ECRH systems in tokamak SST-1 and Aditya

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Plan of Talk

• Introduction in short to ECRH in tokamak Plasma
  • (Launching of ECRH in SST-1 and Aditya)

• 82.6GHz ECRH System on SST-1
  • (Gyrotron, transmission line and launcher)

• 42GHz ECRH system on SST-1
  • (Gyrotron, transmission line and launcher)

• 42GHz ECRH System on Aditya

• Future plan

• Summary
Applications of ECRH

• ECRH for reliable start-up in tokamak at lower loop voltage and even at higher error magnetic field
• ECRH for plasma heating
• ECCD and NTM suppression / plasma control
• Gyrotron’s further application on diagnostics – CTS
• Other experiment related to plasma wall interaction in linear devices
• So ECRH a very promising heating scheme in fusion plasma
Terminology (ECR waves in plasma):

In a homogeneous plasma the two possible modes are given by well known Appleton Hartree dispersion relation, for a wave propagating at an angle $\theta$ to the toroidal magnetic field $B$ is:

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

The +ve sign is for O-mode where as -ve sign is for X-mode.

$$\Gamma = \left[ \omega_{ce} \sin^4\theta + 4\omega^2 (1 - \alpha)^2 \cos^2\theta \right]^{1/2} \quad \& \quad \alpha = \frac{\omega_{pe}^2}{\omega^2}$$

Where $k$ is the propagation vector , $\omega$ is operating frequency , $\omega_{ce}$ is cyclotron frequency , $\omega_{pe}$ is plasma frequency (in rad./sec) , $N$ is the refractive index and $\theta$ is the angle between propagation vector and magnetic field.

The condition for cyclotron resonance can be expressed as:

$$\omega = \omega_{ce} + k_{||} v_{||}$$
Type of modes in ECR Plasma

O-Mode: If $\theta = \pi / 2$, O-mode is independent of magnetic field & the dispersion relation is given as:

$$N^2 = 1 - \frac{\omega_{pe}^2}{\omega^2}$$

For X-mode, dispersion relation is:

$$N^2 = \frac{[\omega (\omega - \omega_{ce}) - \omega_{pe}^2] [\omega (\omega + \omega_{ce}) - \omega_{pe}^2]}{\omega^2 (\omega^2 - \omega_{pe}^2 - \omega_{ce}^2)}$$

If, $N = 0$. Cut Off, $N = \propto$ Resonance

For O-mode, $N = 0$, at $\omega = \omega_{pe}$ (Density cut off)

At, $\omega^2 = \omega_{pe}^2 + \omega_{ce}^2 = \omega_{uh}^2$

$N = \propto$ Resonance (Upper hybrid Resonance)

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Theory (CMA Diagram and density cut offs):

\[ \omega_{ce}^2 / \omega^2 \]

\[ \omega = \omega_{pe} \]

\[ \omega = 2 \omega_{ce} \]

**HFS**

**LFS**

\[ w = w_{ce} \]

\[ w = 2w_{ce} \]

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Low field side launch of O1 and X2

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ECRH systems in Tokamak SST-1 and Aditya

HFS is not feasible in SST-1 and Aditya
low field side (LFS) launch of O₁ and X₂

SST-1 ECRH systems:
82.6GHz ECRH System
42GHz ECRH system

ECRH in Aditya
42GHz ECRH systems

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ECRH Schematic in SST-1

- Frequency: 82.6GHz, Maximum Power: 200kW, Maximum Pulse duration: 1000s
- Fundamental O-mode and second harmonic X-mode launch from Low field side (Radial port)
- Transmission line consists of DC break, Corrugated waveguide, bends, polarizer and bellows
- Launcher – mirror based launcher used to focus the beam plasma
SST-1 ECRH system Gyrotron:

Microwave Source (Gyrotron):
- Depressed Collector type
- Frequency: 82.6±0.2GHz
- Power: 200 kW / CW
- Pulse duration: 1000s
- Duty Cycle: 17%
- Gyrotron output: lateral-horizontal
- Output mode: TEM$_{00}$ – Gaussian beam
- Gyrotron output window: CVD diamond
- Magnet of gyrotron: cryo-cooled

Cooling of gyrotron:
- Collector, body, anode, ion pump and ballast load: cooled with DM water
- CVD Window: CC-15 mixed with DM water

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Subsystems of Gyrotron

- Mechanical
- Electrical
- Magnet
- Microwave
- DAC
- Interlocks
- Instrumentation
Prior to high power test of Gyrotron:

- Electrical layout
- Mechanical layout
- Calibration of electrical instrument
- Calibration of microwave components
- Commissioning of Cooling system
- Test of DAC with dummy signal
- Test with real field signal
- HV connections to Gyrotron with professional wiring
- Dedicated HV ground close to Gyrotron
Interlocks

Fast Interlocks
\(< 10\mu s\)

Slow Interlocks
\(~ 100 \text{ ms}~\)

Action
Crowbar

Action
Software I/L

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Fast Interlocks

- Arc
- Beam voltage
- Beam current
- Anode over current
- dI/dt
- Body current
- Vac-ion current?

