

Equilibrium of Plasma constrained by Myxines in a Galathea Magnetic Confinement System

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Abstract. The structure and magnetic field configuration of a non-Tokamak magnetic controlled fusion device—Galathea—is introduced. The force balance of plasma confined by myxines in a toroidal topology is semiquantitatively analyzed and the computing formula of vertical magnetic field used to compensate the toroidal force is given, on a Galathea device “Trimyx”, which has three myxines; A magnetohydrodynamic model is built for describing plasma confined by only one straight myxine, to solve the steady distribution of plasma pressure and explain the unavoidability phenomenon that plasma energy loss caused by contacting with myxines; Stationary and time-varying model are built and simulated by software COMSOL, to solve the separation of plasma and myxines, an effective separation method is given.

Introduction

In modern world, the seriousness and urgency of the issues related to energy field have become increasingly prominent. Galathea was proposed by Russian famous scientist A.I. Morozov in 1970s, which belong to a kind of small, multipole, non-tokamak magnetic confinement device. Different from other types of devices, the current-carrying conductor (myxine) is imbedded in plasma in Galathea, while in Tokamak and Stellarator, the current-carrying conductors are mounted in the periphery of the device. The Levitated Dipole Experiment (LDX) developed by America and Japan could be considered as a kind of Galathea with only one myxine. Figure 1 shows the structure of Trimyx, which proposed by Moscow State Institute of Radioengineering, Electronics and Automation (MIREA).

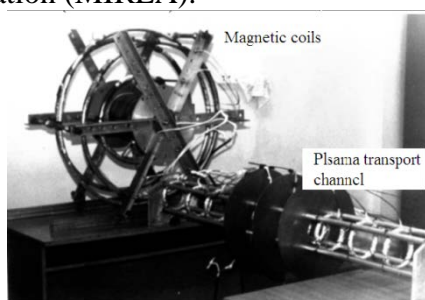


Figure 1. Trimyx trap and plasma guide

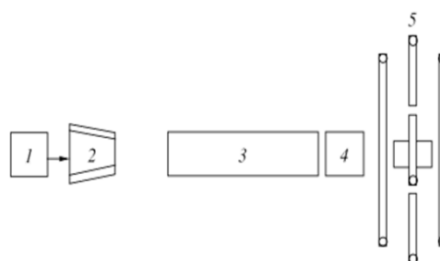


Figure 2. Block diagram of the Galathea Trimyx

In this paper, the toroidal and radial equilibrium of myxines constrained plasma in Galathea Magnetic confinement device are analyzed and researched on the object Trimyx.

Trimyx Galathea

The Trimyx Galathea contains five components: (1) power supply system, (2) plasma gun, (3) plasma guide, (4) lock chamber, (5) Trimyx trap system. The block diagram of Trimyx device is shown in figure 2.

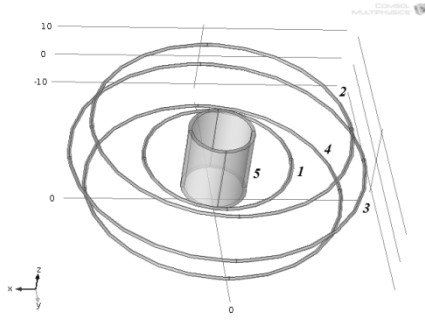


Figure 3. Structure of Trimyx trap

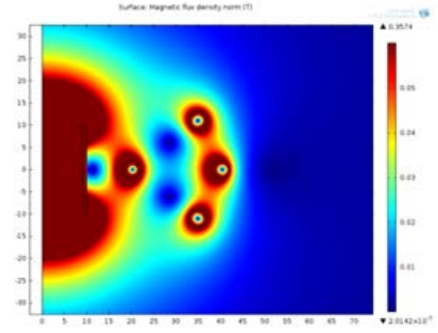


Figure 4. Magnetic configuration of Trimyx

Magnetic trap is the core component of magnetic confinement device. Figure 3 shows the structure of magnetic coils: all 5 coils are coaxial, the one closest to axis is solenoid 5, which serves to compensate effect of toroidal coil by producing vertical magnetic field; farther in the radial direction, inner myxine 1 and outer myxines 2 and 4 are located; between 2 and 4, repulsor coil 3 is placed, which serves to reduce the electrodynamic interaction between them.

