HIGH POWER MICROWAVES: APPLICATIONS AND DEVICES FOR THEIR GENERATION AND AMPLIFICATION

B. N. Basu

bnbasu_bhu@rediffmail.com

Centre of Research in Microwave Tubes
Department of Electronics Engineering
Institute of Technology
Banaras Hindu University
Varanasi

Organisation

Historical timeline

Conventional applications of microwaves: radar, communication, heating,
material processing, etc.

Microwave hazards and safe limits

Civil applications of high power microwave (HPM): Satellite power station,

Artificially ionised layer: Long-range communication, and Protection of ozone layer: Atmospheric purification of admixtures that destroy ozone layer, and Ozone generation

Military applications of HPM: Electronic warfare and directed energy weaponry:
Microwave bomb or E-bomb

Vulnerability of electronic devices to microwave energy: modes of entry and upset and
threshold limits

High power microwave tubes

Devices driven by intensive relativistic electron beam: VIRCATOR, BWO, MILO, etc.

Fast-wave devices: gyrotron, gyro-TWT, CARM, Peniotron, etc.

Applications of microwaves/ millimeter waves

Microwave oven

Microwave heating

Industrial heating

Peaceful use of high power microwave energy

Power beaming

Medical application

Material processing

Satellite power station (SPS)

Plasma electron cyclotron resonance heating

Interaction of high power microwave energy with atmosphere

Ozone layer and its depletion

Extension of range of radio by artificial ionosphere mirror

Ozone generation

Atmospheric purification of freons

Historical Timeline

1820-40

Effect of an electric current on a magnetized needle — Oersted (1819)

Effect of an electric current on another electric current — Ampère (1820)

Electric induction — Faraday (1831)

1841-60

Faraday rotation (1845)

Morse telegraph — Samuel Morse (1844) (between Baltimore and Washington)

Atlantic Cable Company — Kelvin (1850-55) — Transmission line theory with distributed line parameters

1861-80

Pantelegraphe — First Telefax between Lyons and Paris (1866)

Maxwell’s equations — J. C. Maxwell (1870)

Maxwell’s Dynamic Theory of Electromagnetic Fields — J. C. Maxwell: A Treatise on Electricity and Magnetism (Clarendon, Oxford) (1873)

> Maxwell’s equations: “Simple enough to imprint on a T-shirt, and yet reach enough to provide new insights throughout a lifetime of study”— J. R. Whinnery
>
> “The teaching of electromagnetics,” *IEEE Trans. Education*, vol. 33, pp. 3-7 (1990)

Phototube — G.R. Carey (1875)

Telephone — Bell and Gray (1876)

Cathode-ray tube — William Crookes (1879)

Piezoelectricity — P. Curie (1880)

1881-1900

Experimental appreciation of nature of electromagnetic waves

— Heinritch Hertz (1887)

Source of electromagnetic waves: 30 MHz

Hertz's Experiments

A spark gap connected to an induction coil.

The interruption of current in the coil produced a high voltage causing a spark at the gap.

Detector of electromagnetic waves:

A circular loop of thick wire with ends separated by a very tiny gap for a small observable spark

Standing-wave pattern

One of the room walls was covered with a large zinc sheet.

The distance between consecutive nulls $(=\lambda/2)$ was measured.

Hence Hertz found $v_p \cong 3\times10^8$ m/s .

Hertz subsequently used 'parabolic' reflectors in his 450-MHz experiments.

Coining the word ‘electron’ — Stoney (1891)

Electric current between a heated filament and a plate
in an evacuated bulb — Edison (1893)

Discovery of X-ray — Wilhelm Rontegen (1895)

Discovery of the electron — J. J. Thompson (1897)

Oscilloscope — Zenneck (1899) following the work of Braun (1896)

Cathode-ray tube — Karl Ferdinand Braun (1897)

Theoretical foundation of quantum mechanics — Planck (1900)

Radio link — G. Marconi, J. C. Bose and others (1895-1901)
Marconi: $\lambda \approx 25$ cm up to 4 miles, parabolic reflector.
Transatlantic wireless message, England-to-Newfoundland (3000 miles)
J. C. Bose: Experiments in the mm wave range: diffraction grating, spectrometer, polarimeter

A typical example of J. C. Bose’s experiment:

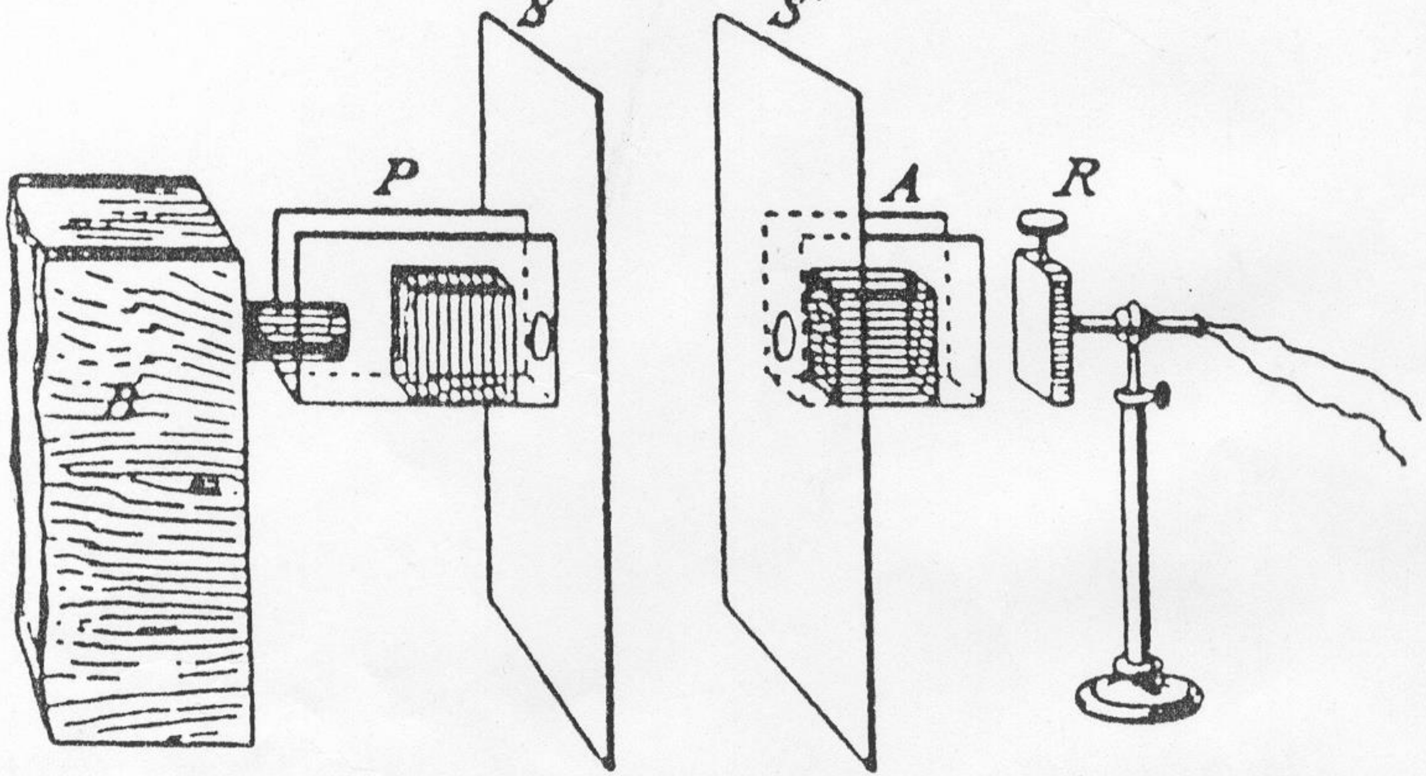
“On the rotation of plane of polarisation of electric waves by a twisted structure,” Proc. R. Soc. Lond a 63 (1898), 146-152 by Jagadish Chunder Bose, M. A., D. Sc., Professor of Physical Science, Presidency College, Calcutta. Communicated by Lord Raleigh, F. R. S. Received February 14, — read March 10, 1898.

Polariser/ Anlyser:
— wire gratings
— Parallel slits cut out of two square pieces of thick copper
— An ordinary book with its pages as absorbers (later improvised with alternate leaves of paper and tinfoil)

Leaves compressed to form a block, enclosed in a brass cell with circular openings on opposite sides for the passage of radiation. Typically, 6×6 cm of 4.5cm thick; opening/ aperture diameter 4 cm. The brass cell is placed on a shelf attached to a screen of thick brass plate 35×35 cm, with a circular opening 4cm diameter for radiation to pass through.

Polariser has vertical leaves. Analyser has horizontal leaves

When two such cells are crossed, the field is completely extinguished. The field is partially restored when one's fingers are placed at 45^0 between the crossed polariser and analyser


S
S'
P
A
R
B

Electro-optic analogues of two varieties of sugar solutions, typically dextrose and levulose

Bundles of elements (‘molecules’) of jute fibres (each element,typically, 10 cm length, 4.5 cm diameter) placed end to end

A: Untwisted

B: Twisted to the right (positive)

C: Twisted to the left (negative)

Restoration of field recorded by the receiver, when the bundles of variety B or C were interposed between the crossed polariser and analyser

No restoration of fields when either the bundles of variety A or the bundles of varieties B and C in equal proportions were interposed between the crossed polariser and analyser

1901-1920

Fleming valve (vacuum tube diode) — John Ambrose Fleming (1904)

First rudimentary radar — C. Hülsmeyer (1904)

Audion or triode valve — Lee DeForest (1906)

Physics of electric oscillation and radio telegraphy — G. Marconi and K. F. Braun (1909) (Nobel prize)

Superconductivity — H. Kammerling Onnes (1911)
Coolidge tube (first practical X-ray tube) — William D. Coolidge (1913)

First transit-time microwave tube (retarding field tube) — Barkhausen (1920)

Commercial electron tube — RCA (1920)

1921-1940

Smooth-wall magnetron — A. W. Hull (1921)

Tube scanning system for television — Philo T. Farnsworth (1922)

Iconoscope or cathode-ray tube and kinescope — Vladimir K Zworykin (1923)

Tetrode valve — Hull and Williams (1926)

Beam diffraction oscillogram
(beam and helix-wave interaction) — Haeff (1933)

Cavity magnetron — Posthumas (1935)

Linear beam microwave tube theory — Oskar and Heil (1935)

Klystron — Metcalf and Hahn (1936)

Klystron — Russel and Siguard (Varian brothers) (1937)

Cavity magnetron — Randall and Boot (1939)

Travelling-wave tube — N. E. Lindenblad (1940)
(PM series focusing, helix pitch tapering)
(U. S. Patent 2,300,052, filed on May 4, 1940 issued on October 27, 1942)

1941-60

Travelling-wave tube — Kompfner (1942)

Travelling-wave tube — Field (1946) (U. S. Patent 2,575,383)

Travelling-wave tube — Pierce (1946) (U. S. Patent 2,602,148)

Generation of microwaves by rotational energy of helical electron beam — H. Kleinwachter (1950)

Maser — Gordon (1954)

ECM interaction theory — J. Schneider (1957)
— R. Twiss (1958)
— A. Gaponov (1959)

1961 onwards

Earliest version of gyrotrons in Russia (1965)

Proposals on JET and ITER (1980 onwards)

Modern gyrotron technology (1990 onwards):

IAP, Russia; FZK, Germany; JAERI, Japan; Toshiba, Japan; CPI, USA; TTE, France; CRPP, France, MURI, USA and so on

Designation of frequency ranges

VLF	<30 kHz
LF	30-300 kHz
MF	0.3-3 MHz
HF	3-30 MHz
VHF	30-300 MHz
UHF	300-3000 MHz
SHF	3-30 GHz
EHF	30-300 GHz

Microwave communication/ Radar

L	1.12-1.70 GHz
S	2.60-3.95
C	3.95-5.85 GHz
X	8.20-12.40 GHz
Ku	12.40-18.00 GHz
K	18.00-26.50 GHz
Ka	26.50-40.00 GHz
V	40.00-60.00 GHz
E	60.00-90.00 GHz
F	90-140.00 GHz

(The highest frequency ever realised by a vacuum-tube source is 1200 GHz from a Russian BWO).

