The properties of helium in tokamak plasmas:

experimental studies and comparisons with theoretical predictions

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EUROfusion

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See the author lists of:
[a]*"H. Meyer et al, 2019 Nucl. Fusion accepted (doi:10.1088/1741-4326/ab18b8)"*
[b]*"B. Labit et al, 2019 Nucl. Fusion accepted (doi:10.1088/1741-4326/ab2211)"*
[c]*"E. Joffrin et al, 2019 Nucl. Fusion accepted (doi:10.1088/1741-4326/ab2276)"*

The Questions

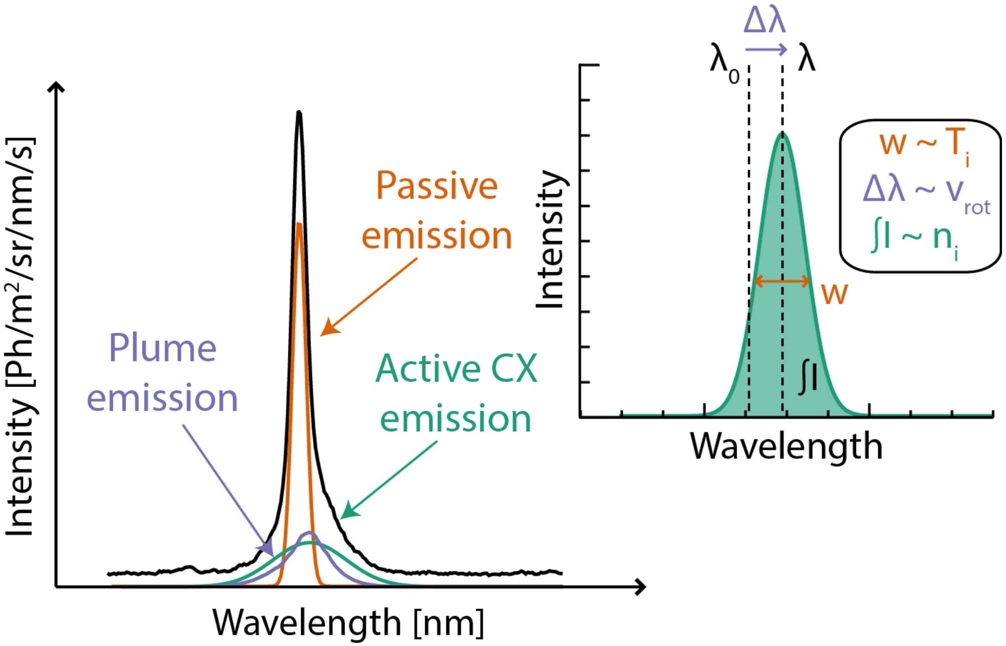
- **What does the helium density profile look like?**
  Is $n_{He} \sim c \cdot n_e$ a good assumption?
  How does the experiment compare with modelling?

- **Is helium affecting the performance and behavior of the plasma?**
  Do helium plasmas have bad confinement?

- **Can we measure confined energetic helium ions?**
  Under which conditions?
  Measurement ←→ Modelling ?

- **Is helium accumulation an issue?**
  Can helium be exhausted sufficiently well?

Helium in the plasma core is measured by Charge eXchange Recombination Spectroscopy



Active charge exchange emission:
CX reactions of fully stripped He with beam neutrals

Passive emission: electron impact excitation of He^+ and charge exchange of He^{2+} with thermal neutrals at the plasma edge

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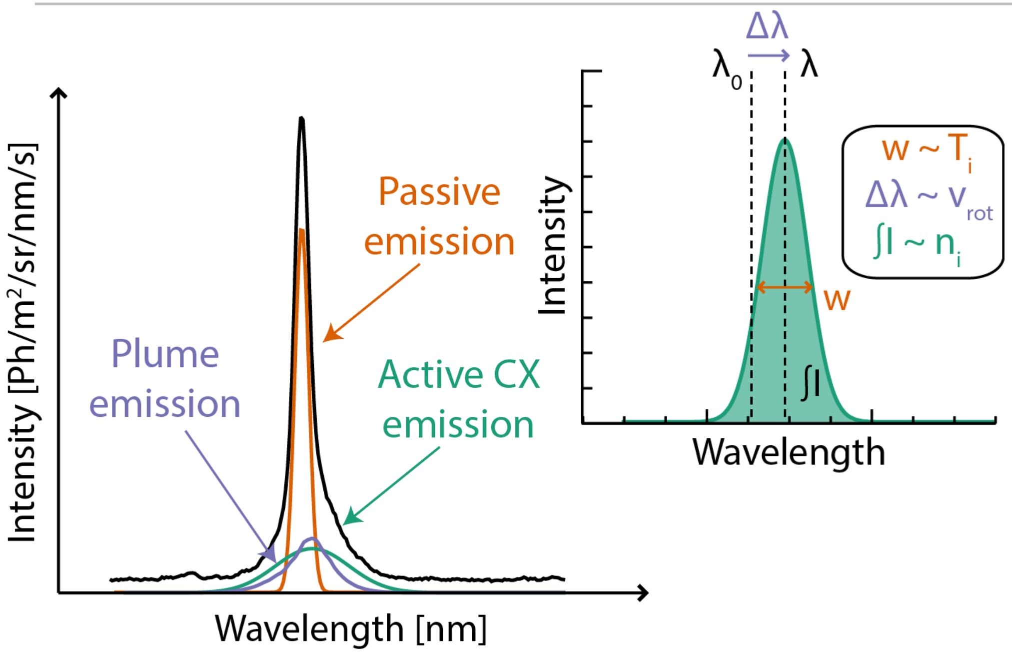

Active charge exchange emission: CX reactions of fully stripped He with beam neutrals

Passive emission: electron impact excitation of He^+ and charge exchange of He^{2+} with thermal neutrals at the plasma edge

“Plume” emission: electron collisional excitation of the He^+ ions produced by charge exchange reactions along the neutral beam.

→ Requires forward modelling to remove this additional emission from the spectra

→ Without it, helium density overestimated

- **What does the helium density profile look like?**

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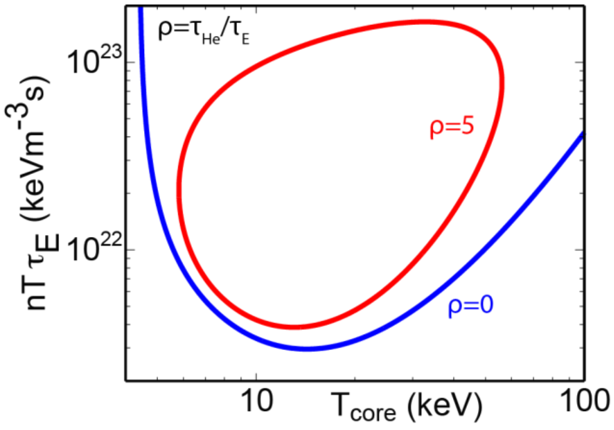


[D. Reiter et al, NF 1990, adapted from T. Pütterich, EPS 2015]

Minimal fuel dilution desired to achieve a burning plasma

→ Low level of seeding impurities and high-Z elements

→ No core accumulation of thermalised helium

In a fusion reactor, n_{He} will be determined by:

Helium source

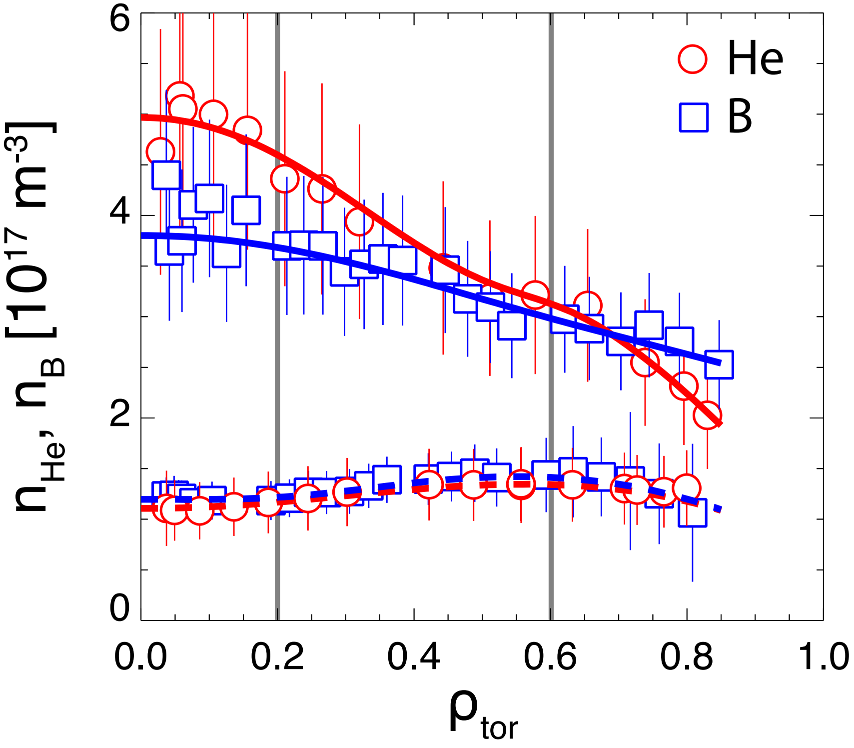
\+ Transport effects

\+ Pumping and recycling

Need validated low-Z impurity transport models to make predictions!

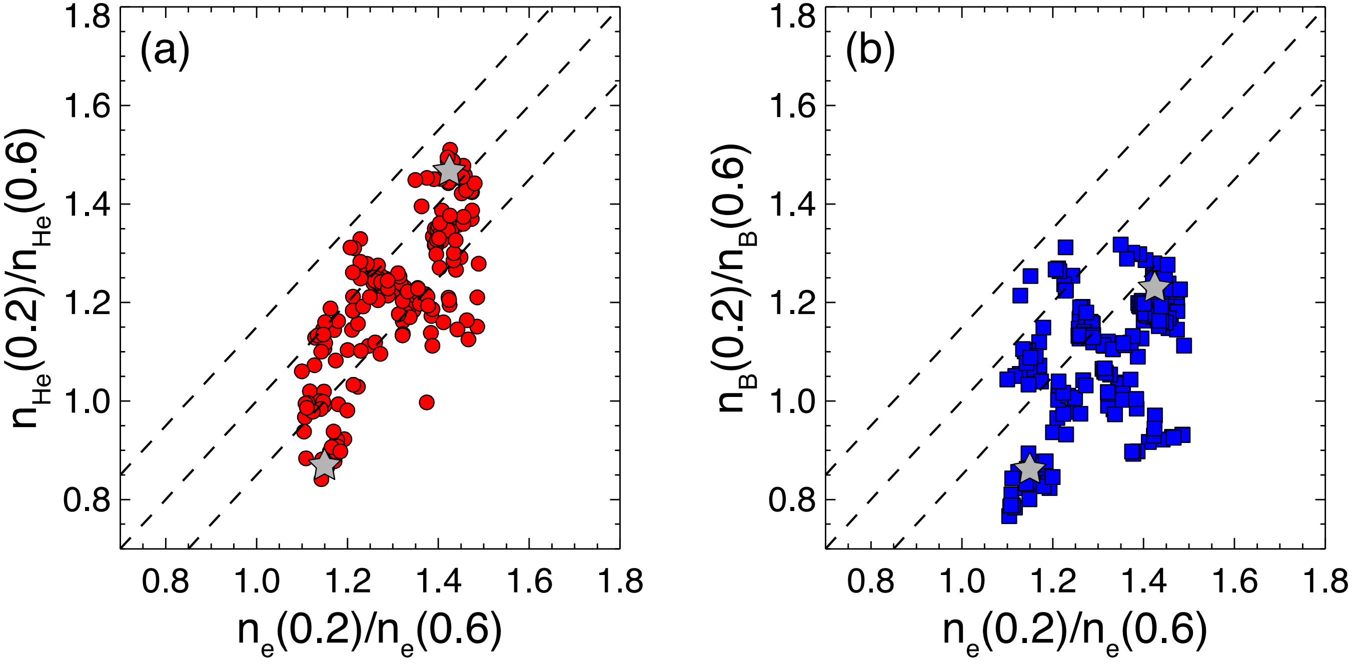
The peaking of the impurity density profiles depends on plasma parameters

A.Kappatou et al, NF 2019



- Peaking of the low-Z impurity density profiles in stationary source free conditions
- Varying transport relevant parameters:
  peaking and/or magnitude of n_e, T_e, T_i, (and T_e/T_i), v_ϕ, ν_{eff}…
- Multi-species studies
- Both He and B “intrinsic” after boronisation (not puffed)

He and B are not significantly more peaked than the electron density → no accumulation



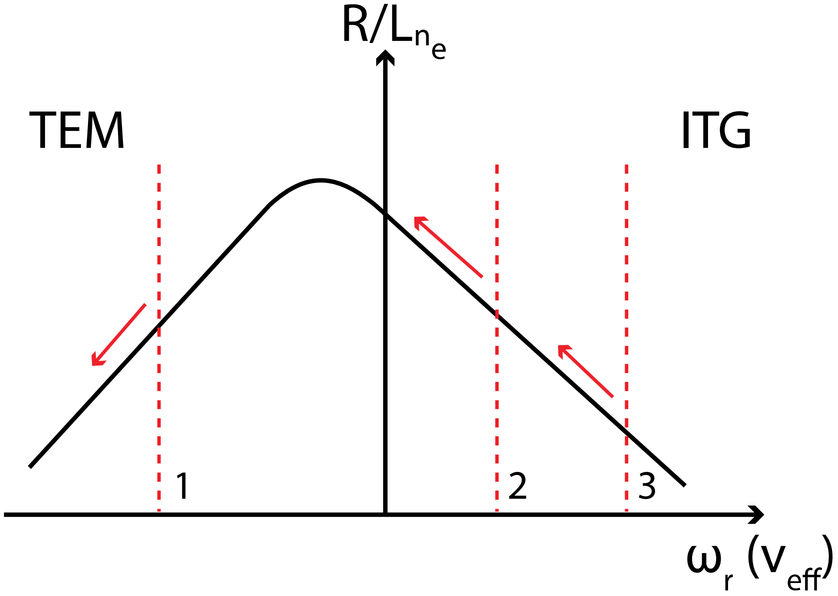
- The helium density profile is **not** more peaked than the electron density profile over a wider range of parameters
- The boron density profile is usually less peaked than the helium density profile
- The helium density is “closer” to the electron density profile

He concentration profiles flat with large ECRH fraction, hollow with dominant NBI

Actuators: Scan $\mathbf{P}_{\mathbf{ECRH}}$ (central), $\mathbf{P}_{\mathbf{NBI}}$, D-fuelling, I_p

Changing: collisionality, peaking of n_e, peaking and magnitude of v_ϕ, T_e/T_i, …

[C.Angioni et al, NF 2011, R.M.McDermott et al, PPCF 2011]



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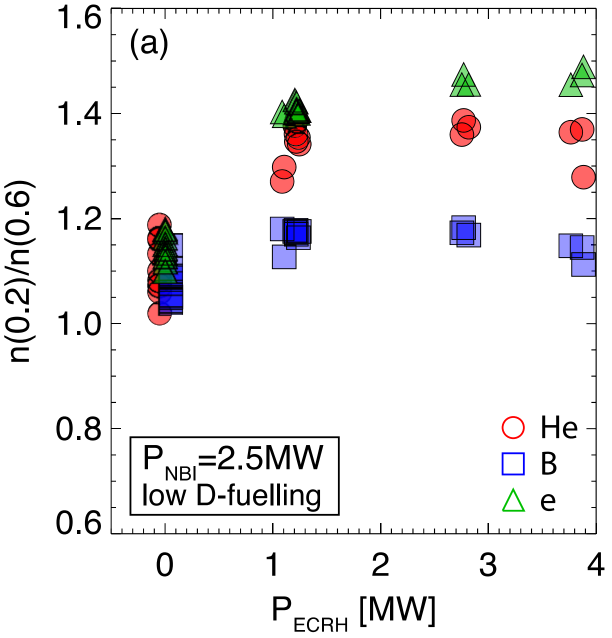
Changing: collisionality, peaking of n_e, peaking and magnitude of v_ϕ, T_e/T_i
[C.Angioni et al, NF 2011, R.M.McDermott et al, PPCF 2011]

With **increasing** $\mathbf{P_{ECRH}}$
→ **Peaking of the impurity profiles**
→ n_{He} less peaked than n_e at low P_{ECRH}/P_{NBI}



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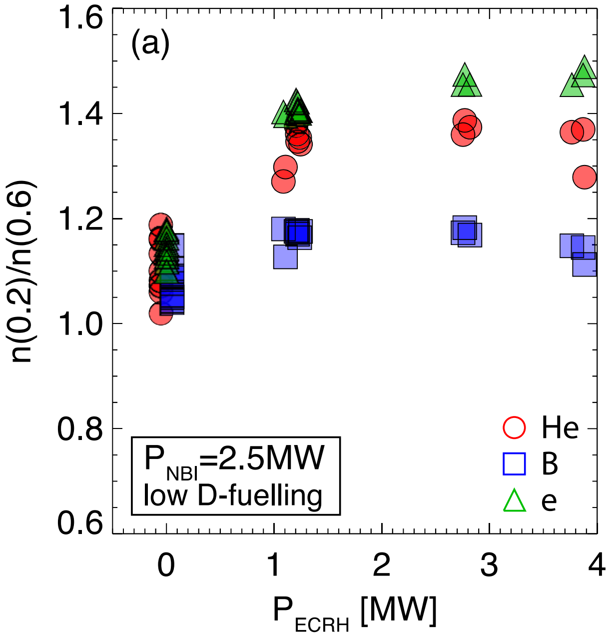
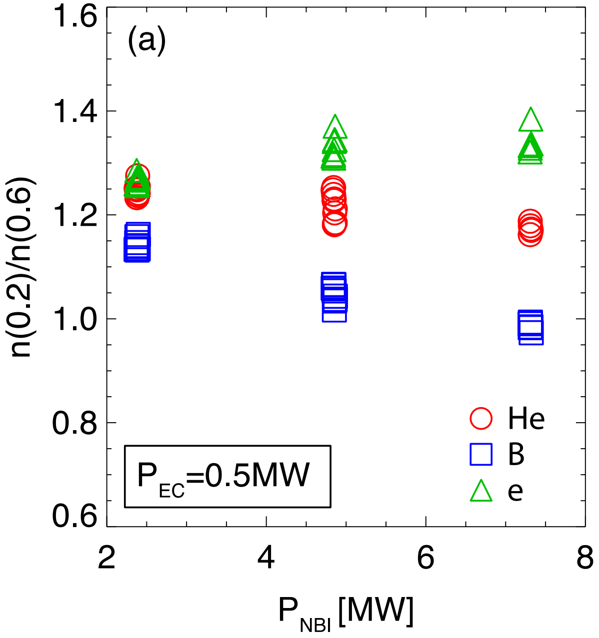


With **increasing $\mathbf{P_{NBI}}$**

→ **Peaking of the impurity profiles decreasing**



Comparison of experimental gradients w/ modelling, or v & D separately

In source free and stationary conditions

$$\frac{R}{L_{n_I}} = -\frac{RV_I^{turb} + RV_I^{NC}}{D_{d,I}^{turb} + D_{d,I}^{NC}}$$

Local quasi-linear gyrokinetic simulations of the turbulent transport with GKW *[A.G.Peeters et al, PoP 2004, A.G.Peeters et al, CPC 2009]*

Neoclassical contributions with Neoart *[R.Dux et al, NF 2000, A.G.Peeters, PoP 2000]*→ Neoclassical diffusion for He, B: negligible at mid-radius, one order of magnitude smaller than turbulent further in

