THz Gyrotrons: novelty, achievements and applications

M. Yu. Glyavin

IAP RAS, Nizhny Novgorod, Russia

Synchrotron and Free electron laser Radiation: generation and application (SFR-2020)
13-16 July 2020 Novosibirsk, Russia

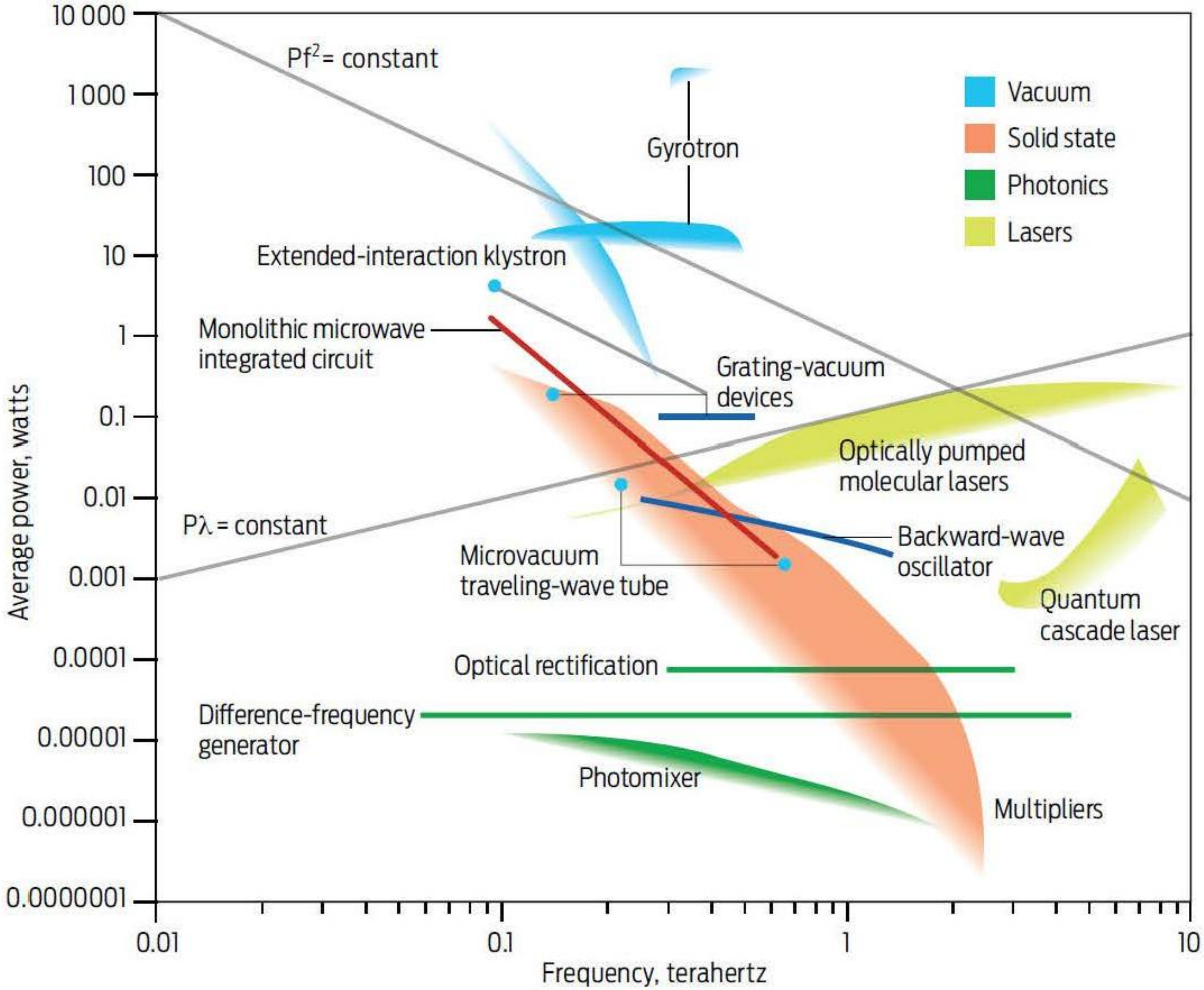
The status of THz sources

H. Booske, R. J. Dobbs, C. D. Joye, C. L. Kory, G. R. Neil,G.-S. Park, J. Park, and R. J. Temkin, Vacuum electronic high power terahertz sources, IEEE Trans. on TST,1 (1), 54–75 (2011)

Convergence of Terahertz Sciences in Biomedical Systems Editors: G.-S.Park, Y.H.Kim, H.Han,J.K.Han,J.Ahn,J.-H.Son,W.-Y.Park,Y.U.Jeong Springer 2012

Handbook of Terahertz Technologies: Devices and Applications Editors: H.-J.Song,T.Nagatsuma Taylor & Francis Group, 2015

M.Glyavin, T.Idehara, S.Sabchevski Development of THz gyrotrons at IAP RAS and FIR UF and their applications in physical research and high-power THz technologies IEEE Trans. on TST, 5 (5), 788-797 (2015)



C.M. Armstrong. The truth about terahertz. IEEE Spectrum , 49(9):36–41, Sept. 2012

Free Electron Laser

N.Vinokurov, G.Kulipanov
(Budker Institute of Nuclear Physics)

in operation since 2003

Wavelenght, microns	**90-240**
Average power, kW	**0.5**
Peak power, MW	**10**
Repetition rate, MHz	**5-10**

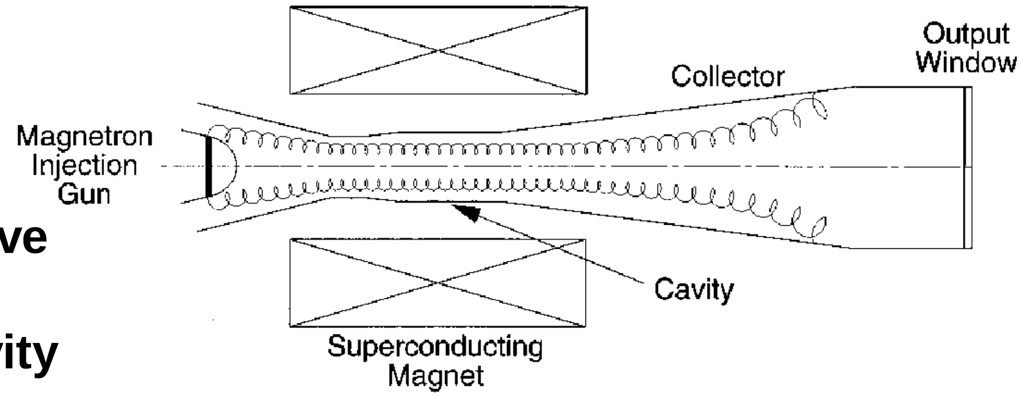
FEL (part only)

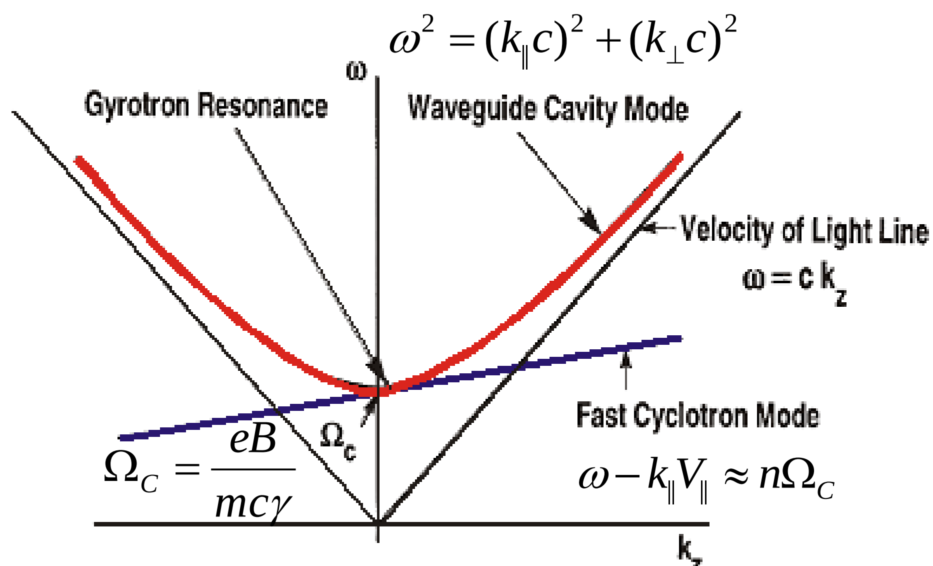
Gyrotrons

Gyrotrons are much more compact than FELs !

Gyrotron: general view

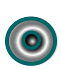
The gyrotron operates at the waves excited near cutoff - operation is less sensitive to the velocity spread. Operation at fast waves in a cavity without small-scale elements – very high power level in long pulses or CW regimes.



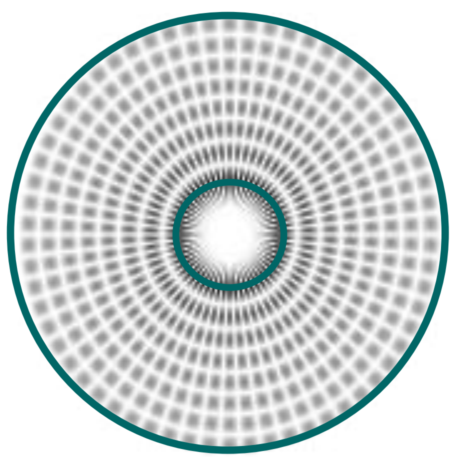


Backward wave interaction k_z<0

Forward wave Interaction k_z>0



$TE_{0.2}$ Ø ≈ 2 λ

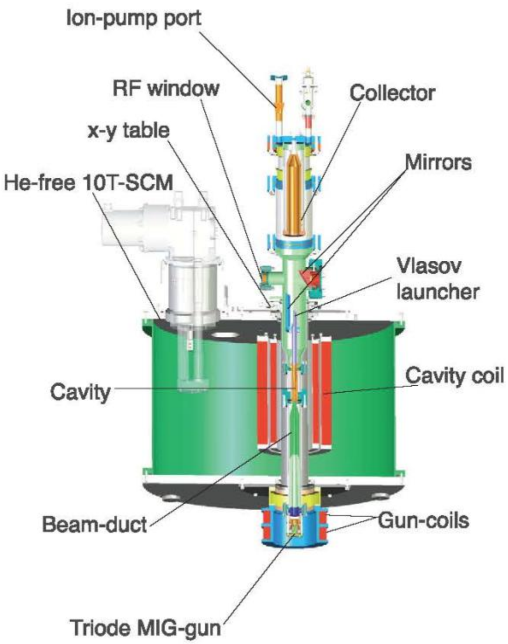


$TE_{25.10}$ Ø ≈ 20 λ

Gyrotrons

Multi-megawatt, quasi-continuous millimeter-wave gyrotrons for ECRC and CD in controlled fusion reactors
1 MW / 170 GHz / CW

CW medium power (tens kW) gyrotrons for technological applications



Low power (tens Watts) THz band gyrotrons for spectroscopy and diagnostic of various media

Gyrotron for ITER: Recent Development

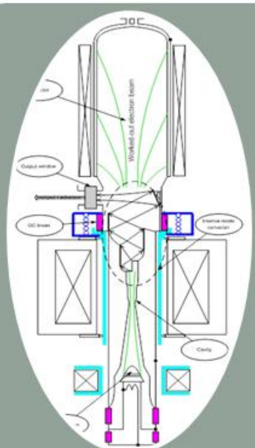
JAEA/TOSHIBA **IAP/GYCOM** **FZK/THALES** **CPI/GA**

170 GHz **1 MW** **CW (1000 s)** **>50%**

Gyrotron for ITER: Recent Development Steps

GYCOM

Conceptual design	Run tests	Final design	Manufacture	Delivery



Long pulse operation of gyrotron pre-prototype in presents of IO representatives , April 2011

Run tests of gyrotron pre-prototype, 2014

1MW output power

500s – 160 pulses

1000s – 55 pulses

Reliability > 95%

Factory tests of Power Source Prototype successfully passed (IO representatives), May 2015

FDR Procedure (Cadarache, October 2015)

Manufacture and Inspection Plan.

Quality Plan

Manufacture readiness review

Start of Manufacture 2016

Planned Delivering of the 1st Gyrotron System

2017

RF Building Readiness

2018

Gyrotron for ITER: Recent Development Steps

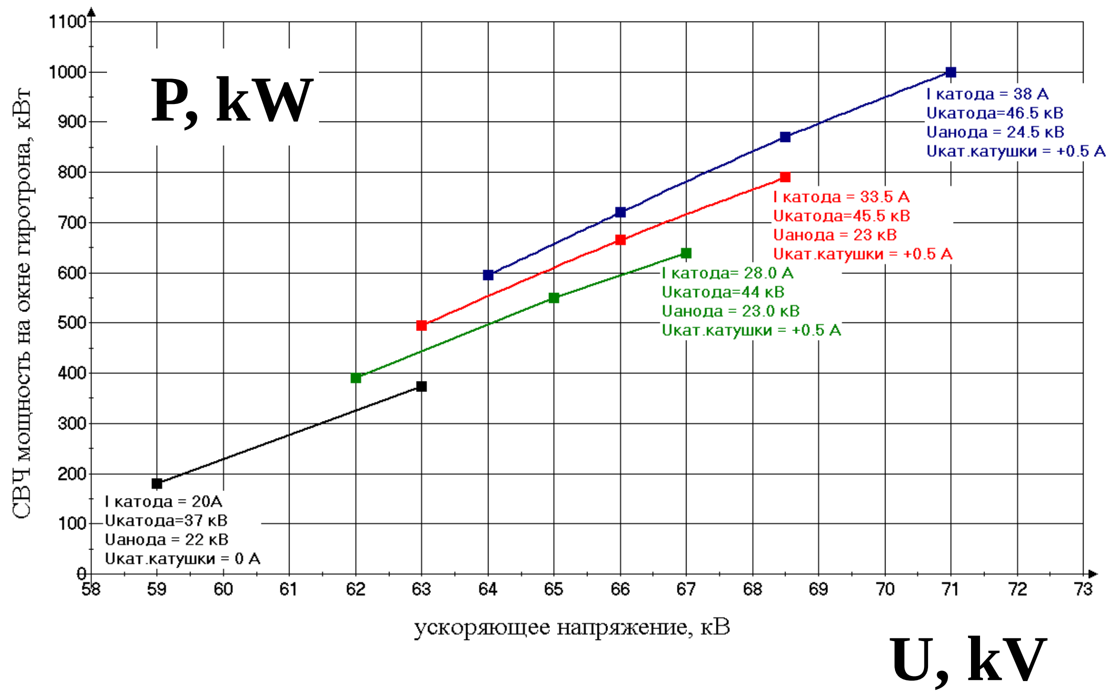
GYCOM

November 2016 – fabrication of first gyrotron complex for ITER

2017 Ø63.5 mm waveguide was changed to Ø50 mm Second complex was fabricated. Required parameters were demonstrated. ITER do not ask for delivery.

