THz applications

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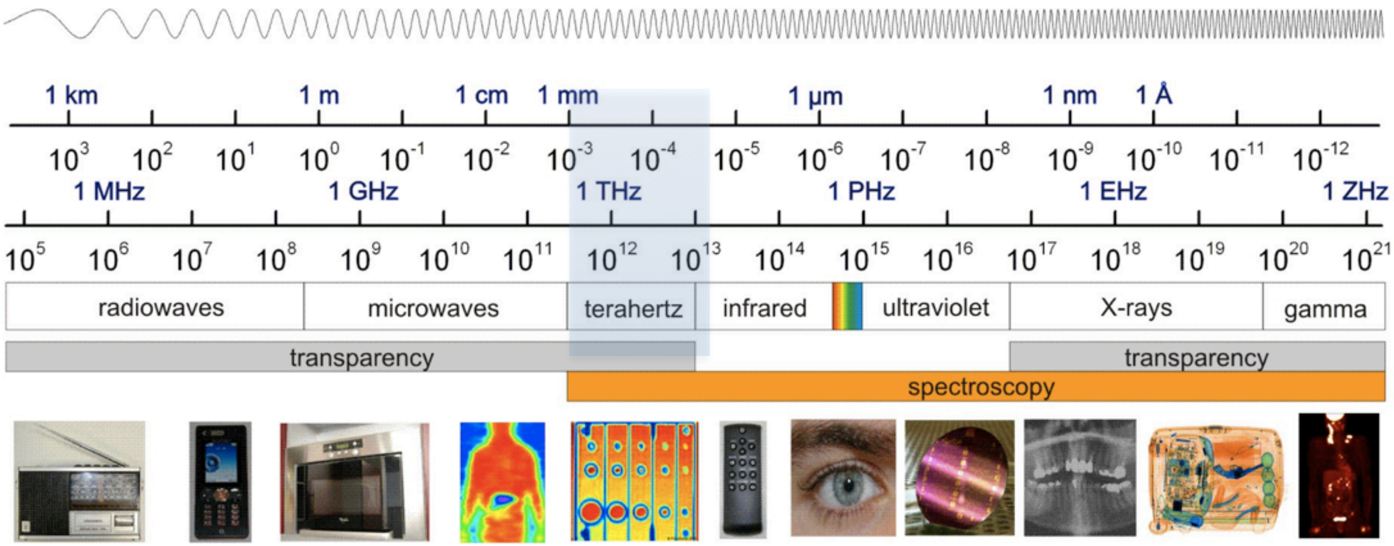
ENGINEERING OF MICROWAVES, TERAHERTZ AND LIGHT AT LANCASTER UNIVERSITY

Summary

- Properties of the THz radiation
- Measurement systems
- THz for substance identification
- THz for food analysis
- THz for Medicine
- THz for plasma diagnostic in nuclear fusion
- THz gap
- THz generation

THz radiation



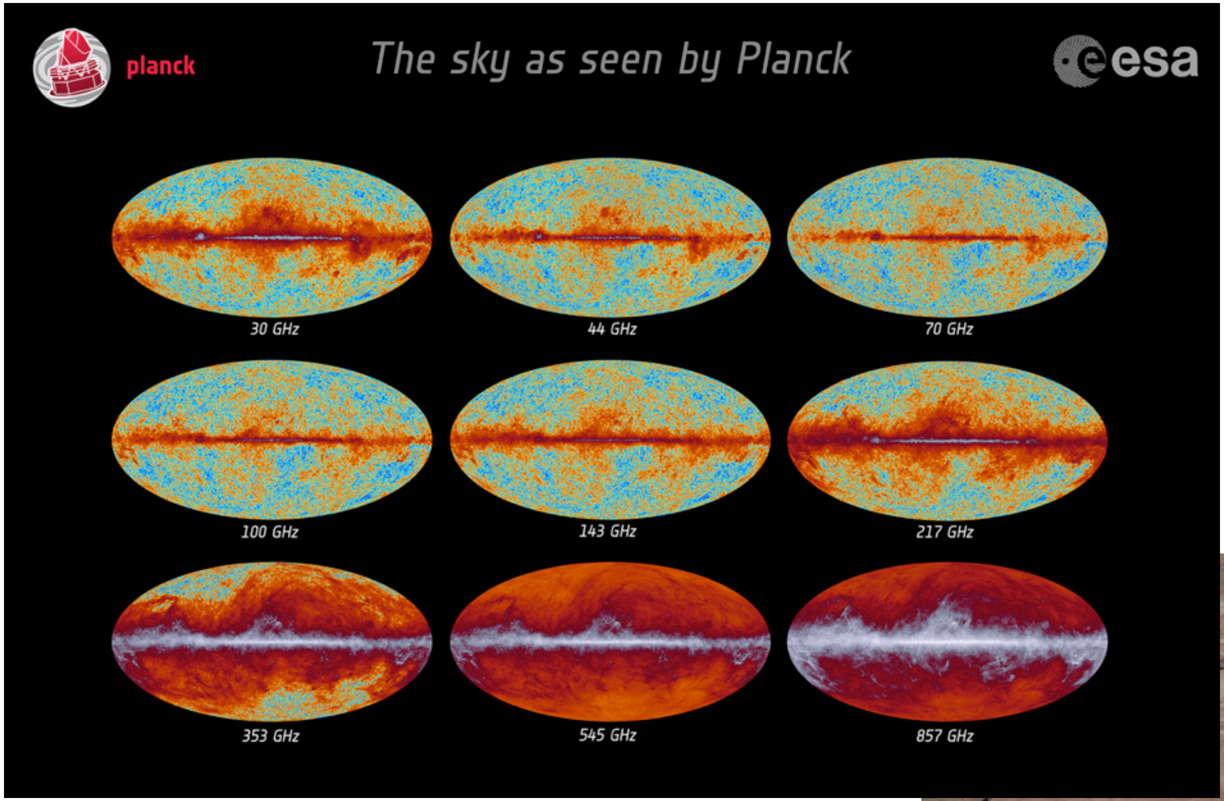
References: Fraunhofer IPM (9), Smiths Detection (1), Forschungszentrum Rossendorf (1)

Significant numbers

- Frequency: $f = 1$ THz = 1000 GHz
- Angular frequency: $\omega = 2\pi f = 6.28\ 10^{12}$ rad/s
- Period: $\tau = 1/f = 1$ ps
- Wavelength: $\lambda = c/f = 0.3$mm = 300µm
- Wavenumber: $\bar{k} = k/2\pi = 1/\lambda = 33.3\ \mathrm{cm}^{-1}$
- Photon energy: $hf = \hbar\omega = 4.14$ meV
- Temperature: $T = hf/kB = 48$ K

where c is the speed of light in vacuum, h is Plank's constant, and kB is Boltzmann's constant

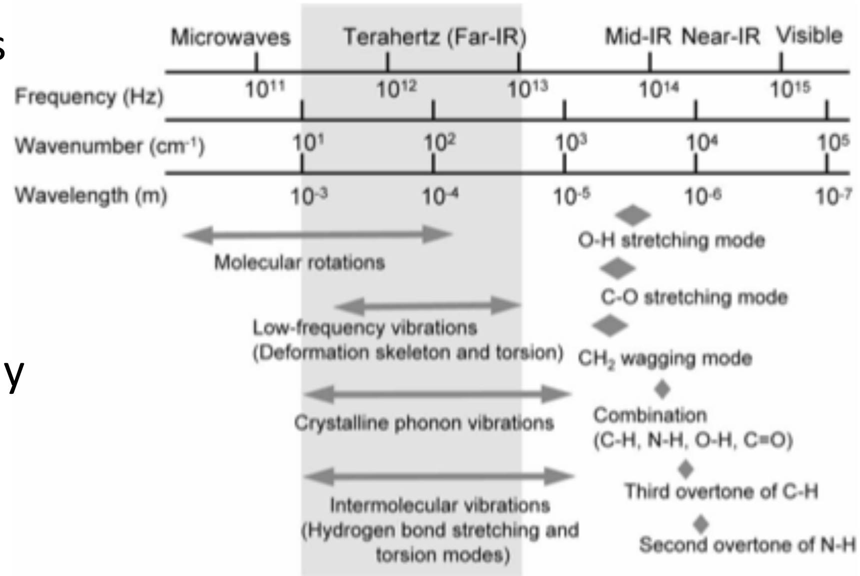
THz radiation in the Universe

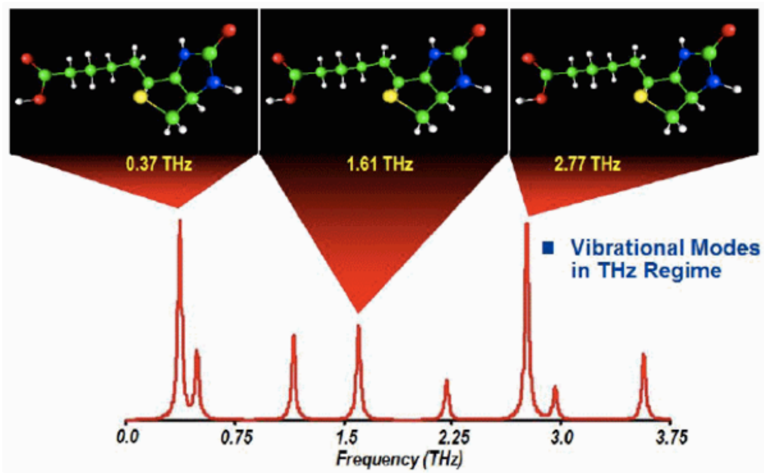


ALMA Atacama Large Millimeter/submillimeter Array

Why Terahertz: Materials

- THz radiation can extract material properties unavailable by using other frequency bands.
- This structural information quite different from all other methods
- The rotational and vibrational modes of many molecules, especially organic ones, are distributed across the THz band.
- These modes can be observed as absorption peaks in the THz spectra, 0.1-10 THz.
- The specific location and amplitude of these absorption peaks can be used to identify the molecules.
- Many chemical substances and explosives exhibit characteristic spectral responses at THz frequencies





Why Terahertz: Penetration

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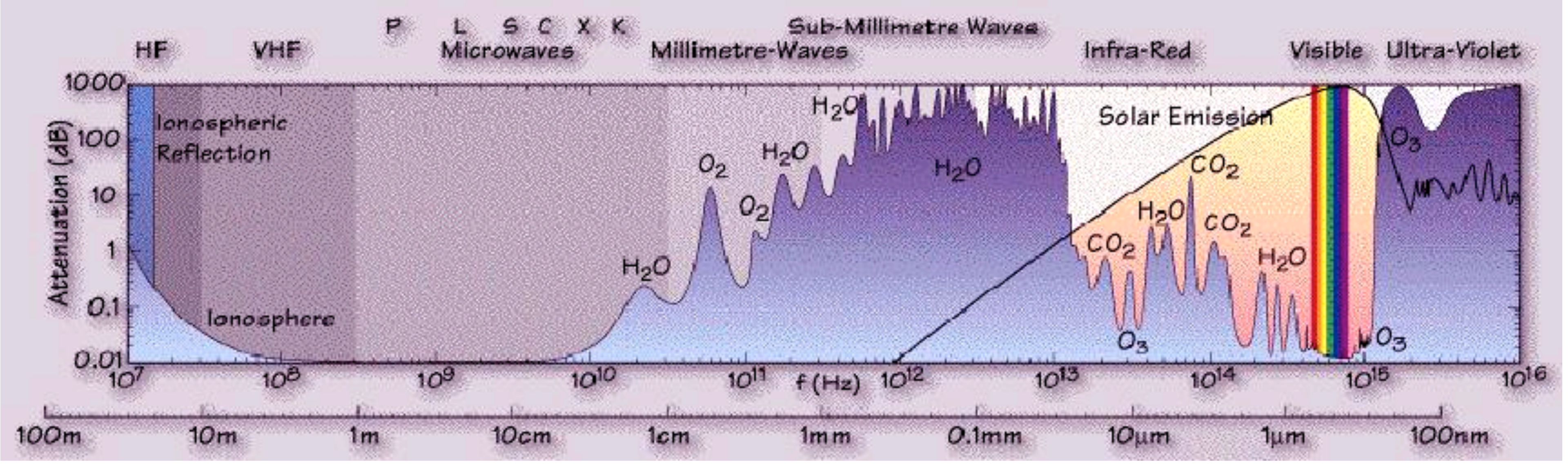
- THz radiation can penetrate materials such as paper, cardboard, clothes, plastics and others.
- This property allows by THz waves inspecting samples that are under cover or inside non-optically transparent containers.
- Infrared waves can provide much better resolution than THz, but cannot see through covers.
- Because the wavelength of THz waves is in the range of mm to tens of microns, THz images of macroscopic objects provide a good level of details and localized data.
- The resolution is higher compared to microwaves.

(Image courtesy by tera view Ltd.)

