Synthesis of full MHD simulation results of neoclassical tearing modes in ITER geometry

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Outline

- XTOR and theory
- NTM: nonlinear thresholds
- NTM: saturation
- NTM: toroïdal interaction

XTOR equations:

$$\rho\frac{D\vec{v}}{Dt} = \vec{J}\times\vec{B} - \nabla p + \nabla\,\nu\nabla\vec{v}$$

$$\partial_t\vec{B} = \nabla\times(\vec{v}\times\vec{B}) - \nabla\times\eta(\vec{J}-\vec{J}_{boot})$$

$$\partial_t T = -\vec{v}.\nabla T - (\Gamma-1)T\nabla\vec{v} + \nabla\chi_\perp\nabla T + \vec{B}.\nabla\chi_{//}\frac{\vec{B}.\nabla T}{B^2} + H$$

$$\partial_t\rho = -\vec{v}.\nabla\rho - \rho\nabla\vec{v} + \nabla D_\perp\nabla\rho + Q$$

$$H = -\nabla\chi_\perp\nabla T_{equil};\quad \eta_{equil}(J_\phi - J_{\phi,boot})_{equil} = const.$$

Full toroïdal geometry.

Mapping: $\eta_{equil}(r);\quad T_{equil}(r)\xrightarrow[\substack{Spitzer,\\ p\_edge}]{}\eta_{equil}(T_{equil})\xrightarrow[t\neq 0]{}\eta(T(t))$

Bootstrap: $\vec{J}_{boot}(t) = f_{bs}\left\|\vec{J}_{boot,equil}\right\|.\nabla_r p(t)/p'_{equil}\,\vec{B}(t)/\left\|\vec{B}(t)\right\|$

Nonlinear theory

- Generalized Rutherford equation

$$\frac{\tau_r}{1.22}\frac{dw}{dt} = \Delta'(w) + \Delta'_{GGJ}(w) + \Delta'_{boot}(w) \quad (+\ non\ MHD)$$

(Rutherford (1973),White(1977),Thyagaraja (1981)
Militello et al., Escande et al., Hastie et al. (2004),
Kotschenreuter (1985), Lütjens & al.(2001), Fitzpatrick (1995))

with

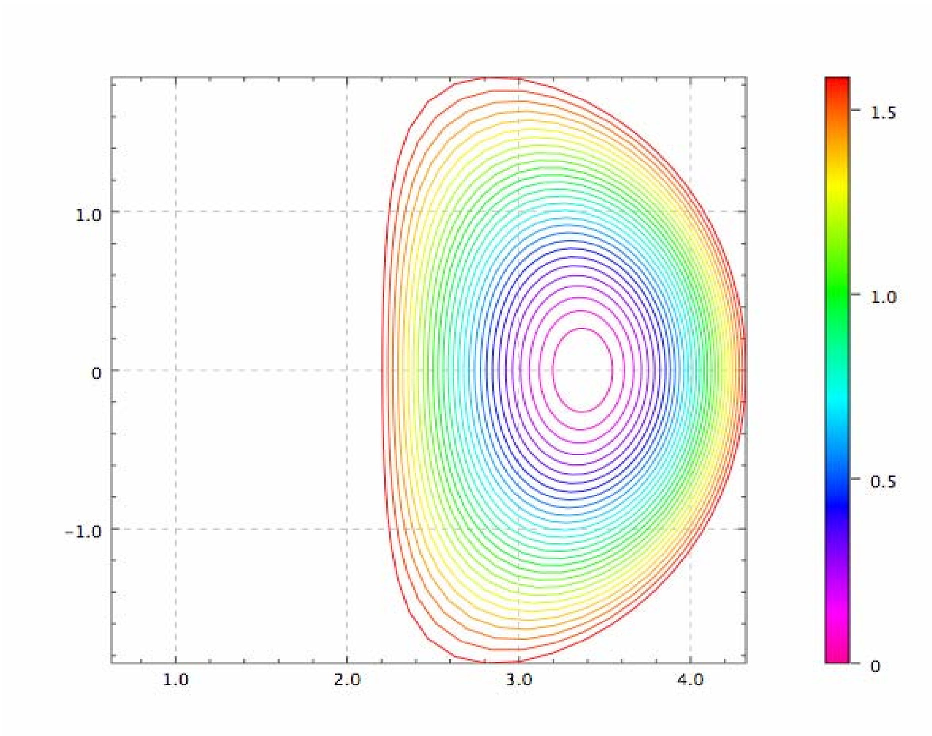
$$\Delta'_{GGJ} = 6.35\frac{D_R}{\sqrt{w^2 + 0.65 w_c^2}} \qquad \text{(curvature)}$$

and

$$\Delta'_{boot} = 6.35\frac{R_o q}{B_o s_s} J_{boot,o}\frac{w}{w^2 + (1.8 w_c)^2} \qquad \text{(bootstrap)}$$

