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KURCHATOV INSTITUTE "КУРЧАТОВСКИЙ ИНСТИТУТ"

A Possible Mechanism for the Seed Island Formation

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Outline

- Spontaneous onset of NTMs - experiments
- Resonant field amplification
- RFA - theoretical model
- RFA: estimates
- Summary

Neoclassical Tearing Modes (NTMs)

Are typically excited by

sawteeth, fishbones, ELMs

Sometimes appear without visible trigger (spontaneously)

(ASDEX Upgrade, JT-60U, T-10, JET)

Can be driven by externally applied error field

(COMPASS-D, JET)

Spontaneous onset of NTMs (ASDEX Upgrade)

Nuclear Fusion **39** (1999) 127

Seed island of neoclassical tearing modes at ASDEX Upgrade

A. Gude, S. Günter, S. Sesnic, ASDEX Upgrade Team

The neoclassical tearing mode (3,2)+(2,2) at ASDEX Upgrade is **often** triggered by a **sawtooth** crash or by **fishbone** activity.

… In **few cases** the NTM starts **spontaneously**.
The corresponding seed island is **smaller** by a factor of at least 3 than in cases with a sawtooth trigger.

Spontaneous onset of NTMs (JT-60U)

Nuclear Fusion **41** (2001) 761

Long sustainment of quasi-steady-state high β_p
H mode discharges in JT-60U

A. Isayama, Y. Kamada, T. Ozeki, S. Ide, T. Fujita, T. Oikawa,
T. Suzuki, Y. Neyatani, N. Isei, K. Hamamatsu, Y. Ikeda, K. Takahashi,
K. Kajiwara, JT-60 Team

… in DIII-D [15, 16] and ASDEX-U [17] … the tearing mode is triggered by **sawtooth** oscillations or the **fishbone** instability, i.e. when q(0) < 1.

sawtooth oscillations **nor** fishbone instability is observed since the central safety factor is kept above unity.

Spontaneous onset of NTMs (T-10)

Nuclear Fusion **41** (2001) 1619

Beta limit due to resistive tearing modes in T-10

D.A. Kislov, Yu.V. Esipchuk, N.A. Kirneva, I.V. Klimanov, Yu.D. Pavlov, A.A. Subbotin, V.V. Alikaev, A.A. Borshegovskiy, Yu.V. Gott, A.M. Kakurin, S.V. Krilov, T.B. Myalton, I.N. Roy, E.V. Trukhina, V.V. Volkov, T-10 Team

… (3,2) mode is **always** triggered by a **sawtooth** crash.

… (2,1) mode can also be triggered by a sawtooth, but in **many** discharges mode onset occurs **without** any observable trigger.

Spontaneous onset of NTMs (JET)

30th EPS Conference on Contr. Fusion and Plasma Phys., St. Petersburg, 7-11 July 2003 ECA Vol. 27A, P-1.93

MHD in JET Advanced Scenarios

S.D. Pinches[1], B. Alper[2], R. J. Buttery[2], C. D. Challis[2], M. Gryaznevich[2], S. Günter[1], T.C. Hender[2], D. F. Howell[2], E. Joffrin[3], Y. Q. Liu[4], J. Mailloux[2], M. Maraschek[1], S. E. Sharapov[2], A.C.C Sips[1] and JET EFDA contributors[*]

At low field (Bt = 1.7 T) NTMs are **nearly always** present. They **lack** any obvious triggering mechanism since there are **no** sawteeth in these discharges and the fishbones typically **don't** commence until after NTM onset, indicating that

seed events are not always required for NTM onset.

