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Physics of Helical Confinement Systems

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Abstract

Recent stimulating studies that contributed to develop the physics of the helical systems are surveyed. In addition to exploring the advantage of the potential steady state operation, resolutions for the problem, *e.g.*, the trapping of energetic particle, existence of stable high-beta equilibrium, ripple transport, etc., have been investigated. The optimization directions in magnetic structure are (i) the high rotational transform, the high shear and moderate well, and (ii) the reduced secondary current and the magnetic well. Both of them try to utilize the radial electric field for the improvement. Representatives of these two are the LHD and W7-X devices. Further optimizing approaches, like quasi-symmetry, are subject to studies. Experimental observations have been piled up. In this article it is emphasized that, based on these active works on the helical systems, the understanding of the general toroidal plasmas has become deeper, even including the tokamak plasma as a special example. The investigations for developing the helical systems have deepened the understanding of the nature of plasmas, and are some of the most important achievements in the physics of high temperature plasmas.

Keywords:

helical plasma, recent progress, improve confinement regime, density and beta limits, divertor, physics of electric field

1. Development of the Concept

The concept of stellarators has been first invented by Spitzer[1]. In the beginning, the rotational transform, which is the very essential element of the toroidal confinement, was realized by twisting the plasma column like "figure-8". Couples of ideas have emerged for the confining magnetic field, and a class of confinement schemes, which would be called as *helical systems*, has grown up. The inherent problem, which is the cost of the potential steady state sustenance of the confinement, has been known, including the trapping of energetic particle, existence of high-beta equilibrium, stability at finite beta, ripple transport, etc. The concept has been developed aiming to resolve such problems and to form a path to a fusion reactor.

If I dare to simplify the evolution of research, the directions of innovations have been seen in two major groups. (Fig.1) The optimization directions in magnetic structure are

(i) the high rotational transform, the high shear and moderate well,

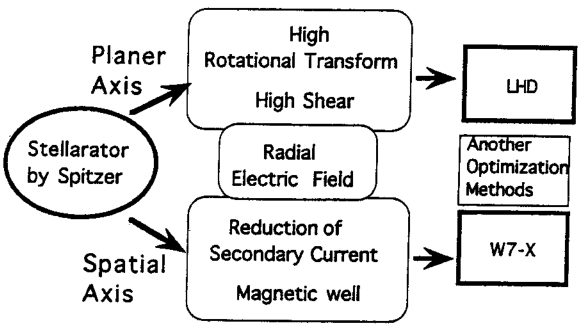

Fig. 1 Two streams of the concept of helical systems and new large scale experiments, LHD and W7-X.

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(ii) the reduced secondary current and the magnetic well.

Both of them try to utilize the radial electric field for the improvement of the performance. Representatives of these two are the LHD and W7-X devices. The experiment on LHD[2] is near at hand. The construction of W7-X[3] has been started. Further optimizing approaches, like quasi-symmetry, are subject to intensive analysis[4]. Experimental observations have been piled up[5-7]. The understanding of the general toroidal plasmas has become deeper, even including the tokamak plasma as a special example. On this occasion, it would be intriguing to survey some of the recent most stimulating studies that contributed to develop the physics of the helical systems.

2. Recent Progresses and Related Physics

2.1 Long-mean-free-path regime

The possible loss of the ripple trapped particle has long been recognized. The remedy was discussed in relation with the radial electric field[8, 9]. Recently, the electron temperature as high as $T_e(0) = 4$ keV (or such as $T_i(0) = 1.6$ keV) was achieved in W7-AS[10]. In CHS, the plasma of the temperature $T_e(0) \sim 2$ keV with the density of a few times 10^{18} m^{-3} is confined, reaching much lower collisionality[11]. The radial electric field develops, together with the increased temperature, and the ripple loss is reduced. The ripple transport could be less harmful in the present experiments than was historically-concerned, if the enough radial electric field develops. Nevertheless, it is still a considerable part of the total plasma loss in these cases, and the tolerance against the ripple loss in future devices strongly depends on how the radial electric field behaves.

