DE LA RECHERCHE À L'INDUSTRIE

ELECTROMAGNETIC GYROKINETIC ANALYSIS OF THE ISOTOPE EFFECT

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Acknowledgements. The simulations presented in this work were carried out using the HELIOS supercomputer system at Computational Simulation Centre of International Fusion Energy Research Centre (IFERC-CSC), Aomori, Japan.

26TH FUSION ENERGY CONFERENCE, 17-22 OCTOBER, KYOTO, JAPAN

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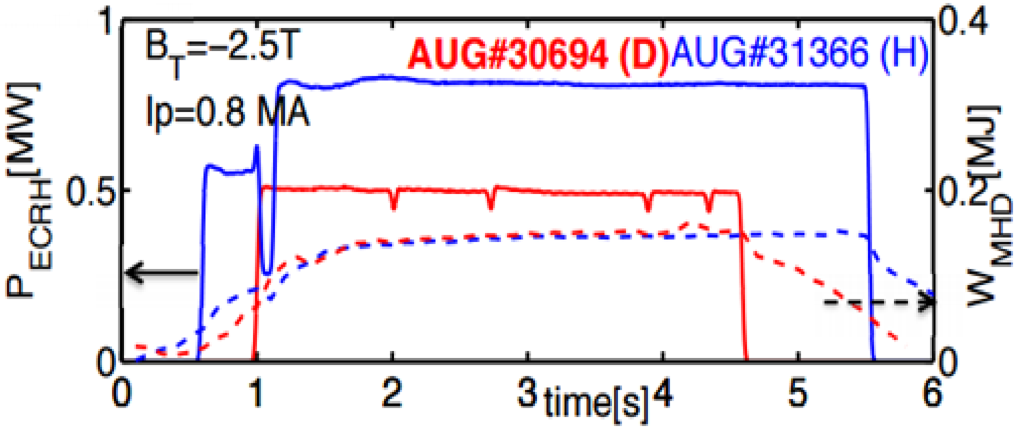
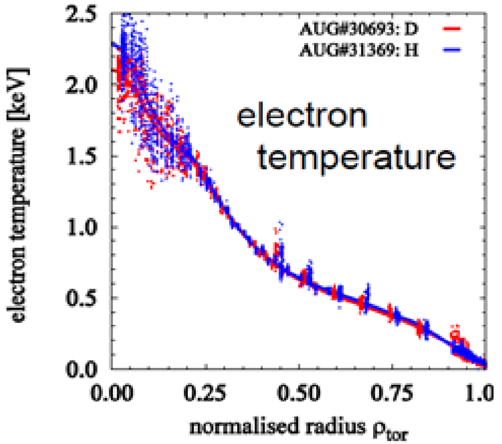
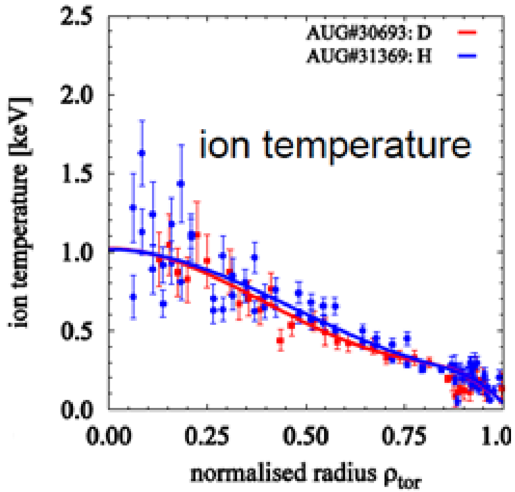
Context: H vs D in ASDEX-U

