Nonlinear MHD simulations of Quiescent H-mode pedestal in DIII-D and implications for ITER

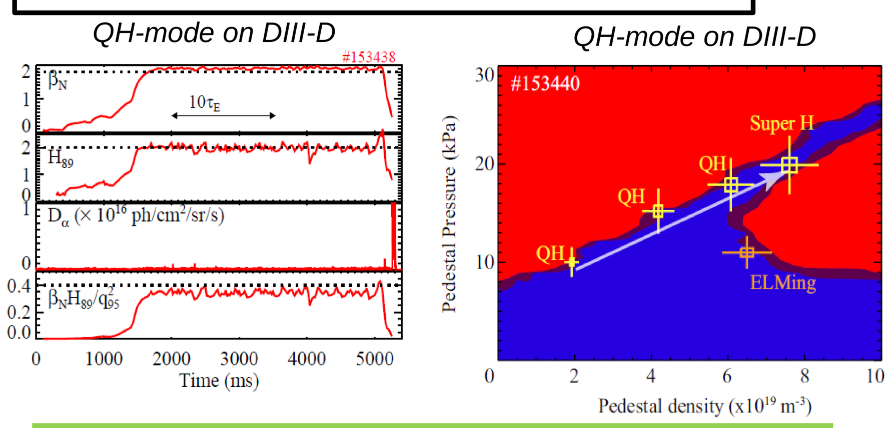
F. Liu[1], G.T.A. Huijsmans[2,7], A. Loarte[3], A. M. Garofalo[4], W. M. Solomon[4], M. Hoelzl[5], S. Pamela[6], M. Becoulet[2], F. Orain[5]

[1]University of Nice Sofia Antipolis, UMR CNRS 7351, Parc Valrose 06108 Nice, France [2]CEA, IRFM, F-13108 Saint-Paul-Lez-Durance, France
[3]ITER Organization, Route de Vinon sur Verdon, CS 90046, 13067 Saint Paul Lez Durance Cedex, France
[4]General Atomics, P.O. Box 85608, San Diego, California 92186-5608, USA [5]Max Planck Institute for Plasma Physics, 85748 Garching, Germany
[6]CCFE, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK [7]Eindhoven University of Technology, Eindhoven, the Netherlands

Motivation

QH-mode

- H-mode confinement (high performance)
- ELM-free (no transient divertor heat loads)
- DIII-D QH-modes approaching ITER-relevant conditions



QH-mode on DIII-D — QH-mode on DIII-D

Apply QH-mode on ITER plasma

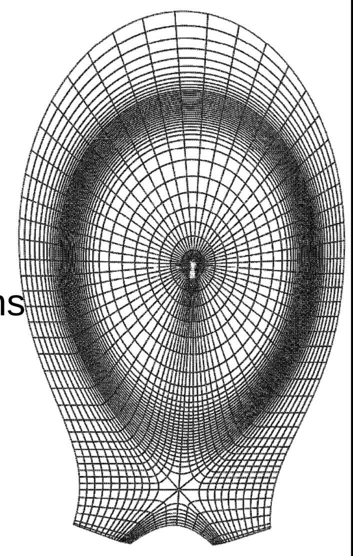
- Towards validation of Non-linear MHD simulations on DIII-D
- Extrapolation to ITER

Nonlinear MHD code: JOREK

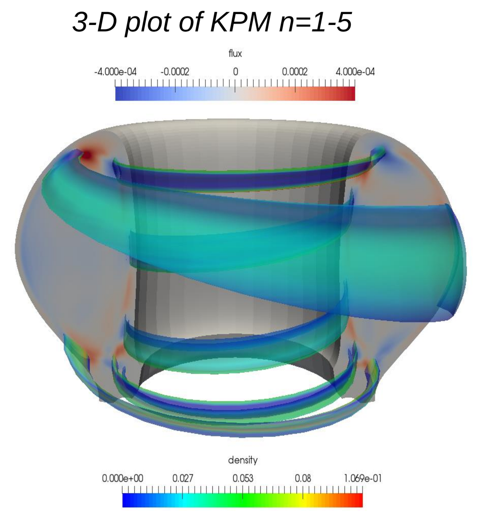
- Full and reduced MHD physics models
- Full plasma domain(open+closed field lines+xpoints)
- Divertor boundary conditions
- 3-D resistive walls, two fluids effect

