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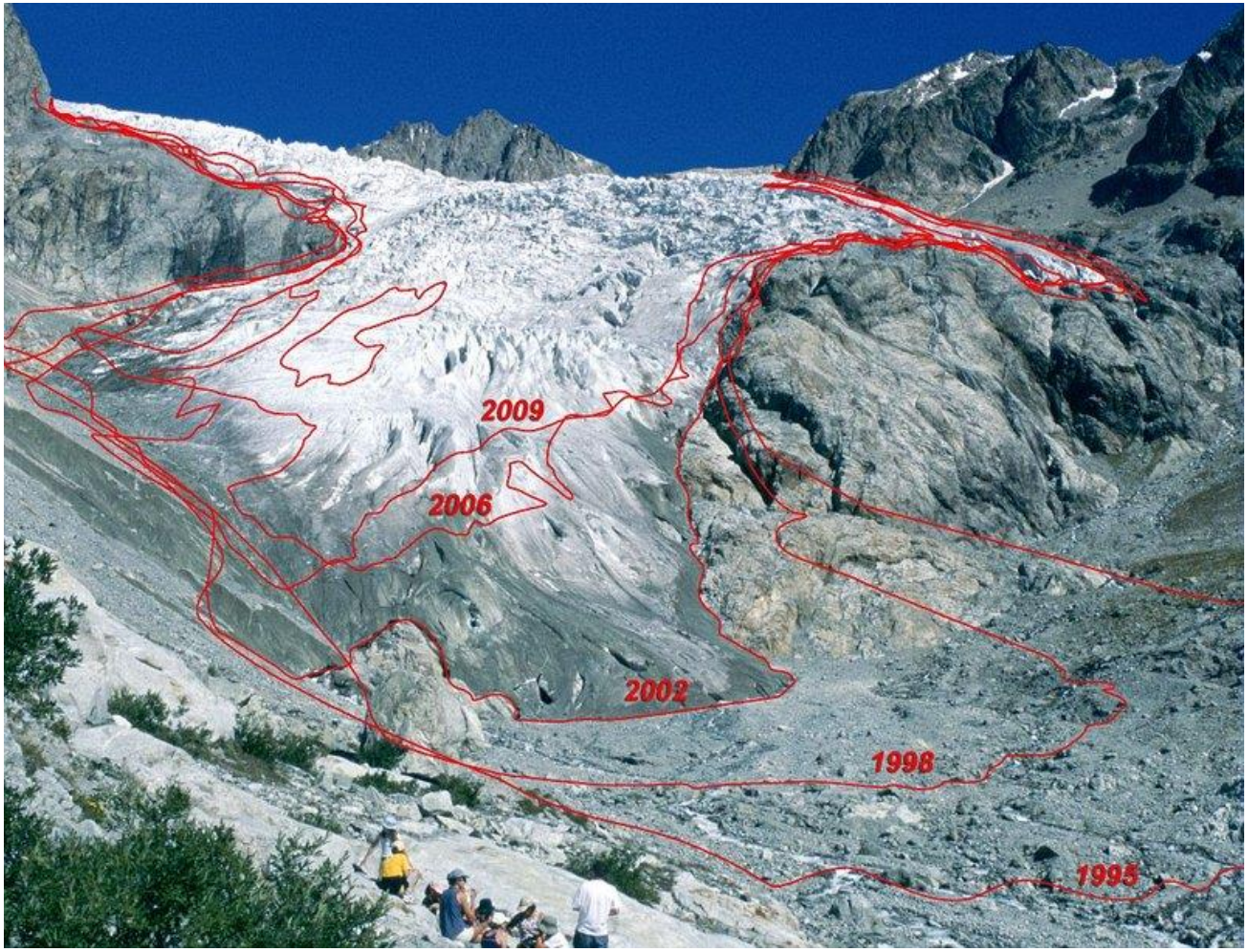
Optimization of plasma confinement through supercomputation: towards clean and efficient energy sources

