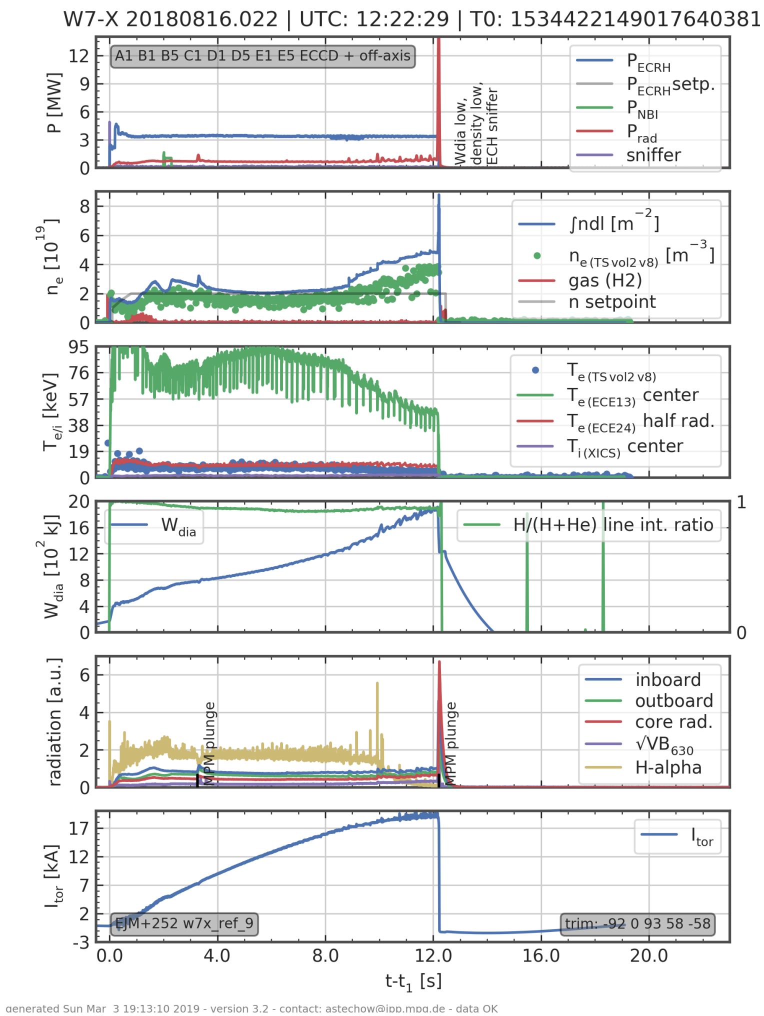
Gyro-kinetic simulations of kink instabilities

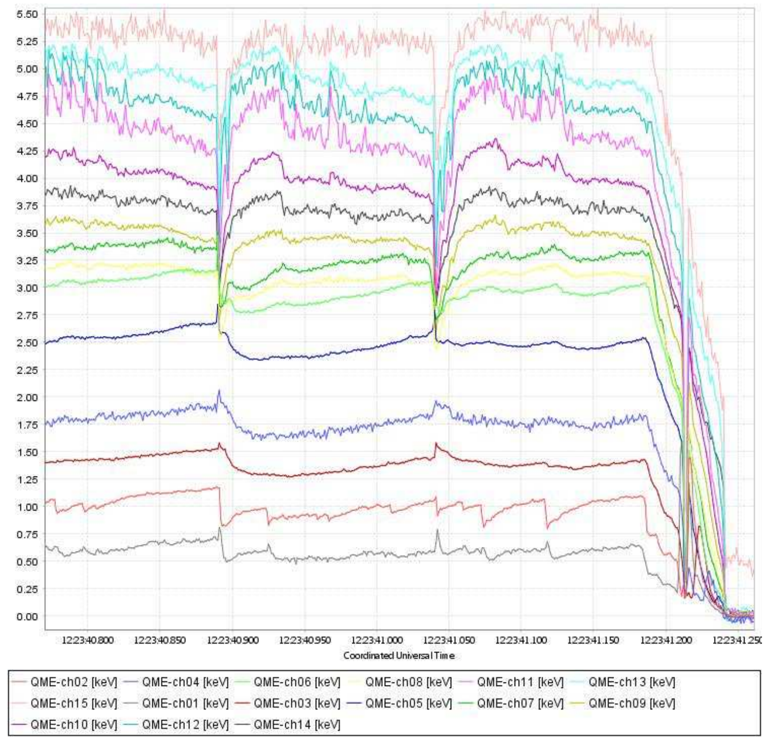
A. Mishchenko, R. Hatzky, A. Könies, A. Zocco, M. Bordhardt, R. Kleiber

Keywords: resonant iota, current quench, precursor, gyrokinetic simulations

Acknowledgements: P. Helander, W7-X MHD Topical Group, ORB5 team

Electron-temperature oscillations on W7-X





Motivation

- Current quench events observed in W7-X (OP1.2a/b) related to $\boldsymbol{\iota \approx 1}$
- A practical issue with limitations of the W7-X operational space
- Likely to be an issue in next stellarators (not limited to W7-X)
  ($\boldsymbol{\iota \approx 1}$ has peculiar optimisation properties [work by H. Weitzner])
- Only parallel current can drive instabilities (diamagnetic current is not destabilising)
  $\boldsymbol{I_{\|} \sim 10}$ MA in tokamaks vs. $\boldsymbol{I_{\|} \sim 10}$ kA in optimised stellarators
- Confinement not lost in stellarators even if parallel plasma current disappears
- Transient effect before toroidal current saturates
- Relation of stellarator quenches to sawteeth/NTM problem in tokamaks
- Low shear makes weak effects important: weak ECCD, profiles, turbulence
  (as in tokamak Neoclassical Tearing Modes, also related to bootstrap)
- Global gyrokinetic description may be needed

Gyrokinetic SPC-IPP global PIC code suite

- 1995: GYGLES is developed at SPC(CRPP) with adiabatic electrons
- 1997: kinetic electrons implemented in GYGLES at IPP
- 1999: ORB5 is developed at SPC(CRPP)
- 1999: EUTERPE is developed at SPC(CRPP)
- 2004: EUTERPE implemented for W7-X at IPP
- 2004: GYGLES becomes electromagnetic at IPP
- 2008: ORB5 becomes electromagnetic, joint development IPP/SPC/UW
- 2009: EUTERPE becomes electromagnetic at IPP

All the codes share the equations solved, physics addressed and the discretisation principles applied. Deeper core routines are often very similar. Normalisation in EUTERPE and ORB5 is almost identical.

