Techniques for Generation of Terahertz Radiation

E.V.Suvorov

Institute of Applied Physics of Russian Academy of Sciences
46, Uljanov Str., 603950, Nizhny Novgorod, Russia

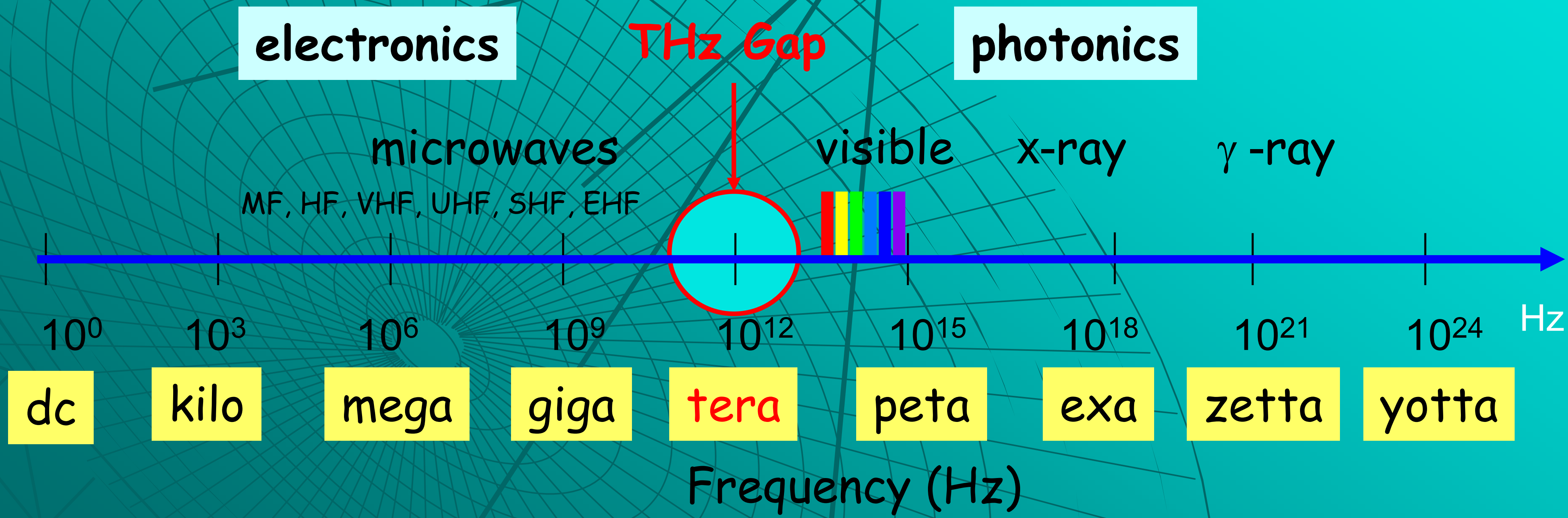
FNP – 2007
July 3 – 9, 2007
"Georgy Zhukov"
N.Novgorod – Saratov - N.Novgorod
Russia

OUTLINE

- Motivation
- Generation by means of vacuum electronics
- Generation by means of “optoelectronics”
- “Exotic” ways
- Conclusions

T-Ray: Next frontier in Science and Technology

Terahertz wave (or T-ray), which is electromagnetic radiation in a frequency interval from 0.1 to 10 THz, lies a frequency range with rich science but limited technology.



1 THz ~ 1 ps ~ 300 μm ~ 33 cm^{-1} ~ 4.1 meV ~ 47.6 °K

APPLICATIONS

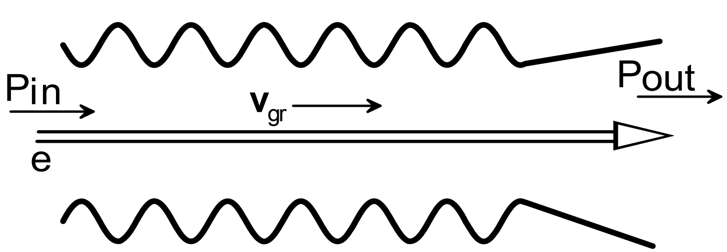
Spectroscopy:	Chemistry, Aeronomy, Ecology, Radioastronomy, …
Tera-imaging:	Biology, Biomedicine, Microelectronics, Technology, Security, …
Plasma diagnostics:	Interferometry, Faraday, Cotton-Mauton, …

…

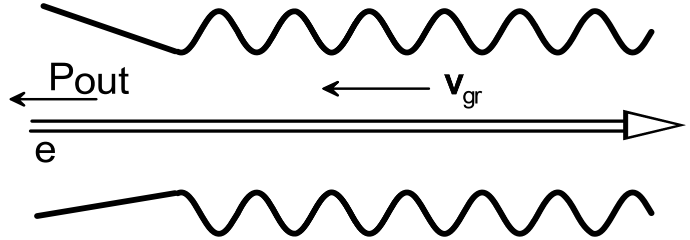
Vacuum electronics

- ♦Cherenkov generation (BWOs, TWTs, Orotrons)
- ♦Transition generation (Klystrons)
- ♦Bremsstrahlung (gyrodevices, FELs)
- ♦Scattering generation

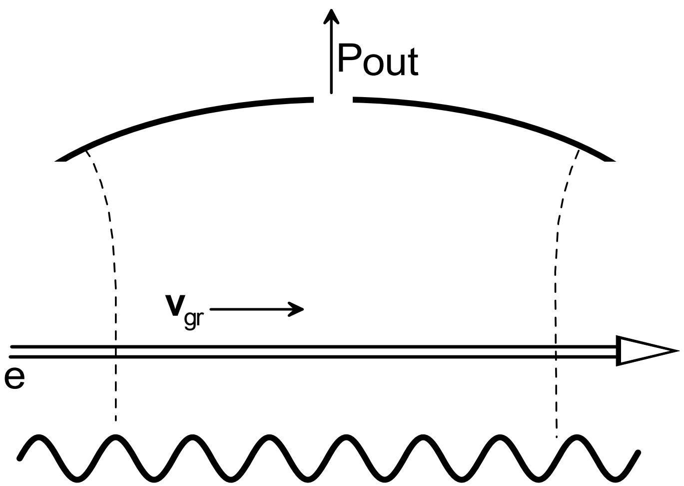
Cherenkov generation



TWT



BWO



Orotron, or Diffraction Radiation Generator

$$\omega = h\upsilon$$

$$h = \frac{2\pi}{d}$$

$$\Lambda_{\perp} = \frac{1}{\sqrt{h^2 - k^2}} = \frac{\beta\gamma\lambda}{2\pi}$$

$$\beta = \upsilon / c$$

Commercial BWOs (“ISTOK”, Fryazino, Russia)

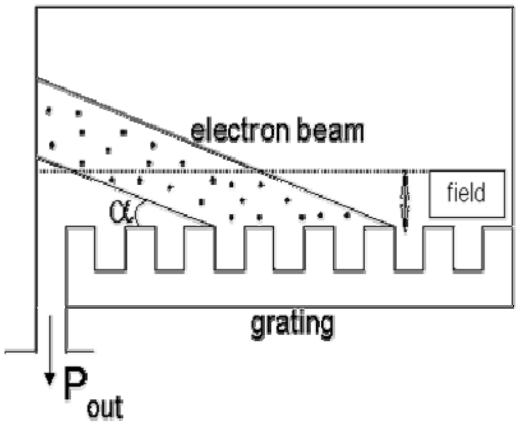
Tube	OB-30	OB-32	OB-80	OB-81	OB-82	OB-83	OB-84*	OB-85*
Band, GHz	258 - 375	370 - 535	530 - 714	690 - 850	790 - 970	900 - 1100	1070 - 1200	1170 - 1400
Output power (min), mW	1 - 10	1 - 5	1 - 5	1 - 5	0.5 - 3	0.5 - 3	0.5 - 2	0.5 - 2
Power variation (over the band), dB	13	13	13	13	13	13	13	13
Acc. Voltage, kV	1.0-4.0	1.0 – 5.0	1.5 – 6.0	1.5 – 6.0	1.5 – 6.0	1.5 – 6.0	1.5 – 6.0	1.5 – 6.0
Cathode current, mA	25 - 40	25 - 40	30 - 45	30 - 45	30 - 45	30 - 45	30 - 45	30 - 45
Guiding magnetic field, kOe	7	9	10	10	11	11	11	11
Output waveguide	1.2x2.4	1.2x2.4	1.8x3.6	1.8x3.6	1.8x3.6	1.8x3.6	1.8x3.6	1.8x3.6

- Temporarily not produced

Submm TWTs have been also designed

Clinotron variety of BWO

(Kharkov Institute of Radio Astronomy)



