Physical Design of MW-class Steady-state Spherical Tokamak, QUEST

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QUEST (R=0.68m, a=0.4m) focuses on the steady state operation of the spherical tokamak (ST) by controlled PWI and electron Bernstain wave (EBW) current drive (CD). The QUEST project will be developed along two phases, phase I: steady state operation with plasma current, I_p=20-30kA on open divertor configuration and phase II: steady state operation with I_p=100kA and β of 10% in short pulse on closed divertor configuration. Feasibility of the missions on QUEST was investigated and the suitable machine size of QUEST was decided based on the physical view of plasma parameters. Electron Bernstein wave (EBW) current drive are planned to establish the maintenance of plasma current in steady state. Mode conversion efficiency to EBW was calculated and the conversion of 95% will be expected. A new type antenna for QUEST has been fabricated to excite EBW effectively. The situation of heat and particle handling is challenging, and W and high temperature wall is adopted. The start-up scenario of plasma current was investigated based on the driven current by energetic electron and the most favorable magnetic configuration for start-up is proposed.

1. Introduction

It is important to conduct the academic basics research supporting high beta and steady state operation approaches. The QUEST project focuses on the steady state operation of the spherical tokamak (ST) which has the capability to attain high β rather than conventional tokamaks. A final target of the project is the steady state operation of ST with relatively high β (10%) under controlled plasma wall interaction (PWI). The program will be developed in increment step such as, I. low β steady state operation in limiter configuration, II. low β steady state operation in divertor configuration, III relatively high β steady state operation in closed divertor configuration. The specific purposes in phase I and II are:

1. To examine the steady state current drive and plasma generation by EBW.
2. To comprehensively establish recycling control based on wall temperature control, advanced wall control under high plasma performance.
3. To improve diverter concepts and to establish the way of controlling particles and heat loads during long duration operation.

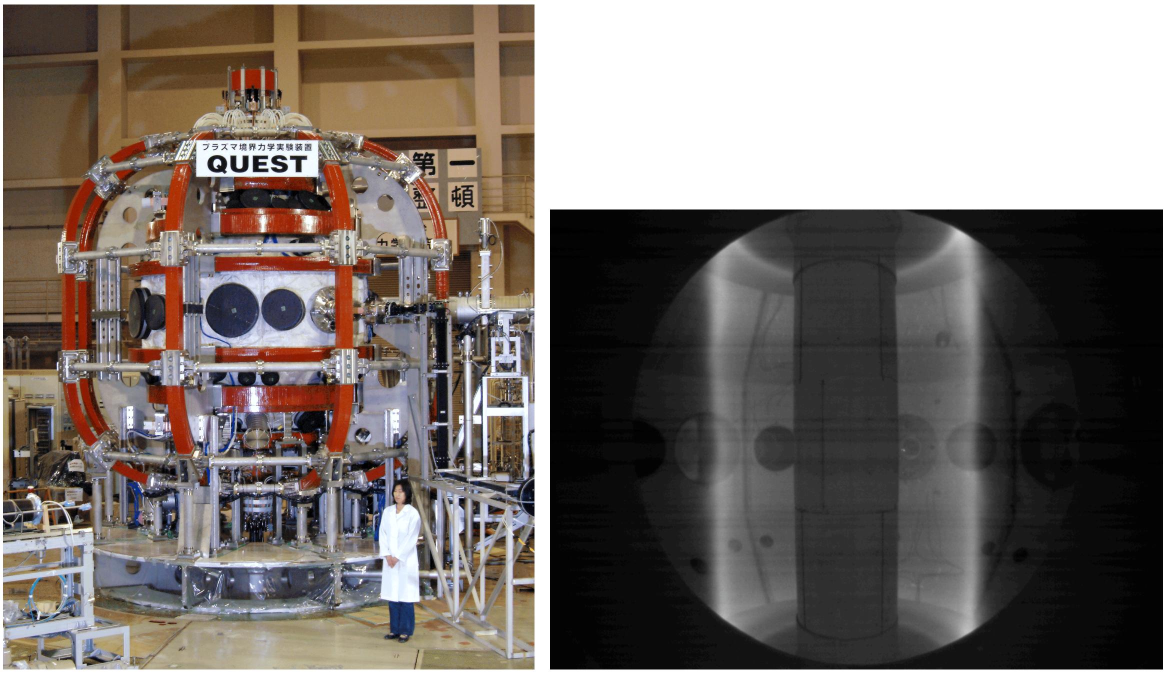

Fig. 1 Left: QUEST (R=0.68m, a=0.4m) and Right: first plasma.