2.2 Anomalous transport and empirical scaling law

In present experiments, anomalous transport plays a dominant role. Empirical scaling law has been studied [5, 12] mainly based on Heliotron configurations, and on Wendelstein devices. A common scaling law has been proposed as International stellarator scaling law (ISS95)[13] and is widely used. Comparative study including tokamaks has been progressed[7, 14]. A factor-two improvement over this scaling is the immediate requirement for the future application to reactors.

Detailed study on the anomalous transport has been piled up. Dependence on plasma parameters has been reported[15]. In L-mode, the effective thermal conductivity is enhanced, if the temperature (or its gradient) increased, as has been expected from the empirical scaling. Recently the role of the magnetic shear has been studied on W7-AS in detail[10]. In the case that the rotational transform $1/q$ (q: safety factor) is close (but not identical) to the low-order rational numbers, the low shear is favourable. (At the low-order rational surface, pressure gradient may be suppressed.) In contrast, when $1/q$ is not close to such numbers, then the magnetic shear is effective to reduce the anomalous transport. This sheds a light on the role of the magnetic shear in the low-shear systems. In Heliotron configurations, the magnetic shear and rotational transform vary from Heliotron-E to CHS. However, the magnetic hill, one of the possible origins of anomaly, changes simultaneously. The quantitative identification of the roles of the magnetic shear and rotational transform in Heliotrons requires further investigations. Theories, which are based on the first principle, are still incomplete to give quantitative understanding. The progress has been made for the turbulence in Heliotrons [16, 17]. Systematic test is required.

2.3 Improved confinement

Owing to the intensive study, several types of improved confinement have been identified. As has been discussed, H-mode is studied on W7-AS and CHS routinely[18, 19]. The high-Ti mode was found on Heliotron-E, and was confirmed on CHS[20, 21]. (Fig.2) The high-Ti mode was also found on W7-AS[22], although it may not be identical to those of Heliotron-E or CHS. The most stimulating is the improved confinement in the case of the NBI heating in W7-AS. The energy confinement time of 50 ms was achieved, which

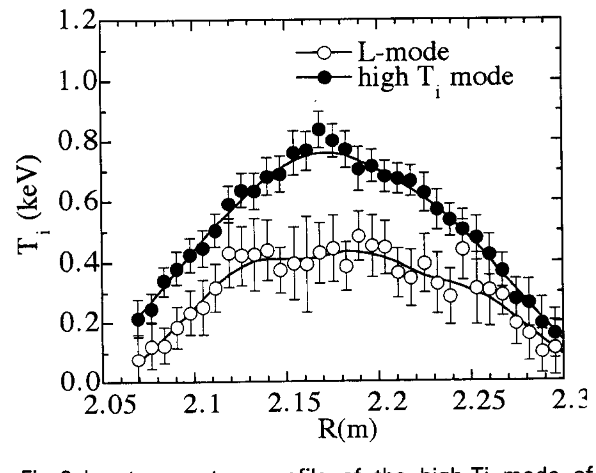

Fig. 2 Ion temperature profile of the high-Ti mode of Heliotron-E.

is twice high in comparison with the scaling law[23]. (Table 1.)

The physics of the high-Ti mode has been discussed. Common feature with the peaked profile in the pellet injection, reheat-mode[24] and high-Ti mode is pointed out[21]. One of the candidates for the origin of the increment of the ion temperature is the enhanced radial electric field. The neutral particles are the obstacle to establish the large radial electric field[9] and the reduction of the neutrals is conjectured to lead to the improvement. In conjunction with it, it should be noticed that the energy confinement is relatively improved in the case of the LID (local island divertor) experiments[25]. τ_E is improved, if normalized to the scaling law, by an amount of 20%.

The absolute value of the improvement of τ_E, at present, is a few tens of percentage in many improved modes, although some parameter is improved considerably. The further study is keenly required.

2.4 Density limit

The limit of density is the key for the reactor concept. This is because the ISS95 scaling-law suggests that the fusion triplet $n\tau_E T$ scales like

$$n\tau_E T \propto [B^{1.86} \iota_{2/3}^{0.8} a^{2.4} R^{0.3}] P^{-0.18} n^{1.02}.$$

For the given device parameters, the attainable fusion triplet is controlled by the achievable density. Attempts to assess the density limit have been given in[5, 12, 14, 24]. The fitting formula for experimental finding was suggested there, but has not been discussed much further. The cause of the density limit has been considered as the radiation instability. Study has been made, and MARFE is observed as one cause of the density limit on W7-AS[26].