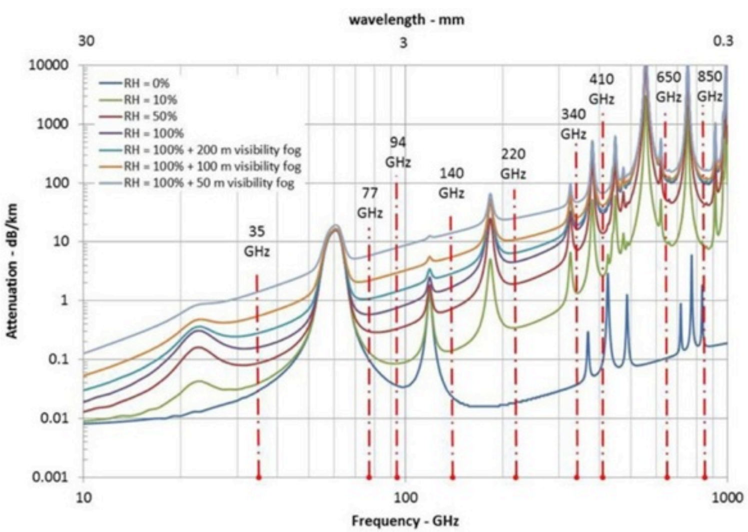
- THz radiation is not ionizing (1THz: about 4meV – X-ray: 100000eV): low risk for health
- THz radiation is very sensitive to water content:

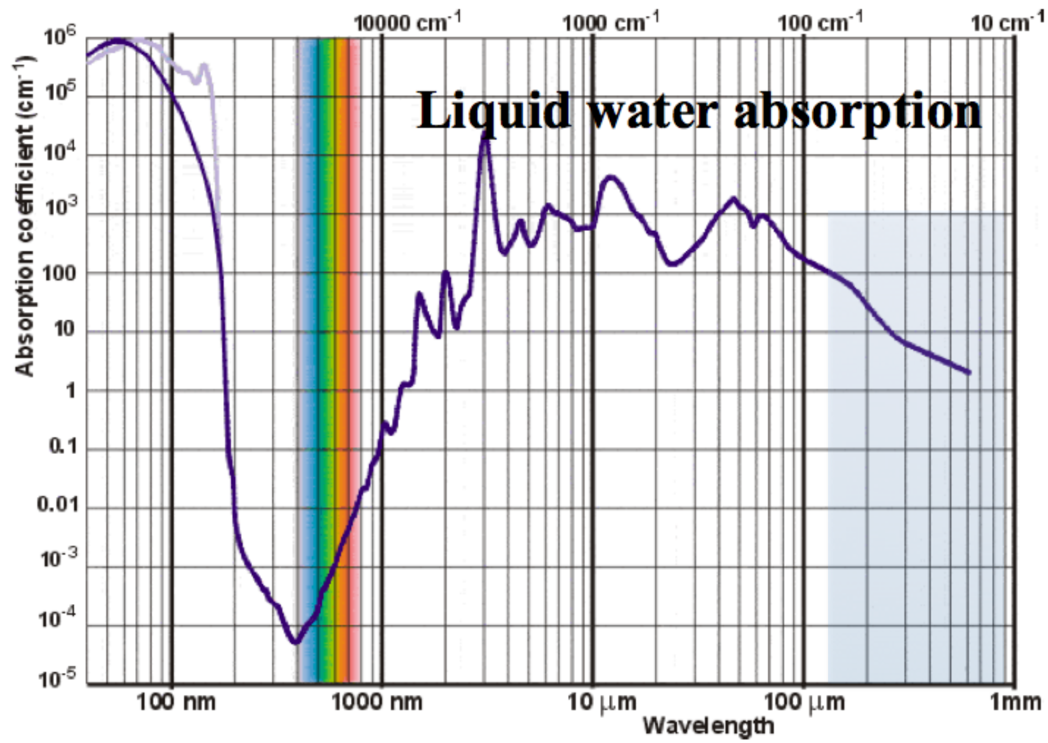
  critical for propagation in atmosphere, important for biology



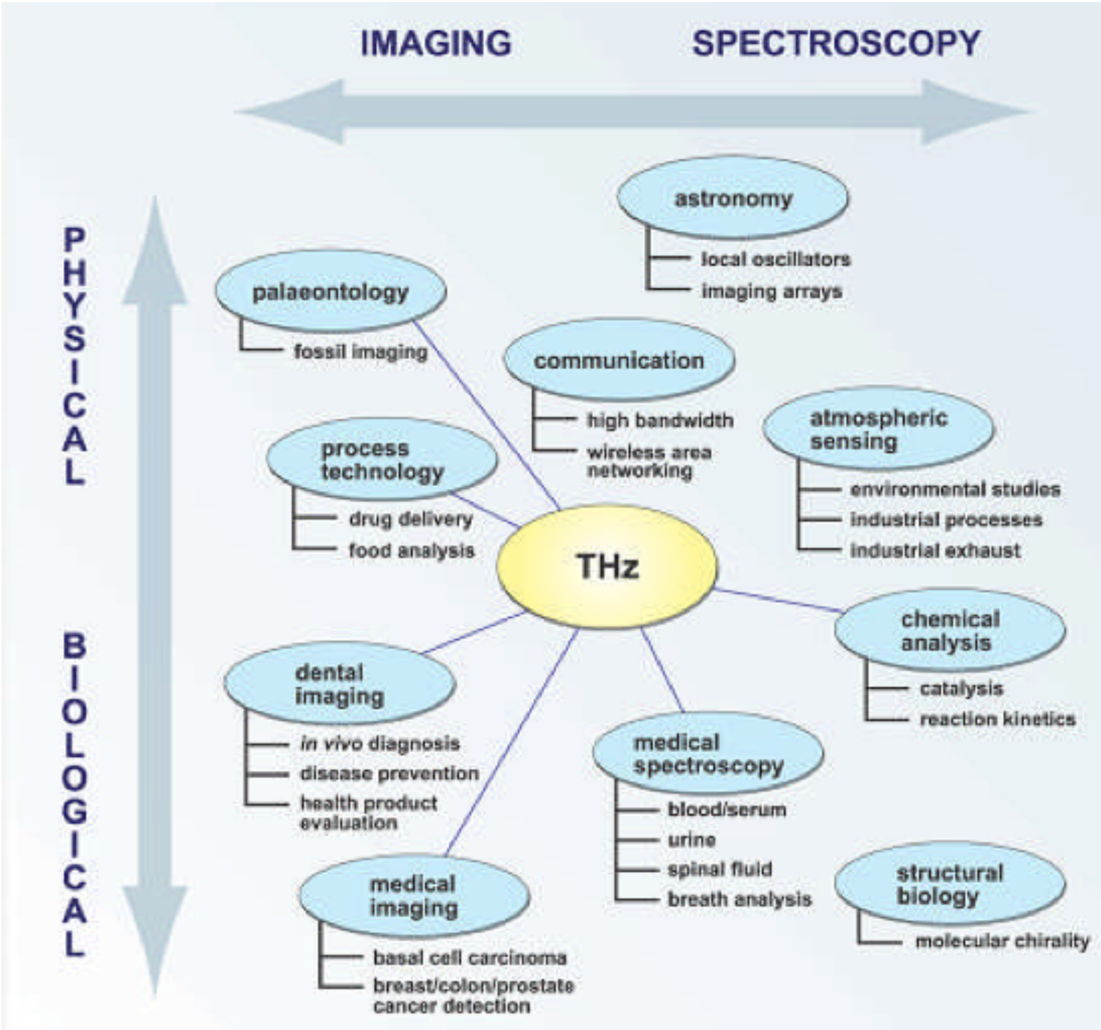
Why Terahertz: Propagation

- Less water absorption (at least two orders) compare to IR and far-IR.
- Less overlap with water or other analytes absorption bands. Liquid samples can be characterized.
- Absorption bands are more narrow in the THz range than in the IR and overlapping of neighbouring bands
- Spectra are more species specific





THz applications overview



J. Cunningham, "Chapter 3: Application of THz-TDS" ELEC5450 Terahertz Technology. University of Leeds.

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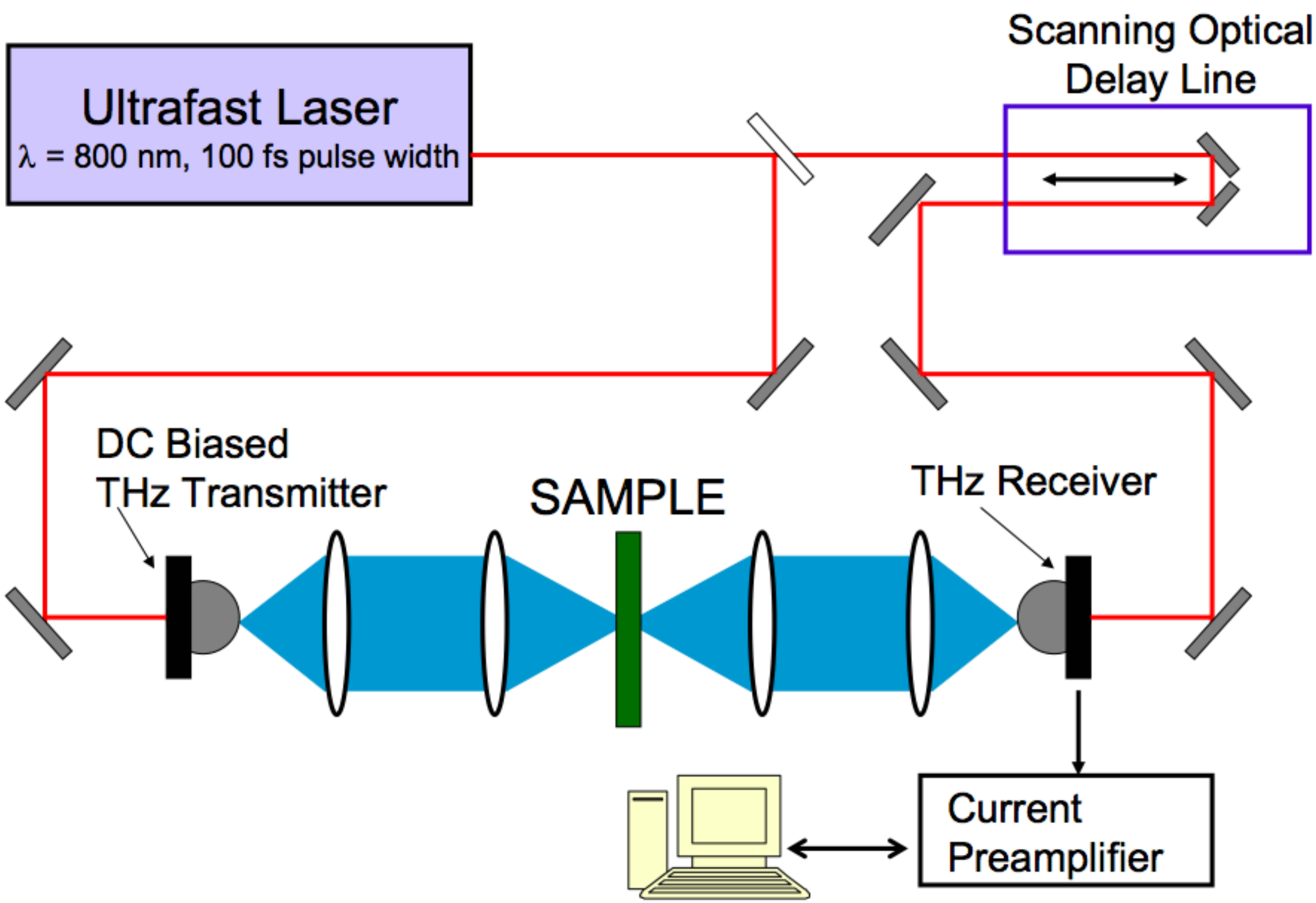
Continuous wave systems

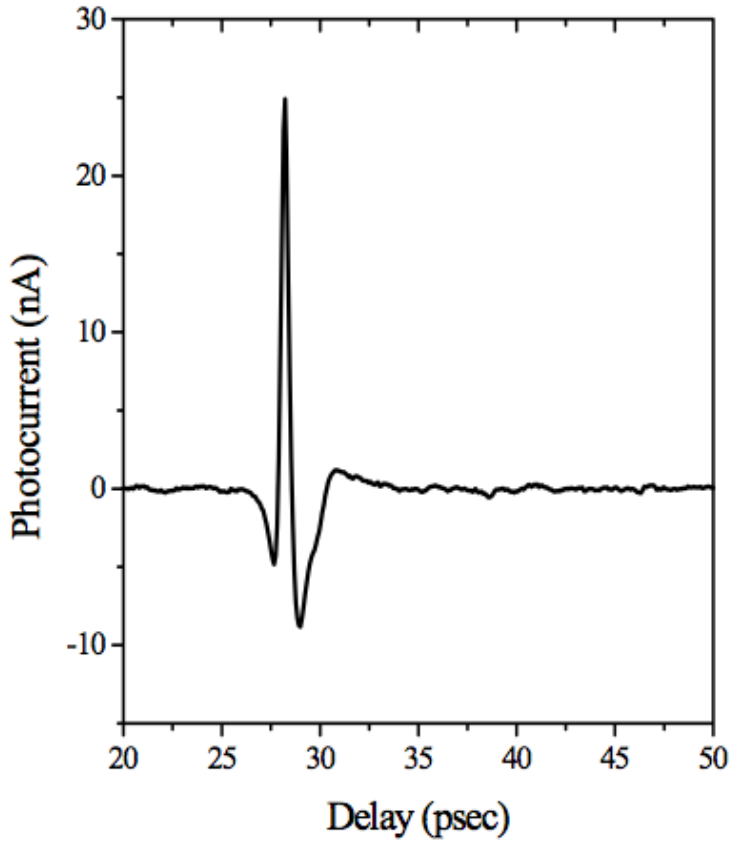
- CW systems operate at a single frequency and emission is continuous or modulated.
- CW systems are narrowband and, often, they have a limited tunability but have high spectral resolution (~10 MHz).
- Provide higher THz output powers than pulsed sources.
- Very sensitive using heterodyne receivers
- Applications: telecommunications, non- destructive testing (NDT), healthcare.
- CW systems can be active or passive.
- A passive system detects the radiation emitted by the sample under test
- An active system illuminates the sample and detects the reflected or transmitted radiation.
- Very fast data acquisition

