Simulation of fully global electromagnetic turbulence in the stellarator W7-X

Y. Narbutt, A. Mishchenko, K. Aleynikova, A. Zocco,
R. Kleiber and C. Nührenberg

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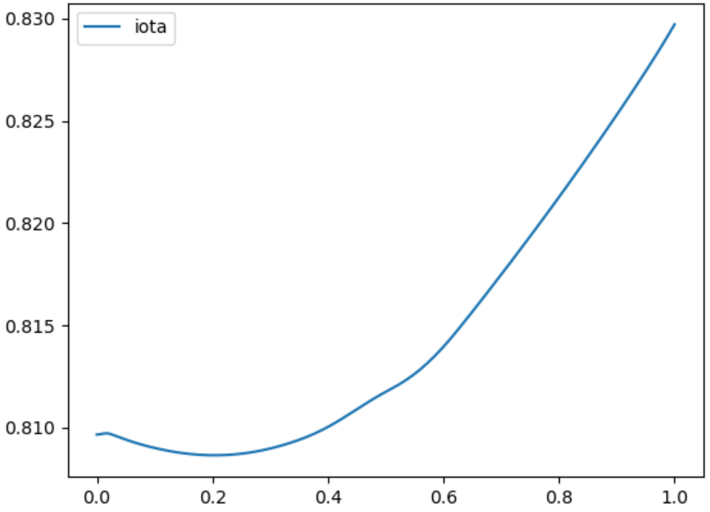
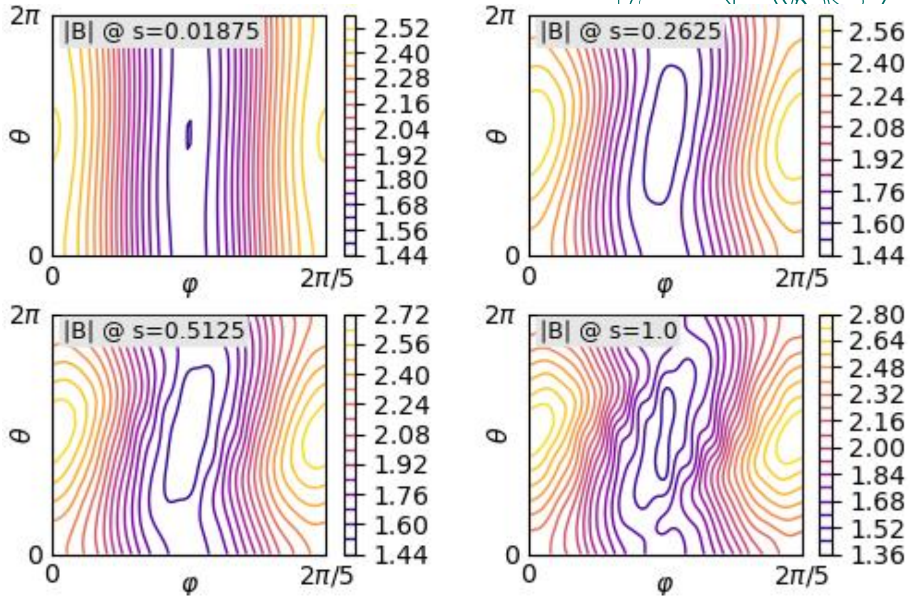
What is the goal:

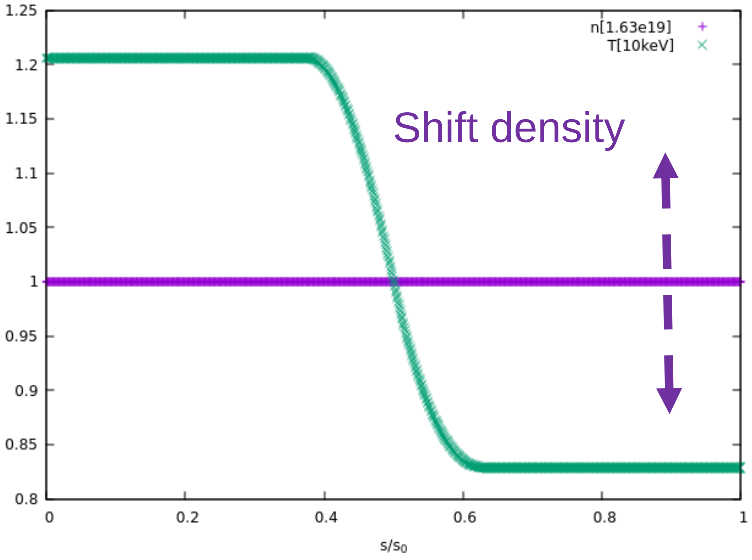
- **Current situation:**
  - With neoclassical optimization turbulence becomes limiting performance factor in stellarators
  - Few data on high-β turbulence in stellarators
  - Global codes necessary but new and demanding tool
- **Simulate W7-X UFM configuration**
  - Interested in KBMs and general high-β behaviour in W7-X
  - Scan beta (EM, linear)
  - Observe γ and ω
  - Other observations?
  - Figure out numerical demand
- **Turbulence simulation to observe particle and heat fluxes**

