Karlsruher Institut für Technologie

Lecture

High Power Microwaves

Prof. Dr.-Ing. John Jelonnek

Institut für Hochleistungsimpuls- und Mikrowellentechnik (IHM)

John Jelonnek

1965, Hamburg

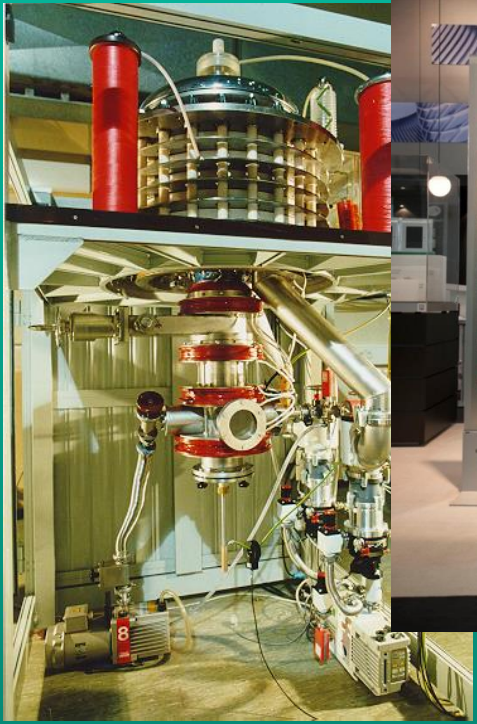
married, 1 son (Thomas, born in 1999)

- 1991 Diplom, Elektrotechnik, TUHH, Hamburg
- 1991 – 1997 wissenschaftlicher Mitarbeiter, TUHH, Hamburg
  Promotionsthema: „Untersuchung des Lastverhaltens von Gyrotrons“
- 1997 – 2000 mmW-Vorentwicklung, EADS, Ulm
- 2000 Promotion
- 2000 – 2011 Nokia GmbH, Ulm
- Seit 10.2011 Professor für Hochleistungsmikrowellentechnik (IHE) / Leiter IHM

Research Field

Pulsed Power Applications

Electron Beam Facility (GESA)



Bioelectrics

Prof. Dr. Georg Müller

High Power Microwave Sources for Fusion Applications

Material Processing with Microwaves

Prof. Dr.-Ing. John Jelonnek

High Power Microwaves

Institute for Pulsed Power and Microwave Technology (IHM)

Director: **Prof. Dr.-Ing. J. Jelonnek**
Co-Director: Prof. Dr. G. Müller

Karlsruher Institut für Technologie

Department Pulsed Power Technology

Head **Dr. G. Müller**
Deputy Dr. W. Frey
Administration Mrs. G. Bertsch

Bioelectrics
Dr. W. Frey

GESA
Dr. A. Weisenburger

KIT-SRG Bioelectrics
Dr. L. Wegner (CS)

Plasma-Wall-Interactions
Dr. I. Landman

Pulsed Power Technologies & Systems
Dr. M. Sack

Department High Power Microwave Technology

Head **Dr. G. Gantenbein**
Deputy Dr. G. Link
Administration Mrs. M. Huber

Gyrotron Simulations & Components
Dr. S. Illy

Materials Processing with Microwaves
Dr. G. Link

Gyrotron Tests & Measurements
Dr. T. Rzesnicki

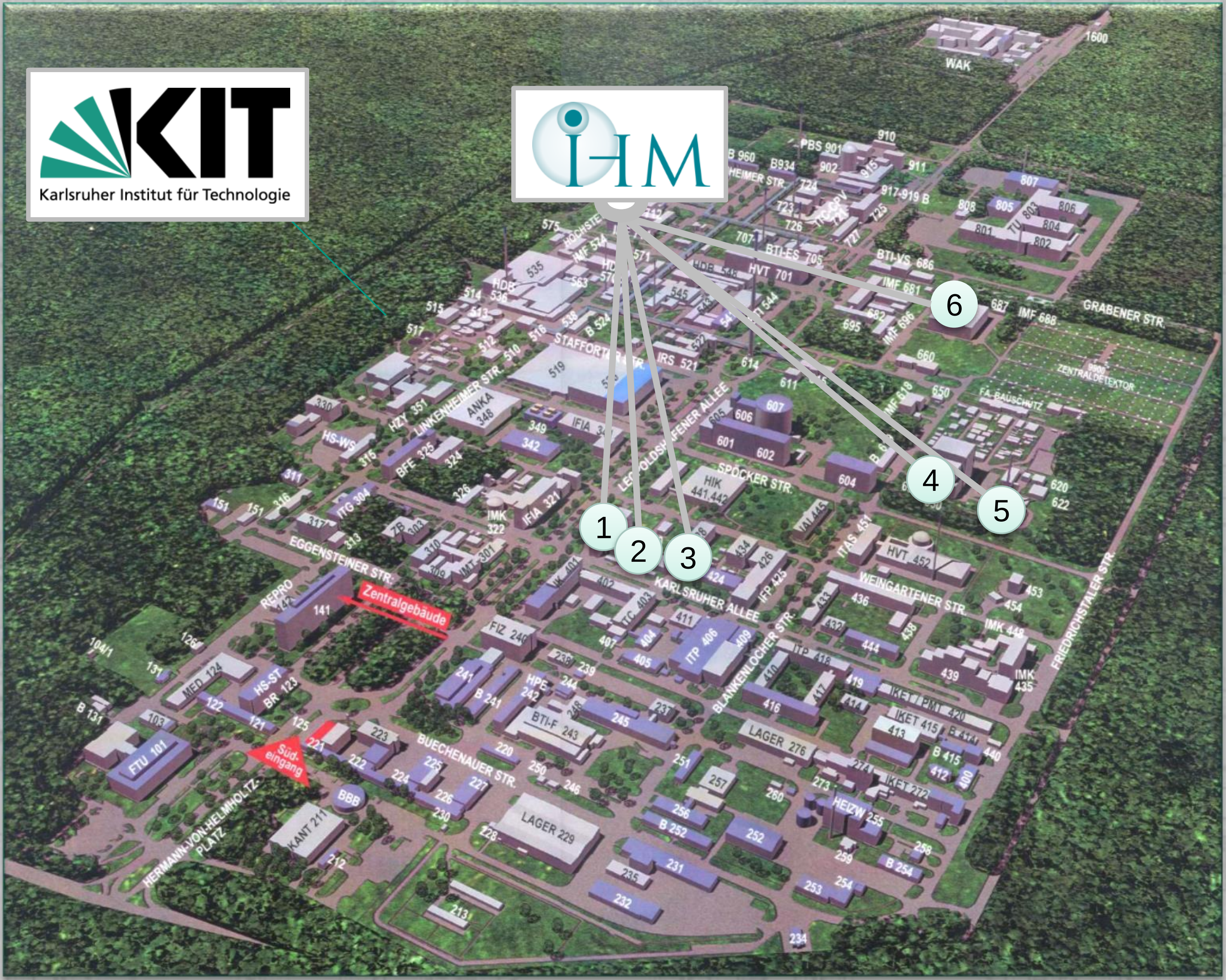
Administration
(finances, budget, travels)
Mrs. M. Huber

W7-X PMW Adm. PL.
Dr. H. Hunger

Mechanics Workshop
K. Schäfer

Electronics Workshop
K. Baumann

IHM Premises



 J. Jelonnek

Institut für Hochleistungsimpuls-
und Mikrowellentechnik (IHM)

Keywords and Definition

Keywords:

- *Generation, transmission and application of high-power micro-, mm- and subTHz- waves*
- *Vacuum Electron Devices and Components, transmission technology and diagnostics*

Definition:

In this lecture the generation, transmission, application and diagnostics of high power microwaves are discussed. The considered frequency range varies from 1 GHz to 1 THz. This corresponds to a wavelength of 0.3 mm – 30 cm.

The considered power range amounts a range of 1 W (lower THz range) till above 1 MW in the classical microwave range (1 … 300 GHz).

Sources and Applications

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- **Sources:**

The focus is on electron vacuum tubes. Those tubes are the unique components which operate in the whole considered frequency and power range.

- **Applications are:**
  - the satellite communication,
  - the spectroscopy,
  - the radar technique,
  - as well as applications in the section of the partical accelerator and the fusion.

The lecture is considered to be interdisciplinary and it shall introduce into the most important vacuum tubes. The particular applications will be explained. High power communication and diagnostic components are presented.

Outline

- **Introduction into the High Power Microwaves**
- **Dominant types of tubes and their modern applications**
  - Klystron: UHF amplifier, plasma accelerator and medical engineering
  - Travelling wave tube: Satellite communication and radar application
  - Backward wave oscillator and amplifier: THz - amplifier
  - Magnetron: Material Processing
  - Gyrotron: Fusion, Radar and NMR- Spectroscopy
- **Components Technologies**
  - Electron emitter and electron-optical systems
  - Collector
  - Microwave Window
  - Magnetic System
  - Vacuum Technology
  - High-Voltage Technology
  - Mode Converter
  - Quasi-optical power coupler and power transmission
- **Diagnostics for high power RF**

Timetable: Hochleistungsmikrowellentechnik WS 2016/17

Nr.	Date	Section	Content
1	19.10.2016	1.1	Introduction
2	26.10.2016	1.2, 1.3	Applications and Classification of RF Sources, Interaction Methods
3	02.11.2016	1.4	Relativistic Correction
4	09.11.2016	2.1	Cathodes- (Emitter-) Technology and Operating Modes
5	16.11.2016	2.2/2.3	Collector and Output Window
6	23.11.2016	3.1	Klystron
7	30.11.2016	3.2	Travelling Wave Tube
8	07.12.2016	3.3	Magnetron
9	14.12.2016	3.4	BWO, Free-Electron Laser
10	21.12.2016	3.5	Gyrotron and Gyro - TWT
11	11.01.2017	4.1	Electro Dynamics and High Power Transmission
12	18.01.2017	5.1	High Power Measurement Systems
13	25.01.2017	6.1	Fusion Technology
14	01.02.2017	6.2	Material Processing and Industrial Applications
15	08.02.2017		Excursion IHM Campus Nord

Organizational Instruction

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Titel	**Hochleistungsmikrowellentechnik**
Lecturer	**Prof. John Jelonnek**
SWS	**2** (15x lecture)
Place	**Geb. 30.35, HSI**
Time	**Wednesday, 8:00 – 09:30 Uhr**
Exam	**oral**
LV No.	**23435**

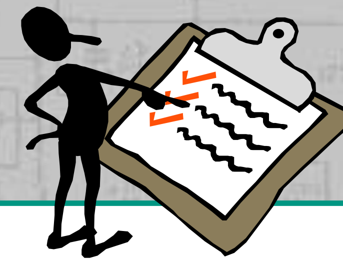
Chapter 1.1: References

Gilmour, A.S., Jr.	**Klystrons, Traveling Wave Tubes, Magnetrons, Cross-Field Amplifiers and Gyrotrons**
	Artech House, Boston, London, 2011
Pozar, D.M.	**Microwave Engineering,**
	John Wiley & Sons, New Jersey 2011
Eichmeier, J., Thumm, M.	**Vacuum Electronics - Components and Devices**,
	Springer, Berlin, Heidelberg, 2008
Tsimring, S.E.	**Electron Beam and Microwave Vacuum Electronics**,
	John Wiley & Sons, New Jersey 2007
Kartikeyan, M.V., Borie, E.	**Gyrotrons: High-Power Microwave and Millimeter Wave Technology**
Thumm, M.K.A.	Springer Verlag, Heidelberg 2004
Whitaker, J.C.	**Power Vacuum Tubes Handbook**
	Boca Raton, Morgan Hill, California, 2000
Gilmour, A.S., Jr.	**Microwave Tubes,**
	Artech House, Norwood, MA, 1986