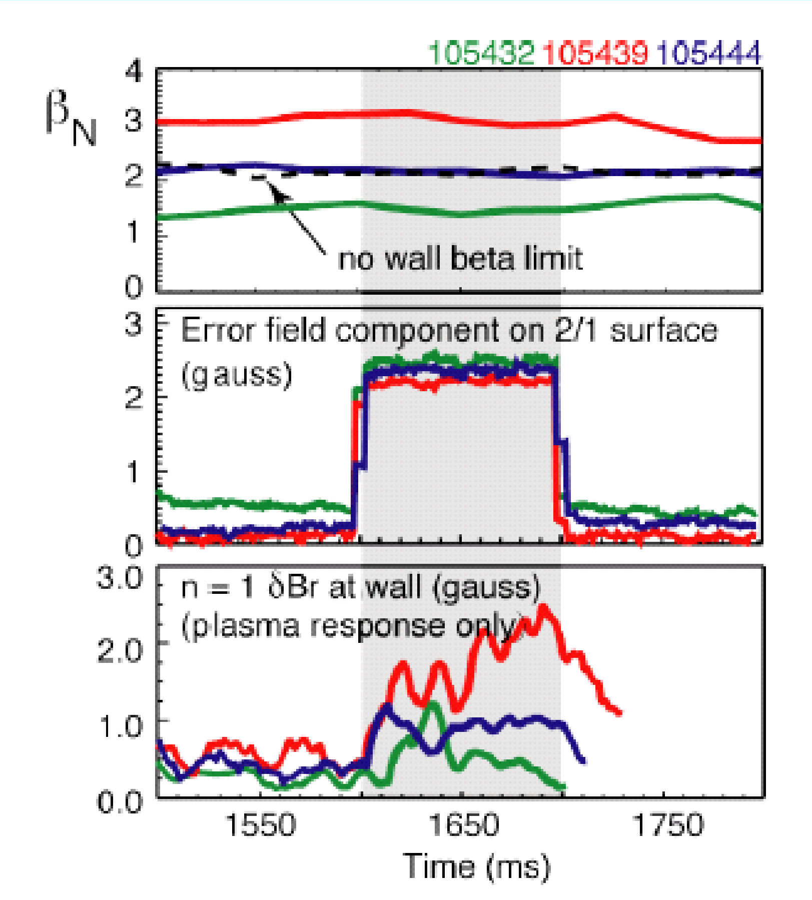
Spontaneous onset of NTMs

A possible onset mechanism:

Resonant Field Amplification

(RFA)

Error field amplification experiments in DIII-D



M. Okabayashi, et al.,

"Stabilization of the resistive wall mode in DIII–D by plasma rotation and magnetic feedback"

Plasma Phys. Control. Fusion **44** (2002) B339

(a) normalized beta,
(b) error field on 2/1 surface
(c) plasma response measured at the wall.

Starting equations

$$\operatorname{rot}\mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t},$$

$$\operatorname{div}\mathbf{B} = 0,$$

$$\operatorname{rot}\mathbf{B} = \mathbf{j},$$

$$\mathbf{j} = \sigma\mathbf{E}$$

Outside the plasma:

vacuum,

wall(s),

active coils

boundary conditions

Inside the plasma: **MHD / reduced MHD**

Analytical model

1. Cylindrical approximation $b_r = \sum b_m(r,t) \exp i(m\theta - n\zeta)$

In vacuum $b_m = B_m^{in} x^{-\mu-1} + B_m^{out} x^{\mu-1}$

$x \equiv r / r_w$, $\mu = |m|$

2. Three sources of perturbation: **plasma,**
wall,
external

$$b_m(r_w) = B_m = B_m^{pl} + B_m^{wall} + B_m^{ext}$$

Main equation

Equation for the mode amplitude at the wall:

$$\boxed{\frac{\partial \mathbf{b}}{\partial t} = \nabla^2 \frac{\mathbf{b}}{\mu_0 \sigma}} \quad \Rightarrow \quad \boxed{\tau_w \frac{\partial B_m}{\partial t} = \Gamma_m B_m + 2\mu B_m^{ext}}$$

