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42GHz ECRH assisted Plasma Breakdown in tokamak SST-1

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Abstract. In SST-1, 42GHz ECRH system has been commissioned to carry out breakdown and heating experiments at 0.75T and 1.5T operating toroidal magnetic fields. The 42GHz ECRH system consists of high power microwave source Gyrotron capable to deliver 500kW microwave power for 500ms duration, approximately 20 meter long transmission line and a mirror based launcher. The ECRH power in fundamental O-mode & second harmonic X-mode is launched from low field side (radial port) of the tokamak. At 0.75T operation, approximately 300 kW ECH power is launched in second harmonic X-mode and successful ECRH assisted breakdown is achieved at low loop_voltage ~ 3V. The ECRH power is launched around 45ms prior to loop voltage. The hydrogen pressure in tokamak is maintained ~ $1x10^{-5}$mbar and the pre-ionized density is ~ $4x10^{12}$/cc. At 1.5T operating toroidal magnetic field, the ECH power is launched in fundamental O-mode. The ECH power at fundamental harmonic is varied from 100 kW to 250 kW and successful breakdown is achieved in all ECRH shots. In fundamental harmonic there is no delay in breakdown while at second harmonic ~ 40ms delay is observed, which is normal in case of second harmonic ECRH assisted breakdown.

1 Introduction

The electron cyclotron resonance heating (ECRH) has shown several advantages from plasma start-up to MHD control in various tokamaks [1-9]. The 42GHz/500kW ECRH system is used in tokamak SST-1 [10] to carry out experiments related ECRH assisted breakdown and start-up at fundamental and second harmonic. The SST-1 [11,12] is a steady-state superconducting tokamak. The major radius of tokamak is 1.1m and minor radius is 0.2m. The operating toroidal magnetic field of SST-1 is 0.75T and 3.0T, however in the beginning phase of tokamak, it is operated at 0.75T and 1.5T magnetic fields. The SST-1 tokamak is equipped with all standard diagnostics to measure the plasma parameters like H_α, density, loop voltage, plasma current, soft X-rays, hard X-rays etc. The 42GHz ECRH system consists of Gyrotron, transmission line and a mirror based launcher. The Gyrotron is capable to deliver 500kW power for 500ms duration at 50kV beam voltage and 20A beam current. Initially, the Gyrotron is tested on dummy load, after successful testing at full parameters on dummy load, the system is connected to tokamak using corrugated waveguide based transmission line system. The transmission

line consists of a matching optic unit, DC break, 63.5mm diameter corrugated waveguides, bend with bi-directional couplers, polarizer and bellow etc. The total transmission loss in the line is less than 1.1dB.

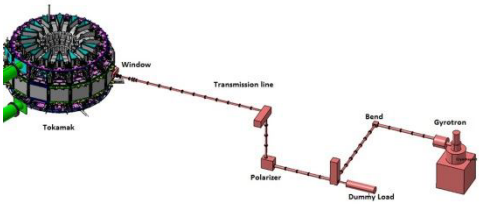

Figure 1 (42GHz ECRH system on tokamak SST-1)

The plasma breakdown and start-up experiments at fundamental and second harmonic are carried out in SST-1 using 42GHz ECRH system. At 0.75T operation, approximately 300kW ECH power is launched in second harmonic X-mode and successful ECRH assisted breakdown is achieved at low loop voltage ~ 3V. The ECRH power is launched around 45ms before the loop voltage. The hydrogen pressure in tokamak is maintained ~ $1x10^{-5}$mbar and the pre-ionized density is ~ $4x10^{12}$ cm^{-3}. At 1.5T operating toroidal magnetic field, the ECH power is launched in fundamental O-mode. The ECH power at fundamental harmonic is varied from 100kW to 250kW and successful breakdown is achieved in all ECRH shots. In fundamental harmonic there is no delay in breakdown while at second harmonic ~ 30ms delay is observed, which has been observed in other tokamaks also [1-3]. The detailed discription of 42GHz ECRH system and SST experiments is mentioned in relevent sections.