No heat flux matching by varying input parameters, but normalisation of turbulent conductivity to power balance conductivity:

$$D^{\mathrm{turb}}/\chi_{i,turb}^{\mathrm{GKW}}$$

$$D^{\mathrm{NC}}/\chi_{i,an}, \ \chi_{i,an} = \chi_i^{\mathrm{PB}} - \chi_i^{\mathrm{NC}}$$

$$\frac{R\Gamma_{nZ}^{turb}}{n_Z} = \underbrace{D_{NZ}\frac{R}{L_{nZ}}}_{\textbf{Diffusion}} + \underbrace{D_{ThZ}\frac{R}{L_{TZ}} + D_{UZ}u' + RV_{pZ}}_{\textbf{Convection}}$$

Thermodiffusion

Rotodiffusion

Purely convective part

[Frojdh Nucl. Fusion 1992, Angioni Phys.Rev.Letters 2006, Angioni Nucl. Fusion 2009, Camenen Phys. Plasmas 2009, Angioni Nucl. Fusion 2012, Casson Nucl. Fusion 2013]

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$$D^{\rm turb}/\chi_{i,turb}^{\rm GKW}$$

$$D^{\rm NC}/\chi_{i,an},\ \chi_{i,an} = \chi_i^{\rm PB} - \chi_i^{\rm NC}$$

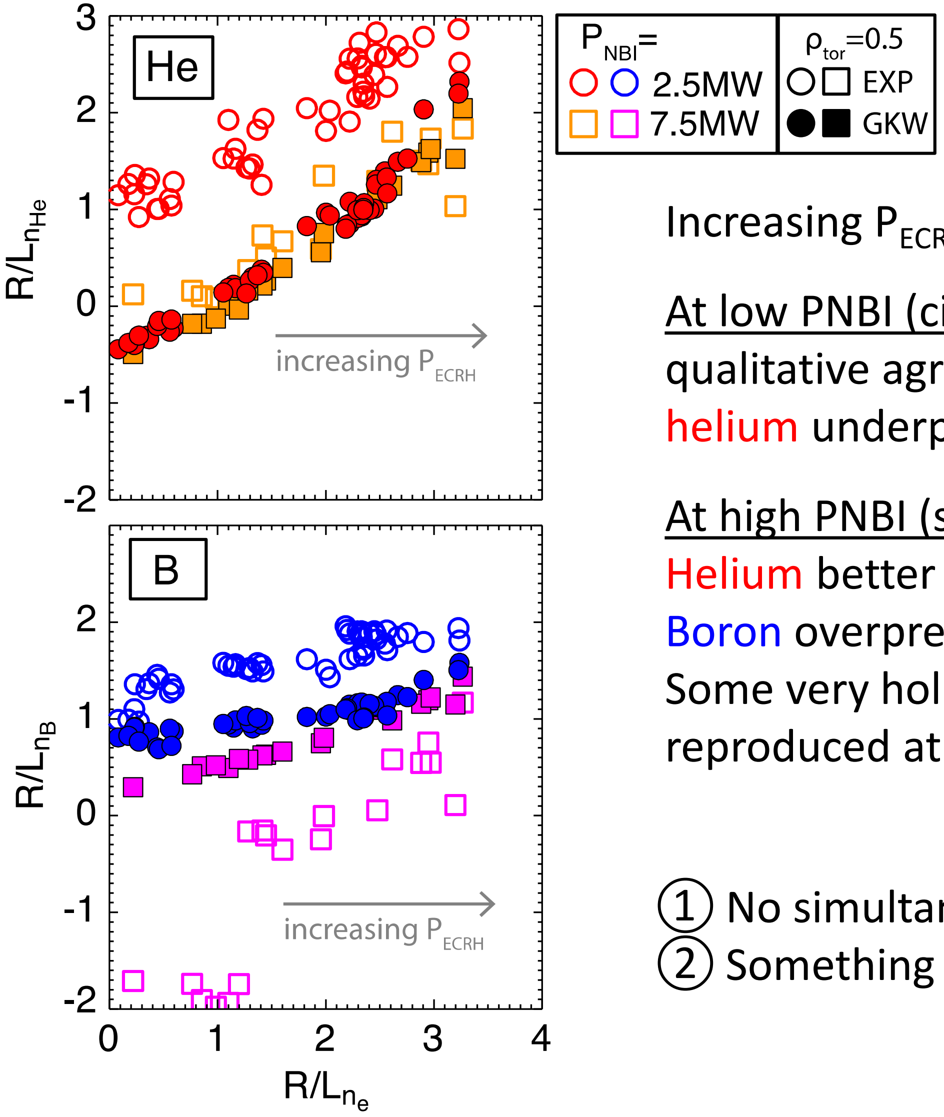
Separate measurement of D and v

- Determination of drift velocity *υ* and diffusion coefficient *D* separately requires **time dependent impurity density profiles**
- Novel method gives a **modulated boron density** by modulating the power of the ICRH antennae

C. Bruhn et al, PPCF 2018

Method not yet experimentally implemented for He (requires appropriate modulation of He gas puff)

Comparison of experiments gradients at mid-radius with gyrokinetic modelling



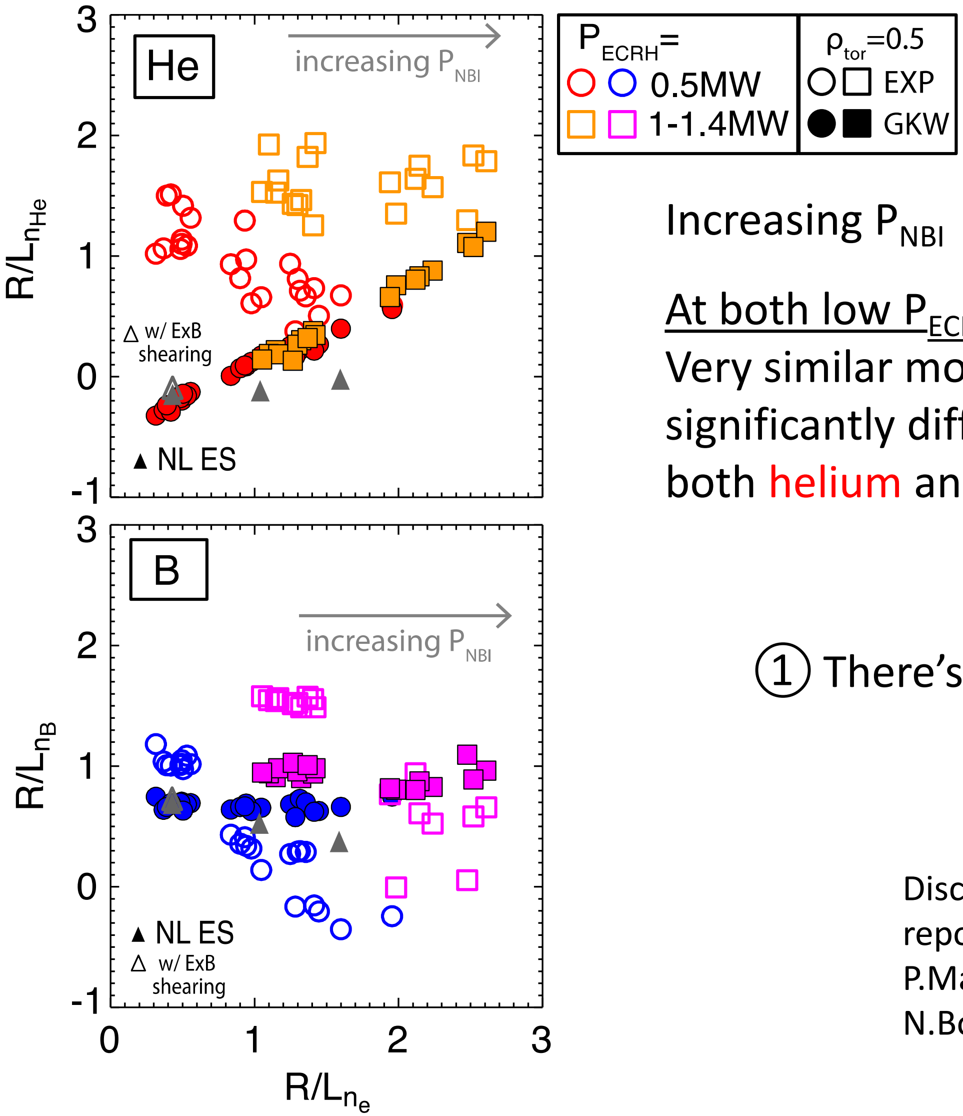
Increasing P_{ECRH}

At low PNBI (circles):
qualitative agreement
helium underpredicted

At high PNBI (squares):
Helium better described
Boron overpredicted
Some very hollow boron experimental profiles not reproduced at all

① No simultaneous good prediction of both impurities
② Something certainly missing at low P_{ECRH}, high P_{NBI}

Comparison of experiments gradients at mid-radius with gyrokinetic modelling



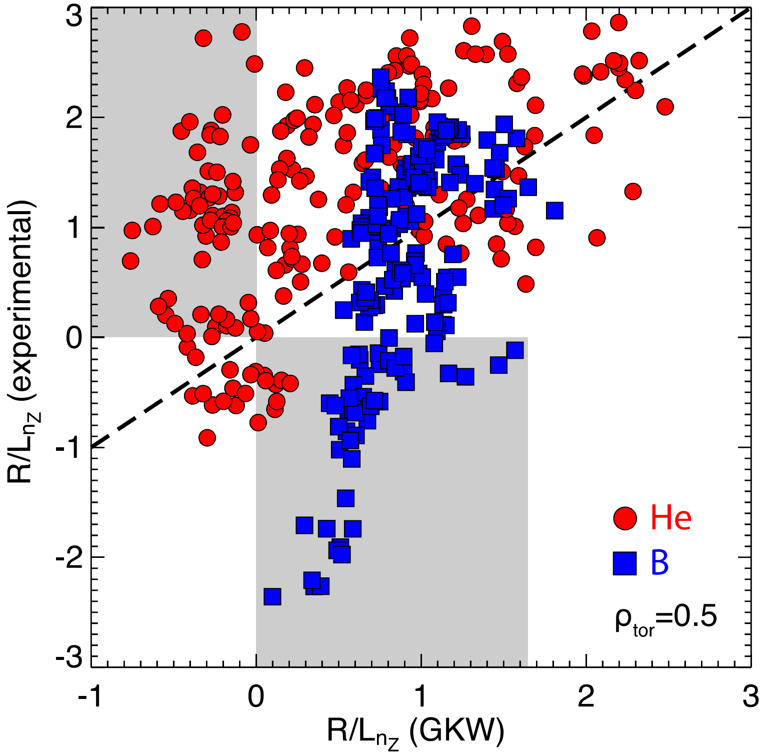
Increasing P_{NBI}

<u>At both low P_{ECRH} (circles) and high P_{ECRH} (squares)</u>:
Very similar modelled gradients
significantly different trends with the experiment for both helium and boron

① There's something missing here…

Discrepancies between modelling and experiments reported also by:
P.Manas et al, PoP 2017
N.Bonanomi et al, NF 2018

Indication for a missing convective contribution

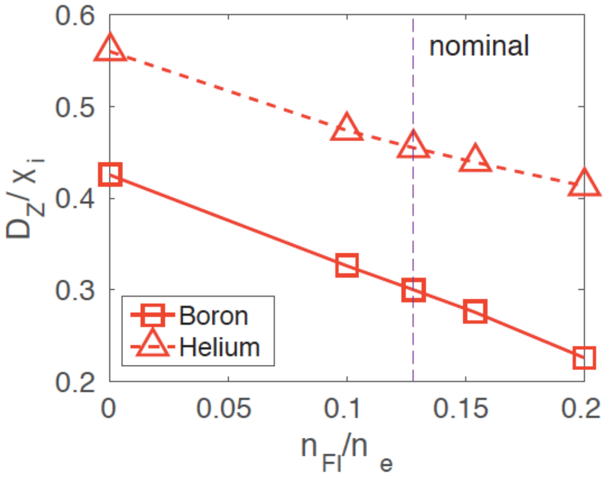


Different "sign" in the comparison between experiment and modelling

→ Convection not correctly described, and/or additional mechanism?

→ Is diffusion correct?

Including NBI fast ions improves the predictions of impurity peaking



P.Manas et al, in preparation

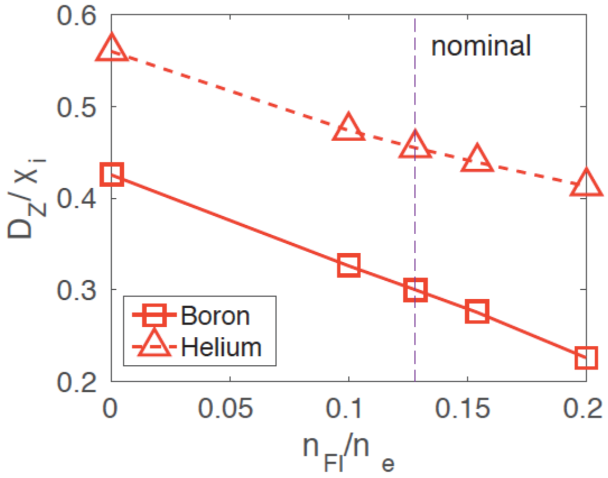
- When considering the fast ion population, the peaking of thermal ions is reduced
- → **reduction of the neoclassical inward pinch**

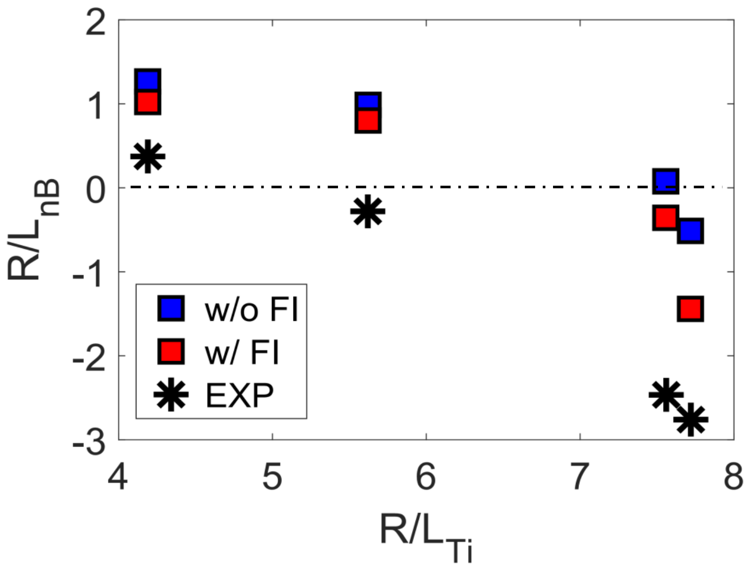
- **Neoclassical contributions become more important** in relation to the turbulent transport

- Effect apparent in cases with increased fast ion population (high P_{NBI})

Including NBI fast ions improves the predictions of impurity peaking

P.Manas et al, in preparation





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- Effect apparent in cases with increased fast ion population (high P_{NBI})

- Hollowness of boron density profiles at high P_{NBI} reproduced *[R.McDermott et al, EPS 2019]*
- For helium, better agreement, but some systematic under-prediction remains.

- **What does the helium density profile look like?**

  Is $n_{He} \sim c \cdot n_e$ a good assumption?

  How does the experiment compare with modelling?

Yes, but…

Boron looks good, helium…not yet.

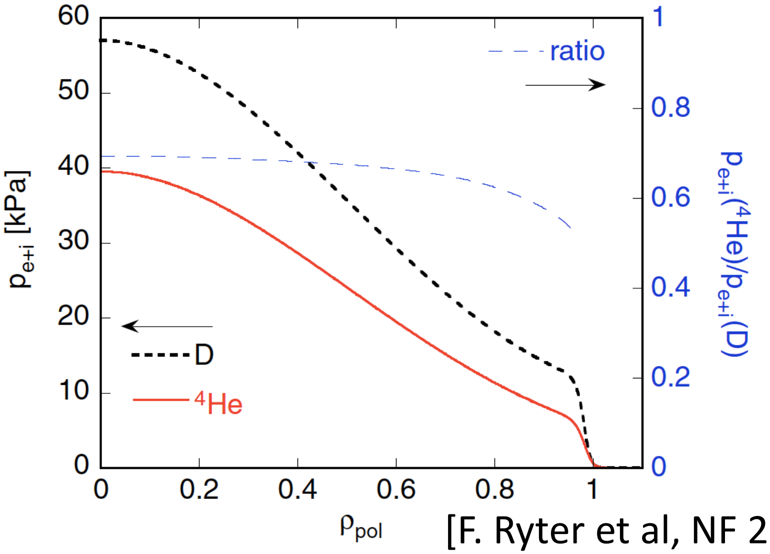
Modelling:
Gyrokinetics (with fast ions) + neoclassical (with fast ions)

Boron ✓

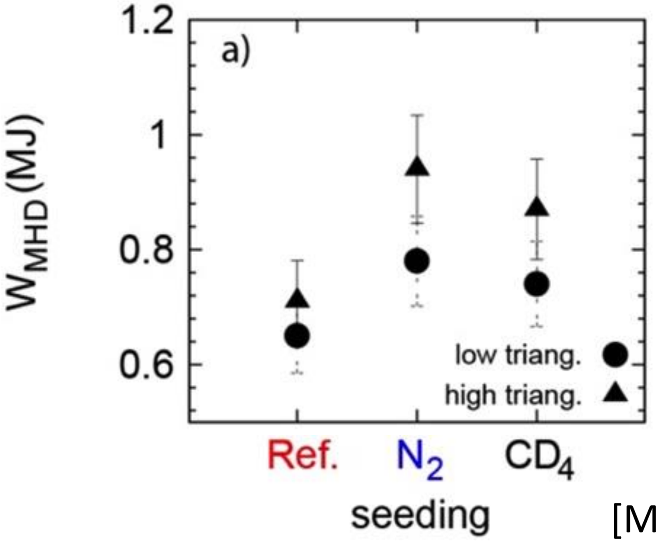
Helium ~

- **Is helium affecting the performance and behavior of the plasma?**

  Do helium plasmas have bad confinement?



[F. Ryter et al, NF 2009]



He?

