



New theoretical insights on the role of ion isotope on transport and turbulence

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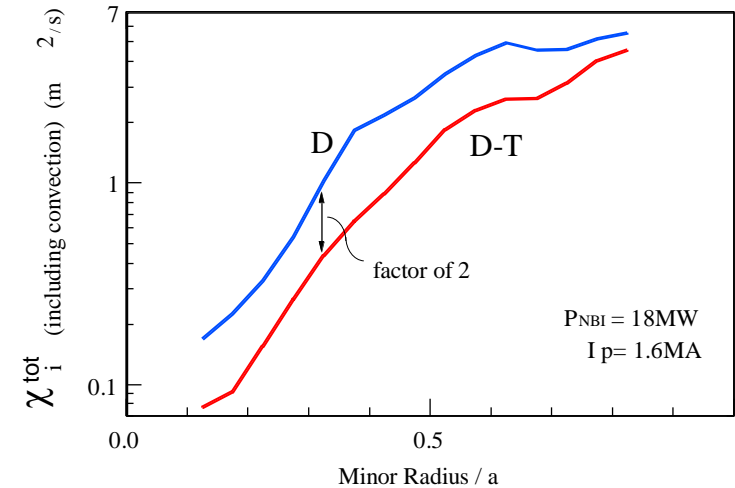
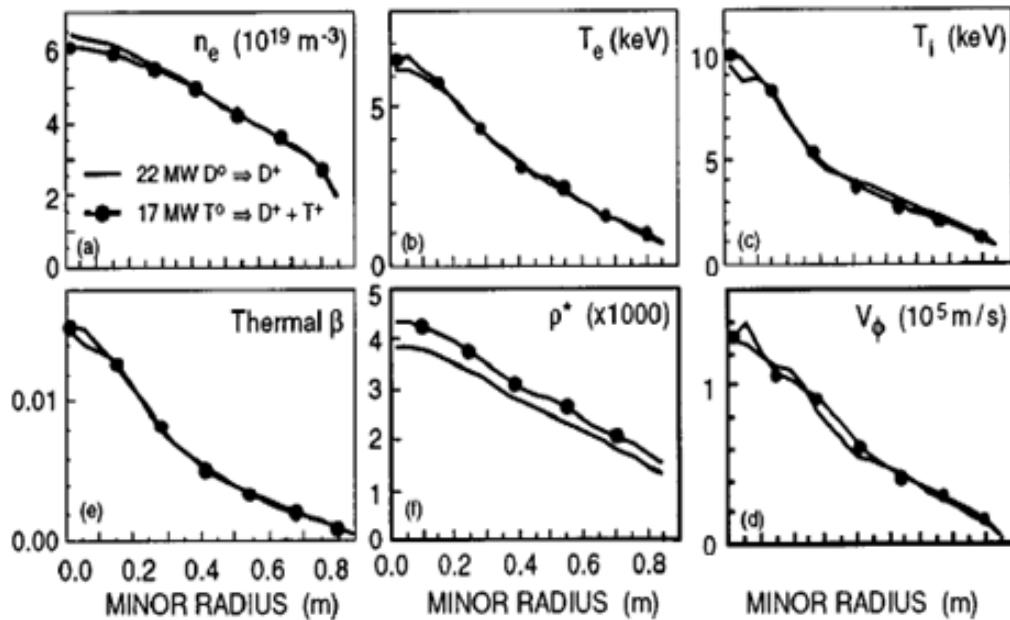
With the help of: A. Banon-Navarro, T. Goerler, C. Maggi, M. Oberparleiter

JET



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Transport differences in DD vs 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?

Context: The isotope effect



- Local heat transport expected to be of local nature and follow Gyro-Bohm (GB) scaling:

$$Q_i \sim m_i^{1/2}$$

- Numerous experiments have shown deviations from those expectations:
 - Asdex-U H/D [P. Hennequin et al., NF 2015] [P. Schneider et al., NF 2017]
 - TFTR, JET DD/DT [S.D. Scott *et al.*, PoP 1995] [J. G. Cordey et al. , NF 1999]
 - JT-60U H/D [H. Urano et al IAEA-FEC 2012]
 - TJ-II H/D [B. Liu et al., NF 2016]
 - Textor H/D [Y. Xu et al. PRL 2013]
 - JET H/D [C F Maggi et al PPCF 2018]

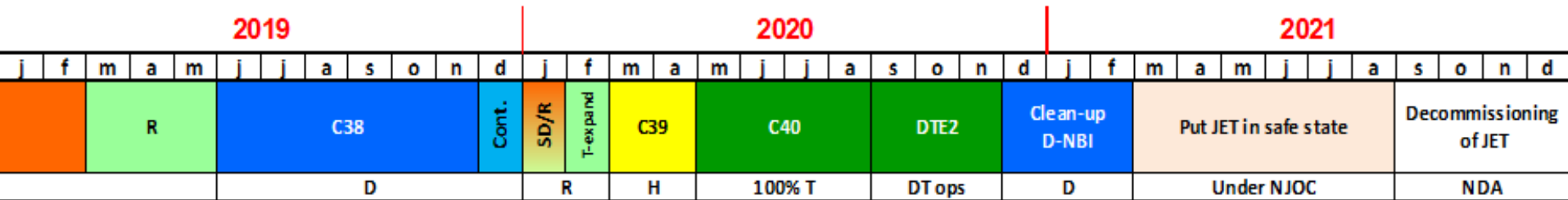
No final explanation has been found yet → Isotope effect

- Better theoretically understanding is **absolutely required**:
 - To guide and expand the experimental domain **where the isotope effect is expected to appear**
 - To perform **credible predictions for future DT campaigns** at ITER, JET
 - To test and create simplified models
 - **Minimize risks in ITER DT campaigns**



