Research activities of RF based negative ion source in the ASIPP

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Abstract. The Comprehensive Research Facility for Fusion Technology (CRAFT) is a large scientific device that is preferentially deployed for the construction of major national science and technology infrastructures. A negative beam source based neutral beam injector (NNBI) with beam energy of 400 keV, beam power of 2 MW and beam duration of 100 s is one of the device. A radio frequency (RF) based negative beam source was designed for the CRAFT NNBI system. In order to understanding the physics and pre-study the engineering problems for RF negative beam source, a prototype source with single driver was developed. Recently, this beam source was tested on the RF source test facility with RF plasma generation, negative ion production and extraction. The long pulse plasma discharge and negative ion beam extraction with a three electrons accelerator were achieved successfully. The extracted ion current is 153 A/m^2 with Cs injection and the ratio of electron to negative ion is around 0.3. It lays good foundation for the R&D of negative ion source for CRAFT NNBI system. The details of design and experimental results of beam source was shown in this paper.

INTRODUCTION

A national big science facility named Comprehensive Research Facility for Fusion Technology (CRAFT) is preferentially deployed for the construction of major national science and technology infrastructures. A negative beam source based neutral beam injector (NNBI) is one of devices of CRAFT project. The NNBI system is expects to deliver a powerful beam with beam energy of 400 keV, beam power of 2 MW and beam duration of 100 s. The radio frequency (RF) beam source can works with long pulse because it has no tungsten contamination compared with hot cathode arc source[1-3]. So, the RF based negative was employed for the CRAFT NNBI system, which was also the reference source for ITER-NNBI system[4, 5]. In order to understand the physics and pre-study the engineering issues for RF negative beam source, a prototype source with single driver was developed[6-8], which shown in Fig.1.

In order to test the performance of beam source, a RF based beam source test facility[9, 10] was developed and shown in Fig. 2. It contains a vacuum vessel, a gas pumping system, a water cooling system, a 100 kW RF power supply with 1 MHz, a matching network , a beam extraction high voltage (-16 kV & 20 A) power supply and diagnostic system.

Recently, the RF source was achieved long pulse discharge of 1000 s with RF power of 47 kW[11] and shot pulse of 60 s with 80 kW on the RF ion source test bed, respectively. And then the RF beam source was tested with negative ion production and extraction with Cesium (Cs) injection[7]. As a results, long pulse of 105 s negative ion beam was extracted with negative ion density of 153 A/m^2. The details about the beam source designs and experimental results are presented.