[M.N.A. Beurskens et al, NF 2016]

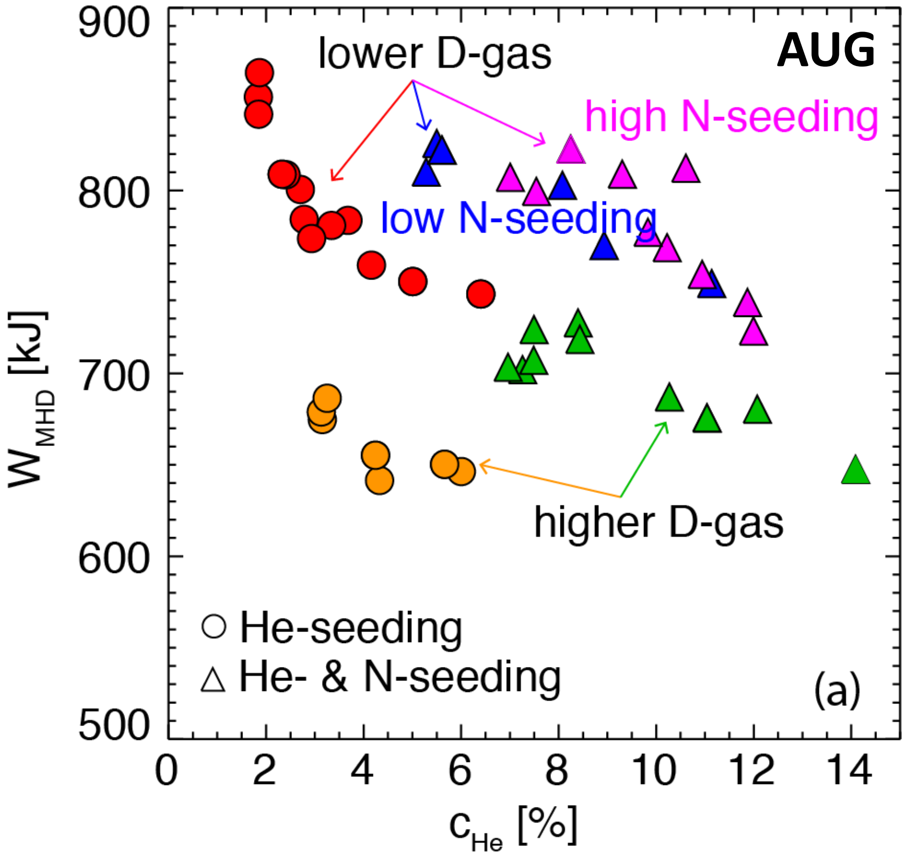
Confinement of helium plasmas systematically lower than that of deuterium plasmas τ_{He}~$0.7\tau_D$

[D.C. McDonald et al, PPCF 2004, F. Ryter et al, NF 2009]

Negative impact of helium in reactor relevant concentrations (<10%) on plasma performance

[R. Neu et al, EPS 2008]

Helium in low concentrations has an influence on the plasma performance … in ASDEX Upgrade



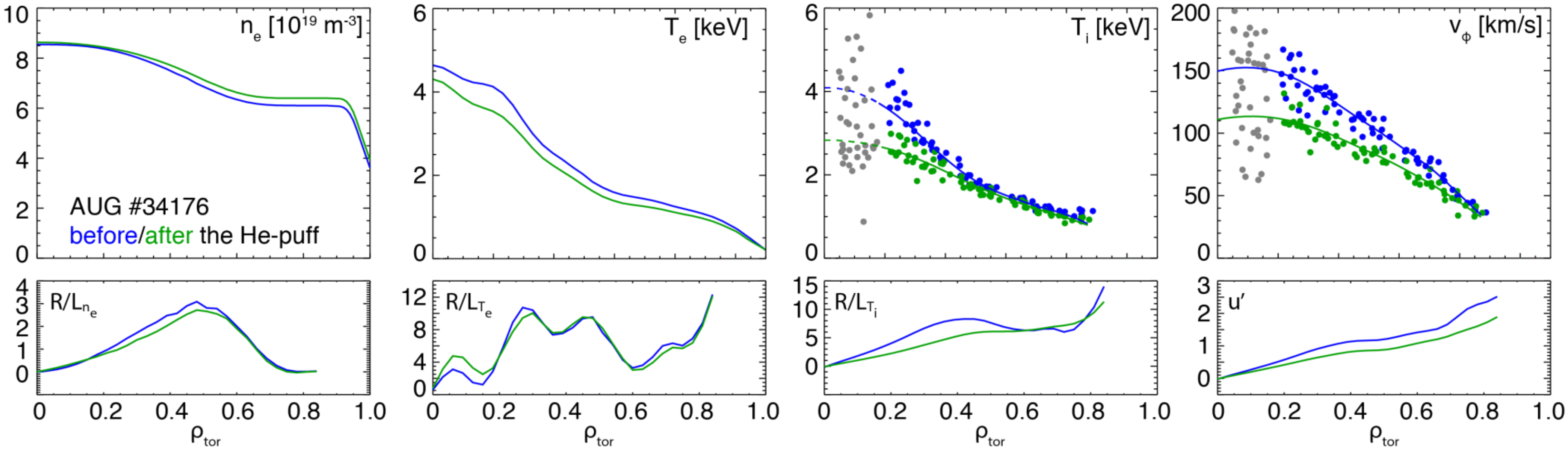
He puffs injected into high confinement D plasmas

- P_{NBI}=10MW, P_{ECRH}=1.3MW, 2.5T/1MA, β_N~1.9-2.3, q_{95}~4.3), D fuelling: $5\cdot10^{21}$ and $7.5\cdot10^{21}$ e^-/s
- With and without N-seeding

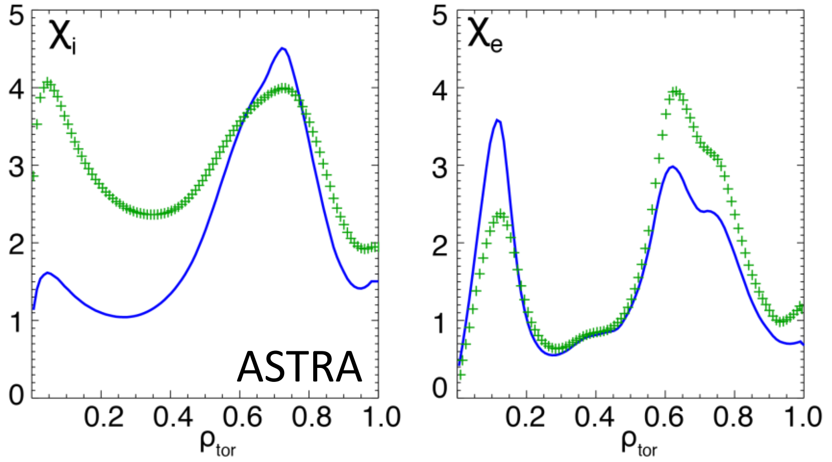
Strong effect on the plasma confinement (stored energy, τ_E,H_{98}) with increasing helium concentration

Note:
No obvious effect on plasma performance if confinement already low

The core kinetic profiles change in the presence of helium



- Δc_{He}~4% (shown case)
- Changes to the core kinetic plasma profiles
  - Core ion pressure loss
- **Increased core transport with (more) helium**



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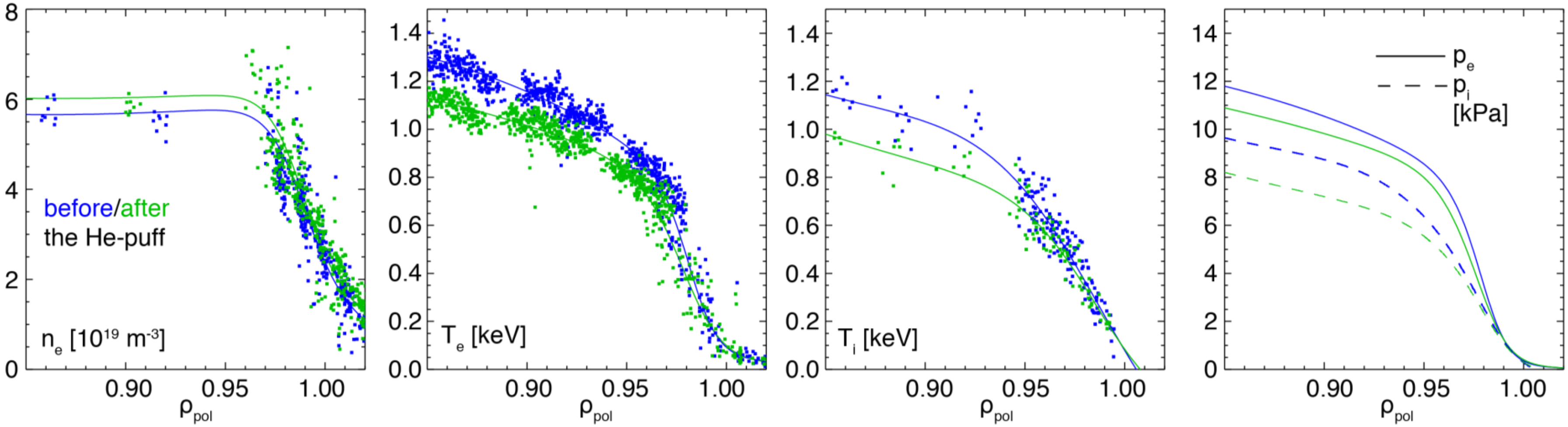

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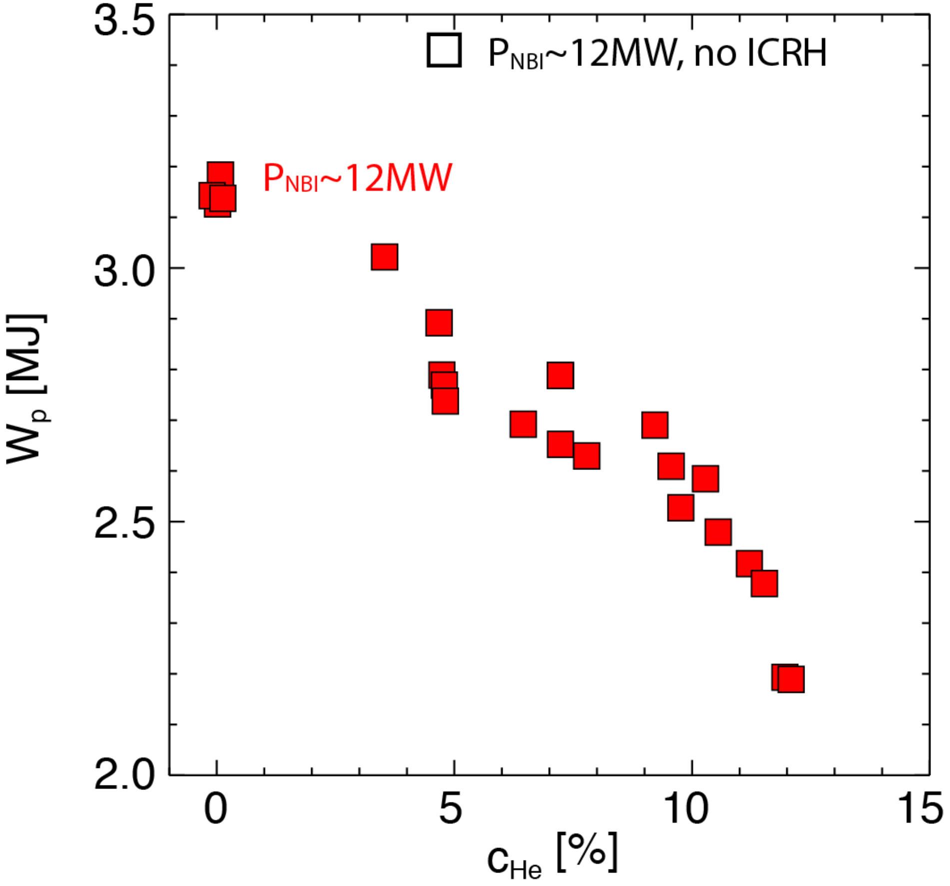
- **Reduction of pedestal pressure, stronger for ions**

Helium in low concentrations has an influence on the plasma performance … in JET

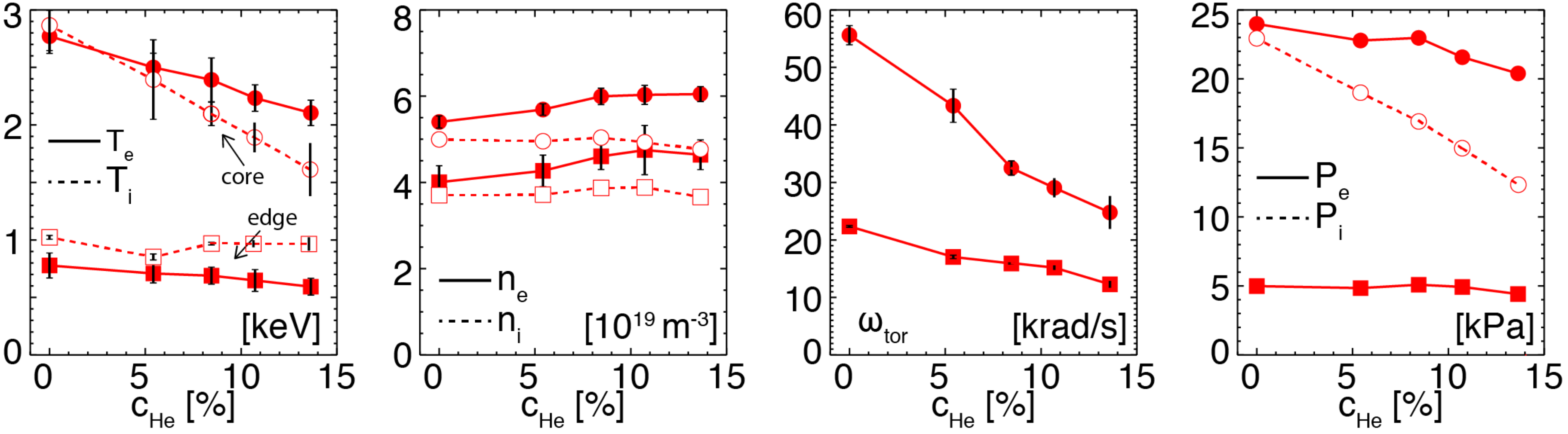


He puffed into baseline H-mode scenario plasmas (c_{He} controlled in real time)

- 2.1T/2MA, D-fuelling $1.6\cdot10^{22}e^-/s$, β_N~1.5, q_{95}~3.1

Strong effect on the plasma confinement (stored energy, τ_E,H_{98}) and neutrons with increasing helium concentration in NBI heated plasmas

The kinetic profiles change in the presence of helium



NBI only heating (P_{NBI}=12MW):

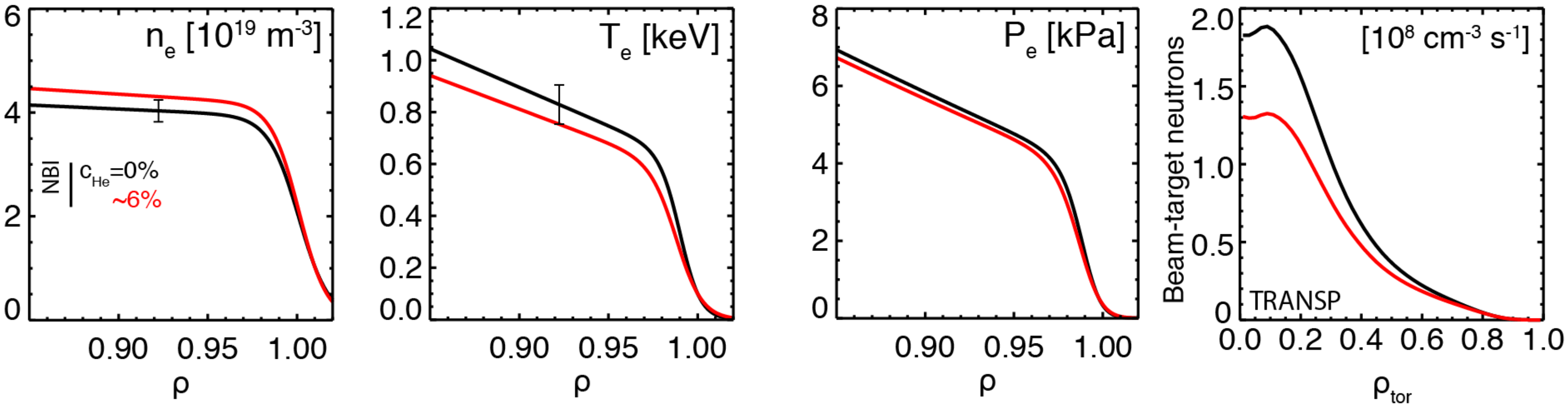
- Changes to the kinetic plasma profiles
  - No significant reduction of p_e^{ped}
  - Core pressure loss

Stronger NBI attenuation

→ Reduced core heating

→ Significant reduction in beam-target neutrons

The kinetic profiles change in the presence of helium



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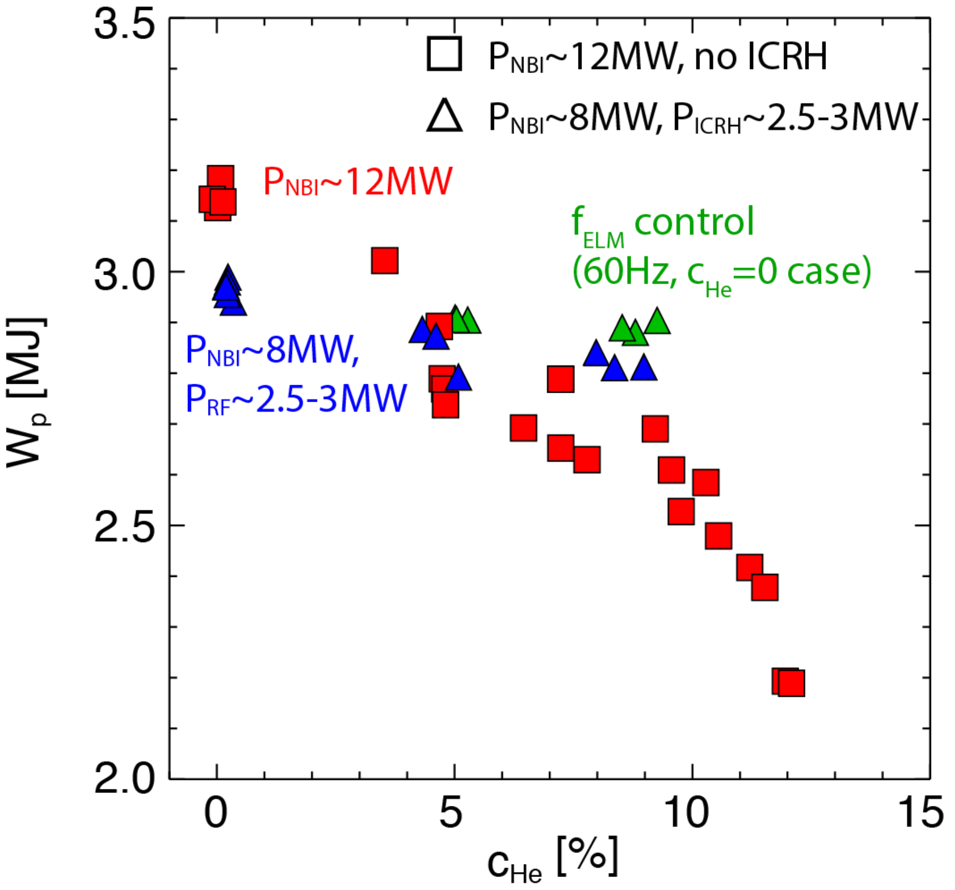

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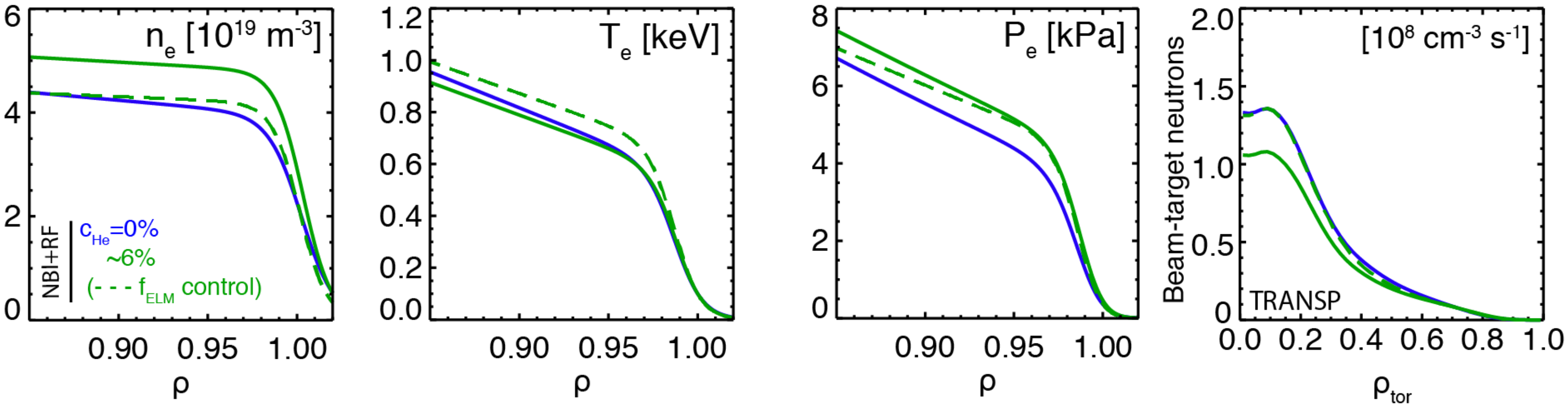
- 2.1T/2MA, D-fuelling $1.6 \cdot 10^{22} e^{-}/s$, β_N~1.5, q_{95}~3.1

