RF Power Systems for Accelerator Application

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BARC

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Outline

• Applications of RF and Microwaves
• Specific RF systems for different accelerators
• Different types of RF systems / electronics used in accelerators
• RF Basics: Devices, Transmission Lines, Class of operation
• RF Safety
Application of Radio Frequency (RF) and Microwave

- Microwave Tea Drying and MW Disinfection System
- C-band And S-band Radar Transmitter
- Transmitter For Doppler weather Radar For Isro
- Medical Linac, LINAC For NDT
- MST Radar VHF Transmitters
- Space / satellite communication
- Plasma generation
- **Accelerators**
  - Mobile communication
  - Microwave Sources for Electronics Susceptibility
  - High Power Microwave (HPM) Sources
  - Fusion Energy / Reactors
  - Military communication systems
  - Electronic warfare systems
  - Medical applications (X ray radiography)
  - Industrial and Research applications (MW heating)
  - Scientific application (High energy particle physics)
## Radio Frequency (RF) / Microwave Frequency allocations

<table>
<thead>
<tr>
<th>Designation</th>
<th>Frequency (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HF</td>
<td>0.003-0.030</td>
</tr>
<tr>
<td>VHF</td>
<td>0.030-0.3</td>
</tr>
<tr>
<td>UHF</td>
<td>0.3-1</td>
</tr>
<tr>
<td>L B</td>
<td>1-2</td>
</tr>
<tr>
<td>S Band</td>
<td>2-4</td>
</tr>
<tr>
<td>C Band</td>
<td>4-8</td>
</tr>
<tr>
<td>X Band</td>
<td>8-12</td>
</tr>
<tr>
<td>K\textsubscript{u}</td>
<td>12-18</td>
</tr>
<tr>
<td>K</td>
<td>18-27</td>
</tr>
<tr>
<td>K\textsubscript{a}</td>
<td>27-40</td>
</tr>
<tr>
<td>Millimeter</td>
<td>40-300</td>
</tr>
<tr>
<td>Sub-millimeter</td>
<td>&gt;300</td>
</tr>
</tbody>
</table>
Use of RF / Microwave

- RF Tx
- Mobile communication
- Satellite communication
- RF Plasma
- Weather Radar
- Accelerator
- Ship borne communication
To demonstrate the scientific and technological feasibility of fusion power

### ITER Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fusion Power</td>
<td>500 MW</td>
</tr>
<tr>
<td>Plasma Major radius</td>
<td>6.2 m</td>
</tr>
<tr>
<td>Plasma Minor radius</td>
<td>2.0 m</td>
</tr>
<tr>
<td>Vertical Elongation</td>
<td>1.7</td>
</tr>
<tr>
<td>Plasma Current</td>
<td>15 MA</td>
</tr>
<tr>
<td>Toroidal Field</td>
<td>5.3T</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>&gt; 300 s</td>
</tr>
<tr>
<td>Plasma Volume</td>
<td>837 m³</td>
</tr>
</tbody>
</table>
Medical Linac: RF / MW system in GHz

High Power RF / MW Transmitters for Radar application

MW peak Pulse power, low duty cycle, High MW radiation lobes, Pulse Transmitter
The Technologies used in accelerator

- Large scale vacuum
- **High power radio waves / microwaves**
- Normal / Superconducting technology
- Very strong and precise magnets
- Computer control
- Beam instrumentation and diagnostics
- Large scale project management
- Accelerator physics (beam dynamics)
Need or Role of RF Systems in accelerators

To Provide Sufficient Accelerating Gap Voltage for Acceleration

In the Synchrotron & Storage Ring (Electron Cyclic Accelerators) circulating electrons lose energy in the form of electromagnetic radiation. To keep them in equilibrium orbits this loss has to be compensated. The RF system provides energy for acceleration as well as compensates for this radiation loss.

The particles gain energy by surfing on the electric fields of well-timed radio oscillations (in a cavity)
An RF high power source is a major power system, affecting the overall Accelerator machine cost. Its major subsystems are low level RF (LLRF), high power amplifier (HPA), Circulator, DC bias supplies, cooling water system, control system, transmission line inclusive of directional couplers, RF loads, magic Tee, bends, straight sections, RF windows, RF couplers etc.
RF Devices
In our case, we are considering only three options from frequency and power requirements for our accelerator application.

