# SIMULATIONS OF ECCD-INDUCED TEARING MODE STABILIZATION

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TECH-X

SIMULATIONS EMPOWERING YOUR INNOVATIONS

swim

Center for Simulation of RF Wave Interactions with Magnetohydrodynamics

SciDAC
Scientific Discovery through Advanced Computing

**CEMM meeting**
**October 28, 2012**
**Providence, RI**

# Tearing modes can be suppressed by electron cyclotron current drive

- Neoclassical tearing modes generate magnetic islands in tokamaks

- Islands grow to macroscopic scales before nonlinearly saturating
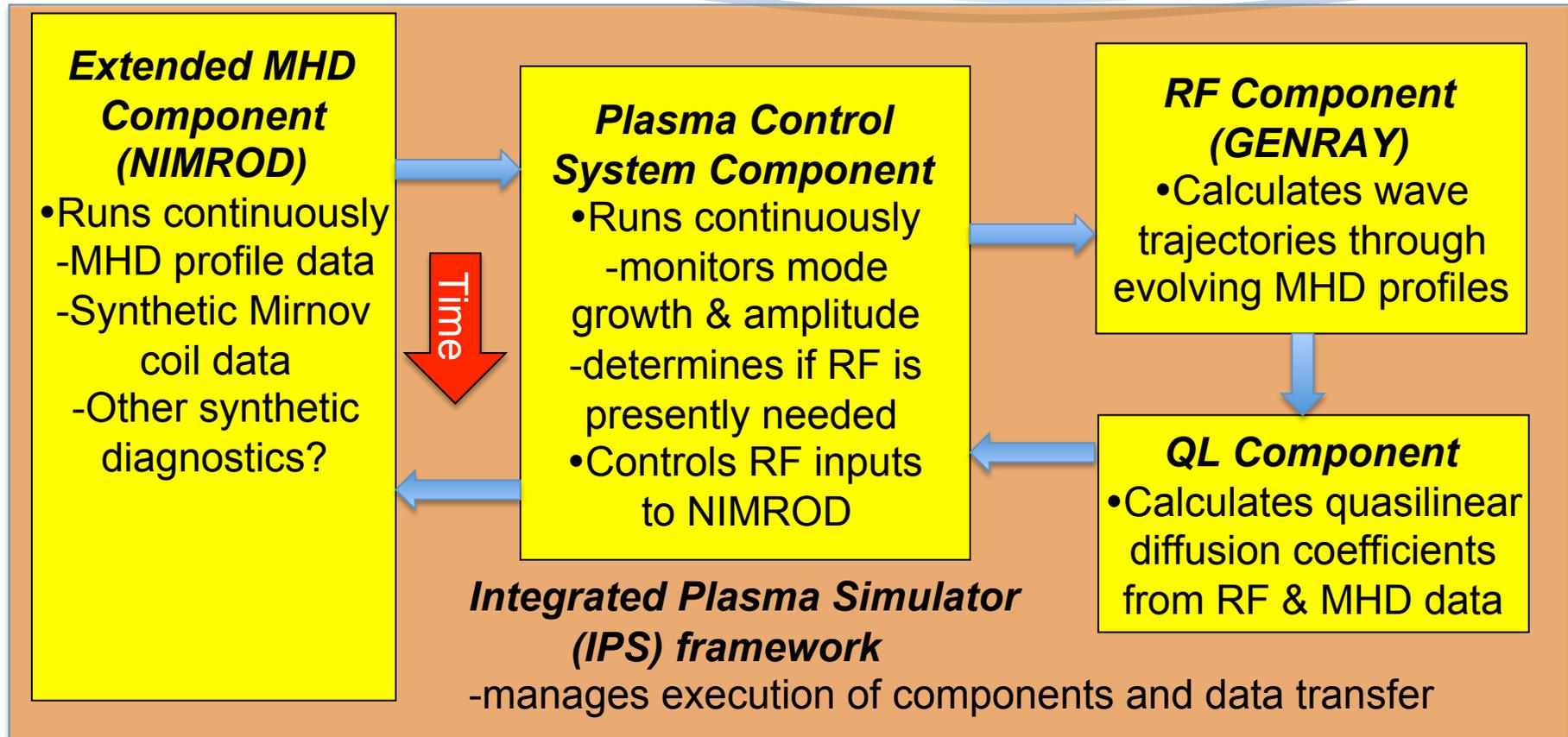  - degraded confinement
  - possibility of disruption

DIII-D shot 122898



Figure from Prater *et al*., Nucl. Fusion **47**, 371 (2007).



(2,1) magnetic island
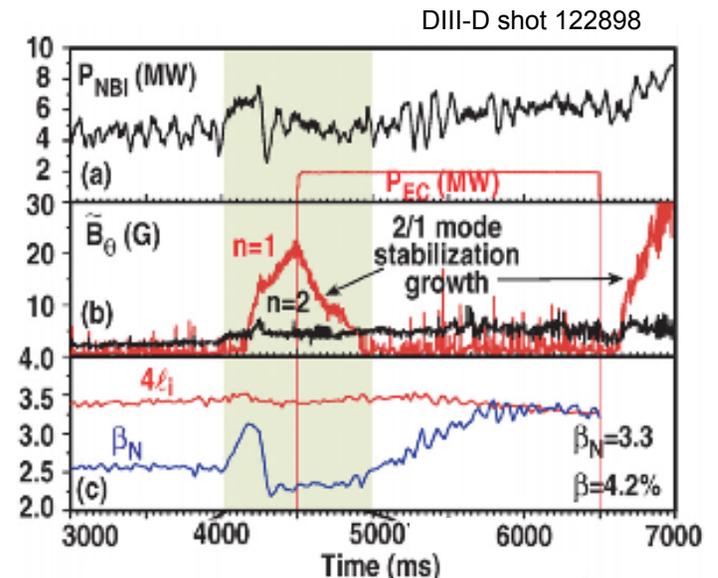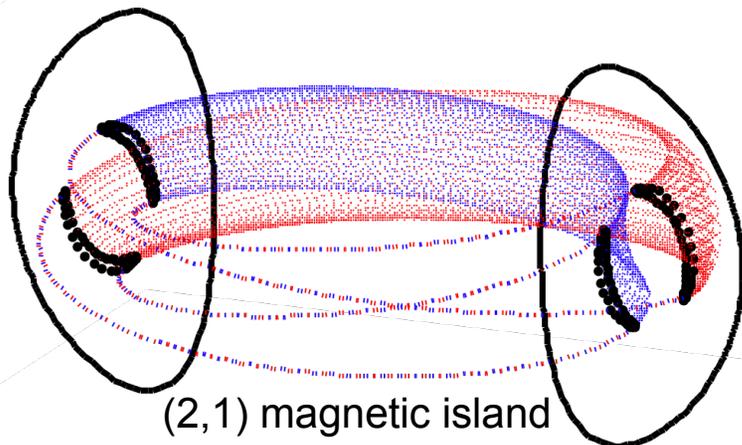
- RF waves resonant with electron cyclotron motion drive currents that alter or suppress island structures

- Goal is comprehensive modeling of:
  - mode growth                    - detection
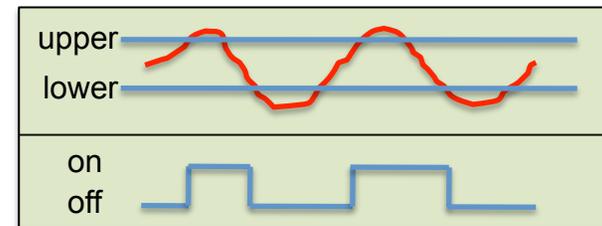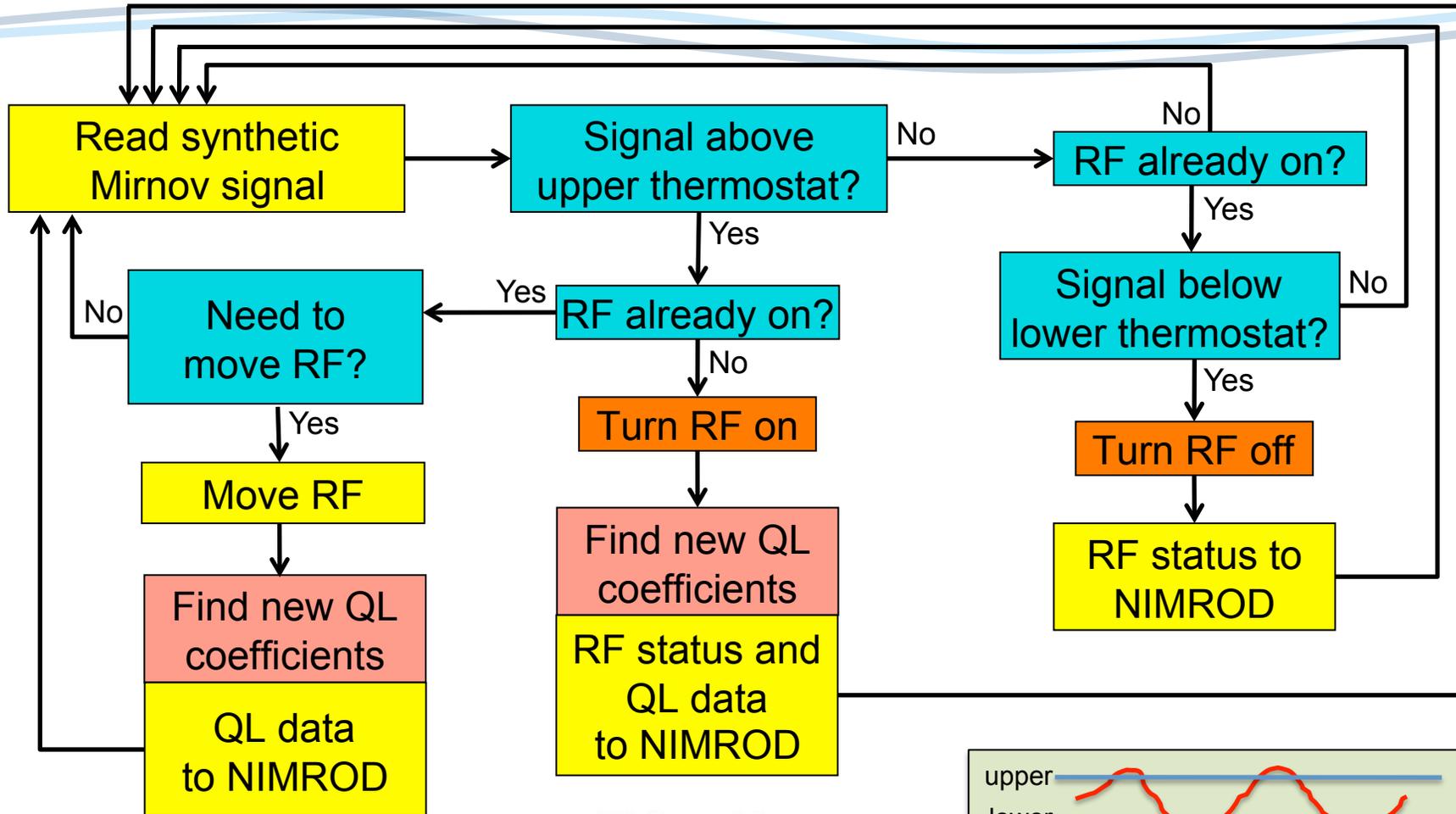  - actively controlled RF suppression

Recent areas of focus: Control algorithms, physics of deposited RF

# Components of the coupled simulation are controlled by SWIM's IPS framework

**Extended MHD Component (NIMROD)**
- Runs continuously
  - MHD profile data
  - Synthetic Mirnov coil data
  - Other synthetic diagnostics?

**Time**

**Plasma Control System Component**
- Runs continuously
  - monitors mode growth & amplitude
  - determines if RF is presently needed
- Controls RF inputs to NIMROD

**RF Component (GENRAY)**
- Calculates wave trajectories through evolving MHD profiles

**QL Component**
- Calculates quasilinear diffusion coefficients from RF & MHD data

**Integrated Plasma Simulator (IPS) framework**
- manages execution of components and data transfer

- Multiple levels of "control" – IPS runs components (including control system); control system then directs when IPS should run other components

# Basic control system: an RF thermostat



Read synthetic Mirnov signal → Signal above upper thermostat?

Signal above upper thermostat? — No → RF already on?

Signal above upper thermostat? — Yes → RF already on?

RF already on? (center) — Yes → Need to move RF?

RF already on? (center) — No → Turn RF on

RF already on? (right) — No (top return)

RF already on? (right) — Yes → Signal below lower thermostat?

Need to move RF? — No → (return to Read synthetic Mirnov signal)

Need to move RF? — Yes → Move RF → Find new QL coefficients → QL data to NIMROD

Turn RF on → Find new QL coefficients → RF status and QL data to NIMROD

Signal below lower thermostat? — No

Signal below lower thermostat? — Yes → Turn RF off → RF status to NIMROD

upper
lower

on

# Neoclassical tearing mode physics can make mode suppression a bit easier

- For NTMs, small islands are self-stabilizing below some threshold width.

- For resistive tearing modes, small islands are not self-stabilizing.

$$\frac{\tau_R}{r}\frac{dw}{dt} = \Delta'r + \frac{\sqrt{\varepsilon}\,\beta_\theta\, rw(L_q/L_p)}{w^2 + w_d^2} - \alpha w$$

Modified from La Haye & Sauter, NF **38**, 987 (1998).

$$q = m/n = 3/2$$
$$\Delta'r \equiv -2 \qquad a_{pol} \equiv 0$$
$$\varepsilon^{1/2} = 0.5$$
$$L_q/L_p = 1.0$$
$$w_d/r = 1/40, \; w_g/r = 1/30$$
$$\Rightarrow \beta_{\theta M} = 0.20$$

$\chi_\perp/\chi_\parallel$ model
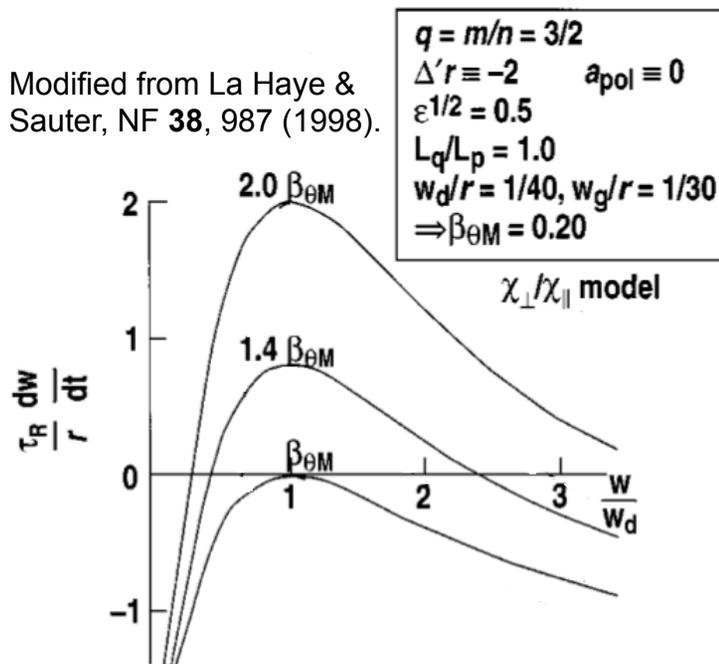
- ECCD-induced changes to Δ' drag curves down (stabilizing) – other changes to curves also ensue as missing bootstrap current is replaced.
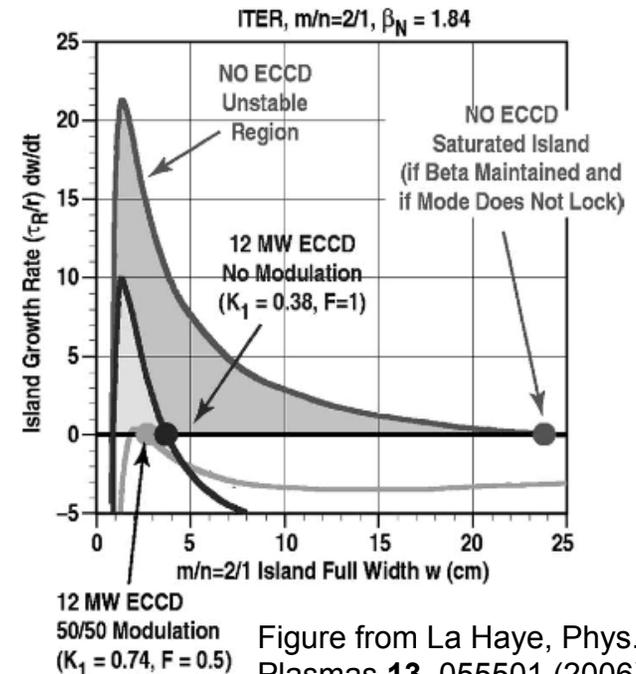
Figure from La Haye, Phys. Plasmas **13**, 055501 (2006).