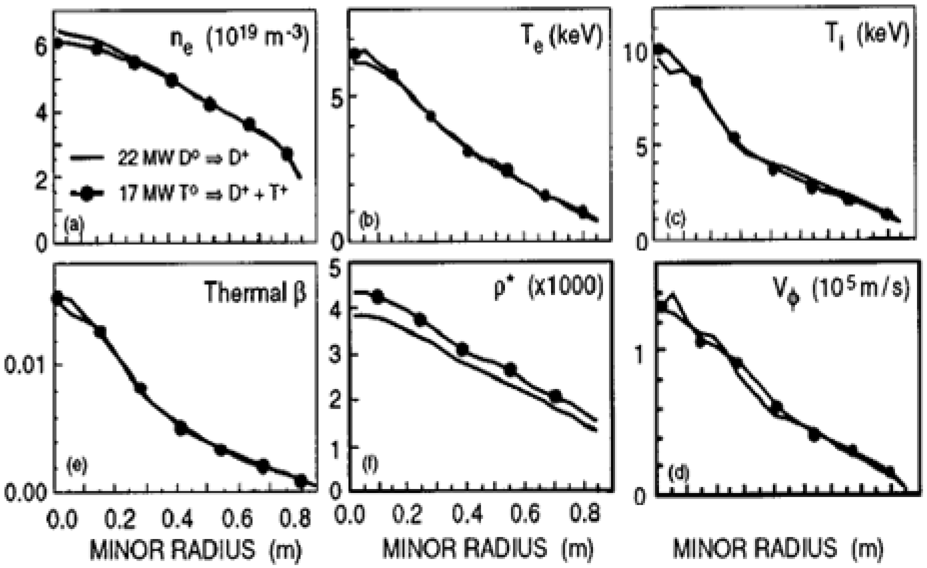


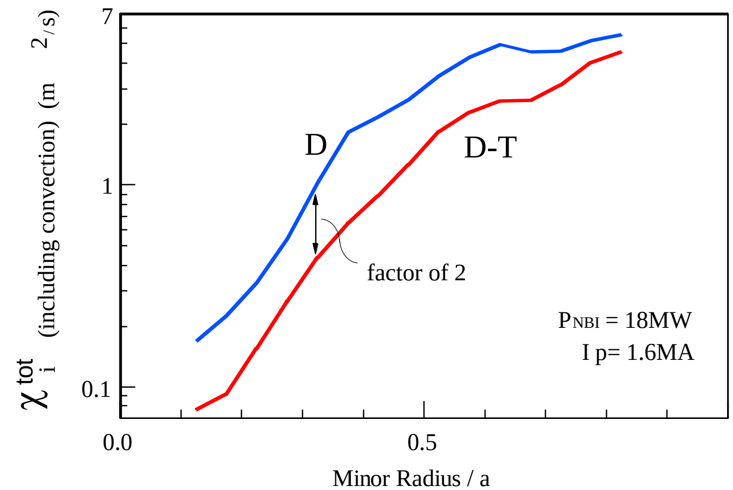


- Asdex-U H vs D experiments in L-mode with pure ECRH heating [P. Hennequin et al., NF 2015]
- $\langle P_{H,ECRH} \rangle \sim 1.4 \times \langle P_{D,ECRH} \rangle$
- Global confinement degradation with H: ion flux for H twice than for D
- Correlation length increases with mass H/D [P. A. Schneider EPS2016 O4.135]



Context: 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]

Context: The isotope effect

- 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]
  - 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]

