MPPC
Max-Planck-Princeton
Center for Plasma Physics

Nonlinear evolution of edge-localized modes in realistic ASDEX Upgrade geometry

ASDEX Upgrade

IPP

I. Krebs[1], M. Hölzl[1], K. Lackner[1], S. Günter[1] and the ASDEX Upgrade team[1]

ikrebs@ipp.mpg.de

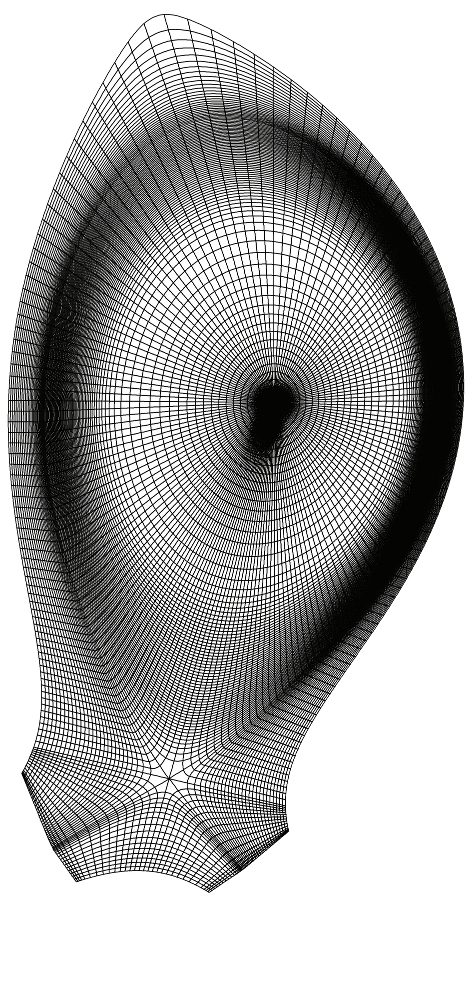
[1]Max Planck Institute for Plasma Physics, EURATOM Association, Boltzmannstr. 2, 85748 Garching, Germany

Abstract

Edge-localized modes (ELMs) were simulated in ASDEX Upgrade geometry using the nonlinear MHD code JOREK. Emphasis was put onto the evolution of the mode structure of the perturbation in the early ELM phase which is characterized by the exponential growth of the unstable toroidal Fourier harmonics followed by a phase of saturation. After a linear phase where the harmonics grow independently of each other, nonlinear mode interaction becomes important at higher amplitudes and energy is transferred among them. Prior to mode saturation, the evolution of the toroidal mode structure can be reproduced to a large extent by a simple quadratic mode coupling model. This model yields a possible explanation for the strong n=1 toroidal harmonic observed experimentally for ELMs in TCV. It is analyzed how the poloidal and radial structure of the n=1 is changed by nonlinear mode coupling.