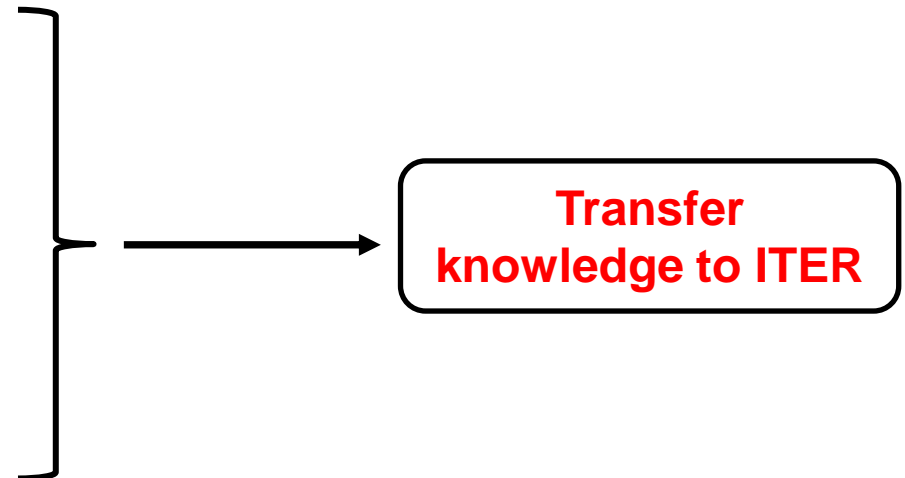
- The isotope physics studies at JET
- Gyrokinetic analyses of JET plasmas:
 - Core L-mode turbulence
 - Core H-mode turbulence
- DD vs DT: the ITER case
- Conclusions

Isotope physics studies at JET



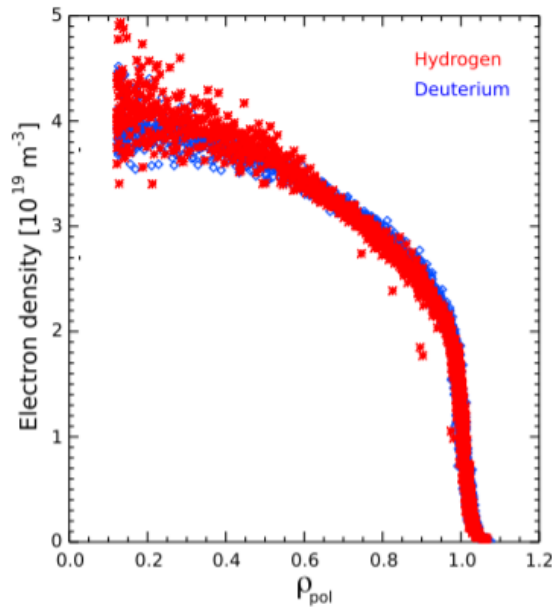
➤ **High level goal of JET:** Determine the isotope dependence of H-mode physics with a W/Be first wall

- Transport/Turbulence
- Pedestal/MHD
- Alfvén Modes/fast ion transport
- SOL/PWI
- Heating/Particle sources

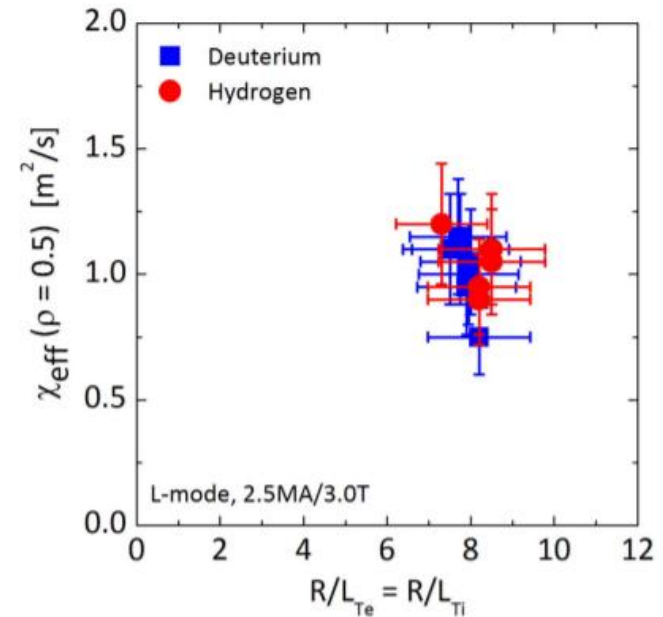
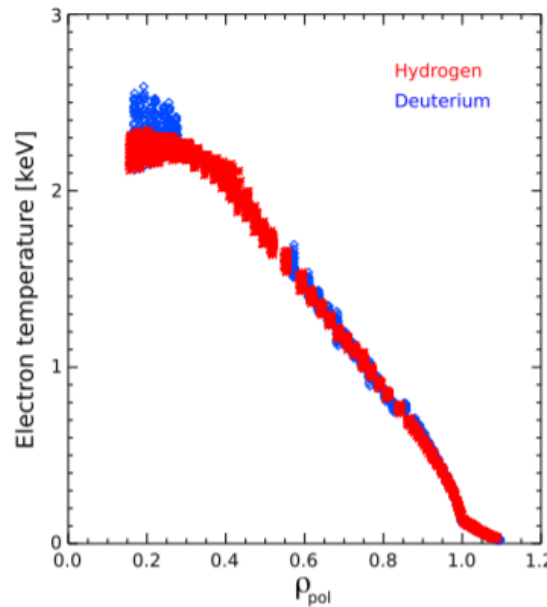


Previous campaign in H. Future campaigns in D,T and DT

Isotope physics studies at JET: L mode



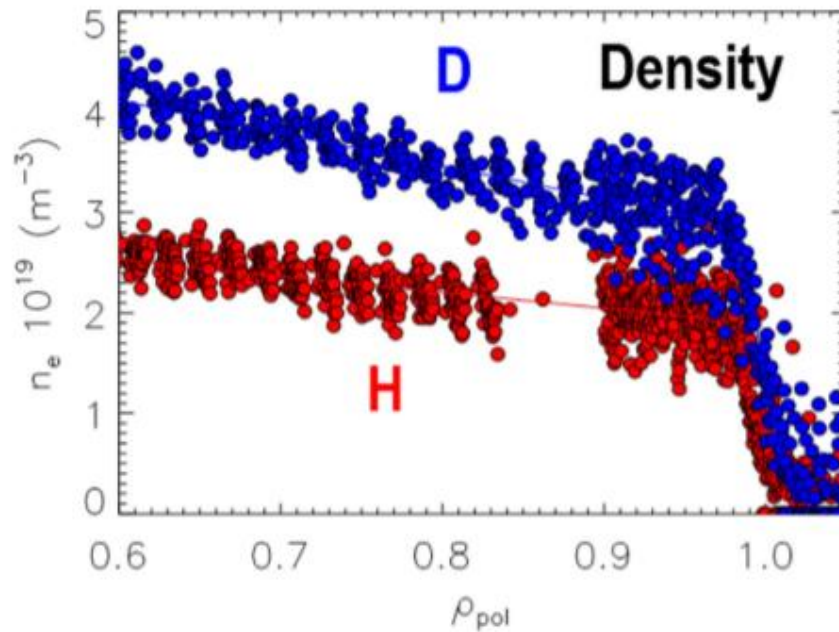
[C F Maggi et al PPCF 2018] [Weisen H. et al IAEA 2018]