Attenuation of the normal atmosphere

Activities in the millimeter-wave range around 35 GHz and 95 GHz ‘atmospheric windows’ and 60 GHz ‘atmospheric wall’ (for secure communication)

Application of electromagnetic waves including microwaves

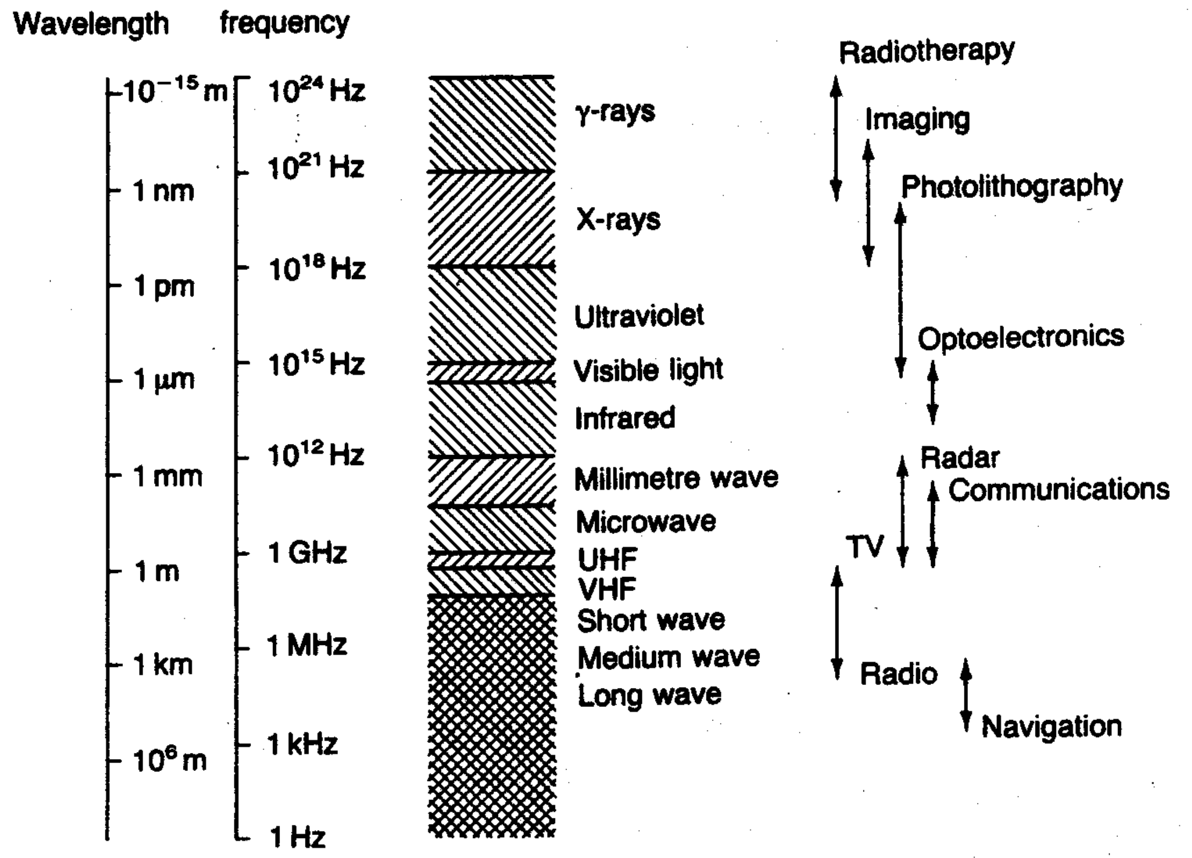


Chart of the electromagnetic spectrum showing some of the uses to which electromagnetic waves are put.

Applications of microwaves/ millimeter waves

Point-to-point communication — more channels, focused radiation

Satellite communication

Deep space and specialised satellite communication

Satellite-to-home communication

High information density communication

Long-range, high resolution radar

Medical applications

Advanced high gradient RF linear accelerators

Plasma diagnostics and chemistry

Material processing (including ceramic sintering and joining)

Laser pumping

Applications of microwaves/ millimeter waves (*continued*)

Waste remediation

Electron cyclotron resonance heating (ECRH) of fusion plasmas to ~10^8 K for controlled thermonuclear reactor

Nonlinear spectroscopy

Power beaming

- City lighting
- Satellite power station (SPS)
- Extension of radio range
- Atmospheric purification of freons
- Ozone generation

Electronic warfare: conventional (ECM and ECCM) and directed energy involving HPM

Microwave heating

Cooking, industrial heating, medical application

ISM (industrial, scientific, medical): 2.45 GHz.

Average power density absorbed in a lossy dielectric

$$= \text{Average } \vec{E}.\vec{J}_c = \text{Average } \vec{E}.(\sigma\vec{E}) = \frac{1}{2}\sigma E_0^2$$

$$= \frac{1}{2}\omega\varepsilon_0\varepsilon_r'' E_0^2$$

E_0 = peak electric field intensity

$$(\varepsilon'' = \varepsilon_0\varepsilon_r'' = \sigma / \omega)$$

For water at 25 C : $\varepsilon_r'' =$ 0.36 at 10 MHz, and =12 at 30 GHz

Large heating at higher frequencies

Volumetric heating at microwaves rather than surface heating (contact, concentration of RF energy at surface)

(skin depth large compared to that of infrared)

Cool surrounding

ISM (Industrial, Scientific, Medical)

0.915 GHz ± 13.0 MHz

2.450 GHz ± 50.0 MHz

5.800 GHz ± 75.0 MHz

6.780 GHz

24.125 GHz ±125.0 MHz

40.680 GHz

Microwave oven

Parcy Spencer (1946) of Raytheon Corporation experienced, while operating a magnetron, observed the melting of candy bar kept in his pocket and the cracking and explosion of popcorn and eggs kept in front

ISM frequencies: 896 MHz, 2450 MHz, 2300 MHz, 10,525 MHz

Typical oven operating frequency: 2450 MHz

Loop extended from central conductor of coaxial output coupler of cavity

Coaxial coupler central conductor (E-probe) launches TE_{10} mode

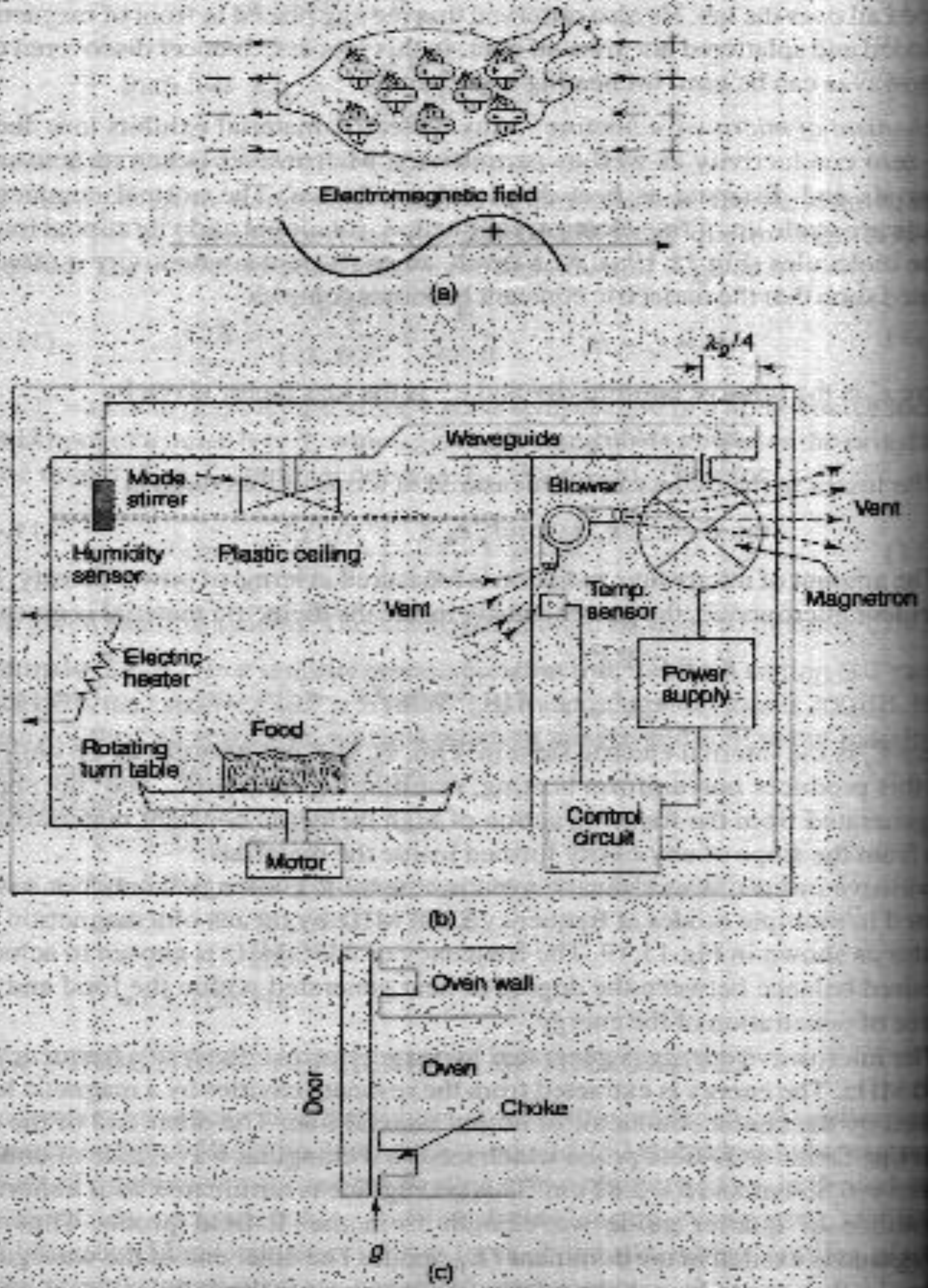
into 6.83 cm x 3.81 cm rectangular waveguide

One end of waveguide shorted at $\lambda/4$ distance from E-probe, and other end open to a cavity (stainless steel)

Rotating-blade stirrer reflects microwaves giving multi-mode excitation

Boundary conditions change by rotation with time to give statistically uniform field for uniform heating throughout cavity

Plastic ceiling between stirrer and oven chambers to ensure environment protection


Electromagnetic field
+
−
(a)
λg/4
Waveguide
Mode stirrer
Blower
Vent
Humidity sensor
Plastic ceiling
Vent
Temp. sensor
Magnetron
Electric heater
Power supply
Food
Rotating turn table
Control circuit
Motor
(b)
Oven wall
Oven
Door
Choke
g
(c)

Input power: 1-1.5 MW. Maximum microwave power: 600-700 W at 2450 MHz

Penetration: 2-3 cm (not suitable for large pieces of food)

Time and temperature microprocessor-based controller

Pre-determined cooking time/ magnetron-on time

Microwave choke (quarter-wave) in series with the door to oven gap that sees an open circuit towards the cavity

Microwave cooking is self-limiting, since ε_r'' decreases with temperature due to water evaporating during cooking

The generator must withstand mismatches for load variation during cooking

Example: $TE_{3,3,3}$ mode cavity,

330 mm width×338 mm depth×268 mm height

Resonant frequency = 2.538 GHz (which gets lowered in the presence of load)

27 regions of high concentration of electric field

The load can be uniformly heated by rotating it (turntable)

Mode-stirrer (rotating metal peddle) providing coupling of the source to different modes using oversized multi-mode cavities

(for TE_{mnp} mode excitation: resonant frequencies are 2.483, 2.512, and 2.538 GHz for *m*, *n*, *p* = 1,4,3;4,1,3; and 3,3,3, respectively)

Time rate of temperature rise

$$\frac{dT}{dt} = 0.239\frac{P_d}{S\rho} \quad \text{(C/s)}$$

$P_d =$ power dissipated (w)

S = specific heat (cal/g)

ρ = density (g/cm^3)

Industrial heating

Cavity type

Liquid may flow through a cylindrical cavity fed by a rectangular waveguide input

Travelling-wave-type

Folded waveguide, through the slots on the broadside face of which a sheet can move on a conveyer belt

Meander-line rectangular waveguides on both sides of a conveyer belt, with holes being provided on the narrow wall for coupling of power in the belt

Free-space applicator

Antenna to heat bulky elements which cannot be fitted within a microwave cavity/ waveguide

Food industry

Precooking, cooking, pasteurising, sterilising, dough proofing, freez drying, thawing, tempering, pasta drying, roasting of food grains/ beans, etc.

Plastic industry

Sealing/ bonding, bulk heating, molding plastic foam, plastic laminate production, drying etc.

Forest industry

Hardwood drying, plywood-veneer drying, pulp/ wood-chip drying, destruction of fungi, and insects in wood, etc.

Rubber industry

Vulcanisation, curing sponge rubber tubing, curing and foaming polyurethane bulk heating, etc.

Chemical industry

Drying paint and varnish, refractory processes, polymerising, etc.

