Development of a versatile central solenoid power supply for spherical tokamaks

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論 文 内 容 の 要 旨
Thesis Summary

A spherical tokamak (ST) is one of the magnetic plasma confinement devices to realize a compact fusion reactor. For tokamaks, ohmic heating (OH) is the fundamental method to initiate plasma and to start up the current. An OH is performed, according to Faraday’s law, by swinging the current in the central solenoid (CS). In STs, the size of CS is limited since a space in the central part of the machine is narrow. Accordingly, various non-inductive plasma start-up techniques have been established. After a long-term research, even though non-inductive start-ups are successful in many ST devices, it may fairly be presumed that removing CS coil from ST is not practical. To establish the plasma start-up method of ST, in this thesis, the hybrid scenario with CS current control is proposed for ST reactors. With versatile power supply for the CS, developed in this work, tokamak parameters have been improved and a variety of plasma experiments have been provided in the QUEST spherical tokamak. Utilizing stacks of insulated gate bipolar transistors (IGBT), two high power current sources (8 kA and 375 V) have been combined so that it works as a bipolar current source.

Tokamak start-up solely by electron cyclotron heating (ECH), as one of the representative non-inductive plasma start-up methods, can achieve plasma current of 100 kA level. In the QUEST experiment, this method has been adopted for the tokamak start-up. By the ECH, energetic electrons are mass-produced. Accelerating energetic electrons by auxiliary OH, plasma current is more driven. The value of plasma current is an essential parameter to confine plasma finely. In QUEST, a CS coil whose 217 turns has been installed in the narrow central space. To drive higher plasma current, OH through a double current swing from negative to positive polarity in the CS current was proposed. Namely, change of the poloidal flux in the CS is also doubled. This double swing property is realized through IGBT bipolar switching with developed real time current monitor and interlock system using Field-Programable-Gate-Array (FPGA). With 28 GHz-ECH, a plasma current over 100 kA can be

achieved stably through the double flux swing. The electron density exceeds the cut-off density for 8 GHz range electron cyclotron (EC) waves, and hence electron Bernstein wave (EBW) can be excited in such over-dense plasma. EBW heating/current drive is a promising method in the QUEST experiment, and furthermore in future ST reactors.

Toroidal electric field is applied by controlling the CS current. Increasing or decreasing the CS current, the electric field is applied positively and negatively. In the case that the electric field drives plasma current through OH, energetic electrons are accelerated more efficiently than bulk electrons in the EC start-up plasma as ECH power also tends to be absorbed in energetic electrons. It is difficult to heat bulk electrons or ions under such situation. Inversely, an opposite toroidal electric field can decelerate energetic electrons efficiently so that a hard X-ray bremsstrahlung is suppressed through the retarding toroidal electric field. Owing to the EC current drive, plasma current does not change the polarity and the tokamak configuration is maintained even with the retarding field. Favorably, the temperature of bulk electrons increases significantly with such retarding electric field. In addition, after applying retarding electric field through decreasing the CS current, OH is applicable through increasing the CS current. One distinctive feature is that the OH is repeatable because the ECH maintains the plasma current with retarding electric field.

A high-voltage capacitor bank has been also installed on the negative side in the versatile power supply. A fast trigger system for the ignitron switch with small jitter is developed, and hence high loop voltage could be applied transiently at a specific timing. Our target for the fast trigger system is co-axial helicity injection (CHI) experiment which is also one of the non-inductive start-up techniques. Plasma generated by CHI is resistive with high density, so OH is likely effective in general. In the experiment, toroidal current is gained from 120 kA up to 170 kA through the OH by the capacitor bank discharged before the CHI. In addition, the OH is applied just after start-up of toroidal CHI current. The pulse duration in the CHI discharge is extended from 2 to 3 ms, which contributes a clear formation of the closed flux surfaces in the CHI discharge.

A versatile central solenoid power supply is developed to encounter the key issue of the plasma start-up in the spherical tokamaks. It can swing double the coil current to conduct the effective OH discharges, and can excite the retarding electric field to suppress the highly energetic electrons evolution in the non-inductive ECH start-up plasma. It also assists the short-pulse non-inductive CHI plasma start-up. These works and techniques would contribute to the development of compact spherical tokamak reactors.