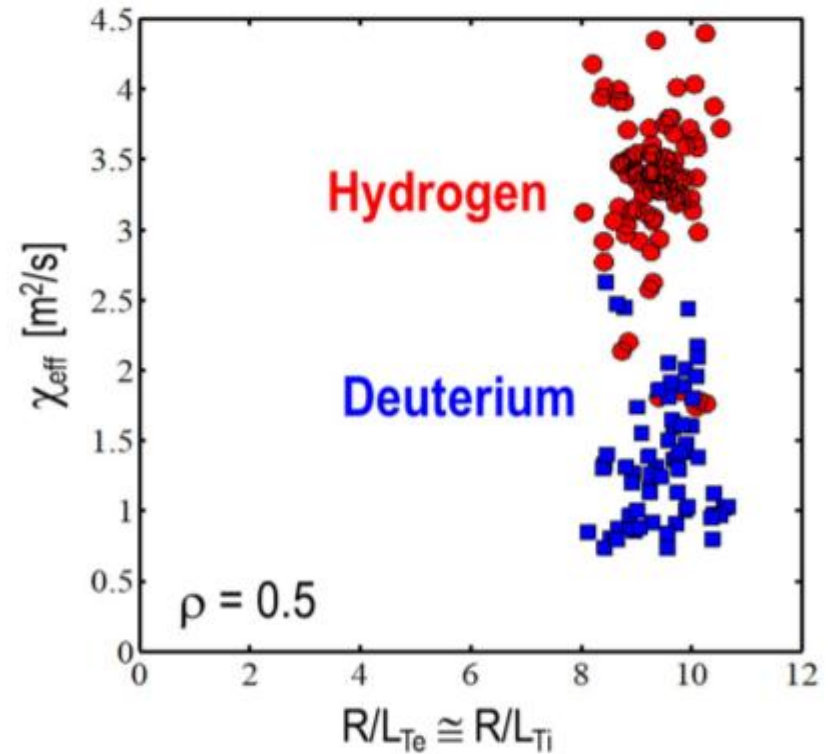
- Less NBI power and gas puff needed in D vs H matched plasmas → **Isotope effect**
- Power scans at constant density: $X_{\text{eff,H}} \sim X_{\text{eff,D}}$ → No GB scaling but no clear isotope effect in the core region
- Clear isotope effect in the edge region

$$\tau_{\text{E,th}} \sim A^{0.15 \pm 0.02}$$

Isotope physics studies at JET: H mode



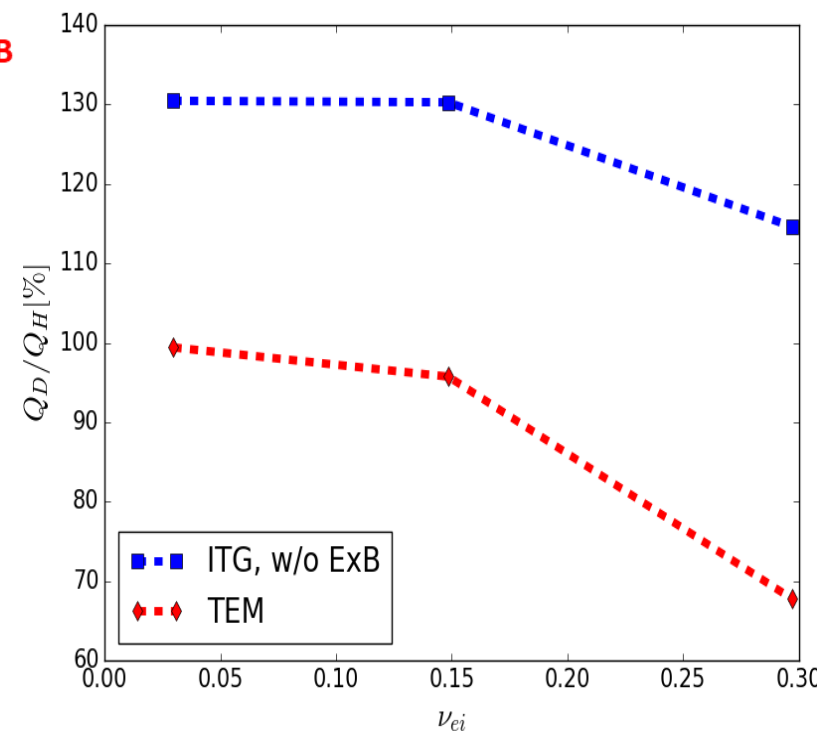
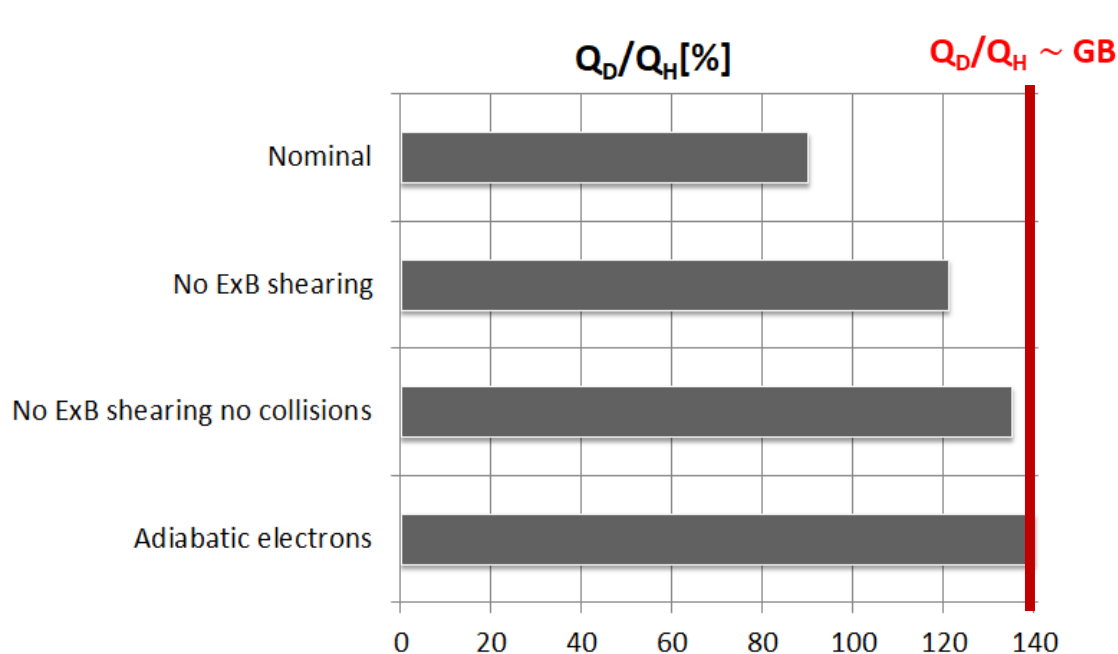
[C F Maggi et al PPCF 2018]