Profiles & configuration



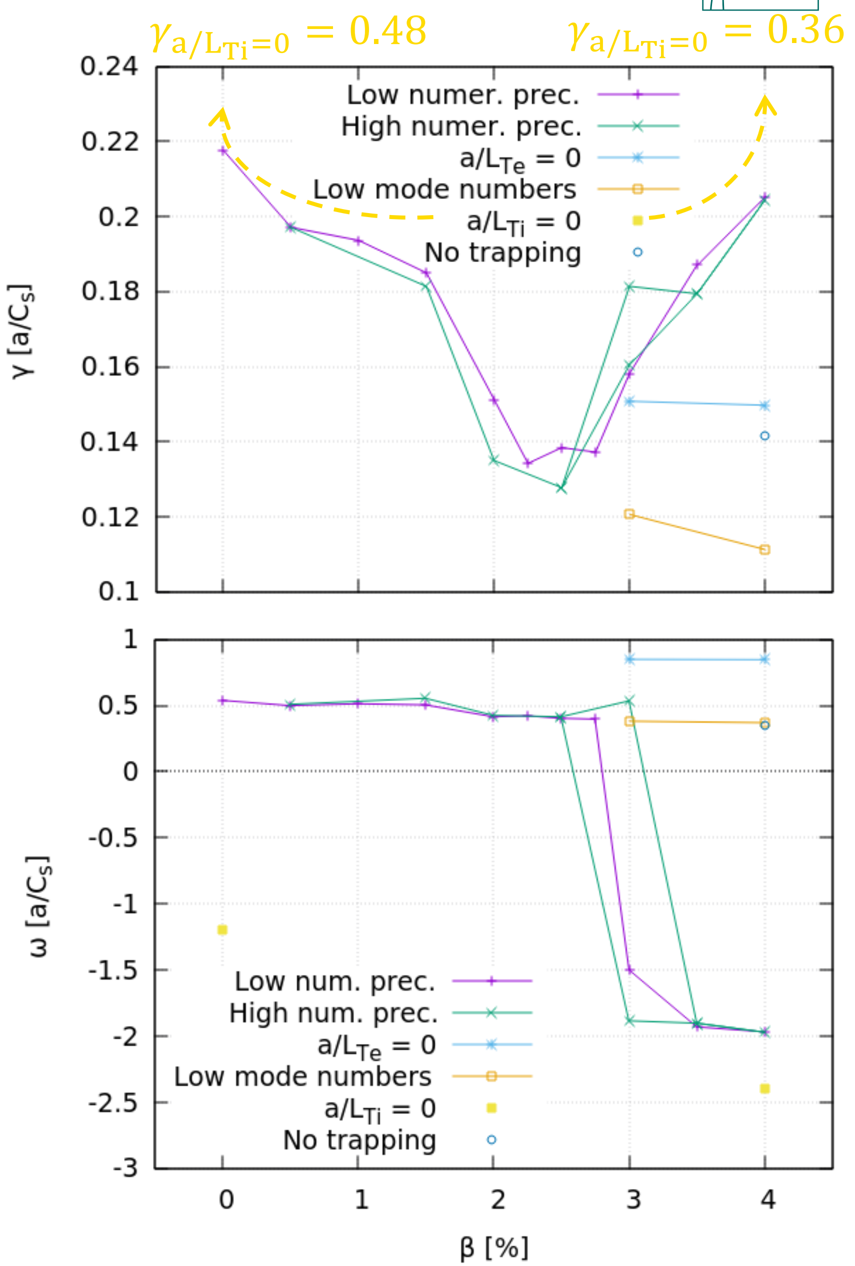


- **W7X-UFM**
  - Low shear
  - QI configuration (not perfect)
- **Profiles**
  - $T_e = T_i$, and finite $\nabla T_{e,i}$: $a/L_T = -4.2$
  - Flat density
  - Scan β via increase in density
- **Simulation with Euterpe:**
  - Global, PIC, δf-code
  - Linear, electromagnetic($\delta B_\parallel$ & $\delta B_\perp$), collisionless
  - Fully gyro-kinetic, but increased mass ratio $m_e/m_i = 0.005$
  - Scale in simulation is $k_\perp \rho_i \sim 0.5 - 1.1$



