INSTITUTE FOR RESEARCH IN
ELECTRONICS
& APPLIED PHYSICS

To Detecting Concealed Radioactive Sources

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**US Low Temperature Plasma Teleseminar,
March 30, 2012**

Research team

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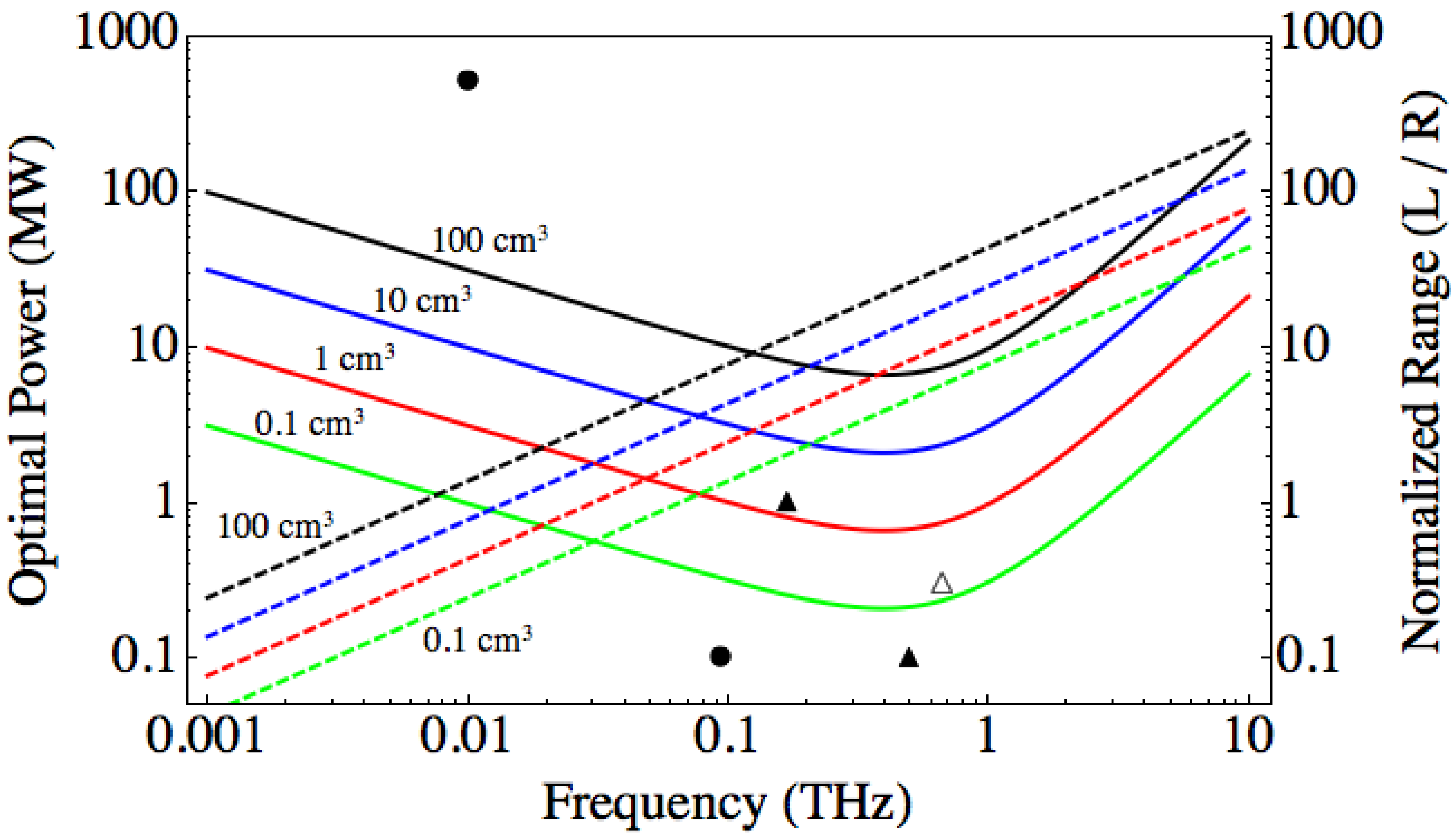
Concept of remote detection

- High-power THz-range radiation
- Focusing in a small spot of a wavelength size
- Initiate the breakdown in the presence of seed electrons
- Ambient electron density is about one particle in cm^3. The breakdown-prone volume is small.
- Breakdown rate (BDR) should be low.
- If you have high BDR, there are additional sources of air ionization.