Mining/ public work

Breaking rock, breaking concrete, tunnel boring, etc.

Some others

Drying leather, inks, paper, pharmaceuticals, tea, coffee, tobacco, textiles

Medical application

Lung water detection

Monitoring of heart beats

Parkinsonism

Orthopedics: arthritis, sciatica, rheumatism, etc.

Internal medicine: asthma, bronchitis, urology, etc.

Dermatology: boils, carbuncles, sores, chilblains, etc.

Oto-rhyno-laryngology: abcesses, laryngitis, etc.

Dental care

Opthalmology

Hyperthermia

Hyperthermia

Local temperature rise speeds up metabolic processes
producing dilation of blood vessels

Increase in blood flow, faster removal of wastes and heat

Selective heating up of the tissues without harming healthy ones

Warmed-up tissues receive more nutrients and antibodies — healing speeded up

Antenna applicator: 2.45 GHz (ISM band) from 100 mW/cm^2 to ~1 W/cm^2 for 15 to 30 minutes

Plasma electron cyclotron resonance heating

Plasma ECRH, required for controlled thermonuclear fusion

Going to contribute largely to electric power production by the middle of the present century

Fusion-based power plants (using abundant ‘raw material’ as an alternative to its fission based counterpart, the latter being associated with the problem of disposing a large quantity of radioactive waste as well as with the danger of disastrous accidents like that occurred in Chernobyl)

Material processing

Millimeter-wave sources (usual for plasma heating) for strong absorption

Processing of new materials, surface heating, focusing and steering a beam to a point

Material processing possible due to volumetric and selective heating: faster ceramic sintering, development of more finely grained ceramics of a more uniform microstructure

Absorption increases with frequency — processing by high power millimeter waves

Focusing millimeter-wave energy to small spots for the implementation of such processes as ceramic joining, surface treatment, etc.

New area of research and development on materials subjected to both high temperature and strong RF fields:

✓ Stronger and less brittle ceramic, new ceramic composite materials that retain their high strength under high temperature and corrosive conditions

Lightweight ceramic engines for aircraft and automobiles

Strong, long-lived ceramic walls for thermonuclear power reactors

Radar

High power microwave/ millimeter wave sources/ amplifiers required in view of generally increasing attenuation coefficient of atmosphere with frequency

Enhancement of radar range (high power) and resolution (small wavelength)

Civilian radar

Weather detecting, Highway collision avoidance, Airport traffic control, Burglar alarm, Garage-door opener, Speed detectors (law enforcement), Mapping of ground terrain or Ground probing radar (for the detection of underground materials like gun emplacements, bunkers, mines, geological strata, pipes, voids, etc.), Remote sensing, Imaging in atmospheric and planetary science, Space debris phased-array mapping, Cloud (as a sensor in environmental research (it being believed that clouds can dominate the effect of greenhouse gases in global warming), etc.

Military radar

EW, Impulse (for range resolution, detection of stealth aircraft, etc.}, Missile guidance and tracking, etc.

Adverse effects of microwave radiation

HERP — hazards of electromagnetic radiation to personnel

From leukaemia to sterility caused by thermal effects of radiated energy when (blood) circulatory system fails to remove heat

HERO — hazards of electromagnetic radiation to ordinance

Caused by peak microwave power triggering electro explosive devices provided with weapon systems, safety and emergency devices, etc., in which no circulatory system could be provided for cooling

(EEDs) React to peak power. Do not have a circulatory system to dissipate heat . Can be protected by metal enclosure which reflects back the incident RF energy

HERF — hazards of electromagnetic radiation to fuel

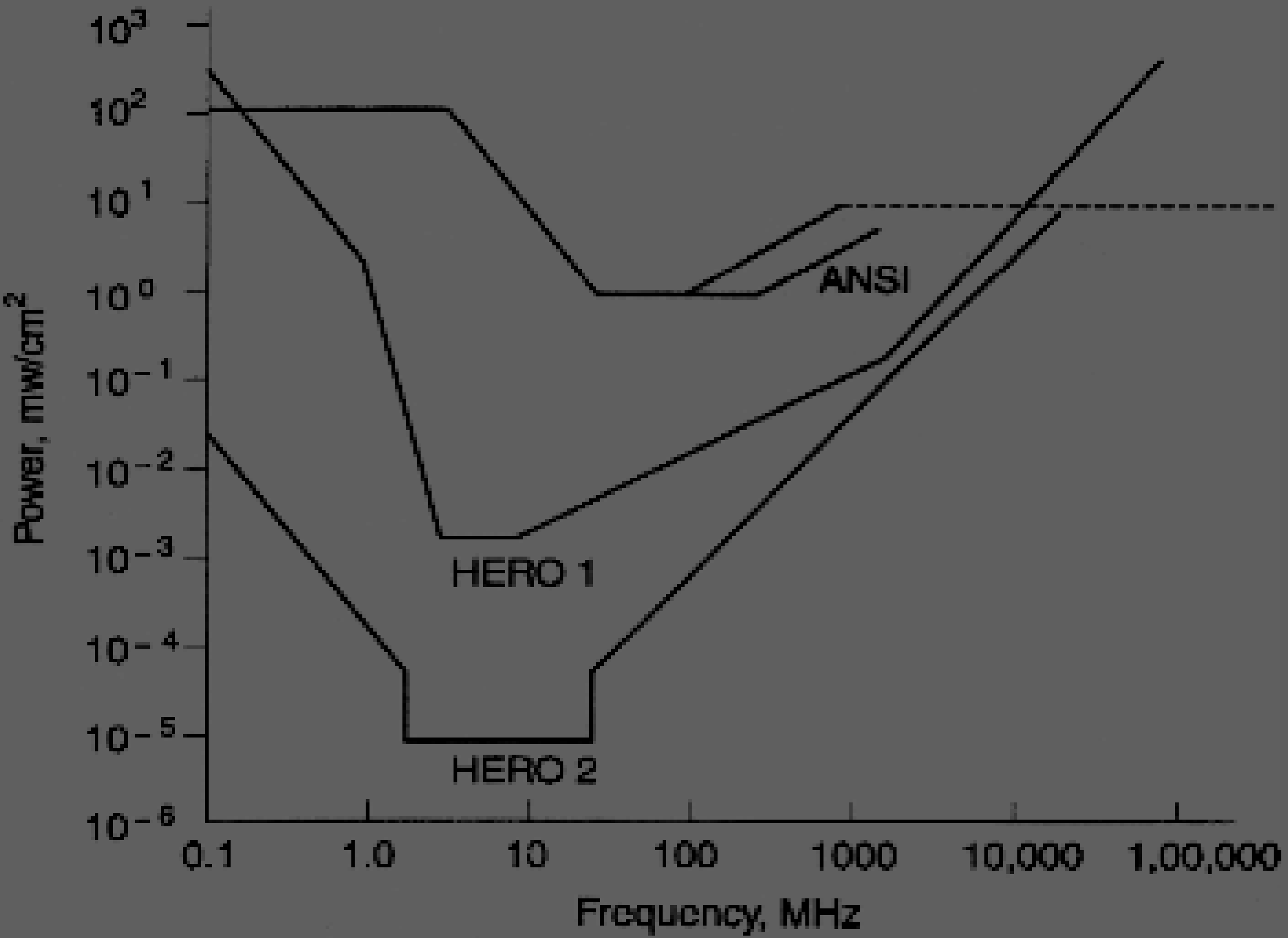
Caused by ignition of volatile combustibles such as vehicle fuels, with significant probability of ignition for more than 50 VA arcs

American National Standards Institute Incorporation (ANSI) HERP

ANSI uses a constant average SAR limit 0.4 W/kg (1/10th threshold for adverse effects)

HERO 1: Safe fields for fully assembled ordnance undergoing normal handling and loading operations

HERO 2: Safe fields for bare electro-explosive devices with lead wires arranged in optimum receiving orientation



Power, mw/cm²
10³
10²
10¹
10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
0.1
1.0
10
100
1000
10,000
1,00,000
Frequency, MHz
ANSI
HERO 1
HERO 2

Biological effects in human

(Reaction of blood, bone, fat, muscle, etc (lossy dielectric) to average power over some time)

Scattering, reflection and absorption of microwaves directed into the body

depends upon

- Field strength
- Frequency
- Dimension of the body
- Electrical properties of tissues
  - Stronger coupling of microwaves for body parts of size on the order of **λ – λ/10**

Absorption of microwave energy into the body

— Molecular vibration and conversion of energy into heat

Temperature rise and **microwave hazard** takes place if the organism cannot dissipate heat, and circulatory (thermo-regulatory) system of organs (eye, stomach, intestine, bladder, etc.) cannot provide sufficient flow of blood for cooling

Eye is specially sensitive to thermal damage from microwaves and prone to cataract.

Electrical field and low frequency magnetic field for large exposure causes severe damage
Considering plane waves, a characteristic parameter is defined as

Average power density P_d for a plane wave is the most widely used parameter:

$$P_d = EH = E^2/377 = 377H^2$$

For majority of hazardous fields not associated with plane waves, having complicated amplitude, phase, and polarization distribution due to their standing wave or near-field or modulation characteristics, another characteristic parameter is defined as

Specific absorption rate (SAR):

$$\mathrm{SAR} = \frac{\sigma E^2}{m_d} \text{ (W/kg)}$$

σ (S/m): conductivity; E (V/m): electric field; m_d (Kg/m^3) : mass density

Conductivity of muscles, blood > Conductivity of fat

Penetration depth is more for fat than for muscle and blood, over most of the frequencies

Microwaves dissipate more in muscle and blood resulting in greater heating rate

$$\text{Skin depth} = \frac{1}{\sqrt{\pi f \mu \sigma}}$$

Microwave absorption also depends on the body size and tilt relative to wavelength

Hot spot within the body wherever the dielectric constant is higher, due to focusing action
and shape of the cavities formed by bones

Theoretically predicted hot spot
in human skull at 918-2450 MHz
in eyeball around 1500 MHz.

Average SAR of human for an incident power density of 1 mW/cm^2

~ 0.03 W/kg at 700 MHz.

~ 0.25 W/kg at 70 MHz (when the average height of a persopn is approximately half the wavelength.

Rate of temperature rise:

$$\frac{dT}{dt} = \frac{Q}{S_p}$$

Q = SAR + metabolic rate of heat produced per unit mass
= Rate of heat loss per unit mass

S_p = Specific heat of the substance

Exposure standards

300 MHz-300 GHz
Exposure limits depend upon

- Radiation frequency
- Exposure duration
- Nature of population (occupational or general public)

Continuous exposure: **10 mW/cm^2 in USA** and **0.01 mW/cm^2 in former USSR**
Difference: attributable to particular experimental data,
acceptable risk, socioeconomic ground, etc.

International radiation protection association (IRPA)

IRPA occupational standard above 10 MHz

0.4 W/kg SAR when averaged over any 6 minutes over the whole body
or
4W/kg SAR when averaged over any 6 minutes and any 1 g of body tissue

Exposure standards *(continued)*

Standard	*Type*	*Frequency*	*Exposure limit*	*Duration*
USSR Government (1977)	Occupational	10 – 30 MHz	20 V/m	Working day (both pulsed and CW)
		30 – 50 MHz	10 V/m 0.3 A/m	
		50 – 300 MHz	5 V/m	
		0.3 – 300 GHz	10 μW/cm^2	
			100 μW/cm^2	2 hr (both pulsed and CW)
			1 mW/cm^2	20 min (both pulsed and CW)
USSR Government (1970)	General public	0.3-300 GHz	1 μW/cm^2	24 hr (both pulsed and CW)

Exposure standards *(continued)*

Standard	*Type*	*Frequency*	*Exposure limit*	*Duration*
US ANSI (1974)	Occupational	10 MHz –100 GHz	10 mW/cm^2 200 V/m 0.5 A/m 1 mWhr/ cm^2	No limit (CW) 0.1 hr (pulsed)
US Industrial Hygienist	Occupational	100 MHz –100 GHz	10 mW/cm^2 25 mW/cm^2	8 hr (both pulsed and CW) 10 min (both pulsed and CW)
US Army and Air force (1065)	Occupational	10 MHz –300 GHz	10 mW/cm^2	No limit (both pulsed and CW)

Exposure standards *(continued)*

Standard	*Type*	*Frequency*	*Exposure limit*	*Duration*
Canada Standards Association (1966)	Occupational	10 MHz – 100 GHz	10 mW/cm^2	No limit (CW)
			1 mWhr/cm^2	0.1 hr (pulsed)
Sweden Worker Protection Authority	Occupational	0.3 – 300 GHz	1 mW/cm^2	8 hr (both pulsed and CW)
		10 – 300 MHz	5 mW/cm^2	– Do –
– Do –	– Do –	10 MHz – 300 GHz	25 mW/cm^2	Any (both CW and pulsed average over 1 s)

