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Stellarator Plasma Start-up Model Based on Energy Confinement Time Scaling Laws, Experimental Verification and Numerical Simulation Results

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ABSTRACT

Based on the energy confinement time scaling law of stellarator in the low-confinement mode, combined with energy balance equation and the plasma propagation and power deposition equations of the electron cyclotron wave in the three-dimensional magnetic field, a stellarator plasma start-up model including electron cyclotron resonance heating (ECRH) and impurity radiation power loss is established. Validation against W7-X experimental data demonstrates good agreement in the temporal evolution of electron temperature and radiation losses, which verified that the model can correctly give the plasma start-up results of the stellarator under ECRH. This model is applied to predict the results of plasma start-up under 28 GHz ECRH for China Helical Device 1 (CN-H1) stellarator. The effects of the ion-to-electron temperature ratio (T_i/T_e), ECRH injection power (P_0), deposition position, and impurity concentrations (iron) on start-up are systematically studied and analyzed. Results show that increasing T_i/T_e enhances the flat-top electron temperature, which indicates that the increase of ion temperature will help the electron temperature to reach a higher level. Higher P_0 accelerates electron temperature rise and increases flat-top electron temperature, radiative losses decrease notably when P_0 > 200 kW. When the power is deposited on the low-field side and moves from the far-axis to the on-axis region, the rising rate of the electron temperature and the flat-top electron temperature increase accordingly. In addition, the concentration of iron impurity should be less than 0.8% to ensure the effective starting and heating of the plasma. Under optimal conditions (T_i/T_e = 1, P_0 = 200 kW, central deposition, 0.1% Fe), the ECRH power absorption efficiency is rapidly increased to 94.8%. At a density of 2×10^{18} m^{-3}, the electron temperature can reach 373.3 eV and the impurity line radiation power peak is 1.1 kW.

BACKGROUND

In the electron cyclotron frequency band, the CN-H1 stellarator is planned to use 2.45 GHz microwave and 28 GHz electron cyclotron heating to initiate and maintain the plasma. Liu Yizhuo et al. developed a 0D ECRH start-up model for CN-H1 stellarator based on physical model of tokamak start-up. Their results showed that electron density obtained by start-up can reach the order of 10^{17}-10^{18} m^{-3} by 28 GHz ECRH start-up. However, this model does not consider the effect of the magnetic field configuration of the stellarator and the energy deposition position of the EC wave in the start-up process.

Using the τ_{97L} energy confinement scaling law for tokamaks, Masayuki Ono established a fundamental-mode non-inductive current start-up model for electron cyclotron wave in the spherical tokamak magnetic field configuration. This model was applied to the SHPD Tokamak Facility and the STAR device. In this model, the EC power absorption (P_{ECH}) is calculated using the ray tracing code RT-4. Compared to other start-up models, this model can better consider the influence of magnetic field configuration and EC wave energy deposition position on the starting process.

In tokamaks and spherical tokamaks, closed magnetic flux surfaces are not inherently present during the initial phase of plasma start-up. As the plasma current increases, it generates a poloidal magnetic field that combines with the toroidal magnetic field produced by external coils, gradually forming a helical magnetic structure and eventually closed flux surfaces. However, in the current start-up model established by Masayuki Ono, the default closed flux surfaces have already existed. Hence the geometric parameters such as the major radius, minor radius, and elongation were set to constant values. This assumption does not accurately reflect the physical process of closed flux surface formation during plasma initiation in tokamaks and spherical tokamaks. In contrast, the helical magnetic fields in stellarators are generated entirely by external coils, so that the closed magnetic flux surface has been formed when the device is started. There is no need to rely on the climb of plasma current to establish the closed magnetic flux surface. Therefore, this model is more consistent with the plasma start-up characteristics of the stellarator.

METHODS

Stellarator L-mode scaling law

$$\tau_E^{ISS04} = f_{ren} 0.134 a^{2.28} R^{0.64} P_h^{-0.61} n_e^{0.54} B^{0.84} l_{2/3}^{0.41}$$

Use A and β in place of a and n_e

$$\beta = \frac{2 n_e T}{B^2 / 2\mu}$$

$$T = T_i + T_e, \quad \frac{T_i}{T_e} = \alpha, \quad n_e = n_i$$

$$\tau_E^{ISS04} = f_{ren} 0.063 A^{-2.28} R^{2.92} P_h^{-0.61} \beta^{0.54} T^{-0.54} \mu^{-0.54} B^{1.92} l_{2/3}^{0.41}$$

