Chapter 1

Introduction

(Tokamak, EC waves and ECRH system)

The Studies on quasi-optical launchers (QoLs) for Gyrotron based ECRH systems and its application to Plasma is a part of research work carried out in the field of ECRH launchers used in tokamak plasma. We are familiar with three state of matters: solid, liquid and gas but there is a fourth state of matter called Plasma, which is identified by Sir William Crookes (English physicist) in 1879. In the universe, almost 99% matter is in plasma state. The Plasma is a collection of charged and neutral particles, if gas particles are heated up with sufficient amount of energy (more than its ionization potential), it breaks into ions and electrons. Then the behaviour of this ionized gas becomes entirely different from solid liquid or gas and this state is known as plasma. The word "PLASMA" was first applied to ionized gas by Dr. Irving Langmuir, an American chemist and physicist, in 1929. As the plasma consists of charged particles, the slow and heavy ions are surrounded by fast electrons and due to this localised accumulation of charge particles, finite electromagnetic forces develop in plasma. These forces affect the other charged particle at remote, which is known as collective behaviour of plasma. In spite of the existence of localized charge accumulation and electric potentials, a plasma is electrically "quasi-neutral," as there are approximately equal numbers of positively and negatively charged particles, so net charge in plasma is zero. Thus the plasma is known for its collective behaviour with quasi-neutrality [1].

The studies on plasma are directly relevant to fusion energy, which is an environment friendly future source of energy. The fusion of hydrogen isotopes (deuterium and tritium: D-T) delivers million electron volt energy (17.6MeV), which can be controlled and used as a main source for power generation in nuclear fusion reactor. The main criteria to get successful energy from fusion depends on the three parameters (*n*: density per meter^3, *T*: temperature in keV and ^{2}*:* confinement time in seconds). In order to achieve Ignition successful, the triple product - nT^2 should be greater than 5 x 10^{21} m^{-3}s keV . Thus in order to achieve the ignition criteria, the sufficiently heated charged particles have to be confined for required duration to achieve the condition of ignition criteria. There are mainly two types of confinement mechanisms for fusion plasma : Inertial confinement and Magnetic confinement. The inertial confinement is related to laser or pellet fusion while in magnetic confinement plasma is confined using magnetic field. There are several devices being explored for the magnetic confinement of fusion plasma like tokamak, stellarator, magnetic mirrors and reverse field pinch (RFP) etc. The tokamak configuration is one of the most-researched candidates for producing controlled thermonuclear fusion power to make a fusion reactor.

1.1 Tokamak: The tokamak [2] is the most researched and widely accepted magnetic confinement system for the design of fusion reactors. It was invented in the Soviet Union during the 1960s and soon adopted by researchers around the world. Tokamak is a descriptive Russian words **to**roidalnaya **ka**mera **ma**gnitnaya **ka**tushka (toroidal chamber with magnetic coil). The tokamak as shown in figure 1.1 can be explained in detail as follows:

- The tokamak is toroidal vacuum vessel which contain plasma. The ultra high vacuum in the vessel is maintained by external pumps. The plasma is created by small puff of gas and then it is heated by driving a current through it.
- In the tokamak, the plasma is confined by magnetic field, which maintain plasma away from the machine walls. There are two types of magnetic field coils used in tokamak: toroidal and poloidal. The combination of toroidal and poloidal field generate a magnetic cage to hold and shape the plasma.
- In tokamaks, there is enormous need of power supplies to generate the magnetic fields and plasma currents.
- The Plasma current in tokamak is induced by a transformer. The central magnetic coil acts as the primary winding and provide required loop voltage for breakdown. In this transformer action, the plasma works as a secondary winding. The heating provided by the plasma current (known as Ohmic heating) supplies up to a third of the 100 million degrees Celsius temperature required to make fusion occur. Since the efficiency of ohmic heating reduces with temperature, additional heating is required for necessary plasma heating and current drive.
- The additional plasma heating is provided by neutral beam injection (NBI). In this process, neutral hydrogen atoms are injected at high speed into the plasma, ionized

and trapped by the magnetic field. As they are slowed down, they transfer their energy to the plasma and heat it.

- The Radiofrequency heating (RF) is also used to heat the plasma. There are various RF system used in tokamak to heat electron or ion. The electron cylotron resonance heating (ECRH) is used to carry out breakdown, heating and current drive in tokamak plasma. The ion cyclotron resonance heating (ICRH) is used to heat ions while lower hybrid current drive (LHCD) is used for steady state current drive in tokamak.