Gyrokinetic system of equations

- **Vlasov equation:** $\partial f / \partial t + \dot{\vec{R}} \cdot \nabla f + \dot{v}_{\|} \partial f / \partial v_{\|} = 0$
- **equations of motion:** Shifted Maxwellian to account for $j_{\|0e} \sim u_{\|0e}$

$$\dot{\vec{R}} = \left(v_{\|} - \frac{q}{m} \langle A_{\|} \rangle \right) \vec{b}^* + \frac{1}{q B_{\|}^*} \vec{b} \times \left[\mu \nabla B + q \left(\nabla \langle \phi \rangle - v_{\|} \nabla \langle A_{\|} \rangle \right) \right]$$

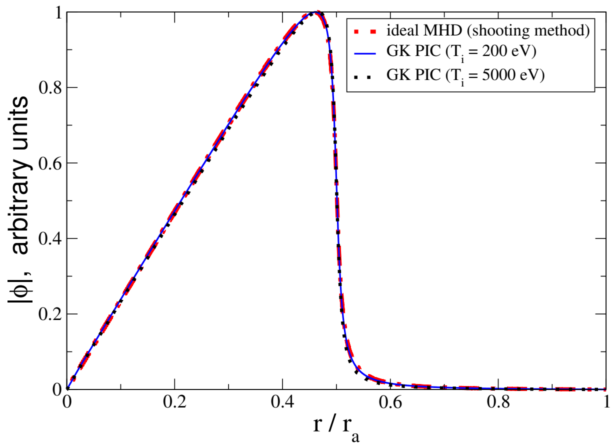
$$\dot{v}_{\|} = -\frac{1}{m} \left[\mu \nabla B + q \left(\nabla \langle \phi \rangle - v_{\|} \nabla \langle A_{\|} \rangle \right) \right] \cdot \vec{b}^*$$

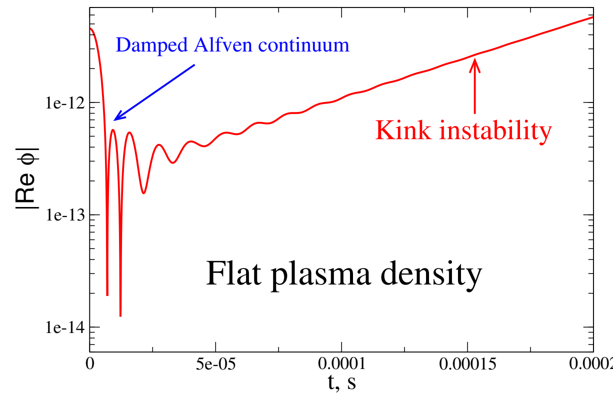
- **gyrokinetic quasi-neutrality equation and parallel Ampére's law:**

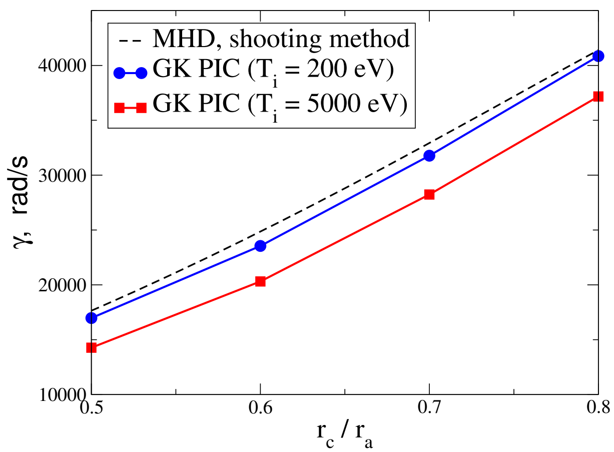
$$-\nabla \cdot \left[\left(\sum_{s=\mathrm{i,f}} \frac{q_s^2 n_s}{k_{\mathrm{B}} T_s} \rho_s^2 \right) \nabla_{\perp} \phi \right] = \sum_{s=\mathrm{i,e,f}} q_s \delta n_s$$

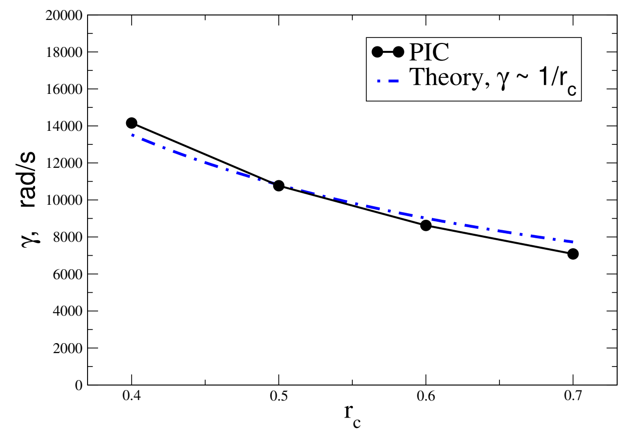
$$\left(\sum_{s=\mathrm{i,e,f}} \frac{\beta_s}{\rho_s^2} - \nabla_{\perp}^2 \right) A_{\|} = \mu_0 \sum_{s=\mathrm{i,e,f}} \delta j_{\| s}$$

Internal kink mode in pinch (gyrokinetic, GYGLES)