Energy balance equation:

$$(1+\alpha) \times \frac{3}{2}\frac{d(nT)}{dt} = P_{ECH} - P_{loss} - P_{rad} - P_{line}$$

$$P_{loss} = (1+\alpha) \times \frac{3}{2}\frac{n_e T_e V_\alpha}{\tau_E}$$

$$P_{rad} = 5.35 \times 10^{-3} Z_{eff} n_e^2 \sqrt{T} V_\alpha$$

$$P_{line} = (1+\alpha) \sum_{imp} \int C_{imp}(T_e) n_{imp} n_e dV_\alpha$$

$P_{ECH}(P_{abs})$:

$$\frac{d\tau_\omega}{ds} = \alpha_\omega$$

$$\frac{dP_{abs}}{ds} = P_0 \alpha_\omega e^{-\tau_\omega}$$

$$\frac{\delta P_{abs}}{\delta V} = \sum_{r,i} \omega_r \left|\frac{\delta s_{r,i}}{\delta V}\right| \left(\frac{dP_{abs}}{ds}\right)_{r,i}$$

In our stellarator start-up model, the ray trajectory of the EC wave and the corresponding absorbed power from ECRH are calculated using the equations governing EC wave propagation and power deposition in a three-dimensional magnetic field. The electron temperature T_e and the normalized beta β are then used to compute the plasma energy confinement time. Based on the τ_{04L} energy confinement scaling law and the absorbed power PECH, the updated electron plasma pressure is obtained. Since the plasma density is pre-specified, a new electron temperature can be derived. With this updated temperature, a new ray tracing calculation is performed to obtain updated values of τ_{04L} and P_{ECH}. This iterative process forms a feedback loop, as shown in Figure 1.

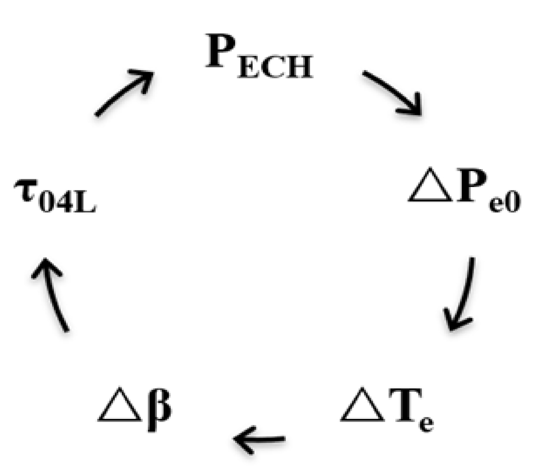

Fig.1 Stellarator plasma start-up model.

Model validation

Validation against W7-X experimental data demonstrates good agreement in the temporal evolution of electron temperature and radiation losses, which verified that the model can correctly give the plasma start-up results of the stellarator under ECRH. Two scenarios were considered, corresponding to injected powers P_0 of 2.7 MW and 5 MW, respectively.

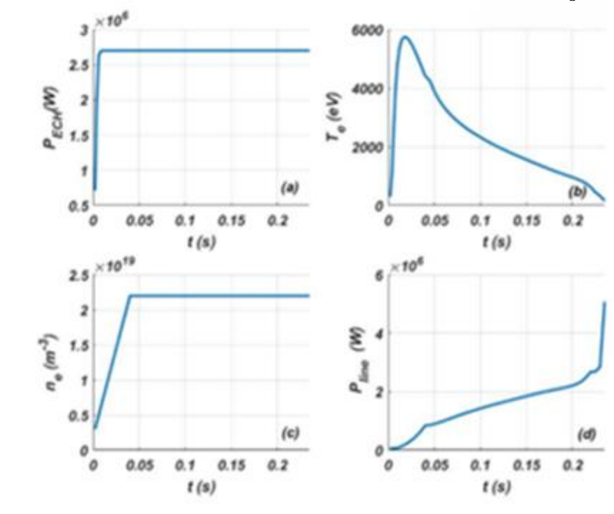

Fig.2 P_0 = 2.7 MW, Temporal evolution of (a) ECRH power absorption, (b) electron density, (c) electron temperature and (d) radiation power with time.

