

Lecture: S9-Part-2

IC and EC Power Source Systems for ITER Indian In-kind Contribution

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- EC System & Gyrotron Sources on ITER
- Gyrotron Concept & Main Design Features
- Power Delivering System & Auxiliary Requirements
- Gyrotron Testing & Diagnostics
- Issues & Future Technology Goals



EC H&CD System on ITER

Electron Cyclotron Heating & Current Drive (EC H&CD) System





Gyrotron Procurement Sharing & Indian Contribution





Typical ITER Gyrotron Specifications

Specification	Specification Detail	Specification Value
Output Power	Nominal output power @ MOU output	≥ 0.96 MW
Frequency	Nominal Frequency	170 GHz
Output Mode	Mode at the MOU output	HE ₁₁
Mode Purity	HE_{11} Content at the MOU o/p	≥95%
Pulse	Maximum Pulse	≥3600 s
	Nominal Pulse	1000 s
Efficiency		≥ 50%
Duty		25 %
Modulation	Power Modulation	1-5 kHz
Reliability		≥95 %



*Data is based on the ITER EC System PDR presentations-Nov-2012; Subject to confirmation; Only for illustration not to be quoted

- State of the art Specifications
- Yet to be fully demonstrated
- R&D ongoing



EC System & Gyrotron Sources on ITER

- Gyrotron Concept & Main Design Features
- Power Delivering System & Auxiliary Requirements
- Gyrotron Testing & Diagnostics



- An Oscillator that works on CRM principles
- Can generate high power electro magnetic radiation at Cyclotron frequencies in the microwave and mm Wave range
- A relativistic electron beam gyrating helically at cyclotron frequency generates coherent radiation by stimulated emission in a suitable wave beam interaction structure (Cavity)
- Cyclotron frequency dependence on relativistic mass promotes phase bunching of Electrons that leads to stimulated emission

Gyrotron working concept

Main Steps

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- Electron Beam Generation & Beam Guidance
- RF Generation through Beam Wave Interactions
- RF Beam Mode Conversion & Exit through an o/p window
- Spent e-Beam Removal & Energy Recovery





• Electron Beam Generation & Beam Guidance

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- An Electron Gun with a Thermionic Cathode
- Acceleration Voltage in the Gun Extracts the e-beam
- Axial Magnetic field profile guides the beam into Interaction cavity





• Electron Beam Generation & Beam Guidance

- An Electron Gun with a Thermionic Cathode
- Acceleration Voltage in the Gun imparts transverse energy & extracts the e-beam
- Axial Magnetic field profile guides the beam into Interaction cavity

Impregnated Dispenser Cathode (Porous W, impregnated with BaO, CaO, Al2O3)

Temperature Limited Regime

$$I = J.S = S.A_0T^2 \exp\left[\frac{-e}{KT}\left(\phi - \sqrt{\frac{eE}{4\pi\varepsilon_0}}\right)\right]$$





- Electron Beam Generation & Beam Guidance
- A Magnetron Injection Gun (MIG)
 - Diode/Triode Configuration
- Beam Currents of the order of 40-50 A (1MW tube)
- A hollow circular electron beam moving in a helical trajectory
- Energy of the order of 70-80 keV
- Substantial Energy in perpendicular direction
- Minimal velocity spread in the beam
- Beam Diameter at the cavity shall be half the cavity diameter





• RF Generation through Beam Wave Interactions

- In the presence of the axial magnetic field E-Beam Interaction with the cavity electric field produces a RF beam
- To minimize flux densities oversized cavities to support very high order volume modes are used
- Hollow Cylindrical cavities are conventionally used
- For > 1MW new Coaxial cavities are under development





• RF Generation through Beam Wave Interactions

- In the presence of the axial magnetic field E-Beam Interaction with the cavity electric field produces a RF beam
- To minimize heat flux densities oversized cavities supporting very high order TE_{m,n} modes are used
- Hollow Cylindrical cavities are conventionally used
- For > 1MW new Coaxial cavities are under development





- RF Beam Mode Conversion & Guidance
 - Using a QO launcher RF beam oscillating in a cavity mode (TE_{m,n}) mode converted into Gaussian Mode
 - Using a Mirror Optics assembly & an output window RF beam is taken out from the Gyrotron







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- Using a QO launcher RF beam oscillating in a cavity mode $(TE_{m,n})$ mode converted into Gaussian Mode
- Using a Mirror Optics assembly & an output window RF beam is taken out from the Gyrotron
- CVD Diamond Window for MW
 CW Class Gyrotrons
- Very Low loss tangent ~ 2e-5
- High Thermal Conductivity~1800
 W/m.K
- Disc thickness is optimized for low reflection



