



Experimental and modeling development at JET for DT preparation and ITER risk mitigation

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JET



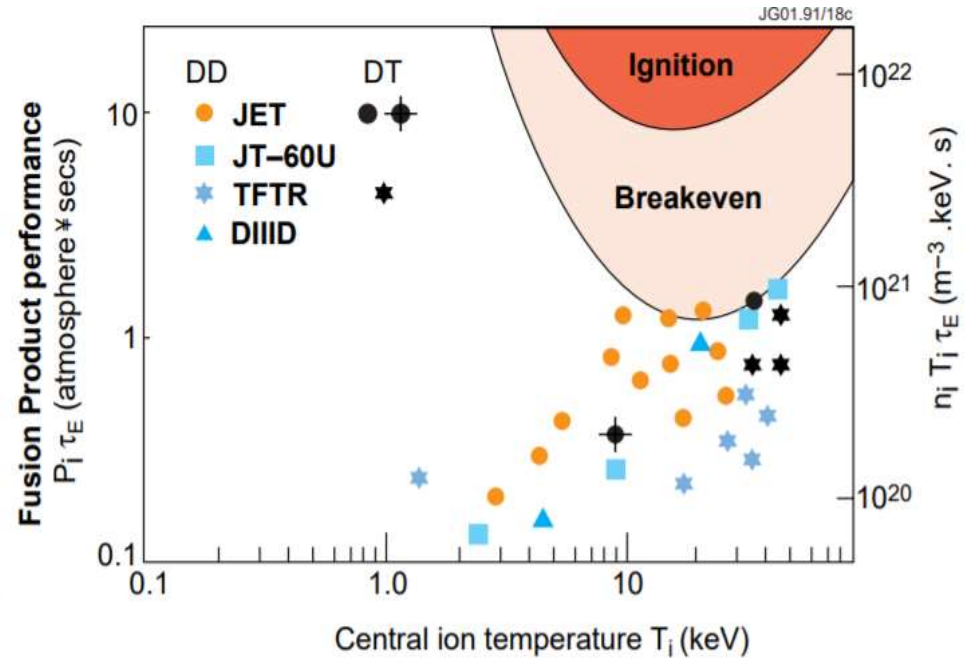
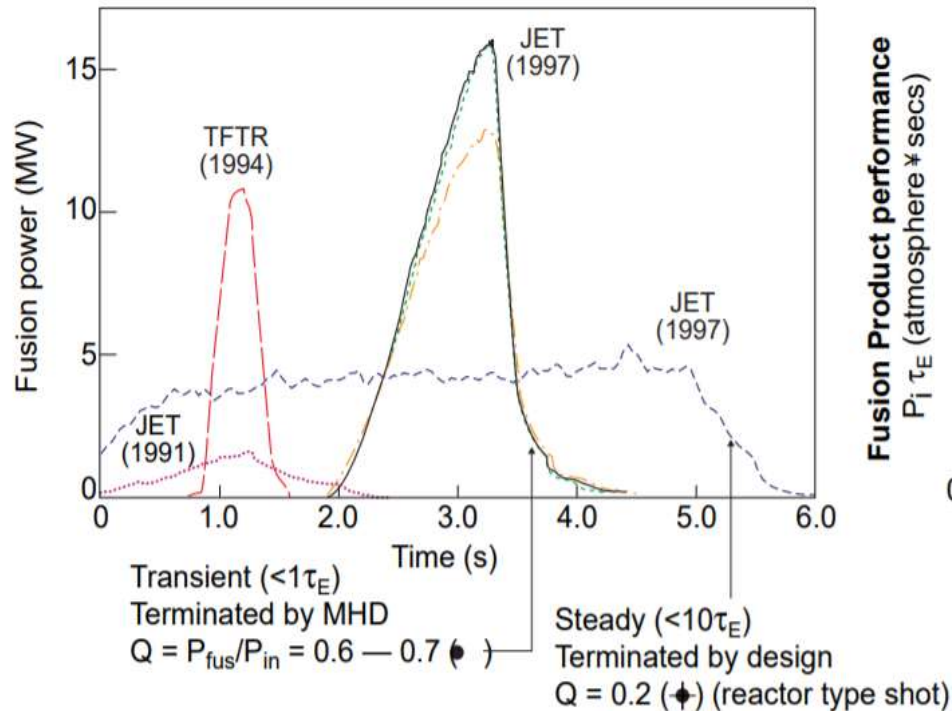
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Contributors



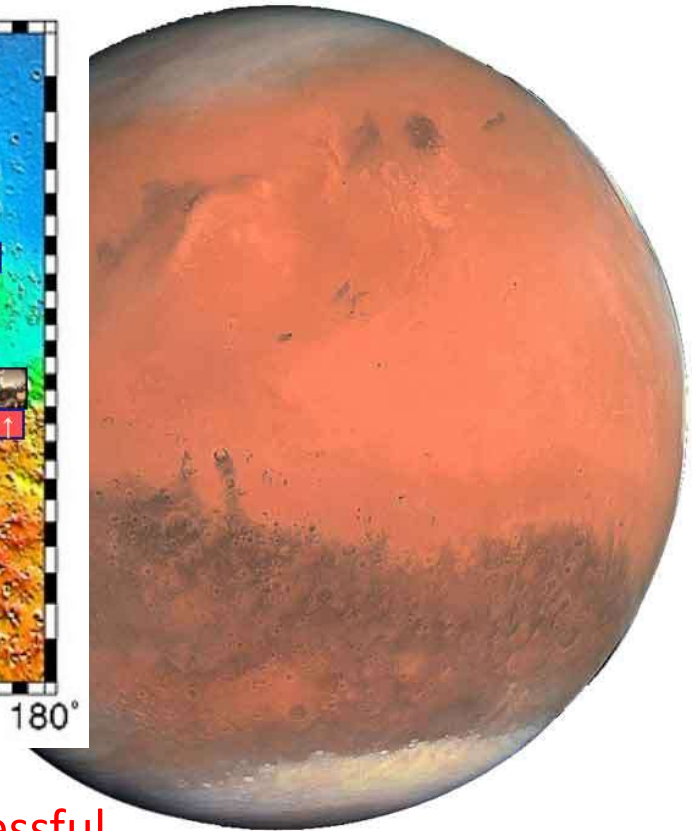
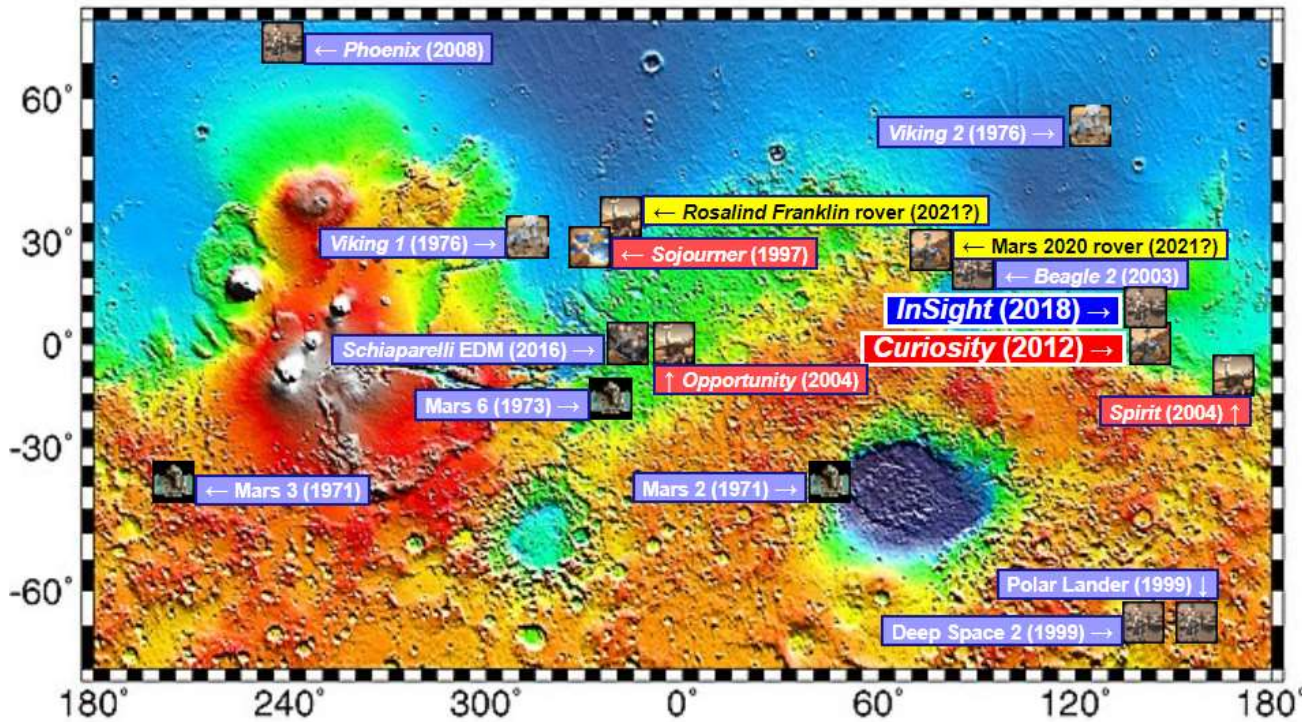
D. Douai, J. Hillesheim, A. Huber, C.F. Maggi, J. Mailloux, E de la Luna, H. Weisen, M. Sertoli, S. Mazzi, L. Frassinetti, D. King, E. Viezzer, C. Challis, J. Hobirk, A. Kappatou, E. Lerche, Y. Kazakov, V. Kiptily, M. Nocente, J. Ongena, F. Rimini, L. Garzotti, D. van Eester, D. Frigione, P. Carvalho, Z. Stancar, G. Szepesi, H-T. Kim, D. Gallart, D. Zarzoso, F. Casson, A. Ho, J. Citrin

