EUROfusion

EnR mid term report: “Operation limiting plasma instabilities in high performance tokamaks”

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T. Barberis, D. Brunetti, S. Brunner, G. Bustos Ramirez , J. W. Connor, M. Coste-Sarguet, A. Dudkovskaia, C. J. Ham, F. Jeanquartier, F. Porcelli , H.R. Wilson

EPFL

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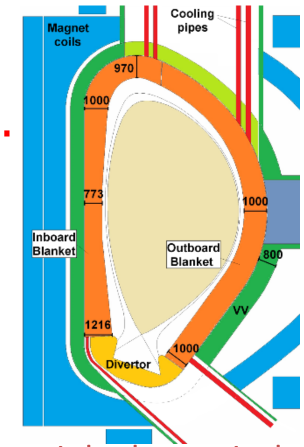
INTRODUCTION

STEP (spherical)

DEMO

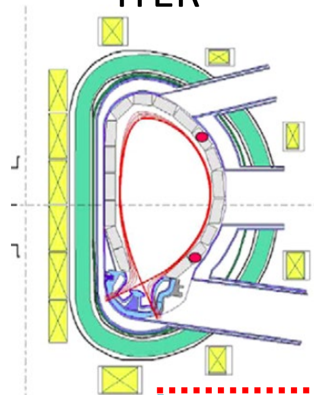


Decisions based on deep model, flight simulator?

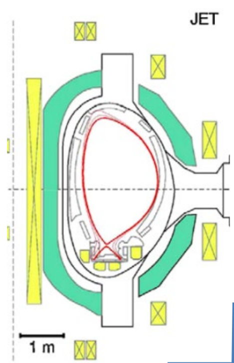
Extrapolation, mainly theoretical, models, new phenomena, sparse experimental data

MAST-U

ITER

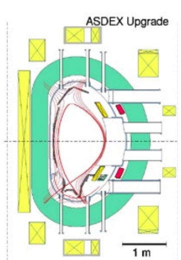


JET



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
- ITER will contribute to DEMO via community, tools and studies. But not from ITER experimental data

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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

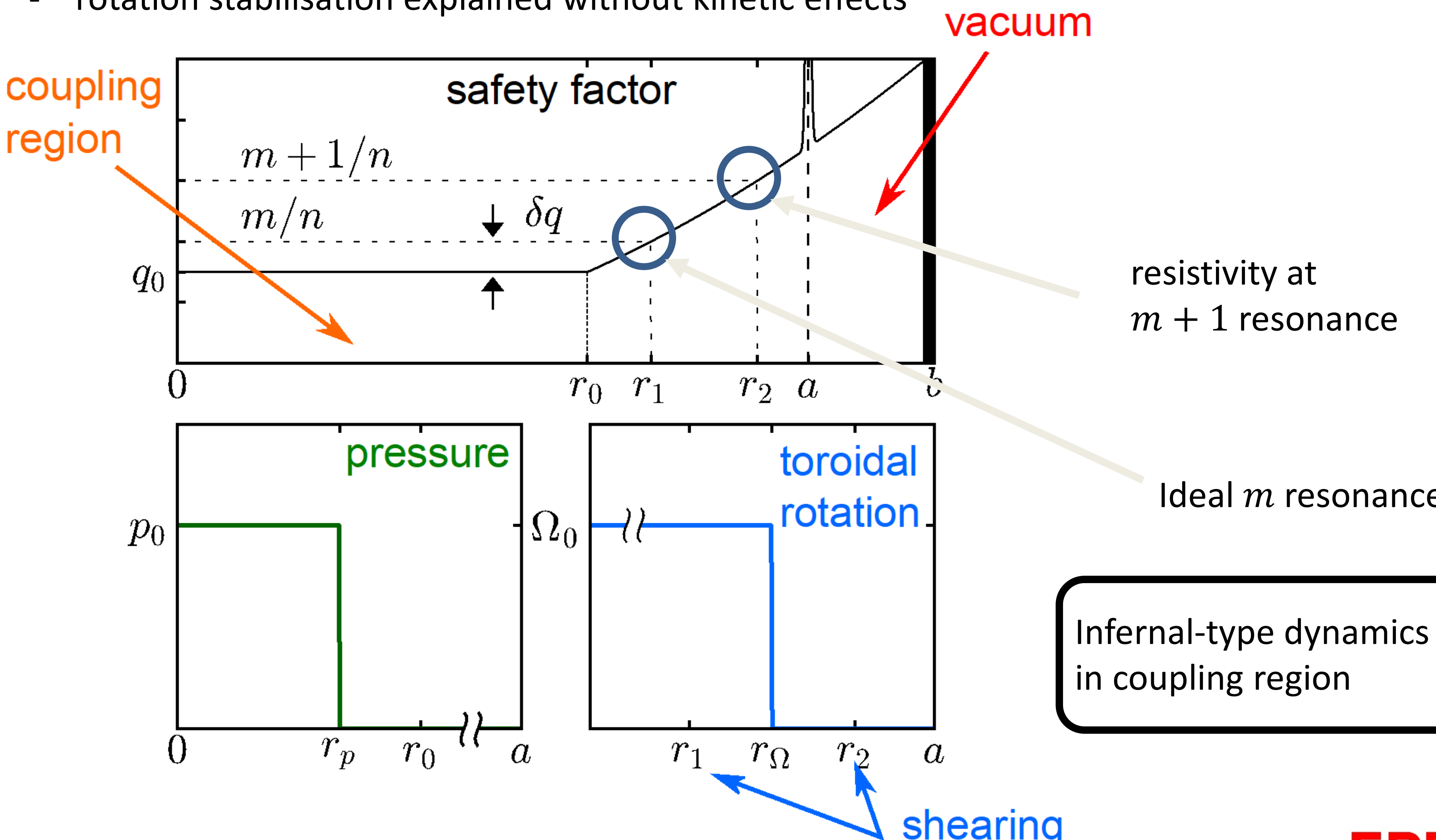
- Our role in EnR is to challenge assumptions and approximations
- We can do this by addressing physics not covered by existing codes, sometimes at the cost of approximations and simplifications elsewhere
- It can be done with analytic treatment and with new dedicated codes
- Of course, we hope to uncover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

Status of tasks June 1st – Dec 31st 2021

Core resistive infernal modes	Develop and solve equations that describe infernal modes with resistive effects in the region of low magnetic shear.	✓
Exfernal modes with finite magnetic shear	Develop and solve equations for exfernal modes (EHOs) with realistic q-profiles, including separatrix effects	✓
Near collisionless-ion infernal modes	Derive the equations for ideal interchange and infernal modes with nearly collisionless ions (for non resonant kink modes in hybrid)	✓
Non-linear ballooning in a slab	Develop a slab model of nonlinear ballooning mode to include an imposed shear flow.	✓
Ideal wall RWM model definition	Derive the RWM equations in the ideal wall limit including plasma beta effects and resistive plasma effects	✓
Ideal MHD n=0 modes and X-points	Develop a model for rigid-shift vertical displacement and the impact of X-point resonances for ideal MHD fluctuations	✓
Separatrix effects for kink-ballooning mode	Identify the essential physics for kink-ballooning that must be captured to describe MHD stability in full separatrix geometry.	✓

