International Journal of Innovative Technology and Exploring Engineering (IJITEE)
ISSN: 2278-3075, Volume-8 Issue-8 June, 2019

A Review: Theory of Plasma Disruption and Prediction in Tokamak

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Abstract*: *The tokamak consists of a series of superconducting magnetic loops in a toroidal chamber that confine and control plasma to generate electricity. Plasma disruptions are rapid results at tokamak that lead to loss of power and magnetic energy stored in the chamber. During disruptions the confinement of plasma is lost within milliseconds where, it provokes severe damages to chamber by releasing extreme forces and heat loads. In this case the last measure to mitigate the effect is injection of pellets or gas in to the chamber vessel. A fundamental knowledge is a pre-requisite to know when to use them to avoid disruption. Theoretical focus is made on two major disruption scenario 1. When does the loss of control becomes likely for a tokamak that is operating in a metastable state? 2. What is the lowest possible level at which we lose plasma control and how the severity of these effects be reduced? The paper shows the theory of tokamak disruptions, tendency to disrupt, avoidance studies, effects of disruption and current disruption prediction techniques.

Keywords: Tokamak, magnetic field, Plasma, magnetic island, signal processing, machine learning.

I. INTRODUCTION

Acatastrophic loss of plasma control is known as disruption, which leads to plasma extinguishing and a large power impact loads over the plasma chamber. In a tokamak reactor these loads results in a possible harm to the chamber and machine itself, hence avoiding such disruptions is beneficial. The success of future tokamak and ITER [1,2] depends on the precision with which the disruption control can be achieved. Exploration of plasma in ITER with high fusion potential need knowledge to preclude based on two major questions 1. When does the loss of control becomes likely for a tokamak that is operating in a metastable state? 2. What is the lowest possible level at which we lose plasma control and how the severity of these effects be reduced?

It is not possible to determine what are the minimal constraints required on plasma operations for disruption avoidance purely from disruption statistics. There is a need for guidance from theoretical operations too. The situation is analogous to the efforts made to identify how fast a car is driven during rainy conditions only with statistical data with count of trees that have fallen in the last one mile. Runaway electrons produce a high destructive power of disruption which requires a technique to reduce the possible effects. However, a mitigation methodology is never a substitute for preventing disruption similar to how a parachute in a plane is never an alternative for a proper landing. There is need for improvement of Tokamaks in means of technology and theoretical guidance should be engineered, so the control system can avoid disruption. Effects and avoidance of disruption are far from the existing capabilities for answering based on theoretical guidance, ITER works [3,4,5] on axisymmetric simulations despite the theoretical and empirical importance of magnetic islands and non-axisymmetry. The dependence on resistance of halo current, island width and disruption effect parameters are not calculated and their physical situation parameters are also not understood. A partial Halo current flows in the plasma beside the magnetic field lines that penetrate the walls. When this flow is strongly toroidally asymmetric, it results in forces that are disruptive.

The force balance equilibria lead to Plasmaevolution, during disruption. The fastest time scale is millisecond, but still is about multiple of times lengthier than an Alfvén time ($\frac{R_0}{V_A} \sim 1\mu s$) and lengthiest duration is in order of seconds. The disruption simulation can be iterated using two types of solution:

i) Finding force balance equilibrium for a specified external magnetic fields and plasma profile
ii) The external field and profile evolution.

For disruption studies and simulation, the safety factor and pressure of plasma profile are not only the profiles but also the magnetic islands width cross section with in the plasma is needed. A tight intertwining[6-10] of transport calculation and equilibria are important for studying disruption in axisymmetric simulation of ITER disruption along with force balance and non-axisymmetric simulation including magnetic islands. Plasma parameters are specified heuristically rather than determination based on boundary conditions.

An important constraint has been provided by Zakharova[11] on disruption effects:

i) During disruption the plasma evolve slowly relative to Alfvén time or else in magnetic field lines a high voltage level would ascend on the plasma to reinstate force balance.
ii) plasma displacement from its equilibria position determine the sign and strength of current in magnetic lines
iii) To preserve force balance, n=1 kink ascends when control of tokomak position in hot plasma is lost and plasma outer parts are peeled away in surrounding structures through seizure.