When $B_m^{ext} = 0$

γ_0 **is the natural growth/decay rate,**

Ω_0 **is the natural toroidal rotation frequency of the mode**

Discharge evolution & RFA

$$\tau_w \frac{\partial B_m}{\partial t} = \Gamma_m B_m + 2\mu B_m^{ext}$$

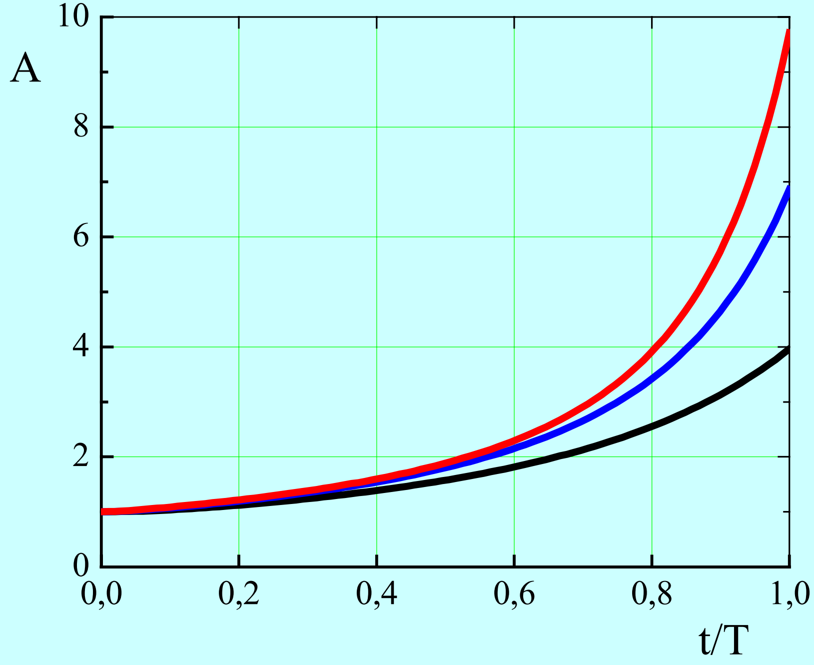
Assume: **constant** B_m^{ext} **and**

$$\Gamma_m = \Gamma_m^0 (1 - t/T)$$

Solution:

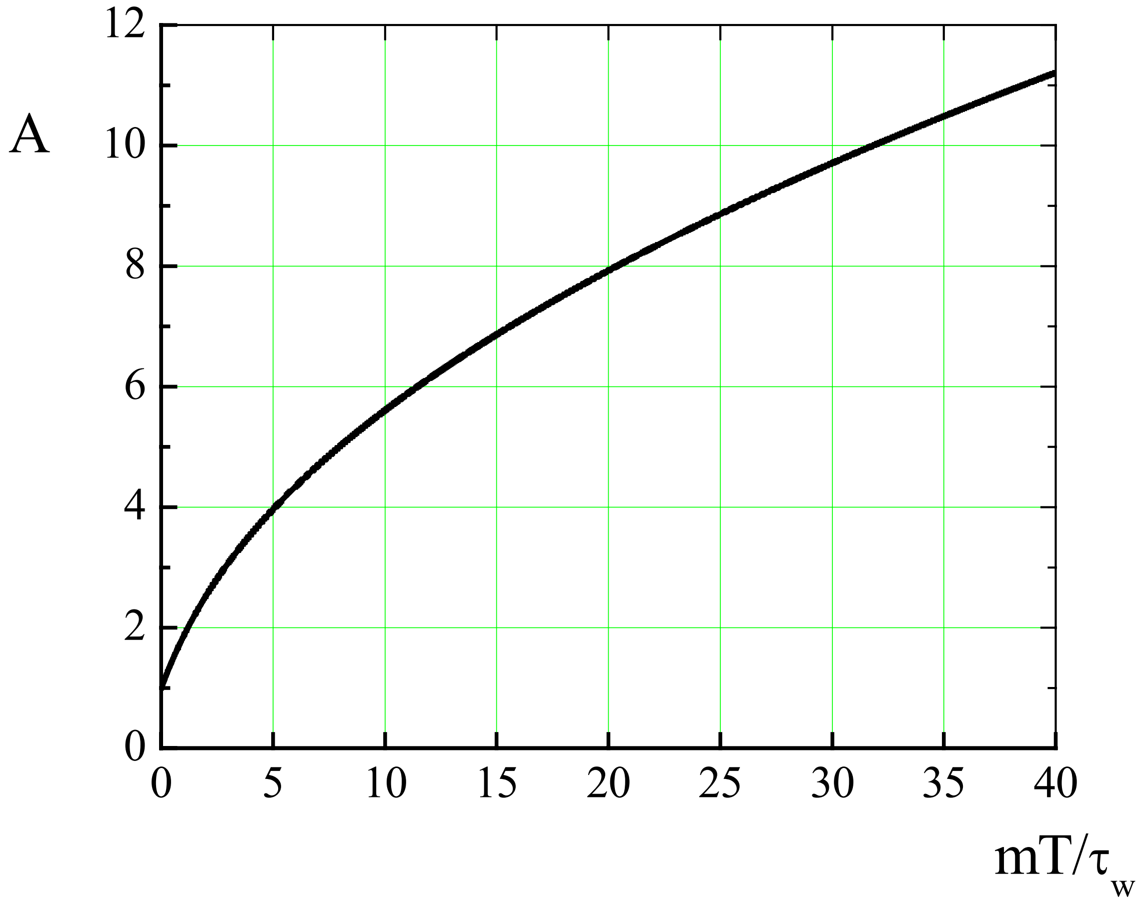
$$B_m = B_m^{ext} A(t)$$

The amplification factor



$\mu T / \tau_w =$ **5, 15, and 30**

Amplification at $t = T$ (marginal stability)



