Fully global linear electromagnetic simulations in the stellarator Wendelstein 7-X

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ABSTRACT

Magnetic confinement fusion requires high $\beta = \langle p \rangle / (B^2/2\mu_0)$, the ratio of plasma pressure to magnetic pressure, to access high performances. Moderate β can be beneficial for ion-temperature-gradient (ITG) driven turbulence. However, as β is increased above a certain threshold, the so-called kinetic-ballooning-mode (KBM) [1] can be destabilized. This is a plasma pressure gradient driven instability, which is inherently electromagnetic and can lead to strong outwards-directed heat fluxes [2], degrading plasma confinement in the process. While, linearly, KBMs have been successfully studied in the stellarator Wendelstein 7-X with flux-tube simulations [3,4], it was also shown that the instability tends to be most unstable while developing a global structure on the magnetic surface. This poster presents results of global linear simulations of KBMs in W7-X geometry using the global gyrokinetic code Euterpe [5].

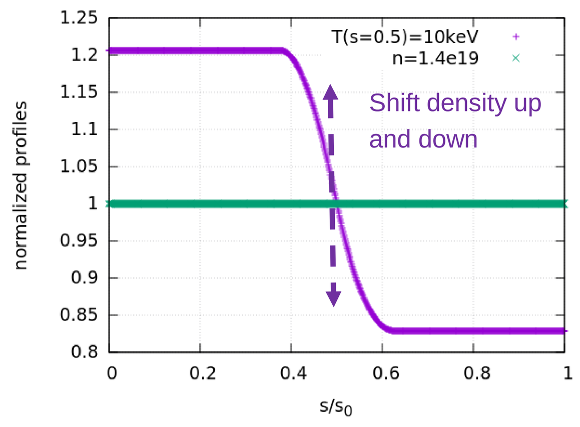
[1] *W.M. Tang, J.W. Connor, and R.J. Hastie. Nuclear Fusion 20.11 (1980)*
[2] *A. Mishchenko et al.. Plasma Physics and Controlled Fusion 64.10 (2022)*
[3] *K. Aleynikova, A. Zocco, and J. Geiger. Journal of Plasma Physics 88.4 (2022)*
[4] *Ksenia Aleynikova and Alessandro Zocco. Physics of Plasmas 24.9 (Aug. 2017)*
[5] *R. Kleiber et. al.. Submitted to CPC. 2023.*

KINETIC-BALLOONING-MODE

- Properties:
  - Electromagnetic ∇p-driven instability
  - Anisotropic $k_\parallel \ll k_\perp$
  - Destabilized for $\beta > \beta_{crit}^{KBM}$ [1]
  - Typically rotates in the ion diamagnetic direction [2]
  - Kinetic modification of ideal ballooning mode
  - In some regimes it can be described as ideal ballooning with diamagnetic correction → $\beta_{crit}^{KBM} < \beta_{crit}^{iMHD}$ [2]
- **Current state of research:**
  - In stellarators successfully studied with flux-tube simulations, but only partially with global codes [2,3,4]
  - Particle fluxes $\Gamma_{i,e}$ and potentially large heat $Q_{i,e}$ [2] make further investigation necessary

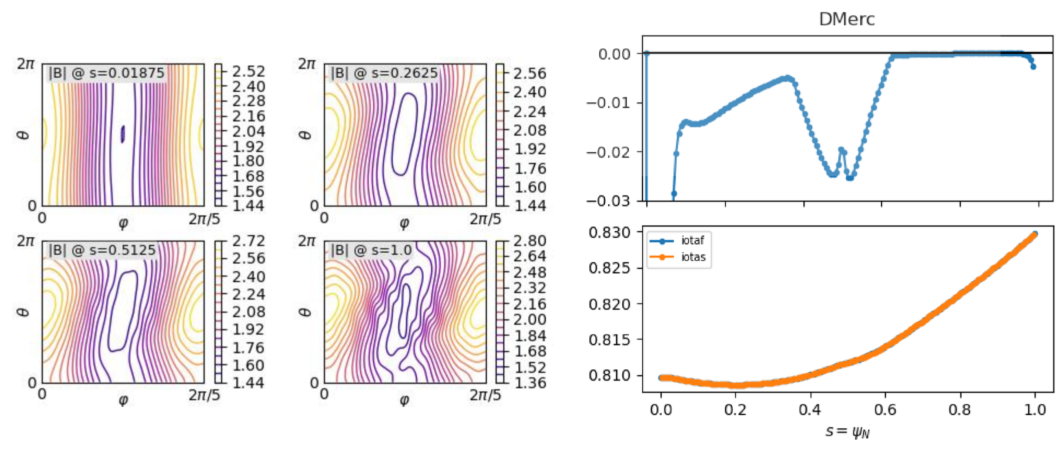
SIMULATION

- **Euterpe [5]**
  - δf particle-in-cell code
  - Fully global
  - Electromagnetic with $\delta B_\parallel$
- **Simulation details**
  - $T_e = T_i$
  - Flat density $a_0/L_n = 0$
  - Finite $\nabla T_{i,e}$: $a_0/L_T = -4.2m^{-1}$
  - Linear, collisionless, two kinetic species,
  - Increased electron mass $m_e/m_i = 0.005$
  - Mode numbers in simulation, $m = 21 - 61$ correspond to an approx. scale of $k_\perp \rho_i \approx 0.3 - 0.8$