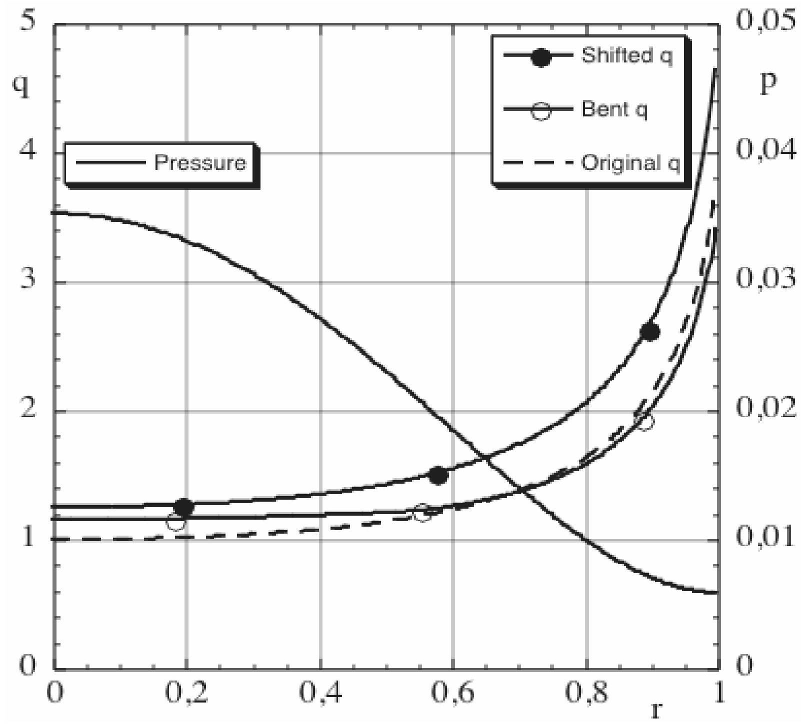
$$w_c = 2\sqrt{2}\left(\frac{\chi_\perp}{\chi_{//}}\right)^{1/4}\sqrt{\frac{r_s R}{n s_s}}; \quad s_s = \frac{r_s q'}{q}$$

Equilibrium (CHEASE):

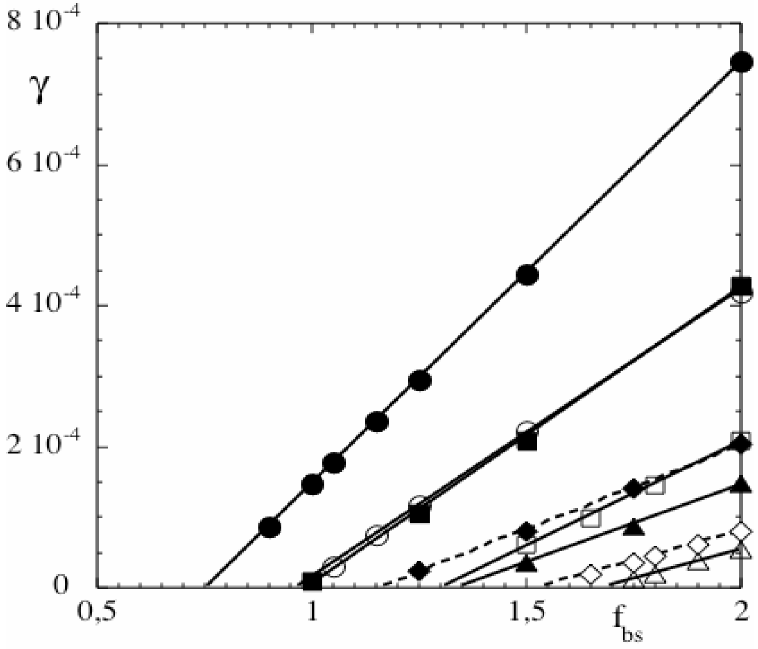


ITER:

A=3; κ=1.75; δ=0.4



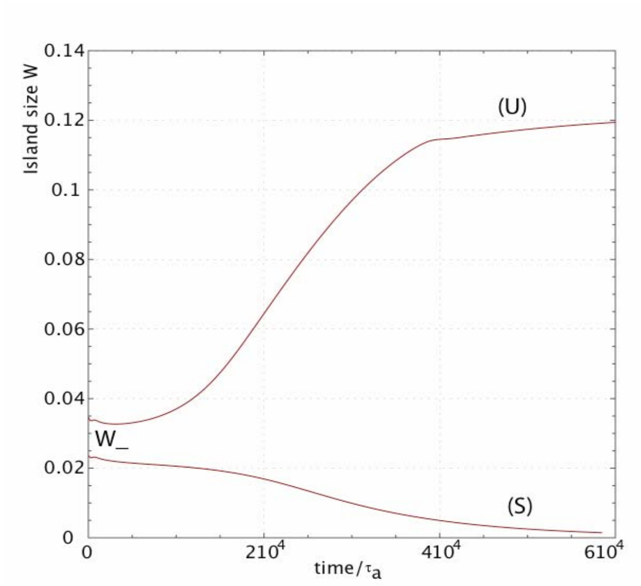
NTM: linear stability thresholds



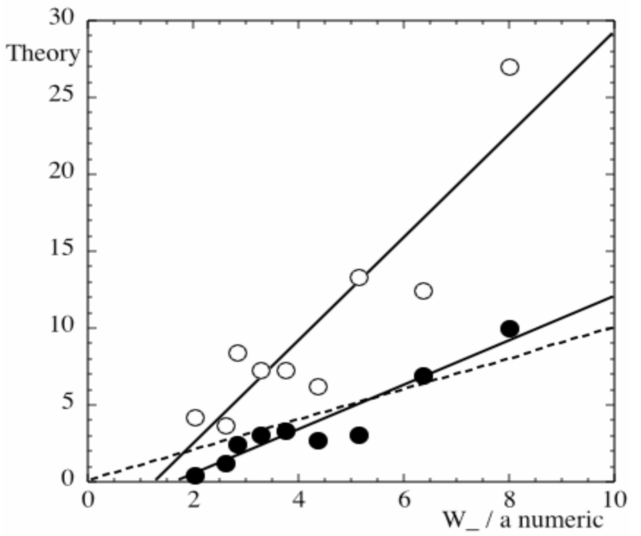
- $S=10^7$
- Open: $\chi_{//}/\chi_{\perp}=10^8$
- Closed: $\chi_{//}/\chi_{\perp}=6.25.10^6$
- ITER:m/n=4/3 (circles)
  m/n=3/2 (squares)
  m/n=2/1 (triangles)
  TS: m/n=2/1 (diamonds)

- Threshold with given geometry and $\chi_{//}/\chi_{\perp}$ depends on S.
- For ITER, $S>10^{10}$----> threshold at $f_{bs} >> 2$

NTM: nonlinear stability thresholds



- NTM dynamics (m=4/n=3) about its nonlinear threshold (ITER)



