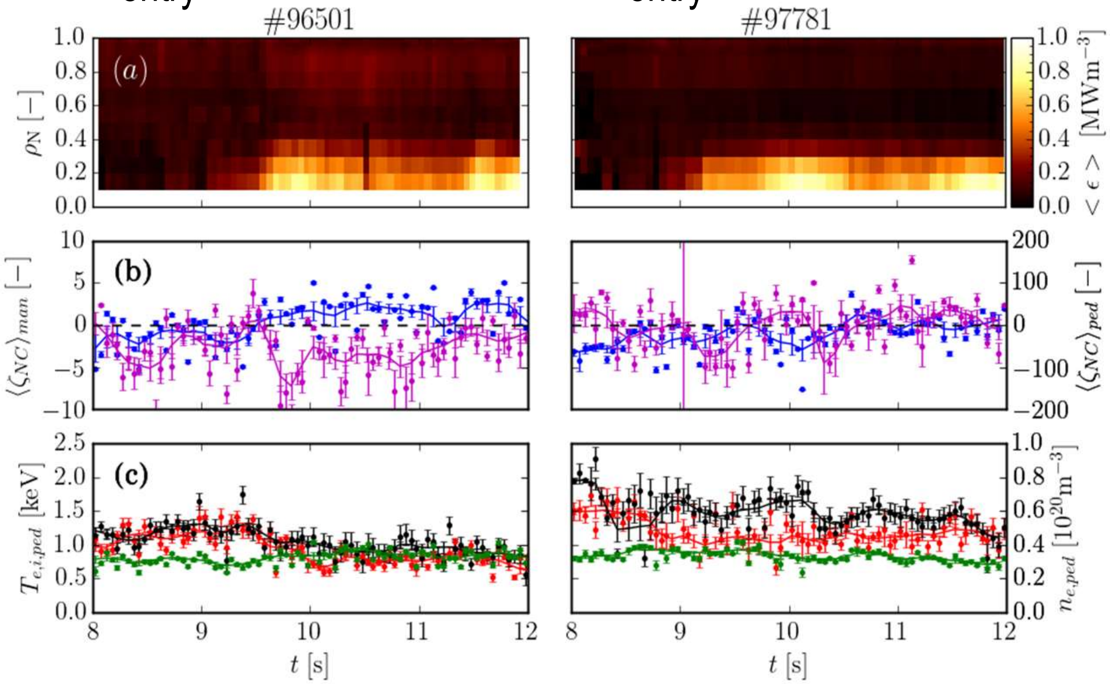


- Strong differences with new H-mode entry:
  - Ti>>Te including the pedestal
  - Increased rotation and rotation shear
  - No impurity accumulation during ELM free phase
  - Similar density with type-I ELMs

Hybrid scenario: impurity accumulation avoidance

Former gas fuelled H-mode entry

New low gas ELM free entry



W neoclassical pinch proxy:

$\varsigma_{NC} = R/2L_T - R/L_n$

(ς_{NC}>0 outward)

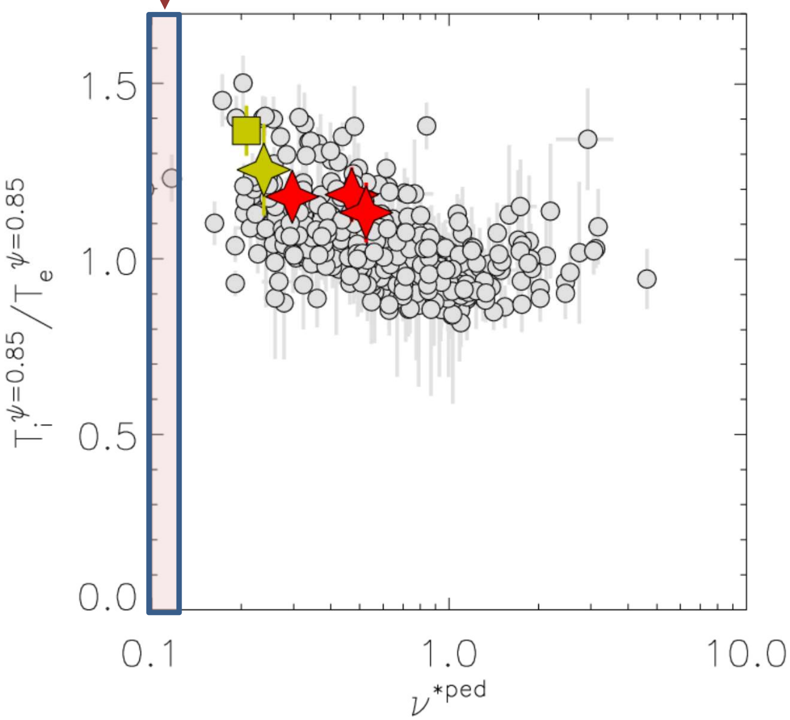
- **New H-mode entry legacy during the flat-top**
  - Low periphery radiated power
  - ς_{NC} largely positive at the edge and the pedestal top
  - High T_i/T_e including the pedestal