- **H-mode**: clear isotope effect in the pedestal, **higher density in D**
- **$\chi_{\text{eff,H}} > \sim \chi_{\text{eff,D}}$ in the core**
- Plasmas in relatively low $H_{98}(y,2)$, β , torque due to the low power available in H

$$\tau_{E,\text{th}} \sim A^{0.4}$$

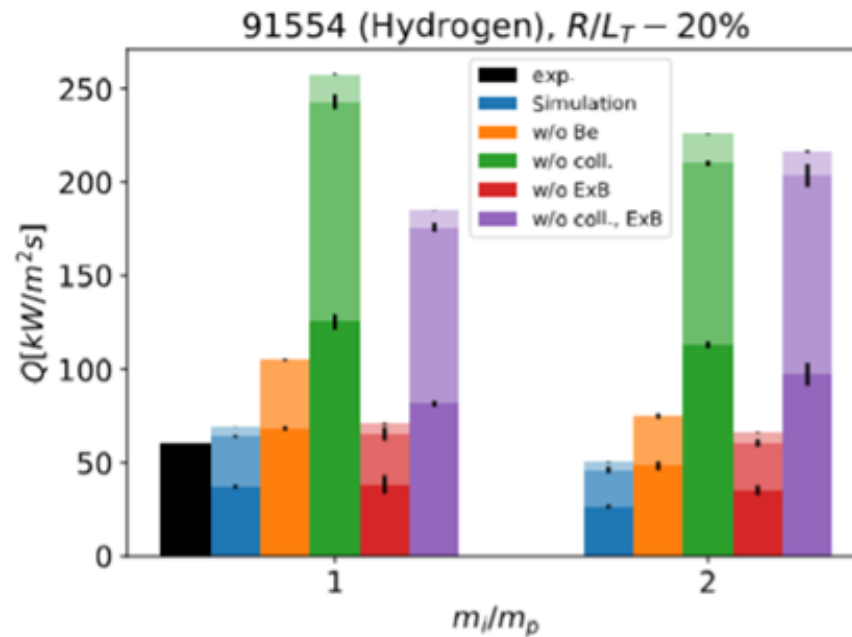
L-mode plasma analyses: GB deviations



[A. Banon-Navarro]

- **GENE** [Jenko et al., PoP 2000] **non-linear local simulations**. Only the mass changed from H to D
- ExB shearing, collisionality and electron transport: deviations from GB scaling.
- Impact of collisionality is turbulence regime dependent: ITG-TEM (weak) or pure TEM (strong)

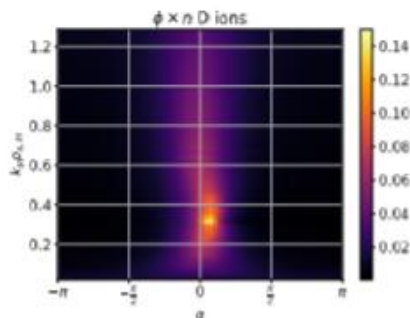
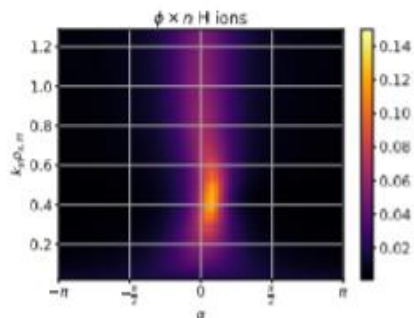
H-mode plasma analyses



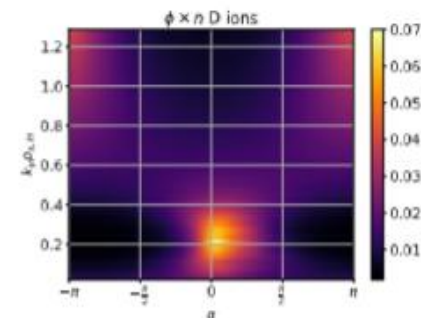
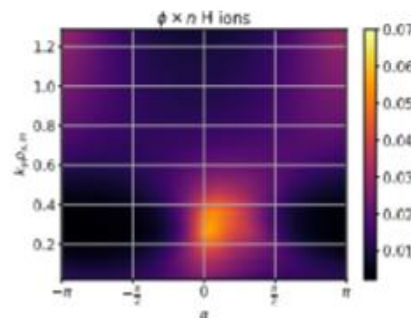
[M. Oberparleiter]

- ITG mode dominant....but **neglecting collisions leads to massive increase of heat transport!**
- Slightly smaller heat flux for D: **ExB, PVG and collisionality**
- Dilution effect of Be impurity reduces flux similarly in both H and D
- **Without collisions and rotational shear flux increases with m_i**

