EUROfusion

Non-linear 3D Hybrid Kinetic-MHD Simulations of ELMs in the ASDEX Upgrade Tokamak with MEGA

J. Dominguez-Palacios, S. Futatani, J. Gonzalez-Martin, M. Garcia-Munoz, M. Toscano-Jimenez, E. Viezzer, Y. Suzuki, Y. Todo, J. Galdon-Quiroga, M. Hoelzl, P. Oyola, J. Rivero-Rodriguez, C. Soria-Hoyo, ASDEX Upgrade and EUROfusion MST1 Teams

Universidad de Sevilla · PSFT Plasma Science and Fusion Technology · NIFS · UPC · IPP · ASDEX Upgrade

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Outline

- Motivation
- 3D non-linear hybrid kinetic-MHD MEGA
- Non-linear MHD simulations of ELMs
- Fast-ion effects on ELM stability
- Summary and outlook

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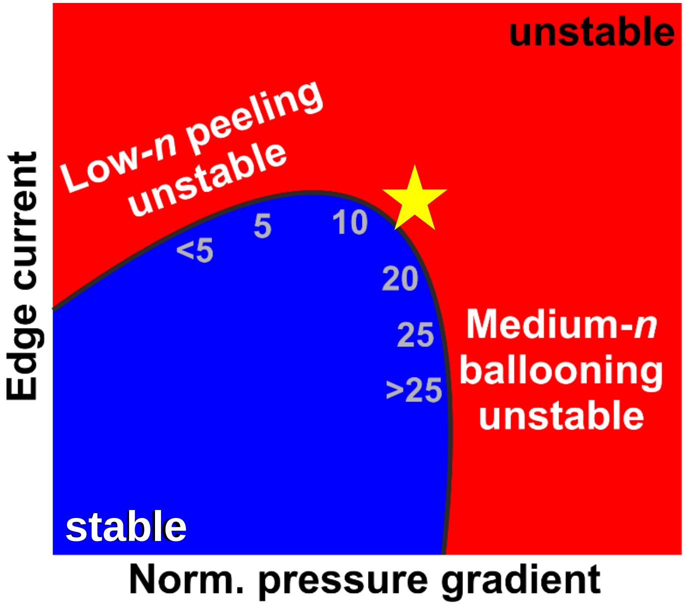
- ELMs appear in H-mode
  → Peeling-ballooning unstable

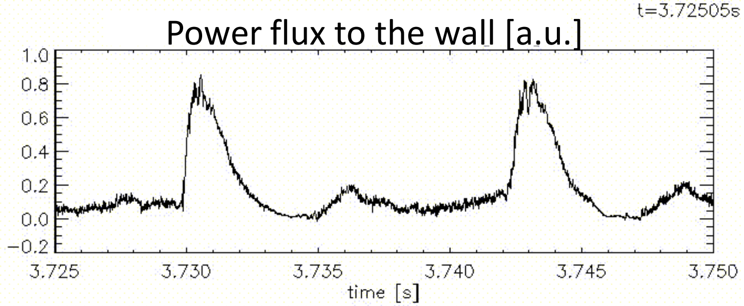


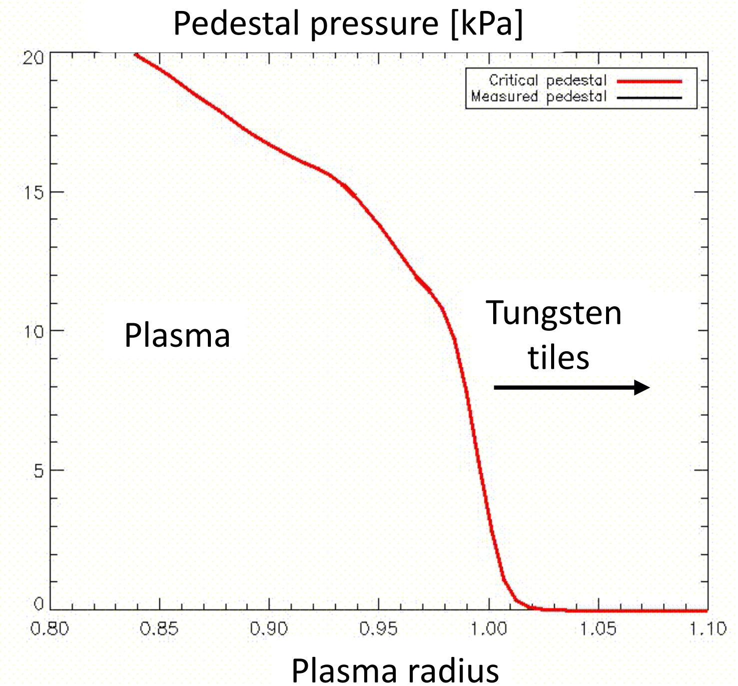
*E. Viezzer

Motivation

- ELMs appear in H-mode
  → Peeling-ballooning unstable

- ELMs expel particles and energy from plasma
  → Degradation of pedestal
  → Untolerable for future fusion devices





*A. Burckhart

Motivation

- ELMs appear in H-mode
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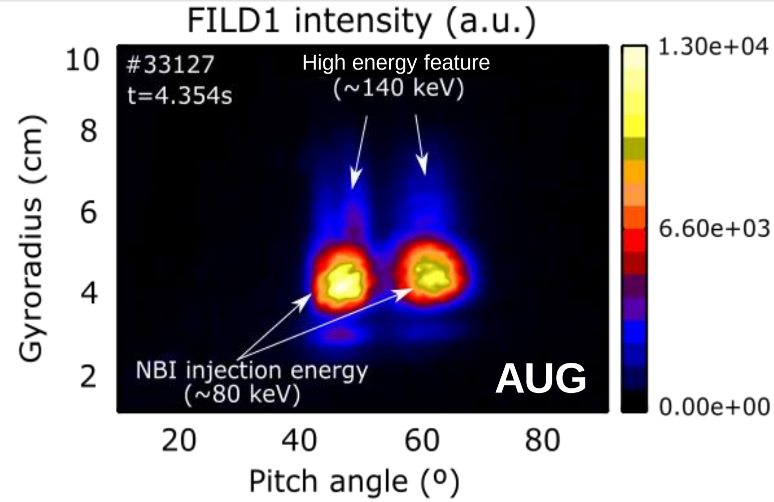
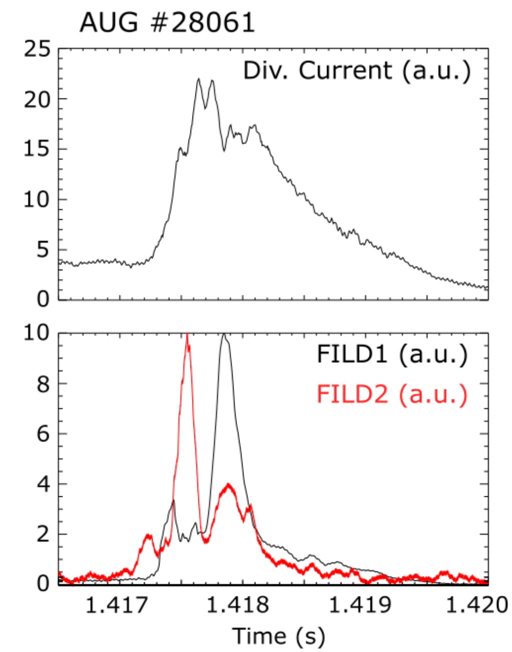
- Recent observations indicate strong interaction between ELMs and fast-ions





**See J.F. Rivero-Rodriguez (I-8, Wed 11:00)

*J. Galdon-Quiroga *et al.*, 2018, Phys. Rev. Lett. **121**, 025002

Motivation

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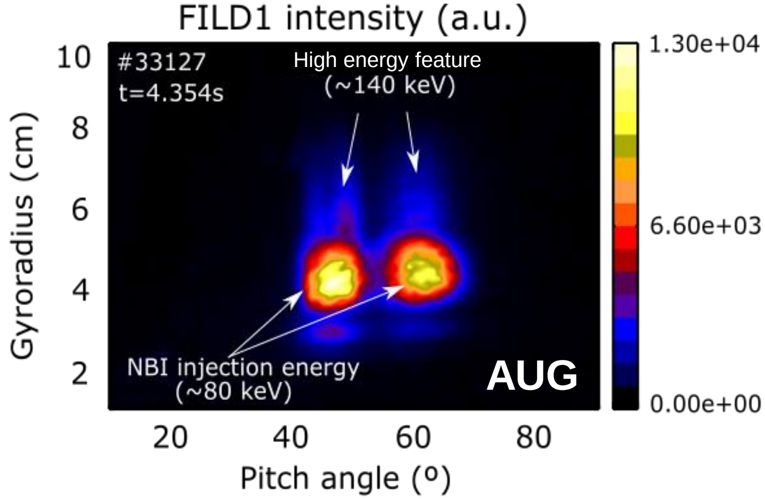
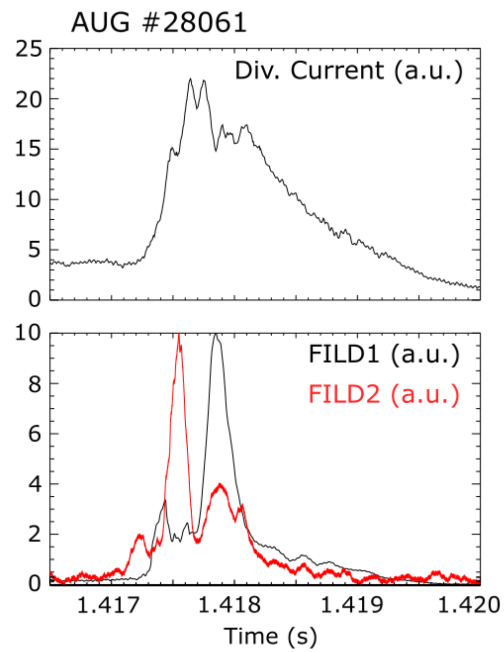
- **Kinetic effects needed in ELM modelling**





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3D Non-Linear Hybrid Kinetic-MHD Modelling of ELMs with MEGA

- Non-linear hybrid kinetic-MHD code[1]: EP and MHD dynamics coupled through EP current density as follows

$$\rho \frac{\partial \vec{v}}{\partial t} = -\rho(\vec{v}\cdot\nabla)\vec{v} - \nabla p + (\vec{j} - \vec{j}_{h'}) \times \vec{B} - \nabla \times (\nu\rho\nabla\times\vec{v}) + \frac{4}{3}\nabla(\nu\rho\nabla\cdot\vec{v})$$