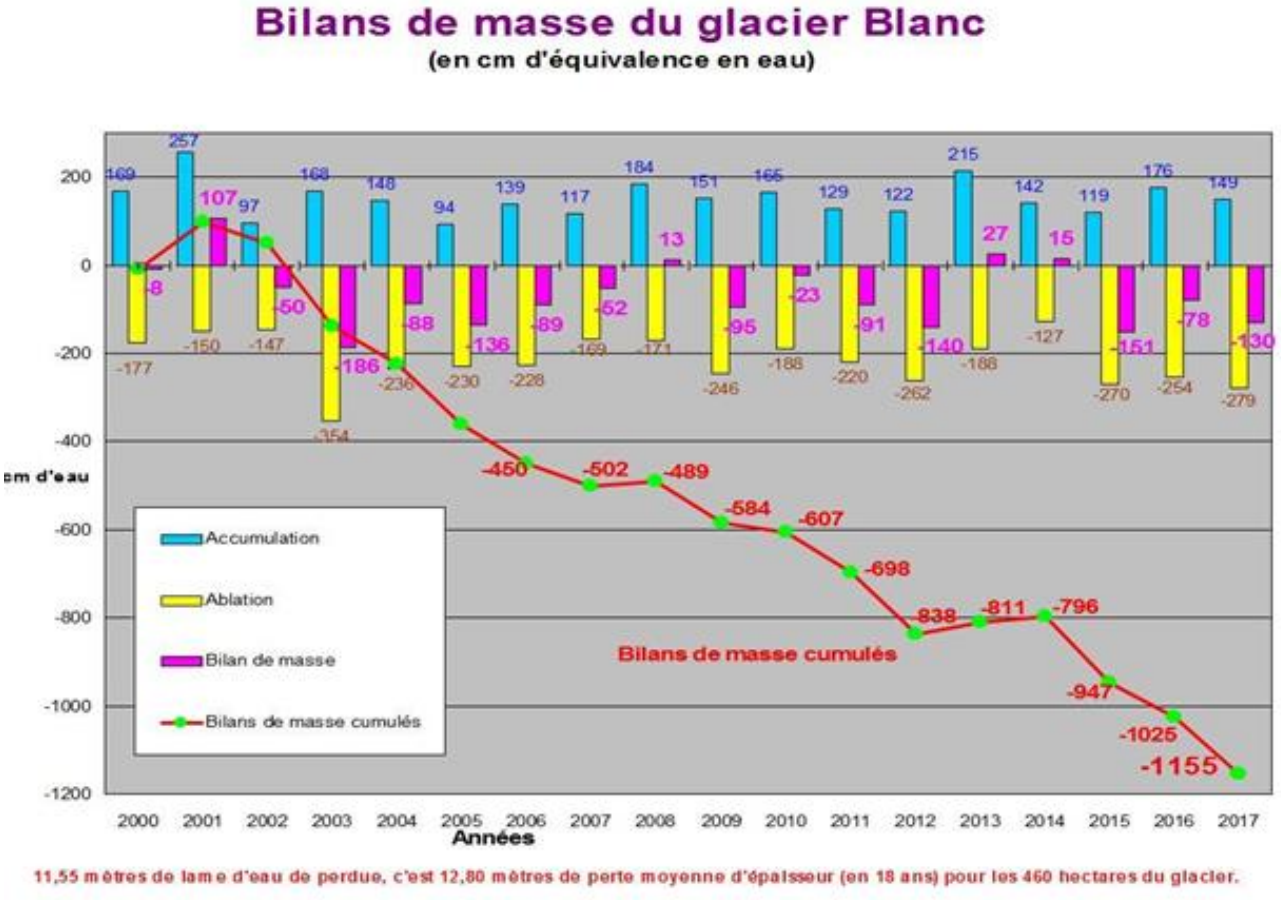
J. Garcia

CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France

WHY FUSION ENERGY

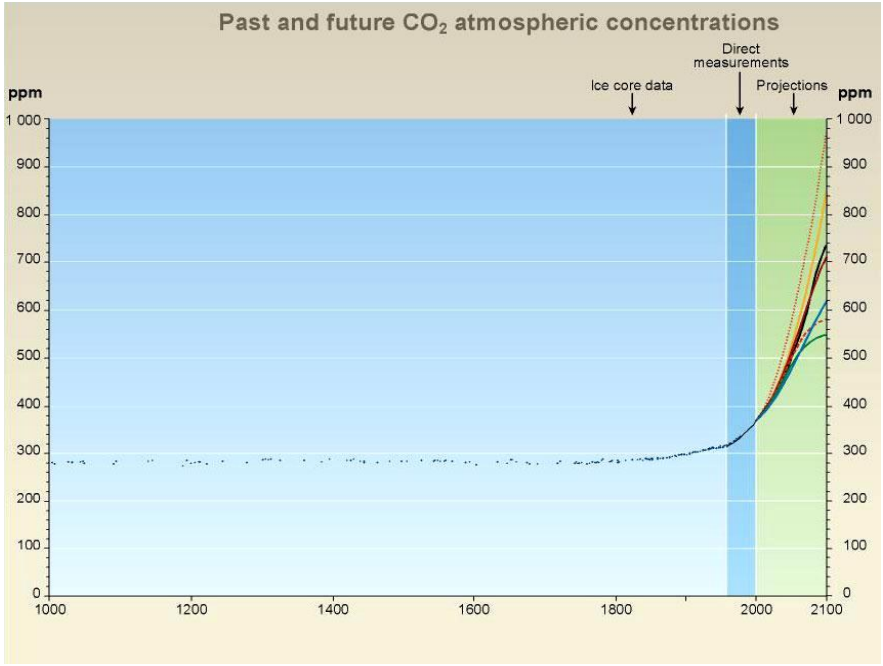


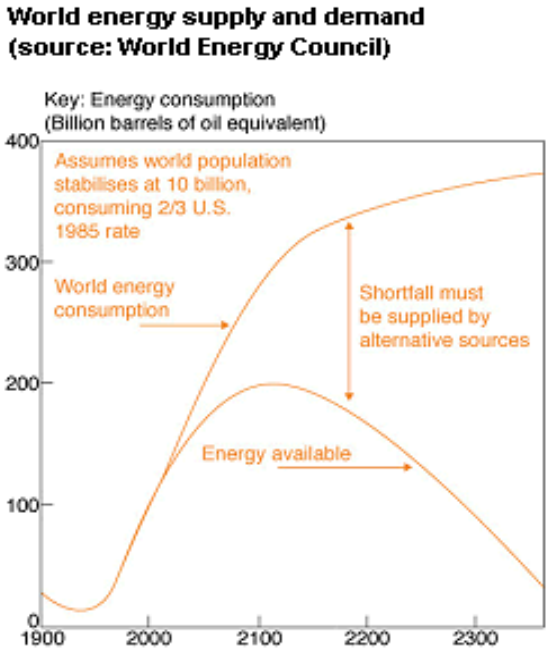
WHY FUSION ENERGY



- Except for few years, the glacier blanc is loosing mass every year at a very fast rate