New theory for *RWM* 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 limited plasmas

β limits in a resistive plasma with rotation

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

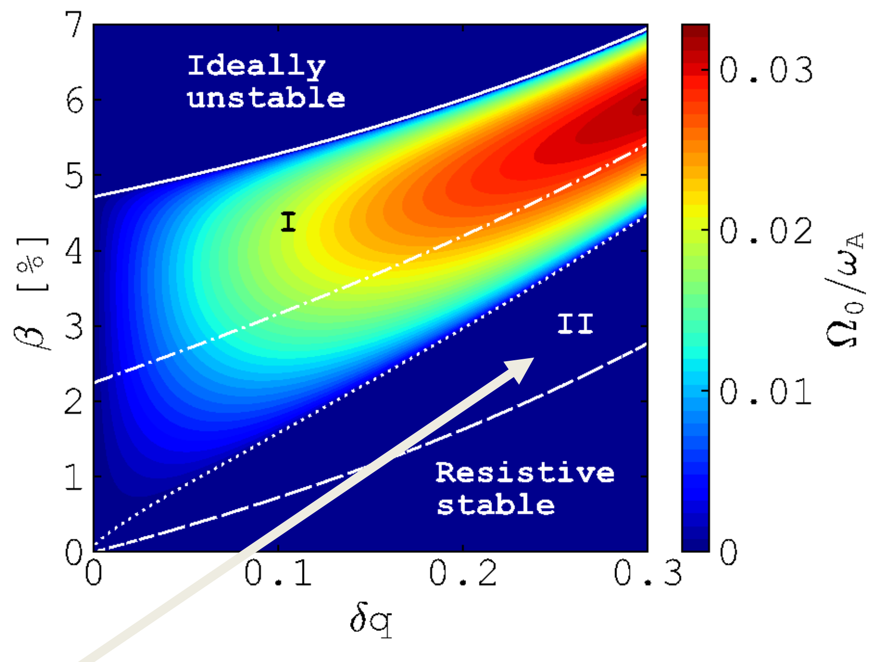
Dynamics described by single equation with smooth matching at r_0

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
- Brunetti, Varenna 2022, subm. PRL 2022



GGJ stabilised region

New theory form RWM limited plasmas

β limits in a resistive plasma with rotation

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

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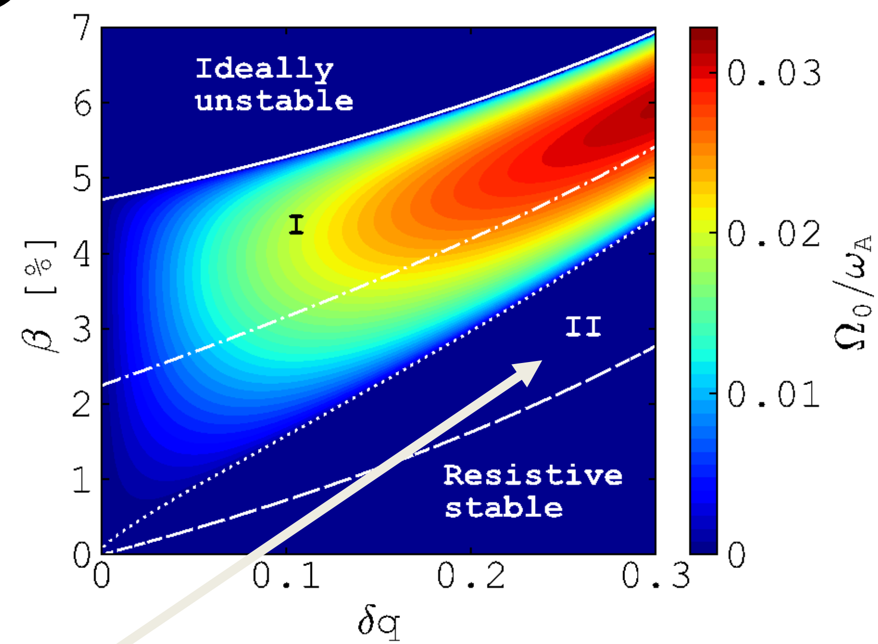
Future work:

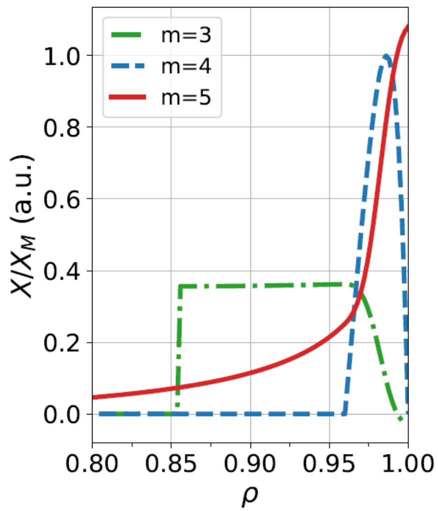
- ferromagnetic effects
- compare with experiments, reactor predictions



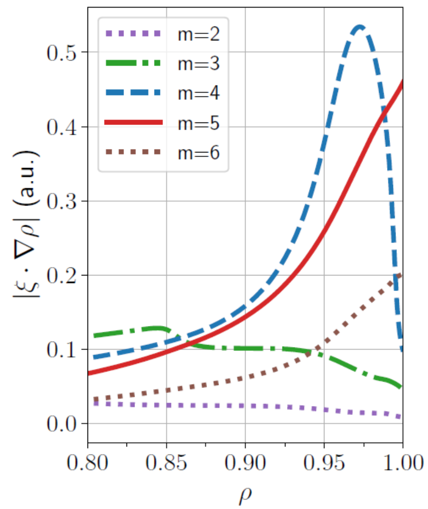
GGJ stabilised region

Edge Harmonic Oscillations (EHOs)