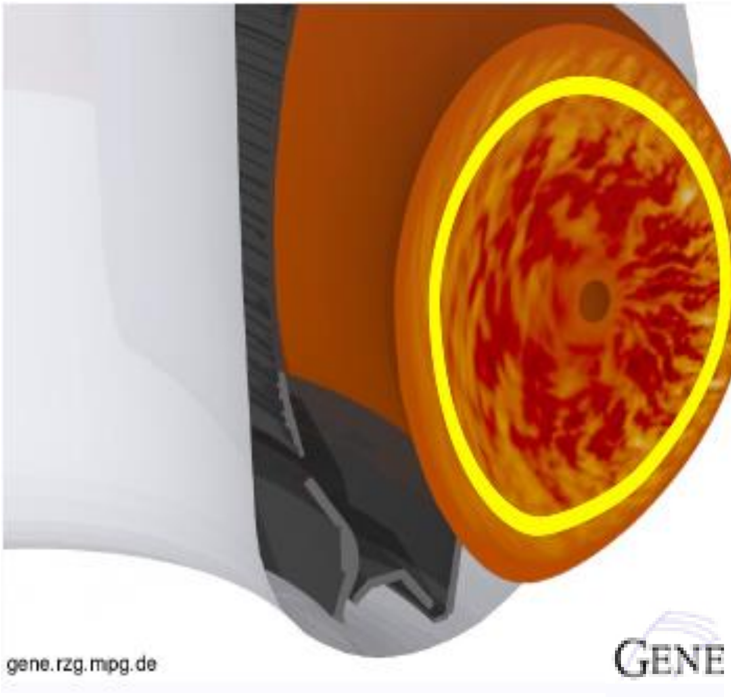
No final explanation has been found yet→ Isotope effect

- 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

Outline

- Gyrokinetic analyses of the isotope effect: GENE code applied to ITER
- Linear and non-linear simulation results
- GB deviations with ExB flow shear and electromagnetic effects
- Mesoscale physics in the origin
- Conclusions