WHY FUSION ENERGY



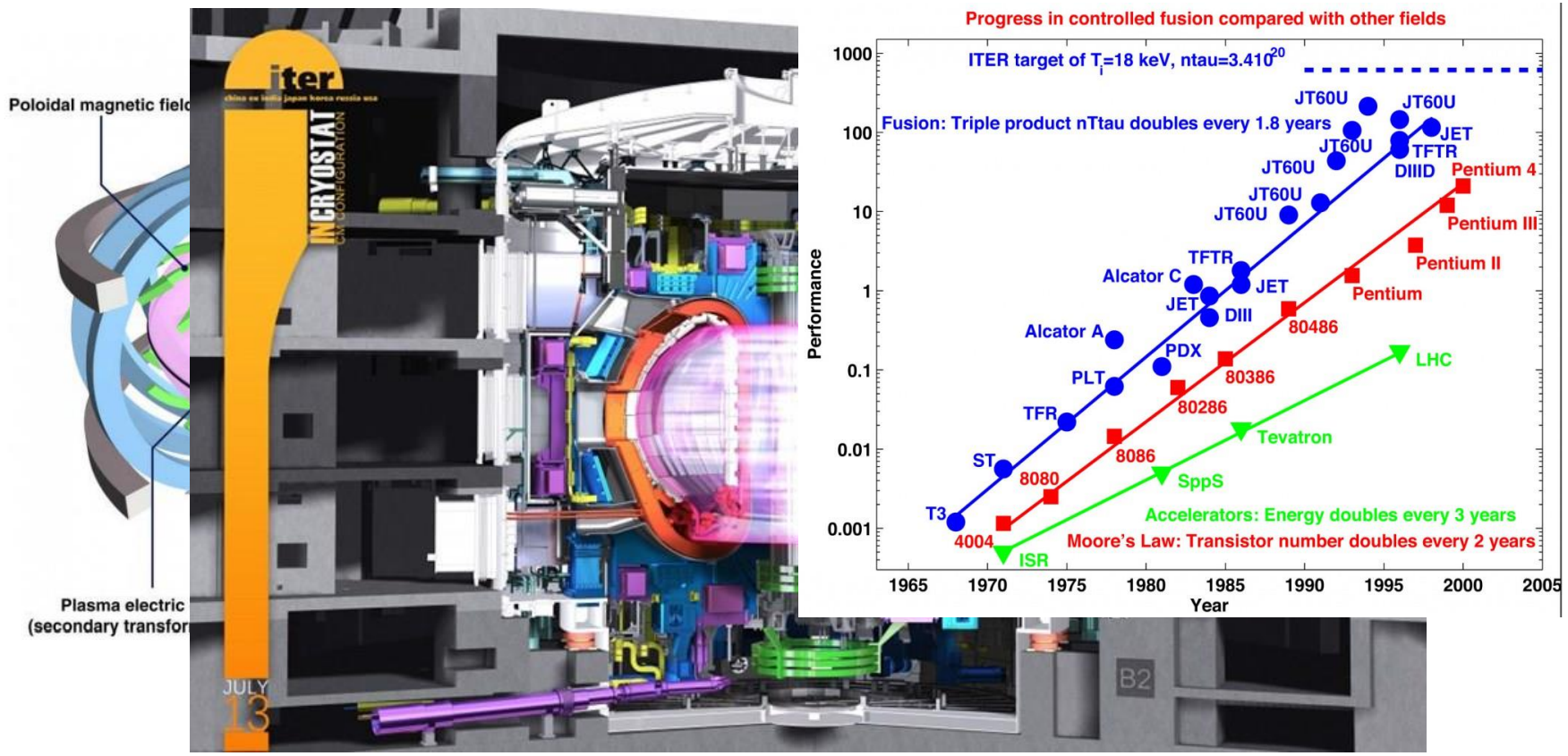


- Global warming is a major concern. It is confirmed by multiple sources
- Sharp increase in CO2 emission in the last century. Fossil fuels are likely to be responsible
- Strong increase of world energy consumption can lead to a shortage of energy available
- Alternative energies, with less CO2 emission, are necessary

Outline

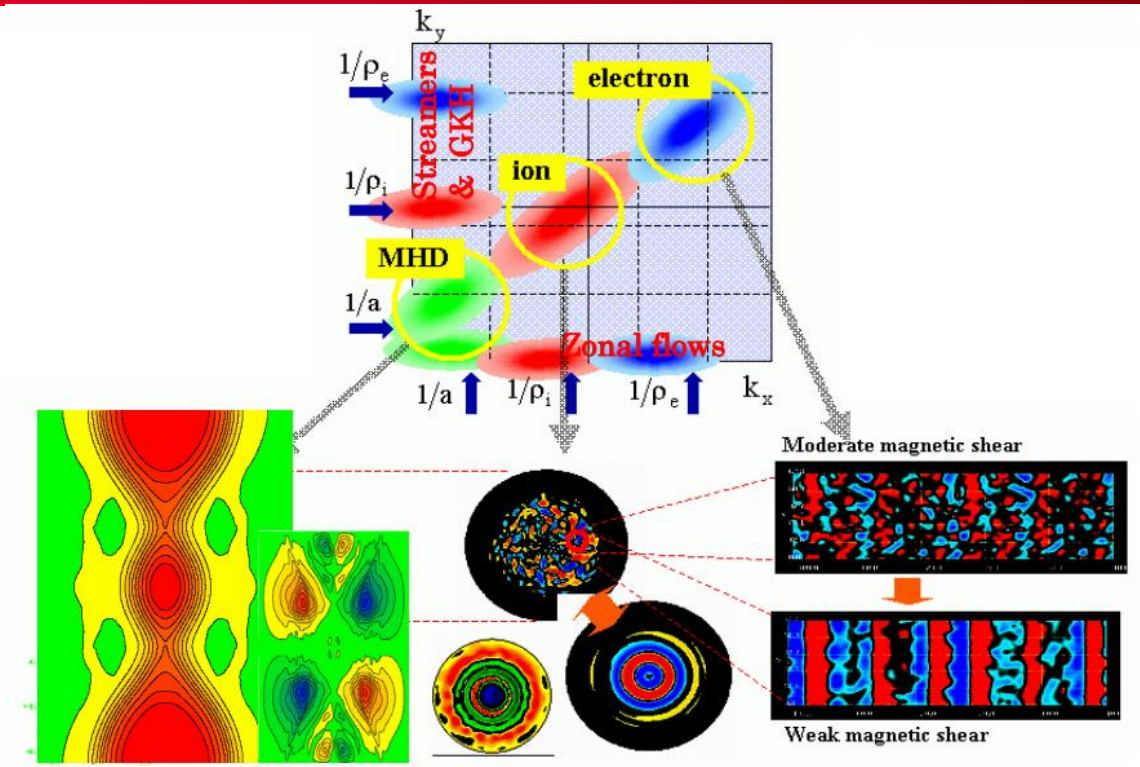
- The tokamak concept
- Plasma instabilities
- Turbulence and control
- The problem of the isotope effect
- Supercomputation on the help
- Conclusions

THE TOKAMAK CONCEPT



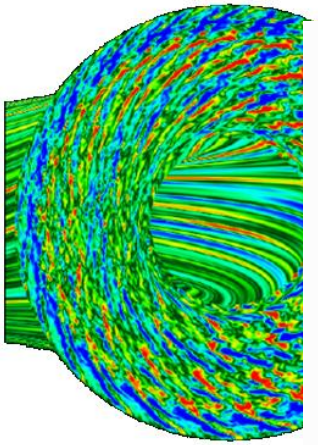
- Plasmas are confined in magnetic cages: Tokamak
- High magnetic fields an currents required in order to fuse D and T
- Progress in plasmas confinement has been significant compared to other fields
- Step forward needed: ITER, being build at Cadarache, should demonstrate fusion energy generation

MAGNETIC CONFINEMENT



- Confinement in tokamaks is a multi-scale problem (in space an time)
- Severe instabilities lead to Magnetohydrodynamics (MHD) and turbulence
- Microturbulence at ion scales $\rho_i/a=\rho^*_i \leq 1$ driven Ion temperature gradient (ITG)
- Microturbuelnce at electrons scales $\rho_e/a= \rho^*_e \leq 1$
- The impact and analysis of each of them is necessarily quite different