From 2018 each year - one more complex.

ECRH system for T15-MD

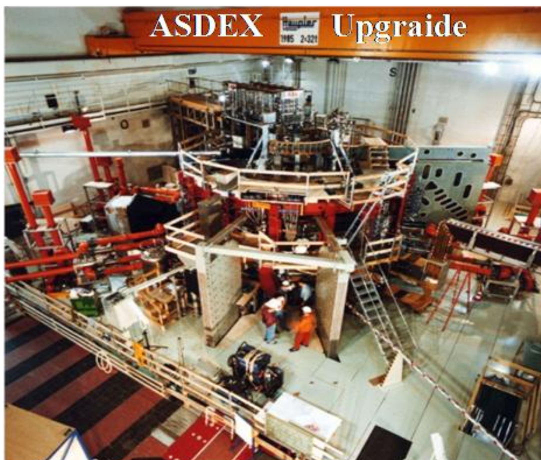


The power 1 MW and efficiency 57% has been obtained for designed frequency 82.6%

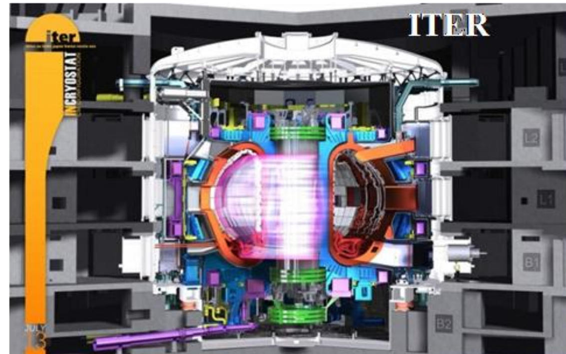
Recent requests & deliveries

GYCOM

140/105 GHz
4 gyrotrons – delivered



170 GHz
8 gyrotrons – to be delivered as components of self-sufficient RF sources



140/105 GHz
2 gyrotrons– delivered

GYCOM
1MW / 3 -1000 s
gyrotrons for ECRH and current drive

140 GHz
2 gyrotrons– delivered
More in discussion

140 GHz
2 gyrotrons – delivered
105 GHz
2 gyrotrons – delivered
2 gyrotrons – is under production
1 gyrotron – is ordered

IVEC2017
18th International

+ TCV, T15-MD

26 April 2017

Gyrotrons

Megawatt millimeter-wave
gyrotrons for
ECRC and CD in controlled
fusion reactors
1 MW / 170 GHz / CW

CW medium power
(tens kW)
gyrotrons for
technological applications

THz band

Low power (tens Watts)
gyrotrons for
spectroscopy and diagnostic
of various media

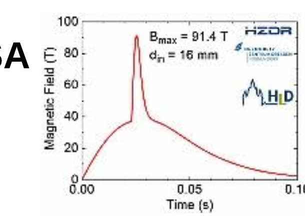
Magnetic fields for gyrotrons

When the Doppler term in the cyclotron resonance condition is negligibly small, $B(T) \approx 35.7\gamma_0 f(THz)/s$ **for 1 THz at s=1 – 36 Tesla!**

R. Hirose et al., IEEE Trans. Appl. Supercond., 2006, p. 953.
Cryogen-free 15 T solenoid
JASTEC, Japan

Hybrid magnets
>30 T in 50 mm
Power consumption
~20 MW CW
NHMFL, France, USA

Pulsed solenoids
> 97 T
LANL, USA



ИПФ РАН

The problem of the right way…

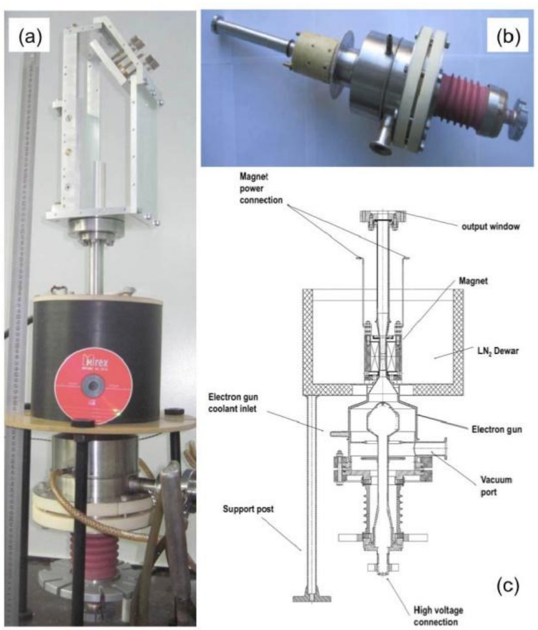
$$\omega = s\omega_H \sim sB$$

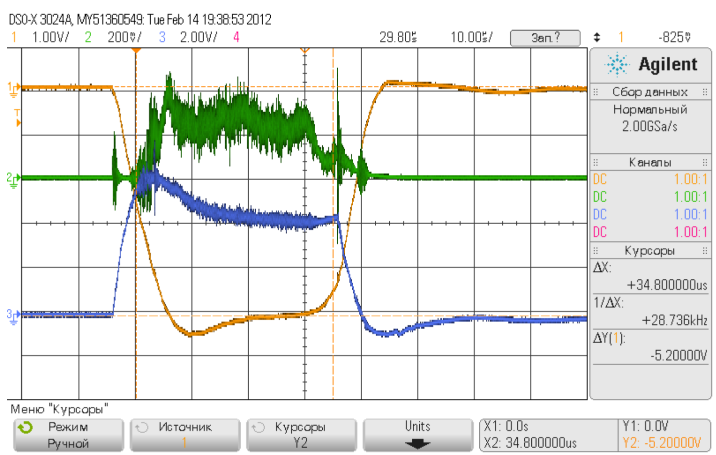
Conventional gyrotron, *s*=1,2
-Strong magnetic field

High harmonic operation
with improved mode selection

Powerful gyrotron with pulsed coil

IAP RAS (Russia) & UMD (USA)
Glyavin, Luchinin, Nusinovich
Fundamental harmonic operation





B ~ 28 T
f = f_c = 0.7 THz
P ~ 200 kW
Efficiency ~ 20%
t ~ 0.05 ms
1 pulse per 1 min
$TE_{31,8}$ mode

M.Yu.Glyavin, A.G.Luchinin, G.S.Nusinovich, J.Rodgers, D.G.Kashyn, C.A.Romero-Talamas, R.Pu "A 670 GHz gyrotron with record power and efficiency", Applied Physics Letters, 101, 153503 (1-4), 2012

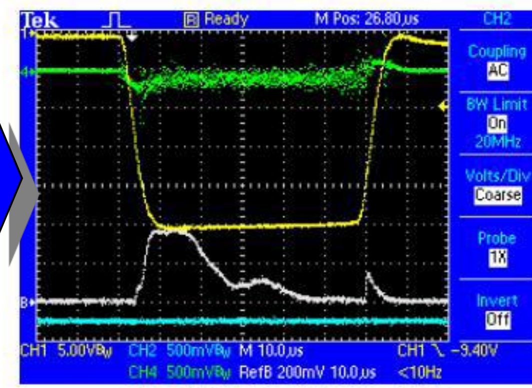
Institute of Applied Physics RAS, Nizhny Novgorod, Russia

M. *Yu. Glyavin, A. G. Luchinin, and G. Yu. Golubiatnikov "Generation of 1.5-kW, 1-THz Coherent Radiation from a Gyrotron with a Pulsed Magnetic Field", Phys. Rev. Lett.,* ***100****, 015101, (2008)*

pulsed coil

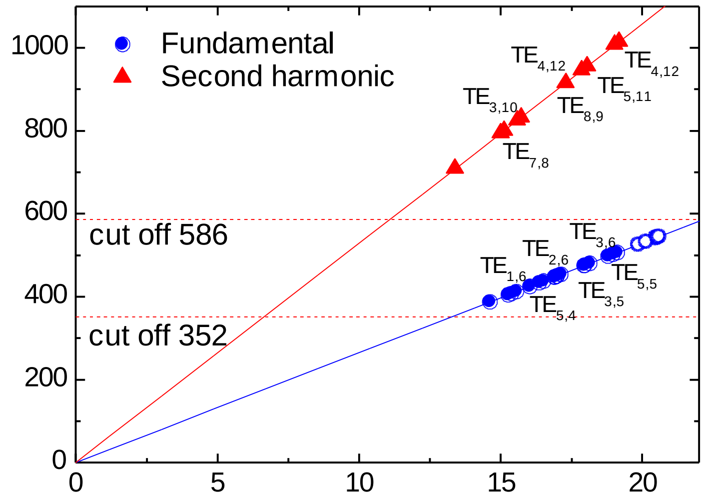
B ~ 38 T
f = f_c = 1.3 THz
P ~ 0.5 kW
t ~ 0.05 ms
f = f_c = 1.02 THz
P ~ 5 kW
t ~ 0.05 ms
1 pulse per 1 min
W_s~ 6 kJ

TDS 2014 - 18:09:38 28.11.06



TDS 2014 - 18:11:58 28.11.06

Gyrotrons successfully pass the magic 1 THz mark



B = 19.1 T

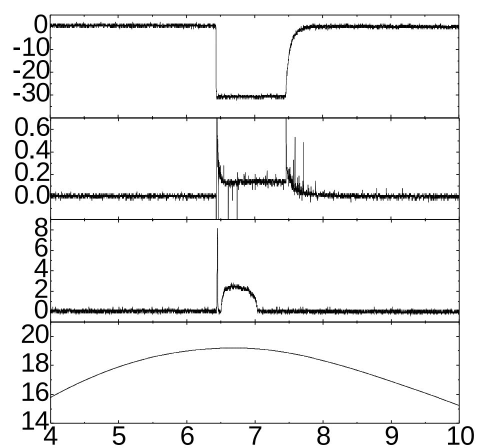
$f = 2 f_c$ = 1.005 THz

P ~ 10 W

t ~ 1 ms

1 pulse per 20 min

W_s~ 300 kJ

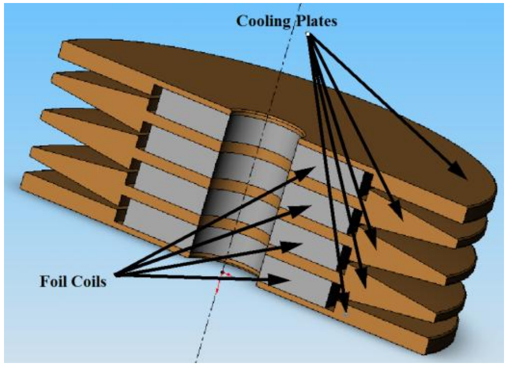


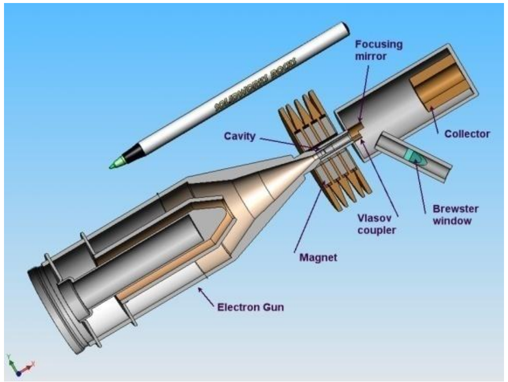
pulsed coil

*T. Idehara, H. Tsuchiya, O. Watanabe, LaAgusu, S. Mitsudo, "The first experiment of a THz gyrotron with a pulse magnet", Int. J. Infrared and Millimeter Waves, **27**, 3, 319-331, (2006)*

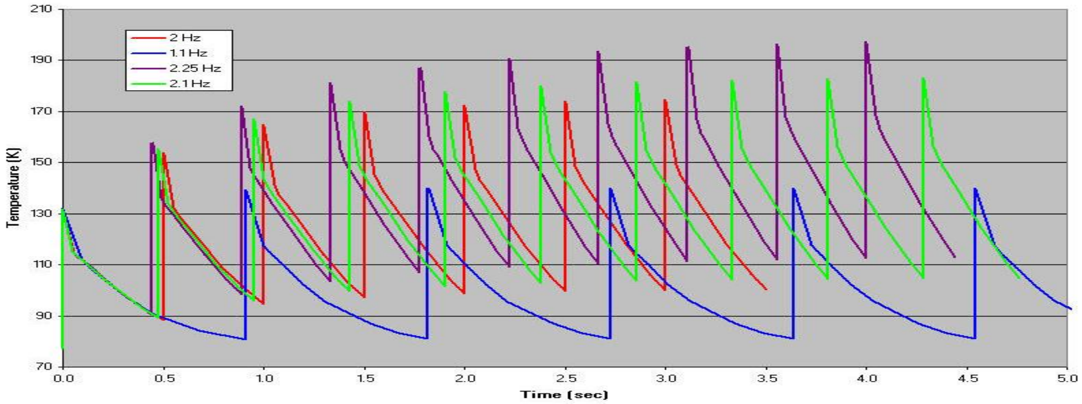
*T. Idehara, T. Saito, H. Mori, H. Tsuchiya, La Agusu, S. Mitsudo "Long Pulse Operation of the THz Gyrotron with a Pulse Magnet", Int. J. Infrared and Millimeter Waves, **29**, 2, 131-141, (2008)* Calabazas Creek Research, Inc.