This paper is formulated as follows. Section 2 explains the physics of disruption, section 3 throws some light upon Disruption Avoidance, section 4 consists of disruption prediction techniques and section 5 provides the discussion and summary.

II.PHYSICS OF DISRUPTION

Plasma disruptions produce rapid results at tokamak that lead to loss of control and magnetic energy stored in the

Revised Manuscript Received on June 07, 2019

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tokamak. The major factors which determine the disruption in magnetically confined plasmas are: 1. The robustness when plasma is magnetically restricted at center and 2. The magnetic surface which encloses the plasma. These two major factors are found to be the empirical causes for tokamak disruptions, when Joint European Torus (JET) disruptions were recently reviewed: "the disruptions at JET[12] were ultimately pushed close to an operational limit resulting in the onset of physics instabilities". In case of unplanned disruptions, edge radiation instabilities (51.8%), growth of internal kink modes (4.4%), mode locking (20.1%), vertical position instability (3.9%), and too low a safety factor (q ~ 2) (2.5%) carry the major share of disruptions. The disruptions triggered by the locked mode can be alienated as low-profile error in field modes (10.3%), neoclassical tearing modes (NTMs) (6.7%) and through too fast current ramp-up edge kink instabilities form locked modes by (3.1%).

A. Plasma centering

To confine the hot plasma at chamber's center a vertical magnetic field is utilized. The plasma state highly influences the magnetic field. A disruption is caused when the internal state of the plasma undergoes a rigorous change or when the feedback system that controls the plasma centering experiences any technical problem which could result in an unmanageable vertical displacement of hot plasma along chamber walls [13].

A large aspect ratio tokamak with a circular cross section has an influence on plasma state on the vertical field can be quantitatively expressed as,

$$B_v = -\frac{\mu_{0I_p}}{4\pi R_0}\left(ln\frac{8R_0}{a} + A - \frac{1}{2}\right)$$

Where,

Ip - Net toroidal plasma current

R_0 – Major radius of the plasma

a - Minor radius of the plasma

$2\mu_{0\langle p(r)\rangle / B_p^2}$ - Poloidal beta

Bp- Poloidal magnetic field at the plasma edge

I_i - Internal inductance is a coefficient within a factor of roughly two of unity

When I_i is larger the plasma current is more strongly peaked towards the plasma centre. For managing the plasma performance, the currents passed in coils above and below for attracting the plasma current and repelling them on sides is balanced by the non-circular cross section in tokamak. Magnetic fields penetrate the surrounding chamber wall due to unstable plasma created by vertical displacements.

B. Magnetic surfaces

In an axi-symmetric tokamak the magnetic surfaces are perfect but, breaking of parts in thousands of that symmetry would terminate the surfaces and make a loss in controlled plasma. The magnetic surfaces are sensitivity to perturbations is a consequence of magnetic field. Resonant perturbations alone break the magnetic surfaces in non-axisymmetric tokamaks. The destruction of magnetic surfaces and resonant magnetic perturbations growth are subtle[14-19] to, 1) magnetic surface of the radial profiles parallel current $K_0(r) \equiv \mu_0 \langle \frac{j_{\parallel}}{B} \rangle$ and pressure, p(r) 2) plasma rotation, 3) bootstrap current and 4) non-axisymmetry external drives.

In tokamak plasmas the magnetic islands grow naturally resilient, when an island size overlaps the safety limit the resulting loss of confined energy is known as thermal quench. The magnetic surface loss is initiated empirically by, a) Greenwald limit- exceeding the plasma density b) rapid plasma cooling and c) a large pressure gradient formed by an internal transport barrier (ITB). Plasma cooling and density limit worsens the plasma stability faster as a source of disruption.