TURBULENCE SIMULATION



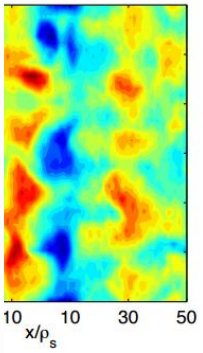
Global Gyrokinetic Simulation of

Turbulence in

ASDEX Upgrade

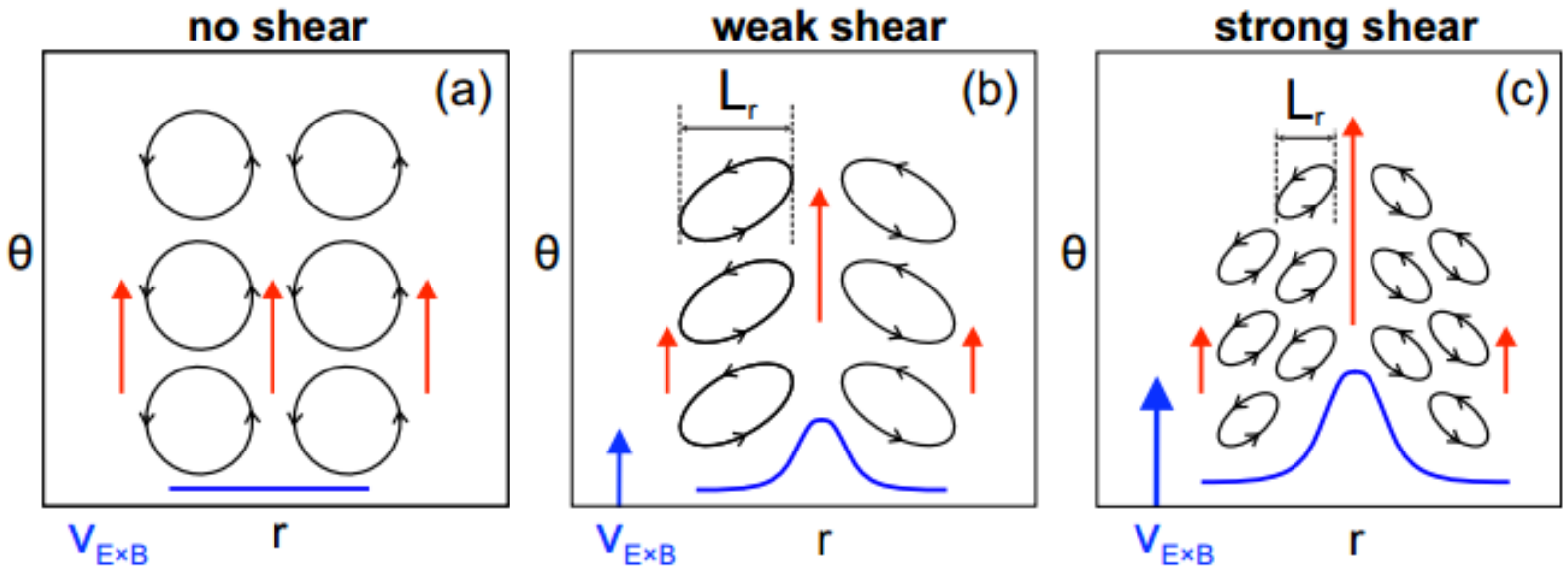
GENE

gene.rzg.mpg.de



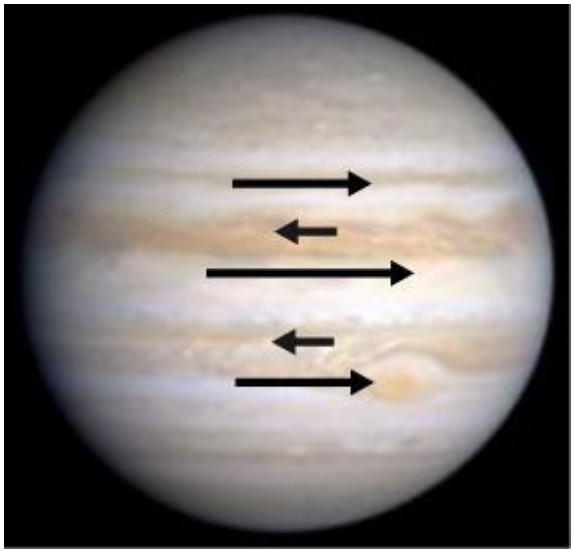
- ITG is the ma
- Turbulence i sion of the Vlasov E ion
- ITG turbulen of plasma eddi

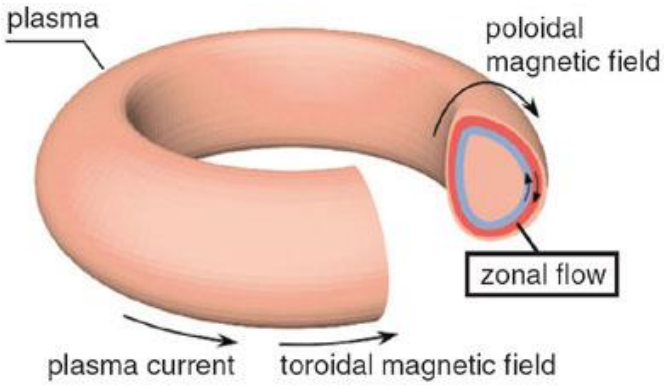
ITG TURBULENCE REDUCTION: EXB FLOW SHEAR

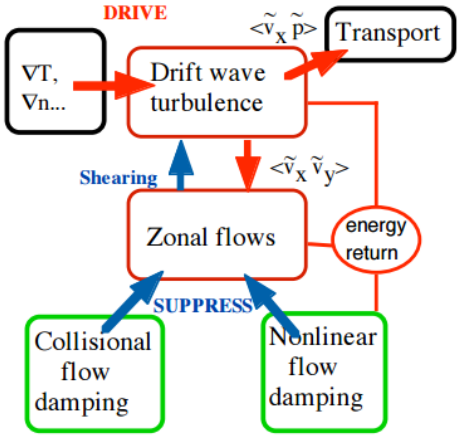


- Turbulence can be partially controlled by some physical mechanisms
- ExB flow shear is a powerful mechanism for eddy decorrelation and turbulence suppression
- This mechanism is meanly generated by rotation shear
- The external torque (mainly from external Heating) is responsible for the rotation

ITG TURBULENCE REDUCTION: ZONAL FLOWS







- Zonal flow are symmetric poloidal and toroidal flows (k_x,k_y=0)
- Unlike ExB mean field flow shear, they are generated by turbulence…
- …in turn they can suppress turbulence by eddy decorrelation
- Feed-back mechanism between turbulence generation and suppression
- What can be expected in DT burning plasmas?

