Gyrokinetic turbulence modelling for JT-60SA

Aylwin Iantchenko[1],
M.J. Pueschel[2], Stephan Brunner[1], Stefano Coda[1]

[1] EPFL-SPC, Lausanne, Switzerland

[2] Dutch Institute for Fundamental Energy Research, Eindhoven, The Netherlands

The goal is to study turbulence at JT-60SA

1. JT-60SA is one of the most suitable reactors yet to explore and study ITER and DEMO relevant scenarios

2. We model the turbulent transport in a representative, planned, high-performance, JT-60SA plasma discharge

3. Originally part of a feasibility study of TPCI at JT-60SA

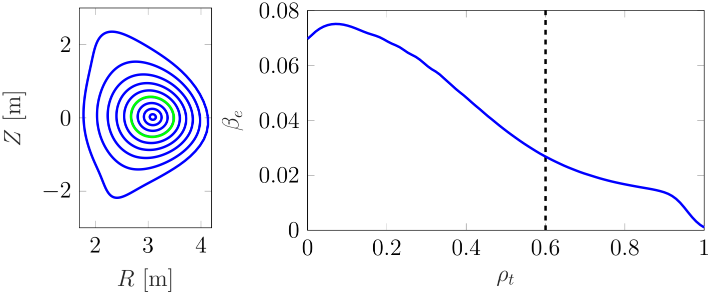
S. Coda, *et al.*, *Nuclear Fusion*, **61** (2021).

Outline

1. The JT-60SA scenario
2. Gyrokinetic simulations
   - I Simulation conditions/parameters
   - II Linear study
   - III Non-linear study
3. Conclusions

We focus on predicted JT-60SA scenario 1

1. Predicted JT-60SA discharge, scenario 1
2. Reduced transport modelling with TOPICS, ACCOME and TOSCA
3. Double-Null with 41 (34 NBH + 7 ECH) MW heating



The GENE code is used to model the turbulence

- GENE solves the gyrokinetic equation
- Both linear and non-linear simulations
- Gradient driven, flux tube model
- Local simulations about a field line, $\rho = \rho_0$
- Field-line following coordinate system
  $(x, y, z) =$(radial, binormal, parallel)

The GENE code is used to model the turbulence

- GENE solves the gyrokinetic equation
- Both linear and non-linear simulations
- Gradient driven, flux tube model
- Local simulations about a field line, $\rho = \rho_0$
- Field-line following coordinate system
  $(x, y, z) =$(radial, binormal, parallel)

Input :

- Experimental MHD equilibrium
- Species information :
  temperature, density, charge and mass
- Electromagnetic and collisional effects

F. Jenko, *et al.*, *Phys. Plasmas*, **7** (2000) 1904.

General settings for GENE simulations

- Local GENE simulations at $\rho_t = 0.6$
- Including 4 kinetic species : e, D, C and fast D ions
- Fast D ions modeled as : Maxwellian with $T_{\text{fast}} > T_{\text{bulk}}$
- Including collisions
- Including $\beta = 2.7\%$ and $\delta B_{\|}$ fluctuations
- $\frac{\gamma}{k_y}\big|_{\text{ion}} > \frac{\gamma}{k_y}\big|_{\text{electron}} \implies$ only including ion scale modes, $\max(k_y \rho_i) \leq 1.5$