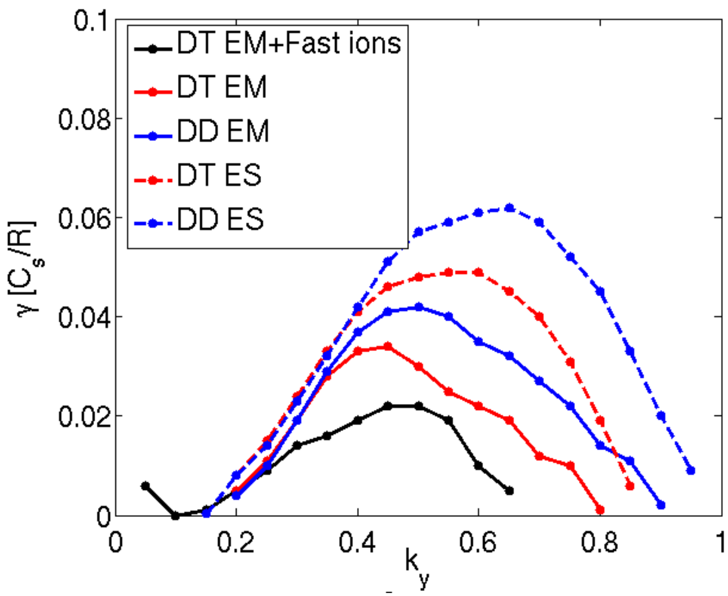
ISOTOPE EFFECT: GYROKINETIC SIMULATIONS

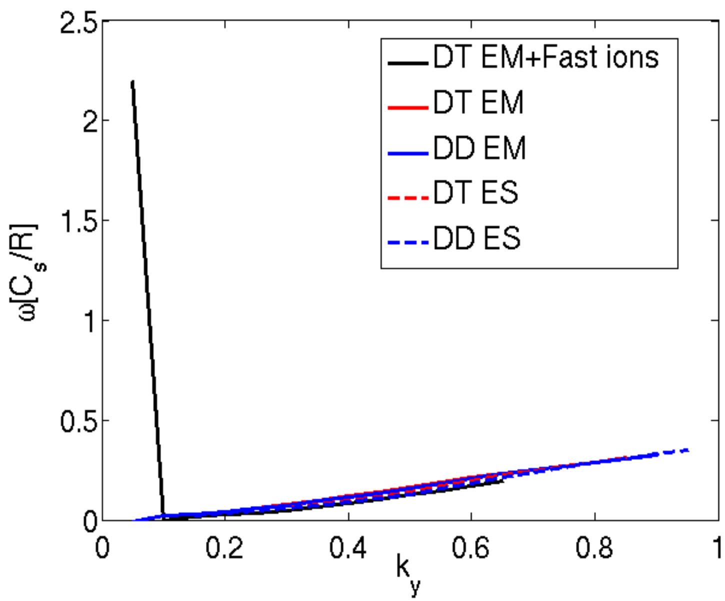


- GENE code [Jenko et al., PoP 2000]: linear and non-linear gyrokinetic analysis of core microturbulence for ITER hybrid (high β) [K Besseghir *et al* PPFC 2013]
- Kinetic electrons, free boundary geometry, electromagnetic effects, up to 7 species (e,D,T, C, He-ash, Fast D (beams), fast He (fusion reactions))
- Electron particle transport originally simulated→ 50%D-50%T assumed
- Local (flux tube) approximation taken
- Both $\delta B_\perp$ and $\delta B_\parallel$ fluctuations included (∇P included the curvature-∇B drift)
- ExB and Parallel Velocity Gradient (PVG) effects included obtained from integrated modelling [R. Budny et al., NF 2008]
- Fast ions approximated by hot Maxwellians

Linear Results: no GB deviation

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

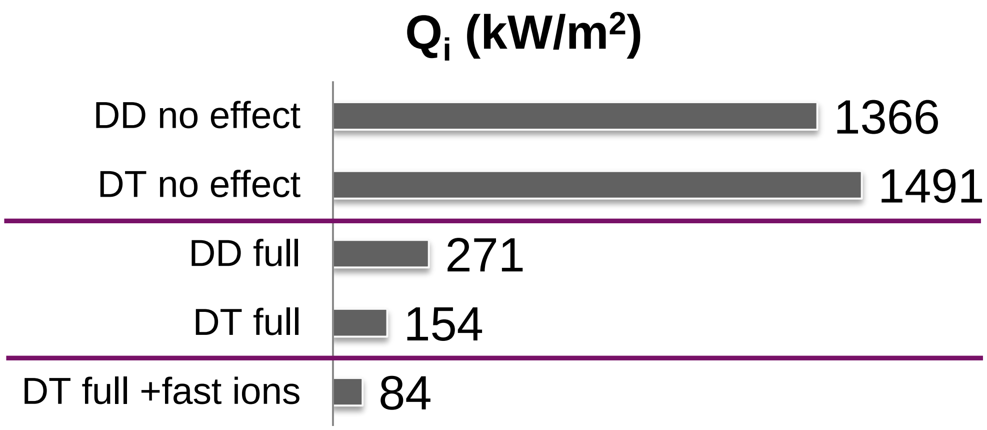


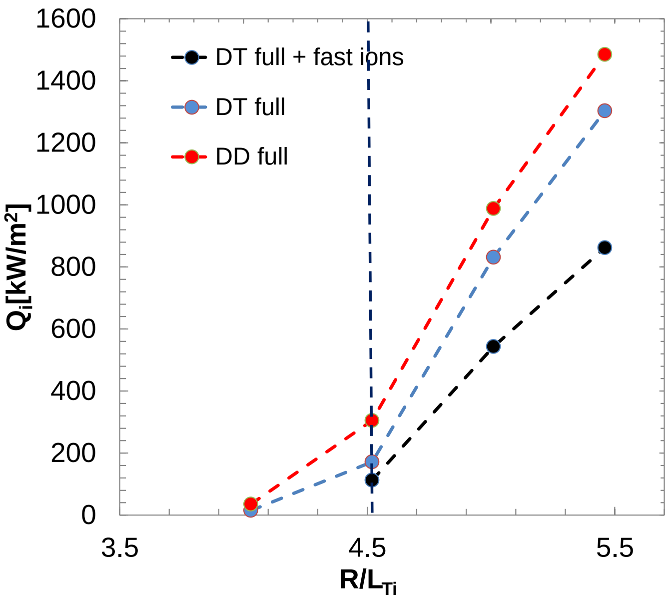


- Unstable modes all in the ITG domain
- BAE modes appear similar to JET hybrid when including fast ions: [J. Citrin PPCF 2014] [J. Garcia NF15] [H. Doerk 2016]
- $\gamma_{max,DT} \sim \gamma_{max,DD}\sqrt{m_{DD}/m_{DT}}$ (for both EM and ES simulations)
- No deviation from GB scaling in linear analysis