- Increasing He concentration in **combined NBI + RF** heated plasmas: **Not as strong reduction** in W_{MHD}, neutrons with combined NBI+RF

- Increasing He concentration with **f_{ELM} control (=reduced D-fuelling)**: **Recovery of confinement**

The kinetic profiles change in the presence of helium



NBI+RF heating

- **Not as strong reduction** in W_{MHD}, neutrons

+ f_{ELM} control:

- **Recovery of confinement**
- Reduction of D gas [C.F. Maggi et al, NF 2015], but much larger than added He (factor ~6 in e^-/s)

Both changes in heat deposition and pedestal stability responsible for loss of confinement

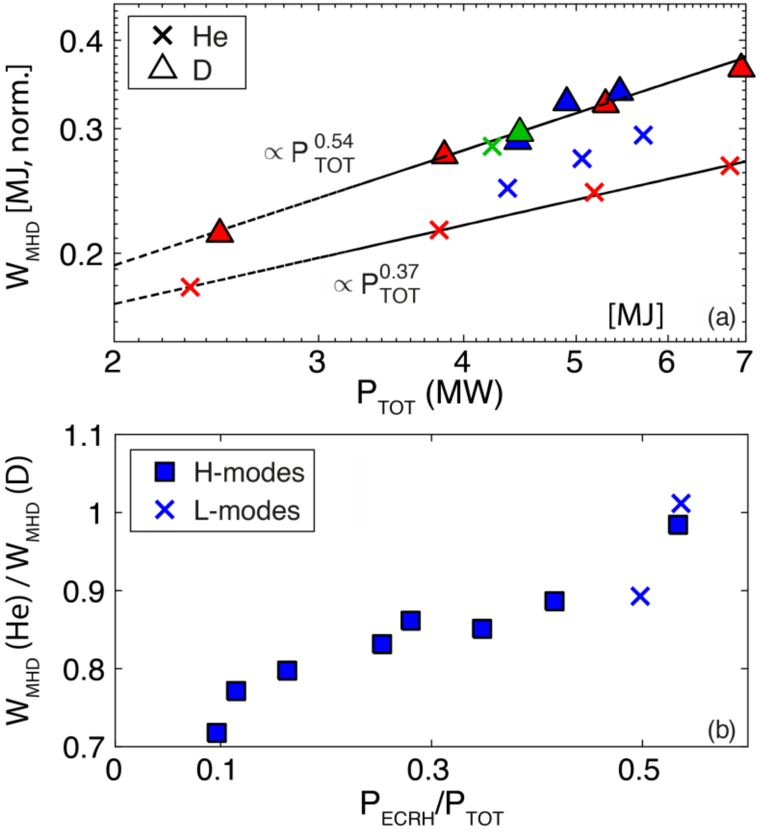
Confinement of helium plasmas improves with increasing electron heating fraction in AUG

P. Manas et al, NF 2019

Comparison of He and D plasmas (L- and H-modes) matching the heating power and the core line averaged n_e

W_{MHD} in He plasmas:

- With low levels of P_{ECRH} and various P_{NBI} (x) → less favorable scaling with P_{TOT} than in D plasmas
- With increasing P_{ECRH} on constant P_{NBI} (x) → more favorable
- With P_{ECRH}>P_{NBI} (x) → equal to D



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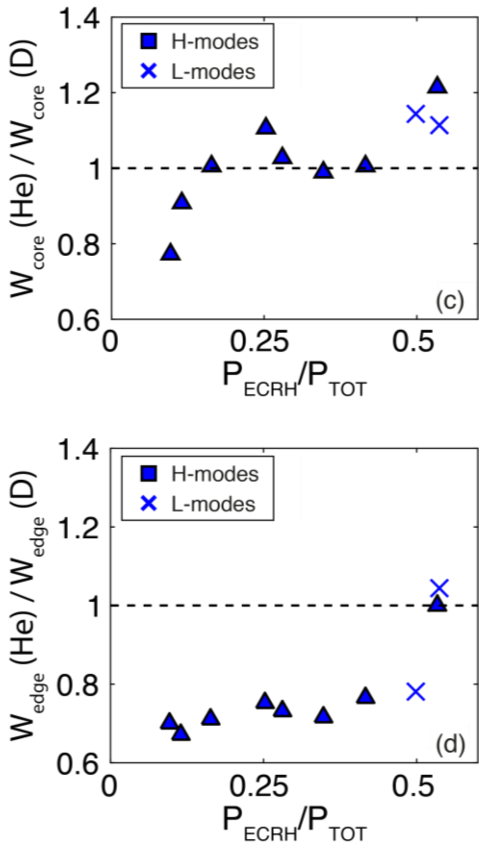

W_{MHD}(He)/W_{MHD}(D) improves with increasing P_{ECRH}/P_{TOT}:

- Core:
  80% (dominant NBI) - 120% (dominant ECRH)

- Edge:
  consistently lower, except at low n_e and highest P_{ECRH}/P_{TOT} → core confinement compensates

Coupling of zonal flows and E/M effects breaks the gyro-Bohm scaling in helium plasmas

P. Manas et al, NF 2019

	Dominant NBI	**Dominant ECRH**
$T_{i,e}$	T_i lower in He	T_i, T_e higher in He
R/L_{Ti}	lower in He (r/a=0.2-0.65)	similar
χ_i^{exp}	x2 higher in He (r/a<0.5)	lower in He

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	χ_i^{exp}	x2 higher in He (r/a<0.5)	lower in He
GK modelling	Turbulent transport	increased in He ITG	
	gyro-Bohm prediction	contradiction	
	Zonal flows (EM regime)	stronger in D, turb. conv. cells pronounced in He	
	χ_i^{He}/χ_i^{D}	2.64	
	Electrostatic regime	Weaker zonal flows in D, lower turb. transport in He	

Nonlinear electromagnetic and electrostatic flux-tube gyrokinetic simulations with GKW

He case simulated switching the main ion species in D case

Coupling of zonal flows and E/M effects breaks the gyro-Bohm scaling in helium plasmas

P. Manas et al, NF 2019

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	χ_i^{exp}	x2 higher in He (r/a<0.5)	lower in He
GK modelling	Turbulent transport	increased in He ITG	lower in He TEM
	gyro-Bohm prediction	contradiction	agreement
	Zonal flows (EM regime)	stronger in D, turb. conv. cells pronounced in He	less dominant zonal flows in D, smaller conv. cells in He [*]
	χ_i^{He}/χ_i^D	2.64	0.56
	Electrostatic regime	Weaker zonal flows in D, lower turb. transport in He	

Nonlinear electromagnetic and electrostatic flux-tube gyrokinetic simulations with GKW

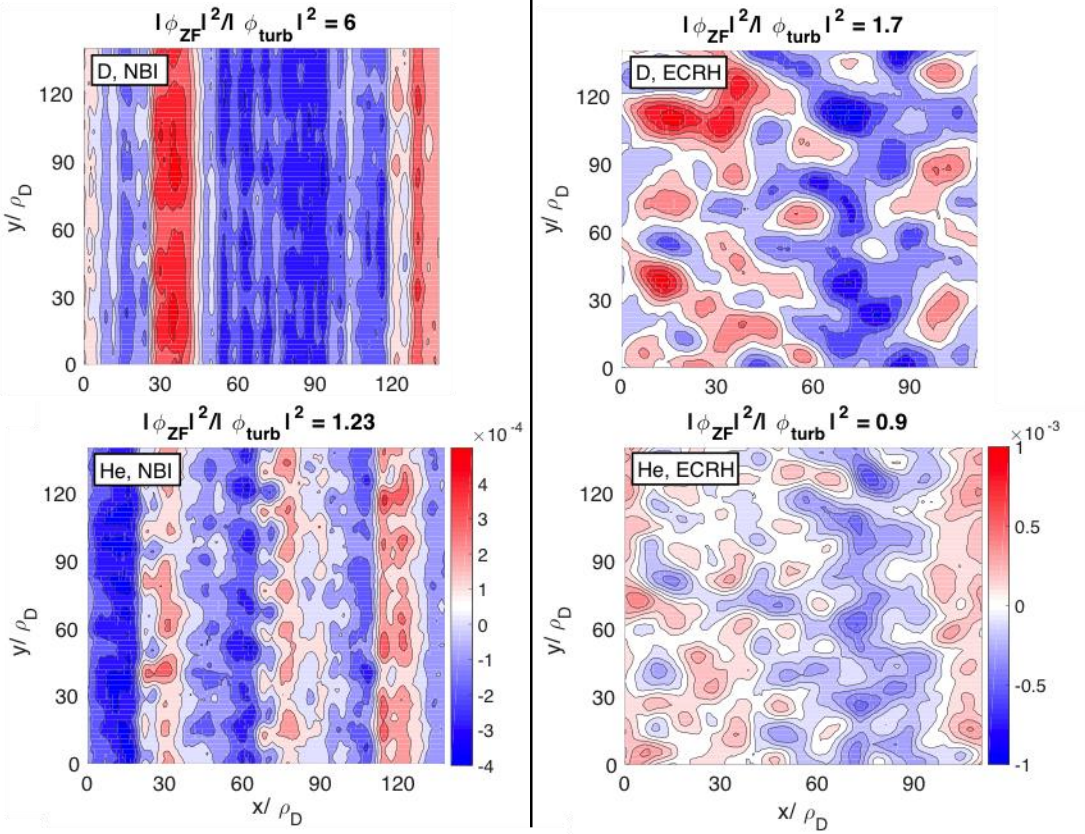
He case simulated switching the main ion species in D case

*A. Bustos et al, Phys. Plasmas 2015, J. Lang et al, Phys. Plasmas 2008

Coupling of zonal flows and E/M effects breaks the gyro-Bohm scaling in helium plasmas

P. Manas et al, NF 2019

		Dominant NBI	Dominant ECRH
GK modelling	Zonal flows (EM regime)	stronger in D, turb. conv. cells pronounced in He	less dominant zonal flows in D, smaller conv. cells in He [*]
	χ_i^{He}/χ_i^{D}	2.64	0.56



Nonlinear electromagnetic and electrostatic flux-tube gyrokinetic simulations with GKW
He case simulated switching the main ion species in D case

Coupling of zonal flows and E/M effects breaks the gyro-Bohm scaling in helium plasmas

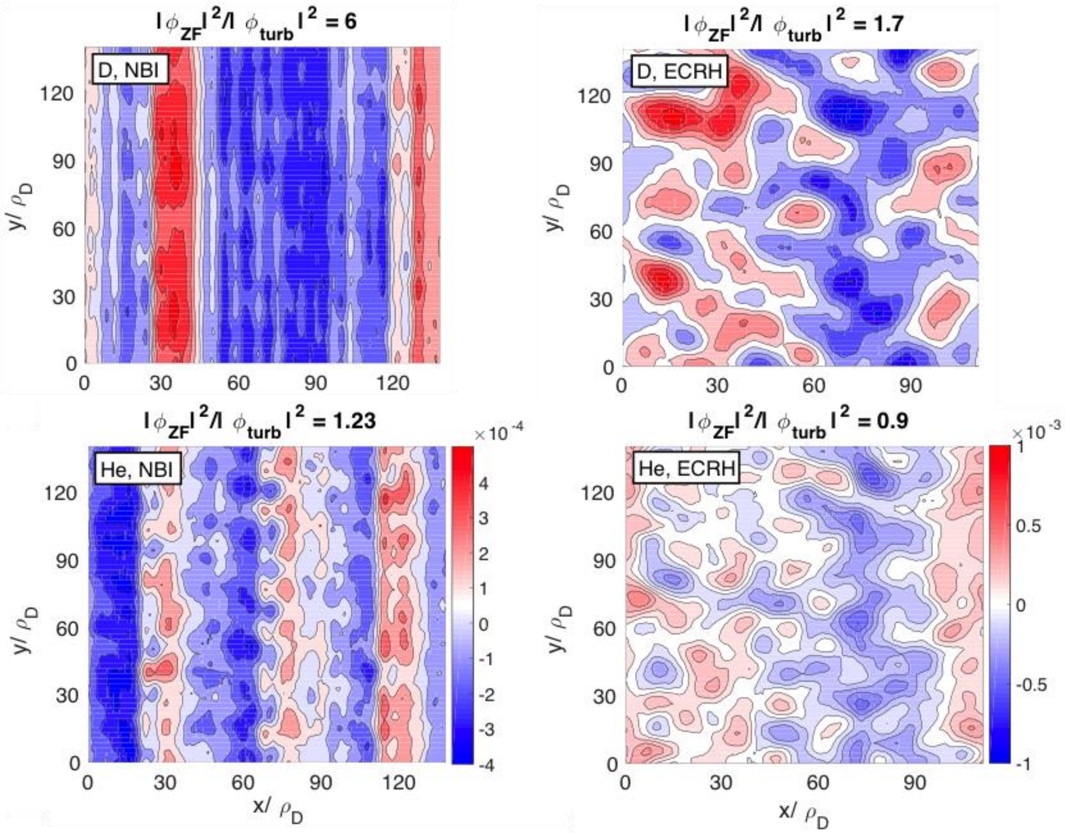
P. Manas et al, NF 2019

<u>CORE</u>: Coupling of zonal flows and electromagnetic effects breaks the gyro-Bohm scaling of turbulent transport

<u>**EDGE**</u>: thermal coupling and ETG destabilisation (not shown here)

Supporting experimental observations and connecting with H isotope studies [A. Bustos et al, PoP 2015, J. Garcia et al, NF 2017, Y. Xu et al, PRL 2013]

→ Input for understanding the ion mass dependence of confinement (see e.g. [P. Schneider et al, NF 2017])



- **Is helium affecting the performance and behavior of the plasma?** Yes

  Helium plasmas have bad confinement? Not always!

Confinement of helium plasmas in ASDEX Upgrade with dominant ECRH or dominant NBI heating explained by means of gyrokinetic modelling.

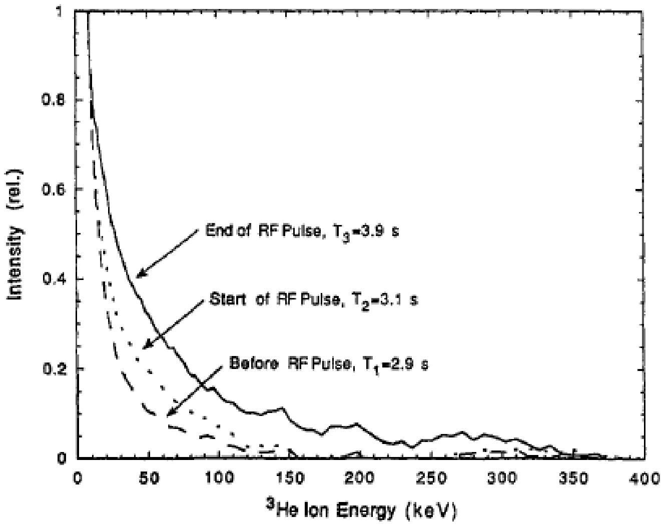
- **Can we measure confined energetic helium ions?**

  Under which conditions?

  Measurement ←→Modelling ?

TFTR

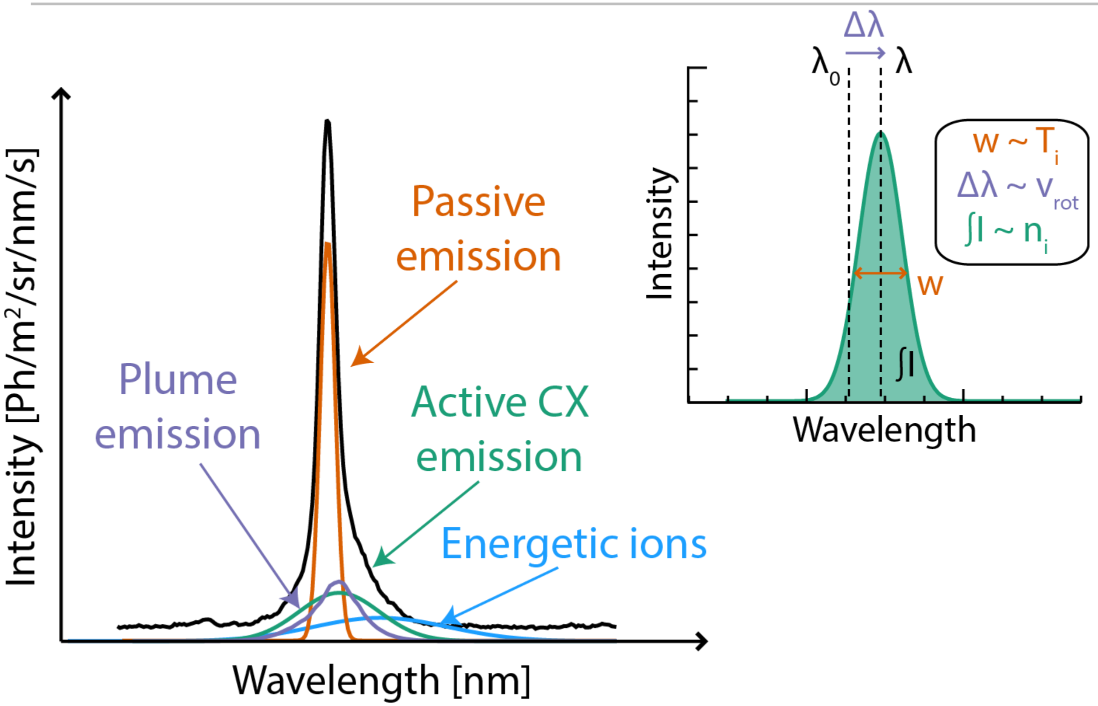
- fusion-produced He
  [G.R. McKee et al, Nucl. Fusion 37, 501 (1997)]
- ^{3}He ions accelerated by ICRH
  [B.C. Stratton et al, Nucl. Fusion 34, 734 (1994)] →



JET

- He neutral beam injection
  [M.G. von Hellermann et al, Plasma Phys. Control. Fusion 35, 799 (1993)]
- ^{4}He-beam ions accelerated by ICRH
  [M.J. Mantsinen et al, Phys. Rev. Lett. 88, 105002 (2002)]

Charge eXchange Recombination spectroscopy can measure confined energetic helium ions



Active charge exchange emission

Passive emission

“Plume” emission

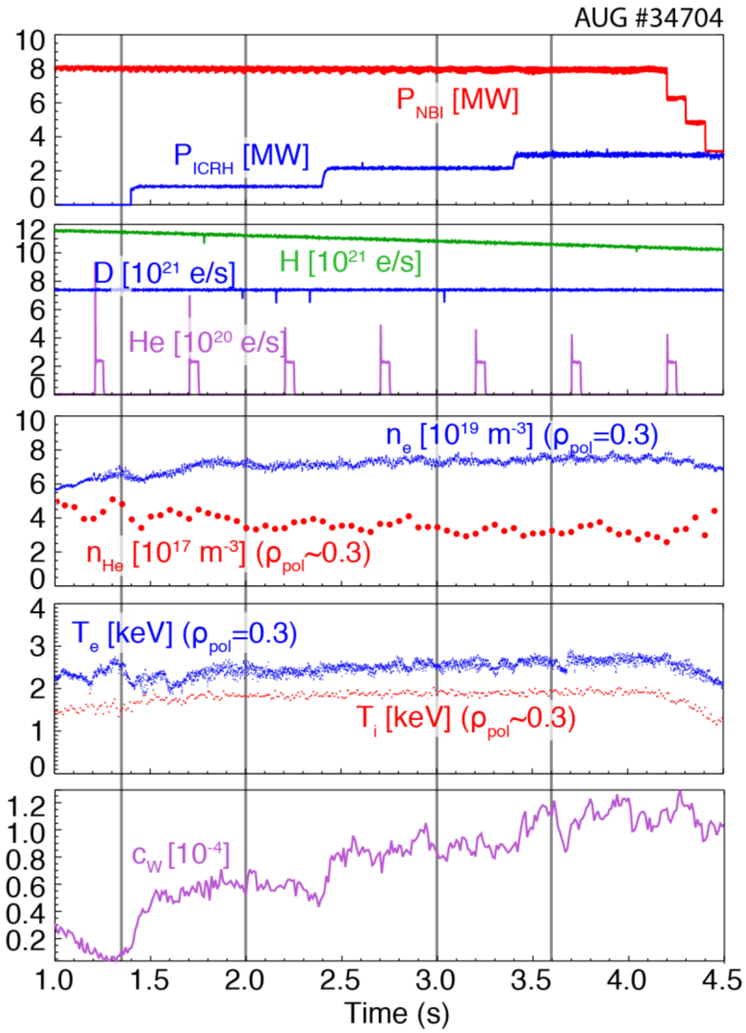
Energetic helium population: additional emission to the spectra, in the wings of the helium spectral line, at higher and/or lower wavelengths.