Physical input parameters

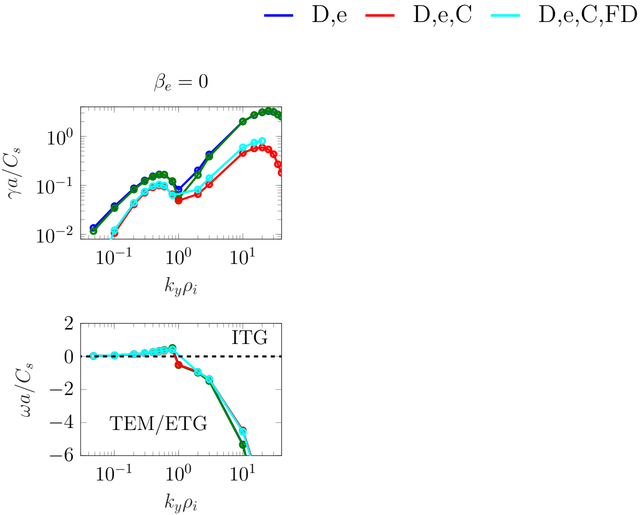
Input at $\rho_t = 0.6$

$n_e[10^{19}\mathrm{m}^{-3}]$	5.87	T_i/T_e	1.0	$a/L_{n,\mathrm{C}}$	0.7224	q_0	1.1571
$T_e[\mathrm{keV}]$	6.27	$a/L_{T,e}$	2.094	$a/L_{n,\mathrm{FD}}$	1.7231	$\hat{s}$	1.5528
n_i/n_e	0.7671	$a/L_{T,i}$	2.093	T_FD/T_e	10.2	$\epsilon = r/R$	0.51
n_C/n_e	0.033	$a/L_{n,e}$	0.7224	Z_eff	2.0	a [m]	1.58
n_FD/n_e	0.033	$a/L_{n,i}$	0.6795	β_e	2.7 %	$B_0[\mathrm{T}]$	2.35

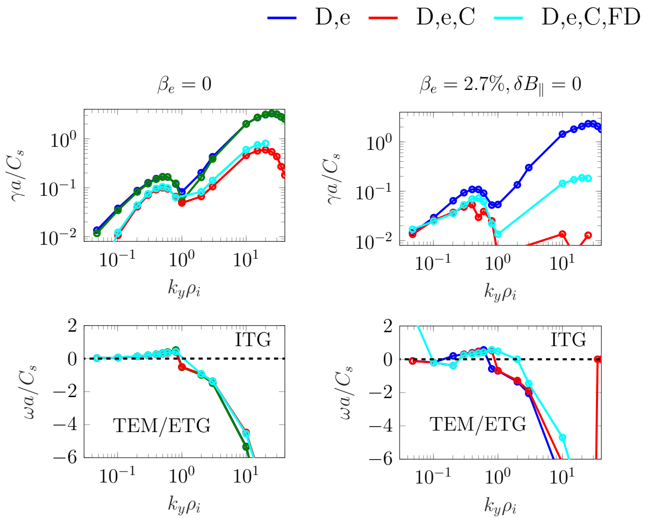
Collisionality $\nu_\mathrm{eff} = 0.1 R n_e Z_\mathrm{eff}/T_e^2 = 0.0925$

Outline

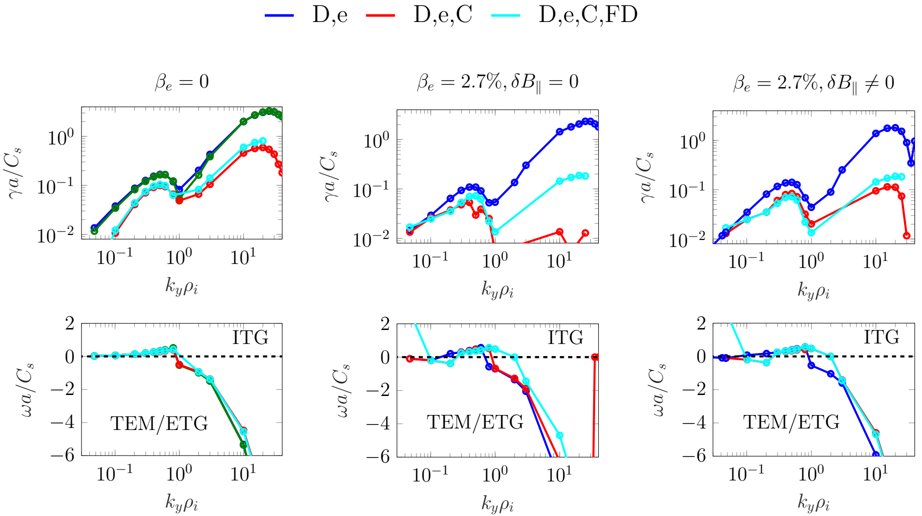
Linear simulations of the most unstable mode



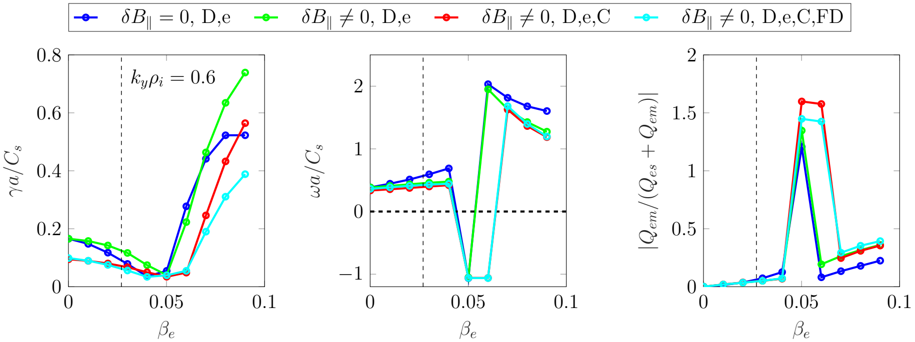
Linear simulations of the most unstable mode