fiscal year items	05 H17	06 H18	07 H19	08 H20	09 H21	10 H22	11 H23	12 H24	13 H25	14 H26	further
construction	▨	▨	▨								
High ξ						>10% (1sec)					20%
Plasma start-up				RF+OH		RF+OH+NBI					
Current drive				RF		RF(8.2GHz)+NBI					16GHz
PWI				W		W, high Temp. wall					Control of Recycling
Divertor				open			closed				advanced
fueling				Gas puff		CT injection					pellet

Table 1 Time table of the important items of physics issues of QUEST. Vertical blue line show the end of construction phase and two red lines show the end of phase I and II.

Present status of QUEST is shown in Fig. 1 and the time table of the important items is shown in table. 1. One of the most important items is the investigation of PWI. QUEST will be used no carbon in the vacuum vessel and only metal wall, that is mainly W, will be available. NBI of 2MW is planned, however it can be operated in short pulse (<1s). NBI can used for the plasma start up and high β experiment in the short pulse. In steady state operation of QUEST. RF of 1MW will work mainly to maintain and heat the plasma. Especially plasma start-up is one of the key issues and only RF and RF+ohmic heating (OH) will be tested. The available magnetic flux for OH is less than 0.3 Vs, which is not enough to obtain the plasma current up to 0.3MA. Therefore the help of RF is quite significant in QUEST. Open divertor is installed in phase I to investigate heat and particle flux to the divertor plate. Based on the experimental results in Phase I, closed divertor will be designed and tested in Phase II. Efficient fueling is important in steady state operation. Advanced fueling is planned on QUEST, which is compact toroid (CT) injection. The fueling using CT injection is challenging, however it is suitable way in low magnetic field device such as ST.

2. Purpose of the QUEST project

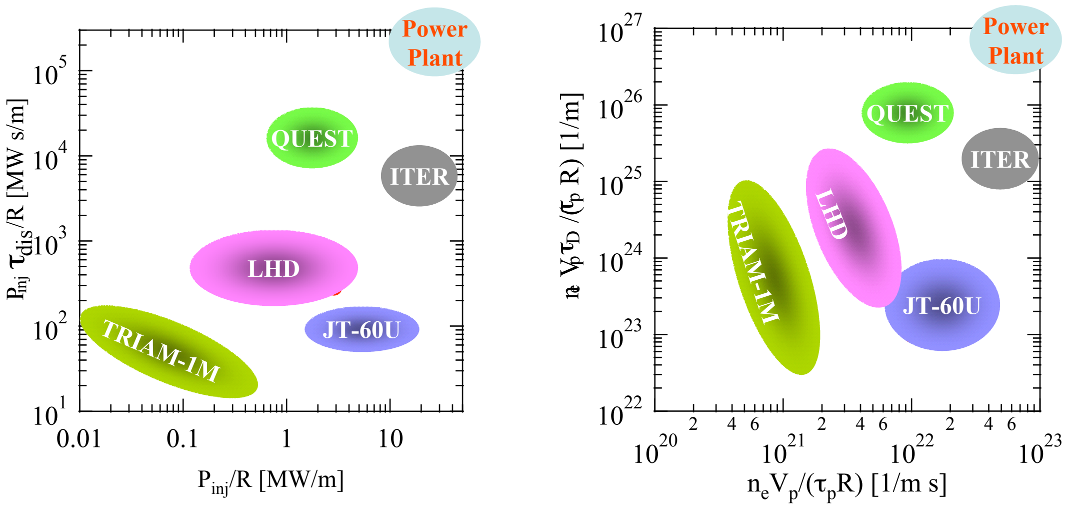

Fig. 1 Operation region of QUEST on heat (left) and particle (right) handling. Left: The vertical axis is injected power (MW) x discharge duration (s) / major radius (R), which is approximately proportional to heat load to divertor and the horizontal axis is injected power (MW) / major radius (R), which is approximately proportional to heat flux to the divertor. Right: The vertical axis is density (m^{-3}) x plasma volume (m^3) x discharge duration (s) / major radius (R) /particle confinement time (s), which is approximately proportional to fluence to the divertor and the horizontal axis is density (m^{-3}) x plasma volume (m^3) / major radius (R) /particle confinement time (s), which is approximately proportional to particle flux, where we assume particle confinement time equals energy confinement time.