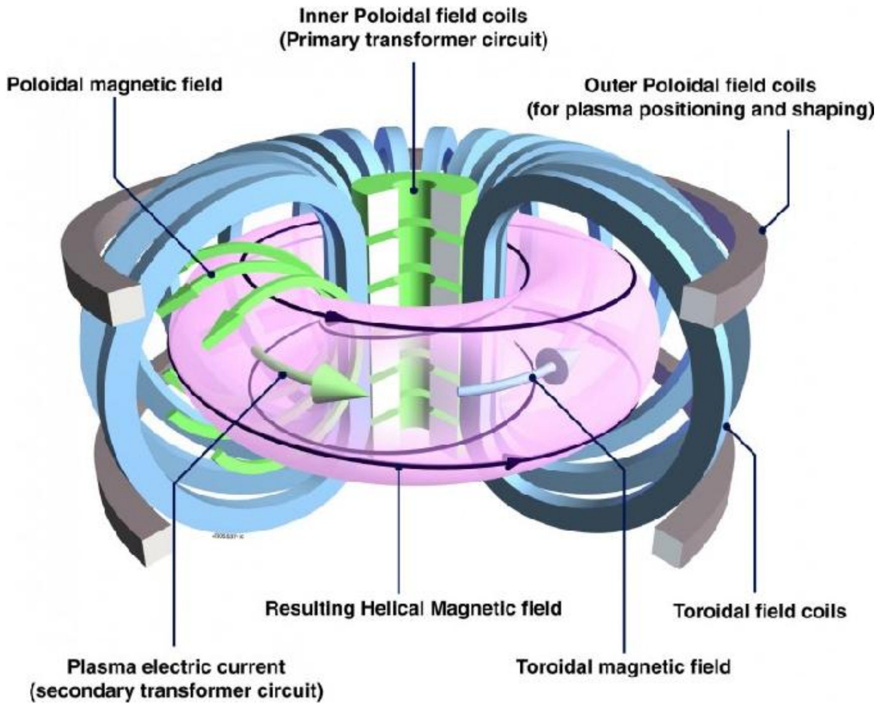

Figure 1.1 (Schematic of Tokamak with plasma)

Steadystate Superconducting tokamaks and requirement of assisted breakdown: In order to achieve steady state operation of tokamak, the choice of superconducting magnet system becomes a priority as resistive magnet would require too much electrical power and it would not be a feasible solution. So superconducting steadysteadystate tokamak is a mandatory basic design for a fusion reactor. For superconducting tokamak, there is a limitation in ohmic breakdown as fast change is the primary of ohmic transformer is not desirable because it may trigger a quench in the magnet system. So in order to achieve a reliable breakdown in superconducting tokamaks, an additional heating system alongwith ohmic is required for pre-ionization and breakdown to assist the ohmic start-up at lower loop voltage. In the tokamaks, electron cyclotron resonance heating (ECRH) is widely accepted heating system for pre-ionization, breakdown and reliable start-up. In ECR heating, the high power EC waves launched in tokamak, which interacts with electrons transfers energy through resonance process. The EC wave propagation in plasma is discussed in next section.

1.2 EC wave propagation in tokamak plasma: In many tokamaks [3-17], the ECRH has shown enormous advantage related to plasma breakdown, reliable start-up, heating, current drive and (MHD) instability control etc.. The EC (electron cyclotron) waves interact directly with electrons and transfer energy through resonance processes. The seed electrons available in the tokamak passes through ECR region, gain high energy (~1keV) [18], these high energy electrons collide with neutral gives pre-ionization in plasma. Since the pre-ionized plasma already consists of more number of high energy electrons, loop voltage requirement is reduced significantly for reliable breakdown in tokamak. Thus pre-ionization with ECRH helps in getting successful reliable breakdown in tokamak at lower loop voltage. There is possibility of error field in tokamak, the ECRH assisted breakdown also helps in successful breakdown even at higher error magnetic field. The operating pressure window is also widen with ECRH assisted breakdown in tokamak.

