Safety Aspects of High Power RF and Microwave Sources for Fusion Reactors

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Plan of Talk

- Introduction to Fusion Reactor
- Why RF and Microwave Power is required for Fusion?
- RF Requirements of Fusion Reactor
- Introduction to RF applications in different frequency ranges
- RF sources for tokamaks
- Microwave sources for tokamaks
- Biological effects of RF and Microwaves
- Safety Aspects
- Conclusions
The sun and stars are powered by fusion. Harnessing these reactions to produce energy on earth presents a grand challenge to scientists and engineers. Steady progress has been made but several scientific and technological advances are necessary before the dream of commercial electricity production will become a reality.
Fusion Criterion

• The main requirement of fusion reactors is the confinement of a D-T plasma at 100 million degrees such that

\[ n \tau T > 5 \times 10^{21} \text{ keV sec/m}^3 \]

\( \tau = \) confinement time
\( n = \) density
\( T = \) plasma temperature

– Heat Plasma to 100 million degrees (>40 keV)
– Confine the plasma to meet/exceed Lawson Criterion (>1000 sec)
– Plasma density (>10^{14}/cm^3)
Methods of producing Fusion Reaction

• Inertial Confinement
• Confinement due to magnetic field: Tokamaks
• Laser Fusion
• Actual Reaction on a small scale
Why Heating is required?

- **Plasma Formation in tokamak**

  The plasma is formed by an electrical breakdown with the help of **ohmic transformer** and the current is driven inductively in the plasma. Since the transformer voltage varies with time, one can produce plasma for less than 1 second. However, for steady state operation, we need to sustain the plasma at least for 1000 seconds.

  With Ohmic heating, one can get temperature of the order of 1-2 keV only.
Plasma Heating

As the plasma temperature rises the efficiency to heat the plasma by ohmic heating decreases. At low temperatures the Ohmic heating is quite strong but because the resistance of the plasma varies with temperature as $T_e^{-3/2}$, it becomes less effective at higher temperatures. Also radiation losses increase with increase in temperature and finally heating and losses get balanced to make Ohmic heating in-efficient further.

To further raise the temperature of the plasma to fusion grade, one has to use auxiliary heating schemes.
Applications of RF Waves in Tokamaks

1. RF heating in ICRH range
   - Fast wave heating at second harmonic
   - Minority heating
   - Ion Bernstein wave heating

2. RF current drive using phasing of antennas (LHCD)

3. RF Pre-ionization using ICRH or ECRH

4. RF wall conditioning in presence of continuous toroidal magnetic field using ICRH
Role of High Power RF and Microwaves in Fusion Reactor

- Pre-ionization, Start-up and Current Drive using 28-170 GHz **Gyrotrons** upto 5 MW
- Ion Cyclotron Resonance Heating and Current Drive using 10-100 MHz **Tetrode** tube based sources upto 40 MW
- Electron Cyclotron resonance Heating and Current Drive using 20-170 GHz **Gyrotron** based sources upto 20 MW
- Lower Hybrid Heating and Current Drive using 2.5-5 GHz **Klystron** based sources upto 35 MW.
- High power RF sources at 1MHz upto 500 kW for DNB using **Tetrodes**
- IFNIF: 24 MW, 175 MHz for neutron flux production using **Dicrodes**
RF Power Requirements for Fusion grade Reactor

RF system

Activities by RF group

<table>
<thead>
<tr>
<th>ICRH</th>
<th>SST-1 (20-40 &amp; 91.2 MHz, 1.5/3 MW)</th>
<th>ITER ICRH (20 MW)</th>
<th>SST-2 (20-100 MHz, 10 MW)</th>
<th>DEMO (35 MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECRH</td>
<td>82.6/140 GHz, 0.2/0.5 MW</td>
<td>140/170 GHz, 3/6 MW</td>
<td>20 MW</td>
<td></td>
</tr>
<tr>
<td>LHCD</td>
<td>3.7 GHz, 1/2 MW</td>
<td>5 GHz, 5 MW</td>
<td>20 MW</td>
<td></td>
</tr>
</tbody>
</table>

(2007-2012) Upgradeation of existing system
(2012-2017)
High Power RF in Fusion Reactor

With available RF tubes one can generate max. 1.5 MW power in the frequency range of 10-100 MHz.

Two generators can be combined to have 3MW power with the help of combiner.

9” co-axial transmission line can be pressurised and water cooled to withstand high power and rf power can be transmitted to tokamak.