Physics applications:

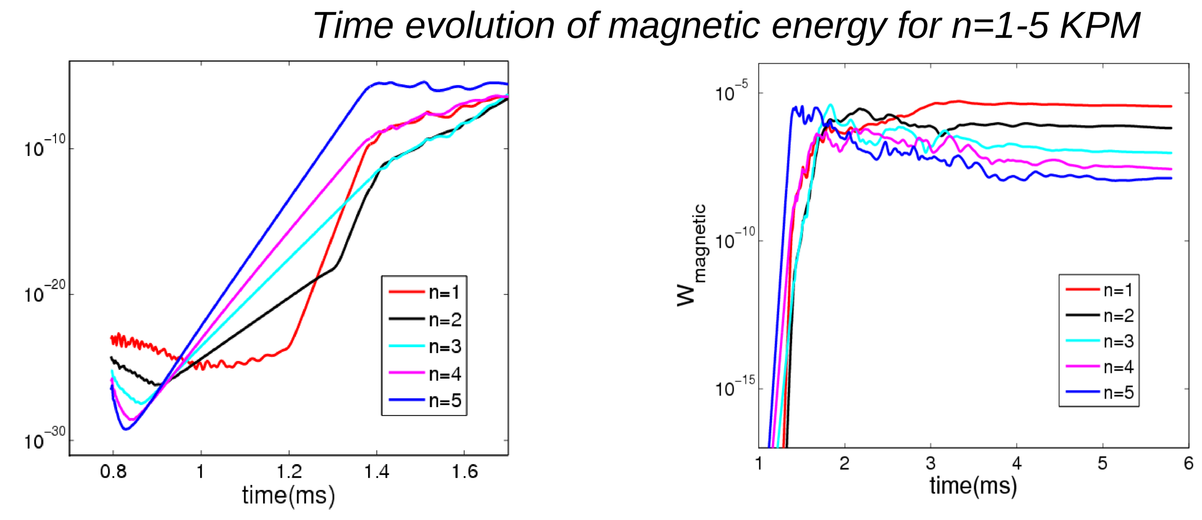
- Edge Localized Modes (ELMs)
- Pellet triggering
- Error field penetration for RMPs
- Mitigation/suppression of ELMs
- gas injection triggered disruptions
- Stabilization of Tearing Modes
- Vertical Displacement Events
- Resistive Wall Modes
- QH-Mode



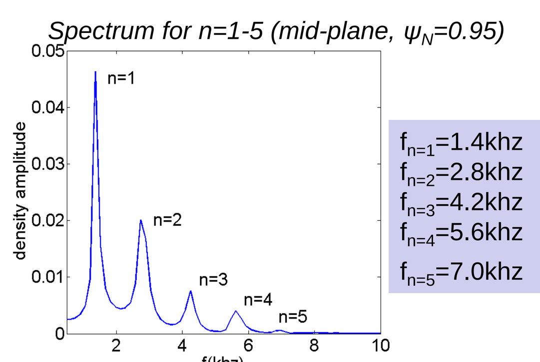
Nonlinear simulation with n=0-5 modes of DIII-D QH-mode plasma



