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Stochastization as a possible cause of fast reconnection in the frequently interrupted regime of neoclassical tearing modes

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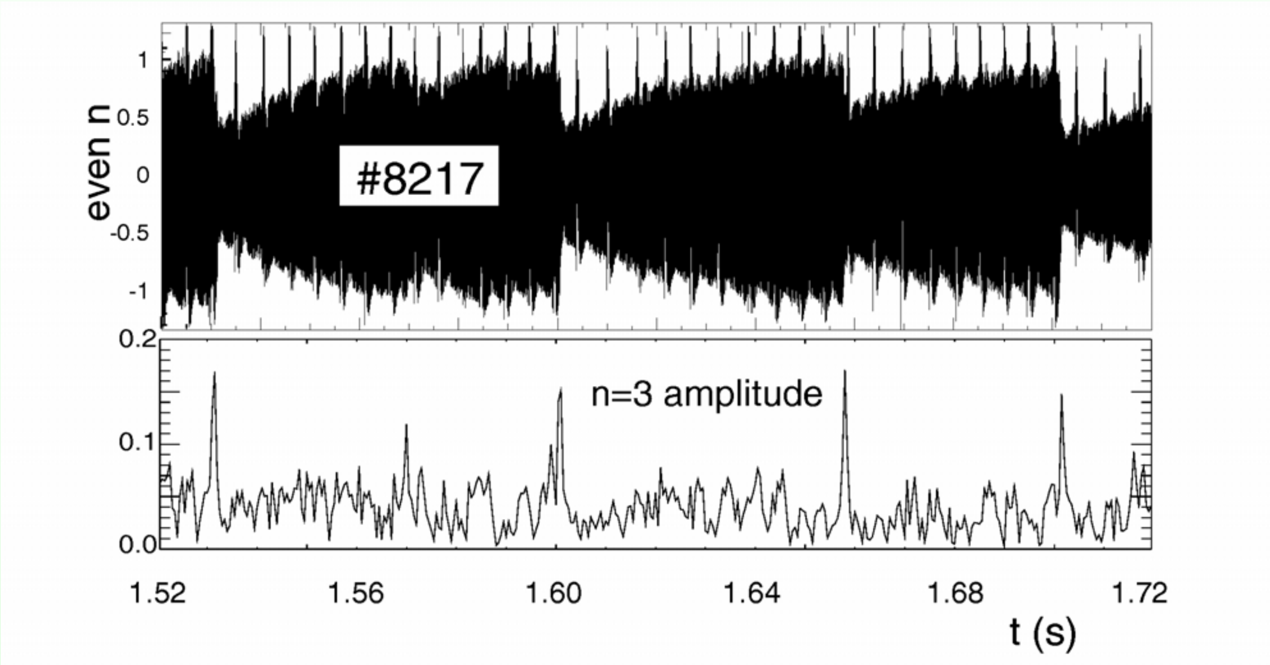
Frequently Interrupted Regime Neoclassical Tearing modes (FIR-NTM) I

On ASDEX Upgrade a regime has been found when the amplitude of the NTM after reaching a certain size suddenly drops to a much smaller value. After this the mode growth starts again. In this way the NTM amplitude never reaches its saturated value. This kind of neoclassical tearing modes was called FIR (frequently interrupted regime) –NTMs. In particular it has been observed that the amplitude of the (m,n)=(3,2) NTM drops as an additional MHD instability (the (m,*n*)=(4,3) mode) occurs.

Frequently Interrupted Regime Neoclassical Tearing modes (FIR-NTM) II



(3,2) NTM amplitude drops

due to large (4,3) activity

The time in which these amplitude drops occur is very short (about 500 microseconds), much shorter than the usual NTM dynamics (resistive reconnection rate, 50s of milliseconds)!

Hypothesis: Stochastization

1. **This experimental observation can be explained by stochastization of magnetic field lines when islands overlap and their separatrix is destroyed. Here the mode coupling plays a decisive role.**

2. **Stochastization is analyzed by means of the mapping technique for the field lines.**

The Hamiltonian formalism

Magnetic field lines can be regarded as trajectories of Hamiltonian systems. In this formalism the equations for magnetic field lines take the Hamiltonian form:

$$\frac{d\psi}{d\varphi} = -\frac{\partial H}{\partial \vartheta}, \qquad \frac{d\vartheta}{d\varphi} = \frac{\partial H}{\partial \psi},$$

where $\psi = r^2 / 2a^2$ is a **toroidal magnetic flux**, φ is a **toroidal angle**, ϑ is a **poloidal angle**, and a is a minor radius of the plasma (50 cm at ASDEX Upgrade).

