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Multi-Scale MHD Analysis of Heliotron Plasma in Change of Background Field

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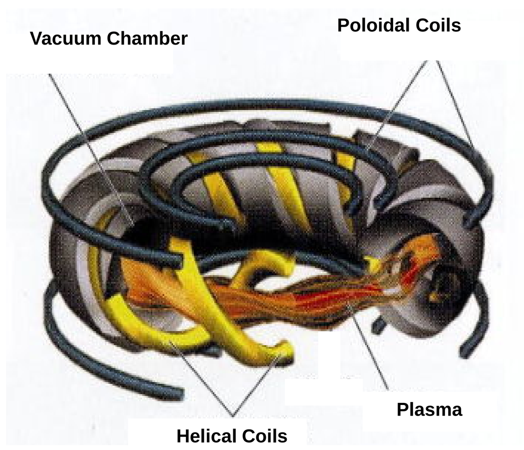
ABSTRACT

A partial collapse observed in the Large Helical Device (LHD) experiments shifting the magnetic axis inwardly with a real time control of the background field is analyzed with an MHD numerical simulation. The simulation is carried out with a multi-scale simulation scheme. In the simulation, the equilibrium also evolves including the change of the pressure and the rotational transform due to the perturbation dynamics.
The result agrees with the experiments qualitatively, which shows that the mechanism is attributed to the destabilization of an infernal-like mode.

Magnetic Axis Swing Operation in LHD Experiments

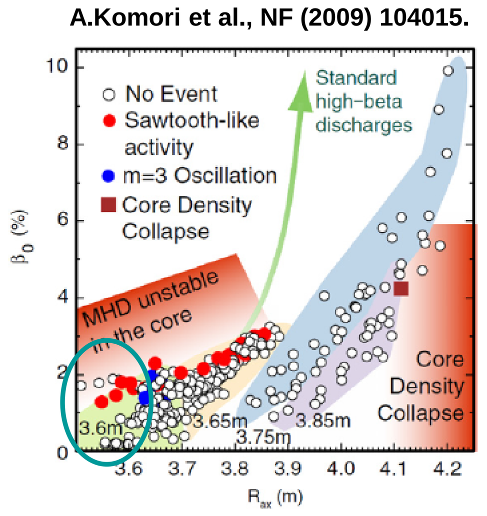
Large Helical Device (LHD) (NIFS,Japan)



Horizontal position of vacuum magnetic axis (Rvax) can be shifted by change of poloidal field.
MHD stability property strongly depends on Rvax, however, the stability boundary on Rvax is not clear.

Dependence of Experimental MHD Property on Rvax

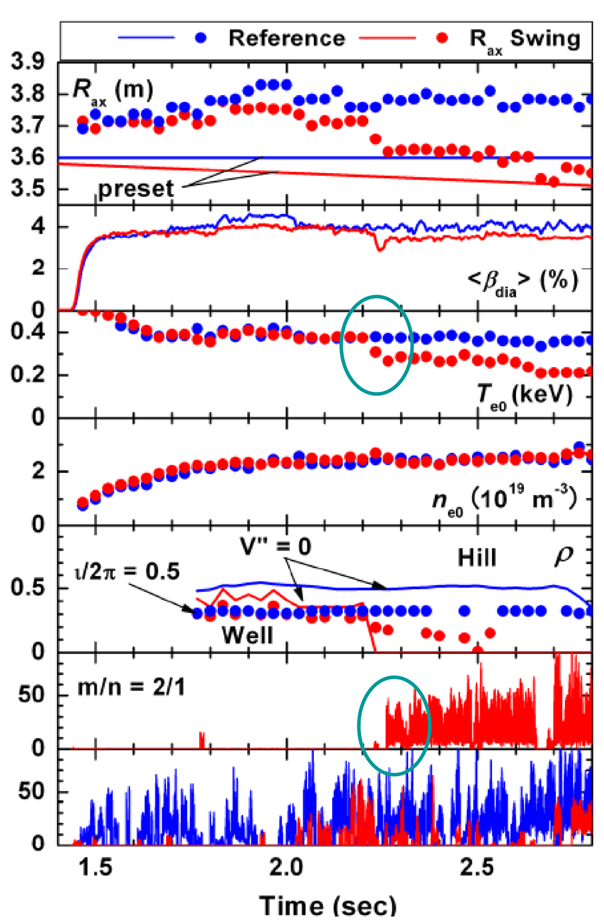
A.Komori et al., NF (2009) 104015.