H-mode plasma analyses



collisional, w/ rotational shear



collisionless, w/o rotational shear

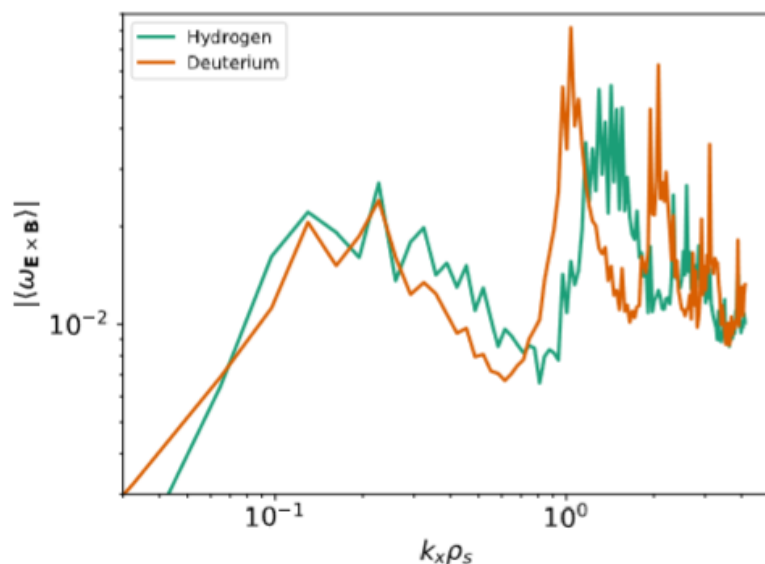
[M. Oberparleiter]

- Collisions suppress other modes besides ITG
- Collisional D ion simulation has slightly smaller phase angle \Rightarrow Less transport
- Other modes (TEM) besides ITG present in collisionless case (as in linear simulations) \Rightarrow Increased transport

H-mode plasma analyses

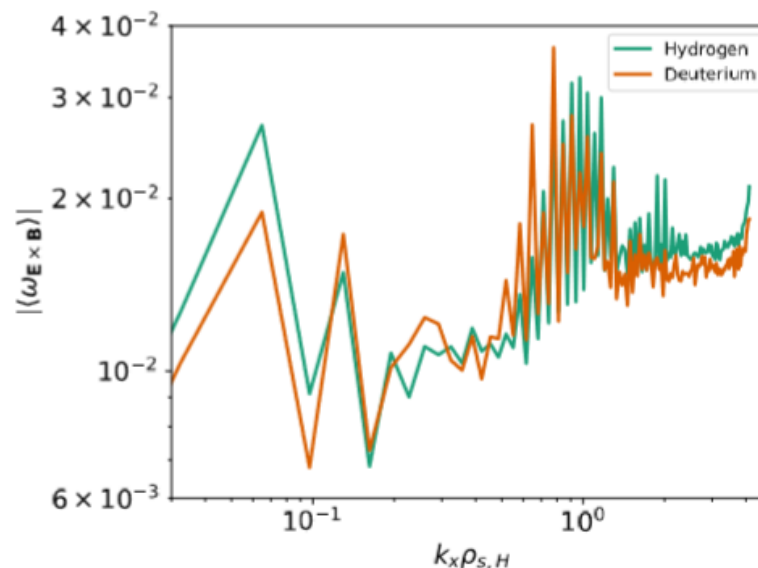


Radial spectrum of zonal $E \times B$ shearing rate in $c_{s,H}/a$ for #91554



[M. Oberparleiter]

collisional, w/ rot. shear



collisionless, w/o rot. shear

Table: RMS average of zonal $E \times B$ shear rate

$\omega_{E \times B} [c_s/a]$	H	D
w/o coll.	0.3019	0.2826
w/ coll.	0.3114	0.3431

- Low-k contribution changes more in collisionless case
- **Zonal ExB** RMS averages qualitatively reflect differences in fluxes [Y. Xu et al. PRL 2013] [T. S. Hahm et al., NF 2013][J. Garcia et al NF 2017] [M. Nakata et al., PRL 2017]



JET H/D experimental results analyses

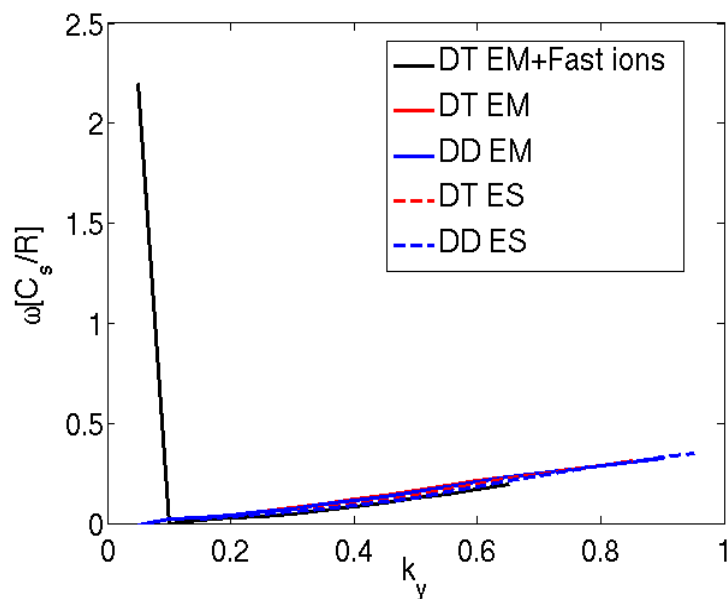
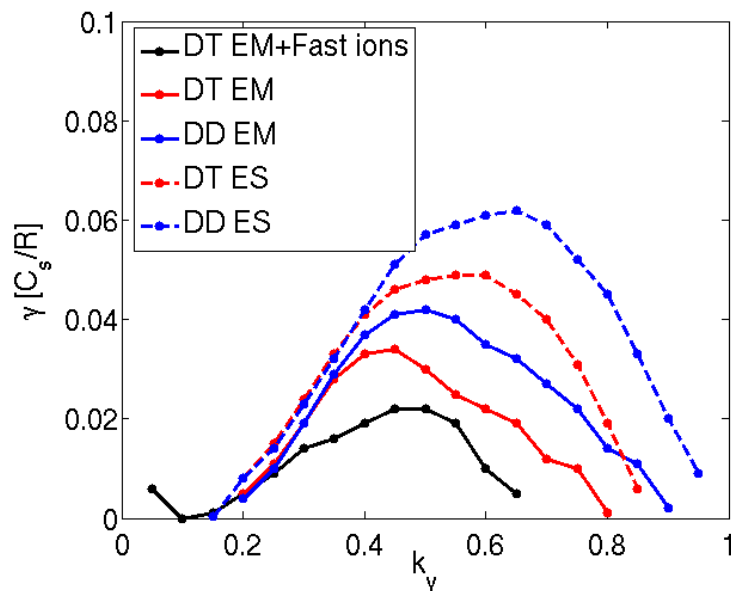
- **Isotope effect identified** with gyrokinetic simulations in JET core ITG dominated plasmas...
- ...but **very weak**, no strong reduction of flux with mass, in agreement with power balance experimental analyses
- **Collisonality, ExB shear, electron transport, zonal flows** → GB transport deviations
- Global isotope effects dominated by edge physics

How to find clear core transport isotope effects?