Generally, the magnetic confinement devices are toroidal topology because the old devices may exist ends escape problems. For the device which produces axisymmetric magnetic configuration, the general research method is to simplify the toroidal system as a linear system, the toroidal effect can be compensated by vertical magnetic field. Figure 4 shows the two-dimensional axisymmetric magnetic configuration of Trimyx trap by simulation.

The magnetic trap is filled by hydrogen plasma generated by plasma gun. The process of hydrogen plasma bunch moves from source to trap is: (1) plasma form an energetic bunch in plasma guide, (2) plasma goes through front barrier magnetic field and blocked by rear barrier magnetic field, (3) plasma fills in the trap of the order of $50\mu\text{s}$, (4) plasma bunch energy decreases with the spreading to barrier magnetic. To be noted that the particle losses caused by contacting with holders (including the stainless-steel and myxines) is also an important factor to result in energy loss.

Toroidal force equilibrium of myxines constrained plasma

The general method to research force equilibrium of magnetic confinement device in toroidal topology is to distinguish radial force and toroidal force. When radial force is researched, the device can be simplified as linear topology, and toroidal effect is ignored. The toroidal effect can be compensated by vertical magnetic field.

Myxines constrained plasma model

Coordinate (r, θ, ζ) is introduced based on cylindrical coordinate (R, φ, Z) to describe the forces in toroidal topology. The new coordinate is shown in figure 5.

For calculating simplicity, we assume that the plasma currents flow in the infinitely thin surface layer and simplify the poloidal field generated by myxine coil or repulsor coil as $B_\theta \approx B_\theta(r) \frac{R_0}{R}$, R_0 is the center of myxine coil or repulsor coil. A simplified model of toroidal force balance can be obtained.

$$\begin{cases} p = p(r) \\ \mathbf{B} = \frac{R_0}{R} B_\theta(r) \hat{e}_\theta + B_V \hat{e}_z \end{cases}$$

For toroidal force balance, should satisfy: $\int \hat{e}_R \cdot [\mathbf{J} \times \mathbf{B} - \nabla p] \cdot d\mathbf{r} = 0$, that is:

$$\hat{e}_R \cdot \mathbf{J} \times \mathbf{B} = \cos\theta \cdot \frac{R_0}{R} \frac{B_\theta}{\mu_0 r} \frac{\partial}{\partial r} \left(\frac{R_0}{R} r B_\theta \right) + \frac{B_V}{\mu_0 r} \frac{\partial}{\partial r} \left(\frac{R_0}{R} r B_\theta \right)$$

The first term right side of the equal sign is hoop force F_H , the second term is compensatory force

F_v . When solving the plasma tire force, we should take the myxine into consideration. Assume that the plasma pressure distribution around a myxine is shown in figure 6.

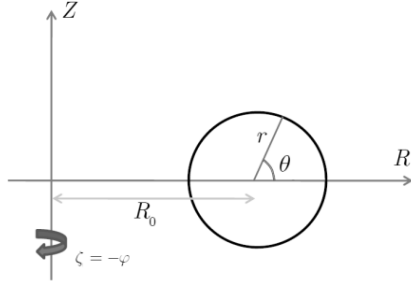


Figure 5. (r, θ, ζ) coordinate

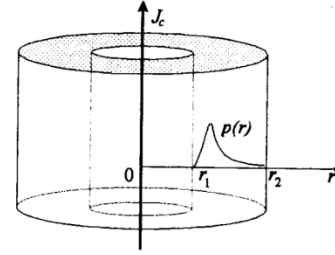


Figure 6. Pressure distribution near a myxine

Hoop force calculation

Tire force F_T

Expression of tire force F_T generated by thermodynamic pressure is:

$$F_T = -\int (\hat{e}_R \cdot \nabla p) d\vec{r} = -2\pi^2 \int_{r_1}^{r_2} r^2 \frac{\partial p}{\partial r} dr = 2\pi^2 (r_2^2 - r_1^2) \langle p \rangle$$