# Deciding when to move the RF, and how to do it, requires care

**Need to move RF?**

No, don't move RF

**Have we waited long enough to tell if the RF is helping?**

No

Yes

Yes

**Is the RF helping enough?**

No

Yes, move RF
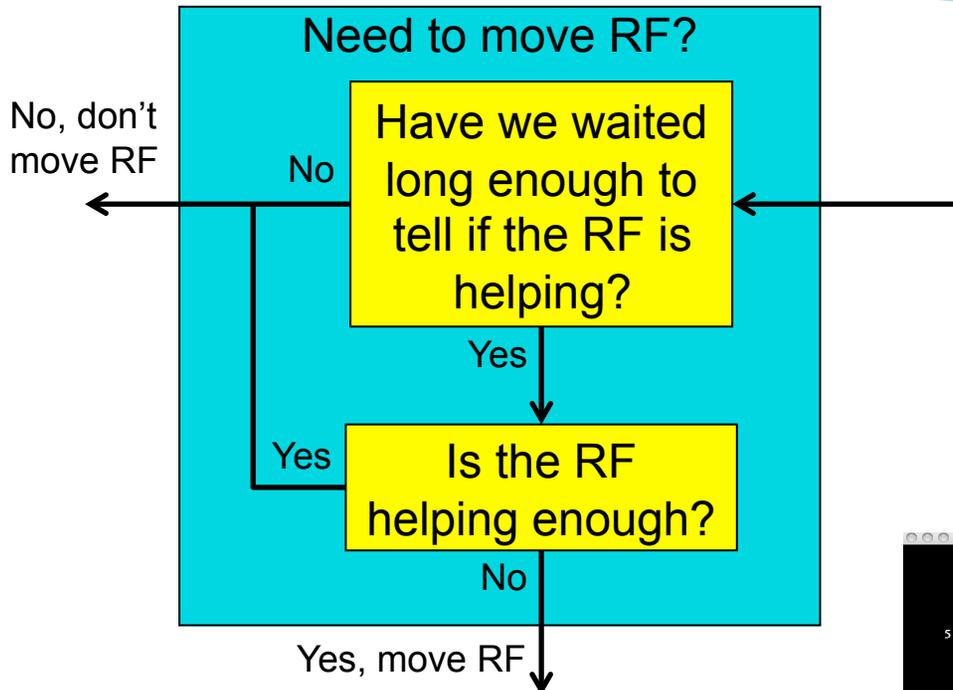
- Need to "dwell" for a time long enough to assess whether or not the RF is contributing adequately to stabilization. Dwell time, and optimal RF adjustment, are problem-dependant.

- RF makes highly localized source terms in NIMROD; too rapid variation in sources causes numerical instability.

- Sweeping RF across the rational surface where the mode grows, and observing the mode response, can give guidance (or, just do test runs for static RF at positions along sweep).



Changes to RF launch angle
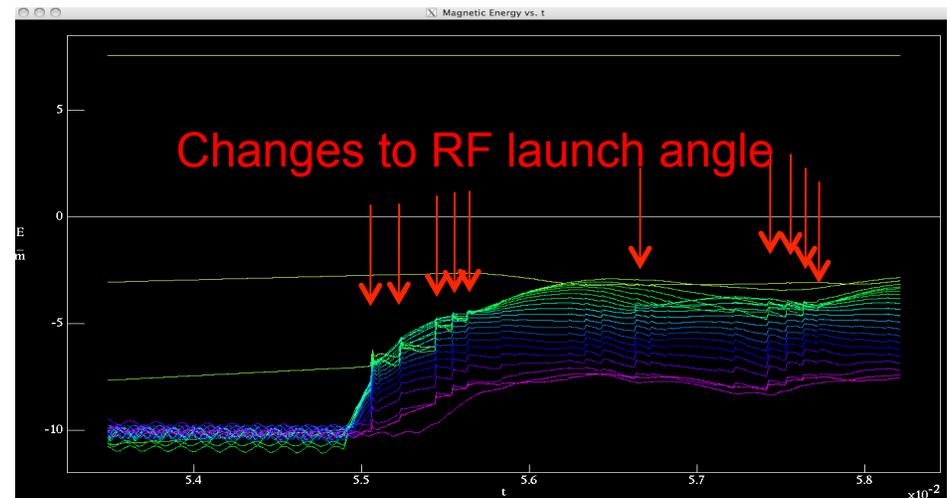
Fourier components of magnetic energy vs. time
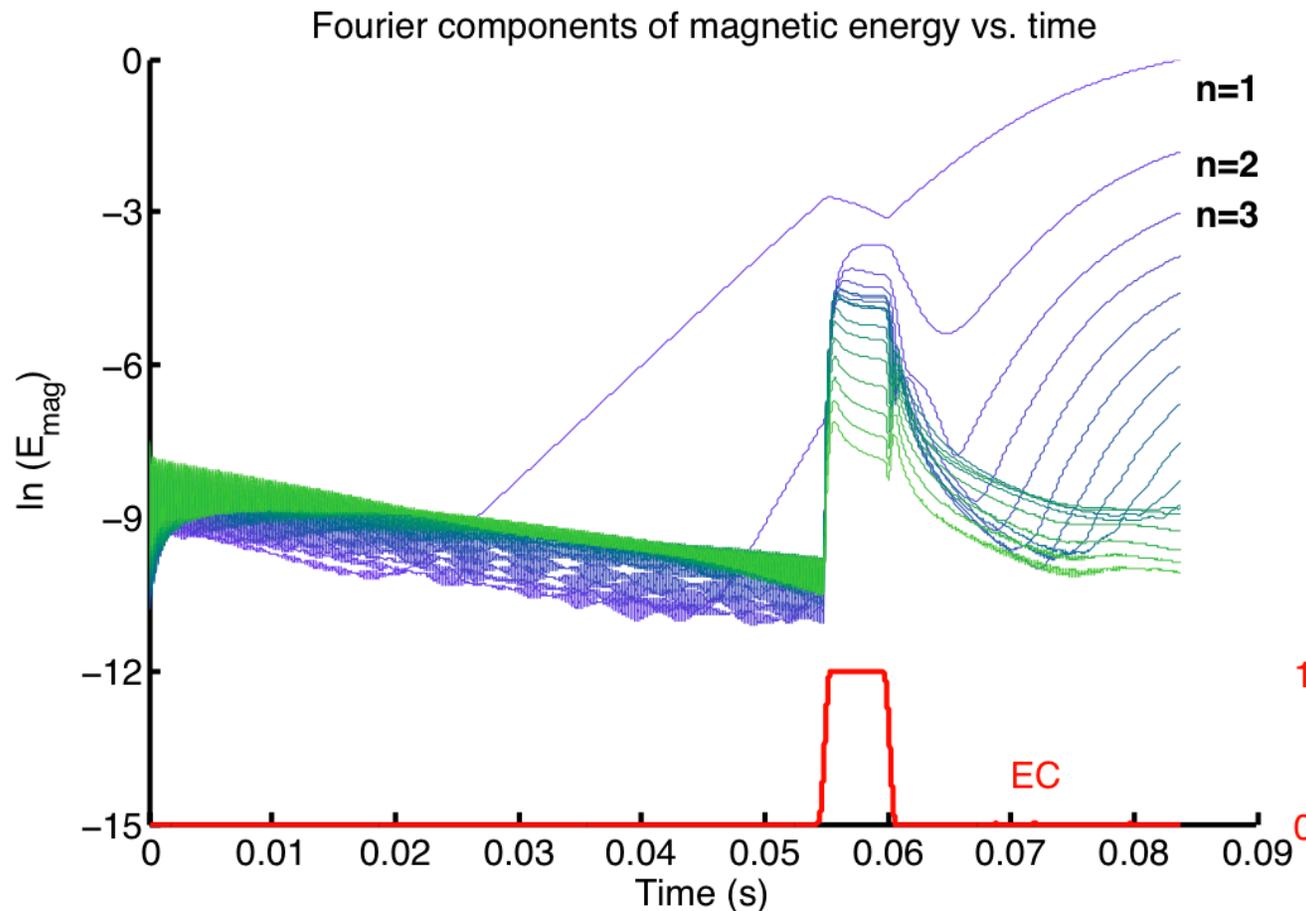


- The control system is initially able to halt the mode growth and shrink the island, if the RF is correctly aligned.  Growth resumes when RF is shut off, as anticipated.

Fourier components of magnetic energy (~island width) vs. time

n=1

n=2

EC
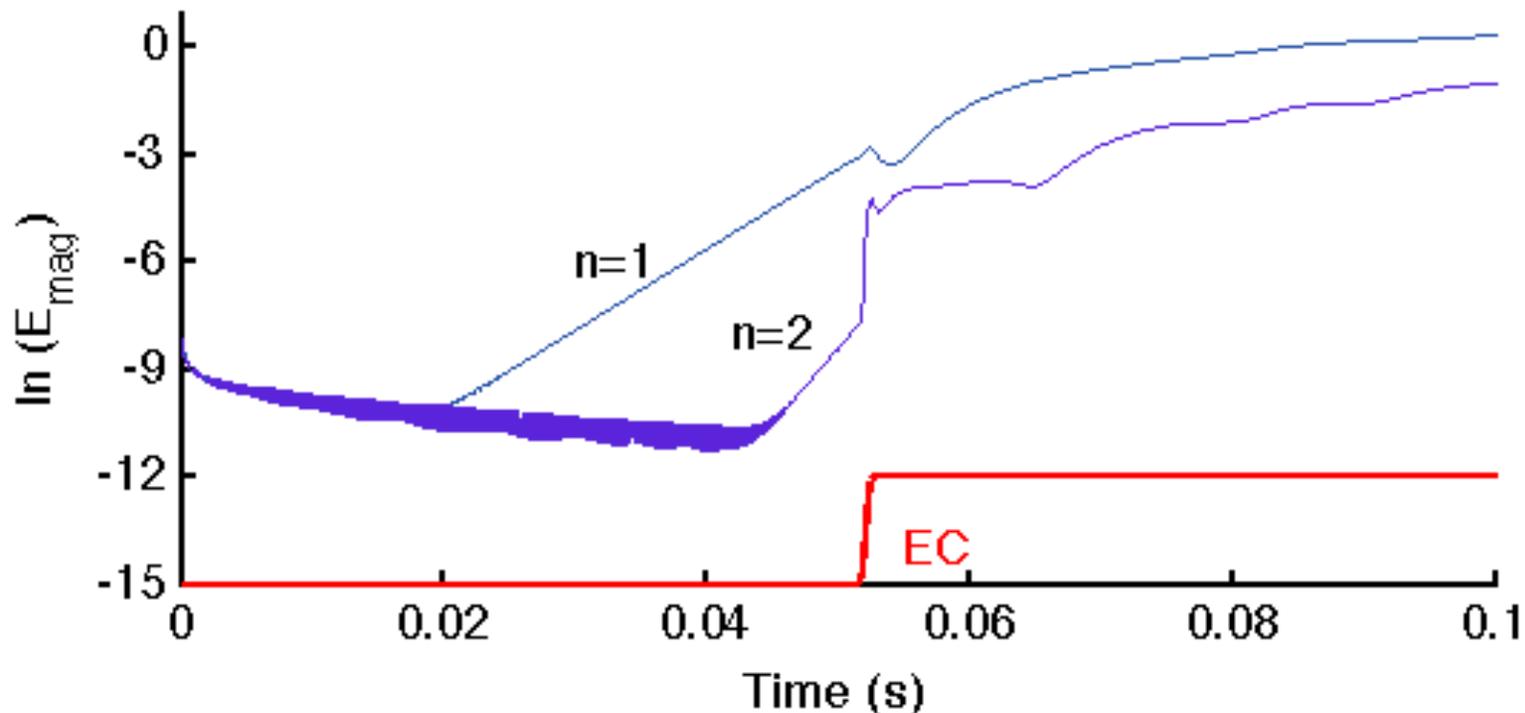
- After an initial decrease, mode growth resumes as the plasma adjusts to the presence of RF – more detailed steering algorithms are being developed.

- In the meantime, explore the physics of static RF in rotating plasmas.

# Misaligned RF can stop island growth, though it doesn't shrink the islands

Fourier components of magnetic energy (~island width) vs. time



- Here, RF is ~5 cm vertically misaligned (inwardly) from rational surface and remains fixed in space.

- Mode growth is halted, island size remains largely fixed; oscillations in magnetic energy signal
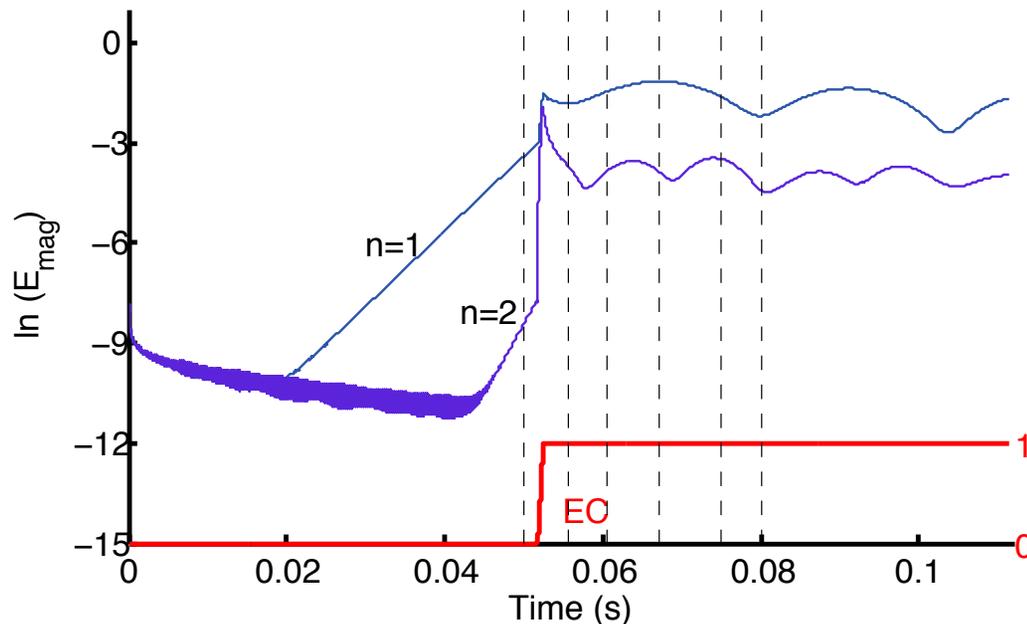
- Period of signal oscillation is the rotation period – this represents (2,1) and (4,2) components of island rotating past the fixed RF