Pulse system

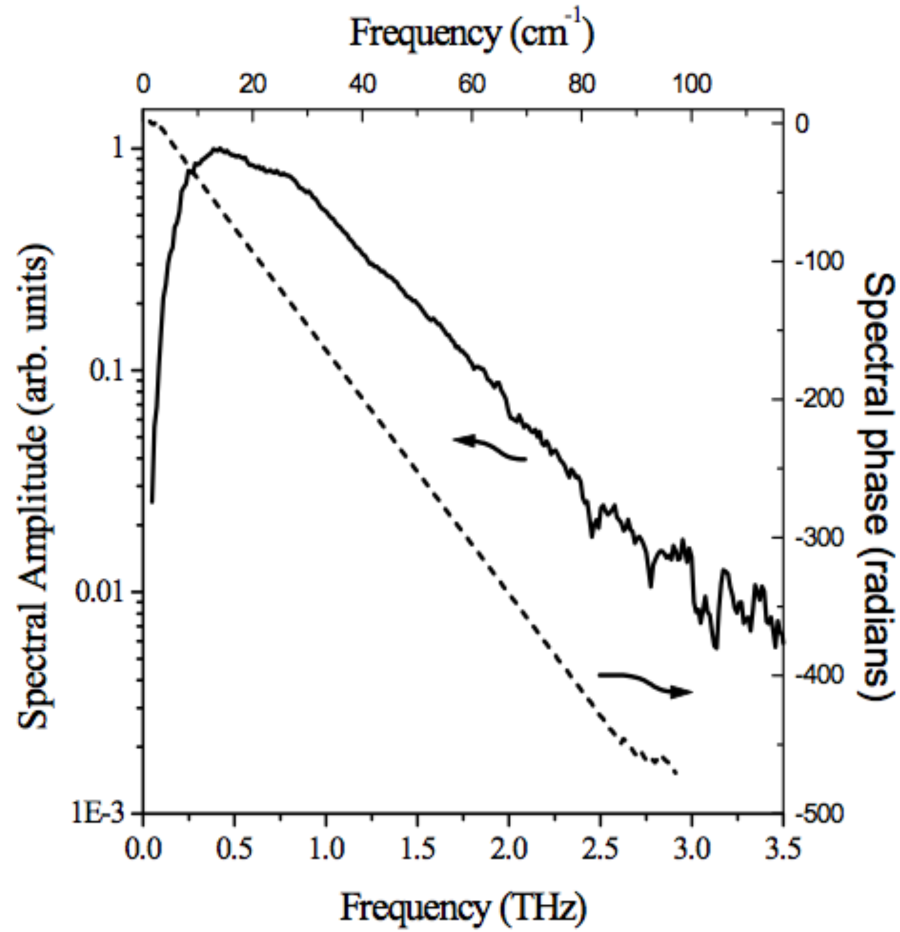
- Based on the generation and detection of an electromagnetic transient of few picoseconds duration.
- The short pulse is made of many frequencies, available by a Fourier Transform of the pulse.
- Pulsed systems are broadband and emission is not continuous.
- Applications: spectroscopy and the study of ultrafast phenomena.
- Pulsed systems are active systems only.
- Low power
- Depth and thickness information

The apparatus for TDS



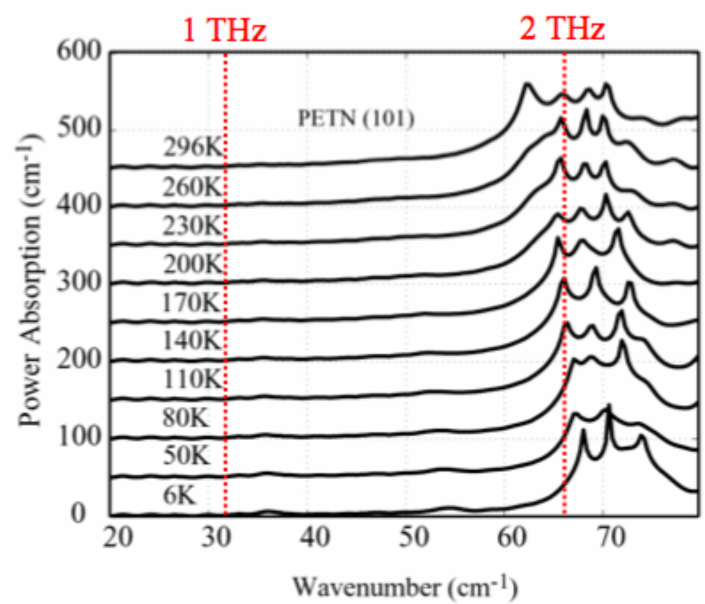


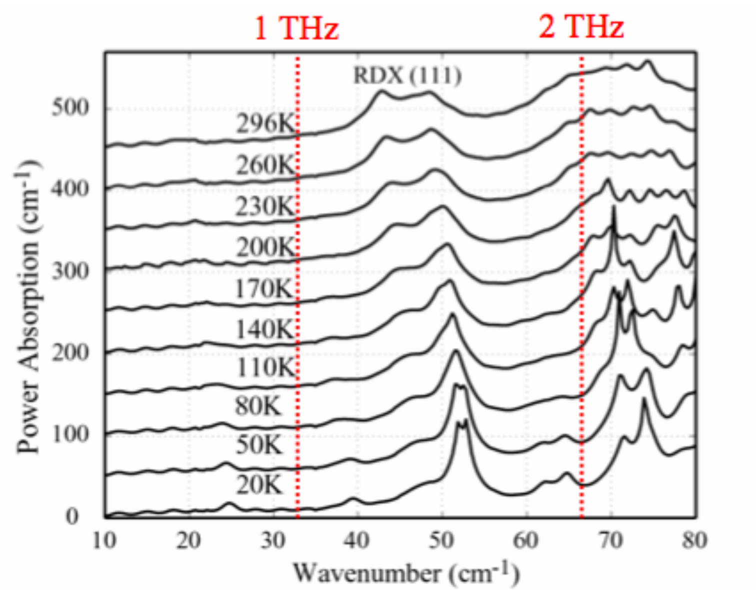
Time - Domain



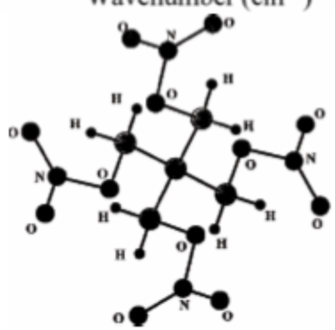
Frequency Domain

THz spectra of "energetic materials"