3-D plot of KPM n=1-5

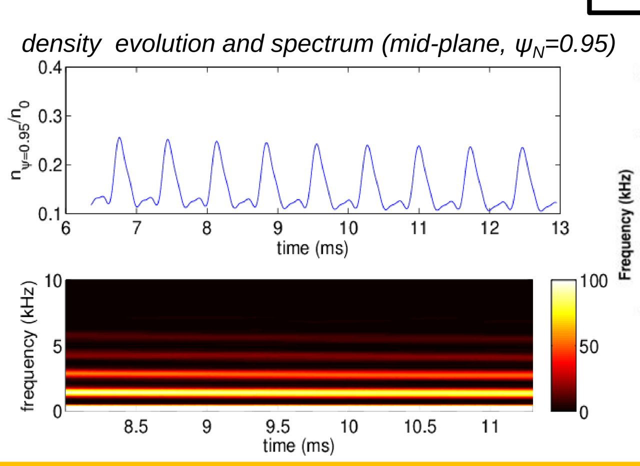


Time evolution of magnetic energy for n=1-5 KPM

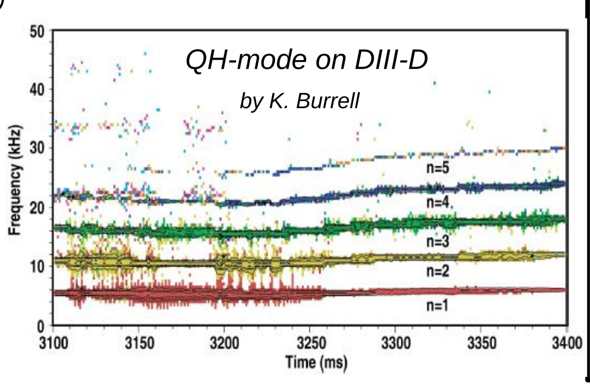


Spectrum for n=1-5 (mid-plane, ψ_N=0.95)

- Stationary state by saturated n=1-5 kink/peeling mode(KPM)
- Initial growth of linearly most unstable n=5 KPM followed by fast growth of n=1 mode due to non-linear mode coupling
- Saturated state with dominant n=1 rotating KPM
- KPM rotates in counter clockwise poloidal direction in the edge ------ due to ExB flow
- Rotation frequency: 1.4kHz



density evolution and spectrum (mid-plane, ψ_N=0.95)



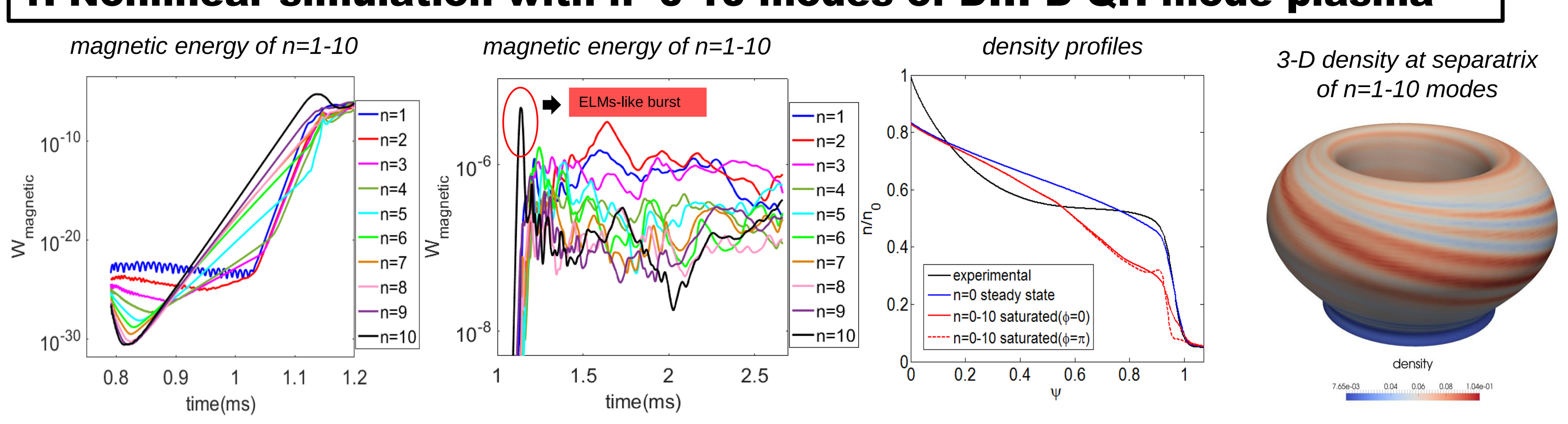
QH-mode on DIII-D by K. Burrell

MHD simulations characteristics:

- Density oscillations due to KPM for EHO observations
- non-sinusoidal oscillations contain multiple toroidal harmonics(n=1-5)
- Frequency rate of harmonics comparable with experiments

Identification: the nonlinear boundary of QH-mode vs ELMs(ballooning mode)

1. Nonlinear simulation with n=0-10 modes of DIII-D QH-mode plasma

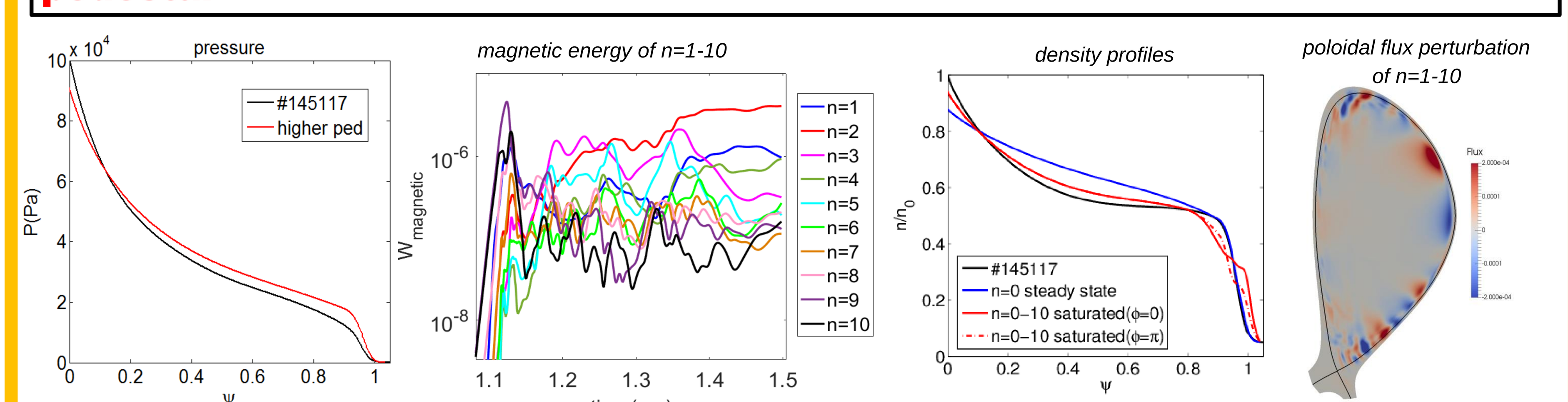


magnetic energy of n=1-10 — magnetic energy of n=1-10 — density profiles — 3-D density at separatrix of n=1-10 modes

- n=10 has highest growth rate in linear growing phase
- nonlinear coupling between n=1-5 makes n=1 growth rate largest
- low-n modes (n=1,2,3) have higher energy amplitude, dominate the saturation phase
- n=10 shows ELMs-like behavior before saturation