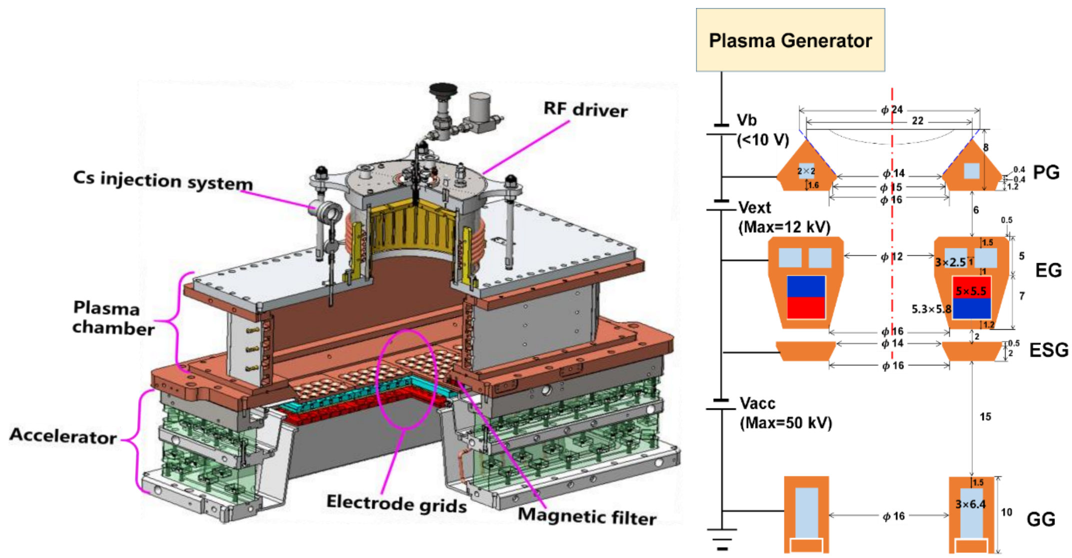

FIGURE 1. The schematic map of prototype negative ion source

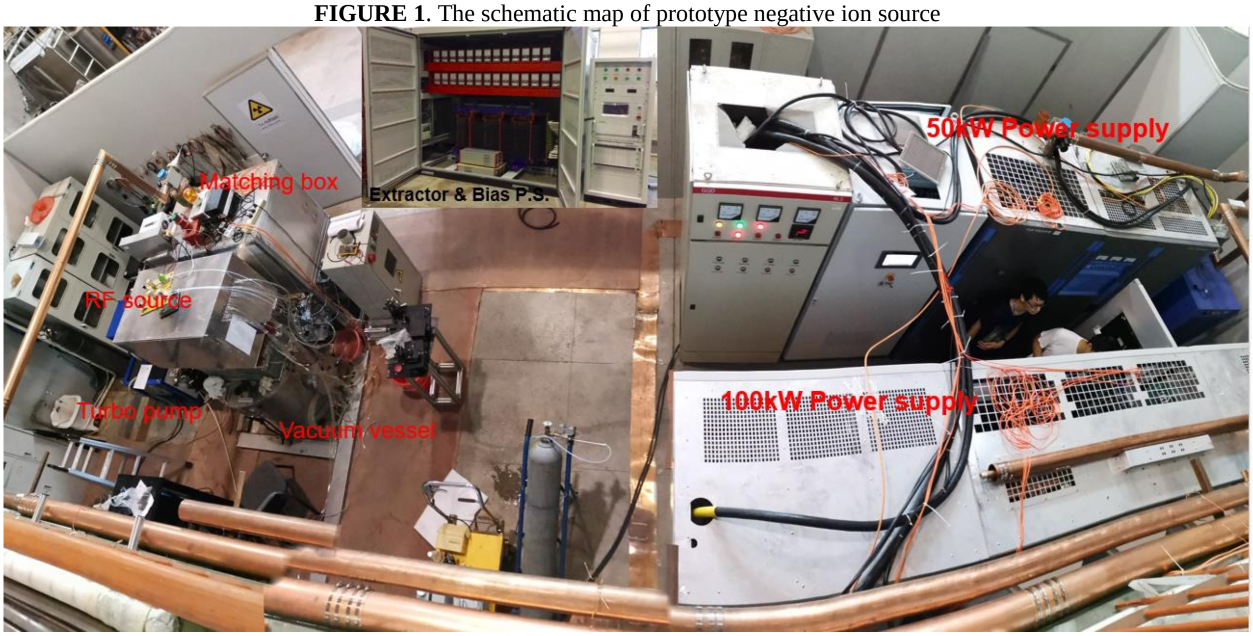

FIGURE 2. The picture of RF beam source test facility

EXPRIMENTAL RESULTS OF PLASMA GENERATION

The plasma generator contains RF driver and plasma expansion chamber. The RF driven plasma generated in the driver and diffuses to the expansion chamber to from uniform plasma. The Faraday shield (FS) is a key part of plasma generator. The structure of ITER-like FS is very complicate and not easy to manufacture, so, a three-route water cooling FS was designed and manufactured[11], which shown in Fig.3. The FS is 200 mm in inner diameter, 210 mm in external diameter and 150 mm in height. The inner diameter of water channel is 6 mm, and size of side-edge water channel is 4 mm×2 mm. Three route of cooling water channels are used to cooling the back plate and two side walls of FS. The FS was installed in the source for RF plasma performance tests.

In order to measure the parameters of plasma, a moveable Langmuir probe was installed in the bottom of plasma expansion chamber. The Langmuir probe can move into the chamber about 16 cm. The electron density was measured in the margin of chamber with different RF power and the results shown in Fig.4. The electron density increased from 2×10^{16} m^{-3} to 9×10^{16} m^{-3} when the RF power is increased from 6 kW to 52 kW, almost increased linearly with RF power. In order to increase the plasma density, and also the plasma uniformity, the cusp magnets are installed surround the expansion chamber. The moveable probe goes into the plasma chamber to measure the plasma parameter without and with cusp magnets. The RF power is 30 kW and source pressure is 0.5 Pa. The measured results are shown in Fig. 5.