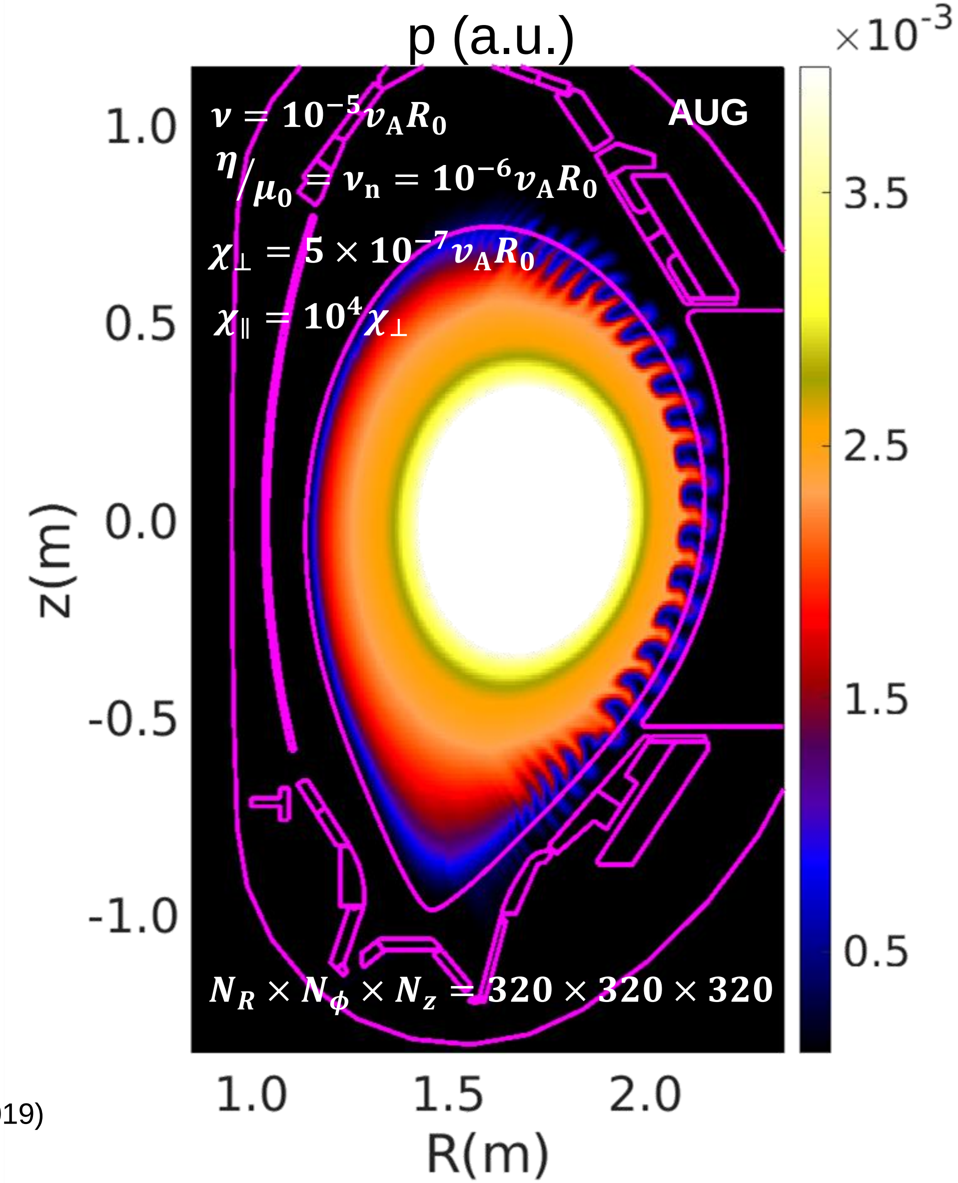
$$\frac{\partial p}{\partial t} = -\nabla\cdot(p\vec{v}) - (\gamma-1)p\nabla\cdot\vec{v} + \nabla\cdot\left[\chi_\perp\nabla_\perp\left(p - p_{\mathrm{eq}}\right) + \chi_\parallel\nabla_\parallel\left(p - p_{\mathrm{eq}}\right)\right]$$
$$+(\gamma-1)\left[\nu\rho(\nabla\times\vec{v})^2 + \frac{4}{3}\nu\rho(\nabla\cdot\vec{v})^2 + \eta(\vec{j} - \vec{j}_{h'})\cdot\left(\vec{j} - \vec{j}_{\mathrm{eq}}\right)\right]$$

- What do we need to consider for ELM simulations?

[1] Y. Todo *et al.*, Phys. Plasmas 5, 1321 (1998)

3D Non-Linear Hybrid Kinetic-MHD Modelling of ELMs with MEGA

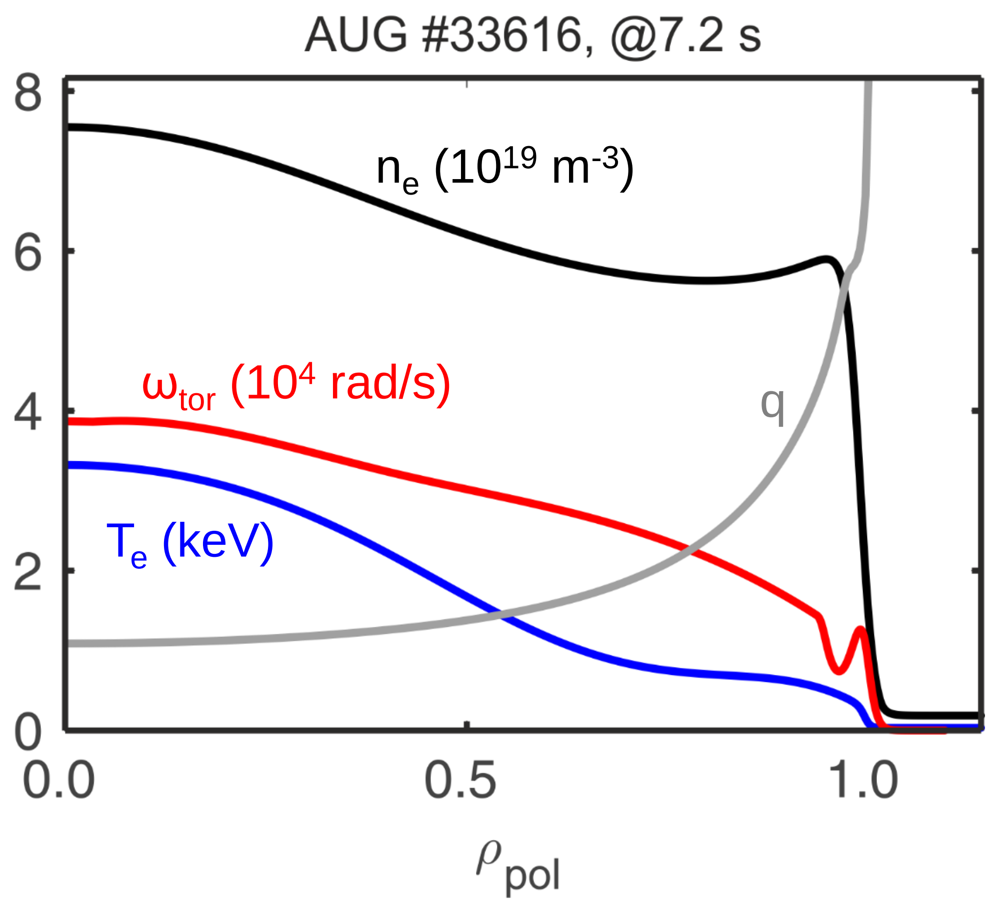
- Cylindrical coordinates (R, ϕ, z)
- Fully 3D rectangular geometry
- SOL and Private Flux Region below X-Point included in simulation domain[1]
  - ELM relevant area
  - Important to study the interaction with fast-ions



[1] S. Futatani *et al*., Plasma Phys. Control. Fusion 61, 095014 (2019)

3D Non-Linear Hybrid Kinetic-MHD Modelling of ELMs with MEGA

- Kinetic and rotation profiles of ASDEX Upgrade shot #33616 used as initial conditions
- Simulations include *n* < 20 (experimentally, dominant mode *n* ~2 - 5 during ELM crash[1])
- Single *n* simulations to calculate linear growth rates, multi *n* for non-linear phase
- Standard MHD model excluding diamagnetic, toroidal and neoclassical flows



[1] A.F. Mink *et al.*, Nucl. Fusion 58, 026011 (2018)

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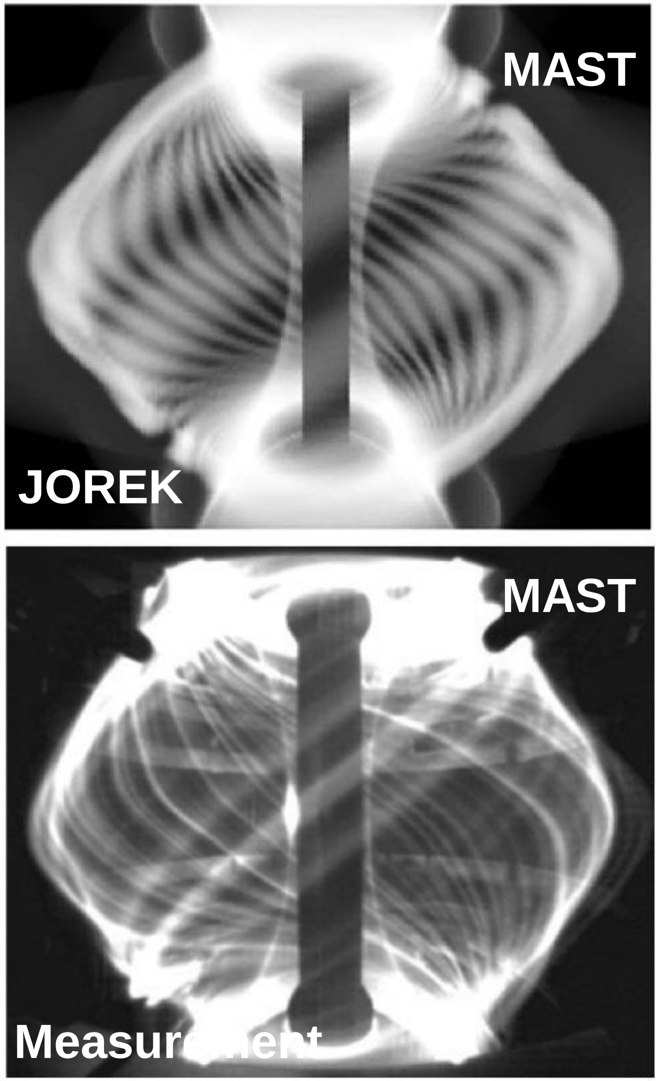
How to Identify an ELM in MEGA

- In standard MHD simulations, ELMs are characterized by[1]:
  - ➢ High *n* ballooning modes when using standard MHD
  - ➢ Non-linear growth of low *n* harmonics
  - ➢ Filamentary structure
  - ➢ Relaxation of profiles

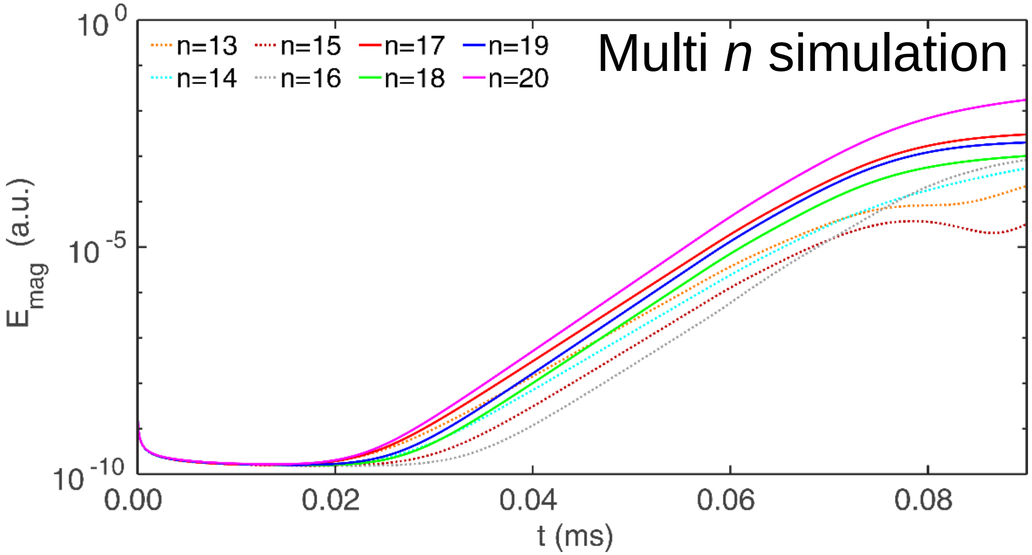
D_α image of an ELM in MAST[2]



[1] G.T.A. Huijsmans *et al*., Phys. Plasmas 22, 021805 (2015)

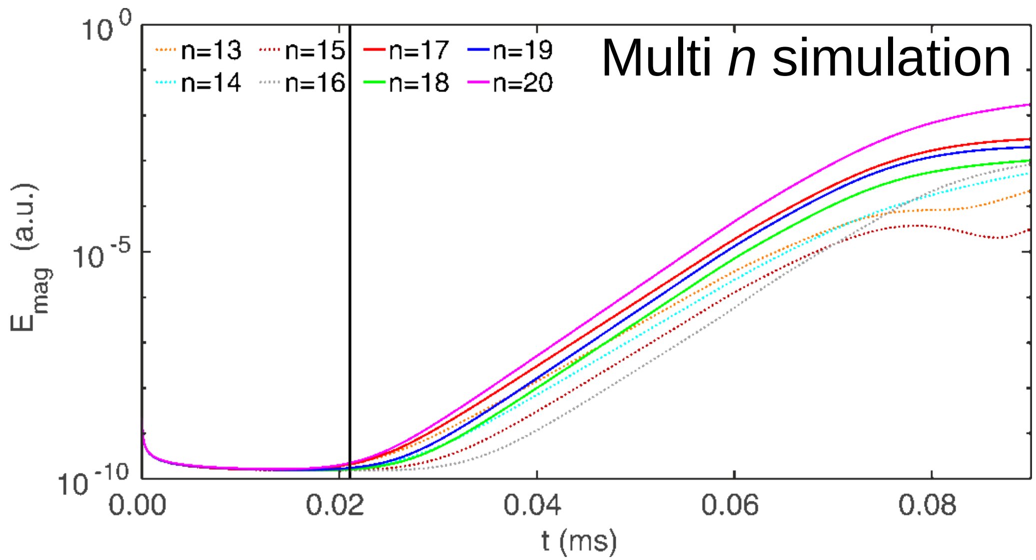
[2] S.J.P. Pamela *et al*., Plasma Phys. Control. Fusion 55, 095001 (2013)

