Magnetic Flux Analysis of the EAST Vertical Field

Lu Qu and Ge Li

***Abstract*— The relation between vertical field B_z and normalized plasma density to the current $\overline{n_e}/I_p$ on Experimental Advanced Superconducting Tokamak (EAST) is derived and the quasi-linearity between them is found in the flat-top phase of the elongated plasma current. The poloidal plasma pressure ratio β_p is formulated to be proportional to $n_e T_e$, the product of electron density n_e and temperature T_e. Thus β_p can be enhanced significantly by compressing the plasma to its outboard boundary by inserting a set of vertical field coils in the EAST vacuum chamber for highly shaped plasma, as suggested by Li and Gourdain. The additional vertical field will work under pulse mode in the flat-top phase and produce the horizontal compression field to improve n_e and T_e, and then realize a high β_p on EAST. Poynting's theorem method is used for calculating the flux and evaluating the volt-second consumption in the EAST discharges. The analysis results show that the external flux is basically equal to the surface flux and only less than 10% of the total flux is consumed in resistive dissipation in typical EAST shots.**

***Index Terms*— Experimental Advanced Superconducting Tokamak (EAST), flux, magnetic strength, tokamak, volt-second.**

I. Introduction

EXPERIMENTAL Advanced Superconducting Tokamak (EAST) is one of the national scientific research projects in China. EAST was built to demonstrate high-power, long-pulse plasma operations with major radius $R = 1.85$ m, minor radius $a = 0.45$ m, plasma current $I_p \leq 1$ MA, toroidal field $B_T \leq 3.5$ T, and expected plasma pulse length up to 1000 s. EAST provides a unique platform to address physics and engineering issues for the next-step high-power long-pulse fusion devices such as ITER and beyond [1]–[3].

In order to improve the confinement and the poloidal plasma pressure ratio β_p for advanced tokamak, the control of the current density (or q profile) has been proposed as a method [4]. Gourdain *et al.* [5] used a straightforward definition of high β_p plasmas based on the toroidal current density alone, so that a high β_p can be realized by means of highly shifting the plasma magnetic axis under a possible route manifesting itself as equilibria stability. Li [6] suggests implementing such a route by magnetic compression in EAST. In this paper, the relation between B_z and $\overline{n_e}/I_p$ is derived and verified based on the EAST discharge first, after that this relation is applied to improve n_e, T_e, and then β_p by inserting a set of the fast-control vertical field coils in the vacuum chamber.

The most widely used method to analyze the flux consumption is Poynting's method, which was first used by Ejima *et al.* [7] on D-IIID devices. This method is based on the electromagnetic power conservation of the poloidal field. In this paper, the Poynting's theorem method is used for evaluating the volt-second consumption in the EAST discharge to accurately predict the volt-seconds required for plasma startup and maintenance.

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TABLE I
Plasma Parameters of Flat-Top in EAST

Parameter	#34128	#43336
Plasma current I_p(MA)	1	0.269
Electron density of plasma $n_e(m^{-3})$	1.8×10^{19}	1.2×10^{19}
Electron temperature of plasma T_e(keV)	1.6	2
Power of LHCD P_{LH}(MW)	0.7	1.2

II. Typical Discharges of EAST

The repeatable large current of 1 MA plasma discharge was achieved in EAST 34128 shot as in [8]. In addition, the 411-s long pulse plasma discharge was achieved in EAST 43336 shot as in [9].

The magnetic strength of vertical field and flux analysis of the EAST in this paper will be based on these two typical shots, and their parameters at flat-top are as in Table I.

III. Magnetic Strength Analysis of EAST

A. Derivation of Relation Between B_z and n_e/I_p

The vertical magnetic field required for maintaining the stability of the elongated plasma is derived as [10], [11]

$$B_z = \frac{\mu_0 I_p}{4\pi R}\left[\ln\frac{8R}{a\sqrt{k}} - \frac{3}{2} + \beta_p + \frac{L_i}{2}\right] \tag{1}$$

where, B_z is the magnetic flux density of the vertical field; μ_0 is the vacuum permeability; I_p is the plasma current; R is the major radius; a is the minor radius; k is the elongation; β_p is the poloidal plasma pressure ratio; and L_i is the internal inductance of the plasma.