Toroidal angle ζ

Direction of rotation

rf

Rotation

rf

Deviation from original rational surface
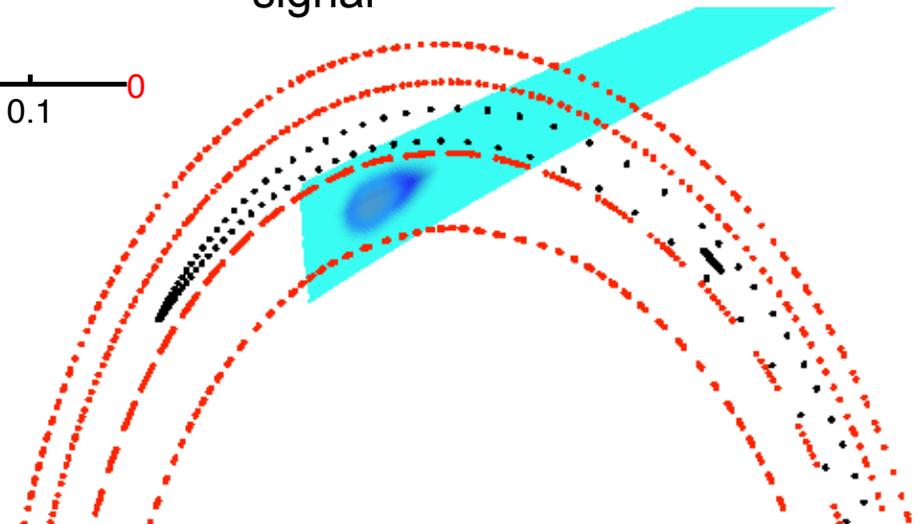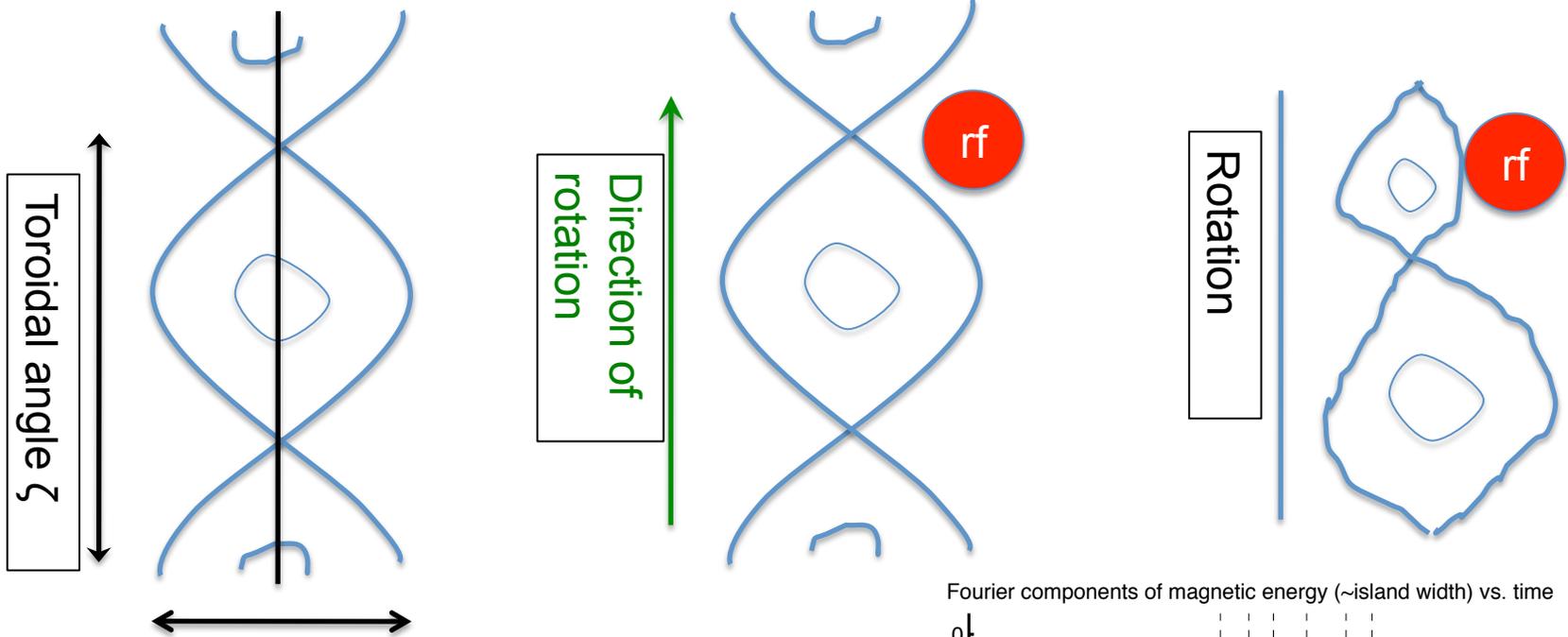
- Rational surfaces are not stationary (2010 PoP)

- The picture is actually more complicated…
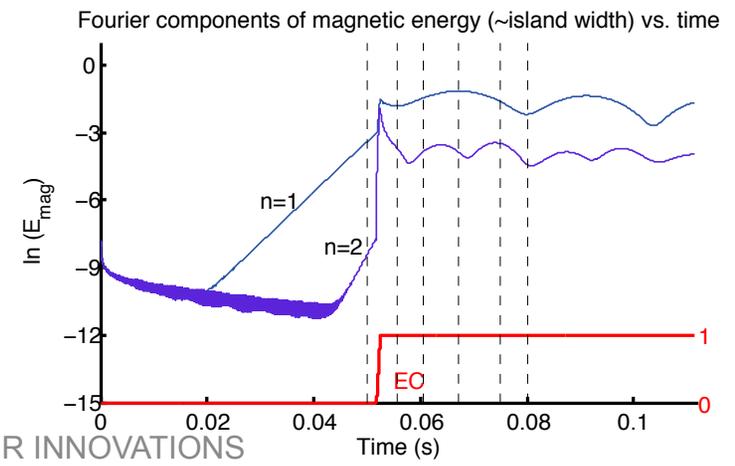
Fourier components of magnetic energy (~island width) vs. time

$\ln (E_{mag})$

n=1

n=2

EC

Time (s)

• But X/O points are offset from RF position at energy maxima/minima

t = 0.0557 s (local n=1 minimum)

Fourier components of magnetic energy (~island width) vs. time



n=1

n=2

EC
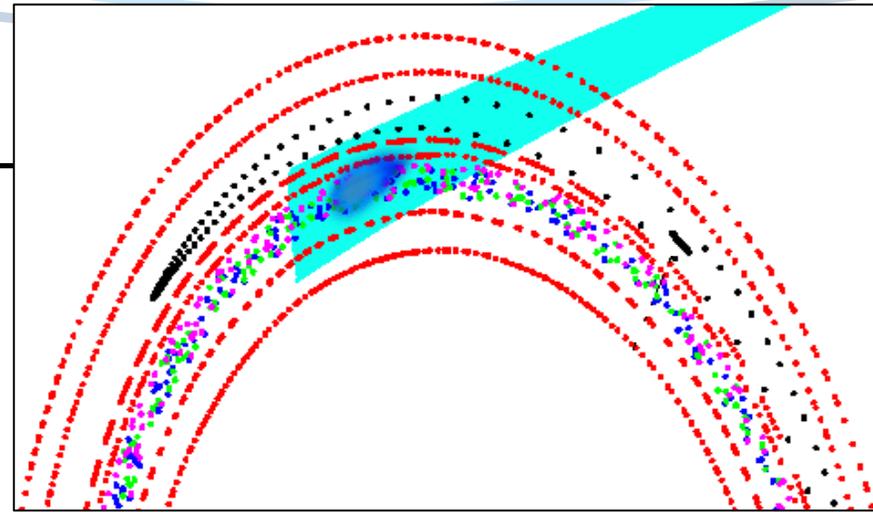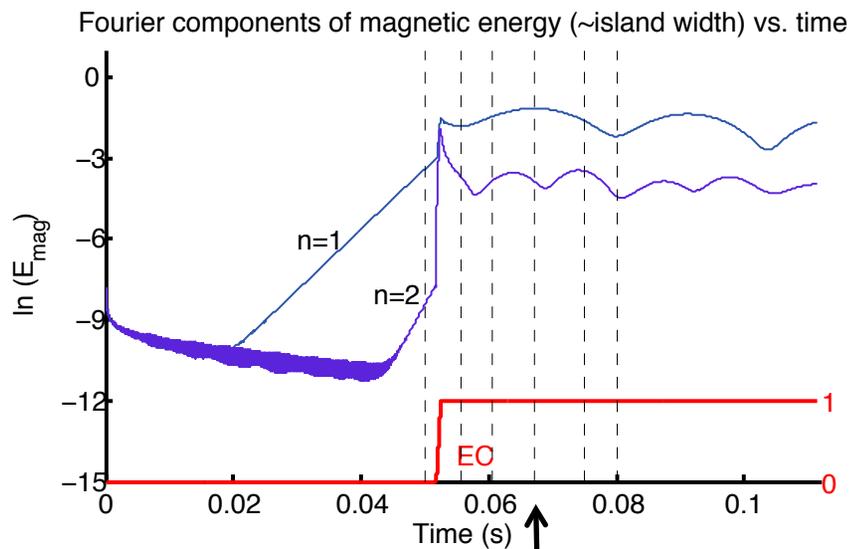
• Look at stochastic layer generated by RF

t = 0.0672 s (local n=1 maximum)

t = 0.0557 s

Fourier components of magnetic energy (~island width) vs. time

n=1

n=2

EC

ln ($E_{mag}$)

Time (s)
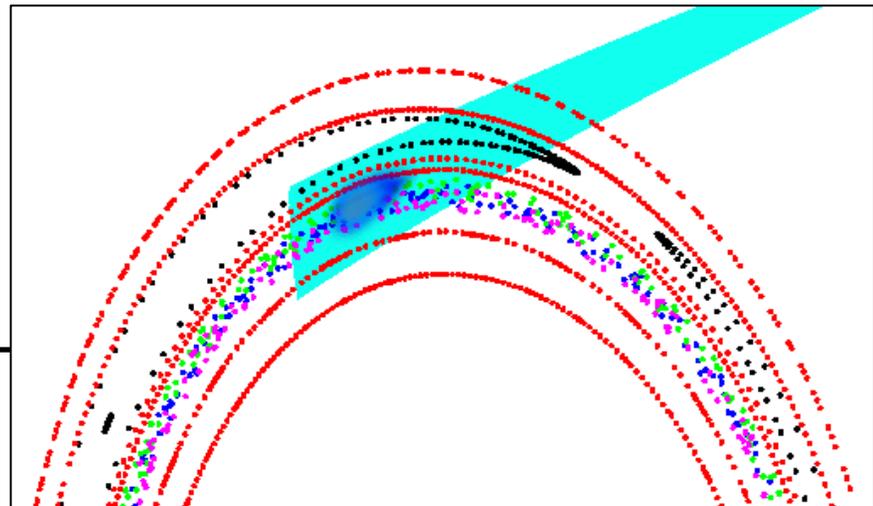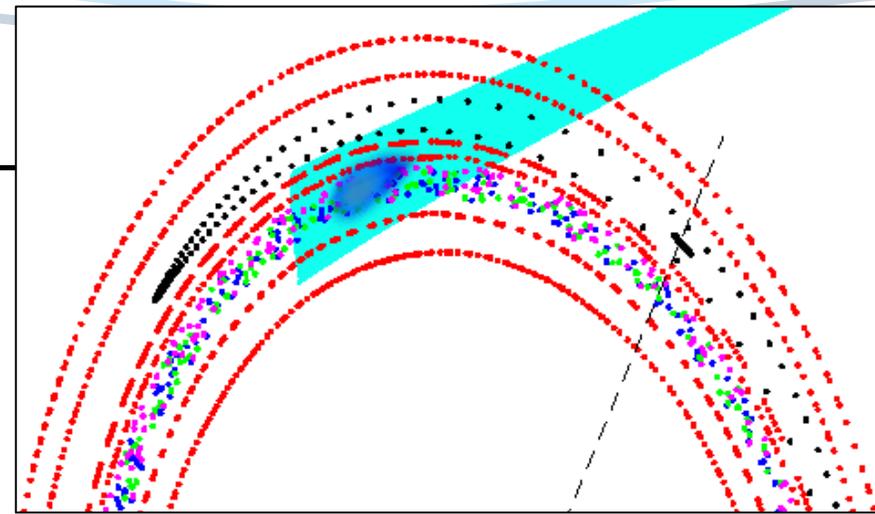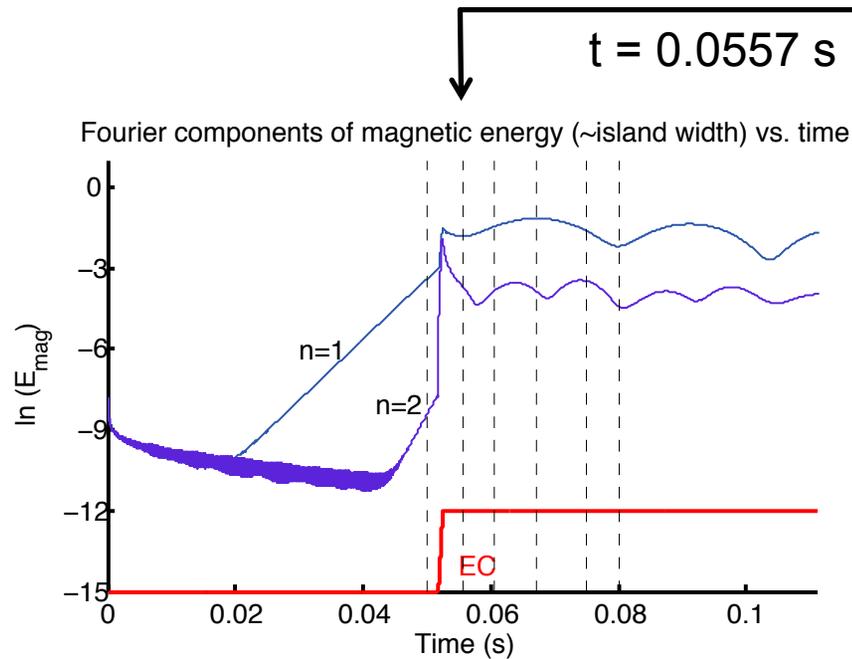
q profile with stochastic layer
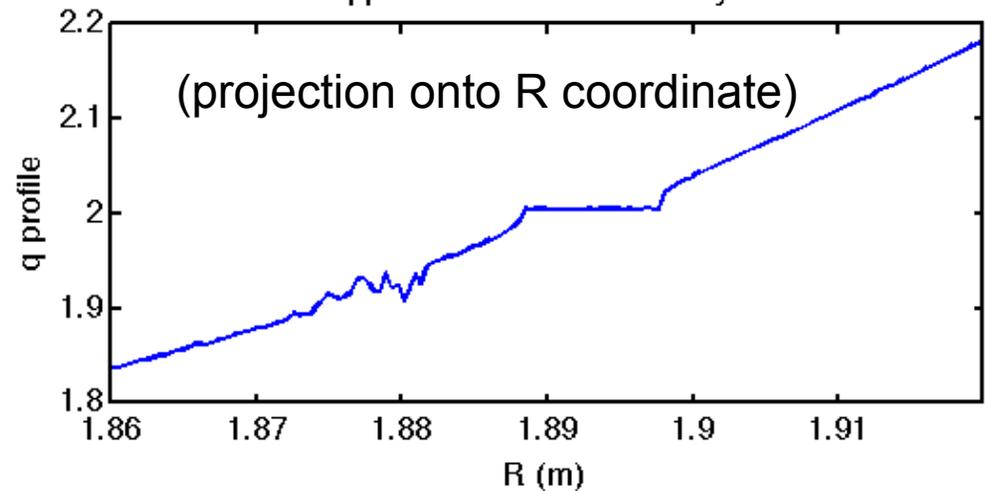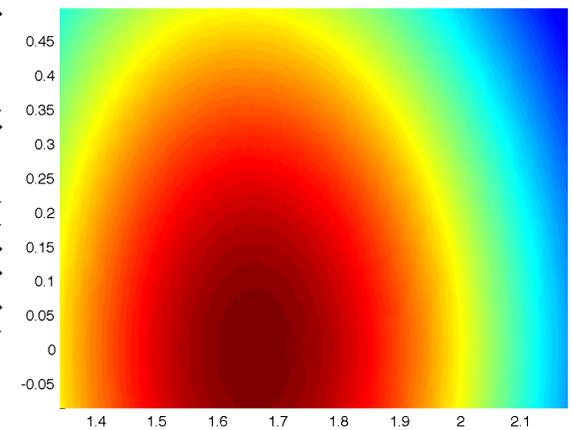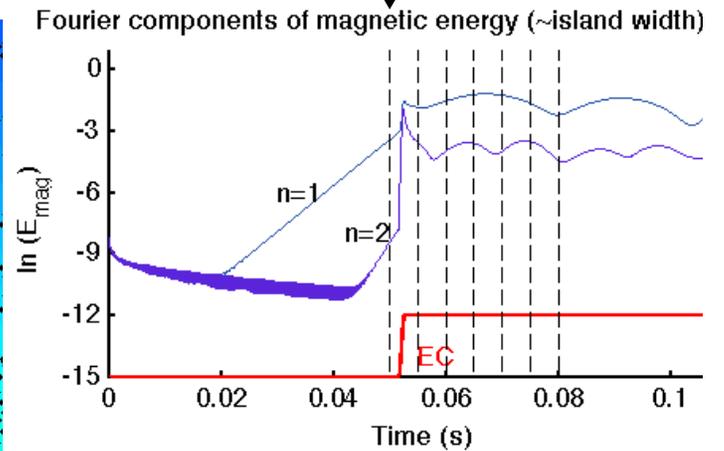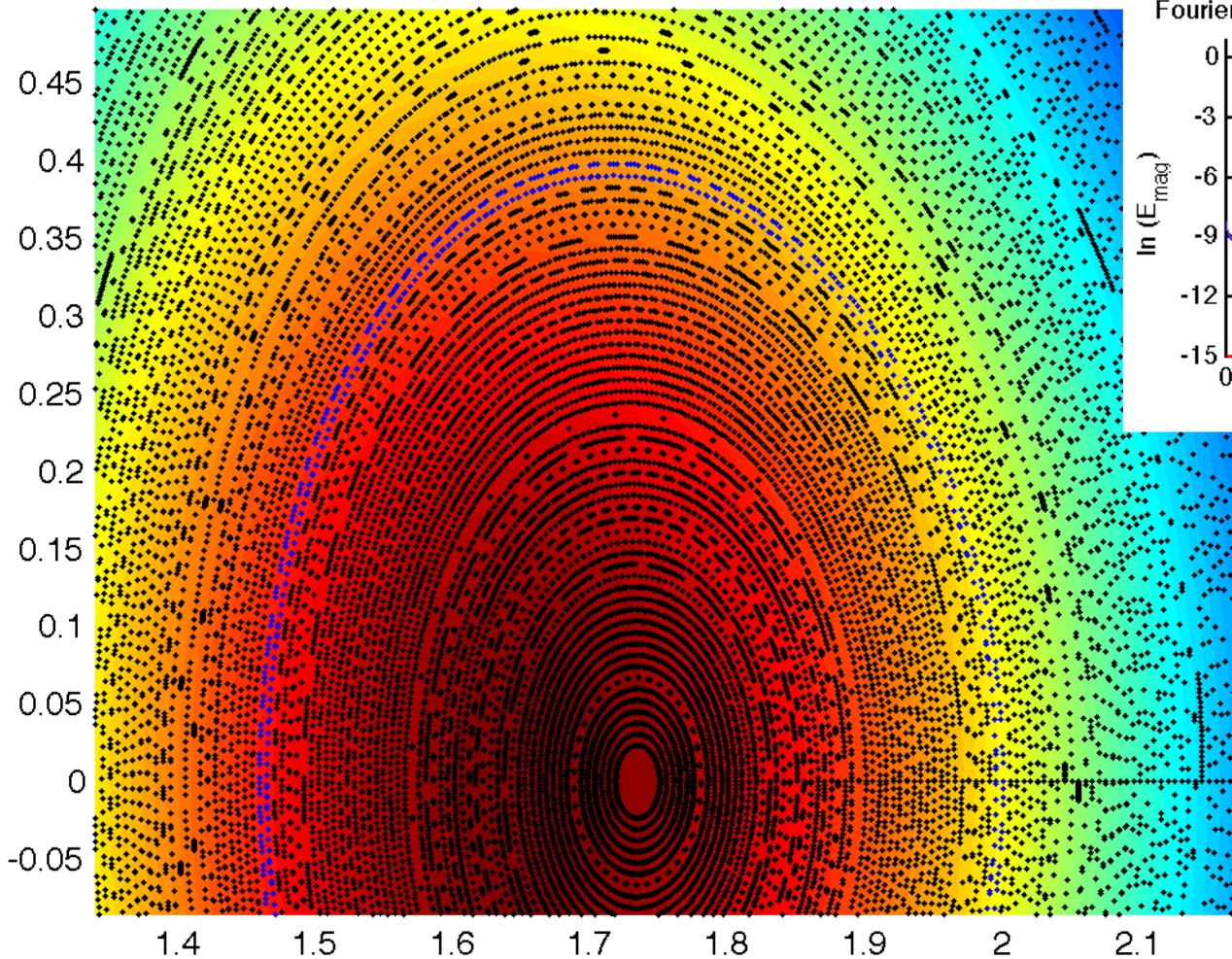
(projection onto R coordinate)