•Thresholds: numerics (XTOR) vs. Theory

•Closed symbols: with linear correction i.e

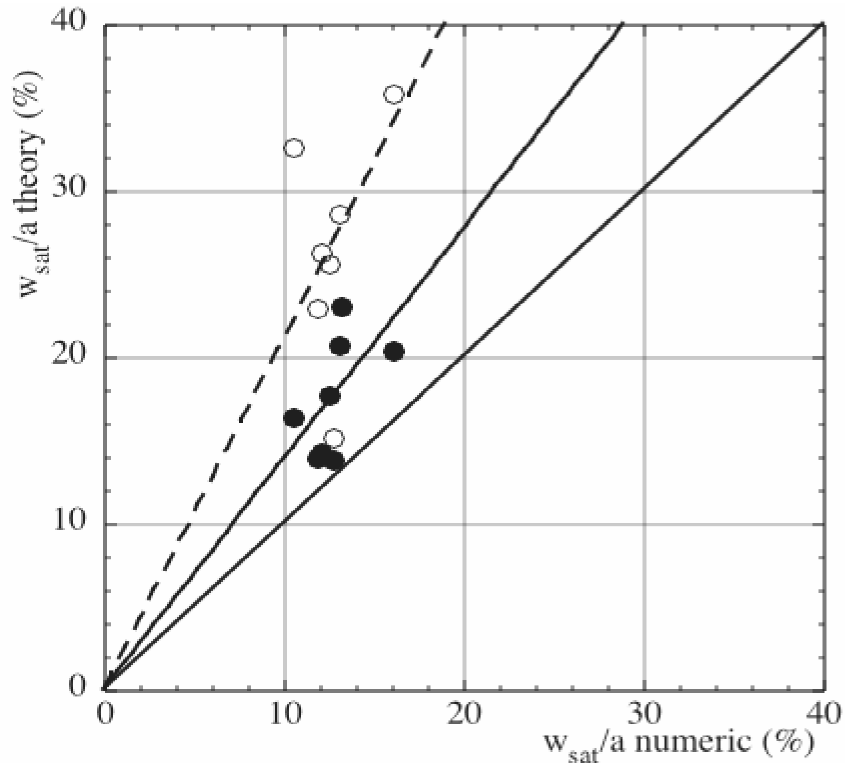
$$\frac{\tau_r}{1.22}\frac{dw}{dt} = \Delta'_{eff}\frac{w}{w+w_{lin}} + \Delta'_{boot}\,; \quad \Delta'_{eff} = \Delta' + \sqrt{2}\,\pi^{\frac{3}{2}}\frac{D_R}{W_c}$$

•Opens symbols: without linear corrections

NTM: saturation

- Comparison of NTM saturation levels in ITER geometry with leading edge theory:

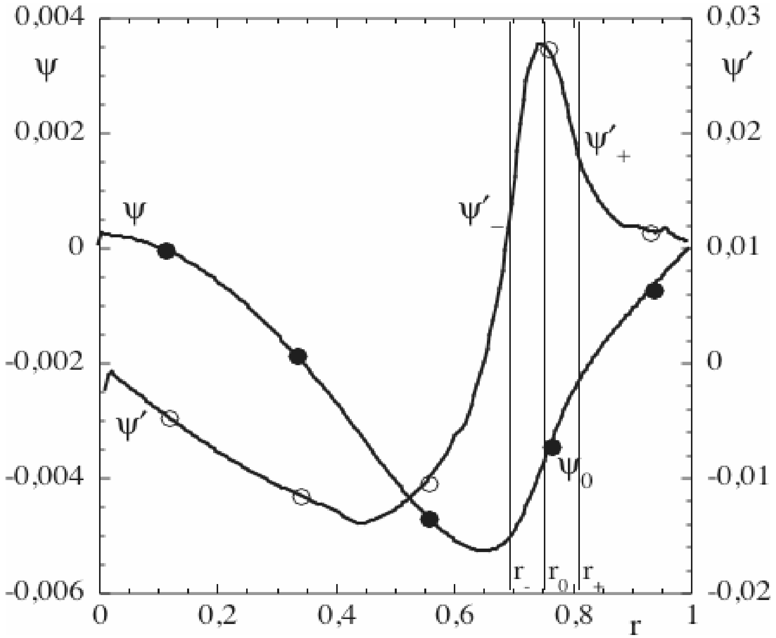
  XTOR gives much smaller saturation sizes than predicted with Rutherford



Validity field of Rutherford vs. Numerical XTOR results:

•Rutherford ---> Boundary layer approximation
---> w and Δ' are small

•XTOR saturation: $\frac{m}{r_s} w \approx 1; \quad \frac{\psi'}{\psi} w \approx 1$