One of the main purposes of QUEST is an achievement of long duration discharge with MW-class injected power. Operation region of QUEST in view of heat handling is shown in Fig. 2. The operation of QUEST in heat handling is so challenging and PWI control on QUEST plays an essential role in realization of a power plant. Moreover, particle handling is crucial to obtain the steady state operation of magnetic confinement devices. As shown in Fig. 3, QUEST is at a dispensable position towards DEMO in operation region on particle handling. Especially, wall phenomena on PWI, which are co-deposition, T retention, dust and so on, strongly depends on fluence rather than particle flux. In this meaning, QUEST has a competitive edge over the other devices. QUEST will equip full-scale closed divertor to control particle flux around divertor region. First wall of QUEST will be completely surrounded by W and keeps high temperature (>600K) during discharge at least to obtain recycling ratio, R=1. A steady state operation under R=1 marks a milestone for realization of steady state magnetic fusion power plant.

3. Feasibility of the missions on QUEST

QUEST has two different types of missions, which are high β_T (>10%) in short pulse (< 1s) and low β_T in long pulse (>1h). A plasma size should be decided by the physical requirement from the missions. The value of toroidal field of QUEST, which is 0.25 T at plasma center was decided in view of the position of fundamental electron cyclotron resonance (ECR) and 2nd one for the frequency of the present RF power sources (f=8.2GHz). Figure 4 shows a feasibility window on minor and major radii considering about the above-described missions. The solid and dotted lines show the line for q_{95}=4 and 3, respectively. Generally speaking, it is difficult to operate on q_{95}<3 in tokamaks and the solid line provide a low q limit. The solid and dotted line shows the heat load limitation (10MW/m^2) to a divertor plate under the condition of the fraction of radiation, P_{rad}=40% and 50% in single null configuration. In steady state, the heat load to any plasma facing components should be kept down on less than 10MW/m^2. This is also the requirement for ITER. When the major radius is less than the solid line, the heat flux to divertor plate goes beyond the boundary of the ITER requirement. The solid and dotted lines show the aspect ratio, A=1.4 and 1.3, respectively. The reduction of aspect ratio leads to the difficulty of the construction of the machine. The solid and dotted lines show the constant β of 10% and 5% based on the ITER 89P L-mode scaling under the condition of I_P=300kA, B_T=0.25T, P_{inj}=3MW, respectively. The selected plasma size (a point on the figure) has the candidate to attain the mission.

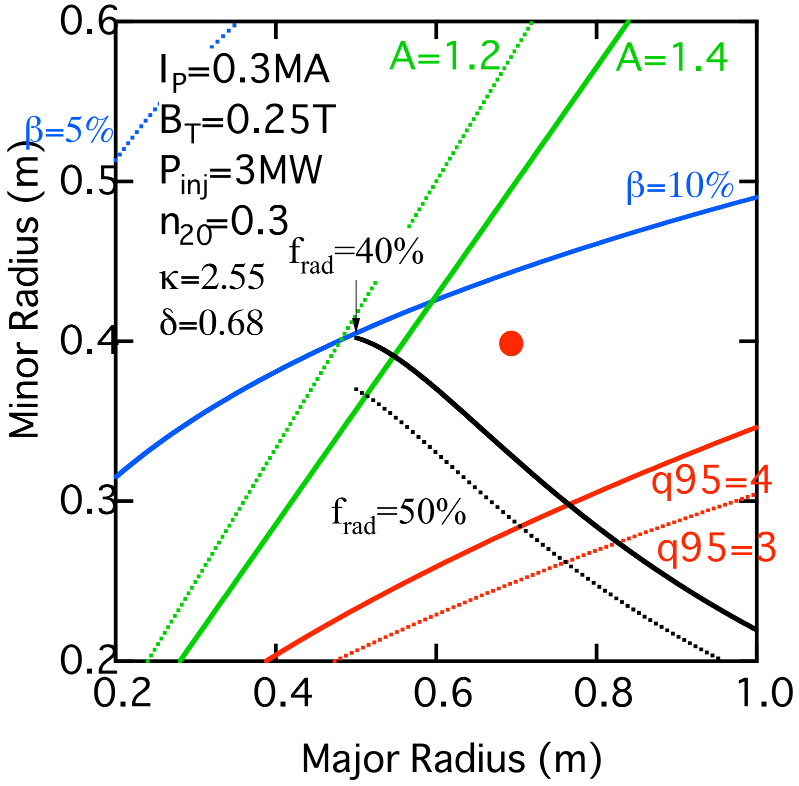

Fig. 4 Plasma size determination.

