EUROfusion Science Meeting on results of Enabling Research Projects: "Operation limiting plasma instabilities in high performance tokamaks"

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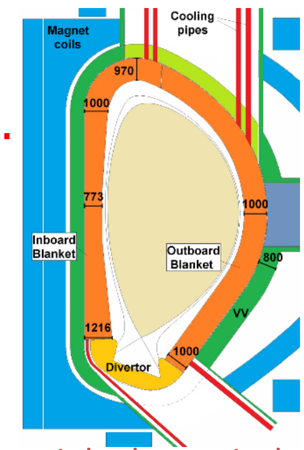
INTRODUCTION

STEP (spherical)

DEMO

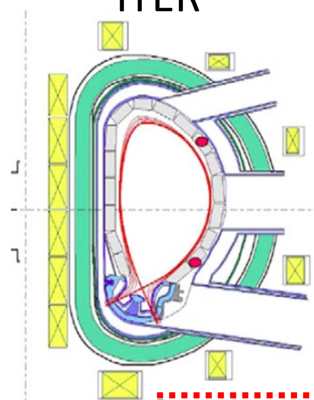


Decisions based on deep model, flight simulator?

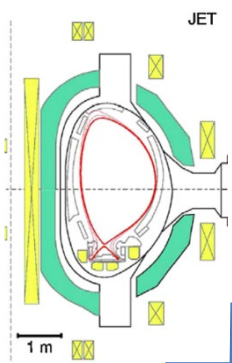
Extrapolation, mainly theoretical, models, new phenomena, sparse experimental data

MAST-U

ITER

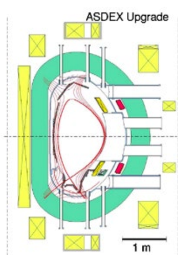


JET



Theory + semi-empirical models, scalings

AUG



Mainly experimental, confronted by theory

- EU-DEMO design will be based on a plasma model e.g. Flight Simulator with full space and time dependence, control, initial and boundary conditions
- DEMO will benefit from ITER will contribute via community tools and studies. But not from ITER experimental data

INTRODUCTION

Why is fundamental theory important?

- EUROfusion can't afford to build tokamaks and technological equipment fast enough to avoid extrapolation studies using codes

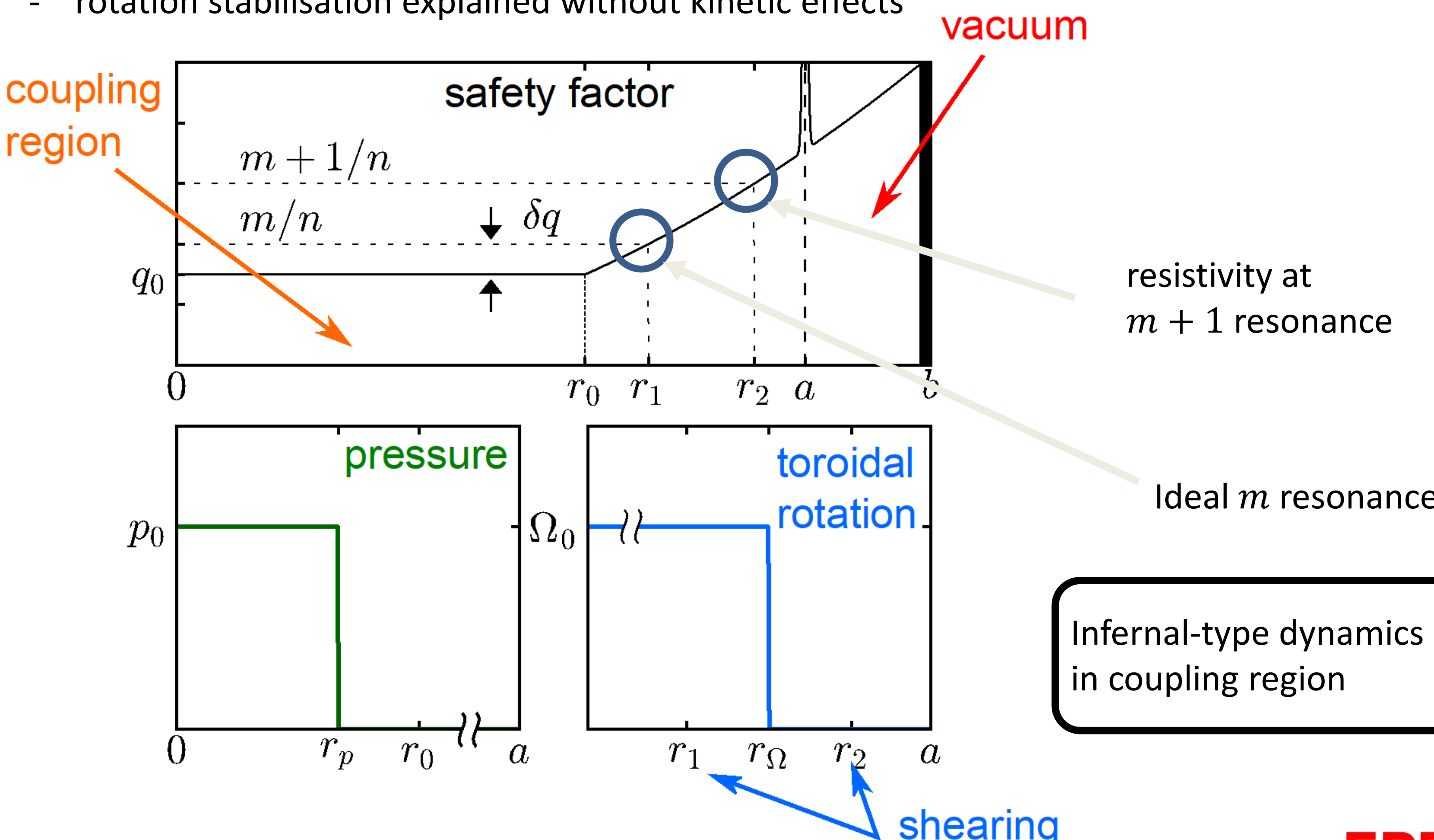
- Based on established models, these codes are becoming highly advanced. And they are being coupled to one another.

- Leaders of experiments, of laboratories and programmes, and even users and developers of codes, often do not have a broader understanding of the limitations and assumptions inherent in the models used in codes

- Our role in EnR is to challenge assumptions and approximations
- We can do this by addressing physics not covered by existing codes, sometimes at the cost of approximations and simplifications elsewhere
- It can be done with analytic treatment and with new dedicated codes
- Of course, we hope to uncover new interesting physics as we do this

New theory for *RWM*-type beta limited plasmas

- Long wavelength **ideal plasma** modes are barely affected by external kink and wall effects when there is a separatrix. New explanation for beta limits attributed to RWMs
- rotation stabilisation explained without kinetic effects



Infernal-type dynamics in coupling region

New theory form RWM type modes

β limits in a resistive plasma with rotation

$$[r^3 Q \xi_m']' - r[(m^2-1)Q + \mathscr{D}_M]\xi_m + \frac{\alpha(1+m)}{2} \times \\ \times \frac{r^{1+m}}{r_0^{2+2m}} \left(\frac{2+m+c}{m-c}\right) \int_0^{r_0} r^{1+m} \alpha \xi_m dr = 0$$

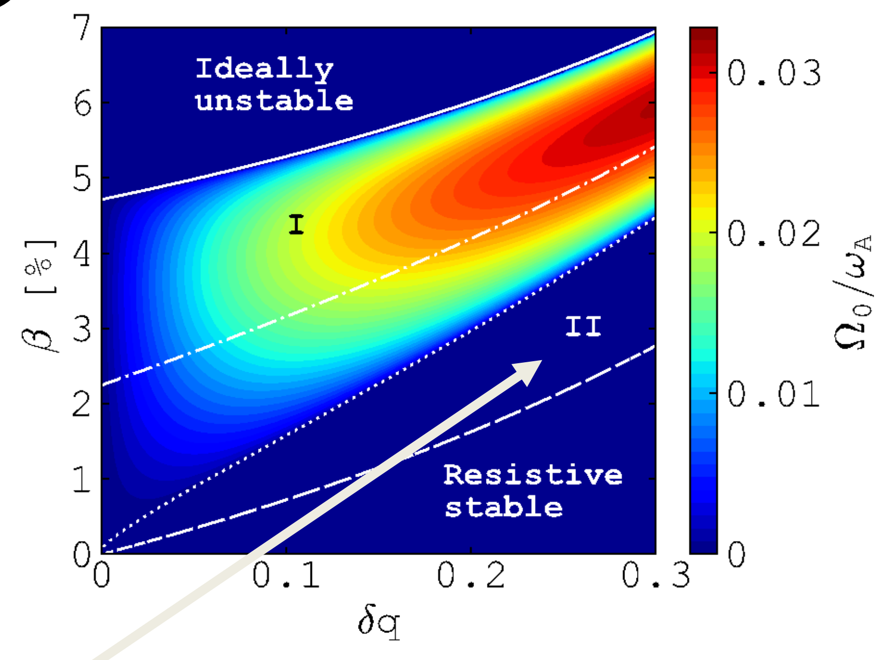
Dynamics described by single equation with smooth matching at r_0

Dispersion relation

$$\lambda_H + \frac{B}{\Delta_{R,m}} + \frac{A}{\Delta_{R,m+1} - \Delta_T'} = 0$$

Unstable global mode

- slowly growing (~10ms), slowly rotating
- bulk plasma rotation stabilisation



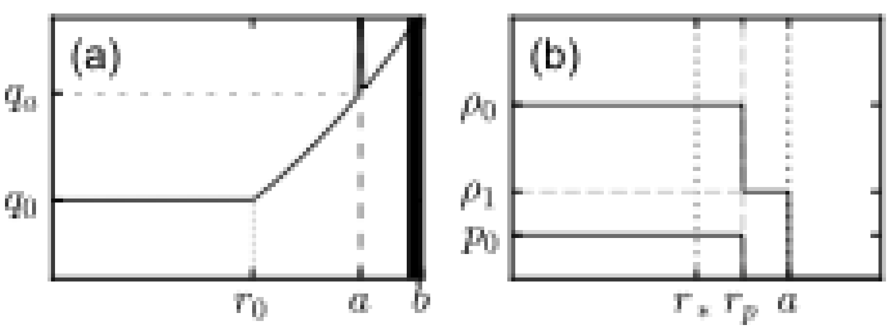
GGJ stabilised region

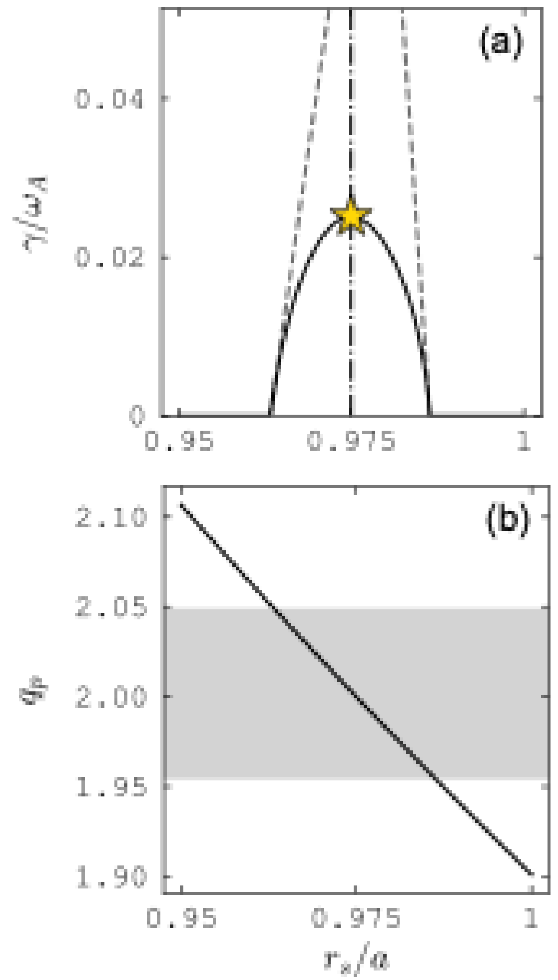
Investigating the q_{95}=2 hard limit

Aim: model fast growth (~ms) of global m=2 instability in condition of stability for XK (separatrix = q infinite at the edge)