Many ports and antennas can be used to introduce 40 MW rf power

On-line fast matching for maximum transfer of the power from generator to the plasma can be incorporated.

Neutron compatible and water cooled antenna for withstanding fusion power, neutrons and for radiating power can be designed
What is Ion Cyclotron and Electron Cyclotron Heating?

The charged particles gyrate along the magnetic field lines and travel along the electric field lines. If we allow EM field to rotate in the direction of rotation of charged particle then the particle sees as if it is moving in the DC field in its own frame of reference and get accelerated and acquires energy from the wave, then transfers energy to other particles through collisions and heating of plasma takes place.

ICRH for ion heating
ECRH for electron heating
What is Lower Hybrid Current Drive?

If the EM wave comes out of a wave guide then it travels in a straight line. However, if we have many wave guides phased together with a constant phase difference between them then the resultant waves can bend and can be made to go in the direction of the particles in toroidal direction. The electric field of the waves can sustain the plasma current and is called as lower hybrid current drive.
RF METHODS OF CURRENT DRIVE

\[ v = \omega / k_\parallel \]

\[ F = 2-8 \text{ GHz} \]

Lower Hybrid Grill

ICRF Loop Antenna
\[ f = 20-100 \text{ MHz} \]

ECRH Horn
\[ v_\parallel = \frac{\omega - \Omega_e}{k_\parallel} \]
\[ f = 28-140 \text{ GHz} \]

FIG. 1 SCHEMATIC OF VARIOUS RF TECHNIQUES
Steps of RF heating

1. Generating RF power
2. Transmitting rf power
3. Course matching in vacuum
4. Conditioning of antenna, interface and tx. Line
5. Characterization of antenna for radiation pattern
6. Launching rf power in the tokamak with Bt.
7. Radiation of rf power
8. Reaching rf power up to resonance layer
9. Absorption of rf power
10. Thermalisation of rf power in plasma
11. Heating of plasma.
ADITYA Tokamak

- First Tokamak designed by IPR and fabricated in India.
- Commissioned in September 1989

**Design Parameters**

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
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<td>Major Radius $R_0$</td>
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<td>Minor Radius $a$</td>
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<td>Toroidal Field $B_T$</td>
<td>1.50 T</td>
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<td>Plasma Current $I_p$</td>
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<tr>
<td>Pulse Duration</td>
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<td>Cross-section</td>
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<tr>
<td>Configuration</td>
<td>Poloidal Limiter</td>
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<tr>
<td>Coils Type (TF &amp; PF)</td>
<td>Copper</td>
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<tr>
<td>Coils Type (TF &amp; PF)</td>
<td>Water cooled</td>
</tr>
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</table>

ADITYA TOKAMAK: A VIEW
Block diagram & brief details of ICRH system on Aditya

- osc
- LPA
- Dummy Load
- SPDT Switch
- Opto-isolator
- Voltage probes, FP, RP
- Matching Network (stub, Phase Shifter)
- Aditya CAMAC
- Aditya Control room
- Pre-Trigger
- RF ground
- DC break
- Ground isolation
- Opto-isolator
- Diagnostics electronics
- VTL / Interface
- Safety ground
- Vacuum window
- RF edge diagnostics for antenna
- Antenna
- Vacuum vessel

2kW ---> 20kW ---> 200kW
RF AMP Stages

2kW

---

> 20kW

---

> > 200kW

RF AMP Stages
RF Generator Stages (20 MHz – 40 MHz)

1. Complete chain
   - 1.5mW oscillator modulator & 30W solid state LPA

2. 2kW Pre-driver stage
   - Using 3CW5000A7

3. 20kW Driver stage
   - Using 3CW30000H7
RF Generator Stages (20 MHz – 40 MHz)

4. 200kW 1\textsuperscript{st} output stage using 4CM300000GA

5. 1.5MW final stage using 4CM2500KG

No harmonic distortion
High Power Co-axial Tx-line components

Reducer Test
- 9 3/16” to 6 1/8”
- 3 1/8” to N type
- Ins. loss < 0.08 dB

Step Reducer

Gas Barrier Test (S21)
- 9/16” 3bar capacity
- Ins. loss < 0.05 dB

Gas Barrier

Bend Test
- 9 3/16” co-axial
- Zo = 50
- Ins. loss < 0.05 dB

Miter bend

D-C test on VNA

Liquid Stub
- 9 3/16”, Zo = 50
- Liquids used as dielectrics:
  (a) silicon oil
  (b) transformer oil