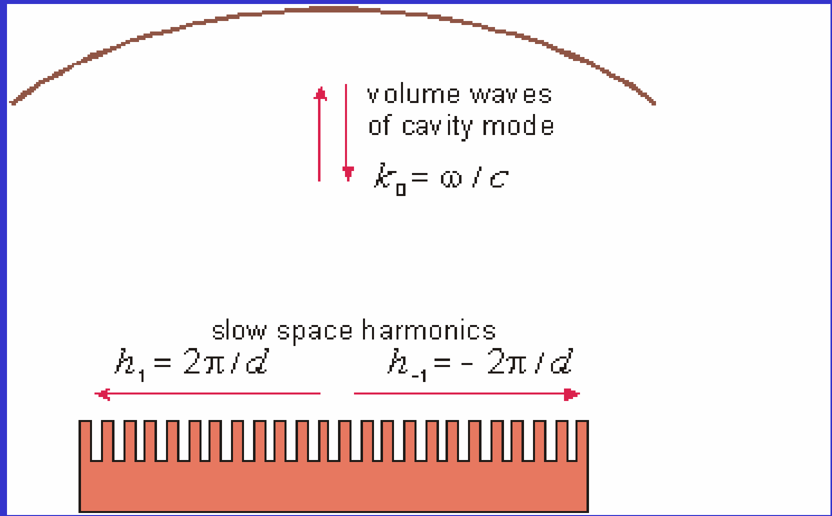
mm-wave clinotron

submm-wave clinotron

Model	Frequency band, GHz	Max Output Power, W	Max. Anode Voltage, kV	Max. Anode Current, mA	Weight, kg	Cooling
CTN-5M3	53-63	11.0	4.0	200	1.2	liquid
CTN-3M3	79-98	5.0	5.0	150	1.2	liquid
CTN-2.5M3	113-122	3.0	4.3	180	1.2	liquid
CTN-2.2M3	120-141	2.0	4.5	160	1.2	liquid
CTN-2.0M3	137-151	2.0	4.5	140	1.2	liquid
CTN-0.8M8	**345-390**	**0.1**	**5.0**	**160**	**12**	**liquid**
CTN-0.5M8	**442-510**	**0.05-0.1**	**5.5**	**200**	**12**	**liquid**
CTN-3MT	82-96	5.0	4.0	160	3.0	heatpipe

LOW-VOLTAGE OROTRONS

Cherenkov oscillator with open cavity and reflecting grating (F.S. Rusin, G.D. Bogomolov) "Diffr. Rad. Generators" (V.P. Shestopalov et al.)



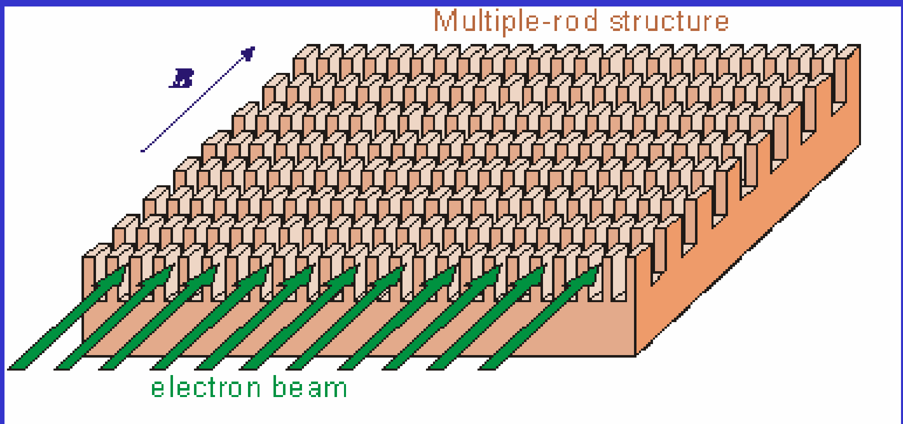
Slow-wave structure creates spatial harmonics of cavity mode. The first harmonic is in synchronism with electrons:

$$\omega = h_1 v = \frac{2\pi}{d} v$$

Amplitude of the synchronous harmonic decreases at the distance $\Lambda = \frac{d}{2\pi}$

Small part of electrons moving over the structure interacts with the wave.

In order to avoid it, electrons move inside a multiple-rod structure!



Rods: 20 μm × 50 μm × 500 μm. Main problem: manufacturing the structures.

OROTRONS IN IAP AND GYCOM

In collaboration with Institute of Metrology of Time and Space and Institute of Spectroscopy

Thermionic cathode 3 mm×0.3 mm. Current density 30 A/cm^2.

Two-mirror open cavity with output Waveguide (Q~3,000 - 8,000).

Multiple-rod periodic structure.

Packaged with permanent magnets (1.25 T, 23 kg).

Electronic and mechanical frequency tuning.

	OR-180	OR-290	OR-360
Frequency band, GHz	100 ÷ 190	120 ÷ 300	200 ÷ 370
Output power, mW	200 ÷ 1000	100 ÷ 200	60 ÷ 100
Period of structure, μm	170	120	100
Voltage, kV	0.8 ÷ 3.0	0.6 ÷ 3.7	1.1 ÷ 4.0
Electron current, mA	< 200	< 300	< 250
Frequency stability	10^{-6}	10^{-6}	10^{-6}
Fine frequency tuning, %	0.03	0.02	0.02
Pulse duration	50ns-1ms	50ns-1ms	50ns-1ms

Submm-wave gyrodevices

$$\mathbf{f}\ (\text{THz}) \approx n\ (B\ /\ 36\ \text{T})$$

Strong magnetic field
OR – **high cyclotron harmonics**
OR – **both**

1. Conventional gyrotrons (n = 1,2)

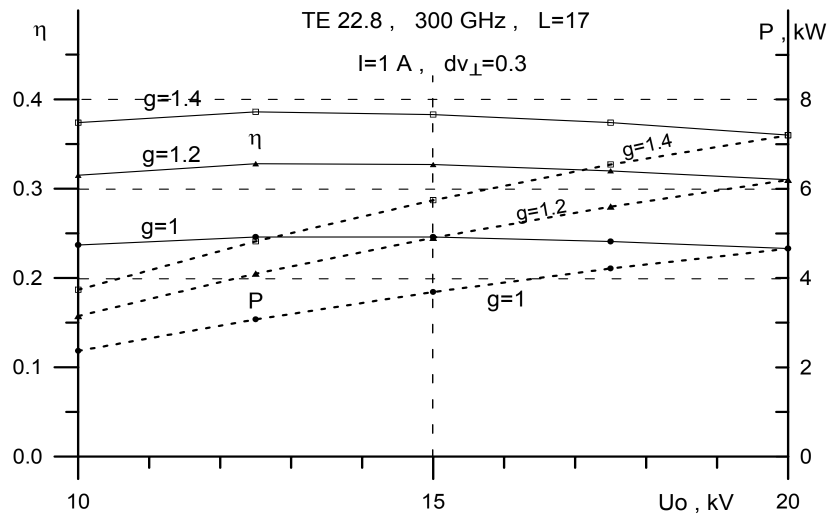
a) CW gyrotrons with frequency up to 600 GHz

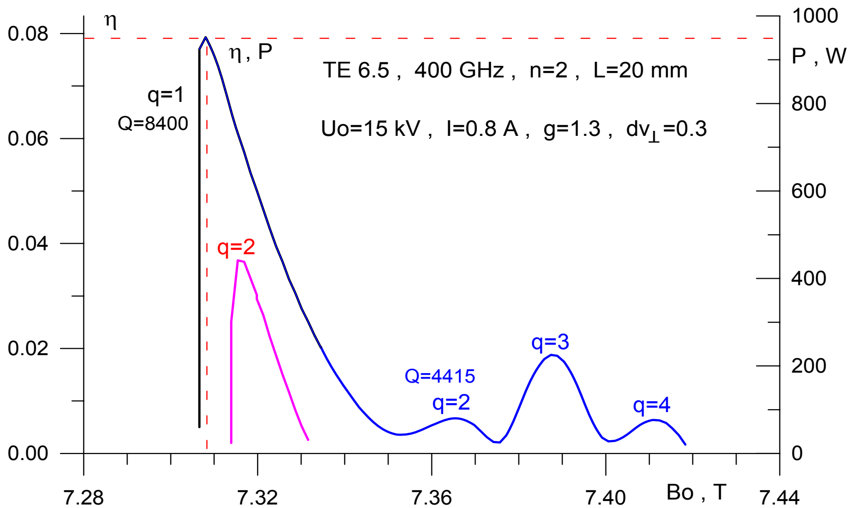
b) gyrotrons with strong pulsed magnetic fields

2. Large-Orbit Gyrotrons (LOGs)

3. Frequency multipliers

300GHz/4kW/CW Gyrotron (n=1); V.Zapevalov, e.a., 2005
MAGNETIC SYSTEM (12T LHe-free SC magnet)
Collaboration with FIR Center FU





Project
400GHz/0.2kW/CW Gyrotron (n=2)

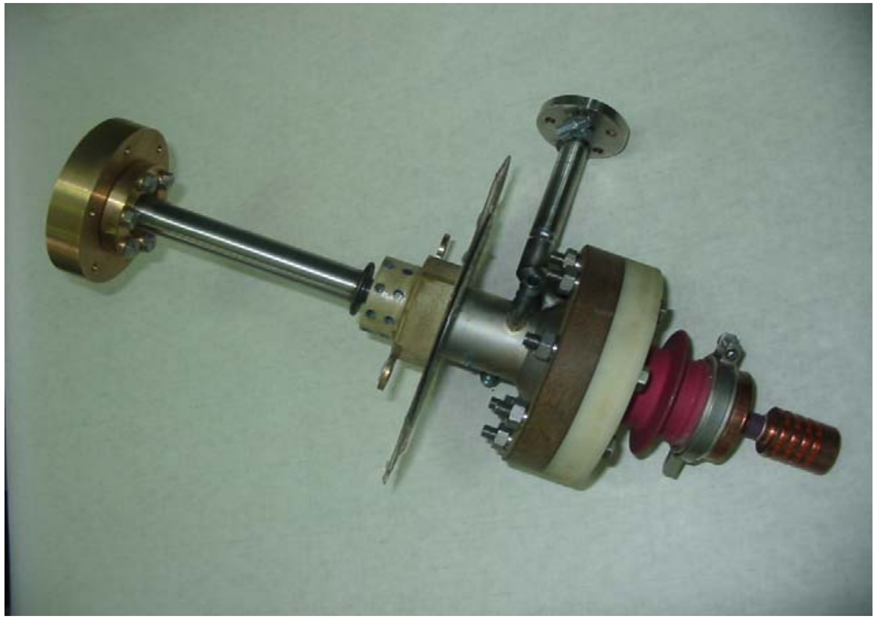
M.I.Petelin et al., 1974: 330GHz/1.5kW/CW Gyrotron (n=2)