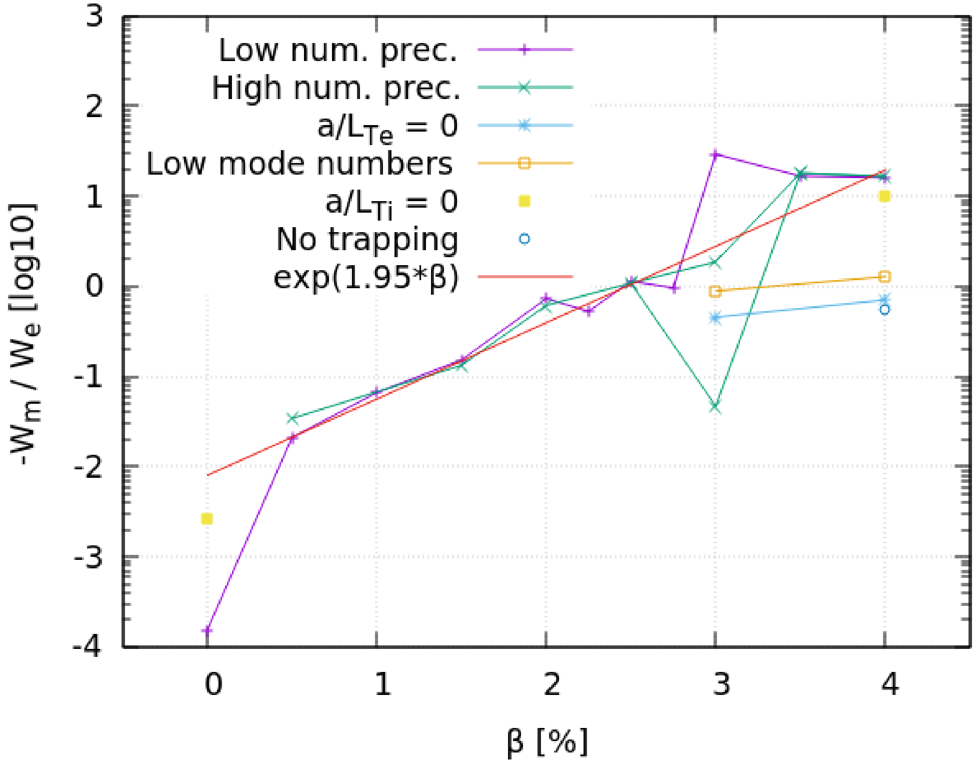
Physics

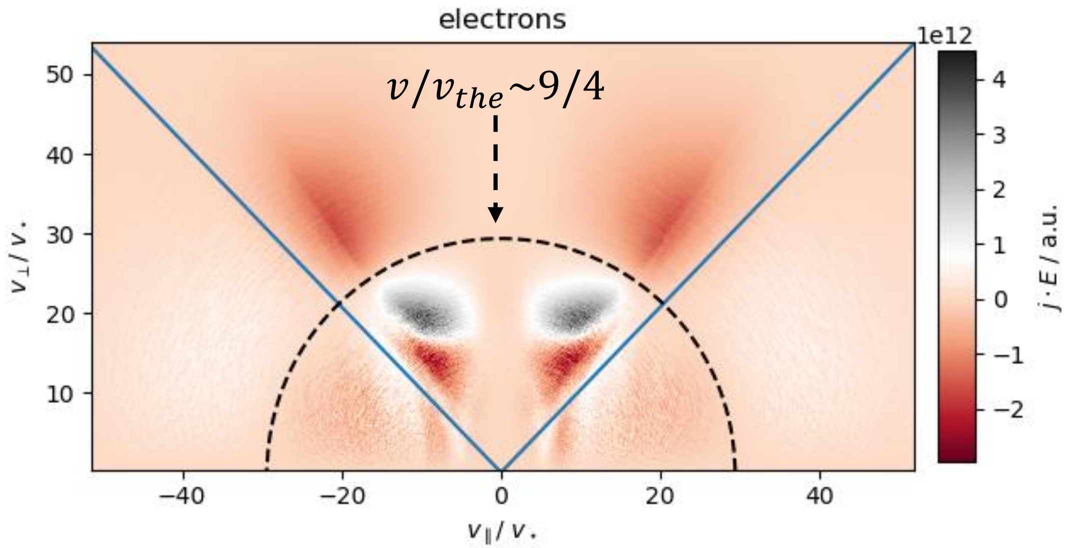
- **As β increases:**
  - Stabilization of ITG until $\beta \approx 2.5\% - 3.0\% = \beta_{crit}$
  - Destabilization of electron rotating mode for $\beta > \beta_{crit}$
- **Furthermore:**
  - Transition back to ITG for :
    1. $a_0/L_{Te} = 0$ and
    2. No particle trapping via $F_{mirror} = 0$
  - Simulation of lower mode numbers ($k_\perp \rho_i \sim 0.0 - 0.5$) => KBM
  - Strong destabilization for $a_0/L_{Ti} = 0$ at $\beta = 0\%$