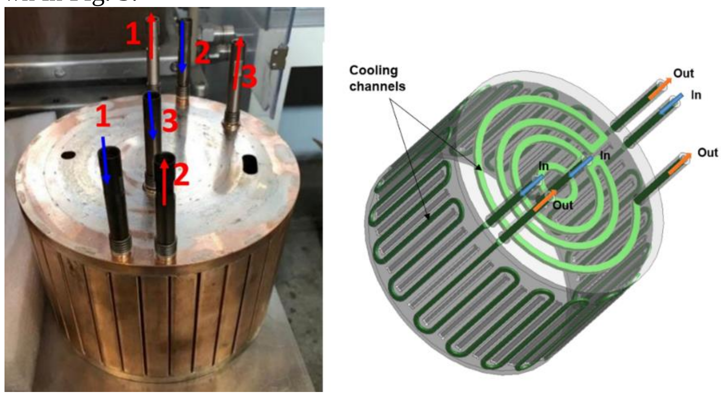

FIGURE 3. The schematic map of Faraday shield for prototype beam source

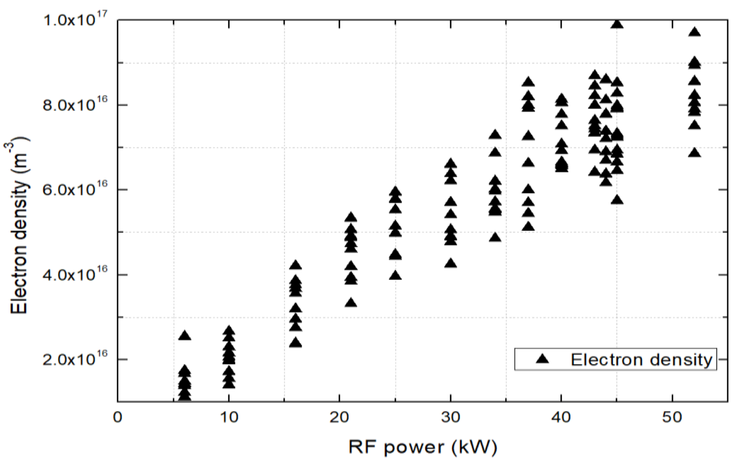

FIGURE 4. The electron density before plasma grids as function of RF power

When without the cusp magnets, too much plasma will lost on the wall, the electron density increased from 6×10^{16} m^{-3} to 1.6×10^{17} m^{-3} when the probe moved from 18 cm to 29 cm. Even the probe can't reaches the center of chamber, the electron density increased about 3 times. When the cusp magnets installed, the plasma only lost in the cusp lines, and the electron density increased from 1.5×10^{17} m^{-3} to 2.6×10^{17} m^{-3} when the probe moved from 18 cm to 30 cm, about 2 times increase. Compared with the results without cusp magnets, the electron density increased about 3 times, and the density difference also decreased. It means the cusp magnets can form good confinement magnetic field. But the uniformity was bad due to single driver used, two RF drivers will be used for good uniformity generation in the future.

The long pulse discharge was also tested. Long pulse of 1000 s with RF power of 47 kW was achieved. The plasma is much stable and the temperature rise of RF driver also under control (maximum temperature rise about 40 degrees on the side wall of FS). High power of 80 kW was also tested with 60 s, the temperature rise of plasma generator can be seen in Fig. 6. The maximum temperature rise about 48 degrees also on the side wall of FS. The results also verified the success of R&D of FS.