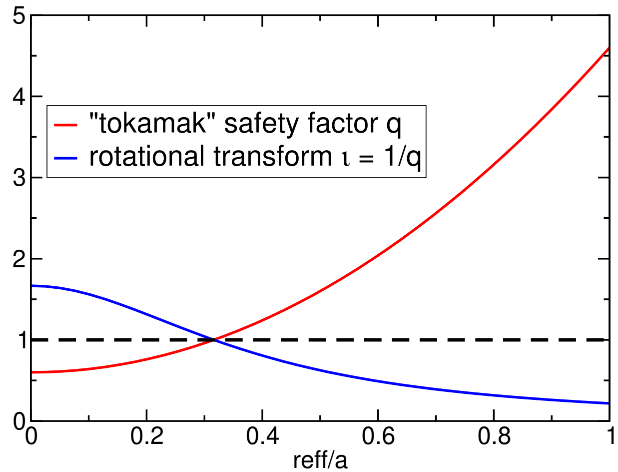


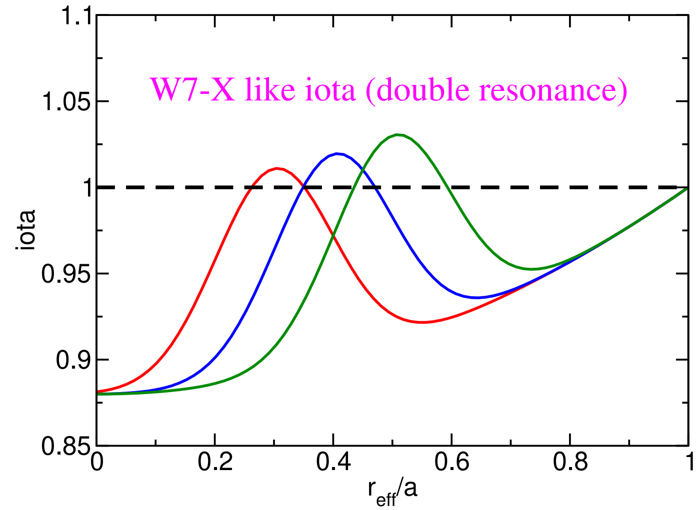


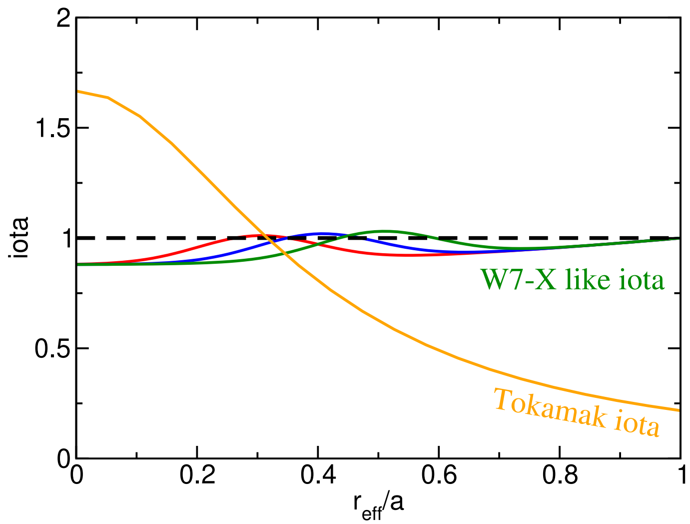


Internal kink mode in straight geometry (screw pinch); MHD regime and FLR regimes;
A. Mishchenko and A. Zocco, Phys. Plasmas **19**, 122104 (2012)

Internal kink mode in pinch (W7X-like iota)

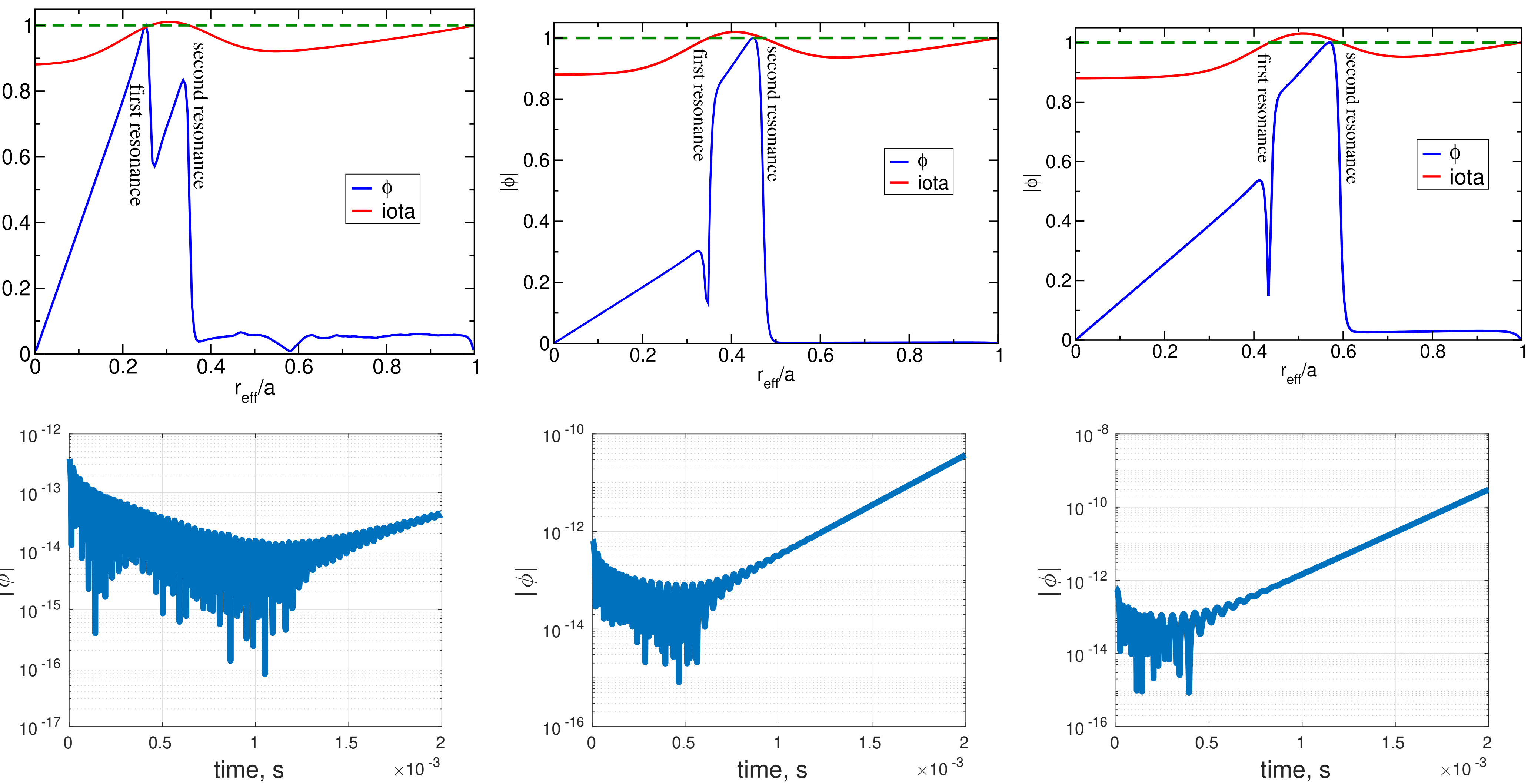






- Consider a set of W7-X like iota (double resonance)
- Consider W7-X like aspect ratio and $\boldsymbol{\rho_*}$
- Here, flat $\boldsymbol{T_i = 2}$ keV, $\boldsymbol{T_e = 5}$ keV
- Here, flat $\boldsymbol{n_0 = 2 \times 10^{19}}$ m^{-3}
- Look for current-driven $\boldsymbol{(1,1)}$ instabilities
- Study dependence on iota profile