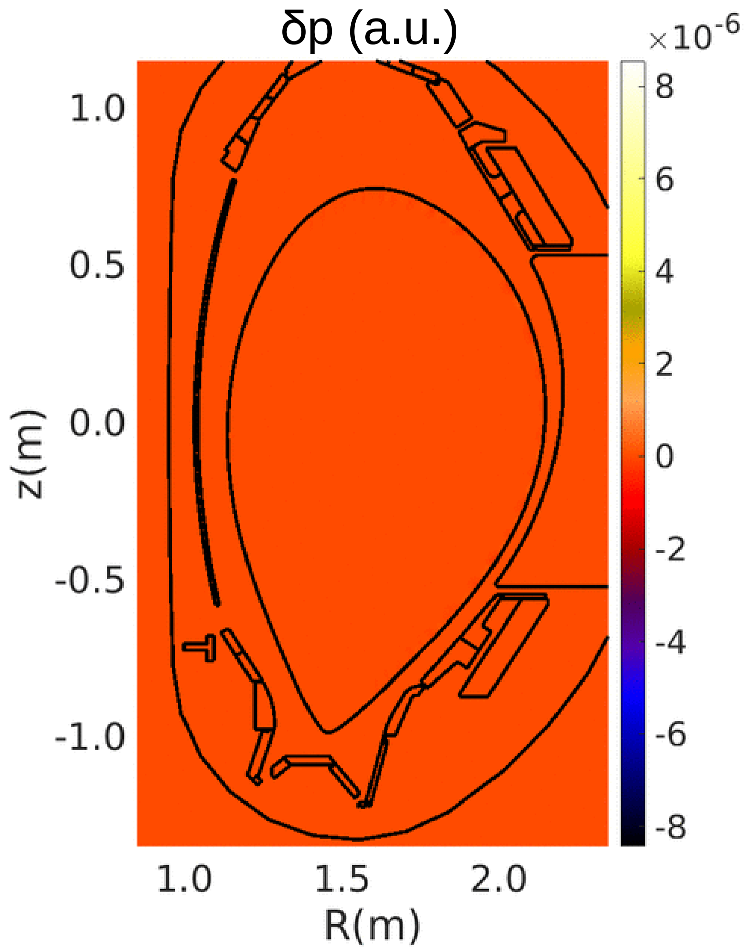
Ballooning Mode Structure Observed in Linear Phase



- High *n* (*n*>13) modes dominate linear phase

Ballooning Mode Structure Observed in Linear Phase





- High *n* (*n*>13) modes dominate linear phase

- Perturbation located at LFS (maximum pressure gradient)

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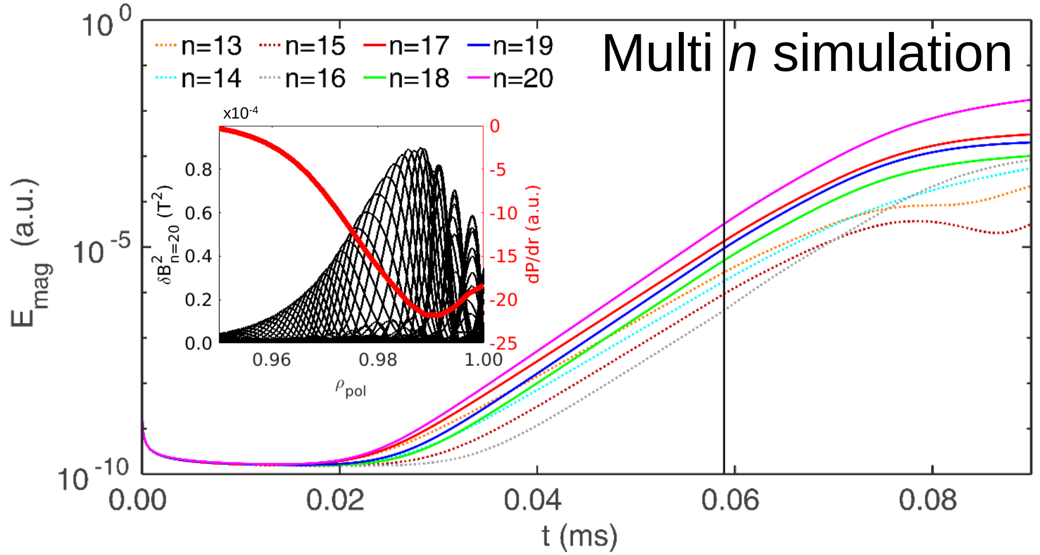

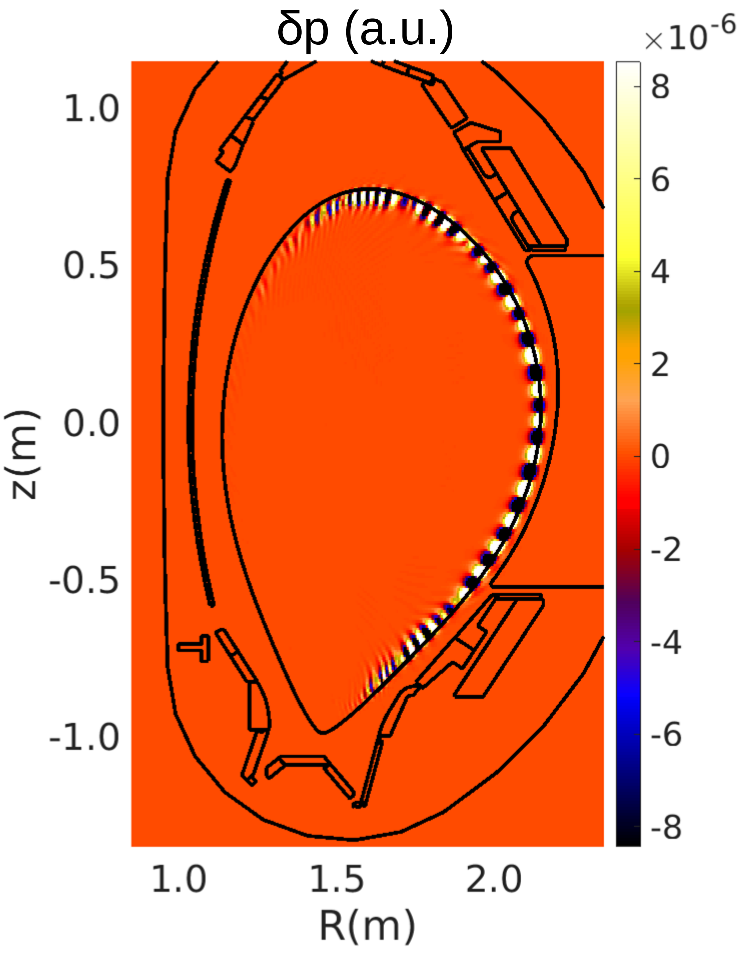

- High n (n>13) modes dominate linear phase
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➢ **Ballooning modes**

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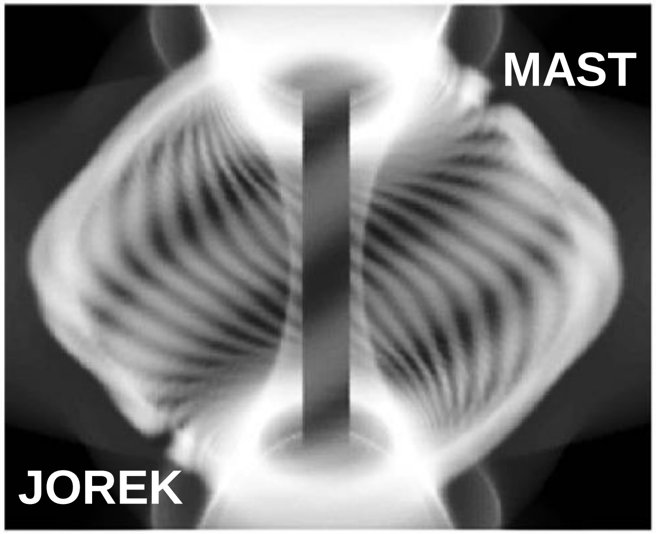
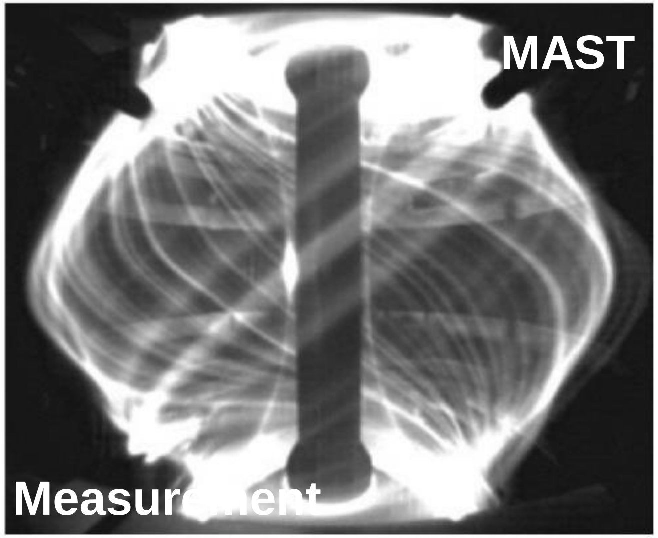
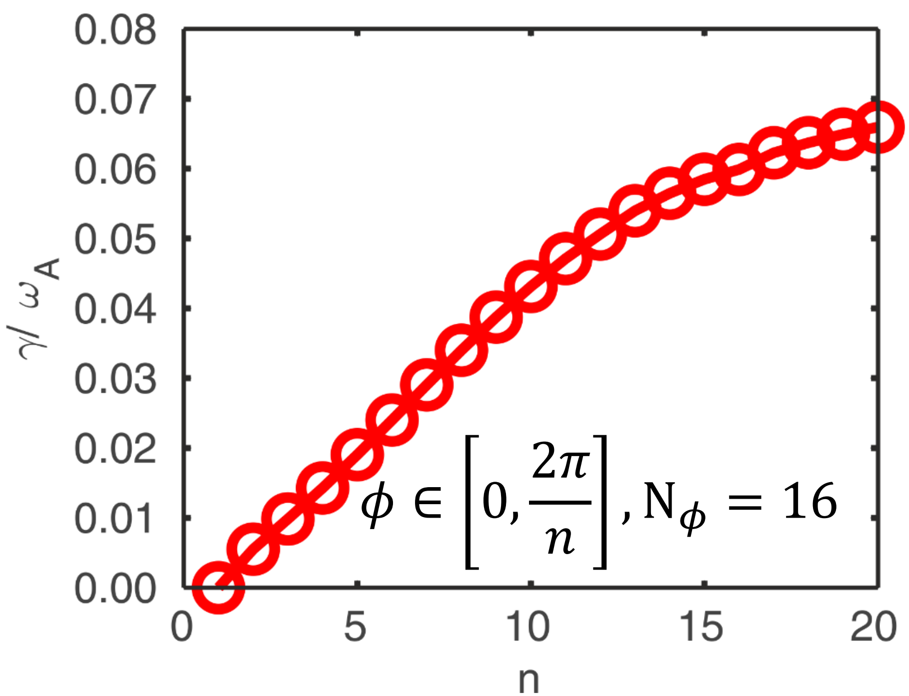




[1] G.T.A. Huijsmans *et al*., Phys. Plasmas 22, 021805 (2015)

[2] S.J.P. Pamela *et al*., Plasma Phys. Control. Fusion 55, 095001 (2013)