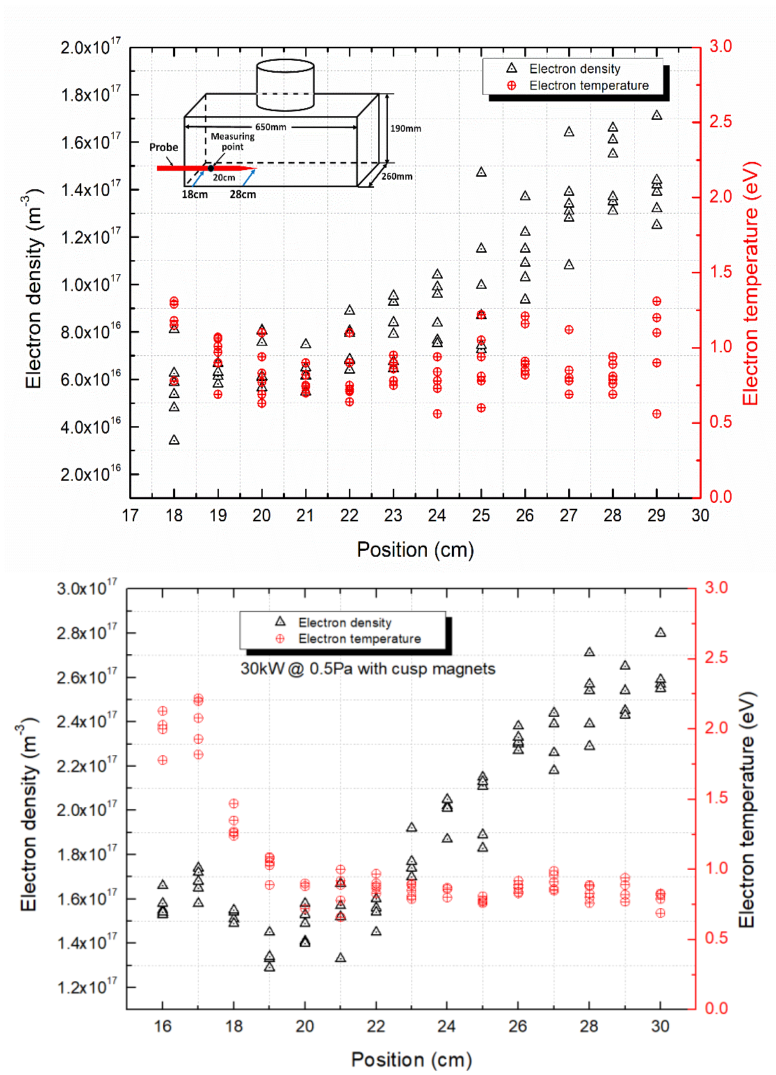

FIGURE 5. The space distribution of plasma parameters without and with cusp magnets

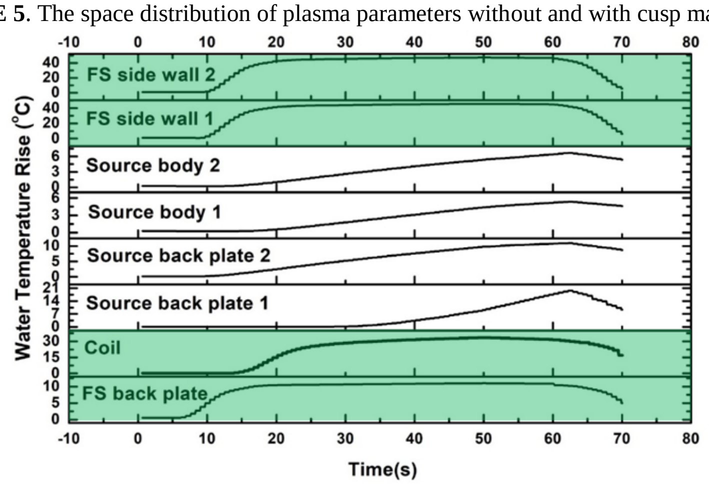

FIGURE 6. Temperature rise of cooling water for each components

EXPERIMENTAL RESULTS OF NEGATIVE BEAM EXTRACTION

The negative ion extraction tests was started when got the stable long RF plasma[12-14]. The design of negative ion accelerator can be seen in Fig.1. It consist of three grids, the plasma grid (PG), the extraction grid (EG) with embedded permanent magnets, and the ground grid (GG), which used to study the performance of negative beam extraction.

On the negative beam source, the magnetic filter is generated by permanent magnets[15, 16]. The electron temperature before PG was investigated with and without magnetic filter, the results are shown in Fig. 7. It can be seen that, the electron temperature was decreased from 5.5 eV to 1 eV with magnetic filter, which can cooling the electron and minimizes the destruction of negative ions.