q profile

R (m)
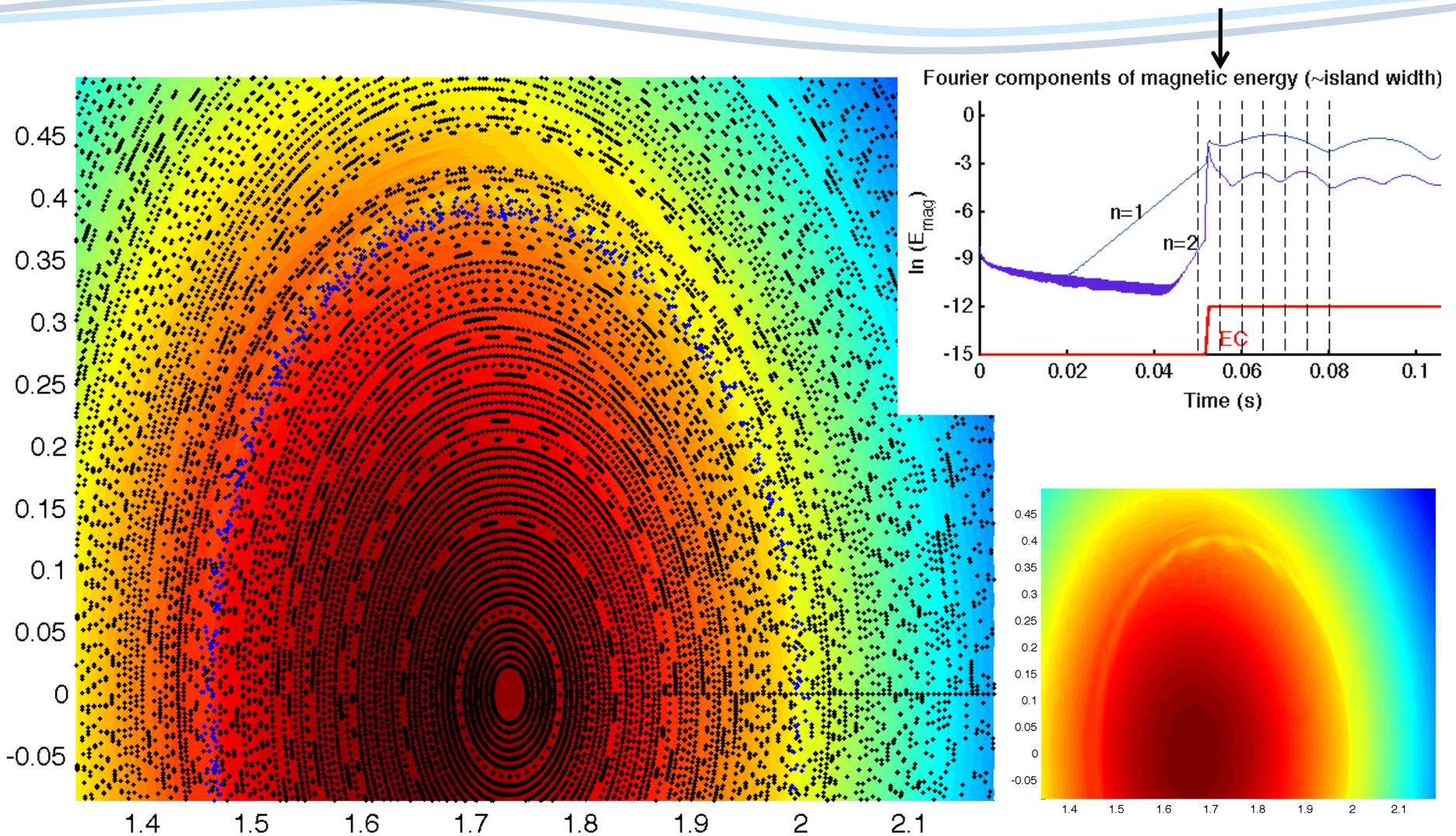
# The current profile is modified at the stochastic layer
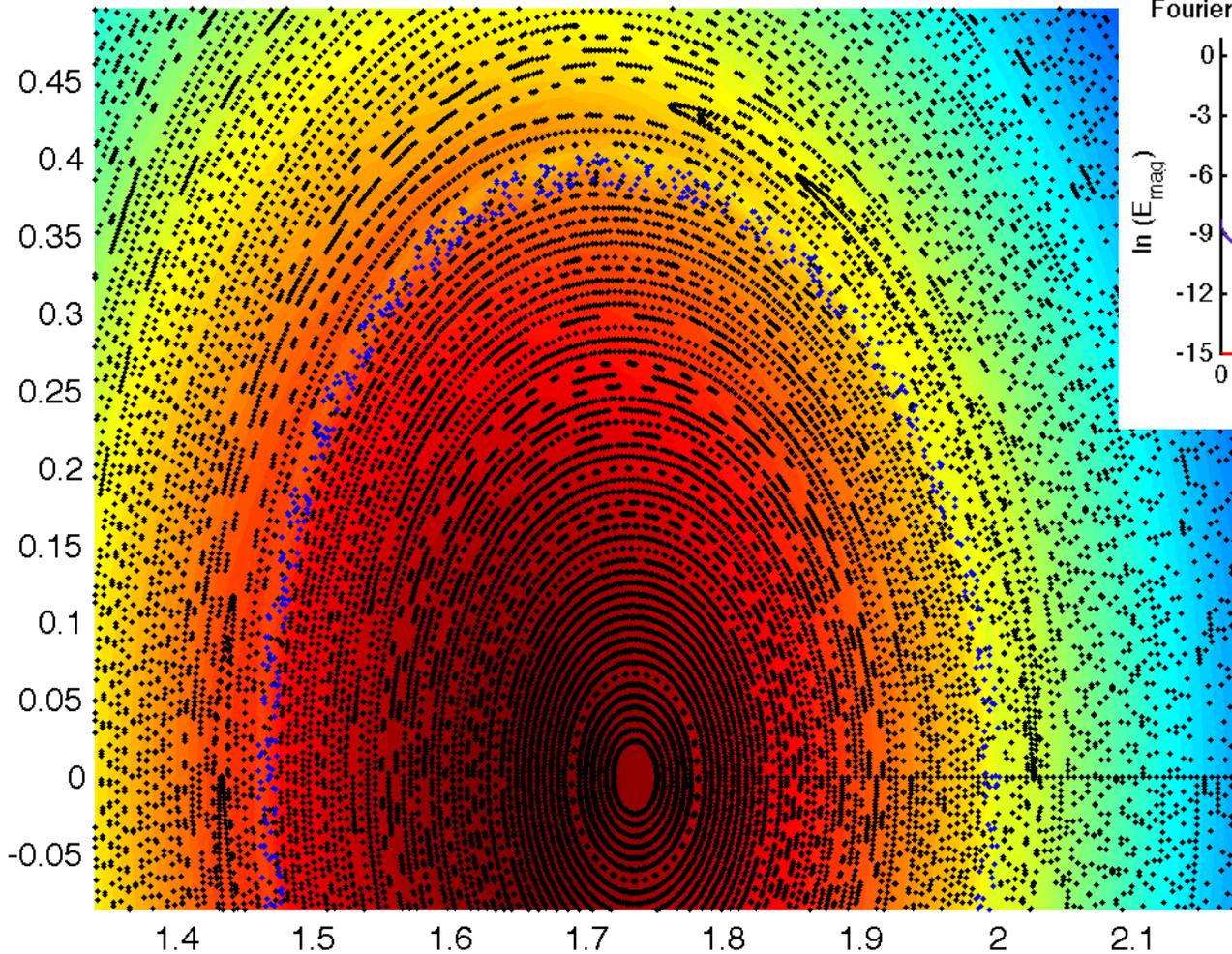


Fourier components of magnetic energy (~island width)