Context: The isotope effect

- The isotope effect is against the general law for heat transport accepted in the fusion community
- Heat transport is thought to follow Gyro-Bohm scaling:

$$x_{GB} = \rho^* x_B$$

Where x_B is the Bohm scaling

$$x_B \sim \frac{k_B T}{eB}$$

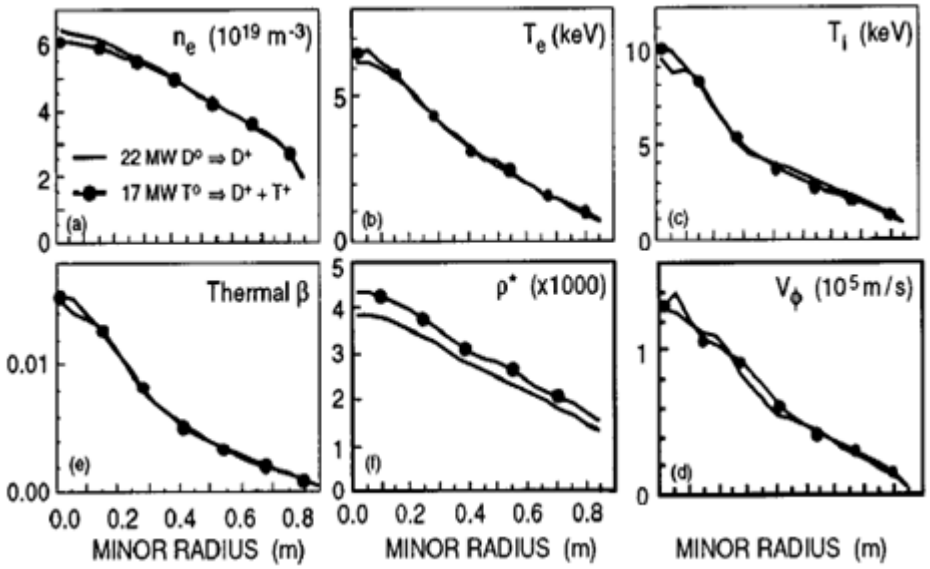
And ρ^* is the normalized gyroradius

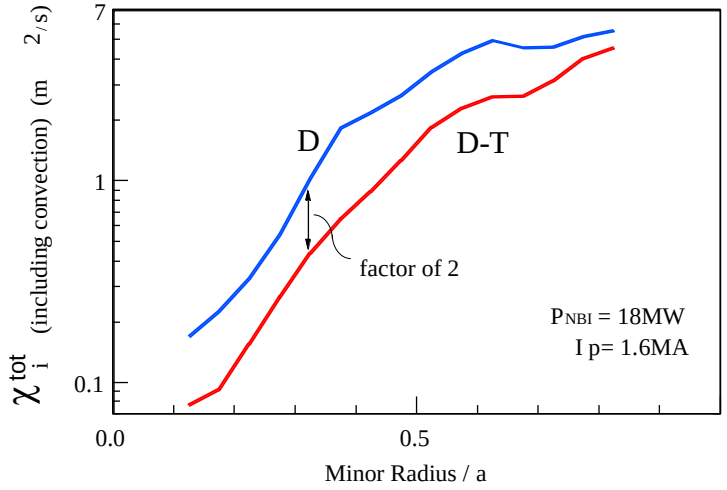
- This leads to a dependence of the diffusivity on the mass of the form:

$$x_{GB} \sim m^{1/2}$$

- Confinement should be worse with higher mass: going from DD to DT plasmas is not efficient? Why then worry about DT plasmas?

Context: DD vs DT



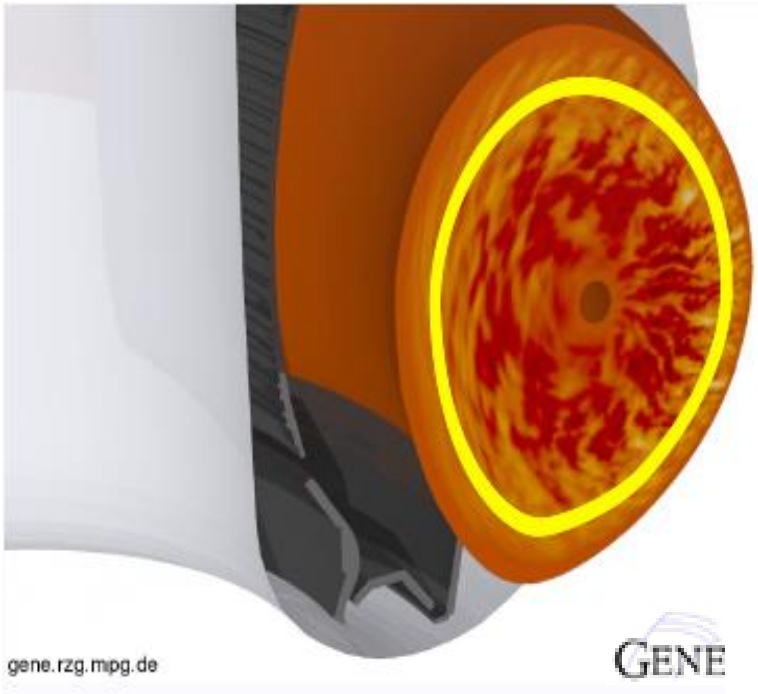


S.D. Scott *et al.*, PoP 1995

- High core β=<P>/B^2 (high core power) plasmas at TFTR obtained in 1997
- Supershot at fixed power, $\tau_E^{thermal} \sim \langle A \rangle^{0.82}$, at lower power $\tau_E^{thermal} \sim \langle A \rangle^{0.5}$
- Confinement is better in DT with respect DD.

No final explanation has been found yet→ Isotope effect
What can be expected in ITER?

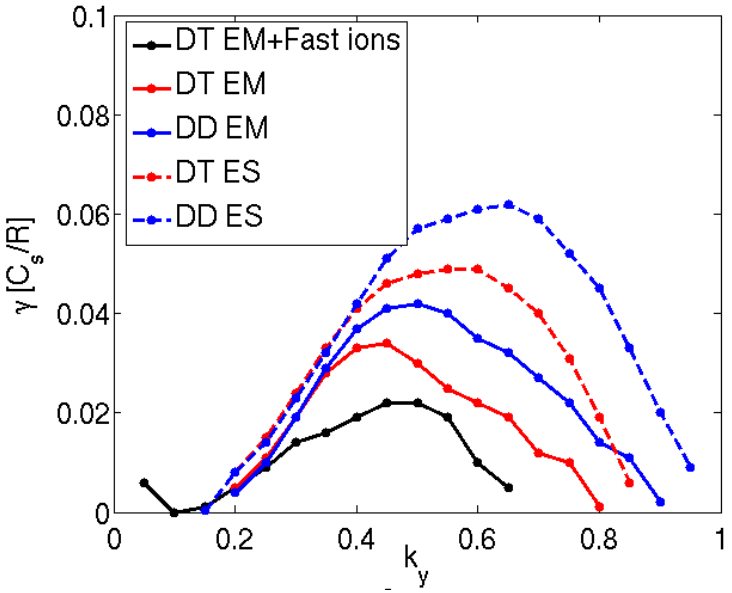
ISOTOPE EFFECT: GYROKINETIC SIMULATIONS IN MARENOSTRUM