Liquid Stub

Inner Conductor Joints
- 9 3/16”, 6 1/8”
- 9 3/16” W/C
ICRH Antenna Details

Material: SS304L with graphite tiles

length (cm): 30 cm

number of straps: 1

strap width (cm): 10.0

Distance between plasma and Faraday shield (cm): 1.0 cm

Distance between plasma and antenna (cm): 3.5 cm

Distance between plasma and wall (cm): 5.8 cm from limiter
Shot no. 24115
RF - 70 kW, TF - 0.75 T, Pr - 7-8e-5 mBar, Vloop - 22 volts
Block diagram & brief details of ICRH system on SST-1

Osc 45.6 MHz

LPA 2kW 20 kW 80 kW 1.5 MW

DC Break

Pre-Trigger

SST-1 Central Control room

RF GEN VME

SST-1 RF- VME

Dummy Load

Hybrid Coupler

SPDT Switch

Dummy Load

Opto-isolator

RF ground

Course Tuner

VVC

PS

STUB

RF GEN VME

VVC

PS

STUB

Diagnostics electronics

Voltage probes, FP, RP

Vacuum Window

Prematching Stub

Bellow: Antenna Movement

Automatic Matching Network

DC break

Ground isolation

Interface (8 inch Tx line in Vacuum)

9 inch Tx line

Electronic signal

ANT I, II

ANT III, IV

RF edge diagnostics for antenna
Matching Systems

Matching of antenna impedance to the generator impedance is important for delivery of maximum power.

Three levels of matching:

(I) Course tuner:

- Single phase shifter ($\lambda/2$) and stub tuner ($\lambda/4$)
- Connected in shunt using Tee
- Involves mechanical movement of inner conductor inside the outer conductor
- Hence more response time $\approx$ few sec
II) Automatic matching system

- Double stub configuration
- Two VVCs (vacuum variable capacitors connected in parallel with two stubs.
- Capacitor is moved by servo drive motor
- Response time ≈ 40-50 msec.
Automatic Matching System

- RF source 1.5 MW
- Hybrid Coupler
- Probe section
- Direction coupler
- Automatic Matching Network
- Coarse Matching Network
- Interface
- Antenna Port6
- Dummy Load
- Probe section
- Direction coupler
- Automatic Matching Network
- Coarse Matching Network
- Interface
- Antenna Port14
Fast ferrite tuner for SST-1 tokamak

- Specifications:
  - Frequency range: 20 MHz – 91 MHz
  - Input power = 1.0 MW
  - Return loss > -25 dB
  - Insertion loss < -0.1 dB
  - Mismatch region $\rho = 0.65$ with all phases.
  - Response time: 6 ms
  - Tested with VNA and then with 1 kW rf generator with random load
Developed 500 kW FFT for SST-1
VME system for Automatic Feed-back and power-supply control

1. Real time Acquisition, Monitoring and Control of FFT Signals
2. SWR calculation using probe signals and RF-Detector.
3. Online matching of plasma load to generator by generating control signals based on Real time calculation
4. Control signals will be fed to power-supply which will change electromagnet current and hence $\mu_r$ of ferrites to achieve matching

Flow chart for real-time calculation

FFT on SST-1
Interface Section

Connects antenna to the transmission line, made up of SS304L
Specification of Hybrid Coupler: To divide power equally in two arms

- 4 port device, Modular setup, F: 22 MHz – 25 MHz, 45.6 MHz & 91.2 MHz
- Power handling capability: 1.5 MW CW, Type: Coaxial line, EIA 9 3/16” 50 Ohm
- Coupling: 3 dB ± 0.07dB, VSWR: > 26 dB, IL: 0.09 dB (Max.), Isolation >35 dB
SST-1 Antenna

Made up of SS304L. One antenna box contains two antennae. Each antenna is shorted strip-line. Each antenna will carry RF power of 250kW.

Antenna is shielded from the plasma by 30 no. of Faraday shields in a single column.

Graphite tiles has to be fixed on all four sides of the box from inside.