# The current profile is modified at the stochastic layer
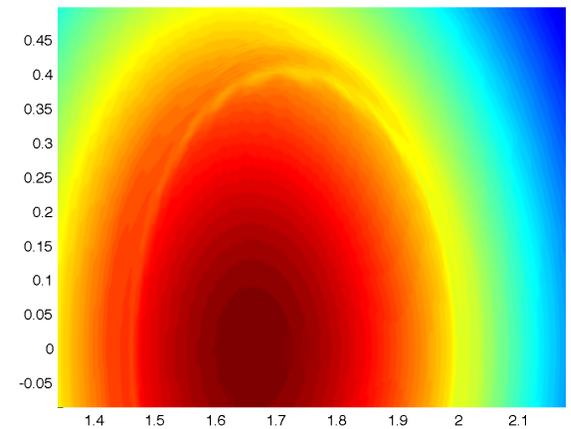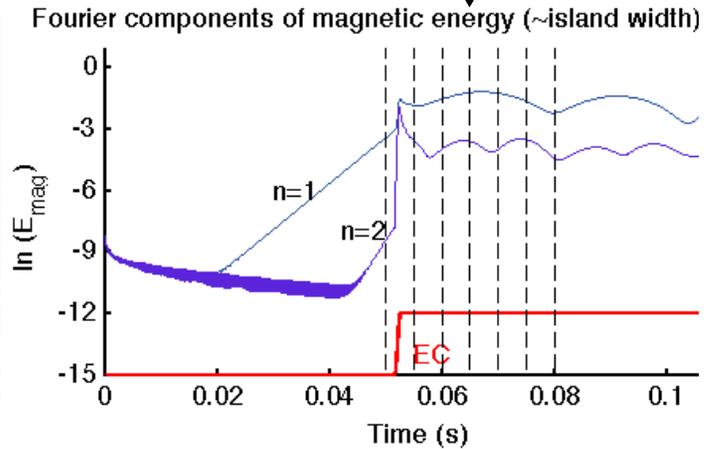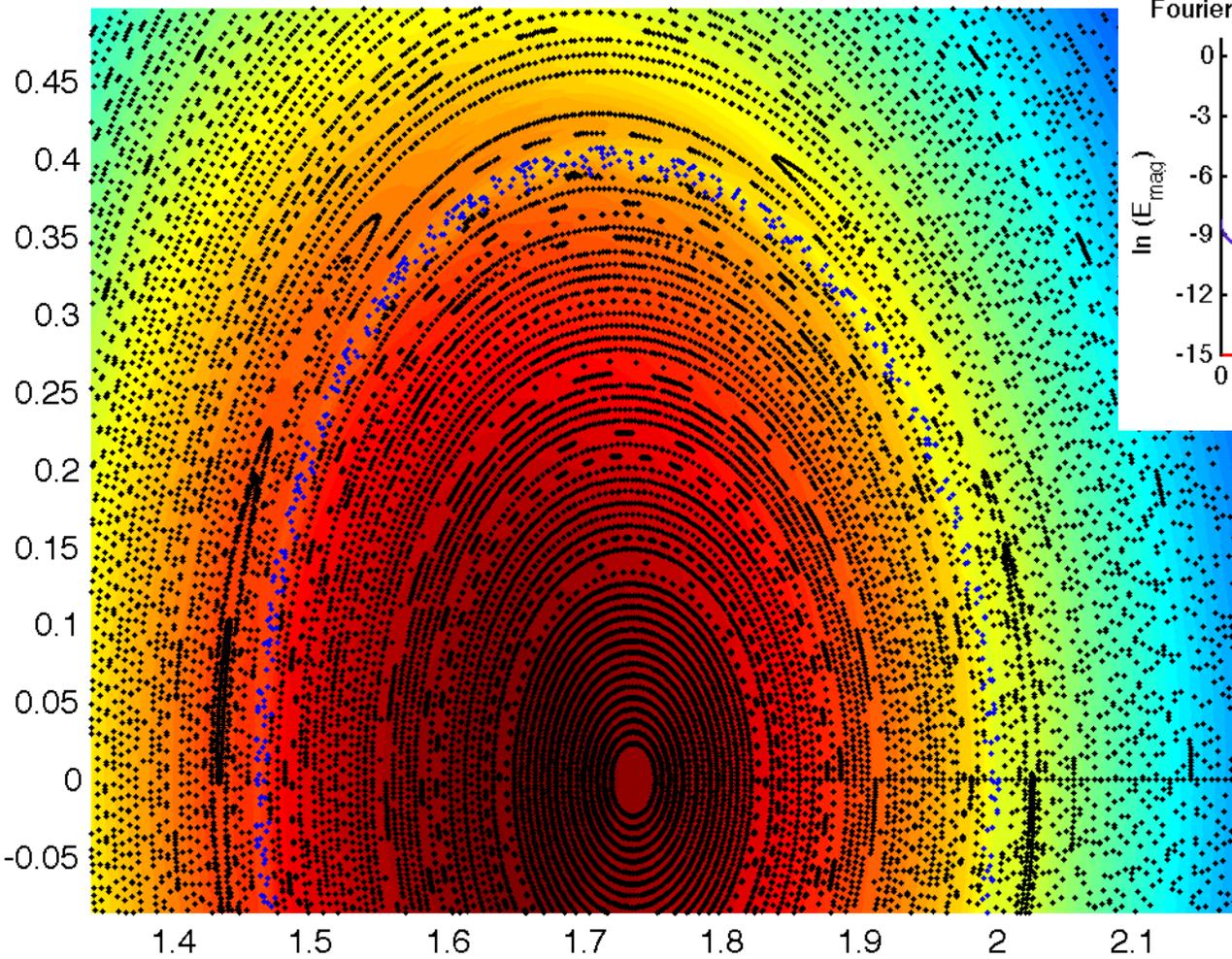


Fourier components of magnetic energy (~island width)

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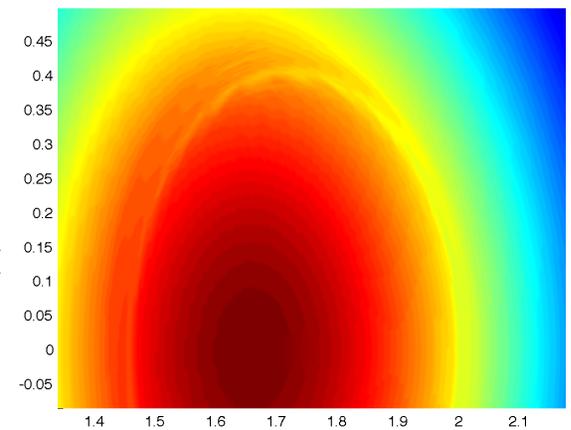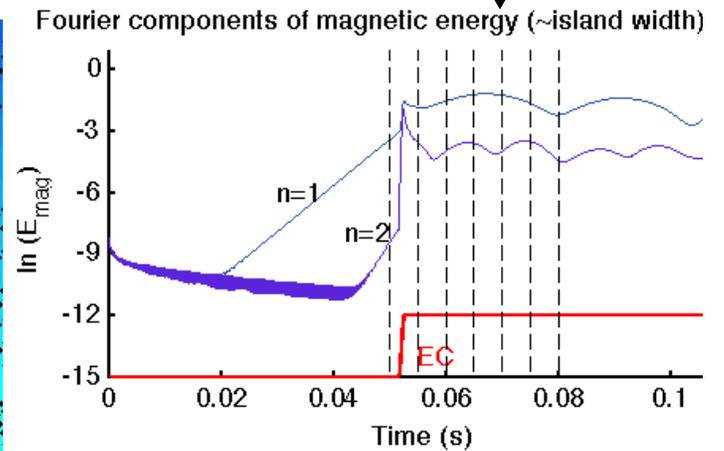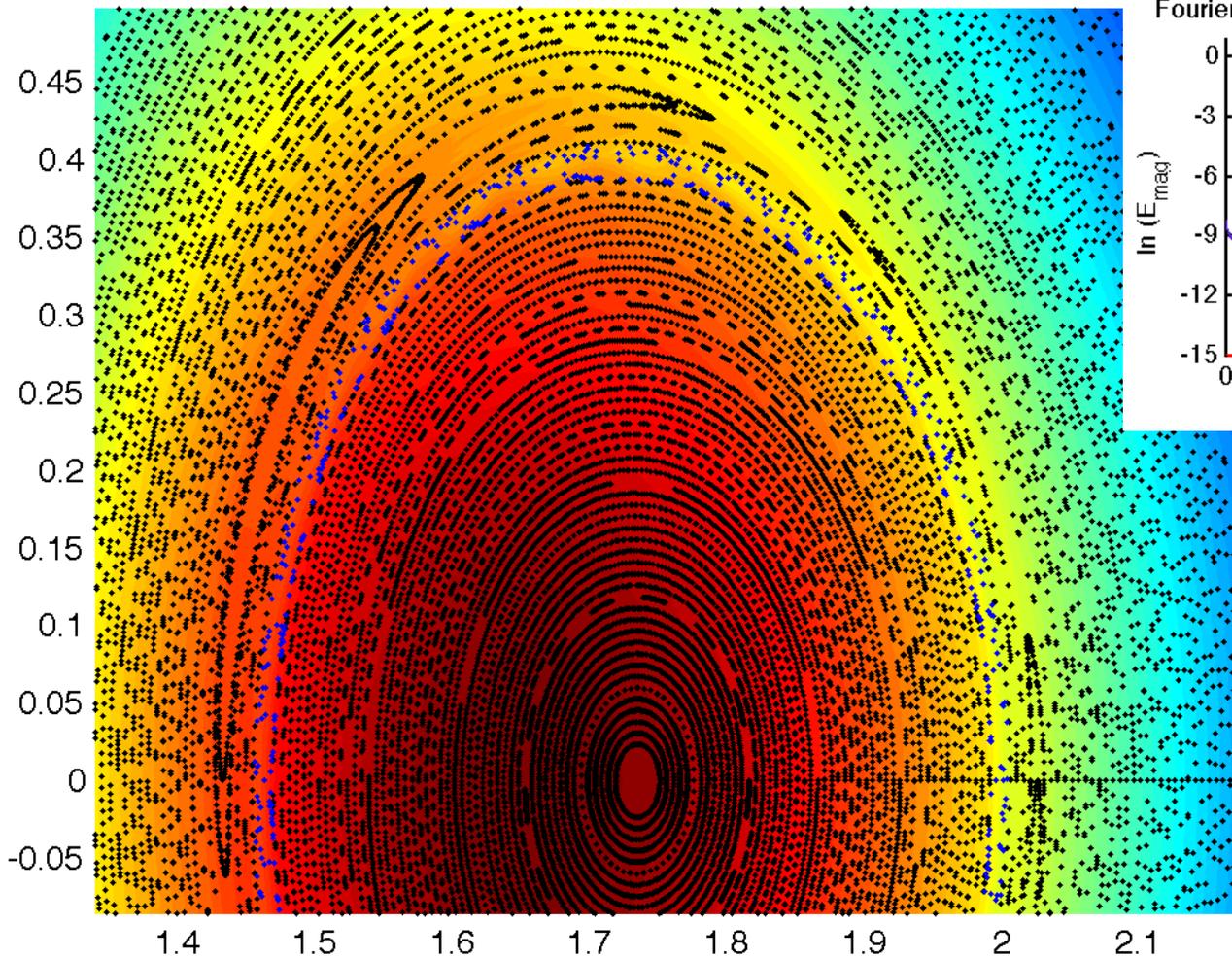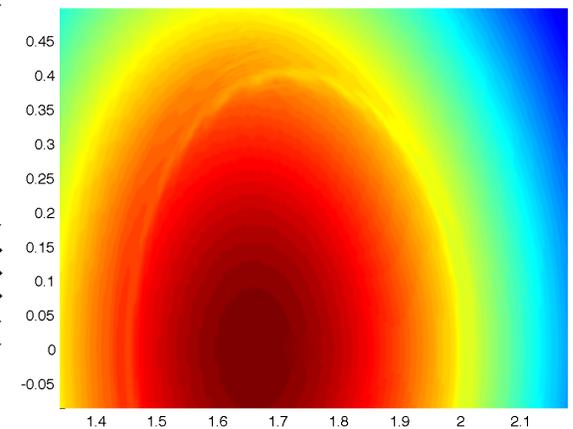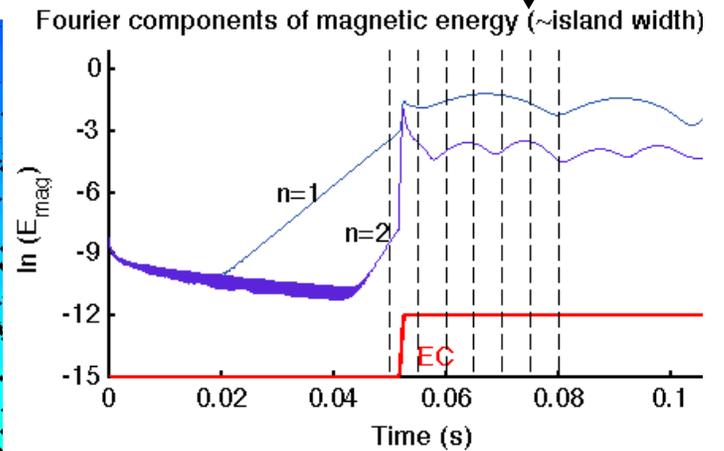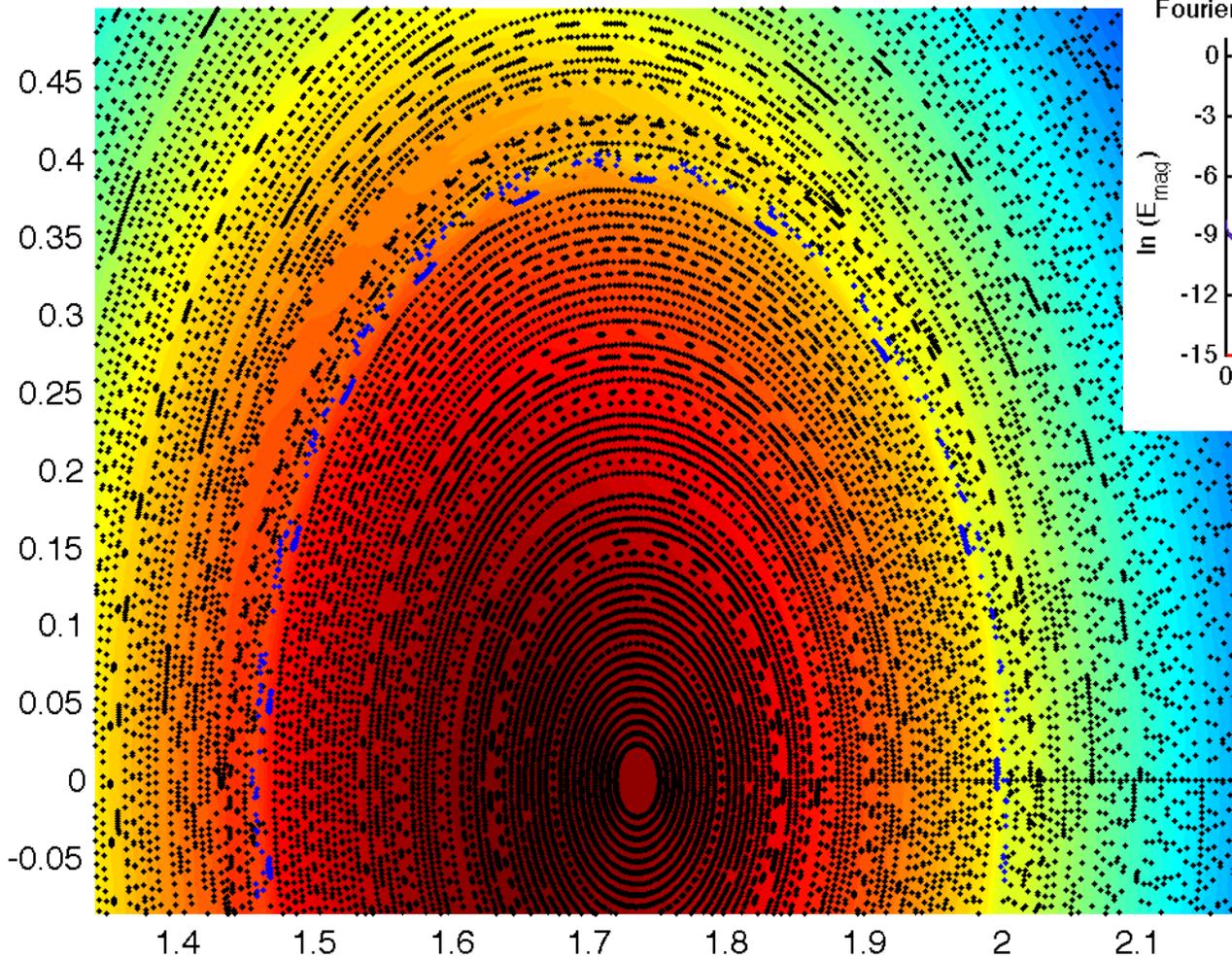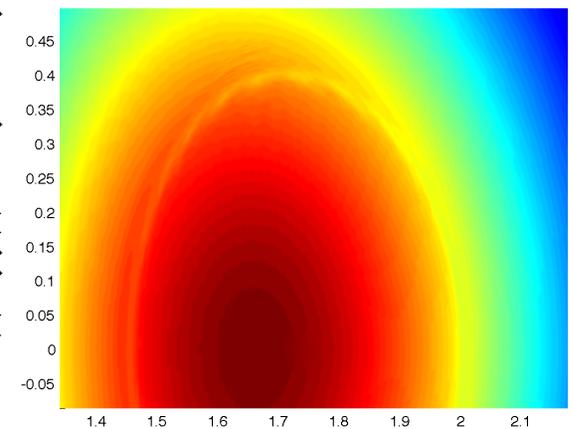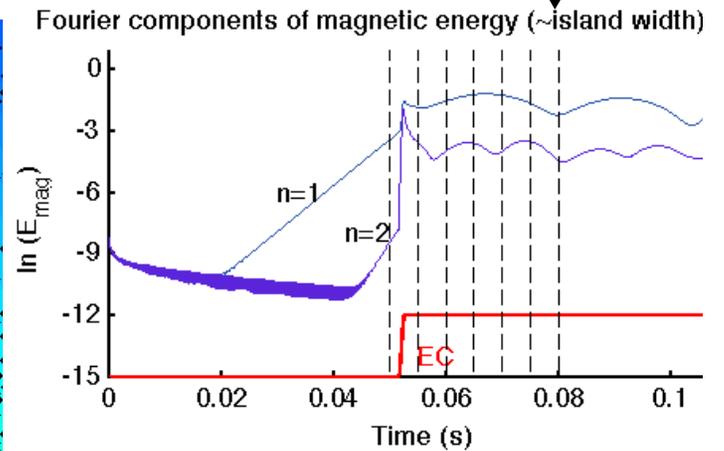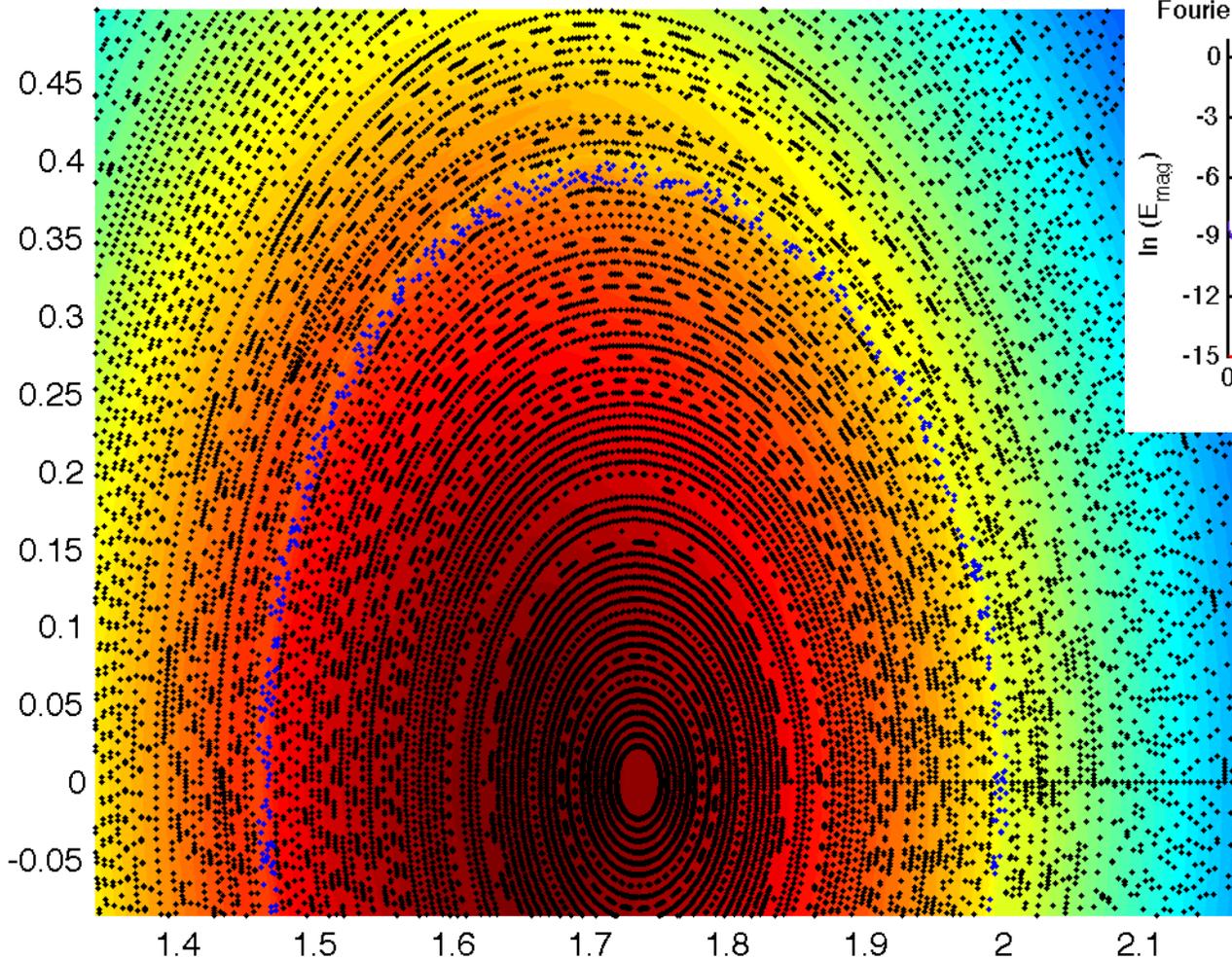
# The stochastic layer replaces a set of nested flux surfaces