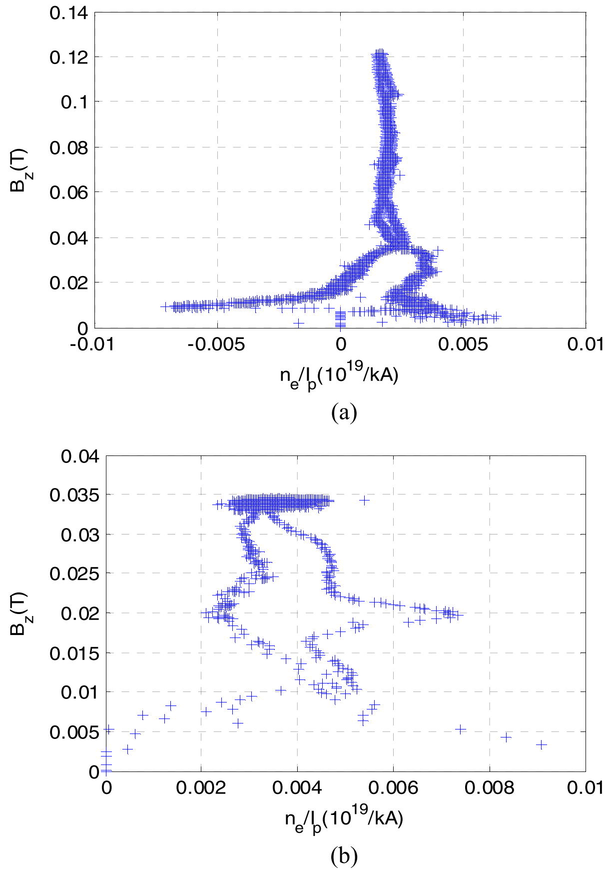


Fig. 1. Relation between B_z and n_e/I. (a) EAST 34128 shot. (b) EAST 43336 shot.

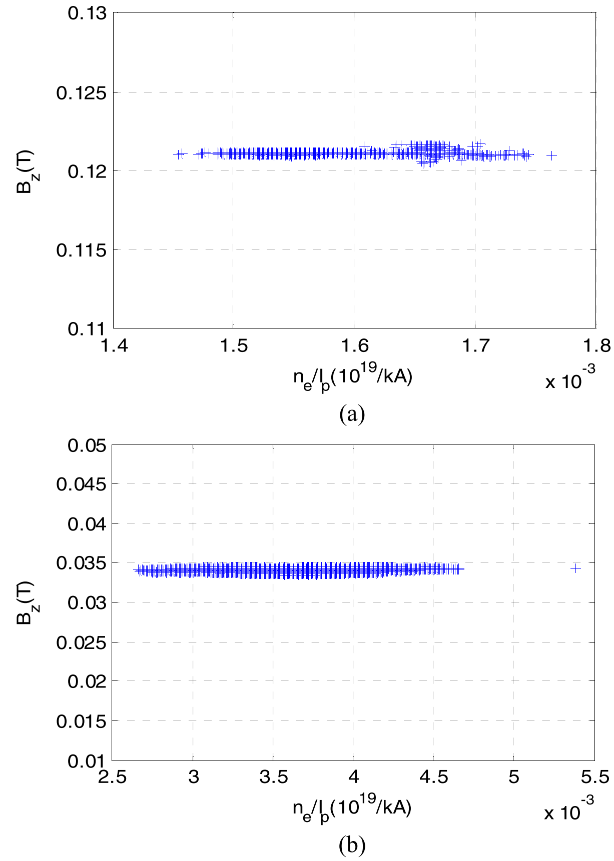


Fig. 2. Relation between B_z and n_e/I_p at flat-top. (a) Flat-top segment of EAST 34128 shot (start point 4.5 s and endpoint 6 s). (b) Flat-top segment of EAST 43336 shot (start point 2 s and endpoint 410 s).

The poloidal beta $\boldsymbol{\beta_p}$ is defined as [11], [13]

$$\beta_p = \frac{4\mu_0}{a^2 B_{\theta a}^2} 2\overline{n_e} K T_e \int_0^a \left(1 - \frac{r^2}{a^2}\right) r dr \tag{2}$$

where, $\overline{\boldsymbol{n_e}}$ is the plasma electron density; K is the Boltzmann constant; T_e is the plasma electron temperature; $B_{\theta a}$ is the magnetic flux density of the vertical field boundary; and a represents the minor radius.