2.5 Density profile

The knowledge of the density profile is also important: The peaked profile may be favourable for the better fusion output. At the same time, high edge density may be required for the high performance of the divertor functioning. So far, the high Ti mode correlates with peaked density profile[21], and the improved confinement may require the particular types of the density profile[7, 27]. The over-all request for the density profile of helical systems is not yet conclusive, but one must clarify the rule that determines the density profile.

The density peaking is dependent on the shift of the magnetic axis in CHS[28] (Fig.3). The direction of the 'pinch' changes. The study on the density profile has suggested a possibility that the radial electric field may play a role for the density peaking. Fairly flat density profile was observed on W7-AS. No strong inward pinch was observed[7]. The impact of the magnetic structure and the mechanism of the particle flow are the important future experimental subject.

2.6 Beta limit and MHD activity

The MHD activity associated with the plasma current would be of secondary impact in helical systems;

Table 1 A number of improved confinement modes of helical systems are found as in tokamaks.

Improved Confinement Modes

n_e ($\times 10^{19}$m^{-3})	mode	CHS	H-E	W7-AS
Very low (<2)	High T_e	2keV		4keV
low (~2.5)	high T_i mode	$T_i^{CXS}(0)$ = 0.7keV	$T_i^{NPA}(0) = 1.1$ keV $\Delta T_i(0) < 80\%$ $\Delta\tau_E < 40\%$	$T_i^{NPA,CXS}(0)$ = 1.6 keV
medium(~ 4)	pellet mode		$T_i^{CXS}(0) = 0.7$ keV $\Delta T_i(0) < 60\%$	
	H-mode	$\Delta\tau_E = 15\%$		$M_{pol} = 0.5 - 1$ $\Delta\tau_E < 30\%$
high (~6)				$\tau_E/\tau_{E(L)} \sim 2$ τ_E=50ms
	reheat mode	$\Delta\tau_E < 20\%$		

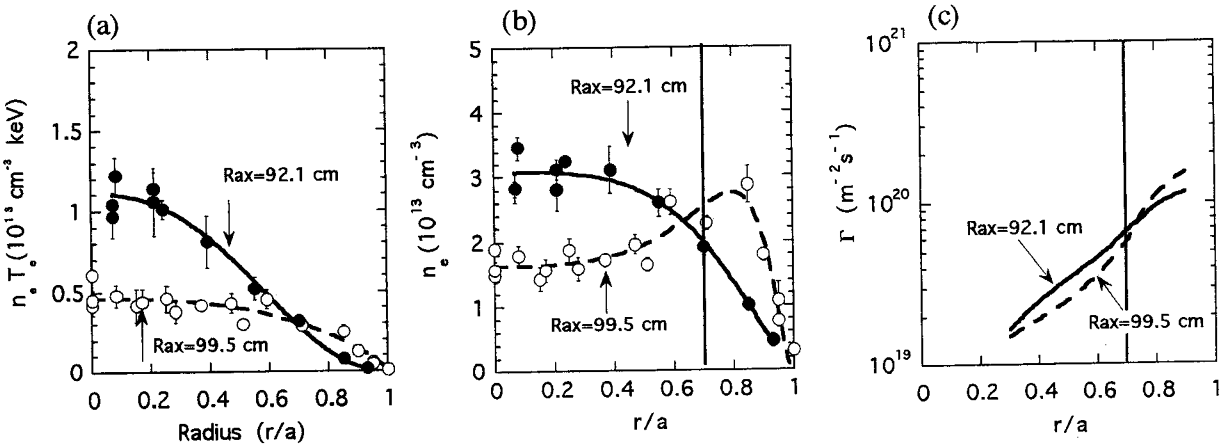

Fig. 3 Change of the density profile owing to the shift of the magnetic axis in CHS. Radial profiles of electron pressure (a), density profile (b) and particle flux (c) are shown. Solid lines indicate the case where the major radius of the magnetic axis is given as R_{ax} = 92.1 cm. Dashed lines are for R_{ax} = 99.5 cm. Plasma is produced by ECH. As the plasma is shifted outward (dashed lines), the density profile becomes flatter, even hollow. (See [28] for details.)

the pressure-driven activity, if any, is important. The prospect of the achievable beta limit in future experiments is based on the MHD theory of helical plasmas [2, 5, 29]. The equilibrium study has confirmed the theoretical prediction, together with the optimization in relation with the toroidal shift by finite beta effect[7]. The prediction for the MHD activities of high-beta plasmas will be more dependable, if our understanding is confirmed by the observations.