Energy and Phasespace

- **Track ratio of perturbed magnetic to electric energy**
  $\mathbf{R} = \frac{W_m}{W_e} = \int J_\parallel A_\parallel dV / \int \rho\phi dV$
  - R increases with β
  - Transition to electron rotating mode when R > 1
  - For $a_0/L_{Te} = 0$, no trapping and low modes numbers R decreases below 1 coincides with transition to ITG/KBM
  - It seems that $R \propto \exp(1.95\beta)$
- **Phase space at $\beta = 4\%$:**
  - Ions only show Landau damping and no trapping effects
  - Strong trapped electron drive but Alfvén resonance for no trapping



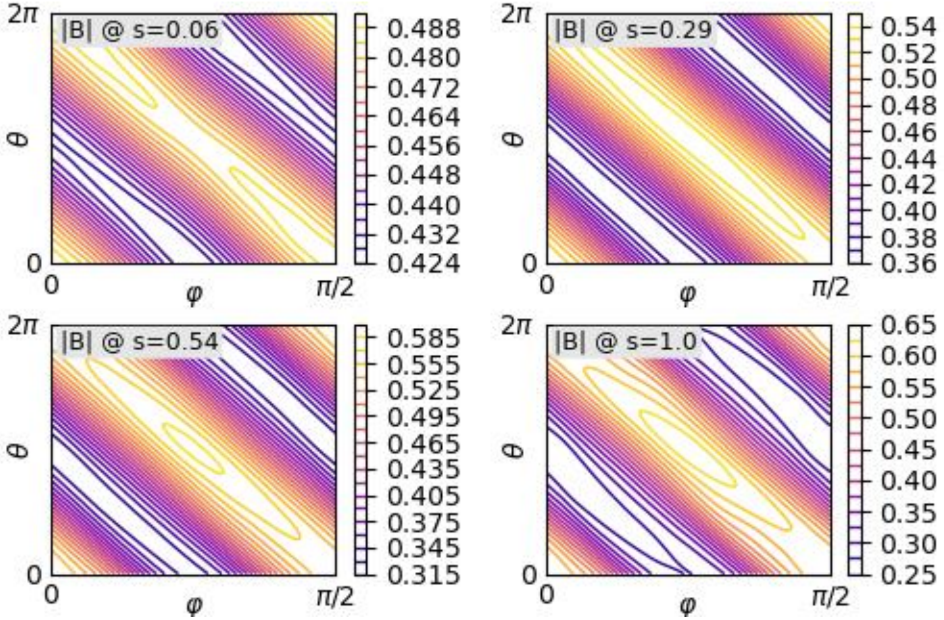


Physics summary

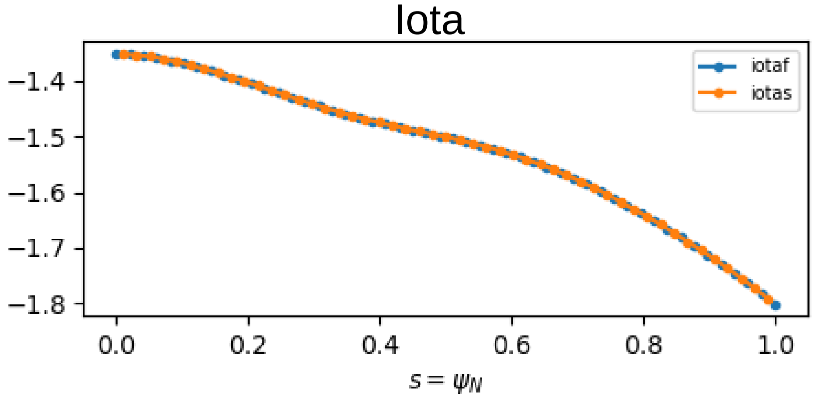
- **Stabilization of ITG with increasing β for $\beta < \beta_{crit}$**
- **For $\beta > \beta_{crit}$:**
  - Transition to electron rotating mode
  - Further destabilization with β
  - Mode becomes more magnetic than electrostatic at β_{crit}
  - Strong drive by trapped electrons
  - Electron rotating mode vanishes for: no trapping, $a/L_{Te} = 0$, low mode numbers ($k_\perp \rho_i \lessapprox 0.5$, KBM)
- **Simulations with Gene (fluxtube, K. Aleynikova) of case show same physics**
- **Conclusion: ∇T_e-driven electromagnetic TEM**
  - Unclear parity: ballooning vs tearing

