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

J. Garcia
CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France.
Contributors

F. J. Casson\textsuperscript{2}, C. Challis\textsuperscript{2}, A. Field\textsuperscript{2}, L. Garzotti\textsuperscript{2}, H.-T. Kim\textsuperscript{2}, J. Mailloux\textsuperscript{2}, F. Rimini\textsuperscript{2}, M. Sertoli\textsuperscript{2}, G. Szepesi\textsuperscript{2}, D. Van Eester\textsuperscript{3}, E. Lerche\textsuperscript{3}, D. Frigione\textsuperscript{4}, J. Hobirk\textsuperscript{5}, A. Kappatou\textsuperscript{5}, S. Mazzi\textsuperscript{1,6}, E. de la Luna\textsuperscript{7}, Z. Stancar\textsuperscript{8}, M. Poradziński\textsuperscript{9}, F. Auriemma\textsuperscript{10}, R. Lorenzini\textsuperscript{10}, J. Citrin\textsuperscript{11}, M. Marin\textsuperscript{11}, J. Ferreira\textsuperscript{12}, E. Fransson\textsuperscript{13}, P. Strand\textsuperscript{13}, R. Gatto\textsuperscript{14}, V. K. Zotta\textsuperscript{14}, L. Frasinetti\textsuperscript{15} and JET contributors\textsuperscript{*}

\textsuperscript{1} CEA, IRFM Saint-Paul-lez-Durance, France. Email: Jeronimo.garcia@cea.fr
\textsuperscript{2} UNITED KINGDOM ATOMIC ENERGY AUTHORITY, CULHAM CENTRE FOR FUSION ENERGY, CULHAM SCIENCE CENTRE Abingdon, Oxon, OX14 3DB, UK
\textsuperscript{3} LPP-ERM/KMS, EUROFUSION CONSORTIUM MEMBER - TRILATERAL EUREGIO CLUSTER Brussels, Belgium
\textsuperscript{4} NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT, ENEA C.R. Frascati, Roma, Italy
\textsuperscript{5} MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK Boltzmannstraße 2, D-85748 Garching, Germany
\textsuperscript{6} AIX-MARSEILLE UNIVERSITÉ, CNRS PIIM, UMR 7345 Marseille, France
\textsuperscript{7} LABORATORIO NACIONAL DE FUSION, CIEMAT 28040 Madrid, Spain
\textsuperscript{8} JOZEF STEFAN INSTITUTE Jamova cesta 39, SI-1000 Ljubljana, Slovenia
\textsuperscript{9} INSTITUTE OF PLASMA PHYSICS AND LASER MICROFUSION Hery Str. 23, 01-497 Warsaw, Poland
\textsuperscript{10} CONSORZIO RFX– CNR, ENEA, INFN, UNIVERSITÀ DI PADOVA, CNR-ISTP Corso Stati Uniti 4, 35127 Padova, Italy, Acciaierie Venete SpA, Padova, Italy
\textsuperscript{11} DIFFER - DUTCH INSTITUTE FOR FUNDAMENTAL ENERGY RESEARCH Eindhoven, the Netherlands
\textsuperscript{12} INSTITUTO DE PLASMAS E FUSAO NUCLEAR, INSTITUTO SUPERIOR TECNICO, UNIVERSIDADE DE LISBOA 1049-001 Lisboa, Portugal
\textsuperscript{13} CHALMERS UNIVERSITY OF TECHNOLOGY SE-412 96 Göteborg, Sweden
\textsuperscript{14} DIPARTIMENTO DI INGEGNERIA ASTRONAUTICA, ELETTRICA ED ENERGETICA, SAPIENZA UNIVERSITÀ DI ROMA Via Eudossiana 18, 00184 Roma, Italy
\textsuperscript{15} DIVISION OF FUSION PLASMA PHYSICS, KTH ROYAL INSTITUTE OF TECHNOLOGY, Stockholm, Sweden

\textsuperscript{*} See the author list of ‘Overview of JET results for optimising ITER operation’ by J. Mailloux et al. to be published in Nuclear Fusion Special issue: Overview and Summary Papers from the 28th Fusion Energy Conference (Nice, France, 10-15 May 2021)
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

\[ P_{\text{NBI}} = 32 \text{MW} \]
\[ P_{\text{ICRH}} = 8 \text{MW} \]

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

- 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

**JET-ILW:**
- $P_{\text{NBI}}=32\text{MW}$
- $P_{\text{ICRH}}=8\text{MW}$

[E. Joffrin NF2019] [J. Mailloux OV/1-2]
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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Results obtained in a wide operational space → Confidence on ITER extrapolability
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
  - $q_{95} \approx 3$
  - $\beta_p < 1$ and $\beta_N \approx 2$

- Improvement of confinement during 2019-2020 campaigns [L. Garzotti NF2018]
  - $H_{98}(y,2) \geq 1$ at $3.0$MA$\leq I_p \leq 3.5$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 (q95=3.1)

- $H_{98}(y,2) = 1.05$, $\beta_N = 2.2$, $\beta_p = 0.9$, $f_{GLD} \sim 0.7$
- 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
Differences between small and Type-I ELMs plasmas at same input power

- 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

- 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

96731 with pellets without Ne

96994 with pellets with Ne
Baseline plasmas: Impurity accumulation avoided

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- 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]

*E. Belli PPCF 2008
Three mechanisms for improved core confinement

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

• Develop D-T scenarios: baseline
• Develop D-T scenarios: hybrid
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Stationary Scenarios for the DT phase achieved: hybrid route

- Hybrid scenario at JET is characterized:
  - $2.2 \text{MA} \leq I_p \leq 2.5 \text{MA}$, $B_t = 3.4 \text{T}$
  - $4.5 \leq q_{95} \leq 5.0$
  - $\beta_p \geq 1$ and $\beta_N \sim 2$
  - 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 $\sim 5-9\%$ 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:
  - $T_i >> T_e$ 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

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

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

W neoclassical pinch proxy:

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

($\zeta_{NC} > 0$ outward)
Beneficial role of low $\nu_{ped}^*$

- New pedestal characteristics play an essential role in JET scenarios
- $\nu_{ped}^*$ at JET approaching ITER
- $T_i/T_e > 1$ even at $I_p=4.0\,\text{MA}$
- ITER might benefit from good transport properties
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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 assess DT fusion power
  - Validated transport and pedestal models with D and H plasmas
  - \( P_{\text{fus}} \sim 12-16\text{MW} \) 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