Chapter 1

INTRODUCTION

Learning Targets



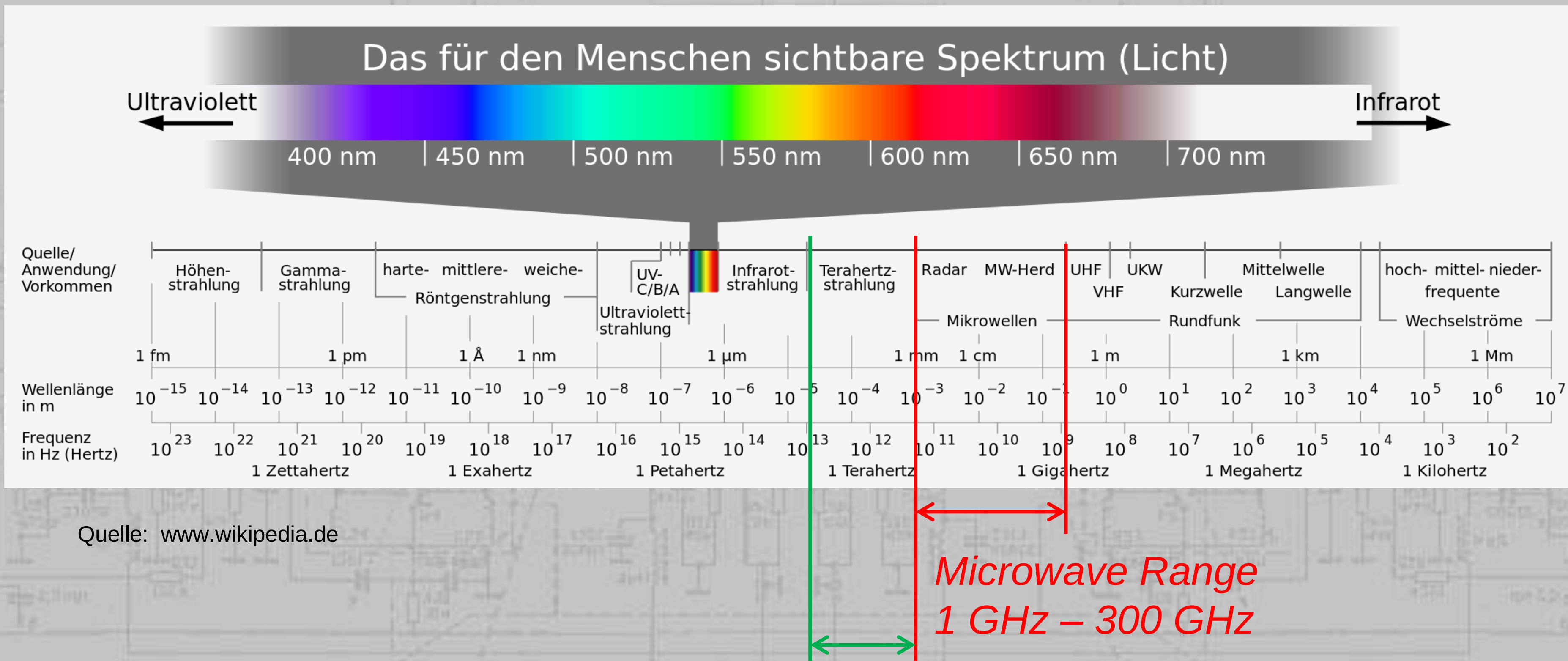
At the end of this chapter you should be familiar with:

- The content of the lecture
- The concept of the high power microwave technology
- A comprehensive overview of the applications
- The power limit of today´s microwave power elements
- The classification of electron tubes
- The necessary basics of the microwave tubes
- The necessary basics of the electro dynamics

Section 1.1

DEFINITION: THE MICROWAVE RANGE AND HIGH POWER

The Microwave Range

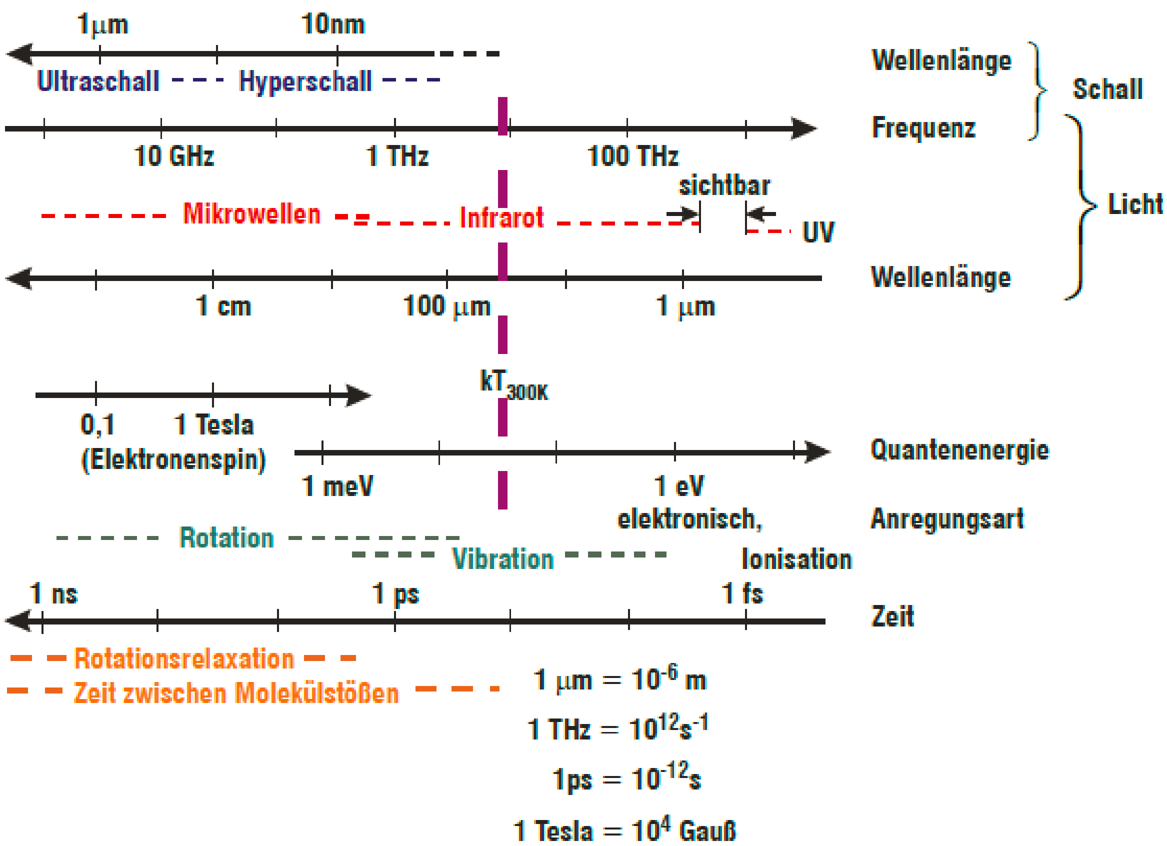


Quelle: www.wikipedia.de

Microwave Range
1 GHz – 300 GHz

THz-Range
300 GHz – 10 THz

The correlation between different



Quantenenergie (300 GHz) :

$E = h \cdot f \approx 0{,}001$ eV

(Quantenhypothese: Max Planck)

Plancksche Konstante

$h = 4{,}136 \cdot 10^{-15}$ eV · s

Therm. Energie (27°C □ 300K) :

$E = k \cdot T \approx 0{,}026$ eV

(Thermische Energie eines freien Teilchens mit der Temperatur T)

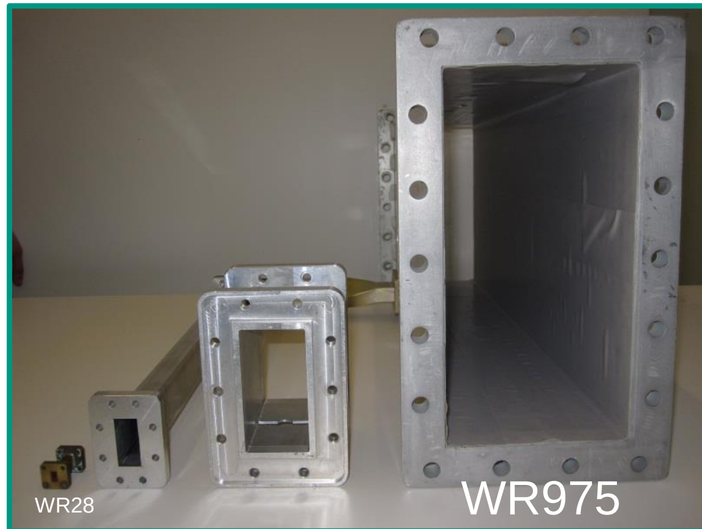
Boltzmannsche Konstante

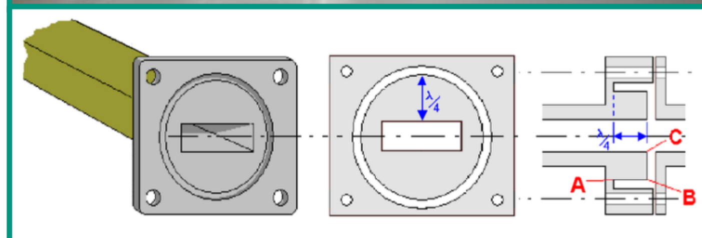
$k = 8{,}617 \cdot 10^{-5}$ eV/K

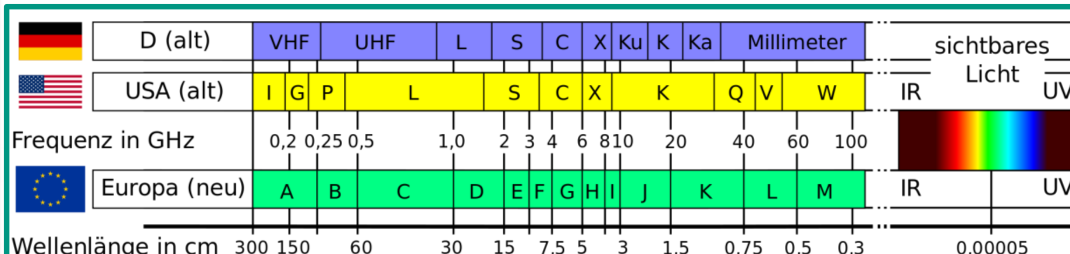
The Planck's law says, that the amount of energy exchange between radiation (e.g. light) and matter is not arbitrarily, but only in certain discrete ‘energy packages’ which are called quantum. The assumption was established by Max Planck in the year 1900, in order to derive the radiation law of the black body. Hence, the amount of energy represents, which is emitted or absorbed by the radiation field, always an integer multiple of the energy quantum. (source: www.Wikipedia.org)

Frequency Bands

Frequency Range/GHz	Band	Declaration		Width/mm	Width/Zoll
		DIN 47302 / IEC 153	EIA		
0,77 … 1,14	UHF/L	R 9	WR 975	247,65	9,750
1,12 … 1,7	L	R 14	WR 650	165,10	6,500
1,7 … 2,6	LA	R 22	WR 430	109,22	4,300
2,2 … 3,3	LS	R 26	WR 340	86,36	3,400
2,6 … 3,95	S	R 32	WR 284	72,14	2,840
3,22 … 4,90	A	R 40	WR 229	58,17	2,290
3,95 … 5,85	G	R 48	WR 187	47,55	1,872
4,64 … 7,05	C	R 58	WR 159	40,39	1,590
5,85 … 8,2	J	R 70	WR 137	34,85	1,372
7,05 … 10,0	H	R 84	WR 112	28,50	1,122
8,2 … 12,4	X	R 100	WR 90	22,86	0,900
10,0 … 15,0	M	R 120	WR 75	19,05	0,750
12,4 … 18,0	P	R 140	WR 62	15,80	0,622
15,0 … 22,0	N	R 180	WR 51	12,95	0,510
18,0 … 26,5	K	R 220	WR 42	10,67	0,420
21,7 … 33,0		R 260	WR 34	8,64	0,340
25,5 … 40,0	R	R 320	WR 28	7,11	0,280
33,0 … 50,0	Q		WR 22	5,69	0,224
40,0 … 60,0	U		WR 19	4,78	0,188
50,0 … 75,0	V		WR 15	3,76	0,148
75,0 … 110	W		WR 10	2,54	0,100
90 … 140			WR 8	2,032	0,080
110 … 170			WR 6	1,651	0,065
140 … 220			WR 5	1,295	0,051
170 … 260			WR 4	1,092	0,043
220 … 325			WR 3	0,864	0,034







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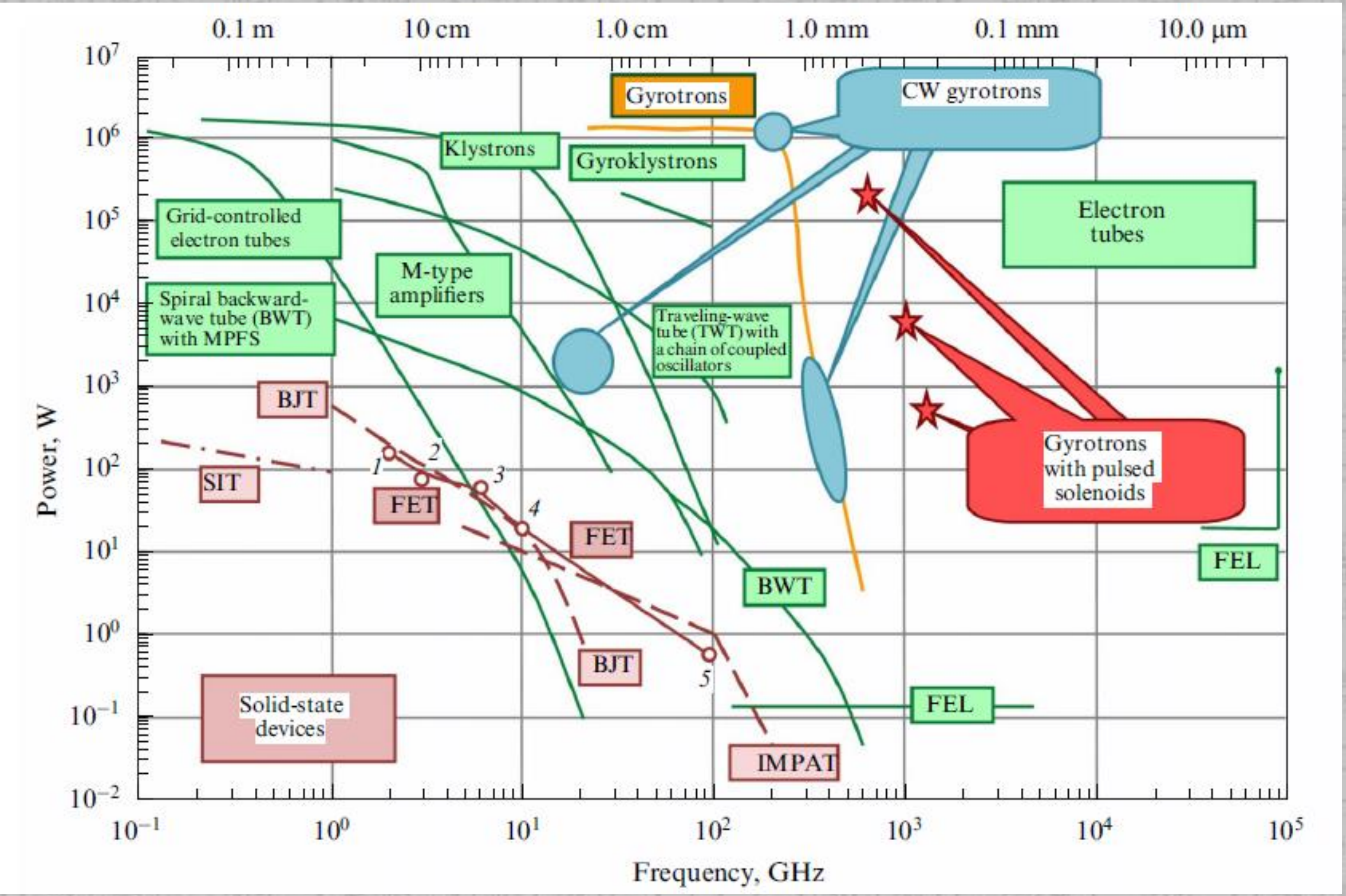
High Power Microwave Range



