EUROfusion

Impact of H, D, T and D-T Hydrogenic Isotopes on Detachment in JET ITER-like Wall Low-Confinement Mode Plasmas

2nd IAEA Technical Meeting on the Collisional-Radiative Properties of Tungsten and Hydrogen in Edge Plasma of Fusion Devices, Vienna, Austria, Nov 29 – Dec 1, 2023

Mathias Groth, et al.

Aalto University, Espoo, Finland; e-mail: mathias.groth@aalto.fi

Full author list and affiliations on the next slides

JET

Aalto University

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

Acknowledgements

M. Groth[1], S. Aleiferis[2,3], S. Brezinsek[4], M. Brix[3], R. Chandra[1], I.S. Carvalho[3,5], P. Carvalho[3,5], G. Corrigan[3], D. Harting[3,4], N. Horsten[1,6], I. Jepu[3,7], J. Karhunen[1,3,8], K. Kirov[3], B. Lomanowski[1,9], K.D. Lawson[3], C. Lowry[3], A.G. Meigs[3], S. Menmuir[3], R.B. Morales[3], A.H. Nielsen[10], E. Pawelec[11], T. Pereiras[3], D. Reiter[12], A. Shaw[3], S. Silburn[3], V. Solokha[1], M.F. Stamp[3], B. Thomas[3], S. Wiesen[4], P. Beaumont[3], J. Bernado[3], P. Boerner[4], D. Borodin[4], I. Coffey[13], N.J. Conway[3], E. Delabie[9], E. De La Luna[14], D. Douai[15], D. Dunai[16], C. Giroud[3], R. Gomes[5], J. Hillesheim[3], L. Horvath[3], A. Huber[4], S. Jachmich[17], H. Kumpulainen[1], P. Lomas[3], C.F. Maggi[3], M. Maslov[3], C. Perez von Thun[18], G. Petravich[16], J.J. Rasmussen[10], D. Refy[16], V.-P. Rikala[1], S. Scully[3], G. Sergienko[4], Z. Stancar[3], N. Vianello[19],M. Wischmeier[20], and JET Contributors*

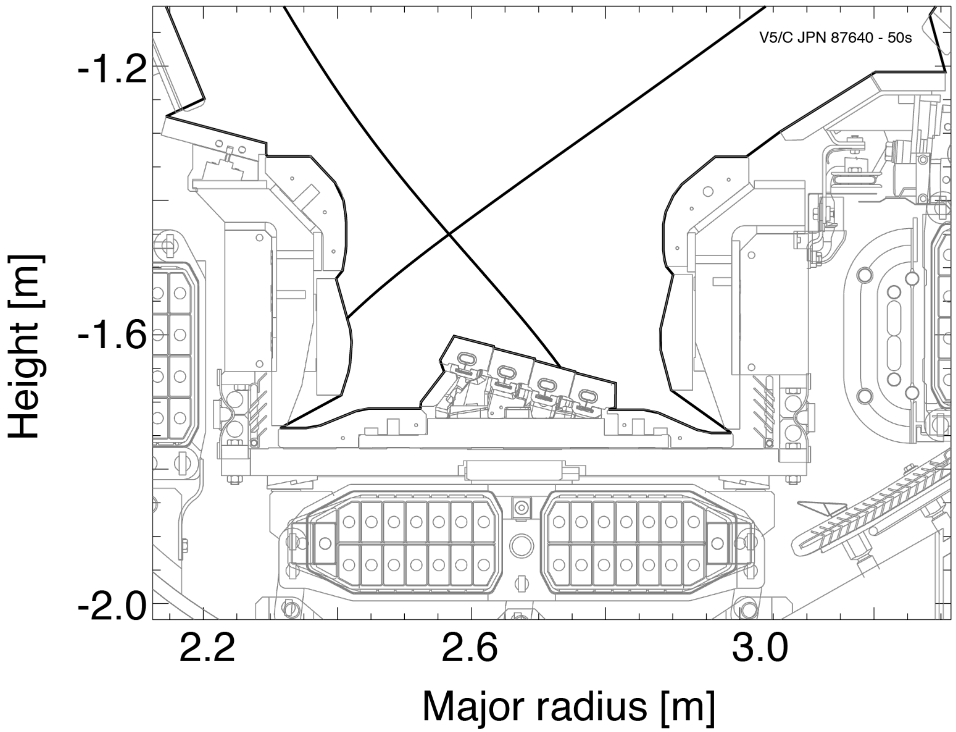
EUROfusion Consortium, JET, Culham Science Centre, Abingdon, OX14 3DB, UK

**See Appendices of F. Romanelli, Proc. 24th IAEA-FEC, San Diego, USA, F. Romanelli, Proc. 25th IAEA-FEC, St. Petersburg, Russia, X. Litaudon, Proc. 25th IAEA-FEC, Kyoto, Japan, E. Joffrin et al., Proc. of the 27th IAEA-FEC 2018, Gandhinagar, India, J. Mailloux, Proc. 28th IAEA-FEC 2020, Nice, France, and C.F. Maggi, Proc. 29th IAEA-FEC 2023, London, UK*

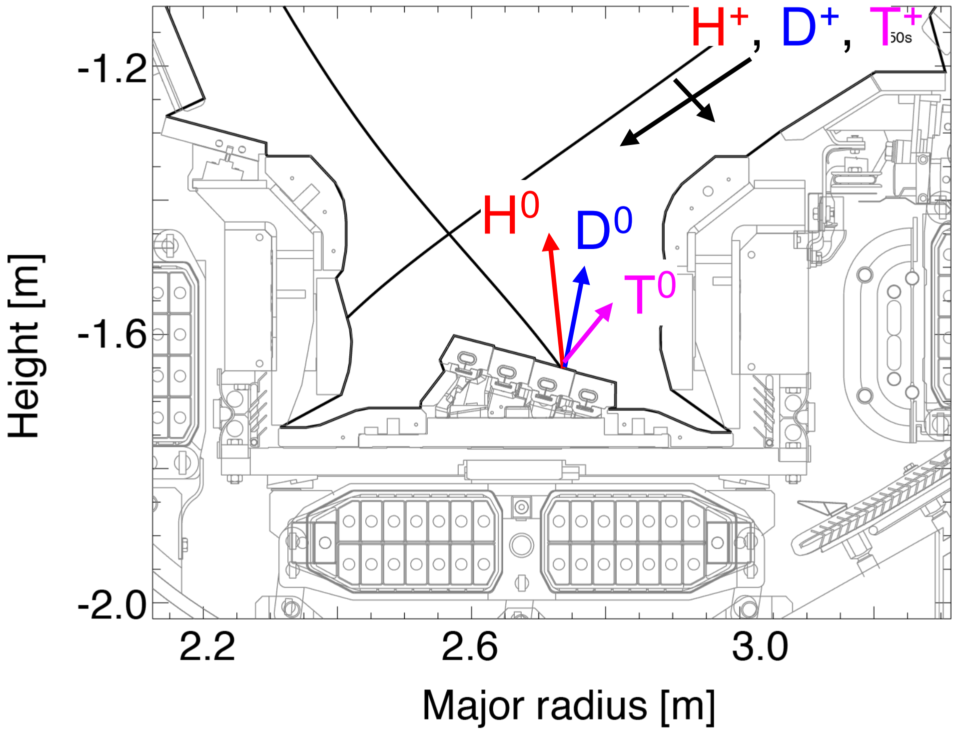
Affiliations

[1]Aalto University, Espoo, Finland; Email: mathias.groth@aalto.fi
[2]NCSR Demokritos Institute of Nuclear and Particle Physics, Athens, Greece
[3]UKAEA, Culham Science Centre, Abingdon, UK
[4]Forschungszentrum Jülich, Institute for Energy and Climate Research Plasma Physics, Jülich, Germany
[5]Instituto de Plasmas e Fusão Nuclear, Universidade Tecnica de Lisboa, Lisbon, Portugal
[6]KU Leuven, Leuven, Belgium
[7]National Institute for Laser Plasma and Radiation Physics, Măgurele, Romania
[8]Department of Physics, University of Helsinki, Helsinki, Finland
[9]Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA
[10]Technical University of Denmark, Kgs.-Lyngby, Denmark
[11]University of Opole, Opole, Poland
[12]Heinrich Heine University Düsseldorf, Düsseldorf, Germany
[13]Astrophysics Research Centre, School of Mathematics and Physics, Queen's Univ. Belfast, UK
[14]Laboratorio Nacional de Fusion, CIEMAT, Madrid, Madrid, Spain
[15]CEA, IRFM, Saint Paul Lez Durance, France
[16]Atomic Energy Research Institute, Centre for Energy Research, Budapest, Hungary
[17]LPP, Ecole Royale Militiare/Koninkllijke Militaire School, Brussels, Belgium
[18]Institute of Plasma Physics and Laser Microfusion (IPPLM), Warsaw, Poland
[19]Consorzio RFX, CNR, ENEA, INFN, Università di Padova, Padova, Italy
[20]Max Planck Institut für Plasmaphysik, Garching, Germany

How significant is the impact of hydrogen isotopes on the divertor conditions and degree of detachment?



How significant is the impact of hydrogen isotopes on the divertor conditions and degree of detachment?

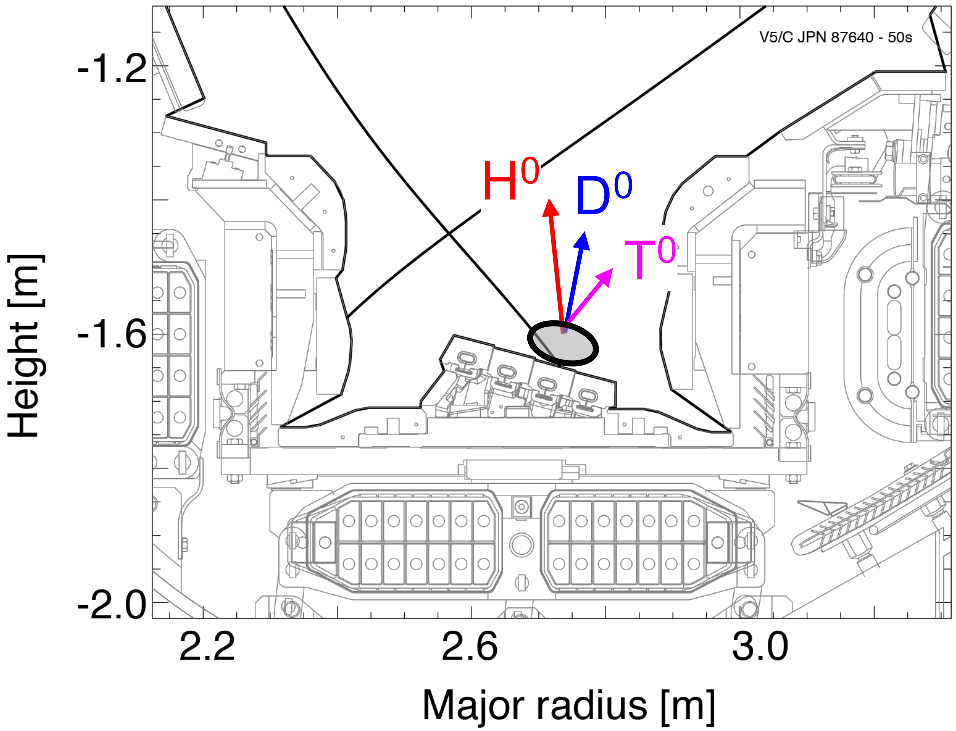


- For the same energy heavier ions are slower

⇒ Widens scrape-off layer ($\propto \sqrt{m_{ion}}$)

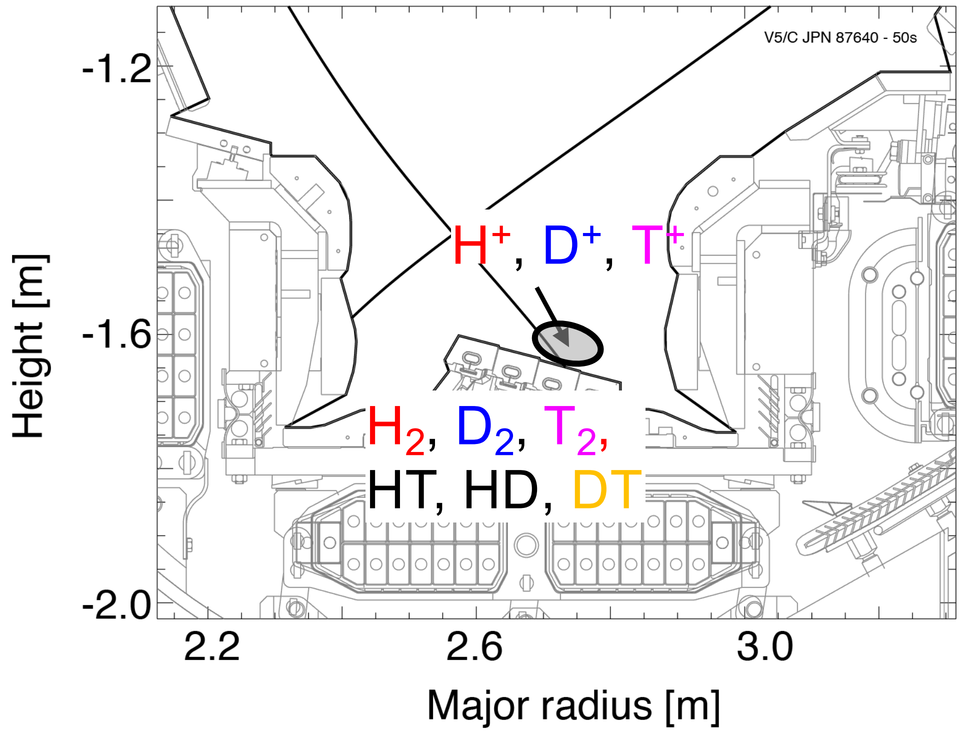
⇒ Reduces veloc. of fast-refl. atoms ($\propto 1/\sqrt{m_{ion}}$)

How significant is the impact of hydrogen isotopes on the divertor conditions and degree of detachment?



- For the same energy heavier ions are slower
  - ⇒ Widens scrape-off layer ($\propto \sqrt{m_{ion}}$)
  - ⇒ Reduces veloc. of fast-refl. atoms ($\propto 1/\sqrt{m_{ion}}$)
- Heavier (F-C and CX) atoms have a shorter ionisation mean free path ($\propto 1/\sqrt{m_{atom}}$)

How significant is the impact of hydrogen isotopes on the divertor conditions and degree of detachment?



- For the same energy heavier ions are slower

⇒ Widens scrape-off layer ($\propto \sqrt{m_{ion}}$)

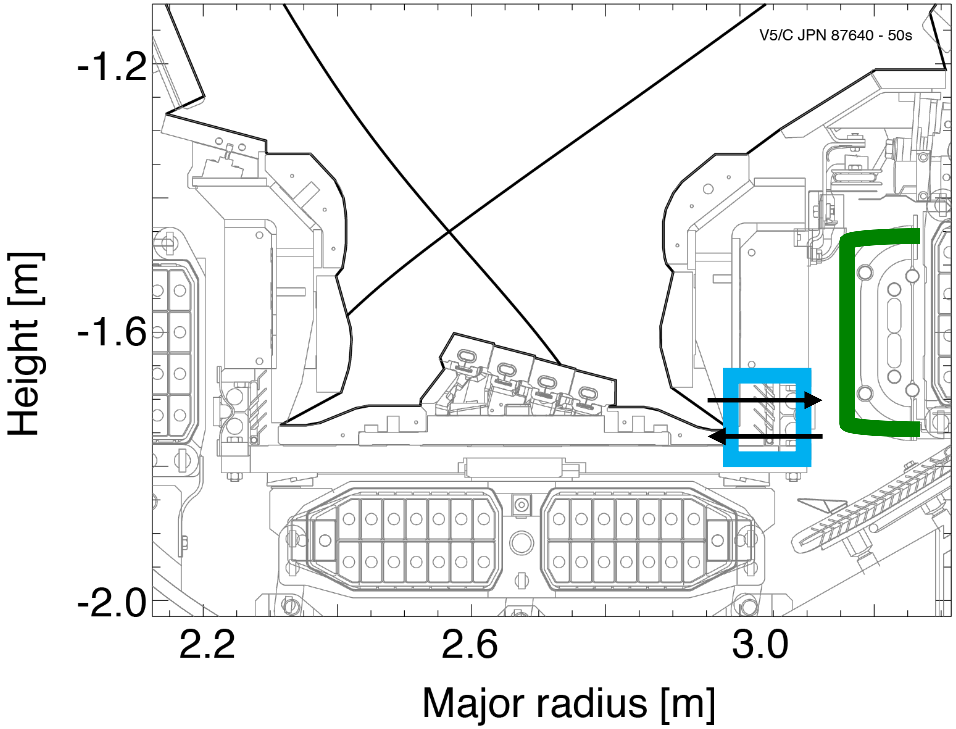
⇒ Reduces veloc. of fast-refl. atoms ($\propto 1/\sqrt{m_{ion}}$)

- Heavier (F-C and CX) atoms have a shorter ionisation mean free path: $\propto 1/\sqrt{m_{atom}}$

- Stronger ion-molecular interaction (rates) for heavier species for temperatures < 2 eV

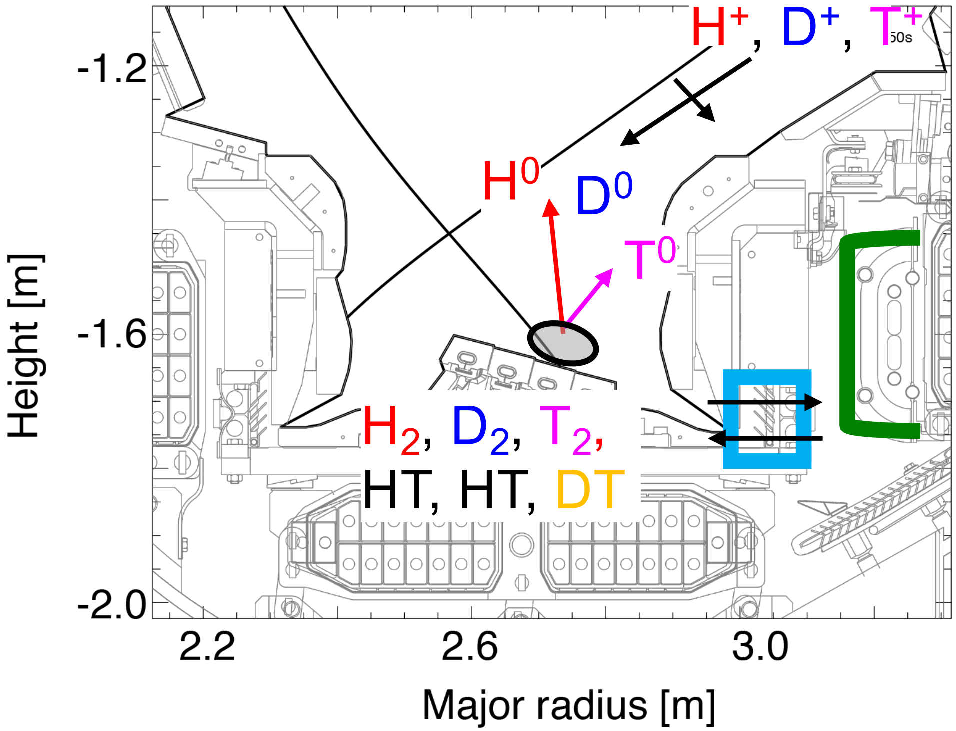
JET

How significant is the impact of hydrogen isotopes on the divertor conditions and degree of detachment?