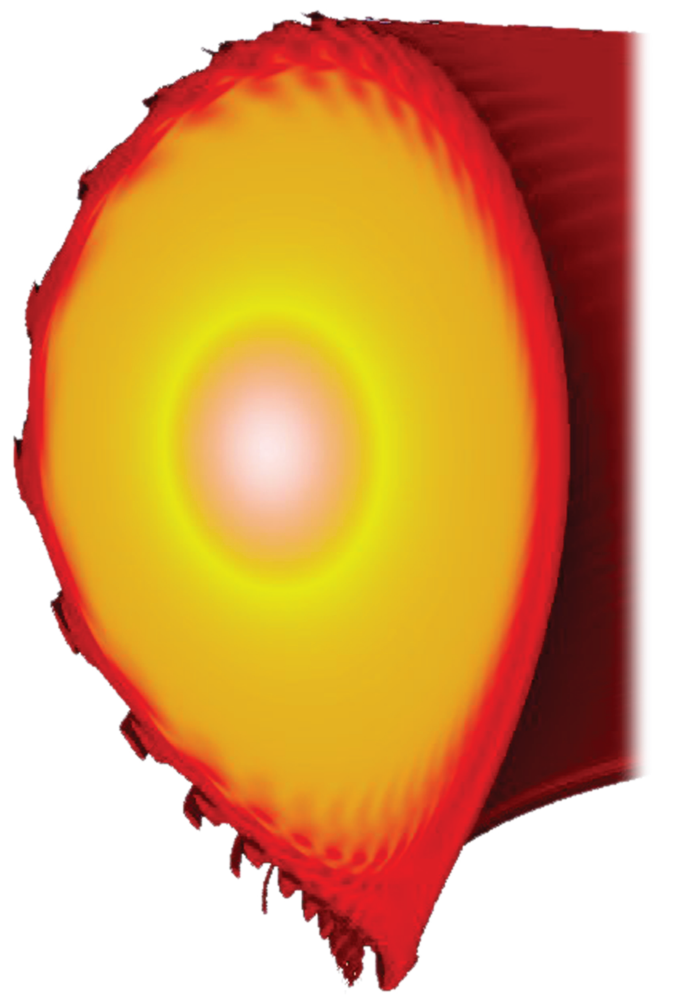
JOREK code

- nonlinear reduced MHD equations
- full toroidal X-point geometry including separatrix & open field lines
- 2D Bézier finite elements in poloidal plane & toroidal Fourier decomposition
- flux surface aligned grid
- fully implicit time stepping
- originally developed by G.T. A. Huysmans [1,2]



Edge-localized modes (ELMs)

- relaxation-oscillation instability in tokamak plasmas
- occur at the edge of H-mode plasmas
- driven by large edge density & temperature gradients
- each event ejects particles & energy from plasma
- **advantage**: help to control particle & impurity content
- **problem**: particle & energy losses degrade performance and high heat fluxes can damage plasma facing components



The simulations

- based on a typical type-I ELMy H-mode discharge of the ASDEX Upgrade tokamak
- ideally conducting wall around the plasma
- realistic values of viscosity & heat diffusion anisotropy, increased resistivity for resolution reasons
- analysis: Fourier decomposition of perturbation

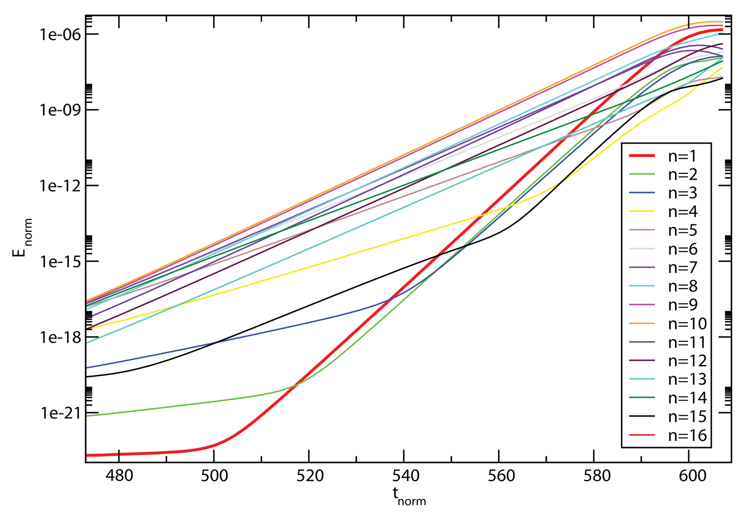
$$\xi(\vec{x}) = \sum_{m,n=-\infty}^{\infty} \xi_{mn}(r)\exp[-i(m\theta + n\varphi)]$$

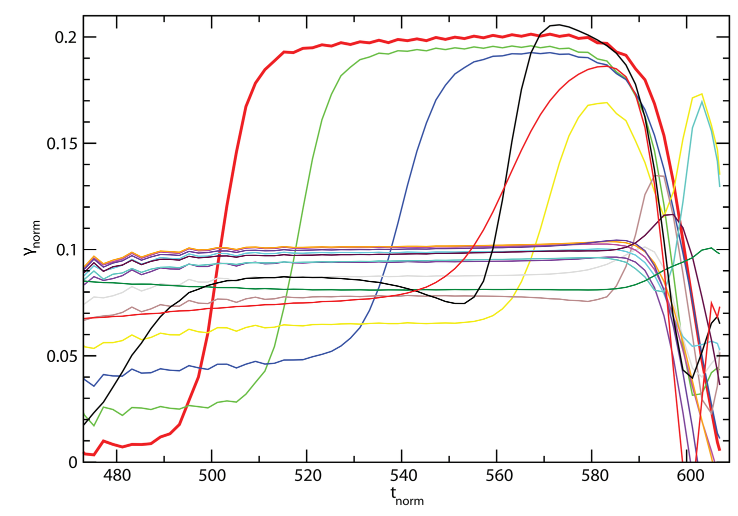
Growth of the toroidal Fourier harmonics

- three phases of time evolution:

→ **linear phase:** constant growth rates, harmonics grow independently
→ **nonlinear growth:** growth rates influenced by interaction between harmonics
→ **saturation:** growth rates decrease

- **simulations:** originally subdominant n=1 becomes important during nonlinear phase
- **experiment:** dominant n=1 observed in TCV [3]