2. 42GHz ECRH system on SST1

The 42GHz ECRH system consists of high power Gyrotron, corrugated waveguide based transmission line and a mirror based launcher. The subsystem of ECRH system are mentioned as follows:

2.1 Gyrotron

The Gyrotron is procured from M/s. Gycom Russia, which delivers 500kW power at 42GHz frequency. The main operating parameters of Gyrotrons are beam voltage: –50kV, beam current: 20A, anode voltage: +20kV, cryomagnet current: 28.2A and filament power ~ 630W.

The Gyrotron system is equipped with two types of safety interlocks: fast interlock and slow interlock. The fast interlocks are arc, dI_{beam}/dt, beam over current, ion pump, while slow interlocks are cooling, filament and cryomagnet. The fast interlocks are hard-wired, which removes the high voltage from gyrotron within 10μs and slow interlocks operate within 100ms. A two series Ignitron based crowbar system is used for the safe and reliable operation of Gyrotron.

Figure 2 (Gyrotron system connected with Dummy Load)

The Gyrotron connected with dummy load is shown in figure 2. Initially the Gyrotron is operated at low power to monitor the normal operation of Gyrotron. Once the Gyrotron is conditioned with transmission line, the power and pulsed duration is increased to achieve the maximum parameters (500kW for 500ms duration). The typical parameters for 500kW power are: beam voltage: ~ –50kV, beam current ~19A, anode voltage: +20kV, cryomagnet current: 28.1A and filament power ~ 630W. The typical ECRH pulse (Gyrotron operation on dummy load) at full parameters is shown in figure 3.

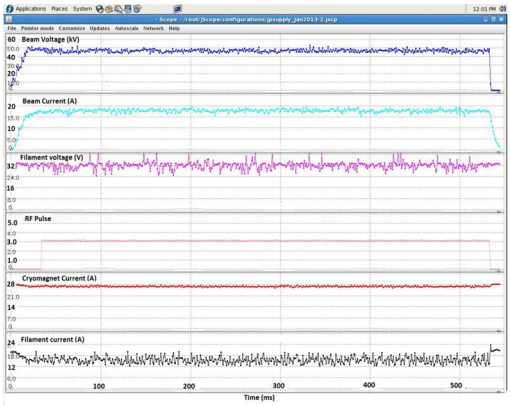

Figure 3 (500kW-500ms shot)

2.2 Transmission line

The transmission line consists of a matching optic unit (MOU), two DC breaks, mitre-bend with bi-directional coupler, polarizer, circular corrugated waveguide (inner diameter ~ 63.5mm), bellows and two waveguide switches.

Figure 4 ECRH Transmission line connected to SST-1 tokamak

The first switch connected in the line facilitates to operate the gyrotron on dummy load or to launch the power in the tokamak, while the second switch gives an option to launch power either in tokamak SST-1 or in tokamak Aditya [10,13]. The total length of line for ECRH system on SST-1 is ~20 meters and total transmission loss of line is less than 1.1dB. The transmission line connected to tokamak is shown in Figure 4.

2.3 Launcher

There are two ECRH systems 42GHz-500kW [10] and 82.6GHz-200kW [11,12] used used in SST-1 to carry out ECRH experiments at 0.75T, 1.5T and 3.0T magnetic fields. A composite launcher with four mirrors has been designned and fabricated to connect both the systems. The schematic of launcher is shown in figure 4. The distance between plasma centre and plane mirror is 900mm. The mirror size for 42GHz ECRH systems are 170mm x 240mm, the focal length of mirror for 42GHz system is 353mm. The mirror's size for 82.6GHz launcher is 140mm x 200mm and focal length for mirror is 481mm. The beam size at plasma centre for 42GHz launcher is 35mm (1/e beam radius) and for 82.6GHz it is 20mm. The material of mirror is stainless steel (SS304L). The mirrors are fixed so beam steering is not feasible with this launcher.