DTE1: first DT operation at JET



JET: M Keilhacker et al, Nucl Fus 39(2)(1999), 209
 J Jacquinot et al, Nucl Fus 39(2)(1999), 235
 TFTR: K McGuire et al, Fusion Energy 1996 (Vol 1), 19
 (IAEA-CN-64/01-2)

Why a new DT campaign at JET?: Mars as an example



- 18 missions to Mars with the aim of landing: **10 successful**
- At least 8 more planned by 2025
- New missions allow for: solving previous mistakes, test new and improved technologies, increasing the scope of the research, answer pending questions, adapt research to new requirements...

DTE1: first DT operation at JET, *unsolved issues*

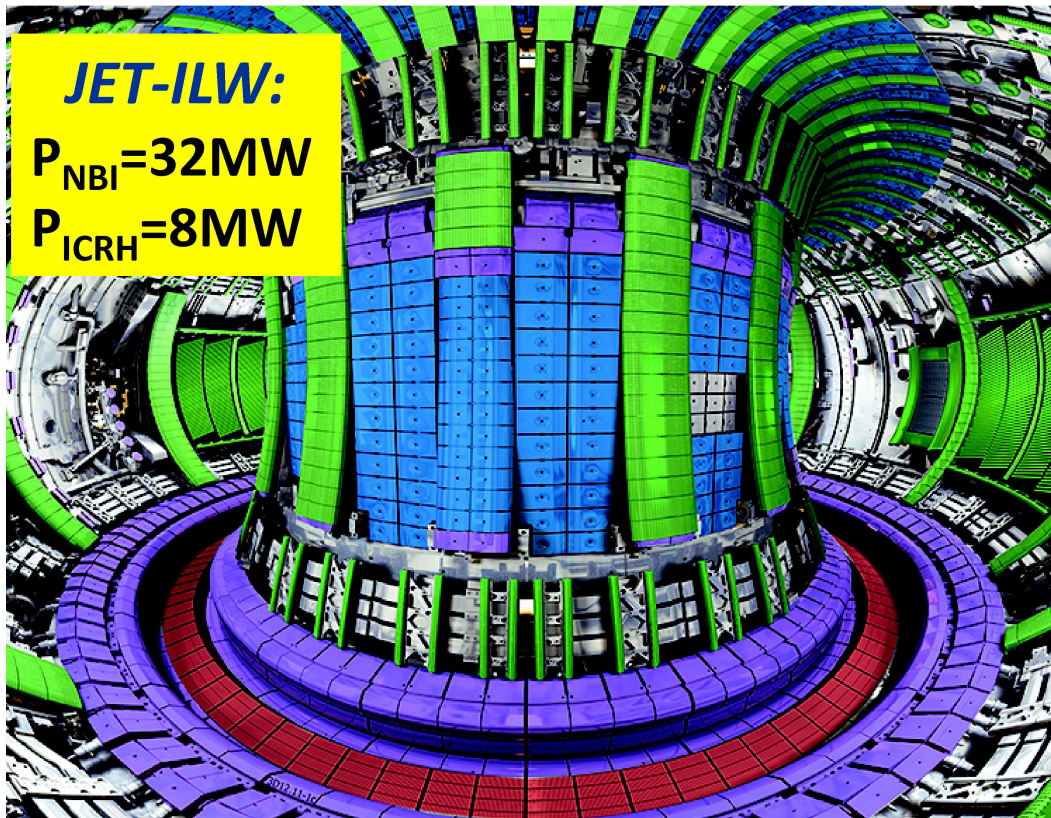


- Record DTE1 plasmas were obtained in plasma conditions less relevant to ITER: transient regime, very low density, $T_i \gg T_e$, ELM free
- H-mode type I ELM plasmas obtained at low power (no high beta plasmas)
- Plasmas obtained in C-wall (high T retention)
- Alpha particle effects weak and difficult to understand
- Alpha heating experiments interpretation difficult
- Isotope effects in contradiction to TFTR
- Diagnostics not as advanced as nowadays

JET is designed for fusion power studies in support of ITER



1975 JET design proposal: “...describes a large Tokamak experiment, which aims to study plasma behaviour in conditions and dimensions approaching those required in a fusion reactor”.



JET-ILW:

$P_{\text{NBI}}=32\text{MW}$

$P_{\text{ICRH}}=8\text{MW}$

- Bulk Be PFCs
- Be-coated inconel PFCs
- Bulk W
- W-coated CFC PFCs

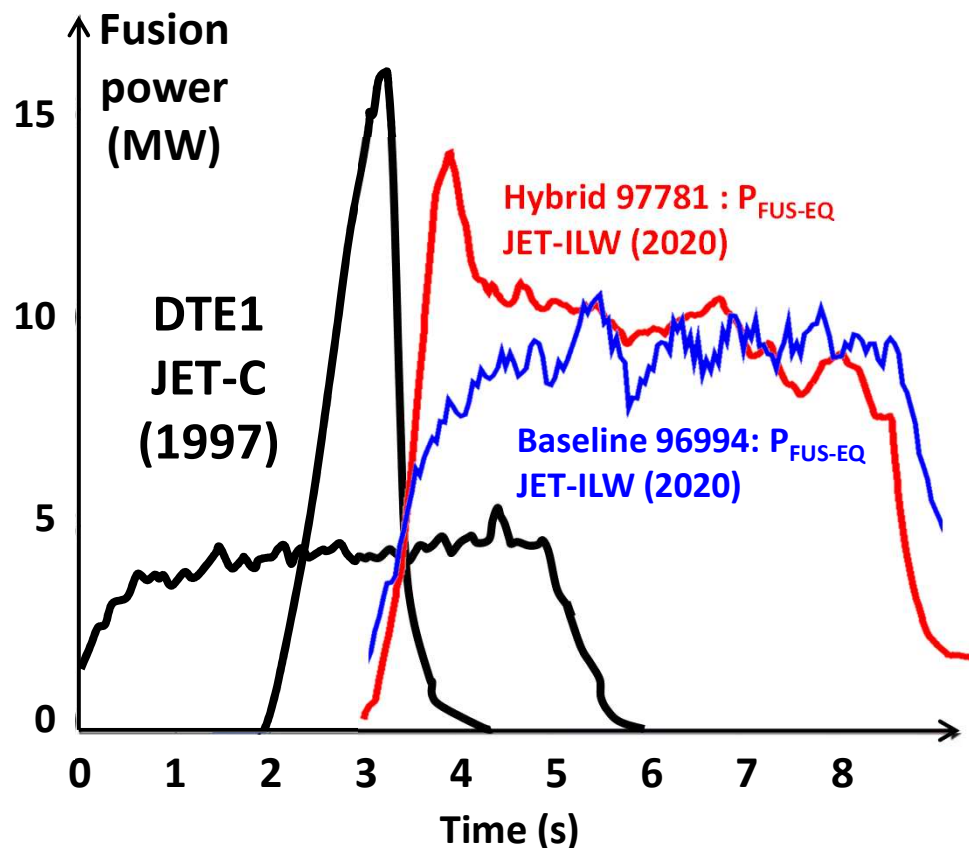
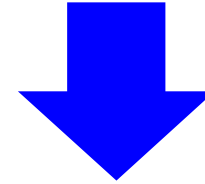
Improved capabilities compared to DTE1:

- ITER relevant wall&divertor
- Diagnostic capabilities
- More heating power
- Disruption prediction and mitigation/control
- RT control schemes
- Sophisticated Modelling
- Better plasma understanding

Objectives and outline



EUROfusion research roadmap: Secure the success of future **ITER operation** via specific preparation and experiments, including D-T operation of JET.