- Usually low signal – difficult to detect. Signal depends on:
  - amount of energetic ions
  - their relative velocity with respect to the neutrals of the beam used for CXRS

Energetic 3He ions generated with ICRH in a novel ‘three-ion’ ICRH scheme

- Mixed H-D plasma
- Resonant minority species: ^{3}He accelerated with ICRH waves (Z/A between two main ions)
- ^{3}He concentrations ~0.5-2%

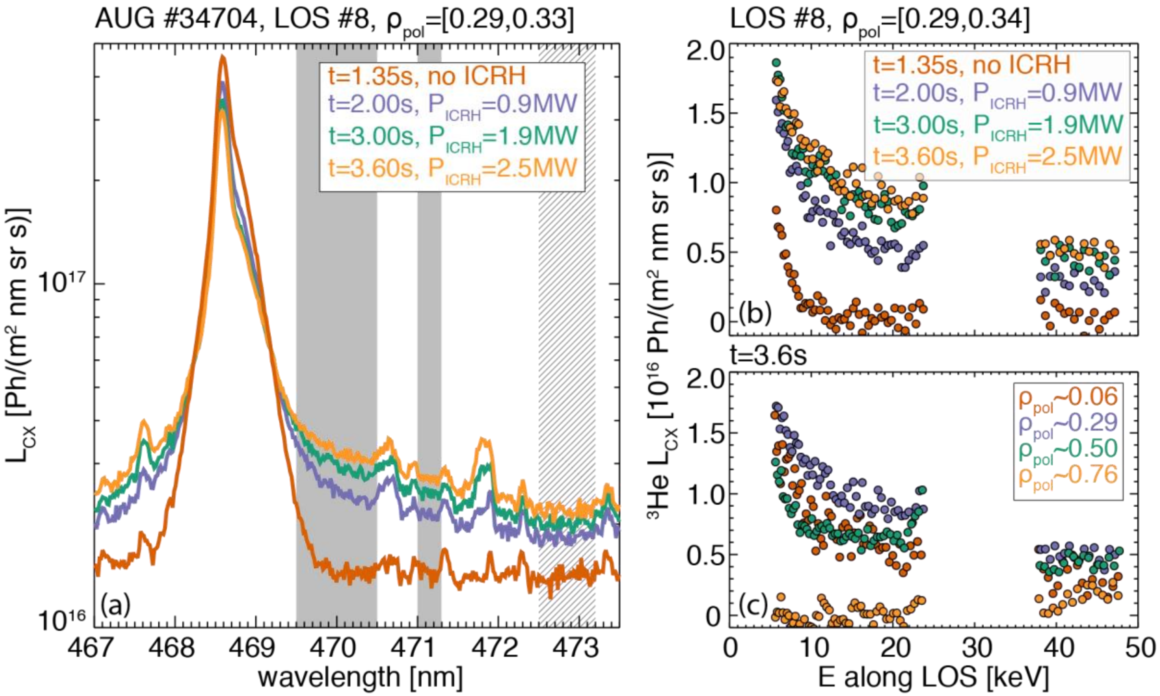
- B_t=−2.8T, I_p=0.8MA
- P_{ICRH} scanned (f=30MHz)
  Resonance deliberately located on <u>off-axis</u> at ρ_{pol}~0.3 on the high-field side
  (reduction of fast ion energies and better RF-heated ^{3}He confinement)



[Ye.O. Kazakov et al, Nat. Phys. 13, 973 (2017),

Ye.O.Kazakov et al, IAEA 2018]

Spectral signature of energetic helium in the spectra correlates with the ICRH power



- Clear **energetic ^{3}He signal** identified when ICRH on and correlated with P_{ICRH}
- **Variation across the plasma radius**
- W emission lines disturb the spectra ($c_W = 0.6\text{-}1.2\cdot10^{-4}$)
- CXRS cannot distinguish between ^{3}He and ^{4}He
- **E projected on LOS**: Toroidal lines-of-sight, almost parallel to magnetic field lines

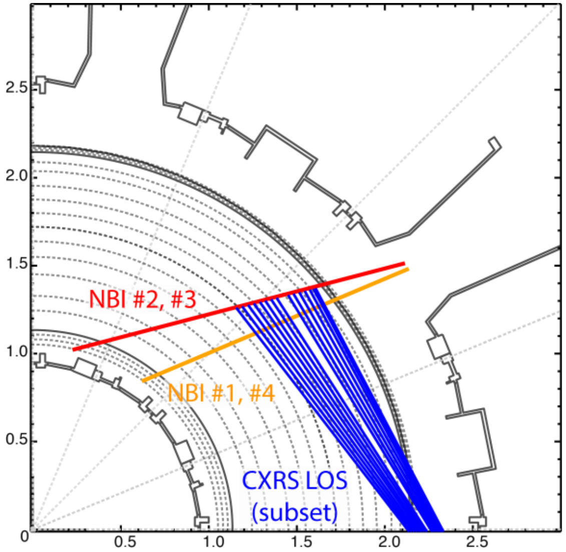
A.Kappatou et al, EPS 2018

Forward modelling of the CX spectrum using a distribution function obtained from the modelling

$$L_\lambda = \frac{1}{4\pi}\sum_{E=1}^{4}\sum_{m=1}^{2}\int_{v=0}^{v_{max}}\int_{p=-1}^{1}\int_{\phi=0}^{2\pi} v^2 f_{^3\mathrm{He}}(v,p)\,\langle\sigma_{\mathrm{CX}}(v_{col})v_{col}\rangle_{E,m}\int_{LOS} n_b^{E,m}(l)\,\mathrm{d}l$$

$$\times\delta\left[\lambda-\lambda_0\left(1+\frac{v}{c}\cos\theta\right)\right]\mathrm{d}\phi\,\mathrm{d}p\,\mathrm{d}v$$

- Distribution function from modelling
- Beam neutrals → COLRAD within CHICA *[R. McDermott et al, PPCF 2018]*
- υ_{col} → collision velocity between beam neutral and ^{3}He ion
CX effective CX emission cross sections
- Projection on the LOS



Distribution functions obtained with TORIC-SSFPQL

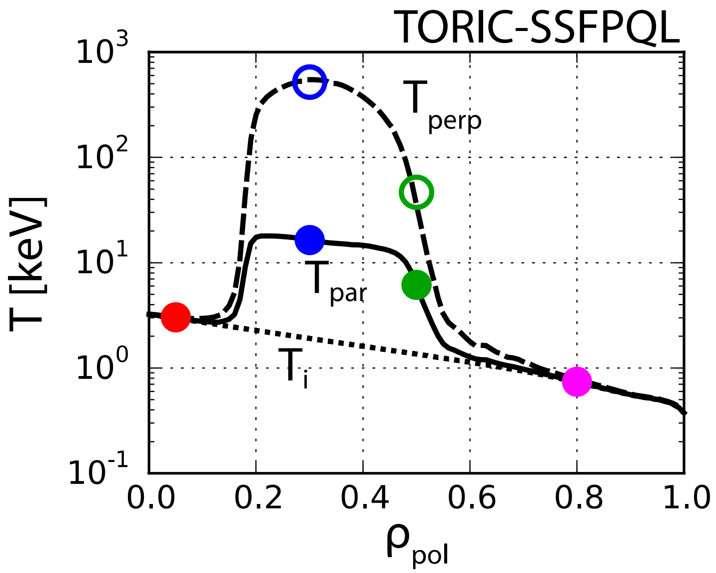
TORIC-SSFPQL modelling:

Coupling of the full-wave solver TORIC and the Fokker-Planck quasi-linear solver SSFPQL

[R.Bilato et al, Nucl. Fusion 51, 103034 (2011)]

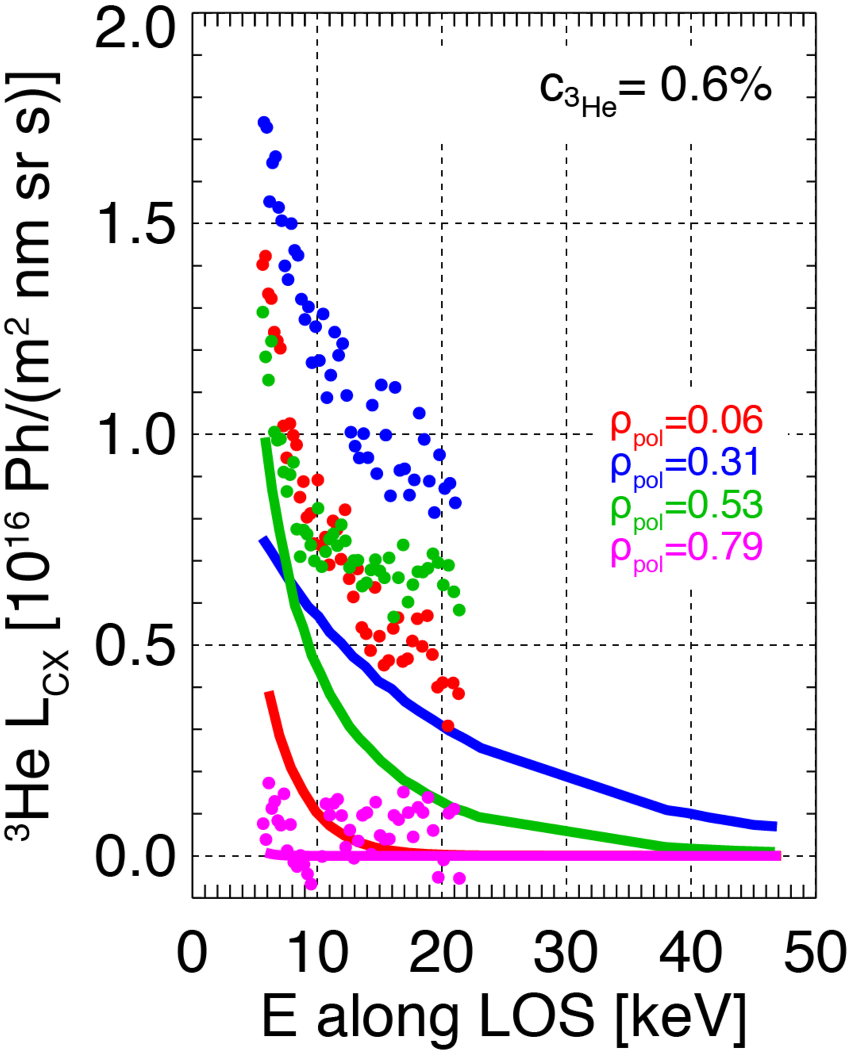
See also R.Bilato et al, this conf. I-06

- Full toroidal spectrum of the antenna
- No orbit losses
- Zero-banana-width assumption
- Assuming $c_{3He} = 0.6\%$:
  - derived ignoring the tails of the CX
  - corresponds to the total He content



Energetic ^{3}He ions predicted only in $0.15<\rho_{pol}<0.55$

Comparison of experimental and forward modelled spectra



- Both the measurement and the prediction show no energetic signal outside mid-radius
- In contrast to the CX measurement, no energetic He signal is predicted close to the plasma core
- Modelling underpredicting the experiment
  - ICRH resonance on the high-field side (ρ_{pol}~0.3)
  - Banana widths large enough to explore also the region close to the magnetic axis

Distribution functions from TORIC-SSFPQL with banana orbit averaging

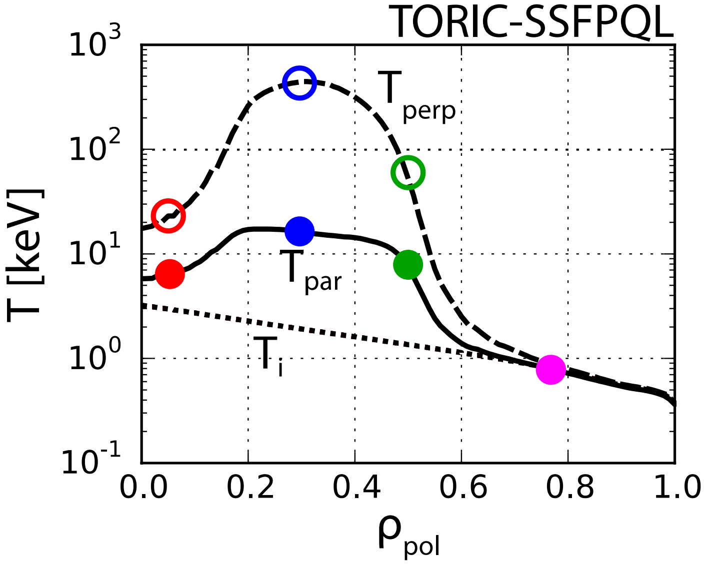
TORIC-SSFPQL modelling:

Coupling of the full-wave solver TORIC and the Fokker-Planck quasi-linear solver SSFPQL

[R.Bilato et al, Nucl. Fusion 51, 103034 (2011)]

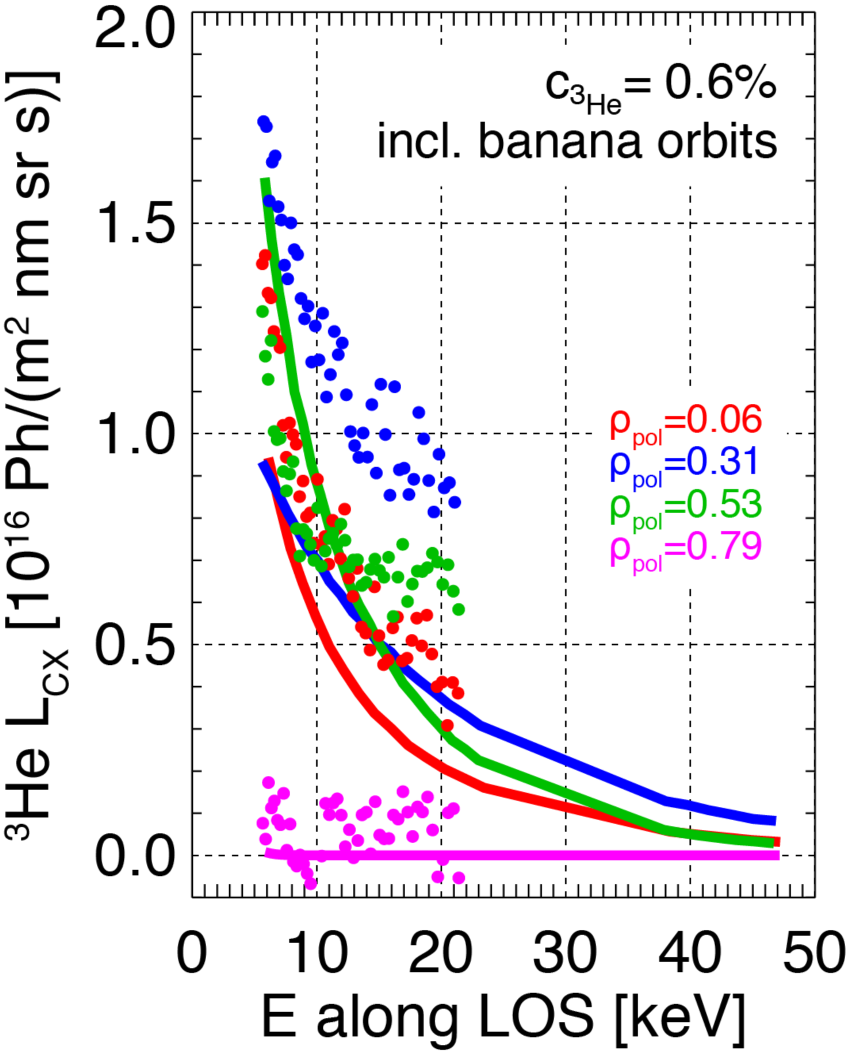
See also R.Bilato et al, this conf. I-06

- Full toroidal spectrum of the antenna
- No orbit losses
- **With an estimate averaging over banana orbits**
- Assuming $c_{3He} = 0.6\%$:
  - derived ignoring the tails of the CX
  - corresponds to the total He content



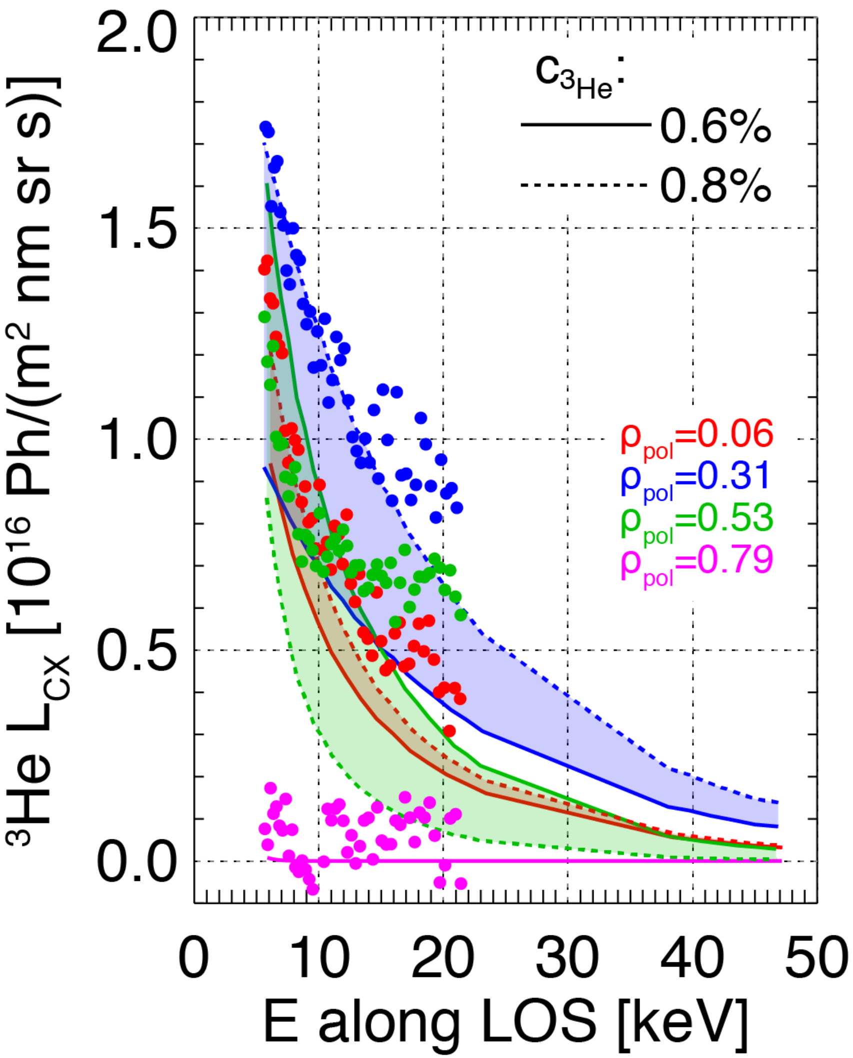
Energetic ^{3}He ions predicted for ρ_{pol}<0.7

Including an estimate of the banana orbits



- Including an estimate (averaging) of the banana-width effects brings the modelling closer to reality

Modelling sensitive to input ^{3}He concentration



One more uncertainty:
Importance of the assumed ^{3}He concentration

- Influence on the TORIC-SSFPQL output and the predicted spectra
- Choice of helium concentration can bring the modelling closer to the experiment
- But not in all locations… importance of the ^{3}He density profile gradient?