- For the same energy heavier ions are slower
- ⇒ Widens scrape-off layer ($\propto \sqrt{m_{ion}}$)
- ⇒ Reduces veloc. of fast-refl. atoms ($\propto 1/\sqrt{m_{ion}}$)
- Heavier (F-C and CX) atoms have a shorter ionisation mean free path: $\propto 1/\sqrt{m_{atom}}$
- Stronger ion-molecular interaction (rates) for heavier species for temperatures < 2 eV
- Conductance of pump duct: $\propto 1/\sqrt{m_{mol}}$
- Sticking probab. of cryo. pump: $\propto X * m_{mol}$

How significant is the impact of hydrogen isotopes on the divertor conditions and degree of detachment?



- For the same energy heavier ions are slower

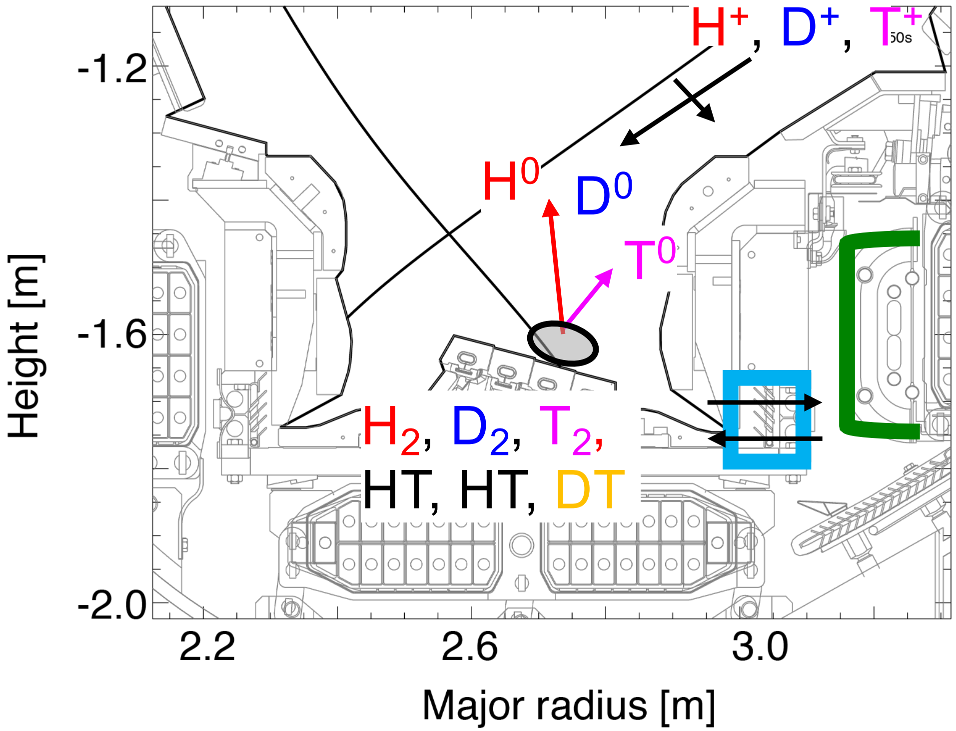
⇒ Widens scrape-off layer ($\propto \sqrt{m_{ion}}$)

⇒ Reduces veloc. of fast-refl. atoms ($\propto 1/\sqrt{m_{ion}}$)

- Heavier (F-C and CX) atoms have a shorter ionisation mean free path: $\propto 1/\sqrt{m_{atom}}$
- Stronger ion-molecular interaction (rates) for heavier species for temperatures < 2 eV
- Conductance of pump duct: $\propto 1/\sqrt{m_{mol}}$
- Sticking probab. of cryo. pump: $\propto X * m_{mol}$

⇒ Individually, isotope effect ≈ 40-70% ⇒ combined effect cumulative or offsetting?

How significant is the impact of hydrogen isotopes on the divertor conditions and degree of detachment?



- JET-carbon, L-mode, VT: 30% higher density limit for T versus H*

*C.F. Maggi et al., Nucl. Fusion 1999

- For the same energy heavier ions are slower

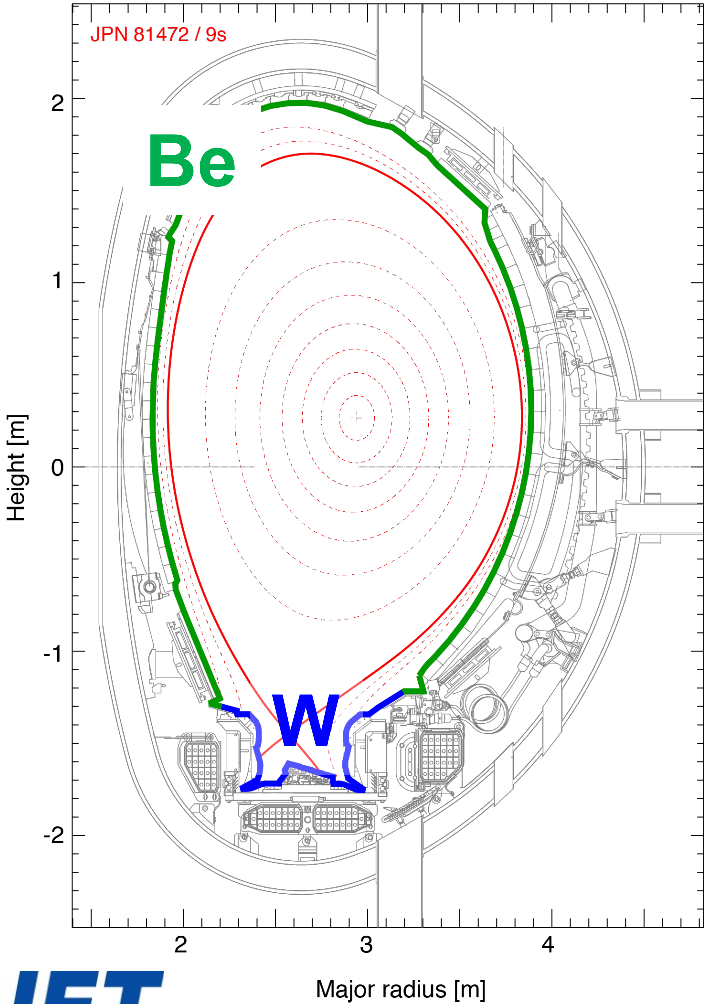
⇒ Widens scrape-off layer ($\propto \sqrt{m_{ion}}$)

⇒ Reduces veloc. of fast-refl. atoms ($\propto 1/\sqrt{m_{ion}}$)

- Heavier (F-C and CX) atoms have a shorter ionisation mean free path: $\propto 1/\sqrt{m_{atom}}$
- Higher ion-molecular interaction rates for heavier species for temperatures < 2 eV
- Conductance of pump duct: $\propto 1/\sqrt{m_{mol}}$
- Sticking probab. of cryo. pump.: $\propto X * m_{mol}$

⇒ Individually, isotope effect ≈ 40-70% ⇒ combined effect cumulative or offsetting?

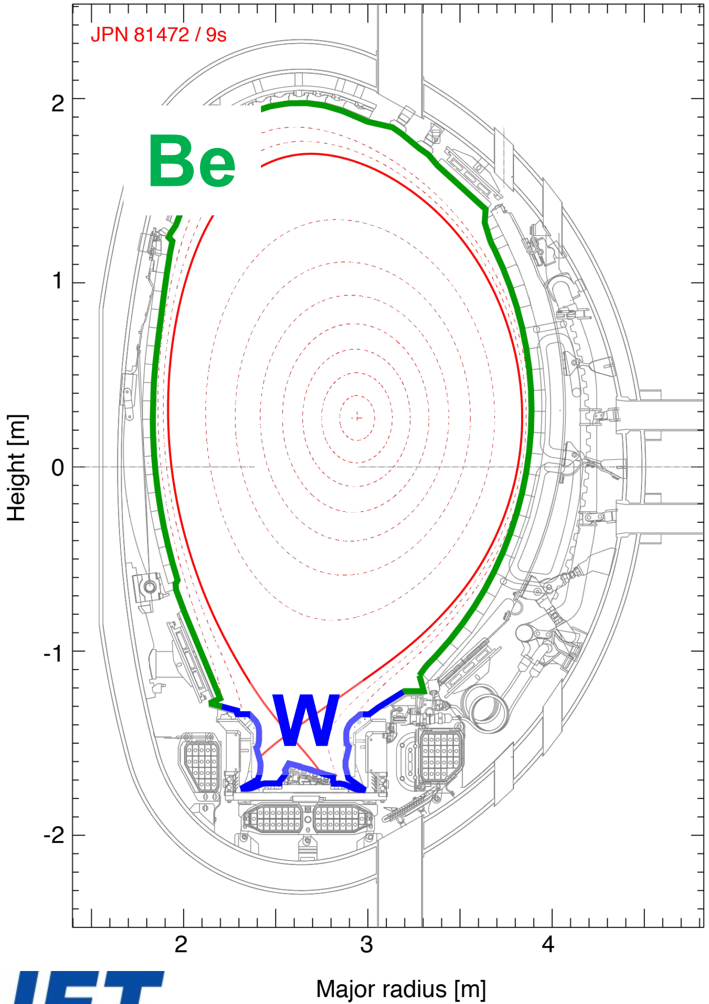
Characterisation of the SOL for detachment physics was performed in JET-ILW H, D, T and DT low-confinement mode plasmas



- JET-ILW wall Be main-chamber, W divertor*

*G.F. Matthews et al., Phys. Scr. 2011

Characterisation of the SOL for detachment physics was performed in JET-ILW H, D, T and DT low-confinement mode plasmas

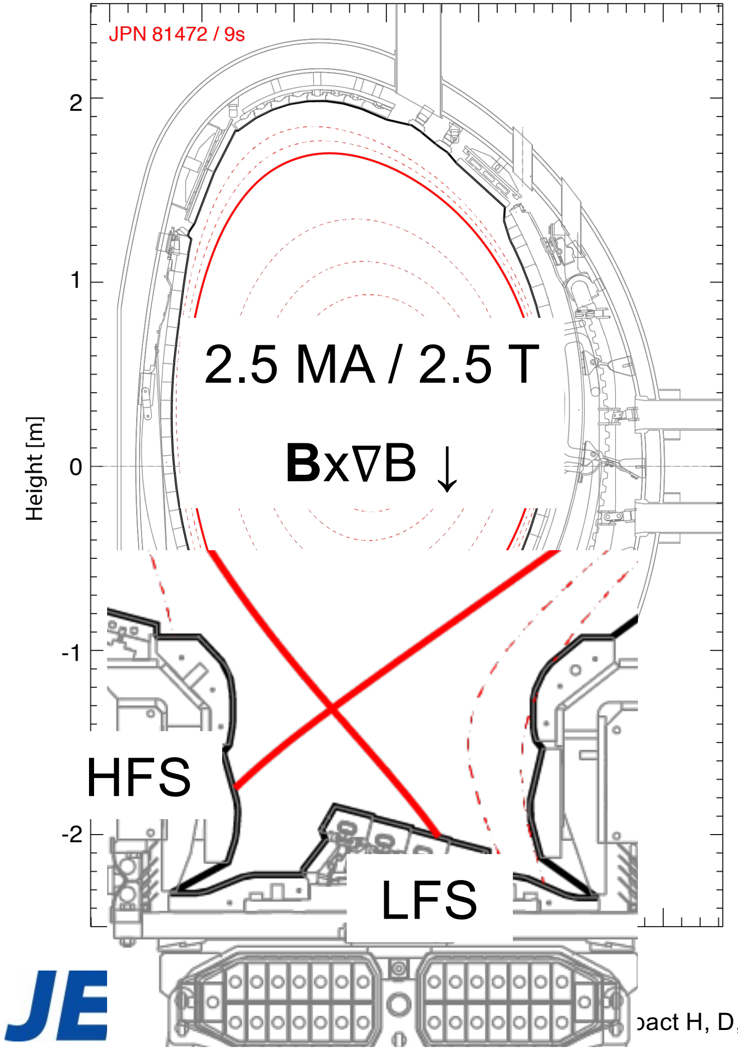


- JET-ILW wall Be main-chamber, W divertor*

⇒ Removed impact of carbon (radiation) on detachment as previously in JET-carbon

JET

Characterisation of the SOL for detachment physics was performed in JET-ILW H, D, T and DT low-confinement mode plasmas

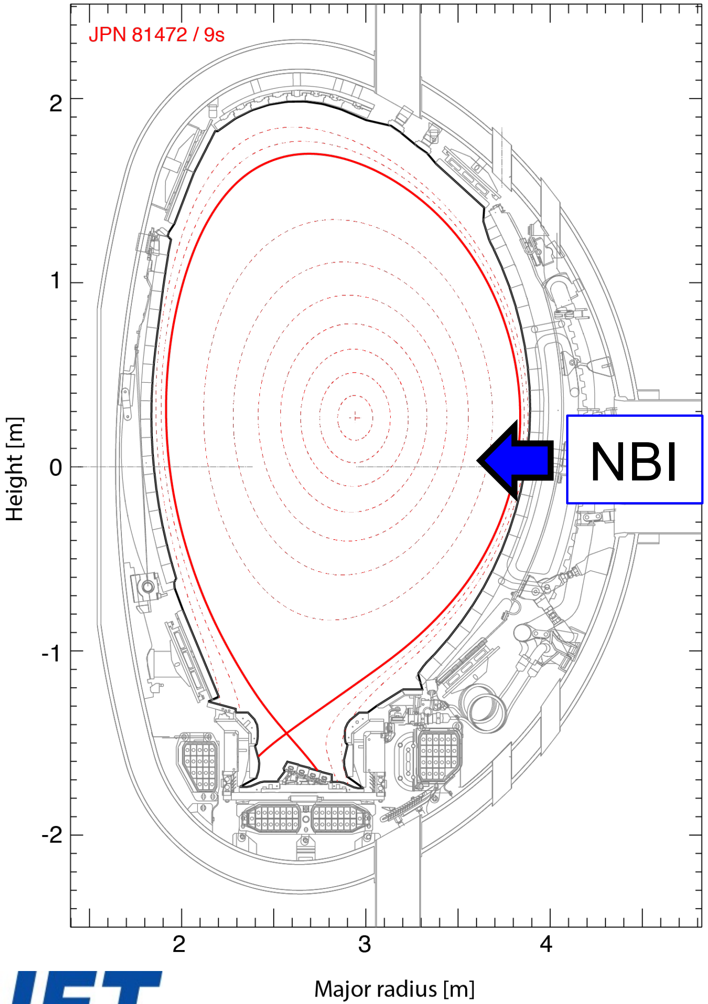


- JET-ILW wall Be main-chamber, W divertor
- Vertical-horizontal configuration, optimised for diagnostics and edge model validation*

⇒ Test physics models to assess uncertainties of predict-first approach

*M. Groth et al., NF 2013

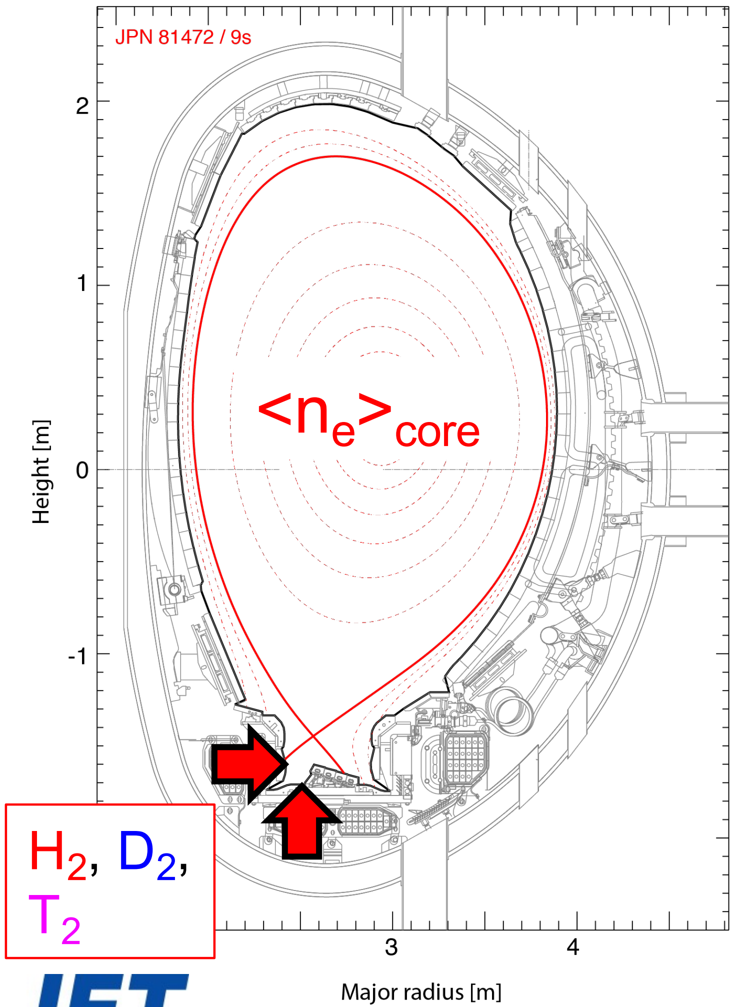
Characterisation of the SOL for detachment physics was performed in JET-ILW H, D, T and DT low-confinement mode plasmas



- JET-ILW wall Be main-chamber, W divertor
- Vertical-horizontal configuration, optimised for diagnostics and edge model validation
- Total heating up to 3 MW: neutral beam 1 MW

JET

Characterisation of the SOL for detachment physics was performed in JET-ILW H, D, T and DT low-confinement mode plasmas

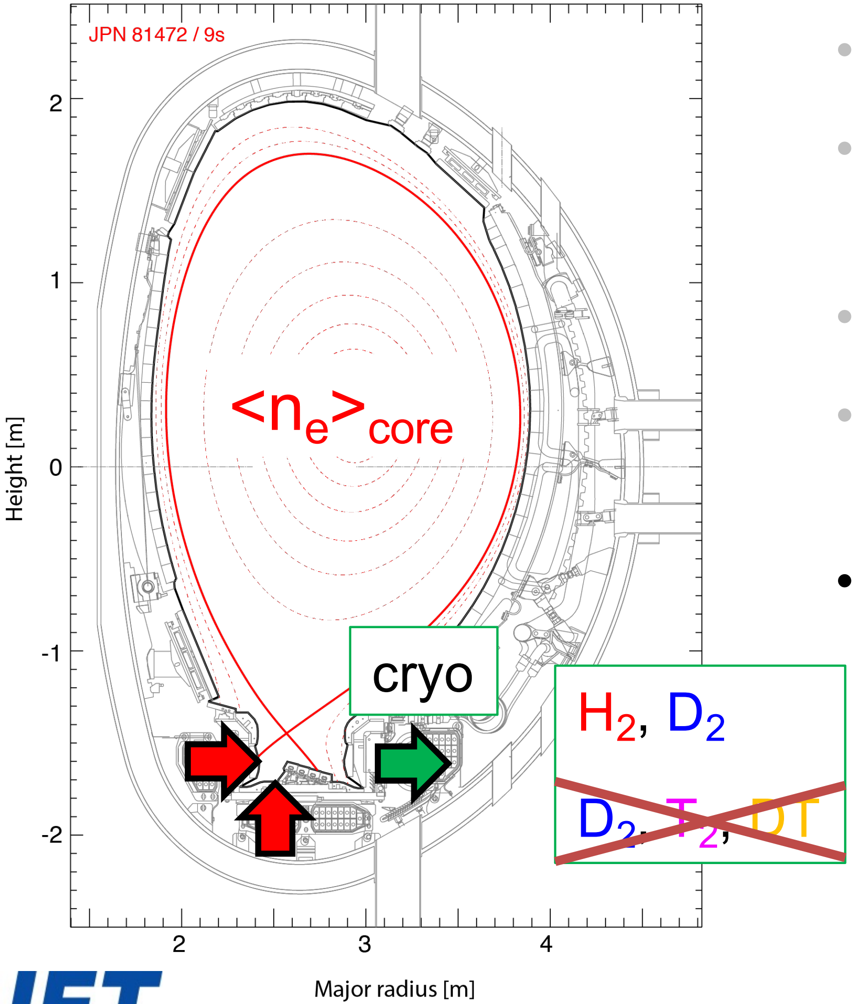


- JET-ILW wall Be main-chamber, W divertor
- Vertical-horizontal configuration, optimised for diagnostics and edge model validation
- Total heating up to 3 MW: neutral beam 1 MW
- Hydrogenic gas injection from the divertor to raise core plasma density to density limit