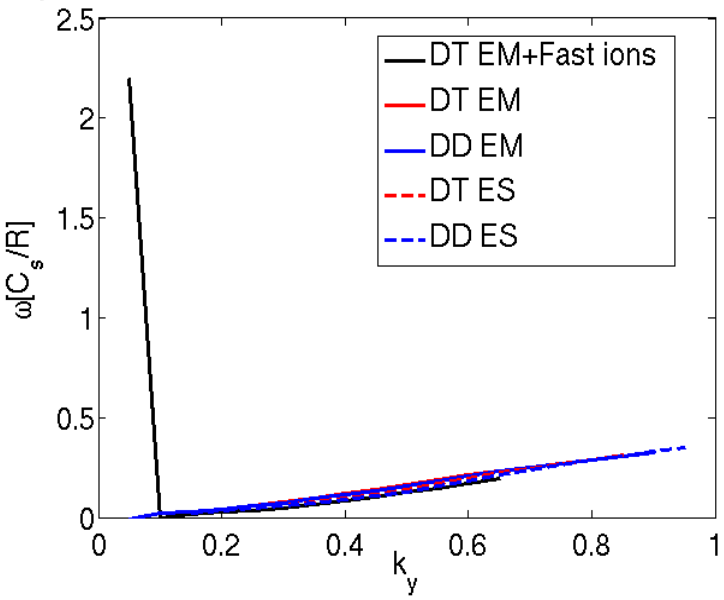


- GENE code [Jenko et al., PoP 2000]: linear and non-linear gyrokinetic analysis of core microinstabilities/microturbulence for ITER high β [K Besseghir *et al* PPFC 2013]
- Kinetic electrons, real boundary geometry from free boundary simulation, electromagnetic effects, up to 7 species (e,D,T, C, He-ash, Fast D (beams), fast He (fusion reactions))
- 50%D-50%T assumed
- Here local (flux tube) approximation taken
- $\delta\Phi$, $\delta B_{\perp}$ and $\delta B_{\parallel}$ fluctuations included
- ExB shear included
- Fast ions approximated by hot Maxwellians

Linear Results: no GB deviation

Electromagnetic (EM: **δΦ , δB$_\perp$ and δB$_\parallel$**) and Electrostatic (ES: **δΦ**) Linear spectra of ITER scenario at $\rho = 0.33$

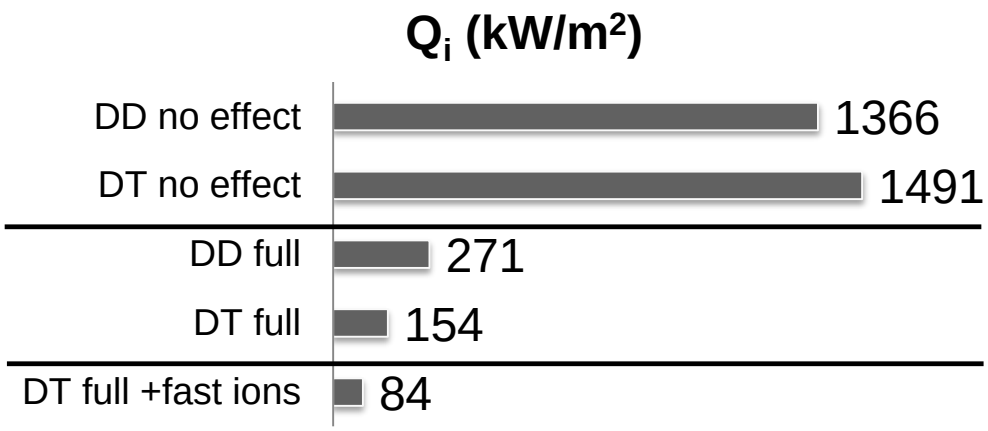




- Unstable modes all in the ITG domain
- High frequency modes appear when including fast ions: [J. Citrin PPCF 2014] [J. Garcia NF15] [H. Doerk 2016]
- $\gamma_{max,DT} \sim \gamma_{max,DD}\sqrt{m_{DD}/m_{DT}}$ (for both EM and ES simulations)
- No deviation from GB scaling in linear analysis

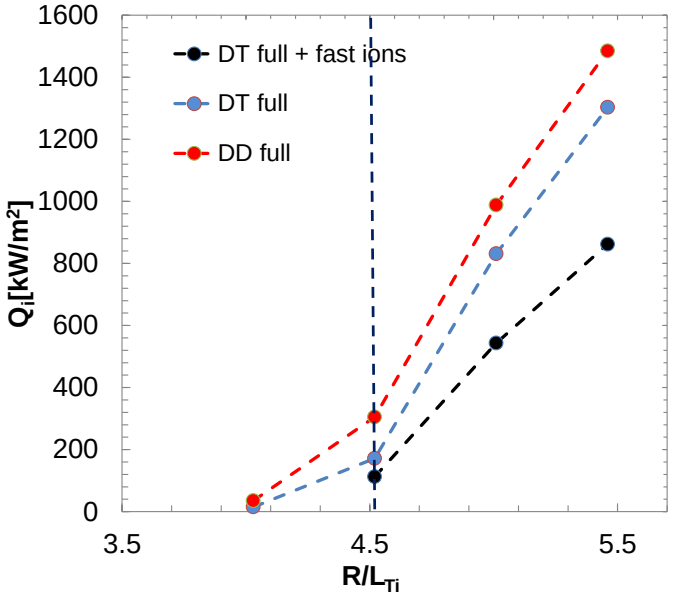
Non-Linear results: GB breaking

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



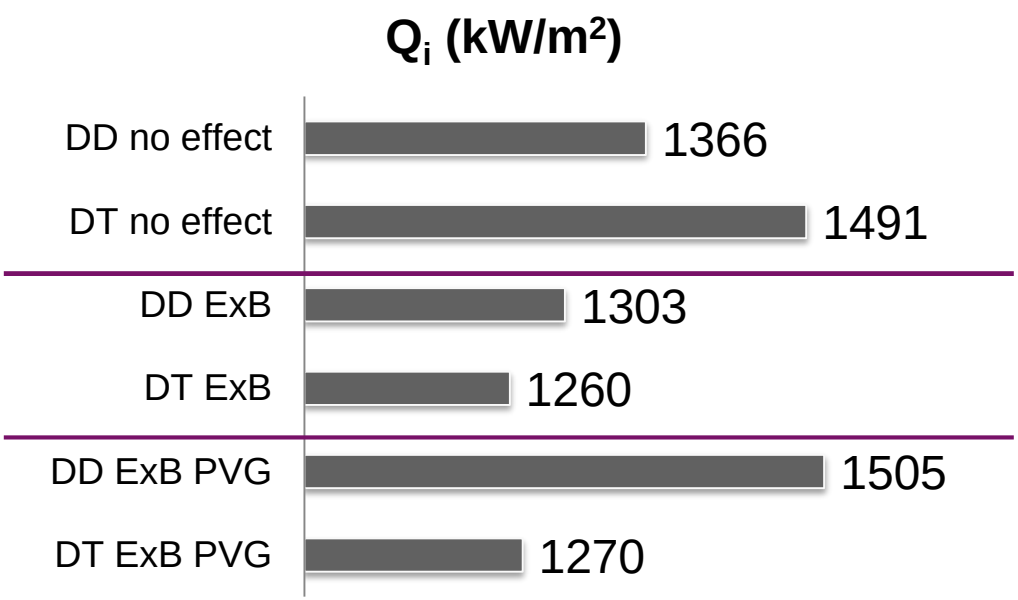
J. Garcia et al., Nucl. Fusion 57 014007 (2017)