Simple mode interaction model

- **idea:** energy transfer among toroidal harmonics via **quadratic mode coupling** ("sum and difference mode number generation")

→ set of coupled differential equations, e.g. for n= 4, 8, 12, 16:

$$\frac{\partial A_4}{\partial t} = \gamma_4 A_4 + \gamma_{(8,-4)} A_4 A_8 + \gamma_{(12,-8)} A_8 A_{12} + \gamma_{(16,-12)} A_{12} A_{16}$$

$$\frac{\partial A_8}{\partial t} = \gamma_8 A_8 + \gamma_{(4,4)} A_4 A_4 + \gamma_{(12,-4)} A_4 A_{12} + \gamma_{(16,-8)} A_8 A_{16}$$

$$\frac{\partial A_{12}}{\partial t} = \gamma_{12} A_{12} + \gamma_{(4,8)} A_4 A_8 + \gamma_{(16,-4)} A_4 A_{16}$$

$$\frac{\partial A_{16}}{\partial t} = \gamma_{16} A_{16} + \gamma_{(8,8)} A_8 A_8 + \gamma_{(4,12)} A_4 A_{12}$$

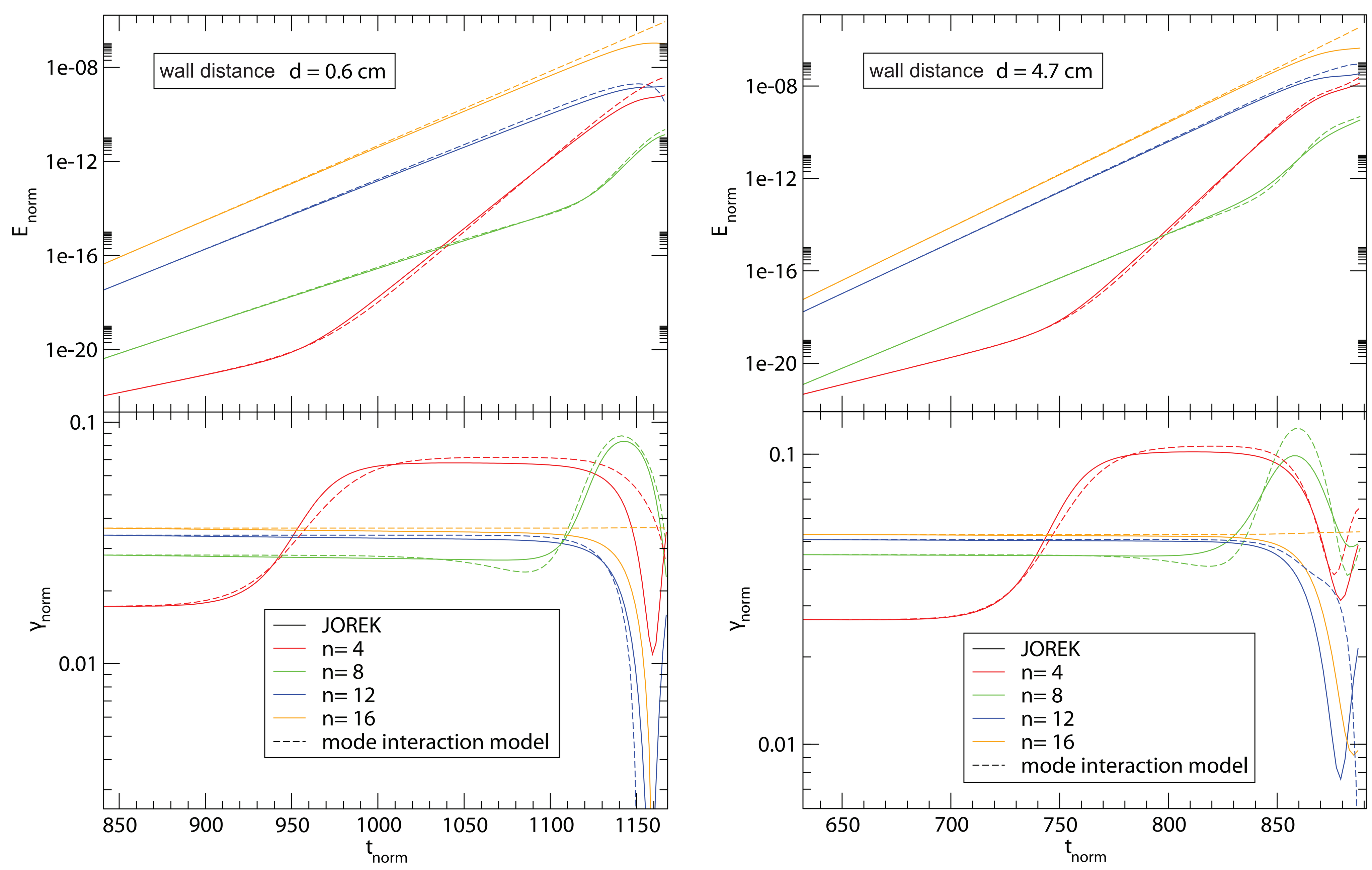
where A_i = amplitudes of toroidal harmonics
γ_i = linear growth rates
γ_{jk} = coupling constants