GYGLES simulations of the “double-kink”



GYGLES simulations of the "double-kink"

Magnetic field in screw pinch

$$\vec{B} = \nabla\psi \times \nabla\varphi + T(\psi)\nabla\varphi \,, \quad \psi = \frac{B_0 r^2}{2} \,, \quad T(r) = \frac{B_0 r^2}{q r_0}$$

$$j_\parallel = \frac{1}{\mu_0 r}\frac{\mathrm{d}T}{\mathrm{d}r} = \frac{B_0}{\mu_0 R_0}\iota(2-\hat{s}) = \frac{B_0}{\mu_0 R_0}(2\iota + r\iota') \,, \quad \hat{s} = -\frac{r\iota'}{\iota}$$

In W7-X like stellarators, large part of ι is provided externally:

$$\iota = \iota_{\mathrm{ext}} + \iota_{\mathrm{pl}} \,, \quad \iota_{\mathrm{ext}} \gg \iota_{\mathrm{pl}}$$

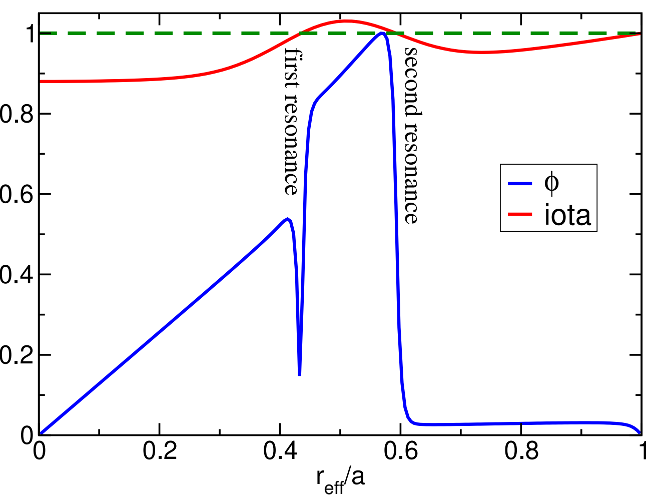
However, the radial derivative of ι is mostly provided by internal plasma currents:

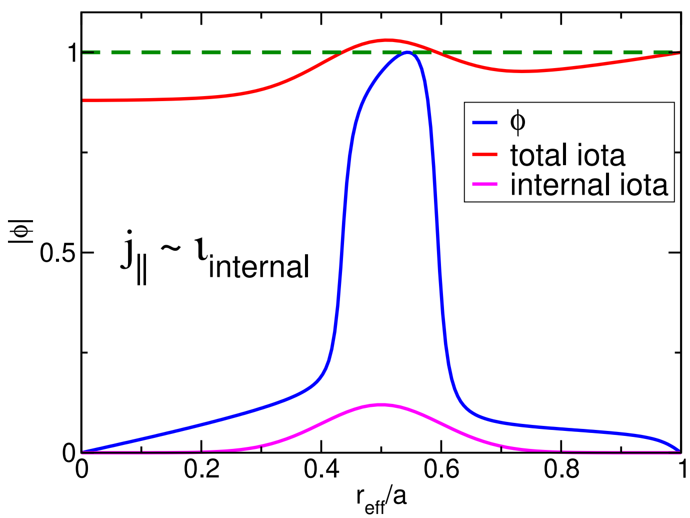
$$\iota' = \iota'_{\mathrm{ext}} + \iota'_{\mathrm{pl}} \,, \quad \iota'_{\mathrm{pl}} \gg \iota'_{\mathrm{ext}}$$

In simulations, we consider for $s = r_{\mathrm{eff}}/a$

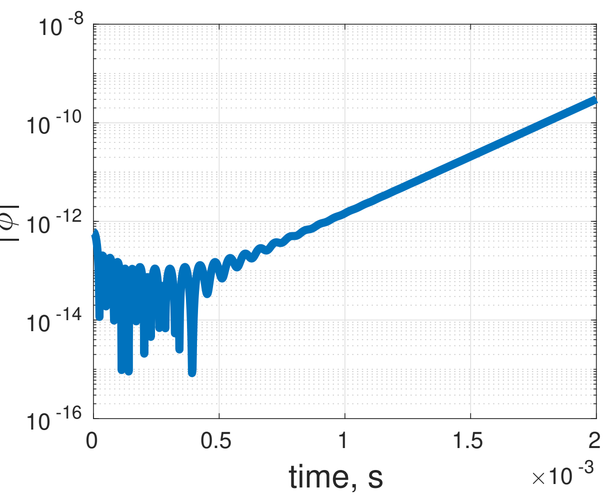
$$\iota_{\mathrm{ext}} = 0.88 + 0.12 s^2 \,, \quad \iota_{\mathrm{pl}} = 0.12 \exp\left[-\frac{(s-0.5)^2}{0.02}\right] \,, \quad \underline{j_\parallel \sim 2\iota_{\mathrm{pl}} + r\iota'_{\mathrm{pl}}}$$