Developed framework within ideal MHD with simplifiedtoy model profiles

- Developed framework within ideal MHD with simplifiedtoy model profiles
- Infernal-type dynamics driven by edge density gradients





Narrow window of instability in q as 2/1 resonance approaches the edge

Contributions

CONFERENCES

- D. Brunetti et al, β limits of free boundary resistive flowing plasmas in a diverted tokamak, Theory of Fusion Plasma, Joint Varenna-Lausanne International Workshop, September 12-16 2022, Varenna Italy.

LIST OF PUBLICATIONS

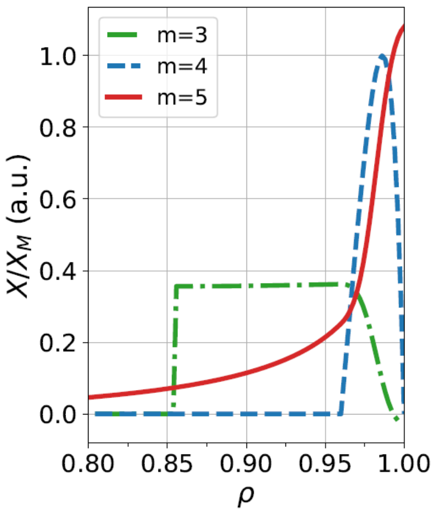
- D. Brunetti et al, Phys. Rev. E **107**, 055203 (2023) [https://journals.aps.org/pre/abstract/10.1103/PhysRevE.107.055203]

- D. Brunetti et al, Plasma Phys. Control. Fusion **66**, 015003 (2024))[https://iopscience.iop.org/article/10.1088/1361-6587/ad0b35]

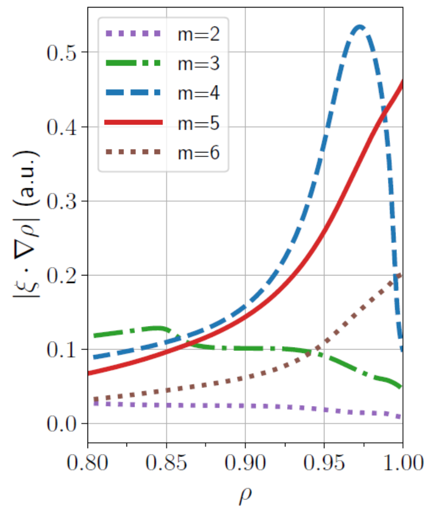
- D. Brunetti, *On the possibility of global modes in diverted tokamaks with low* q_{95} , in preparaion

Edge Harmonic Oscillations (EHOs)

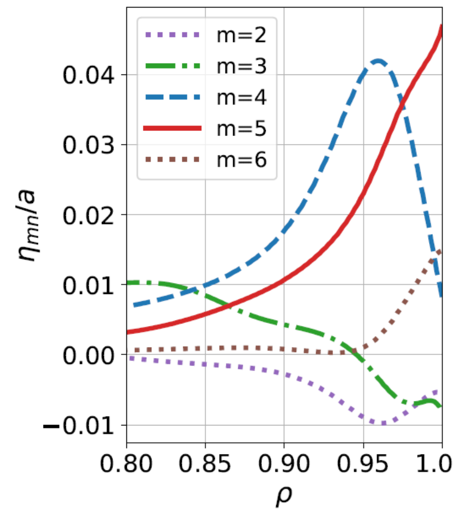
Analytic eigenfunctions



KINX numerical eigenfunctions

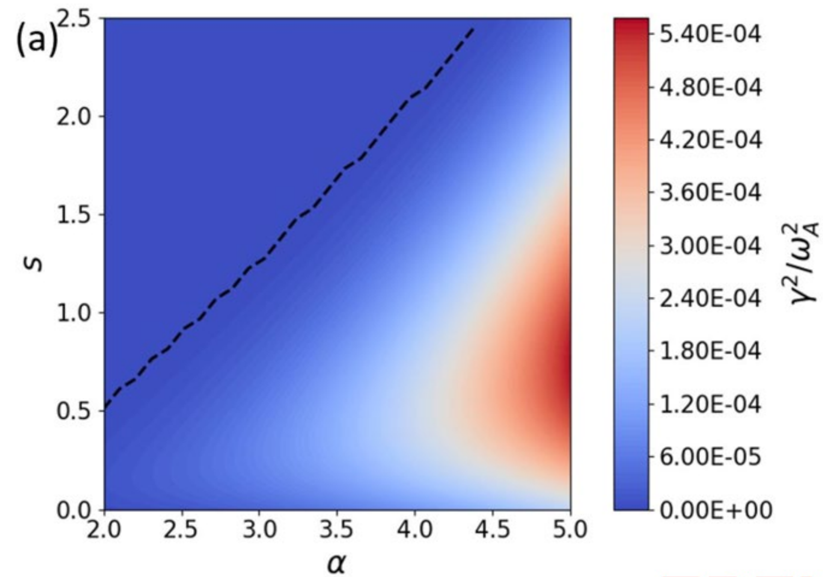


VMEC nonlinear displacements



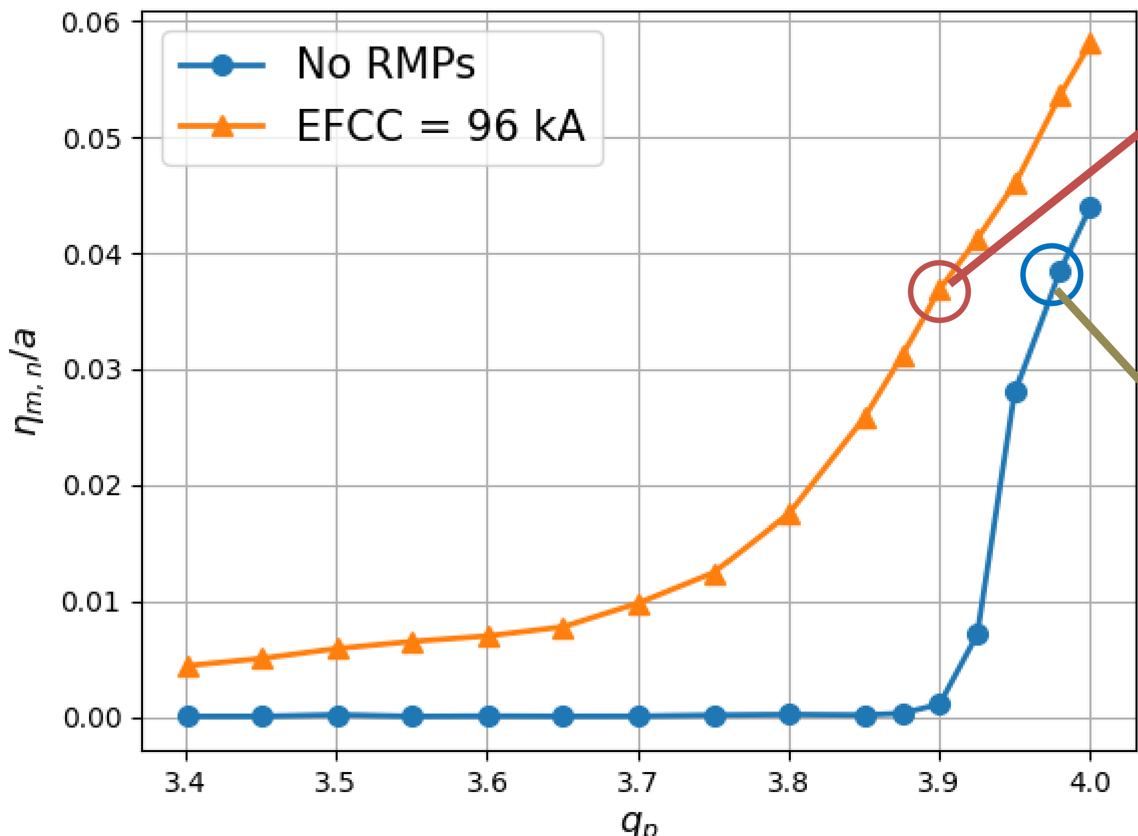
- Explore ELM free regimes via EHOs
- Agreement with KINX and VMEC modes
- Analytic *exfernal* mode model extended to include magnetic shear effects.
- Modes continue to exist despite shear near the edge

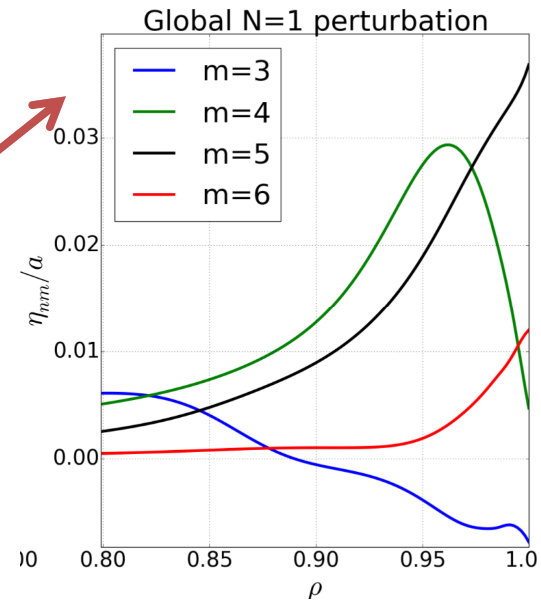
[Bustos Ramirez, Graves, Brunetti, PPCF 2021]