⇒ Plasma effective charge state 1.4 ↘ 1.0

JET

Characterisation of the SOL for detachment physics was performed in JET-ILW H, D, T and DT low-confinement mode plasmas

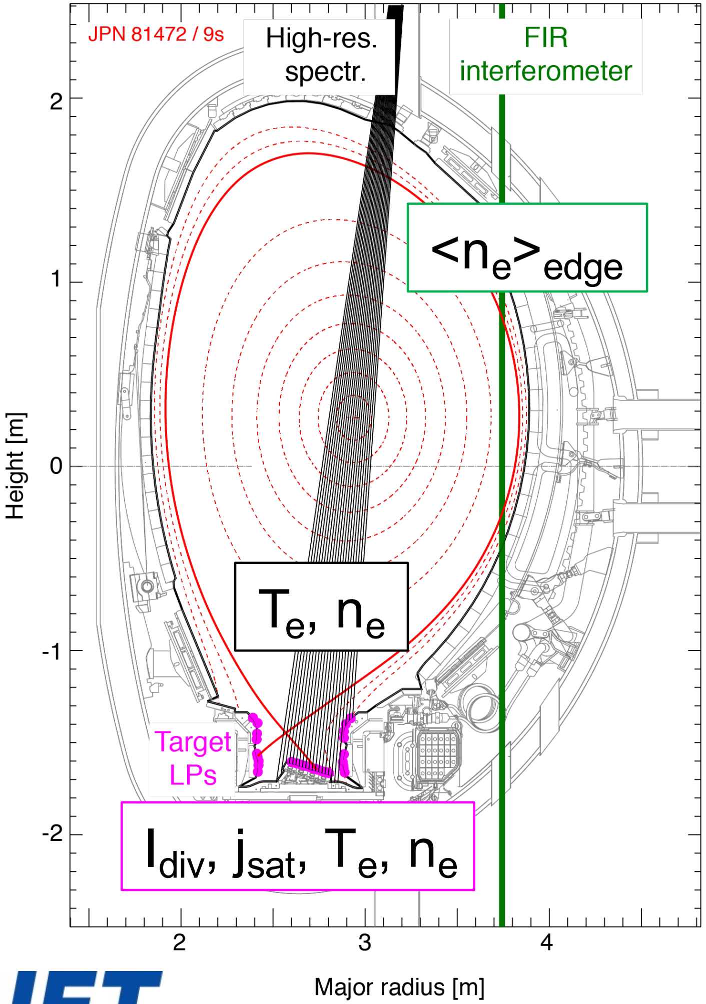


- JET-ILW wall Be main-chamber, W divertor
- Vertical-horizontal configuration, optimised for diagnostics and edge model validation
- Total heating up to 3 MW: neutral beam 1 MW
- Hydrogenic gas injection from the divertor to raise core plasma density to density limit
- Operational constraints on throughput in tritiated plasmas ⇒ raised temperature of cryogenic panel from super-critical He to liquid N_2

  ⇒ (Divertor) pumped for H_2 and D_2, and unpumped for D_2, T_2 and DT

JET

Characterisation of the SOL for detachment physics was performed in JET-ILW H, D, T and DT low-confinement mode plasmas

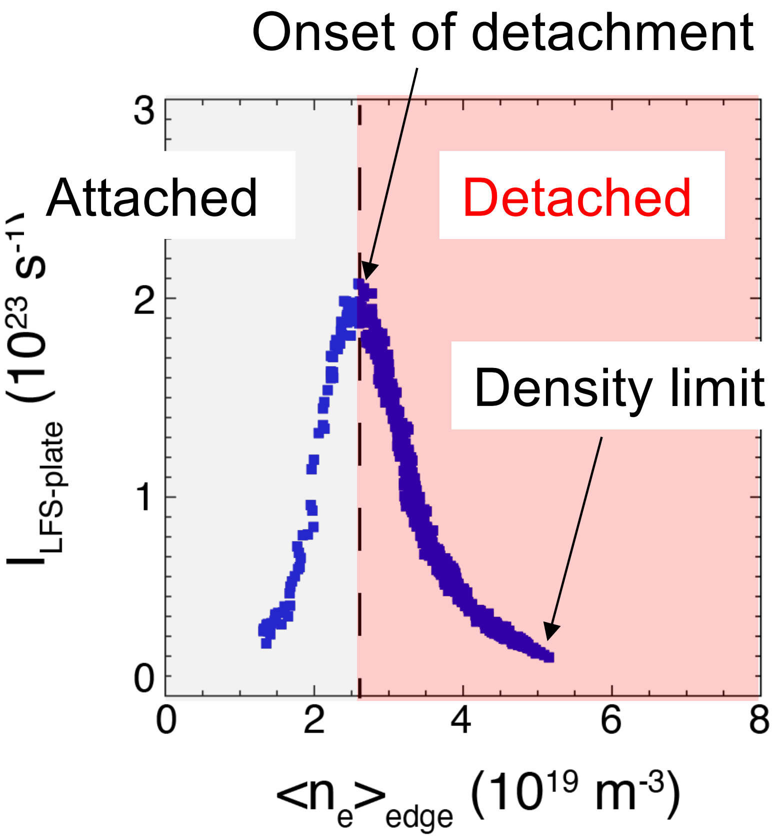


- JET-ILW wall Be main-chamber, W divertor
- Vertical-horizontal configuration, optimised for diagnostics and edge model validation
- Total heating up to 3 MW: neutral beam 1 MW
- Vary core plasma density to density limit by hydrogenic gas injection from the divertor
- Operational constraints on throughput in T and DT: divertor pumped (H_2, D_2) and unpumped (D_2, T_2 and DT)
- Ion fluxes from Langmuir probes + spectro. inferred T_e and n_e across LFS divertor (for high-recycling and partially detached conditions*)

*A.G. Meigs et al., JNM 2013, B. Lomanowski et al., NF 2015

Onset of detachment is characterised by saturation and reduction of ion current to plates with increasing core density

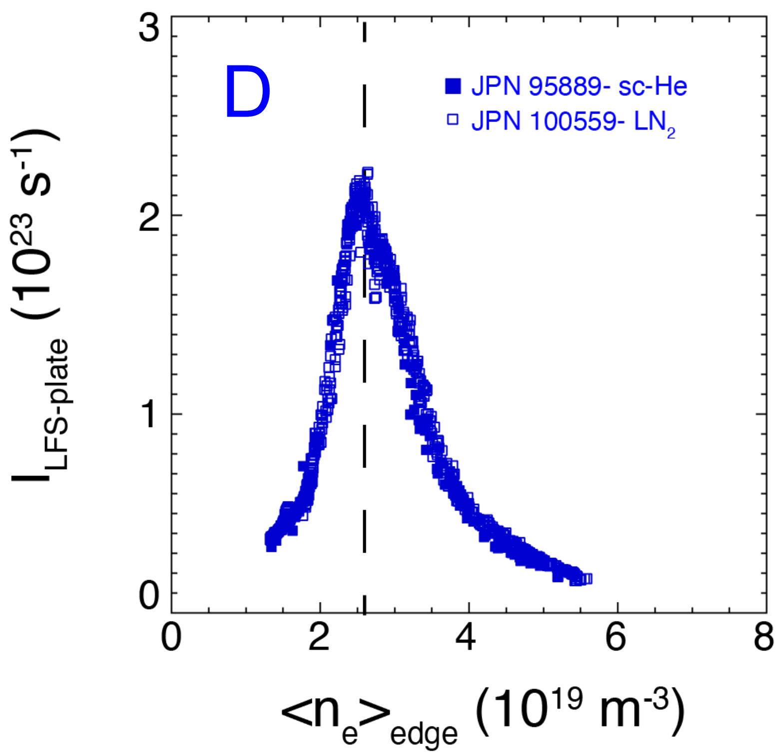
LFS



- Density limit = maximum achievable density

Eliminating divertor cryogenic pumping resulted in nearly identical detachment characteristics as in the pumped setup*

LFS

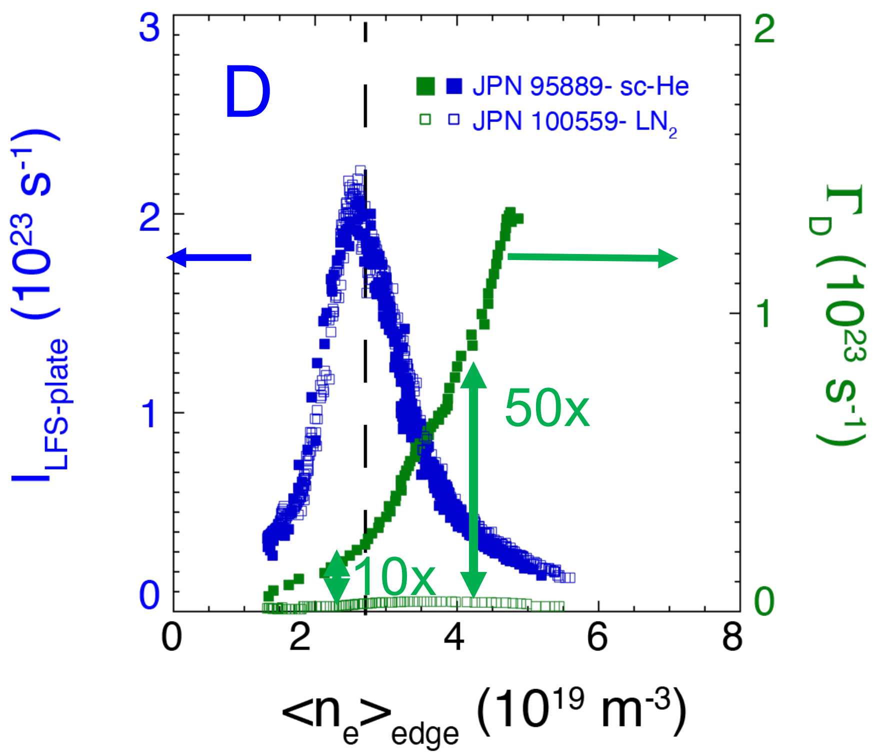


- Onset of detachment characterised by saturation and reduction of ion current to plates ⇒ density limit = max. density

*M. Groth et al., NME 2023

Eliminating divertor cryogenic pumping resulted in nearly identical detachment characteristics as in the pumped setup

LFS



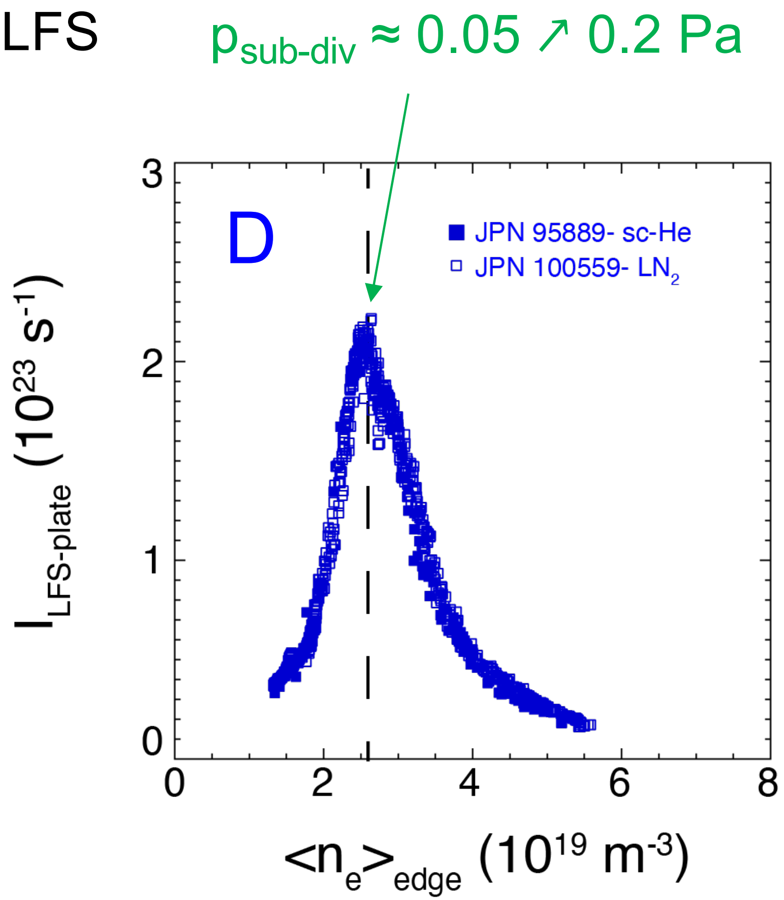
- Onset of detachment characterised by saturation and reduction of ion current to plates ⇒ density limit = max. density
- 10-50x reduction in fuelling rates

⇒ (In particular vert.-horiz. config.) Divertor plasma conditions decoupled from throughput

⇒ Core plasma density set by surface recycling, volume recombination and transport

Eliminating divertor cryogenic pumping resulted in nearly identical detachment characteristics as the pumped setup

LFS



- Onset of detachment characterised by saturation and reduction of ion current to plates ⇒ density limit = max. density

⇒ 10-50x reduction in fuelling rates

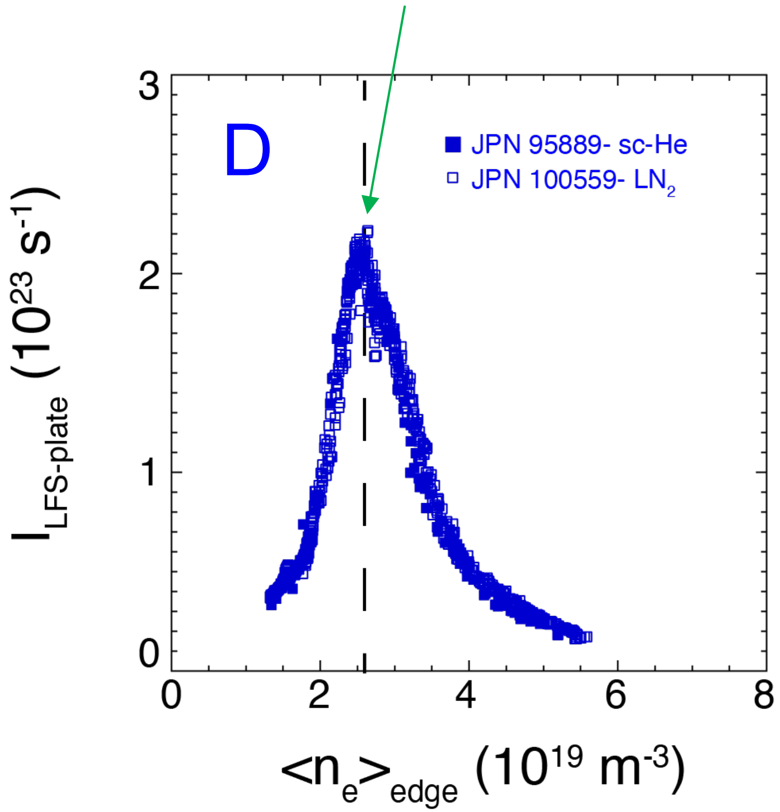
- Sub-divertor pressure increased 5x

⇒ Gas flow into and out of sub-divertor, and pumping in sub-divertor do not impact surface recycling

Eliminating divertor cryogenic pumping resulted in nearly identical detachment characteristics as the pumped setup

LFS

$p_{sub\text{-}div} \approx 0.05 \nearrow 0.2$ Pa



- Onset of detachment characterised by saturation and reduction of ion current to plates ⇒ density limit = max. density

⇒ 10-50x reduction in fuelling rates

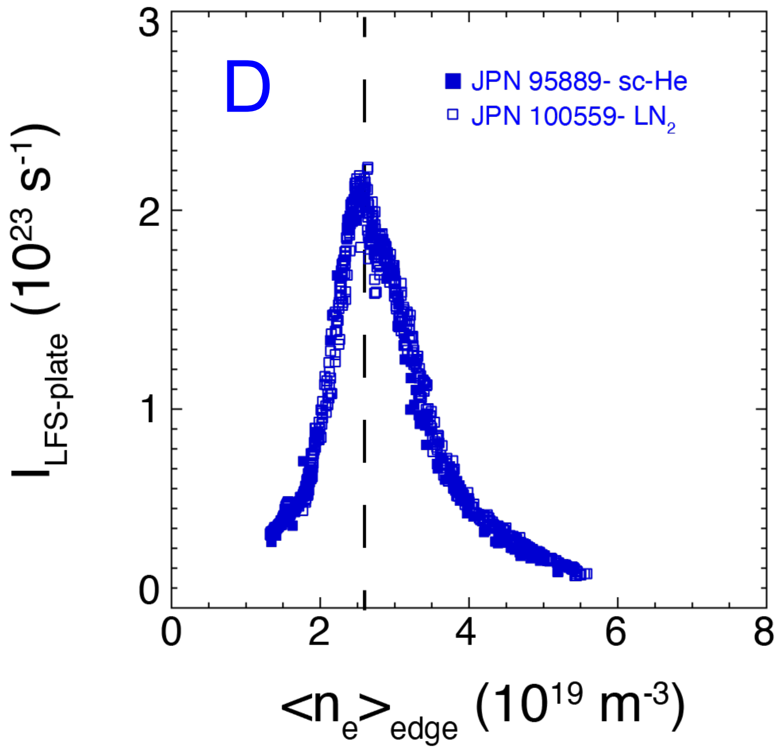
- Sub-divertor pressure increased 5x

⇒ Gas flow into and out of sub-divertor, and pumping in sub-divertor do not impact surface recycling

⇒ Removed impact of pump duct conductance and cryogenic pump on divertor conditions wrt. isotopes

Eliminating divertor cryogenic pumping resulted in nearly identical detachment characteristics as the pumped setup

LFS



- Onset of detachment characterised by saturation and reduction of ion current to plates ⇒ density limit = max. density

⇒ 10-50x reduction in fuelling rates

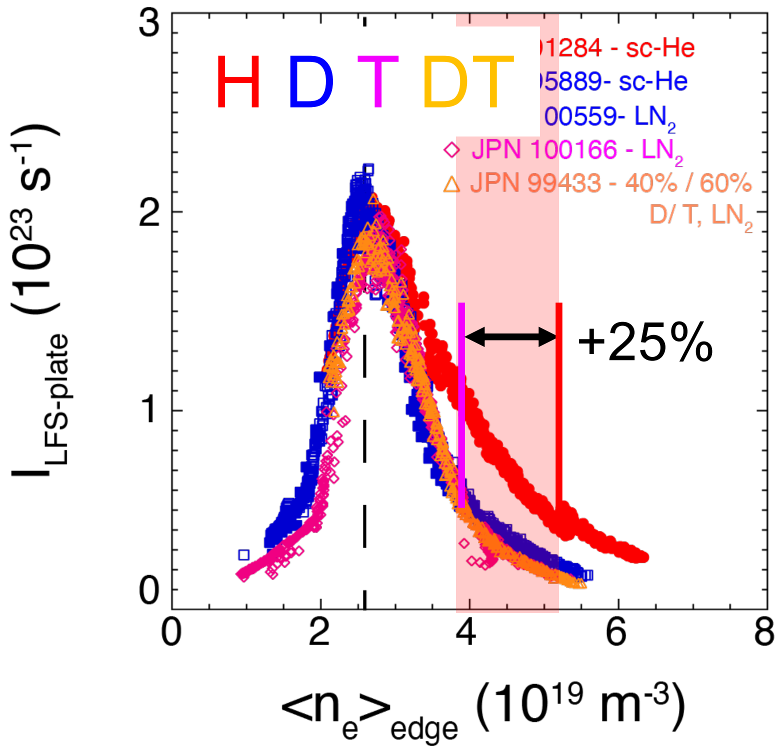
- Eliminating divertor cryogenic pumping resulted in the same detachment characteristics