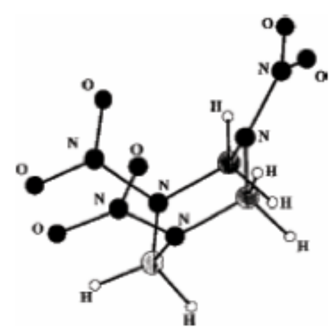




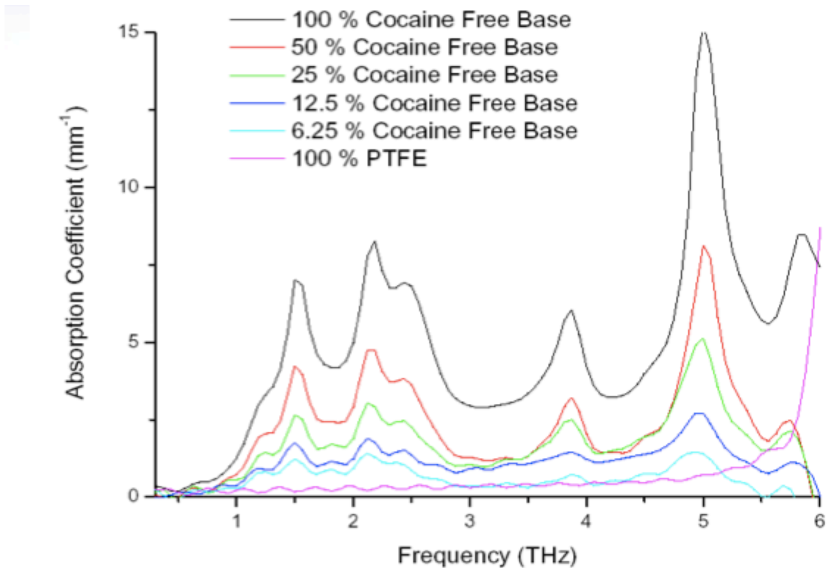
PETN
$C_5H_8N_4O_{12}$

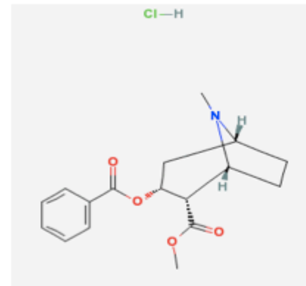


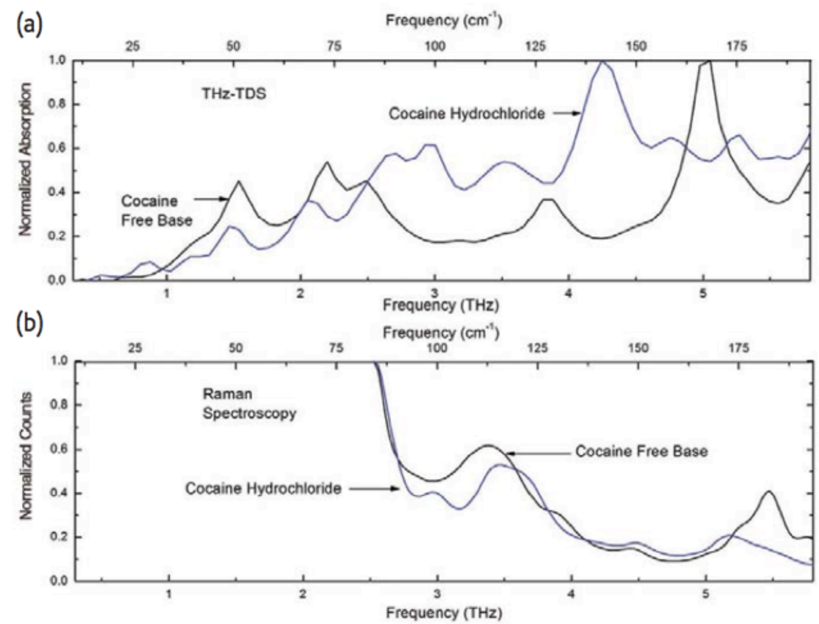
RDX
$C_3H_6N_6O_6$



R. Averitt and T. Taylor, LANL

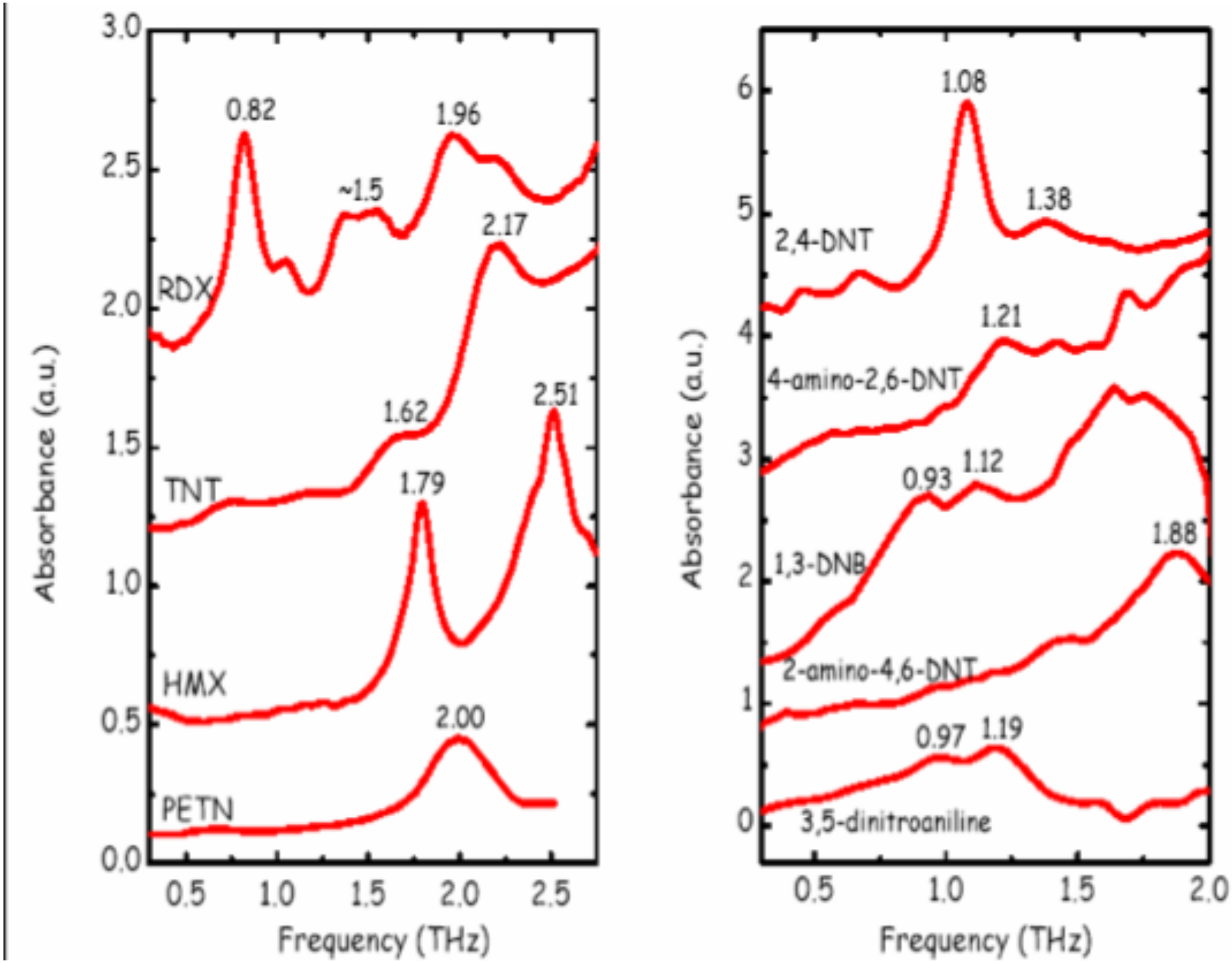


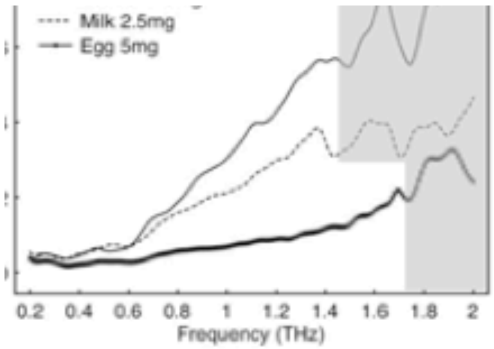




A. G. Davies,, Materials Today, Volume 11, Issue 3, March 2008,

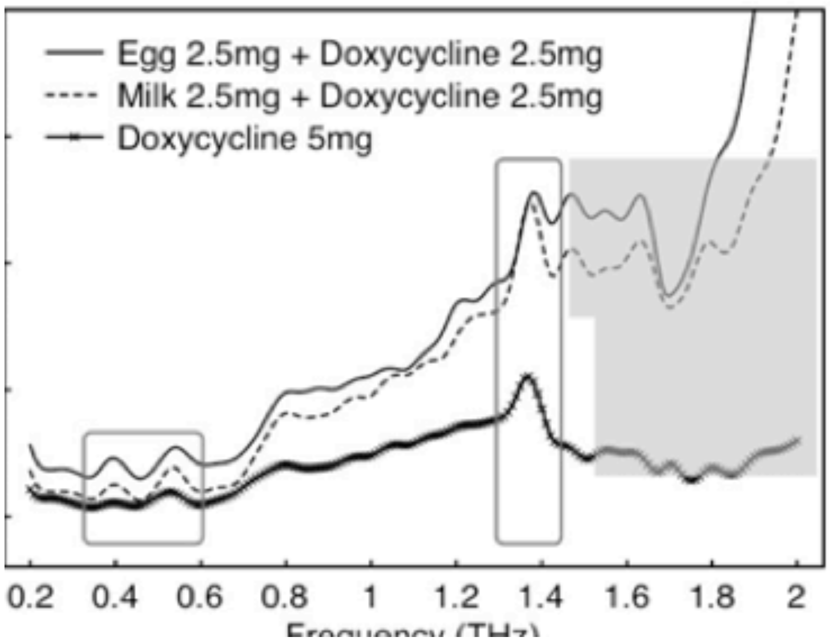
THz for substance identification

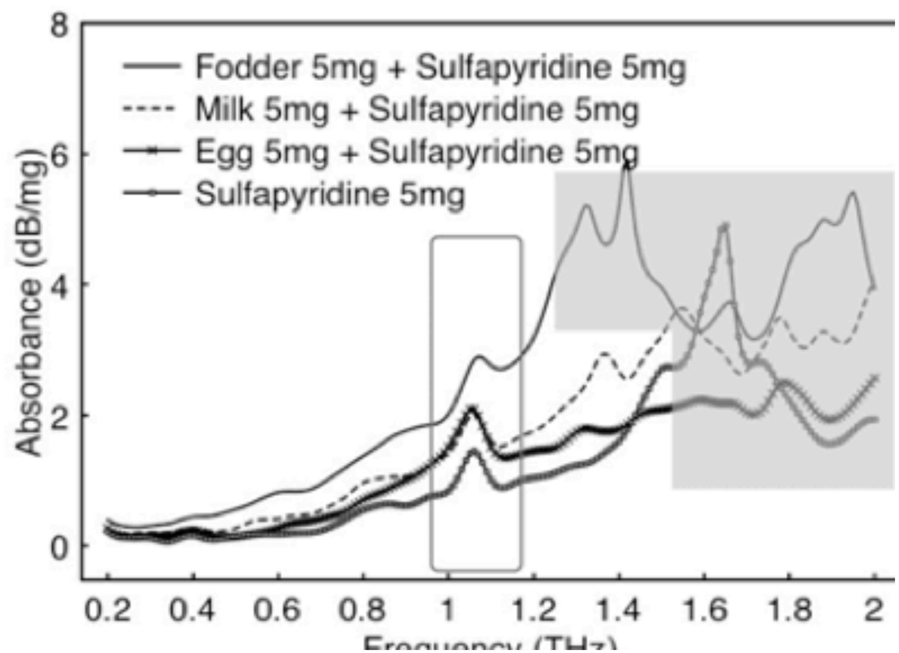




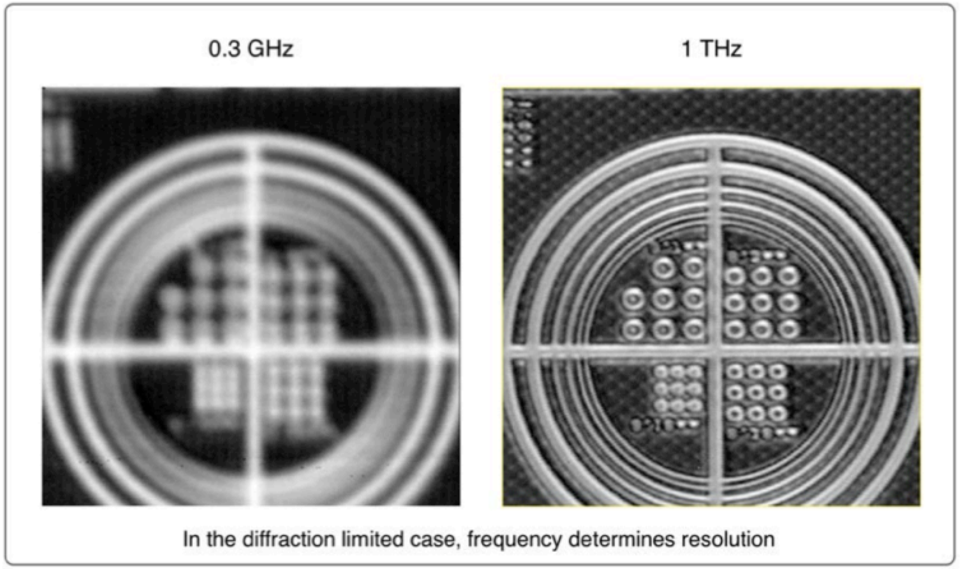
- ✓ Doxycycline and sulfapyridine are antibiotics used to treat chickens grown for human consumption
- ✓ Antibiotics can be present in chicken derived products and mixtures
- ✓ Antibiotics fingerprints can be identified in highly scattering food matrices

Courtesy of University of Barcelona



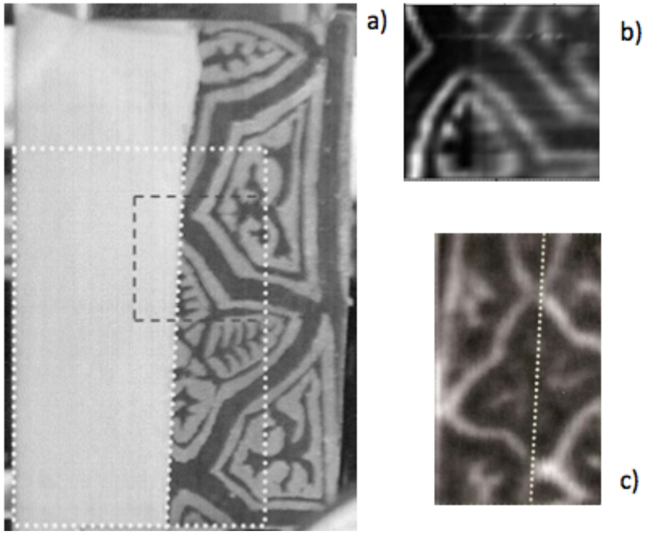


THz for Imaging



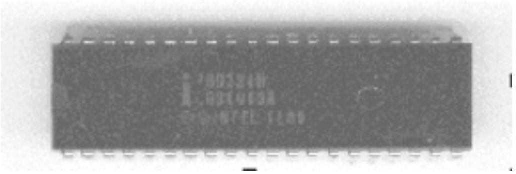
In the diffraction limited case, frequency determines resolution

Resolution
Diffraction limit at 1 THz about 300 μm

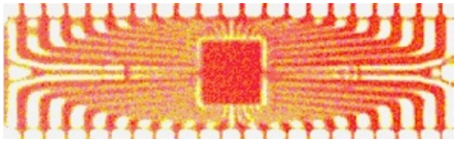


Images at different depths

Gallerano, THZ APPLICATIONS IN ART CONSERVATION AT ENEA



visible



THz

W. L. Chan, IOP Rep. Prog. Phys. **70** (2007) 1325–1379

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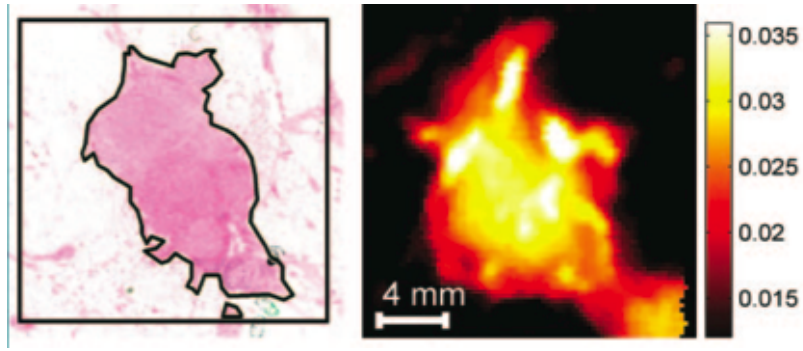
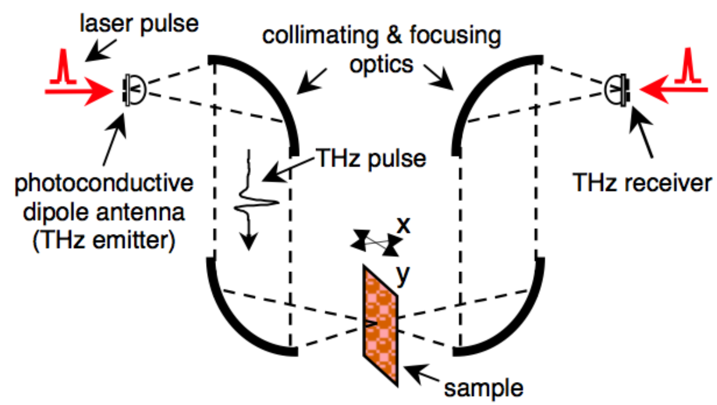
- Terahertz wavelengths are longer than infrared and optical radiation.
- Scattering in biologic tissue is small.
- The wavelength is sufficiently short that a submillimeter lateral resolution of more than 200 μm at 3 THz is readily achievable with an axial resolution of 40 μm (3).
- Terahertz radiation is nonionizing; the power levels used do not cause any detrimental effects to dividing human keratinocytes and are many orders of magnitude lower than those in the recommended safety guidelines.
- The technique has a very high signal-to-noise ratio because of efficient elimination of the background noise



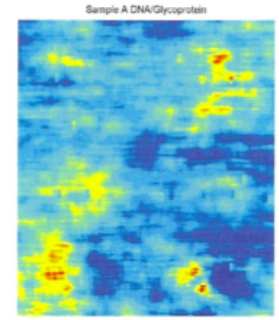
Invasive ductal carcinoma
Radiology: Volume 239: Number 2—May 2006

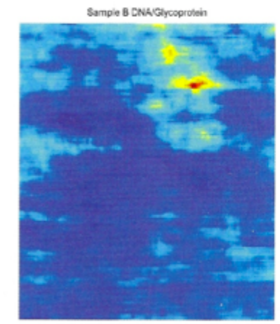


THz for Medicine

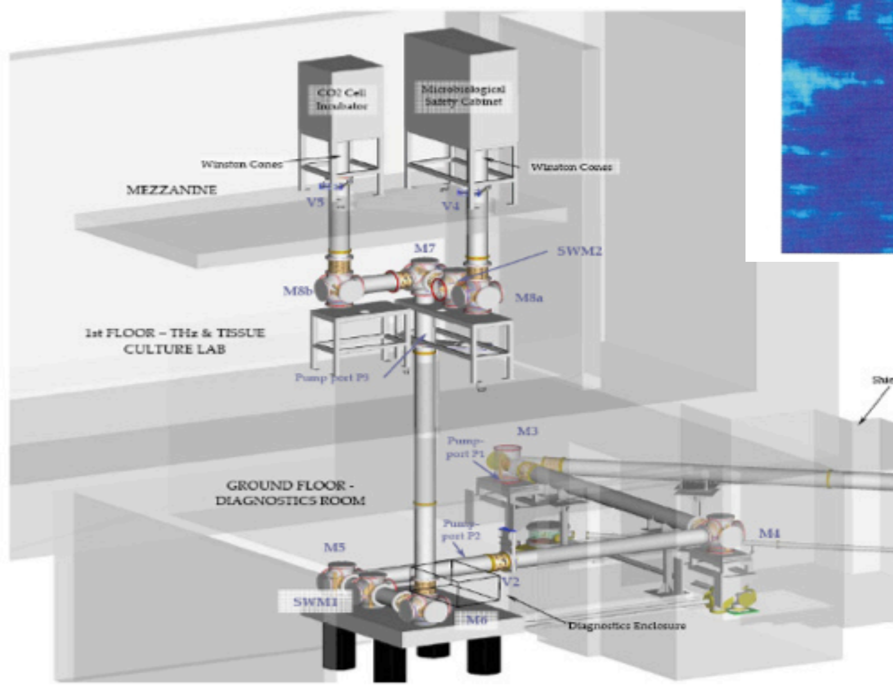
Professor Peter Weigthman (Liverpool) is leading a research by the THz beamline and tissue culture facility (TCF) on ALICE at Daresbury, an energy recovery linear accelerator, based on superconducting technology.

- Frequency < 0.5 THz
- Peak power 70kW
- Average power of micropulse 23mW.



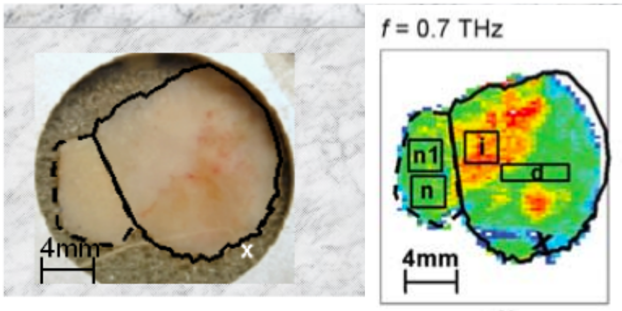


The instrument permit to reveal in extraordinary detail, the character and chemical processes that underlie the malignant behaviour of oesophageal cancer, which will mean real developments in diagnosis and the development of therapies.