High average power, high repetition rate





CCR, USA, Ives et al

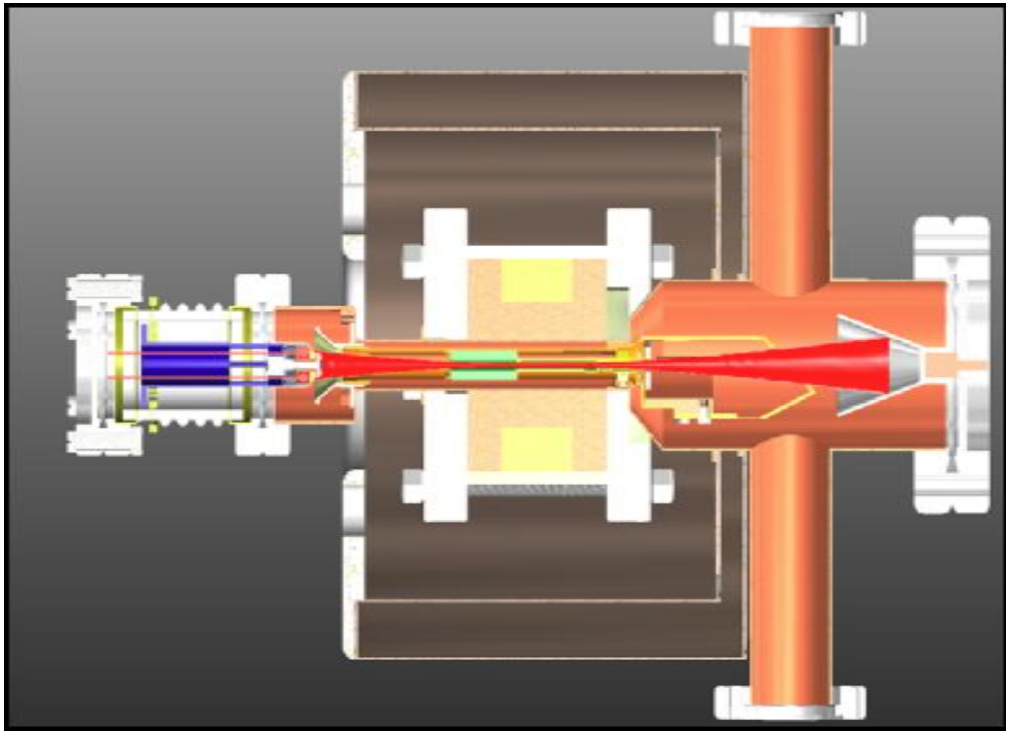


In calculations f up to 2 THz at second harmonic, repetition frequency up to 2 Hz, pulse duration 0.01 ms, average power 10 W

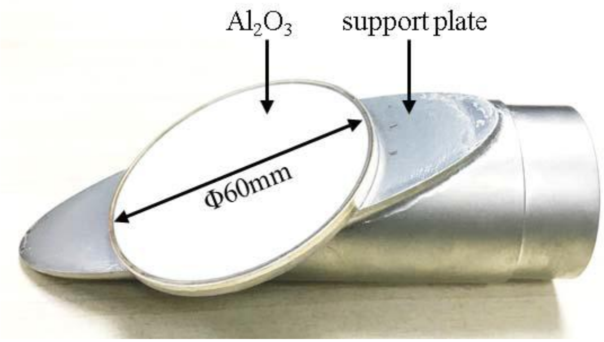
M. Read, L. Ives, J. Neilson, G. Nusinovich, "Development of a High Power Pulse THz Gyrotron", IEEE Int. Vacuum Electronics Conf. IVEC '07, 347-348, (2007)

Development of a 0.33-THz broadband pulse-magnet Gyrotron oscillator

C.-H. Du et al (2017)
Institute of Applied Electronics School of Electronics Engineering and Computer Science Peking University, Beijing 100871, China



frequency：330 GHz (B<14 T)
tuning bandwidth：~10 GHz
peak power： 1.0 ~ 2.0 kW
pulse width：10 ms
Brewster window (2018)



"…over 0.33–0.50 THz, propagation is better than 90%..."

The problem of the right way becomes more and more complicated…

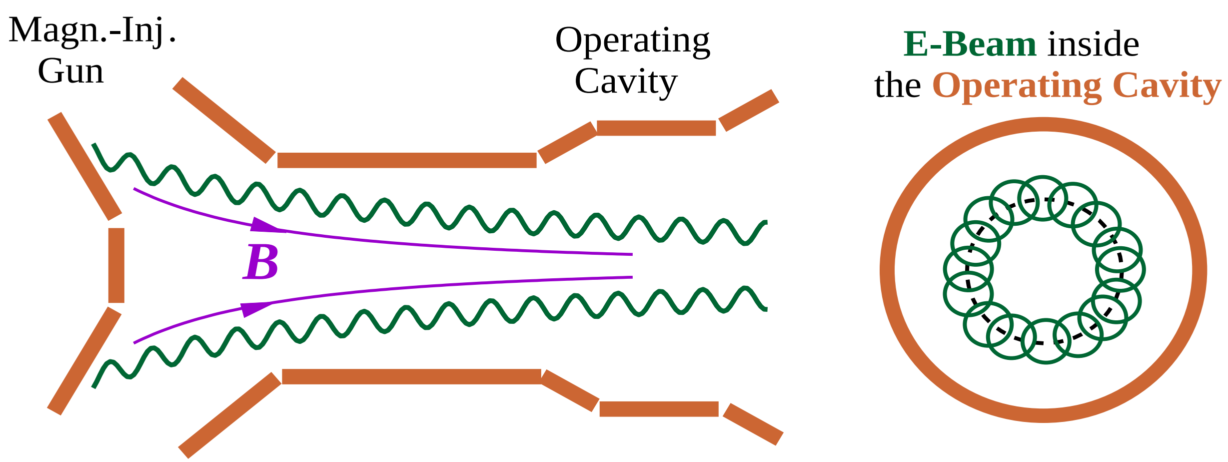
It depends on the goal:
power,
frequency,
stability.

The problem of the right way becomes more and more complicated…

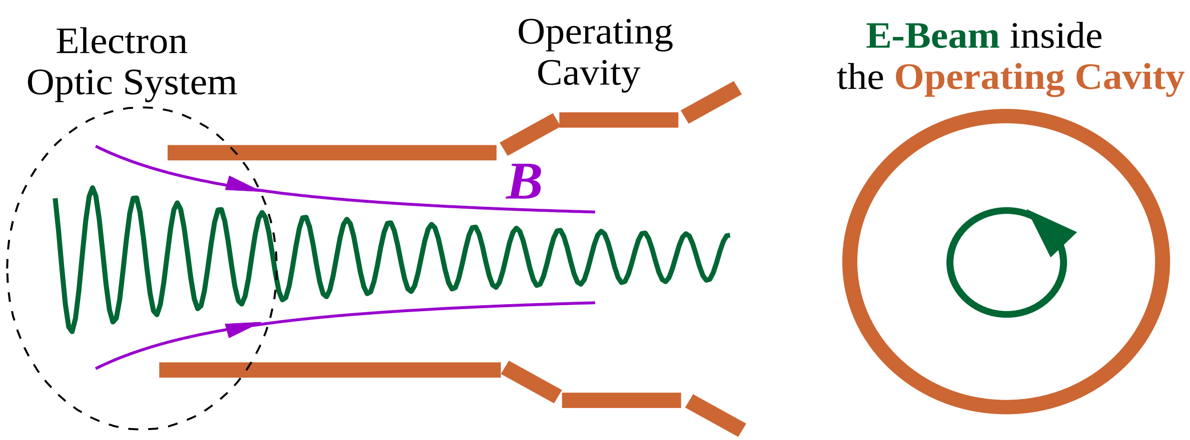
… and sometimes looks insoluble

Improved selection based on axis-encircling electron beam. Only mode with m=s are excited (modes which are characterized by zero Bessel function)

Traditional Gyrotron

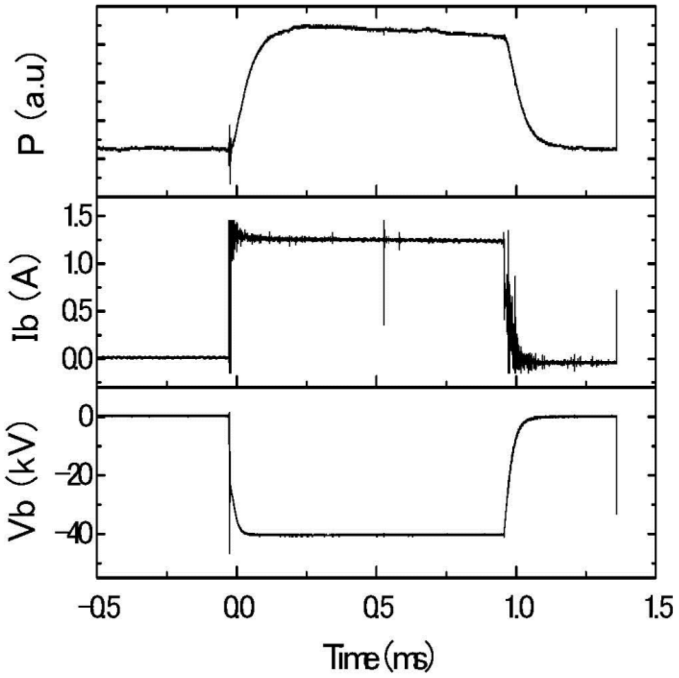


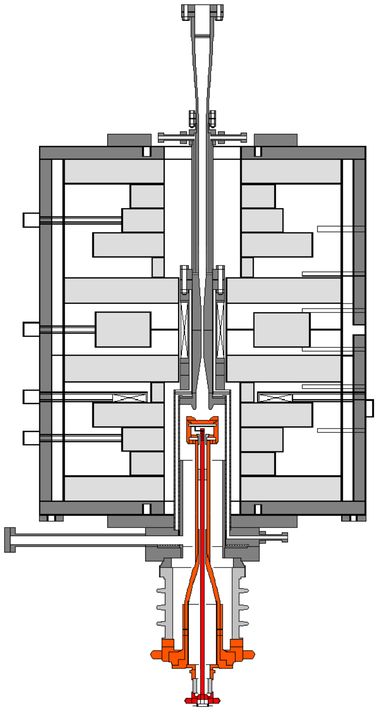
Large-Orbit Gyrotron



Pulsed gyrotrons (LOG)

FIR FU





Idehara, T.; Zapevalov, V.; Glyavin, M. et al.
"A High Harmonic Gyrotron With an Axis-Encircling Electron Beam and a Permanent Magnet", IEEE Transactions on Plasma Science, 32, 3, 903- 909, 2004

B ~ 1.1 T

f = 5f_c = 0.15 THz

P ~ 0.1 kW,   t ~ 0.05 ms

LOG

Yu.Kalynov, A.Savilov, V.Bratman, et al
IAP RAS, Russia. From pulsed to CW operation
Report 4.1 this conference

B ~ 5 T
f = 2f_c = 0.26 THz (CW)
P~ 1 kW
f = 3f_c = 0.39 THz (CW)
P ~ 0.3 kW
Obtained in 2018 – in press

B ~ 15 T
f = 2f_c = 0.6 THz
P ~ 2 kW
f = 3f_c = 1 THz
P ~ 0.3 kW
t ~ 0.01 ms

f = 3f_c = 0.4 THz
P ~ 20 kW
t ~ 0.01 ms

U~250 kV

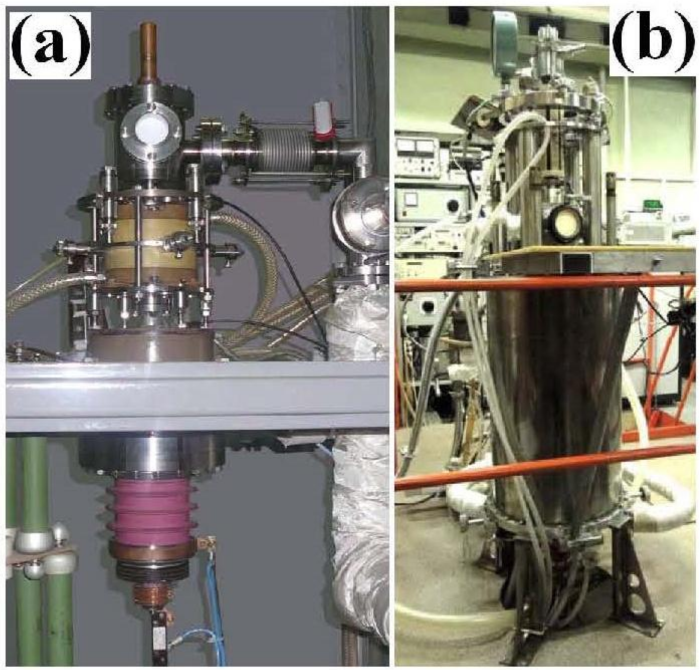
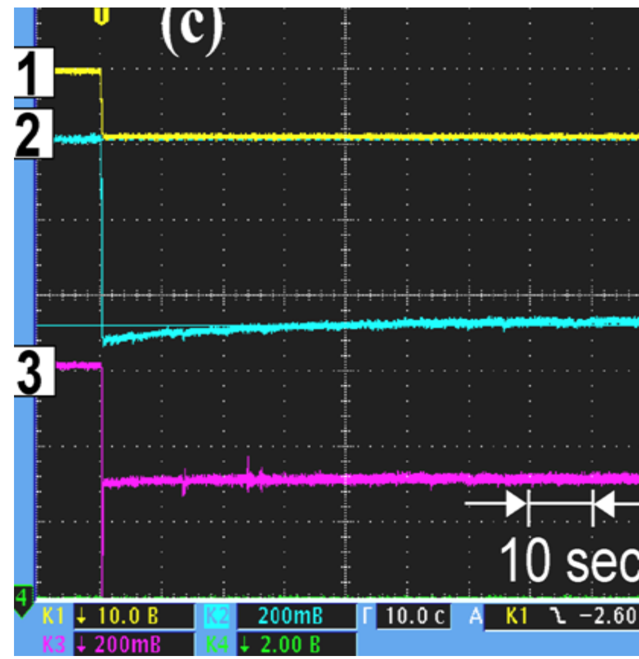


Fig. 1. Two high-harmonic gyrotron setups operating at the IAP. (a) 80-keV "pulsed LOG." (b) 30-keV "CW LOG."