Slow Interlocks

- Cooling (all)
- Filament
- Magnet currents
- Waveguide (vac or Pr.)
- HVPS Over voltage?
In an event of fault, the fault energy to the Gyrotron should not exceed its critical fault energy known as critical crater energy.

Remove high voltage fast enough i.e. $< 10\mu s$

Demonstrate 10-Joule Wire test

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Crowbar Protection

Beam Voltage power Supply (60kV, 10A)

C = 35Ω

R = 190Ω

Ratio 1000:1

Rail gap Crow-bar

Cryo-Mag. PS

HV+

Protection & monitoring

FPS

Vac-ion PS

AMPS 30kV 300mA

Protection & monitoring

Monitoring

Earth Pit

HV+

Pulse-CT 0.1V/A

DCCT 0.2V/A

Rogowski

Protection Ckt.

V(Beam)

I(Beam)

Monitoring

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10-Joule wire test

- Connect a wire at the place of Gyrotron
- Generate manual fault
- Detect the fault and trigger the crowbar
- If wire safe, test successful

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Ignitron crowbar system developed at IPR

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HV switch OFF within 10µs
Integrated test of HVPS and AMPS

The integrated test to turn OFF HVPS (Voltage ~ -43kV) and AMPS (Voltage ~ +20kV) together is checked and it is found that both the power supplies switch OFF within 8 microseconds. During this test, 10Joule wire is used and it was safe during the HV shot.
Gyrotron test set-up with water Dummy load:
Gyrotron test results:
(Pulsed operation for burn pattern test)

Electrical parameters for burn-pattern test:

- Beam Voltage : -35kV
  Anode voltage : + 16kV
  Filament Voltage : ~ 30V
- Filament current : 18.5A
- Cryomagnet current : 45.33A
- Pulse duration: 30ms
- A : Paper at the output of MOU
- B : Paper at the output of 400mm waveguide at the output of MOU

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175 kW / 1000s Shot
Transmission line system and its high power test:
Burn Pattern at the exit of transmission line:

Beam Voltage: 35kV
Anode Voltage: 16kV
Pulse duration: 30ms

Beam Voltage: 36kV
Anode Voltage: 16kV
Pulse duration: 40ms
High power test of CVD diamond window
Schemes of CVD window test:

- On tokamak (×)
- Brick load (limitation 3 seconds only)
- On dummy load using a QO matching unit (Mirror-box) (√)
Mirror box inside view
High power test of CVD Diamond window
High power test of CVD window (Power @ the Gyrotron ~ 80kW for 10 minutes)
CVD window test:

1) **UHV test:** Vacuum 10-9 range is achieved with baking of ~150 deg. for ~ 24hrs

2) **High power microwave test:** Maximum power at the window: ~ 60kW / duration 10minutes in 1000s pulse as shot terminated manually without any problem

Looking the risk in operation with two diamond windows with a new approach of testing, the operation is limited to 60kW power. The test is restricted in power due to safety of CVD window and Gyrotron.

• The similar CVD diamond window on the Gyrotron is already tested for 200kW/1000s. **So window can be accepted at IPR.**
Present status 82.6GHz ECRH system is ready

160-180kW @ 82.6GHz
Second harmonic breakdown @ 1.5T
Second harmonic ECRH breakdown in SST-1

**Ionization growth rate** \( \beta = P^{1/2} a^{-1} \omega d_0 \cdot \)

For SST1: \( P: 160\text{kW}, a: 0.2\text{m}, \omega: 82.6\text{GHz} \) and \( d_0: 63.5\text{mm} \)

For DIII-D-1 (\( P: 250\text{kW}, a: 0.65\text{m}, \omega: 110\text{GHz} \) and \( d_0: 60\text{mm} \))

\[ \frac{\beta_{\text{SST1}}}{\beta_{\text{DIII-D-1}}} \approx 2 \]