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$$H = H_0(\psi) + H_1(\psi, \vartheta, \varphi)$$

$H_0(\psi) = \int \frac{d\psi}{q(\psi)}$ Is the **unperturbed flux**

$H_1(\psi, \vartheta, \varphi) = \sum_{m,n} H_{mn}(\psi) \cos(m\vartheta - n\varphi + \chi_{mn})$ is the **perturbed part of the flux**

$q(\psi)$ is the **safety factor** characterizing the winding of the magnetic field lines,

$H_{mn}(\psi)$ is the **perturbation Hamiltonian** which corresponds to the perturbations of the modes (m,n) with the phases χ_{mn}

The mapping technique

$$\Psi_k = \psi_k - \frac{\partial S^{(k)}}{\partial \vartheta_k}$$

$$\Theta_k = \vartheta_k + \frac{\partial S^{(k)}}{\partial \Psi_k}$$

$$\overline{\Theta}_k = \Theta_k + w(\Psi_k)(\varphi_{k+1} - \varphi_k)$$

$$\Psi_{k+1} = \Psi_k$$

$$\vartheta_{k+1} = \overline{\Theta}_k - \frac{\partial S^{(k+1)}}{\partial \Psi_{k+1}}$$

$$\psi_{k+1} = \Psi_{k+1} + \frac{\partial S^{(k+1)}}{\partial \vartheta_{k+1}}$$

ψ is the **magnetic flux**, ϑ is the **poloidal angle**, $w(\Psi)$ is the **frequency** of the perturbed motion, and $S^{(k)} \equiv S(\vartheta_k, \Psi_k)$ is the value of the **generating function** $G(\vartheta, \Psi, \varphi, \varphi_0; \varepsilon)$ taken at sections $\varphi = \varphi_k$, i.e. $S(\vartheta_k, \Psi_k) = G(\vartheta_k, \Psi_k, \varphi_k, \varphi_0)$

The first order generating function in the interval $\varphi_k < \varphi < \varphi_{k+1}$ is given by the expression

$$G(\vartheta, \Psi, \varphi, \varphi_0) = -(\varphi - \varphi_0)\sum_{mn} H_{mn}(\Psi) \times [a(x_{mn})\sin(m\vartheta - n\varphi + \chi_{mn}) + b(x_{mn})\cos(m\vartheta - n\varphi + \chi_{mn})]$$

$$a(x) = [1 - \cos(x)]/x \qquad b(x) = \sin(x)/x \qquad x_{mn} = (m/q(\Psi) - n)(\varphi - \varphi_0)$$

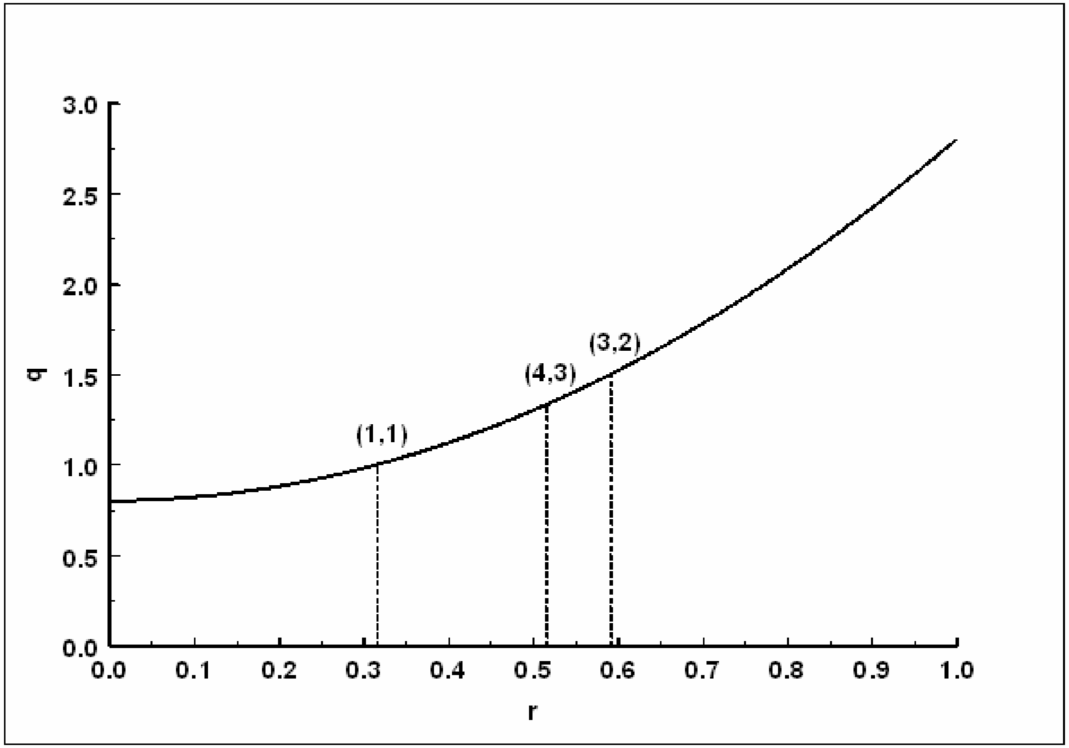
where χ_{mn} are **phases**, $w(\Psi)$ Is the frequency of the perturbed motion,