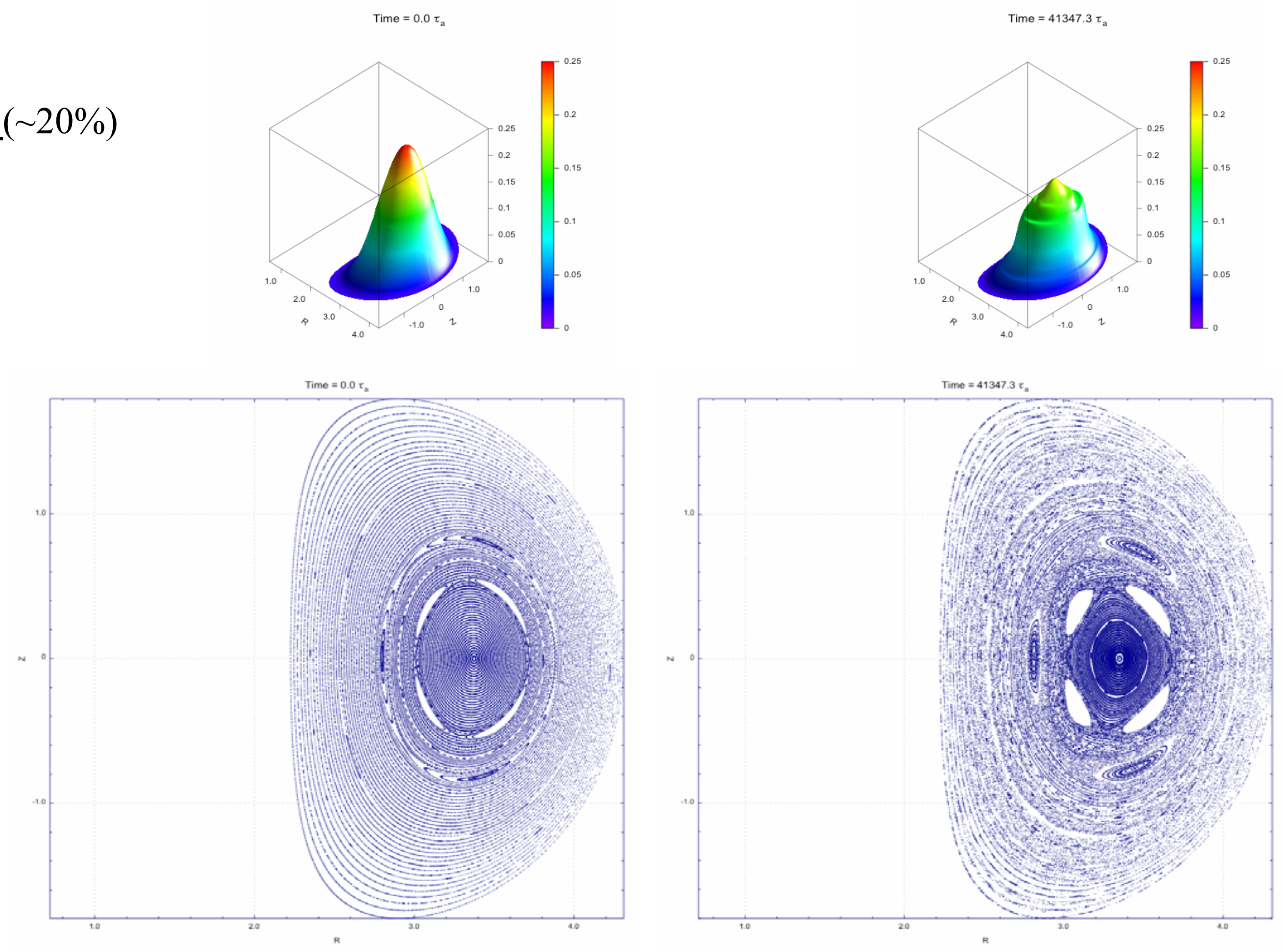


•Theory derived with constant Ψ approx. Shape of Ψ(r)
•XTOR does not satisfy these assumption.

NTM: toroïdal interactions

<u>Equilibrium bootstrap:</u>(~20%)

<u>Example:</u>
Growth of 2 NTM's
m/n=4/3 et 3/2



•NTM’s with m/n=2/1,3/2,4/3
•Single, double or triple mode simulations
•Initial perturbation W_ or W_{sat}.
•$S=10^7$ and $\chi_{//}/\chi_{\perp}=10^8$
•Iter geometry

Observations:

•Within the framework of the XTOR model, and the Simulations times (about 60000 τ_a), no toroïdal coupling was observed. No interaction as measured in experiments
•In multiple mode simulations, island overlap cause large stochastics zones, which empty the central pressure.

Conclusions

•Full numerical simulations show a reasonable agreement with generalized Rutherford’s equation in the small island regime. Acceptable results are obtained for nonlinear NTM thresholds.

•In the NTM saturation regime, simulation results and theory disagree. XTOR results give much smaller saturation sizes than theory.

•We have not observed toroïdal mode coupling effects in multiple NTM runs.