IRPA occupational exposure limits to electromagnetic fields corresponding to SAR = 0.4 W/kg when averaged over any 6 minutes over the whole body

Frequency range (MHz)	*Unperturbed RMS electric field (V/m)*	*Unperturbed RMS magnetic field (A/m)*	*Equivalent plane-wave power density*	
			W/m^2	**mW/cm^2**
0.1-1	194	0.51	100	10
1-10	194 /$f^{1/2}$	0.51/$f^{1/2}$	100/f	10/f
10-400	61	0.16	10	1
400-2000	3 $f^{1/2}$	0.008 $f^{1/2}$	f/40	f/400
200-300,000	137	0.36	50	5

Use of high power microwave energy

Peaceful use

Military use

Peaceful use of high power microwave energy

Power beaming

City lighting

Satellite power station (SPS)

Extension of radio range

Atmospheric purification of freons

Ozone generation

Satellite power station (SPS)

Proposed in 1960’s under NASA for 24-hour, 365-day power from solar energy → DC → power beaming of microwave energy to a rectenna on the ground

SPS in synchronous geocentric orbit 22,400 miles above the earth’s equator
→ position with respect to a specific ground location fixed

On-time for the entire year is more than 99% for 22 days eclipse for the maximum period of 72 minutes maximum
If SPS and ground antenna are at the same longitude, the eclipse would be during night
On-time for the entire year could be in excess of 99%

10 GW of CW power, 2.45 GHz SPS

Higher frequencies can give reduced antenna size but increased attenuation

Space station: 10×20 km, 86×10^6 kg
Antenna: 1 km dia
Main lobe bandwidth
for 90% power = 0.0123^0
10^6 backward CFAs (amplitrons)
each 10 kW output
(HPM may be competitive)
Life 30 years (indefinite with continual
replacement of photovoltaic
cells, etc.)

Ground station:
Main-lobe power density on axis
= 25.2 mW/cm^2
Main-lobe power density at 90% radius
= 2.7 mW/cm^2
Radius to 90% power = 4.06 km
First side-lobe maximum
power density = 0.083 mW/cm^2
First side-lobe radius = 7.6 km
Antenna: Area = 9.7x12.6 km
~ 10^{10} half-wave dipoles
(separated 0.6 λ×0.6 λ)
Power pickup by elements at
the centre = 1.5 W

Cost: Development: $44 billion; Installation: $1500/ kW; Operating: $140 million; Revenue: $35 billion over a 30-year period

“Coming to understanding of Nature, with a possible view to harnessing its potential for the benefit of the men or women, is the reason for the being of scientific enterprise. In doing so, the scientific method enjoins the seeker to remain objective, as if the seeker were divorced from nature. This Baconian approach, fashioned during the seventeenth century, has led to the spectacular growth in humankind’s scientific and technological endeavour, and — as is often claimed — with its attendant ills.”

—***Akhilesh Lakhtakia***, in “***Essays on the Formal aspects of Electromagnetic Thoery***,”
—World Scientific, 1993

Environment Control

System developers should not torture Environment
‘Engineering’ and ‘Environment’ have to be treated together for the avoidance of the ills of technological development.

Examples:
Poisonous carbon **monoxide** emission caused by burning of fuels in petrol and diesel engines
Roadside Oxygen cylinders for traffic police in Tokyo
Carbon monoxide used as reducing agent to obtain iron from iron core, raw material for the manufacture of organic chemicals, etc.

Industrial waste seeping from a refuse pipe containing poisonous chemicals killing humankind and wildlife need to be treated before disposal.

Household rubbish

Burning pollutes the air and dumping in rivers and seas pollutes the water

Immediate solutions like burying chemicals and plastics lead to land pollution

- ✓ The case of Love Canal near Niagara Falls: A housing complex built on a filled-in-dump had to be abandoned after 20 years due to leakage of poisonous chemicals

This calls for the **recycling of the rubbish** as the raw material

Global warming due to heat trap

Solar radiation → absorbed and re-radiated as infrared → absorbed and re-radiated back by greenhouse gases (carbon dioxide, methane, chloroflurocarbons (CFCs or freons)

The earth's temperature has risen by 0.5^0c during the last one hundred years!

If the amount of carbon dioxide in the atmosphere were to double, the temperature of the earth would rise by 3^0c!

→ polar ice cups would melt

→ sea-levels would rise, and the Netherlands and Bengal be submerged first!

Ozone layer and its depletion

Ozone layer protects earth from harmful
ultraviolet radiation from the sun

✓ 4% increase in the cancer corresponding to 1%
decrease in ozone

Depletion of ozone owes to **catalytic destruction**
through chemical reaction involving **chlorine**, which is
produced from **freons — chloroflurocarbons CFCs —**
$CFCl_3$ and CF_2Cl_2 (✓ causing 70% ozone depletion).

Freons initially dispersed in the troposphere diffuse across the tropopause into the stratosphere in a few years

✓ 1 kg release of freons per person per year from air-conditioners, refrigerators, industrial activities, such as manufacture of aerosols and foams, solvents like those used in microelectronics, fire-extinguishers, etc.

Ozone Depletion in Antarctic region

More pronounced in Antarctic region attributable to the role of polar stratospheric cloud in activating chlorine by transforming the inactive form HCl to the active form ClO

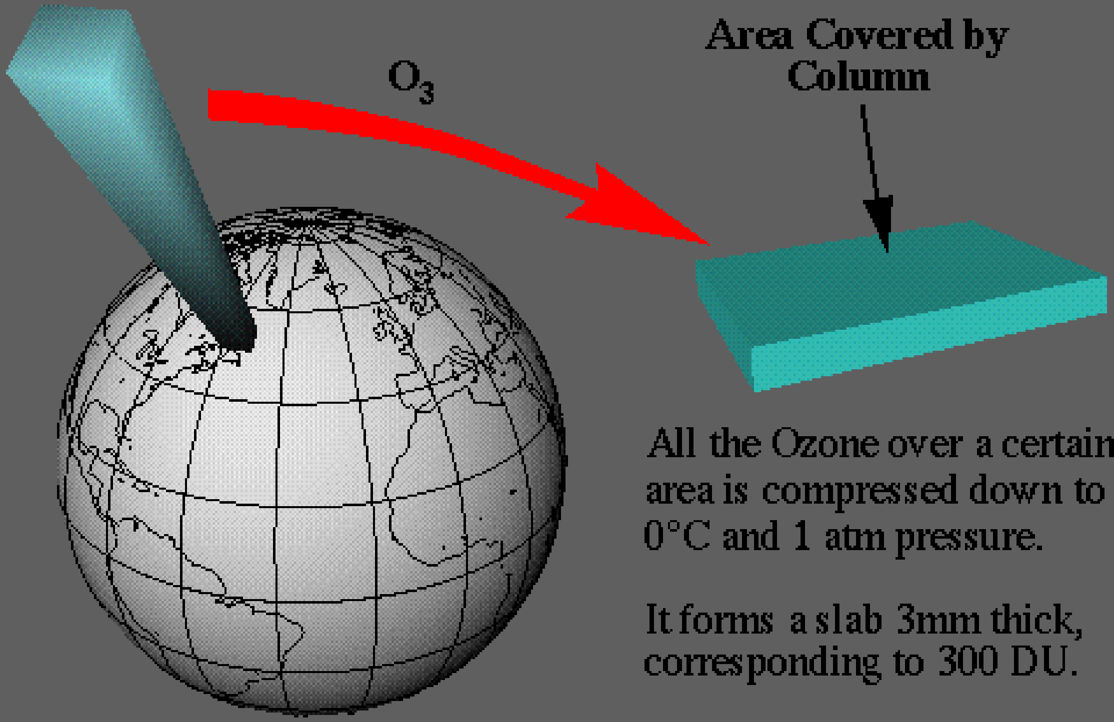
Content	**1950**	**1990**
Chlorine	0.6 ppbv	3 ppbv
Ozone	300 DU	100 DU

Daily global average ozone thickness:
One April-May maximum and the other September-October maximum

	Max	**Min**
Ozone thickness	April-May	July
	September- October	December

What is a dobson unit?

A ***dobson*** unit is the most basic measure used in ozone research. The unit is named after G.M.B. Dobson, one of the first scientists to investigate atmospheric ozone. He designed the 'Dobson Spectrometer' — the standard instrument used to measure ozone from the ground. The Dobson spectrometer measures the intensity of solar UV radiation at four wavelengths, two of which are absorbed by ozone and two of which are not.



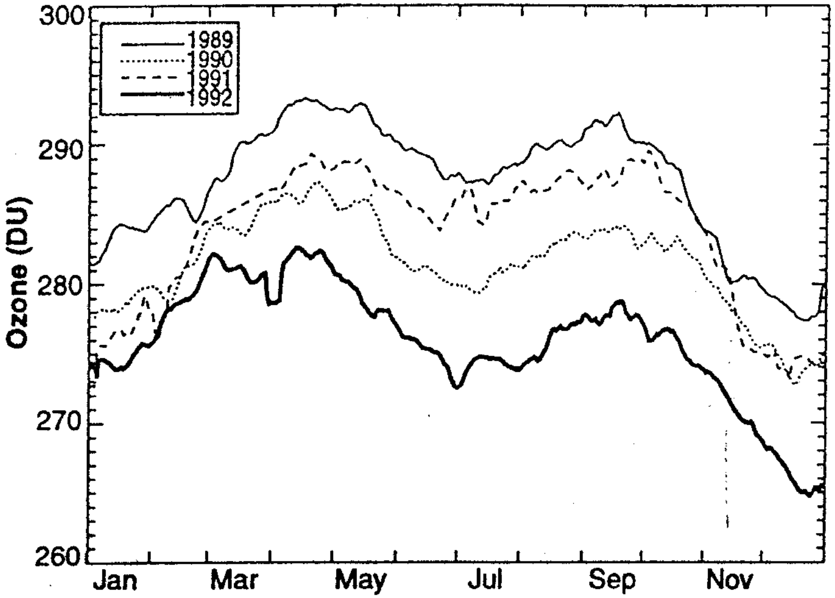
All the Ozone over a certain area is compressed down to 0°C and 1 atm pressure.

It forms a slab 3mm thick, corresponding to 300 DU.

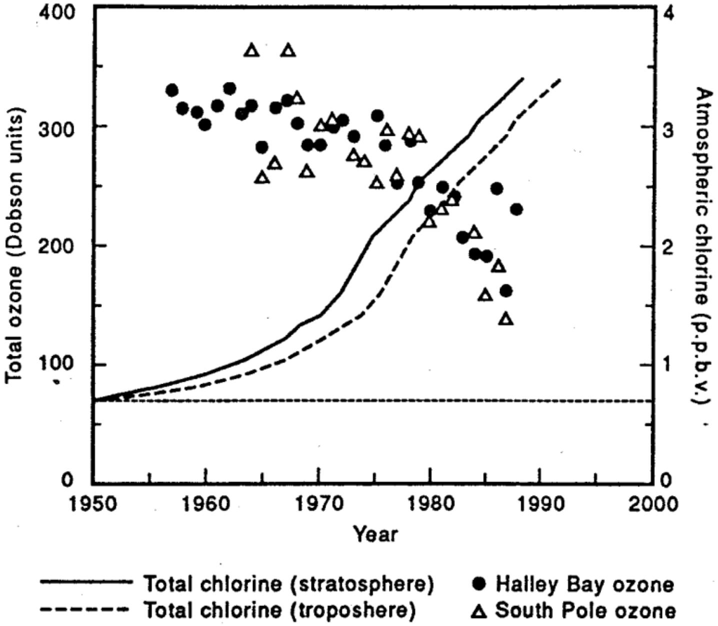
The illustration above shows a column of air, 10 deg×5 deg, over Labrador, Canada. The amount of ozone in this column (i.e. covering the 10×5 deg area) is conveniently measured in Dobson Units.

If all the ozone in this column were to be compressed to STP (0 deg C and 1 atmosphere pressure) and spread out evenly over the area, it would form a slab approximately 3mm thick.

1 Dobson Unit (DU) is defined to be 0.01 mm thickness at STP; the ozone layer over Labrador then is ~300 DU.



Daily global average ozone amount (area-weighted 65°S to 65°N) from NOAA-11 SBUV/s. The 1992 data are represented by the thick solid line. The 1991 data are represented by the dotted line. The 1990 data are represented by the dashed line. The 1989 data are represented by the thin solid line. (From J. F. Gleason, et al., *Science*, Vol. 260, 1993, p. 523.)