1) Klystrons  2) IOTs  3) Solid State Devices e.g. MOSFETs
## 4. RF Amplifiers: Some Criteria

### Output Power, Efficiency and Gain:

<table>
<thead>
<tr>
<th></th>
<th>Klystron</th>
<th>IOT</th>
<th>SSA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Power</strong></td>
<td>60 - 1000 kW</td>
<td>80 kW</td>
<td>700 W</td>
</tr>
<tr>
<td><strong>Efficiency</strong></td>
<td>62 %</td>
<td>71 %</td>
<td>70 %</td>
</tr>
<tr>
<td><strong>Gain</strong></td>
<td>40 dB</td>
<td>25 dB</td>
<td>20 dB</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IOT</td>
<td>Klystron</td>
<td>MBK</td>
<td>SSPA</td>
</tr>
<tr>
<td>-----</td>
<td>----------</td>
<td>-----</td>
<td>------</td>
</tr>
</tbody>
</table>
| **Adv.** | • Reduced size  
• Replacement of tube only  
• Low group delay  
• Good efficiency in a broad power range  
• Grid modulation  
• Tube possibly Off between pulses  
• Good Efficiency | • Large return of experience  
• Certainty of feasibility  
• High gain  
• Possible anode modulation  
• High reliability & long lifetime  
• MW operation | • Klystron technology with subsequent spin-offs  
• Low cathode voltage (half of klystron) |
| **Drawbacks** | • Gain : 22 to 25 dB  
• Grid power supply referenced to the cathode potential  
• Experience limited to lower power levels | • Relatively large size  
• Large no. of Bias supplies  
• Low overall efficiency  
• High dependability on single device | The same as the klystron + still a limited return of experience |

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- High Cost  
- Low to Medium Reliability  
- Limited up to 200 kW
Vacuum Tube based RF amplifiers

Klystron
gain ~ 40 dB ($\times 10^4$ power gain)
e.g. 100 W in, 1 MW out

Klystron gain ~ 25 dB ($\times 300$ power gain)
e.g. 200 W in, 60 kW out
Klystron - a microwave generator

- The $e^-$ beam enters in an RF cavity with $L_{\text{cavity}} \approx \frac{\lambda_{\text{RF}}}{2}$.
- In the cavity there is a velocity modulation of the $e^-$ beam.
- In the drift region the velocity modulation induces a beam bunching.
- The bunched beam induces a wake modulation in the second cavity.
- The initial RF power is amplified in the second cavity.
- The residual $e^-$ beam is absorbed in a stopper.
- If the two cavities are coupled we have instead an oscillator.

Other RF power amplifier:
- the magnetron,
- the travelling wave tube (TWT)
Inductive Output Tube (IOT)

Technical Specifications

• High Efficiency
• Small Drift tube length
• Small Size
• Class B Operation
• Low Gain
• Frequency is limited to 1.3 GHz
• Power < 40 kW
• Small Size
## Transmission Lines:

Used for carrying the RF power from high power RF source to its application like Accelerator.

### Comparison between transmission Line Types

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Coax</th>
<th>Waveguide</th>
<th>Stripline</th>
<th>Micro stripline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modes: Preferred Other</td>
<td>TEM TM, TE</td>
<td>TE10 TM,TE</td>
<td>TEM TM,TE</td>
<td>Quasi TEM TM, TE</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>High</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Losses</td>
<td>Medium</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Power Capacity</td>
<td>Medium</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Physical size</td>
<td>Large</td>
<td>Large</td>
<td>Medium</td>
<td>Small</td>
</tr>
<tr>
<td>Ease of fabrication</td>
<td>Medium</td>
<td>Medium</td>
<td>Easy</td>
<td>Easy</td>
</tr>
<tr>
<td>Integration with</td>
<td>Hard</td>
<td>Hard</td>
<td>Fair</td>
<td>Easy</td>
</tr>
</tbody>
</table>