HSK Turbulence

- **HSK configuration [Roberg-Clark, Xanthopoulos, Plunk - 2022]**
  - Optimized quasi-helical stellarator
  - Focus on high $(a/L_T)|_{crit}$ => decreased ITG heat flux, less MHD stable
  - $N = 4$; $A = 4.1$; $a_0 = 0.95m$; $B_0 = 1T$

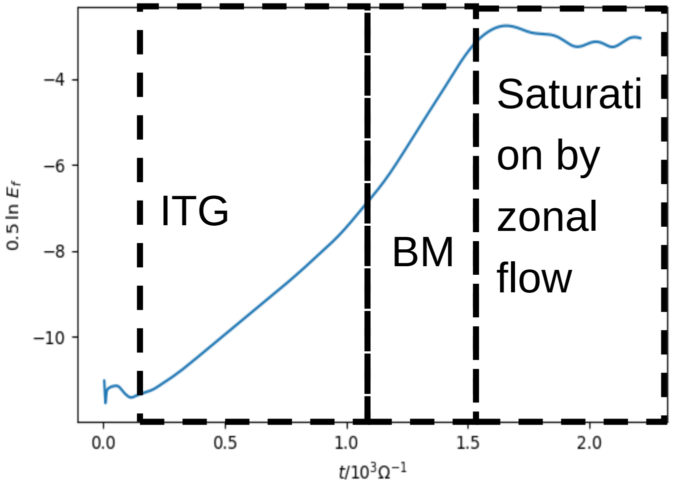


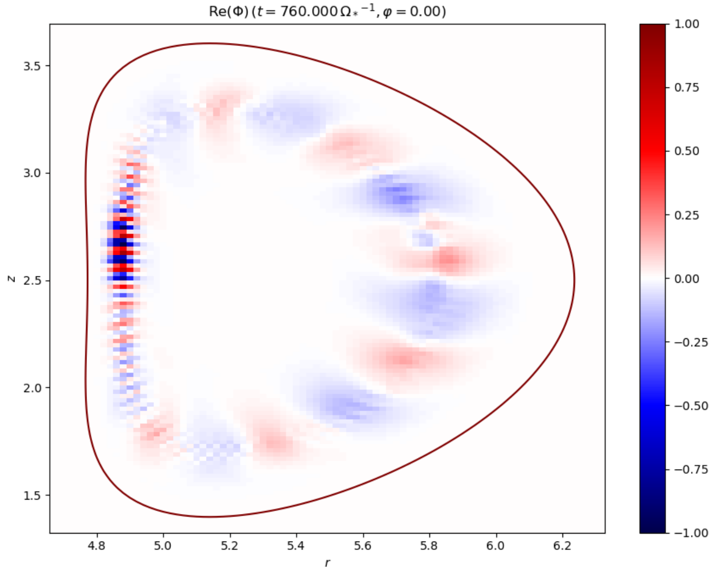
- **Simulation with Euterpe:**
  - Non-linear, electromagnetic ($\delta B_{\parallel}$ & $\delta B_{\perp}$), collisionless
  - Fully gyro-kinetic, but increased mass ratio $m_e/m_i = 0.005$
  - $T_e = T_i$, finite $\nabla T_{e,i}$: $a/L_T = -4.23$ but flat density
  - $\langle\beta\rangle = 1.31\%$



HSK Turbulence

- **First ITG with $\boldsymbol{\gamma_{ITG} = 0.192 a_0/C_s}$, $\boldsymbol{m_0 = 76}$ => $\boldsymbol{k_\perp \rho_i \sim 0.6}$ => close to linear GENE in paper**
- **Then BM with $\boldsymbol{\gamma = 0.385 a_0/C_s}$, $\boldsymbol{m_0 = 8}$ => $\boldsymbol{k_\perp \rho_i \sim 0.06}$**
  - Why BM and not KBM?
    1. Cas3D MHD stability code (C. Nührenberg): $(m_0, n_0) = (8, -12)$ same as in Euterpe, but $\gamma_{Cas3D} = 0.75 a_0/C_s$
    2. $k_\perp \rho_i \sim 0.06$ too small for KBM
- **Turbulence saturation by zonal flow => observation of flows:**
  - Heat flux oscillating back and forth due to oscillating particle flux: finite ∇n => turbulence + outwards flux => $\nabla n = 0$ => curvature pinch (inward particle flux) => finite ∇n