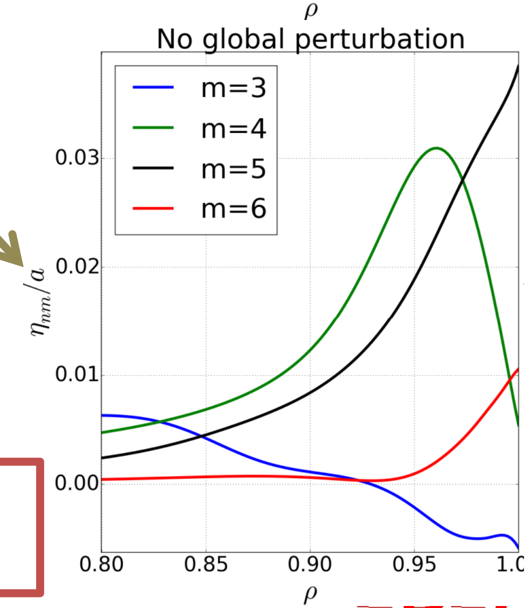


Extending EHO existence with EFCC coils

- EFCC coils might be feasible in EU-DEMO (see 1st gate review)
- Potentially use EFCC for extending access to EHOs and avoiding ELMs, as seen with free boundary 3D VMEC





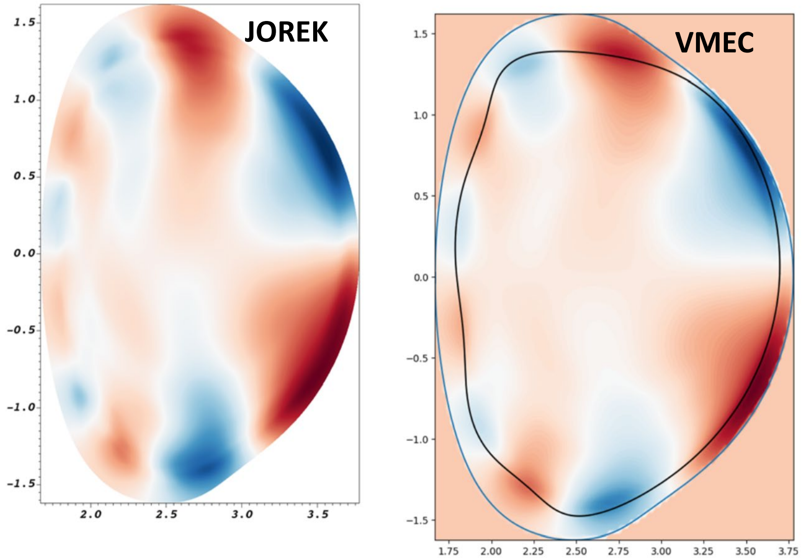


- RMPs help to **induce** EHOs over broader parameter space

[G. Bustos Ramirez, Varenna 2022]

Further EHO understanding

- Current driven EHOs enjoy good agreement between codes:



[Ramasamy, Bustos, Graves PoP 2022]

But these current driven modes are essentially ideal external kink modes

Current driven modes disappear for realistic diverter-like q-profile

Pressure driven cases don't agree well between codes. JOREK can't run with ideal MHD at the edge. VMEC can't recover JOREK results. Neither are optimal

Future work: undertake fundamental physics studies:

- treat pressure driven instabilities with more realistic q-profiles (divertor)
- include resistivity and correctly treat ideal limit and weak resistivity.
- include weak shear flow effects

Contributions

CONFERENCES

- G Bustos Ramirez, J. P. Graves, "The operating space of Edge Harmonic Oscillations in static plasmas," oral and abstract for 10th International workshop on Stochasticity in Fusion Plasmas (SFP)
- G Bustos Ramirez, "Advanced modelling and existence conditions of Edge Harmonic Oscillations," Abstract (invited oral) for THEORY OF FUSION PLASMAS JOINT VARENNA - LAUSANNE INTERNATIONAL WORKSHOP 2022

LIST OF PUBLICATIONS

G. Bustos Ramirez, J. P. Graves and D. Brunetti "Effect of edge magnetic shear on Edge Harmonic Oscillations in plasmas with separatrix," published PPCF 2021

R. Ramasamy, G. Bustos-Ramirez, M. Hoelzl, J. P. Graves, “Modeling of saturated external MHD instabilities in tokamaks: A comparison of 3D free boundary equilibria and nonlinear stability calculations”, Phys. Plasmas 29, 072303 (2022)

Vertical Displacement oscillations with X-point

F. Porcelli, T. Barberis (with D. Banerjee, A. Yolbarsop (Hefei), C. Kin (GA), S. Sharapov (UKAEA))

Analytic Theory (I)

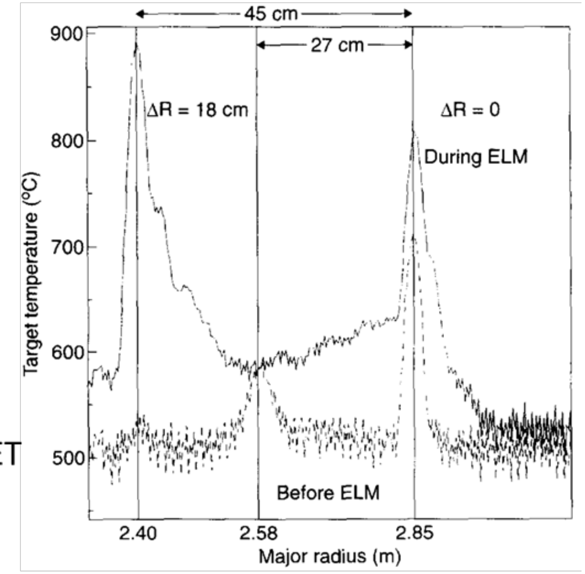
The impact of n=0 modes the are resonant at the X-points of a magnetic divertor configuration was studied analytically within the framework of the ideal-MHD mode in Refs. [1] and [2].

The main result is that axisymmetric currents peaked at the X-points can easily be driven by n=0 modes. This is likely to have an impact on plasma edge dynamics, an aspect of developing theory that is outside the scope of the present project.

Under certain circumstances, n=0 X-point currents may actually play a beneficial role in that they can improve the stability of vertical displacements in the ideal-MHD limit.

The experimental evidence for the occurrence of X-point currents was assessed (see, e.g., Ref. [3], where n=0 X-point currents were observed on JET during giant-ELM activity, as well as more recent experimental observations as discussed in Ref. [2]).

Fig. 1: Surface temperature distribution on the divertor target plate before and during an ELM (JET shot 35273, from Ref. [3]).

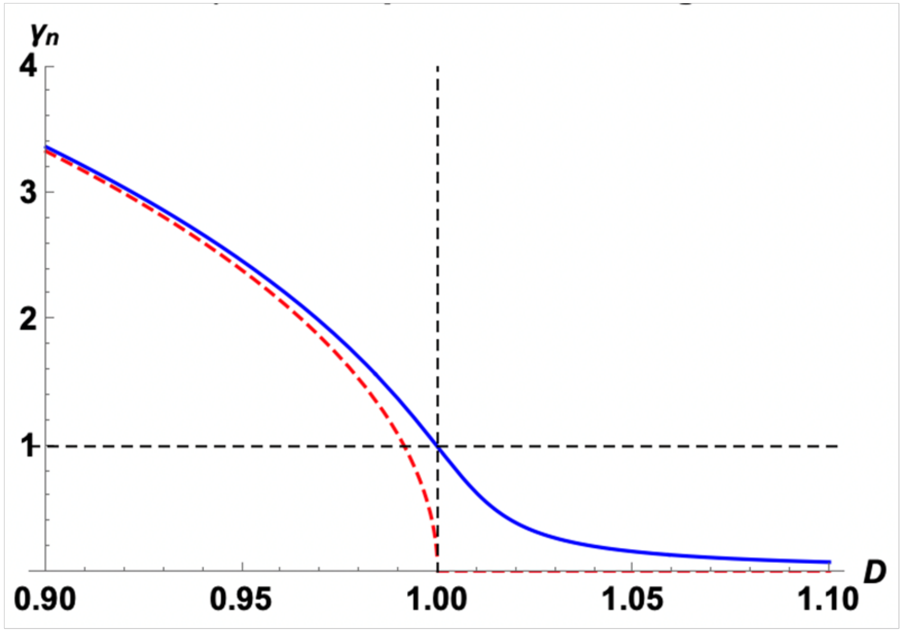


[1] A. Yolbarsop et al, *Impact of magnetic X-points on the vertical stability of tokamak plasmas*, Nuclear Fusion Letter (2021).
[2] A. Yolbarsop et al, *Analytic theory of ideal-MHD vertical displacements in tokamak plasmas*, Plasma Phys. Contr. Fusion (2022).
[3] *J. Lingertat et al , J. Nucl. Mat. (1997).*

Vertical Displacement oscillations

Analytic Theory (II)

The dispersion relation for n=0 modes in the linear regime was derived analytically in Ref. [4]. This dispersion relation is cubic. One root corresponds to a zero-frequency mode that is unstable on the resistive wall time scale, And which requires active feedback stabilization to avoid VDE events. It was shown in Ref. [5] that, under certain Circumstances, the n=0 resistive wall mode can be unstable with a growth rate scaling with a fractional power (below unity) on a wall resistivity, posing more stringent conditions for active feedback stabilization.



Growth rate $\gamma_n = \gamma(D)/\gamma(D=1)$ for the the thin wall limit, with $\gamma(D=1)$ given in Eq. (16), as function of the ideal wall parameter D close to ideal-MHD marginal stability. The blue curve shows the numerical solution of the full cubic dispersion relation (Eq. 13), while the dashed red line represents the ideal wall solution.

$$\gamma \approx \frac{\gamma_\infty}{(1-\hat{e}_0)^{1/3}(\gamma_\infty \tau_{\eta w})^{1/3}} = \frac{(a_w/\delta_w)^{1/3}\gamma_\infty}{(1-\hat{e}_0)^{1/3}(\gamma_\infty \tau_\eta)^{1/3}}. \tag{16}$$

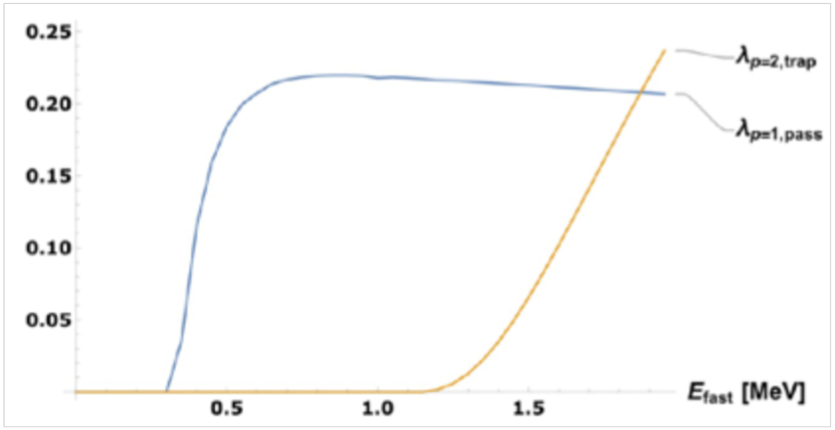
[4] T. Barberis et al, *Vertical displacement oscillatory modes in tokamak plasma*, Journal of Plasma Physics (2022).
[5] F. Porcelli et al, *Vertical displacements close to ideal-MHD marginal stability in tokamak plasmas*, Fundamental Plasma Physics (2023).