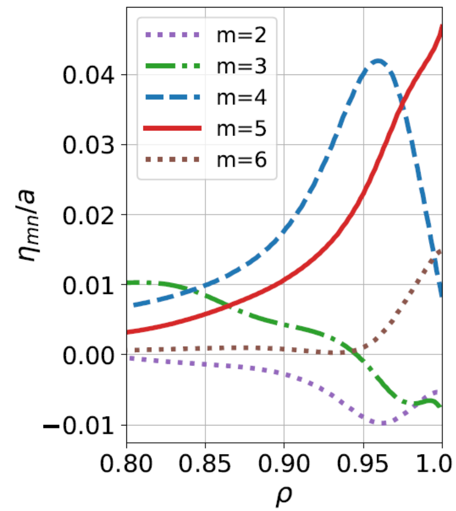
Analytic eigenfunctions



KINX numerical eigenfunctions

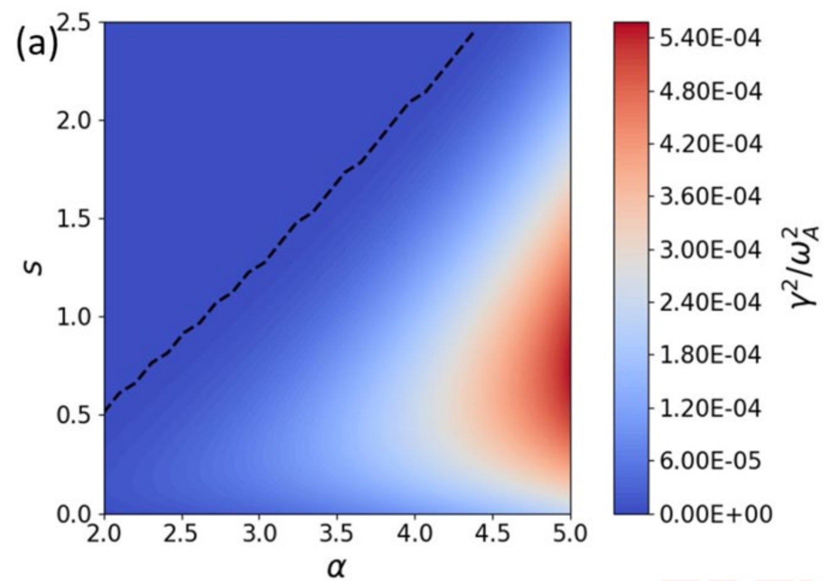


VMEC nonlinear displacements



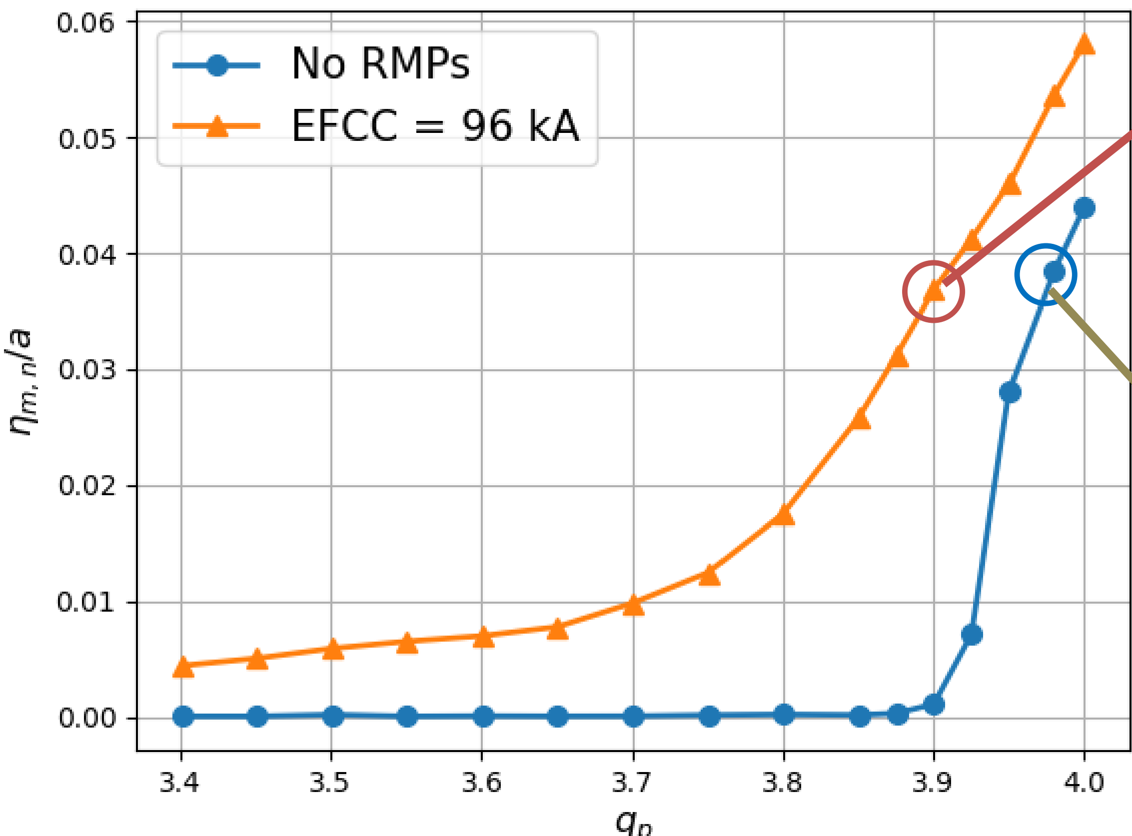
- Explore ELM free regimes via EHOs
- Agreement with KINX and VMEC modes
- Analytic *exfernal* mode model extended to include magnetic shear effects.
- Modes continue to exist despite shear near the edge

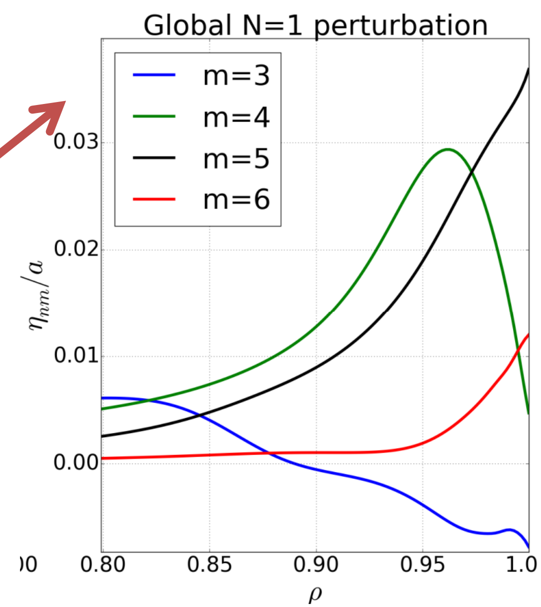
[Bustos Ramirez, Graves, Brunetti, PPCF 2021]