Oscilloscope traces of the electron beam voltage (*U*), current (*I*) and rf signal passed through two (250 and 350 GHz) filters

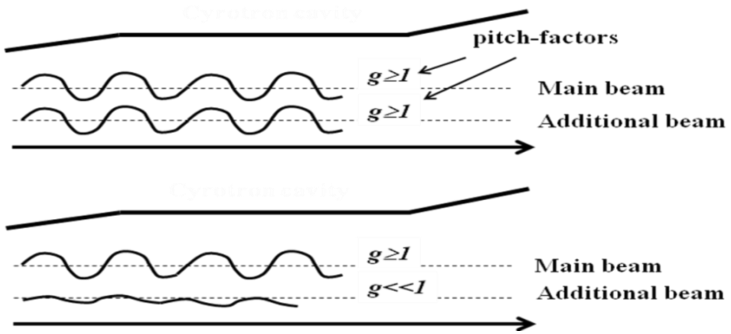
V. L. Bratman, Yu. K. Kalynov, and V. N. Manuilov "Large-Orbit Gyrotron Operation in the Terahertz Frequency Range" Phys. Rev. Lett. 102, 245101 (2009)

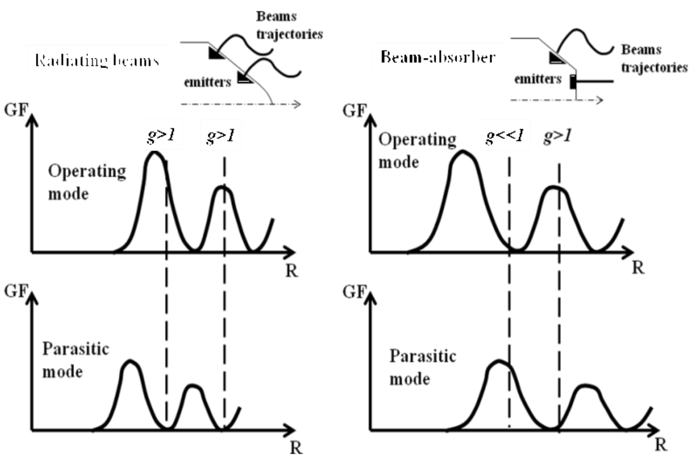
I.V.Bandurkin et al. "Terahertz Large-Orbit High-Harmonic Gyrotrons at IAP RAS: Recent Experiments and New Designs" Phys. IEEE TED, 65, 6, 2287 (2018)

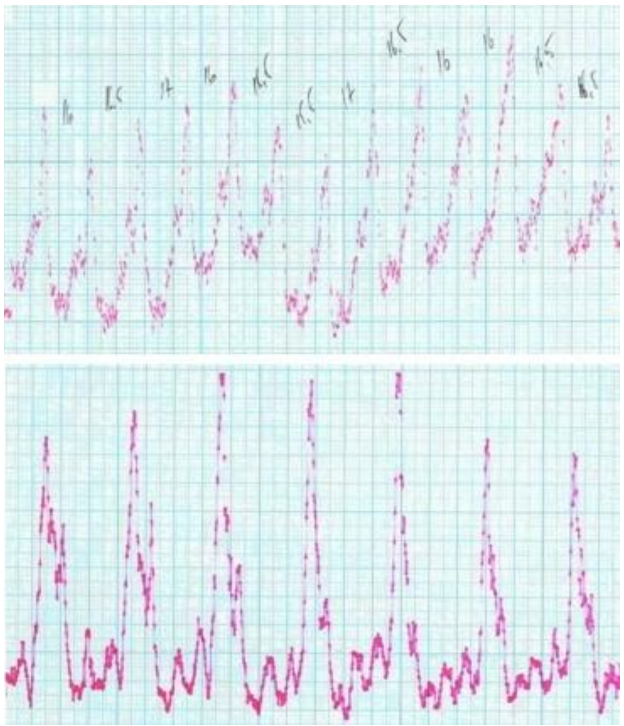
Double-beam gyrotron tests

FIR UF

Concept of multi-beam gyrotron was proposed by V.Zapevalov et al., "Inventor's Certificate No. 786677 USSR with priority from July 25, 1979. "Cyclotron-Resonance Maser"







s = 2, P~ 10 W
f = 770 ± 20 GHz

s = 1, P~ 100 W
many modes

200 GHz < f < 400 GHz

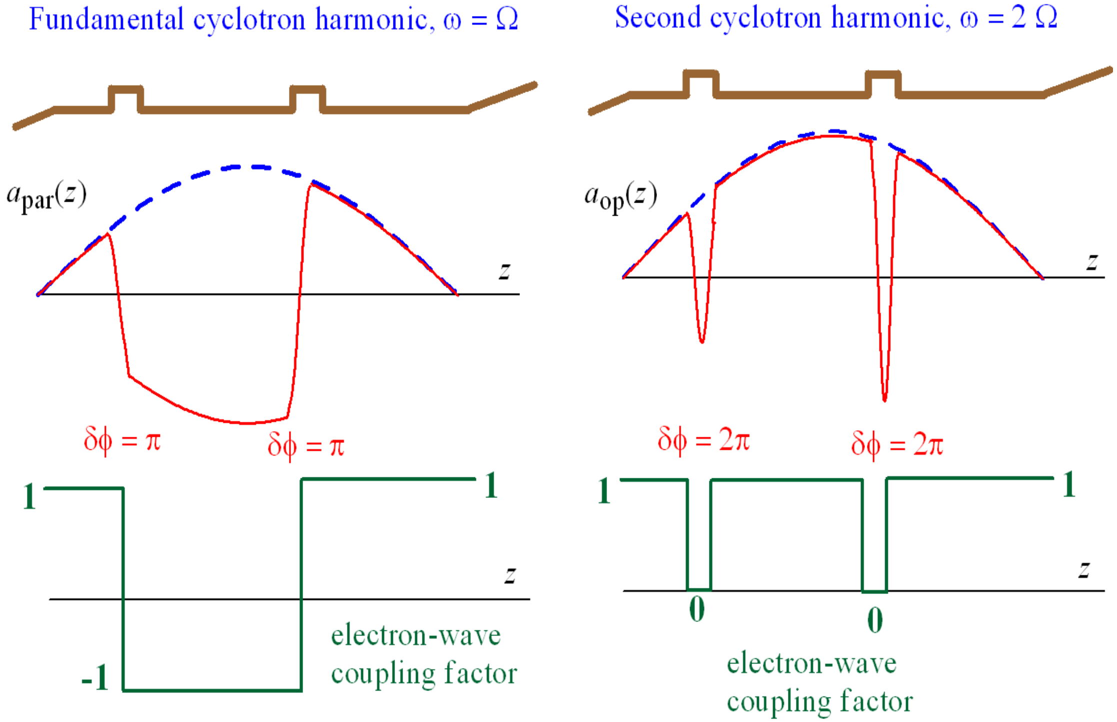
T.Idehara, M.Glyavin et al. "A Novel THz-Band Double-Beam Gyrotron for High-Field DNP-NMR Spectroscopy", Review of Scientific Instruments, 88, 094708 (2017)

Pulsed coil gyrotron – excitation of second harmonic

A.V.Savilov, I.V.Osharin, I.V.Bandurkin et al.

A method for suppression of spurious fundamental-harmonic waves in gyrotrons operating at the second cyclotron harmonic

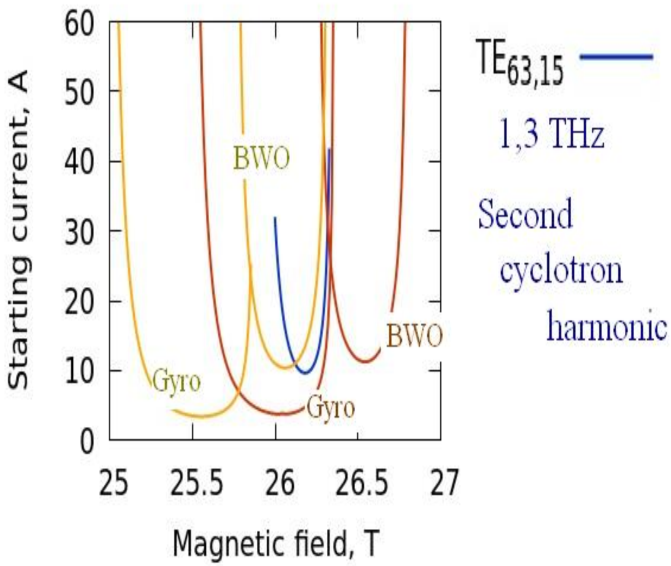
600 GHz*2 ~ 1200 GHz



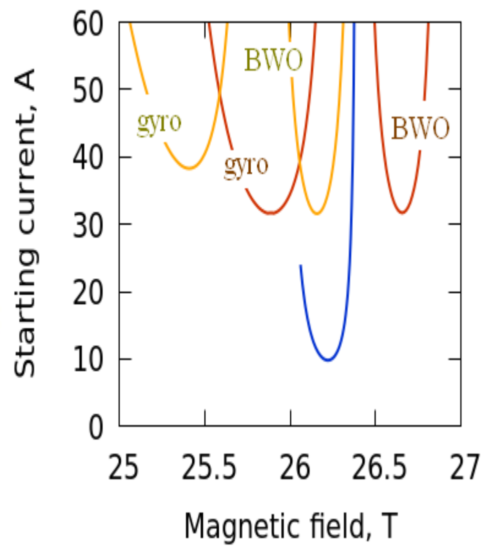
The starting currents of fundamental harmonic modes can be increased by an order of magnitude

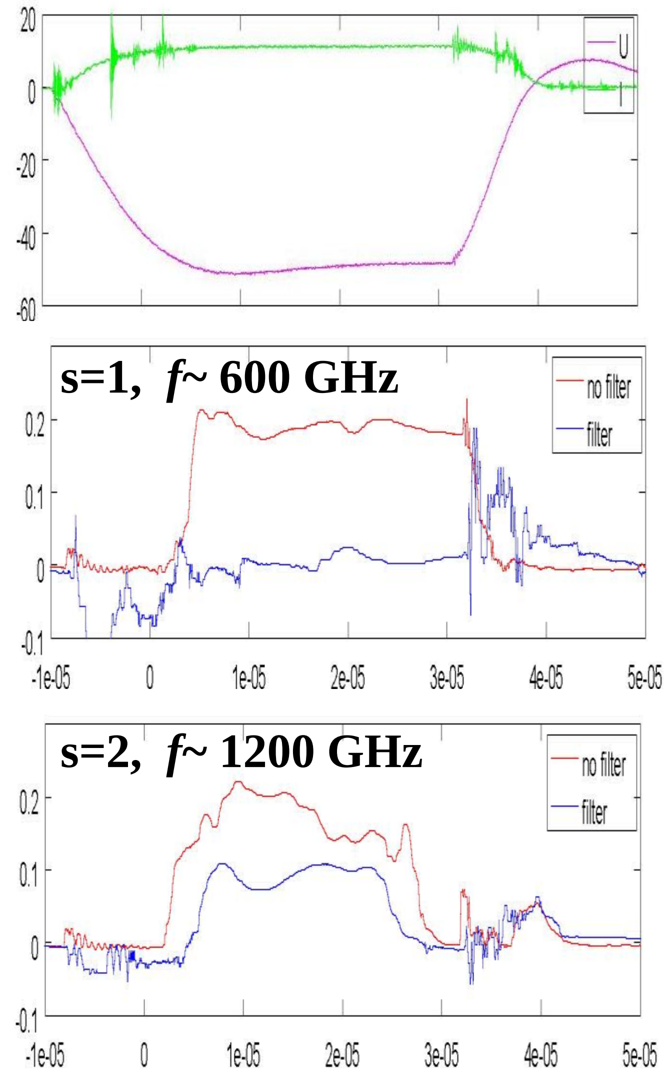
Pulsed coil gyrotron – excitation of second harmonic

Regular cavity



Irregular cavity





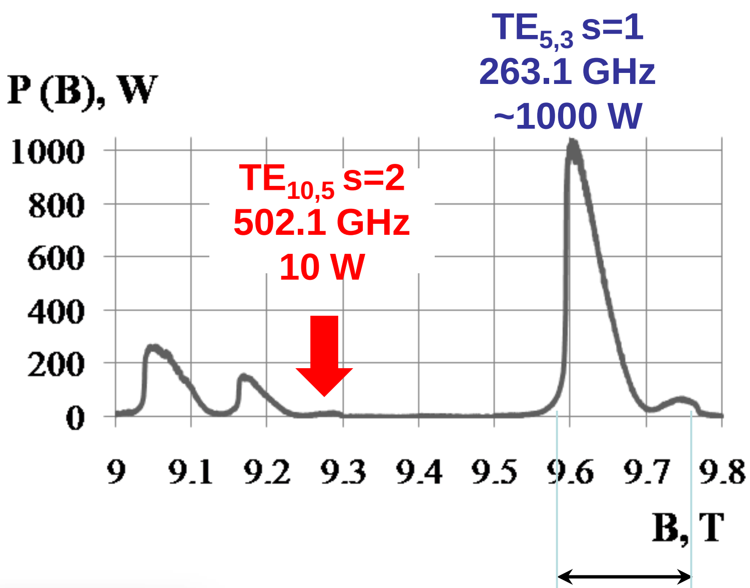
$TE_{31,8}$ — 670 GHz, fund. harm

$TE_{30,8}$

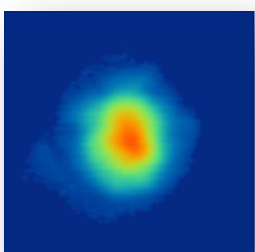
Gyrotron (1st axial mode)

BWO (2nd axial mode)

IAP RAS CW gyrotron



263.1 GHz
U ~ 15 kV
I ~ 0.4 A
P ~ 1 kW CW (η= 17%)



TEM_{00} ~ 93%

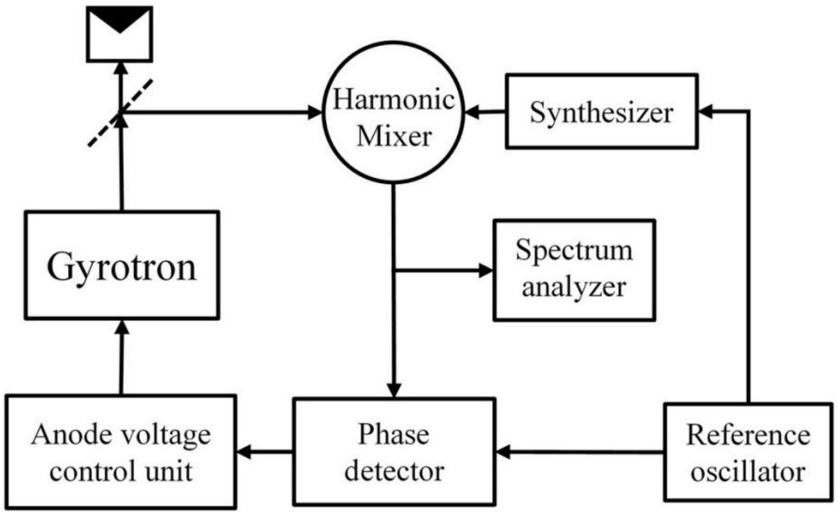
F = 263.06 GHz – 263.65 GHz
ΔF ~ 0.6 GHz
Continuous frequency tuning
by variation of the magnetic field
(*T*, *U*, *I* = const)