Vertical Displacement oscillations

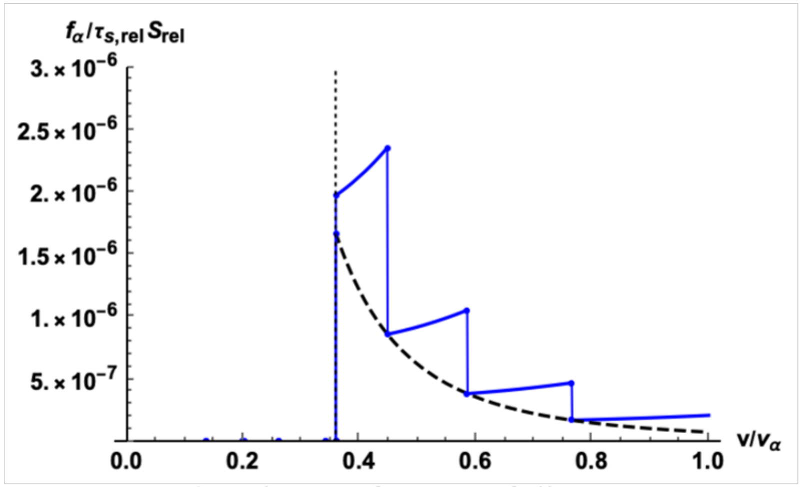
Analytic Theory (III)

The other two roots of the cubic n=0 dispersion relation correspond to oscillatory modes, dubbed Vertical Displacement Oscillatory Modes (VDOM) in Ref. [6], with a frequency close to the poloidal Alfvèn frequency, just below the continuum spectrum. These modes are normally damped (e.g., by wall resistivity) in tokamak experiments, but can be driven unstable by their resonant interaction with fast ion orbits.

Instability requires fast ion distributions with a positive slope in velocity space, or with significant anisotropy. This type of distribution function may be produced following sawtooth crashes, as discussed analytically in Ref. [7] (with reference to relevant experimental observations).



Fast ion drive as function of energy, for both trapped And passing orbits. From Ref. [6].



Fast ion distribution function following consecutive sawtooth crashes. From Ref. [7]-

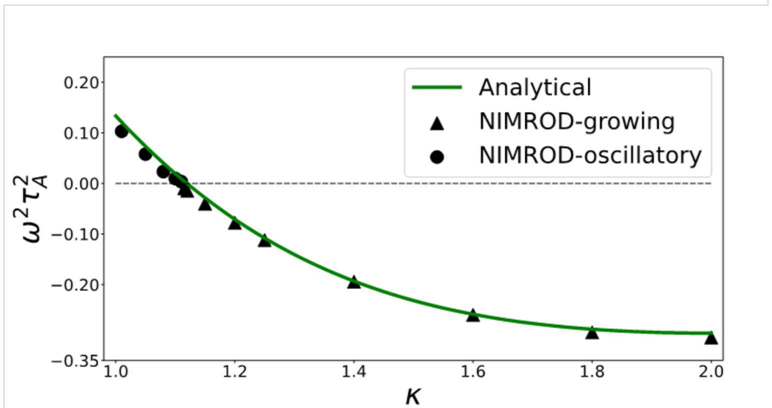
[6] T. Barberis et al, *Vertical displacement oscillatory modes in tokamak plasma*, Journal of Plasma Physics (2022).
[7] T. Barberis et al, *Velocity space distribution of fast ions in a sawtoothing plasma*, Plasma Physics and Controlled Fusion 2024.

The observation of n=0 modes on JET prompted us to spend more time simulating JET discharges and discussing the conditions under which fast ion distribution functions with positive slopes in velocity space can be obtained. These drive VDOM's

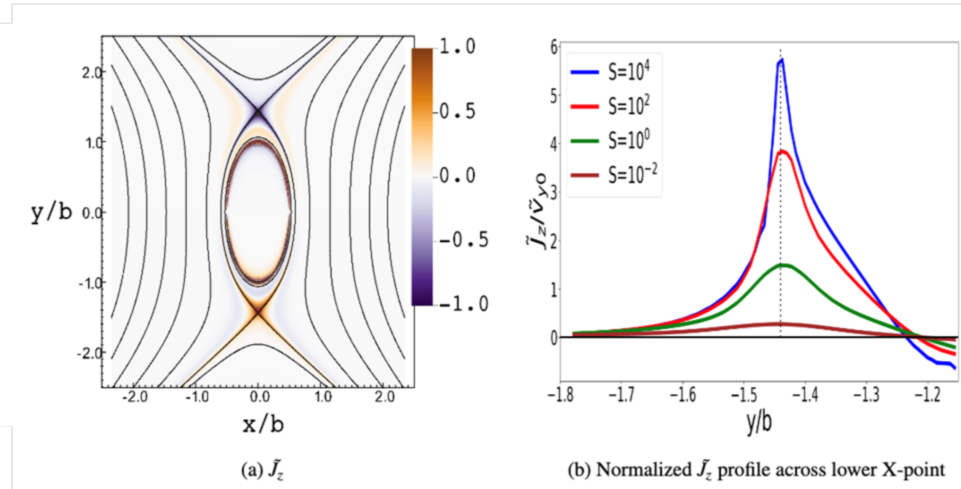
Vertical Displacement oscillations with X-point

Numerical Results

A benchmark between analytic results on n=0 modes and numerical results using the extended-MHD code NIMROD was carried out in Refs. [8] and [9]. The benchmark used the simplified, straight-tokamak equilibrium adopted in analytic work. The agreement between analytic and numerical results is very satisfactory.



Agreement between analytic dispersion curve (green) and numerical results (dots and triangles), showing the transition between an ideally-unstable vertical displacement and VDOM. From Ref. [8].



Axisymmetric currents formed on the X-point and along the separatrix of a double-null, straight tokamak equilibrium. From Ref. [8].

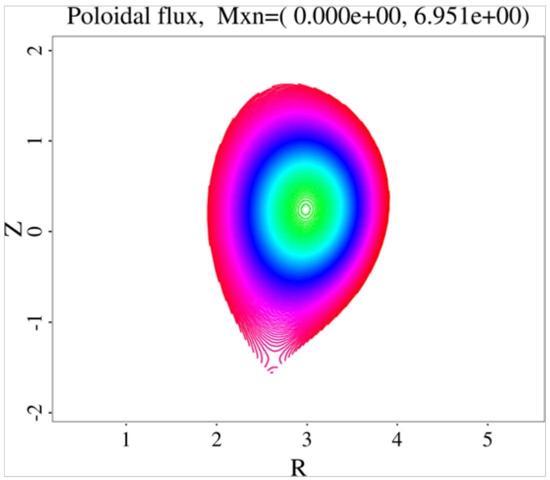
[8] D. Banerjee et al, *Linear NIMROD simulations of n=0 modes for straight tokamak configuration and comparison with analytic results*, Physics of Plasmas 2024.
[9] A. Yolbarsop et al, *Axisymmetric oscillatory modes in cylindrical magnetized plasma bounded by a conducting wall*, Physics Letters A (2023).

The work shows that axisymmetric X-point currents are easily driven near magnetic X-point.

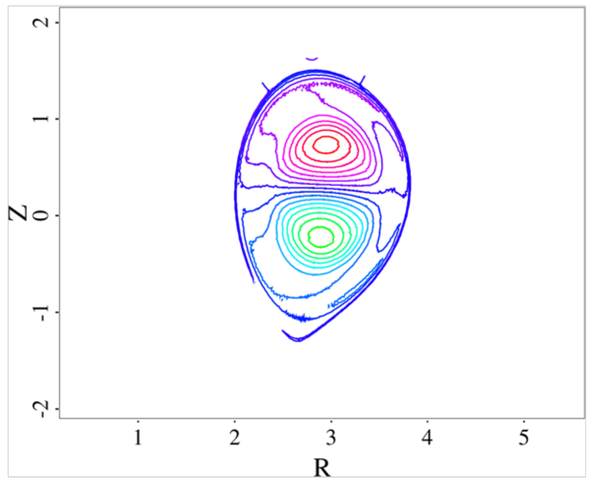
Vertical Displacement oscillations with X-point

Analysis of JET experimental data

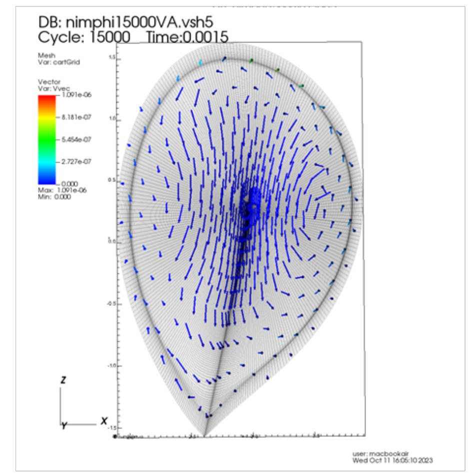
The NIMROD code has then been used to analyzed n=0 modes in realistic JET geometry. JET pulse #102371, were n=0 modes driven by fast ions were observed, as been chosen as reference equilibrium for NIMROD simulations. Our work confirms the existence of VDOM in single-null, realistic tokamak geometry. Results published in Ref. [10].



JET equilibrium, pulse #102371



VDOM pressure perturbation



VDOM vertical flow structure

In the NIMROD simulation, the VDOM has a frequency of approx 280 kHz. A second mode, identified as a GAE with a frequency of 470 kHz, was also found in the simulations. Both modes are good candidates to explain the observed n=0 fluctuations. In our work, we list additional features that may help distinguish between the two modes. Unfortunately, JET pulse #102371 did not have sufficient diagnostic to reach a firm conclusion.

[10] T. Barberis et al, *Vertical Displacement Oscillatory Modes and Global Alfvén Eigenmodes in JET geometry*, Nuclear Fusion 2024.

Vertical Displacement oscillations with X-point

Publications

Analytic theory: Impact of X-points on n=0 stability, X-point current sheets, Vertical Displacement Oscillatory Modes (VDOM):

- A. Yolbarsop et al, *Impact of magnetic X-points on the vertical stability of tokamak plasmas*, Nuclear Fusion Letter (2021).
- A. Yolbarsop et al, *Analytic theory of ideal-MHD vertical displacements in tokamak plasmas*, Plasma Phys. Contr. Fusion (2022).
- T. Barberis et al, *Vertical displacement oscillatory modes in tokamak plasma*, Journal of Plasma Physics (2022).
- F. Porcelli et al, *Vertical displacements close to ideal-MHD marginal stability in tokamak plasmas*, Fundamental Plasma Physics (2023).
- A. Yolbarsop et al, *Axisymmetric oscillatory modes in cylindrical magnetized plasma bounded by a conducting wall*, Physics Letters A (2023).

Analytic theory: Fast-ion-driven n=0 modes:

- T. Barberis et al, *Fast ion driven vertical modes in magnetically confined toroidal plasmas*, Nuclear Fusion Letter 2022.
- T. Barberis et al, *Velocity space distribution of fast ions in a sawtoothing plasma*, Plasma Physics and Controlled Fusion 2024.

Linear NIMROD numerical simulations and comparison with JET experiments:

- D. Banerjee et al, *Linear NIMROD simulations of n=0 modes for straight tokamak configuration and comparison with analytic results*, Physics of Plasmas 2024.
- T. Barberis et al, *Vertical Displacement Oscillatory Modes and Global Alfvén Eigenmodes in JET geometry*, Nuclear Fusion 2024.