The electron cyclotron resonance heating (ECRH) transfers energy to the electron at cyclotron resonance ($\mu = \mu_{ce}$) and upper hybrid resonance (μ = Ě($\mu^2_{ce} + \mu^2_{pe}$). There are two modes propagate in a magnetised plasma, ordinary (O-mode) and extra ordinary (X-mode). The O-mode corresponds to *E* field parallel to toroidal magnetic field B_T of tokamak while X-mode corresponds to *E* perpendicular to B_T. In a homogeneous plasma the two possible wave modes are given by well known Appleton Hartree dispersion relation [19-22], for a wave propagating at an angle θ to the toroidal magnetic field B is :

$$N^2 = \frac{c^2k^2}{\omega^2} = 1 - \frac{2\alpha\omega^2(1-\alpha)}{2\omega(1-\alpha)-\omega_{ce}^2 Sin\theta \pm \omega_{ce}\Gamma} \qquad (1.1)$$

where dZxμ_{ce} *sin*$^{4—}$H 4μ^2 (1 J~)^2 *cos*$^{2—}$z$^{1/2}$

and ~ Z μ^2_{pe} / μ^2

The + sign is for Ordinary mode where as – sign is for extraordinary mode. *k* is the propagation vector, μ is operating frequency, μ_{ce} is electron cyclotron frequency, μ_{pe} is plasma frequency (in rad./sec), *N* is the refractive index and ¯ is the angle between propagation vector and magnetic field.

The propagation of electron cyclotron can be easily seen for specialized case of perpendicular launch ($\theta = \pi/2$) and the above equation (1.1) can be simplified as:

The Ordinary mode is independent of magnetic field & the dispersion relation is given as :

$$N^2 = \frac{c^2k^2}{\mu^2} = 1 - \frac{\omega_{pe}^2}{\omega^2} \qquad (1.2)$$

The dispersion relation for the extraordinary mode is :

$$N^2 = \frac{c^2k^2}{\mu^2} = \frac{[\omega(\omega-\omega_{ce})-\omega_{ce}^2][\omega(\omega+\omega_{ce})-\omega_{ce}^2]}{\omega^2(\omega^2-\omega_{pe}^2-\omega_{ce}^2)} \qquad (1.3)$$

From the above expression it is clear that in case of O-mode, the wave will propagate until the density reaches the point $\mu_{pe} = \mu$. So in this case for the ordinary mode density limits are defined as

$$\mu_{pe} < \mu_{ce} \qquad \text{(for fundamental harmonic)} \qquad (1.4a)$$

and

$$\mu_{pe} < 2\,\mu_{ce} \qquad \text{(for the second harmonic)} \qquad (1.4b)$$

The behaviour for X-mode is slightly complicated since there exists a cut off where $N = 0$ and an upper hybrid resonance (UHR) where $N = \propto$. The density limit (cut-off) for X - mode can be given as:

$$(\mu^2_{pe} - \mu^2)^2 = \mu^2_{ce}\mu^2$$

The condition for upper hybrid resonance is given as

$$\mu_{uh}^2 = \mu^2_{ce} + \mu^2_{pe} \qquad (1.5)$$

In the tokamak geometry the ECR resonance layer, upper hybrid resonance layer and cut-offfor ordinary and extraordinary mode are shown in figure 1.2

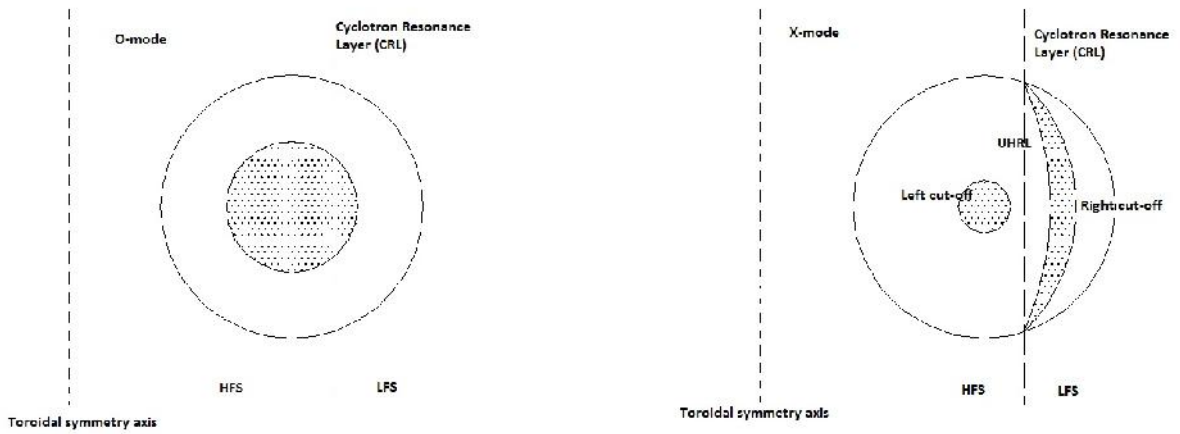

Figure 1.2 (ECR Resonance and cut-off in tokamak for O- and X-mode)