Conclusion: strong QH-mode dominant

2. Nonlinear simulation with n=0-10 modes with increased pressure at pedestal

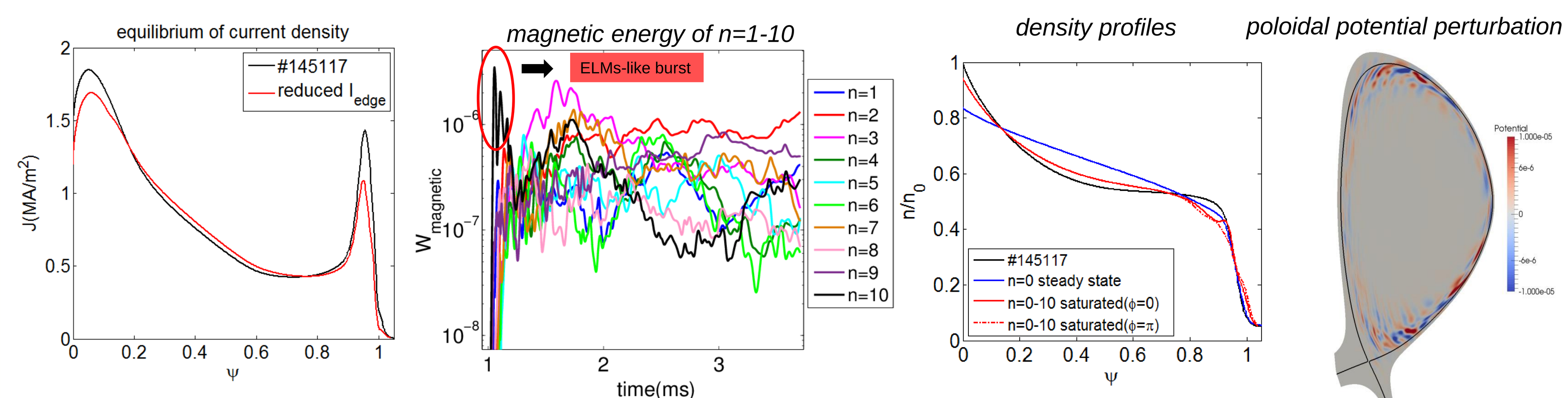


pressure — magnetic energy of n=1-10 — density profiles — poloidal flux perturbation of n=1-10

- Pressure at pedestal increased ~30% based on experimental equilibrium
- Low-n mode (n=2) dominates the saturation phase
- High-n modes(n=8,9,10) have lowest energy amplitude
- EHO behavior, 50% density loss, ~1.5cm displacement
- kink/peeling modes localized at the edge of plasma

Conclusion: strong QH-mode dominant

3. Nonlinear simulation with n=0-10 modes with reduced edge current

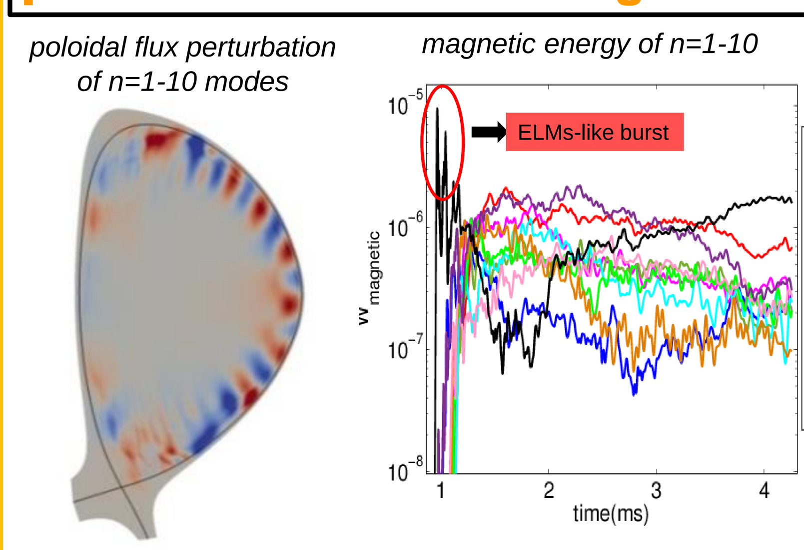


equilibrium of current density — magnetic energy of n=1-10 — density profiles — poloidal potential perturbation

- n=10 shows ELMs-like behavior before saturation phase
- low-n mode (n=2) is dominant in saturated phase of plasma
- high-n mode(n=9) is next strongest mode after n=2
- EHO with small density pedestal loss, displacement ~ 1cm---plasma is more stable
- Both Kink/peeling (QH) modes and Ballooning modes exist but QH-mode dominates