### Types of Transmission Lines

1. Two wire line
2. Coaxial Cable
3. Waveguide: Rectangular or Circular
4. Planer Transmission Line
   i. Strip Line
   ii. Microstrip Line
   iii. Slot Line

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Transmission Line Details

\[ V(l) = V_+ e^{+l} + V_- e^{-l} \]
\[ I(l) = I_+ e^{+l} - I_- e^{-l} \]
\[ \Gamma(l) = \frac{Z_L - Z_c}{Z_L + Z_c} \]

Coaxial Cables

Micro strip details

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Amplifier Classes represent the amount of the output signal which varies within the amplifier circuit over one cycle of operation when excited by a sinusoidal input signal. The classification of amplifiers range from entirely linear operation (for use in high-fidelity signal amplification) with very low efficiency, to entirely non-linear (where a faithful signal reproduction is not so important) operation but with a much higher efficiency, while others are a compromise between the two.

Amplifier classes are mainly lumped into two basic groups. The first are the classically controlled conduction angle amplifiers forming the more common amplifier classes of A, B, AB and C, which are defined by the length of their conduction state over some portion of the output waveform, such that the output stage transistor operation lies somewhere between being “fully-ON” and “fully-OFF”.

The second set of amplifiers are the newer so-called “switching” amplifier classes of D, E, F, G, S, T etc, which use digital circuits and pulse width modulation (PWM) to constantly switch the signal between “fully-ON” and “fully-OFF” driving the output hard into the transistors saturation and cut-off regions.
### Class of operation

<table>
<thead>
<tr>
<th>Class of operation</th>
<th>Conduction Angle</th>
<th>Gain (dB)</th>
<th>Efficiency %</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 A</td>
<td>360</td>
<td>25 to 30 (max.)</td>
<td>30 to 50</td>
<td>Low harmonic distortion</td>
</tr>
<tr>
<td>2 AB</td>
<td>270</td>
<td>20 to 25</td>
<td>Upto 60</td>
<td></td>
</tr>
<tr>
<td>3 B</td>
<td>180</td>
<td></td>
<td>66</td>
<td>IMD, audio amplifier</td>
</tr>
<tr>
<td>4 C</td>
<td>90 or &lt; 180</td>
<td>15</td>
<td>75</td>
<td>Low linearity, high harmonics</td>
</tr>
<tr>
<td>5 D,F,G,I,S,T</td>
<td>~ 0</td>
<td></td>
<td>90 to 100</td>
<td>Non linear, High harmonics</td>
</tr>
</tbody>
</table>

![Amplifier Classes Diagram](image-url)
High Power RF systems
For each high power RF system, development of following subsystems are needed:

1. RF driver
2. High power RF devices/components like tetrode, circulator, RF loads
3. RF amplifier chain low to high power
4. RF Transmission lines
5. Special RF grounding
6. DC/AC bias supplies with protection
7. PLC based Interlocking and protection
8. Fast protections (20 micro seconds)
9. Low conductivity water (LCW) cooling
10. Thermal management
Low Energy High Intensity Proton Accelerator (LEHIPA) at CFB

ECR Ion Source
50 KeV
50mA

Low Energy
Beam Transport (LEBT)

RFQ Accelerator
(4 -Vane type)
3 MeV, 30mA
500 kW

Medium Energy
Beam Transport
(MEBT )
inclusive of
Buncher cavity

Drift Tube LINAC
(DTL1&2 and 3&4)
10 / 20 MeV, 30mA
DTL-1&2 ~ 900 kW and
DTL-3 &4 ~ 900 kW

Beam Dump

Waveguide (WR 2300 based)
RF Power Transmission
system for RF Power
distribution

3-1/8”, 50 ohm
coaxial
Transmission Line

Waveguide (WR 2300 based)
RF Power Transmission
system for RF Power
distribution

A) RF Power Source
(1 MW / 352.21 MHz) and
Power distribution System
(WR 2300 based)

A) RF Power Source
(1 MW / 352.21 MHz) and
Power distribution System
(WR 2300 based)

Three 1 MW, 352.21 MHz RF systems with transmission lines for carrying 1 MW RF power to respective RF cavity

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**Accelerator subsystems**

1. High Power Radio Frequency systems
2. Low Level RF & control systems
3. Beam Instrumentation and diagnostics
4. Vacuum
5. Ion source
6. Accelerator cavities
7. Cooling

**Various disciplines involved in RF power**

1. High voltage engineering
2. Vacuum
3. RF engineering
4. Fast protections & interlocking
5. Effective thermal management
6. RF interference (RFI) suppression
7. Successful grounding techniques for DC and RF subsystems etc.