Linear simulations of the most unstable mode



We are below the kinetic Ballooning Mode β_e threshold

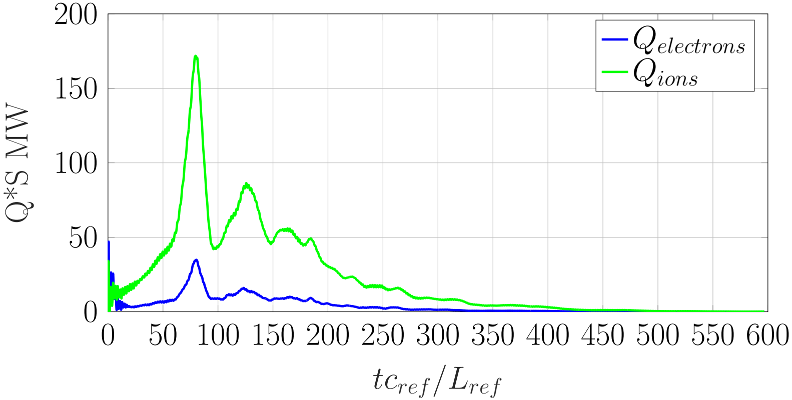


- $\delta B_\parallel$ **destabilising** for $\beta_e < 5\%$ (KBM threshold) and for $\beta_e \geq 8\%$
- Impurities **stabilising** at all β_e
- Fast ions **stabilising** at $\beta_e \geq 7\%$, very little effect at $\beta_e \leq 4\%$

Outline

Simulations at nominal parameters $\implies$ too low heat flux

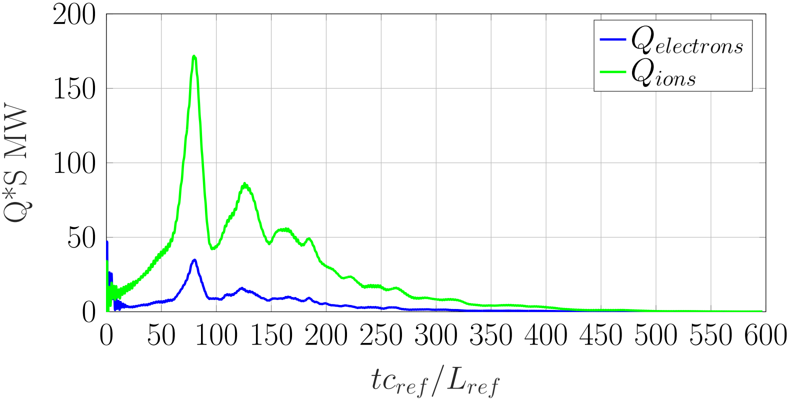
Turbulent heat flux should match injected power of 41 MW...



Total heat flux $< 1\text{MW}$

Simulations at nominal parameters $\Longrightarrow$ too low heat flux

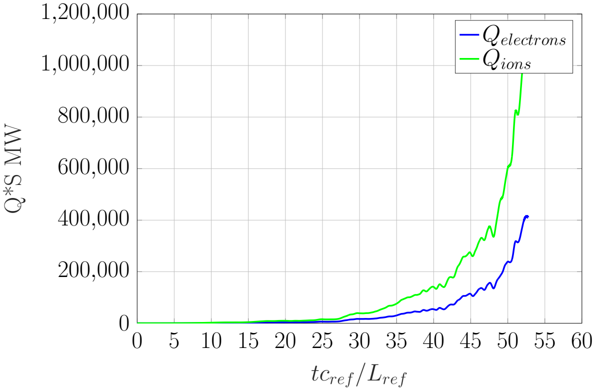
Turbulent heat flux should match injected power of 41 MW...



Total heat flux $< 1\mathrm{MW}$ $\Longrightarrow$ need to increase gradients.