Conclusion: QH-mode dominant

3. Nonlinear simulation with n=0-10 modes with increased pedestal pressure and reduced edge current

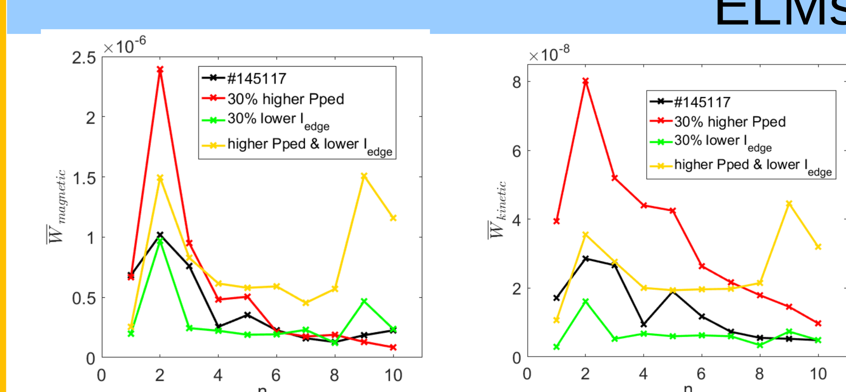


poloidal flux perturbation of n=1-10 modes — magnetic energy of n=1-10

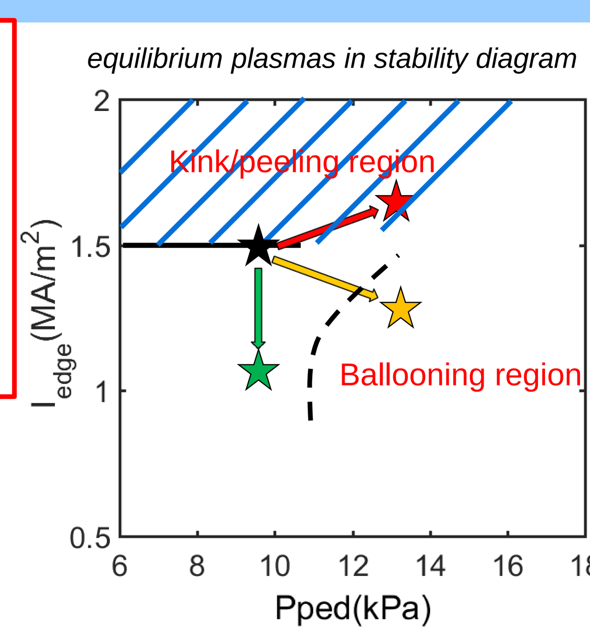
- High-n modes (n=9,10) dominate the saturation phase with highest amplitude
- High-n mode(n=10) has strong ELMs-like behavior
- n=2 mode energy amplitude level is below n=10(after 3ms), is secondary unstable mode
- EHO behavior, 50% pedestal loss
- Ballooning mode dominates the plasma more than kink/peeling modes(QH-mode)

Conclusion: Ballooning mode dominant

Conclusion for boundary identification of QH-mode vs ELMs(Ballooning)



Sufficiently high edge current is essential for plasma to saturate to QH-mode while high pressure pedestal is important for having ballooning mode