Total Antarctic ozone observations above Halley Bay and the South Pole, showing the development of the ozone hole. Total chlorine abundances in the troposphere and stratosphere are also indicated, based on an assumed 3- to 5-year lag time between the two atmospheric regimes. Natural chlorine abundances are believed to be about 0.6 ppb, with manmade chlorine making up the remainder of the stratospheric chlorine budget. (From S. Solomon et al., *Nature*, Vol. 344, 1990, p. 347.)

Interaction of high power microwave energy with atmosphere

Remote spectroscopy of the atmosphere

Extension of range of radio by artificial ionosphere mirror

Restoration of ozone composition in the upper atmosphere

Atmospheric purification of the admixtures that destroy ozone layer

The last two refers to environmental control

Extension of range of radio by artificial ionosphere mirror

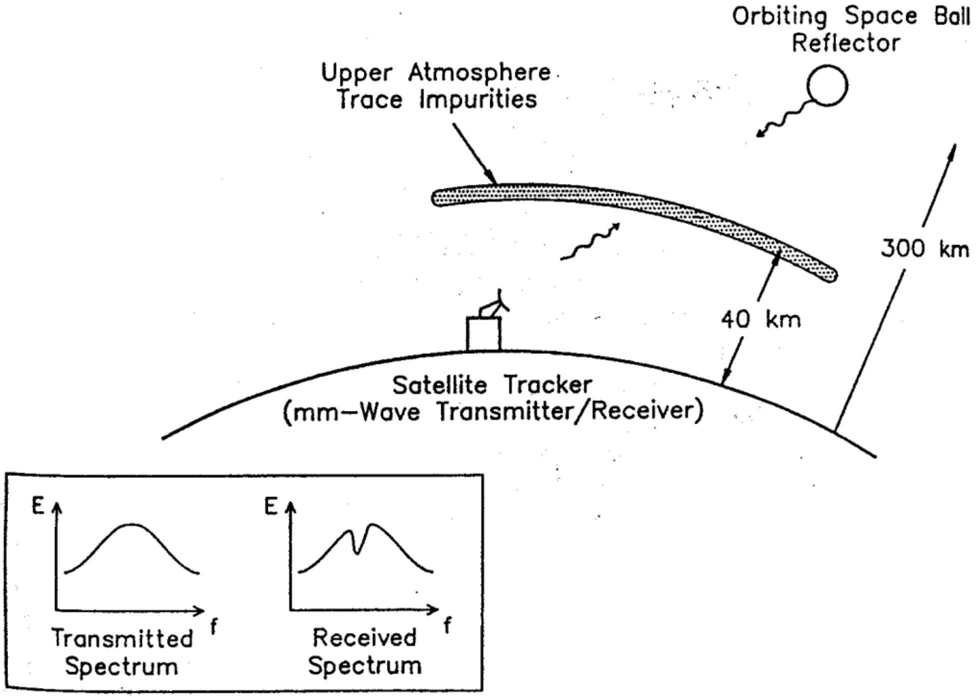
Over-the-horizon radar and long-range communication
Target range of 1000 km
Return signals from the plasma patch
Ionisation by crossed microwave beams
Microwave frequency> local collision frequency
Typically 10 GHz at 30 km altitude and 3 GHz at 40 km altitude
Russian proposal: two crossed beams at 1 GHz, 100 m antenna diameter, 11 GW, ionisation at 50 km

Remote spectroscopy of the atmosphere

Monitoring of molecules such as Cl, ClO and NO at 20-26 km height

Excitation of electron levels of the molecules at collision with electrons generated during the microwave breakdown and the corresponding radiation of photons

An estimate: 4 GW, 10 GHz, 100 ns pulse duration, 1 kHz prf, 40 m antenna diameter



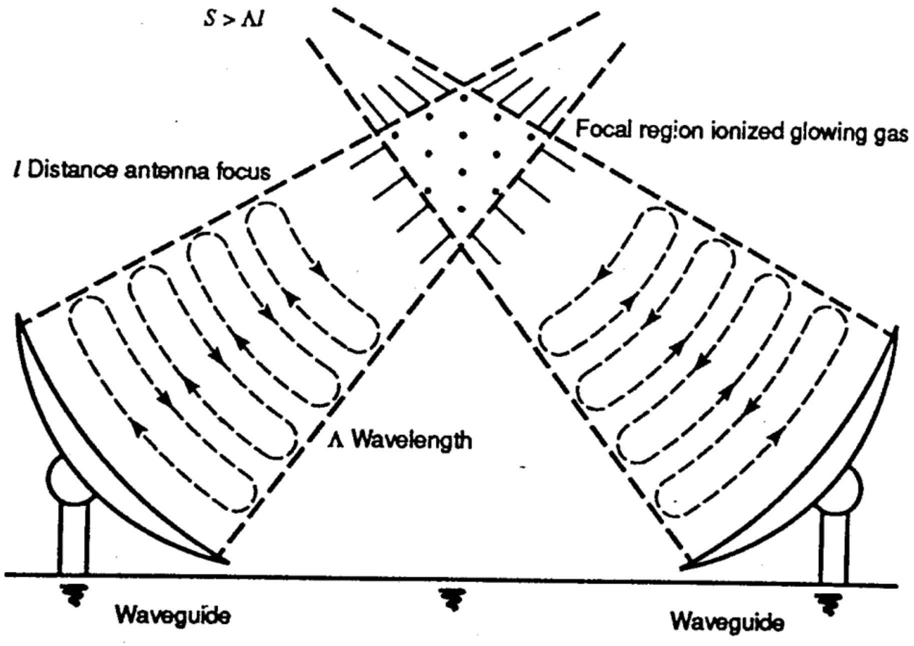
Schematic for detection of upper-atmosphere trace impurities. (Courtesy of W. Manheimer.)

Restoration of ozone composition in the upper atmosphere — ozone generation

Microwave power complex for ozone generation
Typically two antennas 60 m diameter and 35 km apart beam power in a common volume region 30 km height.
Transmitter: 4 GW, 10 GHz, 40 ns pulse duration, 1 kHz prf
— 24 hrs to generate ozone in 1 km^3 volume.

Steering the **microwave** beam can **repair** local **ozone holes** at the launching of space shuttles.

Microwave complex has also been proposed for **lighting cities** and **showering nitrogen fertilisers** on earth by **microwave discharge**



Schematic of artificial plasma production using two ground-based microwave transmitters

Microwave Power Station

Atmospheric purification of freons

Purification to be carried out below the tropopause
Dissociative attachment of slow electrons (about 0.1 eV) (created by microwave discharge) to CFC molecules with splitting out of chlorine atoms
Chlorine forms water-soluble products, subject to rain-out, say, in the form of HCL

Energy cost: 30 keV per molecule for splitting CFC
Cost: to purify air basin over Europe a microwave set up of total average power of 15 GW has to work for one year → $100 billion!

A typical example of microwave power station for atmospheric purification:

Wavelength = 1 cm, Antenna diameter = 10 m, Antenna gain = 70 dB, Transmitter power = 10 GW, Pulse width = 100 ns, Energy per pulse = 1 kJ.
Spot size at 10 km will be 10 m, Power density 10 kW/cm^2

An estimate of energy cost and expenditure

Present rate of CFC injection = 1 megaton /year (1 megaton = 10^{36} particles)

(Already present inventory = 20 megatons)

Klystron 10 GW peak power, 100 ns pulse width and 1 kHz prf giving 1 MW average power

$$10 \text{ GW} \times 100 \text{ ns} \times 1 \text{ kHz} = 10 \times 10^{9} \times 100 \times 10^{-9} \times 1000 \text{ W}$$

$$= 10^{6} \text{ W} = 1\text{MW (average)}$$

10,000 Klystrons would be required to get 10 GW (average) (1 X 10^{4} MW=10 GW)

One microwave power station of 10 GW (average) will eliminate 30 kilotons of CFCs per year.

Therefore, 33 (=1 megaton / 30 kilotons) microwave power stations have to be employed in order to eliminate 1 megaton /year (present rate of CFC injection)

The entire atmospheric purification would cost $ 300 billion a year!!

HPM can generate ozone or repair ozone hole and purify atmosphere of freons destroying ozone.

Although the cost would be heavy, yet perhaps we have to take up such mission to save the life on the planet!

Military use of high power microwave energy

Electronic warfare (EW)
(Military control of electromagnetic spectrum)

Electronic warfare support (ES)

Threat recognition –
intercepting,
identifying,
analysing and
locating
enemy
radiations

Electronic attack (EA)

Non-destructive (soft- kill) jamming (ECM)
Destructive (hard-kill) jamming (ECM)
Anti-radiation missile (ARM)
DEW

Electronic protection (EP)

Electronic hardening
ECCM
Emission control
Electronic masking (coding)

HPM electronic warfare (EW)

Refers to:

i) long pulse duration, high-prf, or CW

ii) high-peak power, short-pulse duration, low-prf or single-shot

Attacks at nearly the speed of light

Ammunition is power supply rather than explosives!

Targeting easier unlike laser warfare. Need not be pointed. Microwaves can spread by diffraction and thus can accommodate lack of precision in tracking

High power EW:

Hard-kill: large-scale physical destruction of targets

Soft-kill: smart HPM: disabling of mission-critical components

10^{-7} Jcm^{-2} is good enough to cause bit error in computers and computer-aided equipment!
Can cause disaster in air-traffic management!

Microwave bomb:

DEW: strategic defence initiative (SDI)

Directed energy weapons (DEW)

High energy lasers (HEL)

Charged particle beam (CPB)

Neutral particle beam (NPB)

High Power Microwaves (HPM)

HEL weapons

Long-range lethal

Highly directed beam

Cause overheating and melting materials

Typical parameters :

- Power > 20 kW (CW), > 5 MW peak
- Energy > 1000 Joules
- Wavelength 0.3 µm to 30 µm

Beam pointing accuracy < 0.25 n-rad @ 250 km (0.5 m spot)

Support technologies :

- Advanced servo systems for beam pointing
- Rapid beam swiveling
- Kill assessment

Limitations : Atmospheric absorptions and related divergence

CPB Weapons

Still under development

Intense high energy electron beam focused on target

Electrons pass through the skin of the target and deliver energy

Very useful for anti-ship missile defense (ASMD)

Requirement: A compact, lightweight, multi-pulse accelerator

Criticality: Propagation of beam through atmosphere

HPM weapons

Non-lethal weaponry

> provides 'friendly' troops with the ability to remotely neutralise the communication systems of 'aggressive' forces without loss of life on either side

Important in low-intensity conflicts and military-operations-other-than war (MOOTW)

HPM Weapons ***(Continued)***

All-weather

Coarse pointing of targets

Large image zone

Uses vulnerability of modern electronic systems, being more effective as the electronic component size decreases

Effective even if the enemy system is switched off

Typical parameters:

Frequency: 10 MHz – 100 GHz
Power: 100 MW – 100 GW
Pulse Width: Up to 1 μsec
Duty Factor: Single shot to 0.002