$m = 2$ **mode:** $A > 10$ **for** $T > 16\tau_w$

Resonant Field Amplification

$$\tau_w \frac{\partial B_m}{\partial t} = \Gamma_m B_m + 2\mu B_m^{ext}$$

Assume

$$\Gamma_m = \text{const}\,,\quad \operatorname{Re}\Gamma_m < 0\,,\quad B_m^{ext} = \text{const}$$ **(static error field)**

Steady-state solution:

$$B_m^{st} = -\frac{2\mu}{\Gamma_m} B_m^{ext}$$

$$\min B_m^{ext} = -\frac{\Gamma_m}{2\mu} B_m^{seed}$$

The most interesting case: $\Gamma_m = 0$

RFA near marginal stability

$$\tau_w \frac{\partial B_m}{\partial t} = \Gamma_m B_m + 2\mu B_m^{ext}$$

When $\Gamma_m = 0$**:**

$$B_m = B_m^0 + 2\mu B_m^{ext} \frac{t}{\tau_w}$$

The seed level B_m^{seed} **is reached in**

$$\Delta t = \frac{\tau_w}{2\mu} \frac{B_m^{seed} - B_m^0}{B_m^{ext}}$$

$m = 2$ **mode:** $A = 10$ **in** $\Delta t < 50 \text{ ms}$ **for** $\tau_w < 20 \text{ ms}$

Effect of the mode rotation on RFA

$$\boxed{\tau_w \frac{\partial B_m}{\partial t} = \Gamma_m B_m + 2\mu B_m^{ext}}$$

$$\Rightarrow \quad B_m^{st} = -\frac{2\mu}{\Gamma_m} B_m^{ext}$$

$\mathrm{Re}\,\Gamma_m < 0$, $B_m^{ext} = \mathrm{const}$

$$\Downarrow$$

$$\boxed{\left|B_m^{st}\right| = \frac{2\mu B_m^{ext}}{\tau_w \sqrt{\gamma_0^2 + n^2\Omega_0^2}}}$$

Amplification when $\left|B_m^{st}\right| > B_m^{ext}$

At small γ_0 **:** $\left|n\Omega_0 \tau_w\right| < 2\mu$

The model represents the following features of RFA:

- **The most dangerous are the locked modes near the marginal stability** $(\Omega_0 = 0)$ $(\gamma_0 = 0)$

- **RFA is suppressed by the mode rotation**

- **Speed of the RFA is determined by error field amplitude,** γ_0**, and** τ_w

- **Saturated RFA is possible below the stability threshold** $(\gamma_0 < 0)$

- **No saturation at the marginal stability of locked modes** $(\gamma_0 = 0)$

- **Near the marginal stability the seed level is achieved in** $\Delta t \propto \mathrm{O}(\tau_w)$

Spontaneous onset of NTMs (theory)

Physics of Plasmas **10** (2003) 1643

A mechanism for tearing onset near ideal stability boundaries

D. P. Brennan,[b)] R. J. La Haye, A. D. Turnbull, M. S. Chu, T. H. Jensen, L. L. Lao, T. C. Luce, P. A. Politzer, and E. J. Strait
General Atomics, P.O. Box 85608, San Diego, California 92186-5608

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SAIC, San Diego, California 92186

… tearing modes can be driven unstable by a **rapid increase** in the linear tearing stability index Δ' just before onset.

Near the ideal kink limit in β, becomes large and positive …

Δ' rapidly increases due to the **approach of the ideal kink limit**. This reduces the neoclassical threshold island width and causes the seed island to transition to the NTM state.

Combined effect of Δ' and RFA near marginal stability

Larger Δ' $\Rightarrow$ smaller seed island

smaller seed island and stronger RFA

$\Rightarrow$ smaller error field for NTM onset

Summary

Error field amplification: is dangerous near stability boundary of locked modes

RFA may produce a seed island for NTM in a time scale of several τ_w