ITER high β scenario: Linear analysis



Electromagnetic (EM) and Electrostatic (ES) Linear spectra of ITER high β scenario at $\rho = 0.33$

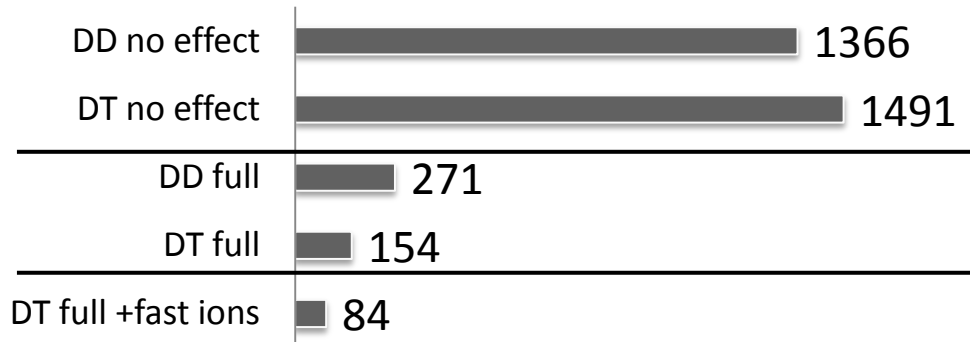


- Unstable modes all in the ITG domain
- **BAE modes appear similar to JET hybrid** when including fast ions: [J. Citrin PPCF 2014] [J. Garcia NF15] [H. Doerk 2016]
- $\gamma_{max,DT} \sim \gamma_{max,DD} \sqrt{m_{DD}/m_{DT}}$ (for both EM and ES simulations)
- **No deviation from GB scaling in linear analysis**

Non-linear: GB scaling drastically broken

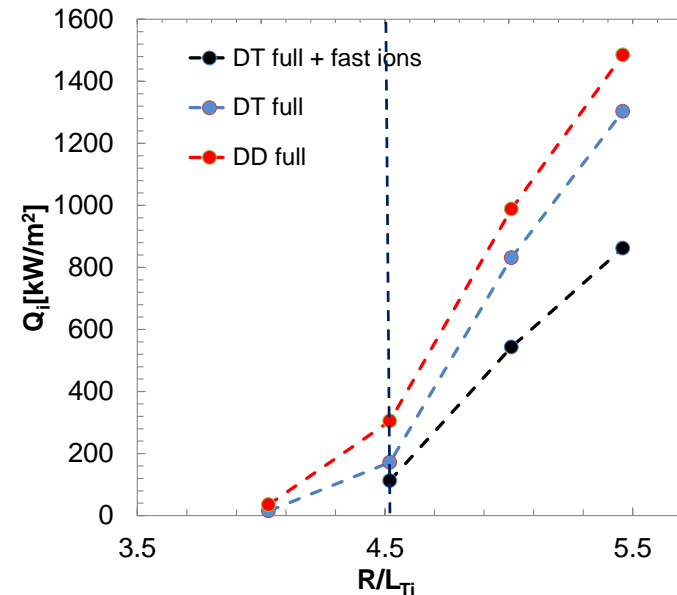
Non-linear results of ITER hybrid scenario at $\rho = 0.33$

Q_i (kW/m²)



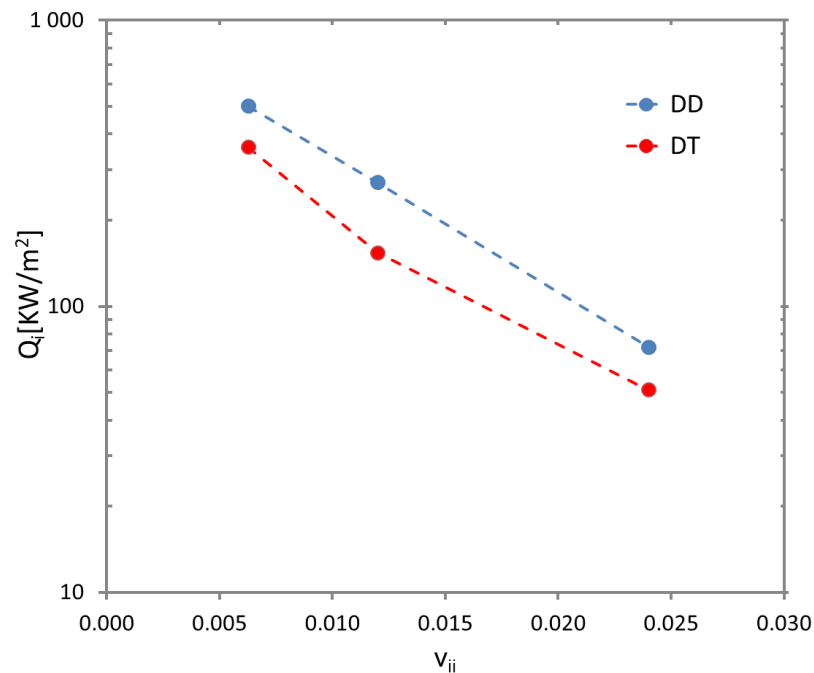
J. Garcia et al., Physics of Plasmas 25, 055902 (2018)