This propagation of ECR waves can be best summarised by the Clemmow-Mullay-Allis (CMA) [19-22] diagram (Figure 1.3) which shows effective relation between density and toroidal magnetic field. The shaded region shows cut-off for extra ordinary mode, with the help of this CMA diagram we can find the access of mode launch in tokamak (O-/X-mode from low field side LFS or from high field side HFS) and calculate the density limits for various launch modes.

As the fundamental X-mode launch from low field side cannot propagate as it face cut-off before it reaches to cyclotron resonance layer, so fundamental X-mode is only accessible from high field side and density limit for fundamental X-mode are defined as:

$$\omega^2_{pe}/\ \omega^2_{ce} < 2 \qquad (1.6)$$

In order to launch X-mode from low field side, the other commonly used scheme is second harmonic ($\omega = 2\omega_{ce}$) which propagates from low filed side and does not face any cut-off. From the CMA diagram, it is clear that the second harmonic (corresponds to $\omega^2_{pe}/\omega^2_{ce} = 1/4$) is accessible from both the sides i.e. low field side (LFS) and high field side (HFS) but with different density cut-offs. From the LFS, the resonance must be reached before the left cut off is reached, giving the condition $\omega^2_{ce}/\omega^2 < 1/2$ when $\omega = 2\ \omega_{ce}$ i.e.

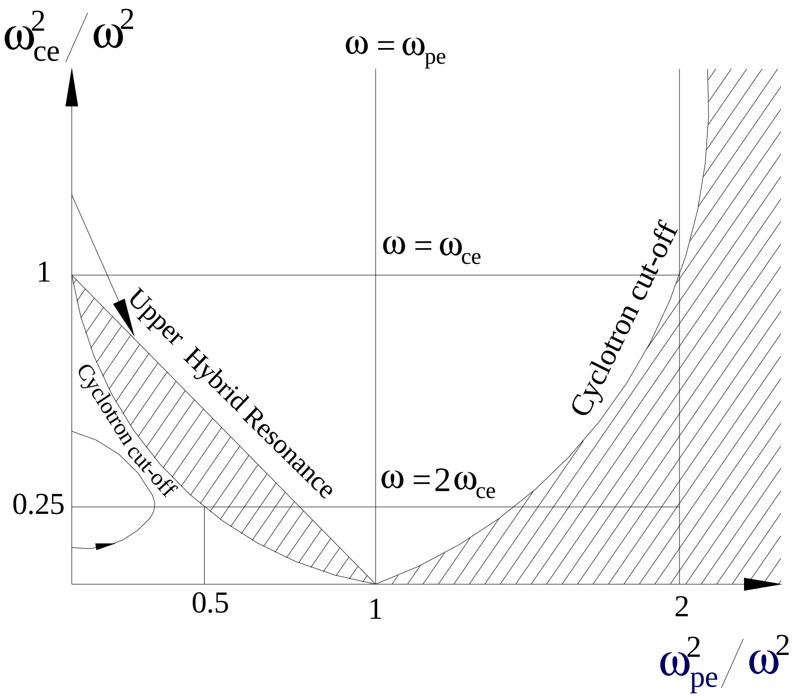

Figure 1.4 (CMA Diagram)

$$\omega_{pe}^2 < \omega^2 / 2 = 2\ \omega^2_{ce} \tag{1.7}$$

The density limit for second harmonic X-mode launch from high field side is defined as $\omega^2_{pe}/\omega^2 < 3/2$,when $\omega = 2\ \omega_{ce}$, the density cut-off appears at

$$\omega^2_{pe} < 3/2\ \ \omega^2\ =\ 6\ \ \omega^2_{ce} \tag{1.8}$$

The high field side (inboard side of tokamak) launch is not technically feasible in tokamak as installation of mirrors with steering mechanism is difficult to install and space on inboard side of tokamak is also a constraint. In this case low field side launch from radial port is a preferred launch for ECRH in tokamak. The fundamental O-mode and second harmonic X-mode are accessible to launch from low field side.