High *n* Instabilities Dominate Linear Phase in Standard MHD



- Higher linear growth rates for higher toroidal mode numbers

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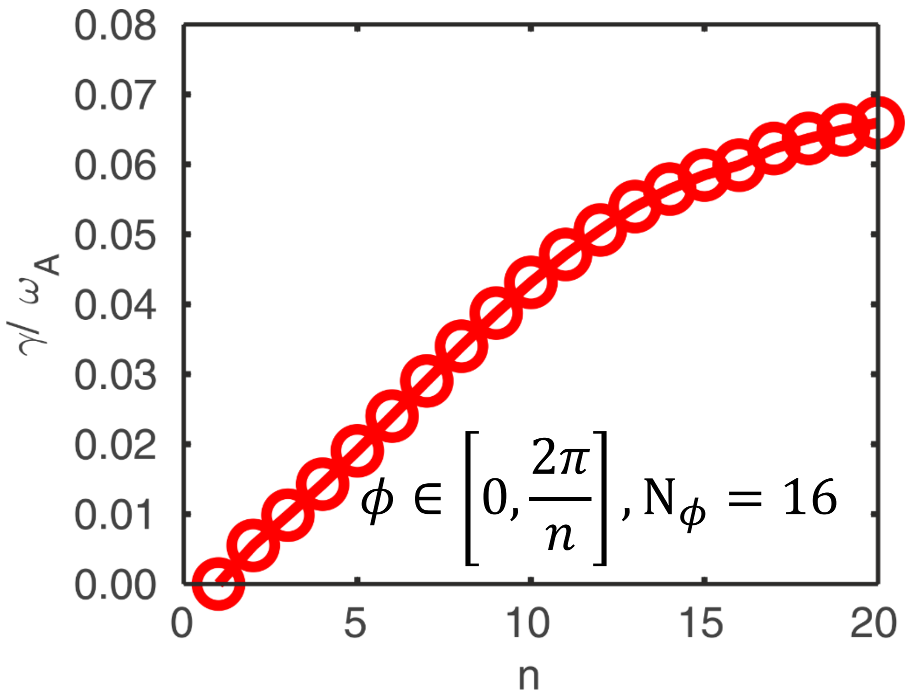
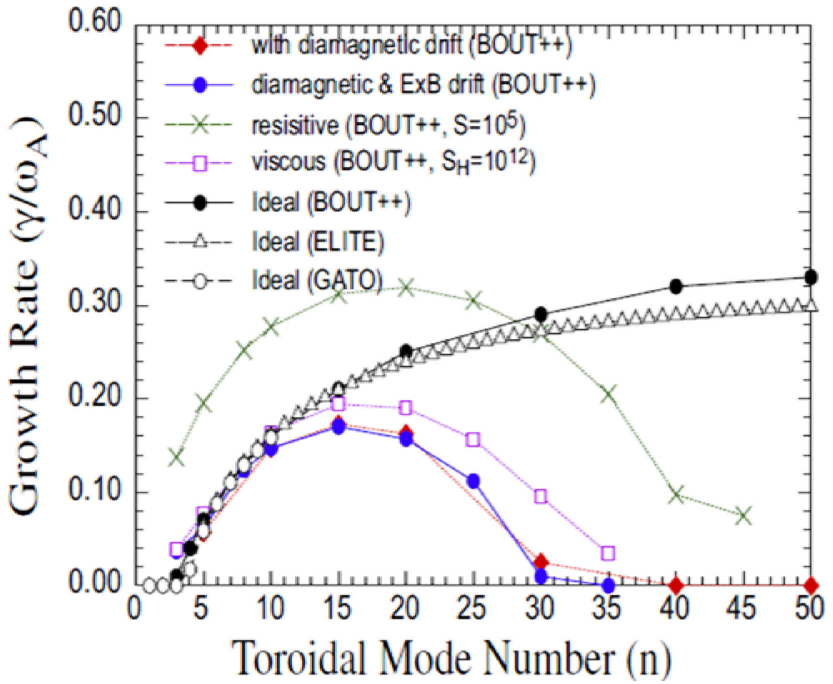
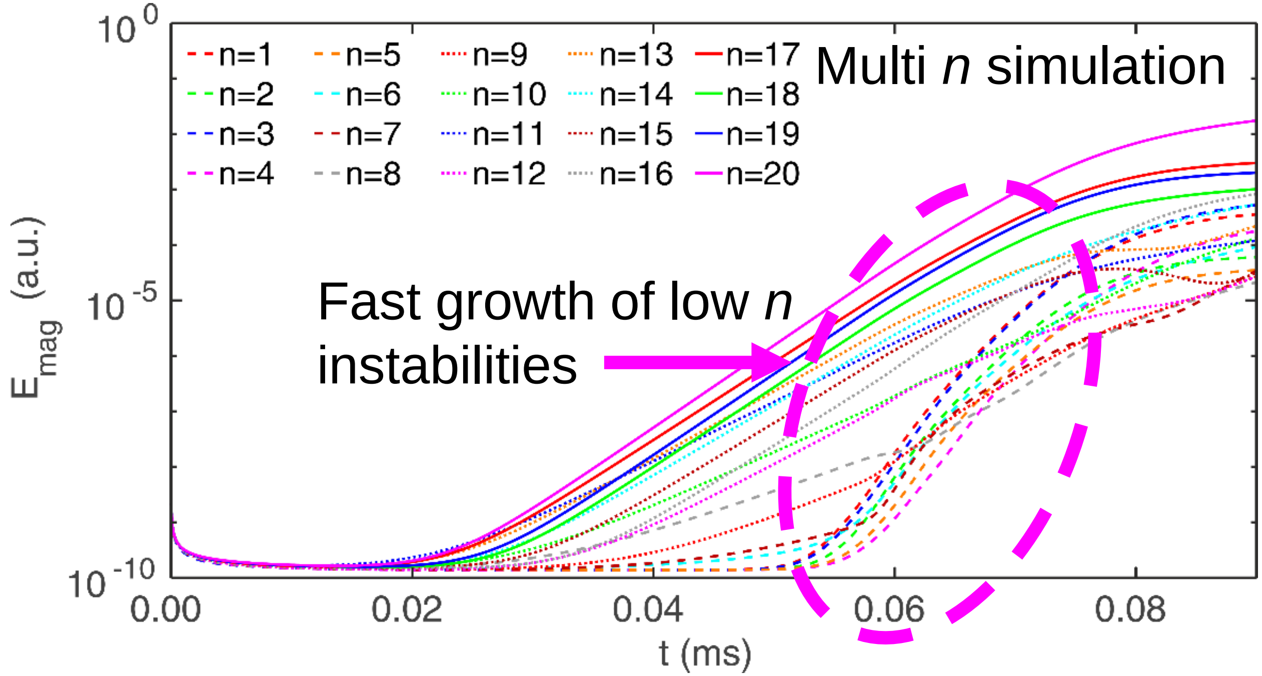




- Higher linear growth rates for higher toroidal mode numbers
- Results are in agreement with infinite *n* ballooning theory[1]

[1] X.Q. Xu *et al*., Nucl. Fusion 51, 103040 (2011)

Low *n* Modes Are Growing Faster Due to Non-Linear Coupling



- Linear phase in multi *n* simulation dominated by high *n* harmonics
- Fast non-linear growth of low *n* modes due to non-linear coupling[1]

[1] I. Krebs *et al.*, Phys. Plasmas 20, 082506 (2013)

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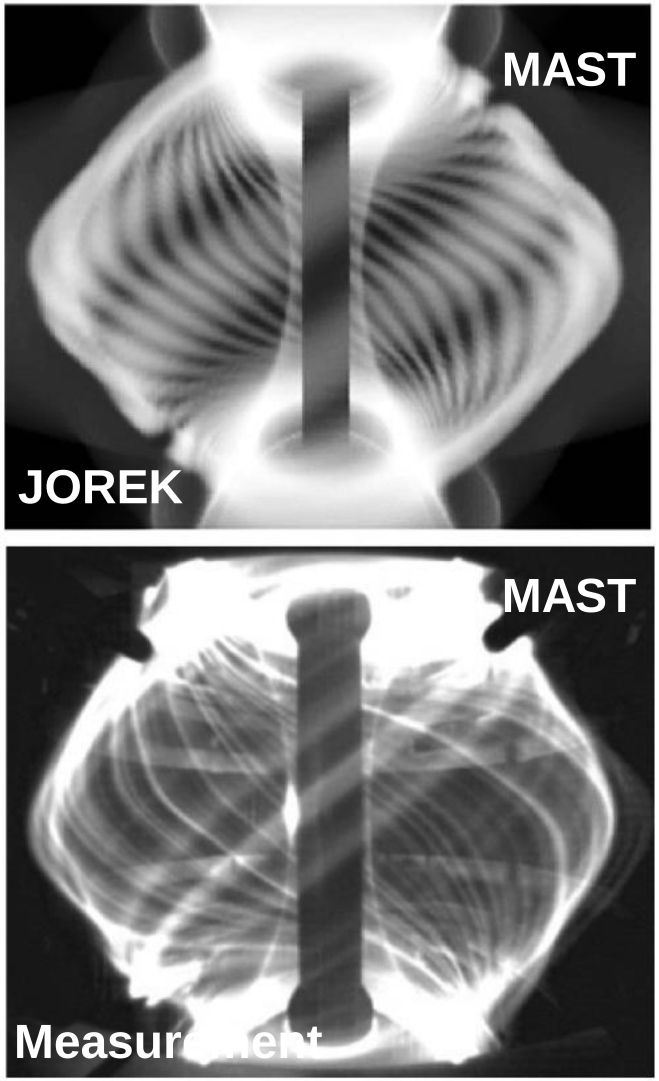

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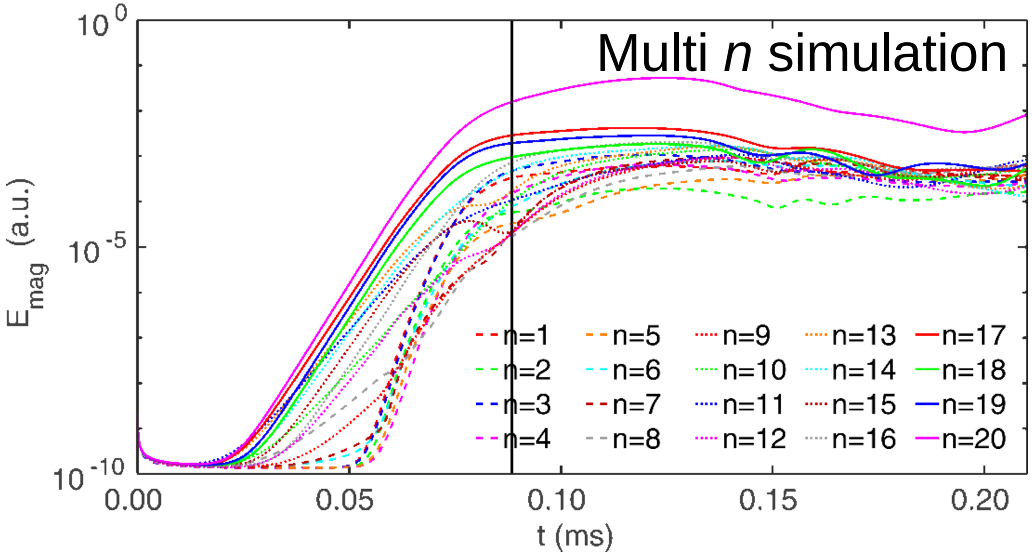
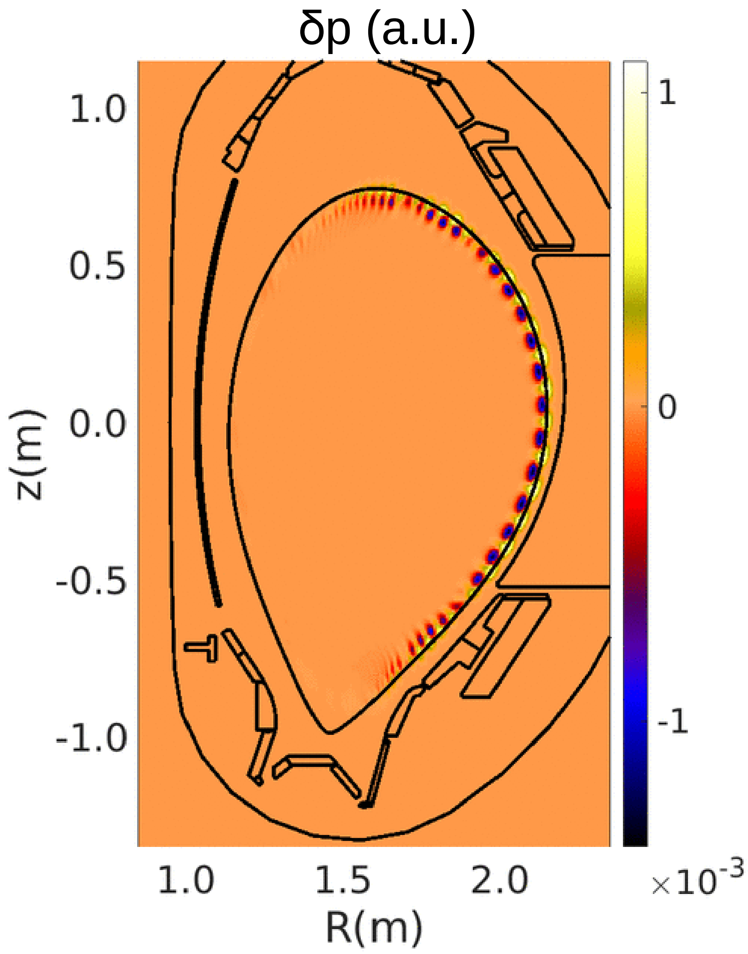
ELM Crash Successfully Simulated With MEGA