• Spent Beam Removal & Energy Recovery Techniques

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- An actively cooled Collector is used to remove the spent ebeam
- Spent beam energy recovery using depressed collector concept
- This in turn increases the over all system efficiency by 15-20 %
- Reduces the heat load on collector
- Effective over all efficiency achieved with this concept > 50 %





• Spent Beam Removal & Energy Recovery Techniques

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- Spent electron beam is decelerated and safely dumped onto an actively cooled Collector
- Spent beam energy recovery using depressed collector concept
- This in turn increases the over all system efficiency by 15-20 %
- Reduces the heat load on collector
- Effective over all efficiency achieved with this concept > 50 %





- **Spent Beam Removal & Energy Recovery**
- Small beam interception leads to High Heat Flux on Collector
 - Heat Flux Reduction **Techniques required**
 - Beam Sweeping using AC collector coils typically employed





Spent Beam Removal & Energy Recovery

- Small beam interception leads to High Heat Flux on Collector
 - Heat Flux Reduction Techniques required
 - Beam Sweeping using AC collector coils typically employed
 - Aimed to reduce the heat flux to < 5 MW/m²





- EC System & Gyrotron Sources on ITER
- Ø Gyrotron Concept & Main Design Features
- Power Delivering System & Auxiliary Requirements
- Gyrotron Testing & Diagnostics
- Issues & Future Technology Goals

Typical Gyrotron Power Delivering System

- Gyrotron Tube
- 2. Magnets

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- 3. Matching Optic Unit
- 4. Auxiliary Power Supplies
- 5. HV Power Supplies
- 6. Local Control Unit
- 7. Cooling & HV Tank
- 8. Waveguide Test Set



Typical Gyrotron Power Delivering System



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Gyrotron Magnets - SCM

• Required for Cavity Oscillations & e-bam guidance

$$\omega_{ce} = \frac{eB}{m_0 \gamma}$$

- Field value is determines the Gyrotron oscillation frequency (~7T for 170 GHz)
- $\frac{B_{cav}}{B_{cath}} = \frac{R_{cath}}{R_{cav}}$

Super Conducting

Main Magnet

- Field profile is tailored to provide the beam compression and expansion
- Good field accuracy of 0.1-0.3 % with that of calculated values is required
- Warm bore radius is of the order of 160-240 mm for ITER Gyrotrons
- Field alignment with geometric axis is crucial
- Cryogen free cooling technology to be used for ITER



Gyrotron Magnets-Collector Coils



- Sweeping Frequency & Amplitude help reduce the average heat flux (beam resident time & duty factor)
- Sweeping frequency is limited eddy current shielding (1-10 Hz)
- Saw teeth/triangular Sweep Function

Collector

Sweeping Coils



Gyrotron Magnets-Gun Coils

- To Control Magnetic field at the cathode region
 - For proper beam compression and gain in perpendicular energy ($\alpha = v_{\perp}/v_{\parallel}$)

• Typical
$$B_{cav}/B_{cath} \simeq 25$$
; Typical $B_{cath} \simeq 0.26$ T

- Separate independent Gun Coils with a reverse field typically is used
- Two variants are typically used
 - Gun Coils built into the SCM/External to SCM

Gun Coils

 B_{cav}

 R_{cath}



Gyrotron Matching Optic Unit



63.5 mm Corrugated waveguide

HE11

Mode

WG

Couple the RF Beam efficiently into WG Mode



Matching Optic Unit (MOU)



Typical Gyrotron Power Delivering System



Gyrotron Tube

Magnets

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- 4. Auxiliary Power Supplies
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Electrical Scheme

Typical Common Collector Configuration for a Diode Tube





High Voltage Power Supply Requirements



Name of the Specification	value		
Voltage			
Cathode-Collector Voltage	\geq 55 kV		
Collector Voltage Depression	> 35 kV	ilament PS Vac-ion	
Output Voltage -Ripple/Regulation/ Accuracy	≤1 %	PS GCPS	
Modulation Requirements			
Modulation (MHVPS)	≤1 kHz	PS K	
Modulation (BPS) GYROTRON	≤5 kHz		
Modulation depth (MHVPS)	100 %		
Modulation depth (BPS)	≥ 50 %	CCPS	
Current			
Nominal Beam Current	50A		
Nominal Body Current	>50 mA		
Fault Energy			
Maximum stored energy delivered to the Load $\leq 10 \text{ J}$			
Voltage switch off time scales	≤ 10 µs	7	

PSM Power Supply (Reference design)