CXRS can provide important information on the confined energetic helium ions
→ validation of fast ion and ICRH modelling codes

- **Can we measure confined energetic helium ions?**

  Under which conditions?

  Measurement ←→Modelling ?

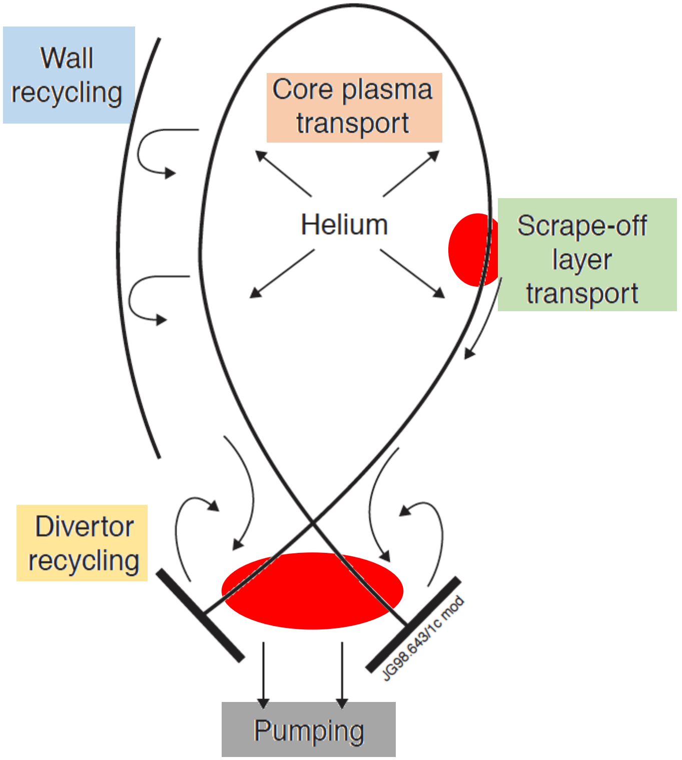
For AUG, limited

Very valuable input to RF modelling

Valuable exchange between the spectroscopic measurements of ICRF accelerated ^{3}He ions and the ICRF modelling: Interpretation of the measurement and improvement of the modelling at the same time

- **Is helium accumulation an issue?**
  Can helium be exhausted sufficiently well?

What is “sufficient” exhaust of He and why is it important?

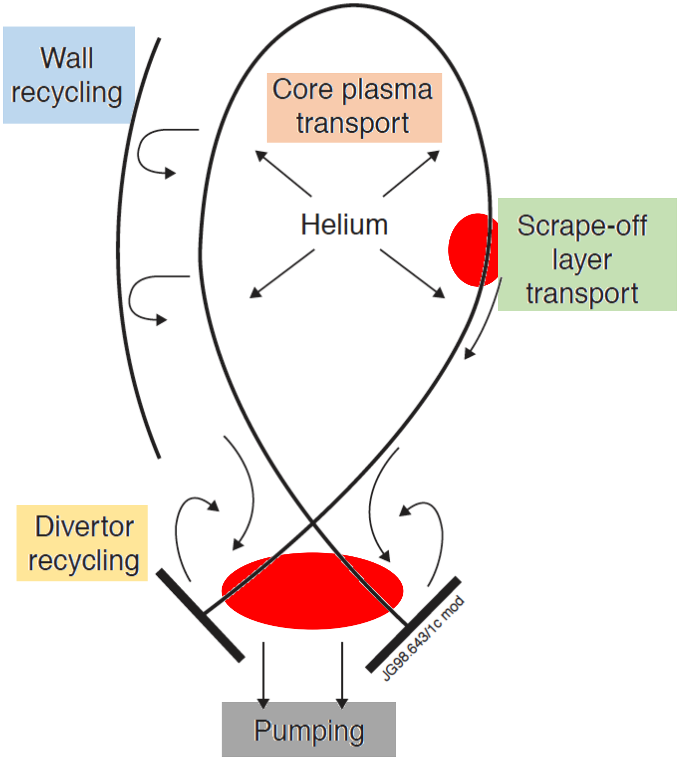


*Adapted from [M.Groth, PhD thesis 2000]

Controlling the helium concentration in the plasma entails constraints on:

- Core transport → Defines peaking of n_{He}
- Edge transport
- Divertor conditions
- Pump engineering parameters

What is “sufficient” exhaust of He and why is it important?



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Controlling the helium concentration in the plasma entails constraints on:

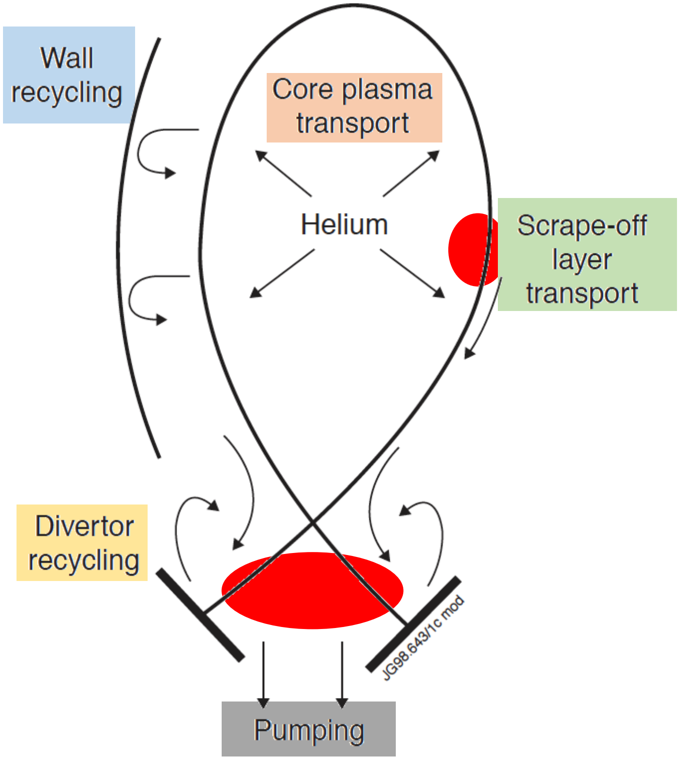
- Core transport → Defines peaking of n_{He}
- Edge transport
- Divertor conditions
- Pump engineering parameters

Maximise helium enrichment:

$$\eta_{\mathrm{He}} = \frac{n^{\mathrm{div}}_{\mathrm{He}^0}\; n_e^{\mathrm{edge}}}{n^{\mathrm{edge}}_{\mathrm{He}^+}\; 2n^{\mathrm{div}}_{D_2}}$$

→ Determines c_{He} in the plasma

What is “sufficient” exhaust of He and why is it important?



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→ Determines c_{He} in the plasma

Validated models necessary for
- Understanding helium exhaust
- Predictions for future devices

- **Is helium accumulation an issue?**

  Can helium be exhausted sufficiently well?

Helium exhaust has still too many uncertainties

Summary

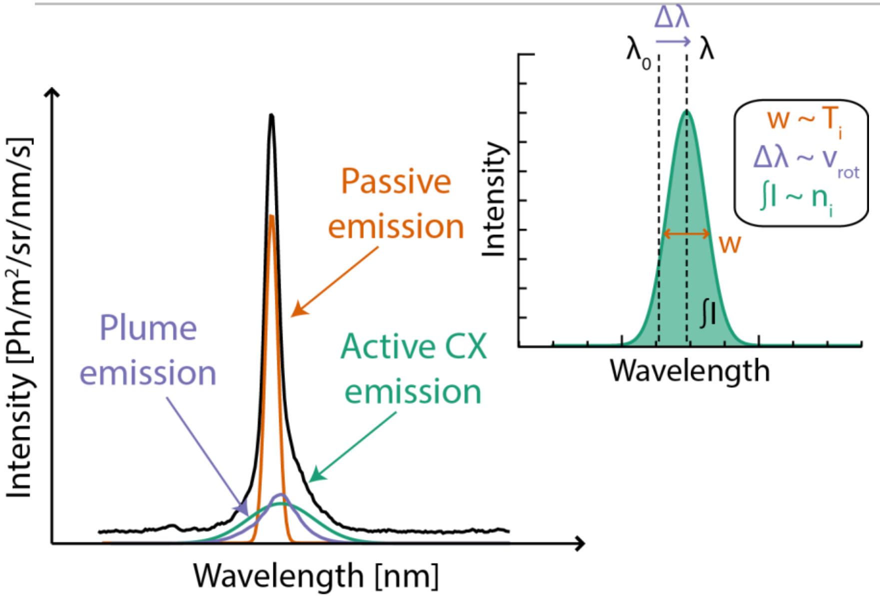
- The modeled impurity density profile peaking does not always reproduce the experimental measurements
    - Role of fast ions on turbulent and neoclassical transport important

- Helium in reactor relevant concentrations (up to 10%) is observed to have a detrimental effect on the plasma confinement in AUG and JET
    - Influence on the pedestal, but mostly changes in core transport
- Confinement of He plasmas in AUG → increasing with the fraction of electron heating

- CXRS measurements of energetic ^{3}He ions compare well with modelled spectra evaluated using TORIC-SSFPQL distribution functions
    - Tool for the validation of fast ion and ICRH modeling codes

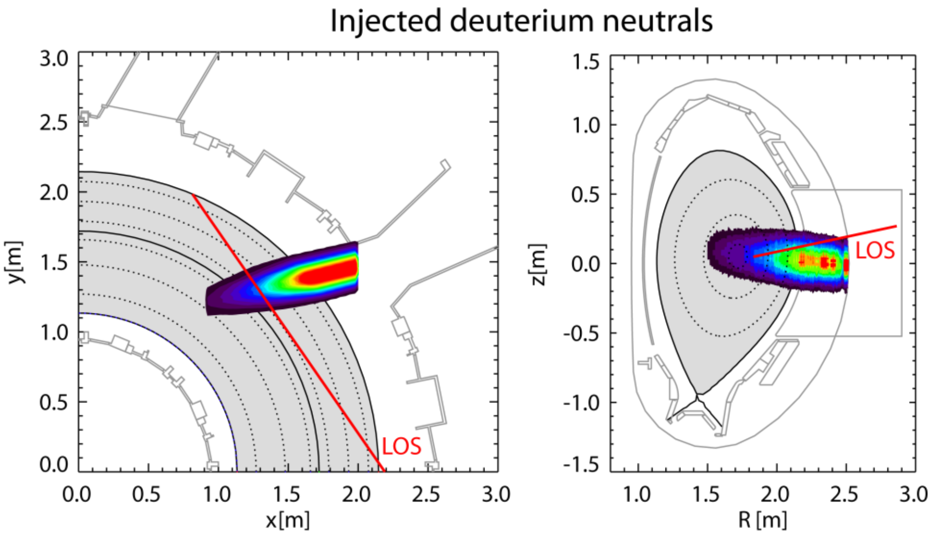
BACK UP SLIDES

Helium in the plasma core is measured by Charge eXchange Recombination Spectroscopy

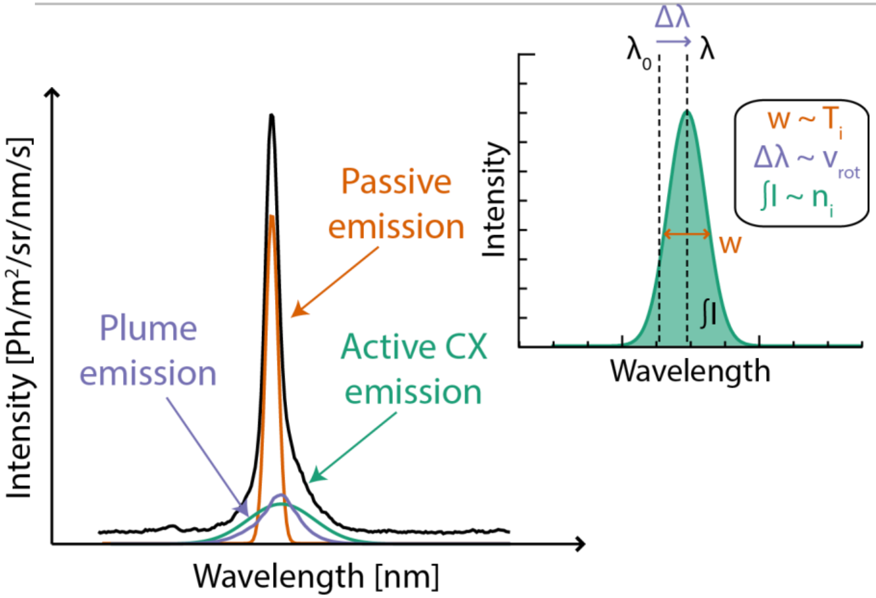


Active charge exchange emission: CX reactions of fully stripped He with beam neutrals

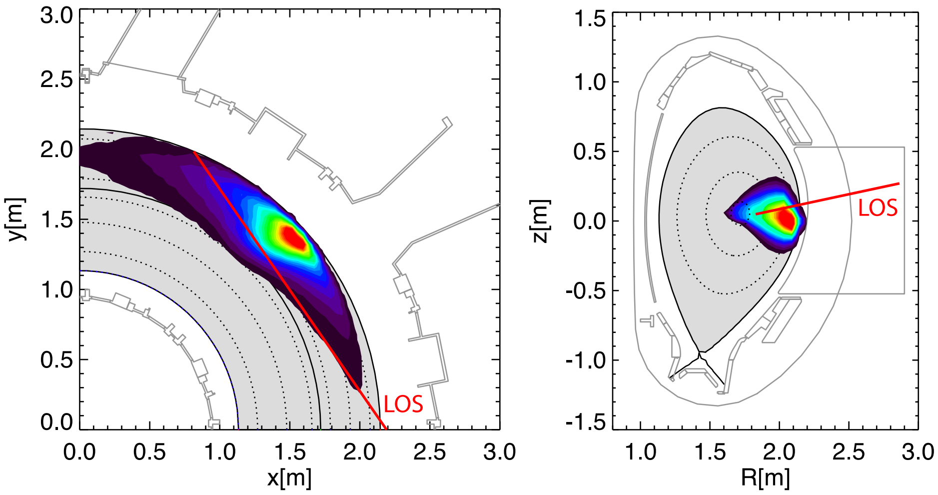
Passive emission: electron impact excitation of He^+ and charge exchange of He^{2+} with thermal neutrals at the plasma edge


Injected deuterium neutrals

Helium in the plasma core is measured by Charge eXchange Recombination Spectroscopy



He⁺ (plume ions)



Active charge exchange emission: CX reactions of fully stripped He with beam neutrals

Passive emission: electron impact excitation of He^+ and charge exchange of He^{2+} with thermal neutrals at the plasma edge

“Plume” emission: electron collisional excitation of the He^+ ions produced by charge exchange reactions along the neutral beam.

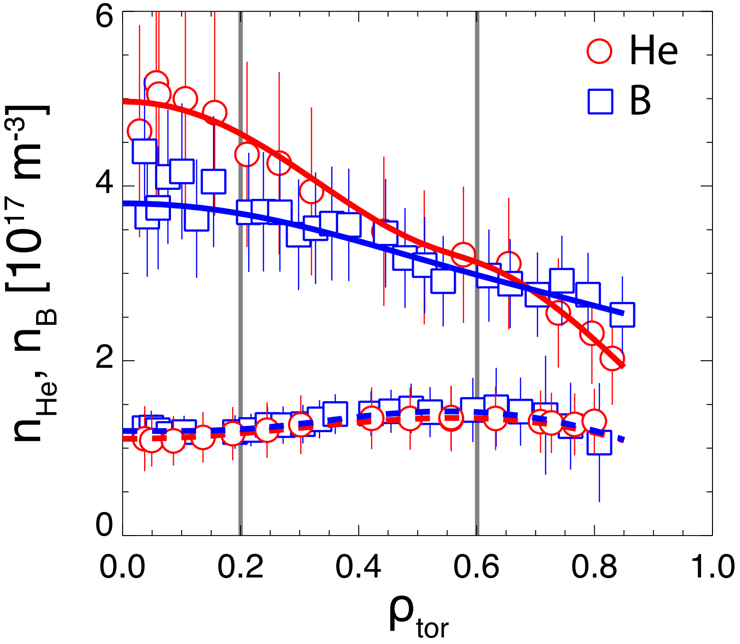
→ Requires forward modelling to remove this additional emission from the spectra

→ Without it, helium density overestimated

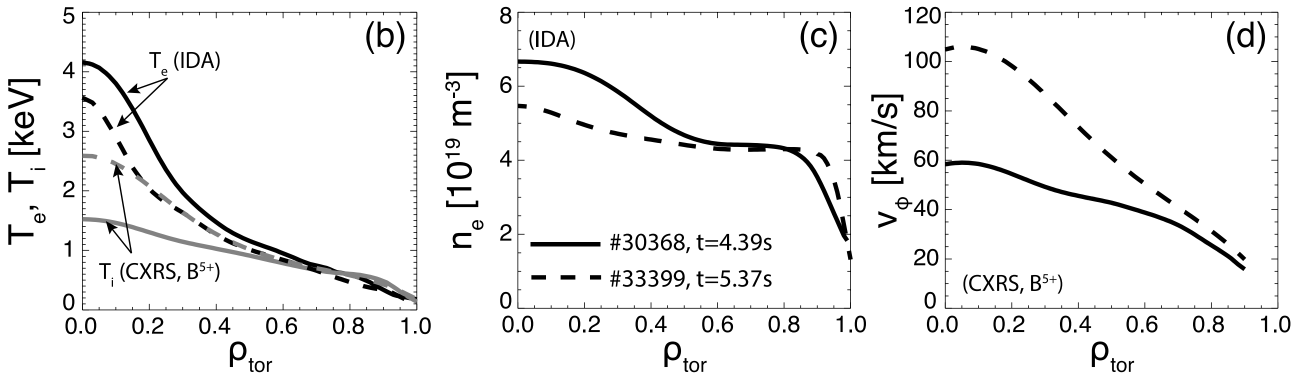
Is the plume too much? (bottom left plots?)