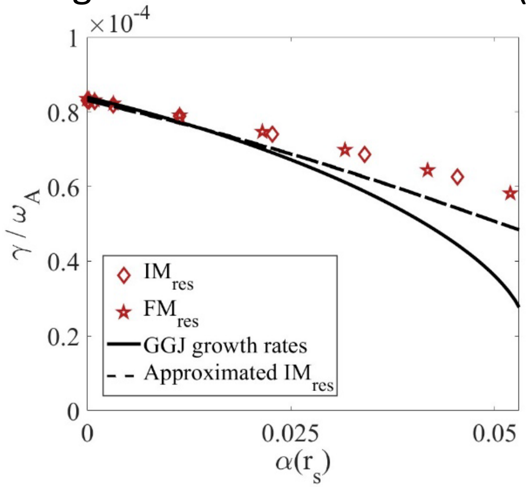
Also, the work earned an invited talk at the 2024 Joint Varenna-Lausanne International Workshop on Fusion Plasma Theory. It has been presented as contributed paper at EPS conferences, 19^{th} EFTC2021, AAPPS-DPP2024 , 10^{th} FPPT-2023, and several other plasma physics workshops. It has been disseminated through several invited seminars, in presence or online, at fusion research institutions worldwide.

Discrete unstable spectra

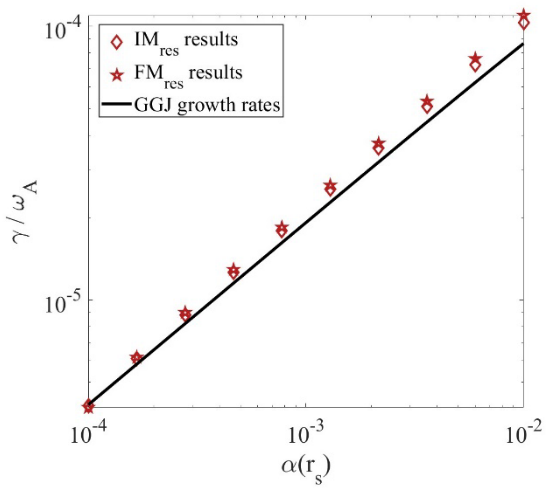
- **Advanced tokamak scenarios → wide region of low magnetic shear** : need to look at higher order effects due to toroidal coupling between poloidal harmonics (**infernal instabilities**).

- Static equilibrium + inverse aspect ratio expansion + resistive dissipation & compressibility: global toroidal equations of [Graves, Coste-Sarguet, Wahlberg, PPCF 2022]. Implemented in a **modular linear eigenvalue solver**.

- Modular solver presented in [Coste-Sarguet, Graves, PPCF 2024], benchmarked against full MHD code FAR (in the zero pressure limit) and GGJ dispersion relation.



m/n =2/1 tearing modes growth rates, reproducing Fig. 1 in [1].



m/n=9/10 resistive interchange growth rates, SL = 10^7, parabolic pressure profile.

[1] T. C. Hender, R. J. Hastie, and D. C. Robinson, *Nuclear Fusion* **27**, 1389 (1987)

Discrete unstable spectra

Extended MHD stability of core plasma: **spectra of fast growing modes in advanced scenarios**

- Dispersion relation describing ideal spectrum of non-resonant infernal modes, in a zero shear in the core *q* profile:

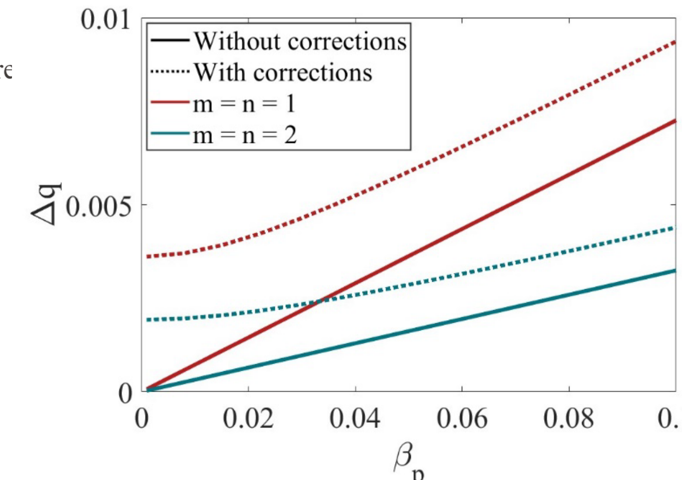
$$1 = \frac{\sigma\, r_1^{2m+2}}{\lambda}\left[\frac{J_{m+1}(x)}{x\, J_m(x)} - \frac{1}{2m+2}\right], \quad \text{with} \quad x = \sqrt{\frac{\lambda\, r_1^2}{Q}},$$

$$Q = Q\left(\gamma^2/\omega_A^2\right)$$

depends on:
- pressure drive
- sideband coupling

depends on:
- *q* profile
- shaping
- higher order Δq and pressure corrections derived in [2]

- Inclusion of higher order corrections → now valid for *m*/*n* = 1 cases, and improved marginal stability analysis.



Analytic marginal stability of non-resonant *m*=*n* modes: effect of the new higher order corrections introduced in [2].

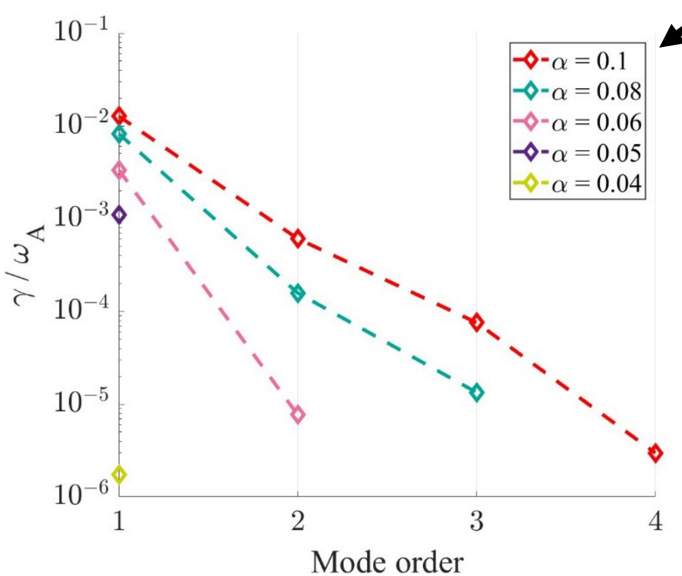
[2] M. Coste-Sarguet and J. P. Graves, *PPCF* **66,** 095004 (2024)

Discrete unstable spectra

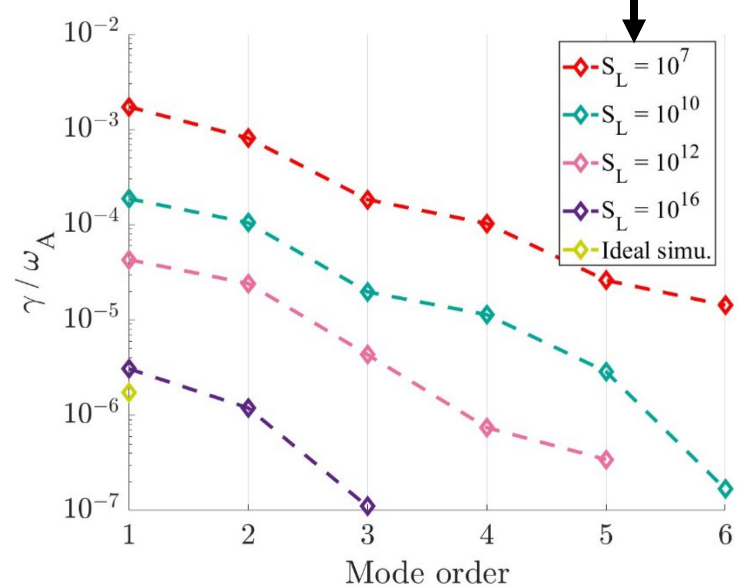
Extended MHD stability of core plasma: **spectra of fast growing modes in advanced scenarios**

- Dispersion relation describing ideal spectrum of non-resonant infernal modes, in a zero shear in the core *q* profile:
- Cascade of modes : emergence of spectrum with pressure or resistivity (resistive results from the modular solver):

Ballooning parameter at rational surface



Lundquist number ∝ 1/resistivity



Emergence of higher order modes, with resistivity or pressure drive in a plasma with parabolic pressure profile, and “infernal type” q profile with $r_s = 0.3$ and $s(r_s) = 0.06$. Modes with γ/ωA < 5 · 10−8 on the right, and γ/ωA < 1 · 10−6 on the left are not displayed.

Discrete unstable spectra

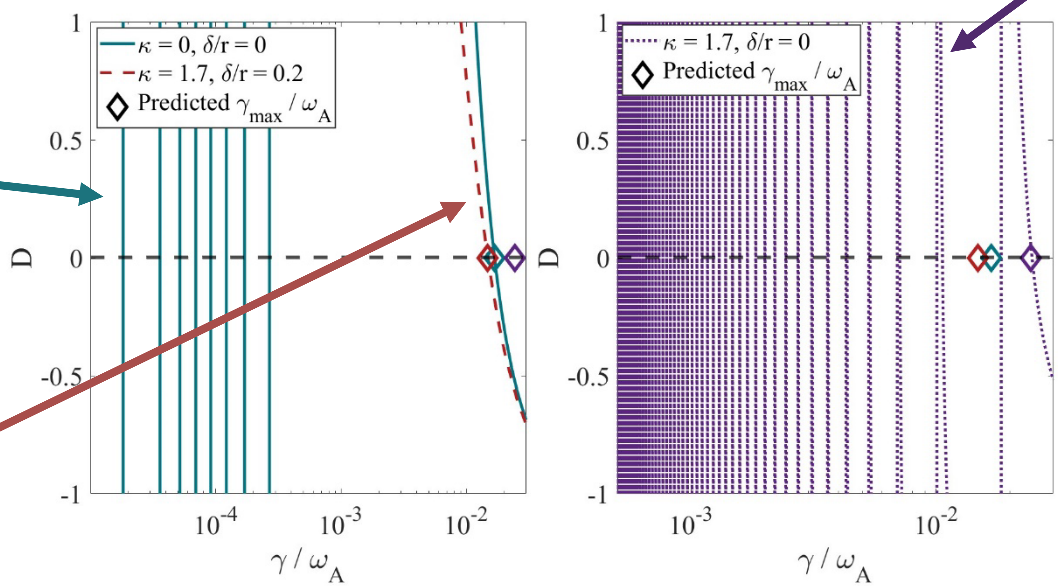
Extended MHD stability of core plasma: **spectra of fast growing modes in advanced scenarios**

- Dispersion relation describing ideal spectrum of non-resonant infernal modes, in a zero shear in the core *q* profile:
- Cascade of modes : emergence of spectrum with pressure or resistivity (resistive results from the modular solver):
- Spectrum sensitive to shaping of the flux surfaces:

Elongation only: infinity of modes

Circular flux surfaces: a few modes

Elongation & Positive triangularity: only one mode



Dispersion relation, for a m/n = 2/2 mode with or without shaping (hybrid *q* and βp(0.4) = 0.4)

Roots of the dispersion relation give the **linear instability growth rate**.