Generation regime with low beam current

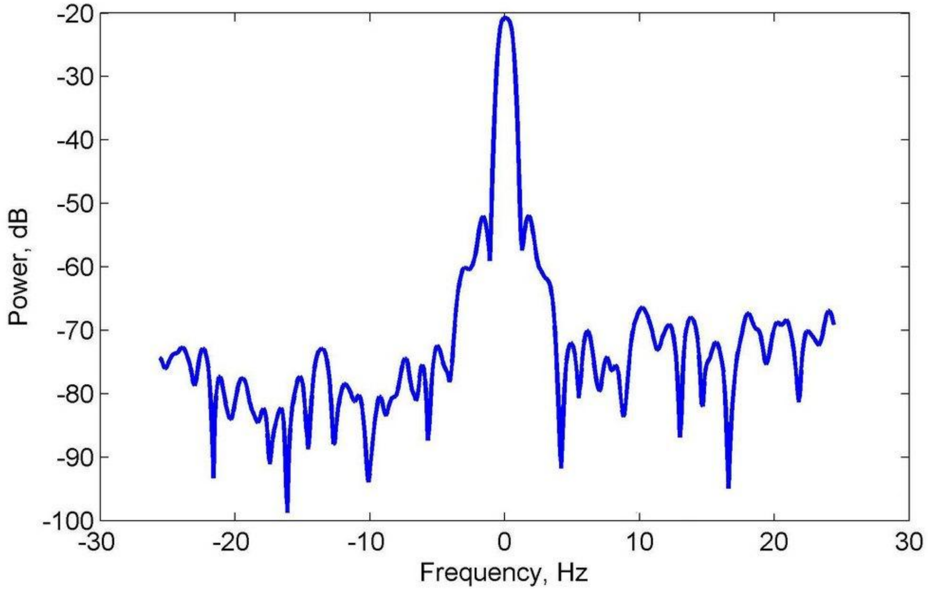
U ~ 14 kV
I ~ 0.02 A
P = 10 W (η= 3%)

M.Glyavin, A.Chirkov, G.Denisov, et al., "Experimental tests of a 263 GHz gyrotron for spectroscopic applications and diagnostics of various media" Review of Scientific Instruments 86 (5), 054705 (2018)

Frequency stabilization - feedback



General view of PLL system



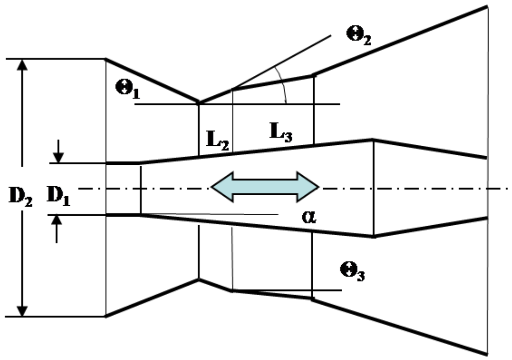
Δf = 1 Hz, f = 263 GHz, $\Delta f/f=3*10^{-12}$

Output radiation power about 100 W,
which is 3 orders of greater than the power of traditional BWOs,
and the spectrum width is 3 orders smaller
than the previously known experiments with gyrotrons

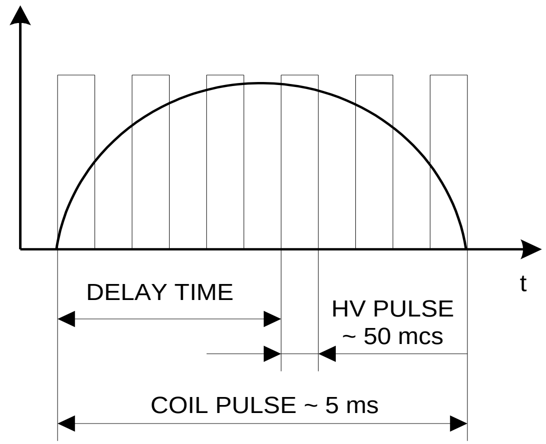
A. Fokin et al. "High-power sub-terahertz source with a record frequency stability at up to 1 Hz", Scientific Reports, V. 8, 4317 (2018)

ИПФ РАН

Frequency tuning

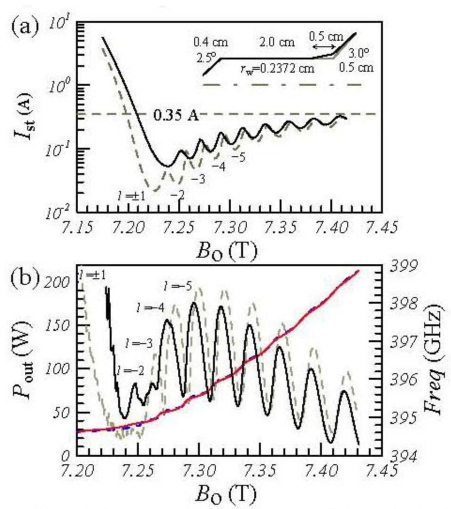


Coaxial cavity gyrotron with movable insert rod

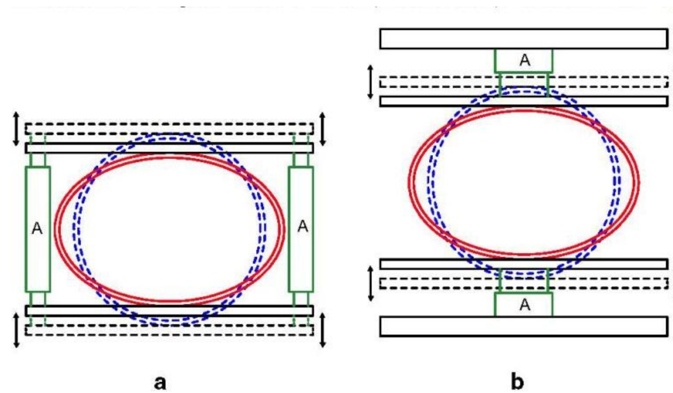


The fine frequency tuning about ***df/f~ 3,5%*** is possible for single mode operation and up to ***df/f~5%*** for step by step excitation of two modes with equal radial indexes for central frequency ***f~300 GHz.***

Variation of delay time in pulsed coil gyrotrons



Excitation of several longitudinal modes



Cavity with piezoelectric control of diameter

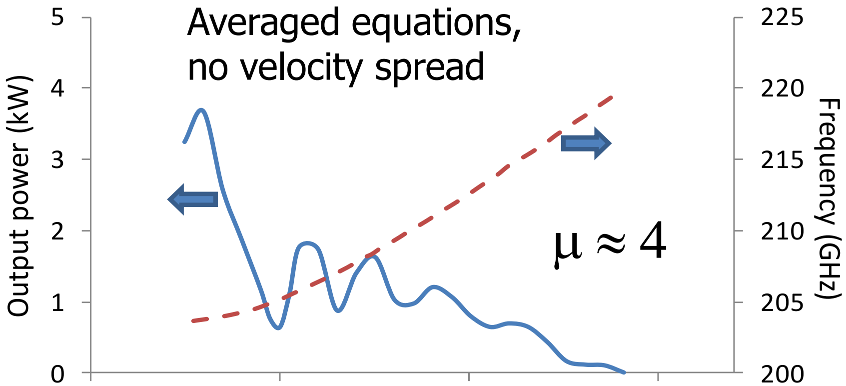
Frequency tuning

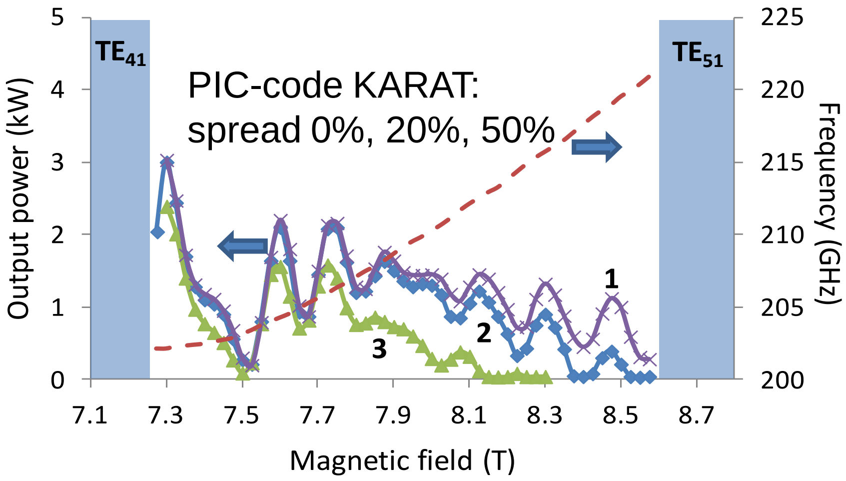
f ~ 203 GHz, P ~ 1kW df ~ 7 GHz for positronium hyperfine structure measurement

- Short-cavity gyrotrons possess a weaker sensitivity to the velocity spread in the electron beam
- Required current can be reduced by operation at low transverse modes due to the growth of the electron-wave coupling coefficient

$$\delta\omega = \frac{\omega-\omega_c}{\omega_c} \approx \frac{1}{2}\left(\frac{\lambda}{g^2 L\delta\upsilon_\perp}\right)^2 = \frac{\pi^2}{2}\left(\frac{\beta_{\|0}}{\mu\delta\upsilon_\perp}\right)^2$$

$\mu\downarrow \quad \delta\omega\uparrow$





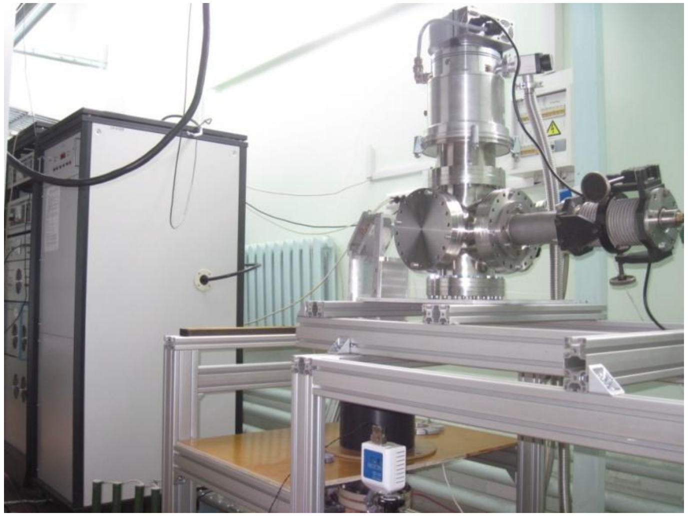
Frequency tuning ~5% (~10 GHz)

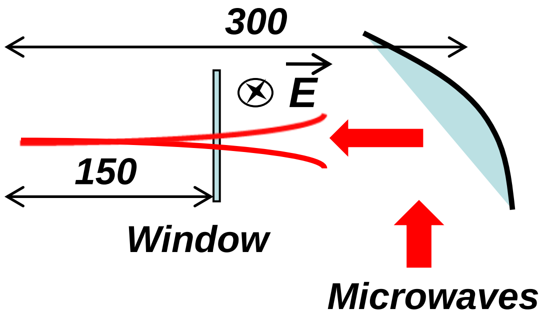
Applications

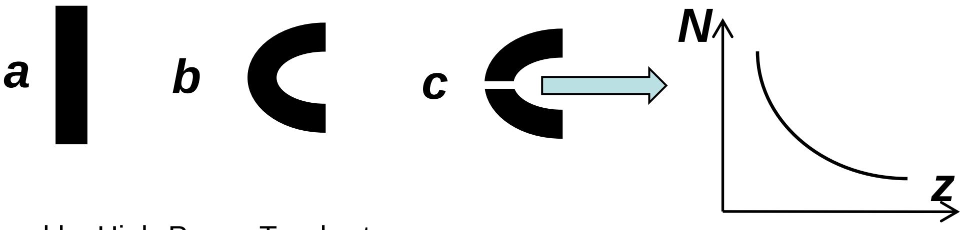
Communication and Information Technology	Secure wireless communication	Instant data transfer (> 30-100 GB/s)	Covert satellite and tactical communication in space
Security	Contraband safety inspection	Screening of people	Non-contact postal screening and Biometrics
Semiconductor and Industrial Applications	Fault analysis in next generation LSI circuits and wafers	Drug inspection	Nanocomposites Material evaluation and inspection of solar cells
Earth and Space Science	Environmental/ air-pollution monitoring	Monitoring of new born Galaxies	Study of invisible dark universe and new solar system
Basic Science	THz spectroscopy	Study of Metamaterials	Cancer imaging and on-site diagnosis

A.Srivastava “Microfabricated Terahertz Vacuum Electron Devices: Technology, Capabilities and Performance Overview”
European Journal of Advances in Engineering and Technology, 2015, 2(8): 54-64

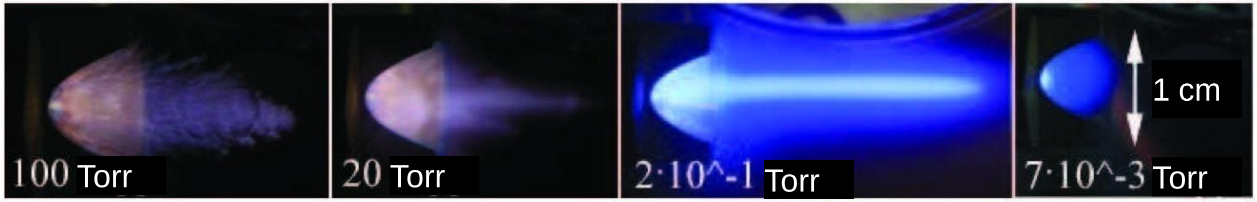
Localized gas discharge

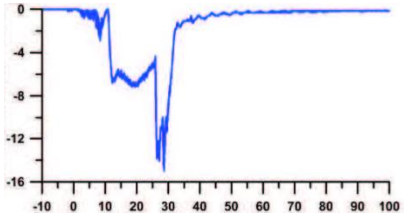






S.V.Golubev, V.G.Zorin, A.G.Litvak et al. The Discharge Maintained by High-Power Terahertz Radiation in a Nonuniform Gas Flow Radiophysics and Quantum Electronics, 2014, 56, 8-9, 561-565





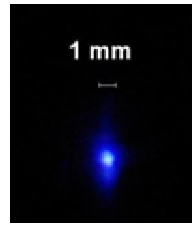
Localized (~1 mm) plasma discharge has been realized in a wide range of pressures (0.01 - 1500 Torr) Such a discharge can be used as the pointed source of UV radiation, including the projection lithography – IAP RAS Golubev et al.

extreme ultraviolet signal from p-i-n diode

λ~112-180 nm P~ 10 kW

Remote detection

V.L. Granatstein, G.S. Nusinovich Detecting excess ionizing radiation by electromagnetic breakdown of air J. Appl. Phys. 108, 063304 (2010)



- Focusing high-power EM wave in a small spot: the wave field intensity exceeds the breakdown threshold
- If there are some seed electrons, this focused wave initiates the RF breakdown.
- In the case of THz waves, the breakdown-prone volume can be small - the breakdown rate in the case of an ambient electron density will be low
- Thus, a high breakdown rate will indicate that in the vicinity of a focused wave beam there are some additional sources of air ionization