4. Preparation for EBWCD in steady state operation

In Phase I, the most important issue of the project is to achieve steady state operation. Non-inductive current drive is indispensable for steady state operation. The different way to drive the plasma current from that in conventional tokamaks should be developed for ST.

Electron Bernstein wave current drive (EBWCD) and higher harmonics fast wave current drive (HHFWCD) are candidates to establish the maintenance of plasma current in steady state by use of RF. As we do not have any heating source for HHFWCD in the view of frequency at present, EBWCD is suitable way to apply to the machine at first. The current drive efficiency of 0.5 x 10^{18} A/W/m^2 at considerable low electron temperature is an overarching goal for current drive in this phase.

At first, two excitation scenario of EBW (O-X-B and X-B) should be discussed, because injection way of RF depends on the scenario of excitation. The O-X-B scenario is utilized a mode conversion from O-mode to X-mode at the cut-off region for O–mode. The conversion rate from O-mode to X-mode is well-understood and depends on the injection angle to the cut-off layer. When we are willing to adopt this scenario, the adjustment of the injection angle is crucial. The converted X-mode will transfer to the upper hybrid resonance (UHR) from high field side and it will convert to EBW. EBW propagates inwards again and is absorbed bulk electrons effectively. By the effect of the magnetic shear, EBW has the single directed momentum in specified situation and it delivered to plasma. Accordingly plasma is provided single directed momentum from EBW and plasma current can be driven. The X-B scenario is the same in delivery and receipt of the momentum, however the mode conversion process is different. The RF will injected perpendicular to the magnetic field and 3 wave coupling play an essential role in mode conversion process and the mode conversion efficiency significantly depends on the scale length of electron density at UHR. To convert to EBW, we should control the density gradient at UHR.

Figure 5 shows the conversion map of EBW [1]. More than 95% mode conversion rate to EBW can be obtained in the three types of parameter regions, the “Perp-X”, the “g1” and the “O-X-B”, where “O-X-B” means O-mode wave converts to X-mode at plasma cutoff and then the converts to EBW and “Perp-X” means X-mode penetrates right hand cutoff and converts to EBW at upper hybrid resonance, and “g1” means the optimal mixture of the O and the X-modes. Increasing the peak density, the optimal injection mode for EBW varies from the O-mode to the g1 mode. Therefore the injected RF should be modified during a shot. To realize the scenario, we designed and fabricated a new phased-array antenna [2] and it will be installed on QUEST.

Experimental observations of EBWCD are obtained in various devices. Driven current of 100 kA at 60GHz 600kW was achieved in COMPASS-D on the O-X-B scenario. Full non-inductive plasma current up to 20 kA in a sequence of plasma start-up on CS-less configuration was achieved on LATE [3]. The X-B scenario was executed on TST-2 by appropriating RF power source of 8.2 GHz, 200kW [4]. Plasma heating could be observed in the case of application to ohmic heated plasma. Full non-inductive plasma current of 4kA for 0.3 sec could be sustained by only-RF on TST-2.

A simulation was done for high β discharge on NSTX and accordingly non-inductive plasma current of 30 kA will be obtained by 1MW injection. Fokker-Planck simulations were executed and some results were presented by B.Jones and C.B.Forst for NSTX and Pegasus, respectively. According to their paper, expected current drive efficiencies were η_{CD}=2.7X10^{18} for NSTX and 1.5x10^{18} for Pegasus. These values are not far from the target value of QUEST. Fokker-Planck simulation was carried out by TASK/FP [5].