Magnetic axis swing operations were carried out for investigation of the stability boundary.

(S.Sakakibara et al., 23rd IAEA-FEC 2010 EXS/P5-13.)

Time sequence of magnetic axis swing experiment

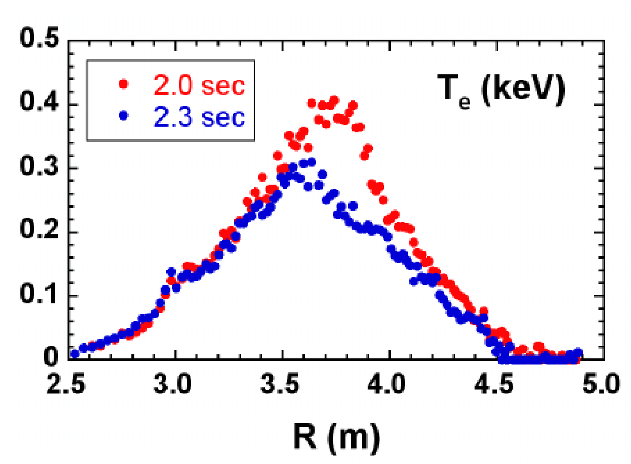


Rvax is changed from 3.6m to 3.5m.

In the swing case, Te0 suddenly drops Rvax~3.55m.

Magnetic fluctuations of (m,n)=(2,1) mode are observed coincidentally.

Te profiles before and after Te0 drop



A partial collapse occurs in the core region.

Mechanism of the collapse is numerically analyzed with an MHD simulation.

Necessity of Multi-Scale Scheme

In the magnetic axis swing operations, equilibrium quantities change due to the background field change.
Time evolutions of both perturbed and equilibrium quantities must be treated simultaneously.

However, big difference in the time scale between perturbation and equilibrium.

Equilibrium evolution	~ 10ms	:	Long
Dynamics of Perturbation	~ 0.5μs	:	Short

A multi-scale scheme has been developed.

(K.Ichiguchi, B.A.Carreras, NF (2011) 053021)

Basic idea of the multi-scale scheme :
Carry out Long time-scale calculation every time interval of Short time-scale calculation

Short time scale : Continuous calculation of perturbation dynamics with the NORM code
Long time scale : Update of 3D static equilibrium with the VMEC code incorporating change of pressure and ι profiles due to the dynamics.

Basic Equations for Nonlinear Calculation

Nonlinear MHD Dynamics Calculation : NORM code (K.Ichiguchi, et al., NF (2003) 1101)

Basic Equations : 3-Field Reduced MHD Equations for
Ψ (poloidal flux) Φ (stream function) P(pressure)

Background pressure diffusion and continuous heating is included.

Variable Separation

Equilibrium and Perturbed Parts

$$\Psi(\rho,\theta,\zeta;t)=\Psi_{eq}(\rho)+\tilde{\Psi}(\rho,\theta,\zeta;t)$$

$$\Phi(\rho,\theta,\zeta;t)=\tilde{\Phi}(\rho,\theta,\zeta;t)$$

Average and Oscillating Parts

$$P(\rho,\theta,\zeta;t)=\langle P\rangle(\rho;t)+\widehat{P}(\rho,\theta,\zeta;t)$$