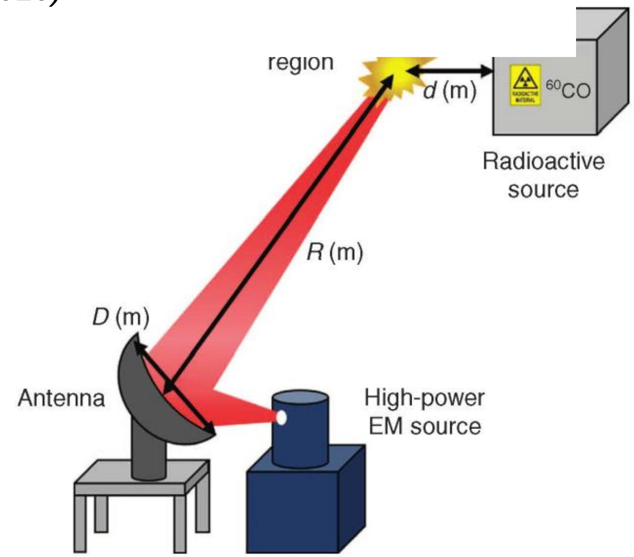
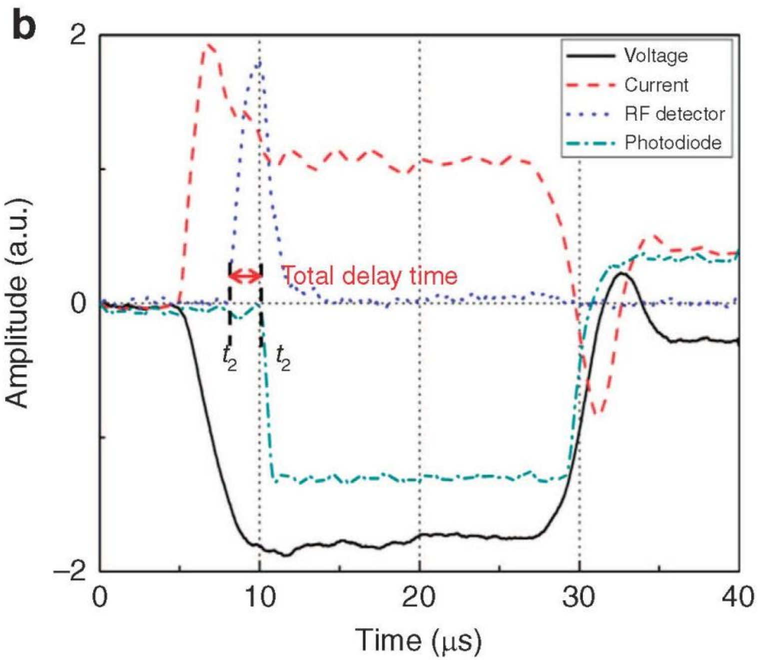


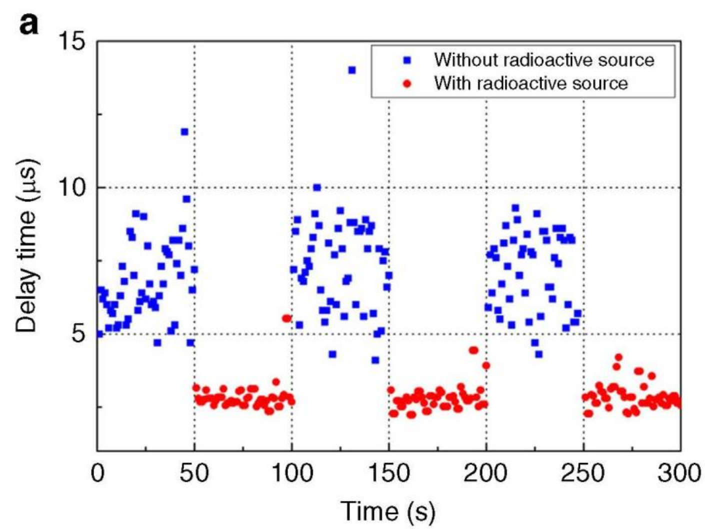
Figure 8 | Schematic of a possible setup for the detection of radioactive material inside a container. The distance from the high-power EM source to the breakdown point is $R(m) = 2D^2/\lambda$, where D is the size of the antenna's aperture, and λ is the wavelength of the incident beam.

E.Choi et al. Ulsan National Institute of Science and Technology, Ulsan 44919, South Korea

E.Choi et al. Remote detection of radioactive material using high-power pulsed electromagnetic radiation. NATURE COMMUNICATIONS (2017) DOI: 10.1038/ncomms15394

"…distance R varies from 50m to 1 km depending on air condition. Therefore, the detection range of the proposed method is limited according to the air refractive-index irregularities..."



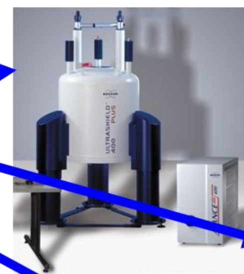


"…We successfully observed plasma breakdown in air at 60 Torr and 760 Torr in the presence of 0.64 mCi of 60Co with incident EM powers of 30 kW at the frequency 95 GHz, that is, around ten times smaller than the power required for plasma breakdown without radioactive material."

Spectroscopy

Low magnetic fields: DNP since 1960s. First DNP experiment with gyrotron: R. Griffin et al., MIT, 1993

NMR frequency	Magnetic field	DNP frequency
400 MHz	9.4 T	260 GHz
600 MHz	14 T	390 GHz
800 MHz	19 T	520 GHz
900 MHz	21 T	585 GHz
1000 MHz	23.5 T	650 GHz

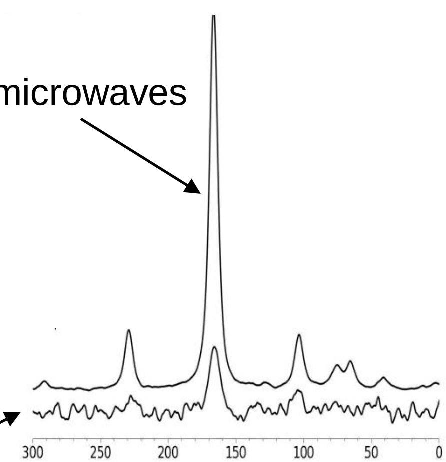


Components for high-field DNP

- **Sub-terahertz microwave sources**
- **Transmission lines**
- **Cavity compatible with NMR coil**

High magnetic fields: lack of powerful high-frequency sources for years – DNP is a new prospective application for gyrotrons. Hundreds of high-field NMR spectrometers all over the world and **resolution can be increased up to two orders** – USA, Japan, Russia, EU

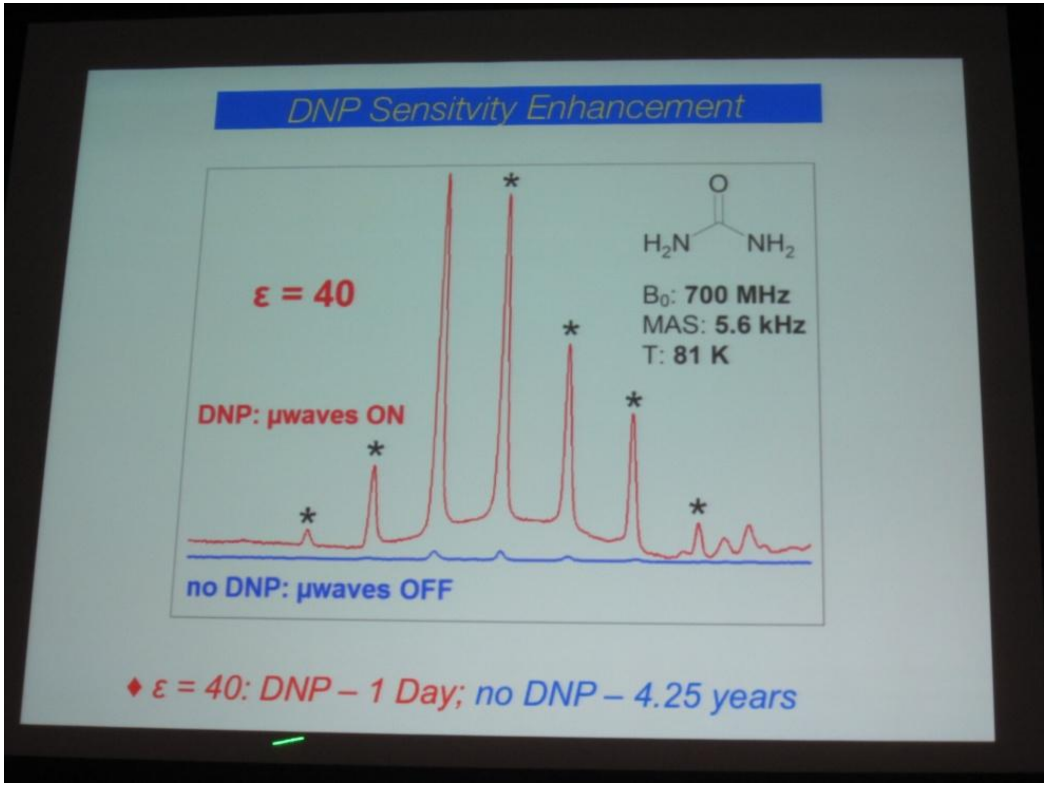
with microwaves



with microwaves x10

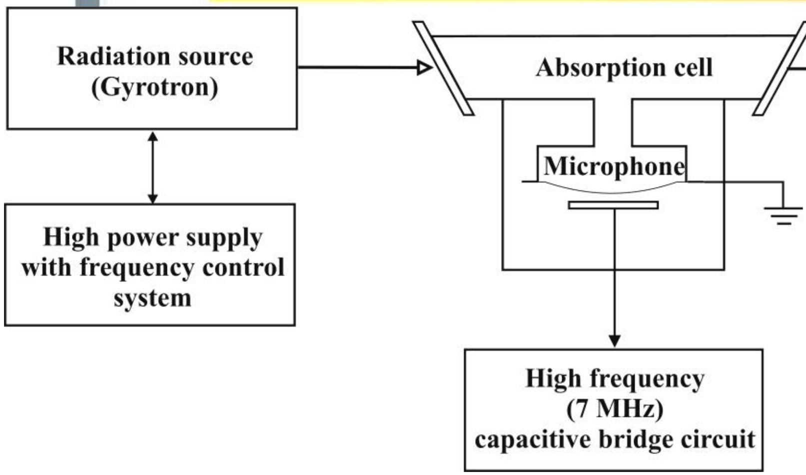
DNP/NMR spectroscopy

R.G. Griffin
High Frequency Dynamic Nuclear Polarization
The 5th International Workshop on Far-Infrared Technologies (IW-FIRT), Fukui, 2014



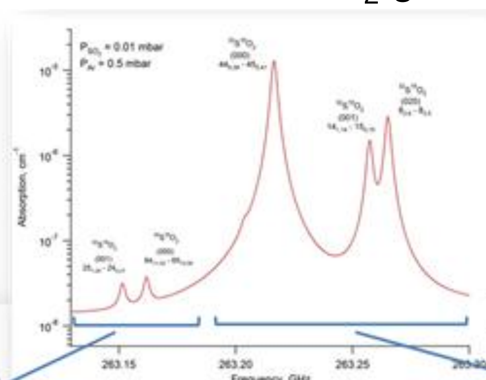
http://www.bruker.com/products/mr/nmr/dnp-nmr/overview.html

Radio acoustic spectroscopy

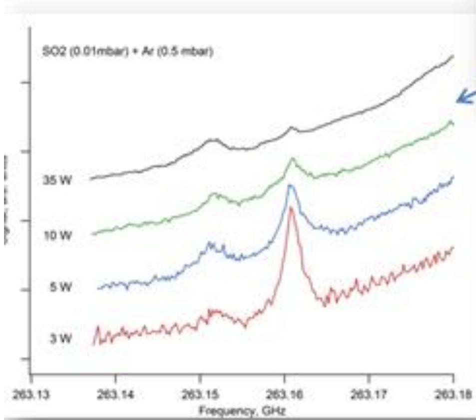


S/N ratio is increased to 1000 times!

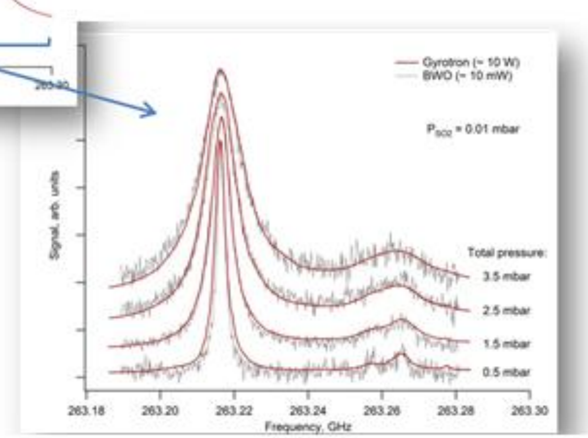
Calculation for SO_2 gas



Experiment



Experiment



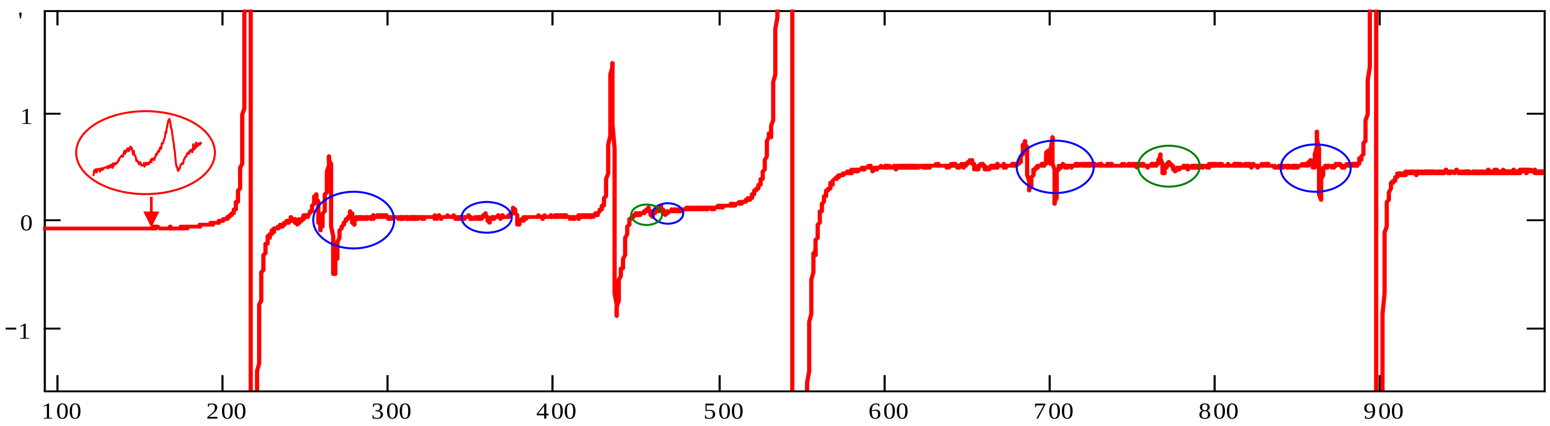
Spectroscopy (RA detectors)