No drastic events have been found on CHS and W7-AS in relation with the beta-limit up to the present beta value (2.1 % for CHS[30] and 1.8 % for W7-AS [31]). An internal collapse has been observed on Heliotron-E with steep edge gradient[32], stimulating the understanding of the MHD activities in helical systems [33].

Presently, the achieved beta is mainly bounded by confinement and heating power. Under such circumstances, moderate MHD activity has been observed. Detailed observations on the global activities have made progress. Figure 4 shows the helical perturbation of the internal potential (CHS), and the internal structure of the perturbation is illustrated[34]. The perturbation has the wave form similar to the interchange mode. Detailed tomographic reconstruction of the internal collapse has also been performed on Heliotron-E [35].

The other issue is Alfvén eigen mode. Energetic particles can drive fluctuations of Alfvén waves, which in turn could expel the high energy particles out of the plasma. The fluctuations of the family of the Alfvén eigenmode are identified in W7-AS when the plasma

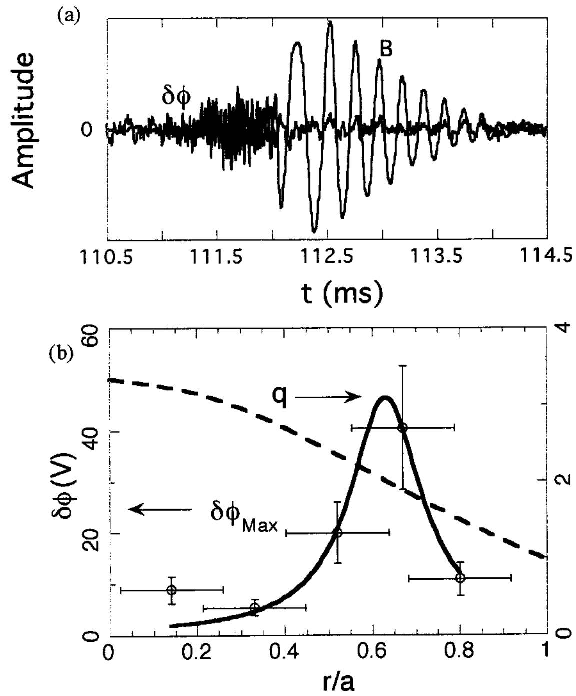

Fig. 4 Helical perturbation (m=2) is observed in the case of NBI injection into CHS plasma. Temporal evolutions of magnetic perturbation measured by Mirnov coil and static potential perturbation that is obtained by HIBP are shown in (a). In (b), the radial profile of the perturbed potential amplitude (fitted by solid line) and q-profile are illustrated.

beta value is increased[36]. High frequency oscillations, of which the frequency is well scaled to the real frequency of the toroidal Alfvén eigen mode, are also observed on CHS associated with the NBI injection [37]. At the moment, the fluctuation of the Alfvén eigenmode in W7-AS does not cause substantial loss. However, the Alfvén eigenmode in an asymmetric plasma has its own merit of study, *i.e.*, how the continuous spectrum behaves in nonsymmetric plasmas[38].

2.7 Divertor and edge control

In Heliotron configurations, helical divertor traces bound the plasma-wall interactions[39]. In W7-AS the use of intrinsic islands is planned[7].

The island divertor is applied to CHS. Enriched plasma density at the pump duct and the reduction of the effective particle confinement have been confirmed. [25, 40] (Fig. 5.) Experiment on particle control shall be studied. The reduced edge neutral density is led, and the edge electron temperature is increased. On W7-AS, the confinement of the dense-cold plasma in the edge islands has been demonstrated. It is expected that there arises an $E \times B$ flow in the edge islands[7].

3. Physics of Electric Field

3.1 Reduction of transport

Physics of the radial electric field has attracted much attention in the research of toroidal plasmas. One is the suppression of neoclassical loss: This effect is partly confirmed by the achievement of the high temperature plasmas in W7-AS experiment[10].