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**Generic High Power RF system of an accelerator**
Klystron based RF power system and its distribution system (1 MW @ 352.21MHz)

Major Subsystems

1. Cathode bias supply [100 kV, 24 A (max.), operating at 90 kV]
2. Anode bias supply (60 kV and floating at 90 kV cathode voltage)
3. HV interface system for three 90 kV HV distributions and 100 kV crowbar protection against arcs
4. High power RF components (e.g. circulator, Harmonic filter, directional coupler, RF load etc.) capable of handling 1 MW RF power
5. Interlock and protection system handling around 80 signals of different formats (e.g. analog, digital, optical, low level RF, DC etc), LCW system for heat removal
6. Waveguide WR 2300 based RF power distribution system comprising of RF window, bends, magic Tees, straight sections, directional couplers etc.

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Results of Coupling of klystron RF system with RFQ initially for RF conditioning and then for proton beam acceleration

i. RF conditioning of RFQ
ii. 220 kW RF power coupled via WR 2300 waveguide transmission line with first 2 segments of RFQ to achieve 1.25 MeV proton beam
iii. Klystron system has operated 24 * 7 operation without any trip during commissioning of 1.25 MeV RFQ accelerator.

RF power 20.99 dBm + 62.5 Att.
= 83.49 dBm = 220 kW
400 KeV RFQ (D+) accelerator is planned as a part of ADS for:

To study

1. RF accelerator technology
2. High Power RF (HPRF) system development
3. RF power coupling to accelerator

A 60 kW, 350 MHz HPRF systems comprises of,

1. high power tetrode TH 571B, its driver amplifier
2. rigid coaxial transmission line (6 1/8”, 50 ohm)
3. coaxial transmission line based components like circulator, directional couplers etc
4. other HV/LV bias supplies,
5. Low conductivity water cooling set up and air cooling
6. An interlock and protection circuit
7. Fast protection circuits (IGBT or crowbar based)
60 KW amplifier

3 kW driver amplifier

RF Load

RF system set up @ V D Graff building at BARC

DC bias

PLC Interlock system

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RF power waveform @ 60.5 kW waveform in pulse mode with 1% duty cycle

**Results:**
- Class: B towards C
- ✓ Gain of power stage: 14.6 dB
- ✓ Efficiency: 68 %
- ✓ RF radiation measured: 5.3 microwatt/sq cm < 0.2 mW/sq/cm (as per IEEE 1991)
- ✓ Rigid and reliable interlock and protection
- ✓ 2\textsuperscript{nd} & 3\textsuperscript{rd} Harmonics is around 30 dB down the fundamental

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60 kW, 350 MHz RF system coupled to RF coupler for conditioning up to 50 kW in pulse mode

Circulator

Directional coupler

RF coupler

RF system
60 kW, 350 MHz RF system successfully coupled to RFQ accelerator in pulse mode for proton beam acceleration.
SSRFPA

Compact DC supplies
Interlock and Protection
Water cooling

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SSRF MODULES DEVELOPED

- Center Frequency: 350 / 352 / 325 MHz
- Bandwidth (3 dB): 10 MHz
- Power output (sat.): 100 W, 300 W, 800 W, 1000 W
- Power Gain: 8.5 - 20 dB
- Efficiency: 50 - 68%
- Protection: Circulator
Power Combiners/Dividers

- Combiners can be designed using coaxial lines.
- 2, 4, 8-way combiners
- Power levels 100 W, 1 kW, 10 kW.
- Return loss of >20dB at input ports (with phase coherence)
- Return loss of better than 25dB at output port.
- Isolation among input ports better than 25dB.
- Transmission loss < 0.15dB