THz for Medicine

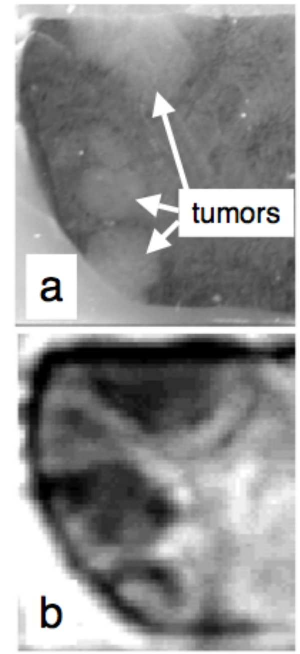
Basal cell carcinoma (Teraview)



Visible THz malignancy in d

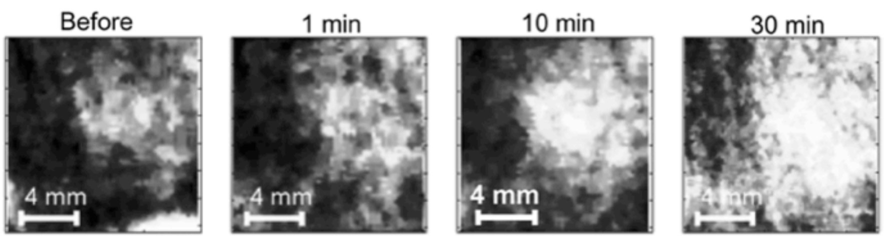
Journal of Biological Physics **29:** 257–261, 2003.

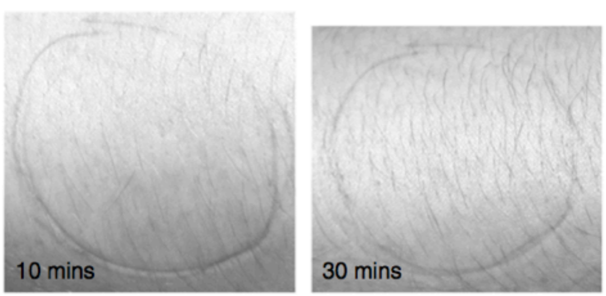
Optical image of the liver sample



THz transmission image of the sample for a window from 0.2 to 1.0 THz.

Proc. SPIE Vol. 4434





THz detection of subcutaneous oedema

P Taday and M Pepper, Teraview Ltd

THz for plasma diagnostic in nuclear fusion

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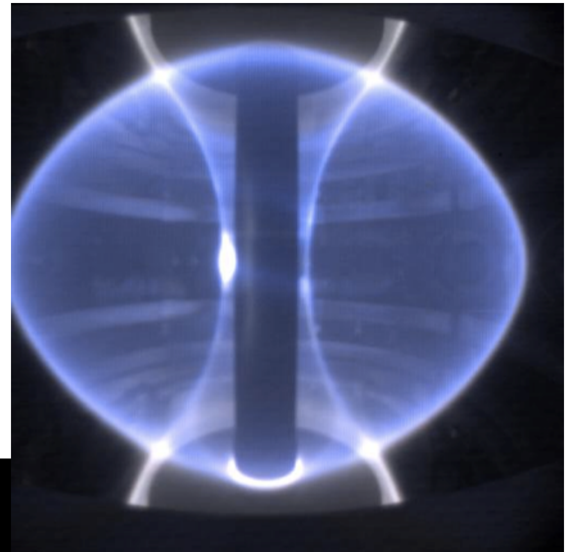
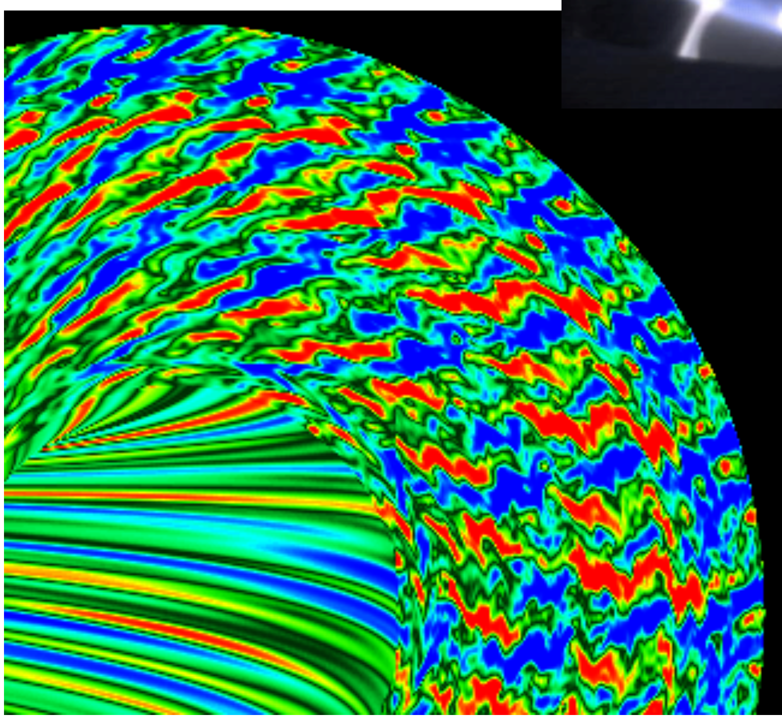
Nuclear fusion is a unlimited source of energy

Plasma turbulence is a serious issue that can degrade or stop the fusion process



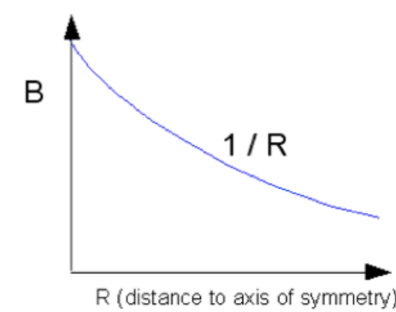


CCFE, UC Davis

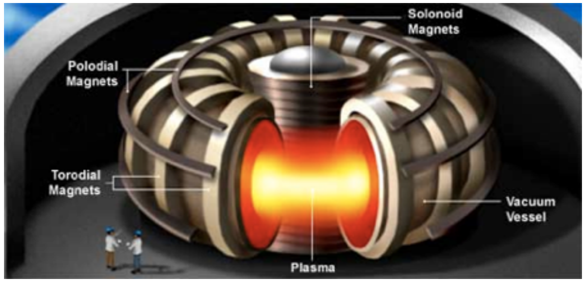
For magnetic fusion devices such as tokamaks and stellarators, the magnetic field ranges from 2 to 8 T.
Electron Cyclotron Emission radiation is in the range ~50 GHz to 0.5 THz

$$\omega_{ce} = |e| \cdot B/m_e$$

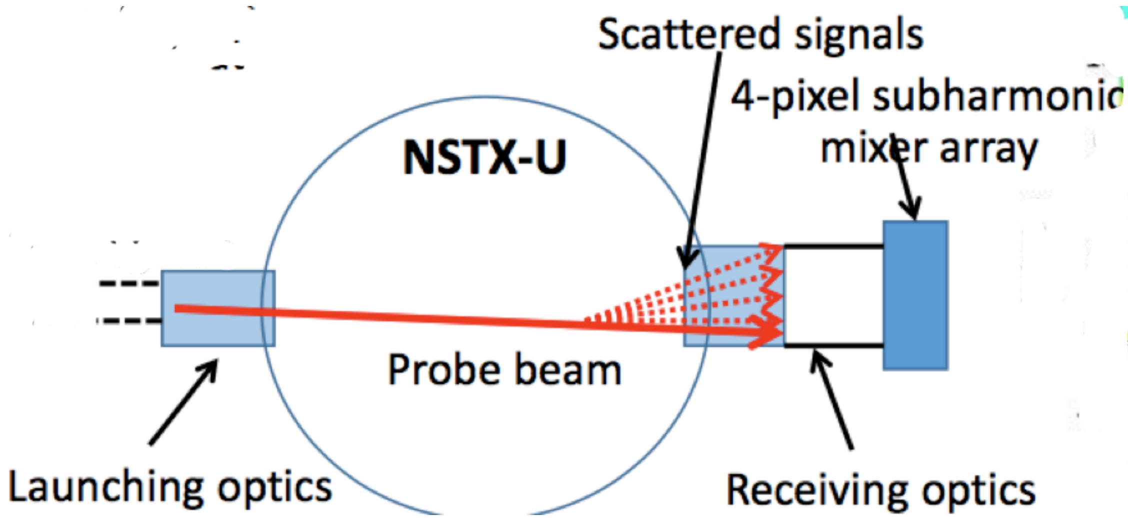
ECE frequency is a monotonically decreasing function of plasma radius toward the outboard side. Each frequency corresponds to a particular horizontal position.



Intensity of the magnetic field as a function of the radius



Thomson scattering to detect density fluctuations of the plasma.
Radiation (k_i) incident on density fluctuations (k) scatters a small amount of power (k_s)



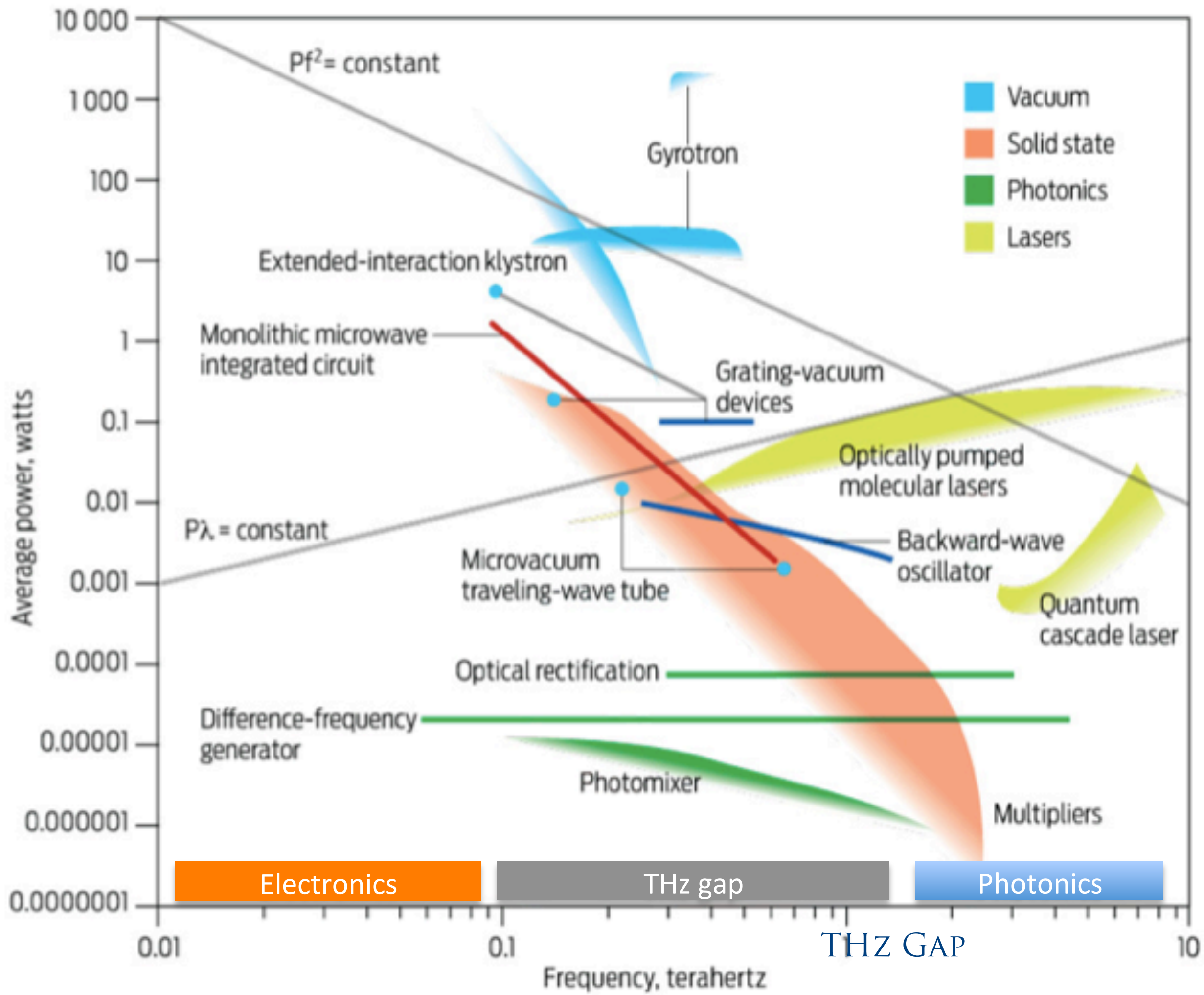
$$\vec{k}_s = \vec{k}_i + \vec{k}$$

$$\omega_s = \omega_i + \omega$$

UC Davis

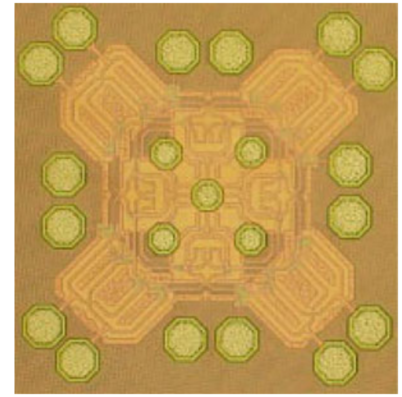
The UK Engineering and Physical Sciences Research Council (EPSRC) funded project “THz backward wave oscillator for plasma diagnostic in nuclear fusion”
aims to design a powerful and compact THz source to be used in tokamaks to replace the bulky FIR laser and increase the region of diagnosis

