PS03: การศึกษาประสิทธิภาพของเครื่องโทคาแมคขนาดเล็ก ด้วยโปรแกรมแบบจำลองทางคณิตศาสตร์แบบรวม

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บทคัดย่อ

การประยุกต์ใช้งานฟิวชันไฮบริด หรือเครื่องกำเนิดพลังงานนิวเคลียร์ฟิวชันขนาดเล็ก สำหรับ การผลิตเชื้อเพลิงนิวเคลียร์ การจัดการกากกัมมันตรังสีด้วยวิธีแปรธาตุ (transmutation) เครื่องกำเนิดไฮโดรเจนพลังงานสูง และระบบทดสอบสำหรับเทคโนโลยีนิวเคลียร์ฟิวชัน ซึ่งงานนี้ได้ทำการศึกษาถึงประสิทธิภาพของกำลังที่ได้จากเครื่องปฏิกรณ์โทคาแมคขนาดเล็ก ในการศึกษาได้ใช้โปรแกรมจำลองทางคณิตศาสตร์แบบรวมชื่อว่า BALDUR เพื่อทำนายผลประสิทธิภาพของเครื่องโทคาแมคขนาดเล็กที่ถูกออกแบบไว้ โดยใช้โมเดลการรวมกันที่เรียกว่า Bohm/gyroBohm (Mixed B/gB) ซึ่งเป็นโมเดลการทำนายการส่งผ่านที่บริเวณใจกลางพลาสมาในเครื่องโทคาแมค ร่วมกับโมเดลการทำนายผลของอุณหภูมิที่บริเวณเพเดสทอล (pedestal) ของพลาสมา โดยโมเดลการทำนายผลของอุณหภูมิที่บริเวณเพเดสทอล ของพลาสมาอยู่บนพื้นฐานของการปรับระดับความกว้างของเพเดสทอล ด้วยความเสถียรของแรงเฉือนของสนามแม่เหล็กและการไหล (magnetic and flow shear stabilization) $(\Delta \alpha \rho_i s^2)$ สำหรับงานนี้กระแสของพลาสมาและกำลังความร้อนสนับสนุน (Power auxiliary heating) ที่ให้กับพลาสมาจะถูกปรับเปลี่ยนเพื่อทดสอบผลของเป้าหมายด้านประสิทธิภาพ

คำสำคัญ: เครื่องโทคาแมคกำลังต่ำ BALDUR Mixed B/gB

A Study of Performance in Low-Power Tokamak Reactor with Integrated Predictive Modeling Code

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Abstract

A fusion hybrid or a small fusion power output with low power tokamak reactor is presented as another useful application of nuclear fusion. Such tokamak can be used for fuel breeding, high-level waste transmutation, hydrogen production at high temperature, and testing of nuclear fusion technology components. In this work, an investigation of the plasma performance in a small fusion power output design is carried out using the BALDUR predictive integrated modeling code. The simulations of the plasma performance in this design are carried out using the empirical-based Multimode95 (MMM95), whereas the pedestal temperature model is based on magnetic and flow shear stabilization $(\Delta \alpha \rho_i s^2)$ pedestal width scaling. The preliminary results using this core transport model show that the central ion and electron temperatures are rather pessimistic. To improve the performance, the optimization approach are carried out by varying some parameters, such as plasma current and power auxiliary heating, which results in some improvement of plasma performance.