- energy conservation

→ constraints on the coupling constants

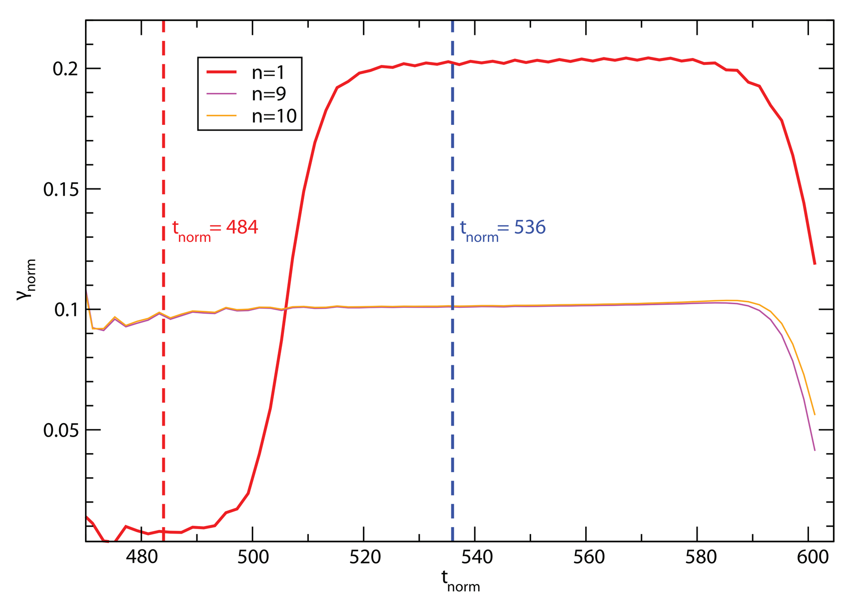
- assumes mode rigidity
- does not include saturation effects
- **reproduces & explains JOREK results**

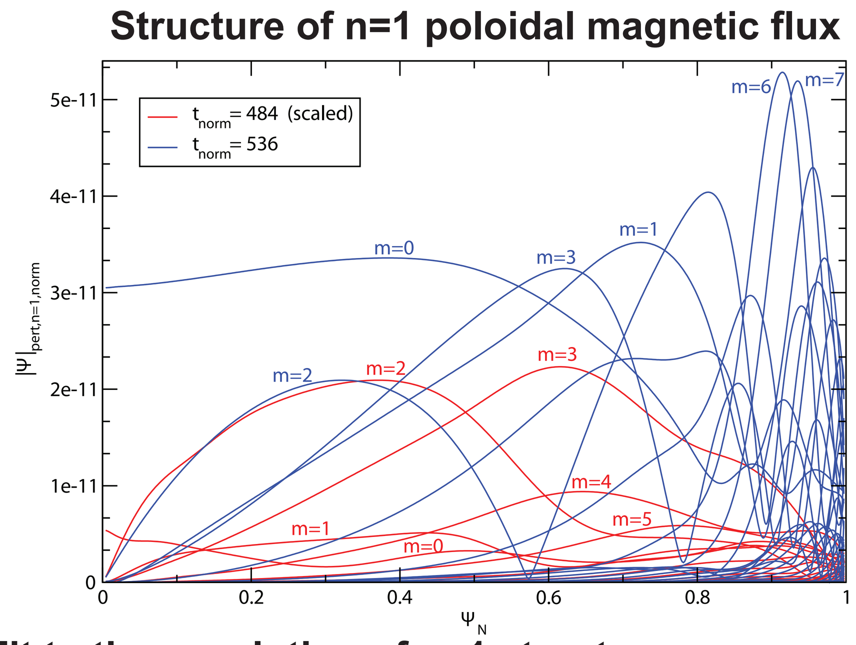
Comparison JOREK ↔ mode interaction model