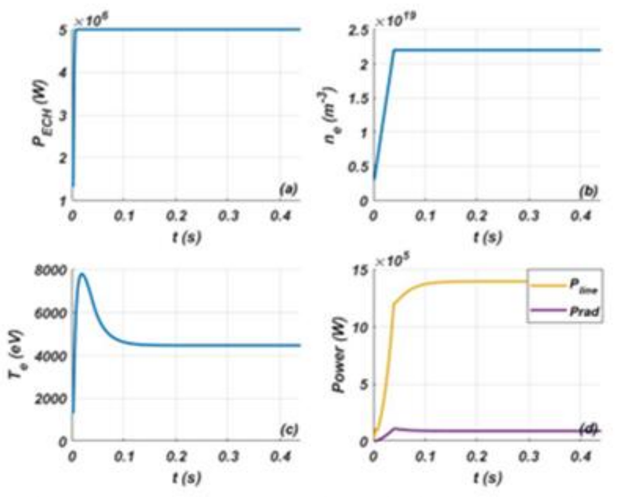

Fig. 3 P_0 = 5 MW, Temporal evolution of (a) ECRH power absorption, (b) electron density, (c) electron temperature and (d) radiation power and diffusive power with time.

OUTCOME

- Effect ion-electron temperature ratio (T_i/T_e) on start-up

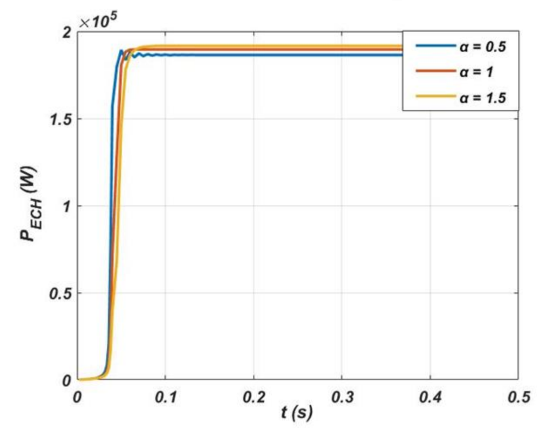

Fig.4 The effect of α on power absorption.

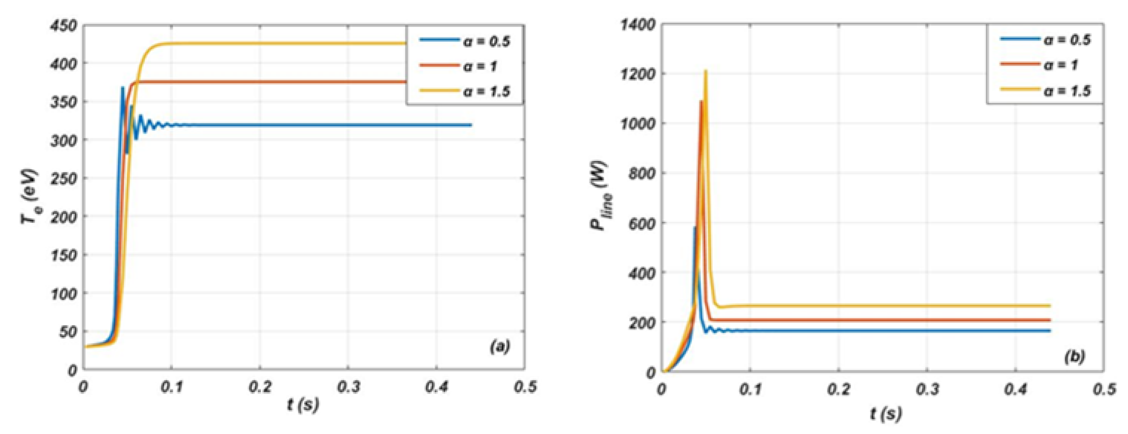

Fig. 5 The effect of α on (a) the electron temperature and (b) the line radiation power.