$q(\Psi) \equiv \dfrac{1}{w(\Psi)}$ is the **safety factor**, $H_{mn}(\Psi)$ is the **perturbation Hamiltonian.**

Safety factor

ASDEX Upgrade:

$$q(r) = 0.8 + 2r^2$$



Definition related to the mapping technique: $\psi = r^2/2$ $\quad q(\psi) = 0.8 + 4\psi$

Parametrization of perturbations (1)

The simplest **step current approximation** **(does not include the screening effect of the plasma):**

$$H_{mn} = \varepsilon_{mn} \left(\frac{\psi}{\psi_{mn}} \right)^{m/2} \quad \text{for} \quad \psi < \psi_{mn}$$

(1)

$$H_{mn} = \varepsilon_{mn} \left(\frac{\psi}{\psi_{mn}} \right)^{-m/2} \quad \text{for} \quad \psi > \psi_{mn}$$

ψ_{mn} is the **rational magnetic surface** of the (m,n) mode.

The **perturbation amplitude**: $\varepsilon_{mn} = B_{mn} / B_T$ where B_T is the **toroidal magnetic field** and B_{mn} is the **magnetic perturbation** due to the (m,n) mode.

Parametrization of perturbations (2)

The **realistic** parametrization:

$$H_{mn} = \varepsilon_{mn} \alpha \left(\frac{\psi}{\psi_{mn}} \right)^{m/2} \left[1 - \beta \left(\frac{\psi}{\psi_{mn}} \right)^{1/2} \right] \quad \text{for} \quad \psi \le \psi_{mn}$$

(2)

$$H_{mn} = \varepsilon_{mn} \frac{\alpha(1-\beta) - \gamma + \gamma \left(\frac{\psi}{\psi_{mn}} \right)^{1/2}}{\left(\frac{\psi}{\psi_{mn}} \right)^{(m+1)/2}} \quad \text{for} \quad \psi > \psi_{mn}$$

α, β, γ are **free parameters** which fix the shape of the perturbation flux.

The **condition** $H_{mn}(\psi = 0.845) = H_{mn}^{\exp}(\psi = 0.845)$ fixes the "normalization coefficients" on the basis of the magnetic measurements of perturbations at the **position of the magnetic probes** located outside the plasma at $r = 1.3 \quad (\psi = 0.845)$