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325 MHz, 3 kW Solid State RF Amplifier

Display of Calorimetric measurement of RF Power

325 MHz, 7 kW Solid State RF Amplifier

RF Power Waveform at 7 kW on spectrum analyzer

3 kW, 325 MHz Amplifier endurance test (210 Hours continuously) at Fermilab

Sensor data of Calorimetric measurement of RF Power

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SAFETY against Non Ionizing Radiation
Non-ionizing radiation

• Electromagnetic radiation is defined as the propagation of energy through space in the form of waves or particles. The higher the frequency of an electromagnetic wave, the greater will be the energy (eV) of a photon associated with it. The photon energies of RF electromagnetic waves are not high enough to cause the ionization of atoms and molecules and RF energy is, therefore, characterized as non-ionizing radiation.

• Electromagnetic radiation consists of waves of electric and magnetic energy moving together (that is, radiating) through space at the speed of light. Taken together, all forms of electromagnetic energy are referred to as the electromagnetic spectrum. Radio waves and microwaves emitted by transmitting antennas are one form of electromagnetic energy. Often the term electromagnetic field or radiofrequency (RF) field may be used to indicate the presence of electromagnetic or RF energy.

• An RF field has both an electric and a magnetic component (electric field and magnetic field), and it is often convenient to express the intensity of the RF environment at a given location in terms of units specific for each component. For example, the unit "volts per meter" (V/m) is used to measure the strength of the electric field and the unit "amperes per meter" (A/m) is used to express the strength of the magnetic field.
Frequency Spectrum of ionizing and non-ionizing radiation (Ref.: FCC OET bulletin 65, Aug 1997)

The photon energies of RF electromagnetic waves are not high enough to cause the ionization of atoms and molecules and RF energy is, therefore, characterized as **non-ionizing radiation**, along with visible light, infrared radiation and other forms of electromagnetic radiation. All forms of electromagnetic energy when taken together are referred to as the electromagnetic spectrum.

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RF and MW Safety : 1) Equipment safety and 2) Human Safety

1. **Equipment safety**: Standards for Electrical equipment for measurement, control and lab uses;

   a) **CISPR standards**
   CISPR standards generally only relate to EMC emission test methods and limits. It is an acronym of Comité International Spécial des Perturbations Radio
   - **CISPR11**: Industrial, scientific and medical (ISM) radio-frequency equipment – Electromagnetic disturbance characteristics - Limits and methods of measurement.

   b) **IEC standards**
   The IEC standards on EMC are mostly part of the IEC 61000 family. Below are some examples.
   - **IEC EN 61000-4-3**: Electromagnetic compatibility (EMC)- Part 4-3: Testing and measurement techniques - Radiated, radio-frequency, electromagnetic field immunity test
   - **IEC EN 61000-4-6**: Electromagnetic compatibility (EMC) - Part 4-6: Testing and measurement techniques - Immunity to conducted disturbances, induced by radio-frequency fields

   c) **FCC standards**
   - **FCC Part 15** regulates unlicensed radio-frequency transmissions, both intentional and unintentional.
   - **MIL-STD 461** is a US Military Standard addressing EMC. Currently in revision F, it covers Conducted and Radiated Emissions and Susceptibility.

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2) Human Safety

Human exposure
Possible harmful effects of human exposure to electromagnetic fields have been considered by a number of international organisations, including the World Health Organization (WHO) and the International Commission for Non-ionizing Radiation Protection (ICNIRP).

Guidelines and directives
• **ANSI C 95.1 – 1974** - American National Standard Safety of Electromagnetic Radiation with respect to personnel
• **ANSI C 95.1 – 1982** – With major revisions in 1974 standard and frequency dependent standard
• **ANSI C 95.1 – 1991** – Up gradations in 1982- standard w.r.t to RF shocks and burns and induced RF currents VLF to VHF range

Because of the more recent research on the problems relating to RF shock and burn and significant induced RF currents for frequencies in the VLF-VHF range of frequencies, these standards are revised to also incorporate limits on induced currents.