The peaking of the impurity density profiles depends on plasma parameters

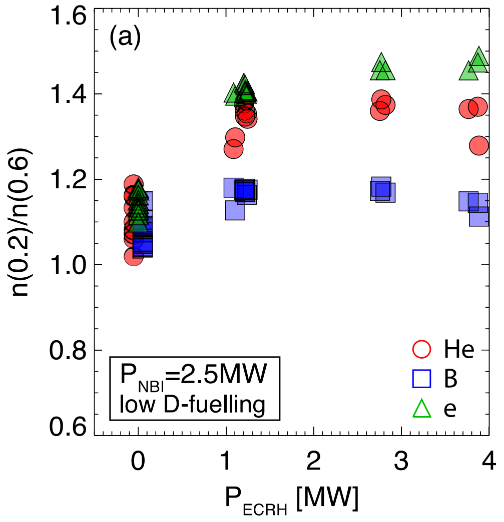
A.Kappatou et al, NF 2019



- Peaking of the low-Z impurity density profiles in stationary source free conditions
- Varying transport relevant parameters: peaking and/or magnitude of n_e, T_e, T_i, (and T_e/T_i), v_ϕ, ν_{eff}…
- Multi-species studies
- Both He and B “intrinsic” after boronisation (not puffed)



He concentration profiles flat with large ECRH fraction, hollow with dominant NBI

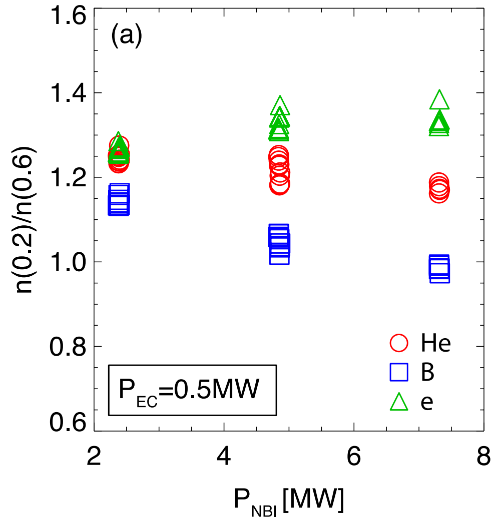


With **increasing P_{ECRH}** (central)

→ Decrease in collisionality, peaking of n_e, flattening of v_ϕ [C.Angioni et al, NF 2011, R.M.McDermott et al, PPCF 2011]

→ **Peaking of the impurity profiles**

→ n_{He} less peaked than n_e at low P_{ECRH}/P_{NBI}



With **increasing P_{NBI}**

→ Decrease in collisionality, increase in Mach, peaking of n_e, or no change

→ **Peaking of the impurity profiles decreasing**

Comparison of experimental gradients w/ modelling, or v & D separately

In source free and stationary conditions

$$\frac{R}{L_{n_I}} = -\frac{RV_I^{turb} + RV_I^{NC}}{D_{d,I}^{turb} + D_{d,I}^{NC}}$$

Local quasi-linear gyrokinetic simulations of the turbulent transport with GKW *[A.G.Peeters et al, PoP 2004, A.G.Peeters et al, CPC 2009]*

Neoclassical contributions with Neoart *[R.Dux et al, NF 2000, A.G.Peeters, PoP 2000]*→ Neoclassical diffusion for He, B: negligible at mid-radius, one order of magnitude smaller than turbulent further in

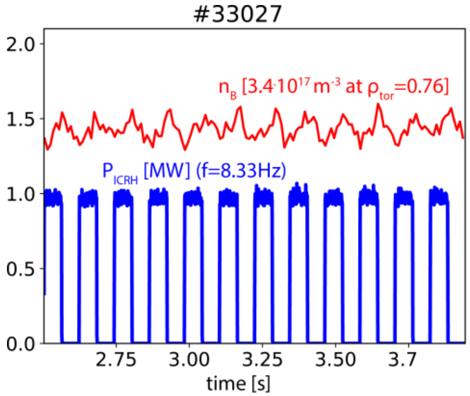
No heat flux matching by varying input parameters, but normalisation of turbulent conductivity to power balance conductivity:

$$D^{\mathrm{turb}}/\chi_{i,turb}^{\mathrm{GKW}}$$

$$D^{\mathrm{NC}}/\chi_{i,an},\ \chi_{i,an} = \chi_i^{\mathrm{PB}} - \chi_i^{\mathrm{NC}}$$

Separate measurement of D and v

- Determination of drift velocity *υ* and diffusion coefficient *D* separately requires **time dependent impurity density profiles**
- Novel method gives a **modulated boron density** by modulating the power of the ICRH antennae
- Minimal modulation of n_e, T_e, T_i



C. Bruhn et al, PPCF 2018

Method not yet experimentally implemented for He (requires appropriate modulation of He gas puff)

Turbulent transport components have a different Z dependence

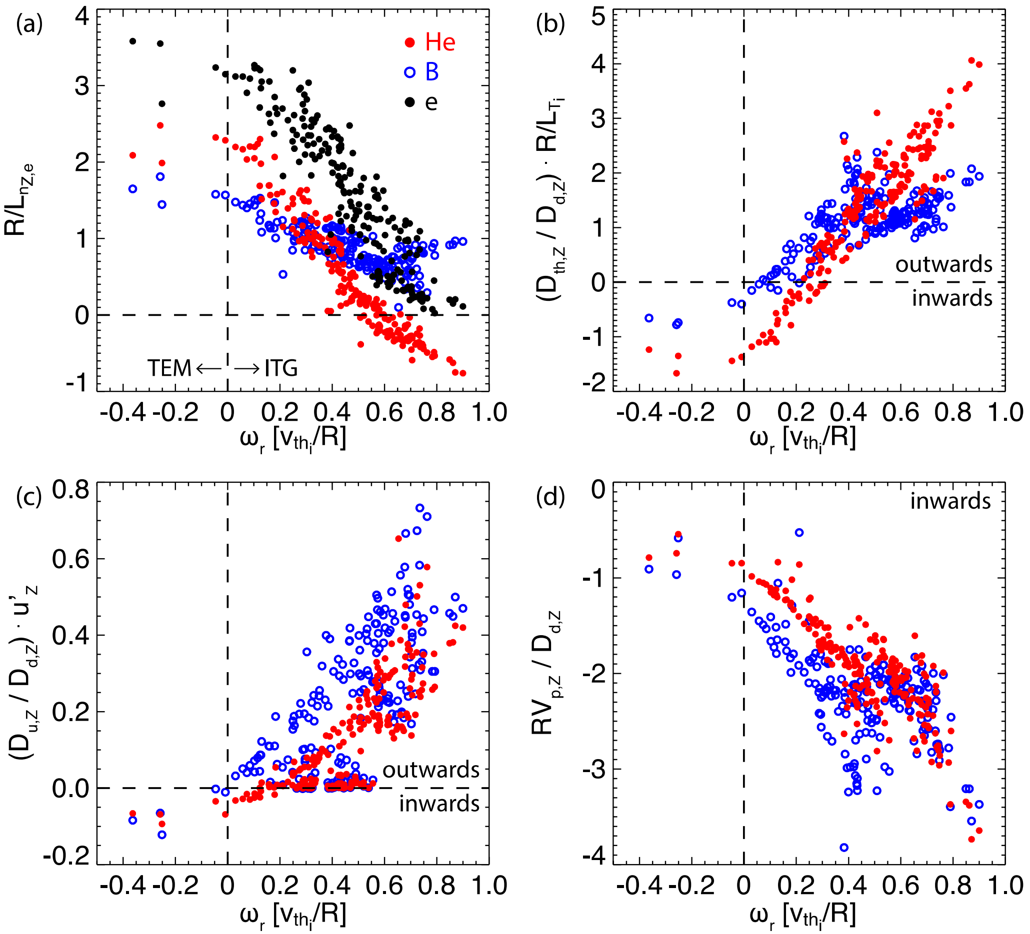
$$\frac{R\Gamma_{nZ}^{turb}}{n_Z} = \underbrace{D_{NZ}\frac{R}{L_{nZ}}}_{\text{Diffusion}} + \underbrace{D_{ThZ}\frac{R}{L_{TZ}} + D_{UZ}u' + RV_{pZ}}_{\text{Convection}}$$

Thermodiffusion

Rotodiffusion

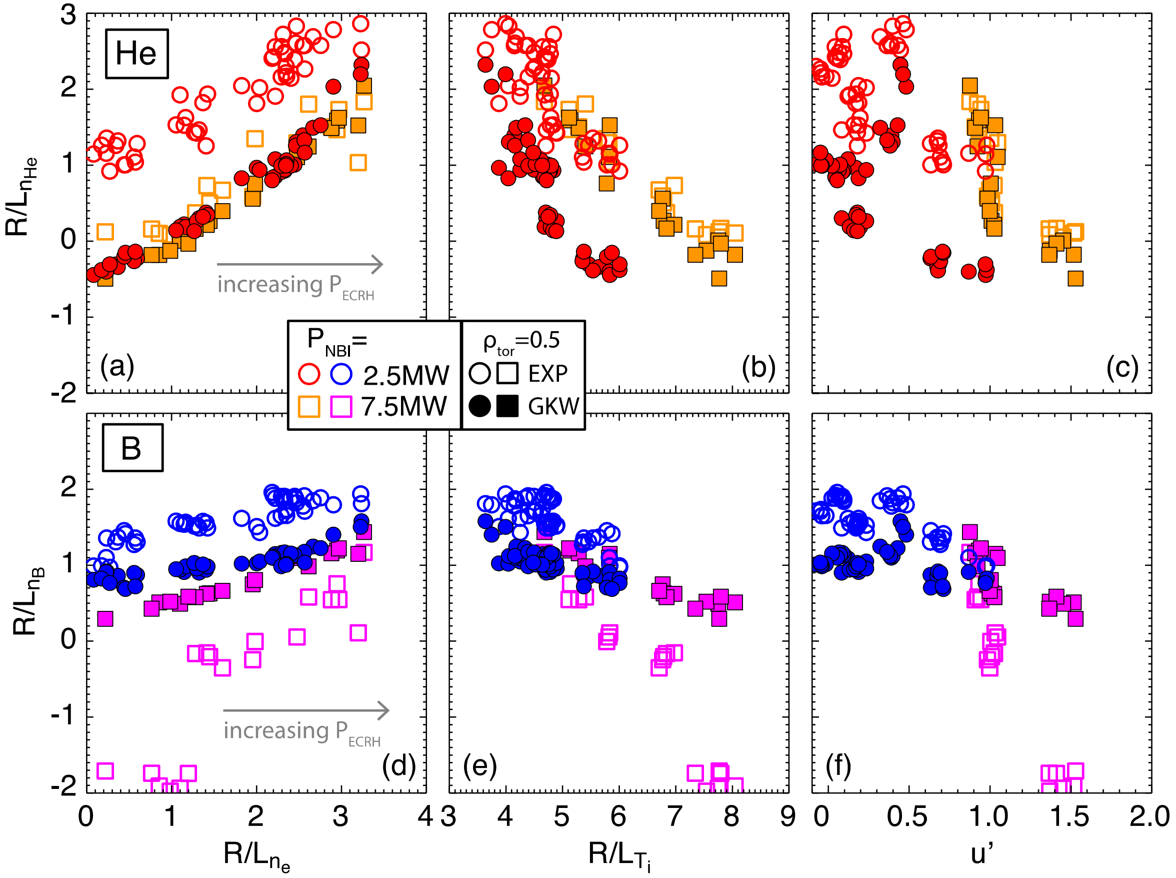
Purely convective part

Steady state
No sources



[Frojdh Nucl. Fusion 1992, Angioni Phys.Rev.Letters 2006, Angioni Nucl. Fusion 2009, Camenen Phys. Plasmas 2009, Angioni Nucl. Fusion 2012, Casson Nucl. Fusion 2013]

Comparison of experiments gradients at mid-radius with gyrokinetic modelling



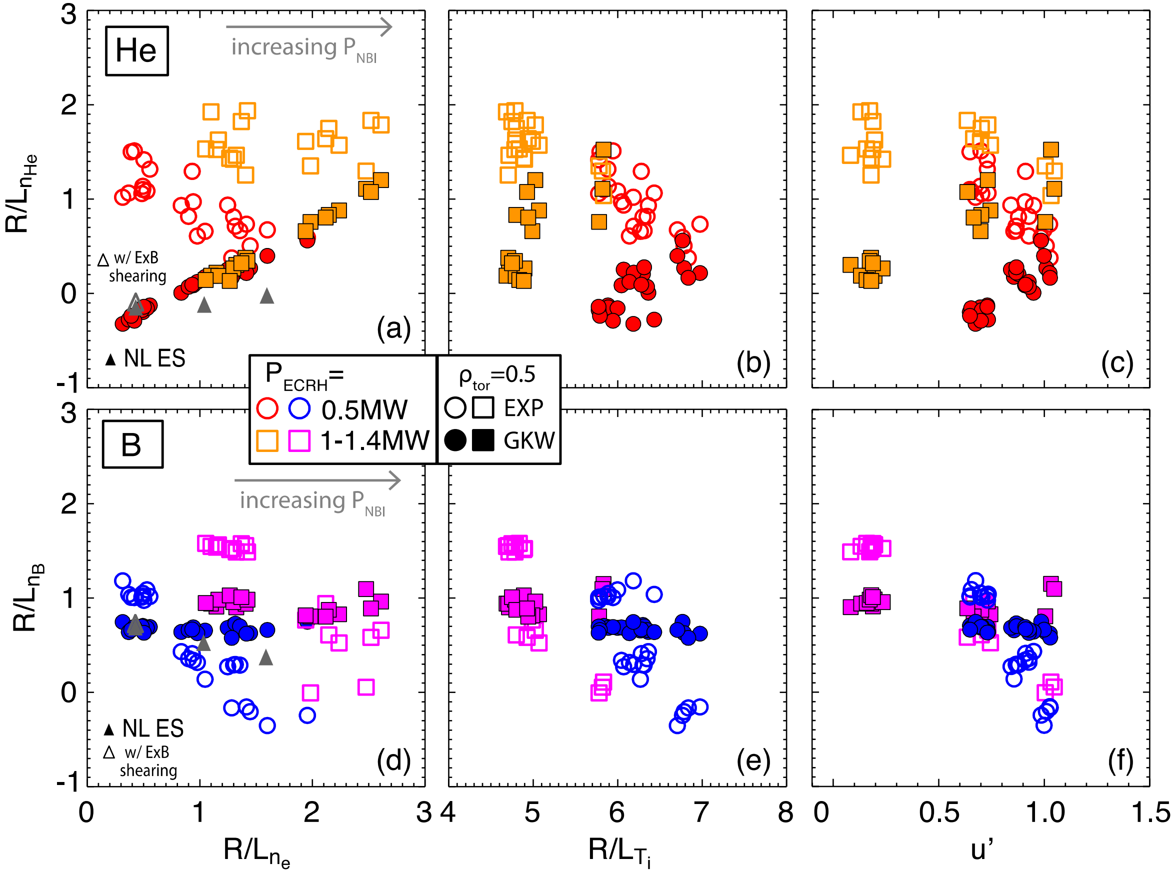
Increasing PECRH

At low PNBI (circles):
qualitative agreement
helium underpredicted

At high PNBI (squares):
Helium better described
Boron overpredicted
Some very hollow boron experimental profiles not reproduced at all

① No simultaneous good prediction of both impurities
② Something certainly missing at low ECRH, high NBI power

Comparison of experiments gradients at mid-radius with gyrokinetic modelling



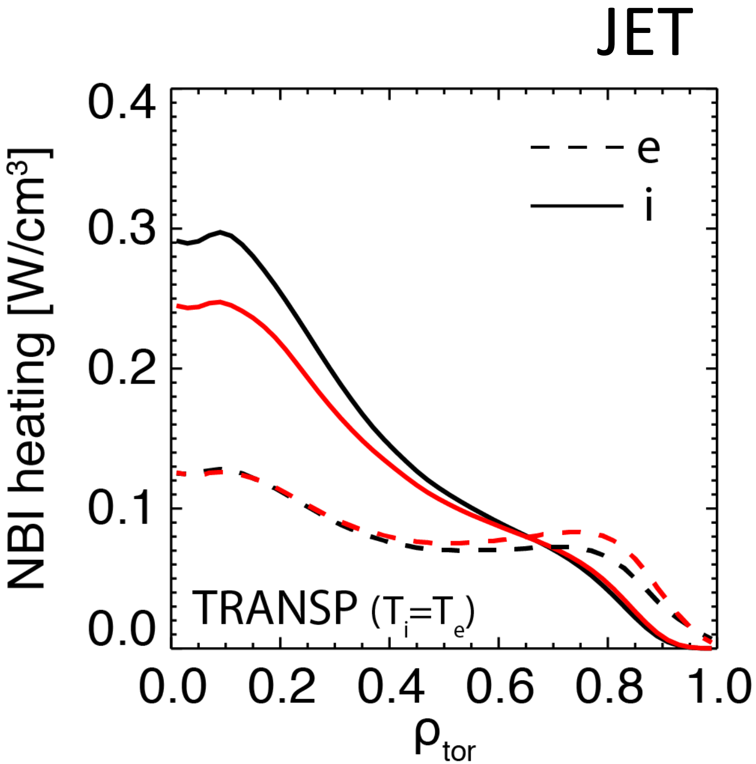
Increasing P_{NBI}

At both low P_{ECRH} (circles) and high P_{ECRH} (squares):
Very similar modelled gradients
significantly different trends with the experiment

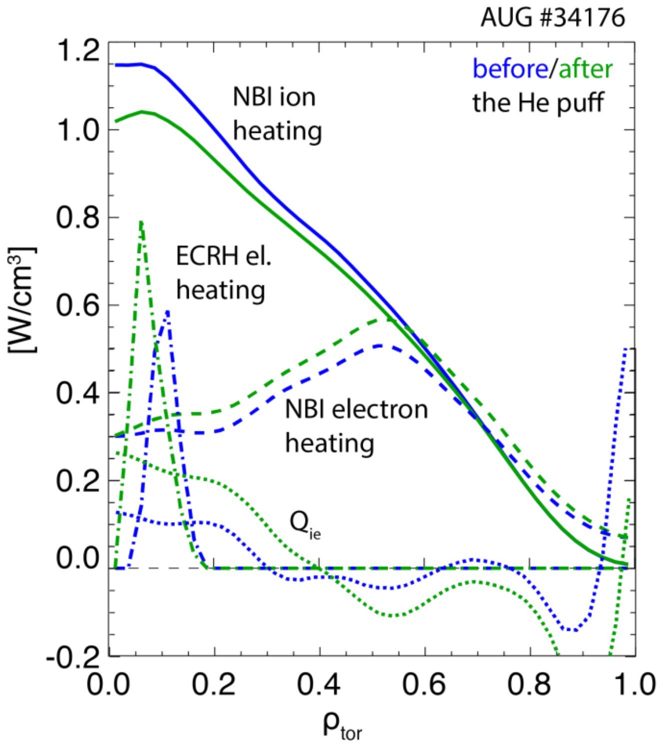
① There's something missing here…

Discrepancies between modelling and experiments reported also by:
P.Manas et al
N.Bonanomi et al