The other important subject is the reduction of anomalous transport. In discharges which are illustrated in Section 2.3, the strong electric field is generated. There are experimental suggestions, *e.g.*, for the pellet mode, high-Ti mode and the case with high electron temperature, though to be confirmed in future, that strong radial electric field is either one of causes of or is related with the improved confinement. More direct comparison has been made for tokamaks[41]. Theory has been advanced associated with the H-mode physics [9]. A formula like

$$\chi \propto \frac{1}{1 + C(\mathrm{d}E_r/\mathrm{d}r)^2}$$

was obtained for helical systems[17, 42]. The dependence of the coefficient C in this formula was given, and theoretical prediction has been discussed on the necessary level of E_r'. In present experiments of CHS, the gradient is not enough or marginal. Future experiments with stronger gradients are particularly interesting.

3.2 Structure

The structure of the radial electric field has vital importance for the absolute trapping, neoclassical loss and anomalous transport. CHS has provided a picture of electric potential (Fig. 6)[43]. The interface of the radial electric field, across which the field changes strongly, is observed. This is a hint for the momentum

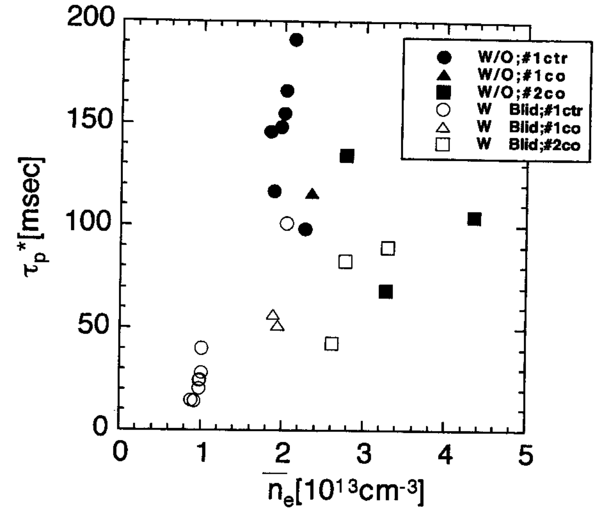

Fig. 5 Reduction of the effective particle confinement (i.e., better controllability of particles) is realized by the local island divertor on CHS. Effective particle confinement time without LID (solid symbols) and with LID (open symbols) are shown. Co and Ctr indicate the direction of neutral beams. (See [40] for details.)

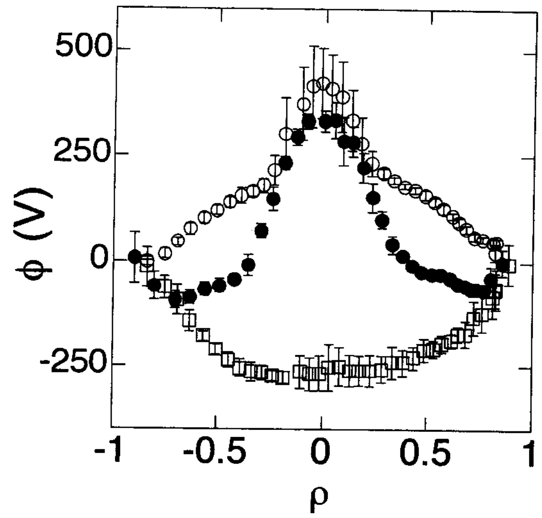

Fig. 6 Electric field structure which is measured by the HIBP in the CHS plasmas. Low density ECH plasma (open circle), combined NBI and ECH heating plasma (solid circle) and NBI heating case (open square). (See [45] for details.)

transport barrier. Such a situation will be a basis for the future finding of the new state of improved confinement. Theoretical method for the analysis of the radial electric field has been developed[9], and has been applied to helical systems[44]. Qualitative agreement has been reported except the interface, but further analysis is still required.

3.3 Dynamics

The dynamics of the electric field bifurcation is experimentally observed. Nonlinear relation in the radial current and the electric field has been observed on CHS [45]. (Fig.7) The nonlinear relation is the essence of the transition in the radial electric field. This measurement on CHS is the basis for understanding the electric field bifurcation of toroidal plasma in general.