- Validation of hydrogenic atomic emission ongoing ⇒ PSI 2024

- Validation of hydrogenic (deuterium) molecular emission still pending

Deuterium, tritium and 40%-60% deuterium-tritium plasmas were more strongly detached than hydrogen plasmas

LFS

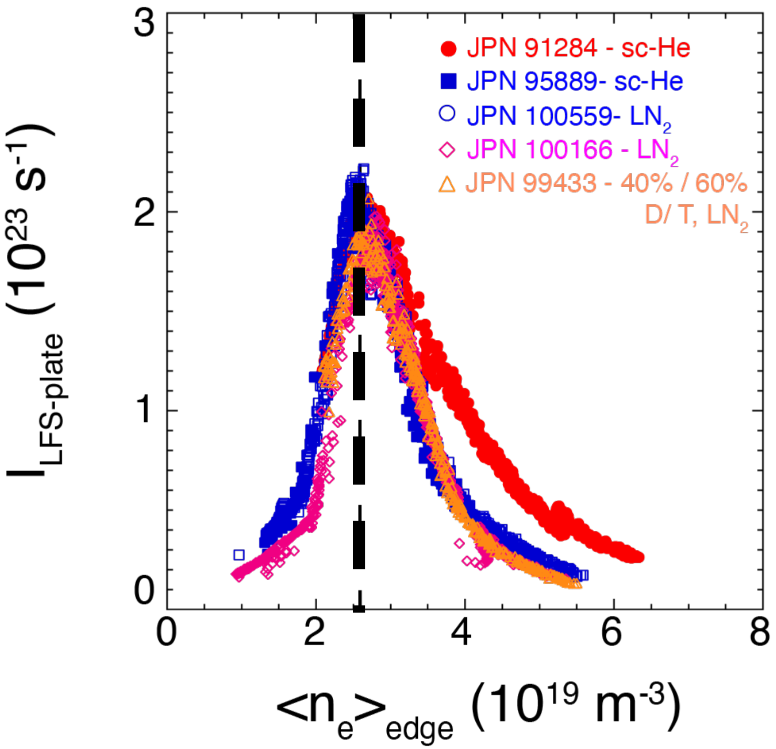


- Onset of detachment characterised by saturation and reduction of ion current to plates ⇒ density limit = max. density
- Eliminating divertor cryogenic pumping resulted in the same detachment characteristics

JET-ILW Ohmic H/D: V. Solokha et al., NME 2020

Deuterium, tritium and 40%-60% deuterium-tritium plasmas were more strongly detached than hydrogen plasmas

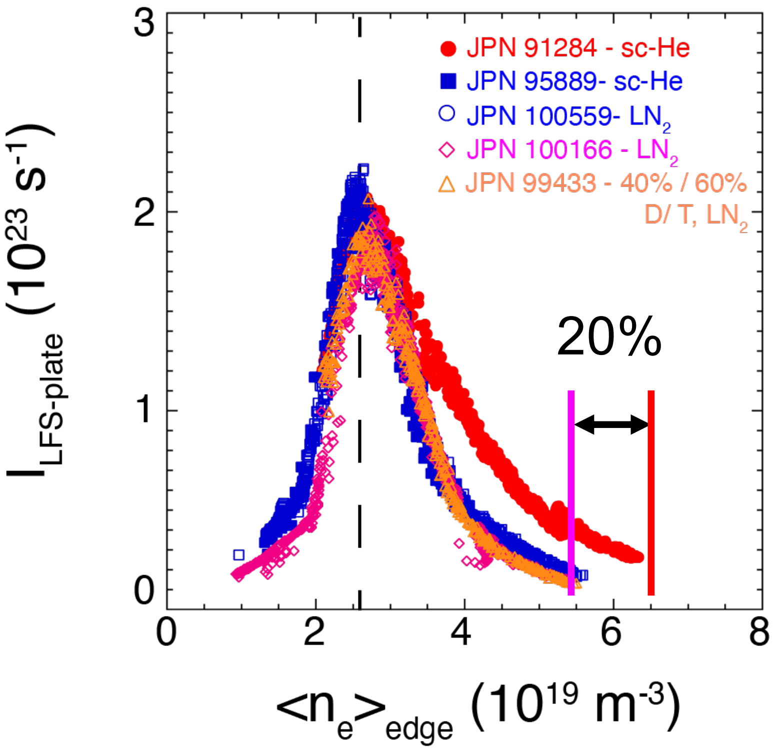
LFS



- Onset of detachment characterised by saturation and reduction of ion current to plates ⇒ density limit = max. density
- Eliminating divertor cryogenic pumping resulted in the same detachment characteristics
- Onset of detachment occurred at the same edge plasma density for H, D, T and DT

Deuterium, tritium and 40%-60% deuterium-tritium plasmas were more strongly detached than hydrogen plasmas

LFS

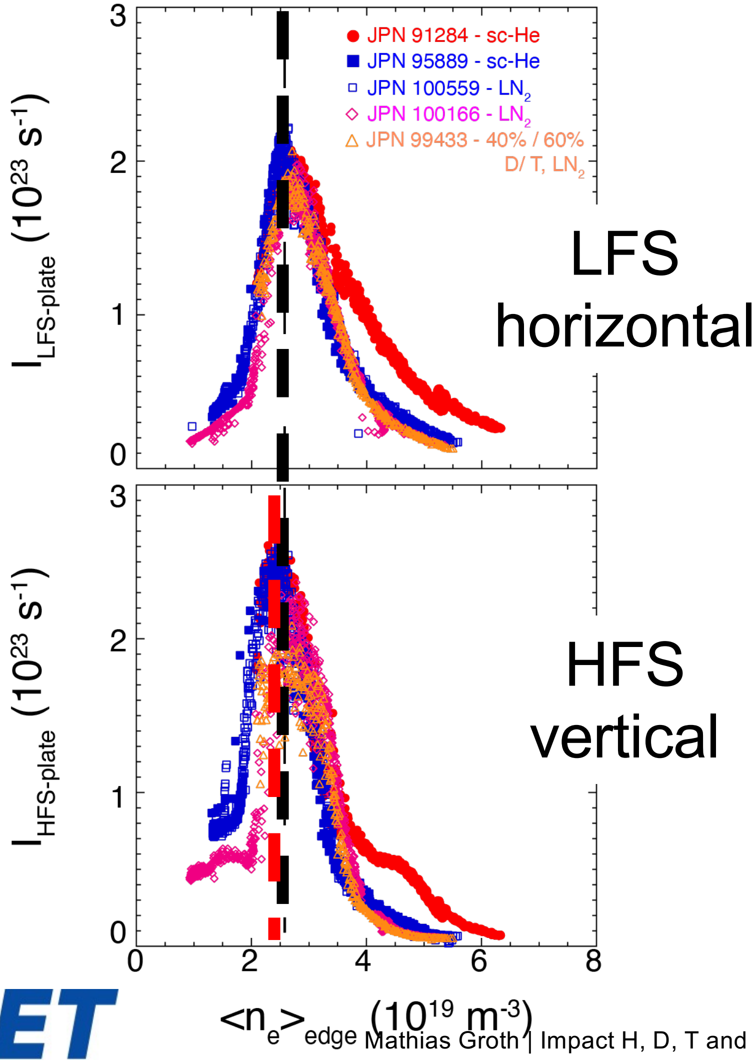


- Onset of detachment characterised by saturation and reduction of ion current to plates ⇒ density limit = max. density
- Eliminating divertor cryogenic pumping resulted in the same detachment characteristics
- Onset of detachment occurred at the same edge plasma density for H, D, T and DT
- Density limit is 20% higher in H than in D, T and DT (consistent with JET-C*, JET-ILW ohmic*)

*C.F. Maggi et al., NF 1999
**V. Solokha et al., NME 2020

JET

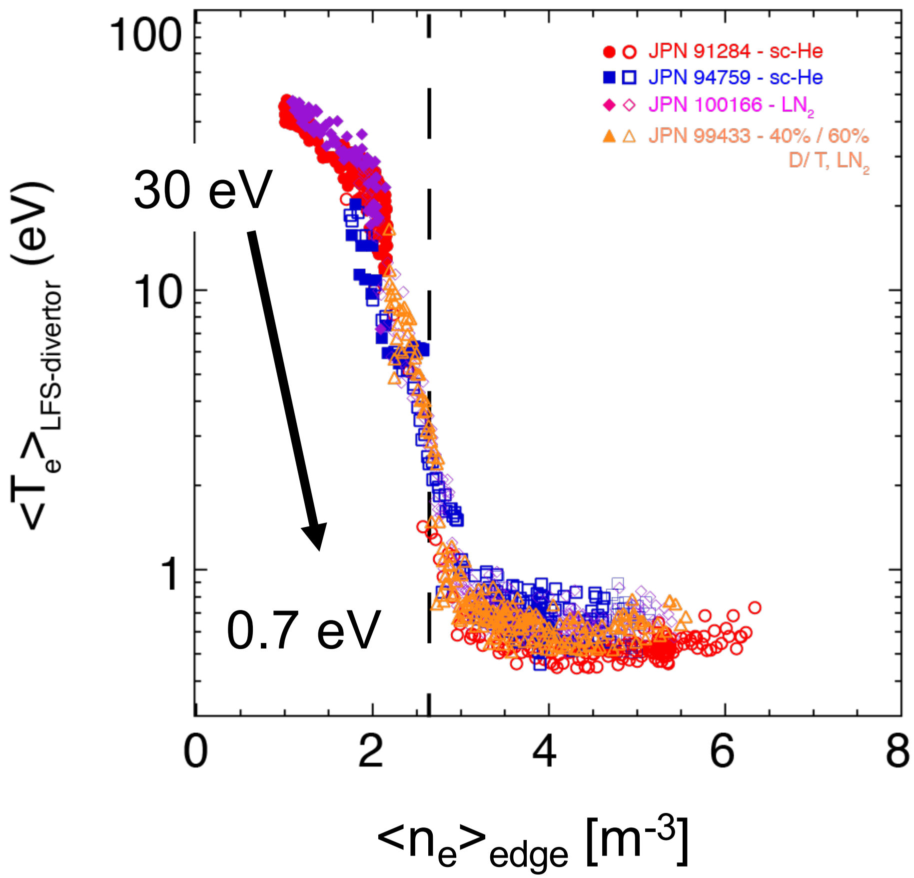
Deuterium, tritium and 40%-60% deuterium-tritium plasmas were more strongly detached than hydrogen plasmas

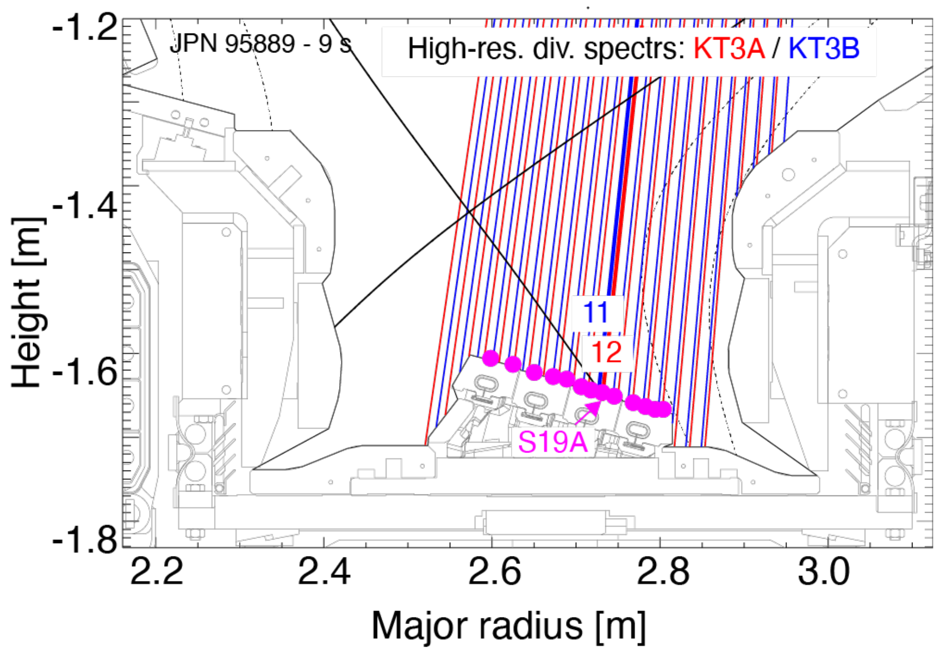


- Onset of detachment characterised by saturation and reduction of ion current to plates ⇒ density limit = max. density
- Eliminating divertor cryogenic pumping resulted in the same detachment characteristics
- Onset of detachment occurred at the same edge plasma density for H, D, T and DT
- Density limit is 30% higher in H than in T (consistent with JET-C)
- Onset of detachment occurred within 10% of the same edge density on both the LFS and HFS plates

(Non-linear) reduction of electron temperature at LFS target plate with edge density is independent of the isotope species

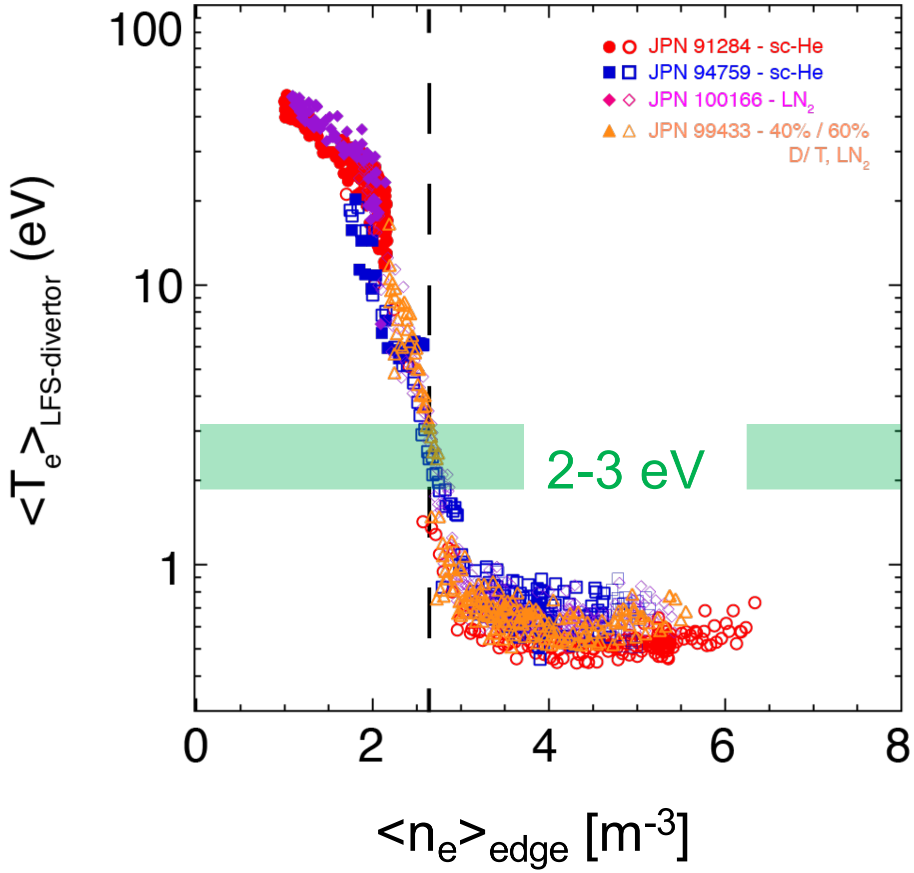
LFS





(Non-linear) reduction of electron temperature at LFS target plate with edge density is independent of isotope species

LFS

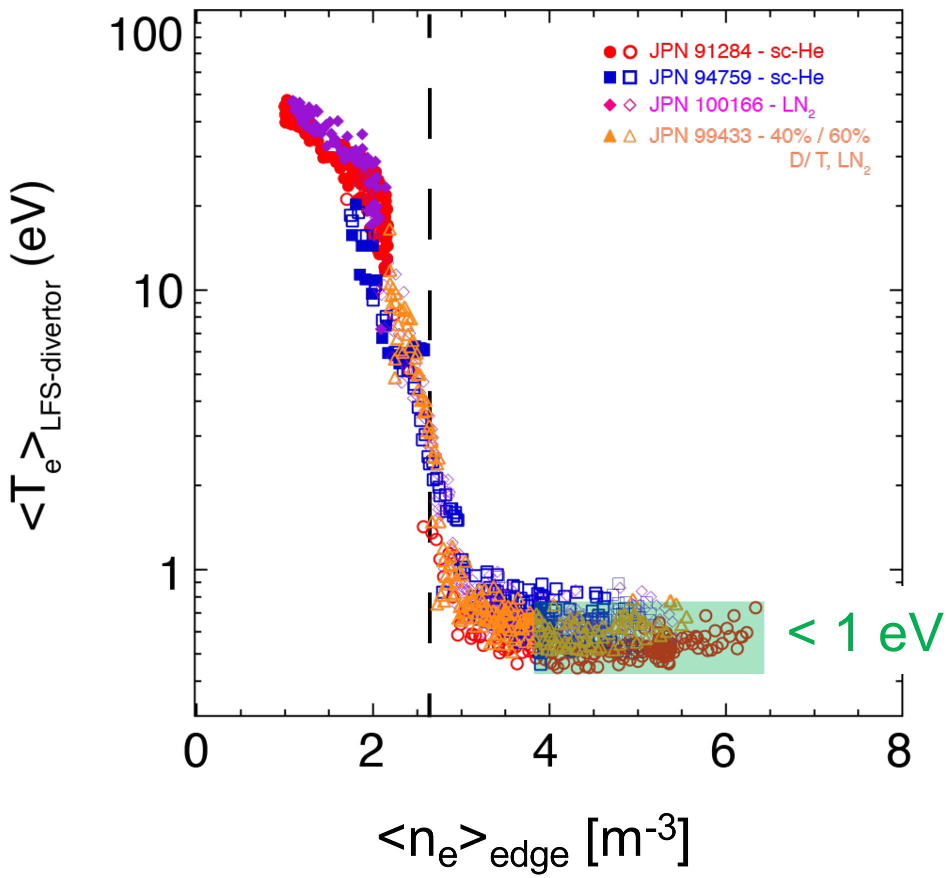


- Onset of detachment when $T_{e,div}$ ≈ 2-3 eV ⇒ onset of ion-molecular interaction*

*R. Janev et al., AM Fusion Edge Plasmas 1995
R. Janev, D. Reiter, JUEL-report 4411, 2018
K. Verhaegh et al., NF 2021, 2023, EX-P2103
J. Karhunen et al., NME 2023

(Non-linear) reduction of electron temperature at LFS target plate with edge density is independent of isotope species