J. Garcia et al., Nucl. Fusion 57, 014007 (2017)



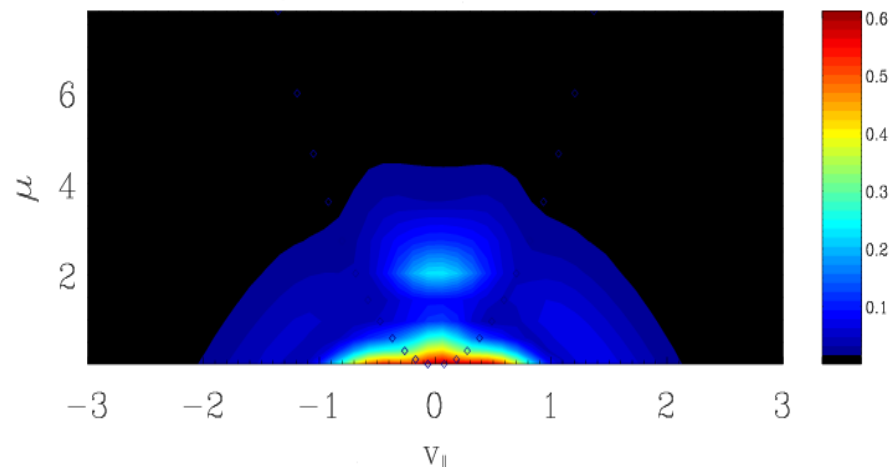
- Non-Linear simulations with electromagnetic (EM) and ExB (PVG) effects (full simulation)
 - Ion heat flux reduction of 42% from DD to DT
 - 3 times reduction of heat flux from DD to full DT+fast ions → Strong deviation from GB scaling
- When excluding electromagnetic effects and ExB flow shear:
 - Ion heat fluxes just follow GB scaling: $Q_{i,DT}/Q_{i,DD} = 1.09 \sim \sqrt{5/4}$

Important impact of collisionality on ITG plasma

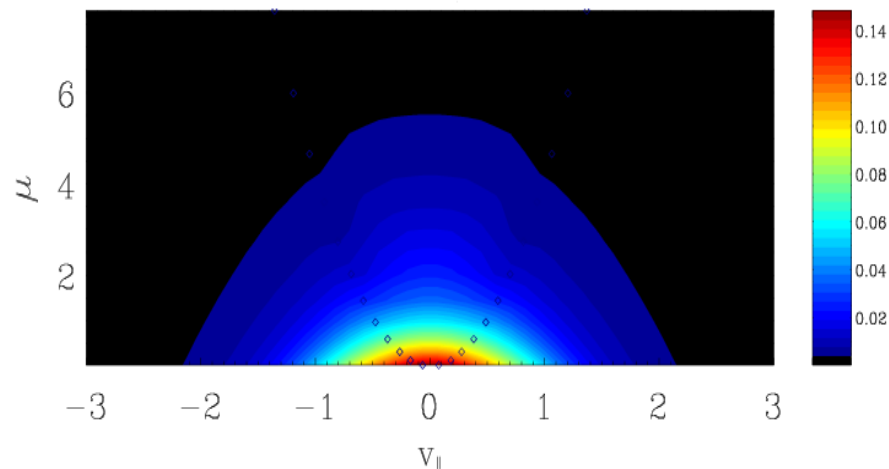


J. Garcia et al., Physics of Plasmas 25, 055902 (2018)

Deuterium

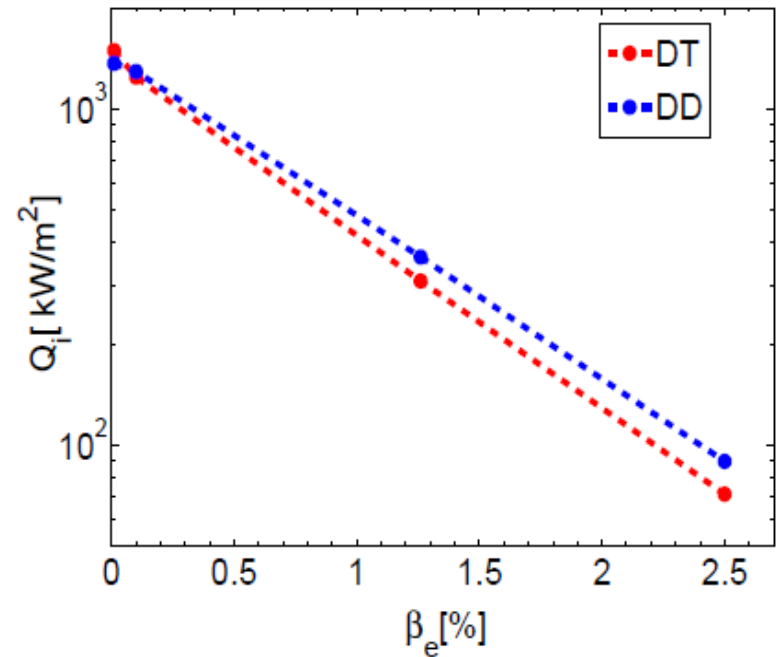
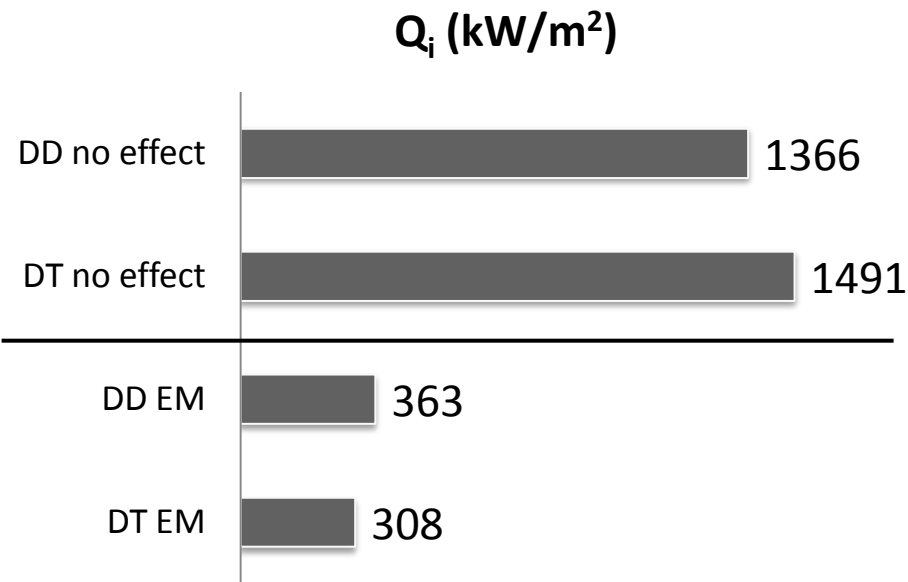


Electrons



- Collisionality scan show important impact on fluxes
- Significant contribution of trapped ions \rightarrow Exotic modes in ITER?