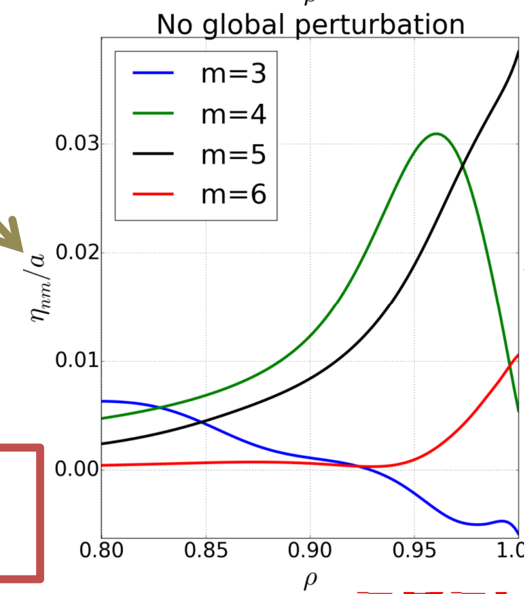


Extending EHO existence with EFCC coils

- 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





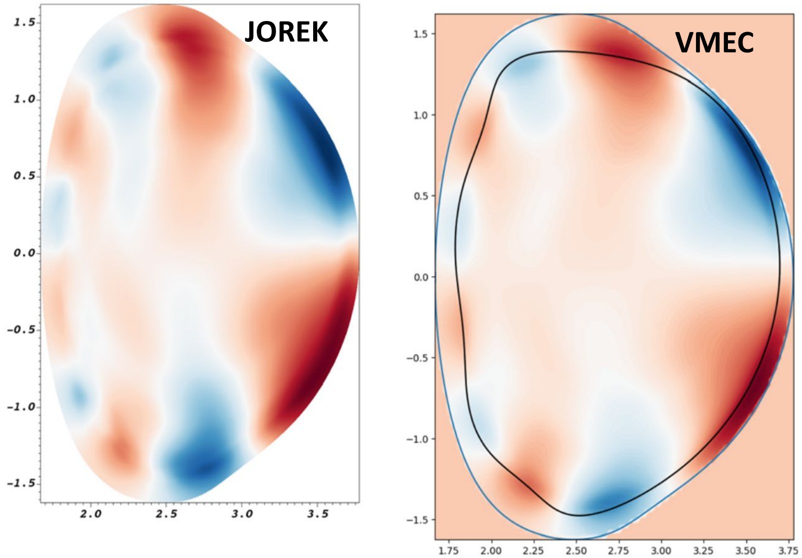


- RMPs help to **induce** EHOs over broader parameter space

[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

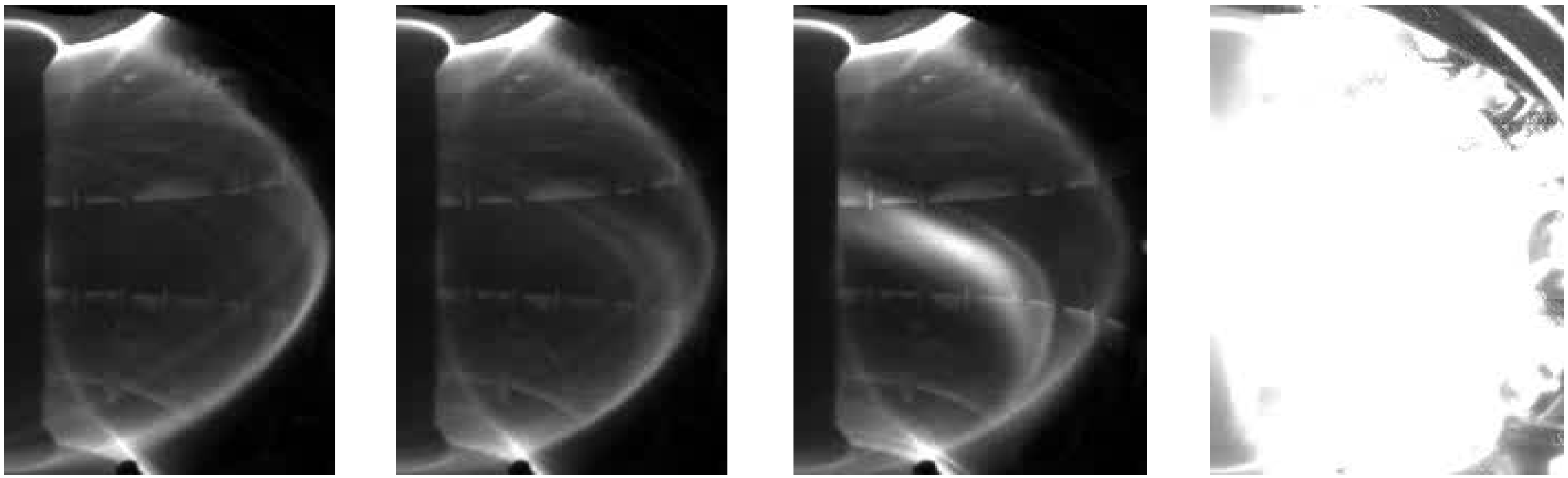
Pressure driven cases don't agree well between codes. JOREK can't run with ideal MHD at the edge. VMEC can't recover JOREK results. Neither are optimal

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

Nonlinear ballooning filaments

Filamentary disruptions MAST shot 29978 [Ham, IAEA TM 2022]. Seen also JET, TFTR



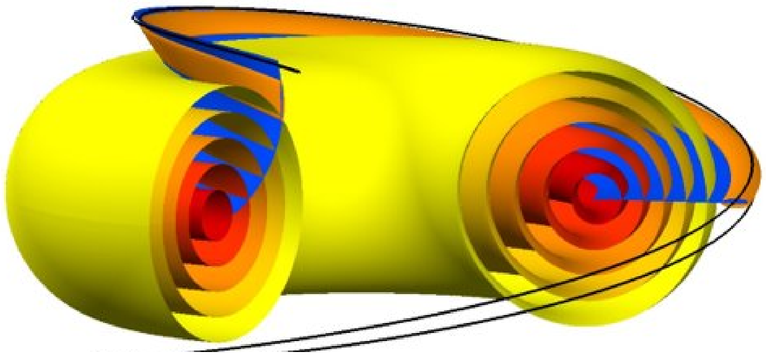
0s 10 micro s 20 micro s 30 micro s

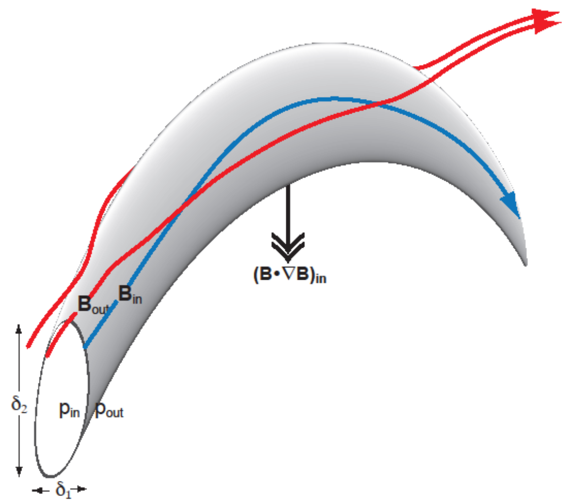
In addition to disruptions, such non-linear filaments are relevant to ELMs, especially type-II ELMs which will need to be avoided in a reactor

Nonlinear ballooning filaments

- Early phase of nonlinear filaments showed narrow finger like structures and a finite time singularity – explosive growth [Wilson & Cowley]
- Full nonlinear phase in analytic tokamak geometry assuming ideal MHD showed the filaments were metastable – the whole profile could be linearly stable to ballooning modes but filaments could still grow if displaced by a finite amount
- Magnetic shear twists and narrows the filament