Cooling connections are done during assembly.
**SST-1 LHCD SYSTEM**

Frequency: 3.7 GHz.
Power (2 klystrons each of 500 kW CW): 1 MW
Antenna type: Grill
# of subwaveguides: 32 x 2 rows
Periodicity (with 2mm thick septa): 9 mm
Subwaveguide opening: 76 x 7 mm²
Design $N_{||}$ (at 90° phasing): 2.25
$N_{||}$ variation (from 40° to 60° phasing): 1.0 - 4.0
Klystron input power: 10 Watt
ECRH System

- 29 GHz, 200 kW Gyrotron for Aditya
- 82.6 GHz, 200 kW Gyrotron for SST-1
- 42 GHz, 500 kW, 0.5 sec. Gyrotron for SST-1
- 170 GHz, 5MW Gyrotron for ITER
- Indigenous development of Gyrotron in India (42 GHz, 200 kW, 3 seconds for Aditya)
Microwave source (Gyrotron)

**Technical Specifications:**

- **Frequency**: 28 GHz ± 0.3GHz
- **Maximum Power**: 200 KWCW (Variable from 10% to 100%)
- **Pulse width**: 20ms to CW
- **Output mode**: TE$_{02}$ (Mode purity: 93%)
- **Critical crater energy**: 10 Joule
- **Maximum fault time**: 10μs
- **Efficiency**: 30 - 40%
- **Life time**: 5000 filament hrs @ 200KW.
- **Vacuum Pumping**: 8 l/s vac-ion pump
- **Output Window**: Double disc alumina, Face cooled with FC-75 coolant
28 GHz, 200kW Gyratron based ECRH system
Microwave Source Gyrotron for SST-1

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
India’s First High Power Gyrotron
42 GHz, 200kW, 3 sec.
Organizational Responsibilities

Magnetron Injection Gun (MIG) and Cathode And Beam Tunnel: CEERI IIT-R
Cavity and Non Linear Taper: BHU IIT-R, CEERI
Beam-wave Interaction Analysis: IIT-R CEERI, BHU
Collector: CEERI IIT-R
Engineering Drawing: CEERI, SAMEER
RF Cold Test of Cavity: BHU, CEERI
Window and FC-40 System Integration: SAMEER, IPR
Gyrotron System
Microwaves are electromagnetic waves with wavelengths ranging from as long as one meter to as short as one millimeter, or equivalently, with frequencies between 300 MHz (0.3 GHz) and 300 GHz. This broad definition includes both UHF and EHF (milli-meter waves). In all cases, microwave includes the entire SHF band (3 to 30 GHz, or 10 to 1 cm) at minimum, with RF engineering often putting the lower boundary at 1 GHz (30 cm), and the upper around 100 GHz (3mm). Applications include cell phone (mobile) telephones, radars, airport scanners, microwave ovens, earth remote sensing satellites, radio and satellite communications and fusion reactors.
NIR

In general, Non-ionizing radiation (NIR) produced due to EM radiation tends to be less hazardous to humans than ionizing radiation (ionizing radiation has a wavelength less than 100 nm or a photon energy greater than 12.4 eV). However, depending on the wavelength/frequency and the irradiance (or power density) value, NIR sources may present a human health hazard.

300 kHz to 1000 MHz is generally called as RF.
ELECTROMAGNETIC SPECTRUM

LOWER FREQUENCY  ---  HIGHER FREQUENCY
LONGER WAVELENGTH  ---  SHORTER WAVELENGTH
LESS ENERGY  ---  MORE ENERGY

<table>
<thead>
<tr>
<th>NON-IONIZING RADIATION</th>
<th>IONIZING RADIATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiofrequency Radiation</td>
<td>X-rays</td>
</tr>
<tr>
<td>Microwaves</td>
<td>Gamma rays</td>
</tr>
<tr>
<td>Infrared Radiation</td>
<td>Cosmic Radiation</td>
</tr>
</tbody>
</table>

Visible Light:
- Red
- Orange
- Yellow
- Green
- Blue
- Violet
Safety Aspects

Microwaves have some of the characteristics of infrared radiation in that they produce localized heating of the skin. However, they penetrate deeper than infrared radiation.

In general, the heating produced is proportional to the field intensity of this type of radiation. Other factors influencing the effects of microwave radiation include:

a. Frequency or wavelength of the radiation from the generating equipment.

b. Period of exposure time.

c. Air currents and ambient temperatures.
d. Body weight or mass in relation to the exposed area.

e. The irradiation cycle rate, referring to the individual ON-OFF periods during a unit time interval (one minute), when total time of irradiation per minute is kept constant.

f. Orientation or position of the body or its parts.

g. Difference in sensitivity of organs and tissues.

h. Effect of reflections.

i. Blood circulation and water content.

j. Exposure occurrence in the near field or far field
The known biological effects of microwave radiation include:

- **a.** Whole-body heating (such as heat overexposure).
- **b.** Cataract formation (damage to the lens of the eye).
- **c.** Testicular heating.
- **d.** RF burns (induction) from contact with metal implants.

