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Progress of Physics Understanding in Steady State Tokamak Research
定常トカマク研究における物理的理解の進展

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Tokamak showed an excellent plasma confinement capability with its symmetry but has intrinsic drawback with its pulsed operation with inductive operation. Efforts have been made in these 20 years to realize steady state operation best utilizing bootstrap current. In this review, progresses of understanding of tokamak physics related to steady state operation are reviewed to cope into the scientific feasibility of steady state tokamak fusion power system.

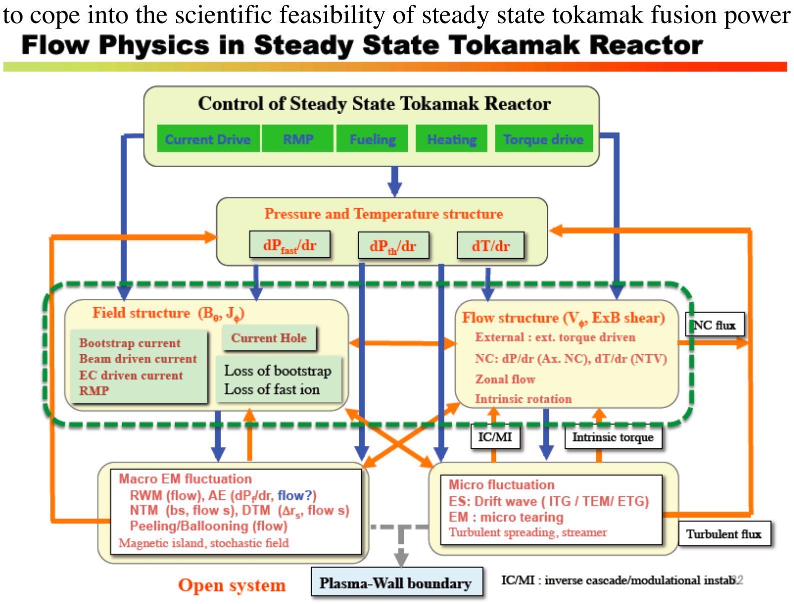

Fig. 1 Flow physics in the steady state tokamak reactor (From lecture in POSTECH, Oct. 5)
(Blue :feedforward, Orange: feedback, dotted green : region of flow physics)

1. Introduction

The tokamak is a front-runner in fusion research, which is the reason why the tokamak concept is selected for ITER. The tokamak has geometrical symmetry in the toroidal direction, which provides robustness in keeping nested flux surface against various parametrical changes [1] and good confinement leading to the achievement of equivalent break-even condition in large tokamaks such as JT-60U[2] and JET[3], and significant DT fusion power production in TFTR and JET[4]. While tokamak shows such superiority in plasma confinement, this symmetry is created by inducing the current in the high temperature plasma through transformer action [5]. Therefore, the operation of the reactor becomes pulsed if we can not develop efficient non-inductive methods to sustain plasma current. Since present power sources such as oil/coal/natural gas fired plants, fission plants operate continuously, it is highly desirable for tokamak reactor to be a steady-state power station. Review of non-inductive current drive methods shows needs for large power to sustain large plasma current for the reactor [6]. Nature blesses human being by providing an intriguing physical process, called bootstrap current to realize efficient steady state operation of the tokamak[7]. Utilization of bootstrap current is fundamental for the efficient steady state operation of tokamak reactor[8],[9]. Since then, extensive research initiatives to advance tokamak physics relevant for steady state operation has been started in tokamak researches such as JT-60U[10] and DIII-D[11] and called advanced tokamak research. Extensive experimental and theoretical works have been done for last two decades. In this presentation, brief introduction of magnetic confinement, the Steady State Tokamak Reactor, advanced tokamak operating regimes, collisional parallel transport in tokamak essential and critical for the steady state operation, ideal, resistive and kinetic MHD instabilities related to high bootstrap current fraction and the steady state are described. The transport properties in advanced tokamak regimes will be described as well [12], [13].

The inter-linkage of physics of steady state tokamak research is given in Fig.1 stressing role of flows on magnetic surface in tokamak physics.

2. Table of Topics

Following topics will be covered in the presentation.

1 Introduction
2 Magnetic Confinement Fusion
  2.1 Magnetic Confinement Topology
  2.2 Integrability and Symmetry
3 Steady State Tokamak Regime
  3.1 Steady State Tokamak Reactors
  3.2 Advanced Tokamak Research
    3.2.1 Weak Positive Shear Operation
    3.2.2 Negative Shear Operation
    3.2.3 Current Hole Operation
4 Parallel Transport in tokamak
  4.1 Collisional Moment Equation
    4.1.1 Moment Equation
    4.1.2 1st Order Flow
    4.1.3 Friction and Viscous flows
  4.2 Generalized Ohm's Law
    4.2.1 Generalized Ohm's Law
    4.2.2 Electrical Conductivity
    4.2.3 Bootstrap Current
    4.2.4 Neutral Beam Current Drive
    4.2.5 EC Current Drive
  4.3 Rotation Physics
    4.3.1 Neoclassical Rotations
    4.3.2 Neoclassical Toroidal Viscosity
5 MHD modes in AT regime
  5.1 Progress in linear ideal MHD
    5.1.1 Spectral Property in MHD
    5.1.2 2D Newcomb Equation
    5.1.3 Flow effect on ideal MHD
  5.2 Resistive MHD modes
    5.2.1 Classical tearing mode
    5.2.2 Neoclassical tearing mode
    5.2.3 Double tearing mode
    5.2.4 Resistive Wall Modes
  5.3 Localized MHD
    5.3.1 Ballooning and Peeling modes
    5.3.2 Infernal modes
    5.3.3 Edge localized mode
    5.3.4 Barrier localized mode
  5.4 Alfven Eigenmodes
    5.4.1 Wave-particle interaction
    5.4.2 Toroidal Alfven Eigenmode
    5.4.3 Linear mode structure
    5.4.4 Non-linear behavior
    5.4.5 Flow effect
  5.5 Stability of Current Hole
    5.5.1 Equilibrium Bifurcation
    5.5.2 Ideal Stability
    5.5.3 Resistive Stability
6 Turbulent Transport in AT regime
  6.1 Understanding L-mode
    6.1.1 Drift Wave Turbulence
    6.1.2 Self-organized criticality
    6.1.3 Magnetic shear and turbulence
  6.2 Turbulence suppression mechanism
    6.2.1 General flow shear suppression
    6.2.2 Equilibrium flow shear
    6.2.3 Zonal flow and GAM
  6.3 Internal transport barrier
    6.2.1 ITB in NS
    6.2.2 ITB in WPS
  6.3 Pedestal transport
    6.3.1 GAM/Zonal flow in L-H transition
    6.3.2 Transport between ELM
    6.3.3 Pedestal width
6.4 Particle and impurity transport
    6.4.1 Neoclassical impurity transport
    6.4.2 Turbulent impurity transport

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