[Ham *et al.* Phys Rev Lett **116** 235001 (2016)]





Non-linear ballooning Filaments

- Investigating conditions under which filaments can break off and either become ELMs or disruptions [IAEA technical meeting on disruptions 2022]
- Linear and quasi-linear studies have been reviewed. Shear flows rotate the filaments. Resistivity allows the filaments to break off

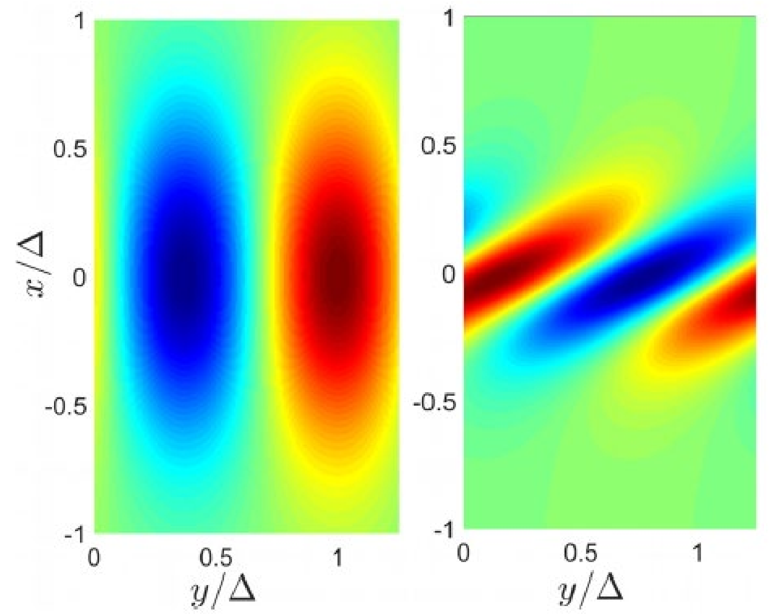


FIG. 2. Eddies of electrostatic potential contour for $\kappa = 5$ and $\Delta/L_n = 1/4$. $V_0' = 0$ for the left panel and $V_0' = 0.2\bar{y}$ for the right panel.

[Zhang, PoP 27, 020701 (2020)]

Future work:

- treat resistivity and rotation in a slab

- verify timescale against experiment

- expect scaling with resistivity similar to resistive interchange

- investigate EM braking by filament

Separatrix effects for kink-ballooning modes

The fundamental challenge:

- MHD and gyrokinetics predict structures that are field aligned (variation along $\boldsymbol{B}$ is $\sim R$, and $\sim \rho_i$ across)
- Linearly, we adopt toroidal dependence $\sim e^{in\phi}$, with n>>1
- At X-point, field lines are purely toroidal, so mode has $e^{in\phi}$ behaviour along $\boldsymbol{B}$ – **inconsistent with field-alignment**

Separatrix effects for kink-ballooning modes

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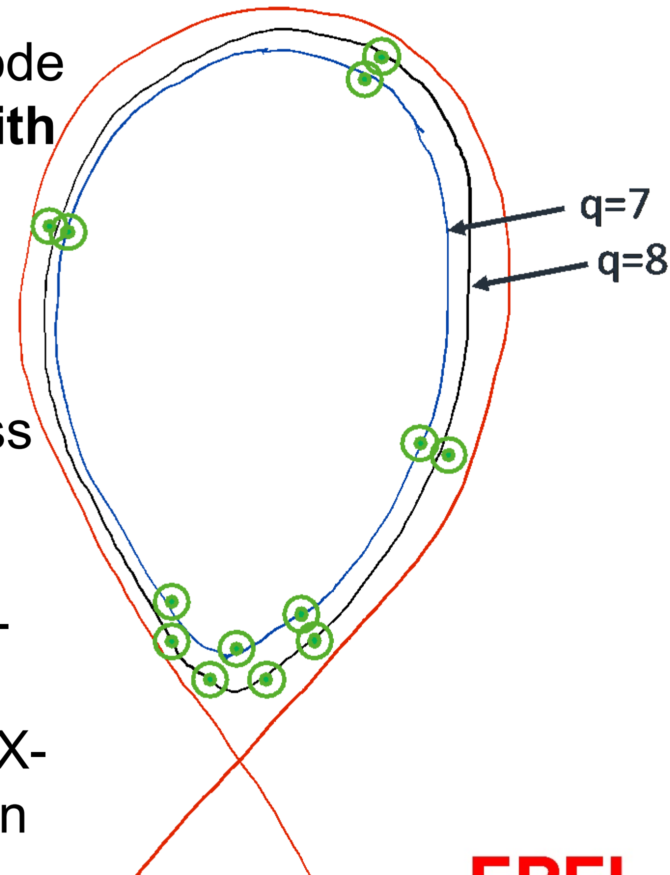


As one approaches the separatrix:

- Field lines linger poloidally near X-point
- Many toroidal turns as field line migrates across X-point region
- In going from one rational surface to the next, field lines do one additional toroidal turn in X-point region (for n=1)
- Meanwhile, nothing special occurs away from X-point – field lines on one rational surface align with those on next

Separatrix effects for kink-ballooning modes

Analytic and ELITE code MHD approaches

MHD hypothesis I

- Many poloidal Fourier harmonics (in straight field line poloidal angle), *m*, each centred on its respective rational surface where safety factor $q=m/n$
- They couple to form a radially extended ballooning mode that can be described by (modified?) ballooning theory
- Mode envelope decays to zero before reaching separatrix
- Then not clear how external kink drives peeling modes

MHD hypothesis II:

As above but…

- Fourier modes combine destructively at X-point → no perturbation there
- Minimises field line bending
- Mode does extend beyond separatrix, coupling to external kink

Future work: distinguish between these models. Extend ELITE to accurately capture separatrix physics

Separatrix effects for kink-ballooning modes

Kinetic ballooning – analytic and Monte-Carlo approaches

- In kinetic theories, field-aligned structures are a consequence of dominant parallel transport
- Gyro-kinetic codes have limited experience with coupling to the vacuum region, and associated coupling to free energy of external kink modes.
- Kinetic theories with separatrix effects in infancy

Future work:

- Investigate trajectories of particles with Larmor radius larger than the local shear scale length in the vicinity of the separatrix
- Consider consequences of modified parallel transport on field aligned mode structures.