1THz/0.5kW/100 μs Gyrotron (n=2)

PULSED MAGNETIC FIELD (20T magnet)

M.Glyavin, e.a., 2005

V.Flyagin, e.a., 1983: 0.65THz/40kW/50μs Gyrotron (n=1)



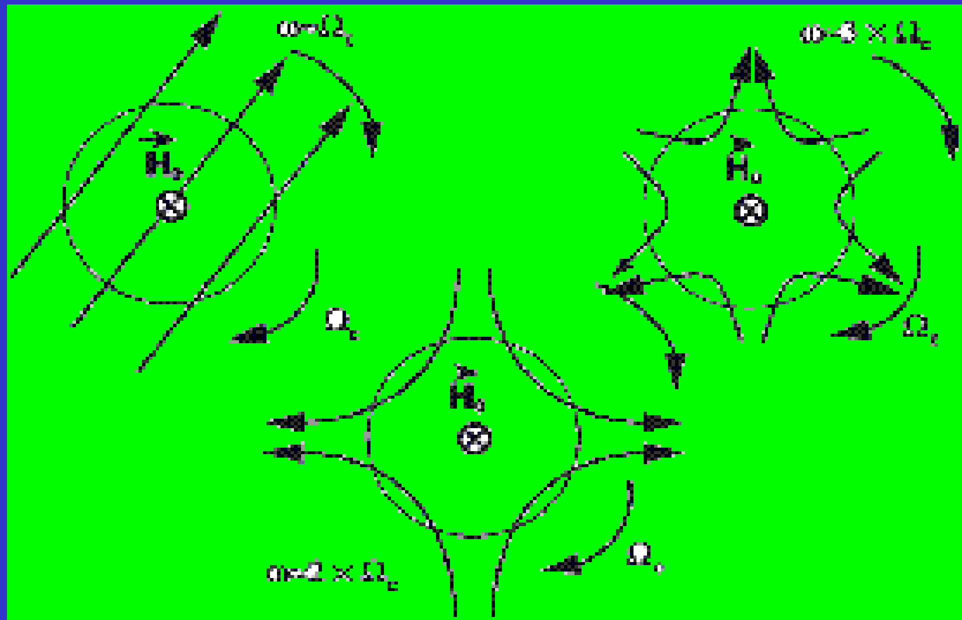
1THz / 1.5kW / 50μs Gyrotron (n=1)

PULSED MAGNETIC FIELD (40T, LN-cooling system)

M.Glyavin, e.a., 2007

ATTRACTIVITY OF HIGH CYCLOTRON HARMONICS IN LARGE ORBIT GYROTRONS

$$\omega \approx s\Omega_c$$



Resonance interaction of a gyrating electron with the synchronously rotating electric multipole (2s-pole)

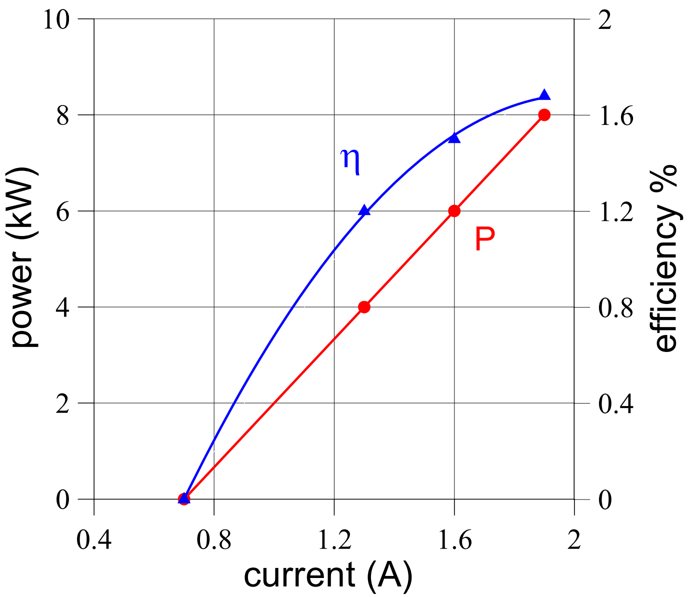
Perfect selection over azimuthal index!

Large orbit gyrotrons

V.Bratman, e.a., 2005

370-414GHz/10kW/10μs LOG (n=3)

PULSED MAGNETIC FIELD (7T magnet)



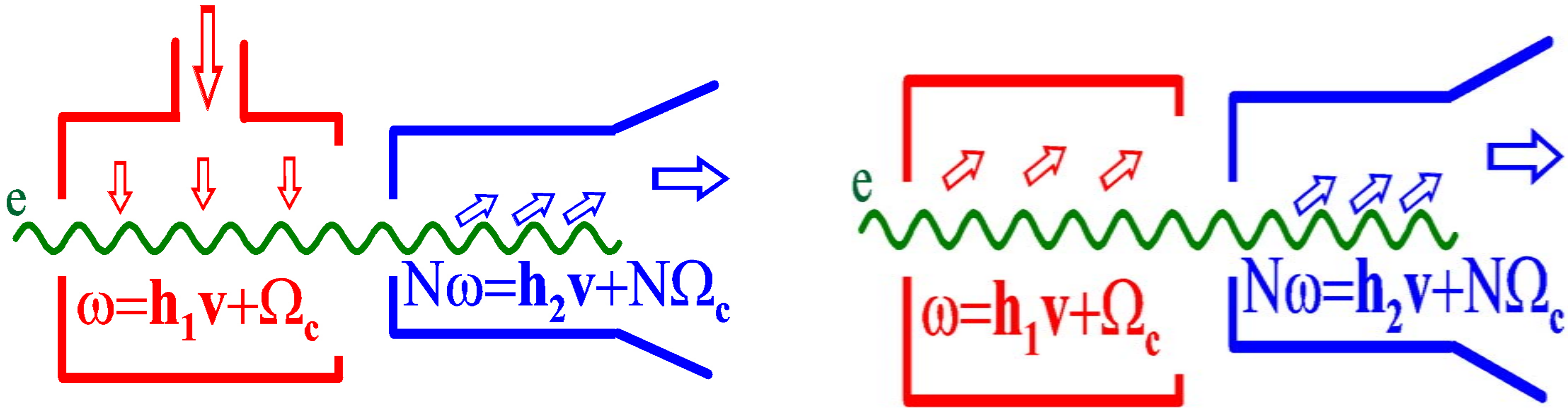
Projects of 3rd-harmonic LOGs with cusp guns:

80 keV/0.7 A/10μs 13.6 T TE3,5 1 THz 1 kW

30 keV/ 1 A/ CW 7 T TE3,5 0.6 THz 0.5 kW

FREQUENCY MULTIPLICATION

Development of old idea: Gyromultiplier *without* external signal
V.Bratman, G.Denisov, e.a.,2005



***LF section*: self-generation at the fundamental cyclotron harmonic N =1 at the frequency ω**

***HF section*: the bunched electron beam radiates the HF wave at a multiplyed frequency, Nω , and at the high cyclotron harmonic, N**

95/285 GHz gyrotron with frequency multiplication

FINAL GOAL:

to obtain THz radiation in a third harmonic CW compact gyrotron, operating in 10T cryomagnet

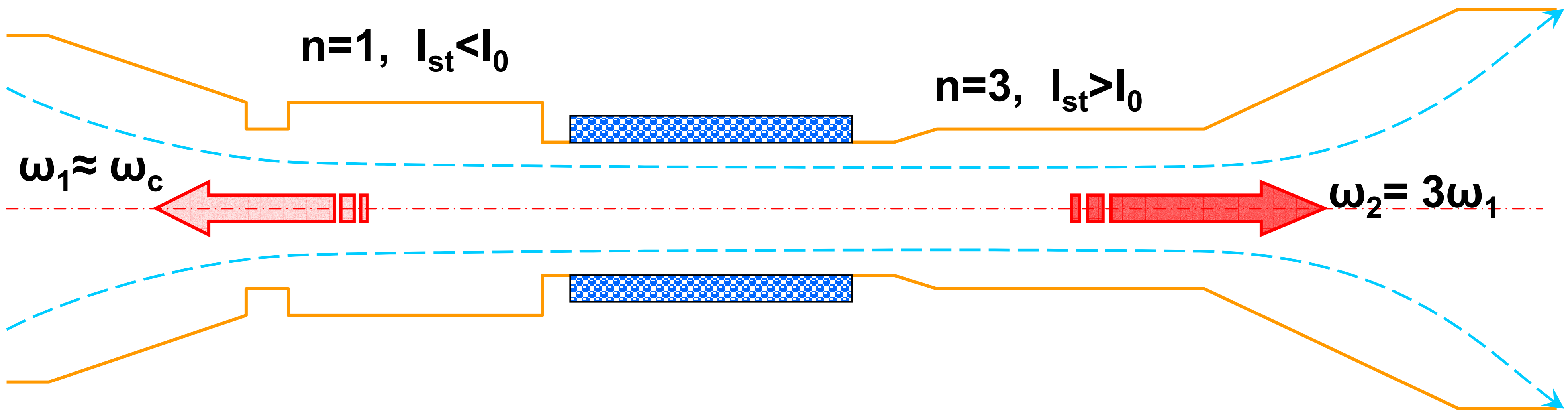
PROBLEMS OF CONVENTIONAL GYROTRONS:

- ✓ high starting current of operating mode
- ✓ strong mode competition
- ✓ high ohmic loses in RF circuit

PROPOSED SOLUTION:

two-cavity gyrotron with frequency multiplication. Its first cavity is self - excited at the first cyclotron harmonic. Modulated and bunched electron beam

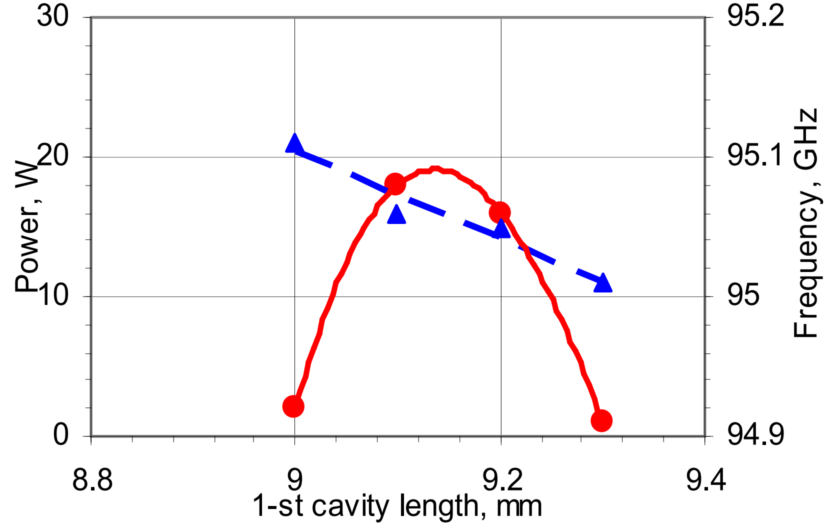
excites forced oscillations in the output cavity at triple frequency .



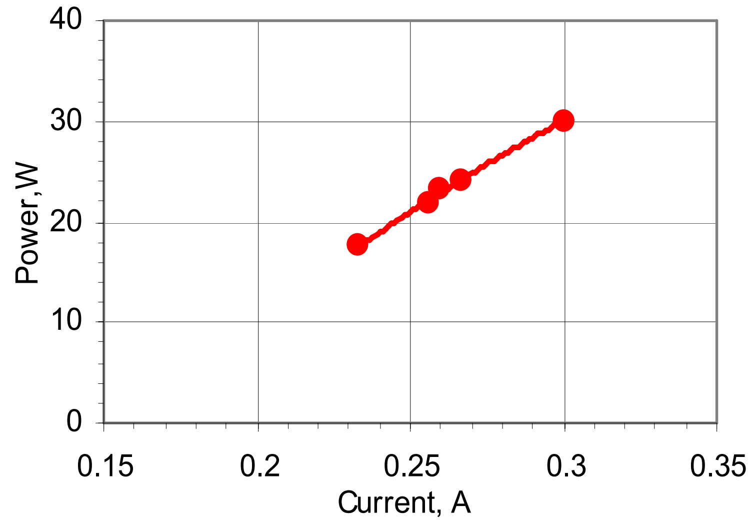
95/285 GHz gyrotron with frequency multiplication. Preliminary Test results.

GYROTRON PARAMETERS:

Voltage		25kV
Beam current		0.3A
Pitch factor		1.4
Operating frequency		95/285 GHz
Operating modes		TE_{011}(n=1)
		TE_{031}(n=3)
Cavity parameters	L_1	8 ÷10 мм,
	Q_1	1780
	L_2	12 мм,
	Q_2	3400
Output power		30W

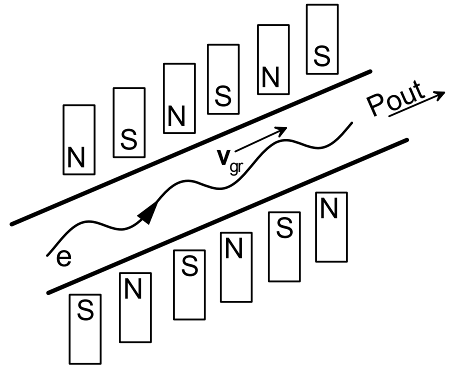


Output power and frequency of oscillations in the first cavity vs. its length at U=23kV, J=0.25A.



Output power vs. beam current at U=23.5 kV f=285.2 GHz

Free Electron Lasers

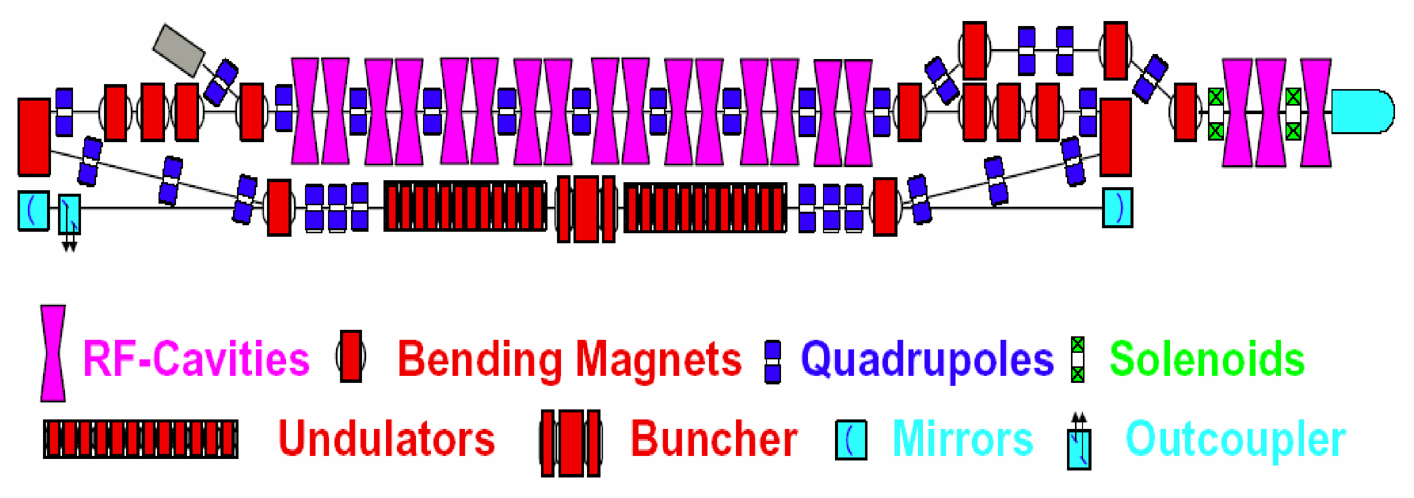


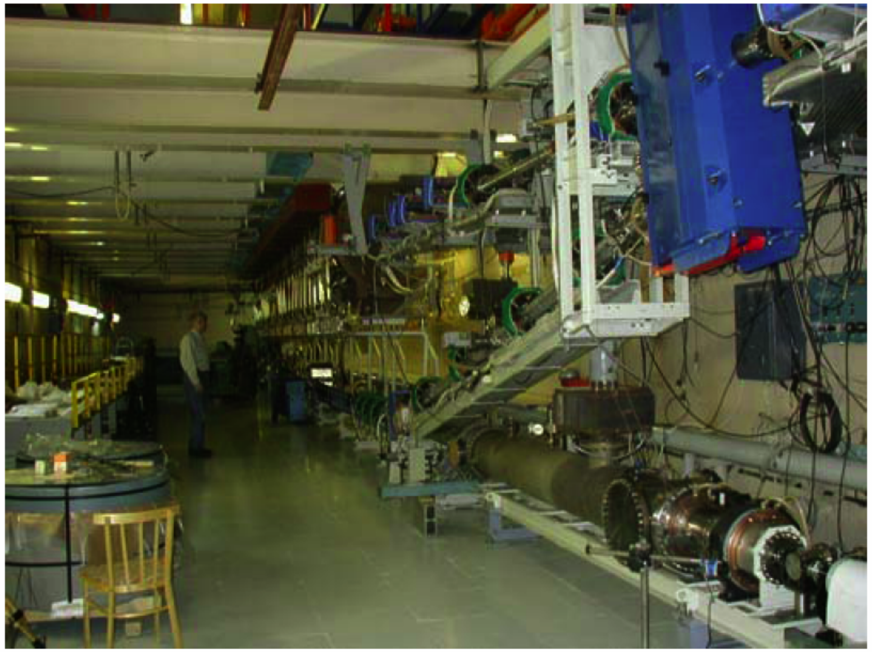
$$\lambda \sim d / \gamma^2$$

Institution	Type	Frequency, GHz	Output Power, MW	Efficiency (%)	Beam Voltage, MV	Beam Current, A
LLNL, Livermore	amplifier	140	2000	13.3	6	2500
ILE Osaka	amplifier	110	1	0.5	0.6	200
Columbia U.	oscillator	150	5	4	0.8	150
ENEA Frascati	oscillator	110-150	0.0015	0.19	2.3	0.35
NSWC/MRC	oscillator	95	10	4	2.5	100
FOM, Nieuwegein	oscillator	200, 165	0.7, 0.4	6	1.7	7
Tel-Aviv U.	oscillator	100	0.012	3	1.4	1.4
UCBS, S.Barb.	oscillator	120-880	0.027	0.5	2-6	2
INP&ICKC, Novosibirsk	oscillator	1,700-2,500	0.6 (200 W av.)	0.5	12	10

Novosibirsk FEL

(Budker Institute of Nuclear Physics & Institute of Chemical Physics and Combustion)





Electron bunches:
12 MeV, 10 A, 0.1 ns

Radiation:
120-180 μm 50 ps 5.6 MHz
0.6 MW (peak) 200W (average)