LFS

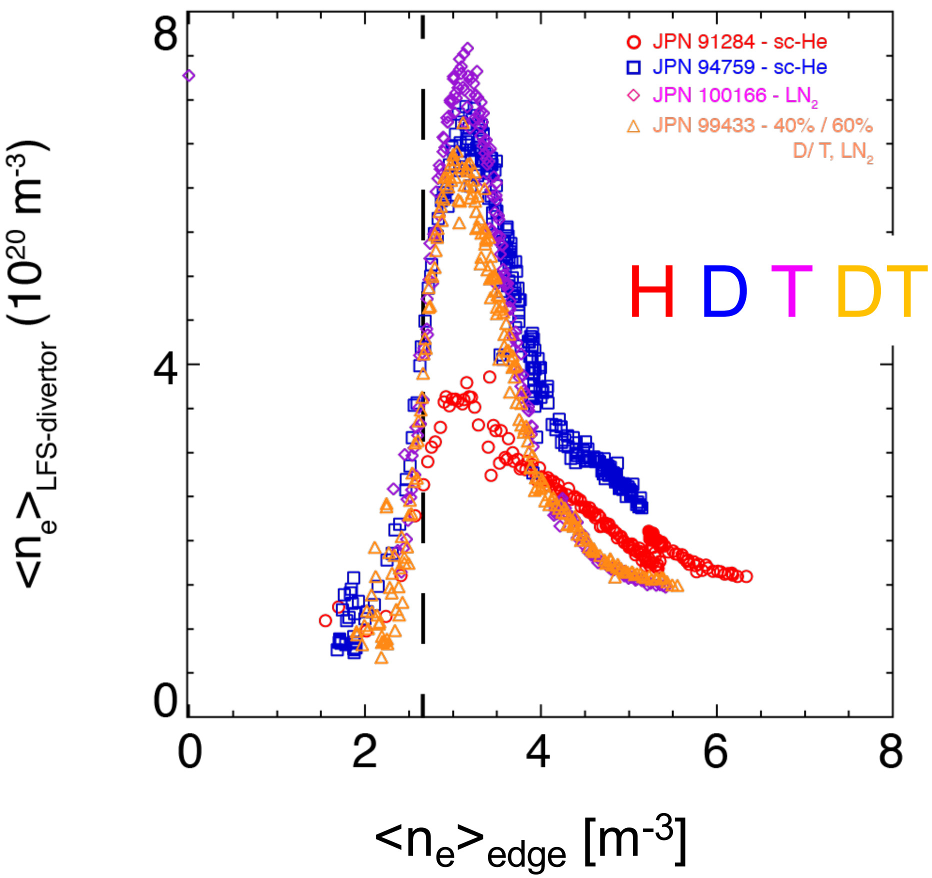


- Onset of detachment when $T_{e,div} \approx$ 2-3 eV ⇒ onset of ion-molecular interaction*
- Above $\langle n_e \rangle_{edge}$ of 4×10^{19} m^{-3}, LFS divertor plasma below 1 eV up to X-point*

*J. Karhunen et al., NME 2020

The maximum electron density adjacent to the target plate was measured lower in H than in D, T and DT plasmas

LFS

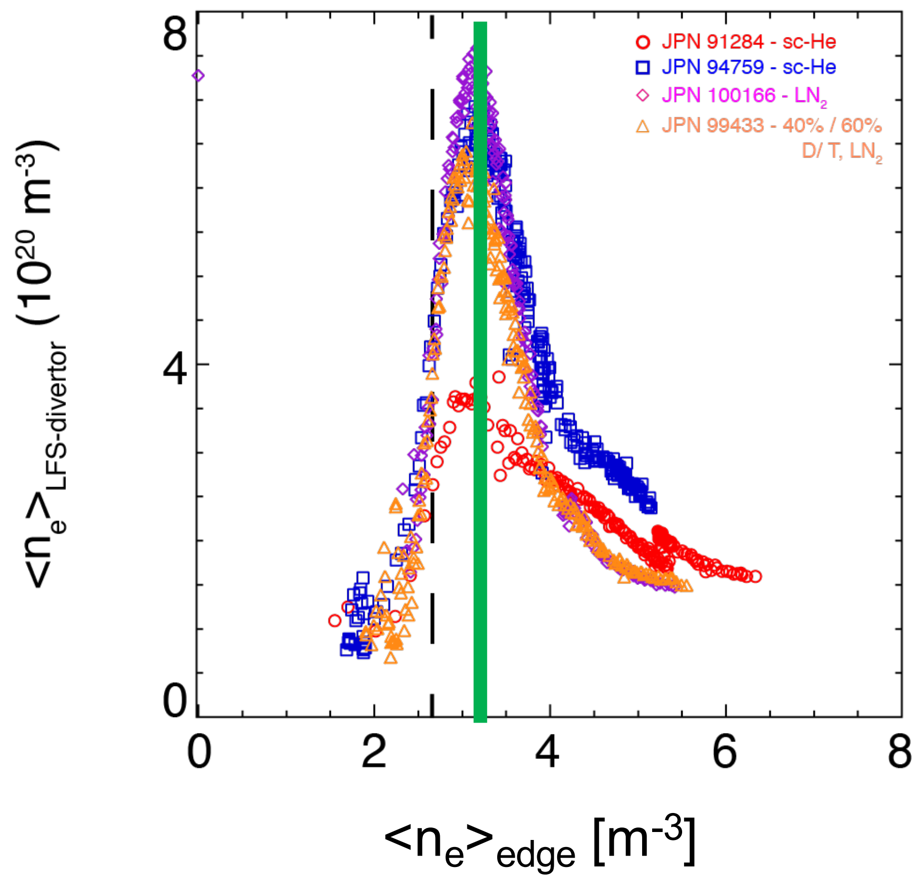


- (Non-linear) reduction of electron temperature at LFS target plate with core density is independent of isotope species

The maximum electron density adjacent to the target plate was measured lower in H than in D, T and DT plasmas

LFS

0.7-1.0 eV

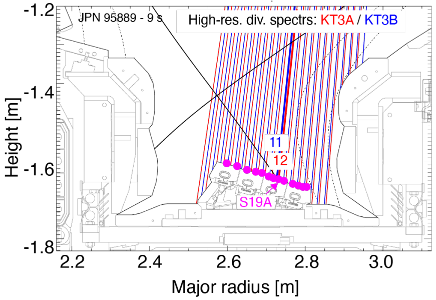


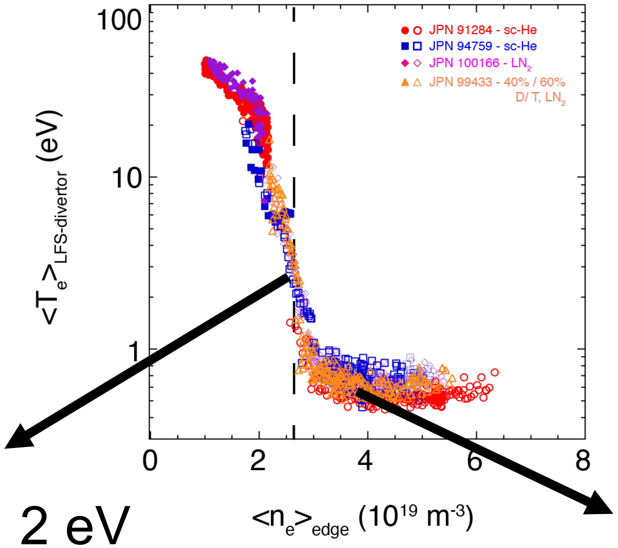
- (Non-linear) reduction of electron temperature at LFS target plate with core density is independent of isotope species
- Max. electron density reached when $T_{e,div}$ ≈ 0.7-1.0 eV* (beyond onset of detachment)

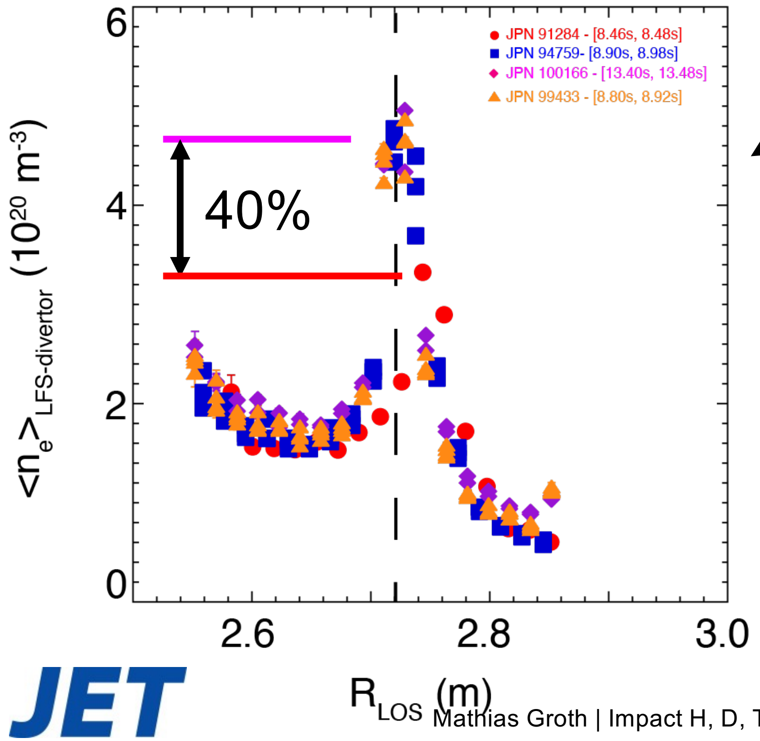
*A.G. Meigs et al., JNM 2013

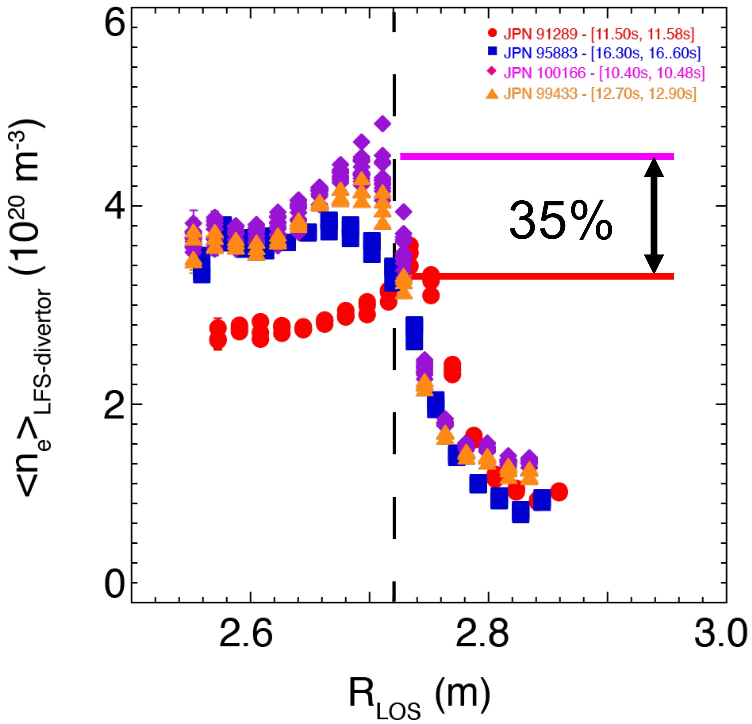
JET

Using actual $\langle n_e \rangle_{LFS\text{-}div}$ profiles, H plasmas are 40% sparser than T plasmas ⇒ high-density front moves off LFS plate*



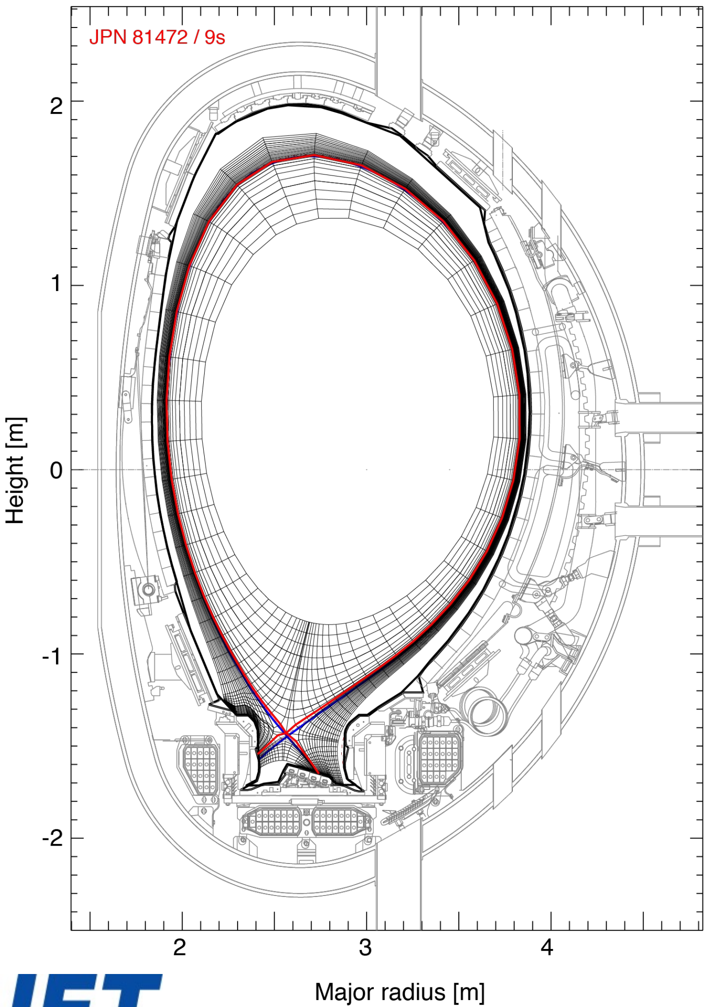






*A.G. Meigs et al., JNM 2013
J. Karhunen et al., NME 2020

EDGE2D-EIRENE was used to simulate the H, D and T L-mode plasmas encompassing both attached and detached conds.



- EDGE2D-EIRENE* is a coupled fluid plasma, neutral Monte-Carlo code package
  - EIRENE**: H_0, H_2, H_2^+ (inst. destroyed), $H_2(v\geq0)$ breakup included through AMJUEL

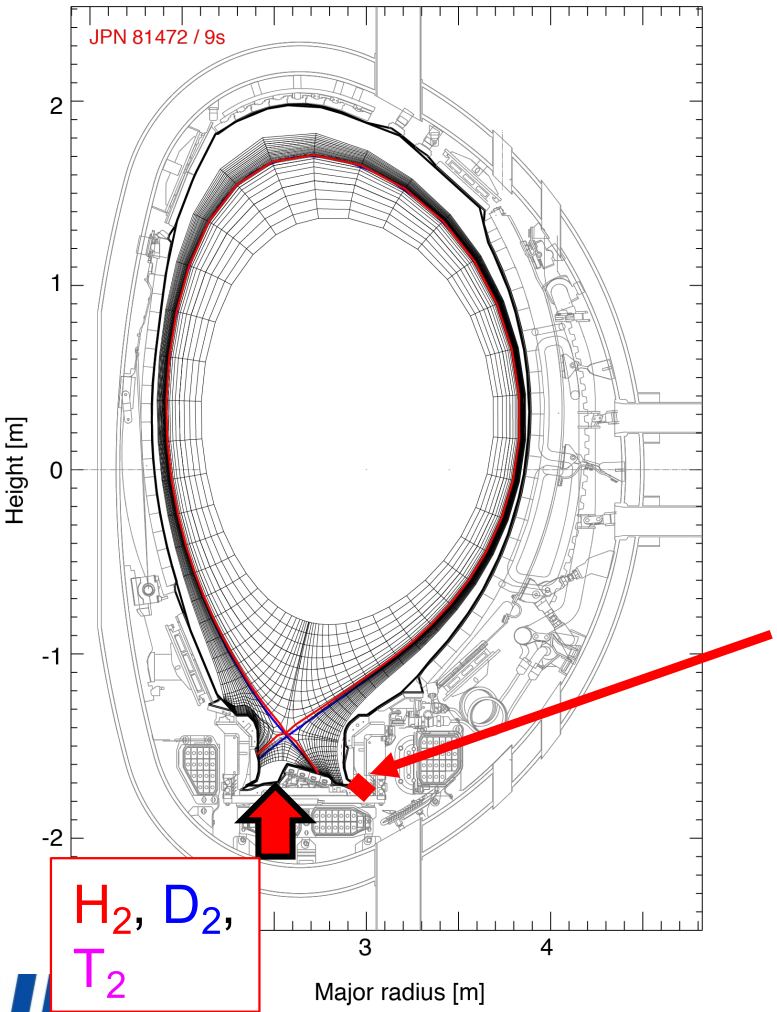
⇒ Isotope effect included by scaling rates according to relative neutral velocities $\propto 1/\sqrt{m}$

  - Beryllium included as primary impurity species ⇒ negligible impact on plasma solutions
  - Cross-field drifts and currents included, assume user-defined, diffusive-convective radial transport ⇒ kept fixed in density scans

JET

*R. Simonini et al., CPP 1994, S. Wiesen, JET ITC-Report 2006, **D. Reiter, FST 2005

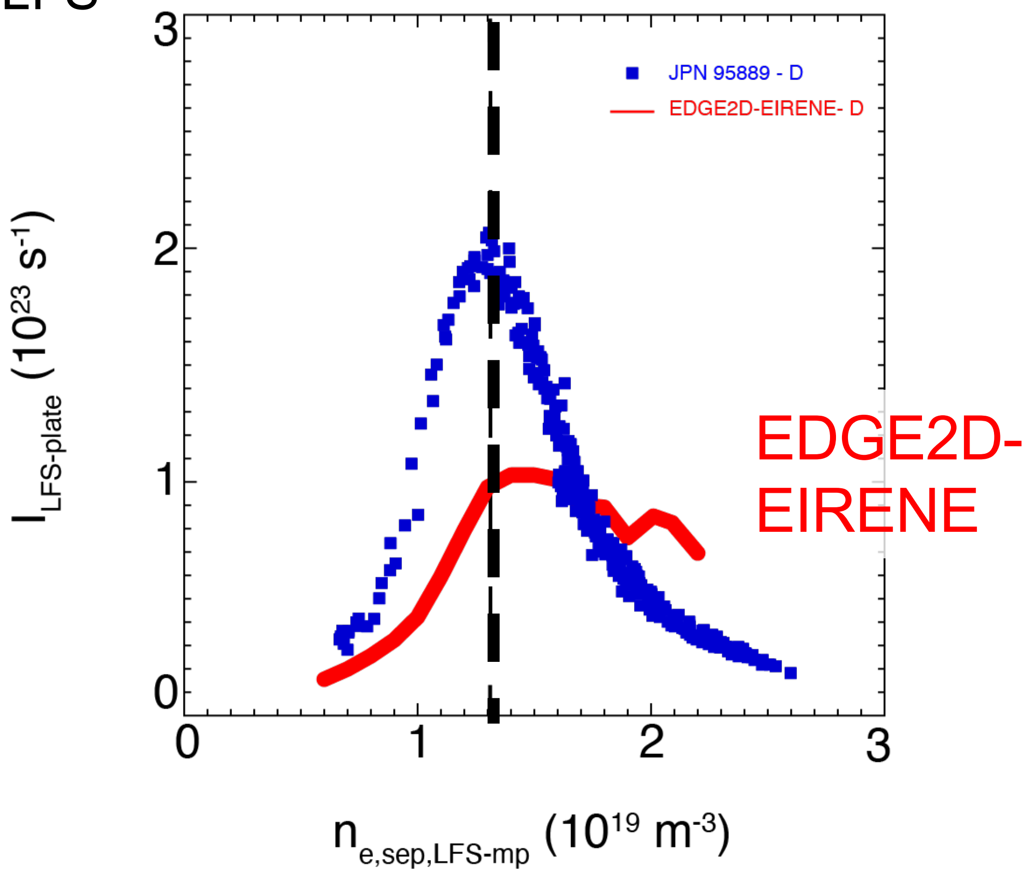
EDGE2D-EIRENE was used to simulate the H, D and T L-mode plasmas encompassing both attached and detached conds.