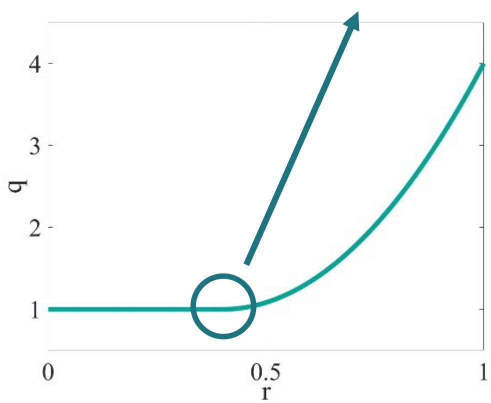
Several roots → instability spectrum

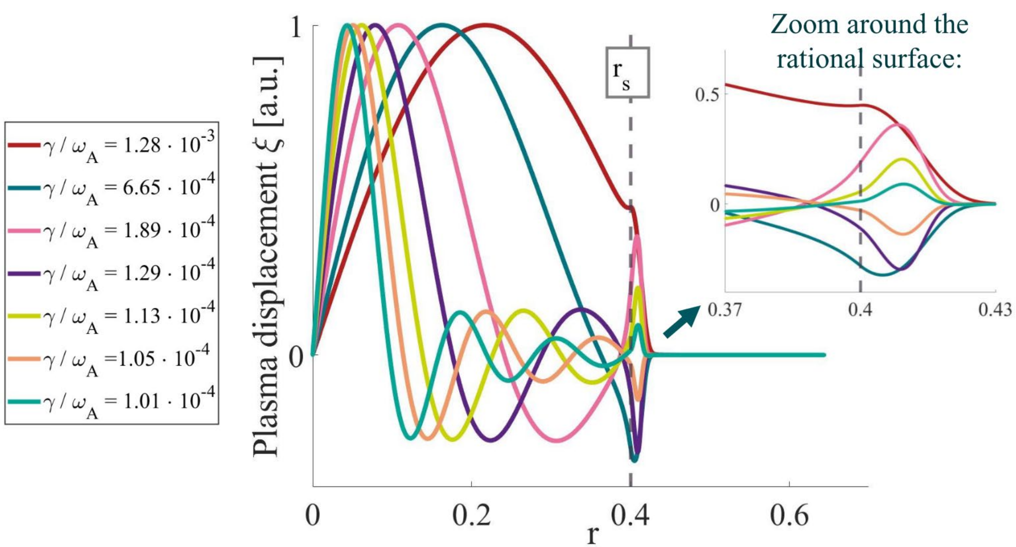
Discrete unstable spectra

Extended MHD stability of core plasma: **spectra of fast growing modes in advanced scenarios**

- Dispersion relation describing ideal spectrum of non-resonant infernal modes, in a zero shear in the core *q* profile:
- Cascade of modes : emergence of spectrum with pressure or resistivity (resistive results from the modular solver):
- Spectrum sensitive to shaping: even for resonant *m/n* =1 scenarios with very low pressure gradient, negative triangularity and resistivity combined give rise to a **resistive infernal spectrum** :

Resonance → resistive spectrum:





Spectrum of resistive m/n = 2/2 modes in NT (κ = 1.3, δ/r = −0.1), γ(ideal)/ωA = 9.7 · 10−4, βp(rs) = 3.75 · 10−3

Discrete unstable spectra

- New benchmarked **modular resistive solver**: simplified exploration of advanced scenario stability, including key toroidal (infernal) effects.

- Sawtooth avoidance / triggering: the wide low shear region in the core is associated (under certain conditions) to a **spectrum of fast growing modes**. We introduce an analytic description for the ideal non-resonant case for general *m* and *n*, and novel spectra of resistive infernal modes.

- Shaping effects on stability: **Combining low magnetic shear with negative triangularity** can lead to an internal (resistive or ideal) kink spectrum otherwise absent → careful consideration is needed

Publications:

M. Coste-Sarguet and J. P. Graves,
Fundamental properties of ideal and resistive infernal modes in tokamaks
Plasma Physics and Controlled Fusion, **66**, 095 004, 2024.
https://iopscience.iop.org/article/10.1088/1361-6587

Poster at Joint Varenna-Lausanne international workshop – Theory of Fusion Plasma, September 2024 conference

New eigenvalue code for kinetic MHD

Novel kinetic-MHD code is required for implementation of global fully electromagnetic equations with strong flows [Lanthaler, Graves]. Inspired by GENE code Van Kampen approach:

Standard Landau approach

- The perturbed distribution function is eliminated in favour of field variables, by harmonic expansion and truncation, e.g.:

$$-\rho\omega^2\boldsymbol{\xi}_\perp - \boldsymbol{j}\times\boldsymbol{\delta B} - \boldsymbol{\delta j}\times\boldsymbol{B} + \boldsymbol{\nabla}(\boldsymbol{\xi}_\perp\cdot\boldsymbol{\nabla}P)$$

$$+2\pi\boldsymbol{\nabla}\int dv_\parallel d\mu\mu\frac{B^2}{m}\left(\frac{-iq(\boldsymbol{\xi}_\perp\times\boldsymbol{B})\cdot\boldsymbol{v_g}\left(\omega\frac{\partial F}{\partial\mathcal{E}} - n\frac{\partial F}{\partial P_\phi}\right)}{(-i\omega + \langle v_g\cdot\boldsymbol{\nabla}\rangle)}\right)\approx 0$$

- Involves solving nonlinear eigenvalue problem.
- Resonances need to be treated carefully, often analytic simplifications have to be made, especially near passing-trapped boundary
- Usually small orbit widths assumed. This means kinetic enhanced inertia can't be captured together with global kinetic effects [Graves, PPCF 2000]

Van Kampen approach

- The perturbed distribution function δf_k itself becomes the eigenvector, the problem can be written as a standard, i.e. **linear** eigenvalue problem
- No approximation made on underlying characteristic equations, i.e. full particle trajectories retained

$$\begin{pmatrix} 0 & 1 & 0 \\ A_{21} & 0 & A_{23} \\ q(.\times\boldsymbol{B})\cdot\boldsymbol{v_g}in\frac{\partial F}{\partial P_\phi} & 0 & -\boldsymbol{v_g}\cdot\boldsymbol{\nabla}\end{pmatrix}\begin{pmatrix}\boldsymbol{\xi}_\perp \\ \boldsymbol{u}_\perp \\ \delta f_k\end{pmatrix} =$$

$$-i\omega\begin{pmatrix} 1 & 0 & 0 \\ 0 & \rho & 0 \\ -q(.\times\boldsymbol{B})\cdot\boldsymbol{v_g}\frac{\partial F}{\partial\mathcal{E}} & 0 & 1\end{pmatrix}\begin{pmatrix}\boldsymbol{\xi}_\perp \\ \boldsymbol{u}_\perp \\ \delta f_k\end{pmatrix}$$

- The spectrum contains unphysical stable modes => accessing physical stable modes is challenging

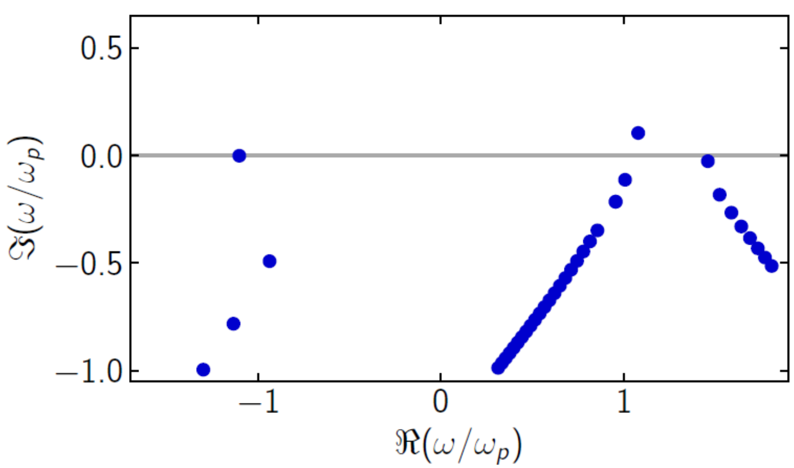
Kinetic description of bump on tail Vlasov-Poisson problem has been verified
[F. Jeanquartier, Brunner, Graves, SPS conference 2022]:

Standard Landau Approach

- The nonlinear eigenvalue problem is

$$\left(1 - \frac{1}{k^2}\int_L \frac{1}{v' - \omega/k}\frac{\partial F}{\partial v'}dv'\right)\delta E = 0$$

- All physical modes obtained

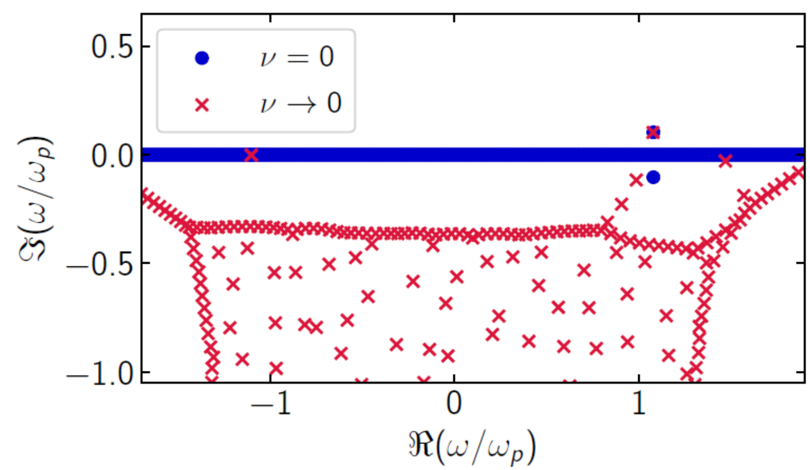


Van Kampen Approach

- The linear eigenvalue problem is

$$kv\delta f - \frac{1}{k}\frac{\partial F}{\partial v}\int_{-\infty}^{\infty}\delta f dv' + i\nu\left(v\delta f + \frac{\partial \delta f}{\partial v}\right) = \omega\delta f$$

- The unstable mode obtained. With collisions the barely stable modes also obtained



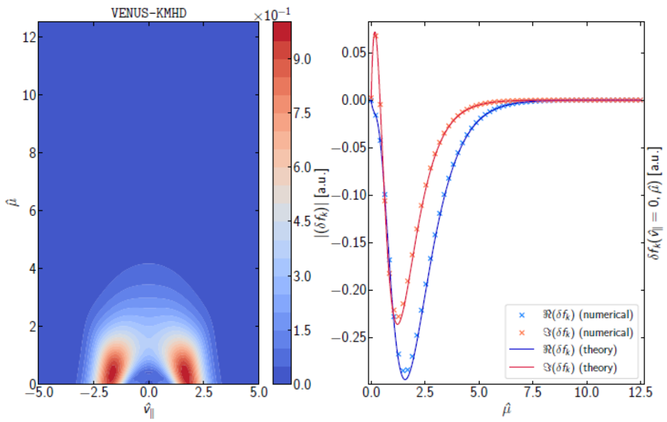
F. Jeanquartier, J. P. Graves, M. Hoppe, S. Brunner, SPS Conference, 2022.