- Effect of injection power on start-up

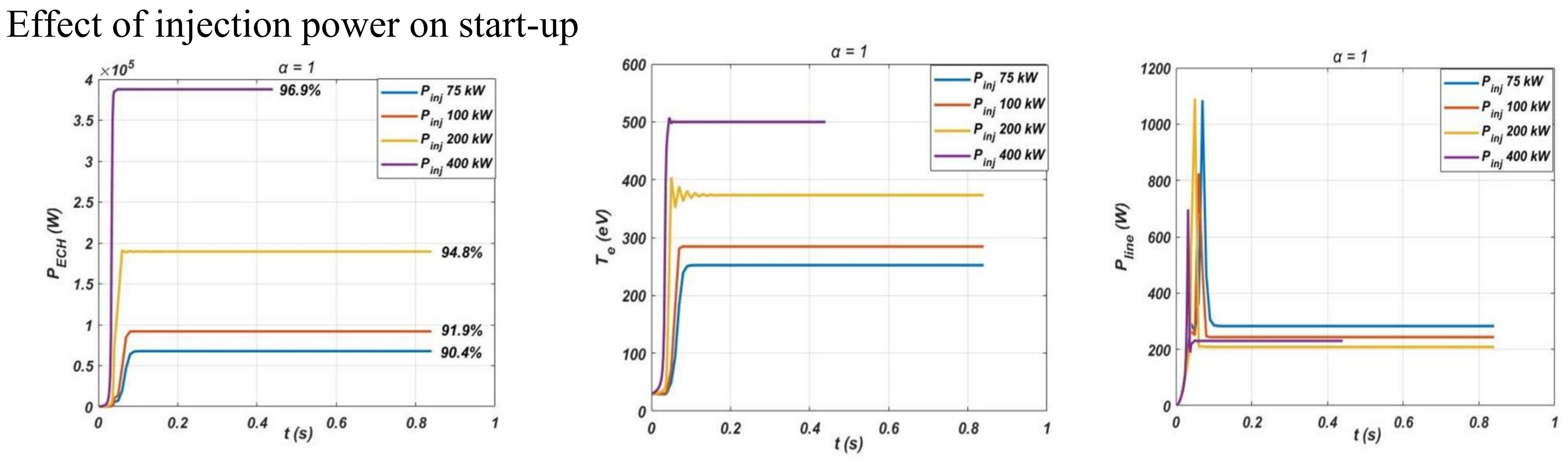

Fig. 6 Effect of injection power on power absorption、 electron temperature and line radiation power.

- Effect of ECRH power deposition position on start-up

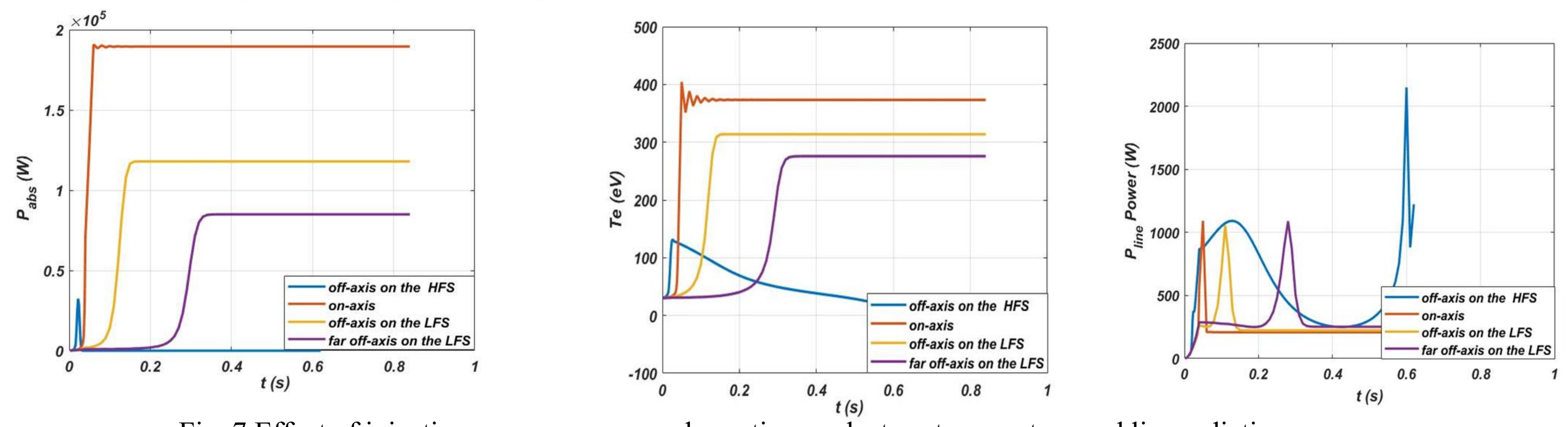

Fig. 7 Effect of injection power on power absorption、 electron temperature and line radiation power.