- EDGE2D-EIRENE is a coupled fluid plasma, Monte-Carlo neutral code package
- H_2, D_2 and T_2 injection through private flux region
- Sub-divertor excluded, approximated by pump surface in LFS divertor corner of user-defined size and albedo; here: same for H/H_2, D/D_2 and T/T_2

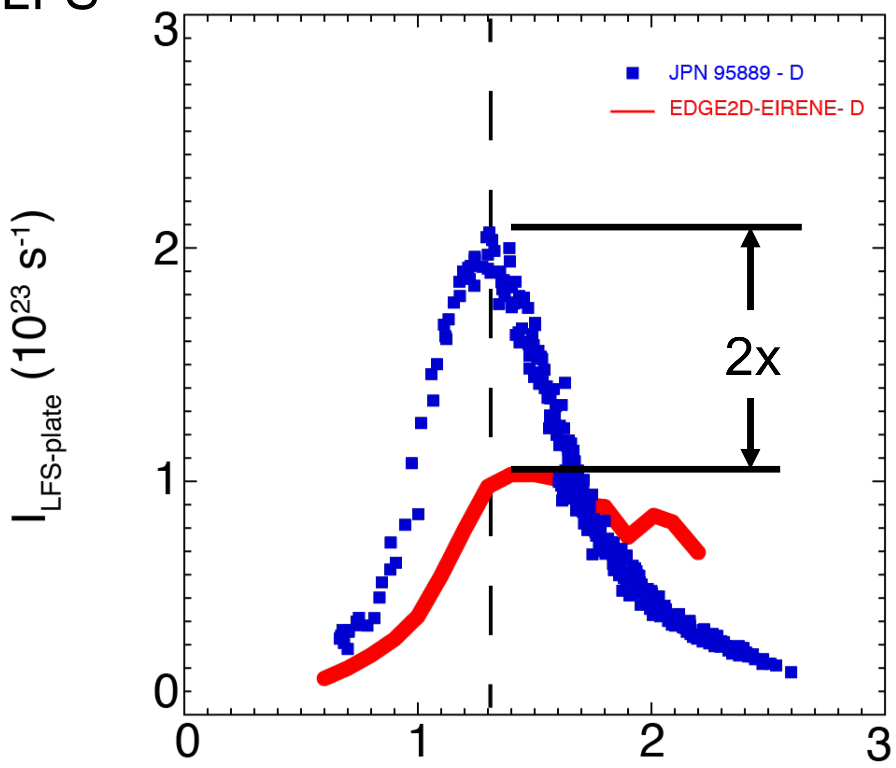
EDGE2D-EIRENE predicts the onset of detachment at same LFS midplane separatrix density as measured

LFS



EDGE2D-EIRENE predicts the onset of detachment at same LFS midplane separatrix density as measured

LFS

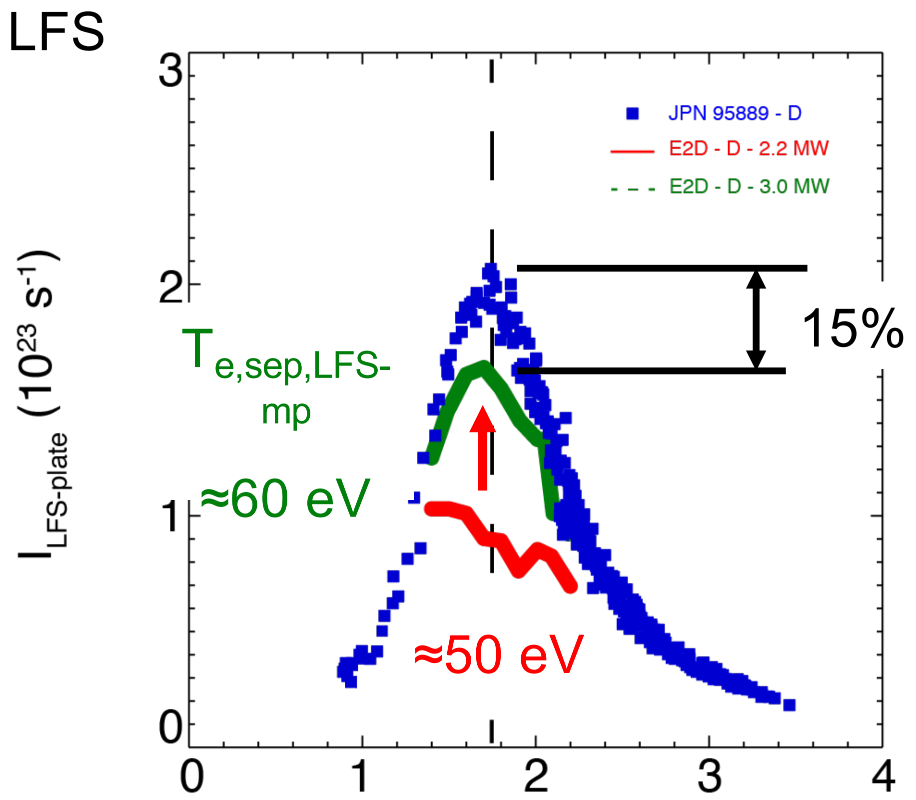


$n_{e,sep,LFS\text{-}mp}$ (10^{19} m^{-3}) ← = 1/2 $\langle n_e \rangle_{edge}$

- Using scaling of $n_{e,sep,LFS\text{-}mp}$ with $\langle n_e \rangle_{edge}$ for low-recycling conds*: at onset of detachment, the predicted $I_{div,LFS}$ factor 2 lower than measured

*M. Groth et al., JNM 2013

EDGE2D-EIRENE predicts the onset of detachment at same LFS midplane separatrix density as measured

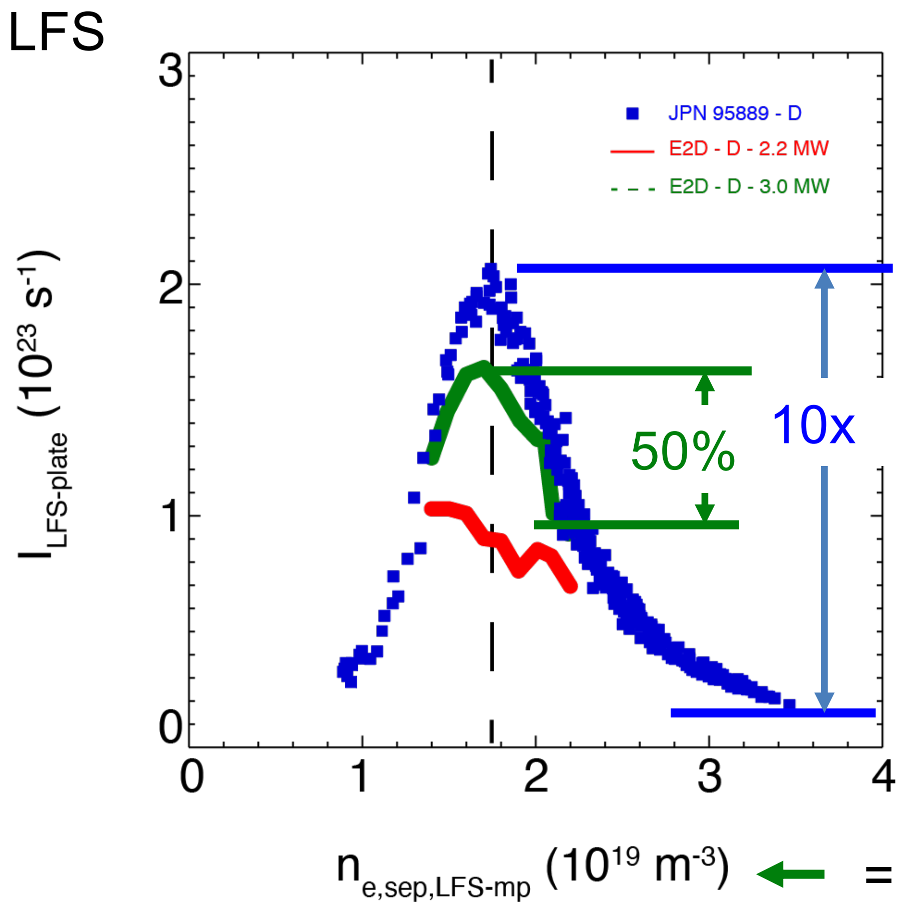


$n_{e,sep,LFS-mp}$ (10^{19} m^{-3}) ← $= 2/3$ $\langle n_e \rangle_{edge}$

- Using scaling of $n_{e,sep,LFS-mp}$ with $\langle n_e \rangle_{edge}$ for low-recycling conds*: at onset of detachment, the predicted $I_{div,LFS}$ factor 2 lower than measured

⇒ Relaxing scaling for high-recycling conds. improves code-experiment agreement for $I_{div,LFS-plate}$

EDGE2D-EIRENE predicts the onset of detachment at same LFS midplane separatrix density as measured



= 2/3 $\langle n_e \rangle_{edge}$

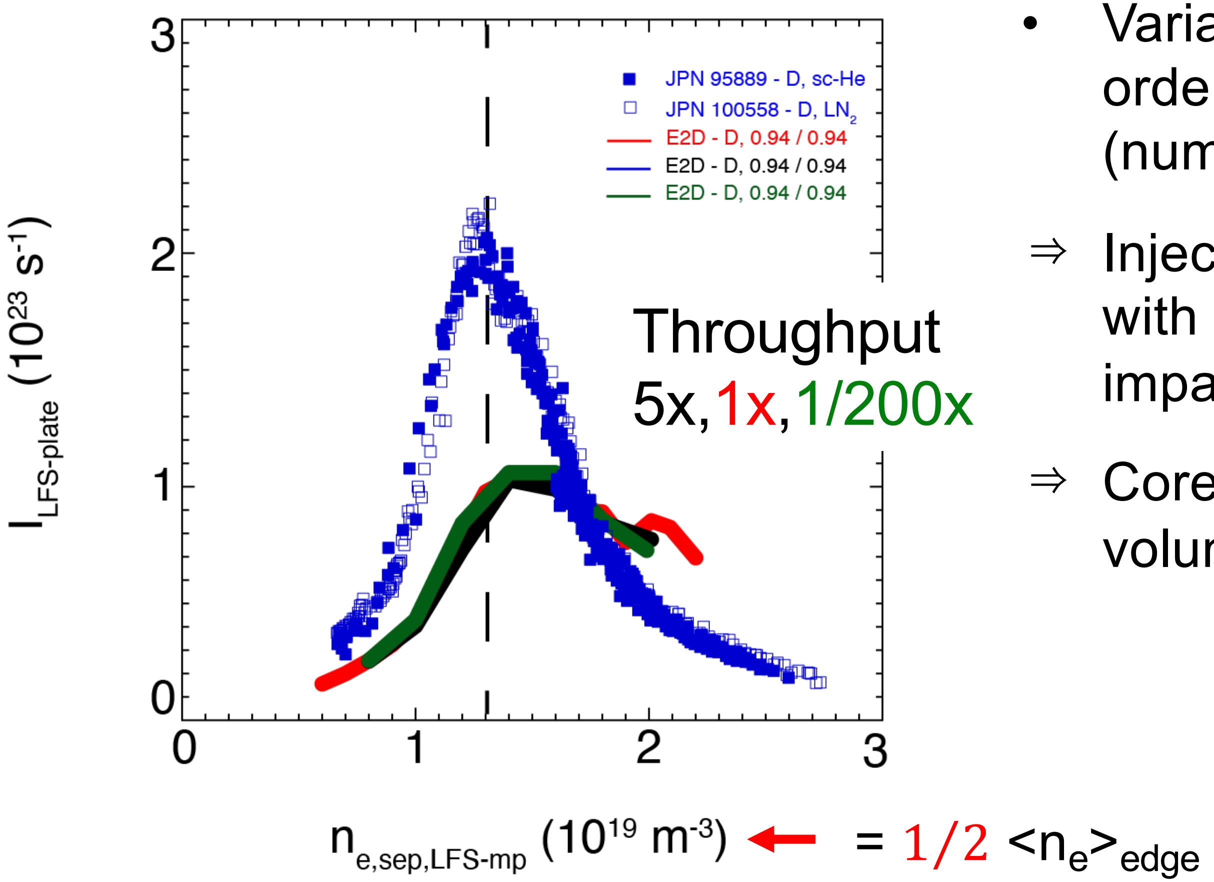
- Using scaling of $n_{e,sep,LFS\text{-}mp}$ with $\langle n_e \rangle_{edge}$ for low-recycling conds*: at onset of detachment, the predicted $I_{div,LFS}$ factor 2 lower than measured

⇒ Relaxing scaling for high-recycling conds. improves $I_{div,LFS\text{-}plate}$ agreement

- Strong reduction of $I_{div,LFS}$ beyond rollover not observed in simulations

JET

As in experiments, predicted divertor currents are independent of the D_2 throughput



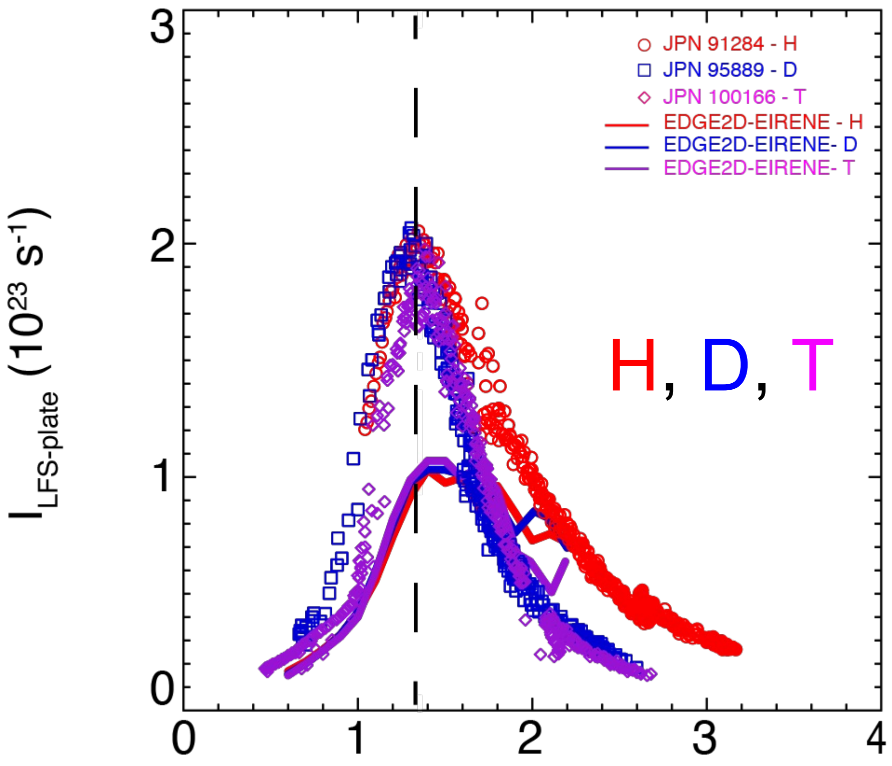
- Variation of D_2 throughput by three orders of magnitude through pumping (number of pump surfaces, albedo)

⇒ Injection rates can be made consistent with rates in experiments without impacting recycling

⇒ Core plasma density set by recycling, volume recombination and transport

JET

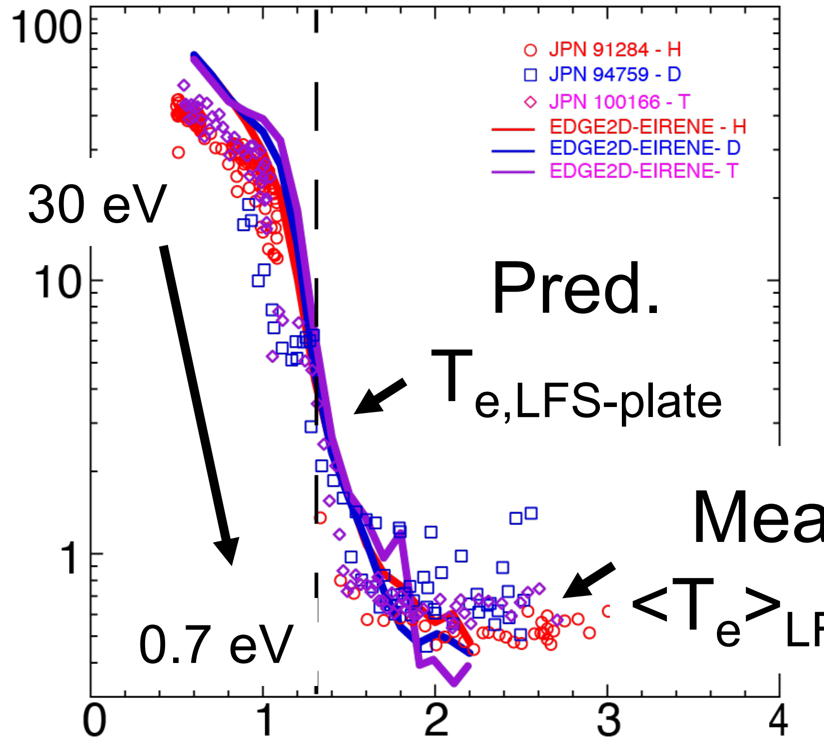
The EDGE2D-EIRENE predicted onset of detachment is independent of the isotope species, as measured



$n_{e,sep,LFS-mp}$ (10^{19} m^{-3}) ← $= 1/2 \langle n_e \rangle_{edge}$

- EDGE2D-EIRENE predicts the onset of detachment at same LFS midplane separatrix density as measured
- Predicted divertor currents are independent of the D2 throughput, consistent with divertor cryogenic pump off case

EDGE2D-EIRENE predicts non-linear reduction of $T_{e,div}$ due to plasma radiation, ionisation and dissociation



$T_{e,LFS\text{-}plate}$

$\langle T_e \rangle_{LFS\text{-}div}$

T_e (eV)

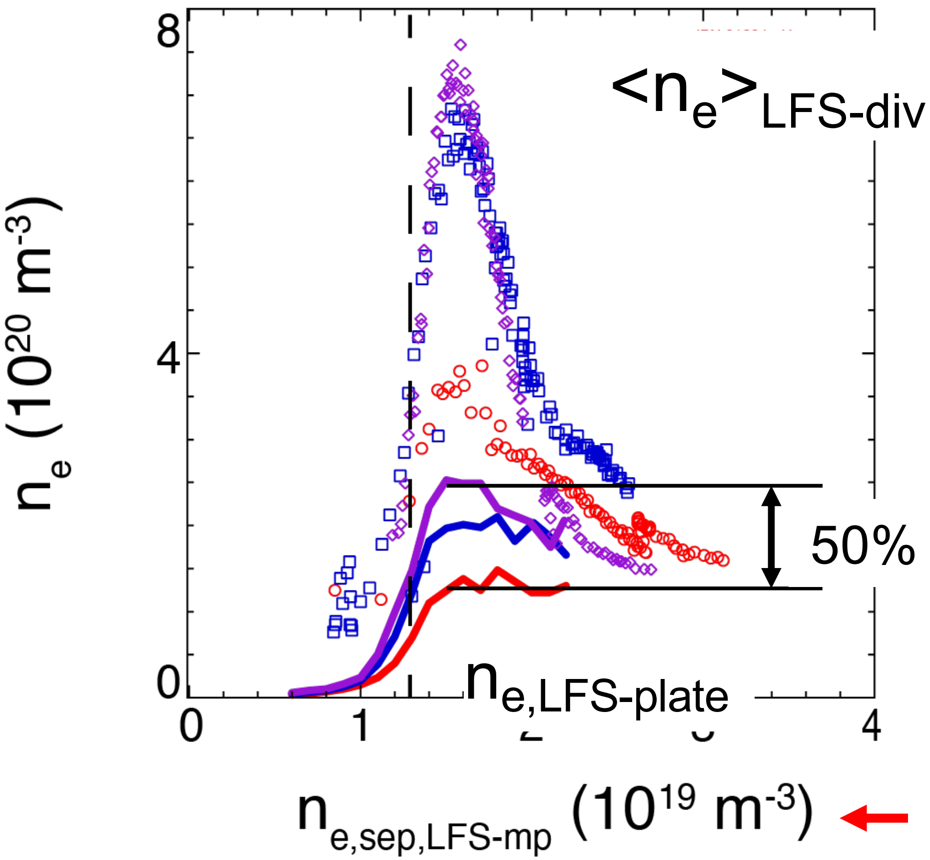
$n_{e,sep,LFS\text{-}mp}$ (10^{19} m^{-3}) = $1/2$ $\langle n_e \rangle_{edge}$

- Isotope effect negligible through transition down to $T_{e,div}$ of 1 eV

⇒ Below 1 eV, predicted $T_{e,div}$ lower for T than for H and D, unresolved experimentally

JET

Predicted divertor density is approx. 50% higher in tritium than in hydrogen plasmas