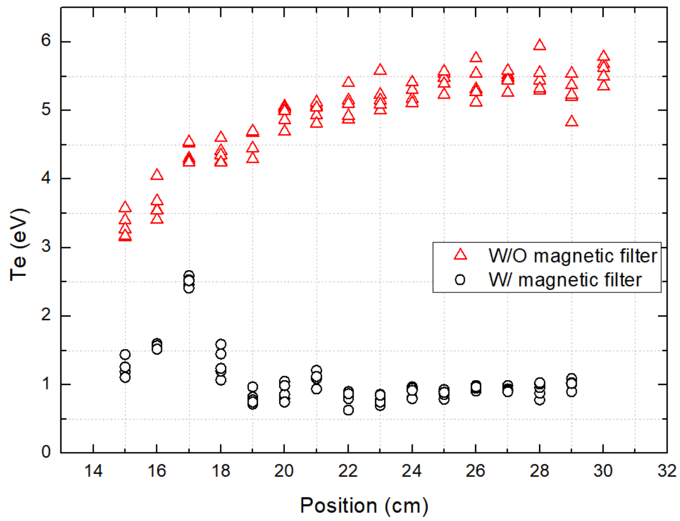

FIGURE 7. The electron temperature with and without magnetic filter

The negative ions was generated and extracted with volume production, and then change to surface production when feeding the Cs into the source. In order to enhance the production of negative ions, the temperature of plasma expansion chamber was actively controlled around 45 degrees. The temperature of PG was heated by plasma. Normally, there need several shots with long pulse of 100 s to heat the PG from room temperature to more than 100 degrees. And then control the discharge interval to hold the temperature of PG. Usually, the temperature of PG controlled around 150 degrees.

The experimental results when conditioning the beam source with Cs is shown in Fig.8. The extracted ion density j_{ex} was started with 40 A/m^2 and increased day by day with Cs conditioning. It reaches about 160 A/m^2 with two weeks conditioning. The ratio of electron density j_e to extracted negative ion density j_{ex} was about 10 at begin, and decreased to 0.3 quickly. Generally speaking, 15 shots were needed to decrease the j_e/j_{ex} from several to 0.3.

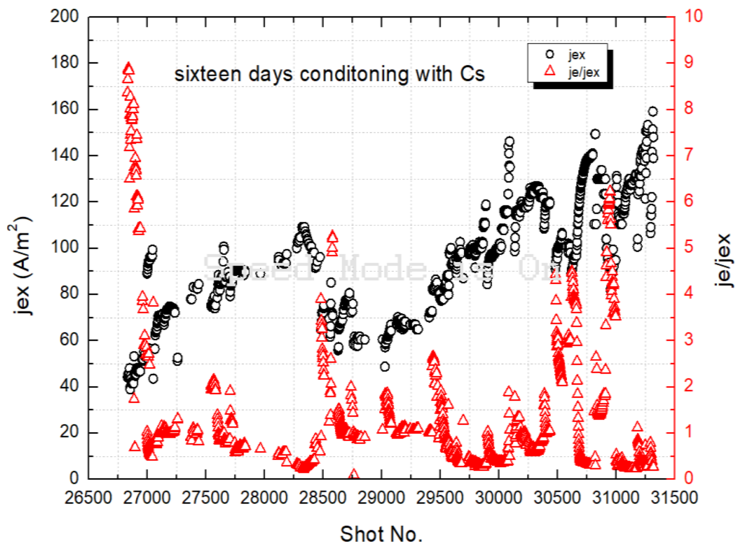

FIGURE 8. The change of extracted ion density and j_e/j_{ex} during Cs conditioning

The results of extracted ion current vary with RF power during conditioning is shown in Fig.9. The extracted voltage is 6 kV. It can be seen that, most shots was conditioned with RF power of 40 kW, the extracted ion density in a large range between 50 A/m^2 to 140 A/m^2. There is not a one-to-one correspondence between extracted ion density and RF power, but more dependent on the conditioning of Cs. It is much complicated about negative ion production and extraction, which needs more experience for conditioning.