Under the assumption of fixed a, solving the integration, the poloidal beta can be expressed as

$$\beta_p = \frac{2\mu_0 \overline{n_e} K T_e}{B_{\theta a}^2}. \tag{3}$$

In addition, the magnetic flux density of the vertical field boundary can be derived as

$$B_{\theta a}=B_\theta(a, \theta = 0) = \frac{\mu_0 I_p}{2\pi a}\left[1 - \frac{a}{R}\left(\ln \frac{8R}{a\sqrt{k}} - \frac{1}{2}\right)\right]. \tag{4}$$

Substituting (3) and (4) into (1), B_z can be expressed as

$$B_z = a_B + b_B \frac{\overline{n_e}}{I_p} \tag{5}$$

where

$$\begin{cases} a_B = \dfrac{\mu_0 I_p}{4\pi R}\left[\ln \dfrac{8R}{a\sqrt{k}} - \dfrac{3}{2} + \dfrac{L_i}{2}\right] \\ b_B = \dfrac{2\pi a^2 K T_e}{R\left[1 - \frac{a}{R}\left(\ln \frac{8R}{a\sqrt{k}} - \frac{1}{2}\right)\right]^2}. \end{cases} \tag{6}$$

B. Identification of Quasi-Linearity Between B_z and n_e/I_p

The relation between B_z and $\overline{n_e}/I_p$, as shown in Fig. 2 with B_z as vertical axis and $\overline{n_e}/I_p$ as horizontal axis, is identified based on (6). It is clear that B_z changes nonlinearly with $\overline{n_e}/I_p$.

If only the flat-top segment is taken into consideration, then the relation between B_z and n_e/I_p at flat-top are shown as in Fig. 2. It is obvious that B_z is quasi-linear with $\overline{n_e}/I_p$ approximately at flat-top. It can be explained substantially as follows. As parameters of the EAST discharge, when plasma lies at the flat-top, the a, R, k, T_e, I_p, and L_i remain constant substantially. What is more, the intercept b_B is related to a, R, and T_e, and the slope a_B is related to a, R, k, I_p, and L_i. Therefore, both b_B and a_B are nearly fixed at flat-top, as shown in Table II.

In general, the experimental results not only validate the quasi-linear relation between B_z and $\overline{n_e}/I_p$ at flat-top, but also provide the basis for further application.

C. Application of Quasi-Linearity Between B_z and n_e/I_p

Based on the quasi-linear relation between B_z and n_e/I_p at flat-top, a set of the fast-control vertical field coils can be inserted in the EAST. In order to improve the compression sensitivity of the vertical field to the plasma, the required vertical field coils should be as close to the plasma as possible, so they are designed to be placed inside the vacuum chamber.

TABLE II
a_B AND b_B AT FLAT-TOP IN EAST

Parameter	#34128	#43336
a(m)	0.459	0.444
R(m)	1.873	1.856
k	1.885	1.700
I_p(MA)	1	0.270
l_i	1.189	1.219
T_e(keV)	1.6	1.6
b_B	0.812	0.819
a_B	0.121	0.003

TABLE III
SCALING PARAMETERS OF EAST SHOT #34128 AT 5.01 s

Parameter	Before compression	After compression
a(m)	0.461	0.3073
R(m)	1.873	2.0249
$n_e(m^{-3})$	1.8×10^{19}	3.7643×10^{19}
T_e(keV)	1.6	2.6082
I_p(MA)	1	0.925
$B_t(T)$	2.45	5.5125
$B_z(T)$	0.1103	0.1503
β_p	0.097	0.1709

A high field within the plasma pulse could be generated as suggested in [14].

When the plasma lies at flat-top, the vertical field coils work under pulse mode and then the electron density of plasma n_e will increase with the horizontal compression produced by the additional fast-control vertical field B_z.

Because of the temperature and density constraints of collisional plasma compression [6]

$$T_e n_e^{-2/3} = \text{const}. \tag{7}$$

Namely, the electron temperature of plasma T_e is proportional to the electron density of plasma n_e. Hence, the electron temperature of plasma T_e also increases with the horizontal compression produced by the additional fast-control vertical field B_z.