EMP coupling Mechanisms

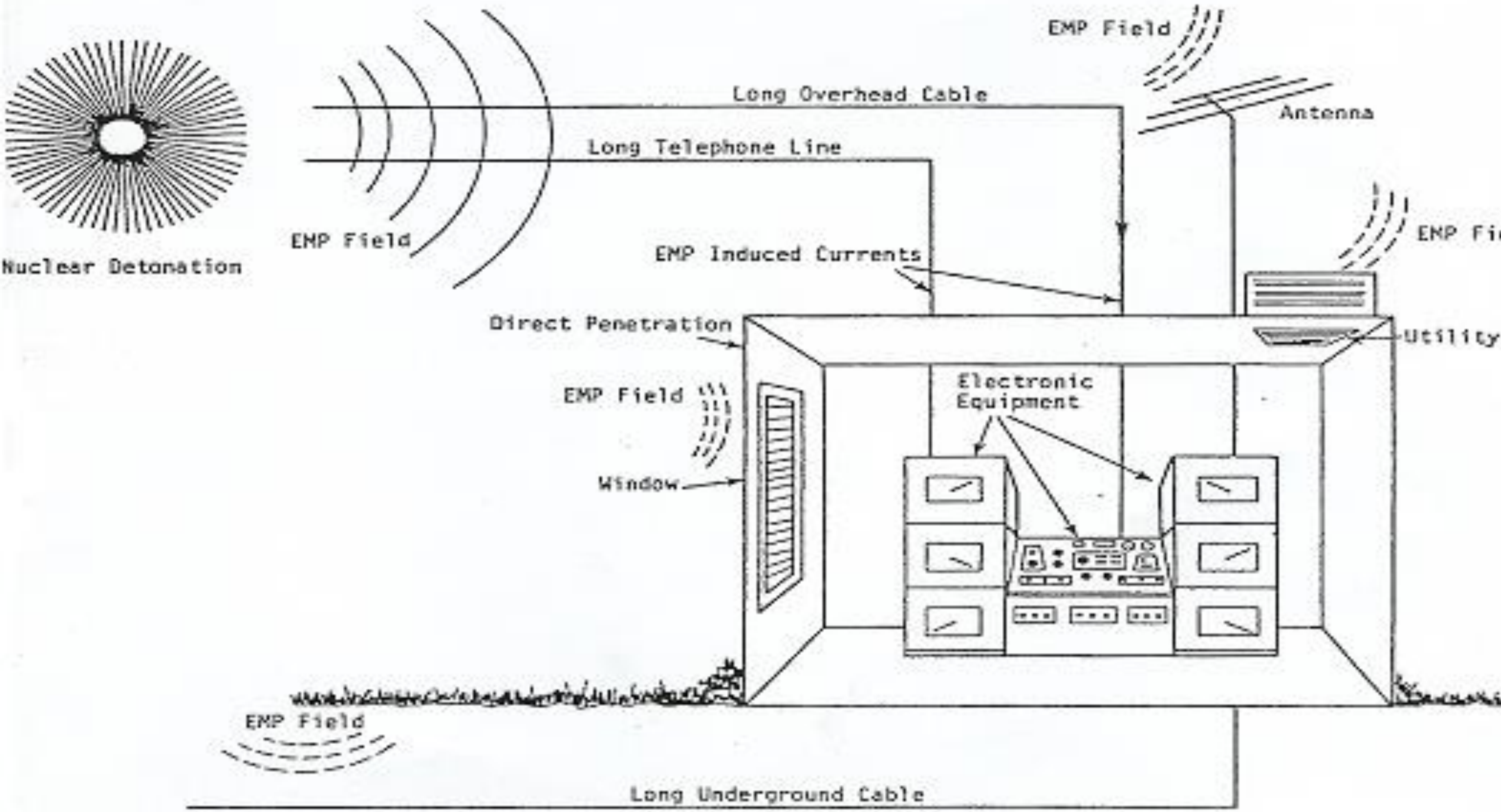
Front-door coupling: through transmitting /receiving antennas associated with radar and communication equipment

Back-door coupling: Power connecting wires and cables, grills / holes in enclosure

display screens of computers, etc.

Caused by large transient currents (spikes) or electrical standing waves on fixed electrical wiring and cables interconnecting equipment, or providing connection to the main power, or the telephone network

MODES OF ENTRY OF EMP ENERGY IN AN ELECTRONIC SYSTEM



Effect of HPM on systems

Dielectric heating

High voltage transients

High voltage breakdown

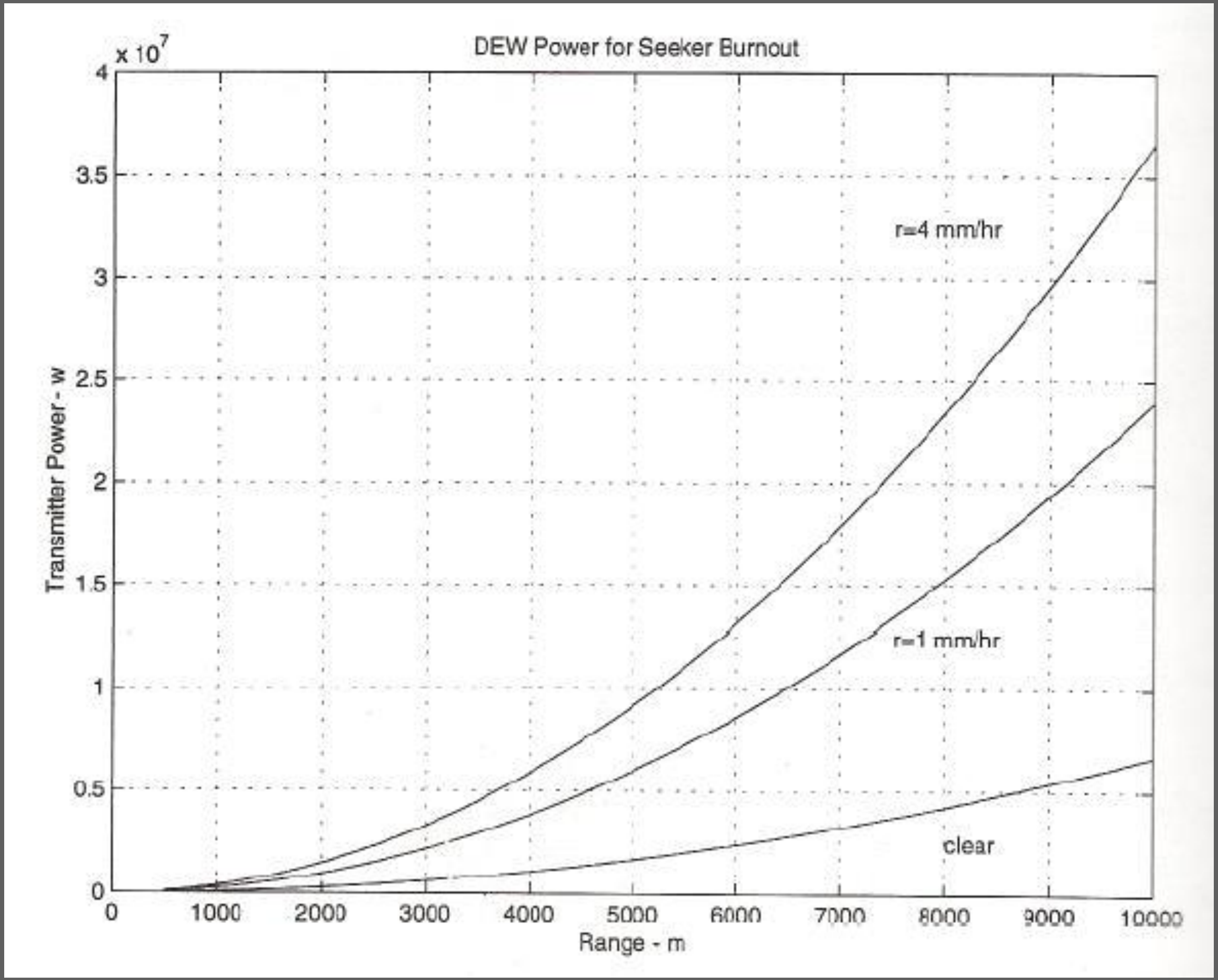
Deception or spoofing of target to mission failure

Jamming of radar, communication or control systems

Temporary upset or disruption of electronic systems

Burn-out of electronic devices

DEW power for seeker burnout



Breakdown voltage ratings of electronic devices

Silicon high frequency bipolar transistor: 15 V – 65 V

Gallium arsenide FET: ~ 10V

Dynamic random access memories (DRAM) ~ 7 V

CMOS logic: 7 V – 15 V

Microprocessor: ~ 5 V

Upset levels for electronic devices

Type	***Power* (W)**	**Energy(J) @ 1μsec**
Operational amplifier	0.0009	9 X 10^{-10}
TTL device	0.008	8 X 10^{-9}
CMOS device	0.001	10^{-9}
Voltage regulators	0.09	9 x 10^{-8}
Comparator (output switches)	0.008	8 x 10^{-9}
VHSIC (pulsed exposure)	0.1	10^{-7}

Electronic device burnout thresholds

Component Class	*Energy* (J)
GaAs MESFET	10^{-7} – 10^{-6}
MMIC	7 x 10^{-7} –5 x 10^{-6}
Microwave diodes	2 x 10^{-6} –5 x 10^{-4}
VLSI	2 x 10^{-6} –2 x 10^{-5}
Bipolar transistors	10^{-5} –10^{-4}
CMOS RAM	7 x 10^{-5} – 10^{-4}
MSI	10^{-4} –6 x 10^{-4}
SSI	6 x 10^{-4} –10^{-3}
Operational amplifiers	2 x 10^{-3} –6 x 10^{-3}

EMP

Intense electromagnetic pulse (EMP) (~10's of TWs peak power) of very short duration (~100's of ns) (shock-wave)
(first observed during the early testing of high altitude airburst nuclear weapons)
Used in non-nuclear confrontations of military significance

HPM in strategic and tactical information warfare (IW)

Attack by short-lived transient voltages (~kVs)
on exposed electrical conductors, such as wires, cables, conductive tracks on printed circuit boards, etc.
(shielding often being ineffective for protection)
Irreversible damage to a wide range of electrical and electronic equipment, particularly radio, radar, ECM, computers, flight control, embedded systems, etc.
(MOS, for instance, being highly sensitive to high voltage transients)

Microwave bomb or Electromagnetic bomb (E-bomb) for EMP!

E-bomb

Magneto-hydrodynamic (MHD) generator

Flux compression generator (FCG)

Combination generator (for instance, FCG or cascaded FCGs feeding a vircator)

IREB-driven and fast-wave microwave tubes, such as virtual cathode oscillator (vircator), relativistic BWO, orotron, MILO, and gyrotron

MHD generator

Based on Lorentz force on a charged particle moving in a magnetic field

Current collected by electrodes in contact with the plasma jet of ionised explosive or propellant gas travelling through a magnetic field.

Not yet mature (issues: size and weight of magnetic field generating devices, propellant gas generator for plasma)

Potential as start current generator for FCG

Flux compression generator (FCG)

FCG is a single-shot device delivering ~ 10’s of MJ of energy, TW – 10’s of TW of peak power in 100’s of μs of time

Used
- as a single device directly
- as a pulse power supply for HPM tubes
- in cascade — a smaller FCG priming a larger FCG for smallest possible start current
- source in application where space and weight are at a premium

Operation is based on transfer of energy from the explosive to the magnetic field

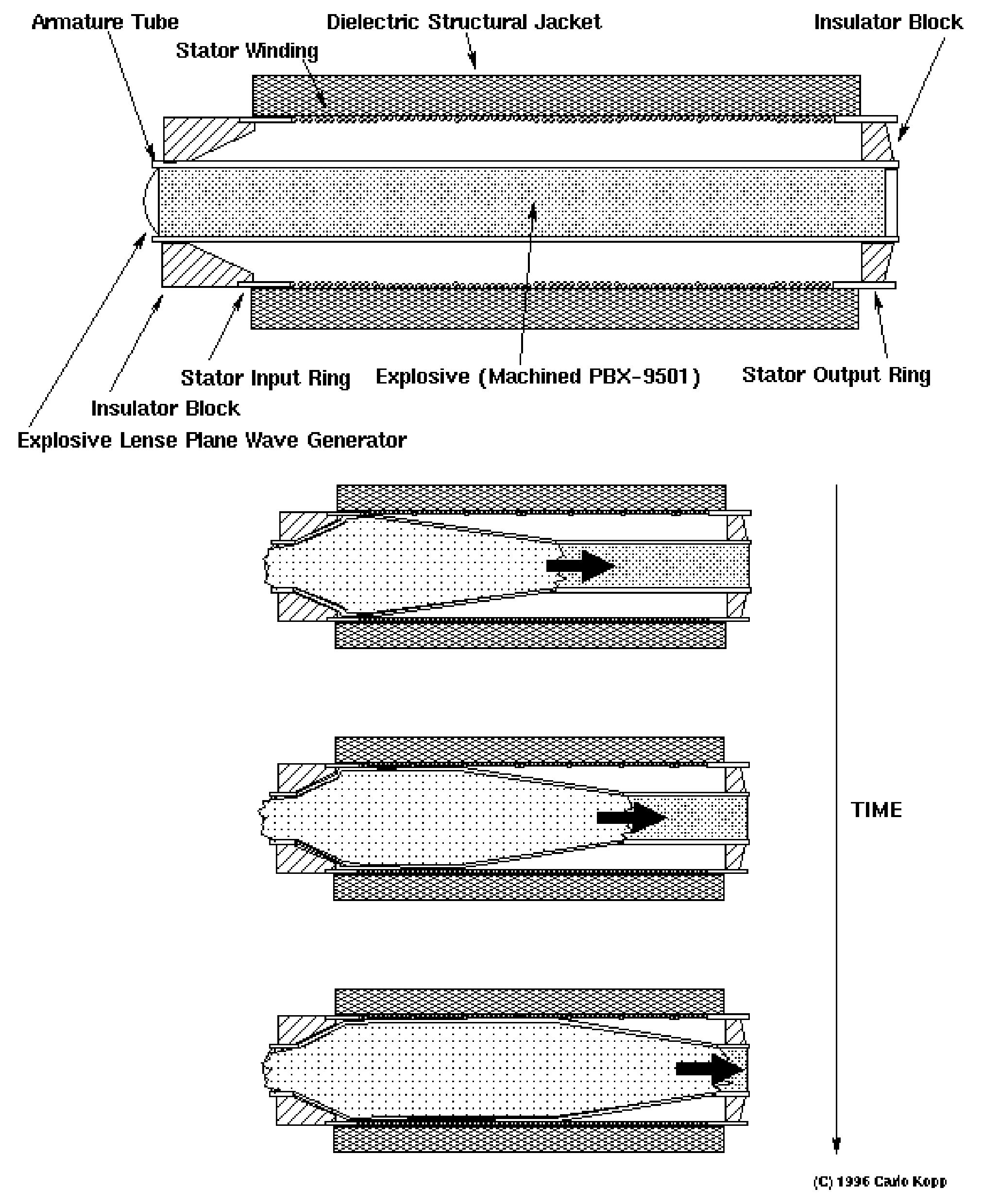
A copper tube (armature), filled in typically by PBX-9501 explosive, is surrounded typically by a helical winding coil of heavy wire typically of copper (stator), the armature tube and the stator coil being separated by an insulator block