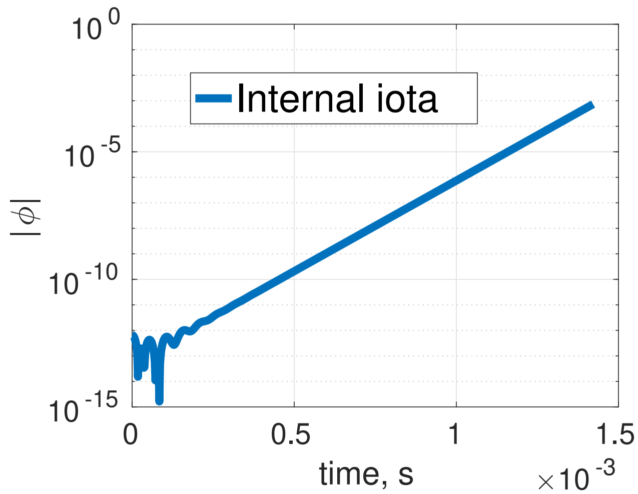
GYGLES simulations of the “double-kink”





$$j_{\|} \sim \iota_{total}$$
$$\gamma = \mathbf{5368.667}\ \mathrm{rad/s}$$





$$j_{\|} \sim \iota_{plasma}$$
$$\gamma = \mathbf{16355.688}\ \mathrm{rad/s}$$

Kink instability drive in gyrokinetic equation

$$\frac{\partial f_1}{\partial t} + \dot{\vec{R}} \cdot \nabla f_1 + \dot{v}_\parallel \frac{\partial f_1}{\partial v_\parallel} = -\dot{v}_\parallel^{(1)} \frac{\partial f_0}{\partial v_\parallel} - \underbrace{\dot{\vec{R}}^{(1)} \cdot \nabla f_0}_{mode\ drive}$$

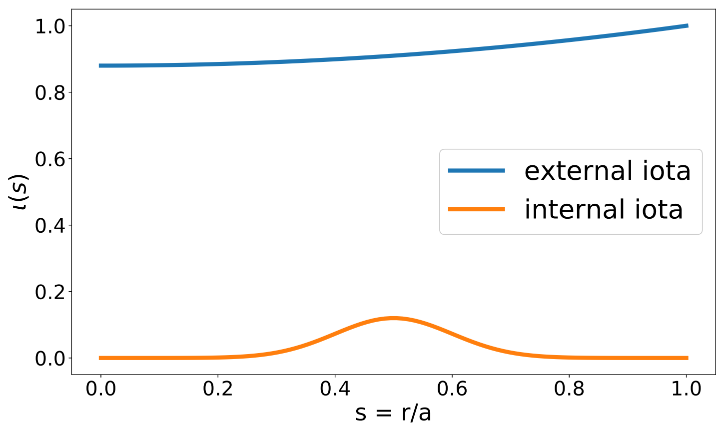
$$f_{0e} = n_0 \left(\frac{2\pi m_e}{T_e}\right)^{3/2} \exp\left(-\frac{m_e v_\perp^2}{2T_e}\right) \exp\left[-\frac{m_e(v_\parallel - u_0)^2}{2T_e}\right]$$

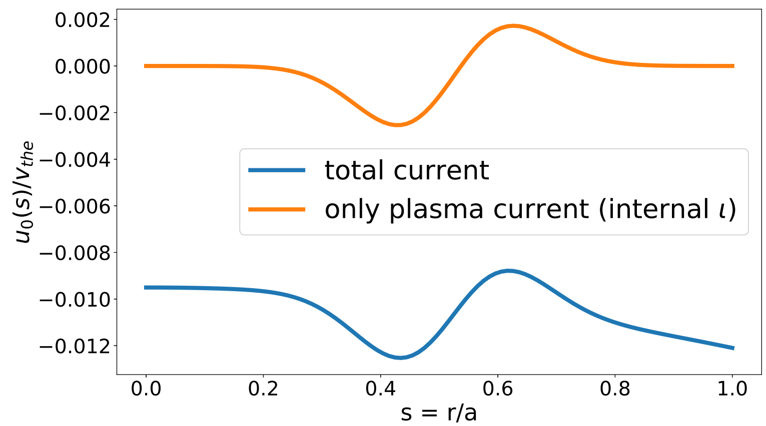
$$u_0 = -\frac{j_{\parallel 0}}{e n_0} = -\frac{\rho_{the}}{\beta_e R_0}(2\iota + r\iota') v_{the}$$

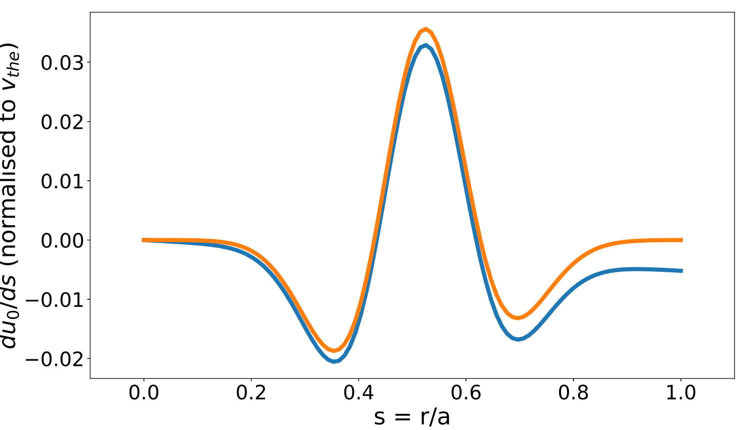
$$\nabla f_0 = \frac{m_e}{T_e}(v_\parallel - u_0)\nabla u_0 f_0 \approx -\frac{\rho_\parallel}{\beta_e R_0}(3\iota' + r\iota'') f_0$$

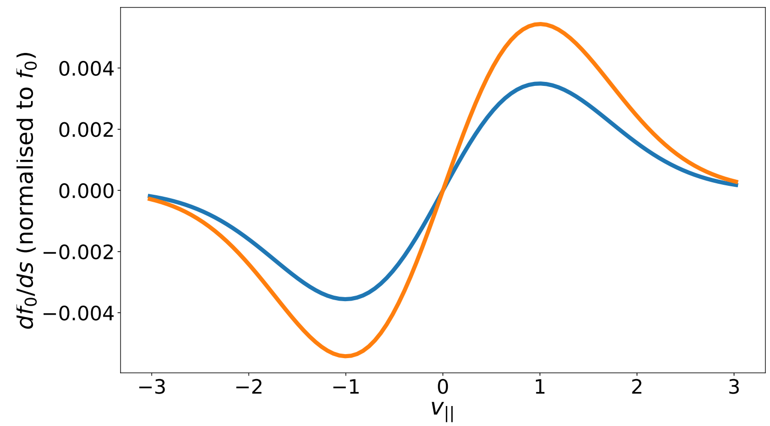
$$v_{the} = \sqrt{\frac{T_e}{m_e}}, \quad \beta_e = \frac{\mu_0 n_0 T_e}{B_0^2}, \quad \omega_{ce} = \frac{e B_0}{m_e}, \quad \rho_{the} = \frac{v_{the}}{\omega_{ce}}, \quad \rho_\parallel = \frac{v_\parallel}{\omega_{ce}}$$