Granatstein and Nusinovich, JAP, vol. 108, 063304, (2010)

Why THz?



Microwaves – large volume, Optics – multi-photon ionization,
THz – bottom of the Paschen curve at the atmospheric pressure

Nusinovich, Sprangle, Romero-Talamas, Granatstein, JAP, vol. 109, 083303 (2011)

Challenge

- This concept is more complicated than the radar concept.
- As in radars, we need: - transmitter and receiver.
- But we also should create the target – plasma blob!

Issues to be addressed

- **Producing high-power THz radiation**
- **Converting it in a wave beam and focusing in a small spot**
- **Propagation in the atmosphere (maritime environment – aerosols)**
- **THz breakdown; statistical lag time, temporal and spatial evolution of a plasma blob**
- **Reflection of THz waves from a blob**
- **Receiver**
- **Production of thermal electrons by radioactive materials**

G. Nusinovich, R. Pu, T. Antonsen, O. Sinitsyn, J. Rodgers, A. Mohamed, J. Silverman, M. Al-Sheikhly, Y. Dimant, G. Milikh, M. Glyavin, A. Luchinin, E. Kopelovich and V. Granatstein, Journal of IR, MM and THz Waves, vol. 32, 380 (2011)

Why gyrotrons?

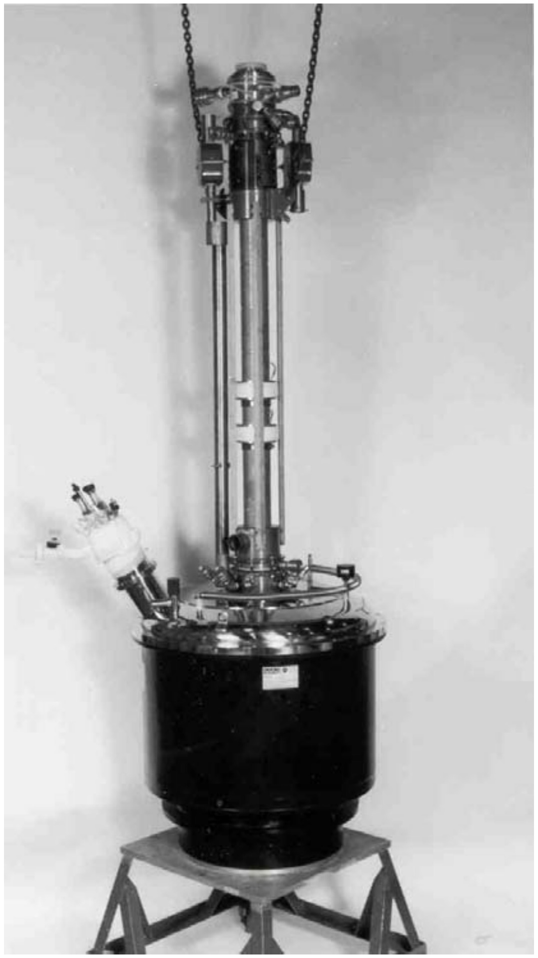
Gyrotrons produce MW-level continuous radiation at millimeter waves

W-band radar (WARLOC), 100 kW peak, 10 kW average

W-band ADS, 1 MW, continuous

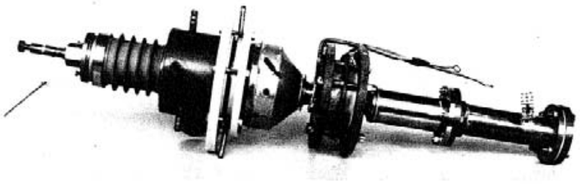
Problem: magnetic fields $B(T) \approx 35.7\gamma_0 f\left(THz\right)/s$