- Modes saturate and filaments extend into SOL

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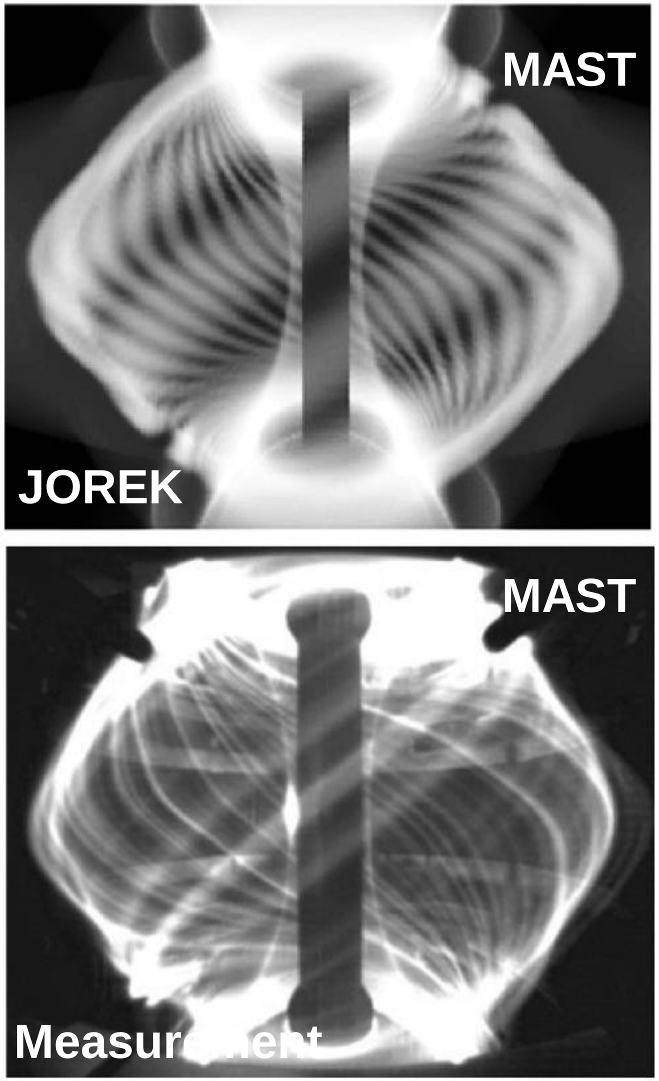

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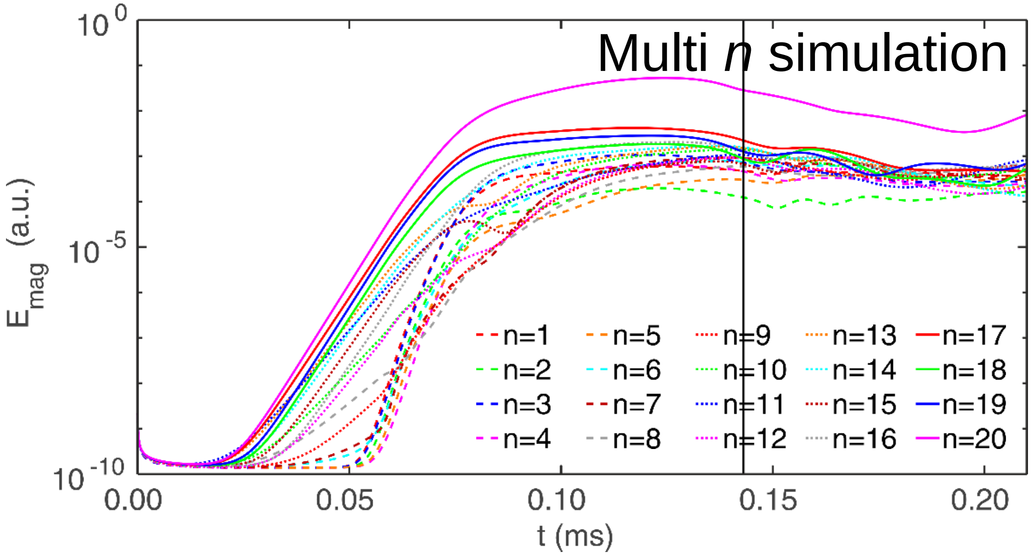

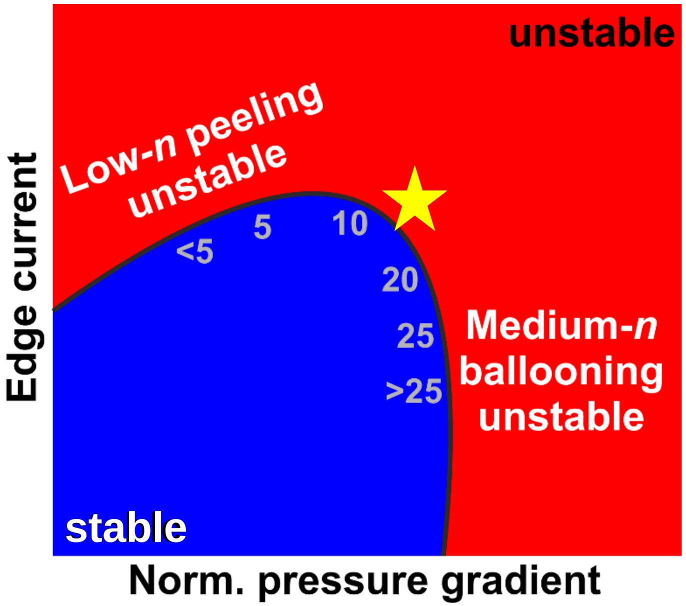

- Modes saturate and filaments extend into SOL

- Saturation due to reduction of drive

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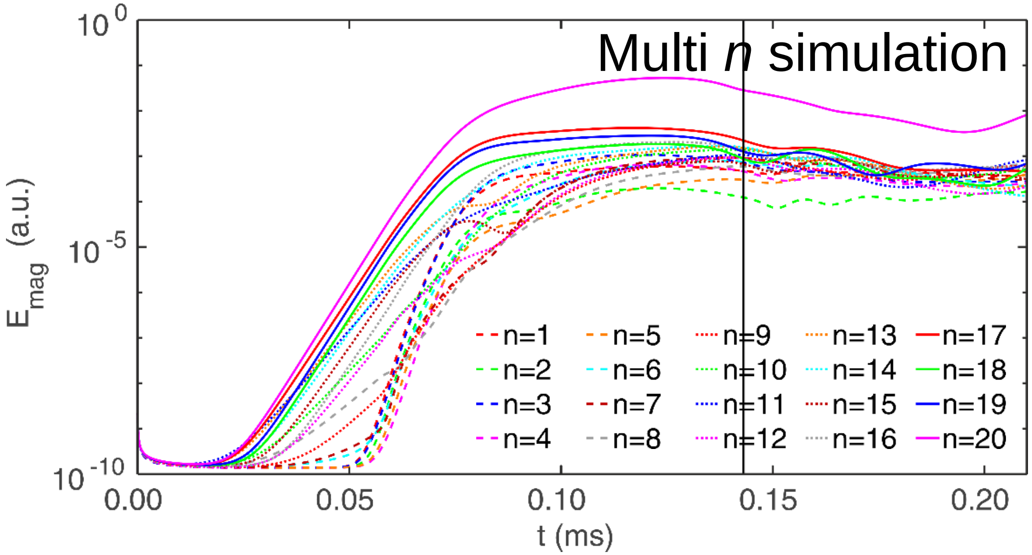

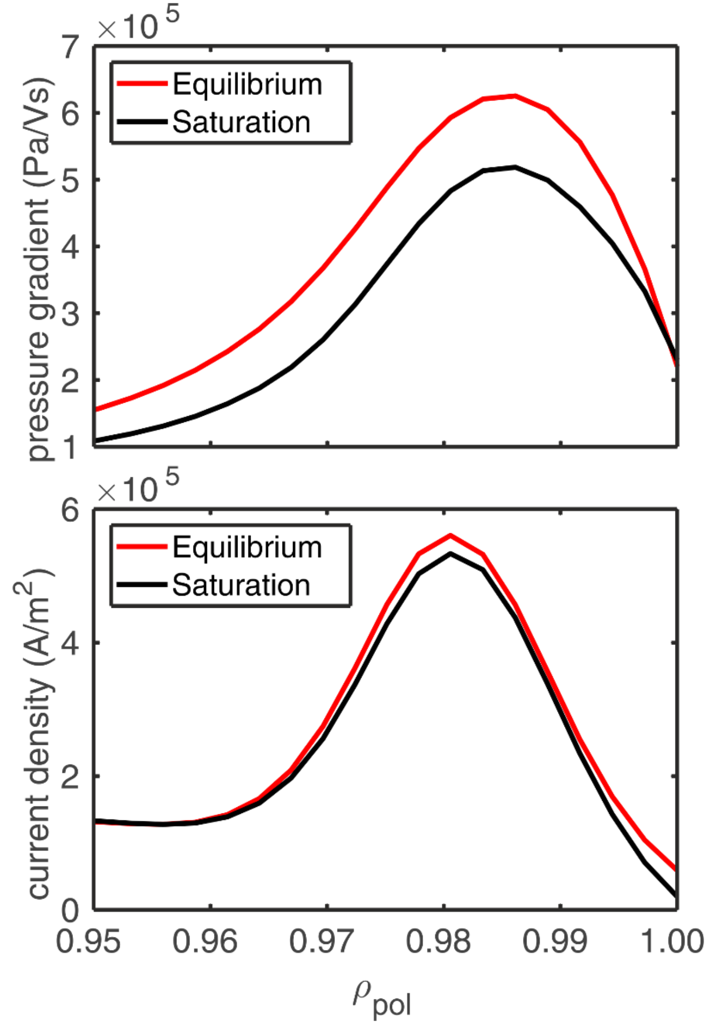

- Modes saturate and filaments extend into SOL
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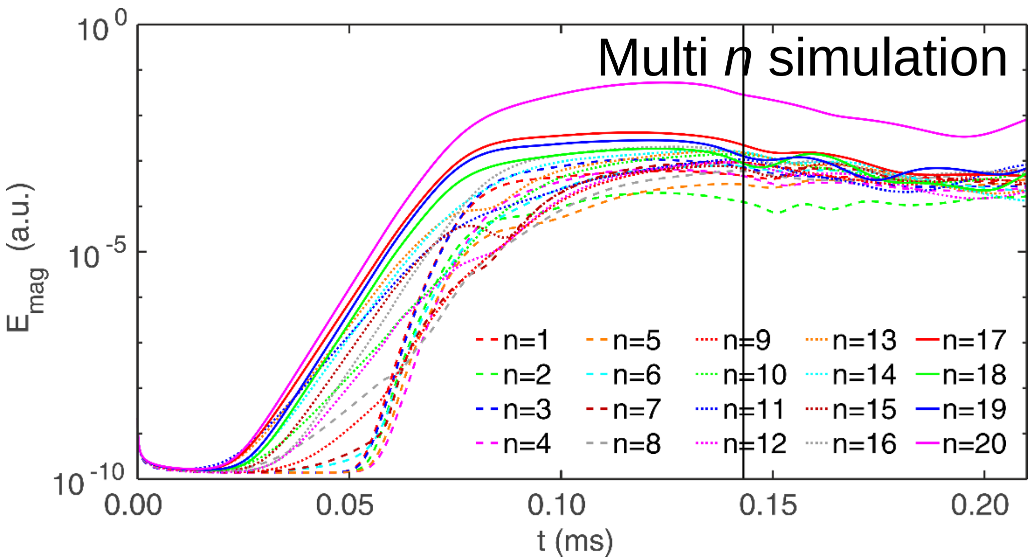
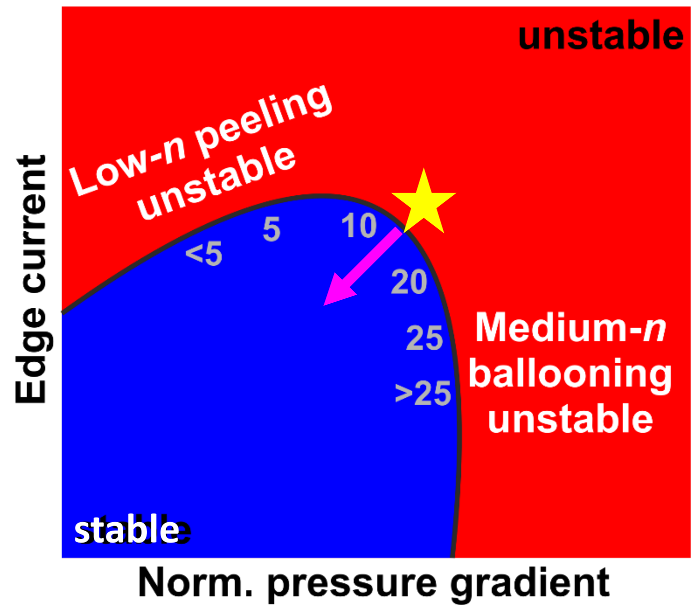
  - ➢ Instability has ballooning nature