Furthermore, because the poloidal plasma pressure ratio β_p is formulated to be proportional to the product of the electron density n_e and the temperature T_e ($\beta_p \propto n_e T_e$), β_p can be enhanced by compressing the plasma with the additional fast-control vertical field B_z. This is a promising way to realize the high β_p in the EAST.

EAST shot #34128 is taken as an example here to demonstrate the parameters scaling by magnetic compression. For compressed plasma, the minor and major radii are defined as $a_{1,2}$, $R_{1,2}$, respectively. The subscripts 1 and 2 refer to the initial and final states of compression. Thus the scaling ratio is $C_a = (a_1/a_2)$, $C_R = (R_1/R_2)$. If $C_a = 1.5$, $C_R = 0.925$ and the in-vessel vertical field coils work at 5.01 s; the scaling parameters are shown in Table III, which are calculated based on the method given in [6] and [11].

It is clear that the n_e, T_e, and β_p have an increase of 109.12%, 63.01%, and 76.19%, respectively, by magnetic compression under an additional in-vessel vertical field under 0.04 T (=0.1503–0.1103).

In order to compress plasma rapidly in the radial direction and maintain the radial equilibrium of the plasma, besides the in-vessel vertical field coils, the fast-control power supply for the magnetic compression and the control system of radial magnetic compression are also required.

IV. FLUX ANALYSIS OF EAST

A. Flux of the EAST Discharges

Poynting's theorem method is used to evaluate the flux of the EAST discharges in this section. The following equation

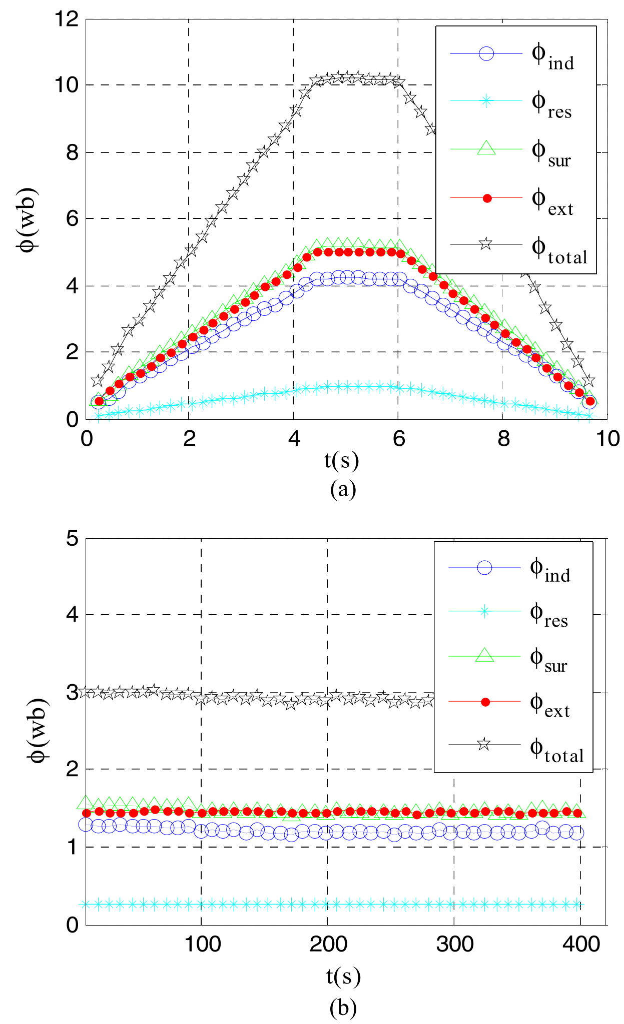


Fig. 3. Flux evolution of the inductive, resistive, and external components. (a) EAST 34128 shot. (b) EAST 43336 shot.