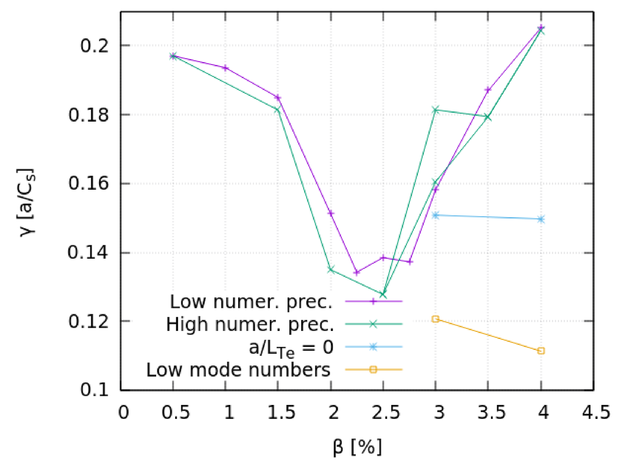
W7-X UFM

- **Theoretical configuration of stellarator W7-X**
- **Faster simulations because:**
  - Mercier unstable, strongly driven
- **We use two VMEC-equilibria for two reference βs; $\beta = 1\%$ and $\beta = 3\%$**



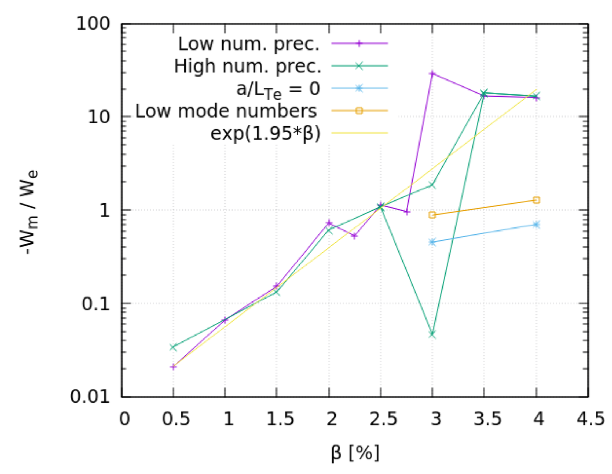
GROWTH RATES

- **As β is increased:**
  - β-stabilization of ITG up to $\beta \approx \beta_{crit} \approx 2.5\% - 3.0\%$
  - For $\beta > \beta_{crit}$ destabilization
- **Furthermore:**
  - Setting $a_0/L_{Te} = 0$ shows strong stabilization with increasing β
  - Lower mode numbers, i.e. $k_\perp \rho_i \approx 0.0 - 0.4$, also show stabilization, despite lower $k_\perp \rho_i$ favoring higher γ for KBMs [4]



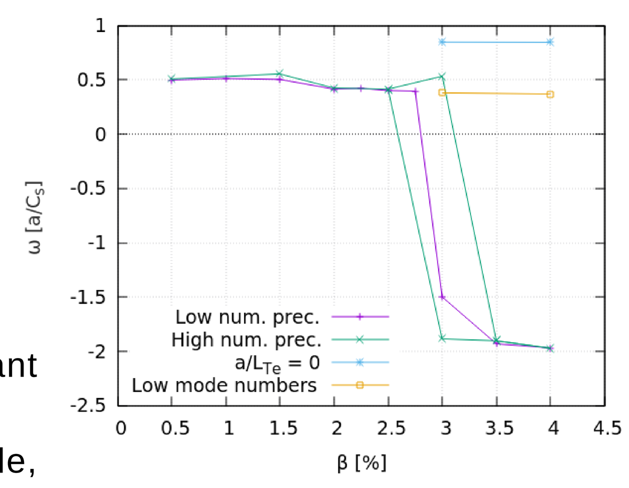
ENERGY

- **Track ratio of perturbed magnetic to electric energy $W_m/W_e = \int \vec{j} \cdot \vec{A_\parallel} dV / \int \rho\phi dV$ [5]**
- **As β is increased:**
  - Ratio increases and crosses ~1 around β_{crit}, shows magnetic nature of mode
  - Ratio appears to follow $\propto \exp(1.95\beta)$ trend. No physical reason known for factor or exponential behavior
- **For $a_0/L_{Te} = 0$ and lower mode numbers predominantly electrostatic**