ELM Crash Successfully Simulated With MEGA





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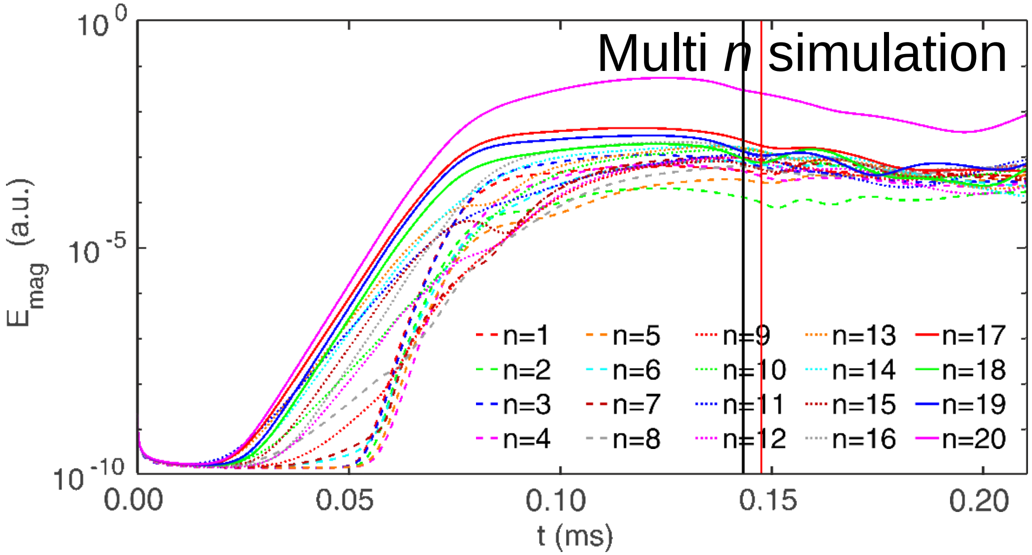

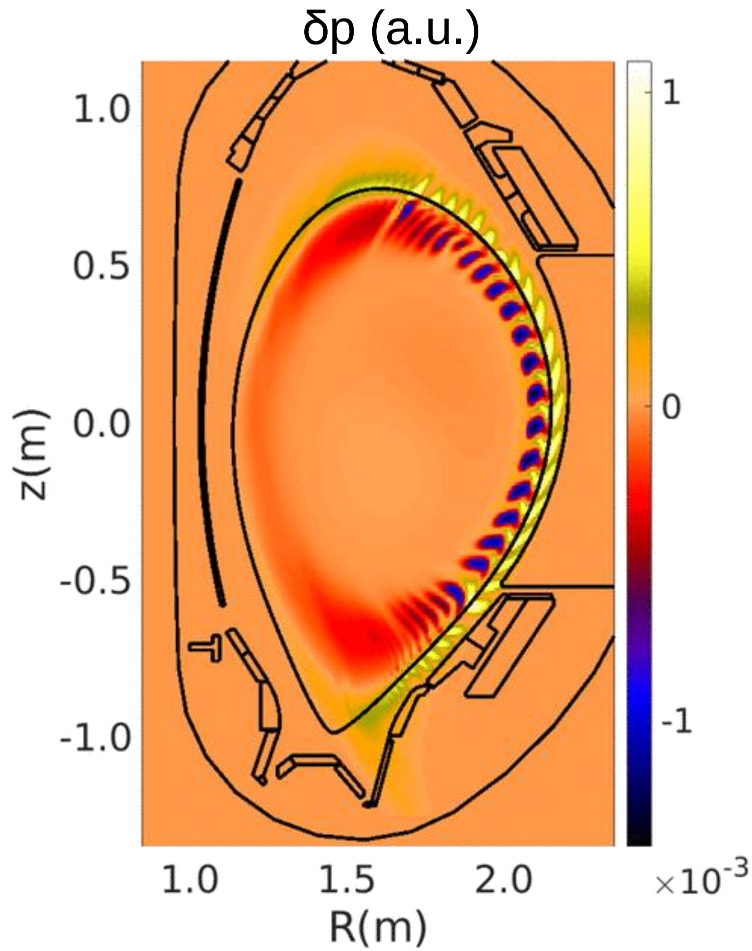

- Modes saturate and filaments extend into SOL
- Saturation due to reduction of drive
  - ➢ Instability has ballooning nature
- Ballooning structure relaxes → ELM signature

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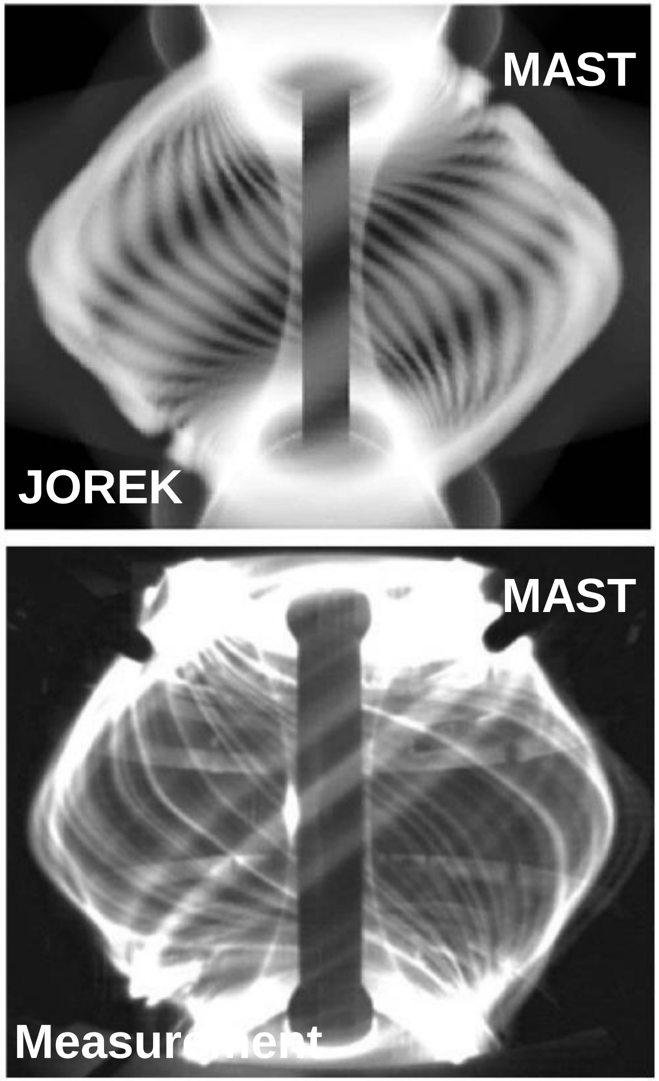

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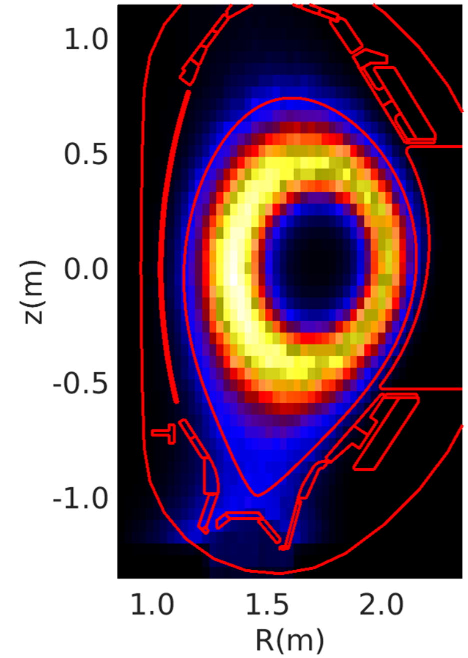
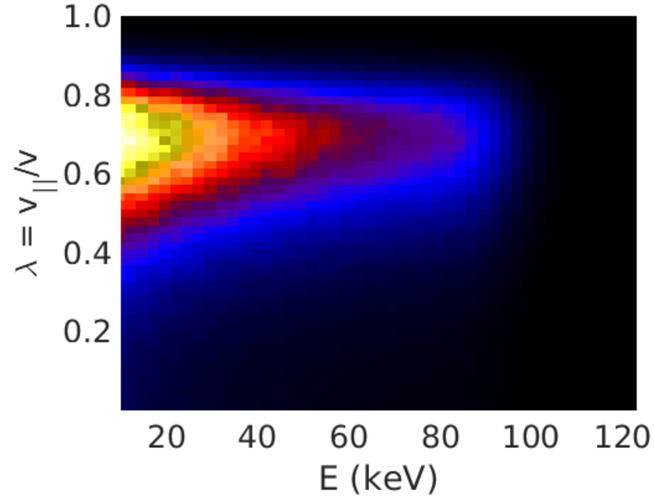
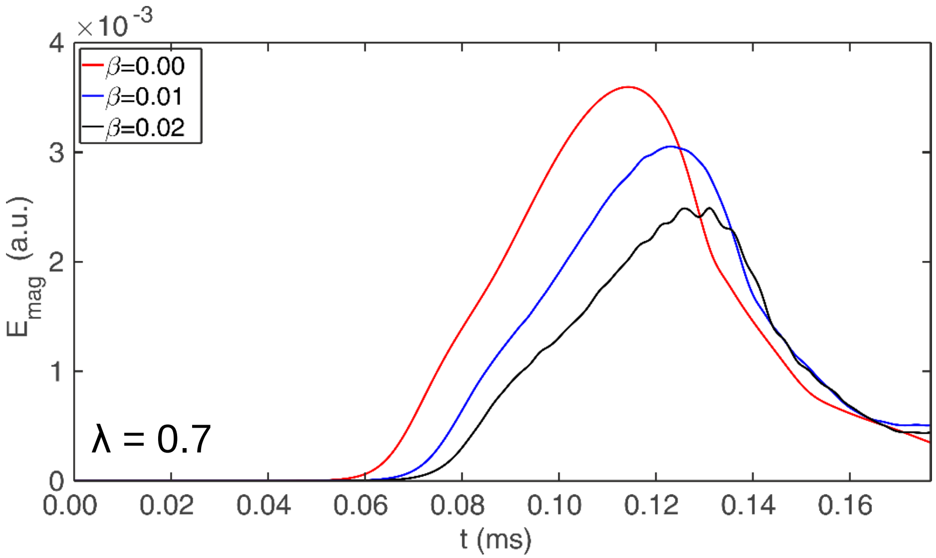
Off-axis Anisotropic Slowing Down Distribution in MEGA

- δf PIC method for gyrokinetic markers
- Collisions and pitch angle scattering not considered
- β_{EP} and pitch angle scan to study impact on n = 20