Gyrotrons

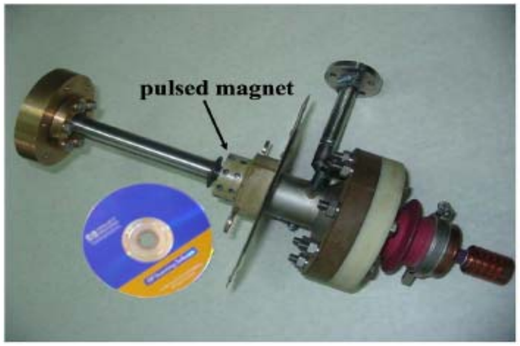


A 140 GHz, 100 kW **CW** gyrotron
in a cryomagnet (courtesy of CPI)

Gyrotrons with pulsed solenoids



**Flyagin, Luchinin, Nusinovich,
1983, 0.5 THz, 100 kW,
magnetic fields up to 27T**



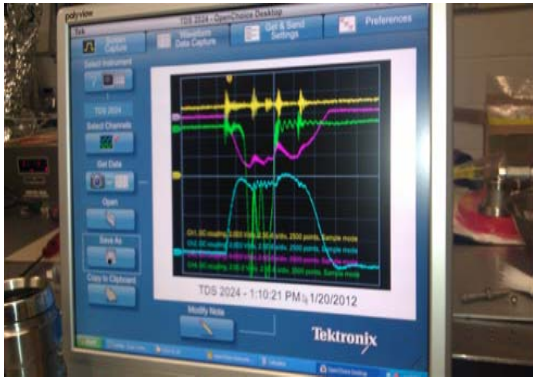
**Glyavin et al., PRL, 2008,
1.5 kW at 1 THz.
B up to 45 T**

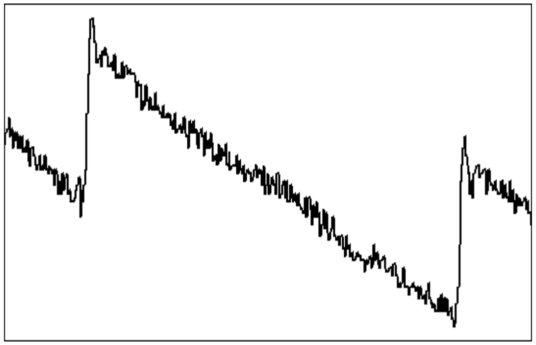
**So far, THz-range gyrotrons with pulsed solenoids operate in single-shot regimes (once in a minute).
Rep-rate operation is highly desirable!**

200 kW, 670 GHz gyrotron with a pulsed solenoid

- **Joint design (IREAP UMd and IAP RAS)**
- **Manufacturing by GYCOM**
- **Parallel experiments**

Pulsed B: up to 28 T
in 2-3 milliseconds





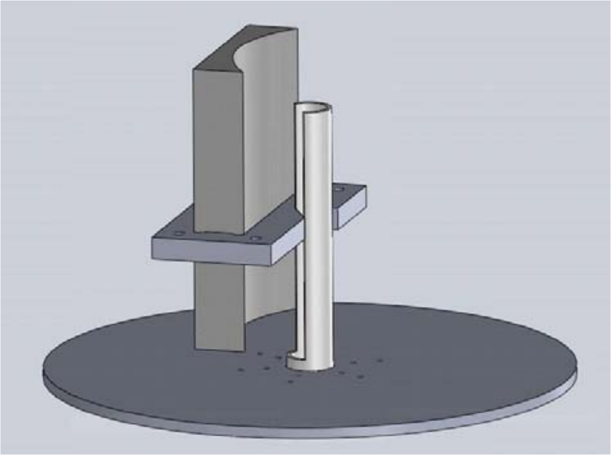
Calorimetric response (IREAP)