Non-Linear results: GB breaking

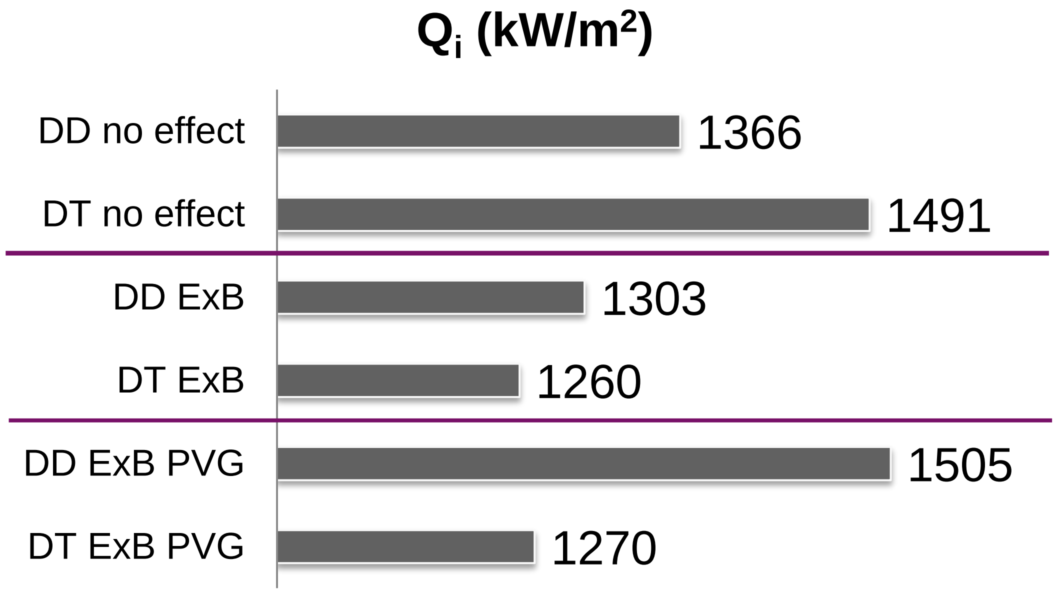
Non-linear results of ITER hybrid scenario at $\rho = 0.33$





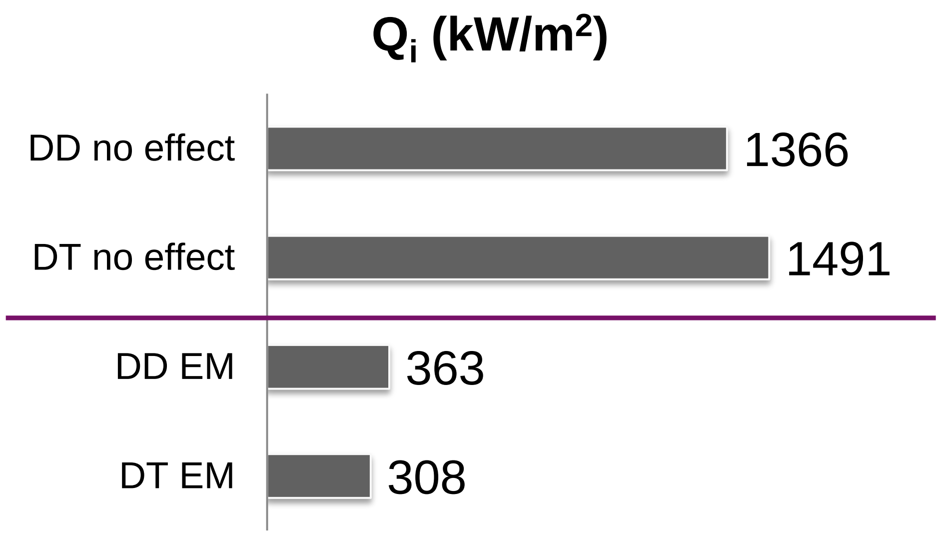
- Non-Linear simulations with electromagnetic (EM) and ExB (PVG) effects (full simulation)
  - Ion heat flux reduction of 42% from DD to DT
  - 3 times reduction of heat flux from DD to full DT+fast ions→ Strong deviation from GB scaling
  - Up-shift obtained from DD to DT
- When excluding electromagnetic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