Keywords: Low power tokamak, BALDUR, Multimode95, MMM95

1. Introduction

Fusion is a form of nuclear energy. Its main application is the production of electricity in large base load power plants. The basis nuclear processes involved occur at the opposite end of the spectrum of atomic masses than fission. Specifically, fission involves the splitting of heavy nuclei such as ^{235}U. Fusion involves the merging of light elements, mainly hydrogen (H) and its isotopes deuterium (D) and tritium (T). The fusion of hydrogen is the main reaction that powers the suns. The concept of nuclear fusion has long been explored in many countries. The International Thermonuclear Experimental Reactor (ITER) is an international collaborative effort with the objective of demonstrating the scientific and technological feasibility of nuclear fusion. The goal of ITER is to produce plasmas (a high-temperature collection of independently moving electrons and ions dominated by electromagnetic forces) with a sufficiently high fusion energy density for a long enough time to achieve a sustained fusion burn. There are three main advantages of fusion power: fuel reserves, environmental impact and safety; on the other hand, there are also several disadvantages to fusion that must be considered. These involve scientific challenges, technological challenges and cost of operations. The key issues are as follows. The science of fusion is quite complex. Specifically, to keep D-T fusion going, it is required to heat the fuel to a high temperature of $150\text{x}10^6$ K, hotter than the center of the sun. At this temperature, the fuel is fully ionized and becomes plasma. Once heated, some methods must be devised to hold the plasma together. The primary method requires a configuration of magnetic fields, which confine a sufficient quantity of plasma for a sufficiently long time at a sufficiently high temperature to produce fusion power. These challenges are the key reason that it has taken so long to achieve a net gain of power from fusion reactors. There are also engineering challenges, such as the development of low-activation materials which can withstand the neutron and heat load generated by the fusion plasma. Moreover, large high-field and high-current superconducting magnets need to be developed to confine the plasma. The new technologies to provide heating power have to be developed in order to achieve high temperature required for fusion. The last disadvantage is cost of operations because a fusion reactor is inherently a complex facility, which includes a fuel chamber, a blanket and a complicated set of superconducting magnets. Also, since the structural material becomes activated, a large remote handling system is required for assembly and disassembly during regular maintenance. The use of tritium plus the structural activation mean that radiation protection is also required. These basic technological requirements imply that the capital cost of a fusion reactor will be larger than that of a fossil fuel power plant, and very likely that of a fission power plant. Balancing this are low fuel costs and low costs to protect the environment, both of which tend to reduce the cost of electricity to consumers. [1]

By these constraints, a new approach to fusion power has been developed to demonstrate early power production in a compact reactor with low first wall load [2]. However, the use of the small fusion power output of the pilot plant has to be optimized either by energy multiplication methods (fuel breeding) or in applications such as high level waste transmutation, hydrogen production at high temperature and testing of fusion nuclear technology components. A low aspect ratio tokamak with increased toroidal field seems to be the ideal candidate for these applications. In [3], G.O.Ludwig has used the concept of figure of merit parameter to analyze the performance of low-power tokamak reactors in a simple way. The figure of merit allows to search for sets of machine parameters that satisfy the performance goal, and to classify tokamak performances.

In this analyze, the main parameters of possible low-power tokamak reactors are explored with the concept of a figure of merit. Simulations are carried out using the 1.5D BALDUR predictive integrated modeling code to simulate the tokamak performance in this design. Our simulation is carried out using the theoretical-based Multimode (MMM95) model.

2. A figure of merit

It defines the performance of tokamak reactor by considering the fusion power from energy balance. This concept is based on a simple global model with the conduction and convection losses modeled by empirical scaling laws. The plasma model includes geometrical aspects, profiles and impurities effects, neoclassical effects, and stability constraints. Stability issues related to the toroidal beta limit, safety factor and density limit are taken into account. Then, a convenient normalization of the plasma temperature and density, and of the auxiliary power, is introduced, which leads to the definition of a figure of merit parameter. In G.O. Ludwig's paper [3] , the first starts to define the physical geometries of plasma inside the tokamak reactor and the radial profiles of the particle density, temperature and current density that are given by the usual binomial expressions. By definition of figure of merit, next he defines the global power balance is described by the equation 1.

$$\frac{\partial W}{\partial t} = -\frac{W}{\tau_E} + P \tag{1}$$

where, $W = 4.81 \times 10^4 \langle n \rangle \langle T \rangle V_p$ is the thermal plasma energy, $\langle n \rangle$ particle density average, $\langle T \rangle$ temperature average, V_p plasma volume and the convection and conduction power losses $P_c = W / \tau_E$ are given in terms of the energy confinement time τ_E , so the net heating power in this equation is showed in equation 2.

$$P = P_\alpha + P_\Omega + P_{aux} - P_r \tag{2}$$

where P_α , P_Ω and P_{aux} are the alpha, ohmic and auxiliary input power, respectively and P_r is the radiation power loss. The auxiliary power distribution depends on the type of heating power source after that normalized power balance equation by using the two reference points. The first is a reference temperature point $\langle T_0 \rangle$, which is independent of the density and corresponds to the threshold between alpha heating and radiation cooling, is defined by the solution of equation 3.