RAD is spectrometer in which the result of the interaction of the radiation with matter is detected by the change of the parameters of the matter and not of the radiation

High power radiation at the fundamental was accompanied by radiation at harmonics s =2,3,4

G.Nusinovich, A.Pavelev, N.Zavolsky. "Toward a theory of parasitic radiation in gyrotrons", RQE , 1988

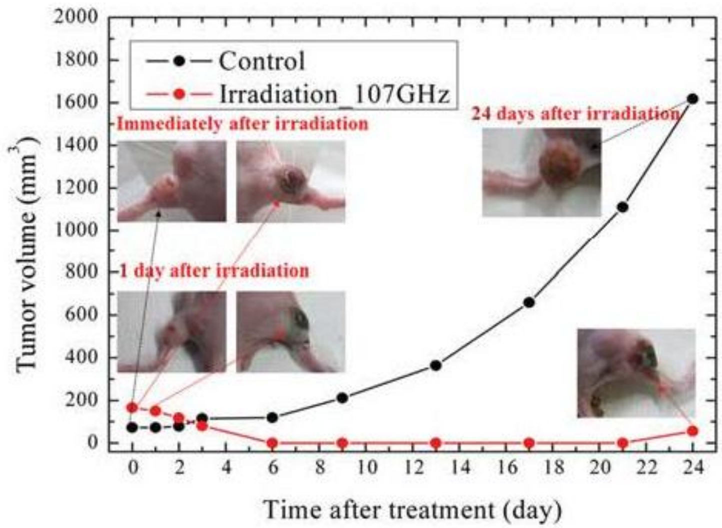
$$\frac{\partial^2 f_p}{\partial \zeta^2} - i \frac{\partial f_p}{\partial \tau} = I_p \frac{1}{2\pi} \int_0^{2\pi} p^n \, d\vartheta_0$$

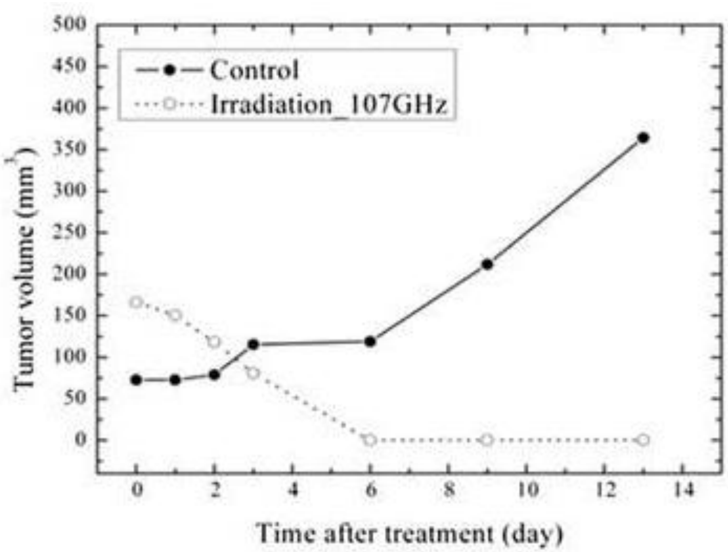


f ~ 263 GHz

FIR FU

Medicine: treatment of tumors
Gyrotron frequency about 0.2 THz





"..we studied combined treatment, namely a preheating of the tumor by a sub-THz wave and a photodynamic therapy. In this case, the temperature to which the cancerous tissue is heated is significantly lower than the hyperthermia temperature (43 °C).

The results show that such combination significantly increases the efficiency of the treatment.

In these experiments, the mouse number 2 was treated only by hyperthermia while the mice with numbers 1 and 3, respectively, were subjected to a combination of hyperthermia and PDT."

N Miyoshi, T Idehara, E Khutoryan et al. Combined Hyperthermia and Photodynamic Therapy Using a Sub-THz Gyrotron as a Radiation Source. Journal of Infrared, Millimeter, and Terahertz Waves, 2016

Terahertz molecular resonance of cancer DNA (2016)

H.Cheon University of Seoul, Republic of Korea

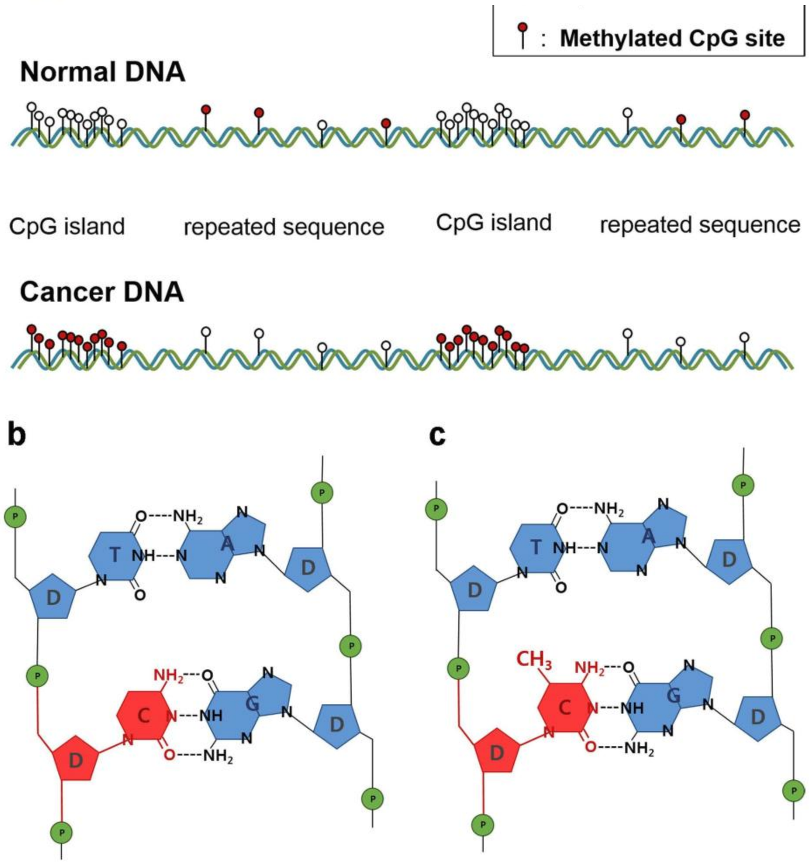
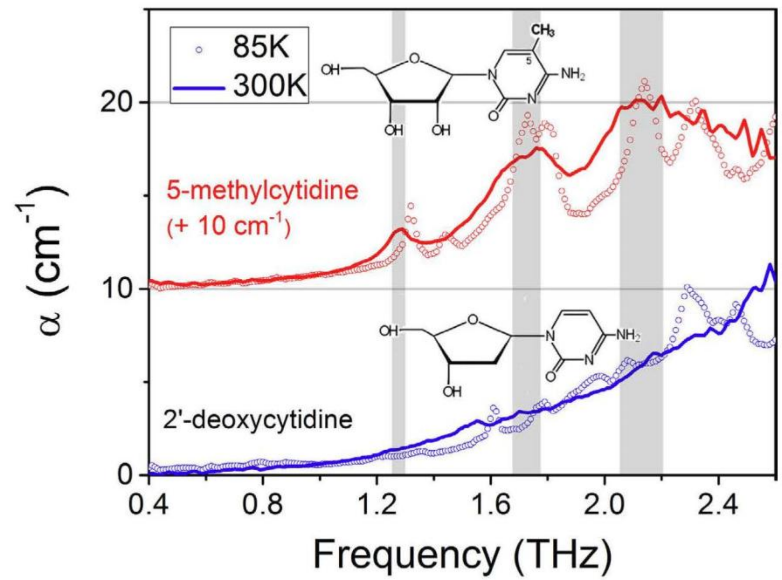


Figure 1. (**a**) Change in the distribution of 5-methylcytidine at CpG sites in cancer. This epigenetic change can be defined as a chemical change of the whole DNA[37] and can be observed in most types of cancer. Schematic of (**b**) cytidine and (**c**) 5-methylcytidine in DNA. The conversion of (**b**) to (**c**) is called DNA methylation.



"…We detected THz molecular resonance fingerprints caused by the methylation of cancer DNA extracted from living cell lines and quantified them to distinguish cancer types. Two major absorption peaks (1.29 THz and 1.74 THz) for methylation were identified."

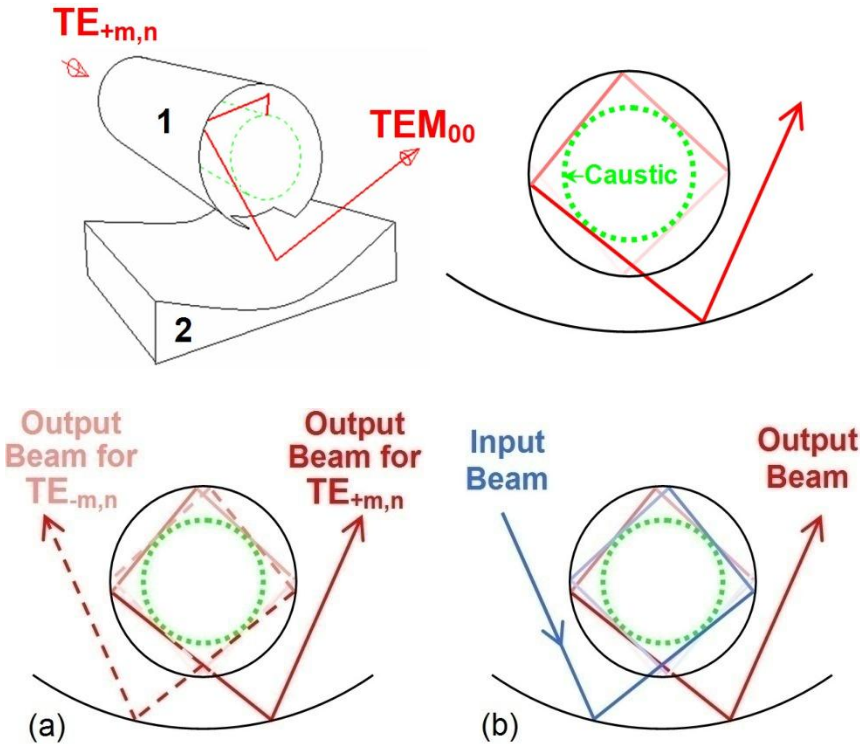
Synhronization of gyrotron by external signal

- **Provide single mode gyrotron operation at very high-order modes**
- **Stabilize frequency while e-beam parameters are not stable**
- **Enhance efficiency**
- **Lock frequency and phase / Make several (many?) gyrotrons coherent**

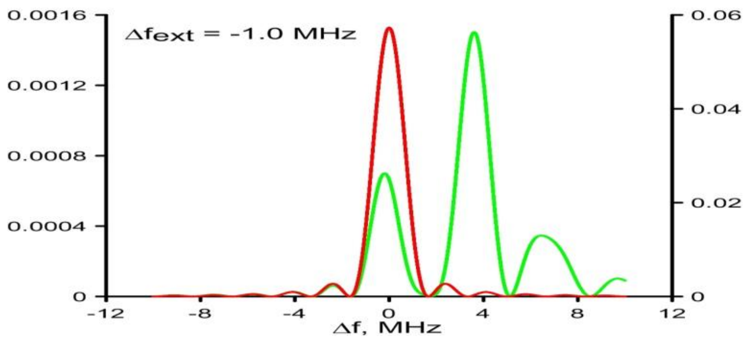
Discussions since 1978
(Ergakov, Fliflet, Nusinovich)
New round since 2012 (IAP)
- Many (e.g. 20) competing modes
- Realistic switching-on scenario in calc.
- **Novel QO input unit**

Beam switching & oscillation locking

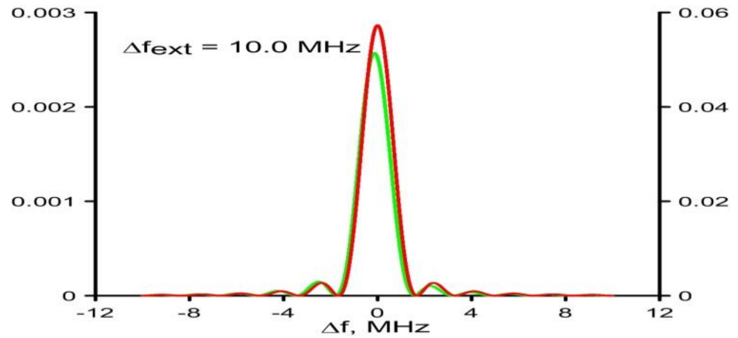
Conventional and improved converters of high order $TE_{m,n}$ mode into Gaussian beam



G.Denisov, A.Bogdashov, I.Gachev, S.Mishakin, S.Samsonov New Radiation Input/Output Systems for Millimeter-Wave Gyrotron Traveling-Wave tubes Radiophys. Quantum Electr. 58 (10), 769-776



No locking



Locking

df~30 MHz (without external signal)
df~4 MHz (with external signal)