Source: M. Yu. Glyavin, et.al, High-power terahertz sources for spectroscopy and material diagnostics, Russian Academy of Science, 2016

Continuous Wave Power at the MW Range

1 MW, 700 MHz Klystron (CPI VKP-7952)

• Output Power:	**1,0 MW (1380 hp)**
• Acceleration Voltage	95 kV (max.)
• Beam Current	21 A (max.)
• Efficiency	65 %
• Dissipation loss of collector	~540 kW CW

0.78 MW WWII Aircraft Engine

$$1\ \text{PS} \triangleq 0{,}986\ \text{hp} \triangleq 0{,}735\ \text{kW}$$

What Corresponds to a Power of 5 MW?

- **Stopping in 0,072 s**
  - 7.2 kg (16 lb) shot traveling @ 1100 km/h (Mach 0.93)
  - 1.000 kg car traveling @ 96 km/hour

- **Alternatively,**
  - Boiling 1.000 l of water, starting from T=0°C in 83 s
  - Heating, melting and boiling a ton of ice @ T=-10°C in 155 s

Specific heat:

$$\text{Ice: } 2220\frac{J}{kg\cdot K};\ \text{Water: } 4190\frac{J}{kg\cdot K}$$

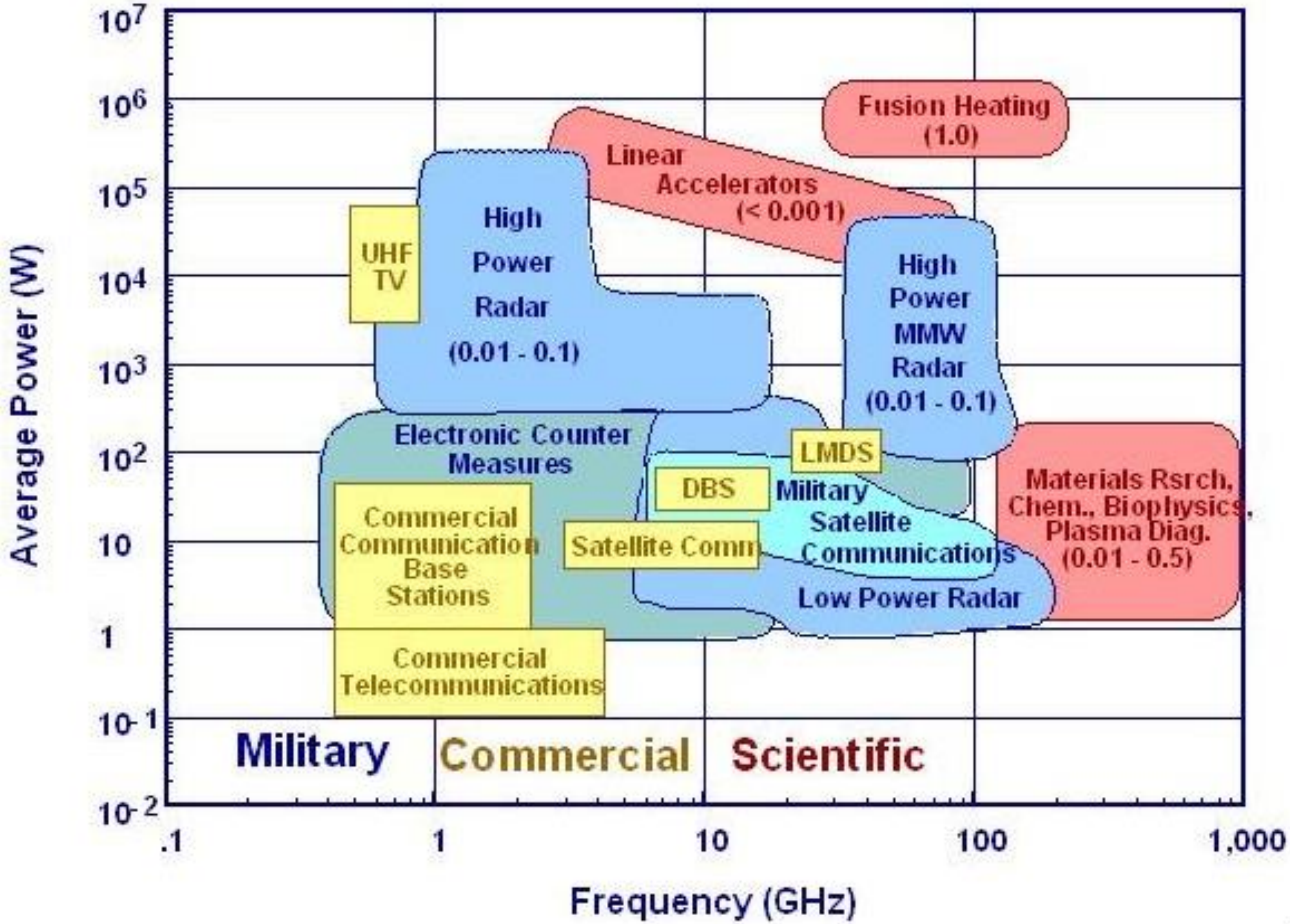
$$\text{Melting heat of ice: } 333\frac{kJ}{kg}$$

Idea: Dave McGinnis, “The European Spallation Source”, IVEC, Paris, 2013

Section 1.2

APPLICATIONS

Microwave Applications (P-f-Diagramm)



Quelle: B. Levush, et al, *Vacuum Electronics: Status and Trends*, Aerospace and Electronic Systems Magazine IEEE (2007)

1

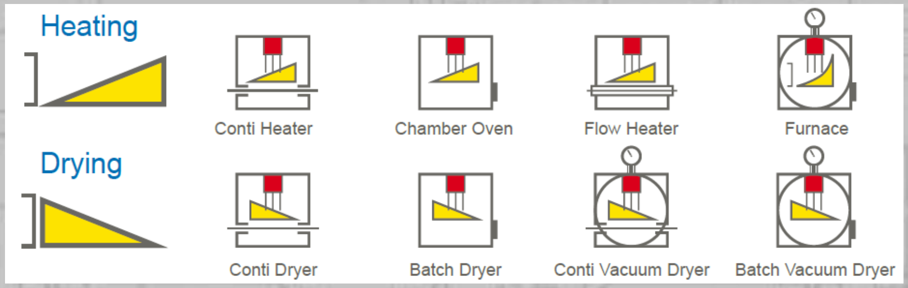
Short Abstract

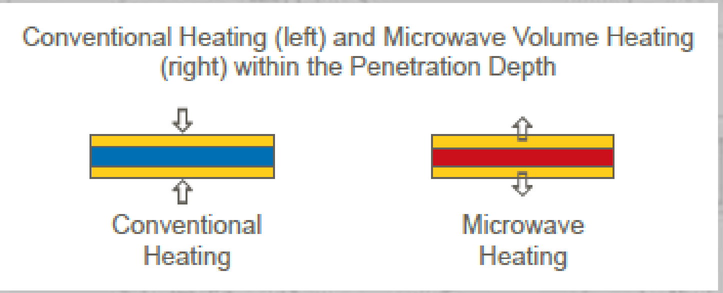
- **Industrial Applications**
  → Moderate continuous wave power at the GHz till THz- range
- **Radar- and Communication Applications**
  → predominant moderate output power, broadband applications
- **Production, Heating and Diagnostic of Fusion Plasma**
  → continuous wave-(CW-) maximum power sources
- **HF-Drive for Linear Accelerator and THz-Spectroscopy**
  → Sources with high pulse power in the mm- and cm-wave section
  (Treatment of caner, particle physic, material science)
- **Further Applications**

Microwave Power Systems / Application Fields

- **Chemistry**
  - Heating and Drying of Metal Oxide
  - Reaction Accelerator in chemical Processing
- **Pharmaceutical**
  - Vacuum Drying of Tablets and active Ingredients removing Solvents
  - Continuous high-end Vacuum Drying
  - Ultra fast Heating/Sterilisation of Sera and Protein Products
- **Plastics**
  - Heating of laminated Sheets and Boards
  - Polymerization of Fiber Glass reinforced Profiles
  - Heating of Epoxy Pipes/Tubes

Source:http://www.pueschner.com/downloads/Flyer_en.pdf





Microwave Freeze Drying for Food/Pharma/Chemical/Medical & Ceramics

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Application:

Ultrafast Microwave Freeze Dryers dry temperature sensitive products

Particular Advantages for Products:

- Cut down drying time from days into hours (***safe energy, safe costs, safe space***).
- Due to 3D heating sublimation is not only limited to layer drying like in conventional freeze drying. Sublimation is taking place throughout the volume therefore better ***textures*** and ***structures*** can be maintained.
- Combined processes in solid and liquid state with ultrafast heat transfer enable to generate ***new products***.

Scale your application easily from lab to production

...from Lab to Production...

Pharma Example:

Drying Time:	*2h*
Max Temp:	*≤ 20°C*
Residual MC:	*600ppm*

24kW/2450MHz Microwave Freeze Dryer

2kW/2450MHz Lab Microwave Freeze Dryer

Food Example: *MW-Freeze Drying of complete fruits like strawberries, raspberries, blueberries etc.*