Hoop force F_H

Expression of hoop force F_H generated by poloidal field B_θ is:

$$F_L = -\frac{2\pi R_0}{\mu_0} \int B_\theta \frac{\partial}{\partial r} \left(\frac{R_0}{R} r B_\theta \right) \cos \theta dr d\theta$$

To calculate hoop force F_H , we introduce self-inductance of micro-circuit related to plasma current. We distinguish the plasma inner inductance and external inductance in vacuum by subscript i, e .

$$\frac{1}{2} L_i I^2 = 4\pi^2 R_0 \int_{r_1}^{r_2} r \frac{B_\theta^2}{2\mu_0} d\vec{r}$$

$$\frac{1}{2} L_e I^2 = 4\pi^2 R_0 \int_{r_2}^{\infty} r \frac{B_\theta^2}{2\mu_0} d\vec{r}$$

Define l as self-inductance normalized in unit length:

$$l \equiv \frac{L/2\pi R_0}{\mu_0/4\pi} = 2L/\mu_0 R_0$$

By calculating, we obtain:

$$F_H = 2\pi^2 (r_2^2 - r_1^2) (l_i + l_e + 2) \frac{B_{\theta R}^2}{2\mu_0}$$

The actual value of normalized inner inductance l_i is related to the plasma current density distribution. From many plasma experiments we get the typical value $l_i \leq \frac{1}{2}$; the value of normalized external inductance l_e in vacuum can be obtained by classical magnetostatics calculation, we let

$$l_e = 2 \ln \left(\frac{8R_0}{r_2} \right) - 4.$$

Vertical magnetic force F_v

The expression of vertical magnetic force F_v is:

$$F_v = -\frac{2\pi R_0 B_v}{\mu_0} \int R \frac{\partial}{\partial r} \left(\frac{r B_\theta}{R} \right) dr d\theta$$

Assume that $r/R_0 \ll 1$, let $\frac{1}{R} \approx \frac{1}{R_0} \left(1 - \frac{r}{R_0} \cos \theta \right)$, we obtain:

$$F_V = -2\pi^2 (r_2^2 - r_1^2) \left(\frac{2R_0 B_V B_{\theta R}}{r_2 \mu_0} \right)$$

So, the vertical magnetic field used to balance the toroidal force is:

$$\frac{B_V}{B_{\theta R}} = \frac{1}{4} \frac{r_2}{R_0} \left[\frac{\langle p \rangle}{B_{\theta R}^2 / 2\mu_0} + l_i + l_e + 2 \right]$$

The vertical magnetic field that myxines and repulsors need are calculated, the results are compared with the magnetic generated by solenoid which flows currents 150A, 200A, 350A, respectively. The comparison can be seen in figure 7.

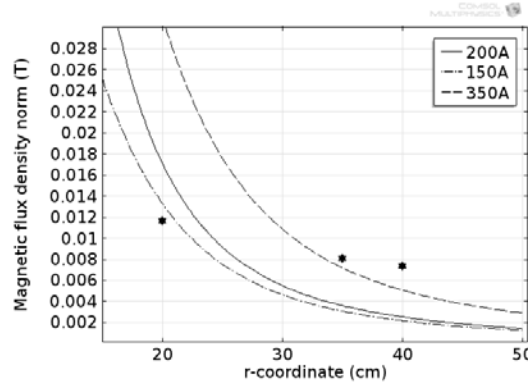


Figure 7. Magnetic flux density produced by the solenoid

Simulation analysis of hoop force balance

MHD plasma model is built in finite element simulation software COMSOL, the hoop force balance in magnetic trap is simulated.