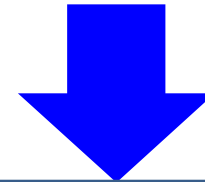
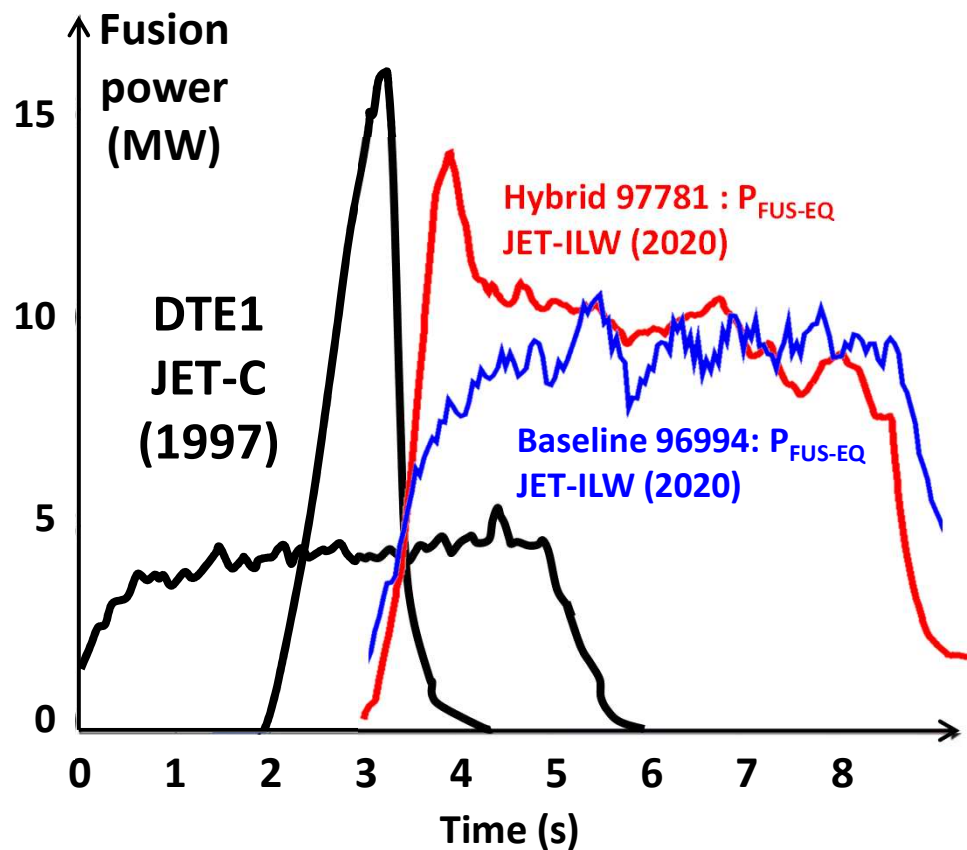


1. Develop D-T scenarios in ITER relevant conditions
2. Understand alpha particle physics
3. Understand isotope physics
4. Prepare the operation in D-T
5. Provide new technology for safe DT operation
6. Understand how to extrapolate from DD to DT and to ITER

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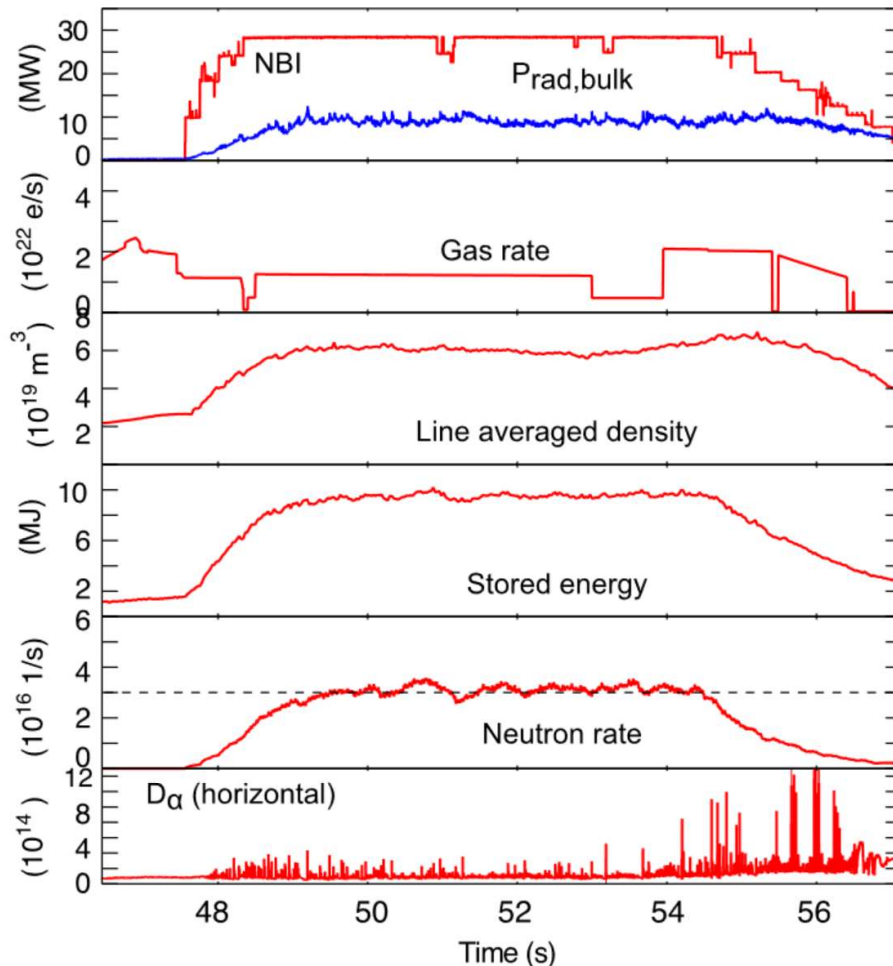


- Develop D-T scenarios in ITER relevant conditions
- Understand alpha particle physics
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- Conclusions

Stationary Scenarios for the DT phase achieved: baseline route



Baseline: 3 MA/2.8 T ($q_{95}=3.1$) 96994

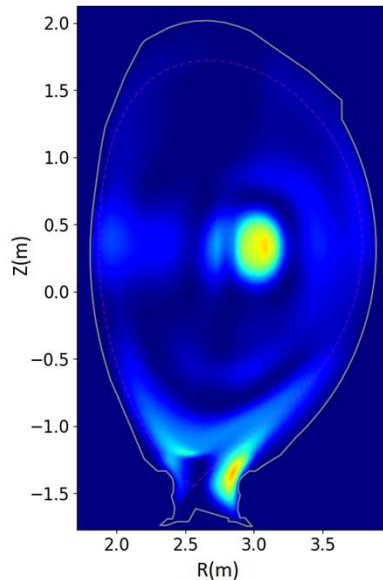


- $H_{98}(y,2) = 1$, $\beta_N = 2.2$, $\beta_p = 0.9$, $f_{GLD} \sim 0.7$
- Significant improvement wrt baseline Type-I ELMs plasmas
 - Reduced gas puff + Pellets (+Ne) open up a route at **high confinement by simultaneously avoiding type-I ELMs**
- Mostly compounded ELMs with **long phases with high frequency small ELMs**
- Core radiated power stable
- Neon (0.5×10^{22} e/s, ~half of D2 throughput):
 - Divertor in 'attached' conditions
- Low or even absent core particle fueling
- Good scenario for alpha particle studies: impact on heating or sawteeth