New eigenvalue code for kinetic MHD

Benchmarking the code in cylindrical geometry

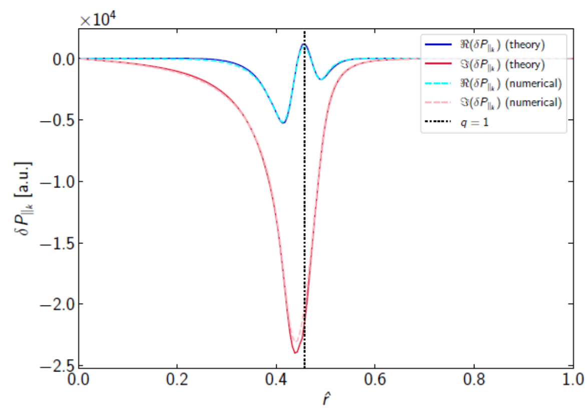
In cylindrical geometry, we find an analytical solution for δf_k:

$$\delta f_k = \frac{q\omega_{d0}^{\phi}\xi_p^{\psi}(\omega - n\omega^*)}{\omega - n(\omega_d^{\phi} + \Delta q\dot{\theta})}\frac{\partial F}{\partial \mathcal{E}}$$



Computing the moments of the analytical δf_k gives an analytical expression for $\delta P_{\perp k}$, $\delta P_{\parallel k}$:

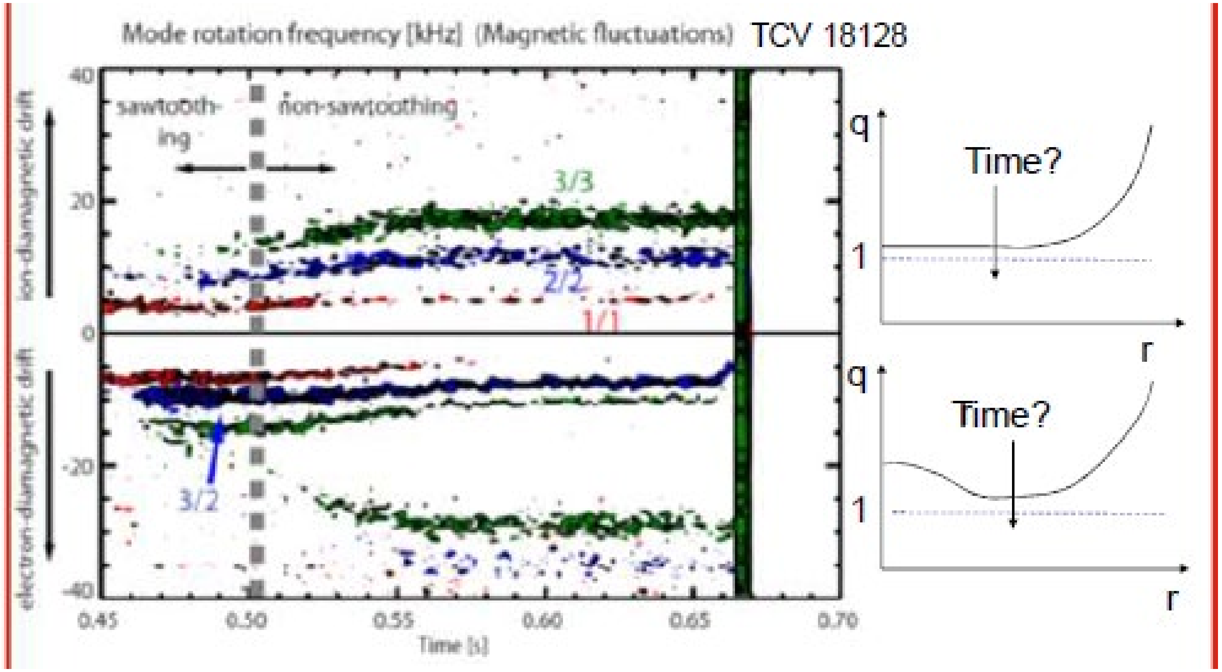
- Using $\lambda, \mathcal{E}$ velocity variables, the integral on $\mathcal{E}$ is done analytically and is expressed using the **dispersion function** $Z(x)$,
- Integral on λ has to be done numerically.



Full dispersion relation benchmarking in cylinder under way. Toroidal geometry next.

Publications: F. Jeanquartier, T. Emerit, J. P. Graves, S. Brunner, EPS Conference, 2023
F. Jeanquartier, A. Renggli, J. P. Graves, S. Brunner, Joint Varenna-Lausanne Workshop, 2024

Stationary q>1 states in tokamaks – non-reconnecting alternative to the flux pump model

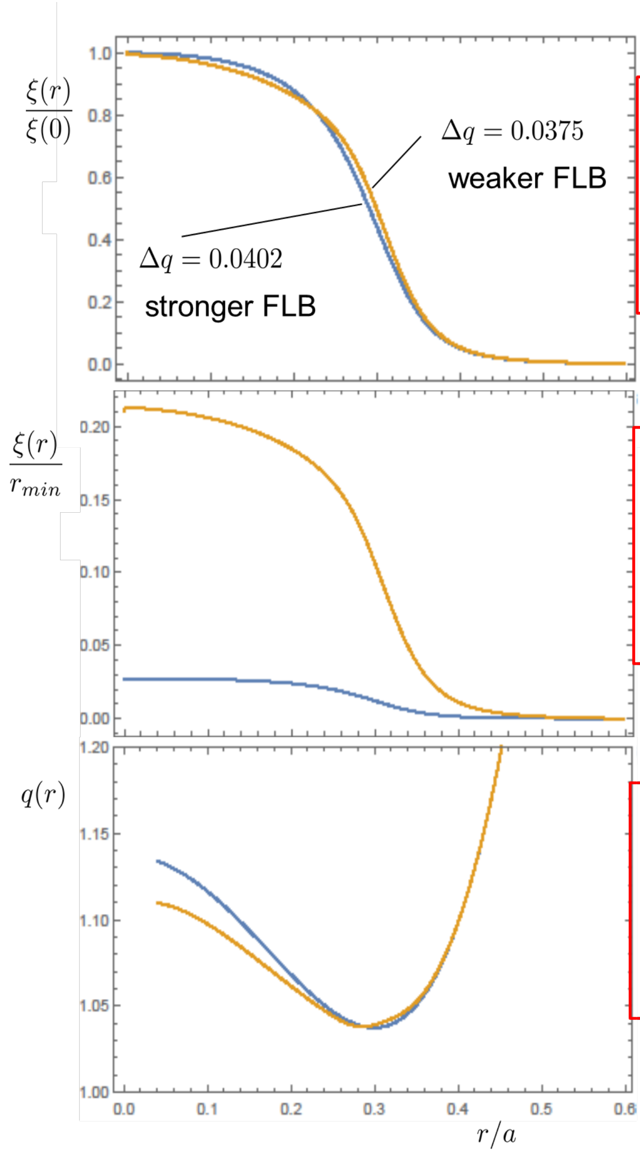


There have been recent theories concerning the role of core kink mode instabilities causing clamping of the safety factor, e.g. Ref. [I. Krebs, S.C. Jardin, S. Günter et al., Physics of Plasmas 24, 102511 (2017)]

Here, I calculate the non-linear saturated 1/1, 2.2 and 3/3 mode cascades, and show these help to sustain q>1 without reconnection at q=1. Alternative to flux pump model.

Stationary q>1 states in tokamaks – non-reconnecting alternative to the flux pump model

Δq



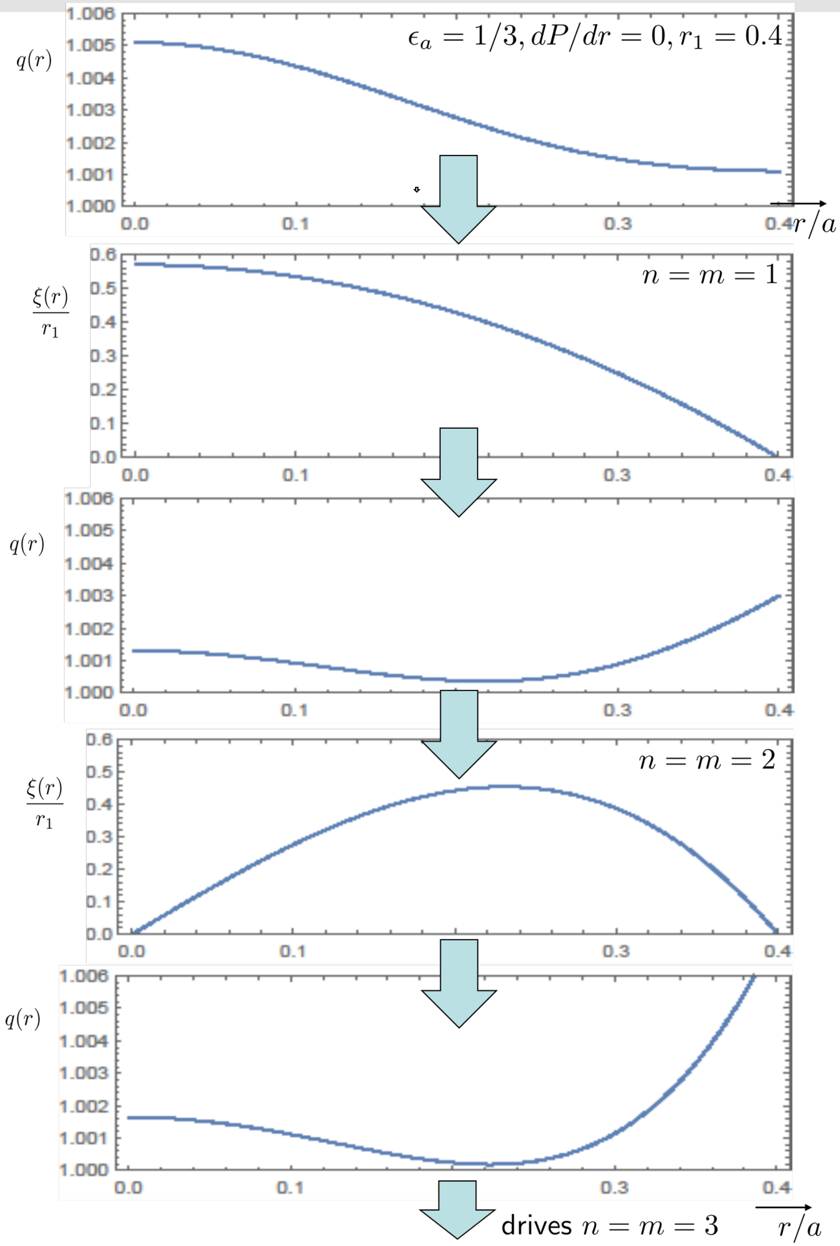
Non-linear change to displacement shape more pronounced for weak FLB (yellow case)

Larger displacement amplitude for weak FLB case (yellow case)

Non-linear effect of mode modifies the q-profile. Case of weaker FLB causes larger mode and reduces q more in the core

[**J. P. Graves, APS conference 2023**]:

Cascade of modes and stationary plasmas



Stationary plasma absent of resistive diffusion

Leading order resistive diffusion of the q-profile can be written as [9]:

$$\frac{\partial q}{\partial t} = -\frac{q}{\mu_0 r}\left[\left(2 - \frac{r}{q}\frac{\partial q}{\partial r}\right)\cancelto{0}{\frac{d\eta}{dr}} - \left(\frac{3}{q}\cancelto{0}{\frac{\partial q}{\partial r}} - \frac{2r}{q^2}\left(\cancelto{0}{\frac{\partial q}{\partial r}}\right)^2 + \frac{r}{q}\cancelto{0}{\frac{\partial^2 q}{\partial r^2}}\right)\eta\right] + \frac{q^2 R_0}{r B_0}\frac{d}{dr}(\eta j_{cd} + \eta j_{boot}).$$

In the limit where the modes in the core prevent the building of temperature gradients, then the resistivity profile is a constant.