Figure 8 shows the plasma equilibrium when the solenoid current 0A, 200A, 150A. We can see: the compensating effect will be better when the solenoid current is 200A.

Furthermore, we established MHD finite element model for Trimyx trap. Figure 9 shows the plasma pressure distribution when the solenoid current is 0A, 200A and when the trap is in an ideal magnetic configuration. The confinement has reached microseconds.

Modeling and analyzing for plasma confined by linear myxine.

Solution of steady state model

Assume that plasma in steady equilibrium, satisfying $\frac{\partial}{\partial t}(\cdot) = 0$ and velocity $u = 0$. Then the steady state model is:

$$\begin{cases} \frac{d\rho}{dr} + jB = 0 \\ vj^2 - Q = 0 \\ \frac{d}{dr}(vj) = 0 \\ \frac{\partial(rB)}{r\partial r} = j \end{cases}$$

By above boundary conditions and initial conditions, we can solve the analytical solutions:

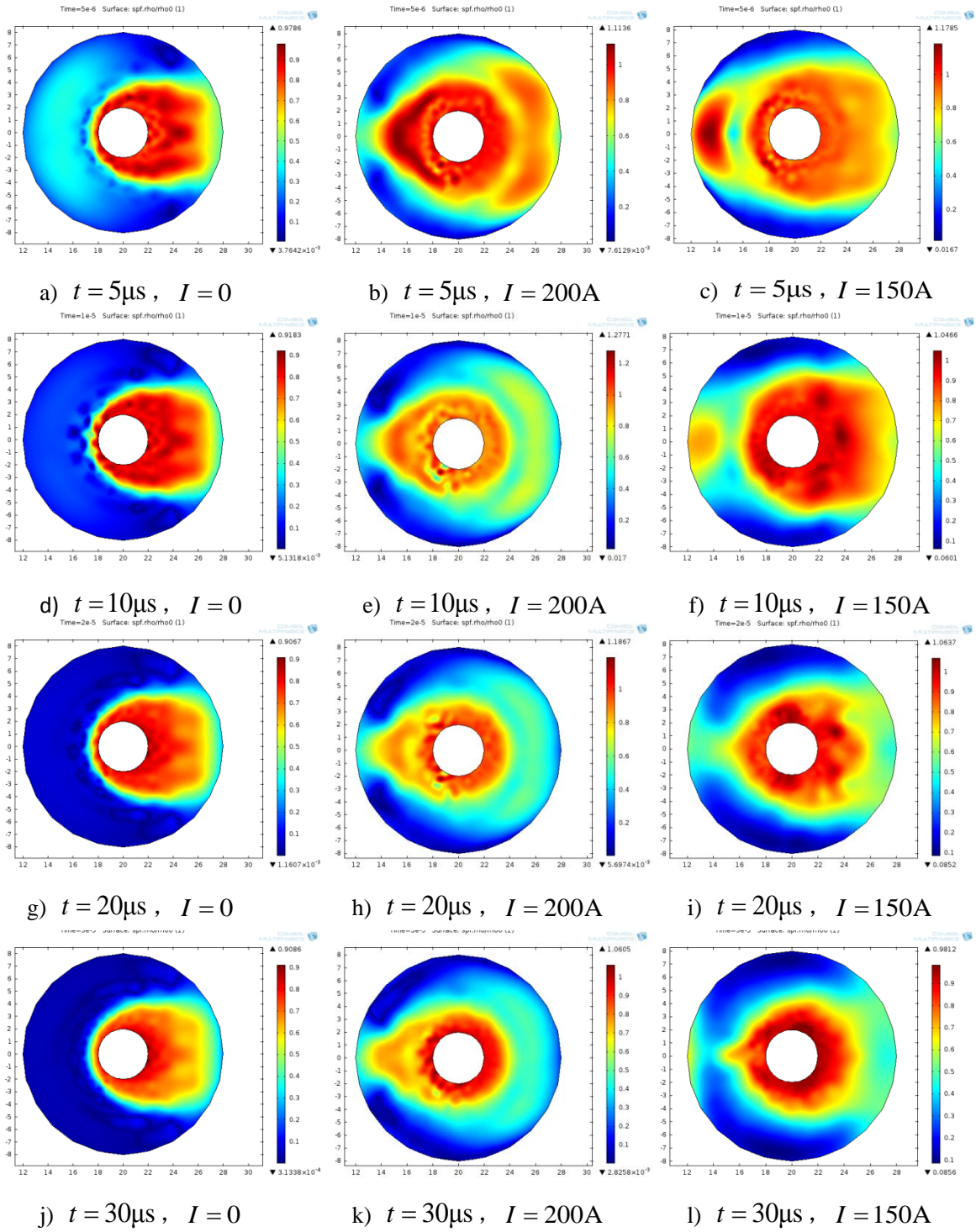