Treating as Background pressure

Application to Reduced MHD equations

$$\frac{\partial\tilde{\Psi}}{\partial t}=-\nabla_{\parallel}\tilde{\Phi}+\frac{1}{S}\tilde{J}_{\zeta}$$

$$\frac{\partial\tilde{U}}{\partial t}=-[\tilde{U},\tilde{\Phi}]-\nabla_{\parallel}\tilde{J}_{\zeta}-[\tilde{\Psi},J_{\zeta eq}]+\frac{1}{2\epsilon^2}[\Omega_{eq},\widehat{P}]+\nu\left(\frac{R}{R_0}\right)^2\nabla_{\perp}^2\tilde{U}$$

$$\frac{\partial\widehat{P}}{\partial t}=-\widehat{[P,\tilde{\Phi}]}+\kappa_{\perp}\widehat{\Delta_{*}P}+\kappa_{\parallel}\widehat{\nabla_{\parallel}^{\dagger 2}P}$$

$$\frac{\partial\langle P\rangle}{\partial t}=\boxed{-\langle[\widehat{P},\tilde{\Phi}]\rangle}+\boxed{\kappa_{\perp}\langle\Delta_{*}\langle P\rangle\rangle+\kappa_{\parallel}\langle\nabla_{\parallel}^{\dagger 2}\langle P\rangle\rangle}+\boxed{Q(\rho;t)}$$

Anomalous transport due to MHD turbulence
Classical diffusion of background pressure
Continuous heat source

$$\left([y,z]=\frac{g}{\rho}\left(\frac{\partial y}{\partial\rho}\frac{\partial z}{\partial\theta}-\frac{\partial y}{\partial\theta}\frac{\partial z}{\partial\rho}\right),\nabla_{\perp}f=\nabla f-\nabla\zeta\frac{\partial f}{\partial\zeta},\nabla_{\parallel}f=g\frac{\partial f}{\partial\zeta}+[\Psi,f],\nabla_{\parallel}^{\dagger 2}f=\nabla_{\parallel}\left[\left(\frac{R_0}{R}\right)^2\nabla_{\parallel}f\right]\right)$$

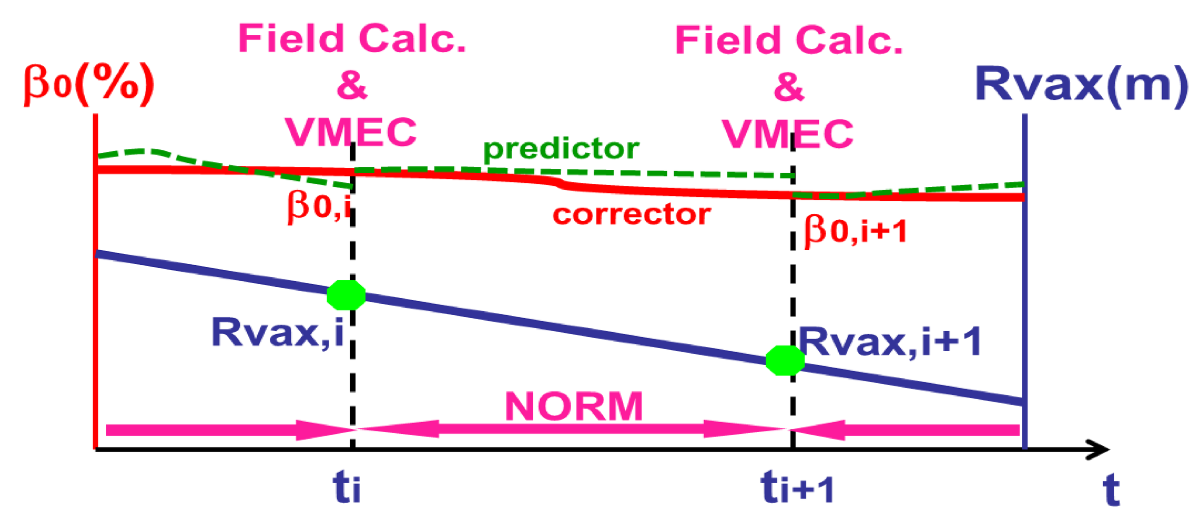
$$\Omega=\frac{1}{2\pi}\int_0^{2\pi}d\zeta\left(\frac{R}{R_0}\right)^2\left(1+\frac{|\boldsymbol{B}_{eq}(R,\zeta,Z)-\overline{\boldsymbol{B}_{eq}}(R,Z)|^2}{B_0^2}\right),\quad \boldsymbol{v}_{\perp}=\left(\frac{R}{R_0}\right)^2\nabla\Phi\times\nabla\zeta,$$