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The most important standard referred is,

- **ICNIRP** gives guidelines for EMF, low frequency, magnetic fields, etc.
- **EU directives** concerning this are based on the ICNIRP guidelines.
- The **WHO** (the World Health Organization) position on human exposure to EMF is to comply with the ICNIRP guidelines.
Specific Absorption Rate (SAR): The quantity used to measure how much RF energy is actually absorbed in a body is called the specific absorption rate (SAR). It is usually expressed in units of watts per kilogram (W/kg) or mill watts per gram (mW/g).

Human safety: Quantification of radiated emission

FCC Limits for Localized (Partial-body) Exposure for human safety: SAR

<table>
<thead>
<tr>
<th>Occupational / Controlled exposure</th>
<th>General / Uncontrolled exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 kHz – 6 GHz</td>
<td>100 kHz – 6 GHz</td>
</tr>
<tr>
<td>&lt; 0.4 W/kg whole body</td>
<td>&lt; 0.08 W/kg whole body</td>
</tr>
<tr>
<td>≤ 8 W/kg partial body</td>
<td>≤ 1.6 W/kg partial body</td>
</tr>
</tbody>
</table>
### Reference levels for occupational exposure to time varying E and B field (unperturbed rms values) (Ref.: ICNIRP)

<table>
<thead>
<tr>
<th>Frequency Range</th>
<th>E field Strength (V/m)</th>
<th>H field Strength (A/m)</th>
<th>B Field (μT)</th>
<th>Equivalent power density ( S_{eq} ) (W/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up to 1 Hz</td>
<td>--</td>
<td>1.63 x 10^5</td>
<td>2 x 10^5</td>
<td>--</td>
</tr>
<tr>
<td>1-8 Hz</td>
<td>20,000</td>
<td>1.63 x 10^5 /f^2</td>
<td>2 x 10^5 /f^2</td>
<td>--</td>
</tr>
<tr>
<td>8-25 Hz</td>
<td>20,000</td>
<td>2 x 10^4 /f</td>
<td>2 x 10^4 /f</td>
<td>--</td>
</tr>
<tr>
<td>0.025 – 0.82 kHz</td>
<td>500 /F</td>
<td>20/f</td>
<td>25 /f</td>
<td>--</td>
</tr>
<tr>
<td>0.82 – 65 kHz</td>
<td>610</td>
<td>24.4</td>
<td>30.7</td>
<td>--</td>
</tr>
<tr>
<td>0.065 – 1 MHz</td>
<td>610</td>
<td>1.6/f</td>
<td>2.0 /f</td>
<td>--</td>
</tr>
<tr>
<td>1-10 MHz</td>
<td>610/F</td>
<td>1.6/f</td>
<td>2.0 /f</td>
<td>--</td>
</tr>
<tr>
<td>10-400 MHz</td>
<td>61</td>
<td>0.16</td>
<td>0.2</td>
<td>10</td>
</tr>
<tr>
<td>400-2000 MHz</td>
<td>3f^{1/2}</td>
<td>0.08f^{3/2}</td>
<td>0.01 f^{1/2}</td>
<td>f/40</td>
</tr>
<tr>
<td>2-300 GHz</td>
<td>137</td>
<td>0.36</td>
<td>0.45</td>
<td>50</td>
</tr>
</tbody>
</table>
Reference levels for general public exposure to time varying electric and magnetic fields (unperturbed rms value) (Ref.: ICNIRP)

