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THEORETICAL AND COMPUTATIONAL STUDY OF PLASMA FLOW IN THE BOUNDARY REGION OF NUCLEAR FUSION DEVICE ADITYA

Bibhu Prasad Sahoo, Aryan institute of Engineering and Technology, Arya Vihar, Barakuda, Khurda, Odisha, India**.** Email: sahoo.bibhuprasad1@gmail.com

Abstract. Nuclear fusion is a process that happens in sun, stars and other celestial objects in our universe. Magnetically confined fusion is the machine to obtain nuclear fusion using magnetic fields called tokamak. Many machines are developed and many experiments and computer simulations are going on to understand and control fusion process worldwide including a machine called Aditya tokamak in India. The boundary region in tokamak called the Scrape-Off Layer (SOL) which is very complex and not clearly understood in many devices. SOL plasma flow and associated plasma transport in boundary region of fusion machines is one of the aspects which is not clearly understood in many devices. In this study plasma flow in SOL region in Aditya tokamak and it's importance to plasma flow shear is discussed from previous experiments and computer modeling results. These analysis and discussion helps to understand many important plasma parameters like plasma density, Mach number, electron temperature and others for SOL plasma fluctuations and transport for Aditya and other machines.

1. Introduction

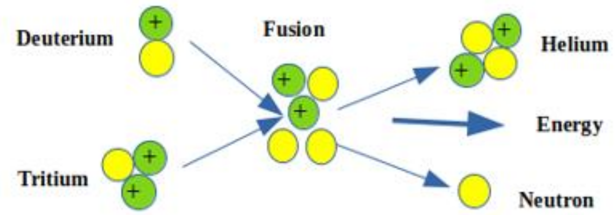

Fig.1: Basic Nuclear fusion process from Deuterium and Tritium nuclei

Nuclear fusion a process in which a light atomic nucleus like deuterium and tritium combine to form heavy nuclei and in the process lots of energy is produced as shown in Fig.1. To harness fusion process the product of plasma temperature, plasma density and energy confinement time should satisfy certain condition called as Lawson's criteria [15]. Many machines are developed worldwide to achieve the necessary condition and produce net power output; among them the one of the most advanced machine is called tokamak which is widely used in many countries including India [1, 8, 15]. Fusion research is going on from last 60 years and many improvements have done still the technology is not developed till now due to many physics and engineering challenges. Now in many countries Machine learning and AI tools are used to understand the huge data obtained from experiments and 2D and 3D simulations and optimize the data and machine parameters still there are many issues and challenges for the technology to be developed.

In a tokamak high magnetic fields are used for plasma confinement and are 2D symmetric in general, but in some machines due to presence of plasma facing components the plasma becomes 3-D in nature and need dedicated experiments and computer simulations [1]. Aditya is a small size tokamak initially with rectangular wall and circular plasma due to presence of a plasma facing component called limiter present at one torroidal location now upgraded to Aditya-upgrade for better performance and new important diagnostics. The boundary region in these machine called Scrape Off Layer (SOL) due to open magnetic field line pattern having complex physics and engineering issues which is generally 3D in nature [3, 11, 15, 14]. Many Experiments and simulations are done previously and many are going on and gave many important results, Still there are many scientific and technological challenges like plasma density fluctuations, anomalous plasma transport, unwanted heat and particle flux on wall and others [1, 1, 10].

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In this work some theoretical analysis is done from some previous data obtained in the machine both from experiment and 3D simulations, based on 1D plasma diffusion equation widely used in many machines. In the next section some discussion is done about Aditya tokamak and its important parameters, further analysis of plasma data like density and mach number is analyzed obtained from previous simulations and measurements and finally summary and conclusion. These analyses not only help to understand plasma parameters but also for further experiments and simulation in this machine and fusion research community.

2. Aditya Complex SOL

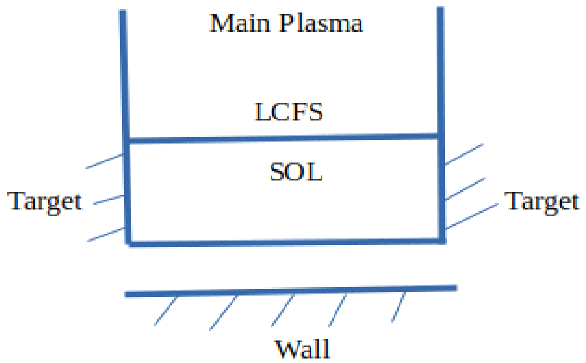

Fig.2: Schematic of tokamak plasma in Rectangular Geometry with main plasma, target, SOL region