Kink instability drive in gyrokinetic equation



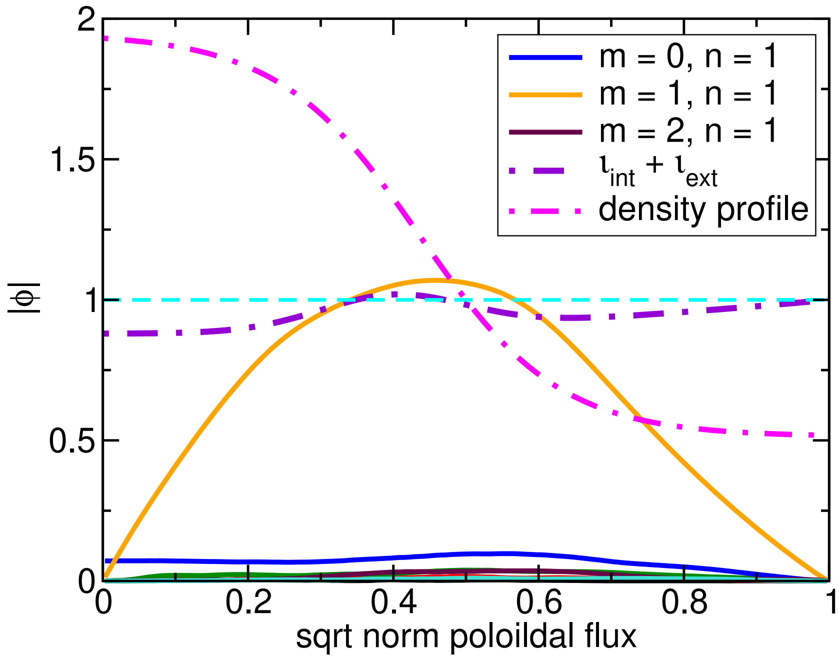


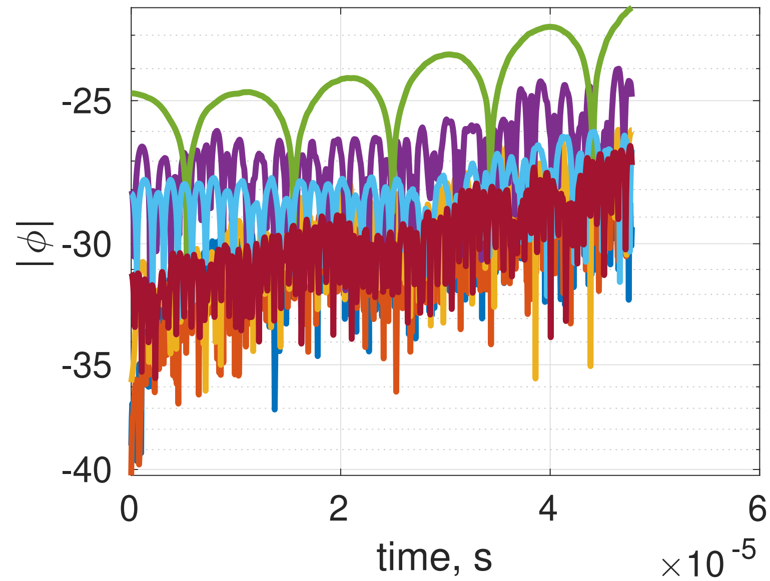




internal $\boldsymbol{u_0}$ is smaller; internal $\mathbf{du_0/ds}$ and $\mathbf{df_0/ds}$ can be larger (cancellation in $\boldsymbol{3\iota'+r\iota''}$)

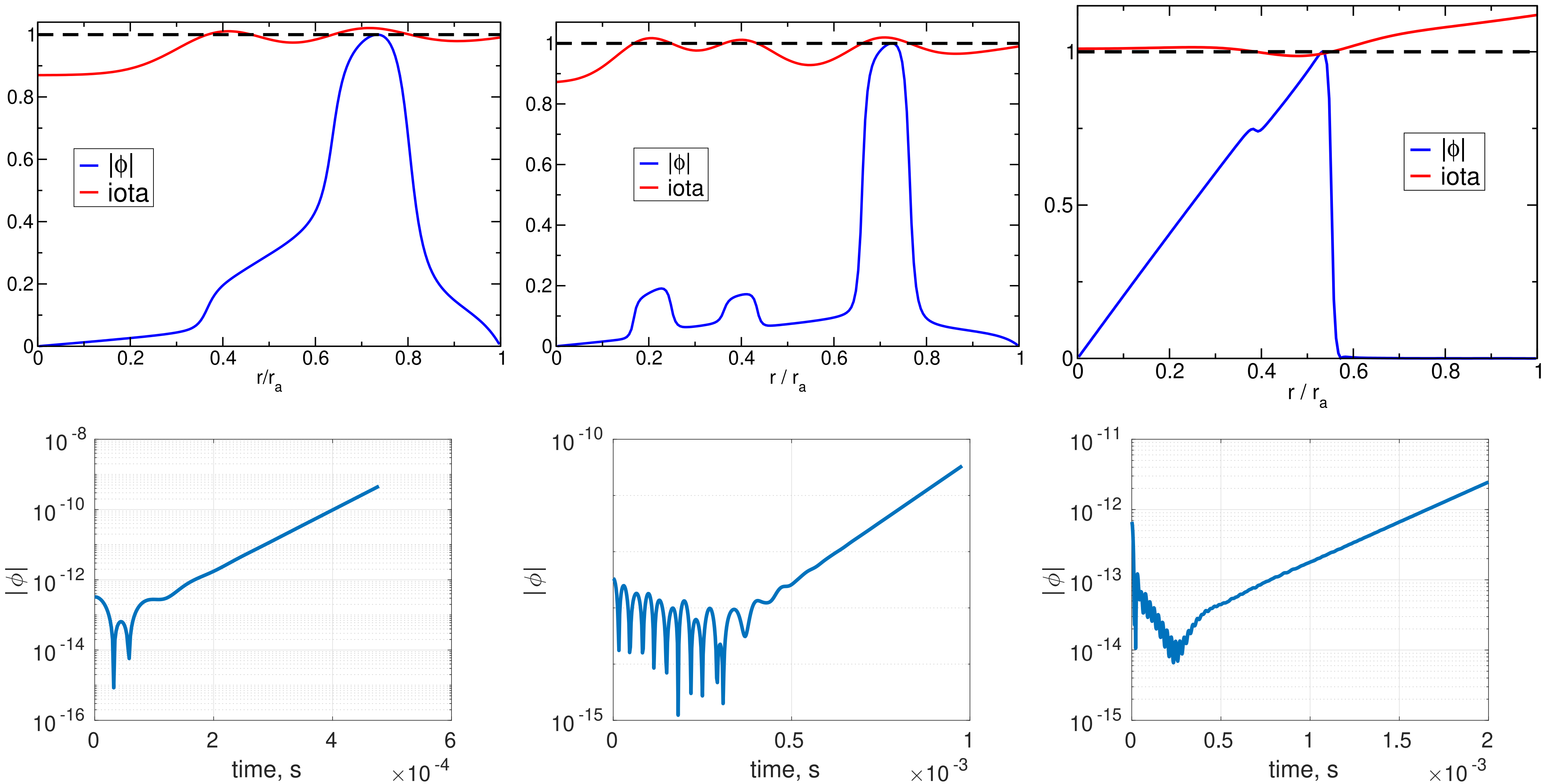
Kink instability in axisymmetric toroidal geometry