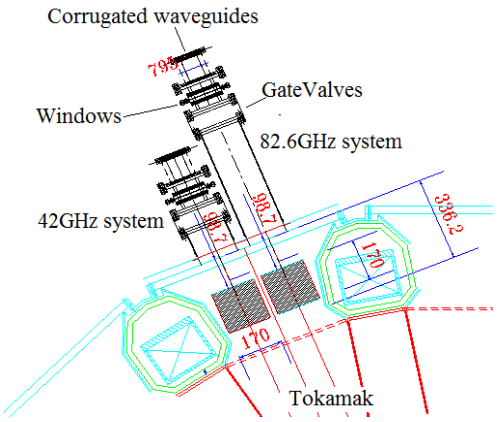

Figure 5 Schematic of ECRH launcher in SST-1

3 ECRH assisted breakdown in SST1

Before starting the experiments on SST-1, entire ECRH system (Gyrotron with transmission line and tokamak window) conditioned and power launched directly in tokamak vacuum. The communication between ECRH control and SST control stablished, ECR pulsed synchronized with SST tokamak control. The plasma breakdown experiment on SST-1 tokamak has been carried out as follows:

3.1 Second Harmonic ECRH assisted breakdown in SST-1

The tokamak is oprerated at 0.75T toroidal megnetic field, which corresponds to second harmonic at 42GHz. The right-hand circular polarization is selected using polarizer, which is X-mode ($E \perp B_T$). The Gyrorotron is operated for ~300kW power and considering ~ 18% loss in the line, approximately 250kW ECRH power is launched in tokamak. The pulse duration for ECRH is varied from 125ms to 200ms and the power is launched around 45ms before the loop-voltage. The sucessful ECRH assisted breakdown is achieved in SST tokamak in all the shots at pressure $1x10^{-5}$ mbar. The standard SST-1 plasma shots assisted with ECRH breakdown is shown in figure 6.

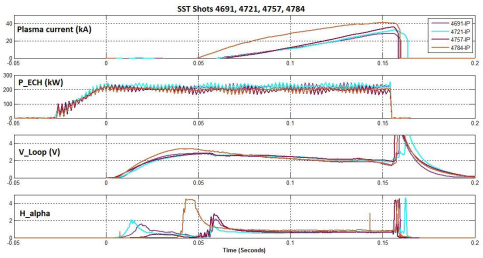

Figure 6 ECRH assisted plasma shots in SST-1

The loop voltage (trace 2) is ~ 2.5V, the appearance of Hα (trace 5) confirms the ECH assisted breakdown in tokamak. There is a delay ~50ms in breakdown (loop voltage and Hα), which is expected at second harmonic ECRH assisted breakdown. From the figure 6 it is clear that ECRH helps in plasma start-up and current ramp-up. The plasma current in typical plsma shots in SST-1 is achieved ~ 53kA.

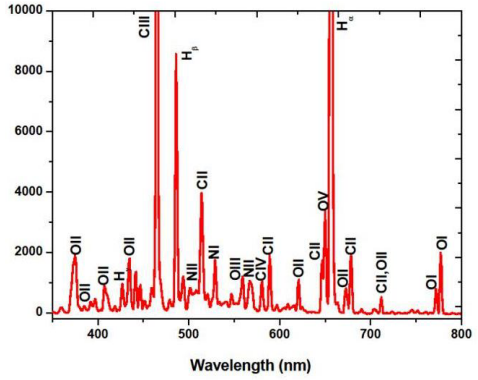

Figure 7 Spectroscopy data at flattop of Ip (SST-1 Shot)

The different plasma species are monitored using spectroscopy. Figure 7 shows the monitoring of hydrogen, carbon, oxygen and nitrogen lines at flat-top of plasma current. The presence of oxygen (O-V) gives the information on plasma temperature, it indicates that the plasma temperatue is more than 30eV.

The position of plasma is also monitored with optical imaging. The camera used in the current set up is a 640 x 480 pixel CCD camera which is directly mounted on the machine. The viewing angle of this camera is around 70^{o} which covers nearly 60 % of the vacuum vessel. The Optical Imaging Diagnostics on SST-1 provides information about plasma shape, vertical position, plasma movement in vertical direction. In the figure 8, the plasma can be seen at a location (geometrical center of the machine) and diameter of the plasma to be around 50-55 cm. A good plasma ring is observed (figure 8) with optical diagnostics which ensures the plasma is in machine center.