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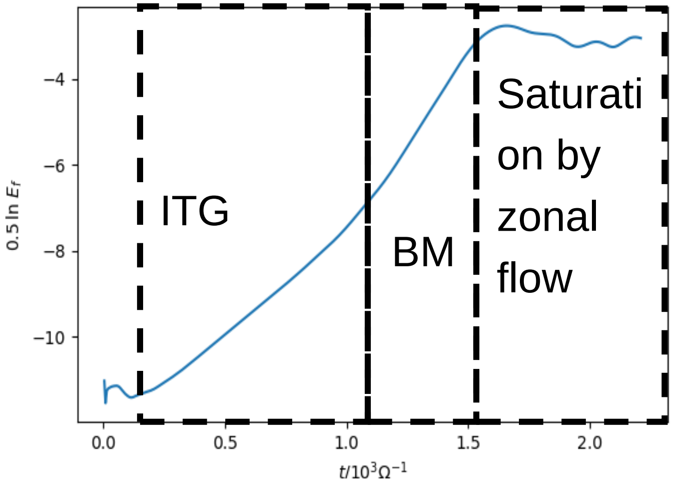

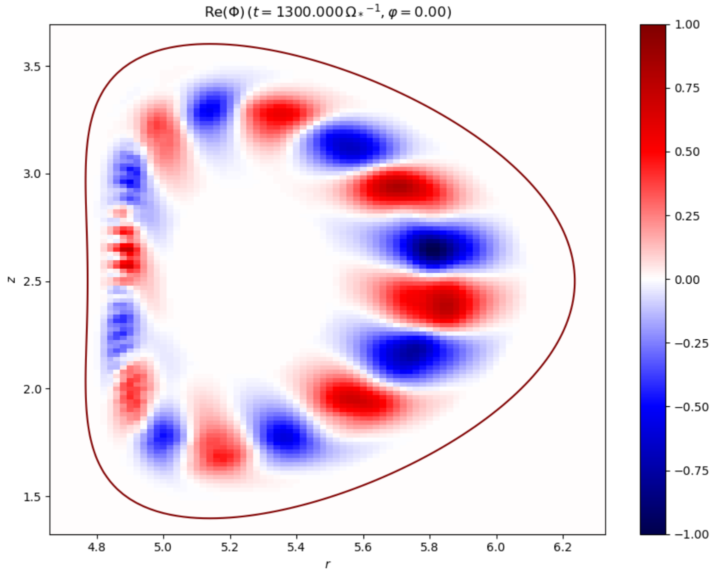

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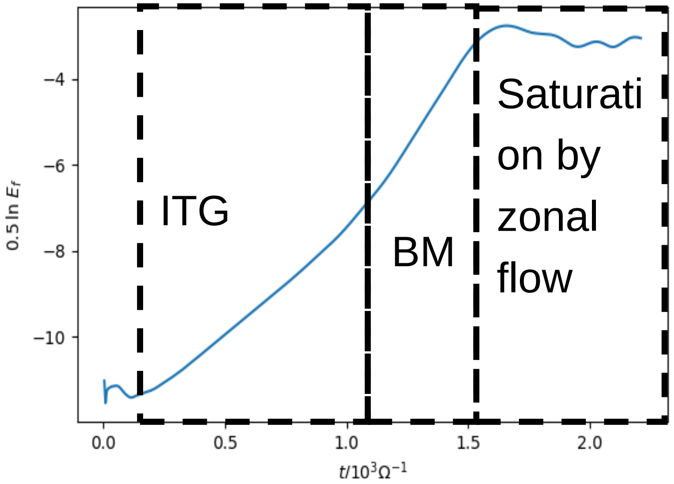