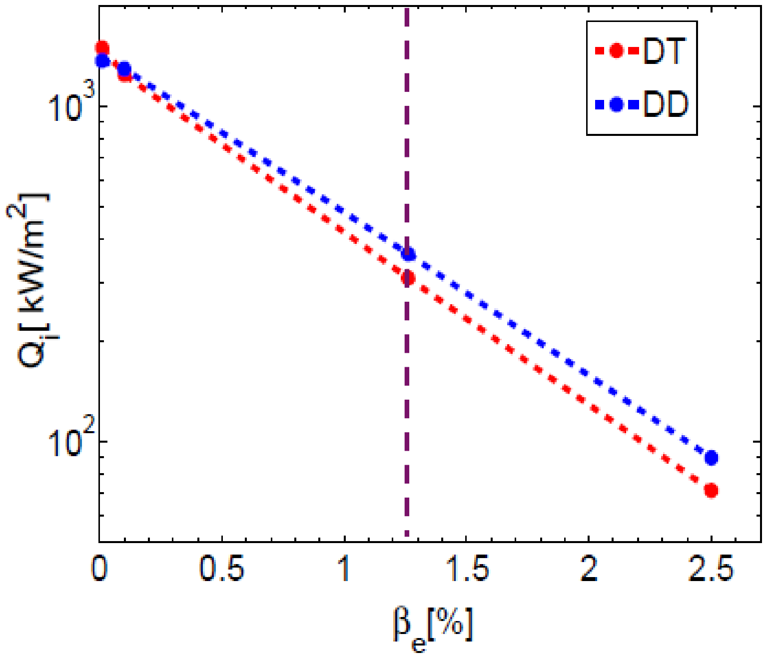
ExB and PVG effects: GB breaking



- Analysis of ExB and PVG effects in electrostatic conditions
- **GB scaling is broken**: Ion heat flux for DT is 15.6% lower than DD
- ExB flow shear impact stronger on DT consistent with naïve explanation: $\gamma_{E\times B}/\gamma_{ITG} \sim {m_i}^{1/2}$ for constant γ_{ExB} [X. Garbet PoP 96]
- Different impact of PVG on DT and DD→ Important role of q/ε (magnetic geometry)