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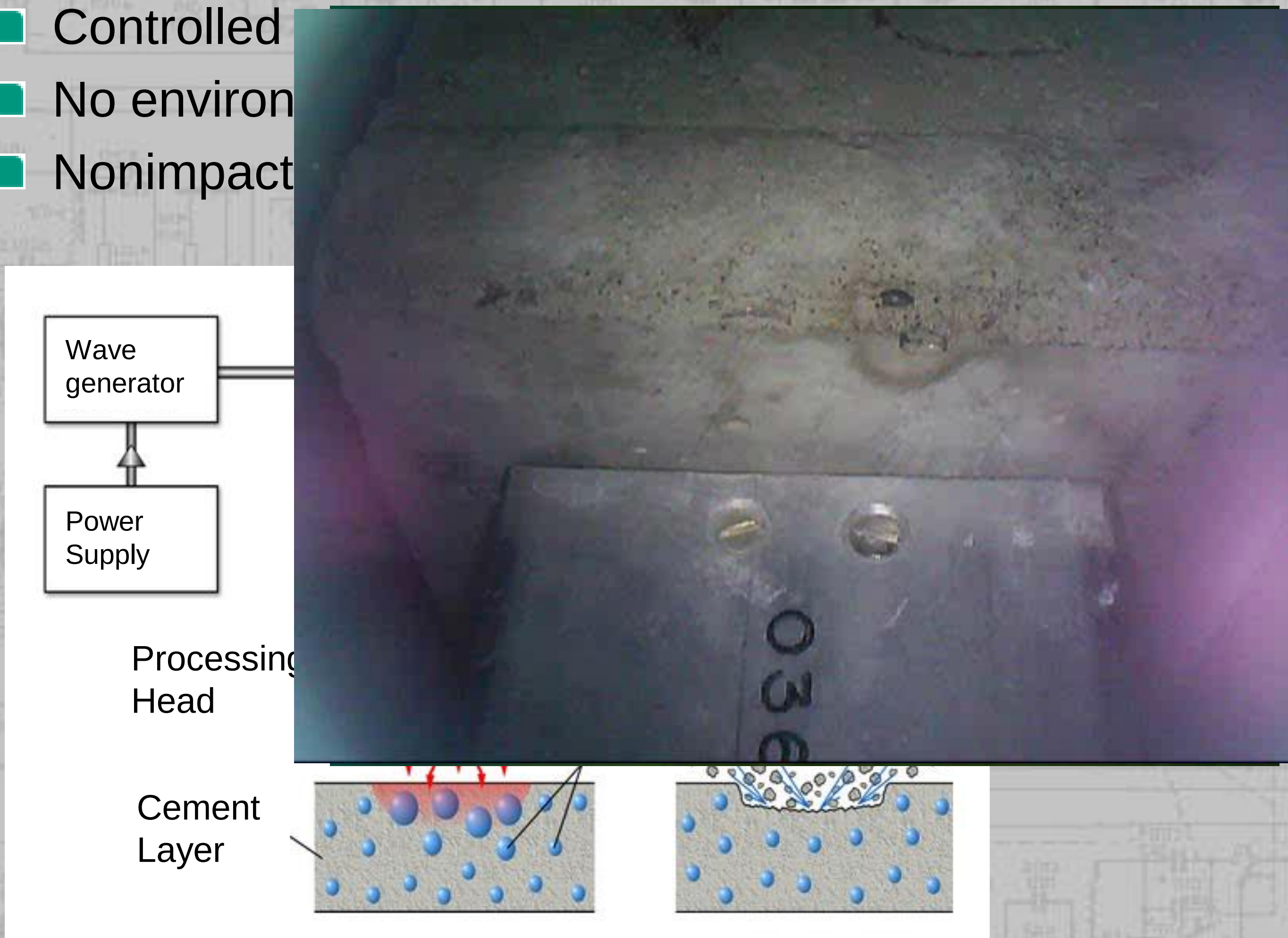
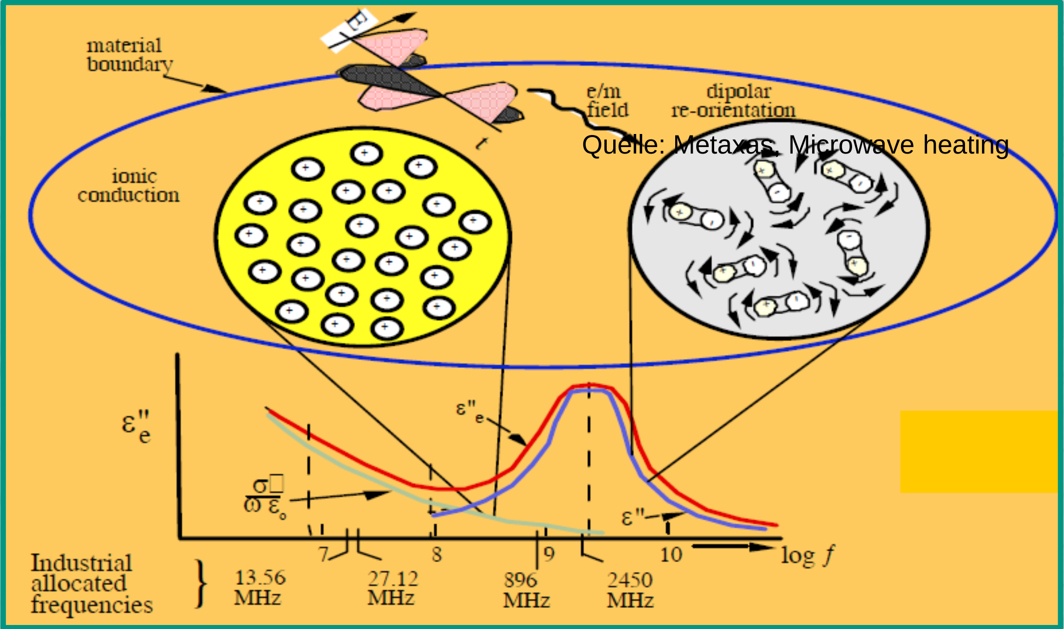
Ablation of Contaminate Cement Layers at Nuclear Reactors (MACOS)

- Controlled … nt layers.
- No environ…
- Nonimpact…



Example: Industrial Applications



Dominant Frequency Range for industrial Operations:

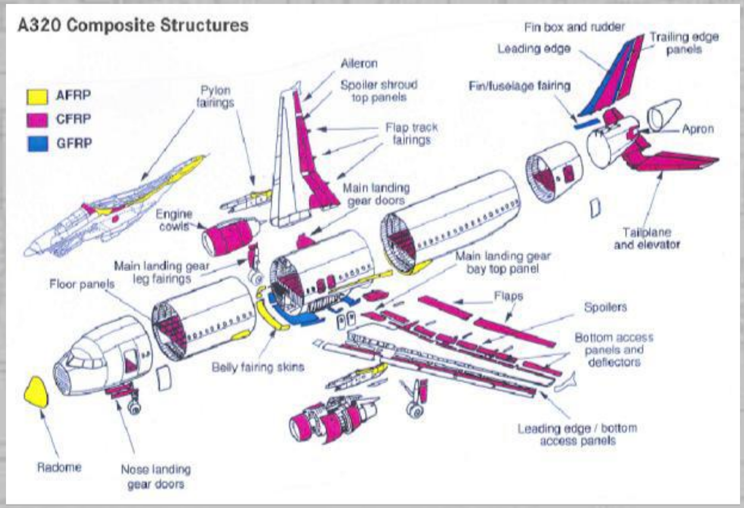
ISM Band:

- 896 MHz (915 MHz in the USA)
- 2450 MHz

Two physical mechanism determine the energy transfer in polar liquids:

- **The production of an ion current at low frequencies.** The loss mechanism is determined by the equivalent dielectric conductivity σ, and thereby an effective loss factor σ/ωεm.
- **Due to the existent of polar molecules at 2450 MHz.** The loss mechanism is determined by the disability of the field polarization. The result is a phase shift of the polarization. A current is produced, which is in phase with the electric field.

System for In-Situ Dielectric and Calorimetric Measurements



A microwave cured Porsche rear hatch

→ Fiber composite materials are very promising because of their high lightweight potential

→ Microwave curing is energy efficient

→ The dielectric properties of the materials must be known for the successful design of microwave applicators and processes.

Industrial Microwave Ovens

Vötsch
a schunk company

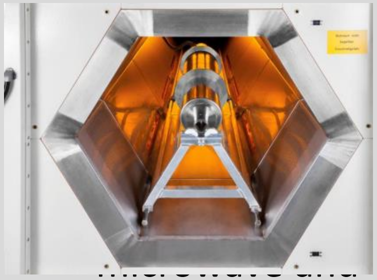
Reiskirchen, Germany

HEPHAISTOS

- Unique hexagonal chamber format
- Multi-source microwave heating

Hybrid

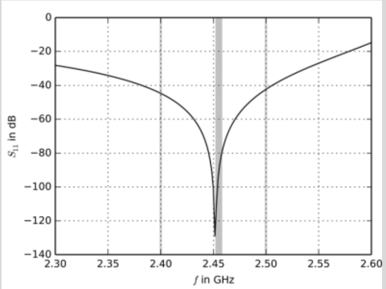
2015



convectional heating

Rotary Drive

2015



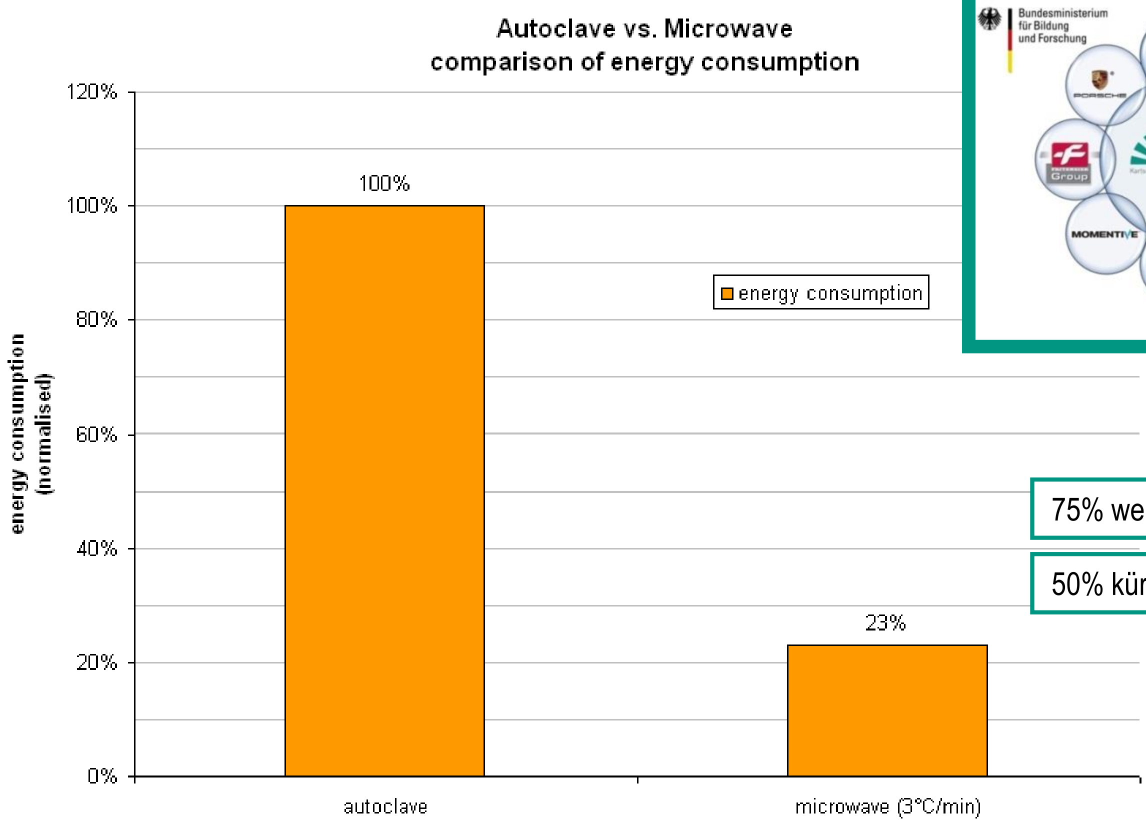
Rotary movement

Conveyor

2015

Throughput system with conveyor belt
Inlet- and outlet filters

Production of Carbon Composite Elements



75% weniger Energie

50% kürzere Prozesszeit

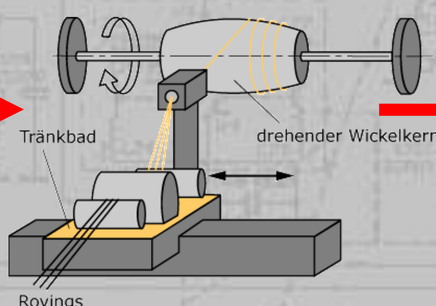
At the **VAP-technology** (vacuum assisted Process) in classical autoclaves respectively thermic oven the productivity is limited due to long-time, energy-intensive hardening process.

Microwave Assisted Pultrusion …#1/2

Manufacturing by filament winding

- Impregnation of fibres
- Layup of fibres on rotating mandrel (e.g. ± 89° for Flywheels)
- Part cures under rotation (Microwave or convectional oven)
- Demolding
- Final machining

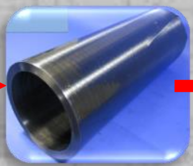

Filament Winding



Quelle: ETH-Zürich

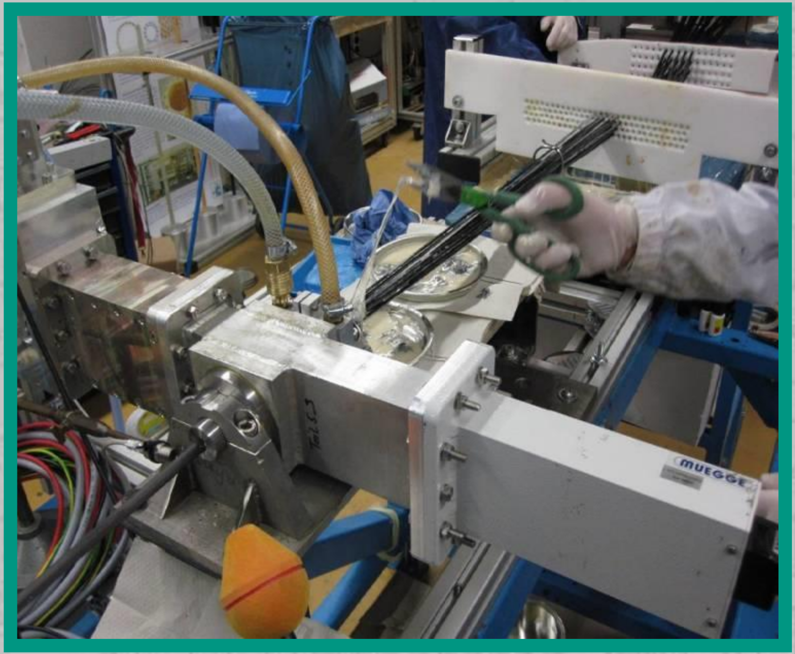
Curing

Demolding

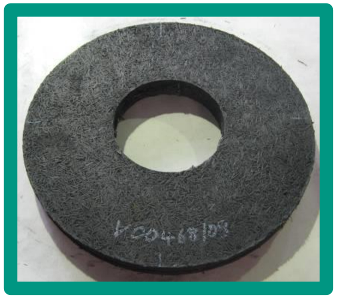


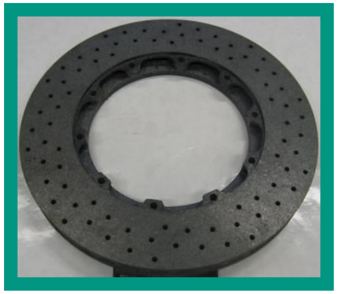
machining

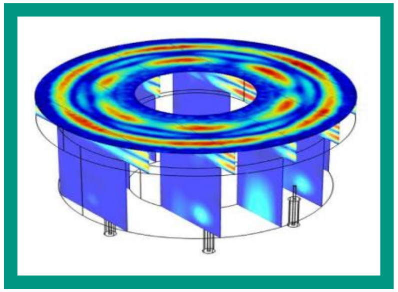
Microwave Assisted Pultrusion ...#2/2



Microwave assisted pultrusion of CFK profiles permit an energy efficient, fast hardening in ‘cold’ tools.