Increasing gradients $\Longrightarrow$ non-saturation

Nominal β_e + gradients increased by more than 10% $\Longrightarrow$
heat fluxes do not saturate due to the **Non-Zonal Transition**



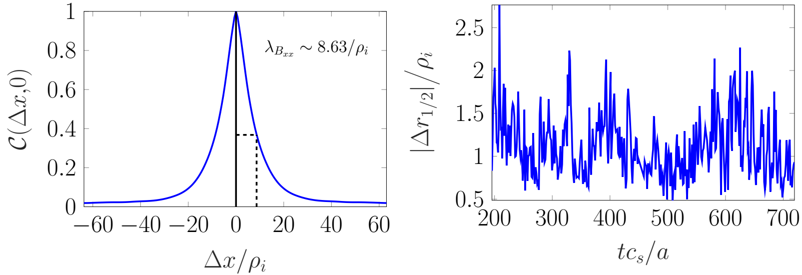
M.J. Pueschel, *et al.*, *PRL*, **110** (2013) 155005.

NTZ characterised by breaking of magnetic flux surfaces

- $\Delta r_{1/2}$: radial displacement of a given field line after half a poloidal turn
- $\lambda_{B_{xx}}$: radial correlation length of the radial magnetic field
- If $\Delta r_{1/2} \geq \lambda_{B_{xx}} \implies$ breaking of magnetic flux-surfaces $\implies$ NZT
- $\Delta r_{1/2}$ scales with β_e

M.J. Pueschel, *et al.*, *Phys. Plasmas*, **20** (2013) 102301.

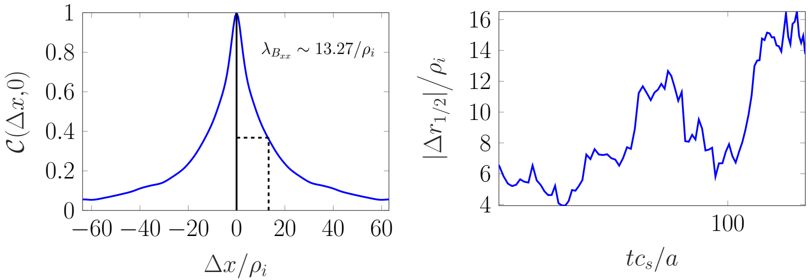
An example without NZT



$\Delta r_{1/2} < \lambda_{B_{xx}} \implies$ No NZT

M.J. Pueschel, *et al.*, *Phys. Plasmas*, **20** (2013) 102301.

Our case : a NZT

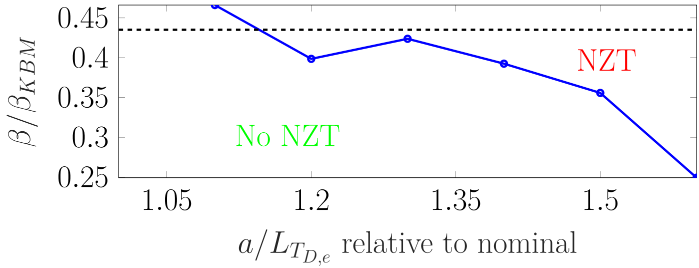


$$\Delta r_{1/2} \geq \lambda_{B_{xx}} \implies \text{NZT}$$

M.J. Pueschel, *et al.*, *Phys. Plasmas*, **20** (2013) 102301.

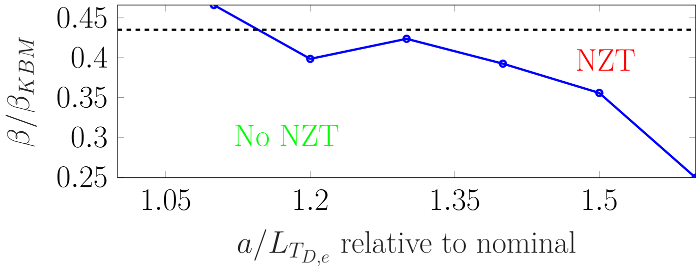
Idenitifying the NZT threshold and how to avoid it ?

Scan in β_e vs. $a/L_{T_{i,e}}$, KBM limit is estimated using $\alpha = 0.6\hat{s}$



Idenitifying the NZT threshold and how to avoid it ?