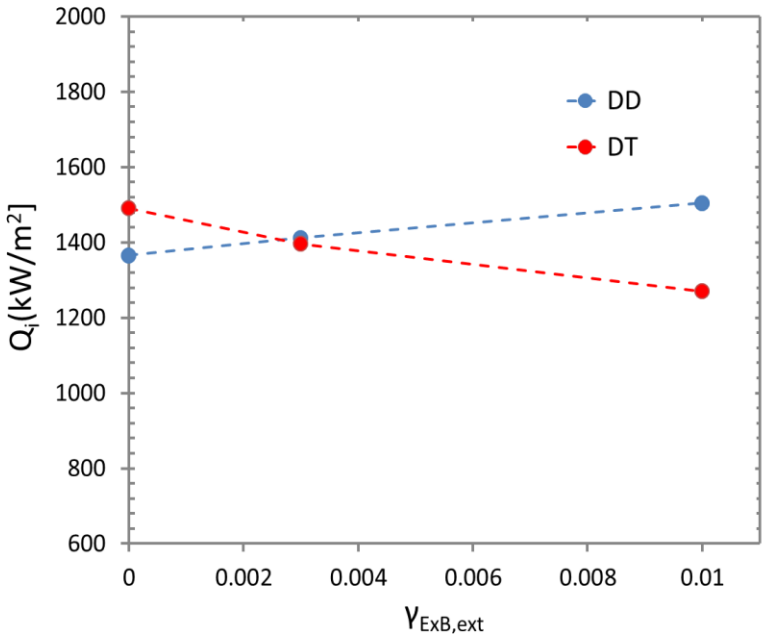
J. Garcia et al., Physics of Plasmas 25, 055902 (2018)



- Non-Linear simulations with electromagnetic (EM) and ExB 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: $Q_{i,DT}/Q_{i,DD} = 1.09 \sim \sqrt{5/4}$

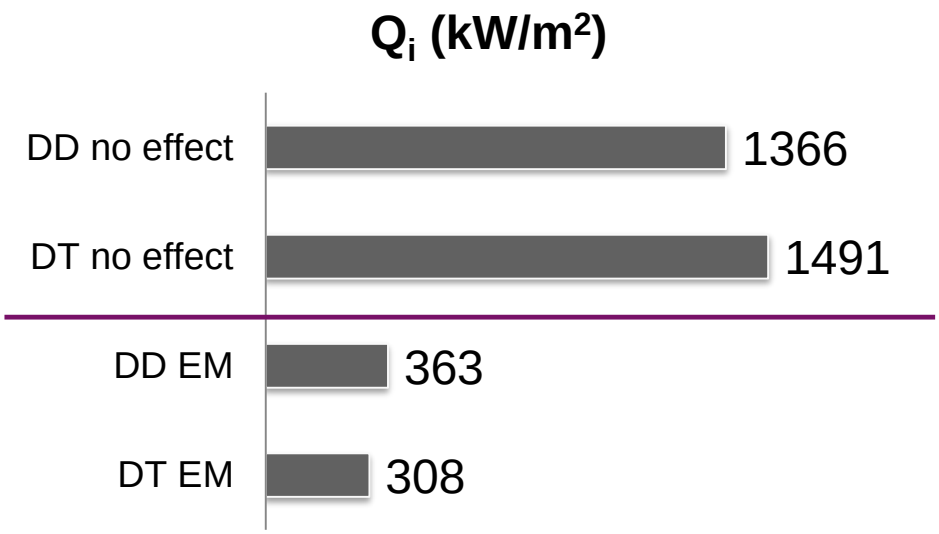
ExB and PVG effects: GB breaking

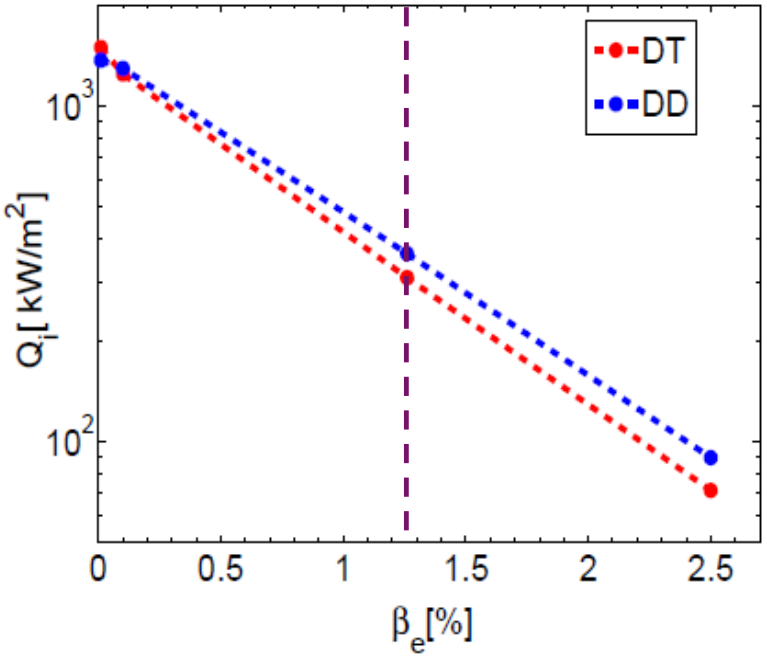




- **GB scaling is broken** : Ion heat flux for DT is up to 15.6% lower than DD
- ExB flow shear impact stronger on DT consistent with naïve explanation: $\gamma_{E\times B}/\gamma_{ITG} \sim {m_i}^{1/2}$ for constant γ_{ExB} [X. Garbet PoP 96]
- Highly accurate ExB shear measurements/predictions required in future experiments