Figure 8. Normalized density of plasma trapped by inner myxine

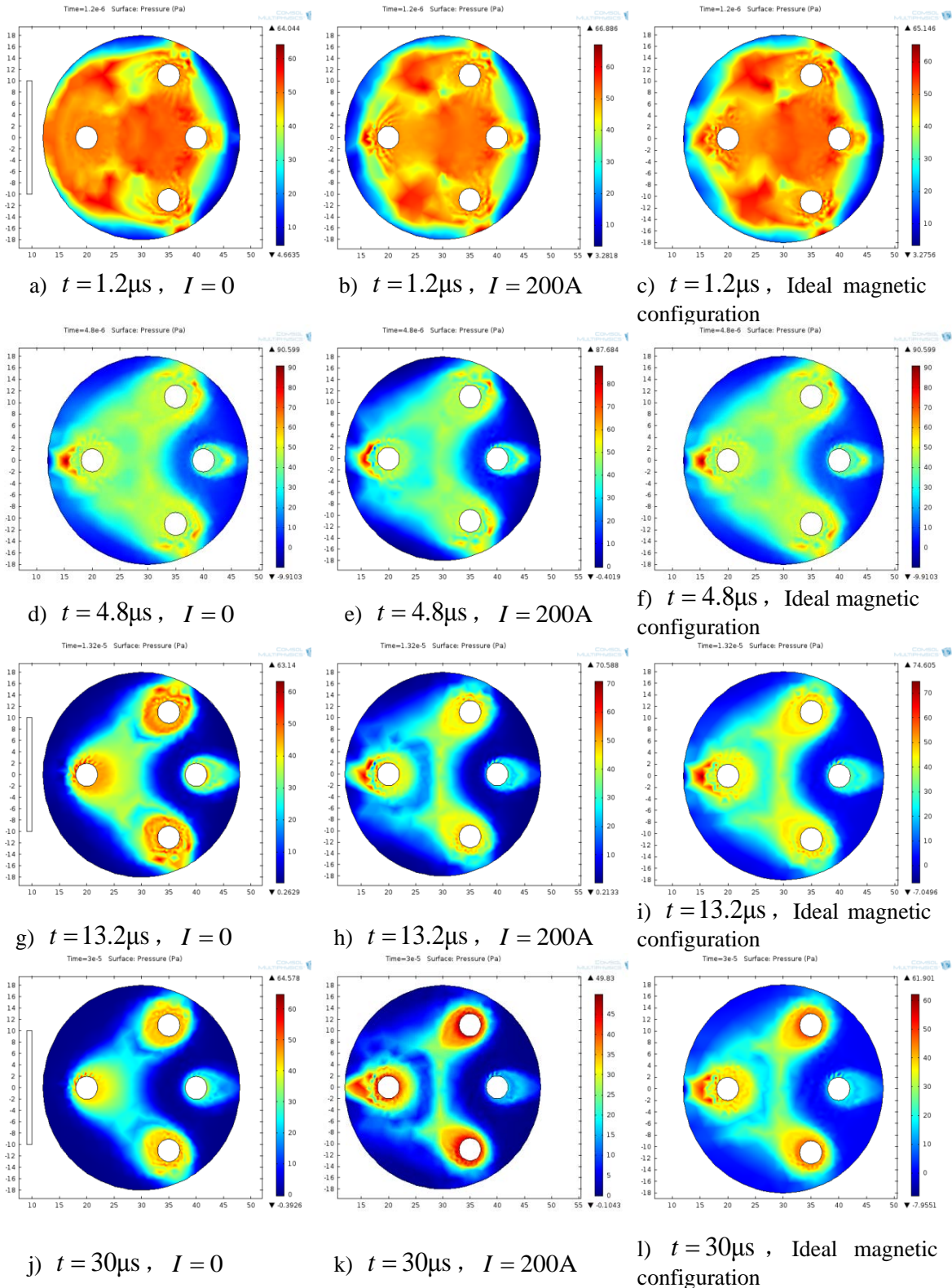


Figure 9. Pressure distribution in Trimyx

Quasi-steady state equilibrium separation model

The comparison of normalized plasma distribution obtained by simulative method and analytical method is shown in figure 10. To separate myxines from plasma, we need transform the plasma volume force into thrust force on the inner boundary, which can be realized by increasing the current in myxine coil. The exciting current applied in myxine is shown in figure 11.

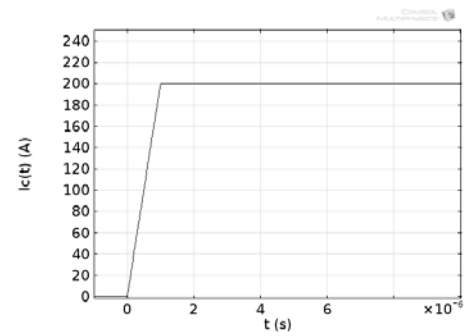
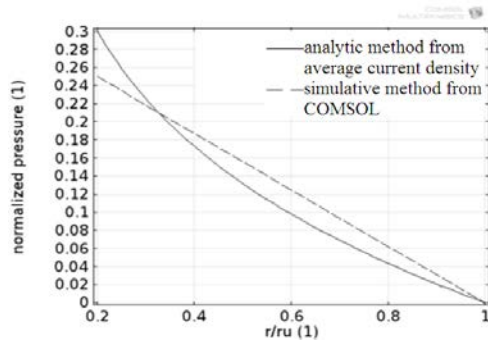


Figure 10. Distribution of normalized plasma pressure

Figure 11. Current density in a myxine

However, the current is transient, will disappear as the magnetic field spreading out. This diffusion process is very slow due to the large fusion plasma conductivity, which is pretty