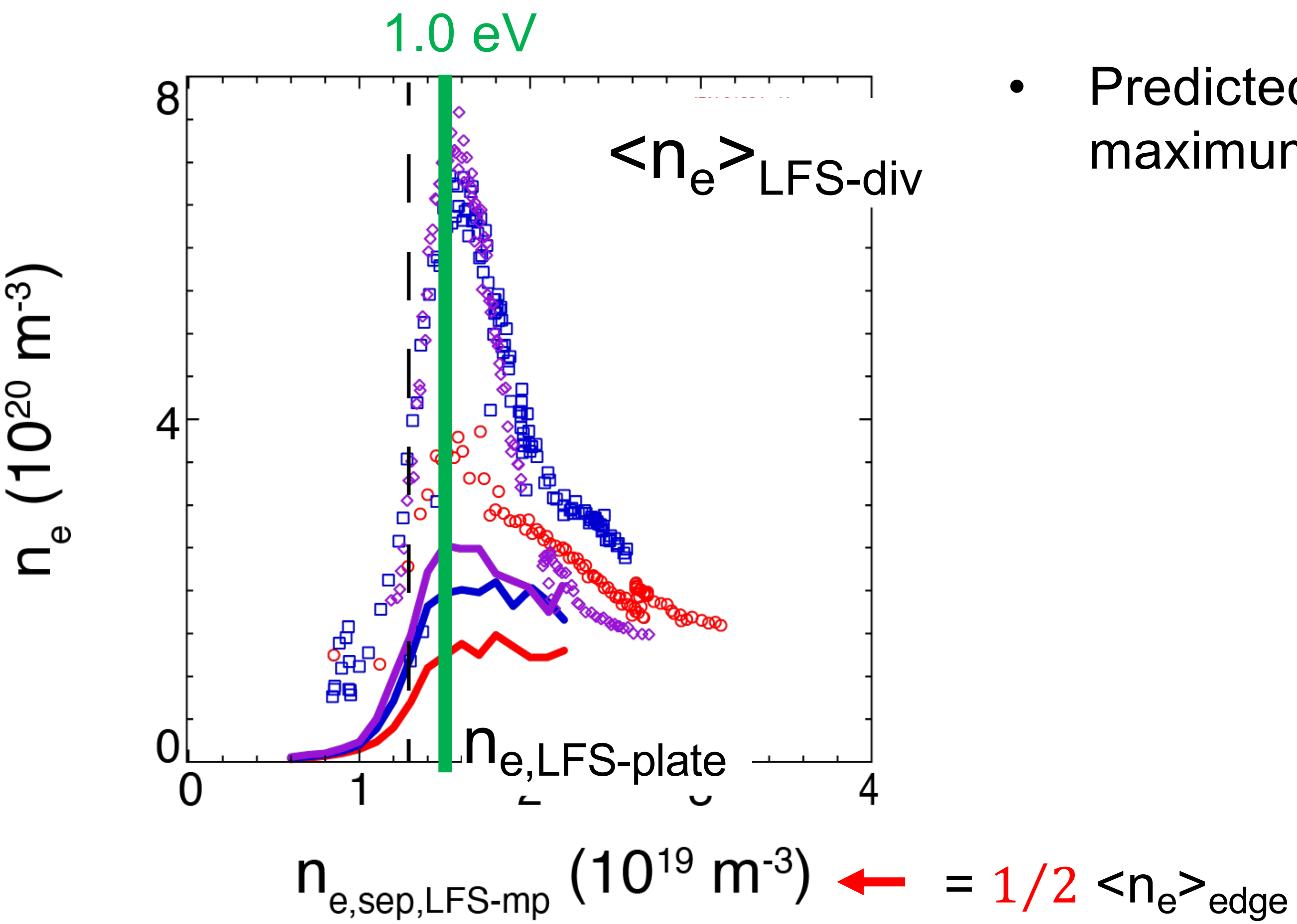


= $1/2\ \langle n_e \rangle_{edge}$

- Conceptually, for similar recycling flux (I_{div}) and $M_{target} \approx$ unity $\Rightarrow n_e \propto \sqrt{m_{ion}}/T_e$

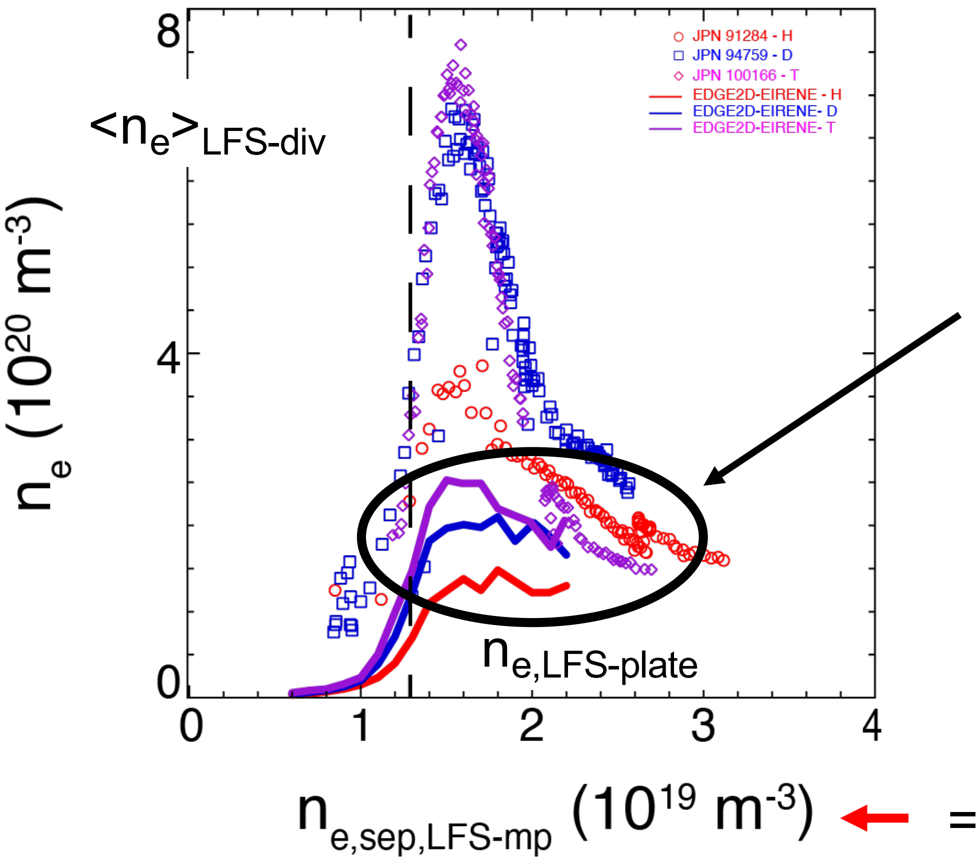
JET

Predicted divertor density is approx. 50% higher in tritium than in hydrogen plasmas



- Predicted n_e at the plate reaches maximum when $T_{e,div} \approx 1$ eV

Predicted divertor density is approx. 50% higher in tritium than in hydrogen plasmas



= $1/2$ $\langle n_e \rangle_{edge}$

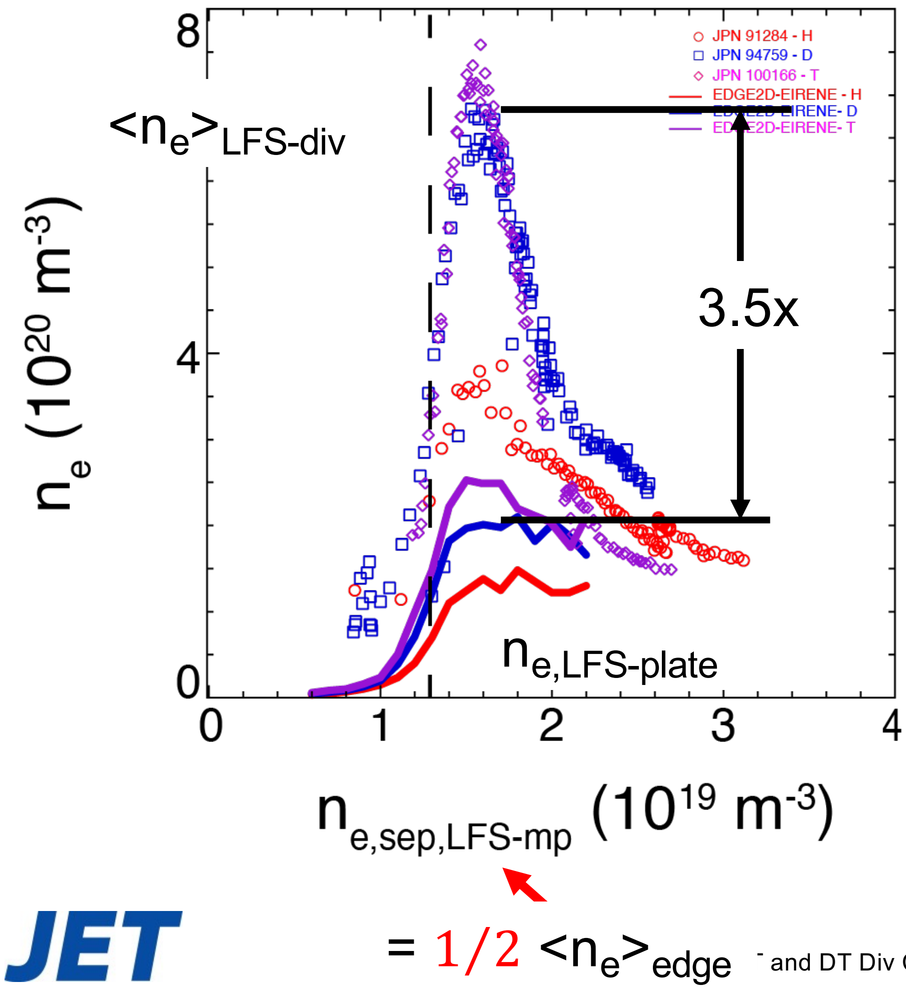
- Predicted n_e at the plate reaches maximum when $T_{e,div} \approx 1$ eV
- n_e predicted to "build up" at plate, but not to decrease toward density limit

⇒ High-density (high-pressure) region does not move poloidally toward LFS X-point region as measured*

*A.G. Meigs et al., JNM 2013
J. Karhunen et al., PPFC 2021

JET

Predicted divertor densities are 3-4x lower then inferred spectroscopically



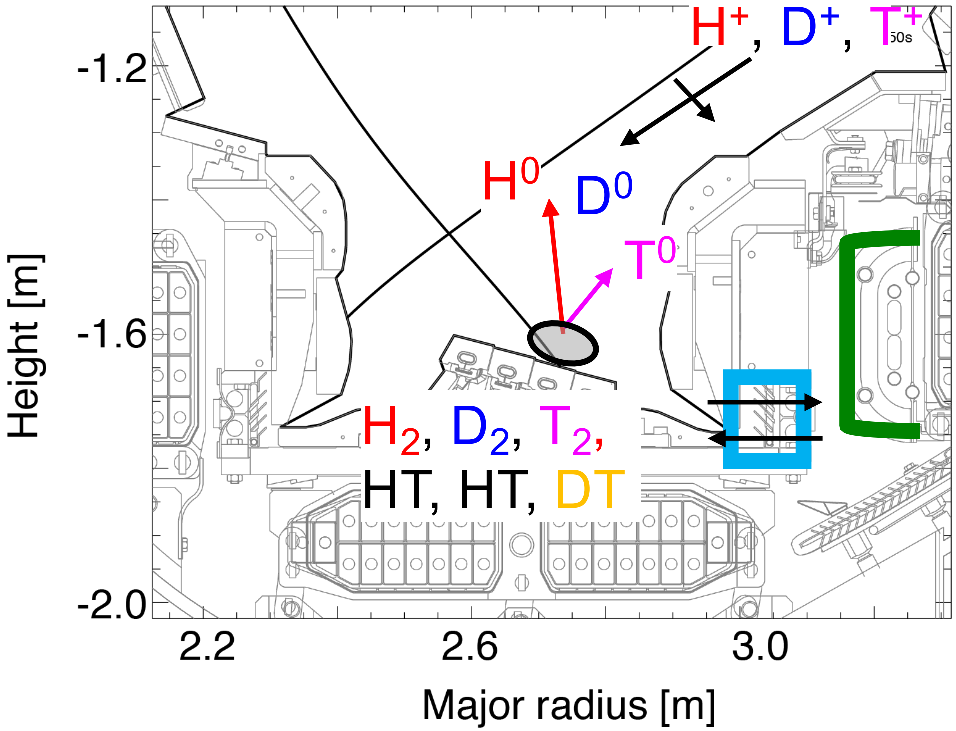
- Predicted n_e at the plate reaches maximum when $T_{e,div} \approx 1$ eV
- n_e predicted to "build up" at plate, but not to decrease toward density limit

⇒ High-density (high-pressure) region does not move poloidally toward LFS X-point region as measured

⇒ Discrepancy can be reduced, but not entirely resolved by assuming higher $n_{e,sep,LFS\text{-}mp}$ (and $T_{e,sep,LFS\text{-}mp}$)

⇒ Discrepancy further exacerbated when considering line-integration

How significant is the impact of hydrogen isotopes on the divertor conditions and degree of detachment?



- For the same energy heavier ions are slower

⇒ **Widens scrape-off layer (∝ $\sqrt{m_{ion}}$)** ⇒ see backup

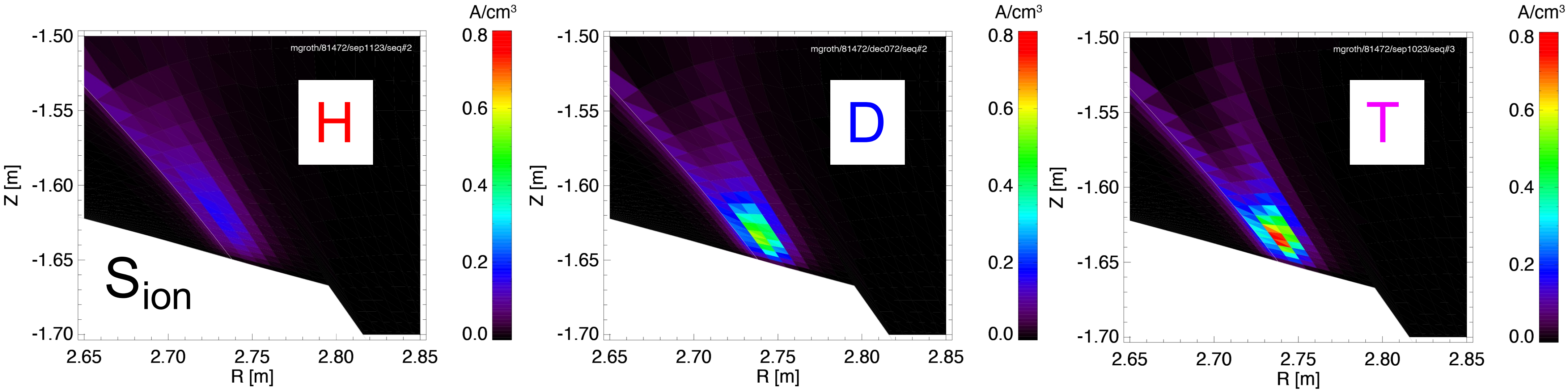
⇒ **Reduces velocity of fast-reflected atoms (∝ $1/\sqrt{m_{ion}}$)**

- **Heavier (F-C and CX) atoms have a shorter ionisation mean free path: ∝ $1/\sqrt{m_{atom}}$**
- Stronger ion-molecular interaction (rates) for heavier species for temperatures < 2 eV **???**
- ~~Conductance of pump duct: ∝ $1/\sqrt{m_{mol}}$~~
- ~~Sticking probab. of cryo. pump: ∝ $X * m_{mol}$~~

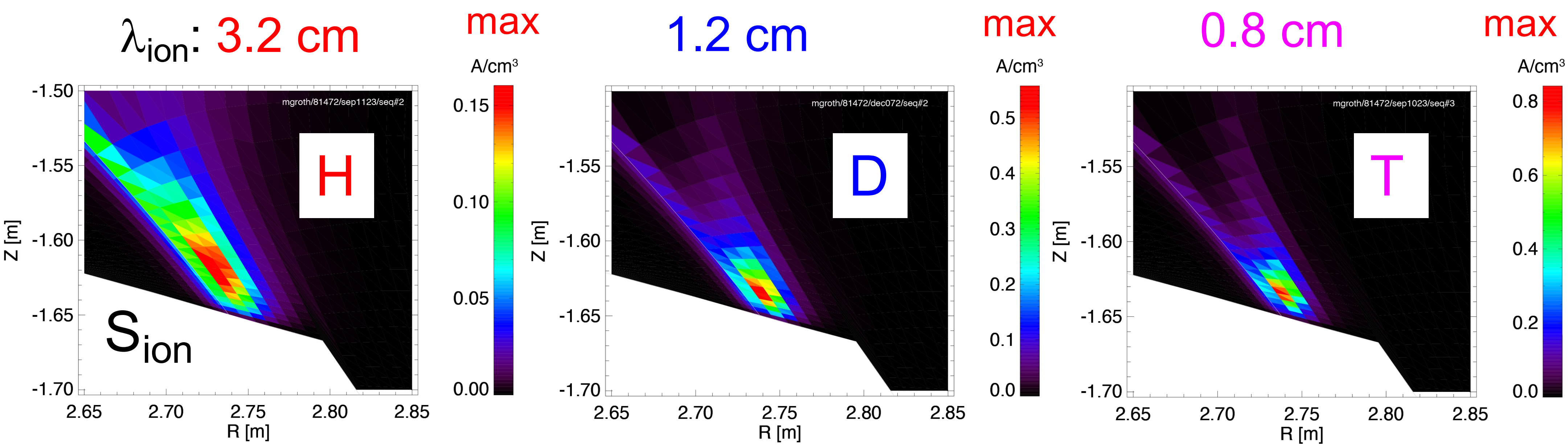
JET

For $T_{e,div} \approx 1$ eV, EIRENE predicts the peak ionisation source to be higher for tritium than for deuterium and hydrogen

0.8 /cm^{-3} 0.8 A/cm^3 0.8 A/cm^3



Predicted ionisation source more spread out poloidally due to approx. 3x longer ionisation mean free path of H than T atoms



- Velocity of Franck-Condon and charge-exchange atoms $\propto 1/\sqrt{m_{atom}}$
- Velocity of (fast) reflected ions off the target is 40% higher for H than for T (25% for D), due to the Mach number at sheath entrance ≈ unity

Impact of hydrogenic isotopes on the SOL/detachment studied in JET-ILW L-mode plasmas in a vertical-horizontal div. plasma config.

- T, D and DT plasmas are more strongly detached than H plasmas, same detachment onset density, but lower DL ⇒ narrower detachment window

- 40% higher divertor densities and broader SOL density profiles at the LFS midplane for T and DT than for H and D

⇒ EDGE2D-EIRENE qualitatively explains higher divertor densities in T plasmas by 3x longer ionisation mean free path of H than T atoms

* V. Solokha et al., Phys. Scr. 2021

Impact of hydrogenic isotopes on the SOL/detachment studied in JET-ILW L-mode plasmas in a vertical-horizontal div. plasma config.

- T, D and DT plasmas are more strongly detached than H plasmas, same detachment onset density, but lower DL ⇒ narrower detachment window ⊖
- 40% higher divertor densities ⊕ and broader SOL density profiles at the LFS midplane for T and DT than for H and D ⊖

⇒ EDGE2D-EIRENE qualitatively explains higher divertor densities in T plasmas by 3x longer ionisation mean free path of H than T atoms

* V. Solokha et al., Phys. Scr. 2021

Impact of hydrogenic isotopes on the SOL/detachment studied in JET-ILW L-mode plasmas in a vertical-horizontal div. plasma config.