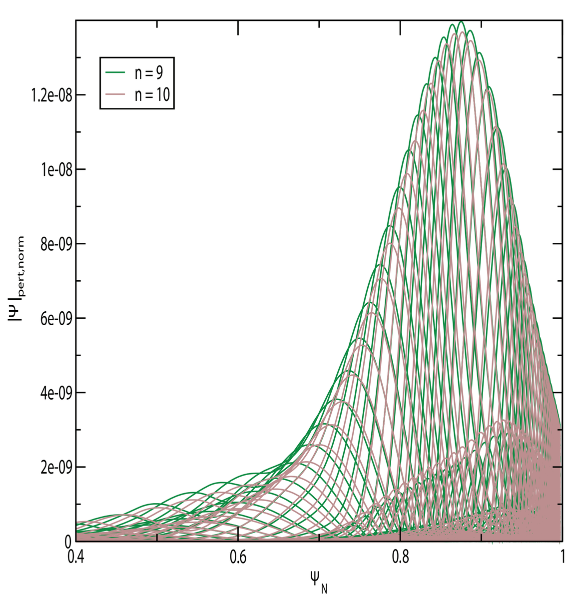


How the structure of n=1 changes due to mode interaction

- **energy transfer** from **pairs** of linearly dominant toroidal harmonics with neighboring mode numbers **to n=1**
- simulations including only n= 1, 9, 10 are used to analyze influence of nonlinear mode coupling on n=1
- poloidal and radial **structure** of n=1 **changes abruptly** when mode interaction becomes important





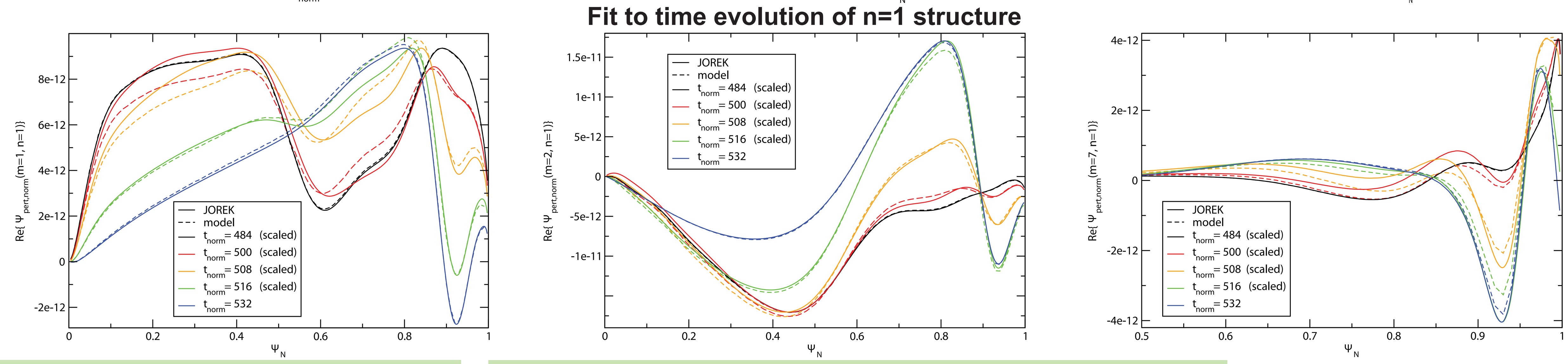


Superposition of rigidly growing structures

- evolution of the n=1 structure can be **reproduced** quite well by superposing two different exponentially growing rigid mode structures with different growth rates:

→ a linearly unstable n=1 and a linearly stable n=1 triggered by nonlinear interaction

Fit to time evolution of n=1 structure



Summary

- ELMs have been simulated using the nonlinear reduced MHD code JOREK in ASDEX Upgrade geometry
- simple quadratic mode coupling model reproduces time traces of energies contained in toroidal harmonics of the perturbation in early nonlinear phase of JOREK simulations
- dominance of the n=1 toroidal harmonic for ELMs in experiments is explained by quadratic mode coupling
- change of the structure of the n=1 in the poloidal plane due to nonlinear interaction is investigated

Outlook

- investigate if superposition of two rigid structures suffices to describe evolution of the n=1 structure
- apply mode coupling model to simulation with n= 1, 2, ..., 15, 16
- analyze influence of ideal wall onto growth of the n=1
- include further extensions of JOREK physics model (two fluid, differential rotation, resistive walls,...)

References:

[1] GTA Huysmans and O Czarny, Nucl Fusion 47, 659 (2007).
[2] O Czarny and GTA Huysmans, J Comput Phys 227, 7423 (2008).
[3] RP Wenninger et al., to be published (2013).