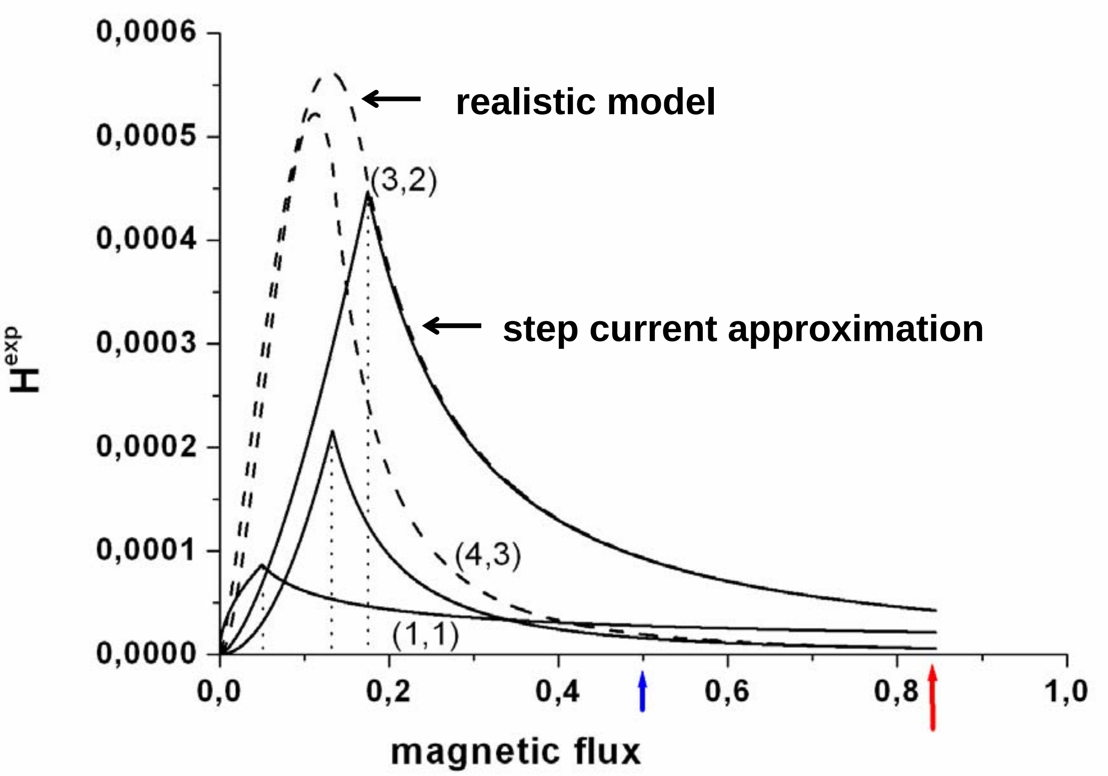
Parametrization of perturbations (3)

$\alpha = 0.04$

$\beta = 0.87$

$\gamma = 0.005$

$\gamma = 0.0005$



$H_{11}^{exp} = 2.1 \times 10^{-5}$

$H_{32}^{exp} = 4.2 \times 10^{-5}$

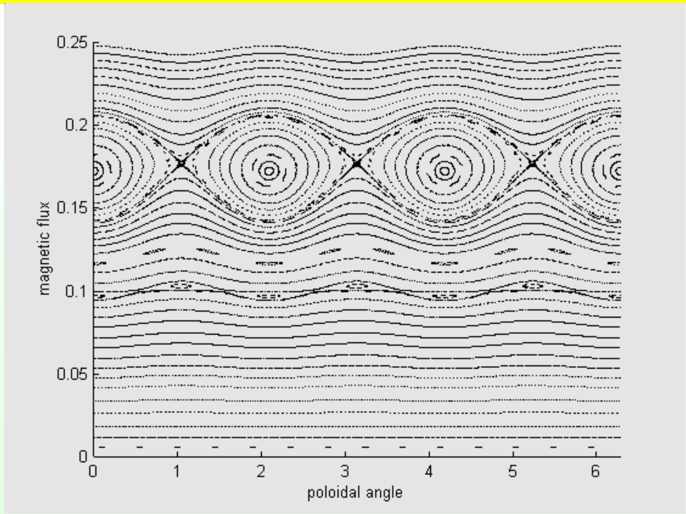
$H_{43}^{exp} = 5.4 \times 10^{-6}$

Dotted vertical lines mark the **positions of resonance** surfaces.