6 working stations

Prospects: 22.5 MHz
40 MeV 5-200 μm

Optoelectronics

Short pulse generation (SPG) – Femtosecond lasers

- Fast photoconducting crystals (photoswitches)
- Optical rectification (nonlinear crystals)

Quasi-cw narrow-line THz Generation
(Difference Frequency Generation – DFG)

- Photoswitches
- Nonlinear crystals

Femtosecond Lasers

- $\lambda \approx$ 600-800 nm
- $\tau \geq$ 50 fs
- W $\leq$ 100 nJ
- F ~ 100 MHz
- <P> ~ 100 mW
- P_{peak} ~ 1 MW
- Fluence ~ 10 GW/cm^{-2}

F ~ 100 kHz, W ~ 1μJ

With amplyfiers: F ~ 1 kHz, W ~ 1mJ

<P> ~ 500 mW, P_{peak} ~ 10 GW

Optical crystals

Photocond.: SOS (silicon-on-sapphire) - $\tau_{\uparrow} = 0.1$ps, $\tau_{\downarrow} = 0.6$ ps

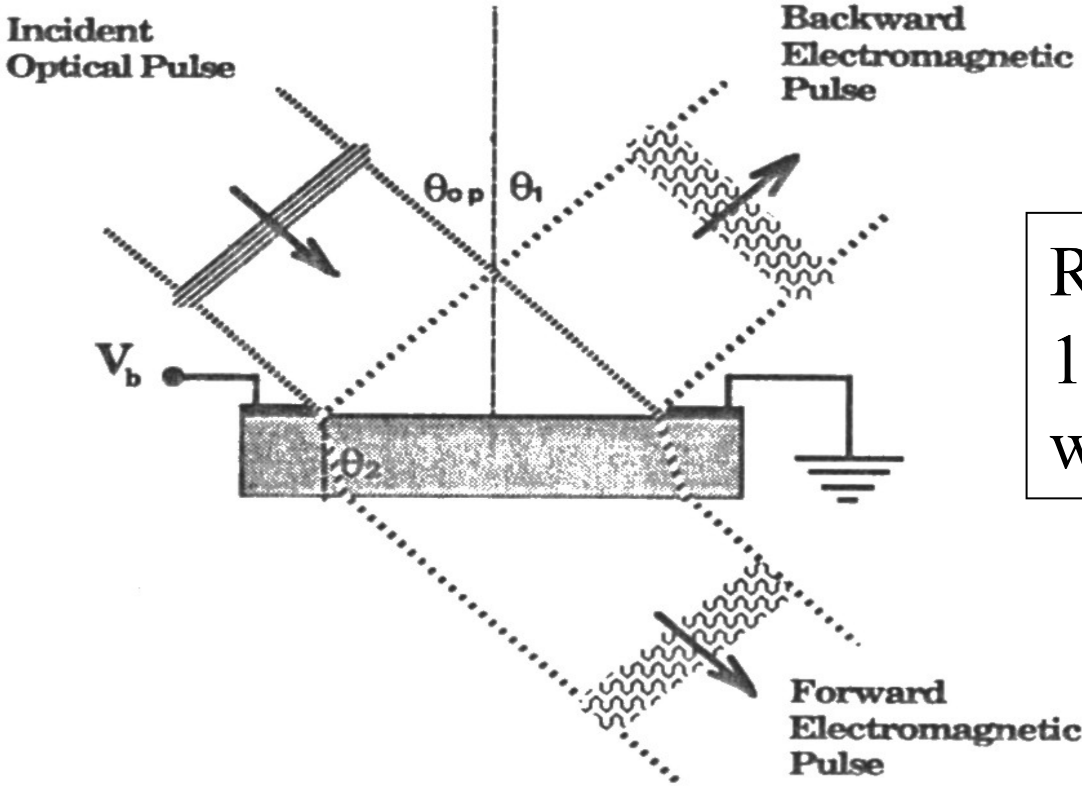
InP, GaAs, CdTe, etc.: $\tau_{\downarrow} = 50 \div 600$ ps

Materials used for the Generation of THz Beams:

EO Crystals	SC Crystals	Organic Crystals
Quartz	GaAs	DAST
$LiTaO_3$	CdTe	MOST
$BaTiO_3$	GaSb	MMONS
$SrTiO_3$	GaSe	
$LiNbO_3$	InSb	
$KNbO_3$	CdSe	
LBO	ZnSe	
GaP	InP	
SiC	Ge	
MoS_2	Si	
ZnO		
KTP		
ZnTe		

Large-aperture photoconducting Cerenkov emitter

625 nm, 75 fs, 10 mW; SOS, InP, GaAs, CdTe:
spacing 2-5 mm, $V_b \sim 100 - 3000$ V;
high "dark" resistance,
strong absorption, fast current rise



Registration:
100 μm SOS-dipole
with lens system

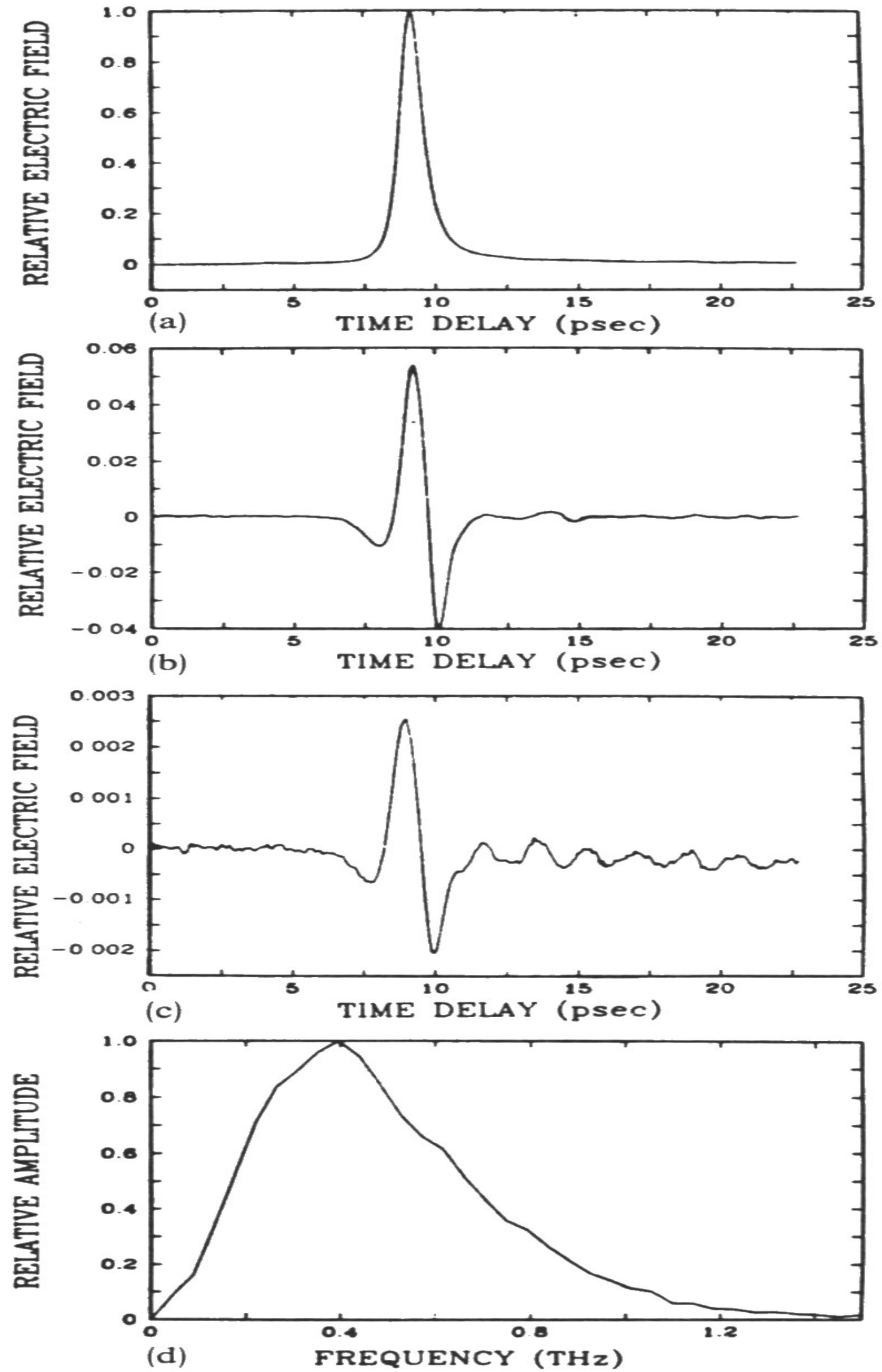
Zhang e.a., 1990

Current Pulse

a) THz pulse at 10 cm distance from the emitter

b) THz pulse at 100 cm distance from the emitter

THz pulse spectrum



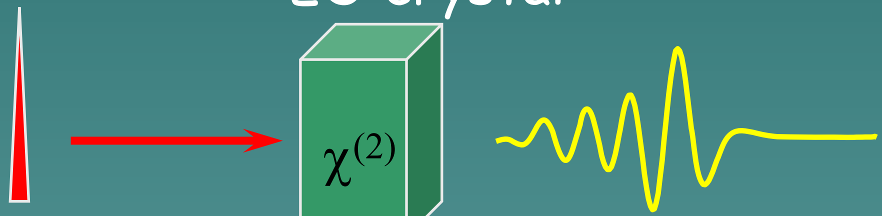
Nonlinear generation & detection of ultra-short THz pulses

Generation of THz pulse:
Optical rectification
(second order nonlinear optical effect)