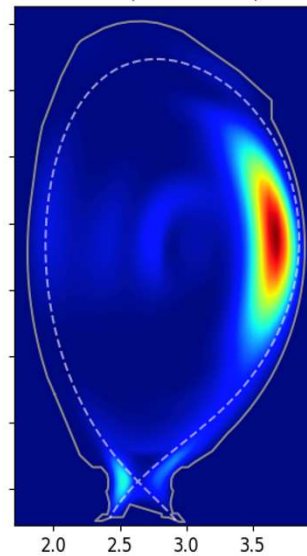
Impurity accumulation avoided



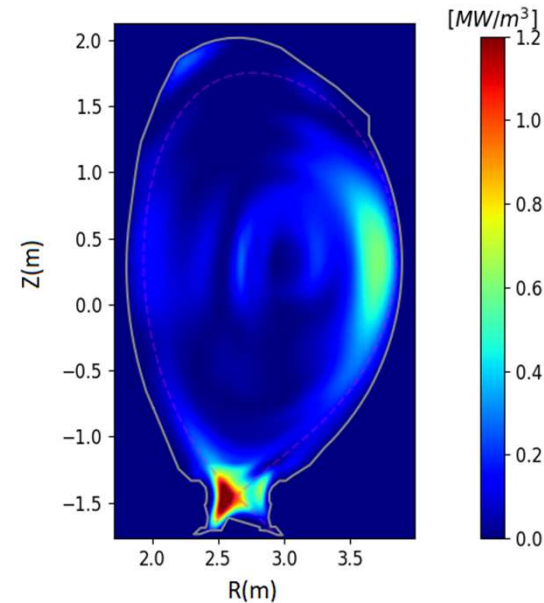
High density peaking
92395



High density peaking 96731
with pellets without Ne



High density peaking 96994
with pellets with Ne

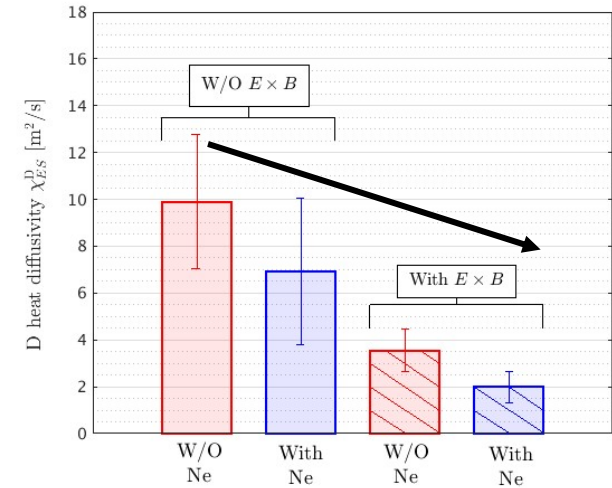
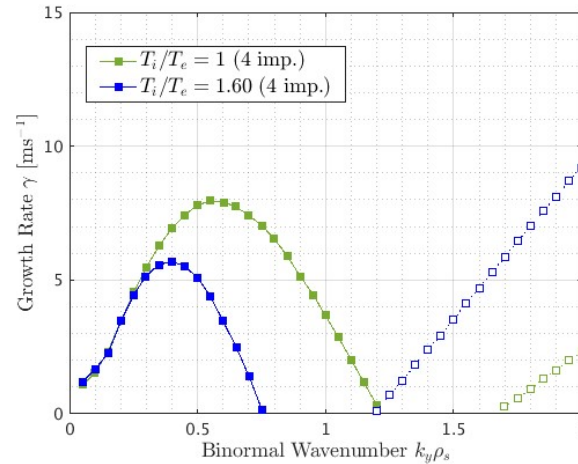
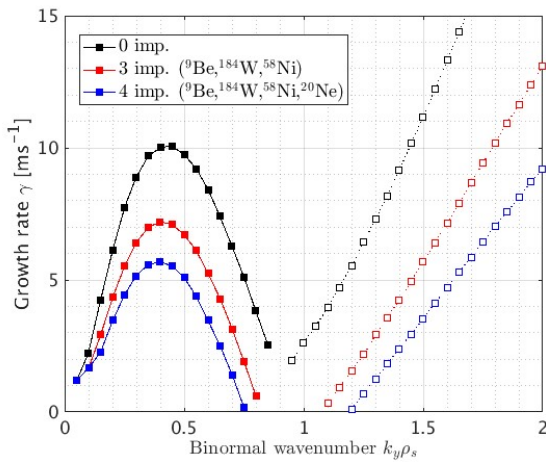


- High density peaking increases W neoclassical inward pinch [F J Casson PPCF 2014]
- Baseline has high density peaking but...
- ...radiated power located in the low field side
- Ne shifts radiation blob to the divertor region
- W density profile is hollow: W is blocked in the outer plasma

Mechanisms for improved confinement



Baseline 96994 @ $\rho=0.8$

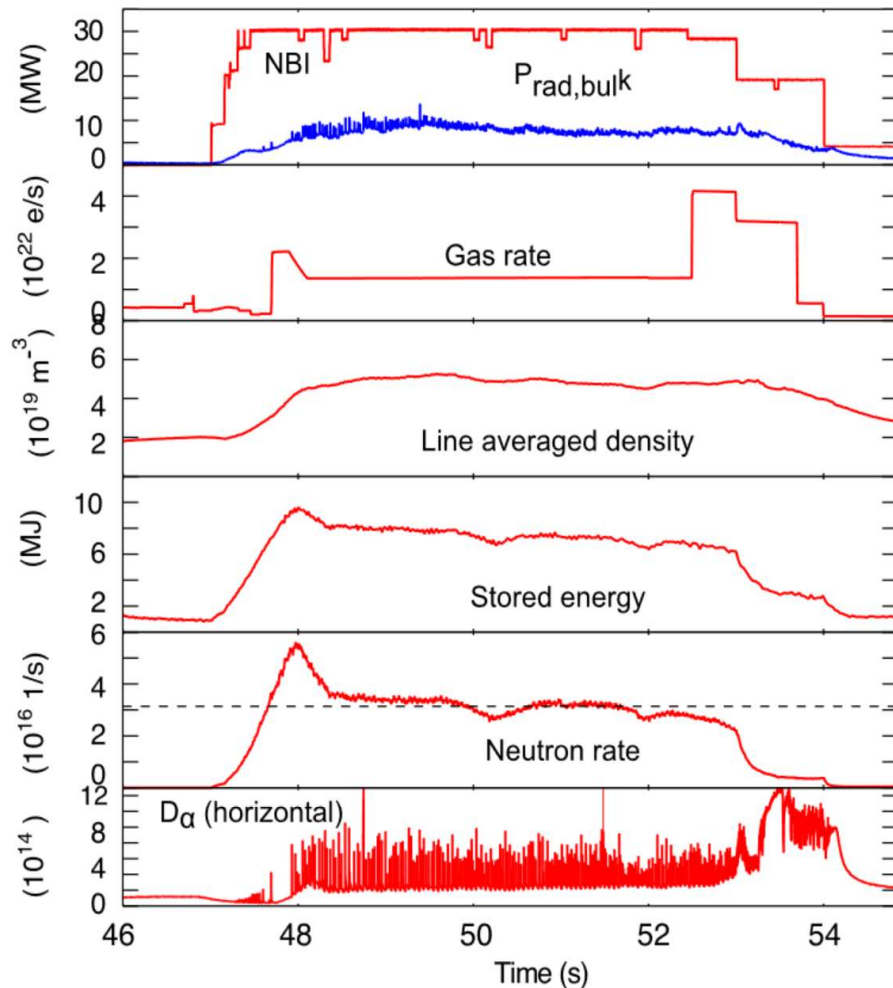


- Gyrokinetic simulations performed with the GENE code
- Three edge physical mechanisms lead to good confinement
- **Ion heat transport reduction** by:
 - Edge impurity concentration dilution (including Ne)
 - $T_i/T_e \sim 1.5$ including the pedestal top
 - Strong edge ExB shearing (as for Hybrid plasmas J. Garcia PPCF 2019)