Of the three effects mentioned above, cataract formation is of the greatest concern and the lens of the eye is the critical organ.

The adverse physiological effects that result from exposures to radiofrequency radiation are due to the absorption of a sufficiently large amount of energy to produce highly localized heating in specific organs.
Potential Bio-effects of Exposure to Microwave/RF Radiation

In general, most biological effects of exposure to microwave/RF radiation are related to the direct heating of tissues (thermal effects) or the flow of current through tissue (induced current effects). Non-thermal effects resulting in carcinogenesis, teratogenesis (birth defects), etc. have been demonstrated in animals but have not been proven by epidemiological studies on humans.
Potential Microwave/RF Radiation Sources (Leakage Sources)

For waveguides, co-axial cables, generators, sealers, and ovens, probably the most important aspect of controlling microwave/RF radiation hazards is a careful physical inspection of the source. Leaking sources will normally show misalignment of doors or plates, missing bolts, or physical damage to plane surfaces. Sources, which are suspected of leaking, should be repaired and then surveyed with appropriate instrumentation to verify they are no longer leaking.
Radiofrequency Radiation (RF) Issues

**RF Sources** - The RF source being used for the fusion reactors should be commercially produced or of equivalent quality if assembled in the laboratory. Units that are lab built or modified/repaired should be checked to assure they are safe and do not leak radiation.

**Waveguides and Coils** - Should be carefully checked to assure there are no gaps or loose bolts that will allow leakage of the radiation. Care should be taken to avoid direct contact with coils to avoid RF burns.

**RF Measurements** - The RF fields in the laboratory needs periodic evaluation with the help of field meters/radiation meters,
Precautions

a. No person should be permitted to enter a radiation field where the power density exceeds those listed in Table 1 by frequency range.

b. Tests involving fields with power densities above the Table 1 values will not be conducted outside a radiofrequency anechoic chamber or equivalent type enclosure. This enclosure will be constructed so as to reduce fields below 10% of Table 1 values at all exits.

c. At least two persons shall be present when the known or suspected power density operating conditions exceed 10 times Table 1 values at any point in the field.
d. Untrained personnel will not operate equipment capable of generating fields greater than 10% of Table 1 values.

e. Warning signs shall be posted at all entrances and a flashing red warning light will be installed in areas with equipment capable of generating fields greater than Table 1 values. This warning light will be energized when the equipment is operating.

f. Interlocks that will cause power interruption when doors are opened shall be installed on all entrances to enclosures in which power densities greater than Table 1 values are generated.

g. All microwave and radiofrequency systems capable of generating fields greater than 10% of Table 1 values will be registered with the corresponding Radiation Safety Office.
Registration will include the following information:
(1) Manufacturer and model number.
(2) Power output.
(3) Frequency range.
(4) Intended use.
(5) Location.
(6) Contact information of the principal investigator and person in charge.

Exposure of employees to microwave and radiofrequency radiation shall not exceed, under normal operating conditions, those levels specified in Table 1.
(1) The above guide applies whether the radiation is continuous or intermittent, or whether whole-body or partial body irradiation is involved.
## Limits for Maximum Permissible Exposure
(47 CFR 1.1310)

<table>
<thead>
<tr>
<th>Freq. Range</th>
<th>Electric Field V/m</th>
<th>Magnetic Field A/m</th>
<th>Power Density mw/cm²</th>
<th>Time min</th>
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<tbody>
<tr>
<td>MHz</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>0.3-3.0</td>
<td>614</td>
<td>1.63</td>
<td>100</td>
<td>6</td>
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<tr>
<td>3.0-30</td>
<td>1,842/f</td>
<td>4.89/f</td>
<td>900/f²</td>
<td>6</td>
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<tr>
<td>30-300</td>
<td>61.4</td>
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<td>300-1,500</td>
<td>…..</td>
<td>…..</td>
<td>f/300</td>
<td>6</td>
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<tr>
<td>1,500-100,000</td>
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<td>…..</td>
<td>1.0</td>
<td>6</td>
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</tbody>
</table>