$$P_\alpha\left(\langle n \rangle, \langle T_0 \rangle\right) = P_r\left(\langle n \rangle, \langle T_0 \rangle\right) \tag{3}$$

At this point, a D-T plasma is heated to thermonuclear conditions the alpha particle heating provides and increasing fraction of the total heating. When adequate confinement conditions are provided, appoint is reached where the plasma temperature can be maintained against the energy losses solely by alpha particle heating. The applied heating can then be removed and the plasma temperature is sustained by internal heating. By analogy with the burning of fossil fuels the event is called ignition. The second is a reference density point $\langle n_0 \rangle$, which is corresponding to the density limit. At this point, the minimum power that sustained the plasma phase is ohmic heating which come from the torodial current. It is necessary for equilibrium in a tokamak is also a source of plasma heating through the resistance to the current caused by electron-ion collisions. At low temperature this ohmic heating is very strong because the resistance of the plasma varies with temperature as $T_e^{-3/2}$ [4], it is less effective at high temperatures. Thus, it is defined by the solution of the Eq. 4

$$P_r\left(\langle n_0 \rangle, \langle T_0 \rangle\right) = P_\Omega\left(\langle T_0 \rangle\right) \tag{4}$$

Finally, a dimensionless figure of merit, which is independent of P_{aux} is defined in equation 5.

$$X = \left(\frac{P_r}{P_c}\right)\left(\frac{P_r}{P}\right)^{\gamma P} \tag{5}$$

where, γP is the exponent of the net heating power in the scaling law (ITER IPB98(y,2)), P_r is the radiation power loss and P_c is the net power.

Therefore, a figure of merit can be described by equation 5 and started from chosen value of *X*. It is possible to search for sets of machine parameters that satisfy the performance goal. Consideration at low-power tokamak reactors with a figure of merit $X = 0.6$ producing 25 MW of fusion power, 500 kW/m^2 of wall loading on a close wall and operating along the Cordey pass; moreover, another assumption is the IPB98 scaling law. The estimation of the success in approaching reactor condition is given by ratio Q (Fusion Q) equal to 1.24. Hence, lists of possible set machine parameters that satisfy the requirements are shown in Table 1.

Table 1: Main parameter of possible low-power tokamak reactors

Parameter (unit)	Value	Description
R (m)	1.89	Major radius
a (m)	0.94	Minor radius
B_0 (T)	3.6	Magnetic field
I_p (MA)	10.0	Plasma current
q^*	2.01	Safety factor
T (keV)	5.89	Temperature
n_{20} (10^{20}m^{-3})	1.33	Particle density
κ	2.0	Elongation
δ	0.4	Triangularity

3. Simulation result and discussion

BALDUR code has been developed to carry out simulations in order to predict the time evolution to the tokamak plasma current, temperature and density profiles. One objective of these simulations is to develop a better understanding of the physical processes and the inter-relationships between experiments [5]. In this work, the BALDUR code is used to compute the fusion performance by a figure of merit concept and the Multimode core transport models (MMM95) [6]. All input parameters for simulations are included in Table 1. In one set of simulations, the plasma density are slowly ramped up in the first 100 sec. After it reaches the targeted value, the plasma density is maintained at that value during the simulation period; see Figure1. The plasma current during the start-up phase is initially 5.0 MA and it is maintained at this value during the simulation period. The auxiliary heating power is chosen as 10, 20, 30 and 40 MW. This constitutes one set of simulations that we also perform two other set of simulations with the plasma current changed to 10.0 MA and 15.0 MA respectively, with other parameters held as described above.

The assumptions of all simulation are the electron and ion pedestal temperatures have the same values, the sawtooth crashes trigger is the Porcelli sawtooth model and the Kadomtsev magnetic reconnection model is used to compute the effects of each sawtooth crash; moreover, the 10 % of magnetic flux is mixed to describe the effect of sawtooth crash. The fusion performance can be evaluated in term of the *FusionQ*, which can calculate as the equation 6.

$$FusionQ = \frac{5 \times P_{\alpha,avg}}{P_{aux}} \tag{6}$$

where $P_{\alpha,avg}$ is a time average of the alpha power and P_{aux} is the auxiliary heating power (10,20,30 and 40 MW).