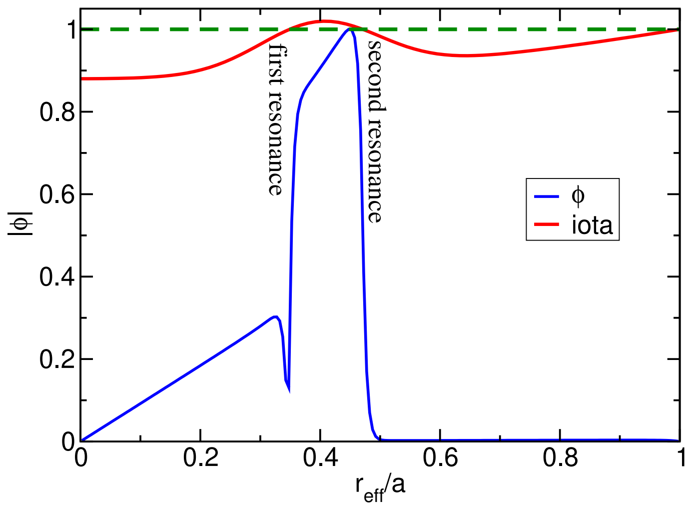


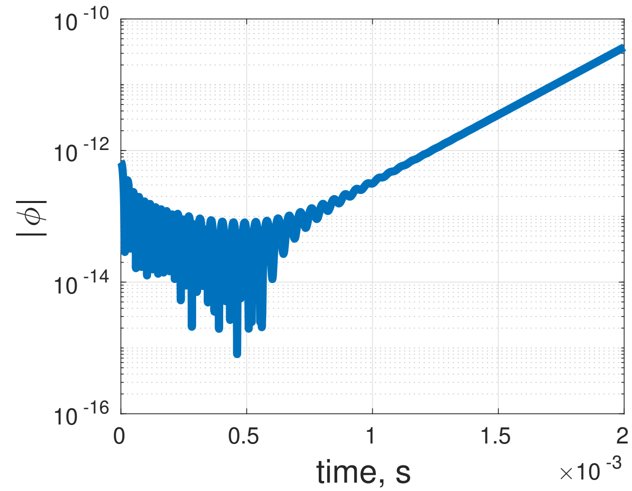
- Toroidal geometry with W7-X parameters: $\boldsymbol{B_0 = 2.5}$ T, $\boldsymbol{\iota = \iota_{\rm int} + \iota_{\rm ext}}$, $\boldsymbol{j_{\parallel 0} \sim \iota_{\rm int}}$ $\boldsymbol{n_0 = 2. \times 10^{19} \exp\left[-0.67 \tanh\left(\frac{x-0.5}{0.2}\right)\right]}$ m^{-3}, flat $\boldsymbol{T_i = 2}$ keV, $\boldsymbol{T_e = 5}$ keV
- Global instability is found in the toroidal geometry $\boldsymbol{\gamma = 80395.521}$ rad/s
- There is a finite frequency $\boldsymbol{\omega = -325859.7405}$ rad/s

GYGLES simulations of the “double-kink”



GYGLES simulations of the “double-kink”



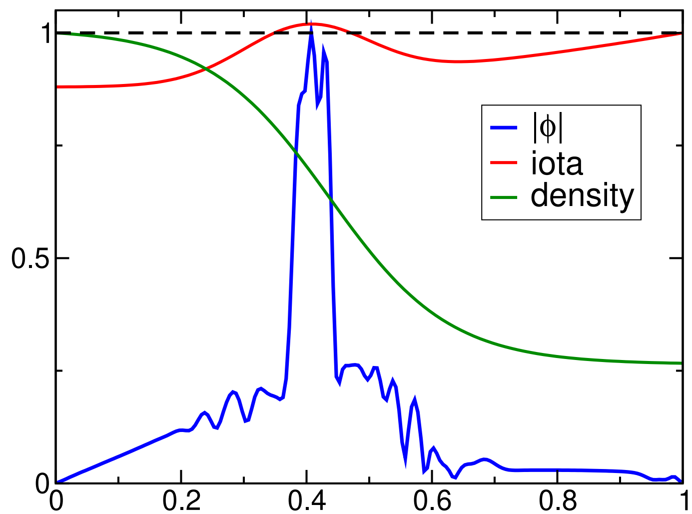


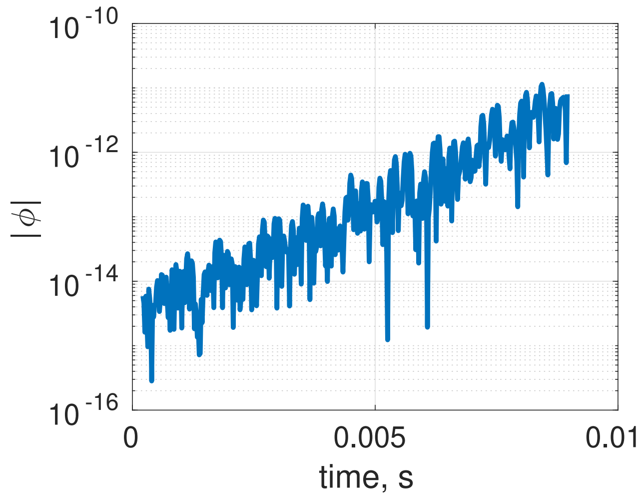
effect of $\boldsymbol{\nabla n}$:

diam. stabilisation?