Electron and ion heating with/without He

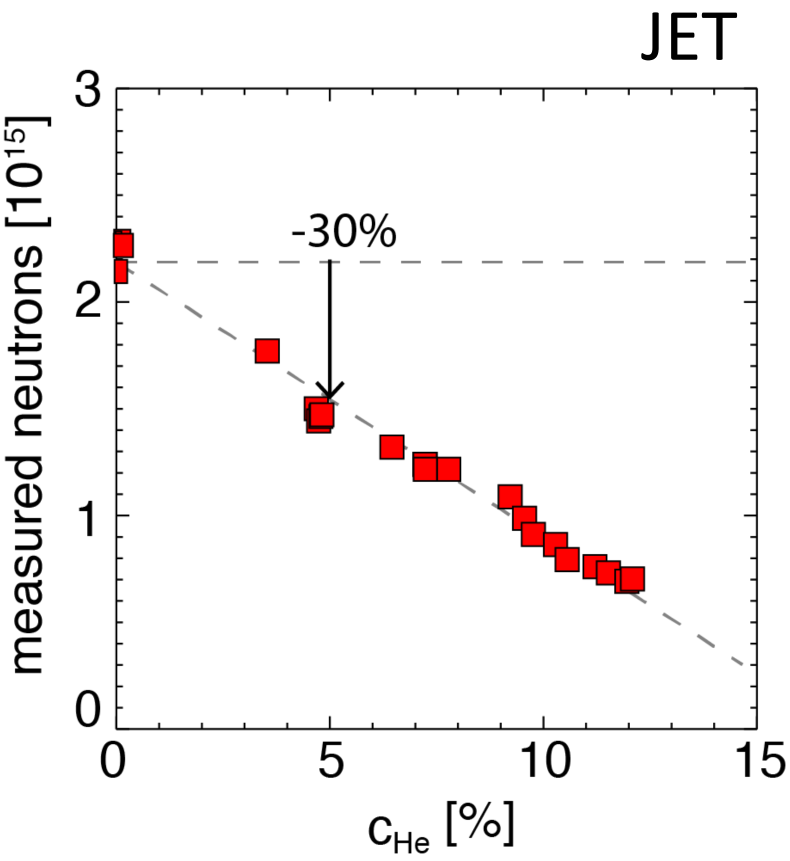


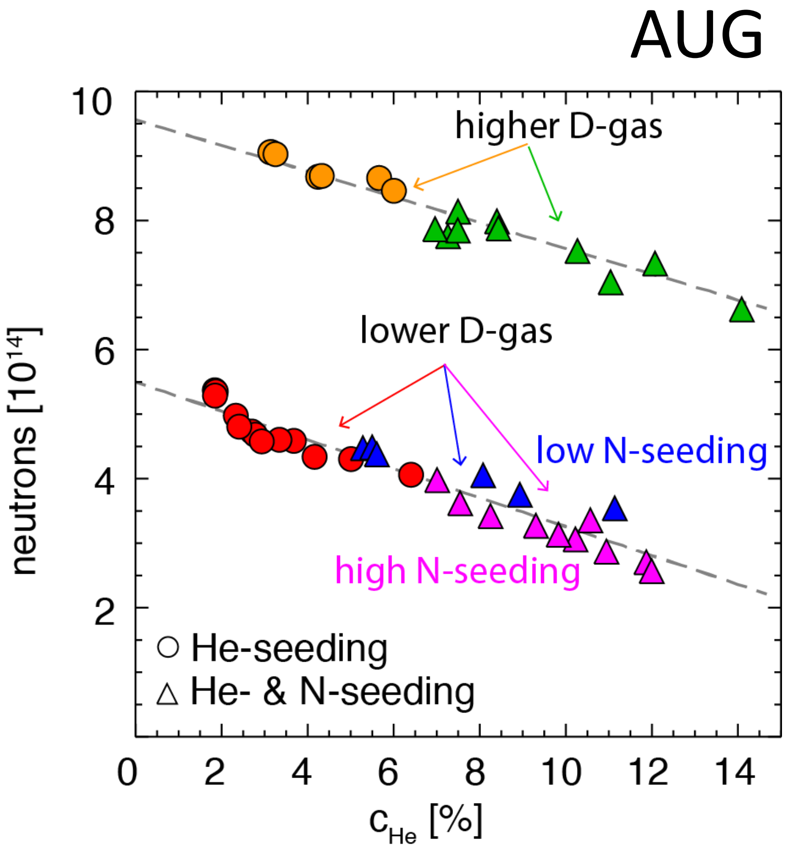
Reduced NBI ion heating in the core (up to 20%), increased electron heating at the edge (up to 30% at ρ_{tor}~0.9) with first c_{He}



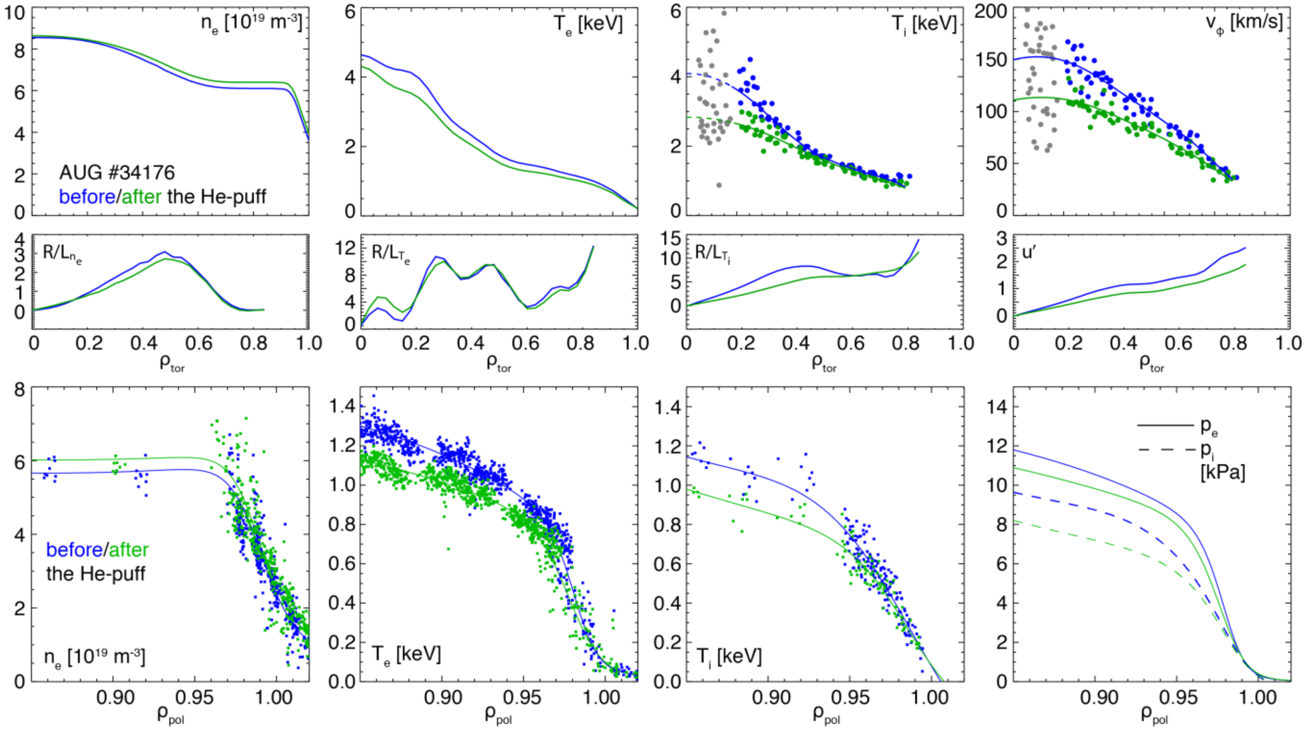
Reduced NBI ion heating (<10%) ρ_{tor}<0.6
Increased NBI electron heating up to 15%

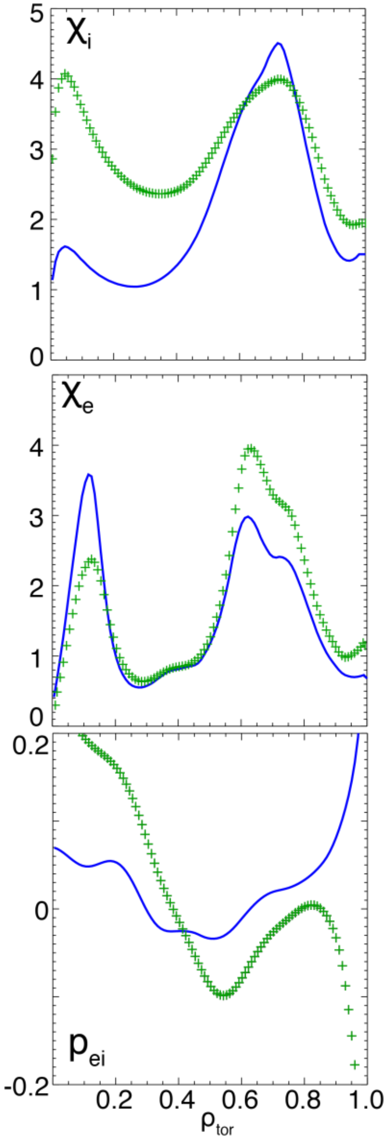
Neutrons with increasing c_{He}





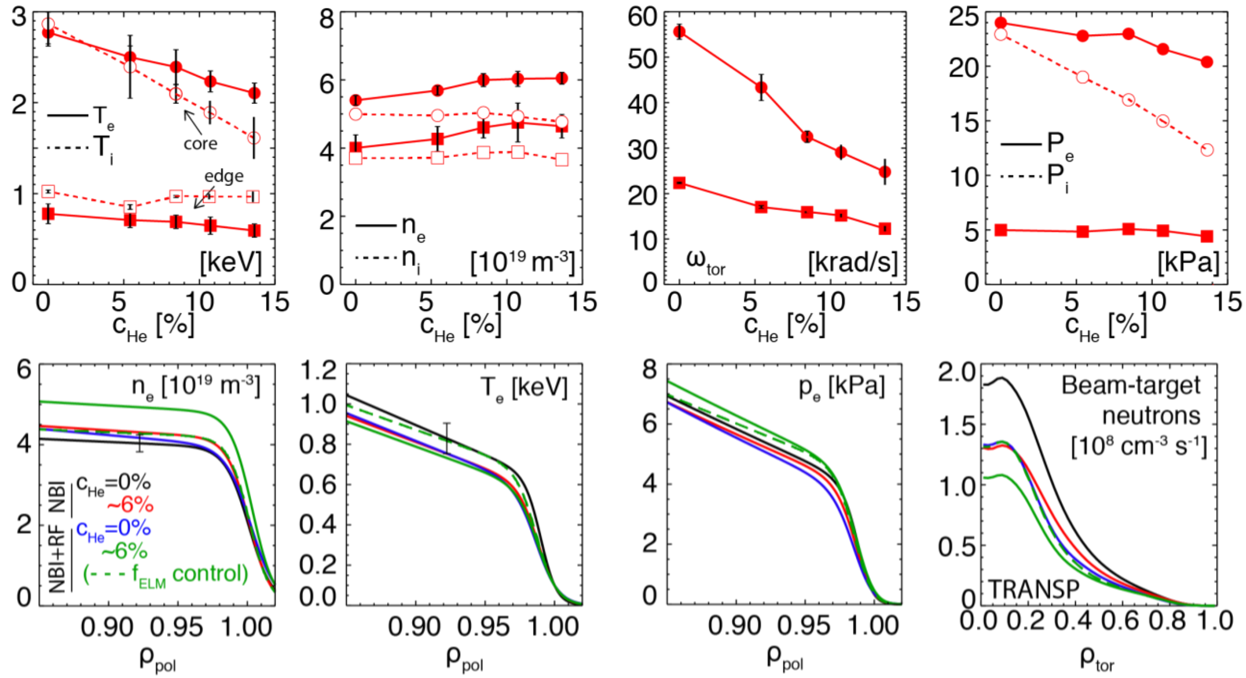
The kinetic profiles change in the presence of helium





- Δc_{He}~4% (shown case)
- Changes to the kinetic plasma profiles
  - Reduction of pedestal pressure, stronger for ions
  - Core ion pressure loss
- **Increased transport with (more) helium**
- Helium increases the ELM frequency (or causes more “faster” ELMs)

The kinetic profiles change in the presence of helium

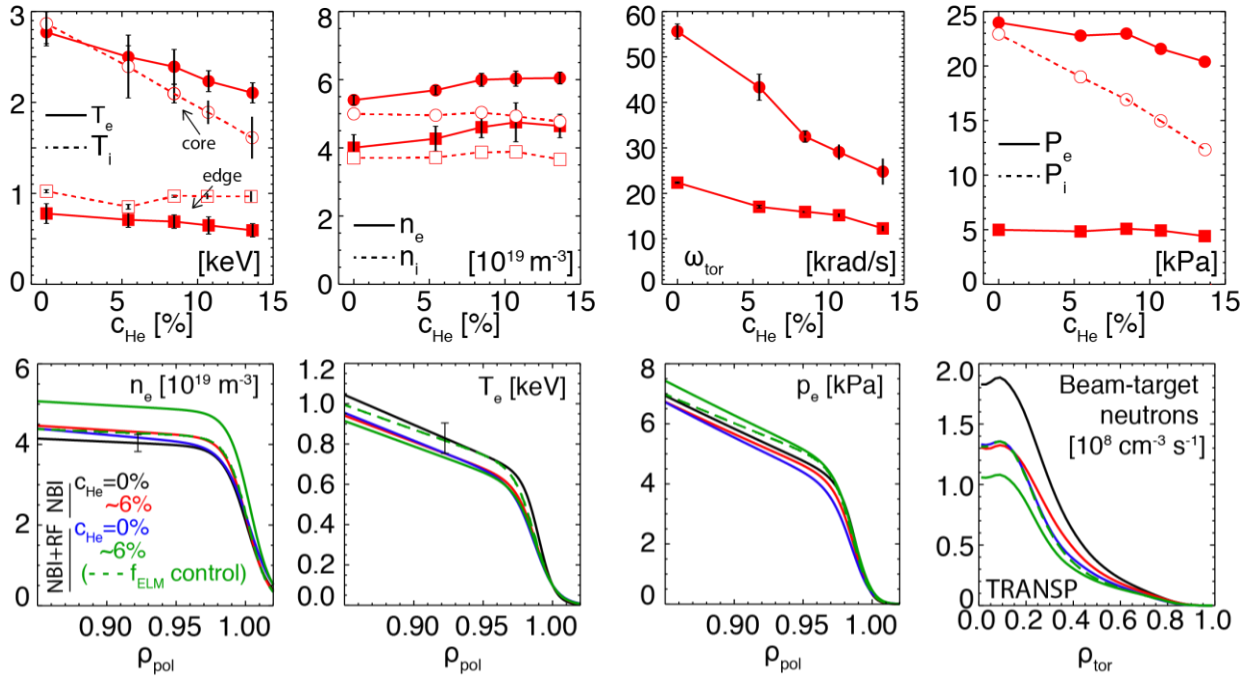


<u>NBI only heating</u> (P_{NBI}=12MW):

- Changes to the kinetic plasma profiles
  - No reduction of p_e^{ped}
  - Core pressure loss
- Two f_{ELM} bands with He
- Reduced NBI ion heating in the core (up to 20%), increased electron heating at the edge (up to 30% at ρ_{tor}~0.9) with first c_{He}

Stronger NBI attenuation and significant reduction in beam-target neutrons observed.

The kinetic profiles change in the presence of helium



Both changes in heat deposition and pedestal stability responsible for loss of confinement

NBI+RF heating (P_{NBI}=8MW, P_{ICRH}=2.5-3MW):

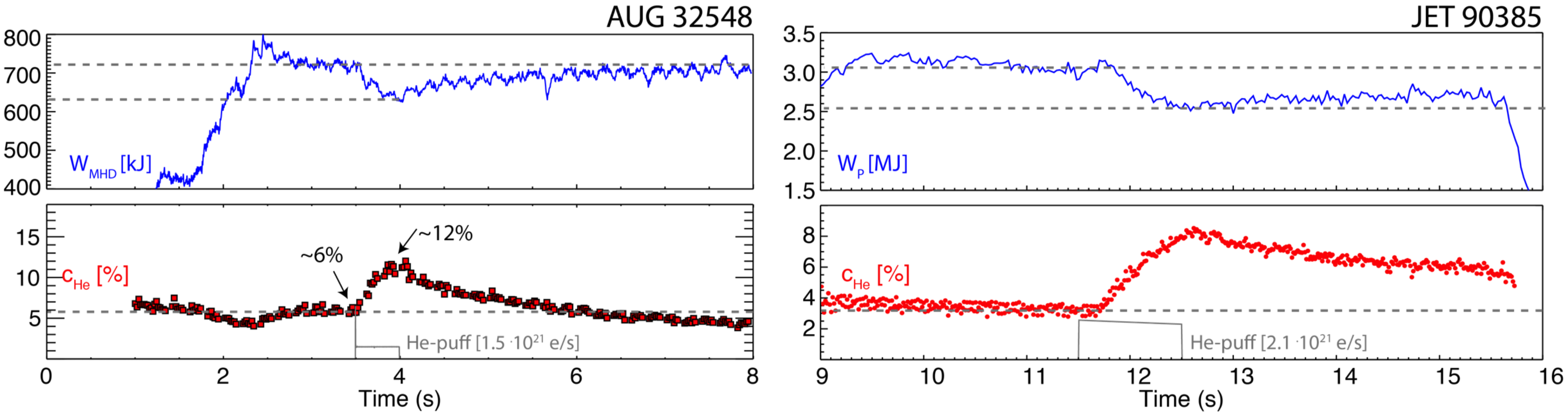
- Not as strong reduction in W_{MHD}, neutrons

+ f_{ELM} control:

- Recovery of confinement
- Reduction of D gas [C.F. Maggi et al, NF 2015], but much larger than added He (factor ~6 in e^-/s)

He puff and confinement recovery

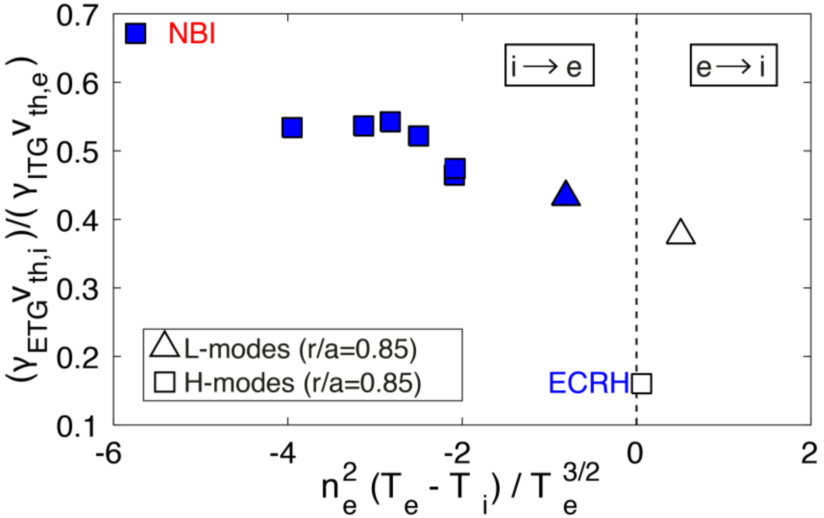
In both ASDEX Upgrade and JET, W_{MHD} recovers after a short He gas puff on the same time scale as c_{He} decays



Helium plasmas: edge confinement

Linear gyrokinetic simulations with GKW

- Medium to high n_e:
  collisional thermal exchange unfavorably i→e
  Increase of turbulent drive R/L_{Te} → strong increase of turbulent transport through destabilised ETG → stiff T_e (no increase)
- Low n_e:
  collisional thermal exchange reversed, ETG less destabilised → increase of both T_e, T_i ('ECRH' case)



Loss of edge confinement in both L- and H-mode plasmas attributed to thermal coupling and ETG destabilisation.
(pedestal stability effects not excluded)