Vertical Displacement oscillations with X-point

- Investigate n=0 oscillations that are resonant with magnetic X-point
- Modes are weakly continuum damped
- Potential to impact vertical stability control loop
- n=0 modes with discrete oscillation frequency just below poloidal Alfven frequency [A. Yolbarsop, F. Porcelli, R. Fitzpatrick, 2021 *Nucl. Fusion Letters* **61** 114003]:

$$\omega = \pm\omega_0 - i\frac{1}{2\tau_\eta}\frac{1-\hat{e}_0}{(D-1)(1-\hat{e}_0 D)}$$

$$\omega_0 = \hat{e}_0^{1/2}\tau_A^{-1}\sqrt{D-1}$$

$\hat{e}_0$: ellipticty parameter
τ_η: resistive wall time
$D > 1$ is a geometric parameter

For JET experiments $\omega_0 \sim 300$ kHz

VDOM structure: rigid vertical shift from axis to separatrix. $n = 0, m = 1$

Vertical Displacement oscillations with X-point

Vertical modes have been driven in JET by fast ions [Kiptily, NF 2021]

Recently this has been understood to be due to resonance of vertical mode with trapped particle bounce frequency [Porcelli, Barbaris et al Varenna 2022]. Also, Barberis, Porcelli NF letter 2022

Discrete unstable mode is a solution of dispersion relation [Porcelli PoP 1994]:

$$\omega^2 = \omega_0^2 - 2i\omega_0/\tau_\eta + i\omega_0^2\lambda_h; \quad \lambda_H = \Im\{\delta W_h\}$$

$$\delta W_h = \sum_\sigma \int dP_\phi \, d\mathcal{E} \, d\mu \frac{\omega}{\omega_b} \frac{\partial F}{\partial \mathcal{E}} \sum_{p=-\infty}^{\infty} \frac{\mathcal{L}_p^2}{\omega + p\sigma\omega_b}$$

Drive for instability requires $\frac{\partial F}{\partial \mathcal{E}} > 0$, i.e. bump on tail, possible via auxiliary heating, or post sawtooth plasma conditions

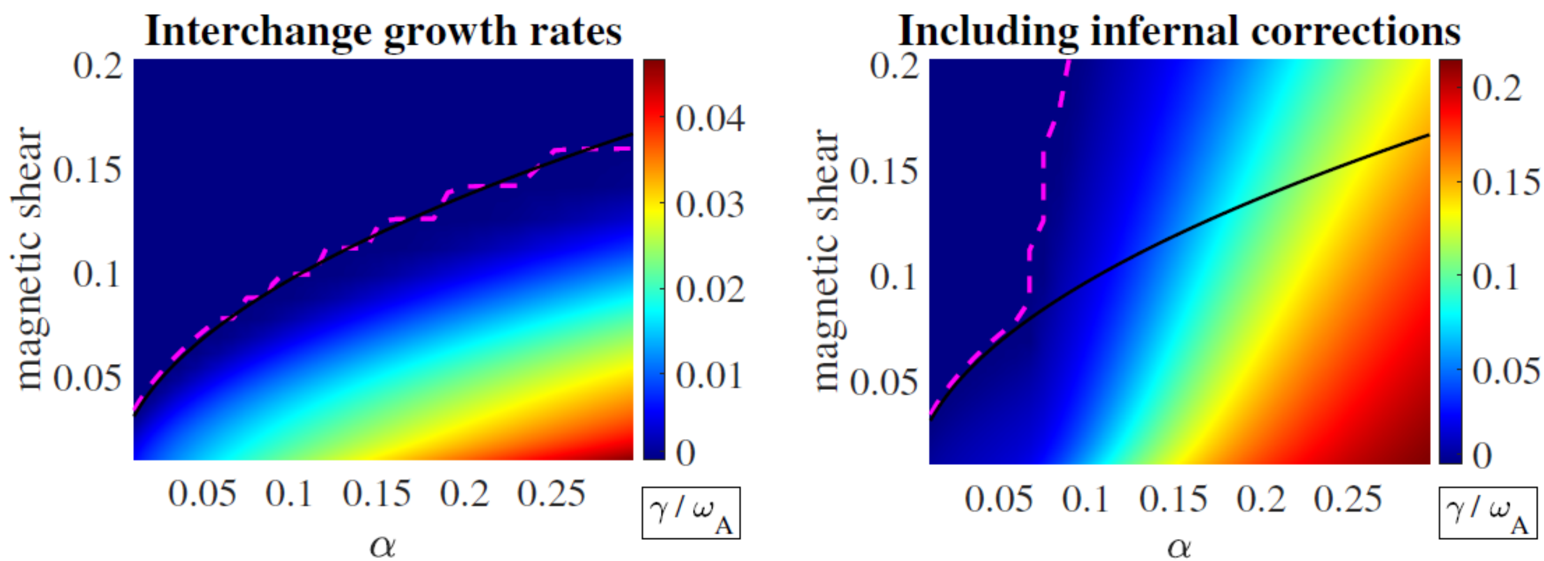
Future work:

- Numerical simulations with MISHKA (S. Sharapov) for reproducing JET experiments
- Simulations with NIMROD (C. Kim) with realistic divertor (X-point) conditions

Necessary conditions for toroidal stability

A light linear eigenvalue code has been developed based on the global toroidal resistive equations of Ref. [Graves, Coste-Sarguet, Wahlberg, PPCF 2022]

For example necessary conditions have been re-visited for tokamak flux surfaces with average poor curvature and conventional monotonic q-profiles.

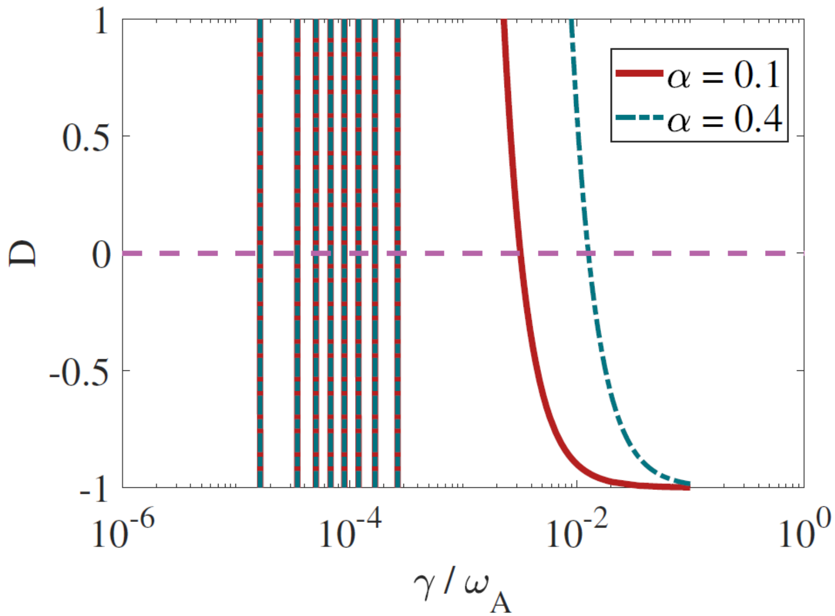


M. Coste-Sarguet, Varenna 2022: showing growth rate of n=10, m=9. Destabilising effects of weak ballooning cause strong correction to Mercier criterion even for q<1.