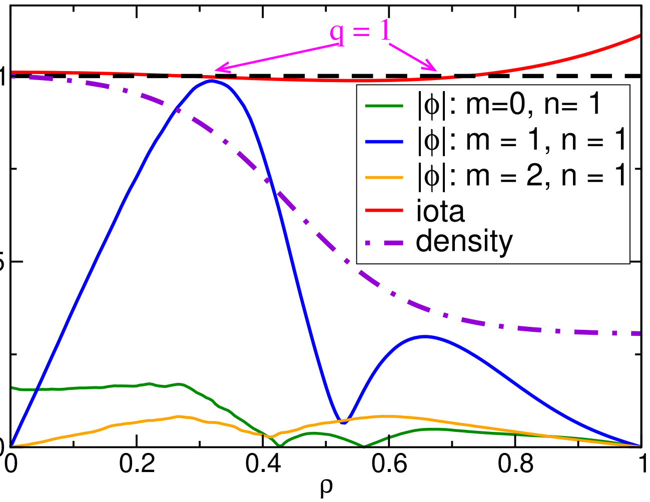
$\boldsymbol{\nabla n}$ location?

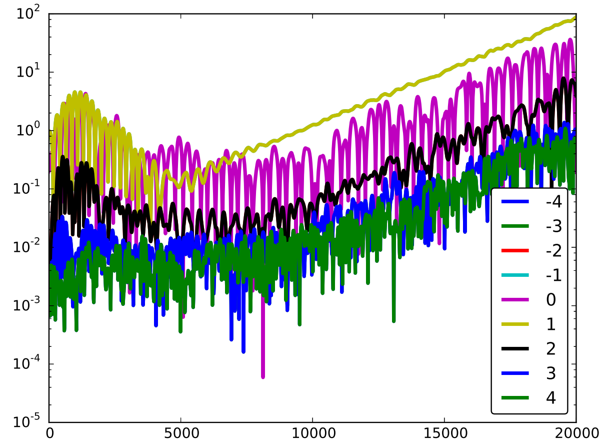
effect of $\boldsymbol{\nabla T}$?

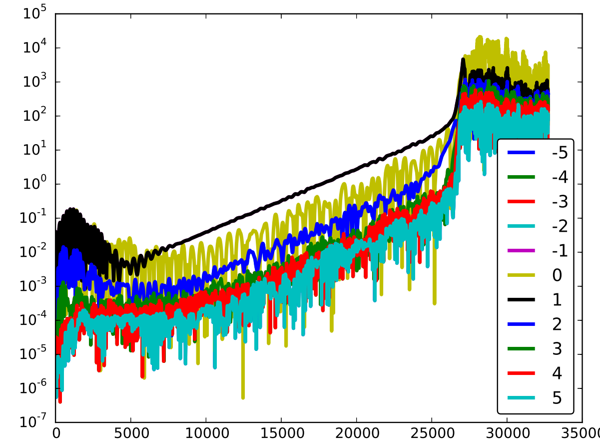


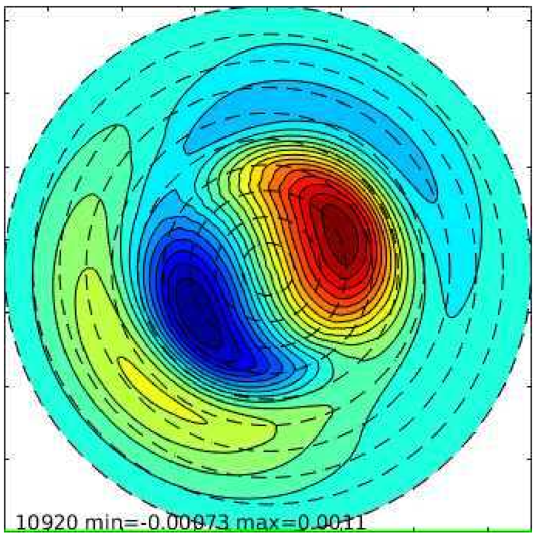


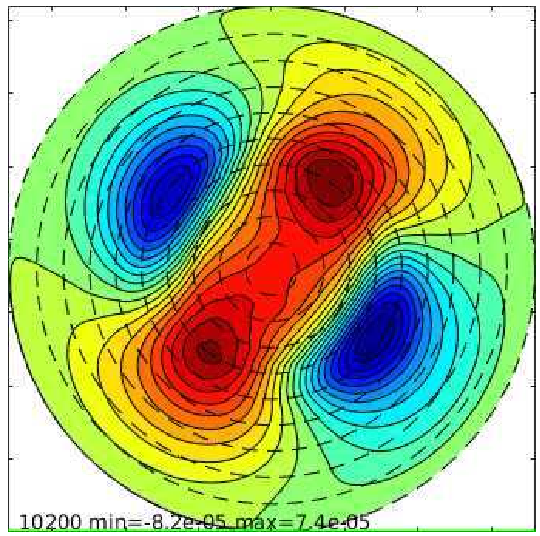
ORB5 simulations of the "double-kink"











Nonlinear run

Left: $\phi(r, z)$

Right: $A_{\|}(r, z)$

small initial pertw $(1e-7)$

only $n = 1$; $m \in [-64, 64]$;

$\Delta m = 5$

no noise control

Better equilibrium needed?

Summary and Outlook

- DONE:
  - In [PoP2012]: gyrokinetic internal kink mode in screw-pinch geometry (GYGLES)
  - Here: GYGLES simulations of "double kink" for W7-X like iota $\longrightarrow$ instability found
  - Instability becomes stronger with double resonances in iota moving outside
- TO BE DONE:
  - Effect of the temperature and density profiles
  - Effect of bumpiness
  - Effect of toroidicity
  - Effect of fast particles
  - Effect of 3D geometry
  - Gyrokinetic external modes?