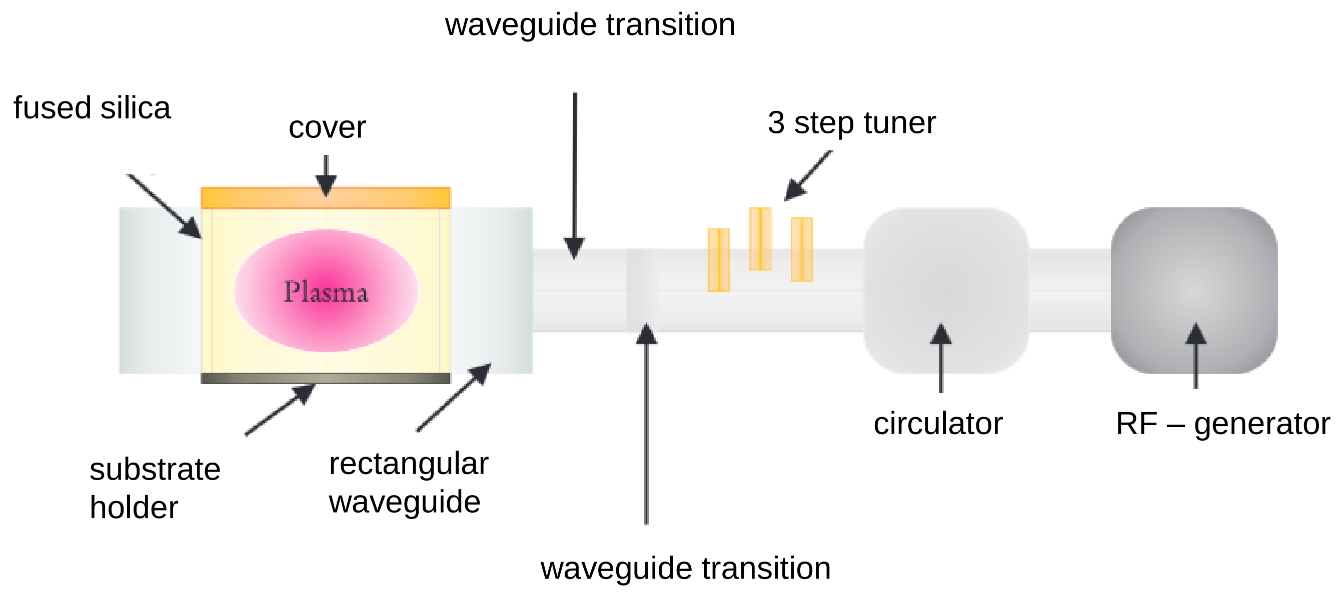




Microwave integrated compression mold for CFK brute hardening (for production of C/SiC brake disc).

Microwave Plasma Applications …#1/2

- In the plasma assisted surface technology process metallic or non-metallic devices will be coated or modified by the help of ionized gases and metal halide as well as steam of non-metals.
- Applications:
  - Ion implantation, plasma-activation, -heat treatment, -cleaning, coating …



Microwave Plasma Applications …#2/2

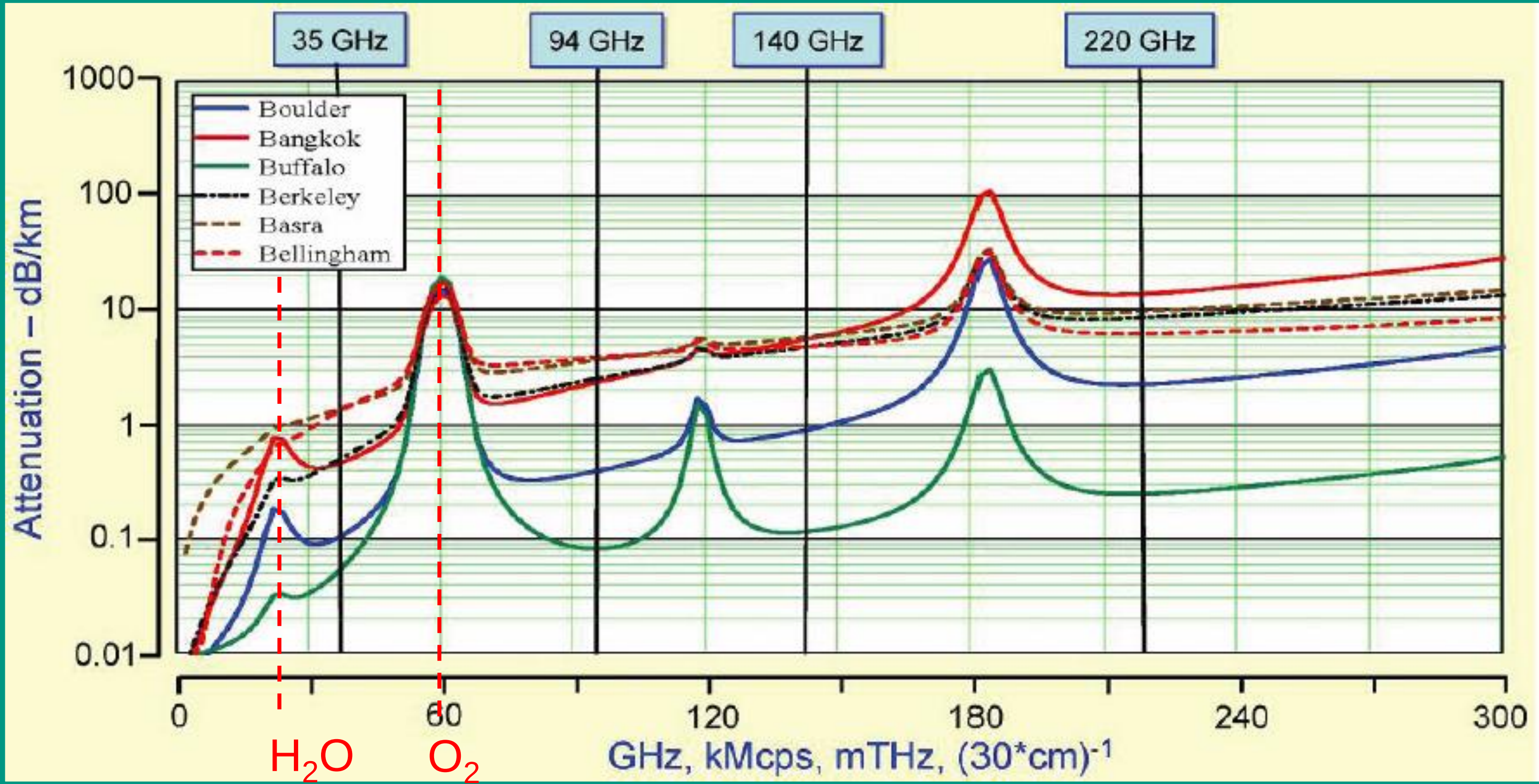
Si – coating for thin film photovoltaic modules

coated cam shaft

coated milling cutter

Surface treatment for better holding force

Wide Range Communication Systems
High free Channel Capacity in the mm- wave range



Quelle: M. J. Rosker, Vacuum Electronics and the World Above 100 GHz

- In the mm-wave range an absorption due to the resonance effects occurs.
- The absorption in the atmosphere depends on the temperature and the relative humidity.

The attenuation losses consists of an atmospheric attenuation as soon as an additional strong weather-dependent attenuation caused by rain and fog.
The electromagnetic waves will be attenuated by the penetration of air and water layers. At this process steam and oxygen molecules are mainly involved. A part of the electromagnetic energy will be changed into heat, while another part will be scattered.

Example: Tracking and Imaging Radar (TIRA) Space Observation

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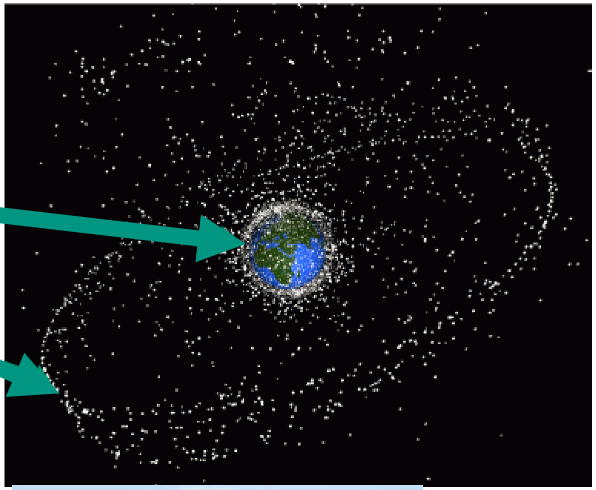
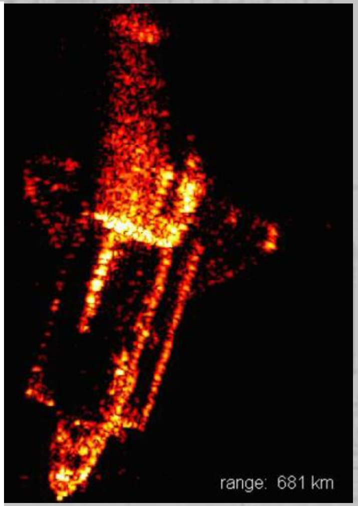
- **16.000** trackable objects >10 cm including ~900 active satellites (Catalogued by the US Space Surveillance Network, SSN)
- ~ 75% of the catalogued objects are in the LEO region (altitude 200 – 2.000 km)
- ~ 9% of the catalogued objects are in the GEO region (altitude 36.000 km)
- **700.000** non-trackable objects >1 cm Detectable only with powerful sensors, e.g. TIRA





Fraunhofer FHR

TIRA Configuration

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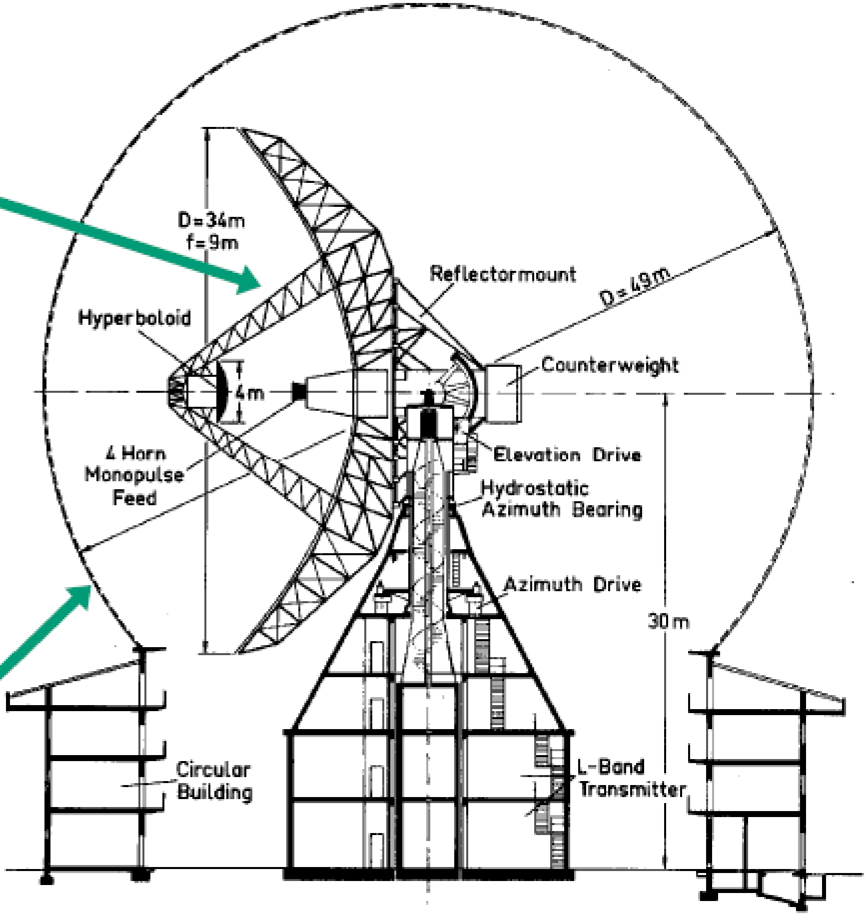
Fraunhofer FHR

TIRA, Wachtberg, Bonn, Germany

Antenna System

- **34-m** parabolic dish in Cassegrain configuration, usable from **200 MHz** to **40 GHz**
- Antenna gain: **50 dB** (L-band)
  73 dB (Ku-band)
- High angular speed (**24°/s** in Azimuth**, 6 °/s** in Elevation) allows tracking also under extreme conditions
- Very high angular resolution: **0.6"**
- System covered by **49-m** radome for protection