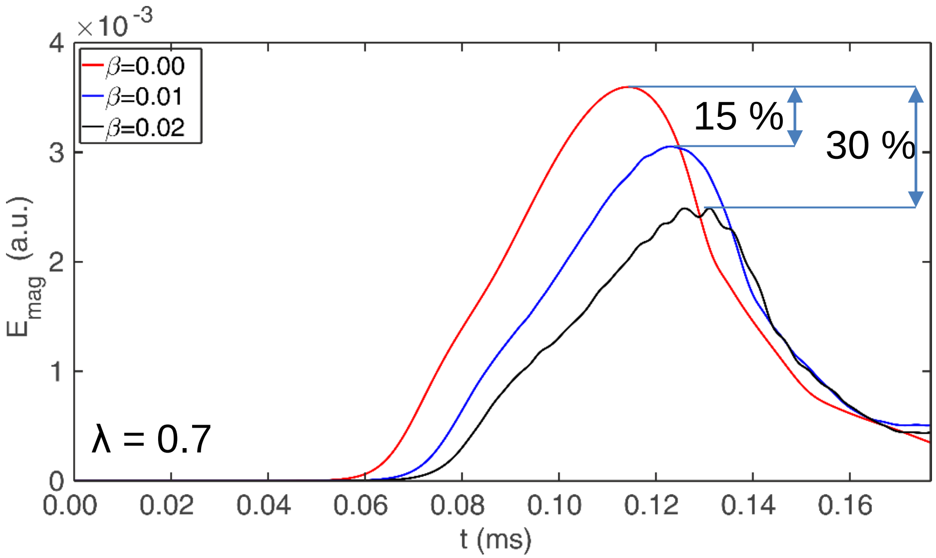


Fast-ions Stabilize n=20 Mode in Single-n Simulation



- Mode maximum amplitude depends on β_{EP}

Fast-ions Stabilize *n*=20 Mode in Single-*n* Simulation



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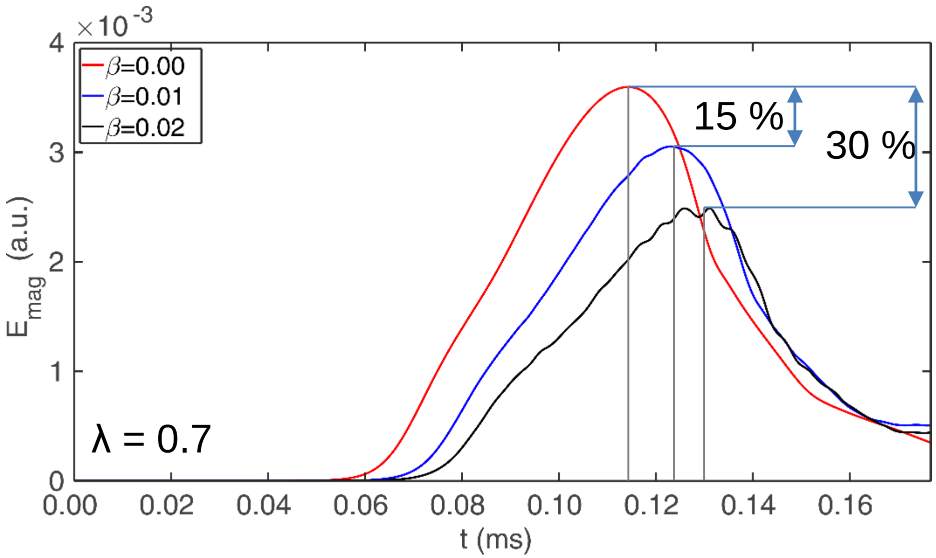

- Mode maximum amplitude depends on β_{EP}
- Saturated maximum amplitude is achieved slighlty later

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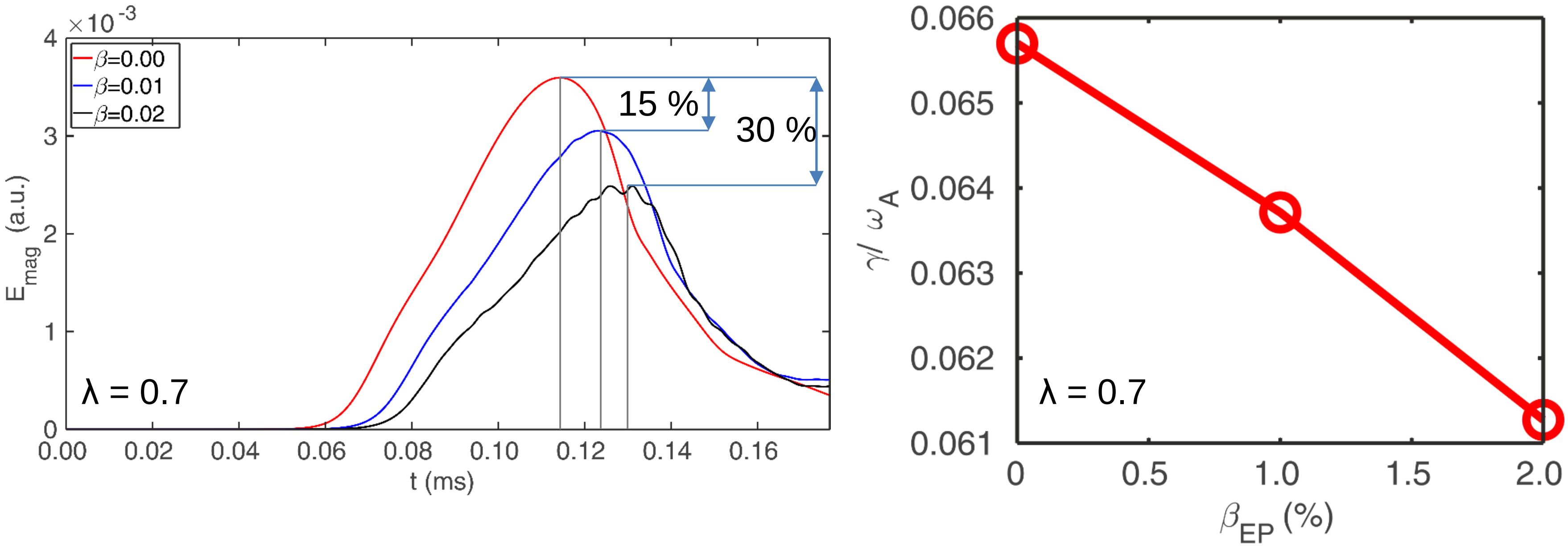
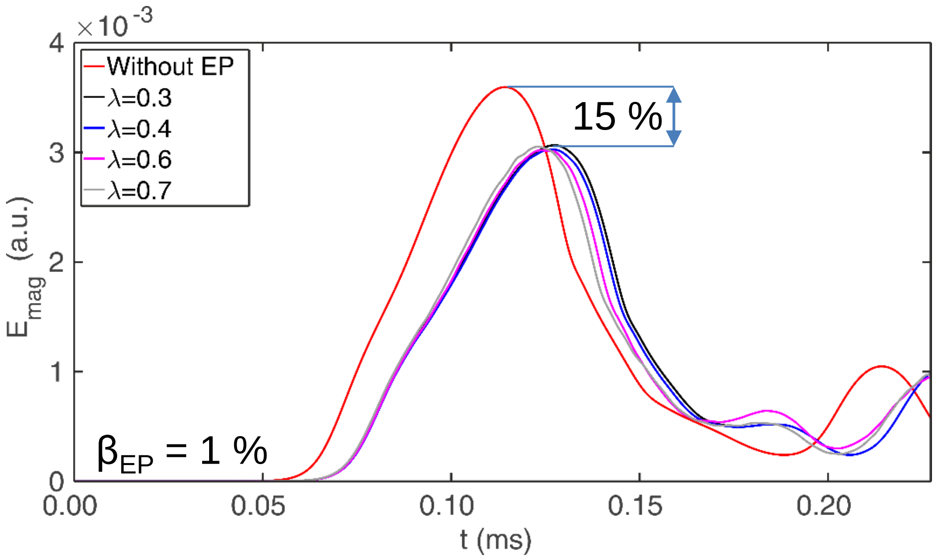
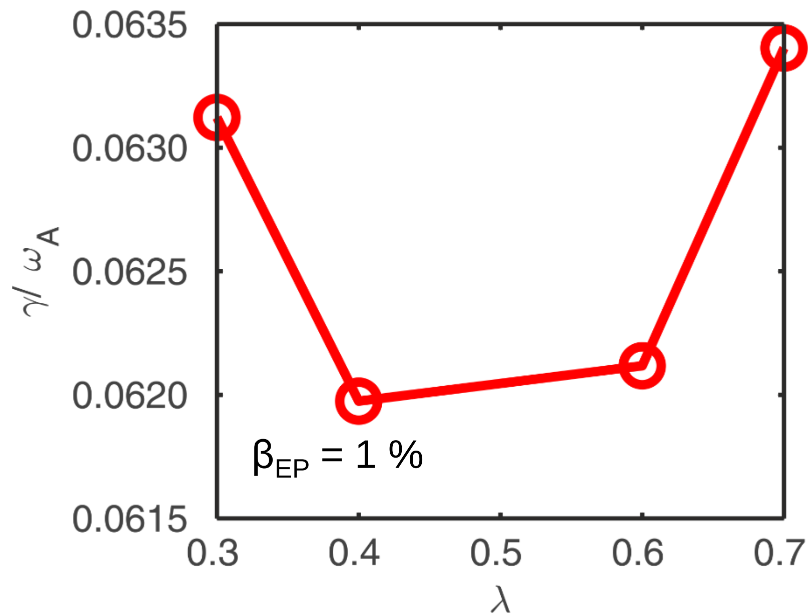


- Mode maximum amplitude depends on β_{EP}
- Saturated maximum amplitude is achieved slighlty later
  - ➢ Linear growth rate slightly decreases with β_{EP}

Fast-ions Stabilize n=20 Mode in Single-n Simulation





- Mode maximum amplitude depends on β_{EP}
- Saturated maximum amplitude is achieved slighlty later
  - ➢ Linear growth rate slightly decreases with β_{EP}
- For different pitch angles, n = 20 saturates at similar energies

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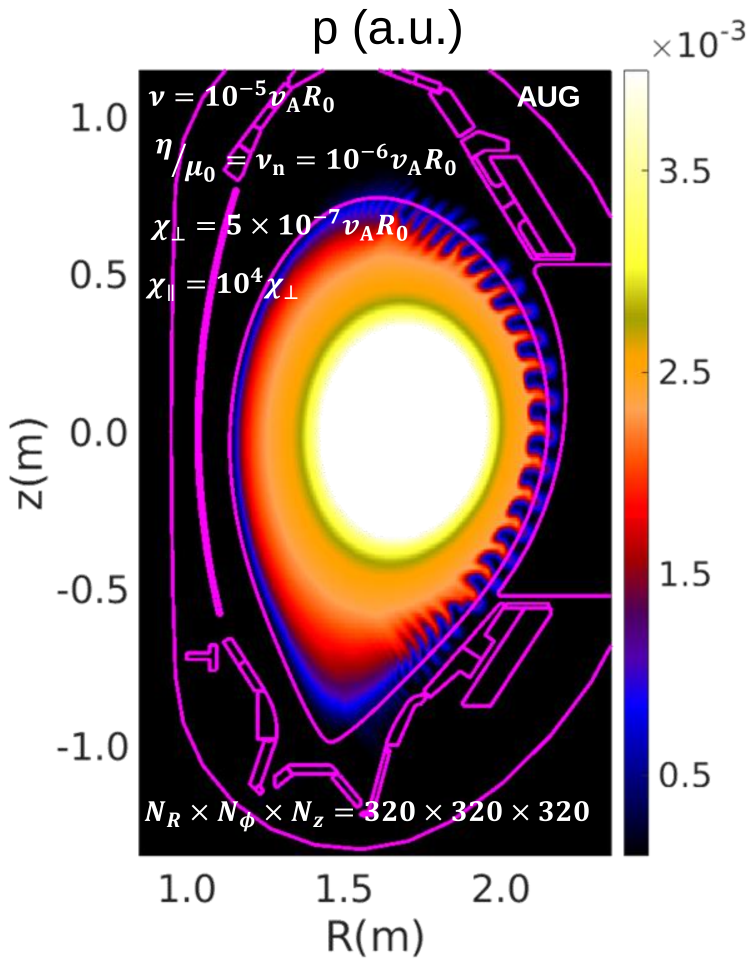
Summary

- ELMs have been successfully simulated with MEGA
- Ballooning mode growth has been observed
- Filaments extend into SOL and perturbation relaxes
- Fast-ions stabilize high *n* ballooning modes



Outlook

- Impact of diamagnetic, toroidal and neoclassical flows on ELM stability
- Benchmark results against other codes, such as JOREK[1], ELITE, GATO
- Study ELM mitigation/suppression by RMPs* including fast-ion kinetic effects
- Study energetic particle transport due to ELMs**

[1] M. Hoelzl *et al*., Contrib. Plasma Phys. 58, 512-28 (2018)

*See J. Gonzalez-Martin Poster (P 1-4, Wed 13:30)

**See J.F. Rivero-Rodriguez (I-8, Wed 11:00)

Back Up

Non-Linear MHD Equations Solved in MEGA (Standard MHD Model)