Outside plasma currents two inter-related effects known as resistive wall mode (RWM) and error field, which has the ability to degrade the magnetic surfaces and lead to plasma disruption. The error field corresponding to amplification of plasma can be strong cause for resistive wall mode. In fusion plasma a feedback system is required to maintain a stable vertical instability where it also plays major role in RWM's, which are kink instabilities resistive of the chamber walls.

C. Tendency to disrupt

Magnetic surfaces and plasmaposition are related with two major features responsible for plasma disruption: 1) thermal quench followed by current quench and 2) vertical displacement. Plasma generally collides with the tokamak walls if there is a vertical displacement with Low- resistivity. When plasma has stripped the chamber walls the safety factor $q_{edge} \sim 2$and kink destroy the magnetic surfaces creating a thermal quench rapidly. In case if thermal quench launches first, the coils providing vertical field will be far from required value such that plasma is showered into chamber walls which are penetrated by magnetic fields and also the q_{edge} may decrease or increase depending on the resistivity profile in plasma.

In tokamak like axisymmetric system the design is chosen between,

High disruption

1. To ease choice design of axisymmetric magnetic field is fixed.

2. Complicate the design

a. feedback system is technically challenging

b. demand is high on components facing the plasma

Low disruption

1. To ease design a no feedback system with steady state magnetic field is chosen

2. Design is complex by selecting axi-symmetric magnetic field with of 10 to 20%

III. AVOIDANCE

Plasma steering and failsafe engineering are the counteracting measure for the axisymmetric tokamak from disruption. Vigilant plasma steering in the tokamak must ensure that plasma does not enter a state in which it's uncontrollable and cause for disruption. The feedback system should operate without any latency or interruption to ensure failsafe engineering and no impurities should fall in plasma that might result in plasma rapid cooling.

For a successful plasma steering in a tokamak from disruption avoidance requires three major elements to be addressed 1. A satisfactory information must be provided by the diagnostic system to guide the plasma steering 2. A controlled modification method in the plasma state during the steering and 3. Advanced mechanism to handle the diagnostic information's for applying modifications in the plasma state.

A tokamak to progress into an uncontrollable state the time scale is always in order of magnitude longer than Alfvén time, it's the time for a force-balance equilibrium and the evolution often takes place in the order of second. In DIII-D it takes half a second between the time rotation stops and the current quench is instigated. The plasma equilibrium is described as a state of plasma force balance; however, the plasma is far from thermodynamic equilibrium is a common meaning for equilibrium in physics.

A. Force-balance solver

The disruption avoidance question does not exist for force-balance solver but it's a feasible one if the codes meet the appropriate requirements. (a) To compute the plasma equilibrium for the islands of a known size - the creation of magnetic islands is one of the vital components for attaining a non-manageable distracting state in tokamak. (b) Particular peripheral constraints for external magnetic fields instead of plasma shape, it may show the way to control failure in time scales and a real-time control of tokamak to avoid disruption. The outer magnetic fields can be appointed by giving the magnetic field to first and foremost wall or the external currents to the plasma. This process makes the force-balance and outer magnetic development is much easier to grasp the knowledge and find out the inference study.

Park has initiated a modification in his IPEC[20] (i.e., Ideal perturbed equilibrium code) which rectifies the problem for the equilibria by giving attention to the continuity equation model to axisymmetry tokamak byincorporating narrow magnetic islands $\delta_1 \ll a$, which has an arbitrary width. The code that calculates the force-balance solver with specified island widths are addressed by calculating equilibria non-perturbatively. The pre demonstration was given by Betancourt for estimating of equilibria with at least one island. The PIES [21-23]discussed the method of placing currents near rotational surfaces to be in command of the island's width. The different moment variations in equilibria code are compared with SIESTA code that allows the calculations of islands. The stepped pressure equilibrium code (SPEC) by Stuart Hudson aims to support the inclusion of specified island width which is related to VMEC. The HINT code permits stochastic region and islands for a force-balance solver.