It is found that the plasma makes a transition to the *H*-mode phase at 1.08 sec with pedestal temperature T_{ped} = 0.86 keV, 1.96 sec with T_{ped} = 3.11 keV, and 1.01 sec with T_{ped} = 10.37 keV for plasma current equal 5.0 MA, 10.0MA and 15.0 MA, respectively. The results are depicted in figure 2 are the time dependence of the alpha power deposition. It can be seen that the alpha power from the simulations with high auxiliary heating power is much higher than those with the low auxiliary heating power auxiliary when compare with the same plasma current. The average of alpha power during the time between 250 sec and 300 sec is summarized in Table 2.

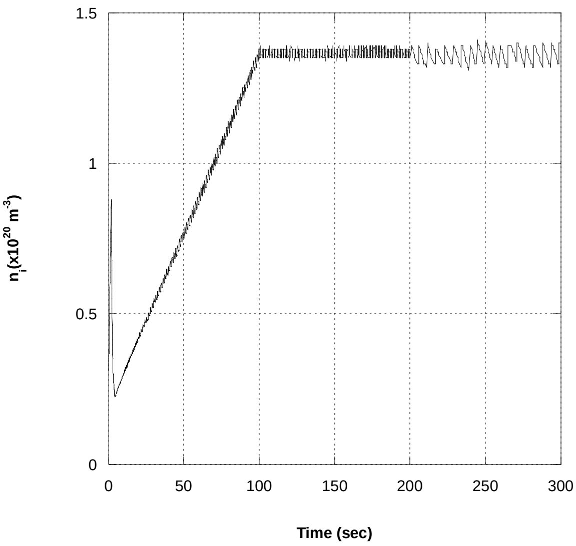
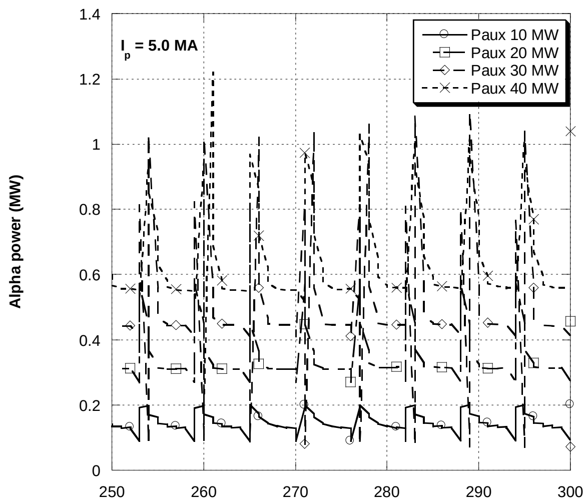


Figure 1: The time evolution of line average density

Table 2: Summary of average of alpha power and Fusion Q during the last 50 sec of the simulation with MMM95 transport model

Plasma Current	P_{aux} (MW)	$P_{\alpha,avg}$ (MW)	*Fusion Q*
5 MA	10	0.15	0.07
	20	0.35	0.09
	30	0.51	0.08
	40	0.66	0.08
10 MA	10	1.63	0.82
	20	2.20	0.55
	30	2.53	0.42
	40	3.01	0.38
15 MA	10	8.77	4.38
	20	9.80	4.90
	30	10.02	5.11
	40	10.08	5.41

It can be seen in Table 2 that the fusion Q increases significantly when the plasma current is changed, thus it seems possible to reach the Q target, which is 1.24 by increase the plasma current in range between 10-15 MA.