The fundamental ordinary mode (O1) launched from low field side reflects back from the inboard side of tokamak and changes its polarization as mixed polarization to ordinary and extra-ordinary modes (Figure 1.4). In this case, it becomes the case of fundamental X-mode launch from high field side, which faces first cyclotron resonance layer (CRL) deposits some energy and travels further to upper hybrid resonance layer (UHRL). At UHRL, there is mode conversion of X-mode to Electron Bernstein (EB) wave which is an electrostatic wave and absorbs efficiently in its first pass.

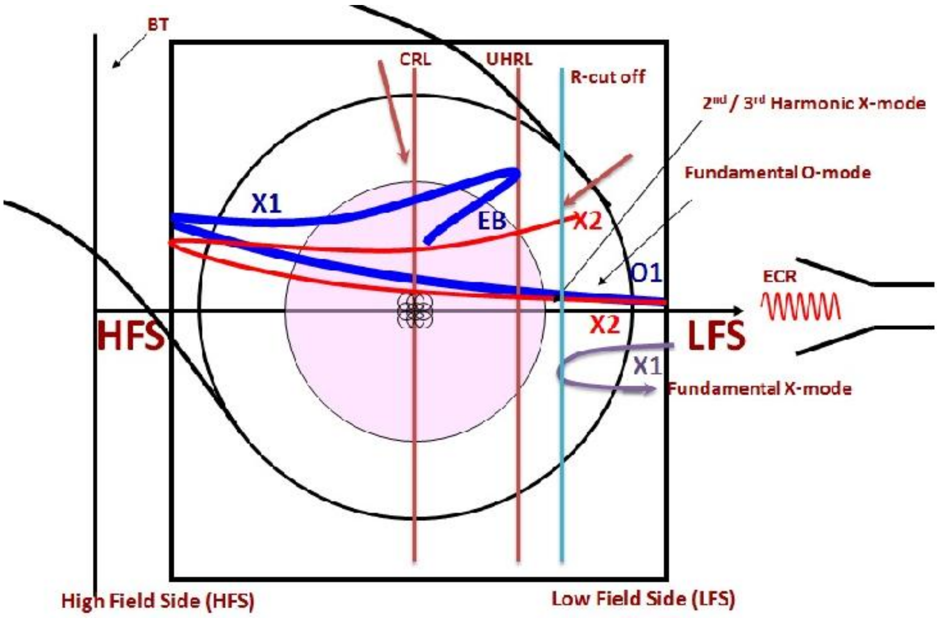

Figure 1.5

The second harmonic X-mode (X2) launched from low field side faces first pass absorption at cylotron resonance layer, at lower density and low temperature the absorption of X2 is not very efficient but it also reflects back from inner wall of tokamak. The X2 does not face the condition like upper hybrid or any mode conversion to EB wave but it also absorbs efficiently at higher density and temperature.

Thus in the tokamaks, the preferred mode of EC wave launch from low field side are fundamental O - mode (O-1) and second harmonic X-mode (X-2).

1.3 ECRH system in tokamak: The ECRH system (Figure 1.5) consists of high power microwave source (Gyrotron), corrugated waveguide based transmission line and quasi-optical launcher. The Gyrotrons deliver megawatt level continuous power at frequencies varying from 28GHz to 170GHz depending on the operating magnetic field. The circular corrugated waveguide based transmission line system is used to transmit high power from Gyrotron to tokamak. The other components of transmission line are matching optic unit, DC breaks, mitre bend with bi-directional coupler, polarizer, bellows and waveguide switches etc. The main advantage of oversized corrugated waveguides is low transmission loss (approximately 1% per 100 meter). The mode of propagation in these corrugated waveguidesis HE_{11}, which is a with plane polarized gaussian beam.