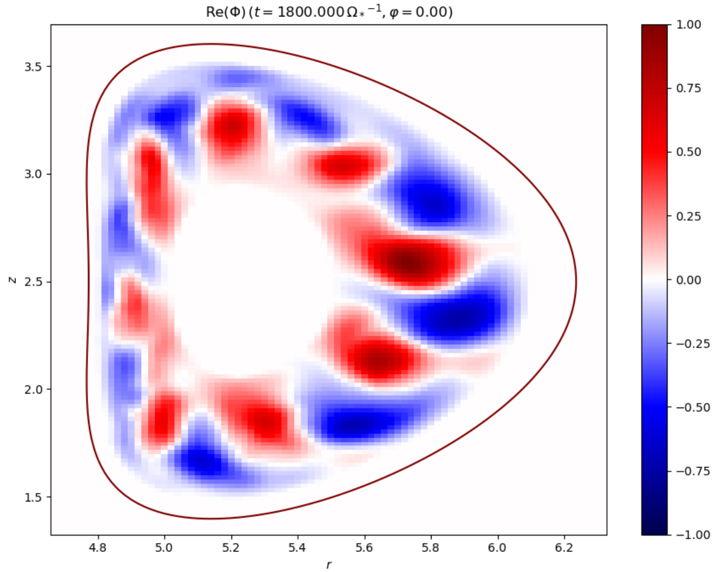

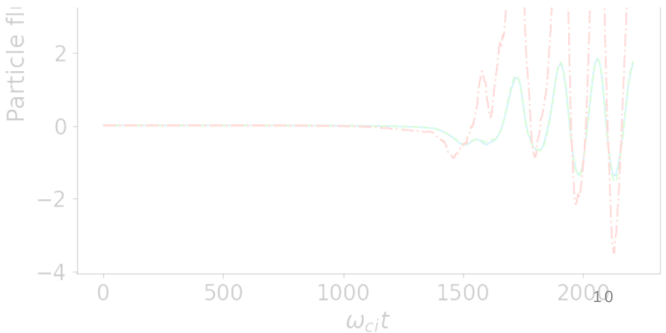

HSK nonlinear Turbulence

- **First ITG with $\gamma_{ITG} = 0.192 a_0/C_s$, $m_0 = 76$ => $k_\perp \rho_i \sim 0.6$ => close to linear GENE in paper**
- **Then IBM with $\gamma = 0.385 a_0/C_s$, $m_0 = 8$ => $k_\perp \rho_i \sim 0.06$**
  - Why IBM and not KBM?
    1. Cas3D MHD stability code (C. Nührenberg): $(m_0, n_0) = (8, -12)$ same as in Euterpe, but $\gamma_{Cas3D} = 0.75 a_0/C_s$
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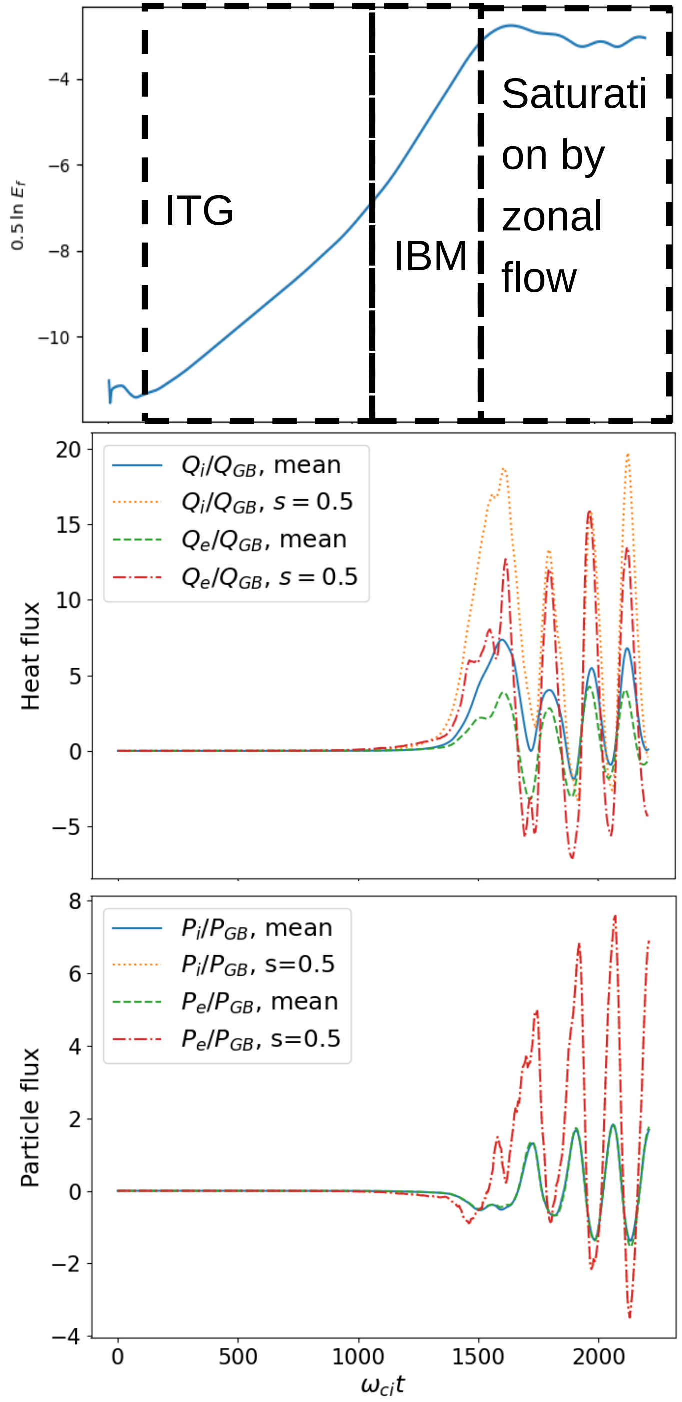
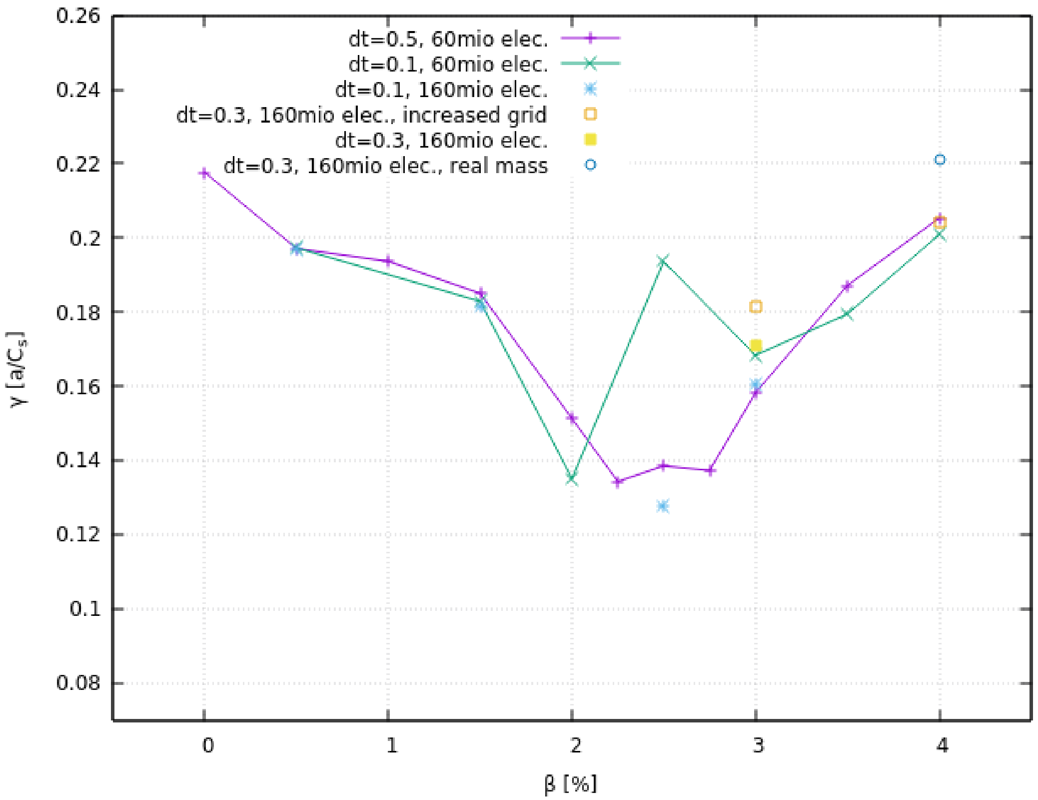