Initial magnetic field prior to explosion is produced by a start current in helical coil supplied by an external high voltage pulse power source like Marx generator

Explosion breaks the insulation and shorts the turn, the short moving with time

Coaxial FCG →

(Explosively pumped)



Flux compression generator (FCG) (*continued*)

Start current is supplied by the Marx generator

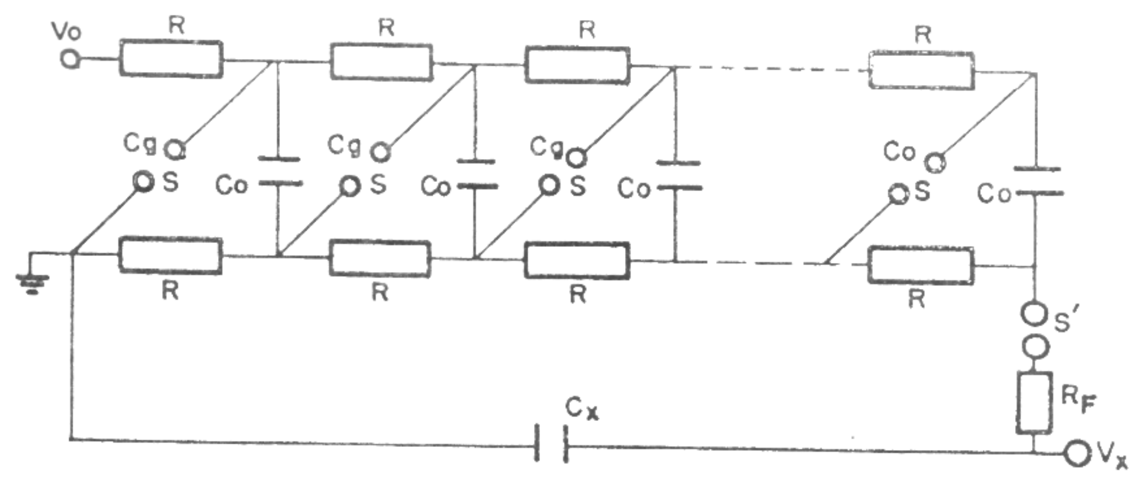
Explosive is initiated when the start current peaks
Accomplished with an explosive lens plane wave generator producing a uniform detonation plane wave front through the armature copper tube

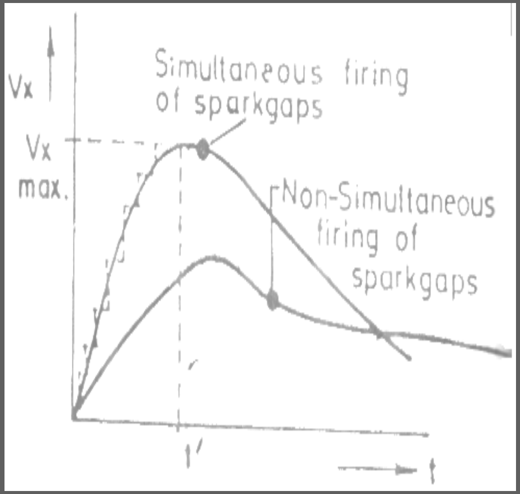
Armature tube distorts and expands into conical shape to the full diameter of the stator coil winding thereby causing a short circuit between the coil ends isolating the start current source and trapping the current within the device

This results in magnetic flux compression; reduction in the inductance of the helical winding; and ramping current pulse

Marx generator

— an assembly of capacitors that are charged in parallel and then quickly switched into a series circuit (discharged in series), allowing the original charging voltage to be multiplied by the number of capacitor stages





Capacitors C_0 are charged in parallel and discharged through spark gaps S initiated by triggering the first one or more spark gaps by an external triggering source, as a consequence of which the remaining gaps get overloaded thus causing their self- breakdown

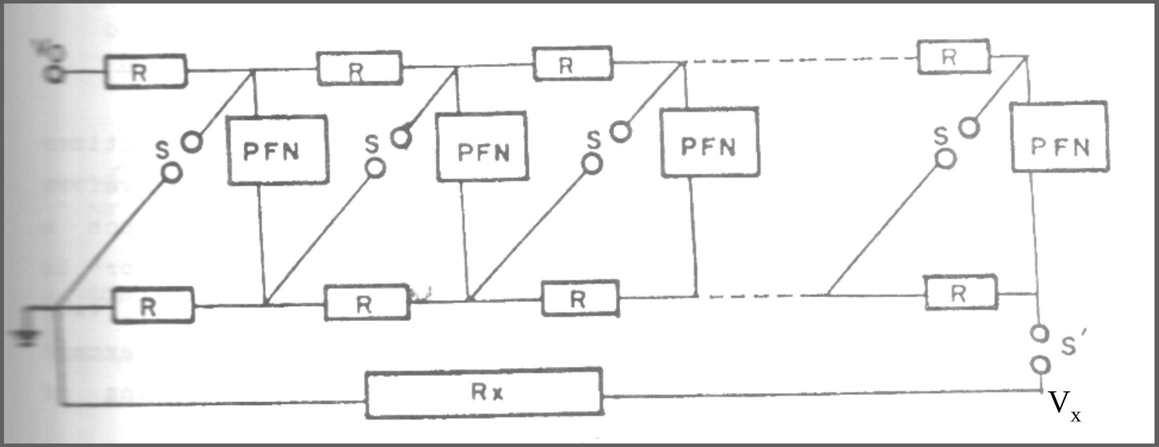
Reduction and distortion of output voltage for non-simultaneous triggering

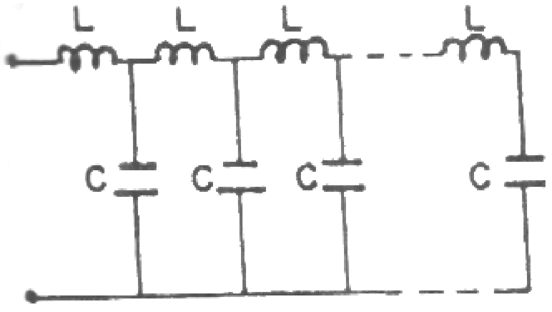
Spark gap S' is used to reduce the charging current though the external load, for instance $C_{x.}$

Maximum pulse voltage is $NV_{0.}$

Front resistor R_F , tail resistor R and number of stages used adjust the pulse duration

Improvised Marx generator with pulse forming network (PFN)





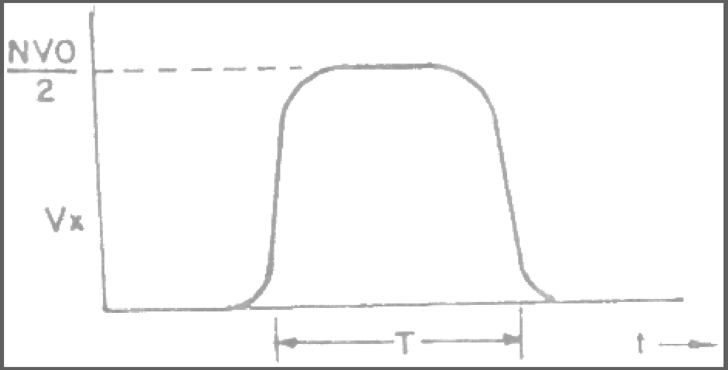
PFN

Characteristic impedance $R' = \sqrt{L/C}$

Load resistance $= NR'$

Output voltage $V_x = NV_0/2$

Pulse duration $= n\sqrt{LC}$



Flat-top pulse

Ramping current pulse

$$H = ni$$

$$B = \mu_0 H = \mu_0 ni$$

$$\phi_B = NAB = NA\mu_0 ni$$

$$L = \frac{\phi_B}{i} = \frac{NA\mu_0 ni}{i}$$

$$= NA\mu_0 n$$

Energy of the coil

$$= 1/2Li^2$$

With the propagation of the detonation wave,
the short propagates

Number of turns N decreases

Length of the coil l also decreases in the same proportion

Number of turns per unit length $n = N / l$ remains constant

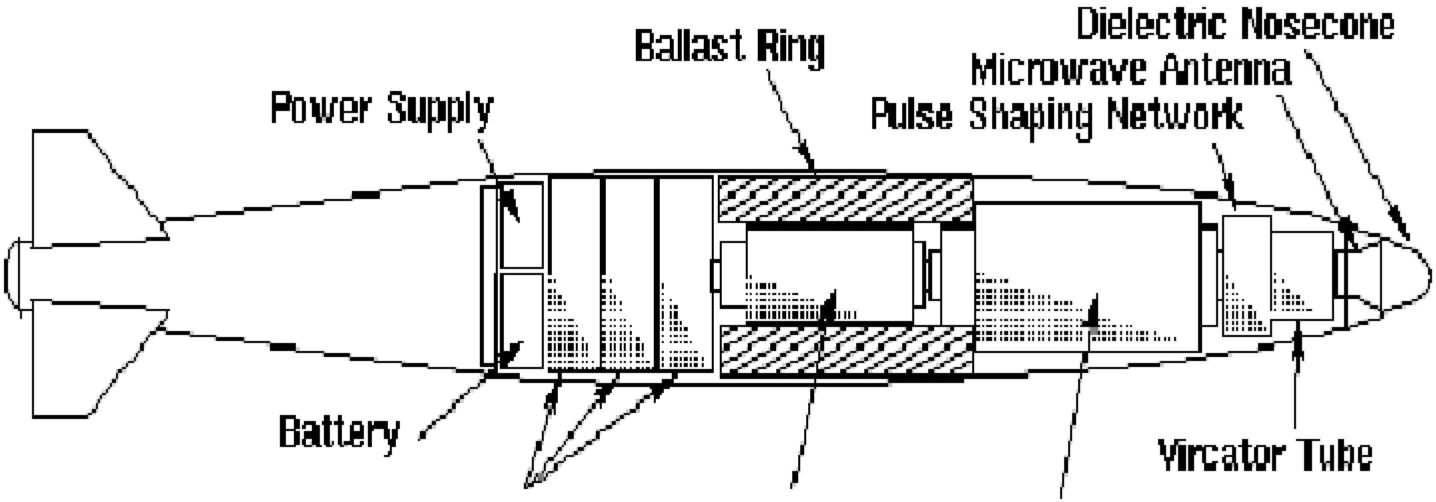
Area of the coil A remains constant

Inductance of the coil L decreases

Energy of the coil $1/2Li^2$ remains constant

Current i increases (spikes)