$$U=\hat{\nabla}_{\perp}^2\Phi=\left(\frac{R}{R_0}\right)^2\nabla\cdot\nabla_{\perp}\Phi,\quad J_{\zeta}=\Delta_{*}\Psi=\left(\frac{R}{R_0}\right)^2\nabla\cdot\left(\frac{R_0}{R}\right)^2\nabla_{\perp}\Psi$$

Procedure of Multi-Scale Scheme

Predictor-Corrector method in interval of $t_i<t<t_{i+1}$ with changing $R_{vax,i}$ to $R_{vax,i+1}$

(K.Ichiguchi, et al., accepted in PPCF)



1. Equilibrium at $t=t_i$ is calculated with the NORM result. $\langle P\rangle_i,\iota_i,R_{vax,i}\Rightarrow E_{eq,i}$

2. Equilibrium at $t=t_{i+1}$ is calculated,
   predictor : with QΔt for pressure. $\langle P\rangle_i+Q\Delta t,\iota_i,R_{vax,i+1}\Rightarrow E_{eq,i+1}$
   corrector : using predictor results. $\langle P\rangle_{i+1},\iota_{i+1},R_{vax,i+1}\Rightarrow E_{eq,i+1}$

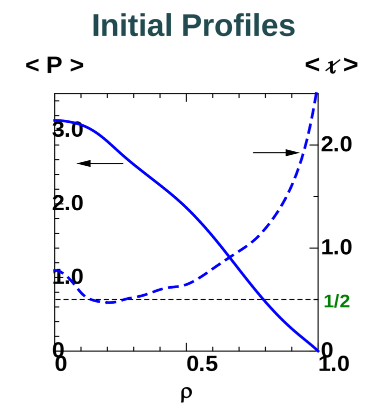
3. Nonlinear Dynamics is calculated with the NORM code for $t_i<t<t_{i+1}$.

Application to LHD Plasma

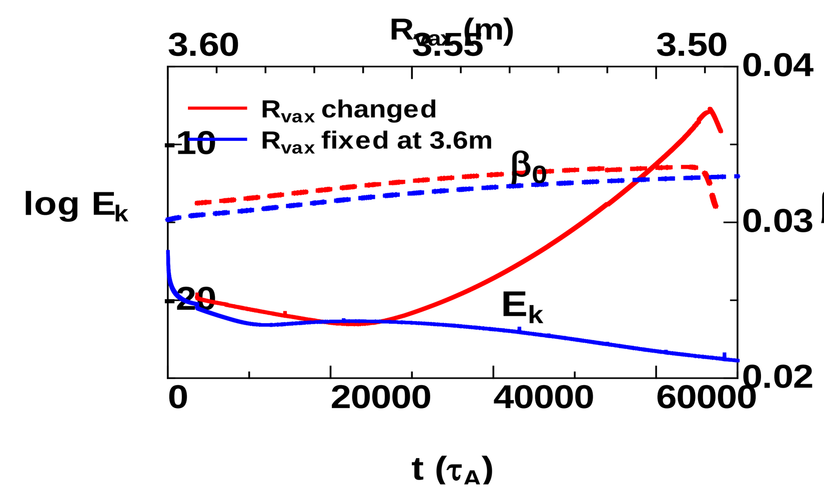
Equilibrium calculation	: Free boundary (Rlim=4.6m) and FCT constraint
Variation of Rvax	: From Rvax=3.60m at t=0, to Rvax=3.50m at t=63500τ_A
Heating profile	: $Q(\rho)=Q_0(1-\rho^2)^{6.2}$
Dissipation parameters	: $S=10^7,\ \nu=1.0,\ \kappa_{\perp}=1.0\times10^{-6},\ \kappa_{\parallel}=3.0\times10^{-4}$