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \vec{v}) + \nu_n \Delta\left(\rho - \rho_{\mathrm{eq}}\right)$$

$$\rho \frac{\partial \vec{v}}{\partial t} = -\rho(\vec{v} \cdot \nabla)\vec{v} - \nabla p + (\vec{j} - \vec{j}'_h) \times \vec{B} - \nabla \times (\nu\rho\nabla \times \vec{v}) + \frac{4}{3}\nabla(\nu\rho\nabla \cdot \vec{v})$$

$$\frac{\partial p}{\partial t} = -\nabla \cdot (p\vec{v}) - (\gamma - 1)p\nabla \cdot \vec{v} + \nabla \cdot \left[\chi_\perp \nabla_\perp\left(p - p_{\mathrm{eq}}\right) + \chi_\parallel \nabla_\parallel\left(p - p_{\mathrm{eq}}\right)\right]$$

$$+(\gamma - 1)\left[\nu\rho(\nabla \times \vec{v})^2 + \frac{4}{3}\nu\rho(\nabla \cdot \vec{v})^2 + \eta(\vec{j} - \vec{j}'_{\mathrm{h}}) \cdot \left(\vec{j} - \vec{j}_{\mathrm{eq}}\right)\right]$$

$$\frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E}, \vec{j} = \frac{1}{\mu_0}\nabla \times \vec{B}$$

$$\vec{E} = -\vec{v} \times \vec{B} + \eta\left(\vec{j} - \vec{j}_{\mathrm{eq}}\right)$$

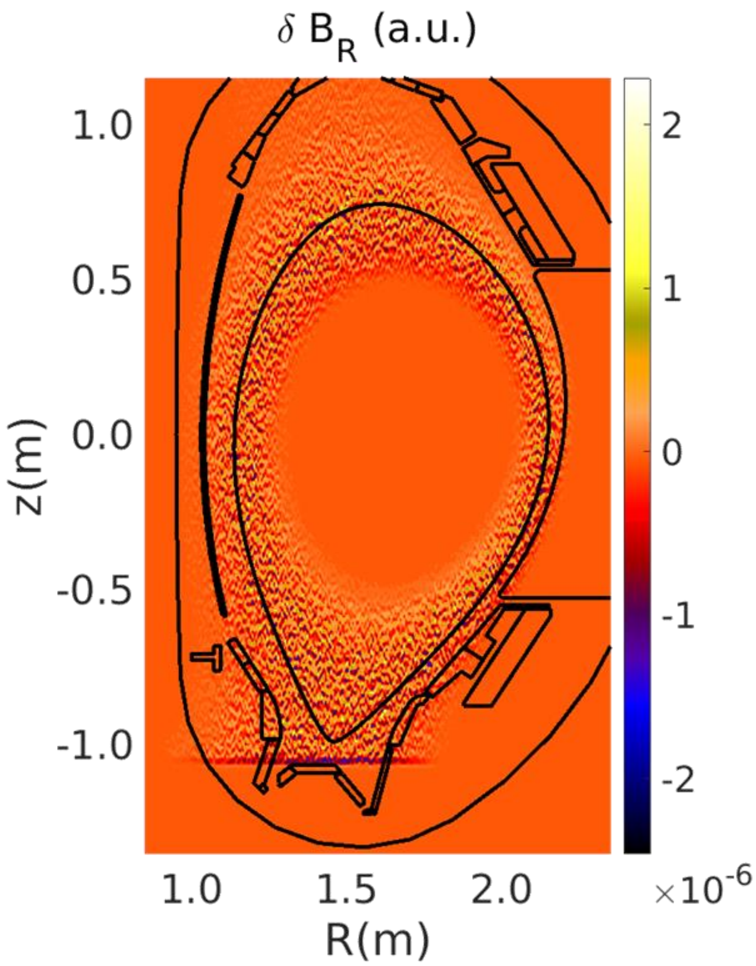
Initializing Simulations in MEGA

- Initial MHD force balance is calculated before time advances, from which perturbations are calculated

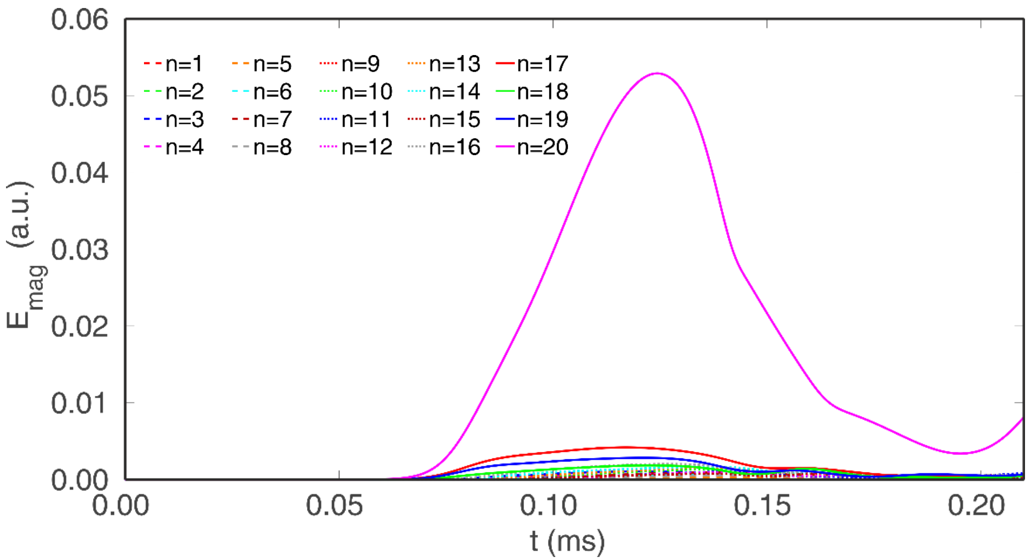
- If fast-ions are included, they are considered in the initial MHD force balance. Then, MHD perturbations are calculated

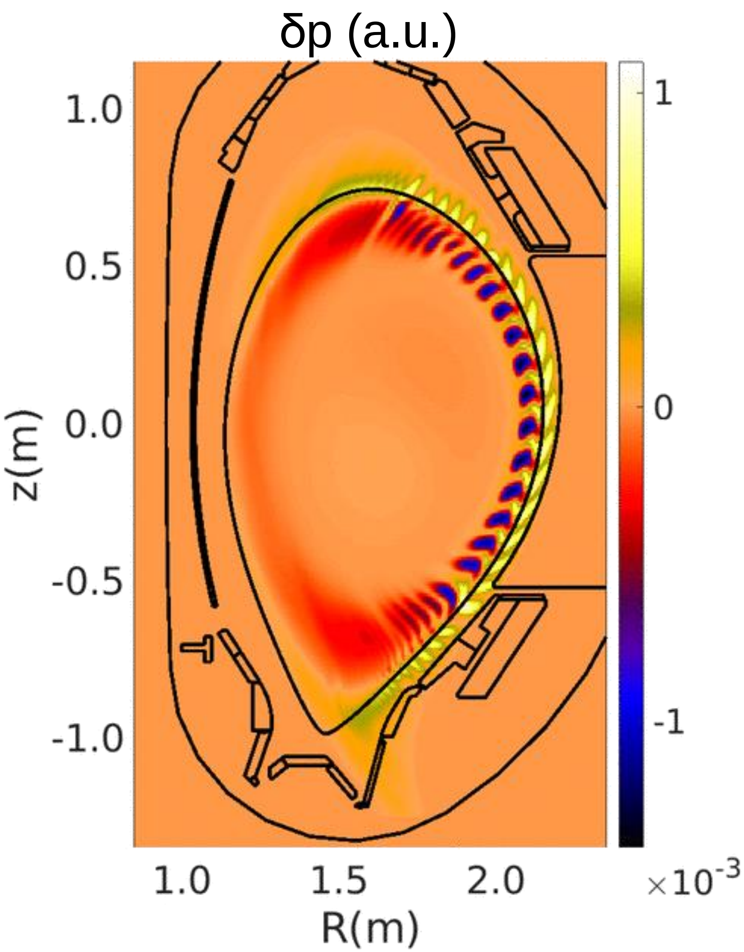
- Initial weak perturbation is later applied at the edge, $0.90 < \rho_{\mathrm{pol}} < 1.05$

- Serves as seed of instability and helps modes to be excited



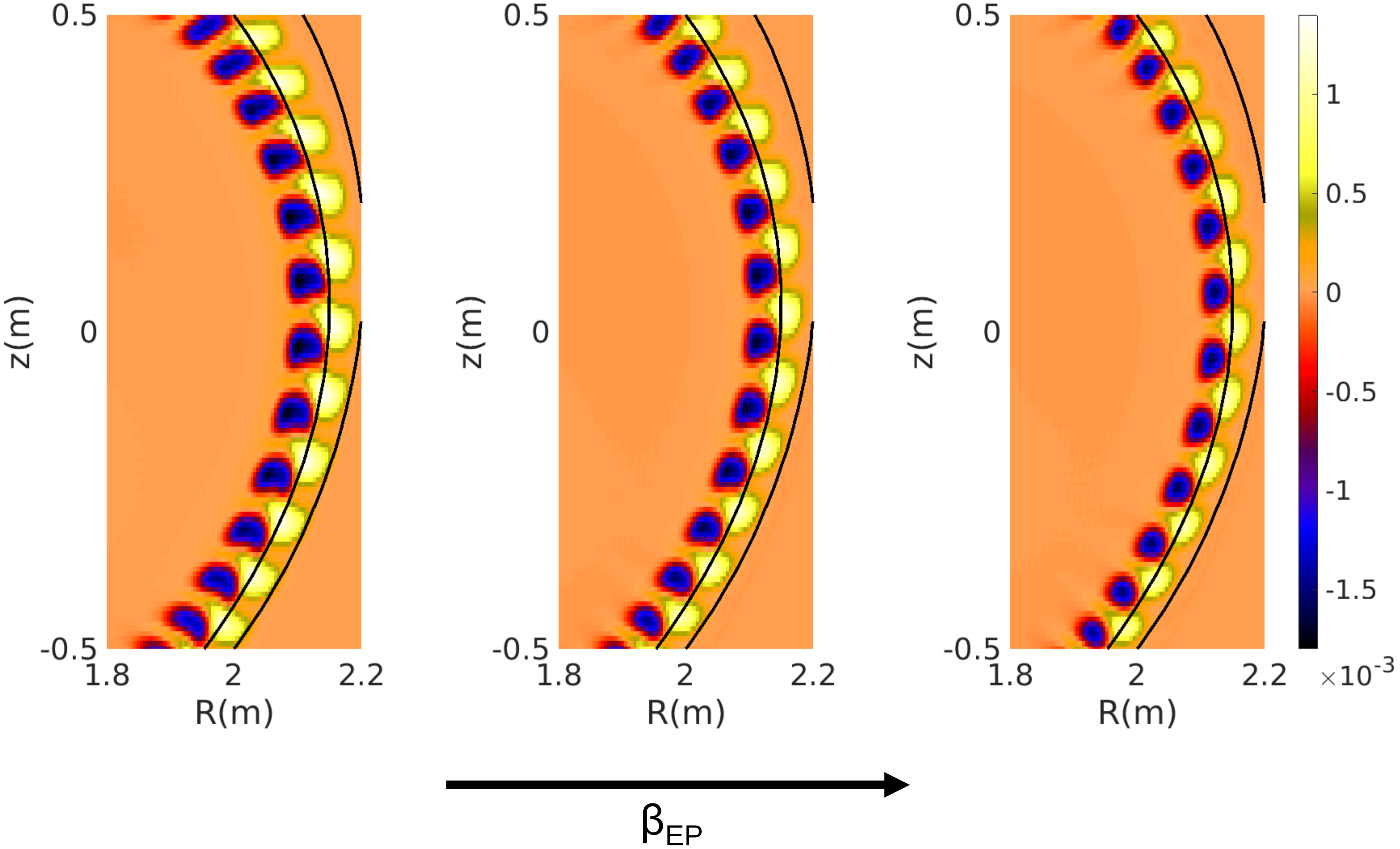
ELM Crash Successfully Simulated With MEGA





- Modes saturate and filaments extend into SOL
- Saturation due to reduction of drive
- Ballooning structure relaxes → ELM signature

Poloidal Structure of Perturbation in Hybrid Simulations



Binary Mask Applied in Non-Linear Hybrid Kinetic-MHD Simulations in MEGA

- Binary mask applied in the white coloured region
- Applied to the perturbed density, pressure and velocity evolved by the MHD module of MEGA
- Binary Mask is necessary to avoid numerical instabilities outside the walls