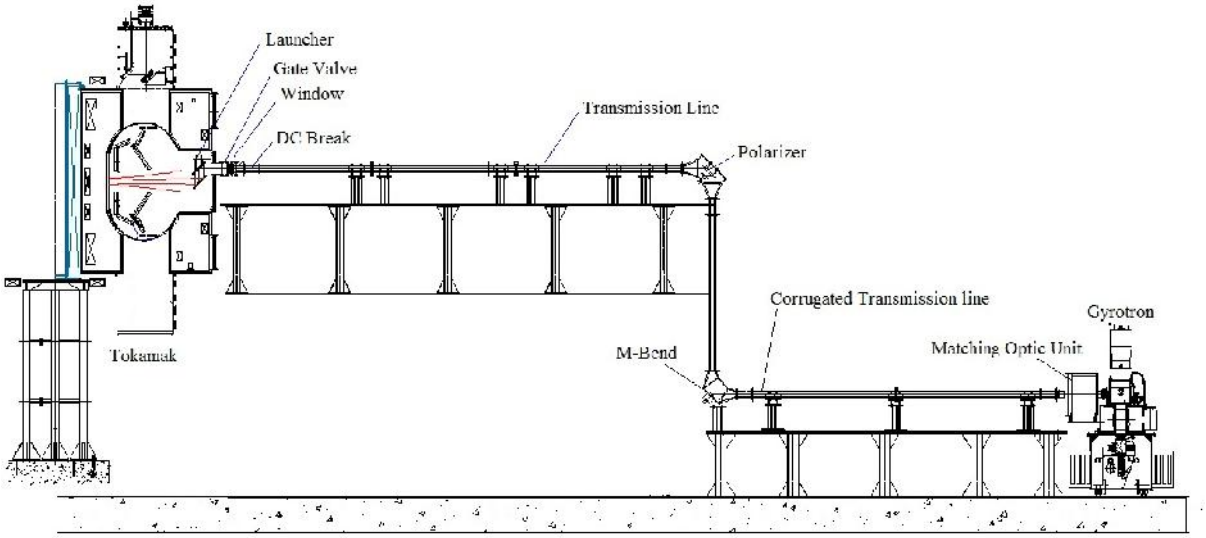

Figure 1.6 (Schematic of ECRH systen in SST tokamak)

In order to launch ECRH power in tokamaks, two types of launchers are used: mirror based conventional launcher and rectangular/square corrugated waveguide based remote steering launcher. The transmission line terminates with corrugated waveguide connected to a vacuum barrier window. Since the mode of propagation in corrugated waveguide is HE_{11}, which is plane polarized gaussian beam. Since the frequency of ECR wave is high, it can propagates in vacuum freely. This gaussian beam emerges out from the waveguide divergence with finite angle which depends on the frequency and beam size. In smaller tokamaks, the divergence is not a critical issue, the waveguide itself is used as a launcher and ECRH system is connected directly to tokamak using a window and UHV gatevalve. However, in case of bigger tokamaks, the mirror based quasi-optical launchers (QoLs) are required to launch focussed microwave beam in tokamak. Since the transmission line system connected to tokamak is not ultra-high vacuum (UHV) compatible, in this case ceramic or diamond window is used as vacuum break between UHV tokamak and transmission line. Thus a standard quasi-optical ECRH launcher consists of profiled and plane mirrors, vacuum barrier window and ultra-high vacuum (UHV) compatible gate valves. These launchers facilitate to focus and steer the beam in plasma volume for various plasma experiments.

The remote steering (RS)launcher consists of rectangular or square corrugated waveguide (SCW) of finite length alongwith a mirror assembly. The main advantage of RS launcher is to avoid the mirror assembly inside UHV tokamak and achieve beam steering remotely by placing the mirror assembly away from the tokamak.

In SST1 tokamak, 82.6GHz/200kW/CW and 42GHz/500kW/pulsed ECRH systems are used, while on Adityatokamak42GHz/500kW and 28GHz/200kW systems have been used to carry out various experiments related to plasma breakdown and tokamak start-up. Various launchers have been designed, fabricated, tested and commissioned on both the tokamaks Aditya and SST-1. The launchers have been characterized with low microwave power. The high power tests are also carried out for launchers. The research work on RS launcher using smaller length of waveguide is an innovative idea in this field and it is verified experimentally. The high power tests on chemically deposited diamond (CVD) are carried out for ECRH launcher in SST-1 tokamak. The 28GHz ECRH system on tokamak Aditya and 42GHz ECRH system on tokamak SST-1 and Aditya are used to carry out various experiments related to ECRH assisted breakdown at fundamental and second harmonic. The ECRH assisted plasma current drive in SST-1 tokamak is a new experiment carried by installing a focussed mirror on inboard side of tokamak. This idea helps not only in breakdown at lower loop voltage also in driving the plasma current in SST1 tokamak.