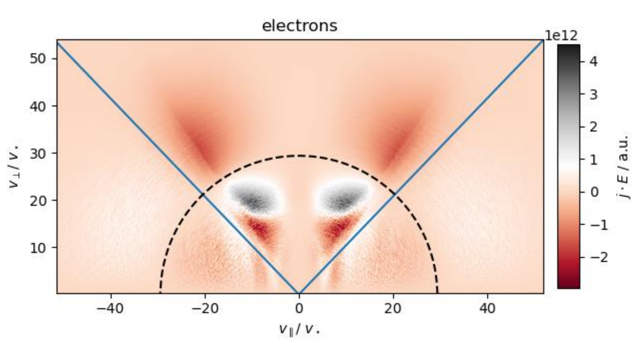
FREQUENCY

- **Before β_{crit}:**
  - Ion direction, weak dependence on β up to $\beta \approx \beta_{crit}$
- **After β_{crit}:**
  - Transition to larger $|\omega|$ into electron diamag. direction
  - Weakly dependent on β
- **Furthermore:**
  - For $a_0/L_{Te} = 0$ $|\omega|$ remains ionic, suggesting a significant influence by electrons
  - For lower mode numbers no change in ω visible, suggesting transition happens for small scale physics



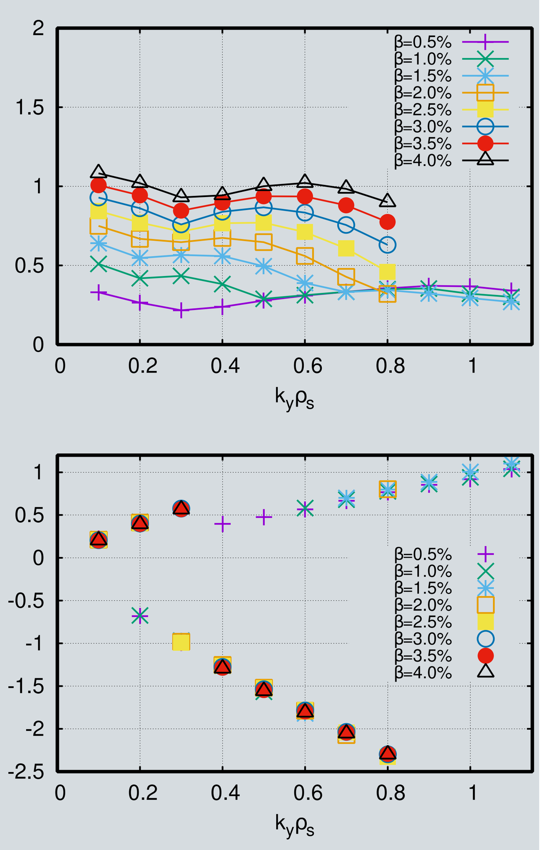
OTHER OBSERVATIONS

- **Trapped electrons with complex phase-space structure seen in $\beta = 4\%$-simulation**
- **Global mode more active at higher mode numbers, indicating stronger growth at smaller scales**



GENE SIMULATIONS

- **Goal: repeat case with same parameters in flux-tube for the sake of comparison**
  - **Different physic regimes observed:**
    - KBM at small $k_y\rho_s$ and ITG for large $k_y\rho_s$ ($\beta = 0.5\%$)
    - KBM at small $k_y\rho_s$, electron rotating mode at intermediate $k_y\rho_s$ and ITG for larger $k_y\rho_s$ ($\beta = 1 - 2\%$)
    - KBM at small $k_y\rho_s$ and electron rotating mode at larger $k_y\rho_s$ covering ITG completely ($\beta > 2\%$)
  - Although small, stabilization of ITG is observed
  - Peak of γ for electron rotating mode moving to larger $k_y\rho_s$ for increasing β
  - Competition of electron mode and KBM due to similar γ
  - Transition to electron diamagnetic direction for ω for $\beta > \beta_{crit}^{GENE}$
  - $\beta_{crit}^{GENE} \approx 0.5\% - 2.0\% < \beta_{crit}^{Euterpe}$, depending on $k_y\rho_s$
  - Ongoing characterization of the electron rotating mode with increased field-line following coordinate resolution



SUMMARY AND OUTLOOK

- **Observing transition to electron mode for $\beta > \beta_{crit}^{Euterpe} \approx 2.5\% - 3.0\%$:**
  - Gene and Euterpe simulations agree qualitatively, as indicated by γ and ω
  - In Gene peak of electron mode moves to larger $k_\perp\rho_s$ as β is increased, explaining higher $\beta_{crit}^{Euterpe}$ in Euterpe due to fixed scale ($k_\perp\rho_i \approx 0.3 - 0.7$)
  - Transition appears for ratio of mag. to elec. Energy > 1
  - Electron diamagnetic frequency and trapped particles hint towards activity being ∇T-driven TEM or ITG-driven MTM
  - KBMs have not yet been observed in Euterpe in this case. This might be due to the competition between KBMs and the electron mode as well as KBMs appearing at lower $k_y\rho_s$, as indicated by Gene simulations
- **Next steps to identify physics at play:**
  - Investigate eigenfunction and parity in Gene, and potentially also in Euterpe
  - Simulate high-β case in Euterpe with lower modenumbers to observe KBM and without trapping to see importance of it
  - Non-linear simulations
- **Close to transition resolving physics becomes expensive and difficult, but is less important far from transition**

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