TIRA High Power Sources

Karlsruher Institut für Technologie

Radar characteristics

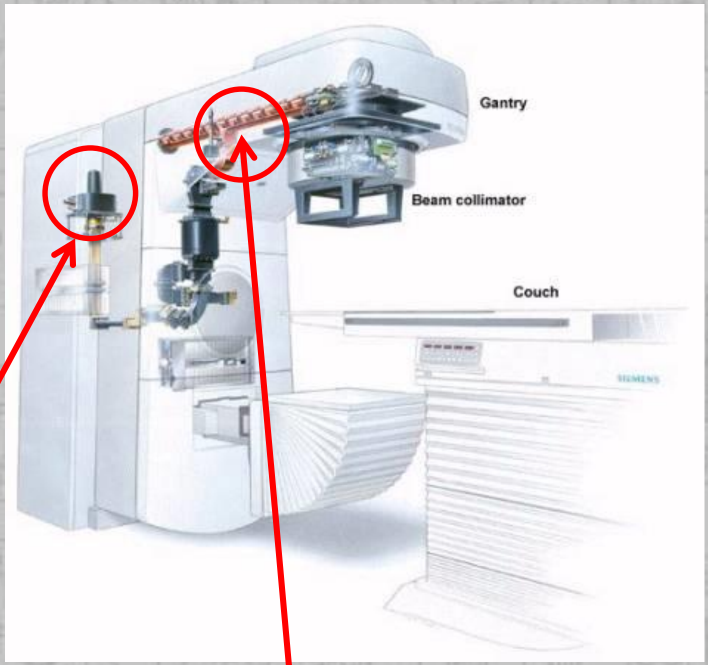
Fraunhofer FHR

- Coherent, narrow-band, BPSK-modulated pulse radar
- 4-horn monopulse system for tracking
- Transmit frequency 1333 MHz (L-band)
- Beam width 0.49° (Pencil beam)
- Current single-pulse sensitivity 2 cm at range *R* = 1000 km

	L-band transmitter („old")	L-band transmitter (upgraded)
Amplifier tube	2 Multi-cavity klystrons in parallel	1 Multi-cavity klystron
RF pulse output power	< 1 MW (EOL)	20 kW – **2 MW**
RF input power	≤ 800 W	≤ 120 W
RF pulse length	250 µs – 2000 µs, nom. 1000 µs	160 µs – 1400 µs, nom. 1000 µs
Pulse repetition rate	5 Hz – 136 Hz	1 Hz – 120 Hz
RF duty cycle	≤ 4 %	≤ 5 %
Start-up time	60 min	**20 min** (**10 min** with hot standby)

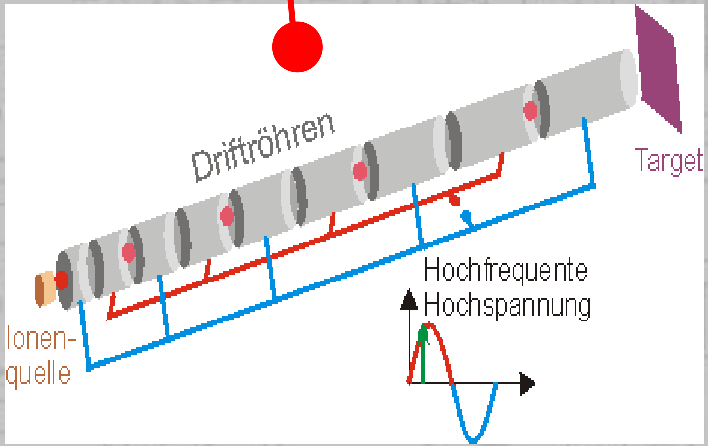
Example: Medical Engineering

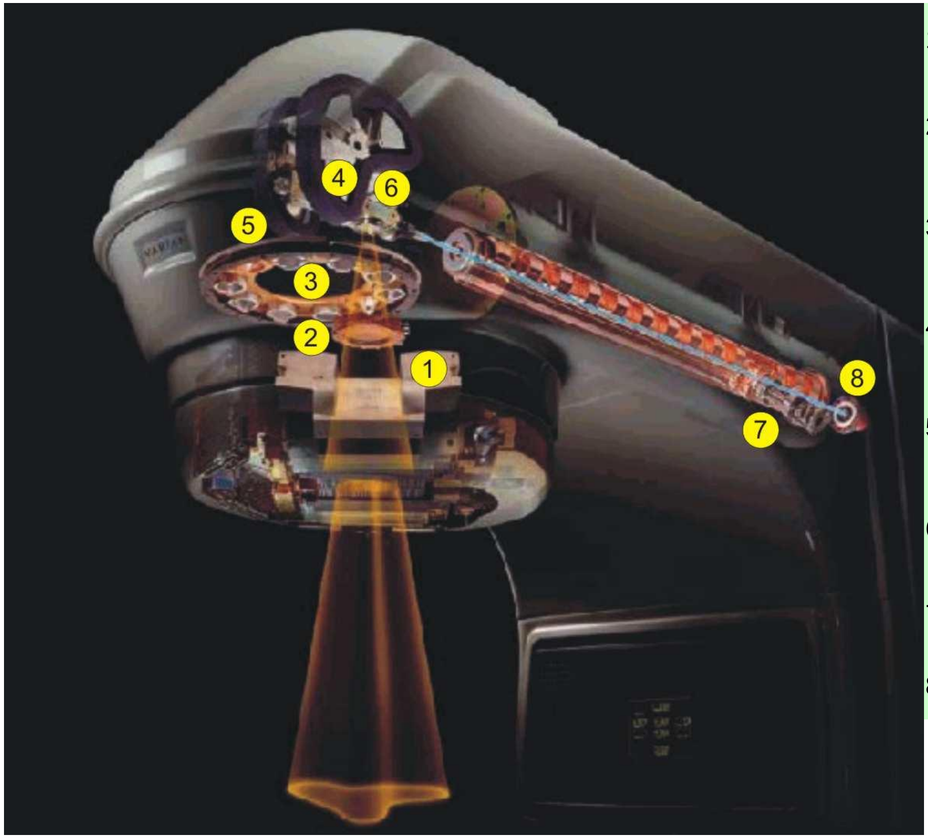

CPI Truebeam linear accelerator



Frequency	2.7 – 2.9 GHz
Pulse Power	3 MW
Duty Cycle	.0008
Anode Voltage	65 kV
Anode Current	100 A
Puls duration	2 ms
Heating Current	9 V @ 21 A
Water Cooling System	

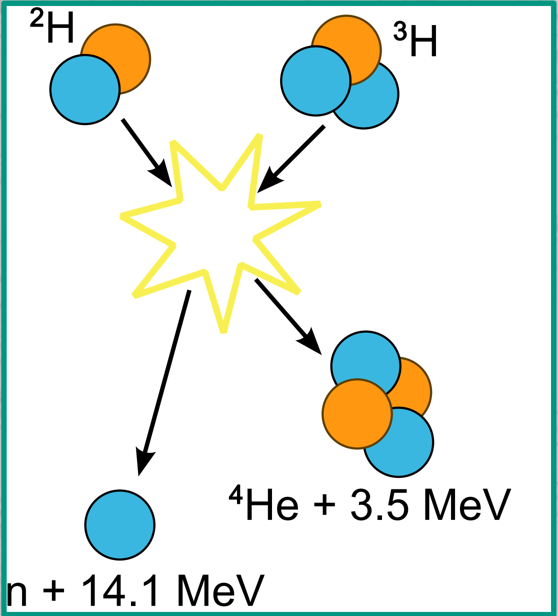

CPI 1143B
3 MW S-Band Magnetron

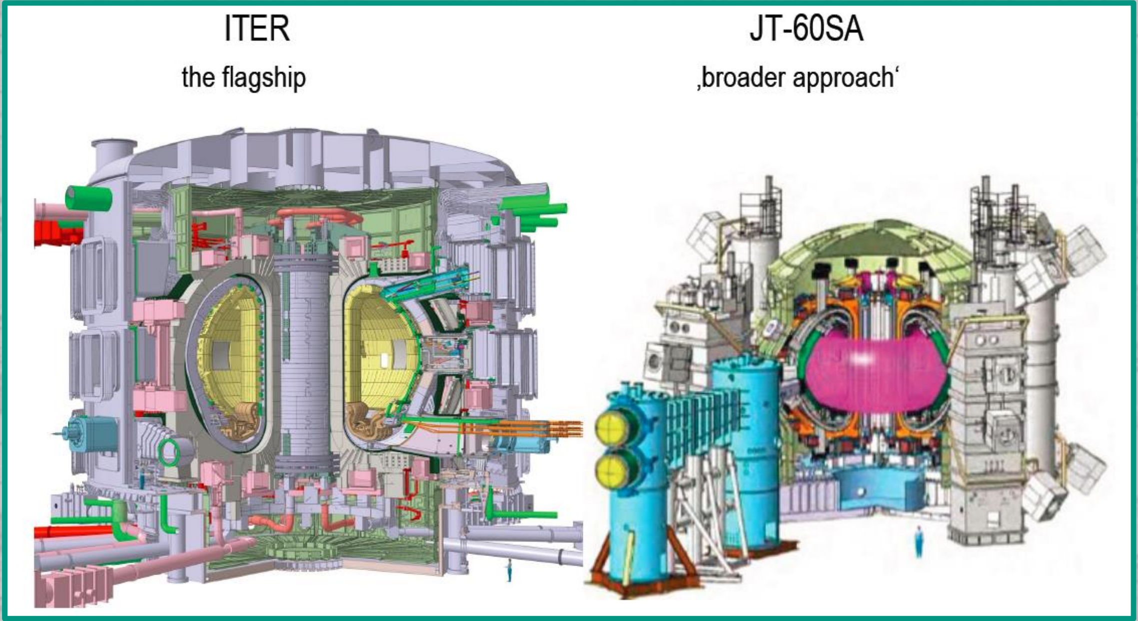




1	Asymmetric Blend	Formation of flexible field strength for the irradiation
2	Ionization Measuring Chamber	Observation of the radiated dose. By a deviation of 2% of the calculated dose, the irradiation will be interrupt.
3	Filter Carousel	Scattering foil for a homogenous electron field. The filter strength are adapted to the corresponding energy.
4	Bending Magnet	In the deflection unit the accelerated electrons will be directed to a 2mm focus caused by the magnetic field.
5	Radiation Unit	In dependence on the Gantry position, the electron beam will be centered to the focus by using the magnetic field strength (max. deviation 2 %).
6	Focus	Origin of divergent radiation. From this place the radiation is spreading like a light beam from the flashlight.
7	Acceleration Unit	In this unit the electrons will be extremely accelerated by means of the RF oscillations.
8	Electron Gun	Production of the electron cloud using thermionic emission.

Example: Fusion (Deuterium-Tritium-Fusion)





In a plasma deuterium- and tritium nucleus fuse to helium-4 and a free neutron.
In addition, a high energy have to be supplied, in order to overcome the coulomb repulsive force.
→ For 1 GW produced fusion power, the RF heating power have to be >100 MW.

RF Heating Principle

Excitation of plasma wave (frequency ω) near plasma edge

$\Downarrow$

wave transports power into plasma center

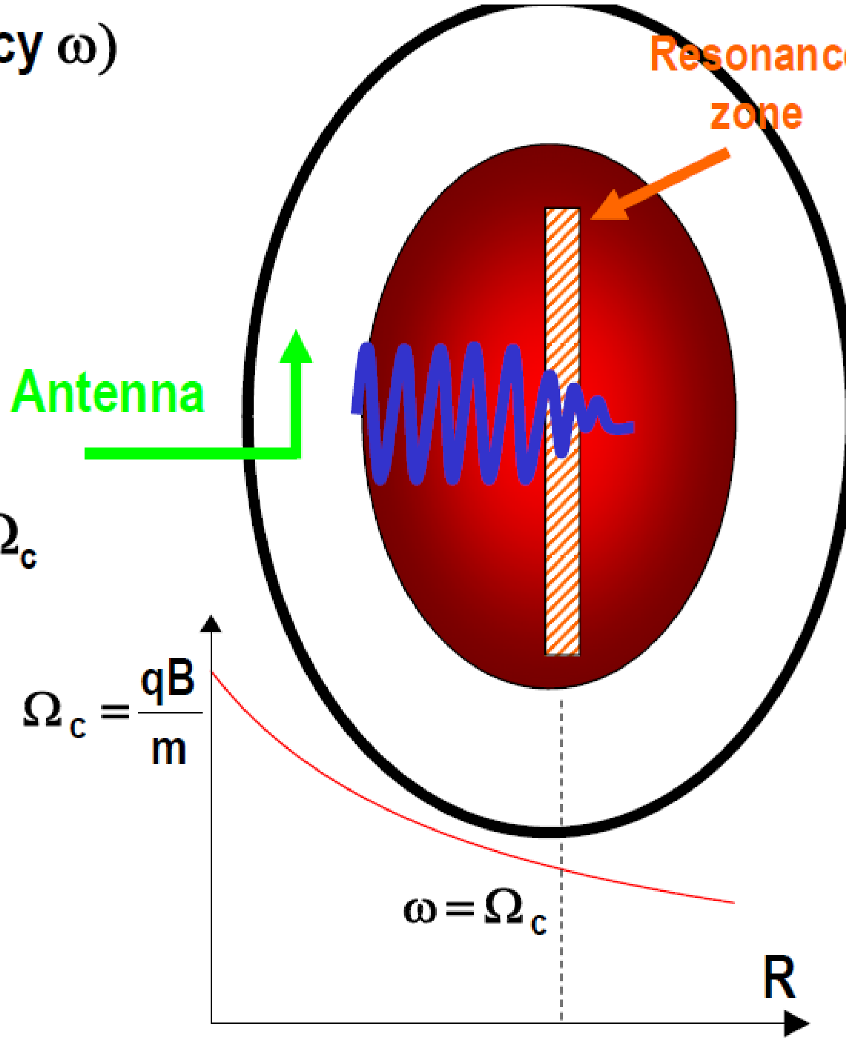
$\Downarrow$

absorption near resonance, e.g. $\omega \approx \Omega_c$,

i.e. conversion of wave energy into kinetic energy of resonant particles

$\Downarrow$

Resonant particles thermalize.