Particle acceleration

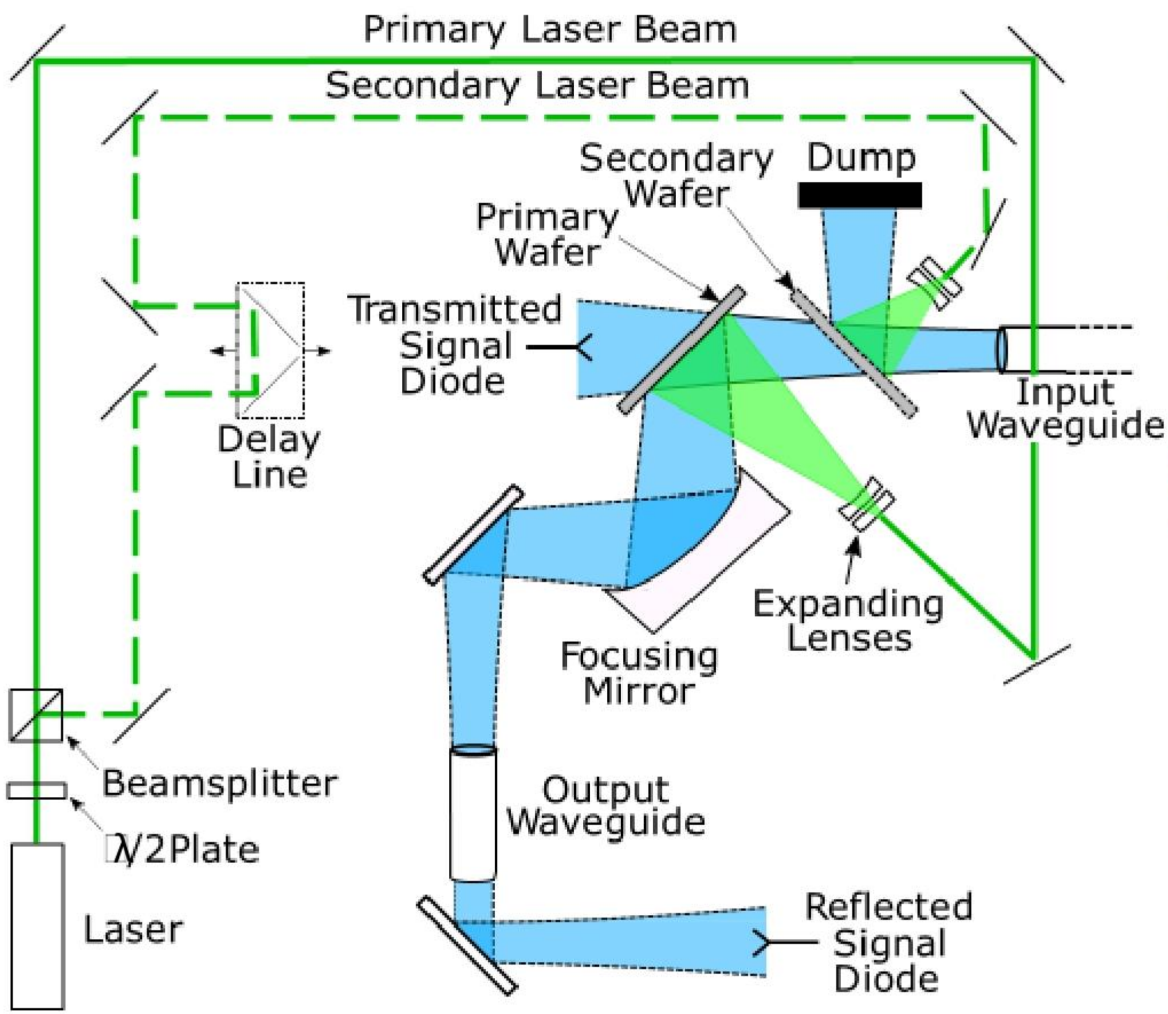
Franz X. Kärtner

DESY - Center for Free-Electron Laser Science, Ultrafast Optics and X-Rays Group, Hamburg, Germany and Department of Physics, The Hamburg Center for Ultrafast Imaging, Universität Hamburg, Germany

THz Acceleration Roadmap for the next 5 years

Year	2019	2020	2021	2022	2023	2024
Driver	Laser Driver	Laser Driver	Gyrotron GHz	Gyrotron GHz	Gyrotron GHz	Gyrotron GHz
Frequency in GHz	300	300	170	170	170	170
Repetition Rate in Hz	10	10	1000	1000	1000	1000
Prim. Pulse Length in ns	0.25	0.5	1000	1000	1000	10000
Pulse Power in MW	8	20	0.03	2	2	5
Pulse Energy in mJ	4 x 2	2 x 10	30	2000	4000	50000
Sec. Pulse Length in ns	0.25	0.5	10	10	10	10
Sec. Peak Power in MW	8	20	3	200	400	5.000
Accel. Field in MV/m	100	200	40	140	200	900
E-Beam Energy in MeV	10	20	60	210	300	1350
Initial Energy in MeV	0.1	0.5	1	2	2	5

MIT initial gyrotron experiment



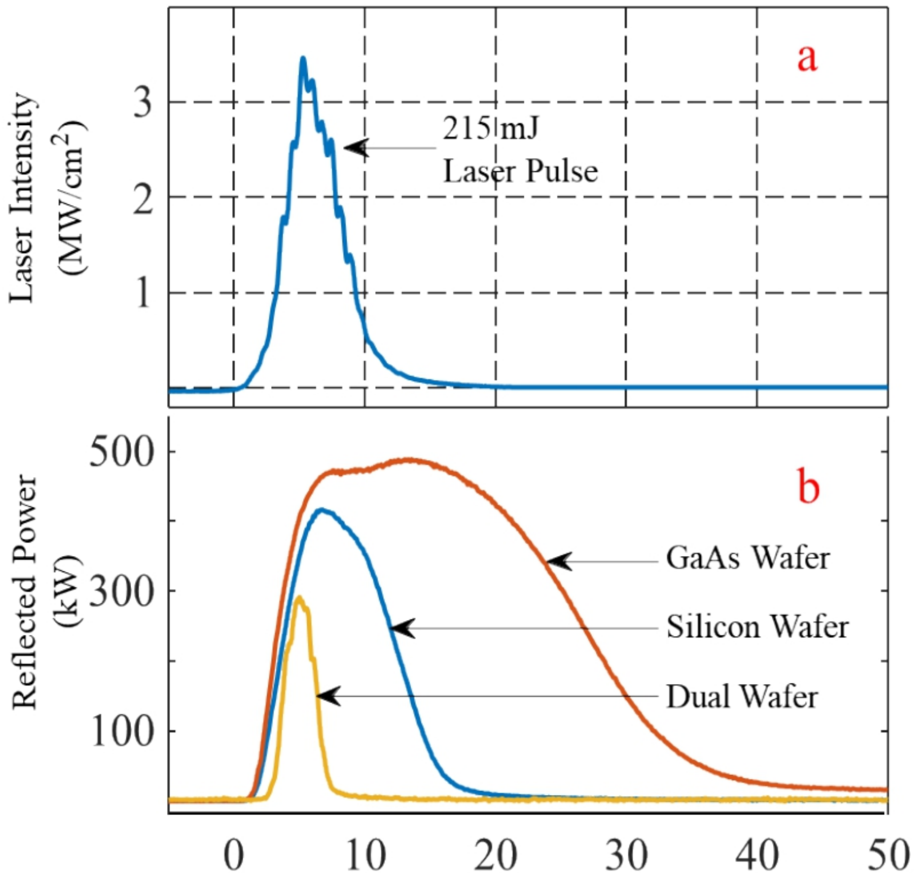
- 110 GHz microwaves generated by gyrotron
- 3 μs rf pulse
- up to 1.5 MW (run at 600 kW max.)

- Laser 532 nm, 230 mJ
- 6 ns pulse

- Exp. 1 – Single Wafer (Si or GaAs)

- Exp. 2 – Dual Switch
  1st wafer Si
  2nd wafer Ga As

J.F.Picard, S.C.Schaub, G.Rosenzweig, J.C.Stephens, M.A.Shapiro, R.J.Temkin
Laser-driven semiconductor switch for generating nanosecond pulses from a megawatt gyrotron Appl. Phys. Lett. 114, 164102 (2019)



- Gyrotron 110 GHz, 525 kW, 3 μs

- Laser 532 nm,
energy 215 mJ,
peak intensity at wafer
3.5 MW/cm^2,
energy density 15.3 mJ/cm^2
- 6 ns pulse

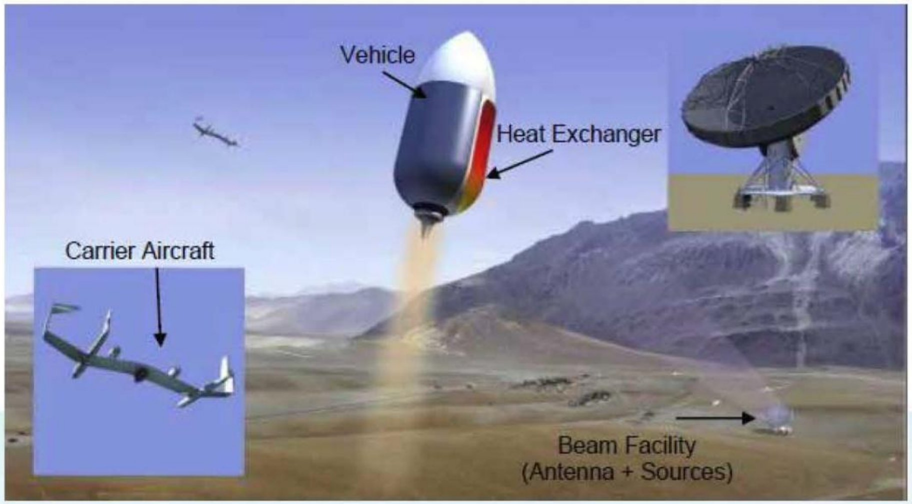
- Dual Wafer:
Laser: 120 mJ primary Si wafer + 100 mJ secondary GaAs wafer

- Si: reflected power drops after laser pulse.
- GaAs: reflectance persists for 10 ns after peak laser intensity
- Dual wafer pulse width 3 ns

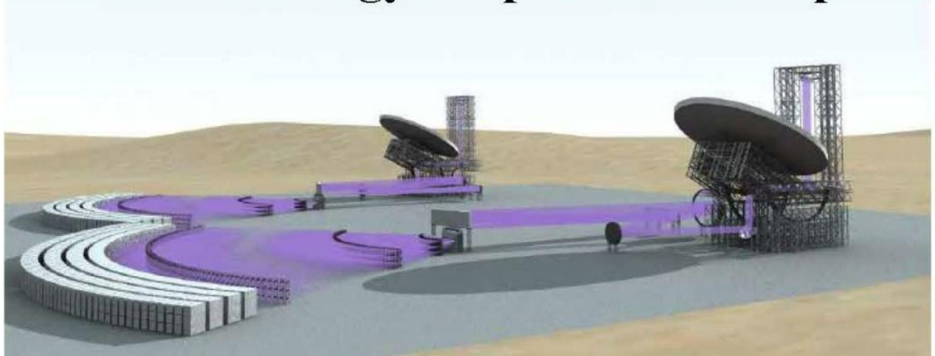
J.F.Picard, S.C.Schaub, G.Rosenzweig, J.C.Stephens, M.A.Shapiro, R.J.Temkin
Laser-driven semiconductor switch for generating nanosecond pulses from a megawatt gyrotron Appl. Phys. Lett. 114, 164102 (2019)

Rocket Launcher (1 GW ~ 1 MW / 1000 tubes)

Gyrotrons synchronization by "master" tube (control signal a few percent)

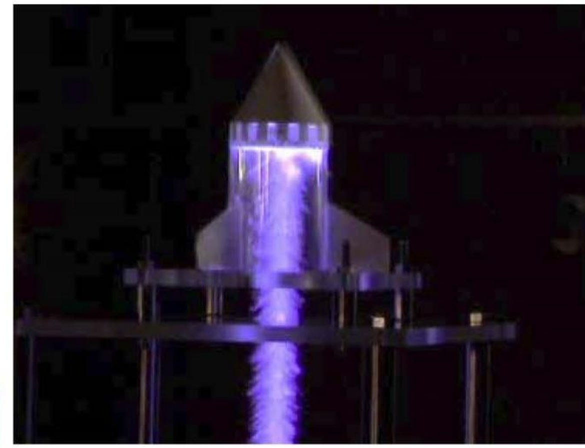


Beamed Energy Propulsion Concept



Rocket Launch – Artist's Concept, NASA

A. Murakami, AIAA, 2012



Lab test of rocket at JAEA by Univ. Tokyo team

J. Oda, JAEA, 2012

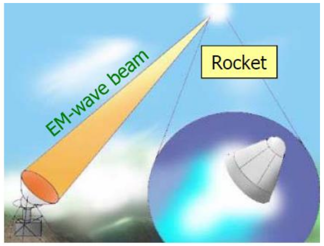
Far future (1 MW / 100 000 tubes synchronization)

Rocket Propulsion Powered by a Gyrotron

Kimiya Komurasaki,
Professor,
Department of Aeronautics & Astronautics,
The University of Tokyo

Electric Power for Launchers

Beamed Energy Propulsion
Power is wirelessly provided from the ground to a vehicle by a laser/microwave beam.



Pulse Detonation Engine type

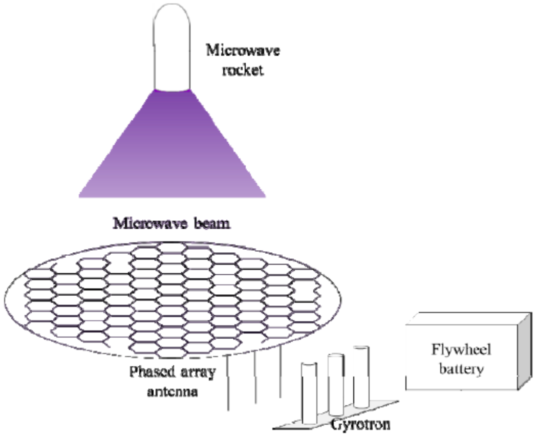
Beam oscillators on the ground → Reusable, redundant → Amortizable construction cost

Coupling with advanced aerospace technologies

Air-breathing → No combustion, infinite I_{sp} → High Payload ratio; Clean, Safe

Pulse detonation → No turbo-pumps → Low manufacturing cost

Requirements for Gyrotrons



Requirements

Item	value
Receiver diameter	8.5 m
Cutoff altitude	20.6 km
Max. acceleration	15 g
Average Beam Power	194 GW
Duty cycle	0.24
Thrusting time	26.8 sec

97 000 tubes

Summary

High average and pulsed power
Low current - 20 mA operation
Low voltage ~ 1.5-2 kV operation
Wide fine frequency tuning (up to 10%) and step tuning (up to 100%)
High frequency – up to 1.5 THz at fundamental and 1.2 at second harmonic
Experimental excitation of high harmonic – up to 5th
Methods of improved mode selection
High stability – 10^{-10}-10^{-12}

Rapid increasing of applications

On the East and on the West ,
powerful THz - gyrotrons are the best !

FIR FU

Research Center for Development of Far-Infrared Region University of Fukui, Japan

Calabazas Creek Research, Inc.

MIT, CPI, UMD, Bridge 12, Calabazas Creek Research Inc, USA

Centre de Recherches en Physique des Plasmas, Ecole Polytechnique Federale de Lausanne (EPFL)

University of Science & Technology of China

Peking University, China

Korea Electrotechnology Research Institute (KERI), South Korea

Ulsan National Institute of Science and Technology, South Korea

Institute of Applied Physics Russian Academy of Sciences, Nizhny Novgorod, Russia

V.Bratman, G.Denisov, N.Ginzburg, V.Manuilov, A.Luchinin, A.Kuftin, A.Savilov, V.Zapevalov et al.

Many thanks to all colleagues from IAP and other countries and institutes who take part in such activity and as “mode competition and cooperation in the cavity” push up gyrotron quality.

Thank you for your attention!