Stationary Scenarios for the DT phase achieved: hybrid route



Hybrid: 2.3 MA/3.4 T ($q_{95}=4.9$) 97781

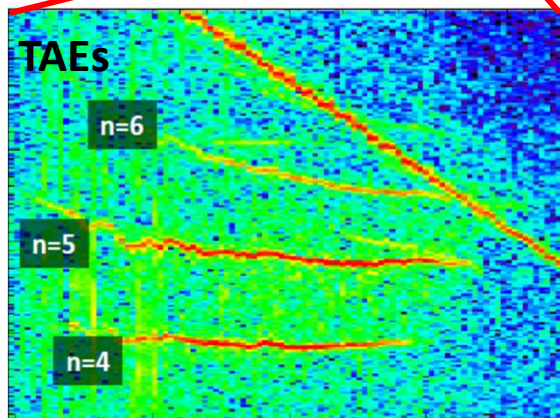
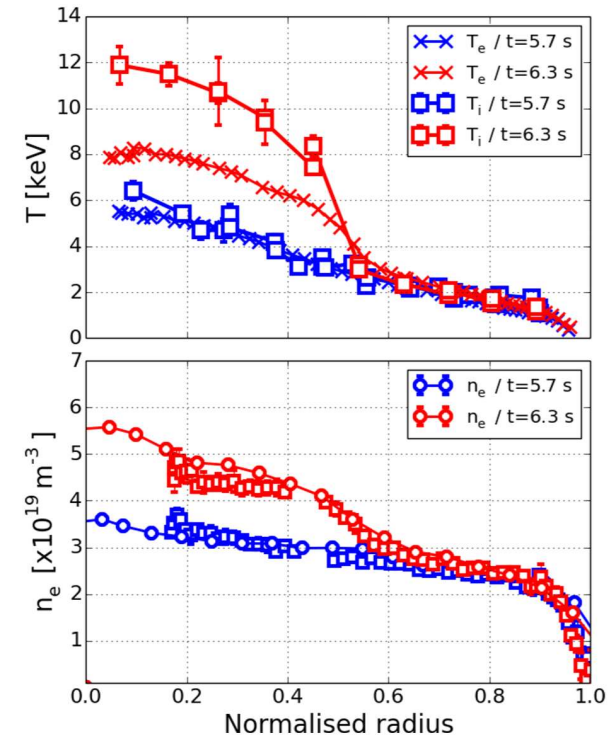
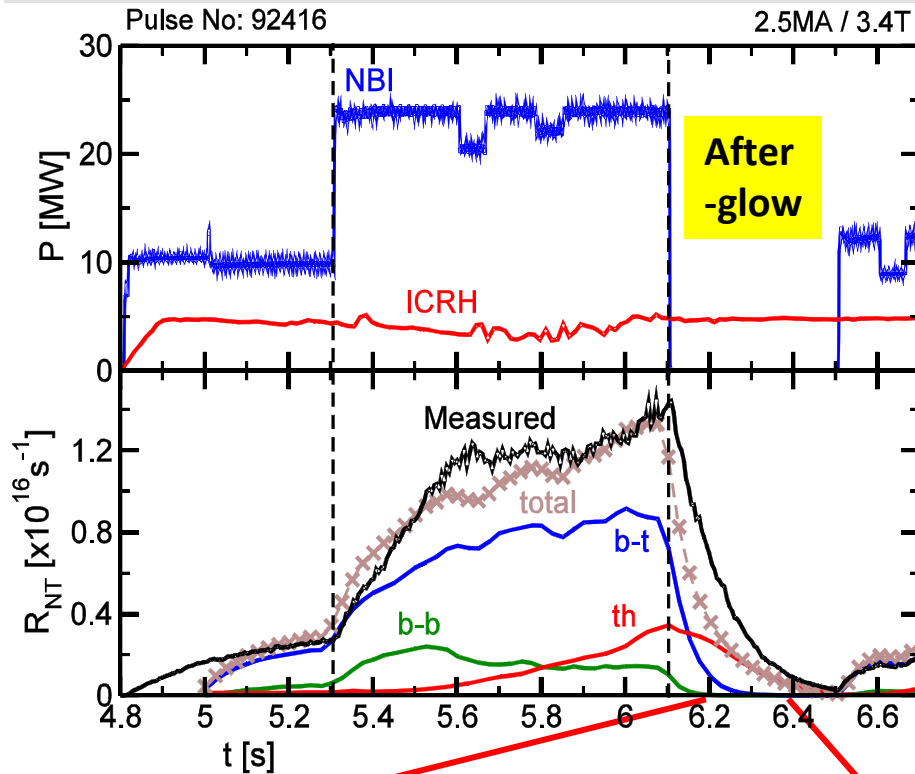


- $H_{98}(y,2) \sim 1.1$, $\beta_N \sim 2.3$, $\beta_p \sim 1.1$, $f_{GLD} \sim 0.65$
- Mix of initial ELM free phase and type I ELMs
- Core radiated power stable and no inner core impurity accumulation
- Unlike baseline scenario, $\beta_p \sim 1.1-1.4$ is necessary for good confinement
- Good scenario for alpha particle studies: impact on turbulence, MHD and fishbones



- Develop D-T scenarios in ITER relevant conditions
- **Understand alpha particle physics**
- Understand isotope physics
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“After-glow” ITB scenario shows promising route for alpha-driven mode studies



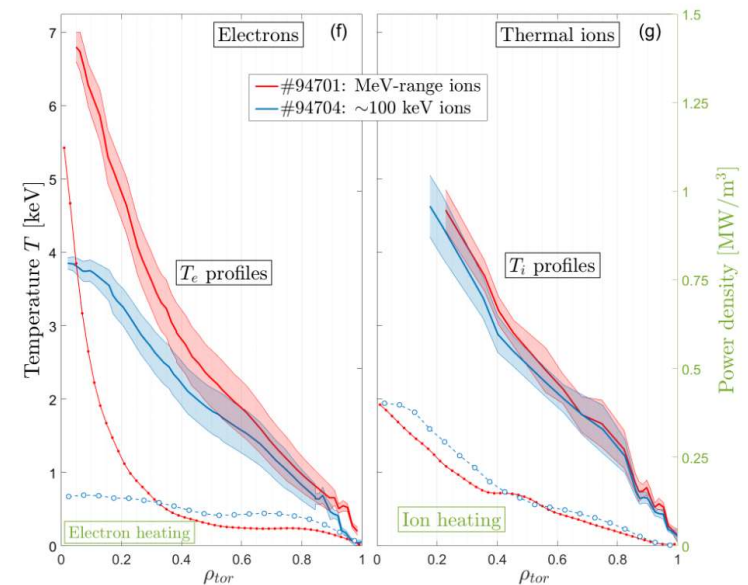
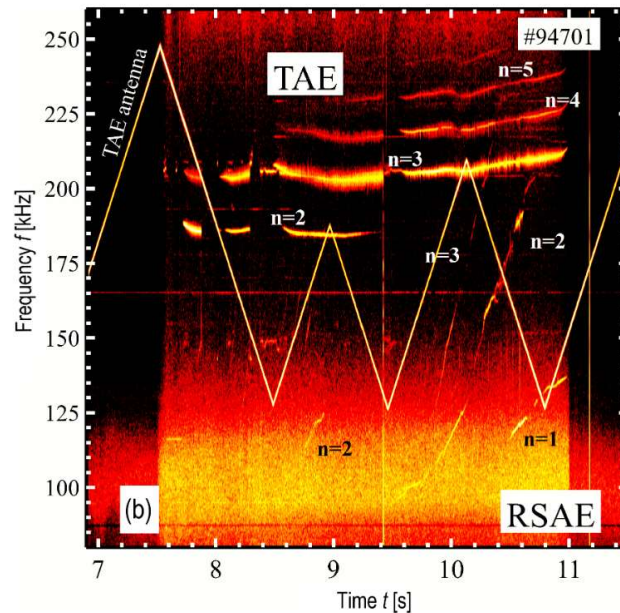
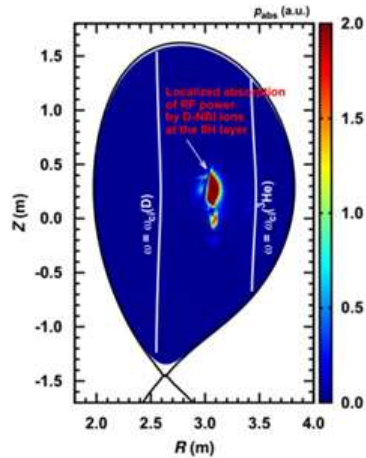
- Afterglow scenario with ITB for TAE studies
- Pellets trigger high frequency ELMs → impurity accumulation avoidance
- Expected performance in DT: $\beta_\alpha(0) \sim 0.33\%$, $\sim 9\text{MW}$ of fusion power