Input laser pulse
$I(t, \omega, \Delta\omega)$

EO crystal

THz pulse
$E_{THz}(t, \Omega)$



$\Delta\tau$

P(t)

$$E_{THz}(t) \propto \frac{\partial^2 P(t)}{\partial^2 t}$$

$\Delta\tau\Delta\omega \approx 1$

Dielectric polarization:
$P(\Omega) = \chi^{(2)}(\Omega, \omega+\Omega, -\omega)\, E(\omega+\Omega) E^*(\omega)$

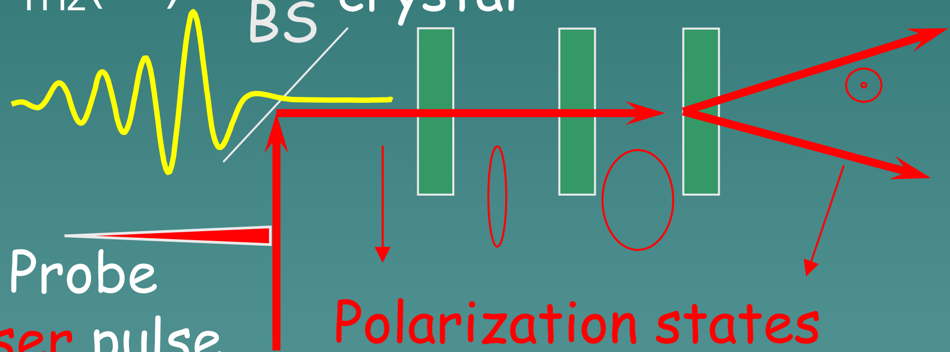
Detection
Electro-optical (EO) sampling
(*direct E field measurements !!!*)

THz pulse
$E_{THz}(t-\tau)$

BS

EO crystal

$\lambda/4$ WP



I_1

I_2

Probe laser pulse
$I(t)$

Polarization states of the probe pulse

$$\frac{I_1 - I_2}{I_1 + I_2} = \pi n^3 r_{41} \frac{L}{\lambda} E_{THz}(\tau)$$

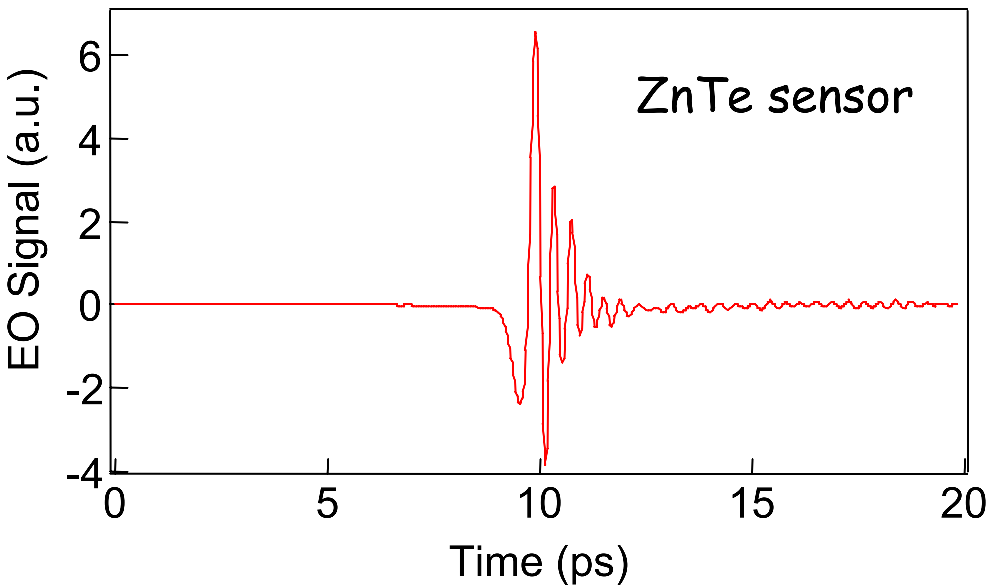
τ - variable time delay

M. Bass, et al. Phys. Rew. Lett. (1962).
G.A. A'skaryan, Sov. Phys. JETP (1962).

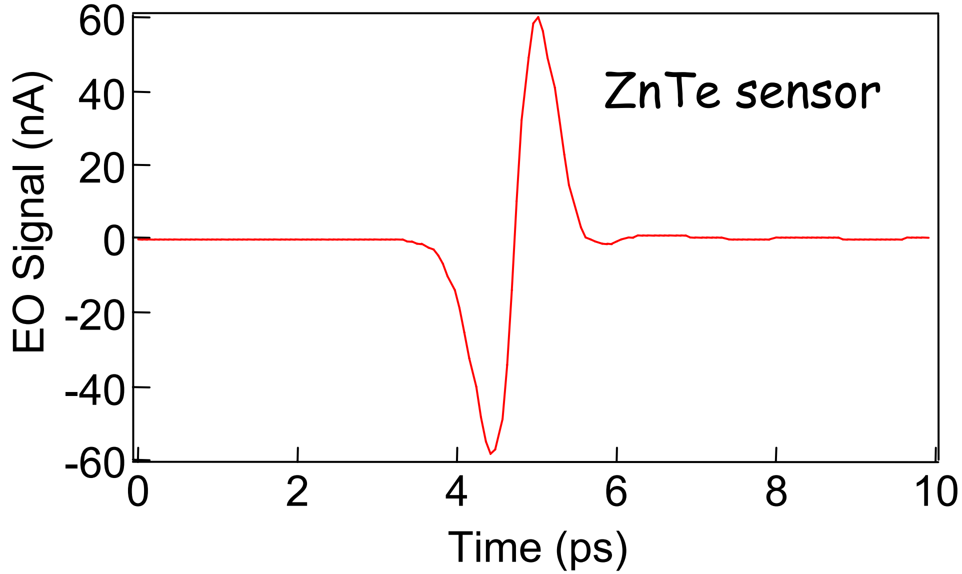
J.A. Valdmanis, et al., *APL* (1982).

Temporal THz Waveforms

0.1 ps THz pulse



1 ps THz pulse



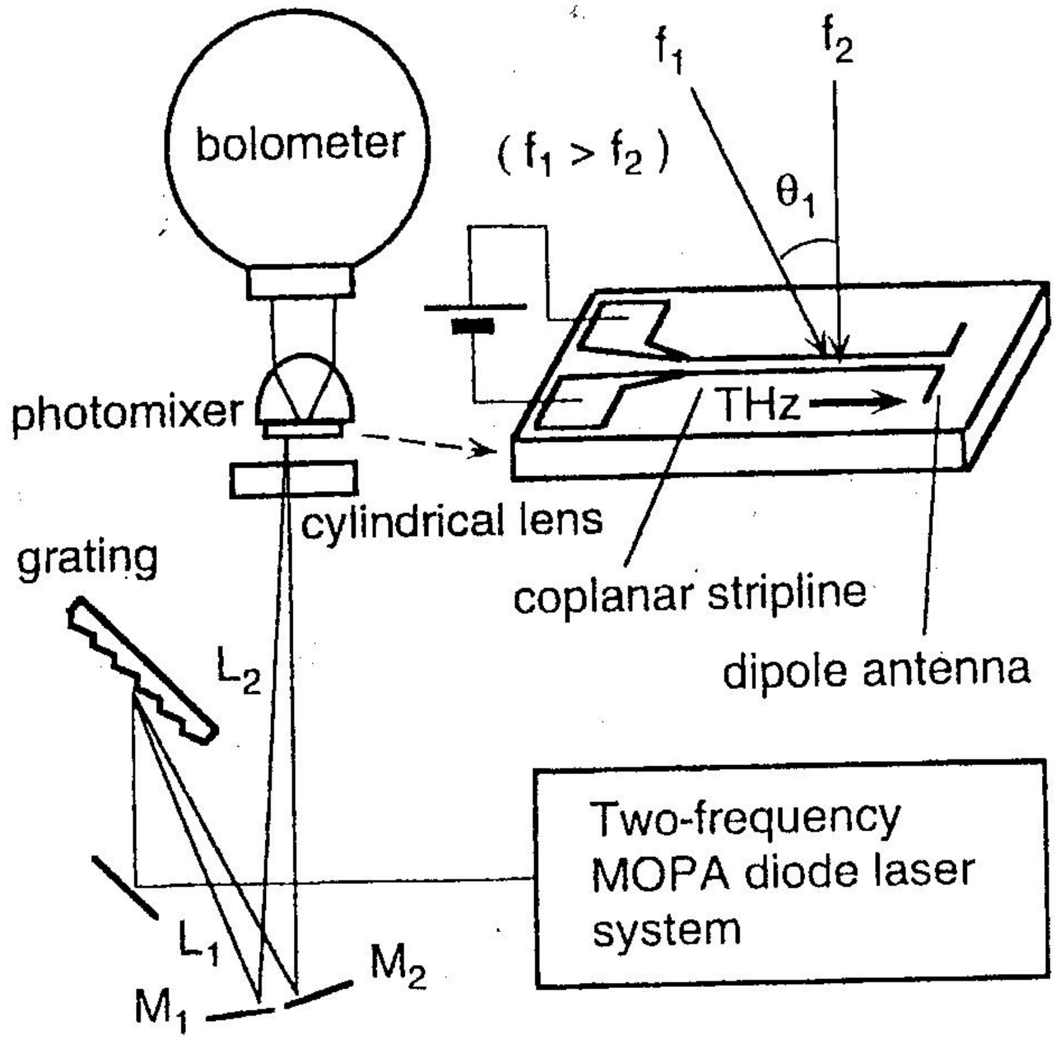
DFG - Photoswitches: microstructures
low intensities ⇒ low THz output
but – cw!