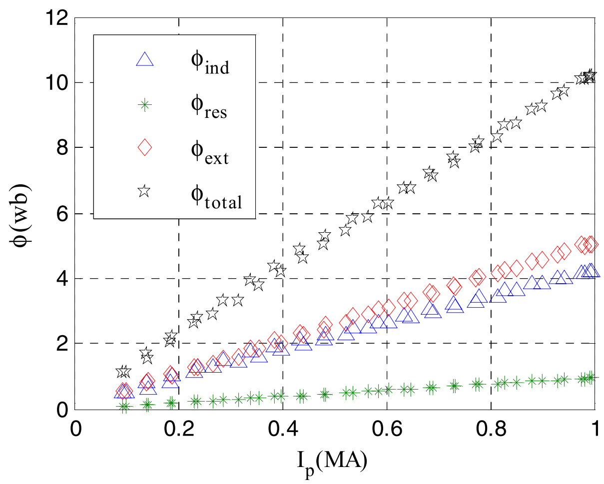
describes the flux balance in the plasma, with the total flux $\Delta\Phi_{\text{total}}$ being the sum of the surface flux $\Delta\Phi_{\text{sur}}$ and the external flux $\Delta\Phi_{\text{ext}}$ [8]

$$\Delta\Phi_{\text{total}} = \Delta\Phi_{\text{sur}} + \Delta\Phi_{\text{ext}}. \tag{8}$$

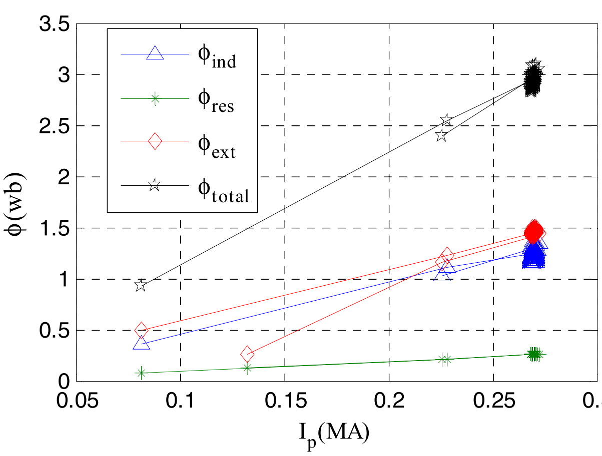
The flux at the plasma surface $\Delta\Phi_{\text{sur}}$ includes the inductive flux $\Delta\Phi_{\text{ind}}$ required to establish the magnetic configuration (inductive volt-seconds) and the resistive flux $\Delta\Phi_{\text{res}}$ necessary to sustain the ohmic dissipation

TABLE IV
FLUX COMPOSITION IN EAST

flux	#34128 shot	#43336 shot
$\Delta\Phi_{ind}(Wb)$	4.20 (41.38%)	1.18 (40.83%)
$\Delta\Phi_{res}(Wb)$	0.95 (9.36%)	0.26 (9.00%)
$\Delta\Phi_{ext}(Wb)$	5.00 (49.26%)	1.45 (50.17%)



(a)



(b)

Fig. 4. Components of the volt-second consumption. (a) EAST 34128 shot. (b) EAST 43336 shot.

(resistive volt-seconds)

$$\Delta\Phi_{\text{sur}} = \Delta\Phi_{\text{ind}} + \Delta\Phi_{\text{res}} = \mu_0 R\left[\ln\frac{8R}{a\sqrt{k}} - 2 + \frac{L_i}{2}\right] I_p + C_E\mu_0 R I_P \quad (9)$$

where $C_E \approx 0.4$ is the empirical Ejima coefficient.

The external flux $\Delta\Phi_{\text{ext}}$ is calculated using

$$\Delta\Phi_{\text{ext}} = L_{\text{ext}} I_p \quad (10)$$

where L_{ext} is the external inductance of the plasma.

Based on the EAST discharge parameters, the evolution of the inductive, resistive, and external components that comprise $\Delta\Phi_{\text{total}}$ is shown in Fig. 3.

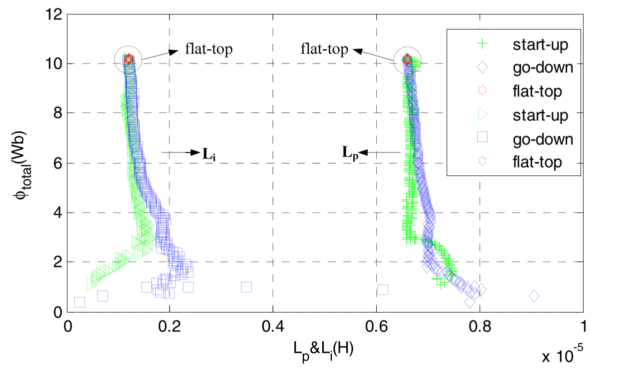


Fig. 5. Time evolution of the total flux state versus the total plasma inductance and its internal inductance.