R. Dumont,
NF 2018

JET



Alpha effects on turbulence and transport

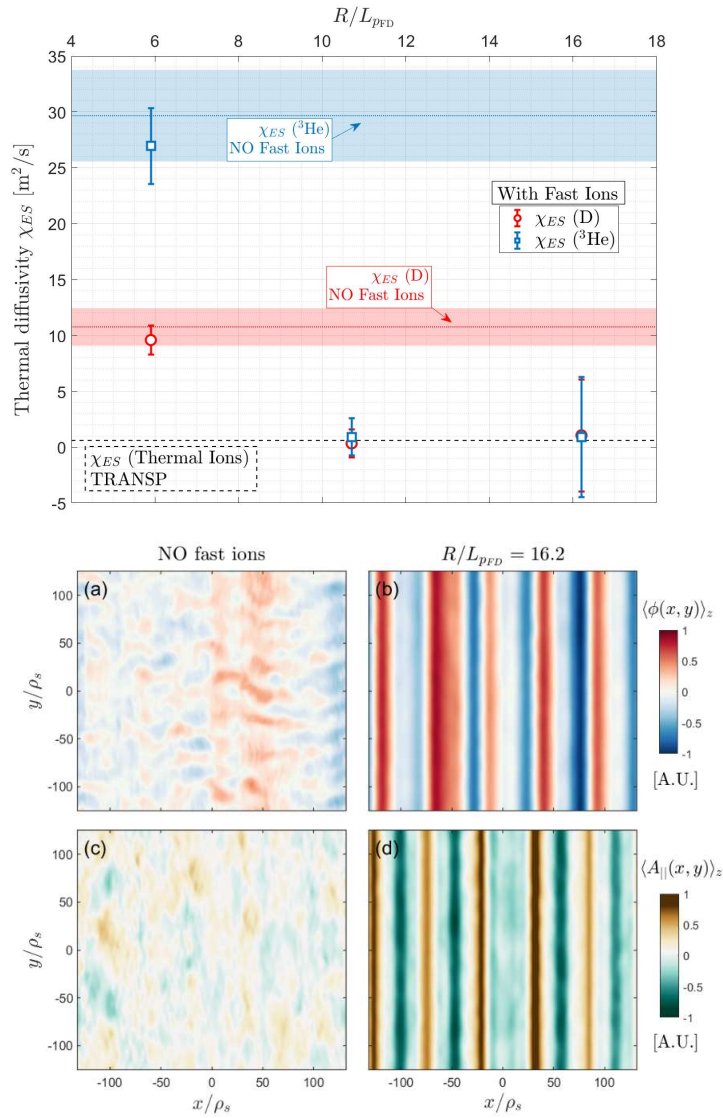


Y. Kazakov NF 2020
M. Nocente NF 2020
V. Kiptily submitted to PRL

- ICRH 3 ions scheme in D-³He provide MeV ions and mostly electron heating
- Strong AE activity obtained
- Plasmas with ICRH electron heating have higher T_i than NBI plasmas at the same total power and density
- Improved confinement with electron heating and AE activity



Alpha effects on turbulence and transport



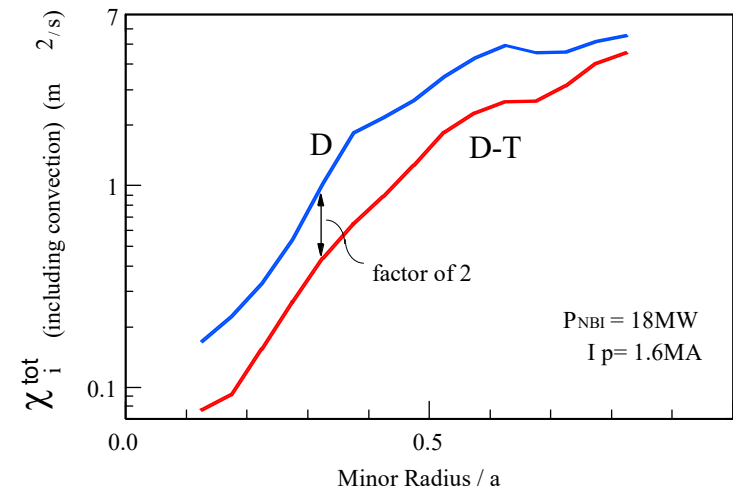
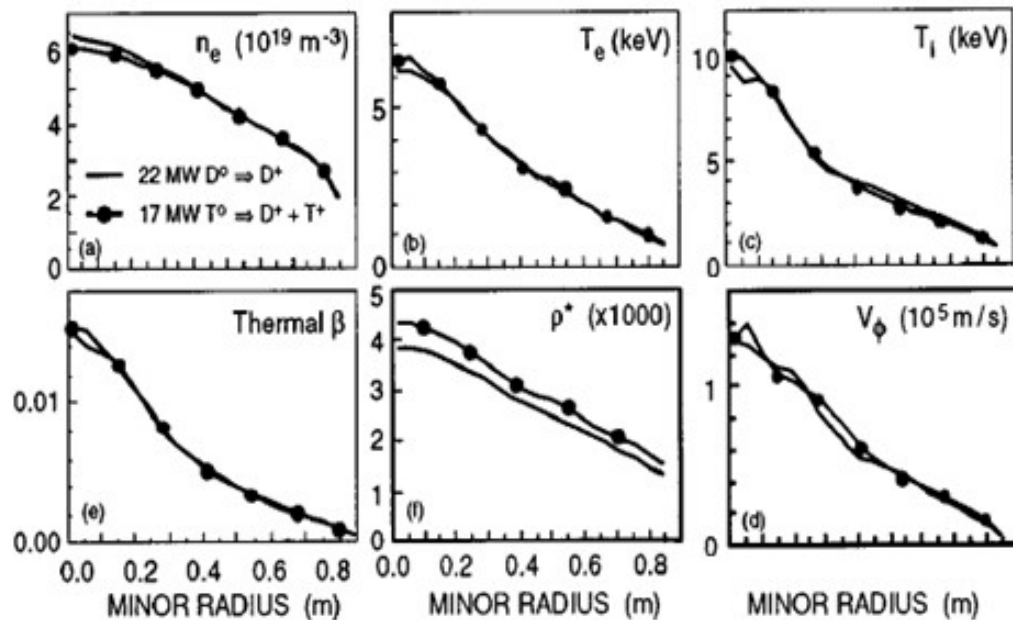
- GENE simulations: MeV ions completely suppress ion electrostatic transport
- Only in the presence of marginally or even fully developed AE
- Fast ions energy is channelled through zonal activity to thermal ions
- Similar effect expected with α 's in DT
- In view of ITER: essential to decouple from alpha heating and pure isotope effects

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Isotope effects in DT?