- Effect of impurity concentration on start-up

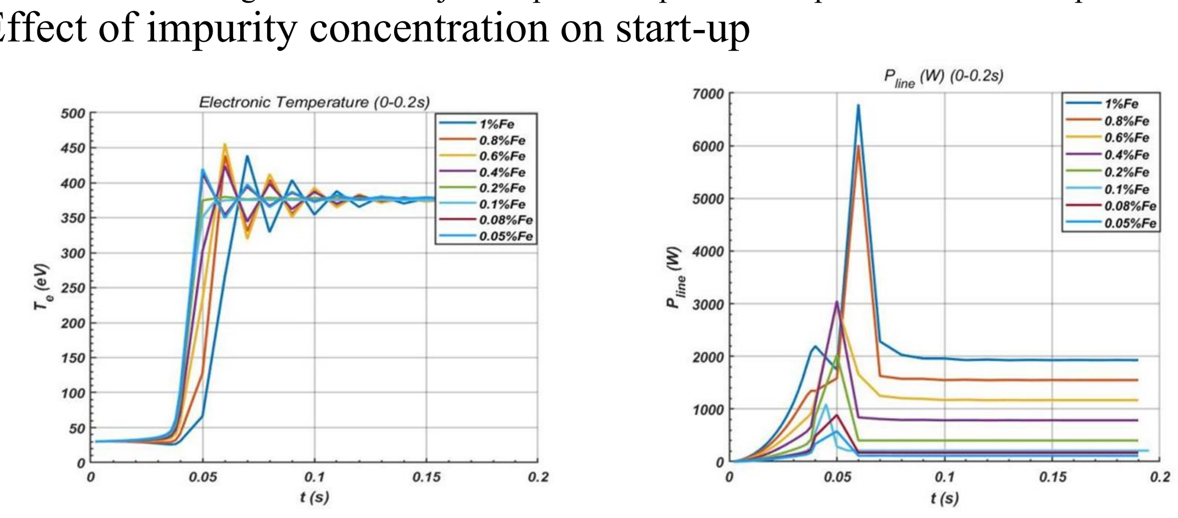

Fig. 8 Effect of injection power on electron temperature and line radiation power.

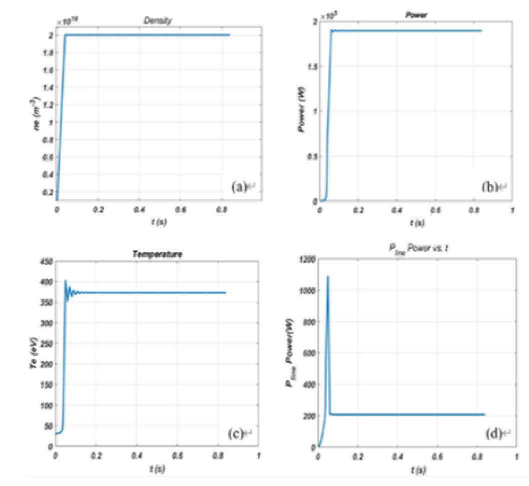

Fig. 9 Start-up results for CN-H1 stellarator predicted by the model under 28 GHz ECRH. (a) Temporal evolution of electron density, (b) ECRH power absorption, (c) electron temperature and (d) impurity line radiation power.

CONCLUSION

The results indicate that with an increasing T_i/T_e ratio, the flattop electron temperature rises significantly, suggesting that elevated ion temperature facilitates the electron temperature in reaching a higher level. As P_0 increases, both the ramp-up rate and the flattop value of the electron temperature increase, and when P_0 exceeds 200 kW, the radiative power loss of the plasma decreases noticeably. When the power deposition is located on the low-field side and shifts from the far-off-axis to the on-axis region, the electron temperature ramp-up rate and its flattop value also increase. Furthermore, the iron impurity concentration should be kept below 0.8% to ensure effective plasma initiation and heating.

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REFERENCES

[1] P HELANDER ET AL 2012 PLASMA PHYS. CONTROL. FUSION 54 124009
[2] A.H. BOOZER 2015 J. PLASMA PHYS. 81 515810606
[3] B. D. BLACKWELL ET AL 2003 AIP CONF. PROC. 669 158
[4] K. NAGASAKI ET AL 2001 J. PHYS. SOC. JPN. 70 617
[5] YIZHUOHANG LIU ET AL 2024 PLASMA SCI. TECHNOL. 26 075101
[6] M. ONO ET AL 2023 AIP CONF. PROC. 2984 110002
[7] M. ONO ET AL 2024 NUCL. FUSION 64 086021
[8] H.P. LAQUA ET AL 2019 EPJ WEB CONF. 203 02002