When the plasma current has reached flat-top, the inductive, resistive, and external flux components remain constant, whose values and percentages are shown in Table IV. It is noted that, the external flux $\Delta\Phi_{\text{ext}}$ keeps the same as the surface flux $\Delta\Phi_{\text{sur}}$ basically, and the inductive flux $\Delta\Phi_{\text{ind}}$ contributes mainly to the surface flux $\Delta\Phi_{\text{sur}}$.

B. Volt-Second Consumption Analysis

Based on (9) and (10), the inductive, resistive, and external flux components increase almost linearly with the plasma current, as shown in Fig. 4.

The total volt-second consumption is

$$\Delta\Phi_{\text{total}}/I_p|_{34128} = 10.07\ \text{V}\cdot\text{s/MA} \quad (11)$$
$$\Delta\Phi_{\text{total}}/I_p|_{43336} = 11.10\ \text{V}\cdot\text{s/MA}. \quad (12)$$

For EAST #34128 shot, the total volt-second consumption is composed of inductive, resistive, and external contributions with about 40.54%, 9.61%, and 49.85%, respectively, while for #43336 shot with about 45.50%, 9.46%, and 45.04%, respectively.

C. Time Evolution of Flux and Plasma Inductance

The mapping of flux state versus internal inductance is very useful for evaluating the capabilities of a poloidal field coil set [15]. In order to analyze the flux in the EAST, the EAST #34128 shot is mapped in Fig. 5 as its time evolution of the flux value versus plasma internal inductance as in [15], and the total plasma inductance developed here.

It is clear that the flux increases and the plasma inductance decreases slightly during startup; both the flux and the plasma inductance remain unchanged basically in flat-top, and then the flux declines and the plasma inductance shows a slight increase.

V. CONCLUSION

In sum, both the magnetic strength B_z and the magnetic flux $\Delta\Phi$ are analyzed in this paper.

1) The quasi-linearity between B_z and $\overline{n_e}/I_p$ is found in the flat-top phase of the elongated plasma current in this paper. A set of the fast-control vertical field coils

can be inserted in the vacuum chamber of the EAST to increase B_z, and then increase the electron density n_e due to the quasi-linearity. Because the poloidal plasma pressure ratio β_p is formulated to be proportional to the product of electron density n_e and temperature T_e, hence β_p can be enhanced by compressing the plasma to its outboard boundary with the vertical field coils in the EAST vacuum chamber. The quasi-linearity between B_z and $\overline{n_e}/I_p$ lays the theoretical foundation for radial compression to transiently achieve a higher β_p in the EAST. An increase in the magnetic strength of the vertical field will, in general, compress and heat plasma, which thus allows high temperature, high density, and high beta to be reached. This is a promising way to realize the high parameters in the EAST.

2) Poynting's theorem method is used to evaluate the total flux in EAST, which is composed of the inductive, resistive, and external components. In both shots #34128 and #43336, the external flux $\Delta\Phi_{\text{ext}}$ is basically equal to the surface flux $\Delta\Phi_{\text{sur}}$; and the surface flux $\Delta\Phi_{\text{sur}}$ is mainly occupied by the inductive flux $\Delta\Phi_{\text{ind}}$. Moreover, the volt-second consumption of EAST is described. The total flux required to bring the plasma current to its flat-top is about $10.07\text{V}\cdot\text{s/MA}$ for the typical large current of 1 MA plasma discharge, and $11.10\text{V}\cdot\text{s/MA}$ for the typical 411-s long pulse plasma discharge. The evolution of the total flux versus the total plasma inductance is given, which reveals the changes in the flux and the inductance of the plasma at different stages. By modifying the plasma inductance, the elongated plasma with high performance could use a similar method to be accounted as that of the circular plasma in J-text [13].

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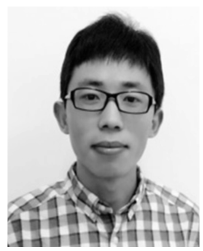

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