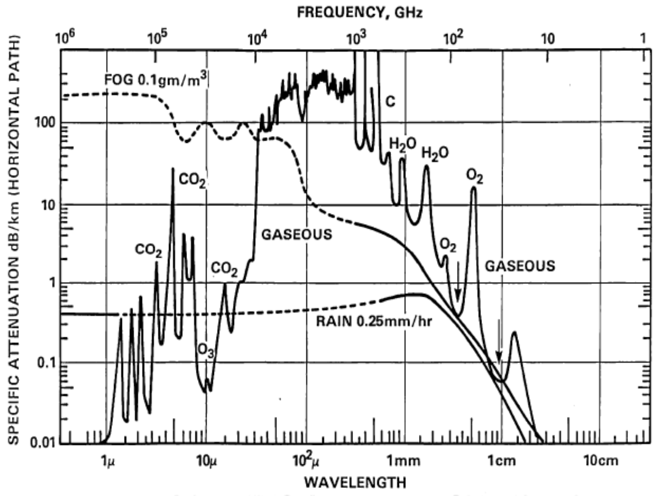
Experiments: IREAP and IAP.
IREAP: gyrotron experimental studies.
THz pulse energy - 0.54 J in a single shot.
Mean power in a shot - 80 kW.
IAP – 100 kW level.
Predicted efficiency – 30%.
Realized efficiency – about 10%.

80-100 kW with 10% efficiency at 670 GHz!

THz wave beams: focusing and propagation

- **Gyrotron operates in a high-order azimuthally rotating $\mathrm{TE}_{31,8}$-mode (the one used in Japanese ITER gyrotrons).**
- **This mode can be converted into a Gaussian wave beam by quasi-optical elements (wave coupler, parabolic mirror, focusing mirror).**
- **Gaussian wave beam – eigenmode of a free space. Propagation with low diffractive losses. Absorption.**





670 GHz – 50 dB/km
50 m – attenuation is less than 3 dB

THz breakdown: statistical lag time

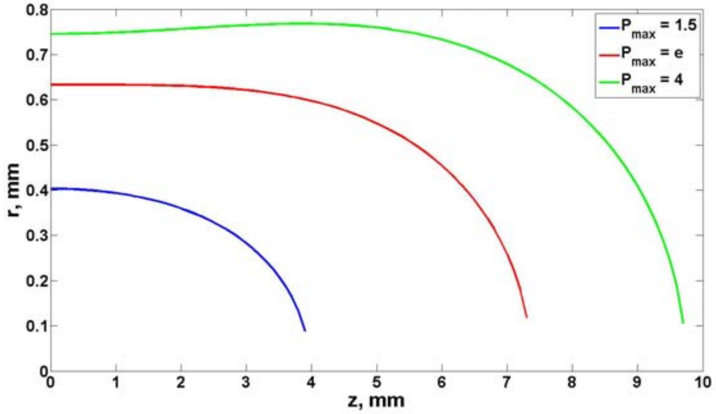
- Statistical lag time = waiting time for the appearance of free electrons in the breakdown-prone volume.
- In our case, the average waiting time is practically equal to its characteristic spread.
- For reliable initiation of the breakdown the THz pulse duration should be larger than doubled waiting time.
- The waiting time depends on the excess of the wave power over the breakdown threshold.
- Detectable mass of the ionizing material.

$$M(g) \geq \frac{4\pi L_{\gamma,a} R^2}{AV\tau_{THz}} \frac{\Delta E}{\langle E \rangle} \frac{\nu_i}{\nu_{i,eff}} \exp\left(R / L_\gamma\right)$$

D. Dorozhkina, V. Semenov, T. Olson, D. Anderson, U. Jordan, J. Puech, L. Lapierre, and M. Lisak, Phys. Plasmas, vol. 13, 013506 (2006).
Nusinovich, Sprangle, Semenov, Dorozhkina and Glyavin (submitted to JAP)