Electromagnetic effects: GB breaking





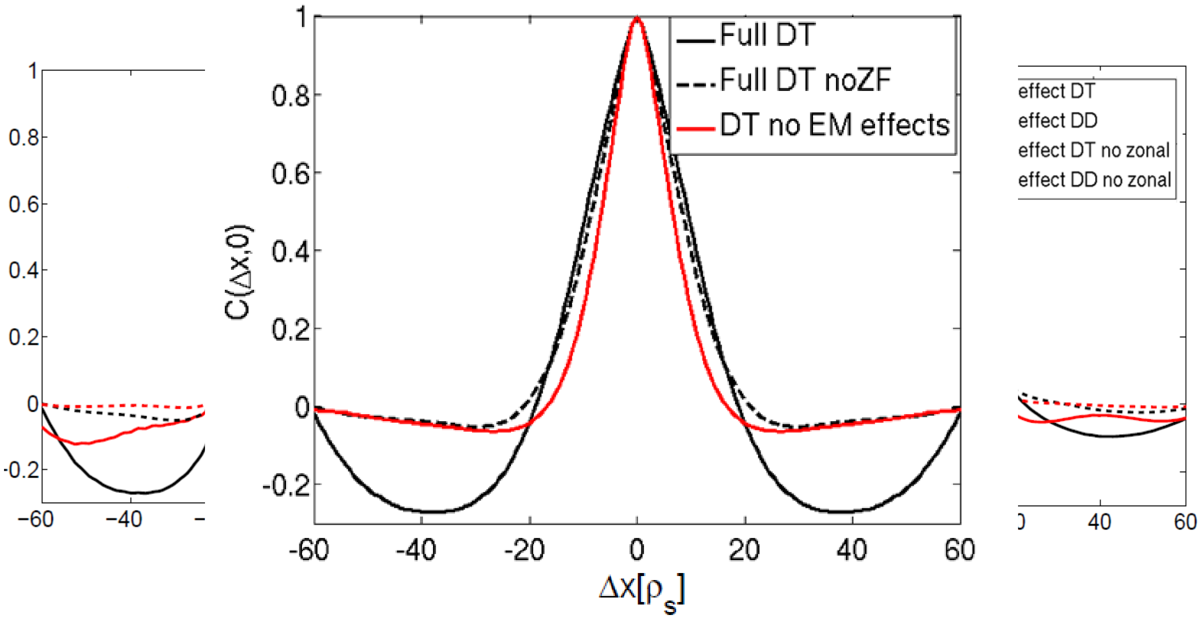
- DD and DT non-linear simulations repeated with just electromagnetic effects
- Electromagnetic effects brake GB scaling. Similar impact than ExB flow shearing
- β_e scan performed: electromagnetic impact is non-linear
- Reminiscent of the non-linear ITG turbulence reduction by fast ions [J. Citrin PPCF 2014] [J. Garcia NF15]

Zonal flow and mass interplay

Case	$Q_i(kW/m^2)$	$\gamma_{ExB,zonal}/\gamma_{max}$
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, $\gamma_{ExB,zonal} = \frac{\partial}{\partial r}\langle v_{E\times B}\rangle$, $\gamma_{ExB,zonal}/\gamma_{max}$ calculated for the cases without ExB
- $\gamma_{ExB,zonal}/\gamma_{max}$ is always higher for DT mixture, higher zonal flow impact for DT…
- …however no direct translation on the fluxes!

Zonal flow, mass and ß interplay



Case	$\lambda_c(\rho_s)$	Q_i(kW/m²)
DT	11.5	154
DD	10.3	271
DT no effect	9.44	1491
DD no effect	8.03	1366

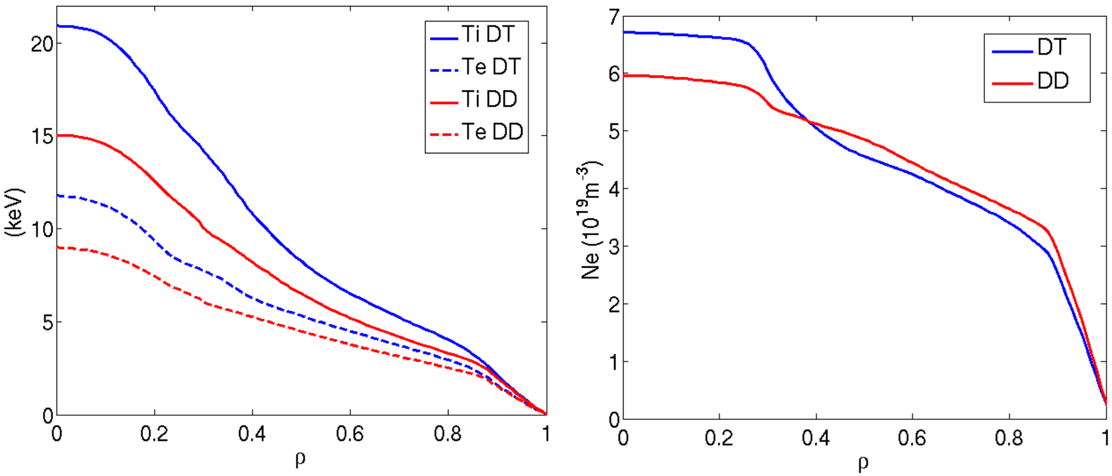
- Electrostatic potential correlation function analyzed. Zonal flow analyzed in post-processing
- Correlation length always follows GB scaling even if there is an isotope effect
- With an isotope effect: anticorrelation region for $\Delta x>20\rho_s$ generated by zonal flows
- Origin of the zonal flow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