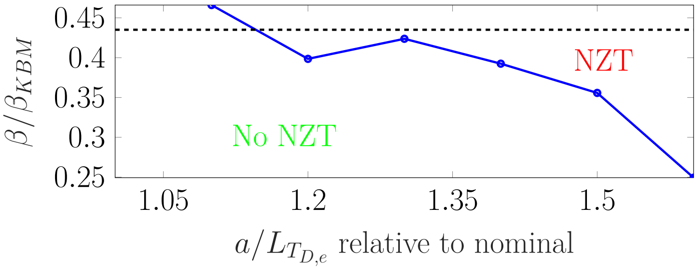
Scan in β_e vs. $a/L_{T_{i,e}}$, KBM limit is estimated using $\alpha = 0.6\hat{s}$



NZT $\Longrightarrow$ near-infinitely stiff transport

Idenitifying the NZT threshold and how to avoid it ?

Scan in β_e vs. $a/L_{T_{i,e}}$, KBM limit is estimated using $\alpha = 0.6\hat{s}$



NZT $\implies$ near-infinitely stiff transport

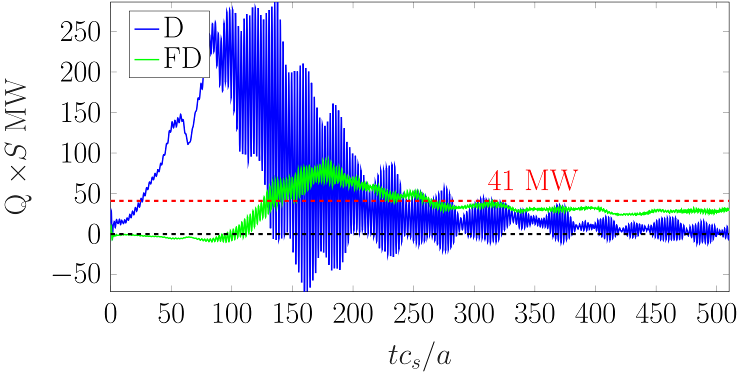
So far only 2 species (D,e) $\implies$ include impurities and fast ions

EPFL

Fast frequency mode is driven by fast ions

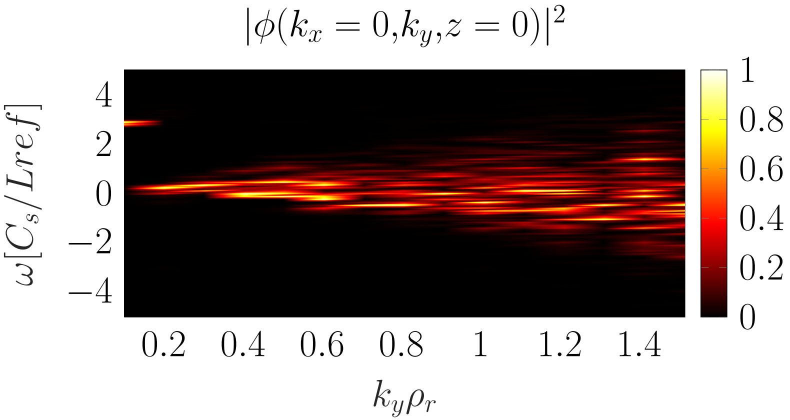
Including fast ions $\implies$ heat flux is dominated by a **high-frequency oscillation**

10% larger $a/L_{n_{D,e}}$ and $a/L_{T_{D,e}}$



Fast frequency mode : at the smallest considered $k_y \rho_i = 0.1$

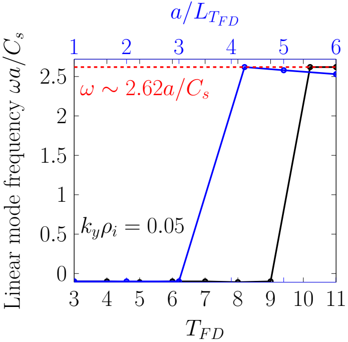
Computing the Fourier transform of $\Phi(t, k_x = 0, k_y, z = 0)$



High frequency mode at $k_y \rho_i = 0.1$

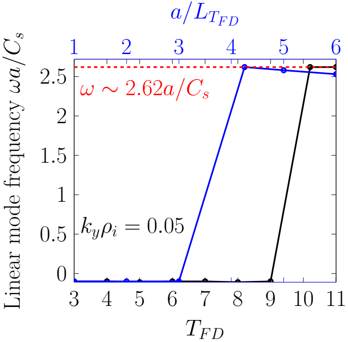
Fast frequency mode : characterising with linear simulations