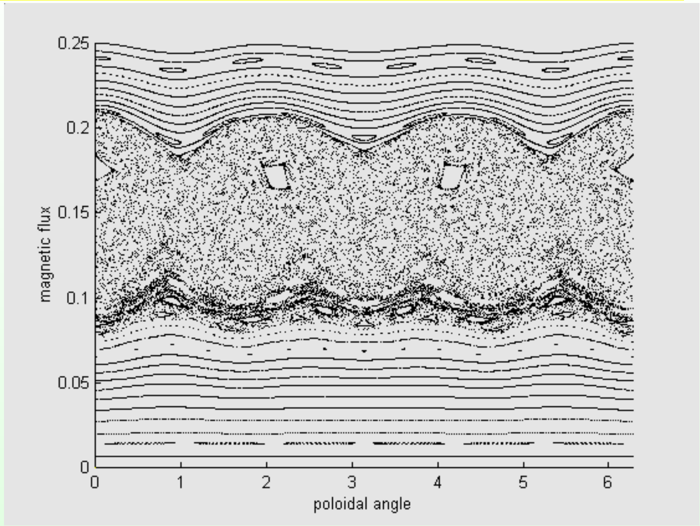
The **plasma boundary** is indicated by the blue arrow and the **position of the magnetic probe** by the **red arrow**.

Results I

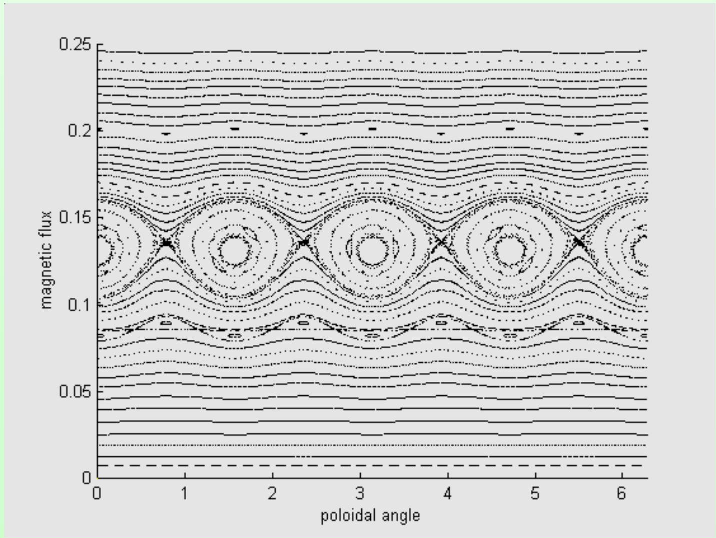
(3,2)



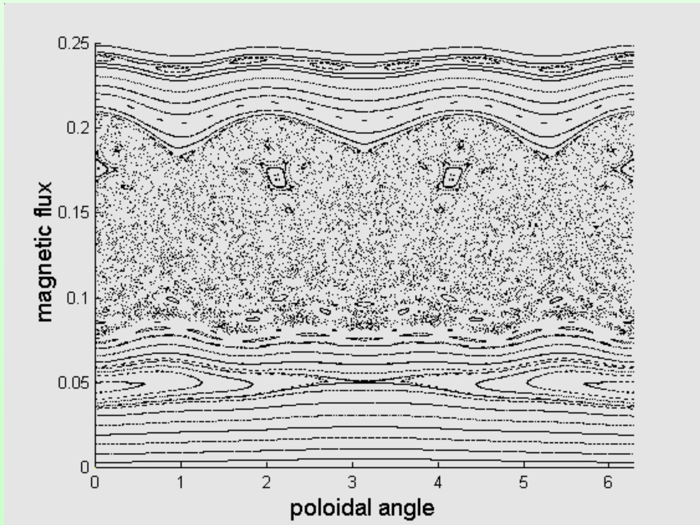
(3,2) + (4,3)



(4,3)

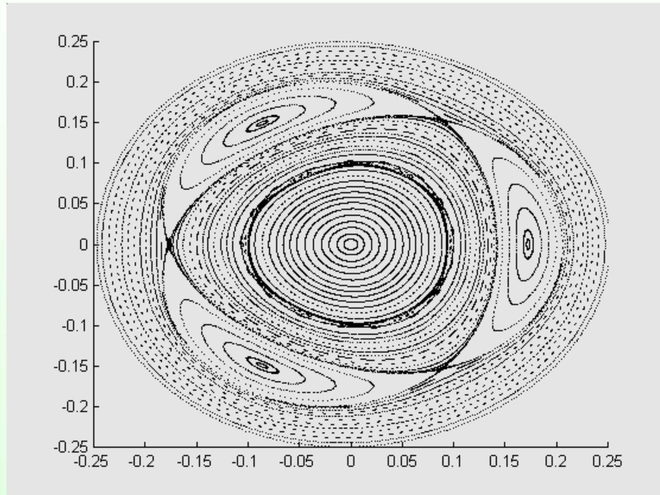


(1,1) + (3,2) + (4,3)