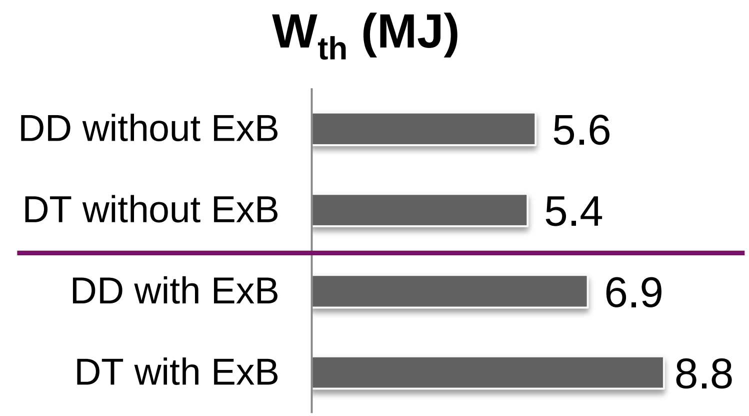
Inherent Gyro-Bohm scaling at short scales counteracted by mass, electromagnetic and zonal flows interplay→ Mesoscale isotope effect

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

Quasi-linear results

JET Projection at 2.5MA/2.9T/40MW





J. Garcia et al., ppcf 2016

- JET DT extrapolation performed with TGLF quasi-linear model [G. M. Staebler et al., Pop 2005]
- Energy confinement improvement for DT with ExB flow shear stabilization
- Equivalent fusion power Pfus (DT): 16.34MW Pfus(DD): 10.94MW
- Results in line with gyrokinetic analyses but no electromagnetic isotope effect found

Conclusions

- Significant ExB flow shear and electromagnetic effects found to break GB scaling for DD vs DT plasmas
- Isotope effect stronger at higher power (higher local β and torque) and low q in line with previous results from TFTR
- GB scaling at short scales broken by mesoscale interplay between zonal flows, electromagnetic effects and mass
- Isotope scans with controllable, β, Mach number and q desirable
- Turbulence reduction in ITER by fast ions and isotope effects can be strong
- Further analyses must be performed for a full understanding:
    - Multi vs single ion effects
    - L-mode plasmas with low β
    - Isotope effect at ρ>0.5
    - Role of collisionality

Particle isotope effect

Case	Γ_D (W/eVm^{-2})	Γ_T(W/eVm^{-2})	Γ_{Total}(W/eVm^{-2})
DT	0.34	0.25	0.59
DD	0.92		0.92
DT no effect	2.36	1.07	3.43
DD no effect	2.6		2.60

- Isotope effect analyzed for particle transport
- Symmetry between D and T broken: transport higher for D [C. Estrada-Mila et al., PoP 2005]
- Isotope effect for particle transport: $\Gamma_{DT} < \Gamma_{DD}$ when all the effects included
- Plasmas with high β and ExB flow shear→ Stronger density peaking with higher mass