S.D. Scott *et al.*, PoP 1995

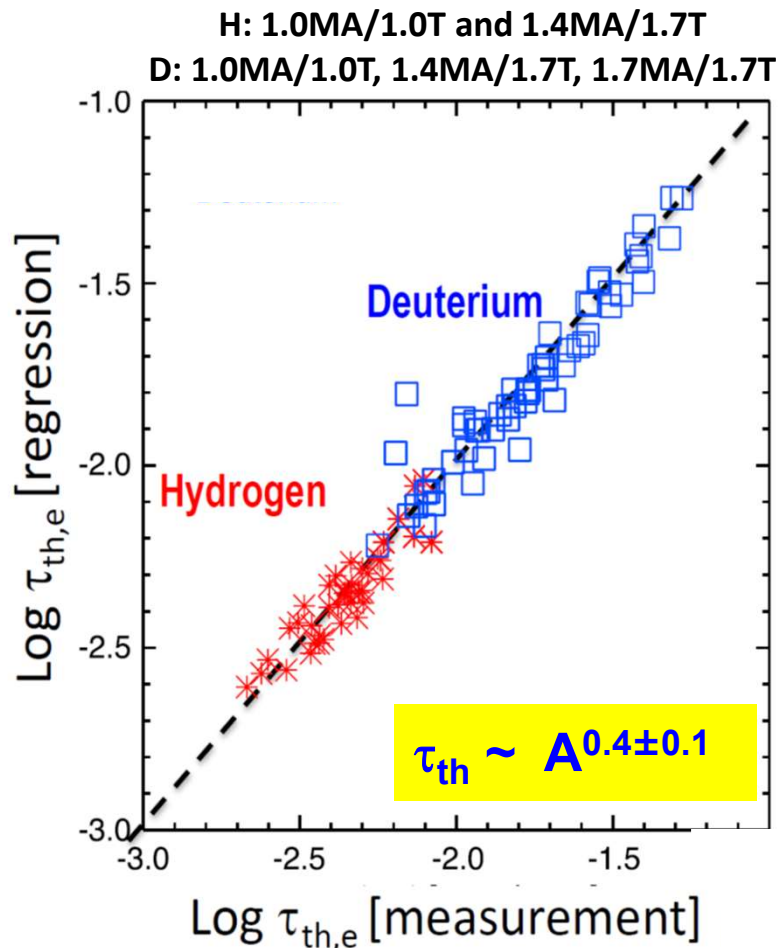
- High core β (high NBI power) L-mode discharges at TFTR
- Supershot at fixed power, $\tau_E^{thermal} \sim \langle A \rangle^{0.82}$, at lower power $\tau_E^{thermal} \sim \langle A \rangle^{0.5}$
- Low core β (low NBI power) ELMy H-mode discharges at JET
- Core scaling in ELMy H-mode: $\tau_{E,core}^{thermal} \sim \langle A \rangle^{-0.16}$ [J. G. Cordey *et al.*, NF 1999]

What can be expected in ITER DT plasmas?

Type I ELMy H-mode: strong positive isotope dependence on thermal confinement



H-mode confinement scaling with mass



Stronger isotope dependence than in JET-C and IPB98(y,2) ($\sim A^{0.2}$)

Global momentum $\sim A^{0.5 \pm 0.15}$

Global particle $\sim A^{0.5 \pm 0.06}$

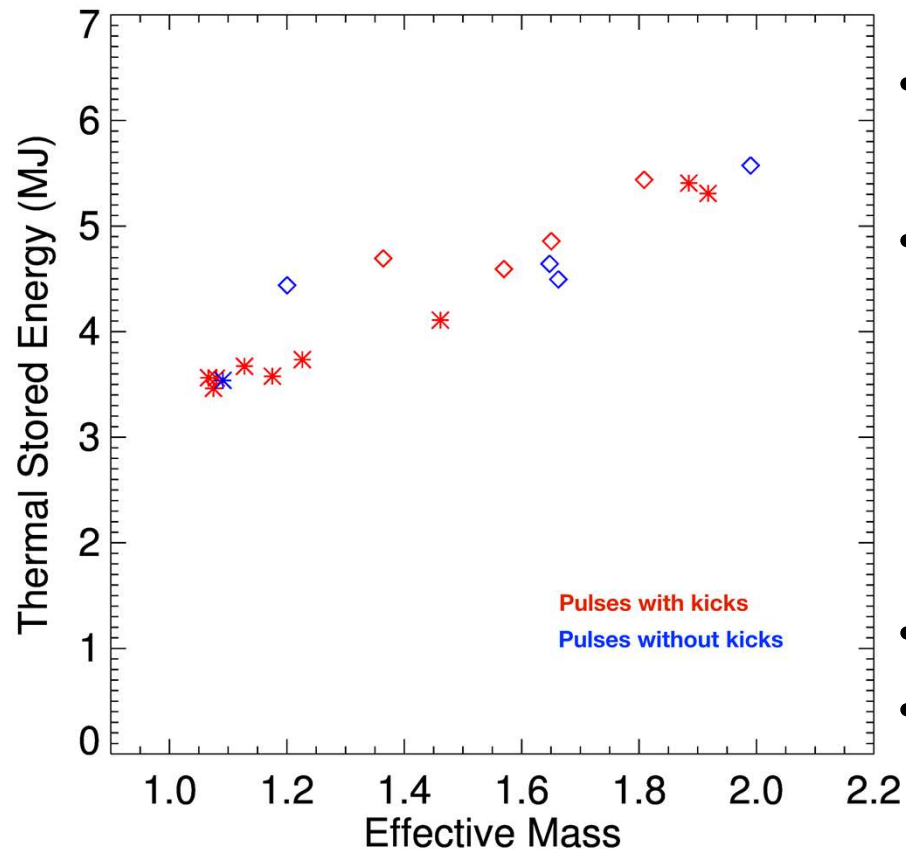
All scalings robust against the set of variables chosen for the regression.

Density systematically lower in H at same external fuelling

C. Maggi, PPCF 2018
H. Weisen JPP 2020

The pedestal is crucial player in the observed isotope dependence

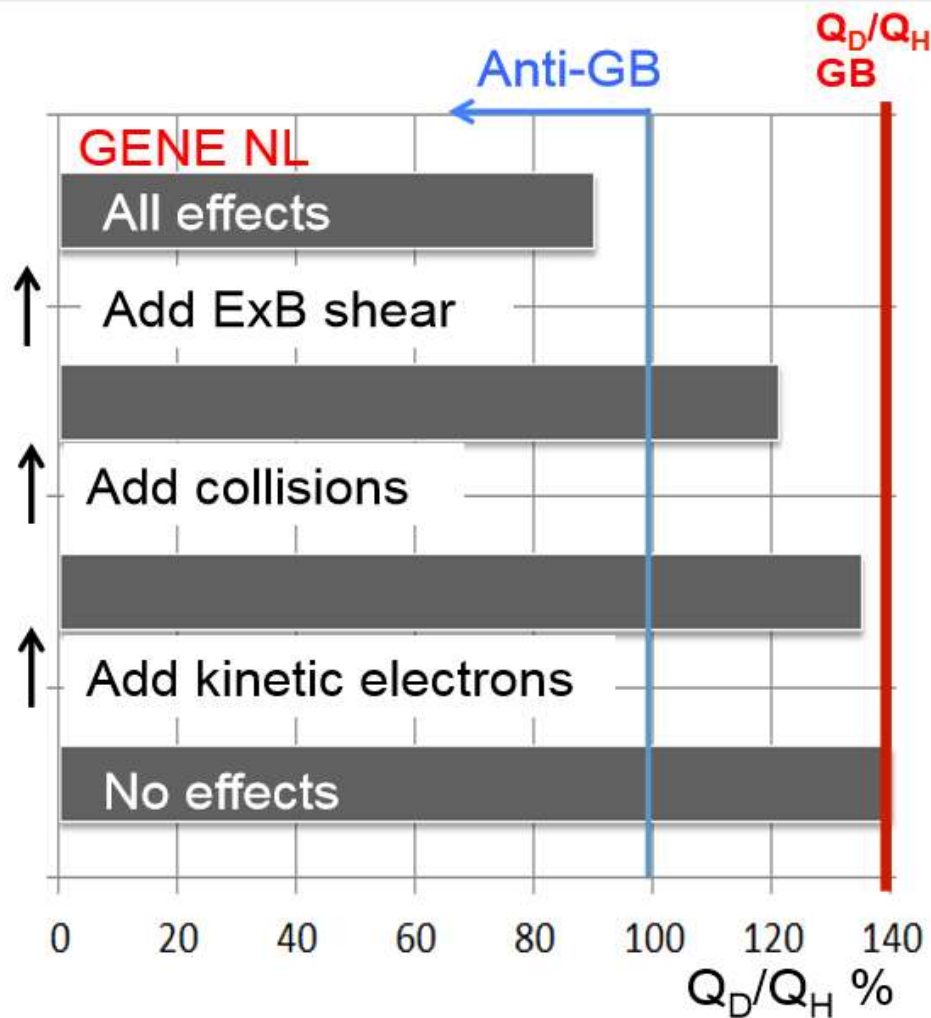
Continuous confinement transition between H and D