Toroidal current
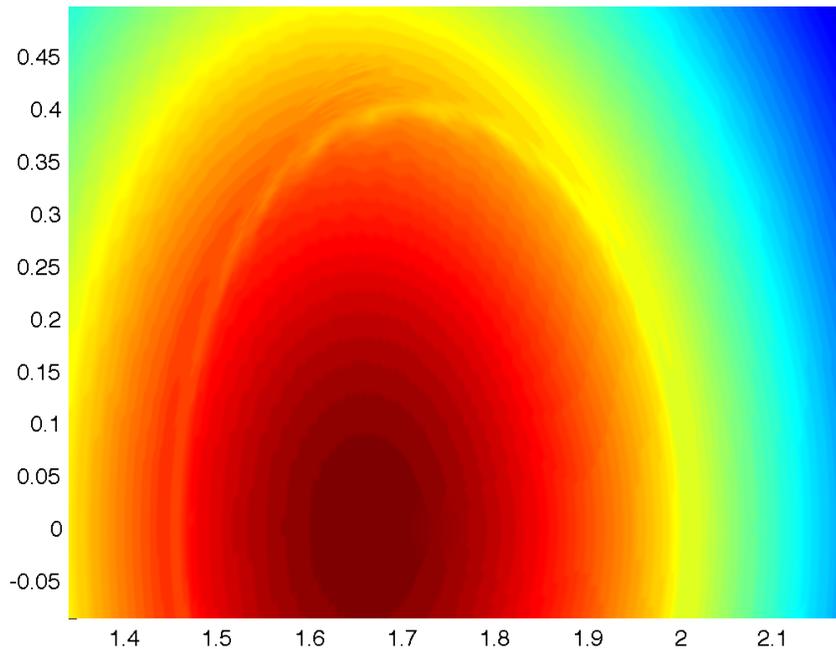
Pressure
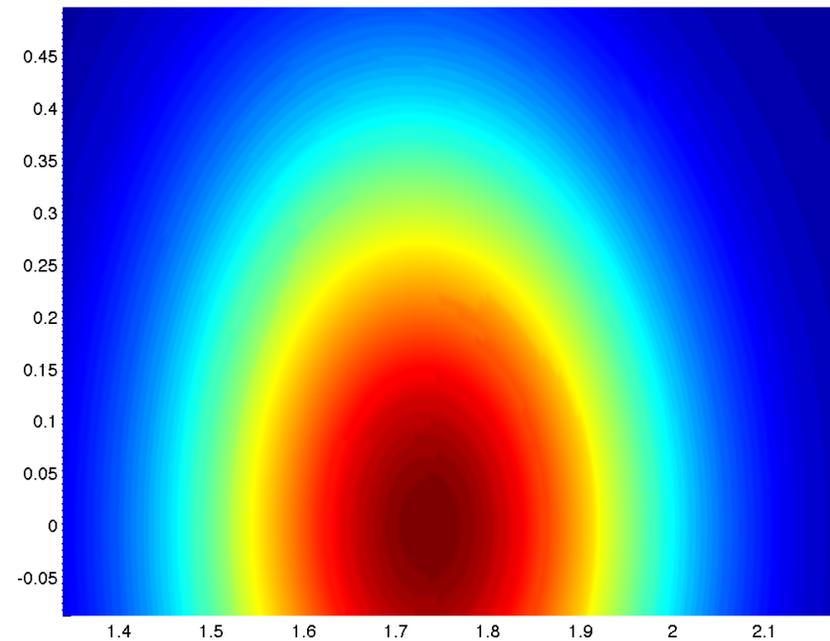


- Position of RF determines which flux surfaces are disturbed

- What happens when these flux surfaces correspond to the rational surface?

# When RF is aligned with the rational surface, it opens an island



t=0.05247



t=0.05474

No stochastic layer!



t=0.05783

Fourier components of magnetic energy (~island width) vs. time



n=1

n=2

EC

## Current perturbations are 5-8% of equilibrium currents



Fourier components of magnetic energy (~island width) vs. time

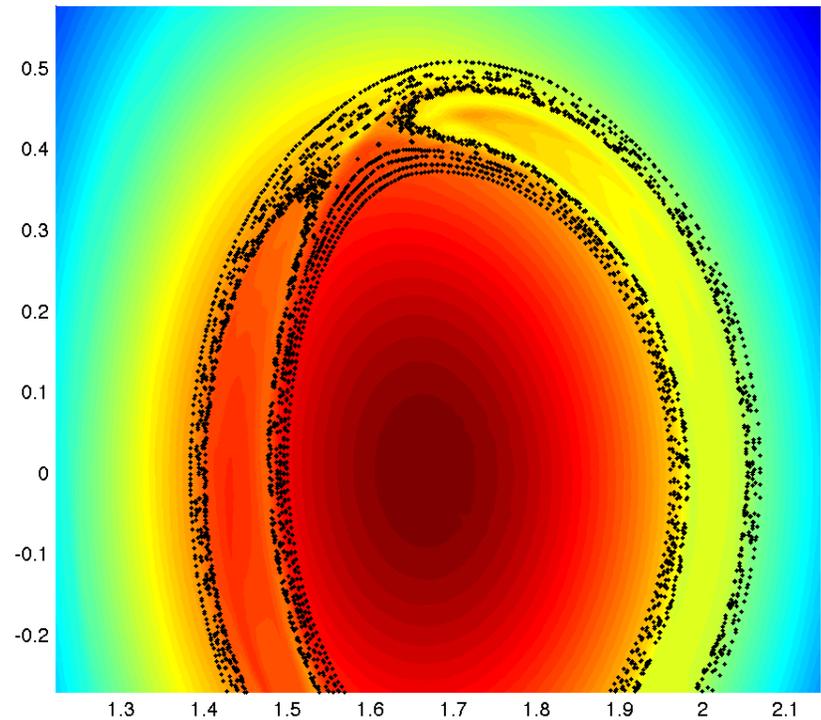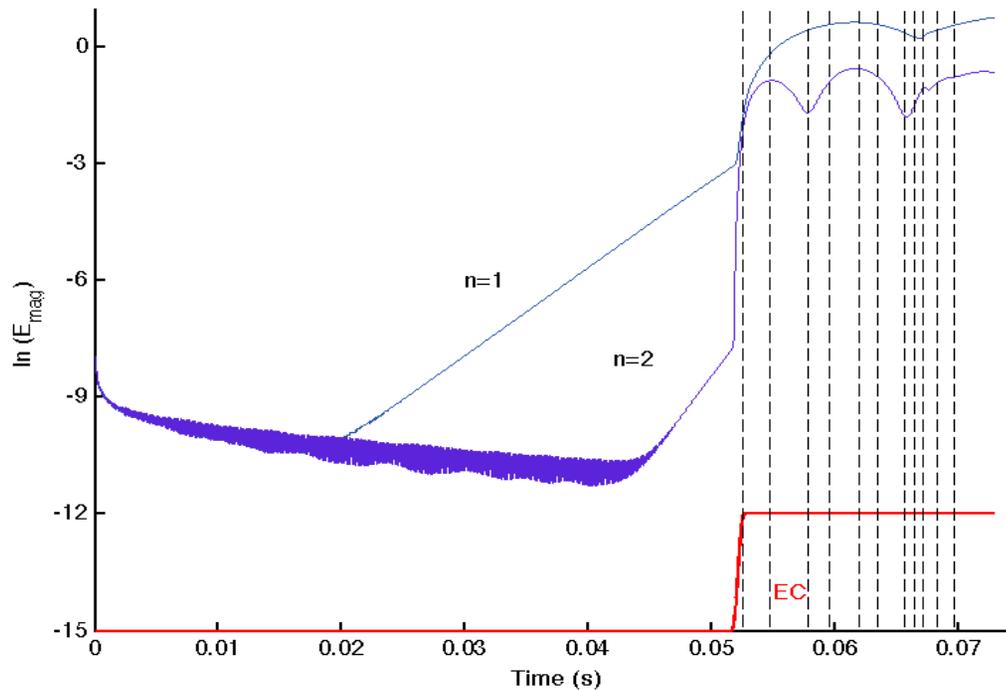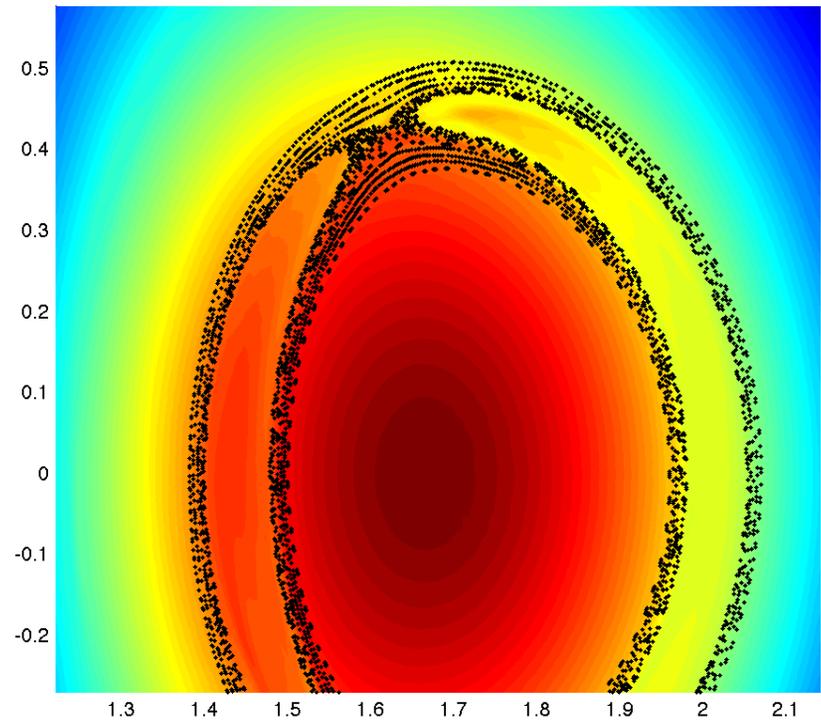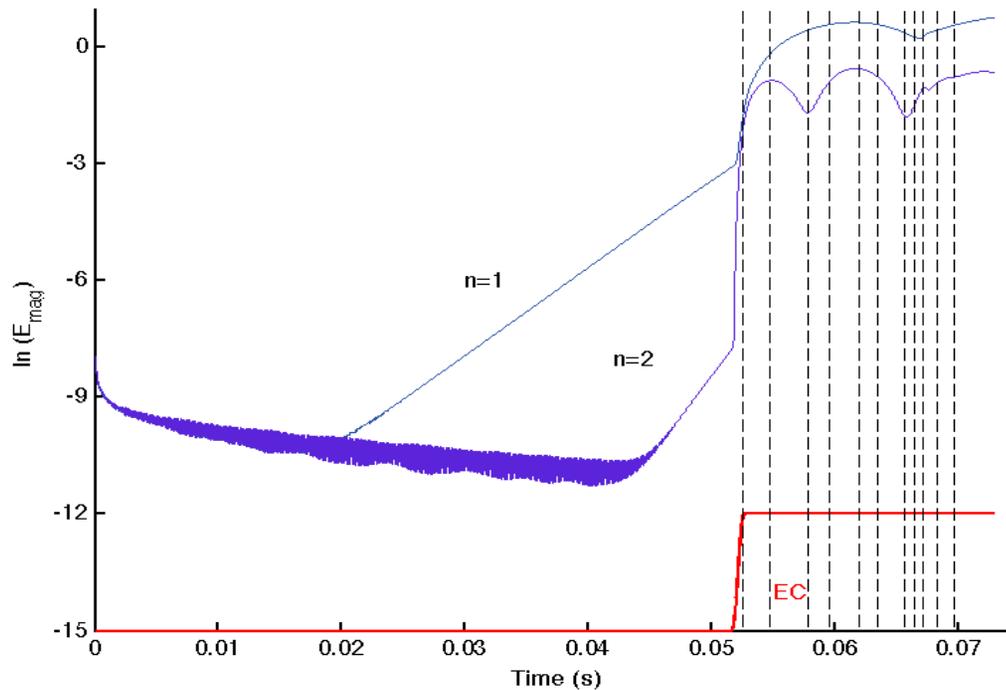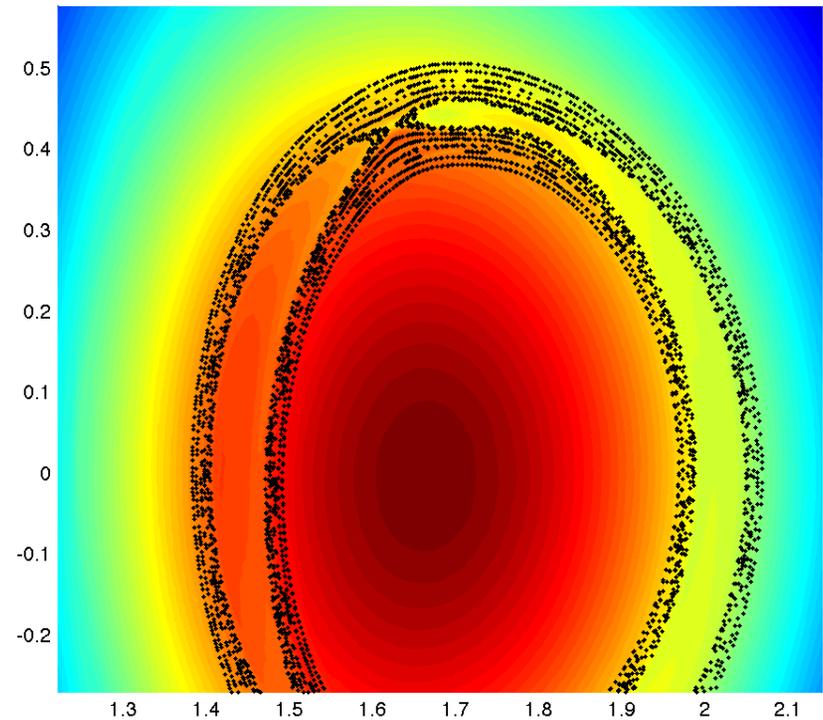**Current perturbations are 5-8% of equilibrium currents**