S.Matsura, e.a., 1999

Two-freq. MOPA
850 nm semicond. laser
λ_1 = 848-853 nm
λ_2 = 854 nm
Power – up to 500 mW

GaAs active area ~ $10^3\ \mu m^2$

THz radiation:
0.5 – 2.5 THz
up to 0.1 μW (> 10 μW exp.)



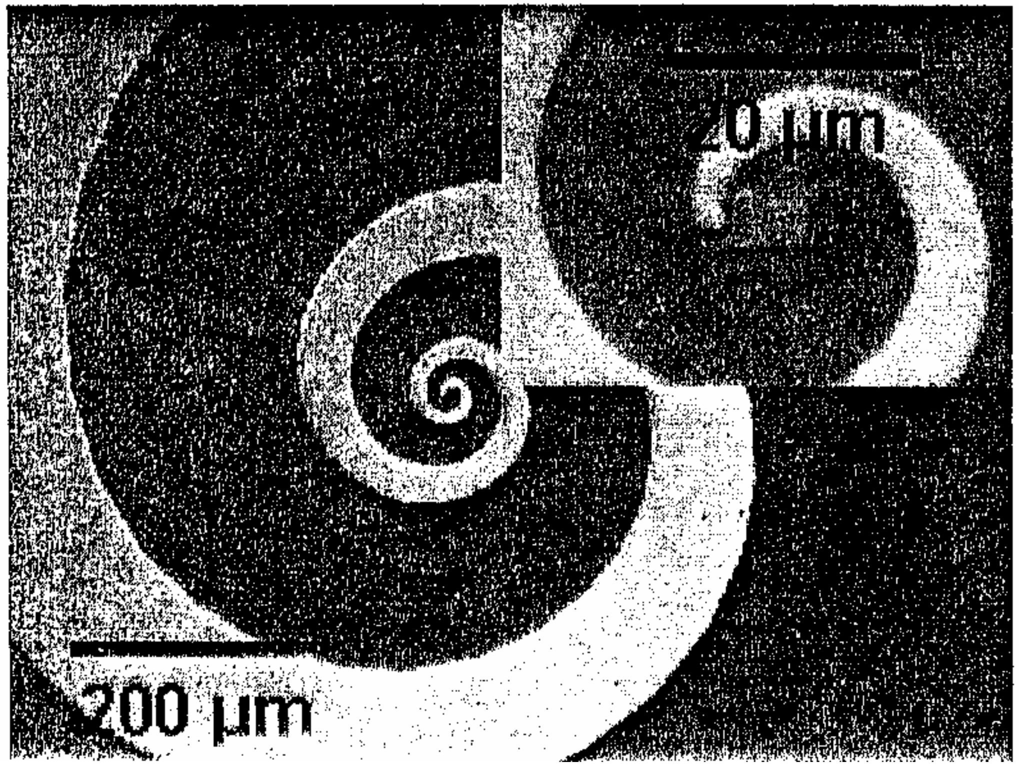
E.Peytavit, e.a., 2002

Ga-AS photodetector

2 cw Ti:Sa lasers
(up to 60 mW of total power)

Active area < 10^2 μm^2

THz radiation:
max. 0.5 μW at 0.7 THz
(essentially less than exp.)



Nonlinear Difference Frequency Generation

- Microstructures are not required
- Potential for high output power

BUT:

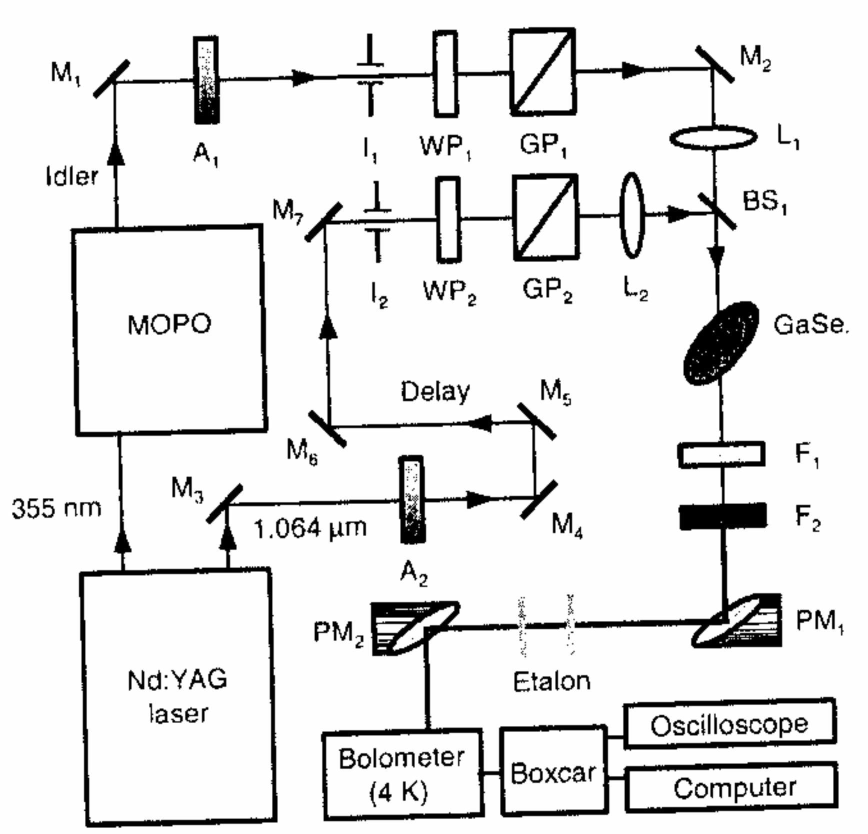
- High intensities and strong nonlinearities are necessary
- Quasi-cw regimes instead of cw

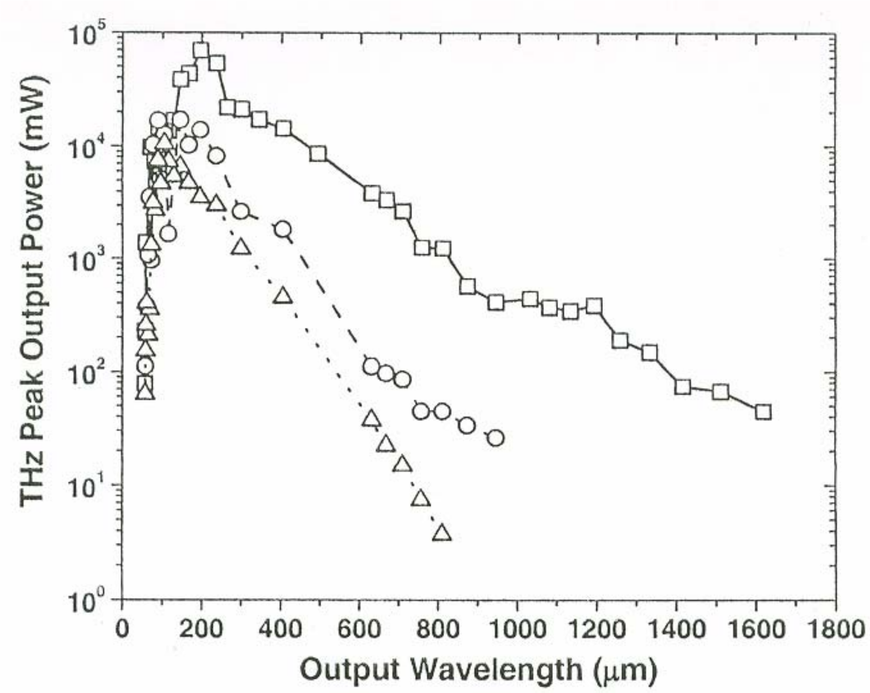
Wei Shi e.a., 2002

Pump: Nd:YAG – 10 nsec, 6 mJ, 10 Hz; $6{\cdot}10^5$ W – peak power, 60 mW – av.
Tunealbe OPO (pumped by 3-rd harm) – 5 nsec, 3 mJ, 10 Hz

GaSe nonl. crystal: peak int. 17 MW/cm^2, (3 mm beam spot, l = 4,7,15 mm

THz radiation: 0.18 – 5.27 Thz, 5 nsec, 10 Hz; peak power 70 W at 1.53 THz





Exotics: Frequency multiplication by multi-element semiconductor structure; THz pulse generation in a laser spark; Quantum cascade lasers.