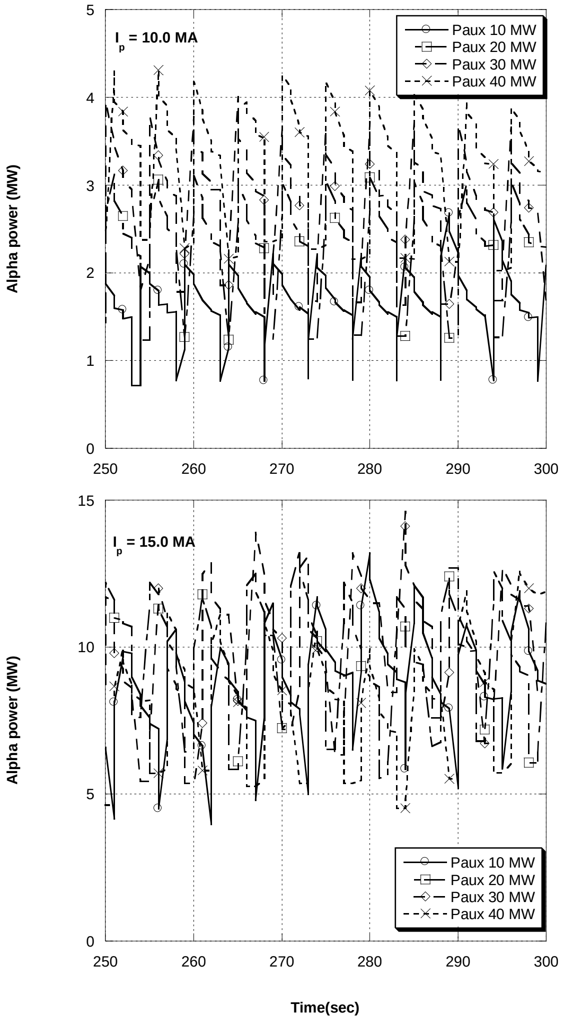


Figure 2: The alpha power production is plotted as a function of time for MMM95 transport model with plasma current 5.0 MA (top), 10.0 MA (middle) and 15.0 MA (bottom)

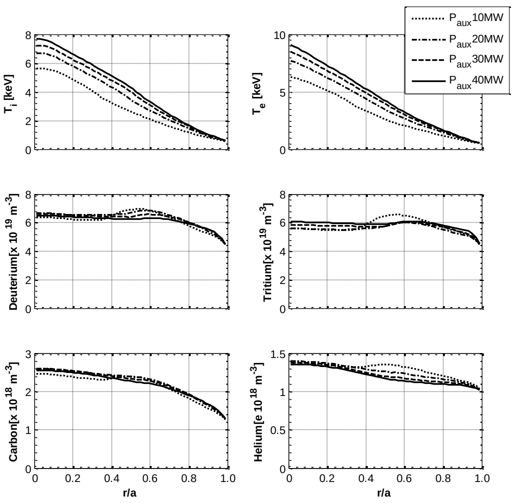


Figure 3: The profiles as a function of normalized minor radius with plasma current 5.0 MA

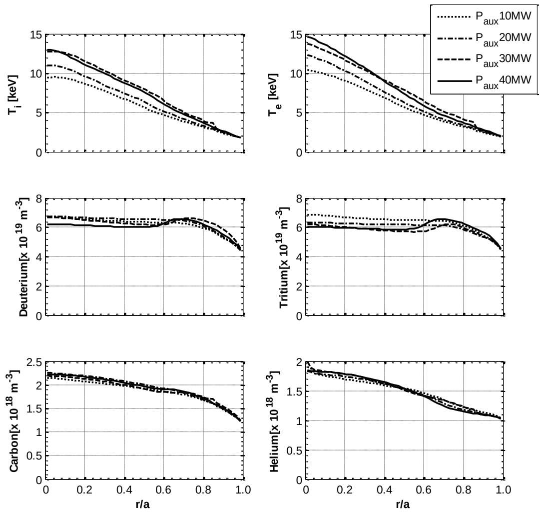


Figure 4: The profiles as a function of normalized minor radius with plasma current 10.0 MA

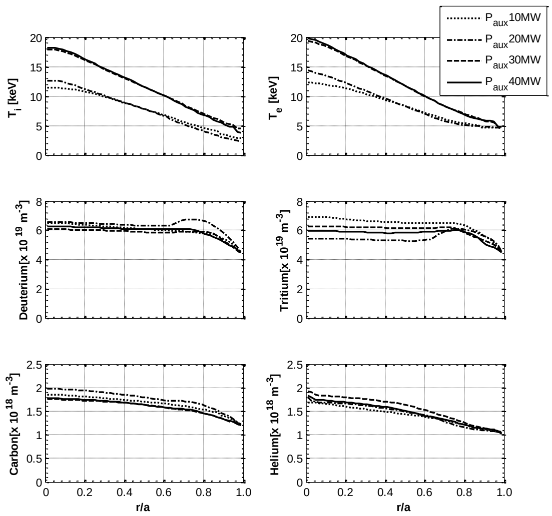


Figure 5: The profiles as a function of normalized minor radius with plasma current 15.0 MA