The fusion process happens when deuterium and tritium nucleus combine with high energy and in the process energy and neutron is produced and In this machine fusion is produced due to fusion of hydrogen nuclei as shown in Fig.1. Aditya is a small size tokamak with major and minor radii of 75 cm and 25 cm, and toroidal magnetic field of 0.7-0.8 T at the center and one tenth of poloidal magnetic field [6]. The schematic rectangular model showing the main plasma, SOL region and Limiter targets are shown in Fig.2. Many important physics and engineering issues are addressed in fusion research still many challenges remain before technological availability of the machine. The Aditya machine has a rectangular vessel and a circular plasma facing component limiter is placed at one toroidal location, due to which a circular plasma is generated in the vessel now upgraded to Aditya-Upgrade. Hydrogen is used as the working gas in the machine in all the plasma discharges. Different diagnostics facilities are used to measure important plasma parameter like plasma density, electron temperature, Mach number, and others. From last 30 years experiments issues like intermittence of plasma turbulence and gas puff induced plasma suppression and many others [5–7, 14] are already reported to world fusion community. The boundary region in this machine is complex as already discussed in Bibhu. et. al Nucl. Fusion (2015) [13]. Different types of plasma flow in the machine are observed such as ExB flow, Grad P, PS flows in the machine by Sangwan. et.al Physics. Plasmas (2013) [7, 14].

The center of the machine is called core region from which power crosses the LCFS (Last close flux surface), which depends on many plasma parameters. The role of plasma density and diffusivity on plasma transport is discussed in Aditya SOL region which is discussed in Bibhu. et. al Phys. Plasmas (2017). The density asymmetry in Aditya cross-section and SOL-Width variation is presented in Bibhu. et. al JPCS (2017) [16]. In this analysis some important points are discussed based on our previous simulation results from a 3D model to support some of previous experimental results measured and gave some important results.

3. Density and Mach number in Aditya

Plasma fluctuations in edge and SOL region in tokamak are common including Aditya tokamak. The reason for these fluctuations is many and their role on plasma transport in not clearly understood including tokamak Aditya. In order to reduce these plasma fluctuations gas-puffs is inserted in Aditya as reported by Rjha.et.al PPCF (2009). Many methods like Electrode biased experiments, pellet injection and other are used to reduce these fluctuations and already reported in many tokamaks [5-7]. The physics understanding of these fluctuation suppression is not understood and effects are going on through many experiments and 2D and 3D computer simulation models. Plasma flow which is measured by a parameter called Mach number, in Aditya it is found that mach number increases as we move close to boundary region and the flow strength decreases due to rise in density of plasma and is also verified from previous simulations on the device [4, 14, 16]. In this section we try to explain fluctuation suppression based on a 3D simulation model EMC3 for Aditya tokamak in terms of poloidal variation of density and Mach number profile. [2–5, 10, 11].

In Aditya as gas puff is increased at the edge region a increase in density is seen which reduces the perpendicular particle flux and increases the particle confinement time as reported Rjha. et. al PPCF (2009). The simulated poloidal variation of Mach number with density is shown in Fig. 3 (a) and this clearly shows that as density is increased at Edge region the Mach number amplitude decreases due to high parallel flow shear although the analysis is approximate and many drifts are not included in the model, which is a indication of fluctuation suppression as measured during gas-puff experiments. Particle flux analysis from 1D model using this mathematical relation shows that at higher density radial gradient increases at constant $D_\perp$ from the radial profiles of simulation data as a result from fick's law $\Gamma_r = -D_\perp (\partial n/\partial r)$ particle flux increases. This analysis indicates that our results obtained from 3D model agree with 1D mathematical relation for Plasma.

4. Summary and conclusions

Probe measurements and spectroscopic investigations of tokamak plasma reveal plasma variations in the Edge and SOL, a phenomenon that is poorly understood in many fusion-grade devices, such as the Aditya tokamak. In the Boundary of Aditya tokamak plasma, plasma flow and fluctuations are discussed, supported by prior 3D simulations and experimental observations. Plasma fluctuations and its related transport along and across the magnetic field line is analyzed and discussed from previous experimental and 3D simulation data on this machine. According to these analyses, when density increases in the edge region, the density gradient lowers, which in turn causes the overall perpendicular plasma flux to drop towards the wall and increase the particle transport time. However, at the limiter site, plasma transport and recycling flux increases. This study and discussion, which is based on 1D fluid plasma equations, partially validates earlier modeling and experimentation work done on this intricate fusion machine and gives valuable input for other plasma fusion devices.

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