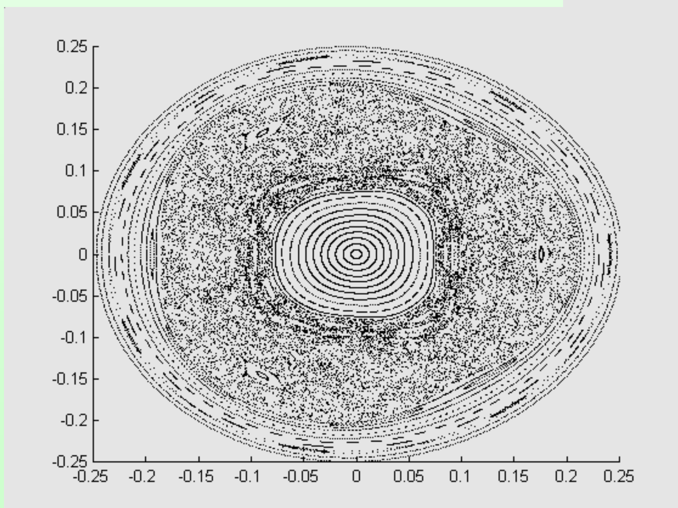


Results II

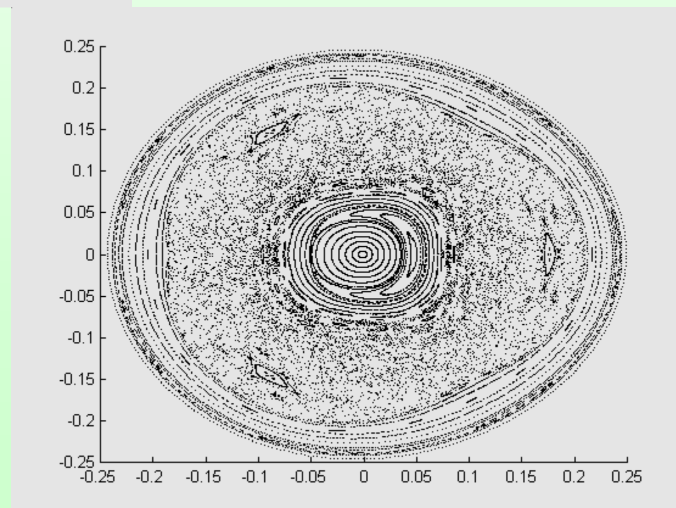
(3,2)



(3,2) + (4,3)



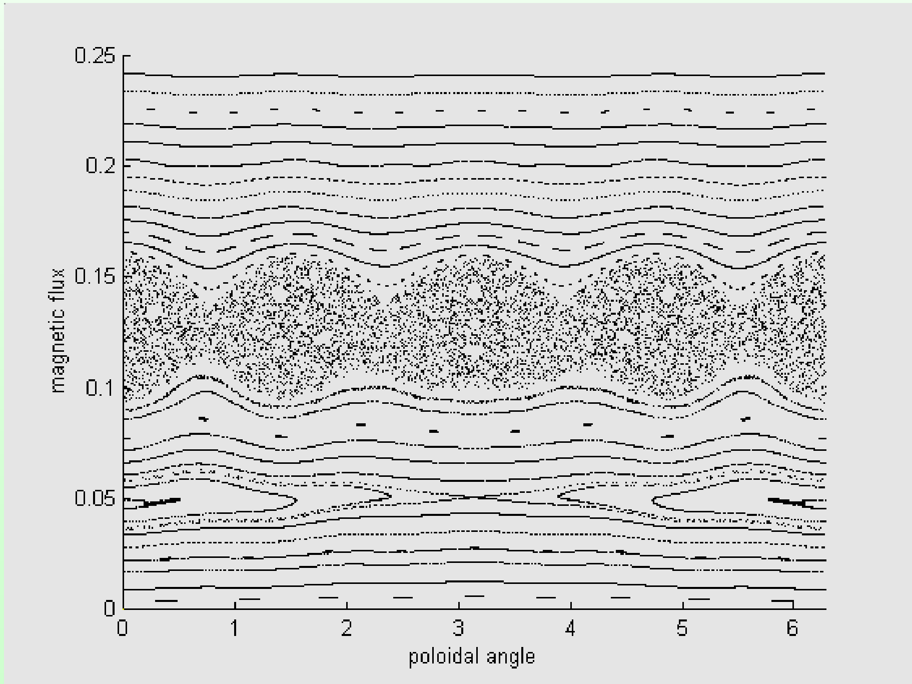
(1,1) + (3,2) + (4,3)