M.Glyavin, e.a., 2003 (experiment):

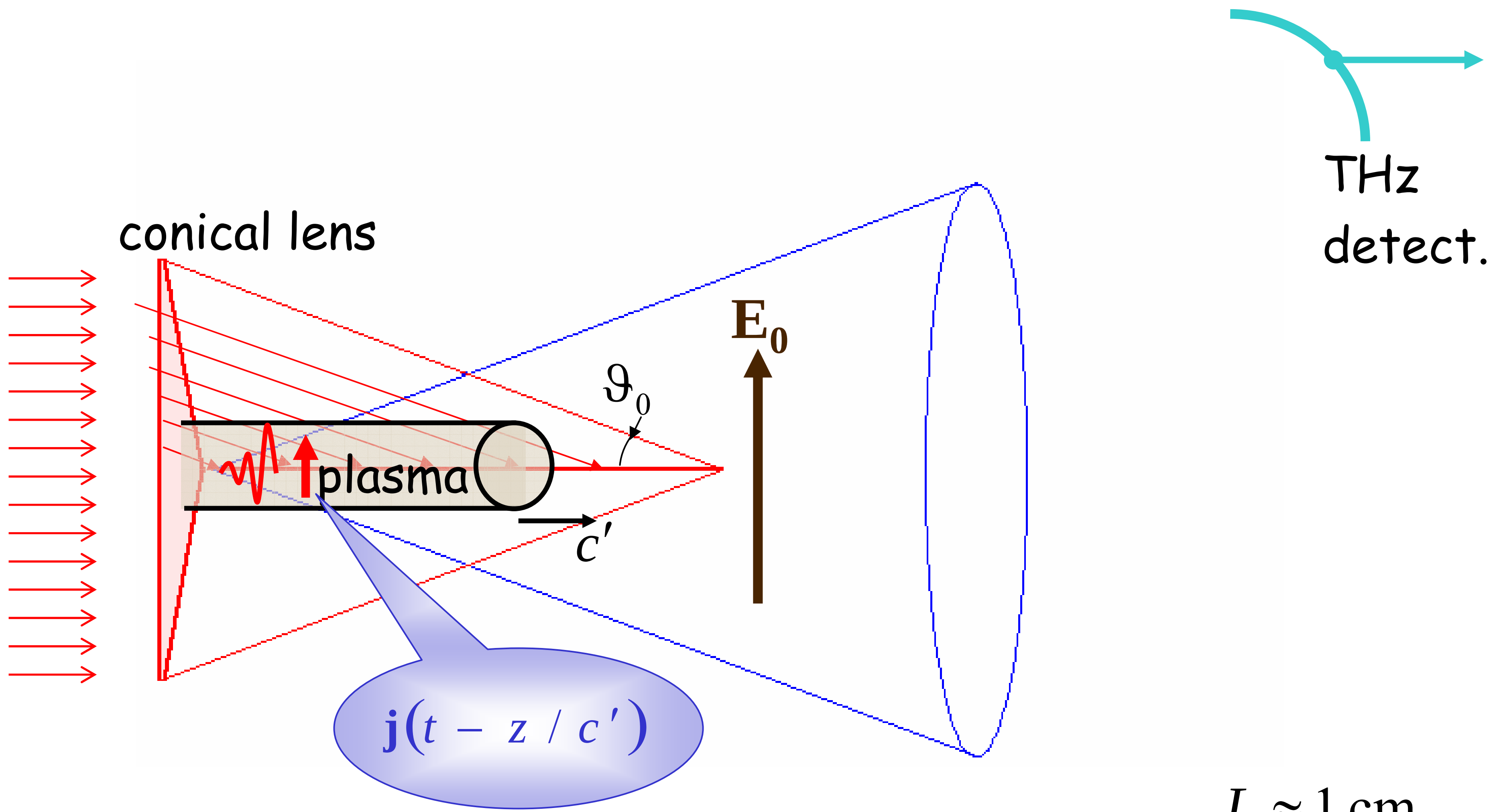
About 30x30 DBSs (10x10 mm^2)

110GHz/10kW/50 μs gyrotron radiation → GaAs structure → 110*3= 330 GHz output radiation 30-40 mW

Project: 150-170 GHz gyrotron *(3-5)

THz pulse generation in a laser spark

A.Shalashov, e.a., 2004



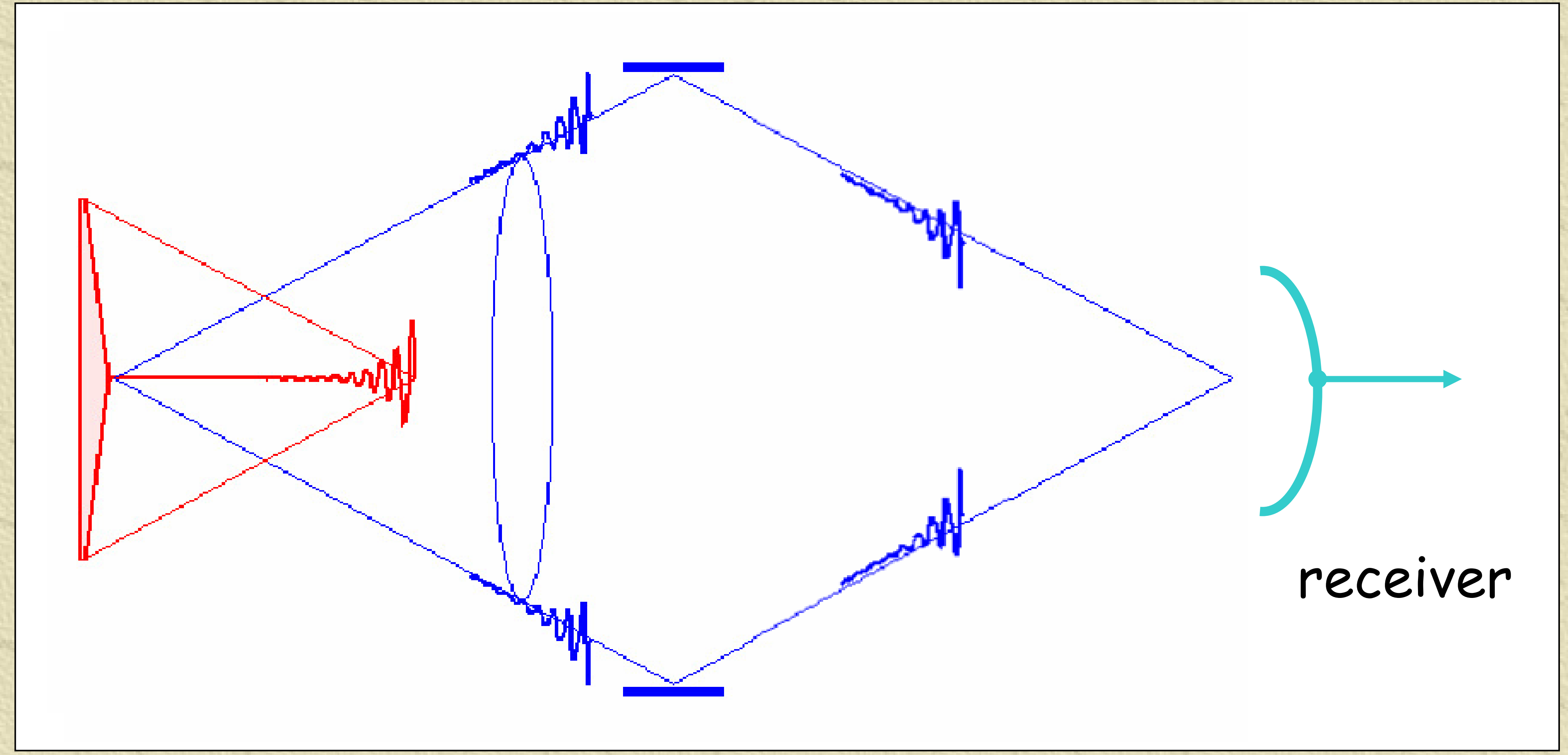
$c' = c/\cos\vartheta_0$ - velocity of ionization front

$L \approx 1\ \mathrm{cm}$

$a \approx 10^{-4}\ \mathrm{cm}$

Experiment planned at IAP

Ti:Sa, λ ≈ 800 nm, pulse duration 50-100 fs
up to 1 mJ/1 kHz, <P> ~ 0.5 W, P_{peak} ~ 10 GW



Expected (atm. pressure) :   30 THz, 10pJ/pulse

Quantum cascade lasers of THz frequency range

(Joint 30th Int.Conf. on IR/MM waves & 13th Int.Conf. on THz Electronics, 2005)

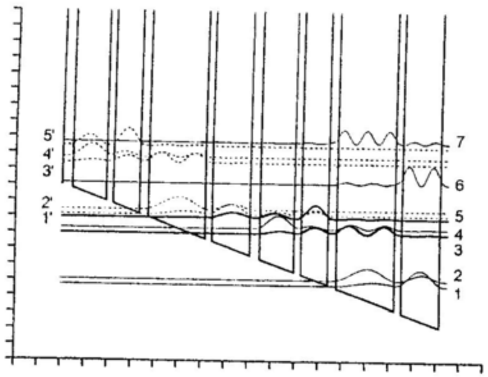


Fig. 1 Calculated conduction band diagram and wave functions of two periods of AlSb / GaSb QCL multi-quantum well structure at E = 5.4 kV/cm. One division of x-axis and y-axis is 10 nm and 10 meV respectively.

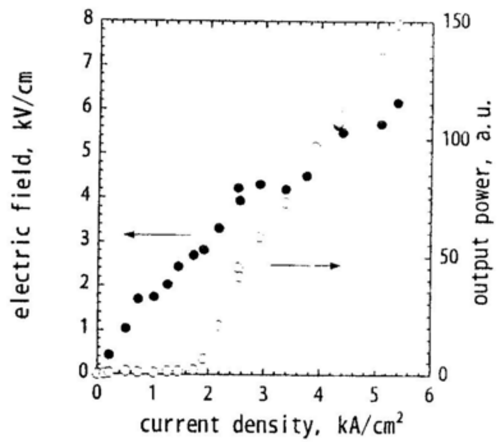


Fig. 3 The L-J and the E-J characteristics of the AlSb /GaSb QCL.

1 period – 8 layers,
4.3/14.4/2.4/11.4/3.8/
24.6/3.0/16.2 nm
230 periods,
4.2 K

12 Hz, 1 μs, **2.6 THz**

Conclusions

- ♦ "Terahertz gap" (from the generation point of view) is filled from both sides (vacuum electronics and optoelectronics)
- ♦ Parameters of needed THz sources are essentially defined by application requirements
- ♦ Large variety of numerous THz sources are naturally developing not being aimed to some definite application
- ♦ Practical applications of THz radiation requires development of appropriate detection and registration techniques
- ♦ A number of impressive examples of THz radiation applications are available based on different radiation sources
- ♦ The evident prospect for the nearest future: enhancement of main parameters of THz sources and of output radiation; in the application field – the progress from demonstration experiments to a wide use in scientific laboratories