[A. Field in preparation]

- Evidence of W screening at pedestal as predicted for ITER [R. Dux PPCF 2014]

Benefitial role of low ν^*_{ped}

ITER 15MA



- New pedestal characteristics play an essential role in JET scenarios
- ν^*_{ped} at JET approaching ITER
- $T_i/T_e>1$ even at Ip=4.0MA
- ITER might benefit from good transport properties

Hybrid

Baseline @ 3.5MA, 3.8MA, 4MA

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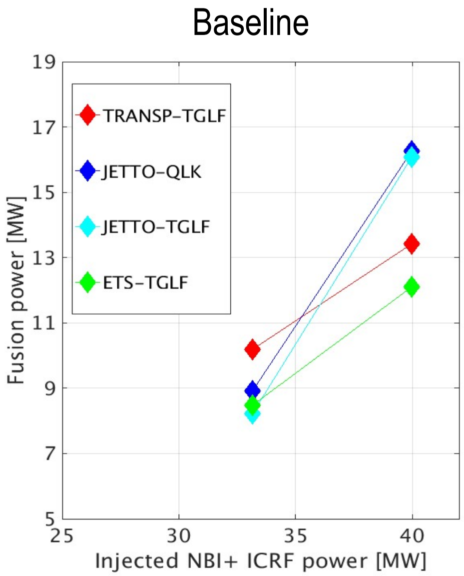
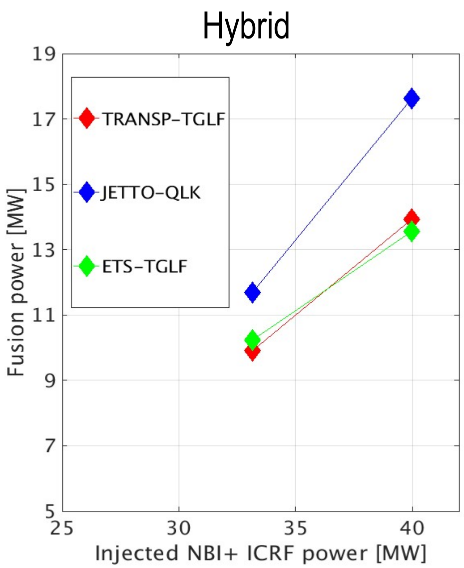
"Predict first": essential activity performed before DT





- Strong JET "Predict first" activity has been helpful for:
  - Identify physics that boost alpha power generation
  - Identify differences between DD and DT plasmas
  - Guide DD experiments and asses DT fusion power

- Validated transport and pedestal models with D and H plasmas
- P_{fus} ~ 12-16MW for hybrid and baseline
- In JET-DT, extensive studies on the role of alpha particles in ITER relevant confined plasmas are possible.

[G. Staebler OV/2-5] [J. Citrin TH/5-2]

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Highlights of the scenario preparation for D-T

- JET Deuterium ITER relevant scenarios developed at JET for fusion power maximization in preparation of DTE2
- Strong improvement of performance and stability during 2019-2020
- Simultaneous high confinement and impurity accumulation avoidance
- High confinement small ELMs plasmas obtained at high current
- Pedestal characteristics at ITER collisionality are essential to explain results
- Predict first activity shows that ~15MW of fusion power in the JET-ILW is possible
- Before DT, TT-campaign in 2021 is contributing to DT plasmas preparation