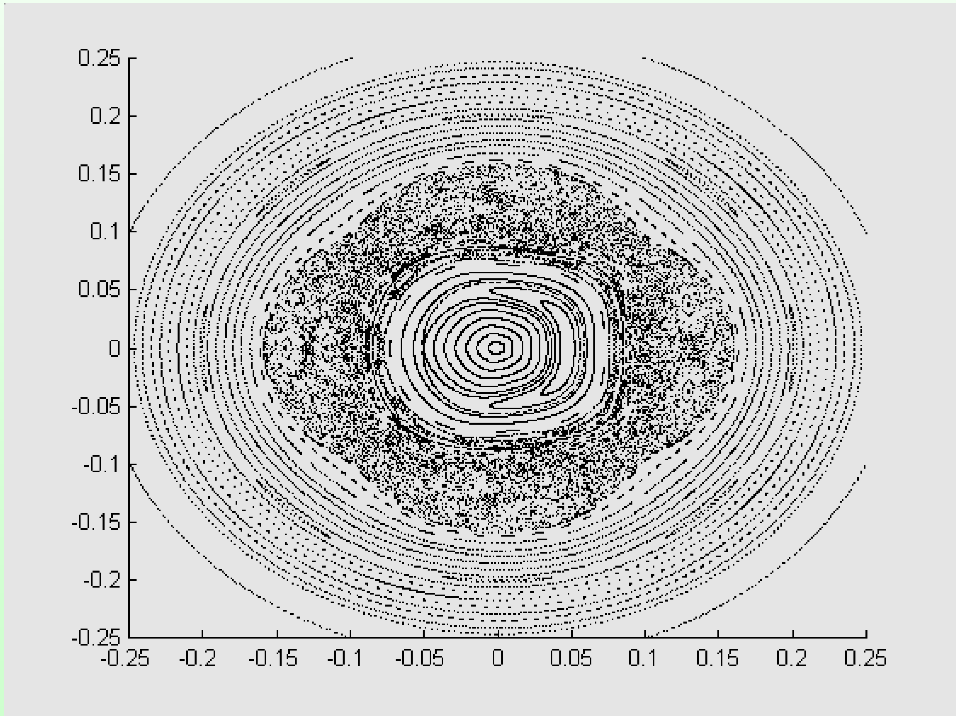


Results III

(1,1) + (4,3) + (5,4) ASDEX Upgrade discharge #11696 t=2.98s $\alpha = 0.04$ $\beta = 0.87$ $\gamma = 0.005$

$H_{11}^{\exp} = 3.0\times10^{-5}$ $H_{43}^{\exp} = 5.0\times10^{-6}$ $H_{54}^{\exp} = 5.0\times10^{-7}$





Conclusions

1. **The mapping method for the field line tracing has been applied to investigate the FIR regime.**

2. **Using the magnetic and ECE measurements the safety factor profile and the perturbation profile have been reconstructed and implemented into the Hamiltonian formalism.**

3. **The nonlinear interaction between the (3,2) and (4,3) modes leads to stochastization. Here the amplitude of the (4,3) mode must be larger than the threshold value and all the modes have to be locked simultaneously.**

4. **The presence of the (4,3) mode prevents the (3,2) mode from growing to its saturated size.**

5. **The (1,1) mode, which is needed for a nonlinear coupling between the modes, has a negligible influence on stochastization itself.**

6. **Similar conclusions refer to the interaction between the (4,3) and (5,4) modes.**

In spite of the relatively large experimetal uncertainies in the parametrizations of the safety factor and the perturbing Hamiltonian the overall physical picture remains valid!

Future work

1. **Investigations will be extended to the framework of a real ASDEX Upgrade geometry.**

2. **The observed stochastization will be described by means of an additional electron viscosity term in Ohm' s law that would lead to faster reconnection. The sensitivity of the reconnection rate to the magnitude of the resistivity is a central issue.**