Fourier components of magnetic energy (~island width) vs. time

### Current perturbations are 5-8% of equilibrium currents



Fourier components of magnetic energy (~island width) vs. time

Current perturbations are 5-8% of equilibrium currents

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Fourier components of magnetic energy (~island width) vs. time

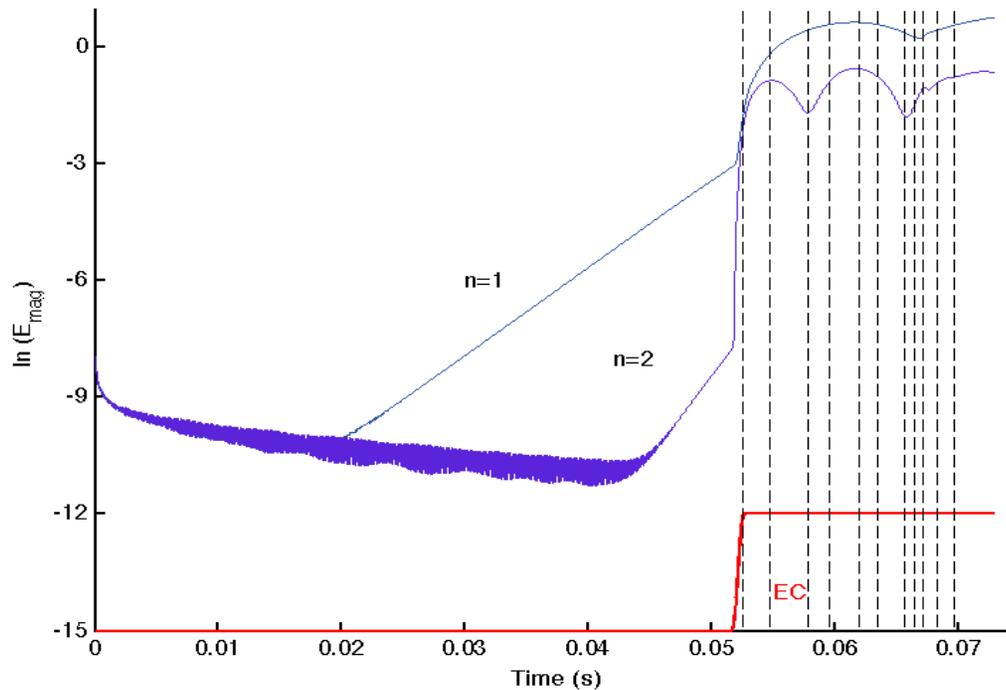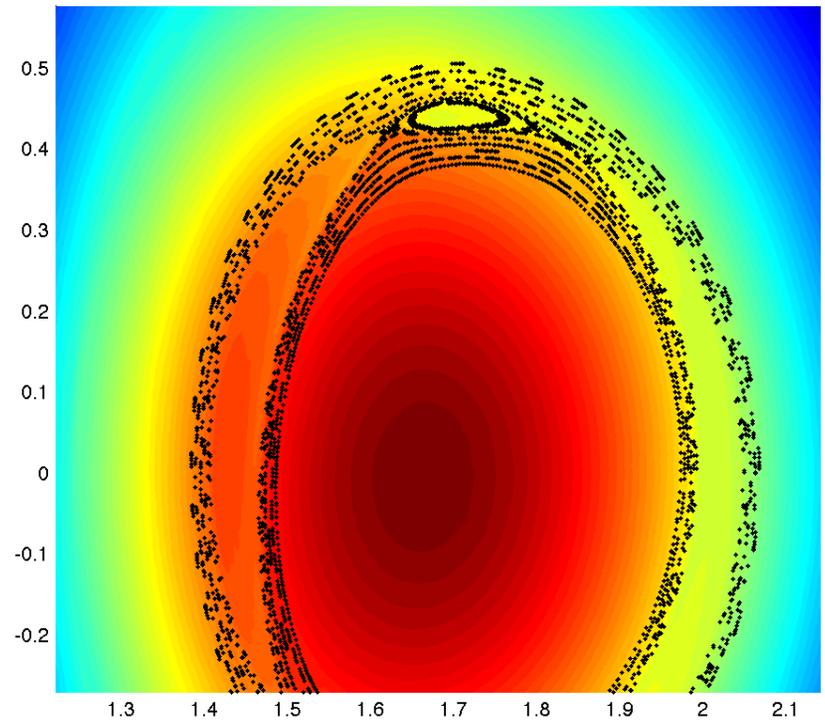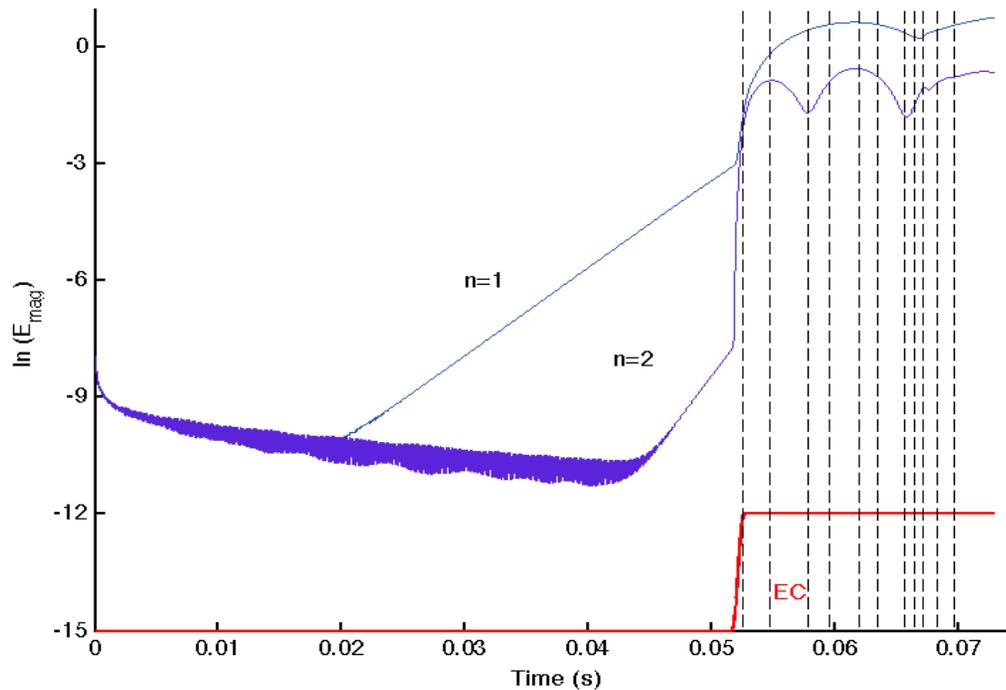## Current perturbations are 5-8% of equilibrium currents