THz breakdown: breakdown-prone volume

- **There can be single focused wave beams and crossing wave beams.**
- **In single beams the angular convergence is small. Therefore the maximum electron density is much smaller than the critical one that corresponds to the electron plasma frequency equal to the wave frequency.**
- **In a single beam the shape of a breakdown-prone volume is cigar-like at low power-to-threshold ratios and peanut-like at high ratios.**



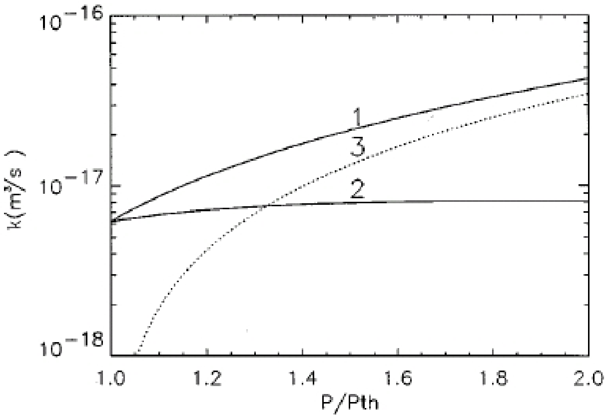
Once a free electron appears in this volume, an avalanche ionization process begins.

THz breakdown: ionization time

- Ionization time.
- At sub-THz frequencies, when the wave power

density exceeds the threshold by two times

it takes less than 40 ns to reach saturation.



Ionization and attachment rates.
Nusinovich, Milikh, Levush, JAP, vol. 80, 4189 (1996)

- It is preferable to use crossed wave beams.

In crossed wave beams a higher electron density can be achieved.

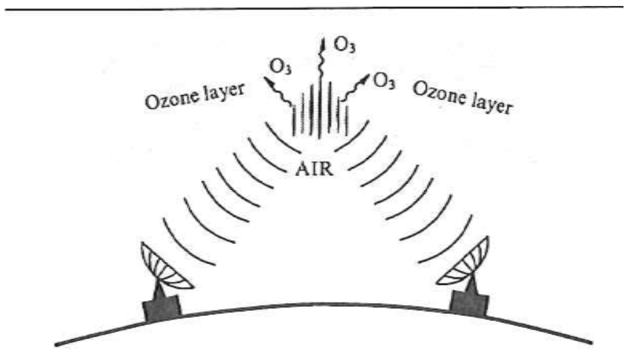


Figure 1. Schematic of AIR formation.

Gurevich, Litvak, Vikharev, Ivanov, Borisov and Sergeichev, Physics – Uspekhi, vol. 43, 1103 (2000)

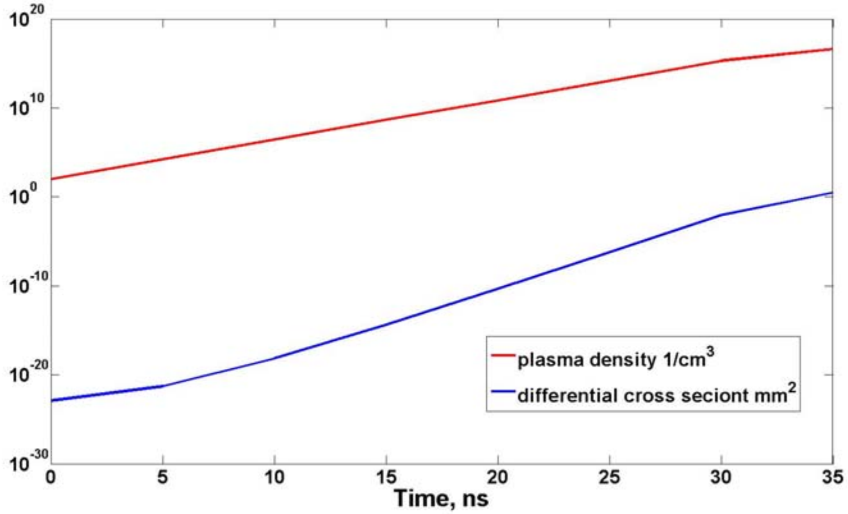
Reflection from a plasma blob

- Born approximation.
- Ratio of reflected to incident wave powers.