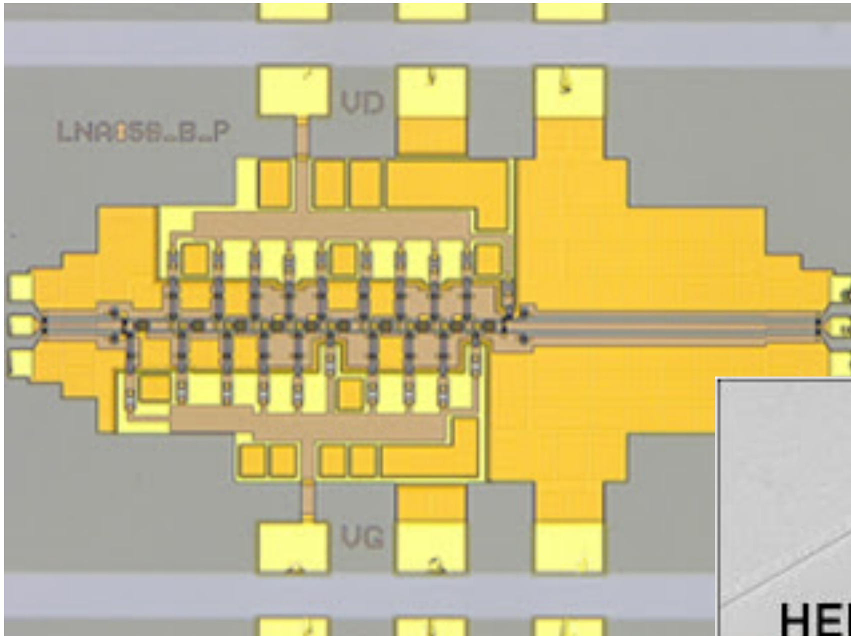
The “THz” gap

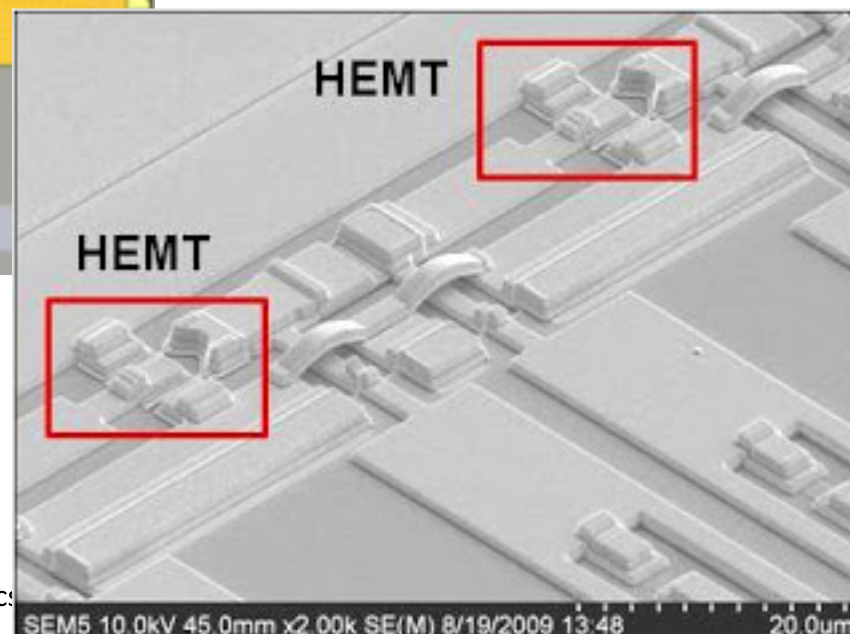


10 000
1000
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
0.0000001
Average power, watts
Pf^2= constant
Gyrotron
Vacuum
Solid state
Photonics
Lasers
Extended-interaction klystron
Monolithic microwave integrated circuit
Grating-vacuum devices
Optically pumped molecular lasers
Pλ = constant
Microvacuum traveling-wave tube
Backward-wave oscillator
Quantum cascade laser
Optical rectification
Difference-frequency generator
Photomixer
Multipliers
Electronics
THz gap
Photonics
0.01
0.1
10
THz Gap
Frequency, terahertz

Solid state: μW of output power up to 0.8 THz





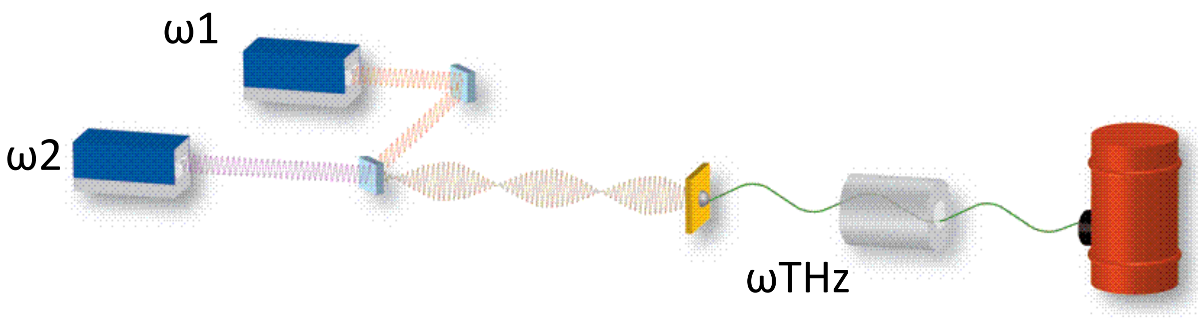


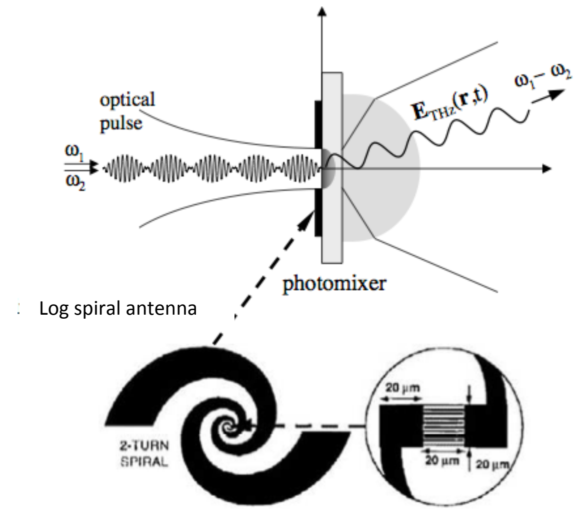
InP HBT and InP HEMT

Deal, Solid--State Amplifiers for Terahertz Electronics

THz generation: photomixing

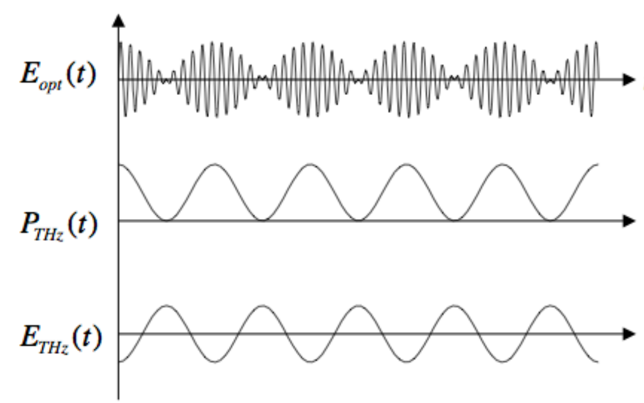
Photomixing: μW of output power above 1 THz and optical-to-THz conversion efficiency is 10^{-6} – 10^{-5}





Photomixing is the generation of continuous wave Terahertz radiation from two lasers. The beams of the two lasers are mixed together to create a beatnote in the THz frequency range.

ωTHz = ω1 − ω2, when ω1 > ω2

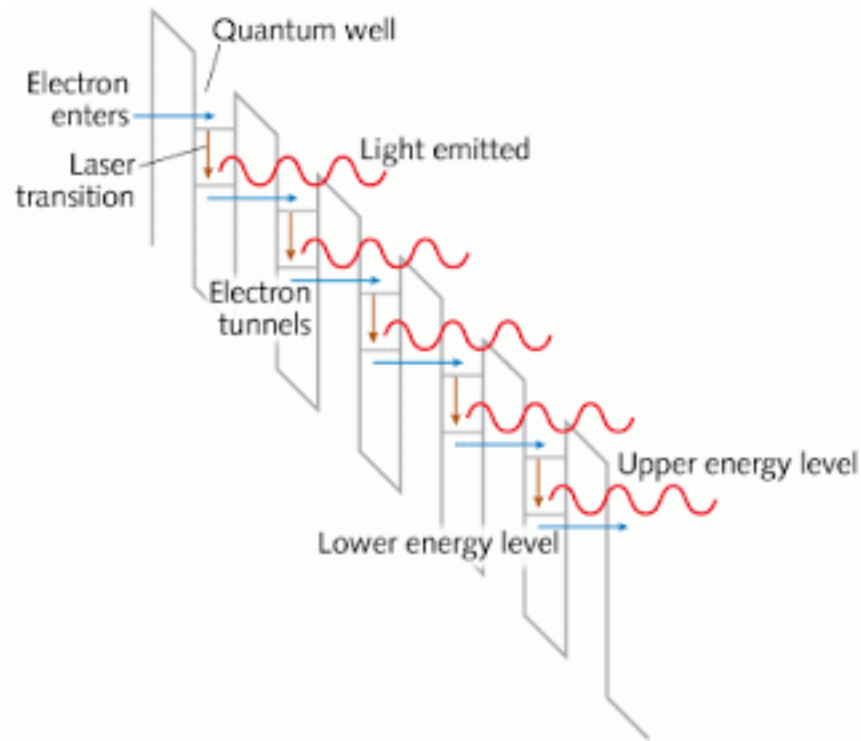


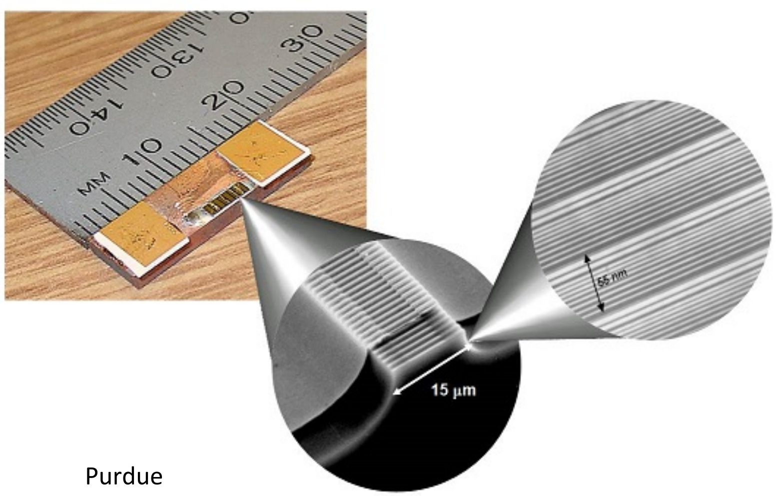
The most common light sources are diode lasers in the spectral range between 800 and 850 nm
A typical photomixer includes an antenna structure of metal on a LT-GaAs layer grown on a SI-GaAs substrate. A silicon hyper-hemispherical lens is attached to the back side of the substrate. A commonly used antenna structure for photomixing is the logarithmic uniplanar spiral antenna (log-spiral antenna) with interdigitated electrode fingers

Quantum Cascade Laser (QCL): μW of output power above 1 THz

A quantum cascade laser (QCL) is a semiconductor heterostructure laser.

It needs cryogenic temperature





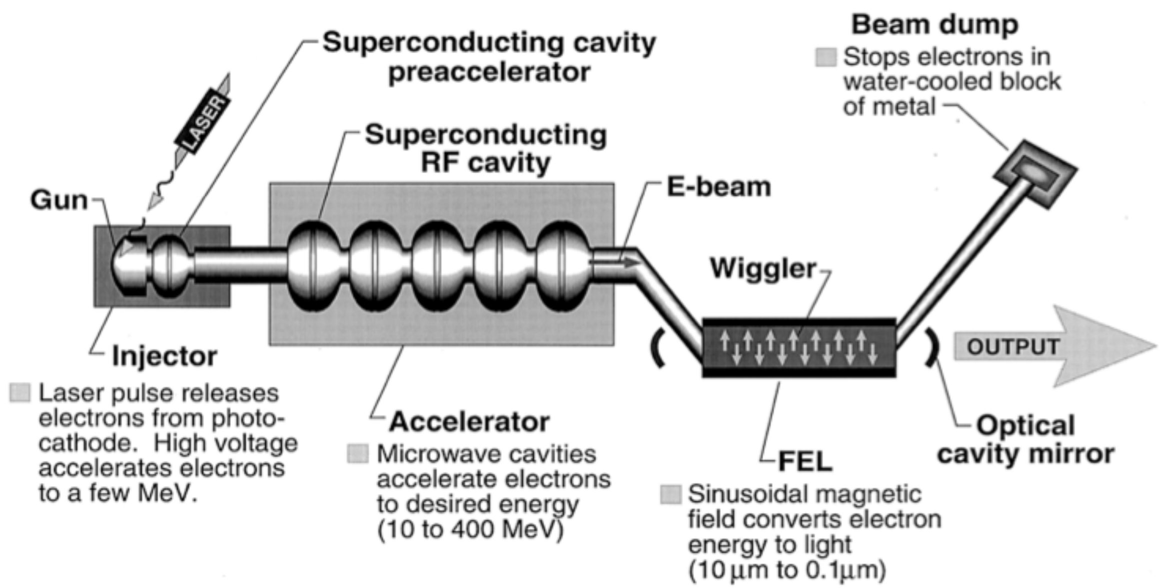
Purdue

Pros: solid state technology
Cons: limited above 1 THz
cryogenic temperature

THz generation: Free electron laser

Free-electron lasers (FELs) use a relativistic electron beam passing through a wiggler

The wiggler consists of a series of magnets arranged to supply periodic, transverse magnetic field, to generate coherent electromagnetic



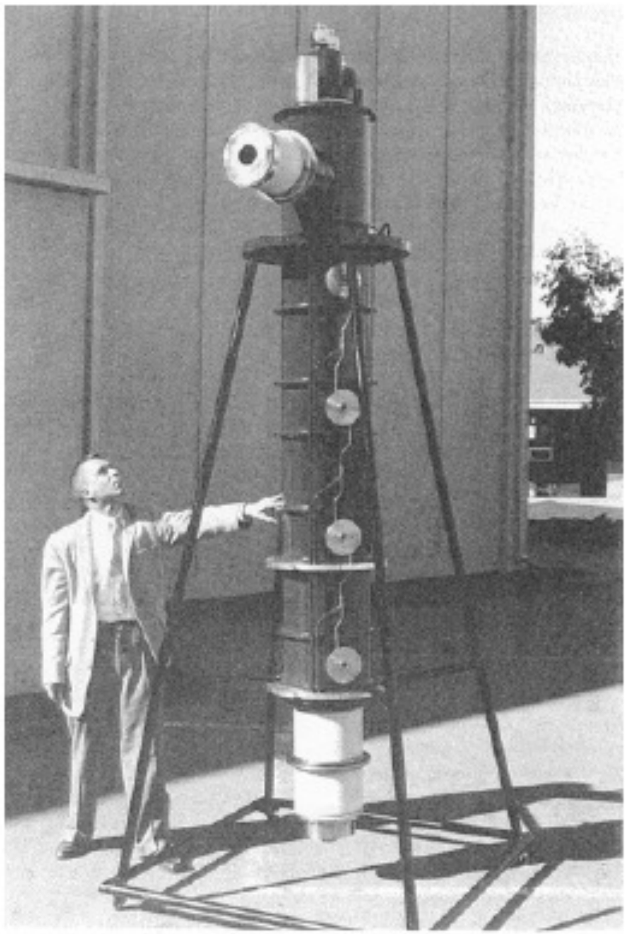
Cons: very bulky

Pros: tunable and high power

PROCEEDINGS OF THE IEEE, VOL. 87, NO. 5, MAY 1999

THz generation: Vacuum electron devices

In the range 0.1 – 1 THz vacuum electron devices are the solution for generating power at Watt level