More exciting is the discovery of the potential pulsation[46]. Electric bifurcation occurs periodically, realizing a new dynamical stationary state. In relation with the H-mode physics, the periodic formation and decay of the transport barrier have been predicted in the theory[47]. This finding of the periodic pulsation sheds a new insight of the stationary state in helical systems, as well as of the generation of the strong radial electric field shear. The impact of these oscillations on the achievable radial electric filed must be studied in future. More generally, there are abundant magnetic activities in current-carrying systems like tokamaks. In contrast, the electric dynamics could be dramatic in helical systems. The observations on the electric field in CHS, combined with the knowledge on tokamaks, provide a physics basis to study the dynamical structural formation and to explore the future progress of the physics in general.

4. Summary and Discussion

Many innovative physics ideas have been investigated in past to explore the concept of helical systems. Many of the proposed schemes of the improvements have now been examined in experiments. Encouraging observations have been obtained progressively, but there remain substantial challenges; they could be overcome only if all the intellectual efforts and innovations will be put forward. Two streams of considerations will be experimentally tested in a near future, *i.e.*, LHD and W7-X. Alternative approaches for optimization are investigated and shall be tested. The principles of optimization and the physics for the improvements should be tested fully on the coming new devices. The empirical database may imply that there could be a difference of the confinement between the Heliotron and optimized stellarator, but this could be concluded after LHD and

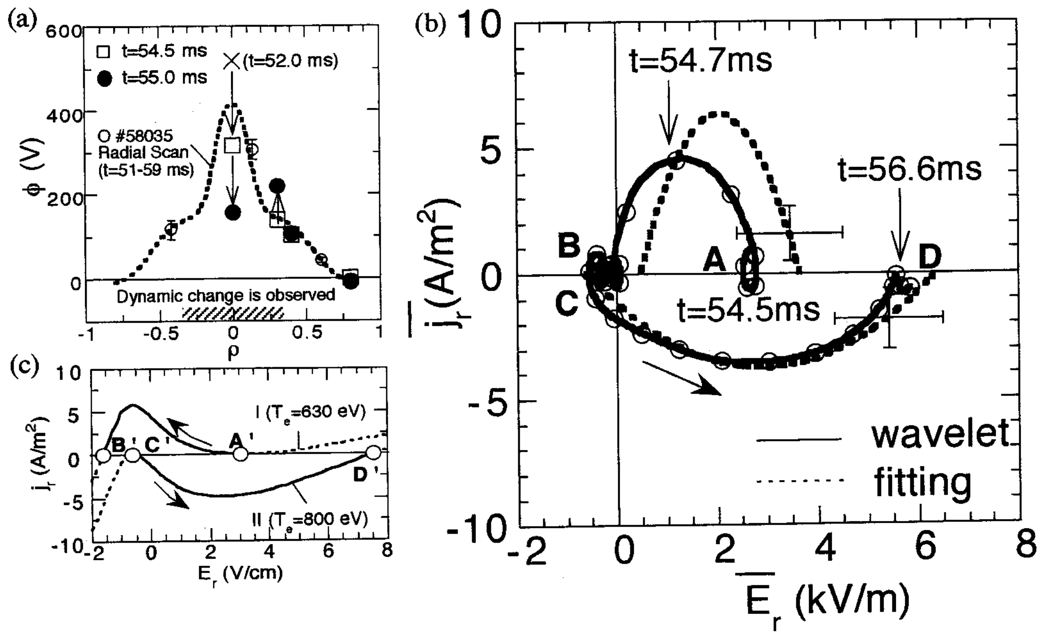

Fig. 7 Electric field bifurcation is observed on CHS. Potential profile (solid line) and measured potential just before (open square) and just after (solid circle) the transition are shown in (a). The E-J curve in (b) shows clearly the nonlinear bifurcation. Example of the neoclassical estimate is shown in (c). (See [45] for details.)

W7-X are operated at full performance with divertors.

The investigations for developing the helical systems have deepened the understanding of the nature of plasmas, *e.g.*, in the problems of the symmetry breaking-and ergodization, turbulent transport, electric field bifurcation, etc. This understanding is some of the most important achievements in the physics of high temperature plasmas. We wish that the science of the helical confinement systems could be judged by its academic standard as well as by its impact to fusion research.

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