- T, D and DT plasmas are more strongly detached than H plasmas, same detachment onset density, but lower DL ⇒ narrower detachment window
- 40% higher divertor densities and broader SOL density profiles at the LFS midplane for T and DT than for H and D

⇒ EDGE2D-EIRENE qualitatively explains higher divertor densities in T plasmas by 3x longer ionisation mean free path of H than T atoms

- Predicted divertor conds. highly sensitive on imposed LFS midpl. conds.: div. densities generally underpredicted in high-rec. and detached conds.

JET

* V. Solokha et al., Phys. Scr. 2021
**K. Verhaegh et al., EX-P4 2103, D. Borodin et al.,, P4-2110
***R. Chandra et al., EPS 2023

Impact of hydrogenic isotopes on the SOL/detachment studied in JET-ILW L-mode plasmas in a vertical-horizontal div. plasma config.

- T, D and DT plasmas are more strongly detached than H plasmas, same detachment onset density, but lower DL ⇒ narrower detachment window
- 40% higher divertor densities and broader SOL density profiles at the LFS midplane for T and DT than for H and D

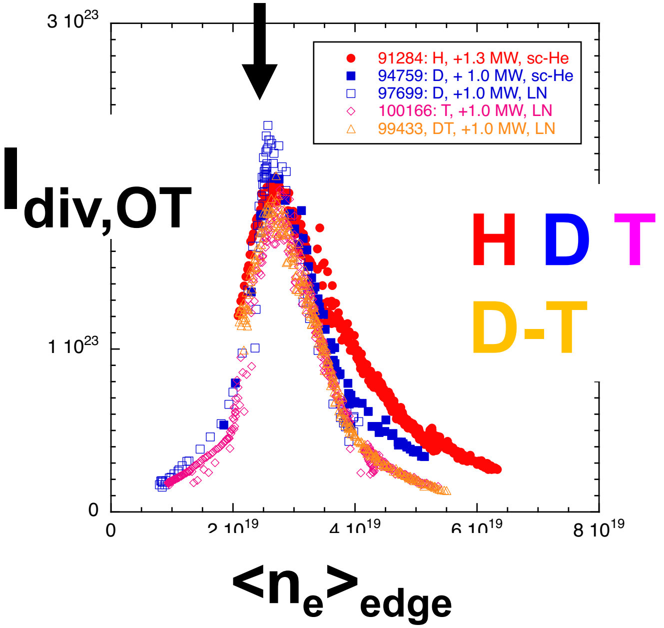
⇒ EDGE2D-EIRENE qualitatively explains higher divertor densities in T plasmas by 3x longer ionisation mean free path of H than T atoms

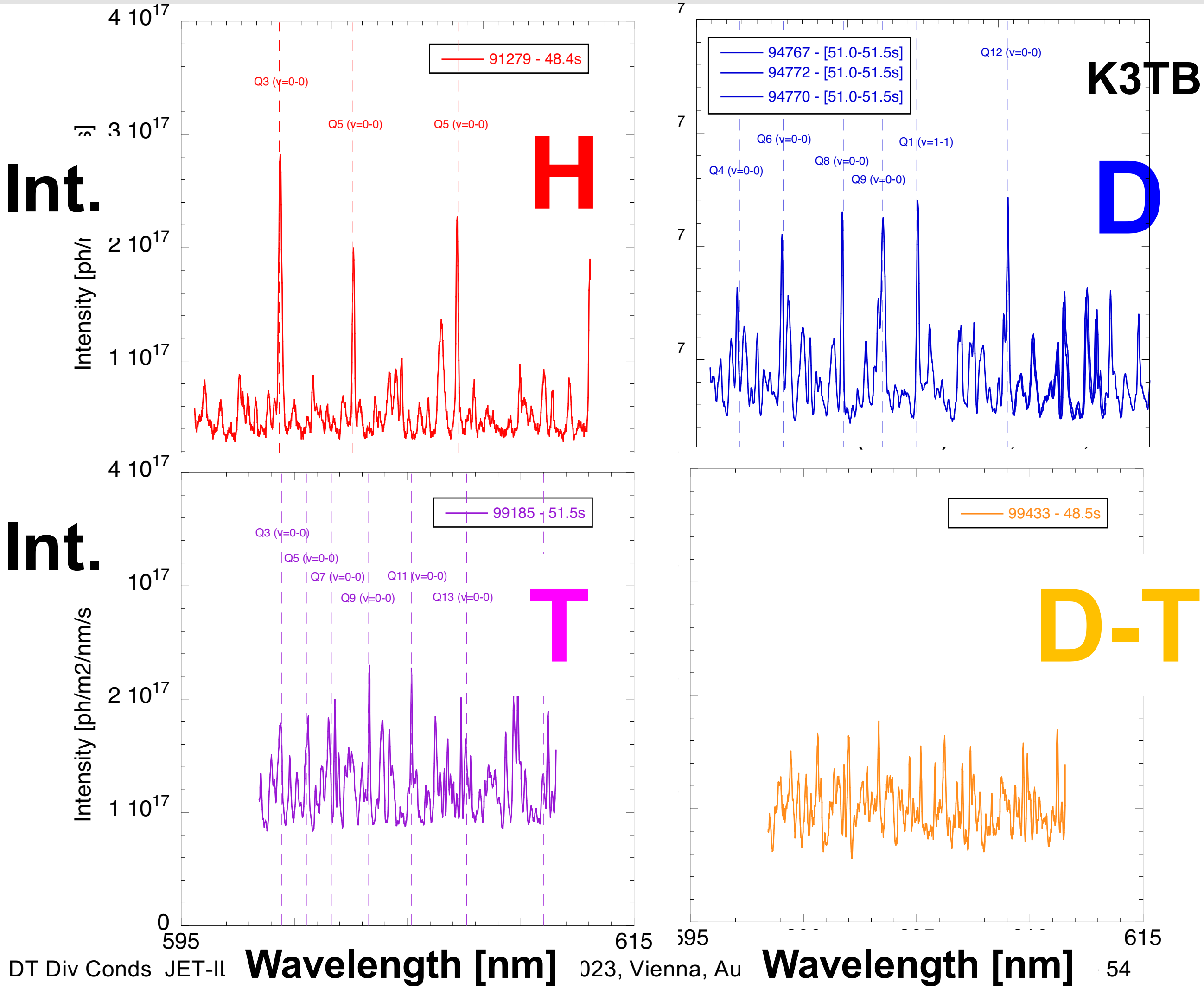
⊖ Predicted divertor conds. highly sensitive on imposed LFS midpl. conds.: div. densities generally underpredicted in high-rec. and detached conds.

⇒ Revisit simulations, also for ion-molecular reaction rates**, Ly-α opacity***

* V. Solokha et al., Phys. Scr. 2021
**K. Verhaegh et al., EX-P4 2103, D. Borodin et al.,, P4-2110
***R. Chandra et al., EPS 2023

Fulcher band spectra Q band is progressively more compressed for T than for H and D ⇒ Ewa Pawelec et al., Tue Nov 29, 2023

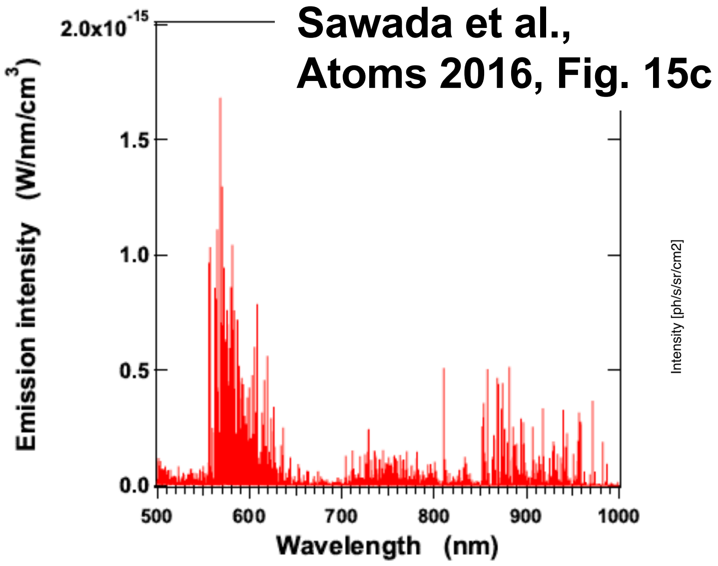


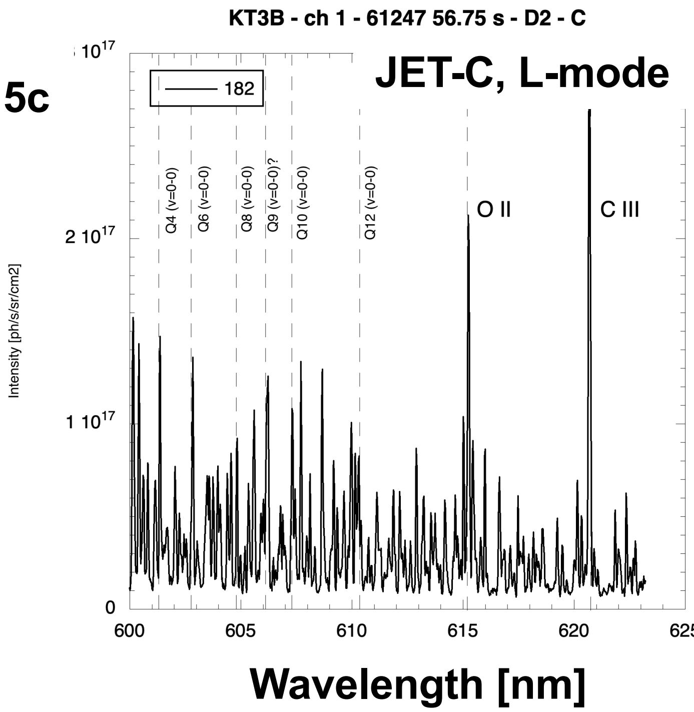


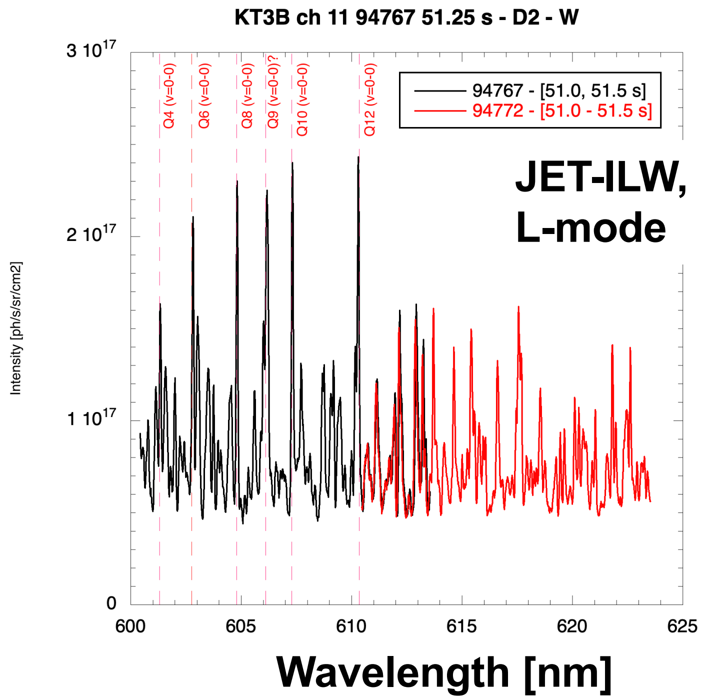
- Sergienko et al., JNM 2013 for **recycling off W surfaces**: high population of the $d^3\Pi_u^-$ (v = 0) vibrational level indicating non-Boltzmann vibr. distribution

JET

Prediction of ($H_2 \rightarrow D_2$, T_2) Fulcher band emission: investigate the role of D_2 recycling off tungsten (versus known carbon) surfaces





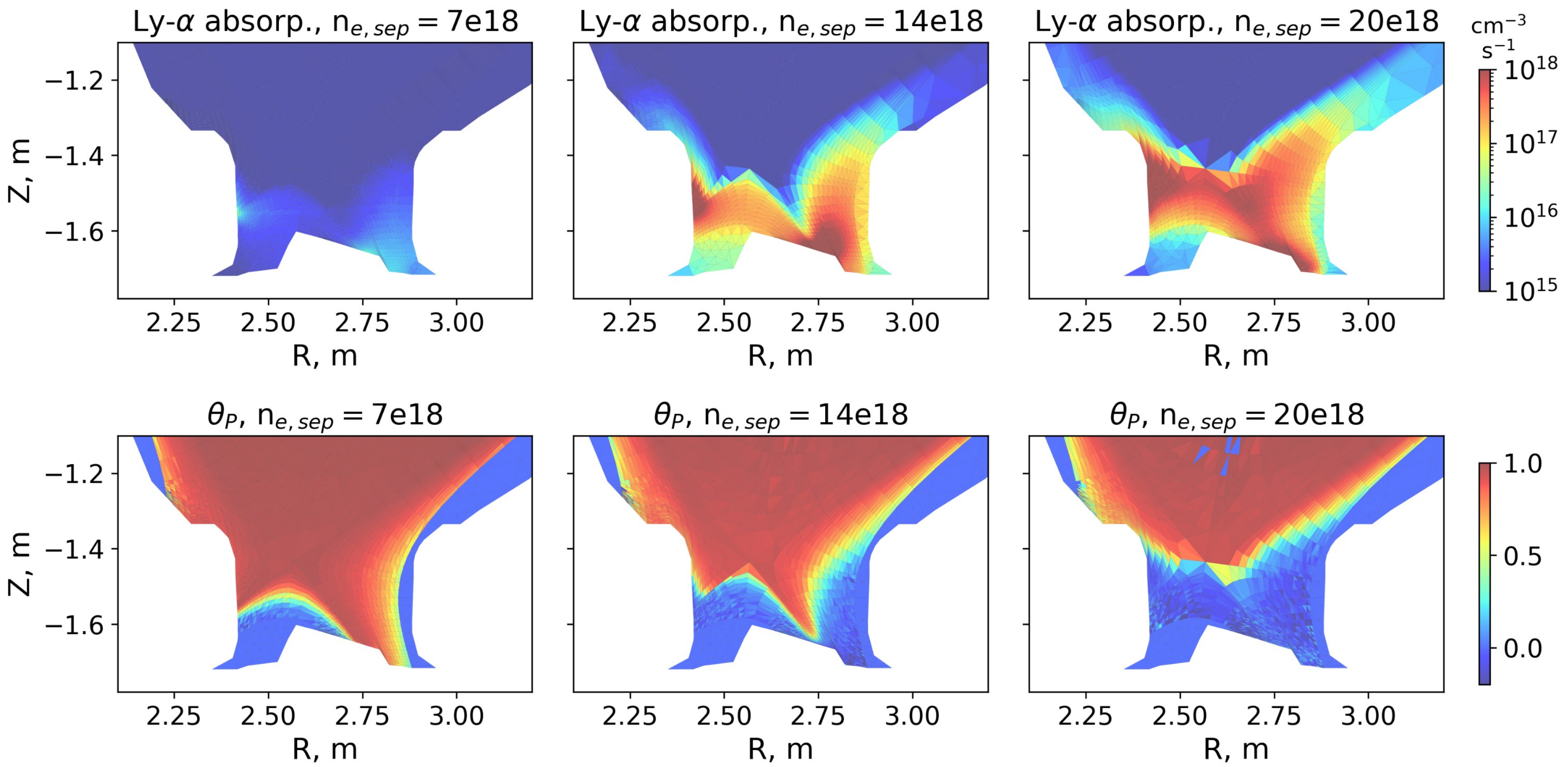


- Validate atomic (Lyman and Balmer series) and molecular (Fulcher) against EIRENE predictions ⇒ validate atomic and molecular influxes
- Prediction of ro-vibrational spectrum: surface activation versus volumetric excitation

Standalone EIRENE on EDGE2D-EIRENE background plasma: divertor is Ly-α and Ly-β opaque in high-recyc. and det. conds.

Low-recyc., $T_{e,OSP} \approx 30$ eV **High-recyc., $T_{e,OSP} \approx 2$ eV** **Part. det., $T_{e,OSP} \approx 1$ eV**

Ray Chandra et al., EPS 2023



$$\theta_p = 1 - \frac{absorption}{emission}$$

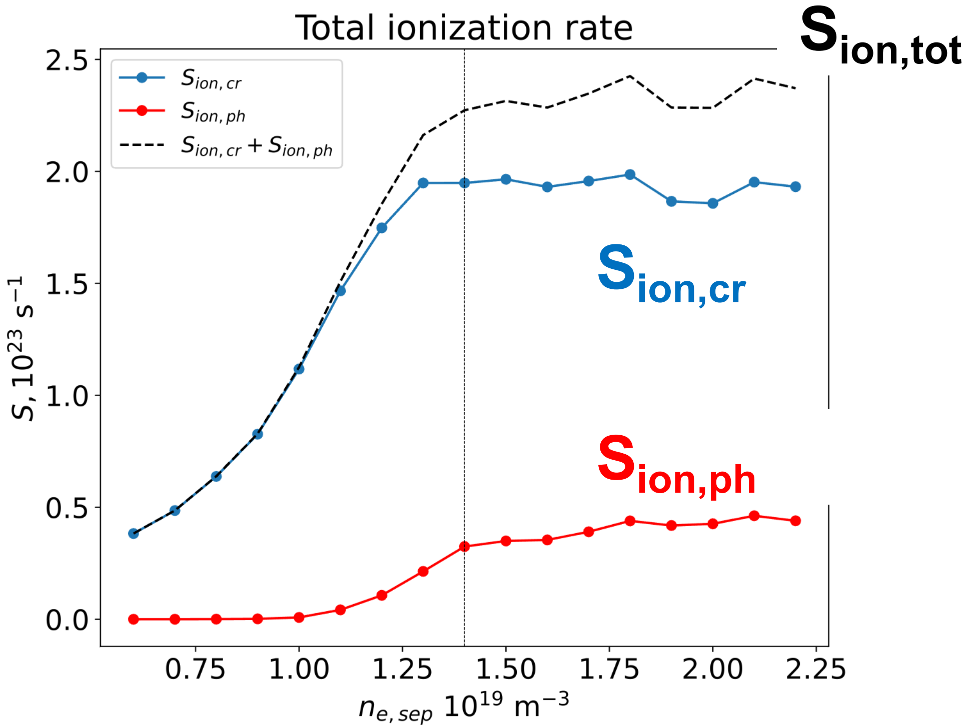
$\Rightarrow \theta_p = 0 \rightarrow$ fully opaque, negative values indicate local effect of absorption

JET

For high-recycling and detached conditions, ionization rate increases ~20% with opacity due to extra D* from line absorption

$$S_{eff} = \underbrace{S_{(1)} + \sum_n \left(C_{(1,n)} - R_{1(n)}(F_{(n,1)} + \frac{A_1}{n_e}) \right)}_{S_{eff,cr}} + \underbrace{\sum_n \left(\Gamma_{(1,n)} - R_{ext(n)}(F_{(n,1)} + \frac{A_1}{n_e}) \right)}_{S_{eff,ph}}$$

Ray Chandra et al., EPS 2023



- Ly-α transparent in low recycling regime due to insufficient gas density
- Effect of excess ionization from Ly-α absorption to the plasma ionization balance under investigation

⇒ R. Chandra et al., PSI 2024: coupling to plasma solver (plasma ⇔ gas ⇔ photons)

(Further) points of discussion

- Inclusion of surface effects in molecule recycling ⇒ full or reduced data from Molecular Dynamics calculations

⇒ Generally:

  - Comparison of energy and angular distributions of recycling H and H2, and their isotopes/isotopologues, between TRIM and MD
  - Surface binding energy for ion impact energies < 10 eV, for W and C

- For Ly-α, comparison of 0D escape factors, pre-run photon transport (e.g., Hoshino et al., CPP 2016), post-processing CRETIN (Scott, J. Quant. Spec. Rad. Transfer 2001) and non-linear gas-photon transports (e.g., Kotov, Wiesen → Chandra et al., PSI 2024)
- Treatment/separation of $D^+ + D_2$ charge exchange and momentum transfer