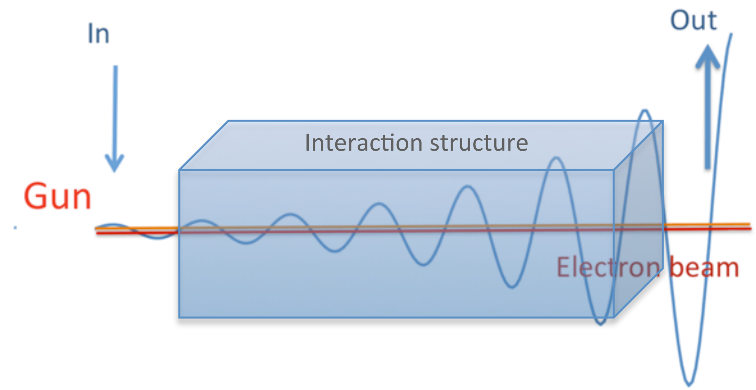
Dimensions are a function of the wavelength:

100 MHz = 0.0001 THz λ = 300 cm

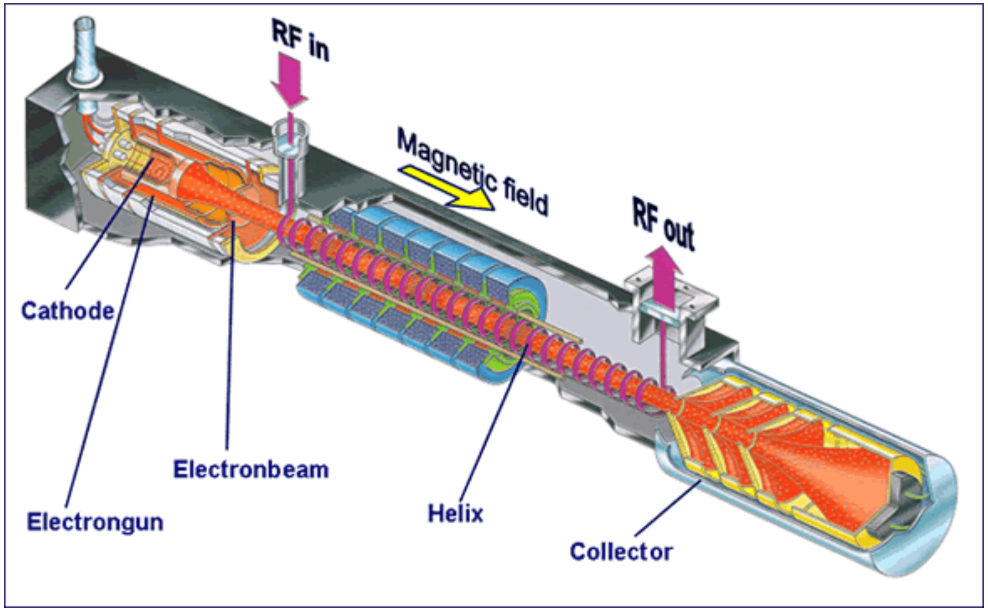
1000 GHz = 1 THz λ = 300 μm

Perfectly scalable.

It depends only if a technology is available



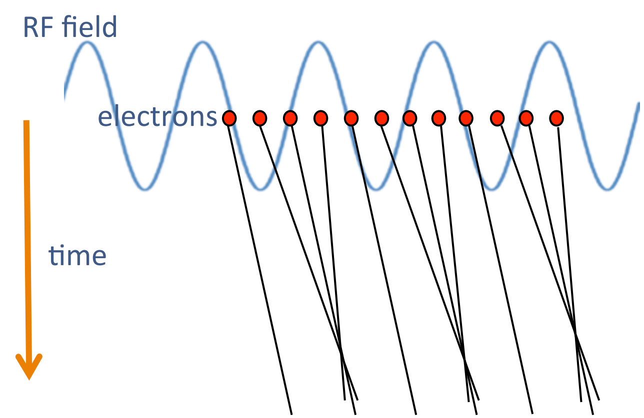
Vacuum electron devices: working mechanism

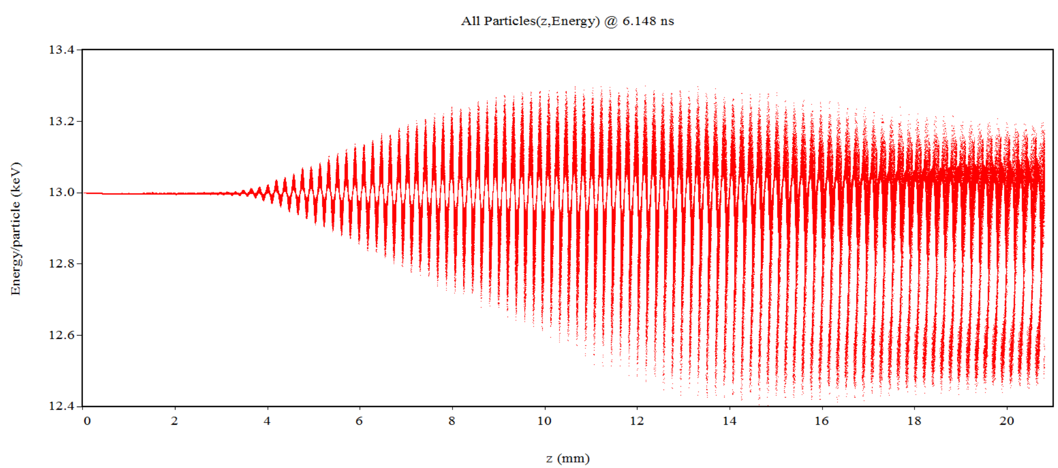


$$v_e \propto V_0 < c \quad (v_e = 5.93 \cdot 10^5 \sqrt{V_0})$$

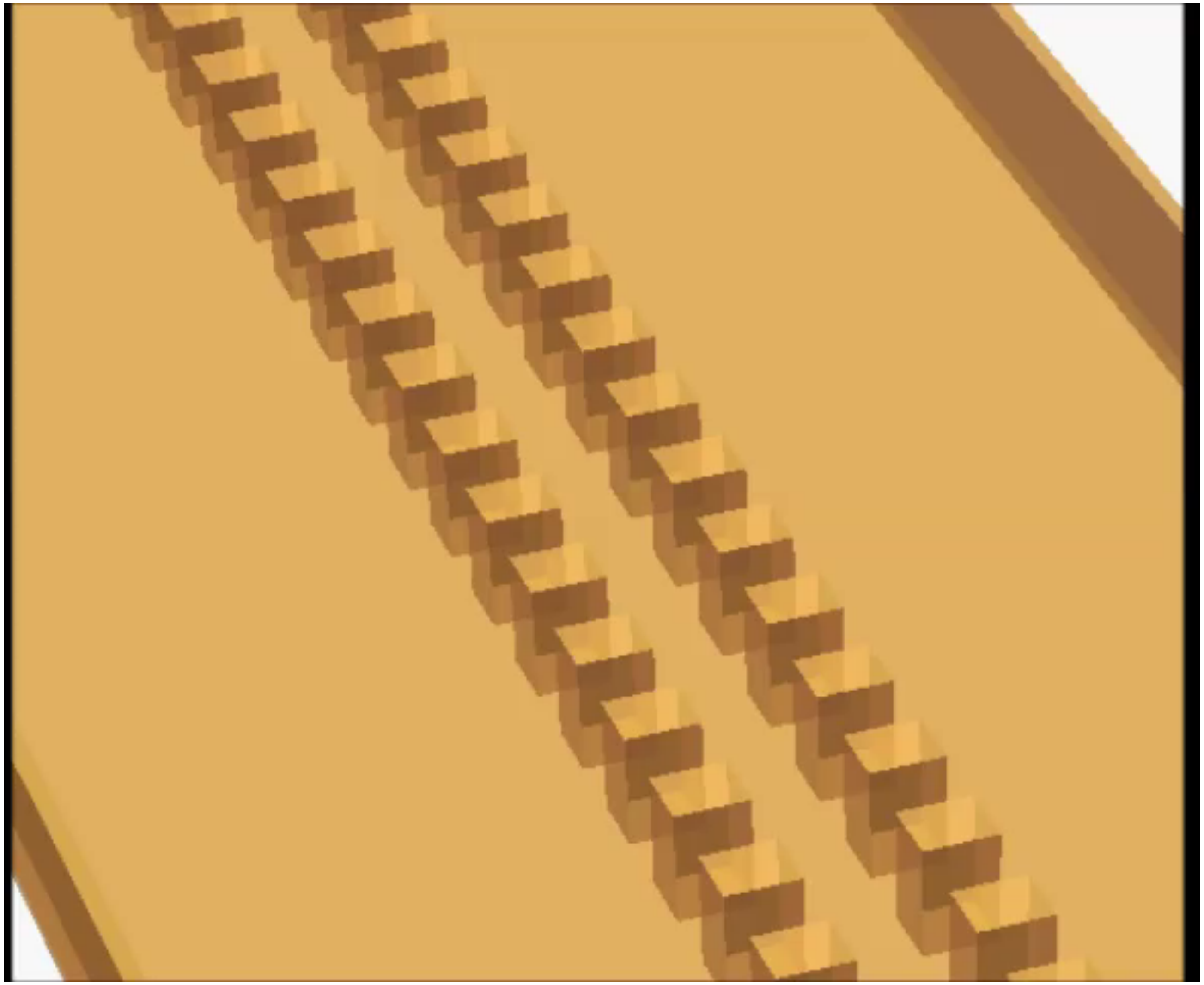
$$v_{ph} \approx v_0$$

Ve = electron velocity





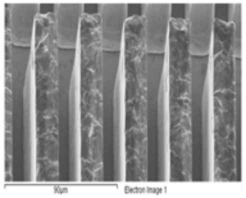
Vacuum electron devices: the bunching



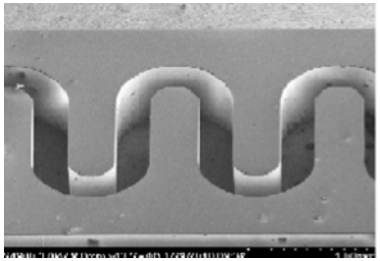
THz vacuum electron devices: challenges

- Fabrication processes with high accuracy and precision at micrometric level
  - Available
- High quality cathode to generate cylindrical electron beam or sheet electron beam with high beam current and narrow diameter
  - Available

- Reliable and repeatable assembly
  - Promising

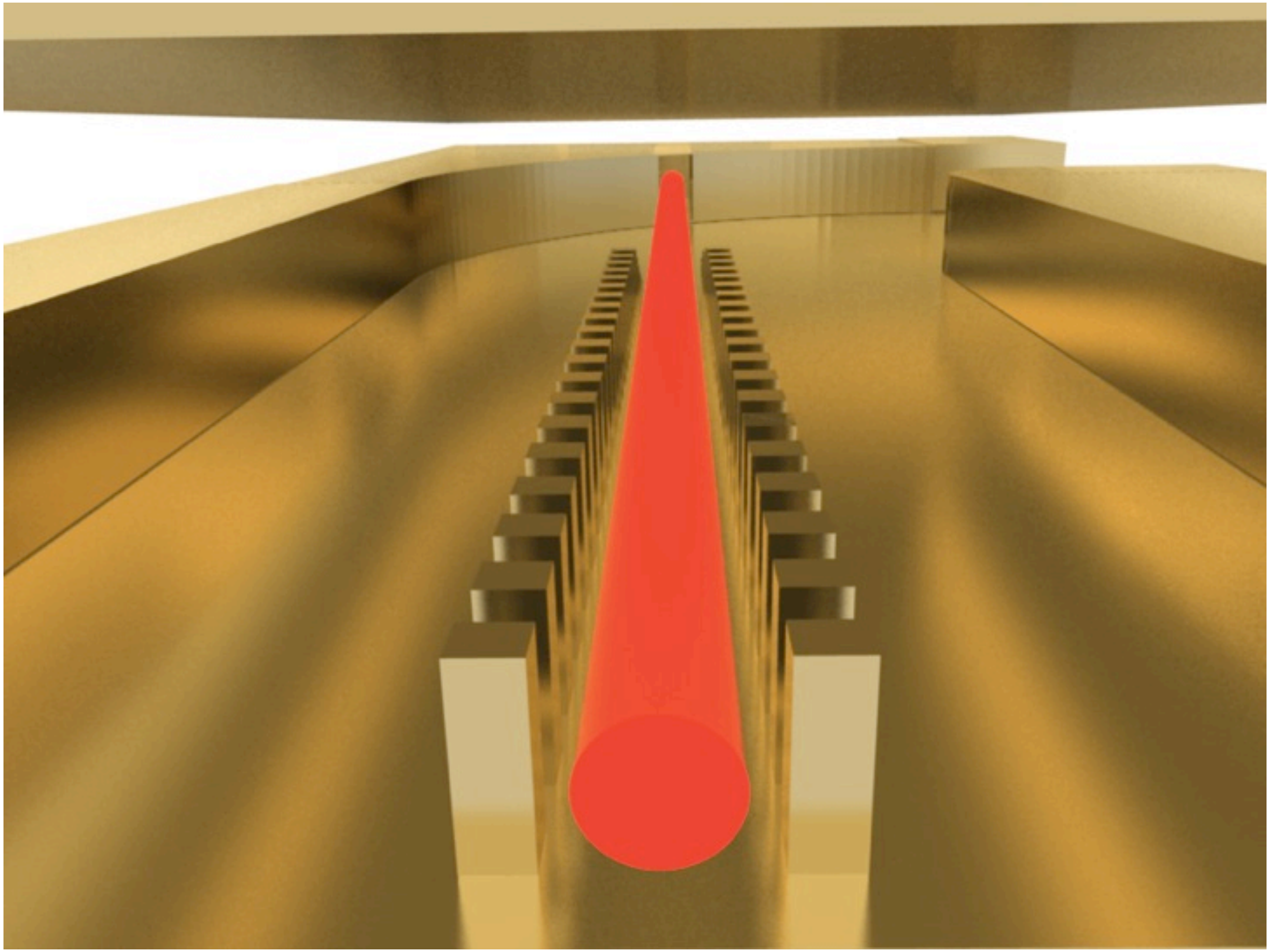


- Low beam voltage e-gun (10-15 kV) for portability
  - Available
- Control of the surface roughness of the metal walls to reduce the losses
  - (100 nm skin depth at 0.6 THz, not more than 50 nm surface roughness)
    - Available