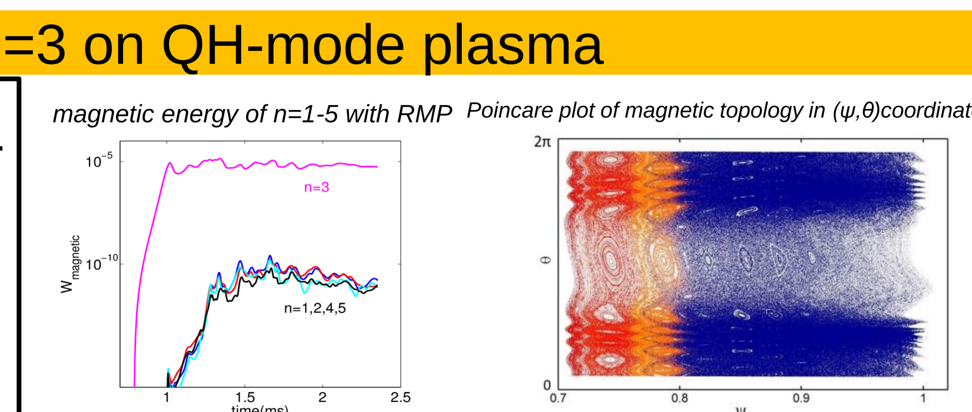


equilibrium plasmas in stability diagram

- Plasma with high edge current(red and dark) are strongly dominated by QH-mode, here dark is experimental equilibrium
- Plasma with lower edge current (green) dominated by QH-mode but mix with ballooning mode
- Plasma with lower edge current and higher pressure pedestal (yellow) is dominated by ballooning mode

Influence of RMP n=3 on QH-mode plasma

- ergodic islands in the edge due to RMP n=3
- n=3 energy linear growth is larger than other modes(n=1,2,4,5)
- n=3 energy amplitude level much higher than other modes
- n=1,2,4,5 modes are suppressed by n=3 mode
- EHO behavior cause 50% density loss, displacement ~1.0cm



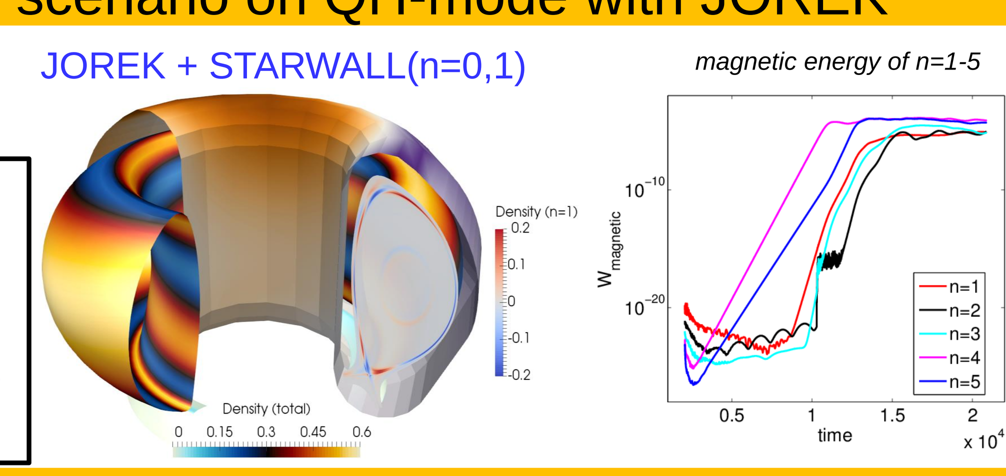
magnetic energy of n=1-5 with RMP — Poincare plot of magnetic topology in (ψ,θ)coordinates

RMP n=3 stabilize other modes in QH-mode plasma

Extrapolation of ITER Q=10 scenario on QH-mode with JOREK

I=15MA, B=5.3T, R=6.2m,a=2.0m,

JOREK + STARWALL(n=0,1)



magnetic energy of n=1-5

- Kink/peeling modes found in the edge of ITER plasma includes n=0-5 with ideal wall and resistive wall
- n=4 is the dominant mode in linear growth phase, n=4, 5 dominant in saturation phase
- More physics investigation is ongoing…

conclusion

Kink/peeling mode is found dominant in the edge of DIII-D QH-mode plasma

EHO behavior, density loss, spectrum physics characteristics are consistent with experimental observations

Edge current and pedestal pressure determine plasma saturation to QH-mode(kink/peeling modes) or ballooning modes

RMP n=3 effectively selects the n=3 kink-peeling mode in simulations of DIII-D QH-mode plasma. Other toroidal modes appear to be stabilized.

First simulations of ITER Q=10 scenario shows the edge current to be large enough to obtain a QH-mode regime.

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F. LIU

Feng.liu@iter.org