Different Methods for Plasma Heating

RF HEATING

Irradiation of Electromagnetic Waves which are in Resonance with cycling frequency of particles

ION CYCLOTRON RESONANCE HEATING (ICRH)

$$f_{ci} = \frac{Z\,e\,B}{2\,\pi\,m_i} \approx 7.63\ B[T]\ MHz\ \ for\ \ D$$

ELECTRON CYCLOTRON RESONANCE HEATING (ECRH)

$$f_{ce} = \frac{e\,B}{2\,\pi\,m_e} \approx 28.00\ B[T]\ GHz$$

LOWER HYBRID CURRENT DRIVE (LHCD)

Non – Inductive Current Drive in Tokamaks

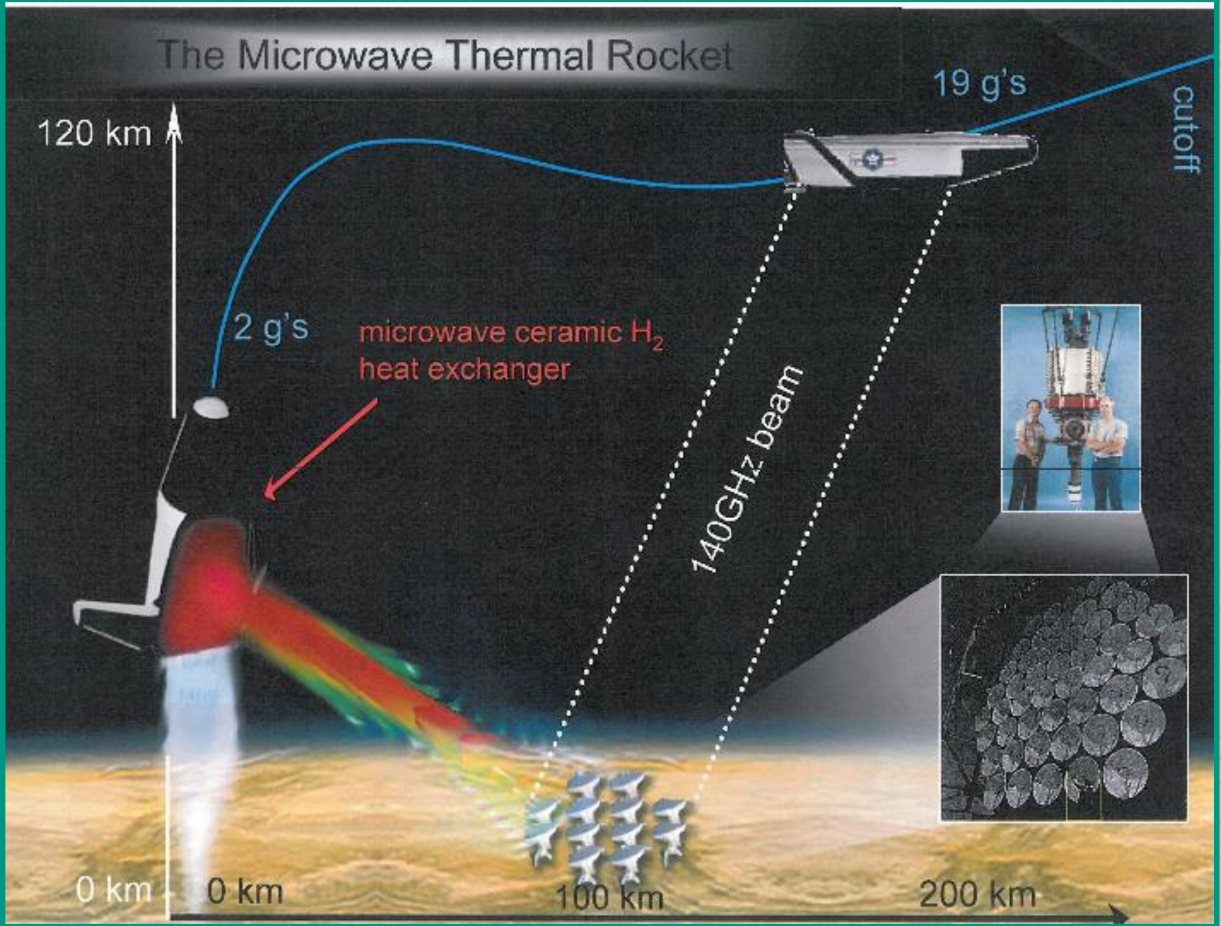
$$f_{LH} \approx \sqrt{f_{ci}\ f_{ce}} = 0.46\ B[T]\ GHz\ \ for\ \ D$$

Different Methods for Plasma Heating in ITER

- **Ion Cyclotron Resonance Heating (ICRH)**
  - Ion cyclotron heating method uses radio waves at different frequencies to deliver additional energy into the plasma.
  - Energy is transferred to the ions in the plasma by a high-intensity electromagnetic radiation with a frequency of 40 to 55 MHz.
  - Tetrode generators produce high-power radio frequency waves that are carried along a coaxial transmission line to a strap antenna located in the vacuum vessel, sending the waves into the plasma.

- **Electron Cyclotron Resonance Heating (ECRH)**
  - Heats the electrons in the plasma with a high-intensity beam of electromagnetic radiation at a frequency of 170 GHz; the resonant frequency of electrons.
  - The electrons in turn transfer the absorbed energy to the ions by Coulomb collisions.
  - In comparison to ICRH, ECRH has the advantage that the RF beam can be transmitted through vacuum which simplifies the design and allows the antenna to be far from the plasma. Power will be provided by powerful, high-frequency gyrotrons as power sources. Power is transmitted and launched to the plasma via oversized waveguides or quasi-optical mirror lines.

The Microwave Thermal Thruster

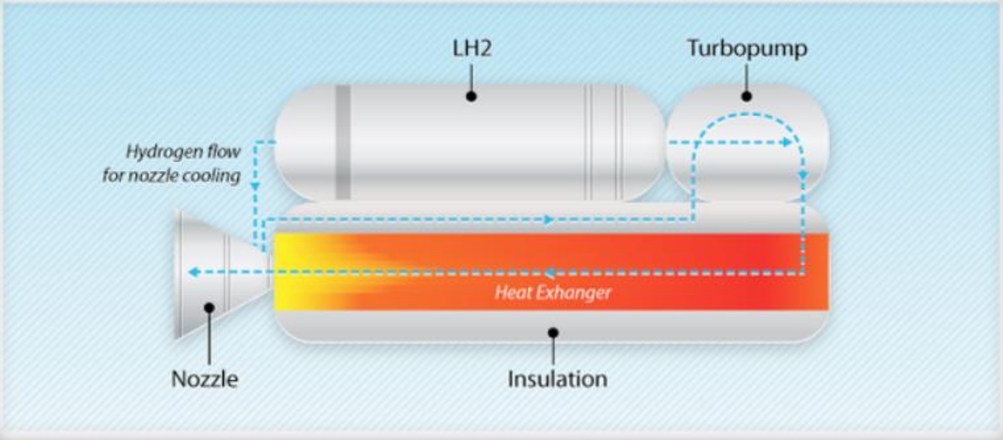


- It is possible to double or triple the proportion of freight charges by transportation in the orbit.
- An earth station microwave system is necessary to heat the propellant in the rocket.
- ~300 MW @100 GHz are enough to transport 1 ton into the orbit.
- Literature: Parkin, 2004-2006

Sources: CPI, S. Cauffman, 37th IRMMW-THz Conference, Wollongong, 2012
Kevin L. G. Parkin, The Microwave Thermal Thruster and its Application to the Launch Problem, California Institute of Technology, 2006

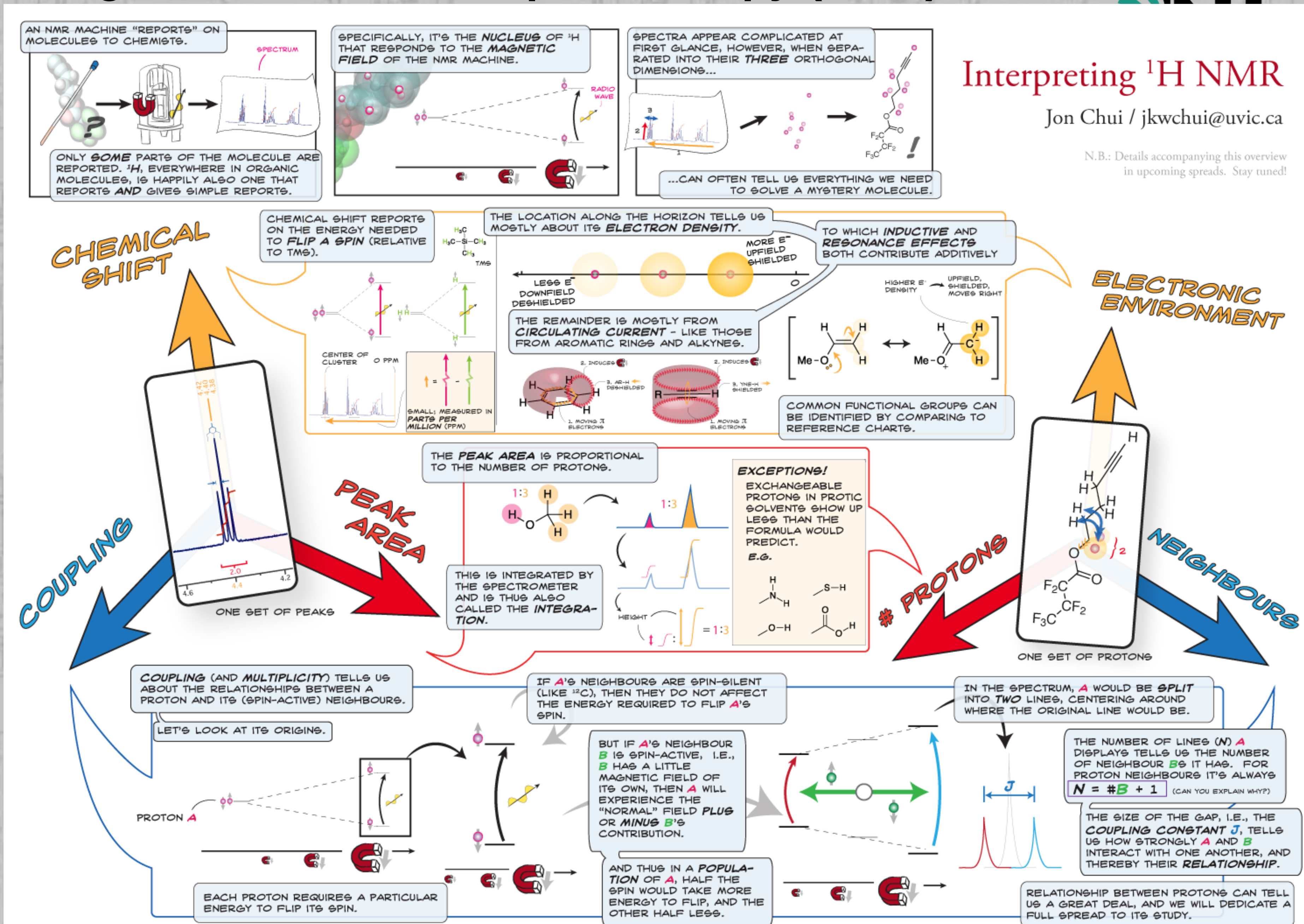
The Microwave Thermal Thruster

- The idea is that microwaves beamed from the ground would heat hydrogen, which would then flow through a heat exchanger and out through the rocket's nozzle.
- The key components of the microwave beam system are a ground-based microwave array and an engine based on the heat exchange between the hydrogen propellant and the incoming microwave radiation.
- Hydrogen heating is achieved with the heat exchanger, which heats the propellant to a temperature above 2,000 deg celsius.