### (A) Limits for Occupational/Controlled Exposures

### (B) Limits for General Population/Uncontrolled Exposures

<table>
<thead>
<tr>
<th>Freq. Range</th>
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<td>1,500-100,000</td>
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<td>…..</td>
<td>1.0</td>
<td>30</td>
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</tbody>
</table>
RF and Microwave Warning Signs

- **DANGER**
  - MICROWAVE FREQUENCIES PRESENT

- **CAUTION**
  - HIGH LEVEL RADIO FREQUENCY AREA
  - NO TRESPASSING

- **CAUTION**
  - MICROWAVE IN USE

- **NOTICE**
  - RADIO FREQUENCY FIELDS
  - NO TRESPASSING

- **NOTICE**
  - Microwave hazard in this area.

- **WARNING**
  - RADIO FREQUENCY HAZARD
Safety Aspects at Laboratory

It is required to avoid the leak of RF power from the RF systems for personal safety, to avoid pick up and interference in other nearby system as well as communication systems and damage to other systems. One can follow all safety rules during design, during testing and also during operation.

During design one needs to take care of double shielded laboratory so that microwave power does not go out of the building. Also one needs to have dedicated solid ground right near the RF source.

Every amplifier needs a perfect shielding to avoid the gap to work as slit antenna from which RF can radiate.

RF sources need many DC power supplies and one needs to add RF filters right at the input of AC power.
Safety Aspects at Laboratory

Arrangement of RF amplifiers and DC power supplies play an important role in avoiding interference. Most of the controllers of the DC power supplies misbehave in presence of RF amplifiers and one needs to take care of it.

Every amplifier stage and power supplies have many interlocks and one needs to use double shielded twisted pair control cables to avoid interference and for safe operation of interlocks.

The cable going to Data Acquisition and control system should be optically isolated and the DAC should be in another shielded room.

All RF sources have less conversion efficiency and need water cooling system at high pressures and one needs to make sure that there is no leak and tubes are operated only in presence of right flow and pressure of the DM water. Also check the conductivity of DM water before starting RF system.
Most of the transmission lines are pressurised with dry nitrogen or SF6 gas and one needs to check the transmission line at higher pressures than the operating pressures before installation. The electrical isolation of cooling and pressurised system also is of importance.

All high power high frequency sources need high voltages and one needs to follow all the protocols of using high voltages. Since the high power high frequency tubes can not withstand a fault energy of few tens of Joules one needs to have crow bar system to bypass the high voltages by detecting faults in few microseconds. There should be two types of interlocks i.e. slow and fast interlocks. The slow interlocks like temperature rise, flow, pressure etc. are normally controlled through DAC and fast interlocks are in a hardwired electronic circuits. All RF systems should be in an additional shielded enclosure and door should have interlock. No person should be inside the enclosure during operation.
Safety Aspects at Laboratory

The **operator** must operate RF system with the help of DAC in another shielded room.

Before producing RF, operator must **check all** electrical systems including interlocks and crow bar system, arc detectors etc. to make sure that tube will be safe during operation.

Before going for high power, the operator **must test the RF leak** in the laboratory with the help of field meters to make sure that it is below safety value. (Testing at low RF power)

One has to make sure that always **two persons** are present to operate the system.

Since RF systems consists of high pressure water, high pressure gases, high voltages, high power RF and delicate electronics and Data Acquisition and Control System, it is necessary to **follow all safety rules** and take necessary precautions to avoid damage to person as well as to the equipment.
Safety Aspects at Laboratory

Extremely high power electromagnetic radiation can cause electric currents **strong enough to create sparks** (electrical arcs) when an induced voltage exceeds the breakdown voltages of the surrounding medium (e.g. air at 30 kV/cm). These sparks can then ignite flammable materials or gases, possibly leading to an explosion. Hence all other grounded objects should be avoided in the vicinity of RF system.

**No person should touch** even the cage to avoid induced voltages.
Conclusions

Although tens of megawatts of RF power in the frequency range of 1-100 MHz and 2-220 GHz is required, the RF and microwave technology is well developed. The single generator can produce MW level of RF and microwave power and one can combine the power with the help of combiners and also one needs to introduce RF power in the fusion reactor with the help of many transmission lines and antennas/launchers.

Safety standards and their implementation is well done in high power RF and microwave sources to avoid interference, pick up in other systems, human safety and electromagnetic leakage etc.

IPR has developed megawatt level RF and microwave sources indigenously and is going for self-sufficiency in design, development and operation for future fusion grade reactors.
Thank You