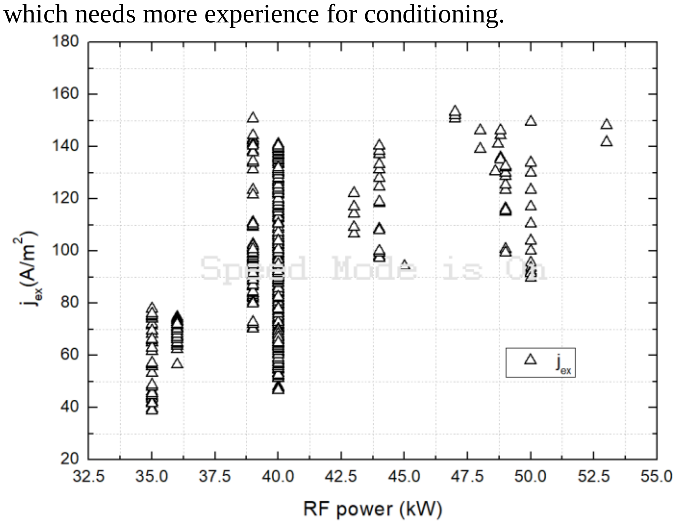

FIGURE 9. The extracted ion density as a function of RF power

Long pulse beam extraction was tested on the test facility too. Due to the week gas pumping ability (two molecular pumps with total pump speed of 5200 L/s), too many breakdowns were happened. So, the holes of PG was reduced from 60 to 10 and the number of breakdowns was obviously reduced, which shown in Fig. 10. On the other hand, we found the Cs conditioning was not good with long pulse operation. The co-extracted electrons were increased with beam duration, the ratio of electron to negative ion was increased from 0.5 to 1.1, and the extracted ion density also had a slight decrease too. We tried to feeding more Cs to weaken this phenomenon and it does work. As a results, we achieved stable long pulse of 105 s negative beam extraction. The extracted ion density is 153 A/m^2, the RF power is 47 kW and ratio of electron to negative ion is 0.3.

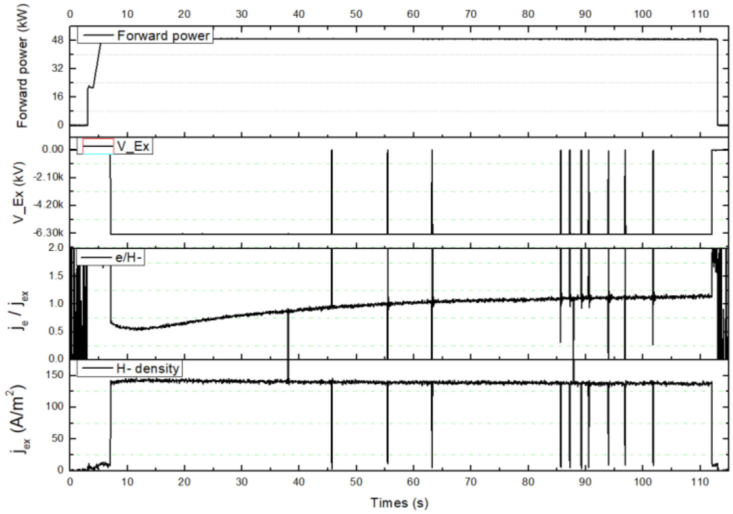

FIGURE 10. Waveform of long pulse beam extraction with poor conditioning

FUTURE PLAN ON NEGATIVE BEAM SOURCE DEVELOPMENT

The prototype of negative beam source is preliminary tested on the test facility. In order to extracts more negative ion beam, several works are considered to do:

i. Add a cryopump to with pump speed of 10,000 L/s for large area extraction;

ii. More researches on the Cs feeding control and Cs recycling, especially with long pulse;

iii. The holes of PG will recover to 60, and then install new accelerator with large area;

iv. The high voltage power of -50 kV can be used for beam acceleration after Oct. 2020;

v. The temperature of PG will be actively controlled by hot water.

CONCLUSIONS

A prototype RF beam source with single driver and three electrodes for CRAFT NNBI system was developed and tested on the RF beam source test facility in the ASIPP. The RF plasma generation and negative ion production and extraction were studied. The characteristics of RF plasma generation was investigated with moveable Langmuir probe. And long pulse of 1050 s RF plasma with RF power of 47 kW was achieved. The negative ion production and extraction were investigated with volume production and surface production. The characteristic of negative ion extraction was studied too. As a results, stable long pulse of 105 s negative ion extraction was achieved. The extracted ion density is 153 A/m^2 and the ratio of j_e / j_{ex} is around 0.3. It is the first time to releases the Cs into the beam source and lays good foundation of the R&D of negative ion source for CRAFT NNBI system.

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