GYROTRON-BASED DNP-NMR SPECTROMETERS INSTALLED AROUND THE WORLD

Magnetic Resonance Spectroscopy (NMR)



Dynamic Nuclear Polarization

Transfer electron spin polarization to nuclear spin polarization

by microwave/mm-wave irradiation of electron spins

Chemically induced DNP = CIDNP

Optically induced DNP (related to CIDNP)

In liquids

In solids

Overhauser effect

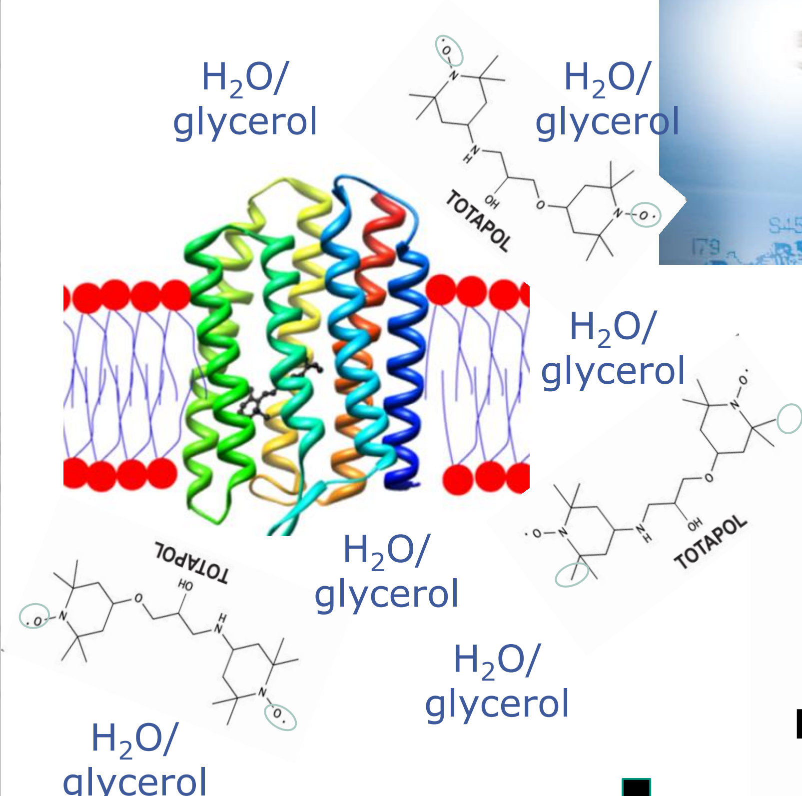
Solids effect
Cross effect
Thermal mixing

Millimeter wave sources for DNP enhanced NMR spectroscopy at frequencies above 100 GHz

- Gyrotrons
- Klystrons
- Clinotrons
- Solid state sources
- …

Institut für Hochleistungsimpuls- und Mikrowellentechnik (IHM)

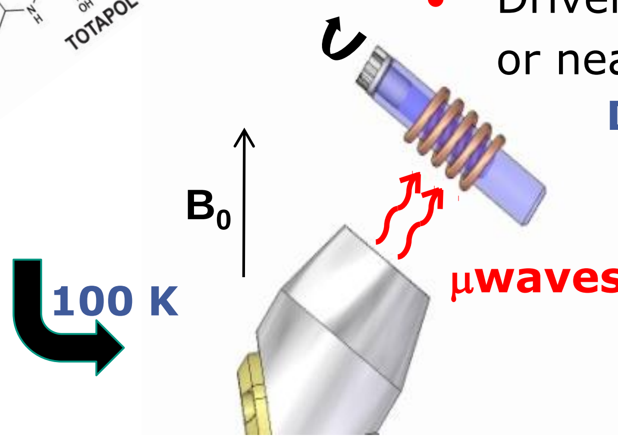
Synopsis
DNP

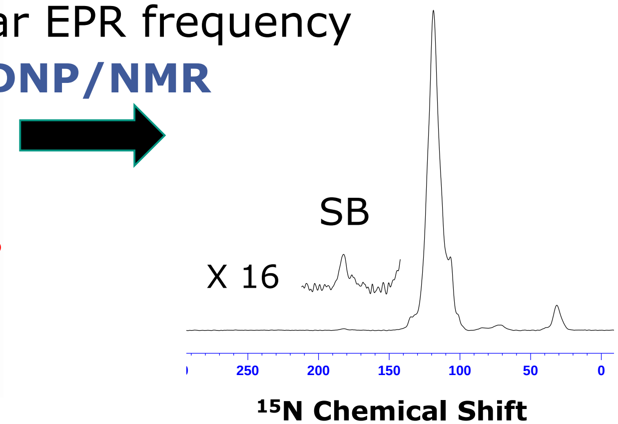


- Transfer polarization from unpaired electron spins to nuclear spins

$\gamma_e >> \gamma_n$

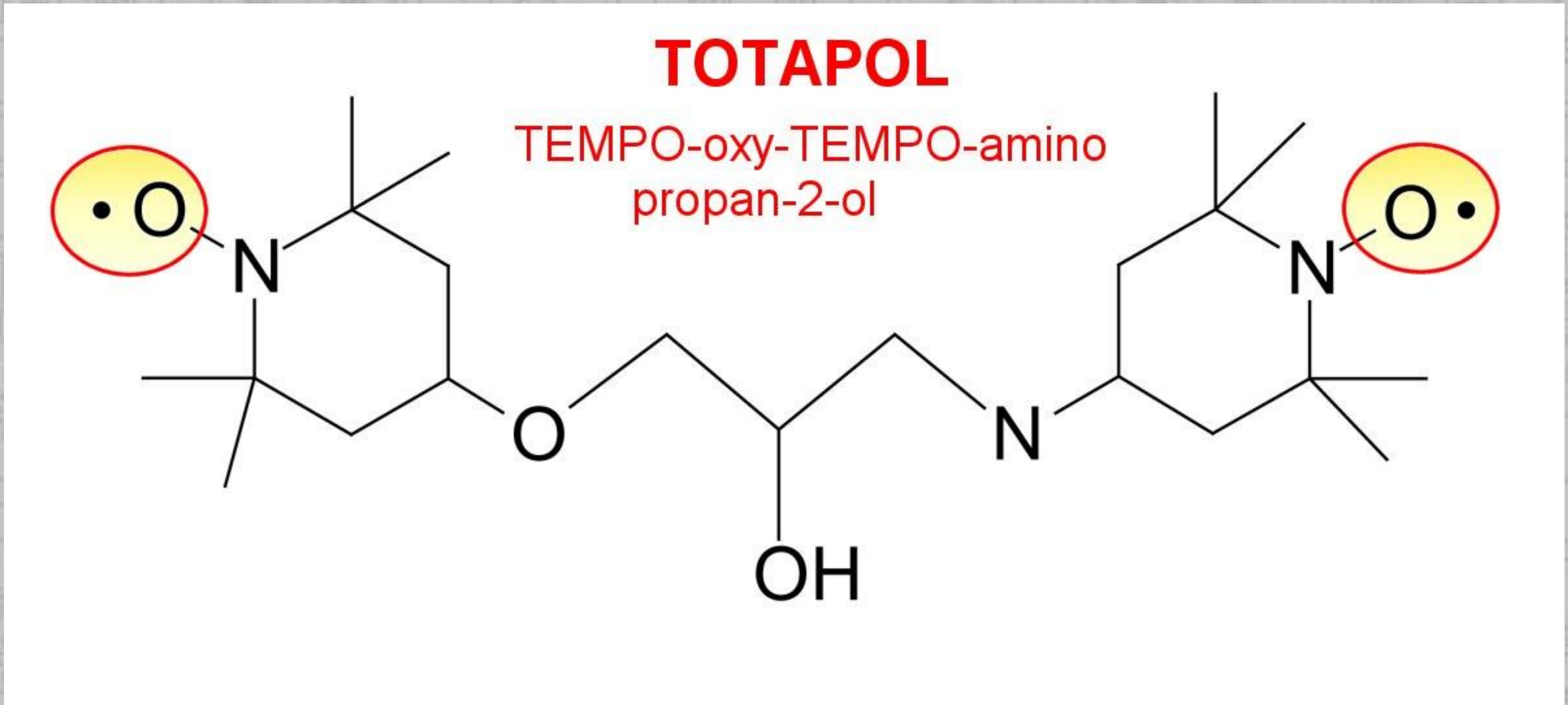
- Driven by microwave irradiation at or near EPR frequency



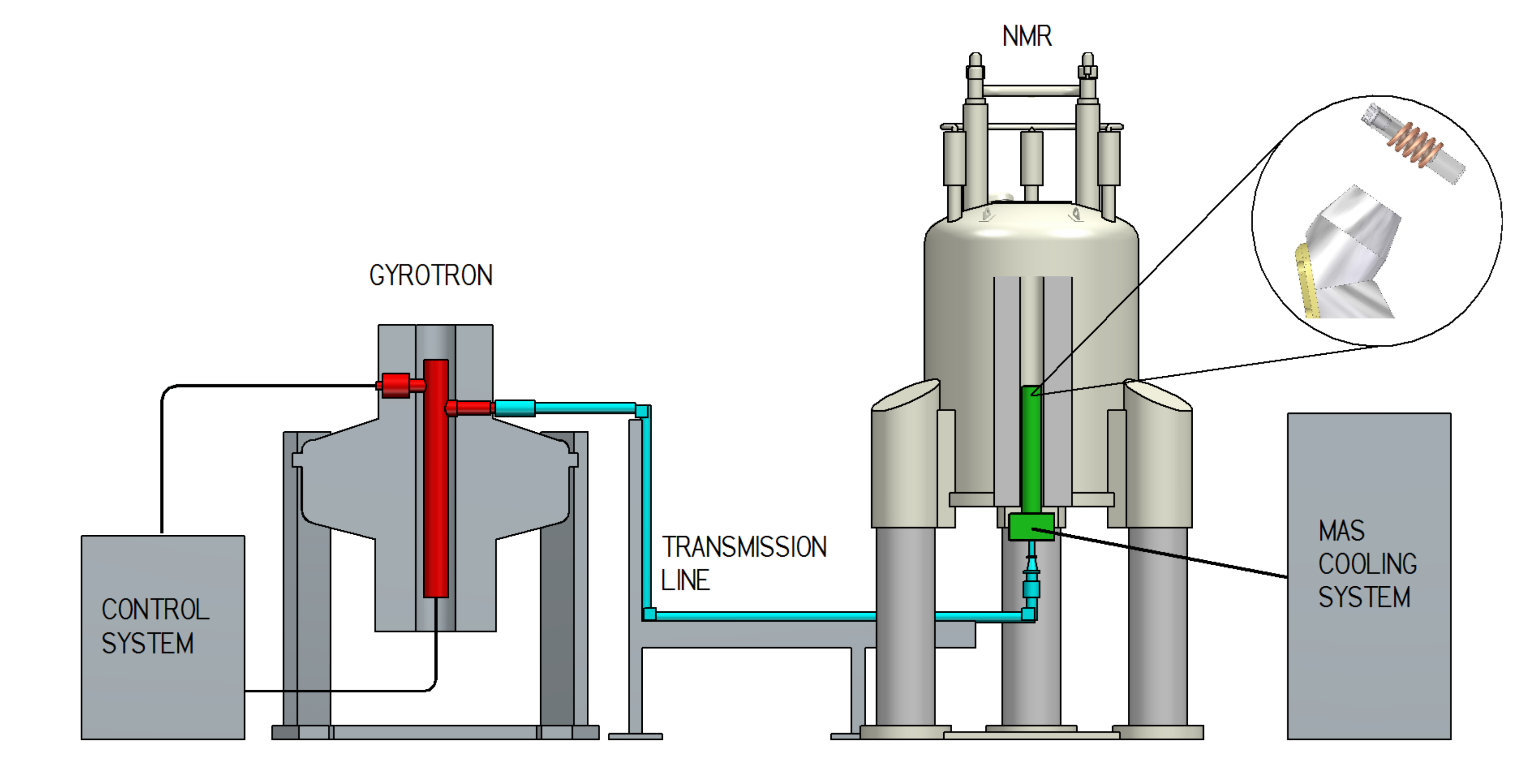


Example: Biradicals for cross-effect DNP

The electrons in atomic or molecular orbitals are usually spin-paired (“spin-up“ and “spin-down“) yielding a net electron spin of zero. In radicals this “rule“ is violated and at least one single electron spin is not paired resulting in a paramagnetic center. A molecule with two unpaired electron spins (not in the same orbital at the same nucleus) forms a biradical.



MAS DNP NMR spectrometer



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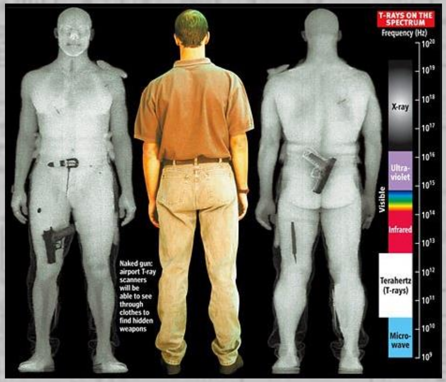
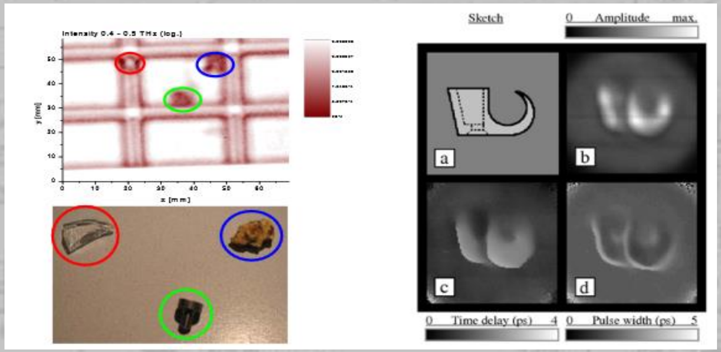
THz Application

- Spectroscopy
- Safety Engineering
  - People control (airport, train station,)
- Medical imaging
  - Imaging of the skin through the bandage
  - Tumor detection
- Industrial Inspection
  - Detection of foreign matter in food
- Communication Systems
  - Higher data rate





Chocolate Farina