For ITER (parameters as mentioned in ref [7]): \( P: 2400\text{kW}, a: 2.0\text{m}, \omega: 120\text{GHz} \) and \( d_0: 60\text{mm} \)

\[ \frac{\beta_{\text{SST1}}}{\beta_{\text{ITER}}} \approx 1.8 \]

For T-10: \( P: 300\text{kW}, a: 0.3\text{m}, \omega: 140\text{GHz} \) and \( d_0: 63.5\text{mm} \)

\[ \frac{\beta_{\text{SST1}}}{\beta_{\text{T-10}}} \approx 0.64 \]

For KSTAR: \( P: 450\text{kW}, a: 0.5\text{m}, \omega: 84\text{GHz} \) and \( d_0: 63.5\text{mm} \)

\[ \frac{\beta_{\text{SST1}}}{\beta_{\text{KSTAR}}} \approx 1.46 \]

The study is being done, it is not yet concluded but 160kW power @ Second harmonic could be at threshold…..

42GHz ECRH system for SST-1 is proposed & now its in advance stage for commissioning on SST-1

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42GHz / 500kW ECRH system for SST-1 and Aditya

For SST-1

Pre-ionization, start-up and heating at fundamental harmonic (1.5T operation)

In Aditya

Breakdown studies at second harmonic (0.75T)
ECRH systems at its application

- **42GHz - 500kW-500ms**
  - Pre-ionization, heating @ second
  - ADITYA 0.75T
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- **82.6GHz - 200kW-CW**
  - Pre-ionization, heating @ fundamental
  - SST-1 1.5T
  - SST-1 3.0T
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42GHz ECRH system for SST-1 and Aditya

**Gyrotron:**
- Frequency: 42GHz
- Power: 500kW
- Pulse duration: 500ms
- Gyrotron with internal mode converter
- Gyrotron output: HE11 (Gaussian output)
- Depressed collector type
- Efficiency ~ better than 45%
- Gyrotron with external MOU
- Calorimetric dummy load

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Layout of 42GHz ECRH system in SST-1

42GHz ECRH system for Aditya and SST–1
Schematic (Tentative floor plan)

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Transmission line system for 42GHz / 500kW ECRH system for SST-1 and Aditya

Two switches, One polarizer, ordinary bends, bends with directional coupler, DC breaks, bellows and 75m corrugated waveguide
42GHz / 500kW ECRH system for SST-1 and Aditya

The entire system has been tested at M/s. Gycon in Russia for 500kW-500ms the efficiency is more than 50%
High power test of 42GHz Gyrotron

Power : 500kW, duration : 500ms
High power test of 42GHz Gyrotron

Power : 500kW, duration : 500ms

Power versus cathode voltage
Frequency measurement of Gyrotron
Transmission line test
Transmission line test

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High power test of windows
42GHz ECRH system on SST-1

Tested at factory for its performance

Planned for commissioning of system on SST-1 & Aditya soon
Launcher for ECRH in SST-1

ECRH is allotted for single port

Launcher is designed such that to accommodate both the systems

82.6GHz and 42GHz system would be connected to same port

One focusing mirror and one plane mirror combination is used for both the systems
Launcher for ECRH in SST-1

Focusing Mirror

Gate Valve
Window
Uptaper
DC Break

Plane Mirror

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Launcher for ECRH in SST-1

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Launcher for ECRH in SST-1

42GHz launcher:
Mirror Size: 170mm x 240mm
Mirror focal length: 353mm
Beam size (1/e radius) at Plasma center: 35mm

82.6 GHz launcher:
Mirror Size: 140mm x 200mm
Mirror focal length: 481mm
Beam size at Plasma center: 20mm
Low power test of launcher

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Launcher for ECRH in SST-1
Launcher for ECRH in SST-1

Advance launcher with further optimized mirrors and feasibility to steer the beam is under design
Future Plan for ECRH

Upgrade the ECRH system with power and frequency

Advance launcher capable to steer the beam in plasma
Summary

• In SST-1 and Aditya ECRH would be launched from Low field side

• In SST-1 82.6 and 42GHz ECRH system would be launched to carry out ECRH experiments at fundamental and at second harmonic

• The 82.6GHz Gyrotron has been tested for pulsed condition using RHVPS.

• In Aditya 42GHz ECRH system would be used for second harmonic ECRH experiments at 0.75T operation

• The 82.6GHz ECRH system is ready for SST-1 tokamak

• The 42GHz ECRH system has been tested at factory and scheduled to commission on tokamak SST-1 and Aditya soon.
Thank You

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