Auxiliary PS requirements



1-10 Hz / ~ 50A ² _____ _{Time (s)}

3/5 kV DC Few mA Precise current monitoring for vacuum measurement

Typ. 5-10 V DC @ 100-120 A Precise current setting ~0.005% Programmable ramp up/down Quench Protection

1-1.5 kW AC/DC Power Supply Precise voltage/current setting Programmable ramp up HV Isolation from Cathode

Typical Gyrotron Power Delivering System



Gyrotron Tube

Magnets

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Matching Optic Unit Auxiliary Power Supplies HV Power Supplies

- 6. Local Control Unit
- 7. Cooling & HV Tank
- 8. Waveguide Test Set



Gyrotron Control Unit

Objective

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- Safe & remote operation of the complete system
- Main Functions
 - Control & Monitoring
 - Protection Interlocks
 - Data Acquisition & Archiving
 - Centralized GUI for easy operation



Control System Architecture (ITER)



LCU-Control & Monitoring

- Control function
- Sequence control handles predefined On/OFF sequence
- Feedback control handles real time control loops (NTM)
- PLC/PXIe based Control loops





Operational Sequence Flow Charts





Operation Timing Diagram

Sequence Diagram

Sequential State diagram



LCU- Protection Interlocks & Acquisition

- Several fault conditions may arise that may be detrimental for the tube or human safety
- Interlock System Plays a very critical role in safe operation of Gyrotron system
- Arc faults are most prominent critical faults
- Interlock Classification on time criticality
 - Critical/Fast interlock (< 10 μsec)
 - Simple/Slow interlock (10 -100 msec)
- The HV Power Supplies are typically turned off in fast time scales
- Hardwired Discrete components based Interlock systems are generally implemented for fail safe and fast action
- PXIe based data acquisition can support Fast (1µs/event based) and slow acquisition requirements

Some critical Interlocks

Interlock Condition	Action
Arcing at the window & Transmission Line	
Fast rate of change of beam current (dI/dt)	Switch off MHVPS & BPS <10 µs
Beam Over Current	
No RF output	

Some Slow Interlocks

Interlock Condition	Action	
Ion Pump Over Current- Bad vacuum	Switch off MHVPS & BPS in 10-100	
Out of window Cooling Parameters	ms	



Interlock Detection

PXIe

Typical Gyrotron Power Delivering System



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Gyrotron Tube Magnets Matching Optic Unit Auxiliary Power Supplies HV Power Supplies Local Control Unit

- 7. Cooling & HV Oil Tank
- 8. Waveguide test set





Gyrotron Cooling & Oil Tank

- About half of the input DC power dissipated across Gyrotron Components – Require considerable active cooling
- Gyrotron Collector with about 50% input power dissipation requires heaviest cooling > 1200 lpm (Tube specific)
- Typically 15-20 cooling circuits would be required
- Instrumentation for flow distribution and cooling parameter measurements would be required



> 1500 lpm
6 bar
5 bar
35-40 degC
1 μS/cm

Typical Cooling Parameters (1MW/Long Pulse class Gyrotron) (Specifications may vary for different makes)



- Oil Tank provides the HV isolation between electrodes
- Also acts like a heat sink for the Gun region
- HV Sockets are provided on to the Oil Tank

Typical Gyrotron Power Delivering System



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Waveguide Test Set







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Gyrotron Testing & Diagnostics

- Installation Tests
- Performance Tests
- Test Facility



Typical Installation Tests

- Mechanical Inspection
 - General Dimensional & Cooling parameters check

Field Mapping & Magnetic axis alignment

- Field mapping with magnetic probes
- Ensure field accuracy & magnetic axis alignment with Gyrotron geometric axis
- HV withstanding tests
 - Check voltage withstanding capability of Gyrotron electrodes
- HV Protection –10J / Wire burn Tests
 - To ensure fault energy deposition in Gyrotron is less than prescribed limit (10 J) (Power Supply Scope)

Interlock Tests

- Dummy testing of interlocks (Arc , Vacuum, Cooling etc.) with loop time for fast interlocks
- Repeated tests to ensure Interlock reliability





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ITER-India Gyrotron Test Facility









- Collector failures
- Window failures
- Pulse limitations- Stray radiation heating
- Insulator heating issues
- Cathode cooling
- Spurious Oscillations in beam tunnel
- Arcing in the tube & transmission line
- Quality Control & Repeatability
- Stray magnetic field issues
- Power Supply Issues
- Control & Protection Issues



Some of the R&D goals for future Gyrotron Sources

- Higher Unit Power (> 1MW)
- Multi Frequency Operation Capability
- High Operational Reliability & Availability
- Higher electrical efficiencies
- True CW devices