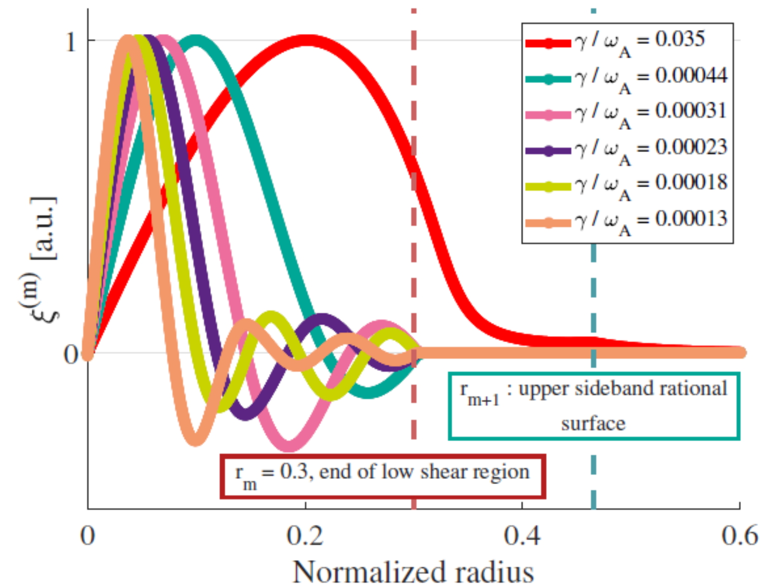
Future work:
- Investigate toroidally coupled resistive instabilities in advanced scenarios [PPCF, in prep]
- Addition of shear plasma flows and vacuum physics to new light global resistive code

Sawtooth avoidance: discrete unstable spectra

It is important to investigate the stability properties of hybrid scenarios which manage to avoid sawteeth. Spectra of unstable discrete resistive modes have been identified [M. Coste-Sarguet, Varenna 2022]



Spectra of unstable modes,
Accumulating towards gamma=0



Eigenfunctions of m=n=2 short radial wavelength instabilities

Future work:

- Compare results with analytic description for cases with marginal and bad average curvature
- Investigate connection with magnetic flux pump for maintaining hybrid plasma conditions [Jardin et al] via quasi-linear extension of the new light code

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

New eigenvalue code for kinetic MHD

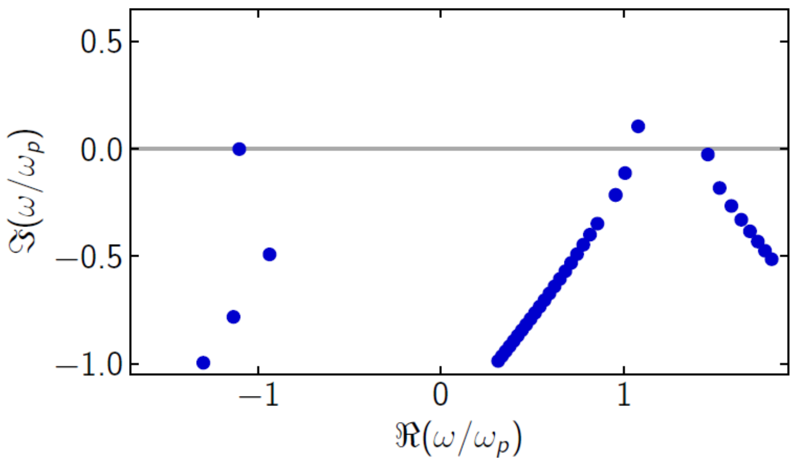
Kinetic description of bump on tail Vlasov-Poisson problem has been verified [F. Jeanquartier, Brunner, Graves, SPS conference 2022]:

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

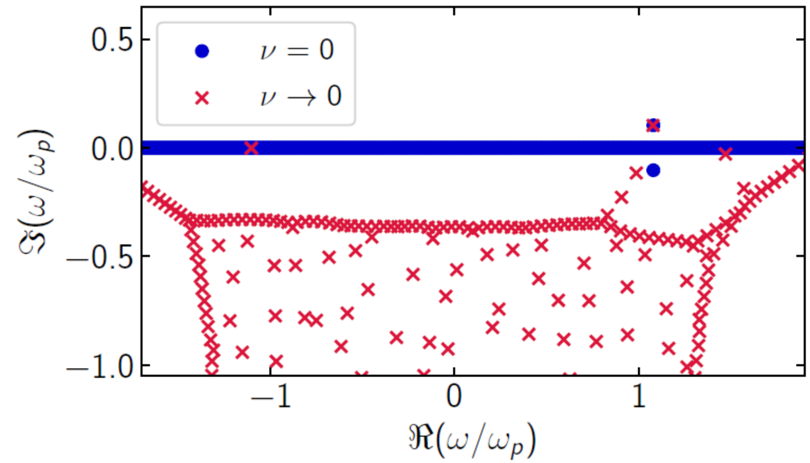


Van Kampen Approach

- 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

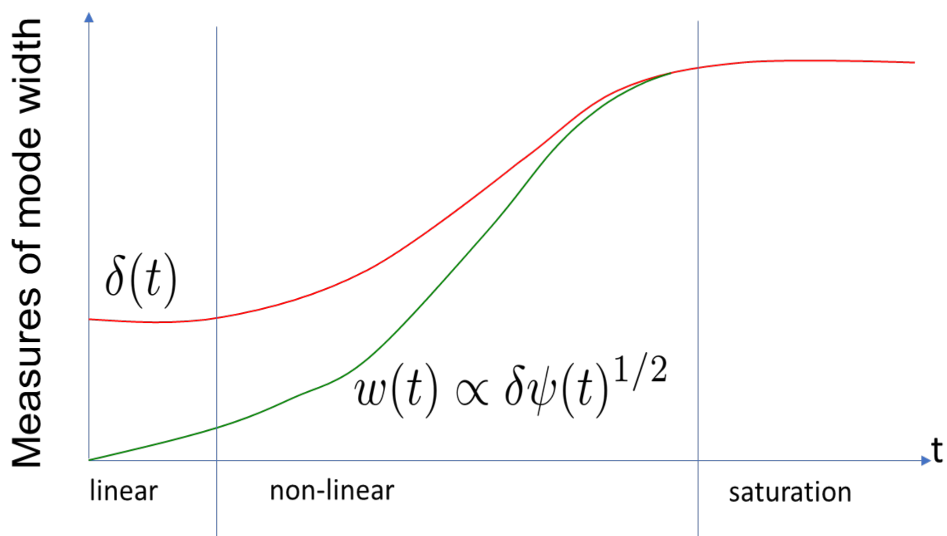


Future work:

- Test toroidally relevant cases, starting with non-resonant kinetic effects of Kruskal-Oberman
- Integration into VENUS-MHD global code (full MHD code with flows)
- Inclusion of parallel electric field effects, resolution of continuum modes (e.g. GAMs)

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

Paradox concerning toroidal corrections and singularities solved [Graves, Varenna 2022]