Frequency of most unstable mode at $k_y\rho_i = 0.05$



Fast frequency mode : characterising with linear simulations

Frequency of most unstable mode at $k_y \rho_i = 0.05$



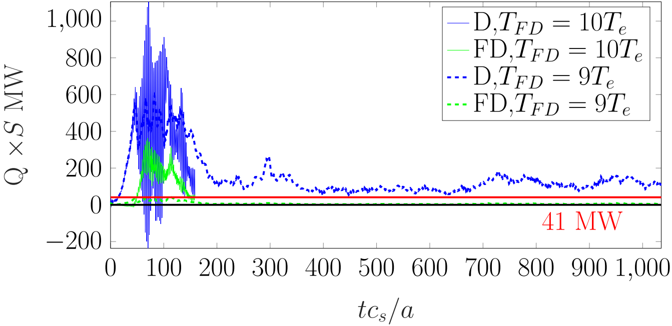
Fast frequency mode is :

1. **Subdominant** in linear simulations for $k_y \rho_i > 0.08$
2. **Not triggered** by non-linear profile variations in $\mathrm{d}T_{\text{fast}}/\mathrm{d}x$ or $\mathrm{d}n_{\text{fast}}/\mathrm{d}x$

Fast frequency mode : suppressed in non-linear simulations

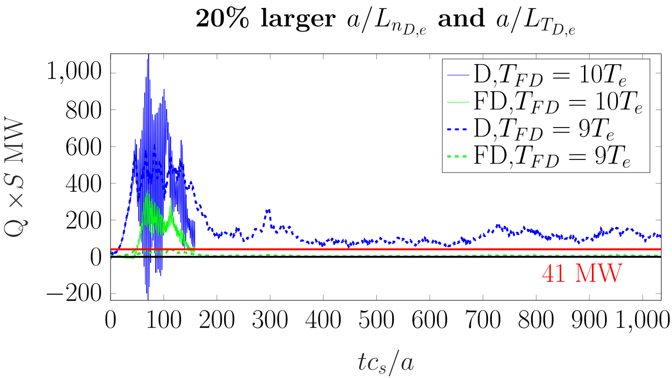
Reducing T_{FD} from $10\,T_e$ to $9\,T_e$ $\Longrightarrow$ no more high frequency oscillation

20% larger $a/L_{n_{D,e}}$ and $a/L_{T_{D,e}}$



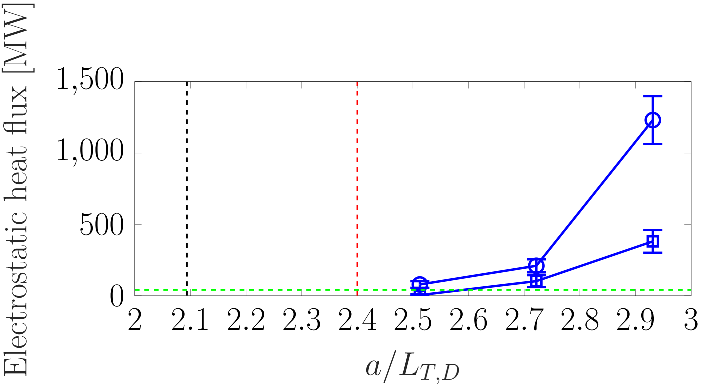
Fast frequency mode : suppressed in non-linear simulations

Reducing T_{FD} from $10\,T_e$ to $9\,T_e \implies$ no more high frequency oscillation



Efficiency of NBH very sensitive to fast ion parameters

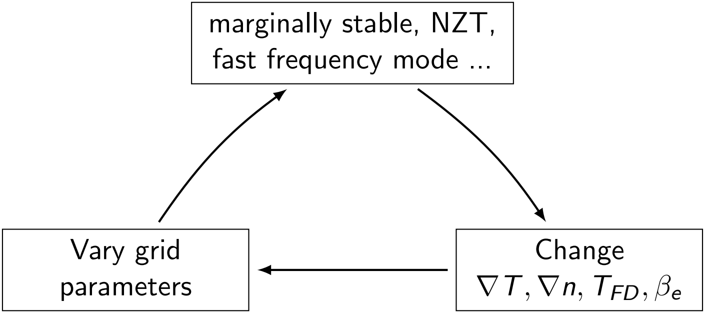
Estimate of the non-linear critical gradient