long compare to classical transportation confinement time $\tau_{class} = \frac{\delta^2}{D_{class}} \approx 280\mu s$ obtained in experiment.

The pressure variation of plasma after normalizing in time-varying model is shown in figure 12.

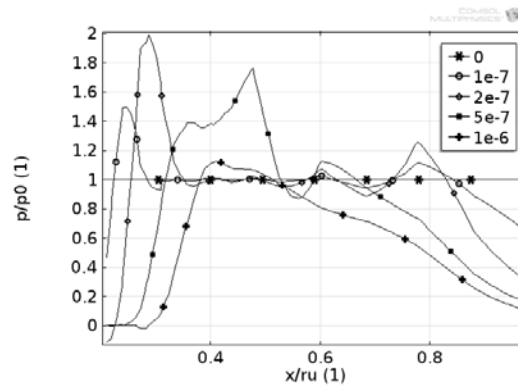


Figure 12. Pressure verse time

Conclusions

This paper introduces a non-tokamak plasma magnetic confinement device. The solenoid makes the device more compact. By simulative and analytical analysis for plasma confined by linear myxine demonstrate that it's inevitable to avoid the contact between plasma and myxines in steady state. A separation method by controlling the myxine coils current is proposed, which confinement time is longer than that confined by Trimyx trap. Further study is adding the thermal field into the finite element model, to get closer analysis to the physical essence.

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