Figure 8 Plasma Ring in SST-1 (ECRH assisted plasma breakdown)

3.1 Fundamental Harmonic ECRH assisted breakdown in SST-1

The breakdown experiments at fundamental harmonic is also carried out in SST-1. The tokamak is oprerated at 1.5T toroidal megnetic field and ECRH power is launched in O-mode. In case of fundamental harmonic, the ECRH power is reduced to 100-200kW. The pulse duration is also reduced from 75ms to 125ms. Since the maximum internal loop voltage in SST-1 appears around 20 ms, so ECRH pulse is also synchronized from -20ms to 0ms with respect to loop voltage. The sucessful breakdown is also achieved at fundamental harmonic in all the shots of SST-1 with pressure range varied from $8x10^{-8}$mbar to $3x10^{-5}$mbar. Figure shows that in case of fundamental harmonic there is instant breakdown without any significant delay, which is also expected at fundamental harmonic. The SST plasma shot assisted with ECRH breakdown at fundamental harmonic is shown in figure 9.

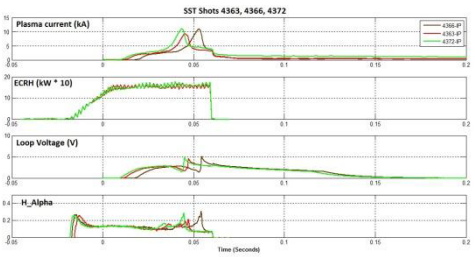

Figure 9 SST plasma shot at fundamental harmonic

4 Discussion:

The 42GHz-500kW ECRH system has been successfully commissioned on tokamak SST-1. The 42GHz system has been used to carry out plasma breakdown in SST-1 tokamak at fundamental and second harmonic. The systematic experimensts are carried out at second harmomic ECRH assisted breakdown in SST-1. In all these exeriments, successful breakdown is achieved at very low loop voltage (~ 2.8V). It is also observed that ECRH is contributing in plasma current ramp-up phase and various shots has been observed with plasma current ~ 53kA. There is delay in brekdown at second harmonic which is similar to breakdown in other machines.

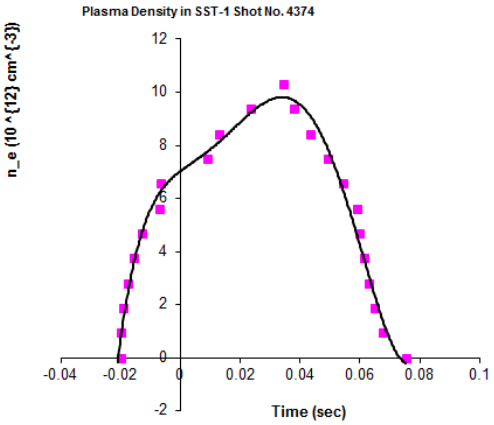

Figure 10a Density evolution in SST-1 tokamak with fundamental harmonic (1.5T) ECRF

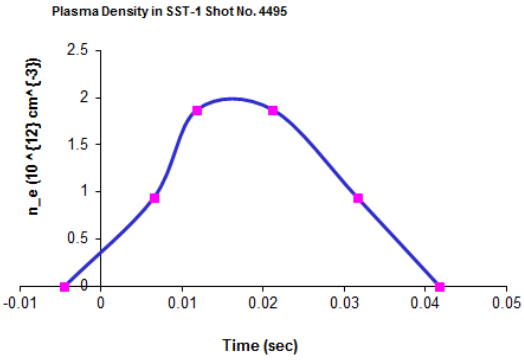

Figure 10b Density evolution in SST-1 tokamak with second harmonic (0.75T) ECRF

The breakdown at fundametal harmonic is also carried out and appearance of H_alpha with ECRH pulse confirms the instant

breakdown at fundamental harmonic. The current ramp is also fast in case of breakdown at fundamental harmonic. The density is measured in case of fundamental and second harmonic breakdown (Figure 8a and 8b). The density is more in case of breakdown at fundamental harmonic. Although small dischares (plasma current ~13kA) are achieved in case of breakdown at fundametal harmonic but it is complete breakdown with burn-through of plasma with ECRH assistance. The systematic experiments at fundamenatl harmonic are scheduled in next campaign of SST plasma exeriments, in which plasma control will be done by various parameters like vertical field, pressure, ECR layer etc.

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