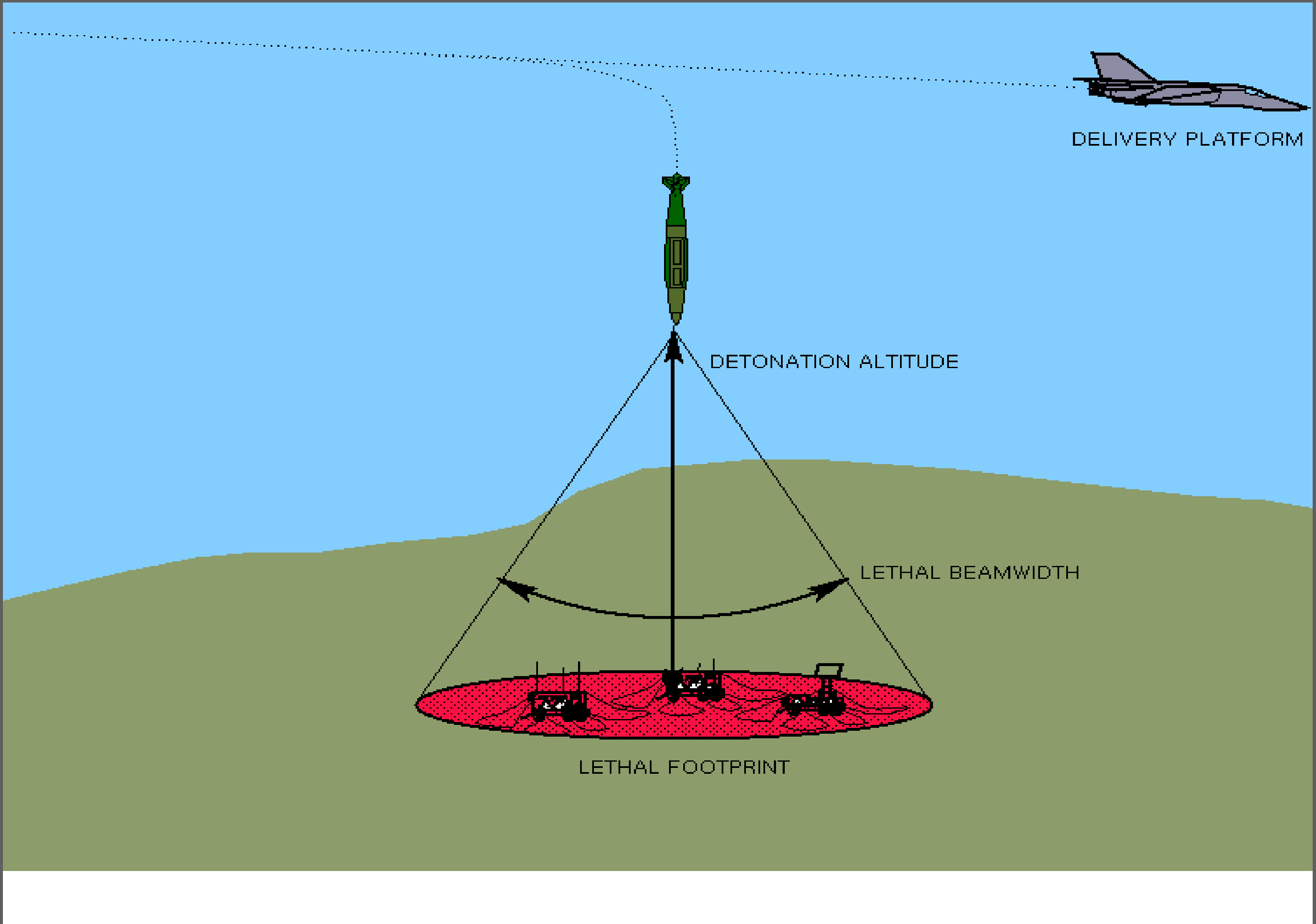
HPM E-bomb warhead



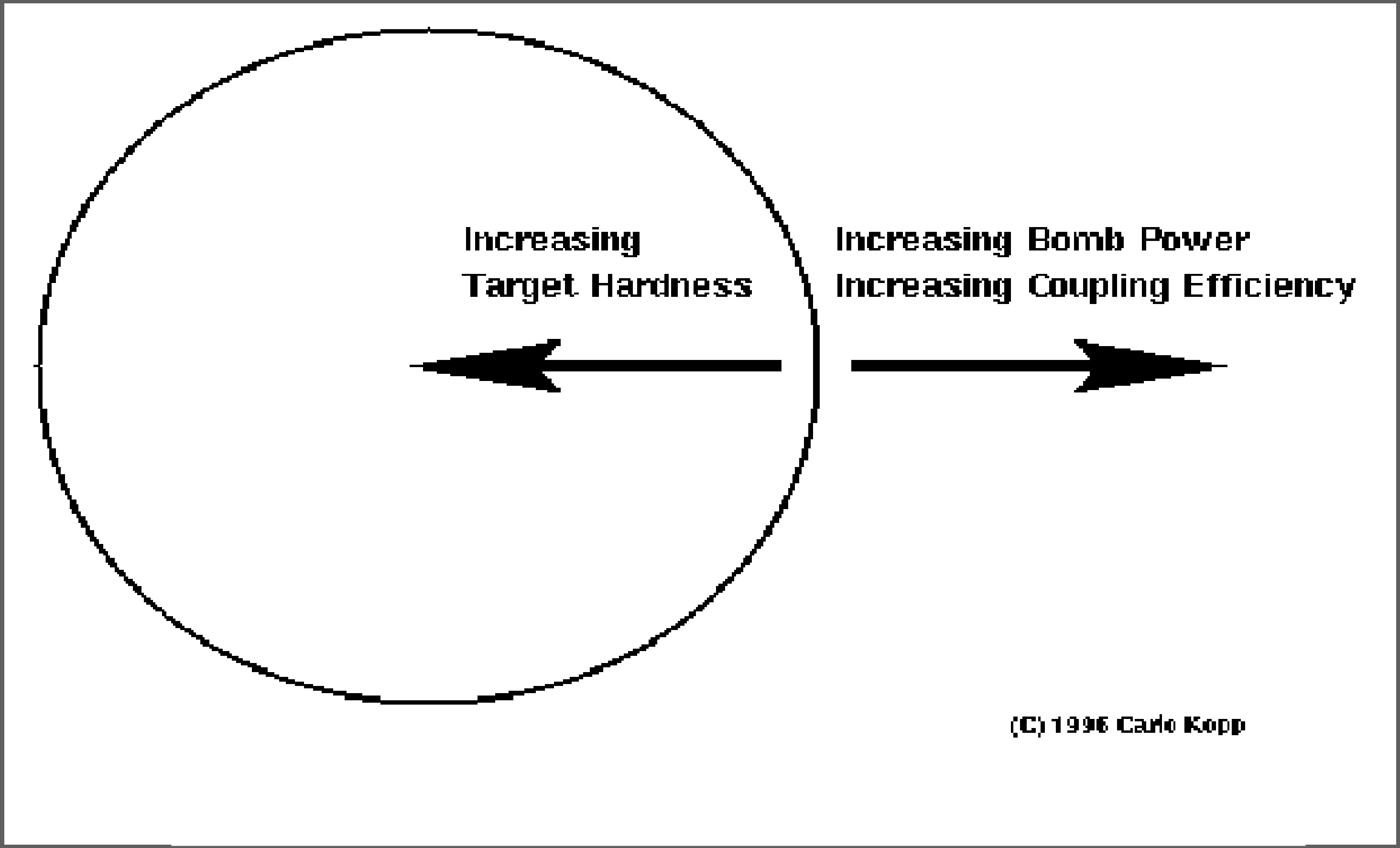
Coaxial Capacitor Bank Coaxial FCG (Stage 1) Coaxial FCG (Stage 2)

900 kg 3.84 m x 0.46 m dia

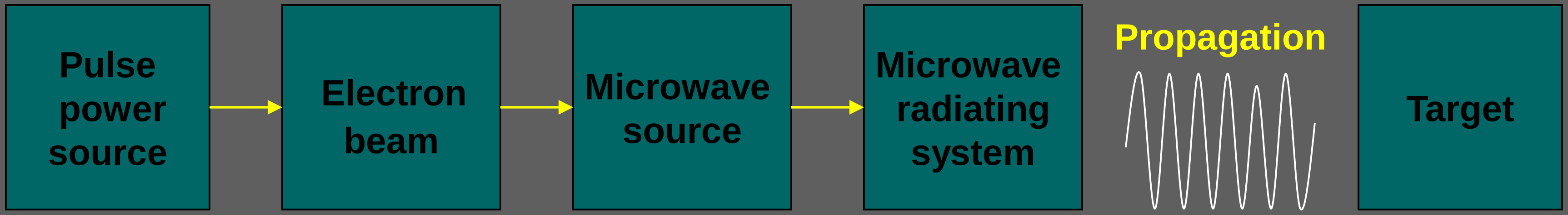
E-bomb



Lethal footprint of an E-bomb in relation to altitude



E-bomb lethality radius



Pulse power source

Electron beam

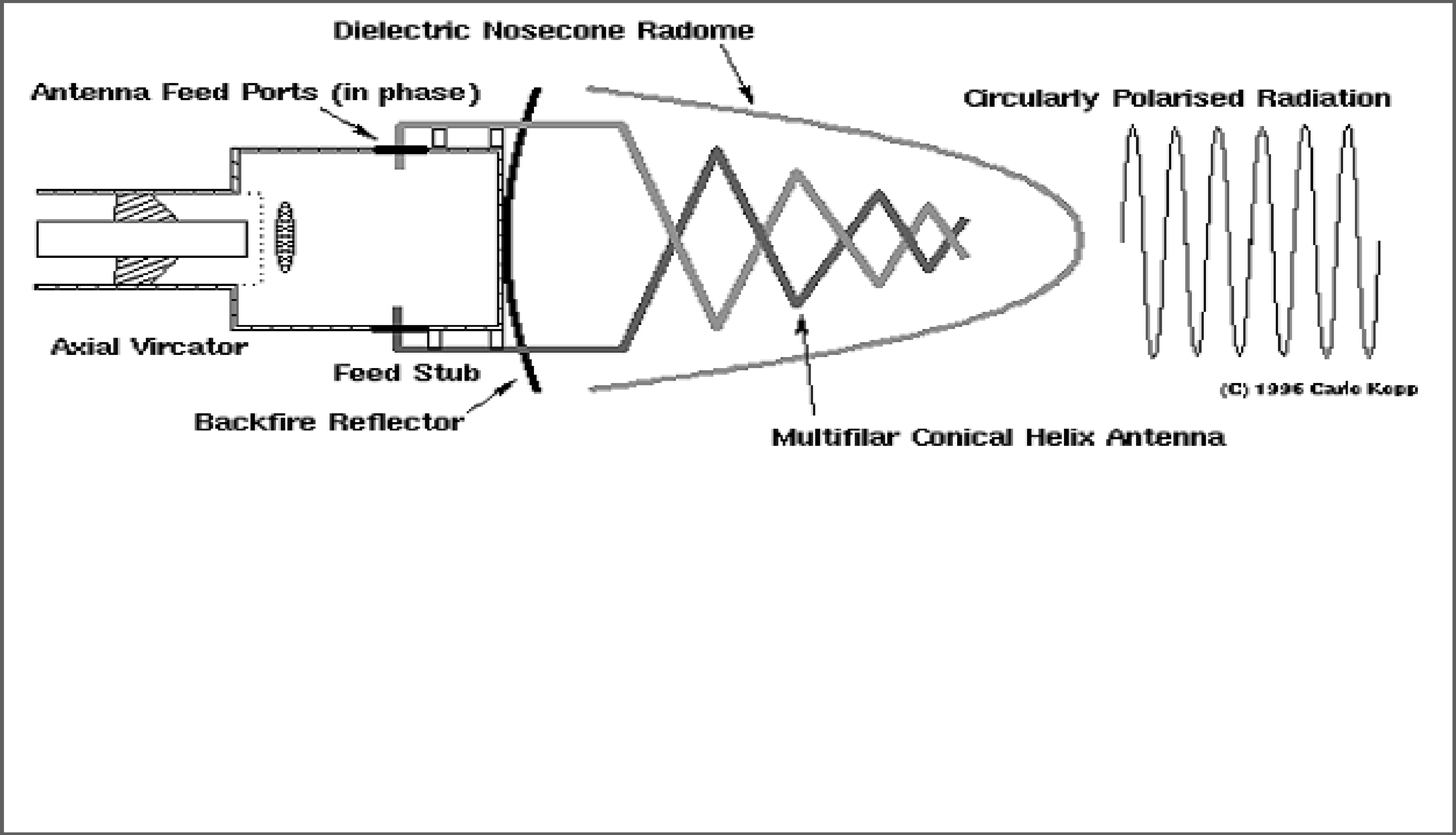
Microwave source

Microwave radiating system

Propagation

Target

HPM system configuration



Typical vircator-antenna assembly

HPM E-bomb lethality

Microwave bombs are potentially more lethal due to better coupling and more focused effects

Chirping allows weapon to couple into any in-band resonance

Circular polarization of antenna allows coupling with
any aperture orientation

Reducing detonation altitude increases field
strength at the expense of footprint size

Major challenges for HPM weapons development

Compact , high peak power or high average power HPM sources

Compact, high gain, ultra wide band antennas

Compact, efficient, high power, pulsed power drives

Compact, efficient prime power sources

Predictive models for HPM effects and lethality

Affordable system integration meeting military platform deployment

Microwave Tubes