B. Evolution of Plasma and magnetic island

Equilibrium solver is less complicated when compared to plasma evolution solver where it requires more physics. Transport effects need to be addressed in an enormous manner for simulating the standard tokamak in control. The outcome of the impurities from the walls can be utilized for controlling the temperature of plasma and the recent profiles in tokamak. Most discussions on evolving usage of impurity effects are raised in disruption effects and mitigation

Magnetic island evolution exists in the tokamak when plasma is non-rotating and the drive for islands is weak as per Rutherford equation. The early phase for understanding disruption evolution will require a knowledge on islands from opening beyond a narrow width, $\delta_1 \sim \rho_s \equiv \frac{C_s}{\omega_{ci}}$, Where $C_s = \sqrt{T_e + T_i}/m_i$ is the sound speed and ω_{ci} is the frequency of ion cyclotron. Both of them require a kinetic treatment and involve hysteresis to drive the islands in order to eradication of bootstrap current. If δ_1 is the magnetic islands semi width and m is mode number of poloidal fields with resonant surface r_r , it will be rapid and deviate strongly during reconnection from Rutherford if $\delta_1 < \left(\frac{m}{r_r}\right)\delta_d^2/4$, where δ_d is half width of the magnetic island if the currents near the resonant surface is nulled having all other fixed.

The large magnetic island presence reduces the magnetic surfaces and also affects non-intrinsically am bipolar transport, this task may stop the motion in plasma and also a large deviation in particles having collision-less trajectories from the magnetic surfaces.

D. External evolution of magnetic-field

During the process of plasma profiles, radiating impurities, plasma pressure, motion and magnetic island widths-external evolution of magnetic fields must also be included for the boundary condition for equilibrium solver. Based on the ohm's law the external magnetic field also involves currents flowing in conducting surfaces. The combination of faradays law and ohms law imply the normal field to a conductor as. This review completely based on progression of external magnetic field is feasible.

IV.DISRUPTION PREDICTION IN TOKAMAK

Magneto hydrodynamics study for disruption prediction has grown drastically in recent years. The approach for disruption prediction of large scale MHD instabilities are carried out using signal processing techniques and machine learning methodologies. The signal processing approach is used to study and predict the disruption earlier for magnetic islands and MHD issues. The mirnov coil signals, Rake probe signals and soft X-ray are the major constituents of input to the signal processing algorithms. The signals collected from mirnov coils are of non-stationary and non-linear in nature so, traditional time-frequency analysis techniques cannot be used. The empirical mode decomposition, time varying filter empirical mode decomposition and variational mode decomposition are recent techniques for disruption prediction by applying singular value decomposition SVD technique to find the poloidal magnetic field and mode numbers.

The advanced machine learning techniques[24-27]has been significantly increased in the recent years. The main objective of using machine learning technique is to determine how early a disruption can be predicted using raw data. A series of supervised and un-supervised learning techniques have been categorized to predict disruption and the current advanced techniques like deep learning has also been utilized to predict disruption earlier for large database tokamak. The basic parameters for machine and deep learning for disruption prediction in tokamak are mentioned below,

Signal/ feature from tokamak	Units
1.plasma current	A
2.poloidal beta	s^{-1}
3.mode lock amplitude	T
4.safety factor 95%	s^{-1}
5.total input power	W
6.plasma internal inductance	s^{-1}
7.plasma density	m^{-3}

These are the signal derivatives used in major for disruption studies in tokamak using artificial intelligence techniques.

V. DISCUSSION AND SUMMARY

Thetheoretical study on disruption prediction must concentrate on three major phenomena: 1) design and development of a computational tool for effects estimation and disruption avoidance, 2) new experiments to be carried out on disruption studies on empirical basis and 3) invention of new strategies for mitigating disruption and avoiding it.

Simulation code for disruption studies should put additional effort on calculation of micro turbulent steroidal damping. This paper explains the 1) the major constraints existing during the manifestation and onset of disruption, 2) computational methodologies applied in current disruption prediction systems. Even though the knowledge on disruption studies have grown extensive but still both empirical and theoretical knowledge is still lagging for higher order tokamaks and comprehensive code for simulation of disruption study. The future focus should be on selection of basic plasma principle that can be achieved by tool should be selected to fit our expectation instead of work to fit the tool.

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