Figures 3, 4 and 5 show the profiles for ion temperature, electron temperature, deuterium density, tritium density, carbon density and helium density as function of normalized minor radius at the time before sawtooth crash from simulations using the plasma current 5.0 MA, 10.0 MA and 15.0 MA, respectively. These results show that the central temperature for both ion and electron in all simulations increases significantly as the plasma current is increased. However, the increment of auxiliary power is less influential on ion and electron temperature than the increment of plasma current possibly because the adequate energy from high plasma current has been transferred to ions and electrons already. the temperatures near the plasma edge change slightly as P_{aux} increases. It can be seen in figures 3, 4 and 5 when the plasma current is increased deuterium, tritium carbon and helium densities change slightly.

Figure 6 shows the simulation results which are the time dependence of the total stored energy (WTOT). The power loss is balanced by the externally supplied power plus the alpha power. In this figure, it can be seen that the total stored energy has the same trend as the alpha power.

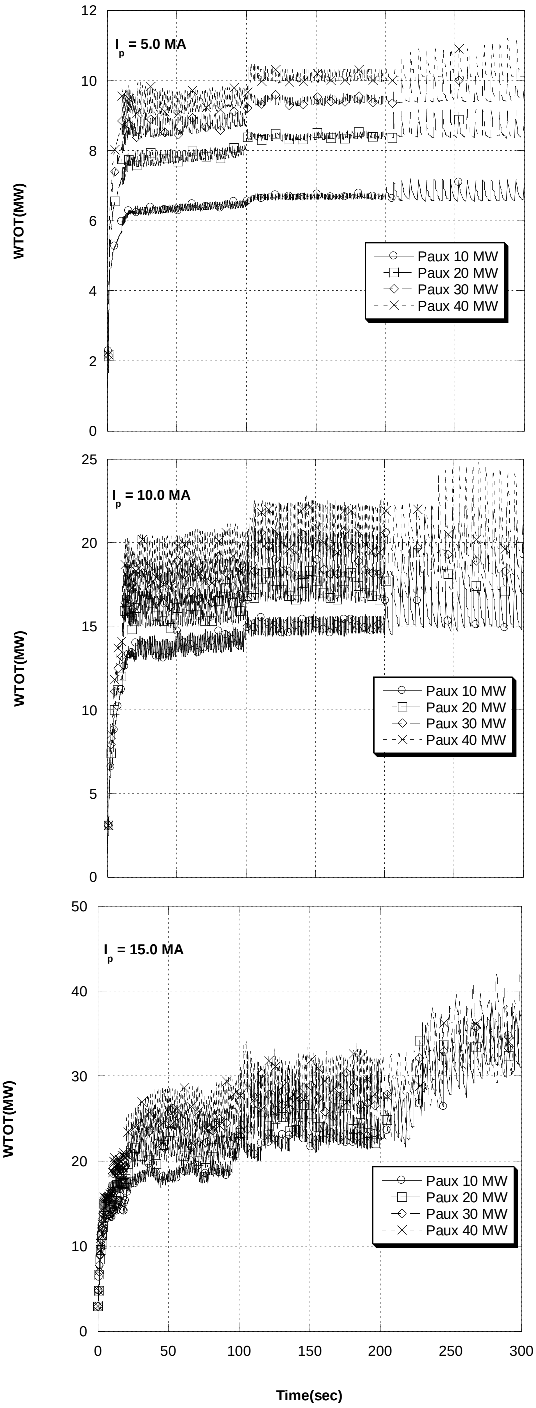


Figure 6: The total stored energy is plotted as a function of time with plasma current 5.0 MA (top), 10.0 MA (middle) and 15.0 MA (bottom)

5. Summary

Fusion Q computation for low power tokamak reactors are carried out using BALDUR code with the transport model MMM95. The results from the model are lower than those predicted by theoretical base model from G.O. Ludwig [3]. The fusion power of 25 MW and the fusion Q target predicted by a figure of merit are reached. In addition, these targets can be reach by increasing the plasma current. The increase of auxiliary power does not significantly affect to the fusion performance.

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