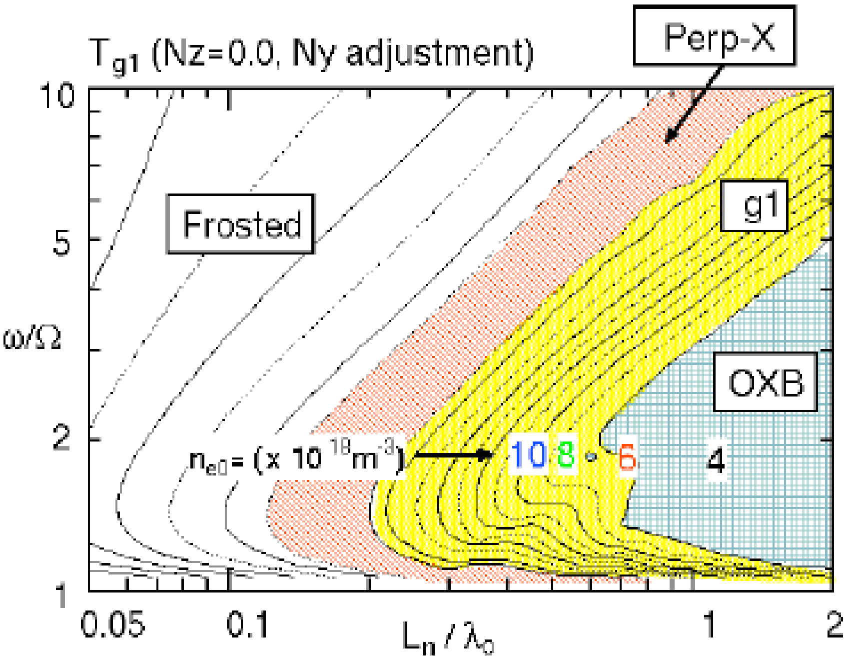

Fig.5 The conversion map of EBW on a slab model. Ln/λ is the ratio of the density scale-length at the plasma cutoff to the vacuum wavelength and ω/Ω is the ratio of the wave frequency to the electron cyclotron frequency. The numbers in this figure correspond to the peak values of the given density profiles of QUEST. The red shaded region indicates the area where the mode-conversion rate is more than 95%, while the green meshed region indicates the area where the mode-conversion rate is less than 10%.

5. Start-up scenario by use of RF

ST has small aspect ratio ($A = R_0/a$, where R_0 is the major radii and a is the minor radii of tokamak plasma) and its central space is limited [1]. Therefore, inductive electric field in ST is weaker than that in conventional tokamak, and it is required that plasma current start-up is conducted by non inductive method such as radio frequency (RF) wave injection or ohmic method supported by RF injection (RF + OH) in very low inductive electric field. In the RF injection method, it is pointed that energetic electrons, which is tail electrons, confined in open field contribute to the plasma current initiation [6]. Thus, plasma current initiation with RF injection has quite different physics from the normal OH initiation with bulk electrons, which is conducted in conventional tokamak. This peculiar condition applies to superconductive tokamak because its inductive electric field is also weak and it needs to use RF injection to initiate plasma. Therefore we can use the knowledge of ST plasma ramp-up to conduct current initiation in operation of superconductive tokamak, like ITER. In terms of it, the study of ST current ramp-up is important to realize future fusion reactor.

Figure 7 shows that the orbits of electrons in the opened field. Electron orbits are classified three patterns. They are named “lost”, “banana”, and “co-moving” respectively. The electrons which are not confined in the opened field are classified into “lost”. The electrons classified into “banana” are trapped in opened field by magnetic mirror because of toloidal field dependence on major radii R, $B=B_0R_0/R$ and poroidal field which transports the electrons to higher magnetic field strength side. The pattern named “co-moving” is for the electrons confined in the open field without magnetic mirror effect. Electrons in tokamak configuration have two poroidal velocities. One is the poroidal component of velocity along the magnetic field line and the other is drift velocity generated by toloidal field curvature and gradient. When these two velocities have opposite direction each other and almost same value, electrons hardly move to poroidal direction and they are confined in small area in opened field. Which orbits a electron traces depends on its initial velocity, pitch angle, poroidal field shape and strength. Thus poroidal field configuration is important to confine electrons in open field. Especially, N-index on mid plane should be positive.