Electromagnetic effects: GB breaking





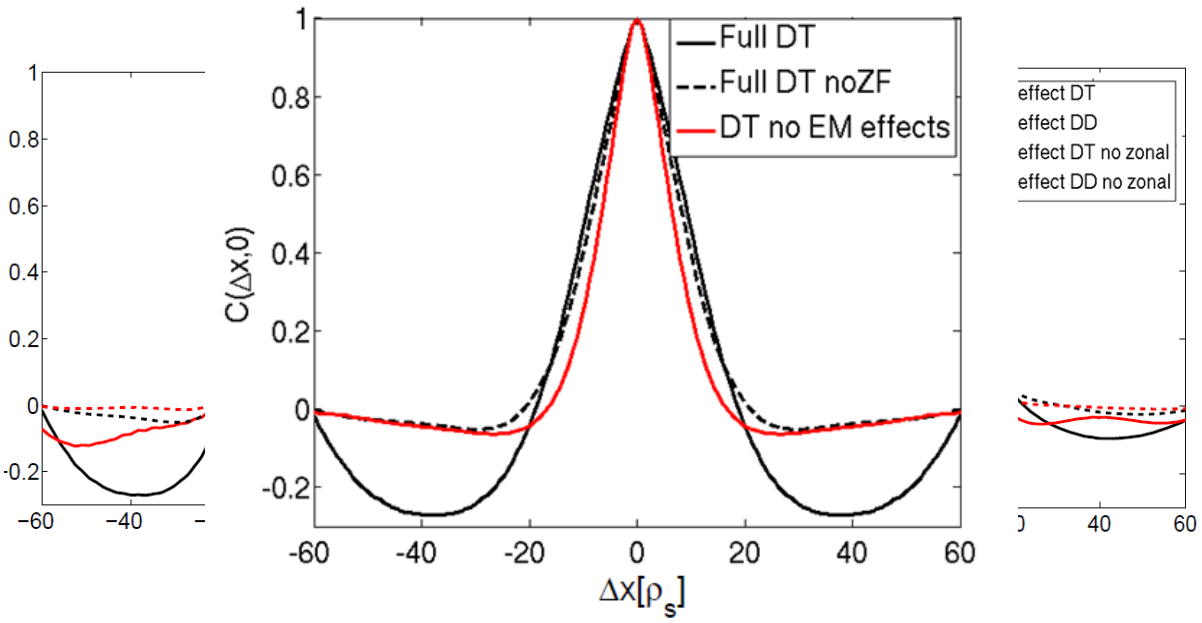
- DD and DT non-linear simulations repeated with only electromagnetic effects
- Electromagnetic effects brake GB scaling. Similar impact than ExB flow shearing
- β_e scan performed: electromagnetic impact is non-linear
- Continuos transition from GB transport to strong deviation by encreasing β_e

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 in the past [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 β interplay



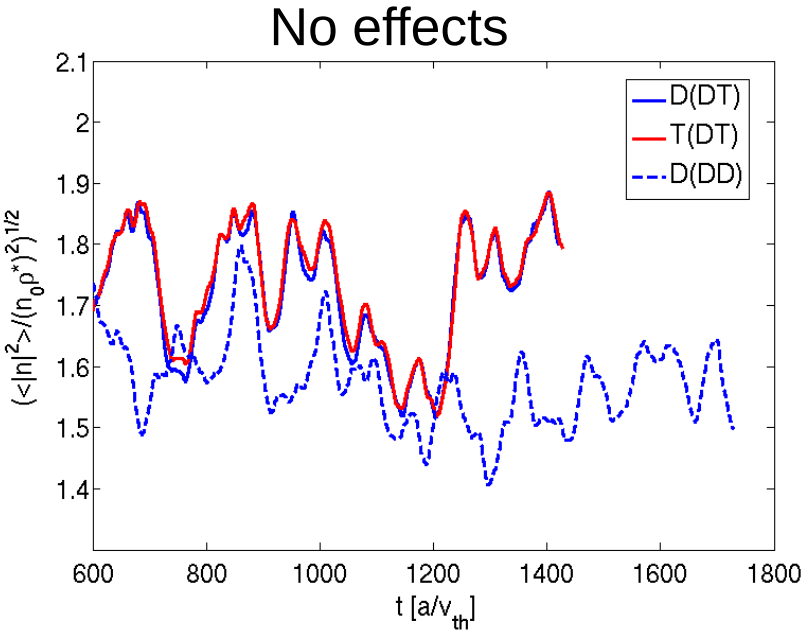
Case	$\lambda_c(\rho_s)$	$Q_i(kW/m^2)$
DT	11.5	154
DD	10.3	271
DT no effect	9.44	1491
DD no effect	8.03	1366

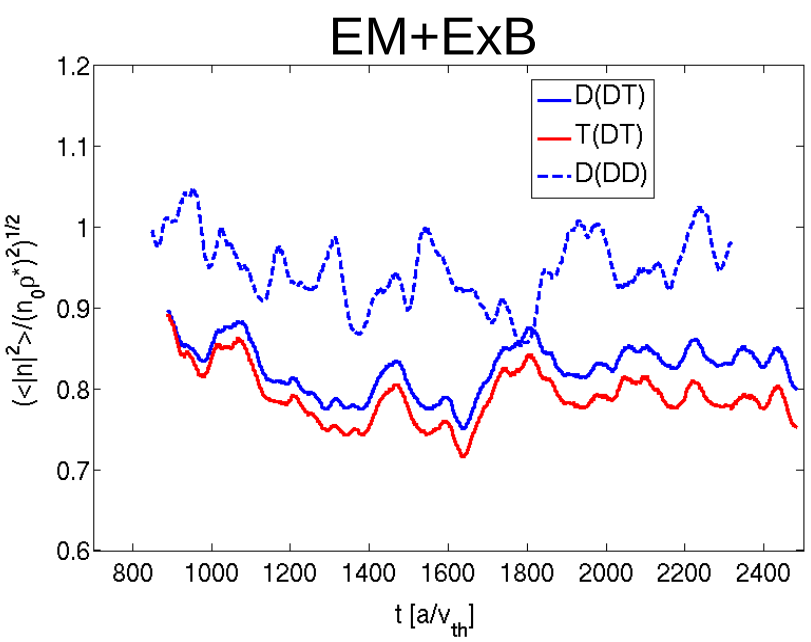
- Electrostatic potential correlation function analyzed. Zonal flow analyzed in post-processing
- Correlation length always follows GB scaling even if there is an isotope effect
- With an isotope effect: anticorrelation region for $\Delta x > 20\rho_s$ generated by zonal flows
- Origin of the zonal flow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

Density fluctuations





- Density fluctuations show the same trend than the heat fluxes
- Different patterns on fluctuations, correlation length and zonal flows when changing the ion mass
- New way of characterizing the isotope effect by means of detailed measurements of turbulence characteristics, rather than comparison of diffusivities by power balance

Conclusions

- ExB flow shear, electromagnetic and fast ions effects found to break GB scaling for DD vs DT plasmas
- The deviation from GB is weak except if all the effects play at the same time
- GB scaling at short scales broken by mesoscale interplay between zonal flows, electromagnetic effects and mass
- Turbulence reduction in ITER by fast ions and isotope effects can be strong
- Supercomputation has provided clues for plasma optimization
- Some of this effects will be tested in future experiments
- Feedback between supercomputation and experiments can solve a long standing problem
- ITER might have a very good energy confinement: good news!