Numerics

Case	Timestep $[\Omega_{ci}]$	Markers [1E6]	Grid $[N_s x N_\theta x N_\varphi]$	Core hours per sim.	Cost rel. to case 1
1	0.5	60	64x128x64	4608	1
2	0.1	60	64x128x64	25398	6
3	0.1	160	64x128x64	55296	12
Electron skin depth	0.3	160	512x128x64	331776	72
True mass	0.3	160	64x128x64	110592	24
6	0.3	160	64x128x64	55296	12

- **Testing numerical convergence:**
  - For $\beta < \beta_{crit} < \beta$: between cases 1,2,3 and "skin depth" no change in γ and ω => cheap far away from transition
  - For $\beta \approx \beta_{crit}$: large differences in γ, ω, R and β_{crit} => large resolution necessary
  - Testing true electron mass at $\beta = 4\%$: ω increases by factor 2. γ, R and phase space similar are almost the same. ~24x more expensive than case 1
- **Good news: EM-simulations rel. Cheap far away from mode transitions**
- **Bad news: For $\beta \approx \beta_{crit}$ expensive due to coexistence of two modes**



Conclusion

- **Scanned W7-X UFM in $\boldsymbol{\beta}$ using Euterpe**
- **Found destabilization of high-$\boldsymbol{\beta}$ TEM at ion scale for $\boldsymbol{\beta > \beta_{crit} \approx 2.5\%}$ as indicated by:**
  - Flip of ω from ion to electron diamagnetic direction
  - Strong drive by trapped electrons in PS
  - Driven by ∇T_e but stabilized by ∇T_i
  - Ratio of energies $W_{A_\parallel}/W_\phi > 1$
- **Numerically cheap for $\boldsymbol{\beta \neq \beta_{crit}}$, but expensive for $\boldsymbol{\beta \sim \beta_{crit}}$ due to competition of modes**
- **Observed turbulent fluxes in optimized HSK configuration**
- **Next steps:**
  - further investigate potential observation of KBMs at lower mode numbers (low $\boldsymbol{k_\perp \rho_i}$)
  - Non-linear simulations to observe fluxes and see whether KBMs or high-β TEM dominates