1.4 Structure of thesis:

The thesis describes the theoretical and experimental work on quasi-optical launchers for ECRH system and its applications to plasma breakdown and current drive in tokamak at fundamental and second harmonic. The organization of remaining chapters of this thesis is outlined as follows:

Chapter 2 describes the theory related to ECRH launcher and discusses about the design and fabrication of launcher for 28GHz ECRH system on tokamak Aditya. In Aditya tokamak, 28GHzECRH system is used to carry out experiments related ECRH assisted breakdown at fundamental harmonic. The ECRH launcher for Aditya tokamak consists of two profiled mirrors, one UHV Gate valve and one boron nitride window. The mirrors are designed using quasi-optical gaussian beam theory. The mirrors are installed in an UHV chamber, which is connected to radial port of tokamak. The entire launcher assembly with feedthroughs and gate valve has been tested separately for UHV (Ultra High vacuum) compatibility. After achieving the ultimate vacuum of 5×10^{-9}mbar, the launcher is commissioned to tokamak Aditya. The high power test of this launcher has been carried out with 28GHzGyrotronsystem and power is launched successfully in tokamak Aditya to carry out ECRH experiments.

(Pub.: Fusion Science and Technology, vol. 50, 4 Nov (2006) 551-560)

Chapter 3 describes the launcher for 82.6GHz ECRH system in tokamak SST-1. In SST-1, two types of launchers are designed at 82.6GHz frequency: Low Field Side (LFS) launcher to launch power from radial port of tokamak and High Field Side (HFS) launcher to launch power from top port. The main subsystems of ECRH launcher in SST1 are:

1) Specially profiled SS mirrors installed inside UHV compatible mirror box

2) CVD diamond window to provide vacuum isolation between tokamak and transmission line

3) UHV Gate Valve to isolate the system and protect the window during the boronization etc.

3.1 82.6GHz Low field side (LFS Radial port launcher) for SST-1: The Low Field Side (LFS) launcher consists of one plane and one focusing (spherical) mirror made of SS304L. The focusing mirror is fixed but it has provisions for adjustment during alignment. The plane mirror is connected with two UHV compatible linear motion feedthroughs to give the facility of steering the beam in poloidal as well as in toriodal direction. The maximum possible steering in either direction is $\pm 15^0$.The LFS launcher has been fabricated, characterized at low microwave power and tested for UHV compatibility.

3.2 82.6GHz High field side (HFS Top port launcher) for SST-1: The HFS launcher also consists of two mirrors one focusing and other plane. The focusing point for HFS launcher is the baffle of tokamak as it requires opening in baffle to launch ECRH power in plasma. *(Pub.: Fusion Science and Technology, vol. 45, 4 (2004) 549-557)*

3.3 High Power test of CVD diamond window for ECRH launcher in SST-1: The window is an important part of ECRH launcher, which serves as a vacuum barriers between UHV tokamak and transmission line. In SST-1, ECRH launcher consists of mirror assembly, UHV gatevalve and CVD diamond window. The high power test of CVD diamond window is carried out to ensure the reliable operation of tokamak window with the launcher. This is an advance technical work in the field of high power test of CVD diamond window for ECRH launchers.In order to test the CVD diamond window with dummy load, a matching optic unit is designed and fabricated. The high power test of diamond window is carried out using Gyrotron and the detail is discussed in the relevant section.*(Pub: IEEE Transactions on Plasma Sciences (TPS)**Volume:** 41, Issue: 7**Page(s):**1794-1798July 2013)*

Chapter 4 discusses about the remote steering launcher, which is also a new research in the field of ECRH launcher for tokamak. In the conventional ECRH launchers, beam steering for Current Drive is achieved by rotating the mirrors of launcher inside the tokamak, which is not very convenient in UHV environment with the mirrors with active cooling. An alternate to this conventional launcher is square-corrugated waveguide (SCW) based remote steering (RS) launcher. The idea of using square corrugated waveguide and achieve beam steering remotely is an interest of research in the field of RS launcher. The innovative idea of RS launcher at smaller length has been explored successfully and a prototype RS Launcher has been designed, fabricated and tested at 82.6GHz frequency. *(Pub.: Fusion Science and Technology, vol. 52, July 2007)*