- High vacuum level (10^{-7} Torr)
  - Available

THz SWS: the double corrugated waveguide



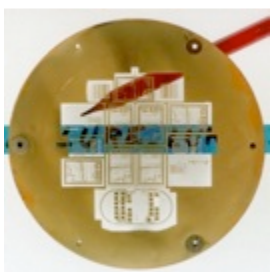
THz waveguide fabrication

DXRL (Deep X-ray Lithography)

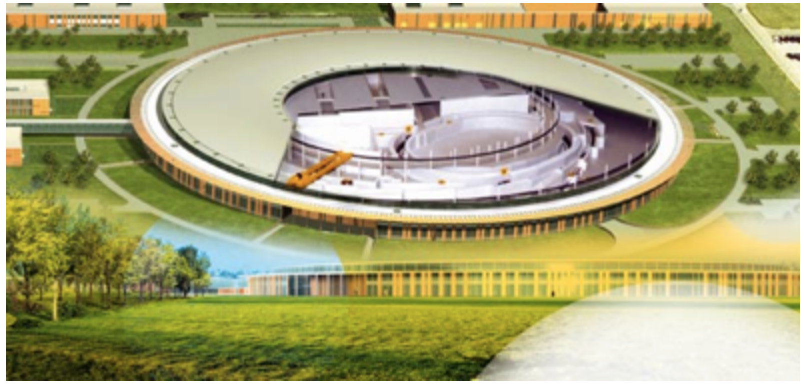
LIGA mask

Gold on Beryllium

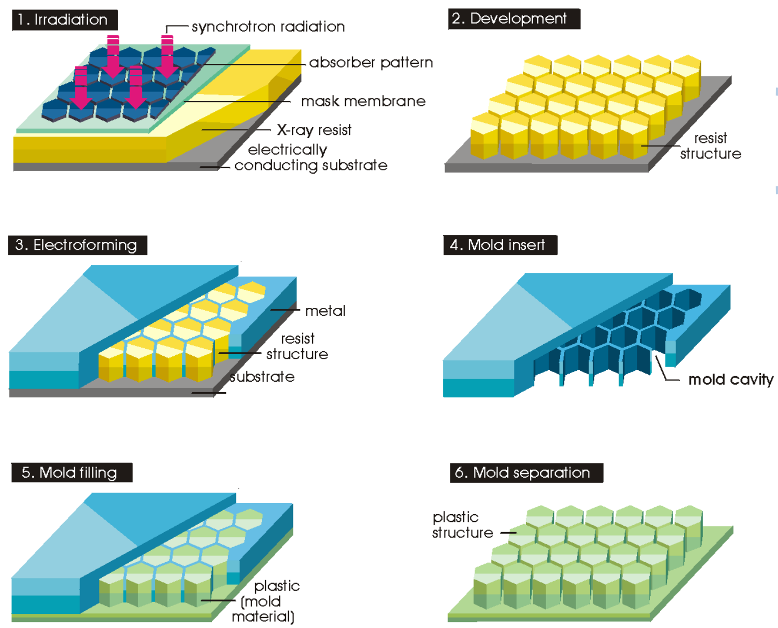
Gold on glass



F 100mm



Soleil Synchrotron



L - lithograpy

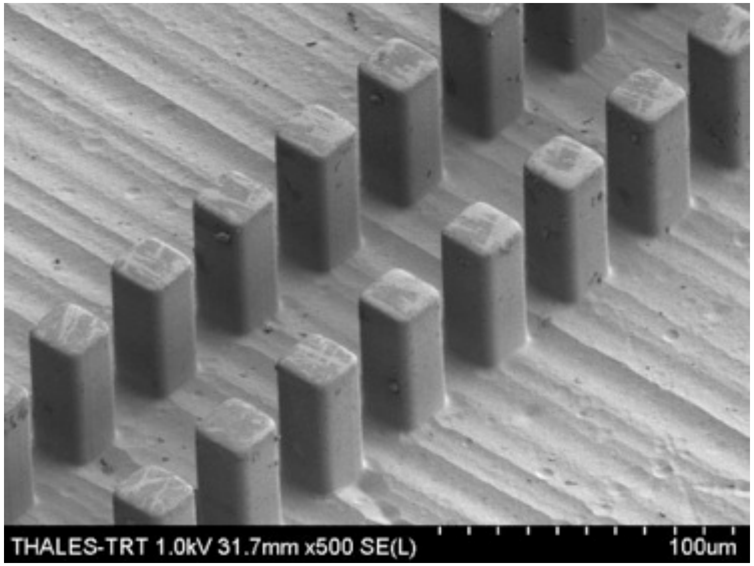
I - Electroforming

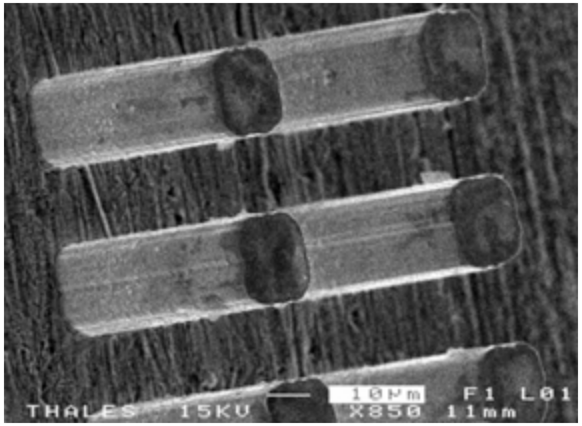
GA - Molding

THz fabrication: DXRL (Deep X-ray Lithography)

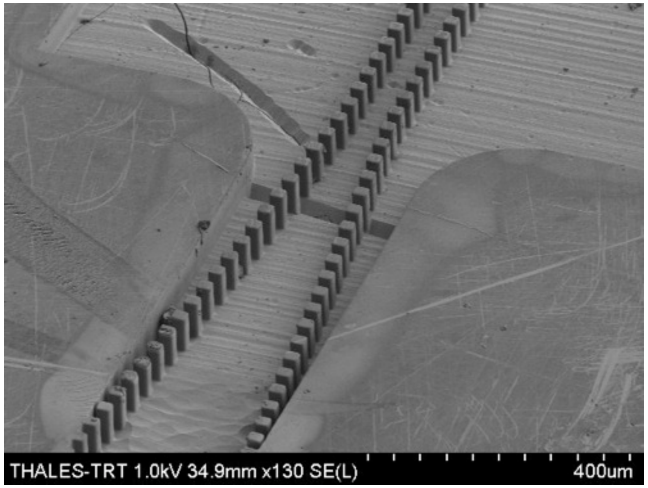
Lancaster University

Scanning electron microscope pictures of the double corrugated waveguide.
The height of the PMMA teeth is 50µm.

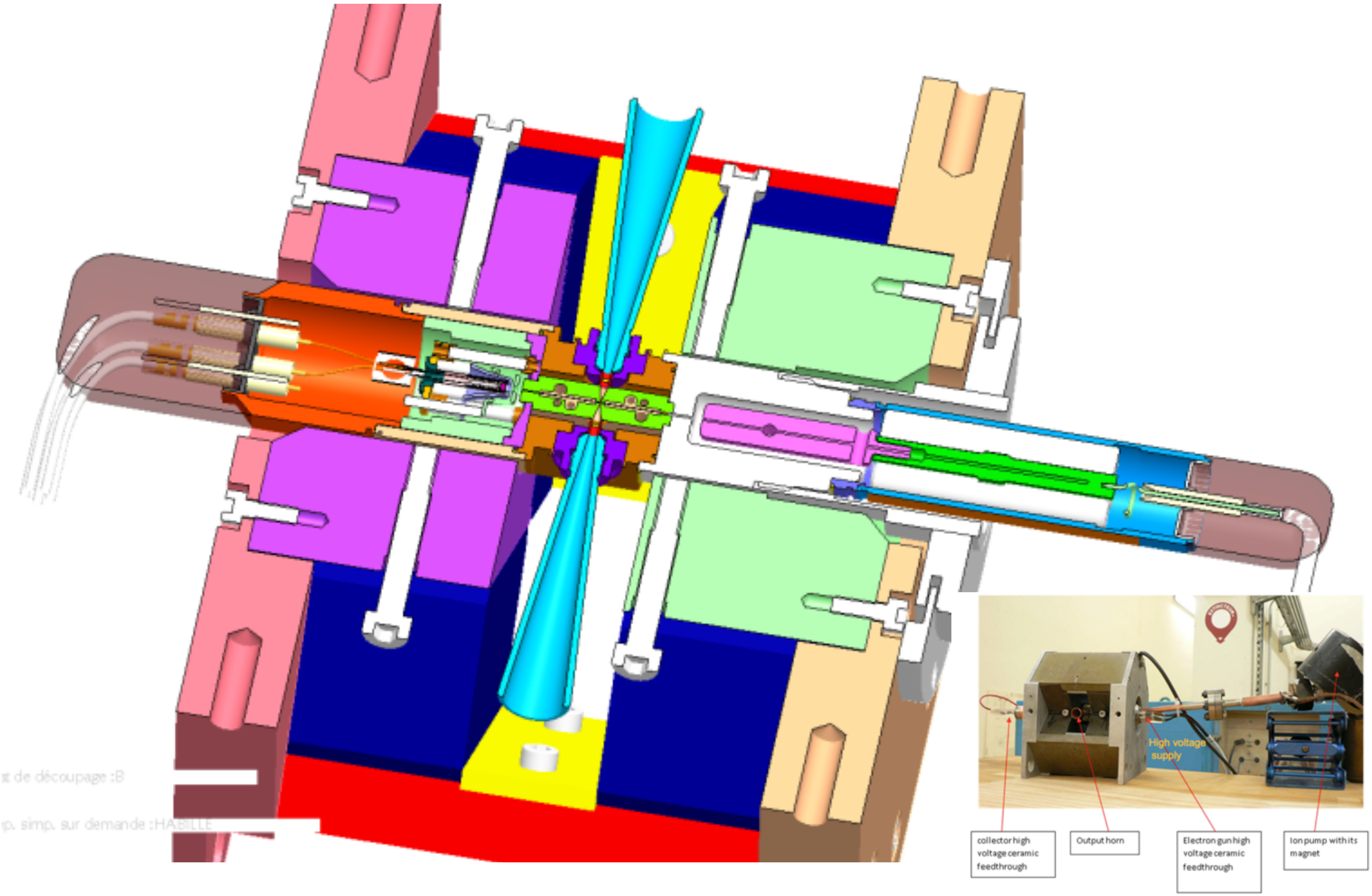




Overview of the self standing PMMA after X ray lithography and development.



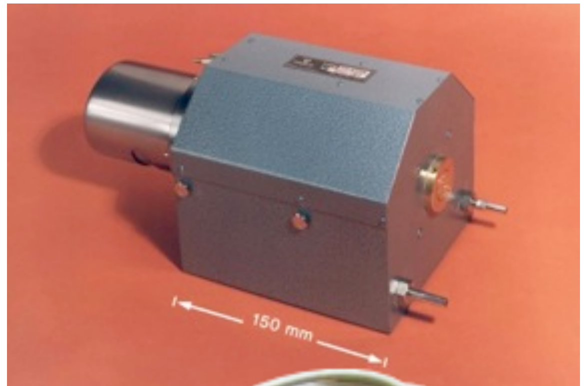
1 THz vacuum tube amplifier

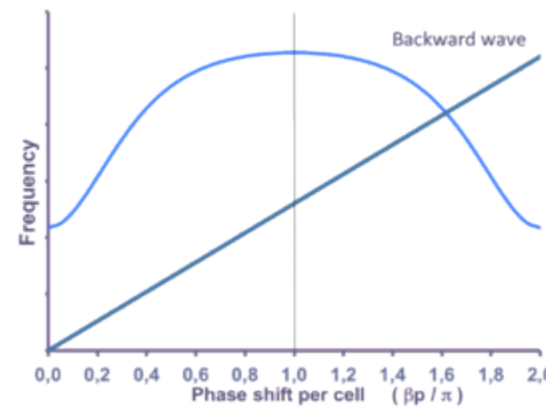


Backward wave oscillators State of the art

- 1984

1mW 0.9 THz Carcinotron
Thales (FR)



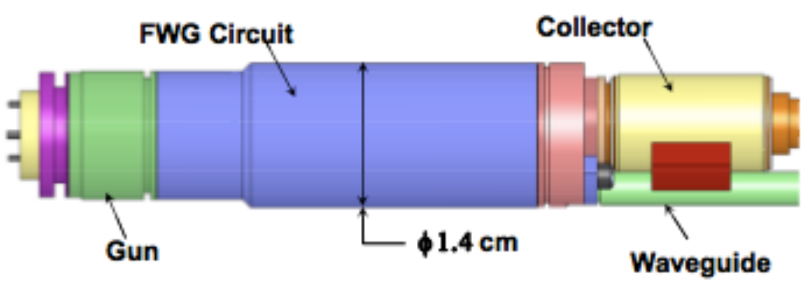


- 1990

THz BWO
(a few mW @ 200 -1100 GHz)
Istok (RU)

- 2009

52mW 0.656 THz Backward wave oscillator
Northrop-Grumman (US)



Thank you!

Stay updated on THz applications:

E-MIT website http://www.engineering.lancs.ac.uk/e-mit/

Twitter Claudio Paoloni @ClPaoloni