D King, E Viezzer et al., NF 2020

- Continuous confinement transition between H and D
- However, **results highly dependent on the pedestal** at:
 - Constant fuelling
 - Constant ELM frequency with Kicks
 - Closeness to L-H transition at constant power
- Core isotope effect less clear
- Results essential to understand DT mixtures

Gyrokinetic isotope effects in core transport

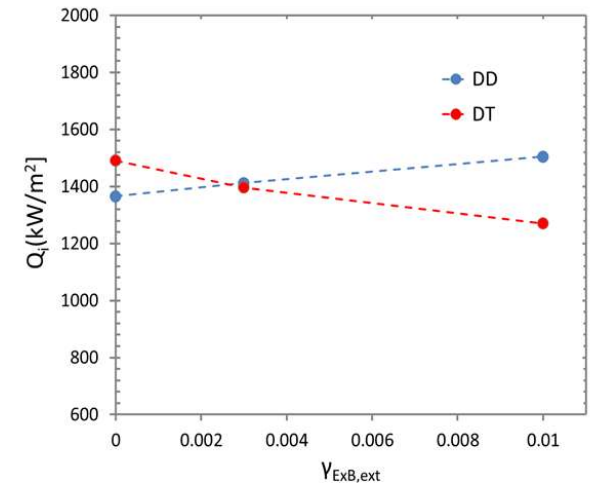
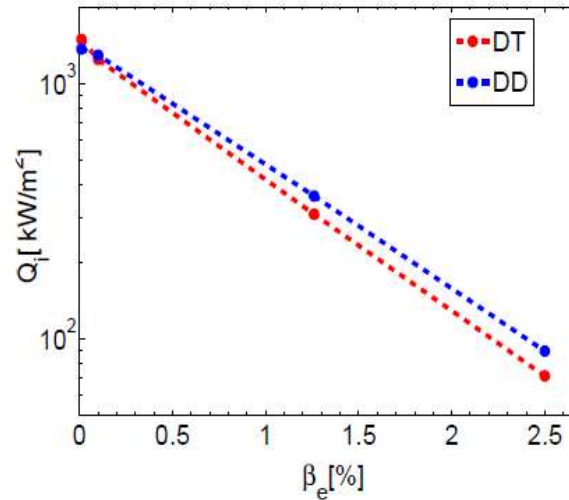
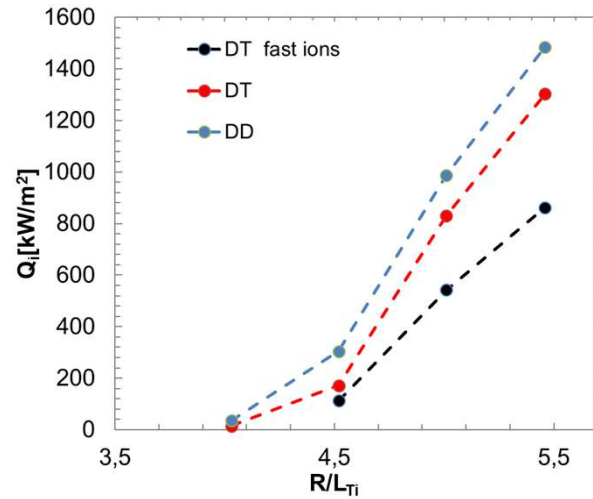


J. Garcia NF 2019

P. Mantica 2019

- Gyrokinetic simulations performed with the GENE code for L-mode plasmas:
 - Local deviations from GB heat flux are caused by different parameters
 - Kinetic electrons, collisions and ExB shearing
 - Deviations are weak
- Different fast ion content can also lead to an “apparent” isotope effect (Bonanomi NF 2019)
- Plasmas at higher torque and power expected to have stronger core isotope effects

Strong Isotope effects expected for DT at high input power and β



J. Garcia POP 2018, J. Garcia NF 2017

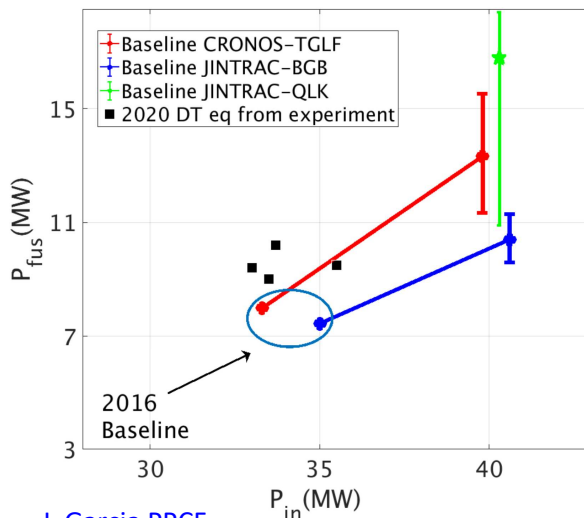
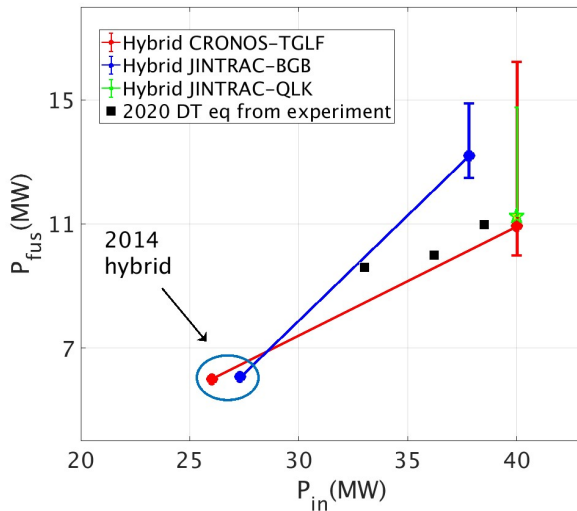
- DT plasmas can lead to strong core transport isotope effects with **simultaneous**
 - Significant presence of alpha particles
 - High core β and pressure gradients
 - Strong rotation

High input NBI power plasmas at high β will be key in JET DT



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"Predict first" essential activity performed before DT



J. Garcia PPCF
2017

J. Garcia NF 2019

J. Morales EPS
2018

S. Saarelma POP
2019

F.J. Casson NF 2020

JET

- Strong JET “Predict first” activity has been helpful for:
 - Identify physics that boost alpha power generation
 - Identify fundamental differences between DD and DT plasmas
 - Guide DD experiments
 - Disentangle non-linear and coupled effects
- Extrapolations performed to DT started in 2014 with **validated models with D and H plasmas**
- **Broad variety of models and integrated modelling suites used** (“Never rely on only one model for extrapolation”)
- Error bars account for: simulations sensitivity and isotope effects
- **$P_{fus} \sim 10-16\text{MW}$ for hybrid and baseline: significant core isotope effects for hybrid route**
- Comparison to 2020 DT equivalent fusion power is encouraging

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Highlights of the preparation for D-T



- ❑ Existing D-T scenarios have reached 9-10MW/5s equivalent fusion power and can attain 10 to 16MW of fusion power with 40MW of input power in the JET ITER-like wall
- ❑ After-glow ITB scenario is a credible route for alpha particle driven instabilities study and code validation for ITER
- ❑ Extended parameter space found in DD for AE excitation
- ❑ Confinement and particle transport show strong positive isotope dependences and is also investigated for ITER conditions
- ❑ First principle modelling show that strong isotope effects can be found at high power
- ❑ Alpha particles expected to play a strong role on transport
- ❑ Before DT, TT-campaign expected to further contribute to DT plasmas preparation