Fourier components of magnetic energy (~island width) vs. time

## Current perturbations are 5-8% of equilibrium currents



Fourier components of magnetic energy (~island width) vs. time

## Current perturbations are 5-8% of equilibrium currents



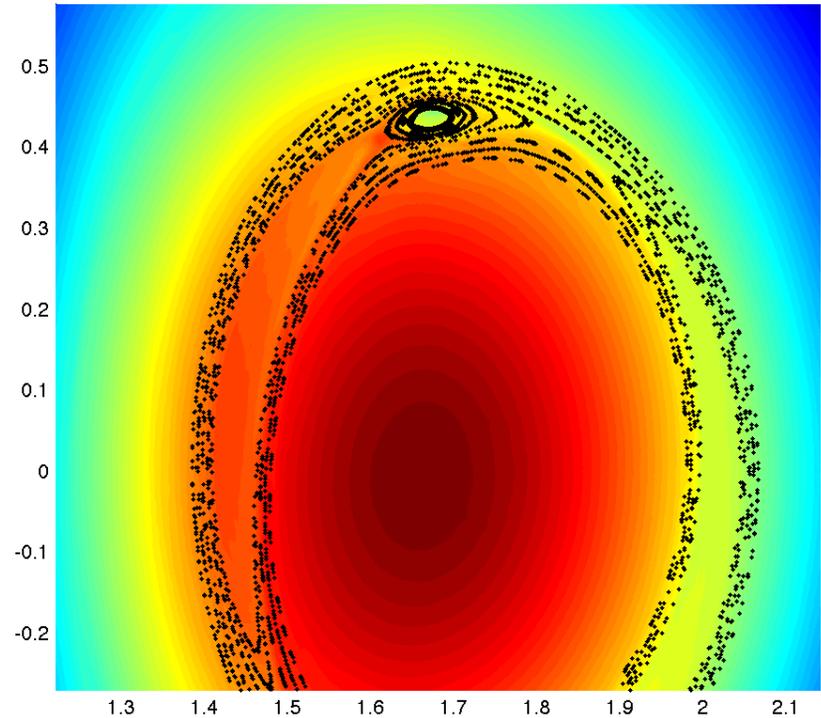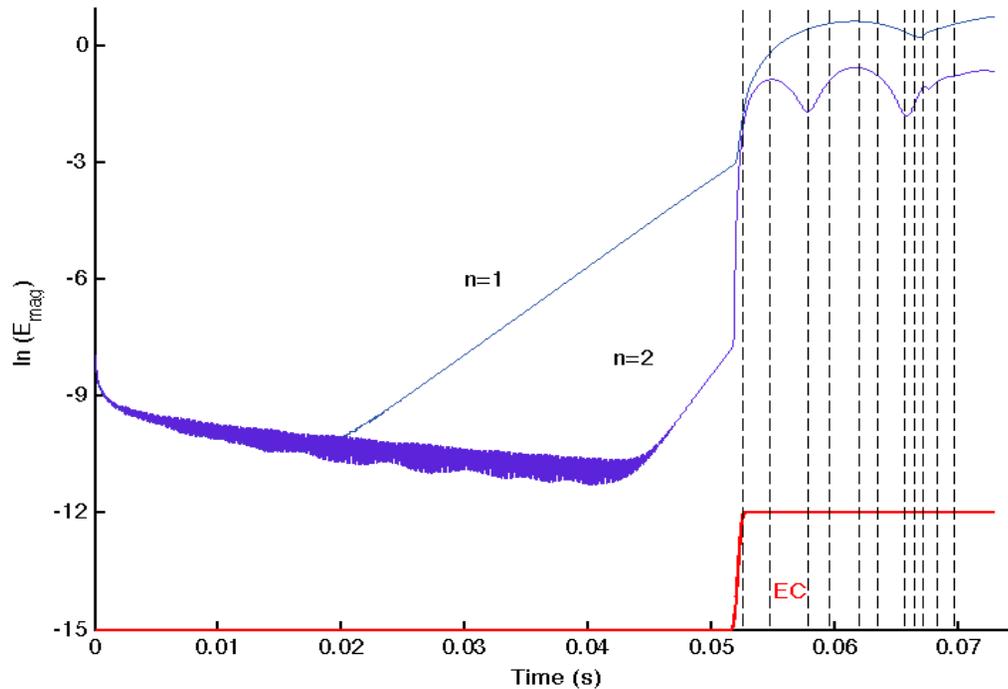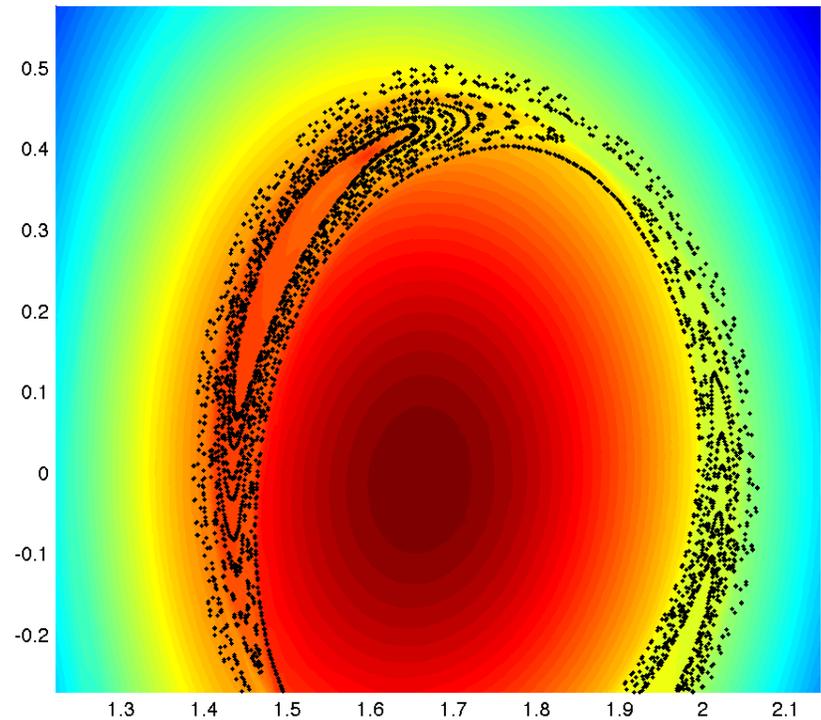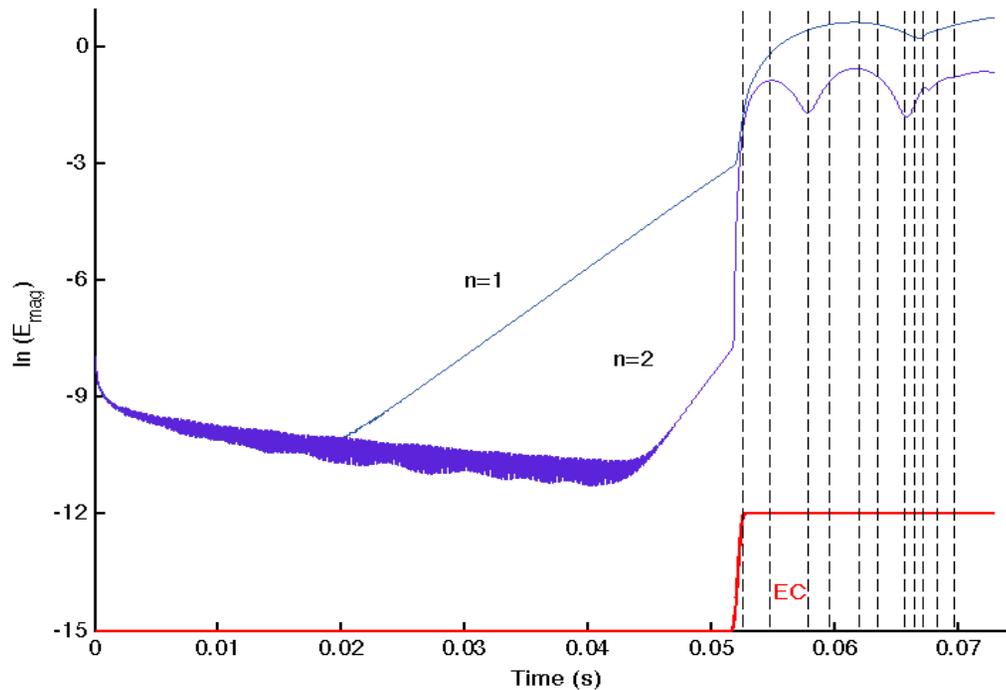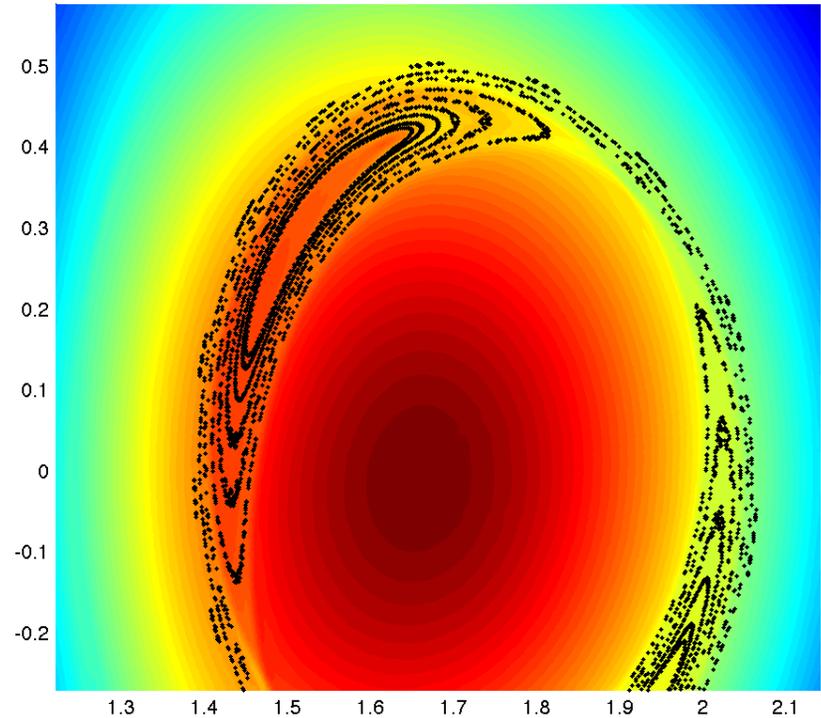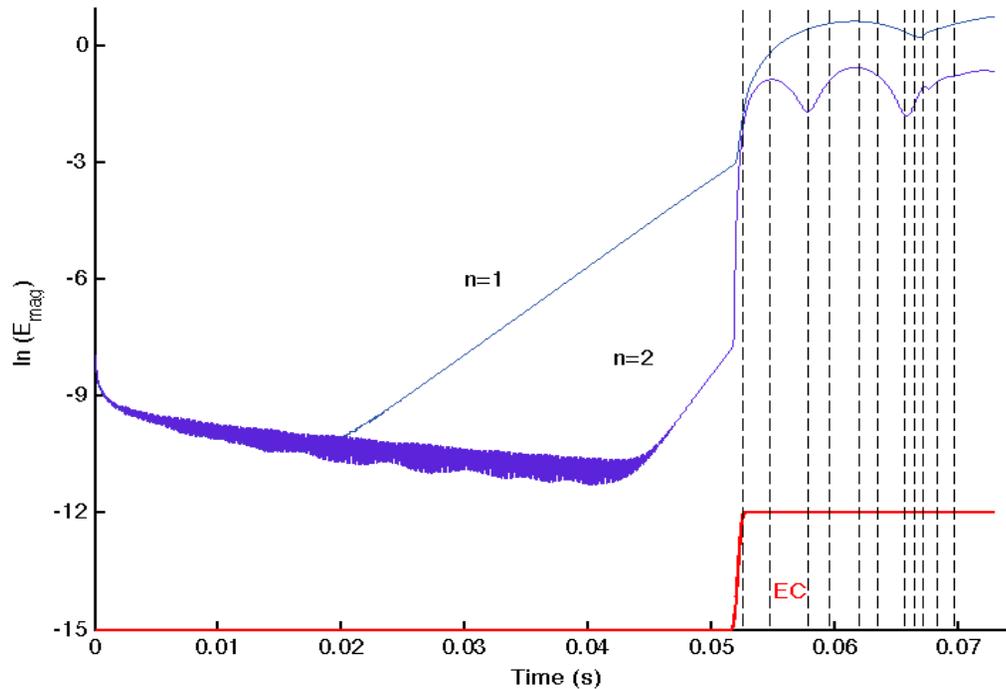Fourier components of magnetic energy (~island width) vs. time

# Total toroidal current plots superposed on the Poincare map: RF opens the island
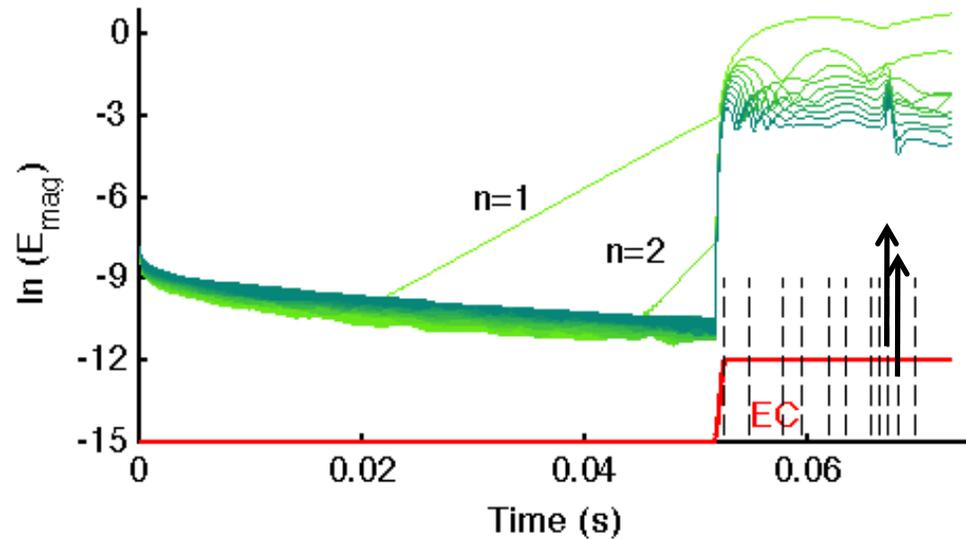
## Current perturbations are 5-8% of equilibrium currents



Fourier components of magnetic energy (~island width) vs. time

Current perturbations are 5-8% of equilibrium currents
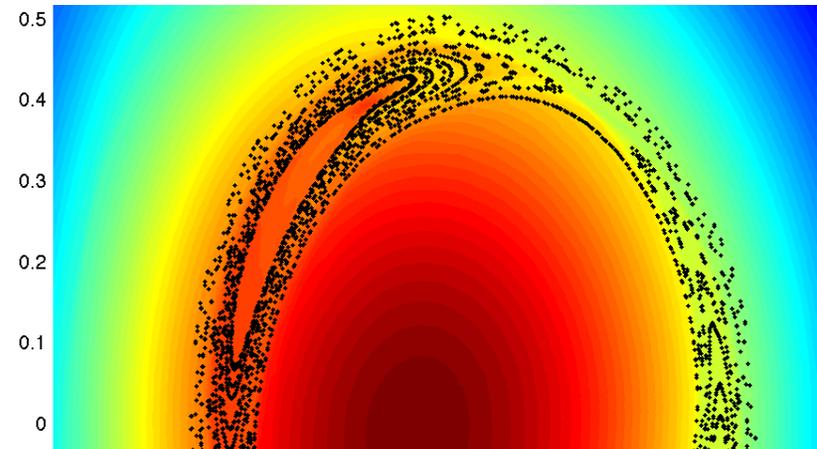
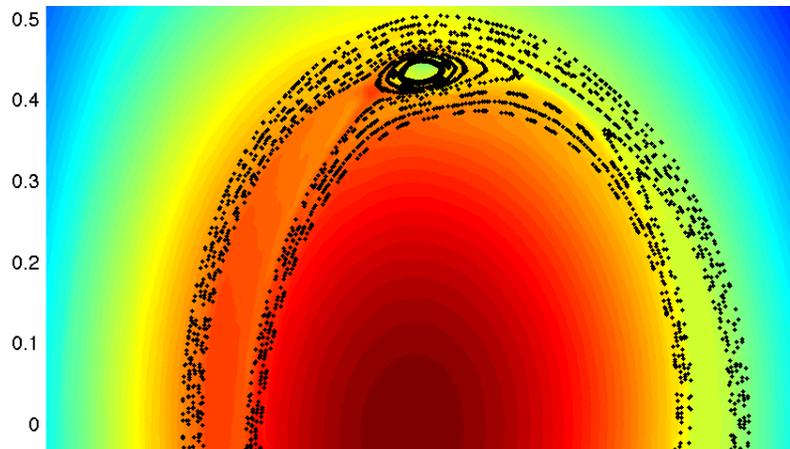Current perturbations are 5-8% of equilibrium currents

# Where did the island go?

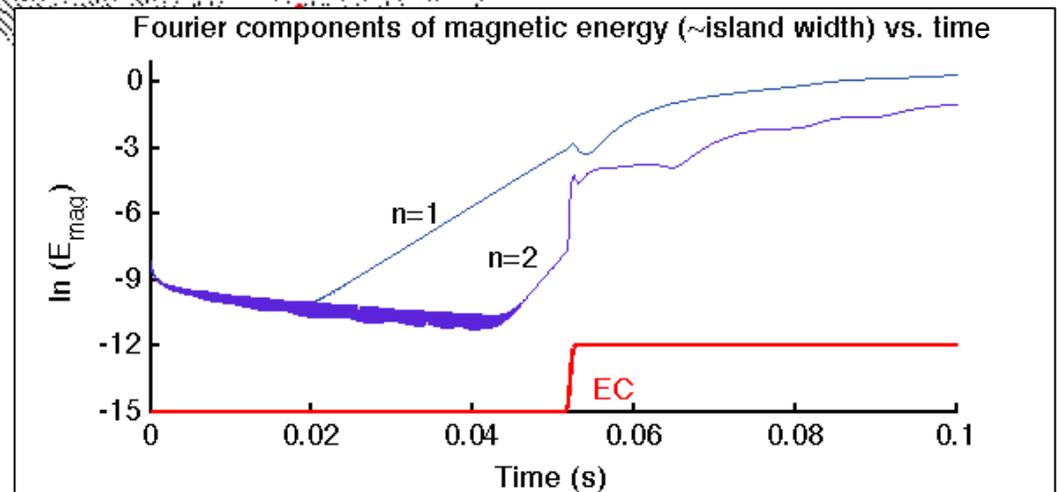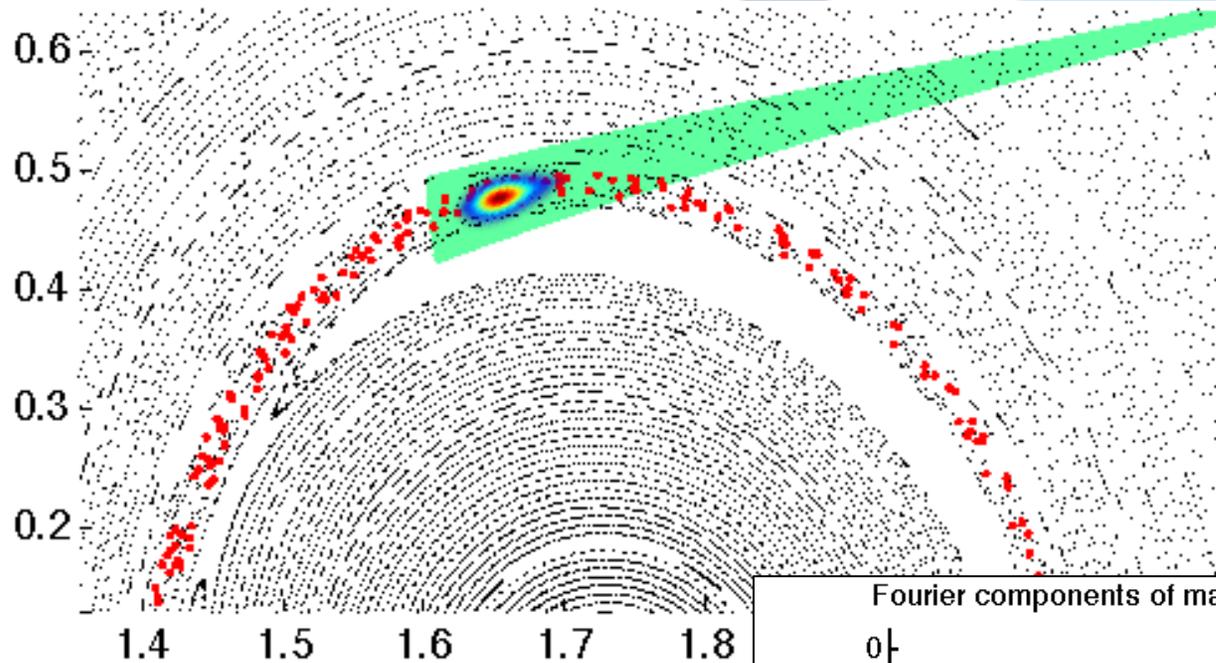Fourier components of magnetic energy (~island width) vs. time



- Large fluctuations in intermediate-n modes (n=4..9) correspond to island disappearance

# The stochastic layer forms whenever the RF is not aligned with the rational surface



Fourier components of magnetic energy (~island width) vs. time

# Present status and plans

- Developments to the control system algorithms are ongoing

- Alignment requirements, and the interaction of stochasticity with the growing island, are being explored in more detail

- Paper in review at Phys. Plasmas, covering the details of RF/MHD interaction

- Other papers are in progress
  - ❖ Computational methods (CPC) - how to translate between the various physics objects in this problem (continuous MHD solutions, discrete RF solutions along rays, collective properties of the RF ray bundle)
  - ❖ Physics results: toroidally asymmetric sources, stochastic layers, optimal placement of ECCD

- QL operator effect on closures to be implemented using Eric Held's methods