Also, in the core, the q-profile is almost constant. Neglecting current drive terms, we have a steady state core q-profile, absent of core resistive diffusion, sustained by the modes which exist in a torus even in the absence of pressure gradients.

Robust to kinetic-MHD corrections (these vanish)

The kinetic MHD model depends on the pressure moments of the perturbed drift kinetic equation: $\delta f = \delta f_{MHD} + \delta f_k,$ with

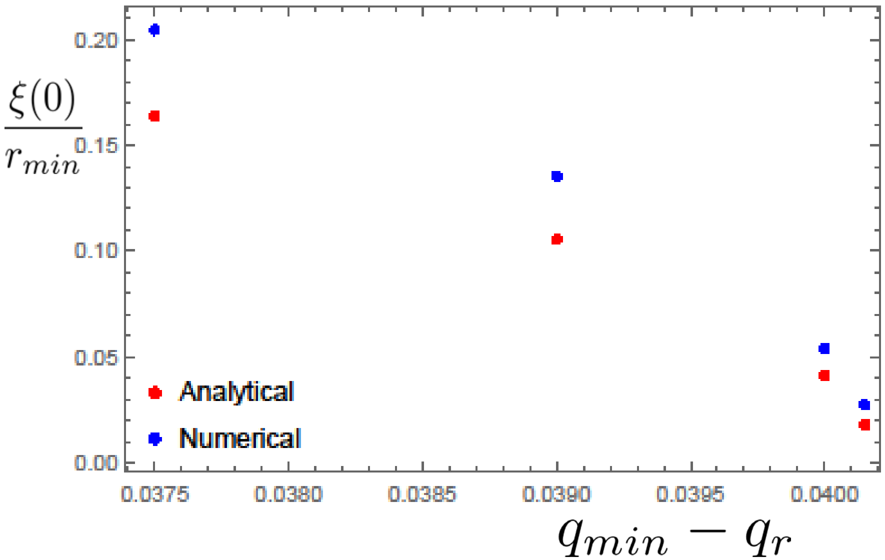
$$\frac{\partial}{\partial t}\delta f_k + \boldsymbol{v}_g \cdot \boldsymbol{\nabla}\delta f_k = \frac{1}{m}\frac{\partial F}{\partial \mathcal{E}}\left[\cancelto{0}{\frac{\partial}{\partial t}} - \frac{m}{Ze}\cancelto{0}{\frac{\partial F}{\partial \psi}}\left(\frac{\partial F}{\partial \mathcal{E}}\right)^{-1}\frac{\partial}{\partial \phi}\right]\delta L$$

$\delta L = Ze(\xi^\psi \omega_{d0}^\phi + q\xi^\theta \omega_d^\psi)$ is the perturbed Lagrangian [10]

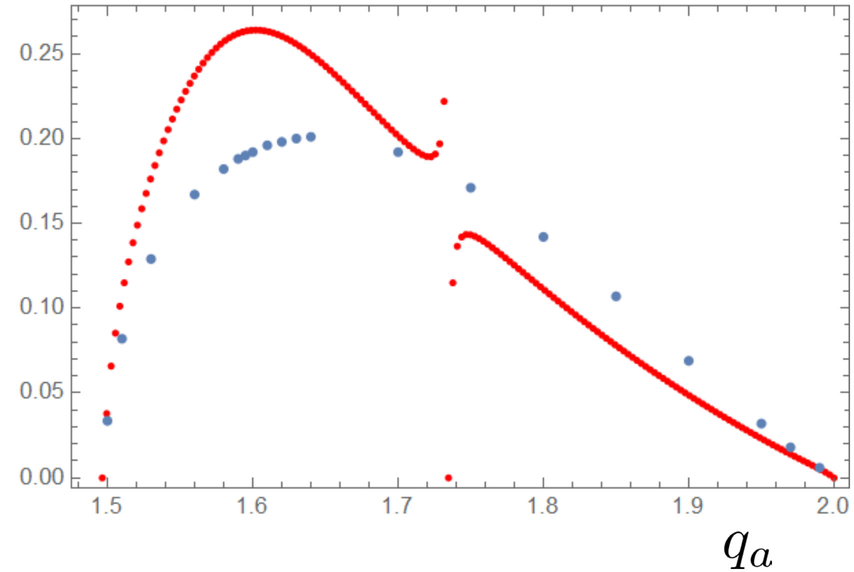
Where the fields are saturated, the time derivative vanishes. And where the mode kills core density and thermal gradients, then the diamagnetic frequency vanishes. Hence $\delta f = \delta f_{MHD}$

A complete non-linear model for long wavelength non-linear amplitudes

Comparison with non-linear kink mode:



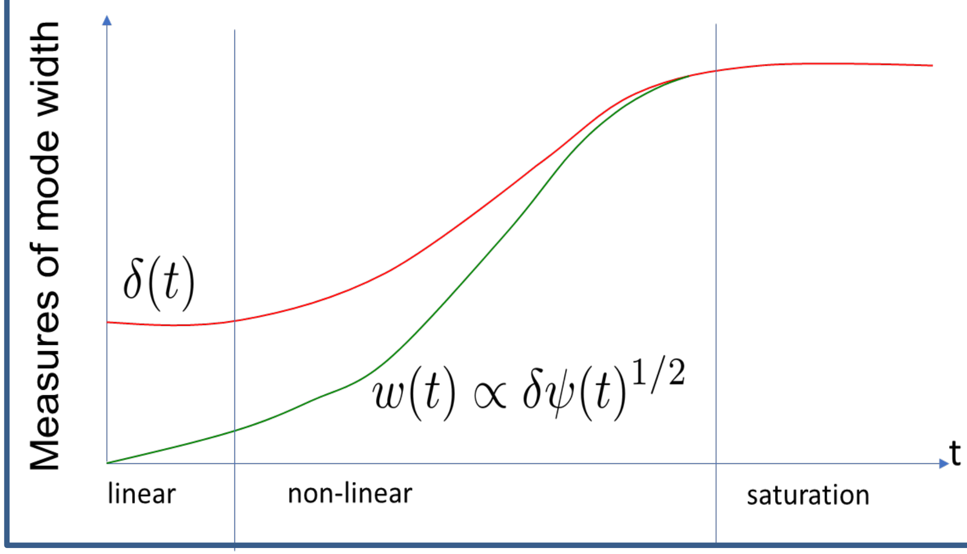
Comparison with non-linear external kink



A full description of seeding of NTMs by internal kink modes has been developed. With complete evolution, linear to non-linear to saturation of both the n/n kink mode and the (n+1)/n tearing mode [Graves, Varenna 2024 and APS 2024.

Tearing mode seeding in reactors

Development of **generalised linear -> non-linear** tearing evolution with bootstrap current, toroidal effects and potential for seeding from kink-infernal modes



Width δ for the electric variable $\delta\Phi$ is the resistive layer width during linear phase, a constant value governed by growth rate

w measures the magnetic field island width and is connected with flux variable $\delta\psi$. Starts arbitrarily small and grows linearly

$$\Delta'_{global}(t) = 2.12\frac{S\delta(t)}{r_s^2\omega_A\delta\psi(t)}\frac{d\delta\psi(t)}{dt} - 1.67\frac{D_R}{\delta(t)} - \frac{J_{BS}w(t)}{\delta\psi(t)}[1-0.7g(t)]\left[\frac{w(t)^2}{w(t)^2+w_c^2}\right]$$

This can be connected to the non-linear kink modes, so that we can investigate seeding of tearing modes

Non-linear MHD, saturated kink modes and Tearing mode seeding in reactors

Related publications:

J. P. Graves, M. Coste-Sarguet, C. Wahlberg, PPCF **64** (2022) 014001
https://doi.org/10.1088/1361-6587/ac3496

J. P. Graves, in preparation PPCF 2024

Graves, Varenna 2022 poster

Graves, EPS 2023, poster

Graves, APS 2023, poster

Graves, IOPP plasma conference 2024, poster

Graves, EPS 2024, poster

Graves, Varenna 2024, poster

Graves, APS 2024, poster

The impact of these achievements in terms of advancing and expanding the mainstream EUROfusion programme

The increase in the window for QH modes via ex-vessel (EFCC) and in-vessel (RMP) coils is quantified. Very important for high performance ELM-free operation

An alternative model for RWM-type modes is provided. The alternative model depends much more sensitively on q-profile and plasma resistivity than the standard description. Explains modes in diverted plasmas. Important for making predictions in future tokamaks.

Ordinarily stable (continua) n=0 modes can be driven unstable by anisotropic fast ion populations. This might be backed up by JET experiments (ICRH). These modes are very dangerous for disruptions. Another concern for a reactor is instability by fast ions with positive velocity gradient, which can occur e.g. by sawteeth

Development of a new kinetic-MHD code with full-electromagnetic effects, and wide orbits, valid for long wavelength modes, will provide an important tool for MHD stability verification in hot future reactors. The code will be able to go beyond the capabilities of many gyro-kinetic codes and kinetic-MHD codes

Calculation of linear and non-linear spectra challenges the alternative models for flux pumping, a candidate for sawtooth avoidance in hybrid-DEMO. Plasmas can be stationary, but tearing modes on satellite surfaces can be triggered.

Recommendations for incorporating promising developments into main Work Packages

Further experiments should be undertaken to verify the expansion of QH modes by RMPs or EFCCs. In fact what we have found is a likely consistent with ELM avoidance by RMPs, at least for cases where RMPs are replaced by EHOs.

Deeper investigations should be made into the causes of legacy disruptions across EUROfusion machines to verify whether they were caused by fast ion driven n=0 modes.

A closer examination of experiments that attempt to trigger continuous modes in the hope of avoiding sawteeth. Core pressure profiles tend to be flattened, but despite that, tearing modes are easily seeded. Also, the impact of core modes on heavy impurity accumulation should be considered [Neto, Graves, PPCF 2022]

All those working for EUROfusion work packages should read journals and attend conferences. We are encouraged to publish and present (at great expense). We should also read and listen.

To conclude, this EnR project has produced many potentially important theoretical results. EUROfusion is in a great position to verify them empirically, and thereby assist the design of safe future plasma scenarios.