Chapter 5 discusses on 42GHz/500kW ECRH system on tokamak Aditya and SST-1. The system capable to deliver 500kW power to carry out ECRH assisted breakdown, heating and current drive experiments on tokamak SST-1 and Aditya. The 75 meter long transmission line consists of two waveguide switches to operate the system on either tokamak. The detailed technical features of Gyrotron and transmission line system are discussed in this chapter. Since in SST-1, there are two ECRH systems (42GHz and 82.6GHz) used to carry out ECRH experiments at 1.5T and3.0T. So a composite launcher is designed to accommodate both the systems. This composite launcher consists of four mirrors (two focusing and two plane), two vacuum barrier windows and two UHV gate valves. This launcher has been commissioned on tokamak SST-1 and successful experiments are being carried out. *(IEEE Transactions on Plasma Sciences (TPS)* ***Volume:*** *40 , Issue: 4* ***Page(s):*** *1234 – 1238 April 2012)*

Chapter 6 discusses about the applications of ECRH launchers on tokamak Aditya and SST-1.The 28GHz, 42GHz and 82.6GHz ECRH systems are used in tokamaksAditya and SST-1 to carry out various experiments related to ECRH assisted plasma breakdown and start-up at lower loop voltage. **The ECRH power generated by Gyrotron is coupled to tokamaks (SST-1 and Aditya) with the help of quasi-optical launchers designed, fabricated and installed under this research work and various experiments are carried our related ECRH assisted breakdown and current drive.** The applications of ECRH launchers discussed in this chapter are summarized as follows:

ECRH assisted Breakdown in Aditya: In Aditya tokamak, 28 GHz ECRH system is used to carry out pre-ionization and start-up experiments. Approximately 50kW ECH power in fundamental O-mode is launched from low field side. The ECRH power is launched ~20ms before the loop voltage. The ECRH pulse duration is varied from 25ms to 40ms. The normal loop voltage required for breakdown in Aditya is ~24V. The successful discharge assisted with ECRH is achieved at~14V loop voltage. Thus approximately 40% reduction in loop voltage is observed for the shots assisted with ECRH pre-ionization.

The 42GHz ECRH system is also used in tokamak Aditya to carry out second harmonic ECRH assisted breakdown in tokamak at 0.75T magnetic field. The 42GHz ECRH system for Aditya consists of ~60 meter long transmission line to transfer power from Gyrotron to tokamak. Approximately ~100-150kW ECH power in X-mode is launched in various experiments and successful breakdown is achieved at lower loop voltage ~6V.

ECRH Assisted Breakdown in tokamak SST-1:In SST tokamak 42GHz/500kW ECRH system is used to carry out ECRH Assisted plasma breakdown at 0.75T and 1.5T operating toroidal magnetic field. Around 200-300kW ECRH power in second harmonic X-mode is launched from low field side using the composite launcher. The successful breakdown in SST-1 assisted with ECRH is achieved at extremely low loop voltage ~ 3 volt.

ECCD assisted plasma current drive in tokamak SST-1: In SST tokamak 42GHz/500kW ECRH system is used to carry out ECRH assisted plasma breakdown and current drive at 0.75T (Second Harmonic) and 1.5T (fundamental harmonic) operation. This is a new experiment carried out on ECCD assisted plasma current drive in tokamak SST-1. In order to carry out this experiment a profiled mirror is installed on the inboard side of tokamak, which reflects the ECR beam ~ 17^0angle to plasma current in co-direction. In second harmonic case, ECCD drives around ~ 10-15kA plasma current and helps in current ramp-up. In case of fundamental harmonic ECCD is further efficient and assists plasma current. We see the decreasing trend in plasma current with the end of ECR pulse. In SST-1 successful ECRH assisted discharges are achieved at 1.5T operation with plasma current ~ 75kA and pulse duration up to 325ms. In these shots approximately 220kW ECRH power is launched for 260ms. This is a remarkable ECRH experiment carried out in SST-1 which is explained in detail in relevant section.*(Pub.: Fusion Science and Technology, Jan 2014)*

Chapter 7 summarizes the work done in the field of Quasi-optical launcher for ECRH systems and discusses the advances experiments carried on tokamak SST-1 and Aditya. This chapter also discusses about the future work/scope in the field of conventional and remote steering launcher and its applications to plasma.