$$\frac{\vec{P}_s}{\vec{P}_{inc}} = \frac{1}{4\pi r^2}\sigma_D(\vec{r})$$

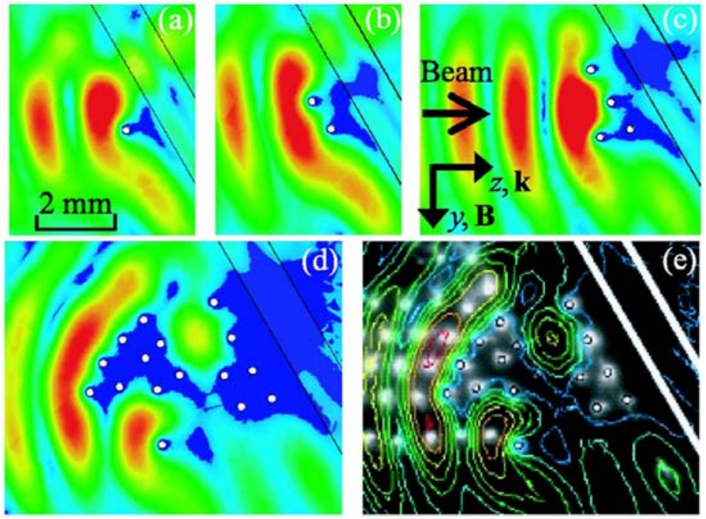
$$\sigma_D = \frac{\left|\vec{r}_0 \times \vec{e}_0\right|^2}{4\pi}\left|\int_V d^3x'\left(\frac{1}{4\pi}\frac{\omega_p^2(x')}{c^2}\right)\exp\left(i\tilde{\vec{k}}x'\right)\right|^2$$

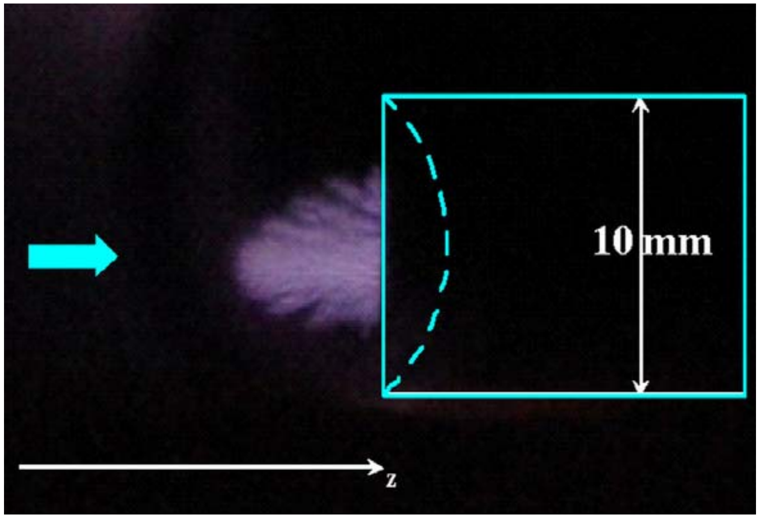
Differential cross-section



Saturation level depends on a number of wave beams: in the case of two crossed beams it is higher than for a single beam.

Spatial and temporal evolution of plasma in the discharge





Formation of a 2D filamentary array in a wave beam reflected from a dielectric plate. MIT, 110 GHz gyrotron. Hidaka et al., PRL, vol. 100, 035003, (2008)

Breakdown in a focused wave beam from a 1 THz gyrotron, IAP, Russia. Bratman, Zorin et al.,PoP, August 2011

The filaments are separated by a quarter wavelength distance one from another. As the wavelength shortens, the diffusion destroys the filamentary array faster.