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

$$\mathrm{g}\,(t) = 0.31\left(\frac{\pi w(t)}{2^{13/4}\delta(t)}\right) + 0.69\left(\frac{\pi w(t)}{2^{13/4}\delta(t)}\right)^2$$

$$\delta(t) = \left\{\left(\frac{d\delta\psi(t)}{dt}\right)^{-1}\frac{1}{(ns)^2}\left[\frac{\tilde{m}^2\delta\psi^2}{2} + \frac{r_s^4(1+2q^2)}{S\omega_A}\frac{d}{dt}\right]\left(\frac{d\delta\psi(t)}{dt}\right)\right\}^{1/4}, \quad w(t) = \frac{2^3}{\pi}\left(\frac{\tilde{m}\delta\psi(t)}{ns}\right)^{1/2}$$

Future work: investigate effect of weaker rotation shear in reactors and ease of seeding. Examine potential avoidance by pre-emptive current drive and kinetic effects

Journal Publications

A. Yolbarsop, F. Porcelli, and R. Fitzpatrick, "Impact of magnetic X-points on the vertical stability of tokamak plasmas," published NF 2021

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

E. Neto, J. P. Graves, M. Raghunathan, C. Sommariva and D. Pfefferle "Heavy impurity transport in tokamaks subject to plasma rotation, NTV and the influence of saturated ideal MHD perturbations," published PPCF 2021

J. P. Graves, M. Coste-Sarguet, C. Wahlberg "Pressure driven long wavelength MHD instabilities in an axisymmetric toroidal resistive plasma," published PPCF 2021

D. Brunetti, C. J. Ham, J. P. Graves, et al "Understanding JET-C quiescent phases with edge harmonic magnetohydrodynamic activity and comparison with behaviour under ITER-like wall conditioning," published PPCF 2021]

D. Brunetti, C. J. Ham, S. Saarelma, J. P. Graves et al "Finite magnetic well effects on resistive and drift-resistive ballooning modes in a shaped tokamak," published Nucl. Fusion 2021

T. Barberis, F. Porcelli, and A. Yolbarsop, "Fast-ion-driven axisymmetric modes in magnetically confined toroidal plasmas," published. Nuclear Fusion (Letter)

A Yolbarsop, F Porcelli, Wandong Liu, and R Fitzpatrick, "Analytic theory of ideal-MHD vertical displacements in tokamak plasmas," publ. Plasma Phys. Control. Fusion

Conference contributions

F. Porcelli, "Impact of divertor X-points on axisymmetric modes in tokamaks," Abstract for 19th European Fusion Theory Conference

E. Neto, J. P. Graves, "Heavy impurity transport in the presence of 3D MHD ideal saturated modes, rotation and ambipolar electric field," Abstract and Invited oral for 10th International workshop on Stochasticity in Fusion Plasmas

T Barberis, F. Porcelli, "Resonant interaction between feedback stabilized axisymmetric modes and energetic ions," Abstract for 17th IAEA Technical Meeting on Energetic Particles and Theory of Plasma Instabilities in Magnetic Confinement Fusion

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)

A Yolbarsop, F Porcelli, Wandong Liu, and R Fitzpatrick, "Analytic theory of ideal-MHD vertical displacements in tokamak plasmas," subm. Plasma Phys. Control. Fusion

T Barberis, "Fast particles resonance with axisymmetric modes in shaped plasmas," Abstract (poster) for THEORY OF FUSION PLASMAS JOINT VARENNA - LAUSANNE INTERNATIONAL WORKSHOP 2022

F. Porcelli, "Vertical displacements resonant at magnetic divertor X-points," Abstract for 48th EPS Conference on Plasma Physics (EPS)

Conference contributions

T. Barberis, "Linear drive of Fast-ion-driven vertical modes," Abstract for 48th EPS Conference on Plasma Physics (EPS)

D. Brunetti, "Free boundary pressure driven instabilities in a resistive plasma," Abstract (poster) for THEORY OF FUSION PLASMAS JOINT VARENNA - LAUSANNE INTERNATIONAL WORKSHOP 2022

J. P. Graves, "Unified linear and nonlinear treatment of tearing modes driven by infernal modes and bootstrap current," Abstract (poster) for THEORY OF FUSION PLASMAS JOINT VARENNA - LAUSANNE INTERNATIONAL WORKSHOP 2022

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

F. Jeanquartier, "Towards a hybrid kinetic-MHD spectral code to study instabilities of tokamak plasmas," Abstract (poster) for Annual Meeting of the Swiss Physical Society

M Coste-Sarguet, "Fundamental and exotic features of global resistive MHD instabilities in advanced tokamak regimes," Abstract (poster) for THEORY OF FUSION PLASMAS JOINT VARENNA - LAUSANNE INTERNATIONAL WORKSHOP 2022

Tasks for 2022

Core resistive infernal modes and rotation	Develop equations that describe resistive infernal modes with strong rotation shear (annex to VENUS-MHD)
Exfernal modes with strong rotation	Extension of VENUS-MHD code for exfernal modes with vacuum perturbations and flows
Near collisionless-ion infernal modes	Solve the equations for ideal interchange and infernal modes with nearly collisionless ions, also allowing for rotation shear and resistive effects on sidebands
Basic spectral code development	Develop drift kinetic solver using main harmonic eigenfunction and eigenvalue from VENUS-MHD code (low n mode)
Non-linear ballooning in a slab	Observe how flow shear rotates the filament of a ballooning mode in a slab and establish timescale of resistive motion of filament.
Ideal wall RWM model definition	Solve the equations in the ideal wall limit for RWMs including plasma beta effects and resistivity, including some separatrix effects
Fast particle interaction with n=0 modes	Develop model for interaction between fast ions and n=0 modes, with linear hybrid kinetic-MHD model.
Separatrix effects for kink-ballooning mode	Identify the consequences of the new ideal MHD theoretical insight for gyrokinetic micro-instabilities in separatrix geometry

Deliverables for 2022

Topic 2022	Detail	Expected status end of 2022
Ideal infernal and exfernal code with strong rotation	Extend infernal and exfernal modes for the application of EHOs by extending VENUS-MHD to handle vacuum perturbations and flows	Expected to be completed by end of 2022
Necessary conditions for stability in burning plasma	Inclusion of kinetic inertia for a consistent treatment of collisonless thermal ion effects on pressure driven MHD instabilities	Completed
Non-linear ballooning in a slab	Report on how flow shear rotates the filament of a ballooning mode in a slab and establish timescale of resistive motion of filament.	Unfinished, expected complete by March 2023
Ideal wall RWM model with toroidal effects	Report on the ideal wall limit for RWMs including plasma beta effects and resistivity, including some separatrix effects	Completed
Fast particle interaction with n=0 modes	Determine stability thresholds for the resonant excitation of these modes by fast ions, and comparison with relevant experimental results from JET.	Completed
Separatrix effects for kink-ballooning mode	Make recommendations for the development of tokamak edge plasma gyrokinetic codes to capture the effects of full separatrix geometry	Unfinished, likely completed end of 2023