Impact of finite β , GB scaling broken



- Electromagnetic effects brake GB scaling.
- β_e scan performed: **electromagnetic impact is non-linear**
- Reminiscent of the non-linear ITG turbulence reduction by fast ions [J. Citrin PPCF 2014] [J. Garcia NF15]

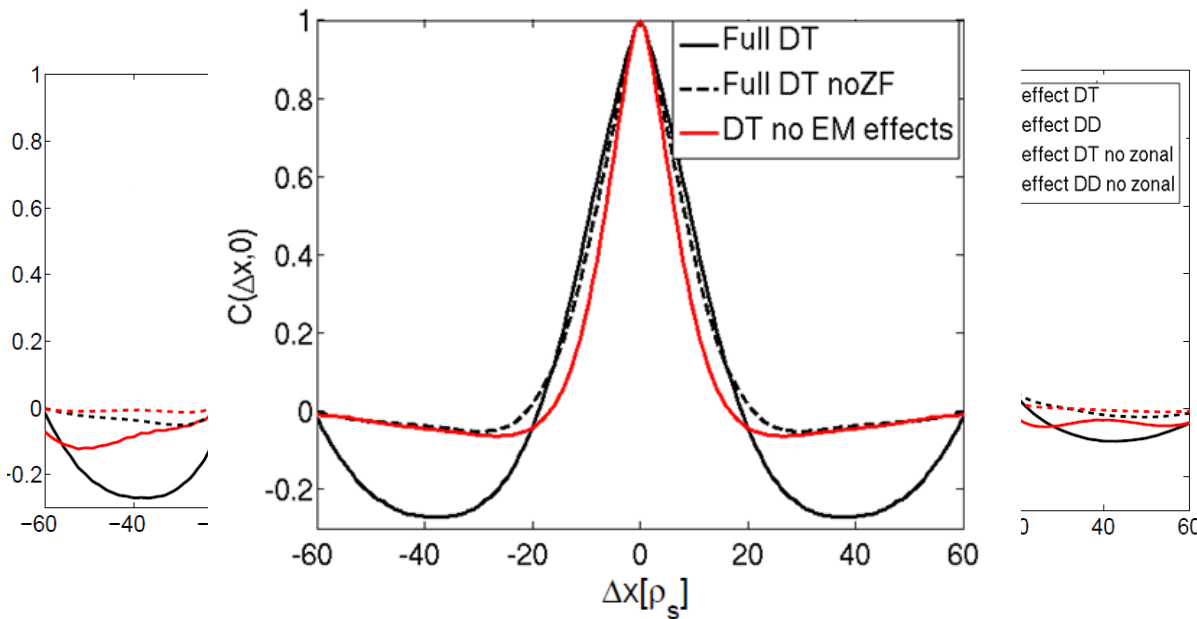
Role of zonal flows



Case	$Q_i(\text{kW/m}^2)$	$\gamma_{\text{ExB,zonal}}/\gamma_{\text{max}}$
DT Electromagnetic	308	12.6
DD Electromagnetic	363	10.7
DT no effect	1491	14.0
DD no effect	1366	10.5

- Interaction between zonal flow and mass proposed to explain the isotope effect [Y. Xu et al. PRL 2013] [T. S. Hahm et al., NF 2013]
- Zonal flow shearing, $\gamma_{\text{ExB,zonal}} = \frac{\partial}{\partial r} \langle v_{E \times B} \rangle$, $\gamma_{\text{ExB,zonal}}/\gamma_{\text{max}}$ calculated for the cases without ExB
- $\gamma_{\text{ExB,zonal}}/\gamma_{\text{max}}$ is always higher for DT mixture, **higher zonal flow impact for DT...**
- **...however no direct translation on the fluxes!**
- Zonal flow mixing model to be investigated [G. Staebler et al Phys. Plasmas 23, 062518 (2016)]

mass, electromagnetic and zonal flows interplay



Case	$\lambda_c(\rho_s)$	$Q_i(\text{kW/m}^2)$
DT	11.5	154
DD	10.3	271
DT no effect	9.44	1491
DD no effect	8.03	1366

- Electrostatic potential correlation function analyzed. Zonal flow analyzed in post-processing
- Correlation length always follows GB scaling even if there is an isotope effect
- With an isotope effect: anticorrelation region for $\Delta x > 20\rho_s$ generated by zonal flows
- Origin of the zonal flow activity for DT are electromagnetic effects

Inherent Gyro-Bohm scaling at short scales counteracted by mass, electromagnetic and zonal flows interplay → Mesoscale isotope effect

[P. Hennequin et al., NF 2015] [B. Liu et al., NF 2016] [P. Manas et al, NF 2019]



- JET H/D plasmas show a significant isotope effect, mainly for H-modes
- Edge region is the main origin, core local transport show only weak deviations from GB scaling
- Collisionality, ExB shearing and electron transport provoke an isotope effect...
- ...but the effect is very weak in these JET conditions
- In ITG DD vs DT plasmas, concomitant electromagnetic, external ExB shearing and fast ions effects lead to very strong isotope effects
- Mass, electromagnetic and zonal flows interplay on the origin
- **Privileged plasma conditions to find core transport isotope effects!**
- To be understood: Multi-scale effects, global effects (stiffness, electron-ion heat exchange, SOL)



- JET will provide crucial information about the physics of the isotope effect in DD/TT/DT campaigns:
 - Core vs edge region in pure plasmas
 - Mixed isotope plasmas
 - Isotope vs operational effects
 - Role of alpha particles in DT isotope effects
 - Role of fueling on the isotope content
 - Role of the isotope on impurity accumulation
- The scientific program will cover broad plasma conditions, including those expected with higher core isotope effects: **high beta, $T_i > T_e$, torque, fast ion content**
- **Essential to understand ITER DT plasmas**
- **Collaboration and participation is very much welcome!**