Expected plasma current driven by energetic electrons, I_{es}, is calculated in the following way. At first we assume that the velocity distribution function of electron is Maxwell distribution and loss electrons do not carry any plasma current. The start point of orbit calculation sets on the ECR layer on the midplane. Density and temperature of energetic electrons are $1x10^{17}$ m^{-3} and 1keV, respectively. Figure 8 shows I_{es} as the function of poloidal magnetic field, Bp in the magnetic configuration on QUEST. From this result, we expect the most suitable magnetic configuration for start-up of plasma current.

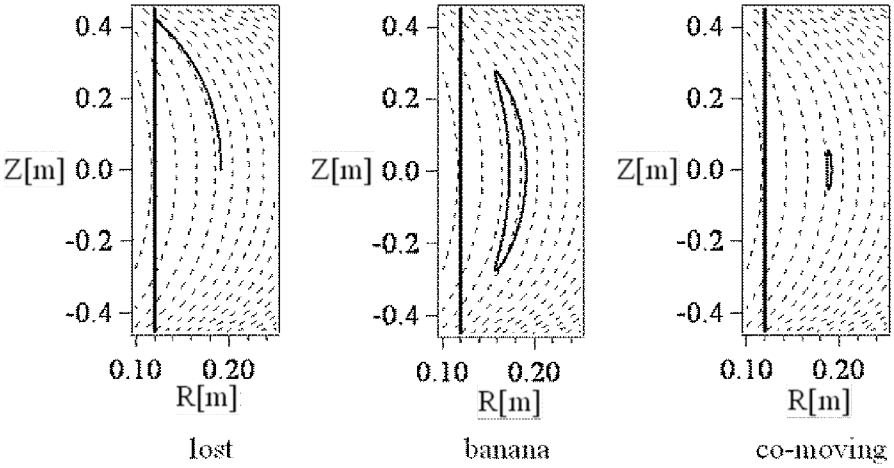

Fig.7 Orbits of electrons in open field. Solid lines show orbits projection and wall of vacuum chamber, and dashed line show magnetic line projection on poroidal plane. The magnetic field strength in left side in the

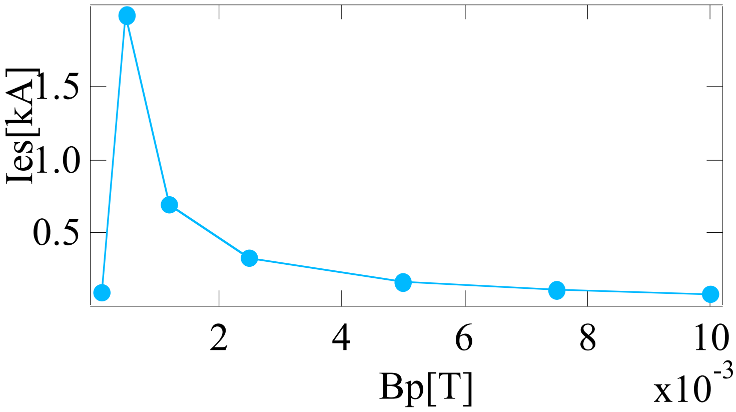

Fig. 8 Expected plasma current driven by energetic electron in open magnetic configuration as the function of poloidal magnetic field, B_p.

Summary

One of the main purposes of QUEST is an achievement of long duration discharge with MW-class injected power in ST. The QUEST project will be developed along two phases, phase I:steady state operation of 20-30kA on open divertor configuration and phase II: steady state operation of 100kA and β of 10% in short pulse on closed divertor configuration. Time table for important physical items of QUEST project is proposed. Feasibility of the missions on QUEST was investigated and the suitable machine size of QUEST was decided based on the physical view of plasma parameters. Non-inductive current drive is indispensable for steady state operation. Electron Bernstein wave current drive (EBWCD) are promising way to establish the maintenance of plasma current in steady state. Mode conversion efficiency to EBW was calculated and 95% conversion will be expected in narrow window. New antenna system was designed to sophisticate the injected wave. The start-up scenario of plasma current was investigated based on the driven current by energetic electron and the most favorable magnetic configuration is proposed.

Acknowledgements

This work is performed with the support and under the auspices of the NIFS Collaboration Research Program (NIFS05KUTR014, NIFS08KUTR022). This work is partially supported by a Grant-in-aid for Scientific Research from Ministry of Education, Science and Culture of Japan.

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