<table>
<thead>
<tr>
<th>Frequency range</th>
<th>E- field strength (V m$^{-1}$)</th>
<th>H- field strength (A m$^{-1}$)</th>
<th>B- field (µT)</th>
<th>Equivalent plane wave power density $S_{cq}$ (W m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up to 1 Hz</td>
<td>----</td>
<td>3.2 X 10$^4$</td>
<td>4 X 10$^4$</td>
<td>----</td>
</tr>
<tr>
<td>1 – 8 Hz</td>
<td>10,000</td>
<td>3.2 X 10$^4$/ f$^2$</td>
<td>4 X 10$^4$/ f$^2$</td>
<td>----</td>
</tr>
<tr>
<td>8 – 25 Hz</td>
<td>10,000</td>
<td>4000/f</td>
<td>5000/f</td>
<td>----</td>
</tr>
<tr>
<td>0.025 – 0.8 kHz</td>
<td>250/f</td>
<td>4/f</td>
<td>5/f</td>
<td>----</td>
</tr>
<tr>
<td>0.8 – 3 kHz</td>
<td>250/f</td>
<td>5</td>
<td>6.25</td>
<td>----</td>
</tr>
<tr>
<td>3 – 150 kHz</td>
<td>87</td>
<td>5</td>
<td>6.25</td>
<td>----</td>
</tr>
<tr>
<td>0.15 – 1 MHz</td>
<td>87</td>
<td>0.73/f</td>
<td>0.92/f</td>
<td>----</td>
</tr>
<tr>
<td>1 – 10 MHz</td>
<td>87/f$^{1/2}$</td>
<td>0.73/f</td>
<td>0.92/f</td>
<td>----</td>
</tr>
<tr>
<td>10 – 400 MHz</td>
<td>28</td>
<td>0.073</td>
<td>0.092</td>
<td>2</td>
</tr>
<tr>
<td>400 – 2000 MHz</td>
<td>1.375 f$^{1/2}$</td>
<td>0.0037 f$^{1/2}$</td>
<td>0.0046 f$^{1/2}$</td>
<td>f/200</td>
</tr>
<tr>
<td>2 – 300 GHz</td>
<td>61</td>
<td>0.16</td>
<td>0.20</td>
<td>10</td>
</tr>
</tbody>
</table>
Basic restrictions for time varying electric and magnetic fields for frequencies up to 10 GHz

<table>
<thead>
<tr>
<th>Exposure characteristics</th>
<th>Frequency range</th>
<th>Current density for head and trunk (mA/m²) (rms)</th>
<th>Whole-body average SAR (W/kg)</th>
<th>Localized SAR(head and trunk) (W/kg)</th>
<th>Localized SAR (limbs) (W/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occupational exposure</td>
<td>Up to 1 Hz</td>
<td>40</td>
<td>----</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td></td>
<td>1 – 4 Hz</td>
<td>40/f</td>
<td>----</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td></td>
<td>4 Hz – 1 kHz</td>
<td>10</td>
<td>----</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td></td>
<td>1 – 100 kHz</td>
<td>f/100</td>
<td>----</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td></td>
<td>100kHz – 10 MHz</td>
<td>f/100</td>
<td>0.4</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>10MHz – 10 GHz</td>
<td>----</td>
<td>0.4</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>General public exposure</td>
<td>Up to 1 Hz</td>
<td>8</td>
<td>----</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td></td>
<td>1 – 4 Hz</td>
<td>8/f</td>
<td>----</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td></td>
<td>4 Hz – 1 kHz</td>
<td>2</td>
<td>----</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td></td>
<td>1 – 100 kHz</td>
<td>f/500</td>
<td>----</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td></td>
<td>100kHz – 10 MHz</td>
<td>f/500</td>
<td>0.08</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>10MHz – 10 GHz</td>
<td>----</td>
<td>0.08</td>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>

(Ref.: ICNIRP)
Effect of microwaves in human body

- The blood vessels are dilating and the blood flow increases substantially as the thermoregulatory mechanism is activated in order to keep the body temperature constant.
- With rising body temperature the metabolic rate rises, which may lead to Stress-Adaptation-Fatigue Syndrome.

- Above 10 GHz (3 cm wavelength or less) heating occurs mainly in the outer skin surface.
- From 3 GHz to 10 GHz (10 cm to 3 cm) the penetration is deeper and heating higher.
- From 150 MHz to about 1 GHz (200 cm to 25 cm wavelength), penetration is even deeper and because of high absorption, deep body heating can occur.
- Any part of the body that cannot dissipate heat efficiently or is heat sensitive may be damaged by microwave radiation of sufficient power.

Electromagnetic radiation in the 1 mm to 1 m wavelength range (300 MHz to 300 GHz) is referred to as microwave radiation.
- A part of which is known as radiofrequency (RF) radiation, which covers 0.5 MHz to 300 GHz range and is considered in the context of adverse biological effects.
THANK YOU !!!