Numerical Results

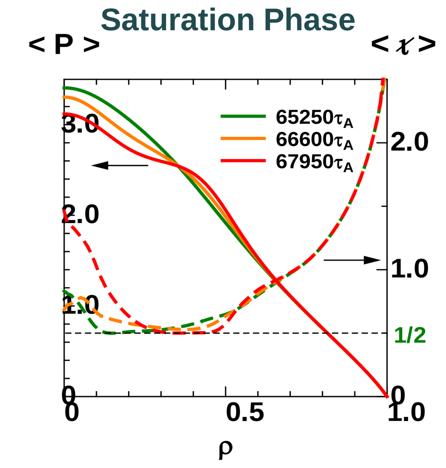
Time Evolution of Kinetic Energy and Axis Beta



Initial profiles are determined from another saturation result obtained with no net current constraint.

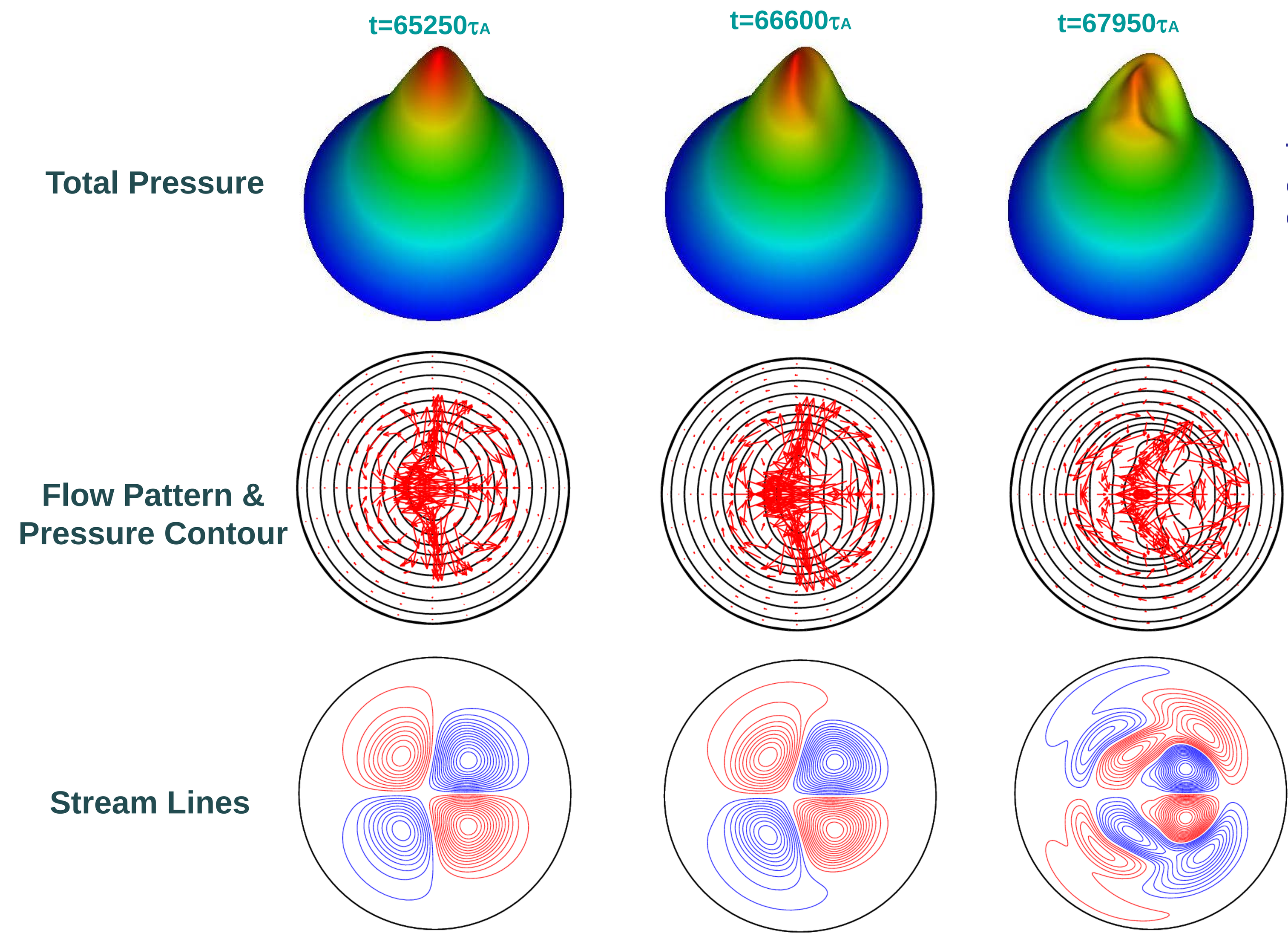


In the case of background field change, an n=1 mode dominantly grows and is nonlinearly saturated with an abrupt drop of axis beta.
In the case of fixed field, the plasma is stable.
This situation agrees with the experiment.



In the saturation phase, core pressure decreases in a short time, which corresponds to the partial collapse.

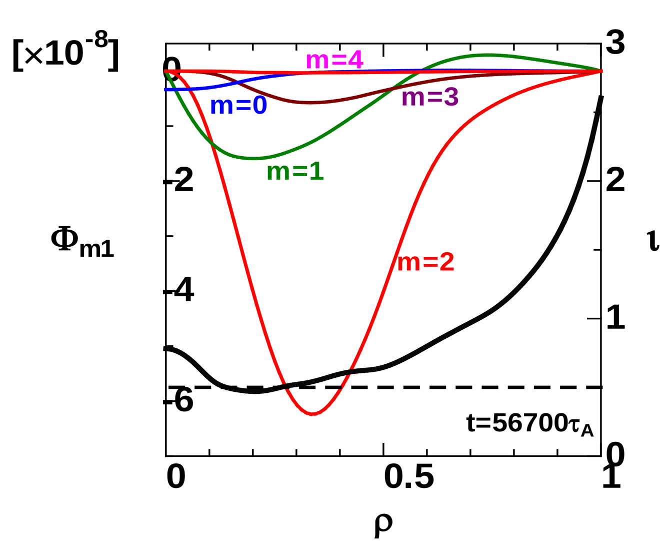
Nonlinear Development



The m=2 deformation occurs in the partial collapse of pressure.

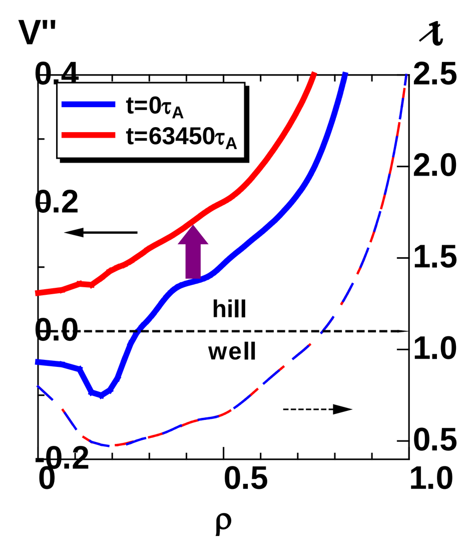
The flow pattern becomes more turbulent as time goes by.

Mode Structure of Stream Function



A (2,1) component is dominant, consistent with the experiment.
Deviation of the peak position and signs of sidebands indicate the mode is like an infernal mode.
The mode is destabilized because of the low shear and ι close to ½ in the core.

Change of Magnetic Hill



Magnetic hill is enhanced in the change of background field.
The enhancement destabilizes the infernal-like mode.

Conclusions

- The partial collapse observed in the magnetic axis swing operation in the LHD experiments is analyzed with a nonlinear MHD simulation incorporating a multi-scale numerical scheme.
- The simulation result qualitatively identifies the collapse mechanism.
  The enhancement of the magnetic hill due to the change of the background magnetic field destabilizes the (2,1) infernal-like mode.
  The nonlinear saturation of the mode causes the partial collapse of the core pressure.
  On the contrary, the plasma is stable for the fixed background field.
  These properties are consistent with the experimental results.