Nominal parameters very close to the non-linear critical gradient

Resolution study is still ongoing

Iterative procedure :



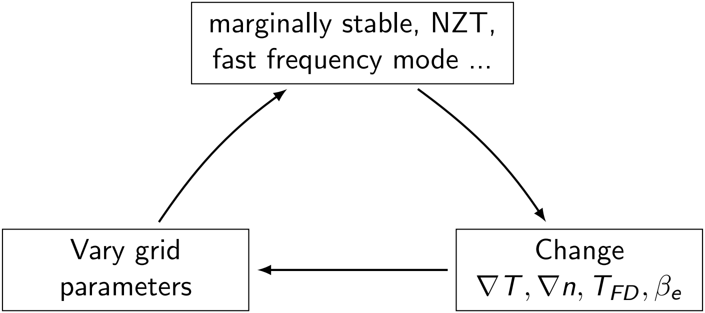
marginally stable, NZT, fast frequency mode ...

Change $\nabla T, \nabla n, T_{FD}, \beta_e$

Vary grid parameters

Resolution study is still ongoing

Iterative procedure :



marginally stable, NZT, fast frequency mode ...

Change $\nabla T, \nabla n, T_{FD}, \beta_e$

Vary grid parameters

Current strategy :
resolution study for a high gradient ($\gg$ nominal) case.

Conclusions

- Gyrokinetic GENE simulations to predict turbulent transport in a JT-60SA scenario.
- Linear simulations $\Longrightarrow$ range of ES and EM modes
- Not simulating experimental data $\Longrightarrow$ difficulties :
  1. Nominal parameters $\Longrightarrow$ too low heat flux
  2. Nominal parameters very close to the non-linear critical gradient
  3. Close to the NZT threshold $\Longrightarrow$ near-infinitely stiff transport
  4. Fast ion driven high frequency mode
  5. Resolution study still ongoing

Conclusions

- Gyrokinetic GENE simulations to predict turbulent transport in a JT-60SA scenario.
- Linear simulations $\implies$ range of ES and EM modes
- Not simulating experimental data $\implies$ difficulties :
  1. Nominal parameters $\implies$ too low heat flux
  2. Nominal parameters very close to the non-linear critical gradient
  3. Close to the NZT threshold $\implies$ near-infinitely stiff transport
  4. Fast ion driven high frequency mode
  5. Resolution study still ongoing

Uncovering new problems with turbulence modelling in reactor relevant regimes $\implies$ template for high β simulations on JT-60SA and ITER

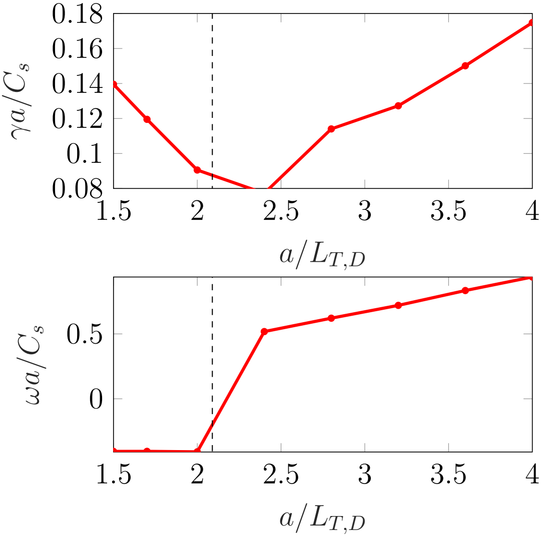
Conclusions

- Gyrokinetic GENE simulations to predict turbulent transport in a JT-60SA scenario.
- Linear simulations $\Longrightarrow$ range of ES and EM modes
- Not simulating experimental data $\Longrightarrow$ difficulties :
  1. Nominal parameters $\Longrightarrow$ too low heat flux
  2. Nominal parameters very close to the non-linear critical gradient
  3. Close to the NZT threshold $\Longrightarrow$ near-infinitely stiff transport
  4. Fast ion driven high frequency mode
  5. Resolution study still ongoing

Uncovering new problems with turbulence modelling in reactor relevant regimes $\Longrightarrow$ template for high β simulations on JT-60SA and ITER

Thank you for your attention !

Estimate of the linear critical gradient



Estimate of the linear critical gradient

Most unstable mode, $k_y \rho_i \sim 0.8$