A point source of extreme ultraviolet radiation based on non-equilibrium discharge, sustained by powerful radiation of terahertz gyrotron

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Outline

- Introduction
- ECR discharge experiments
- Scaling calculation
- THz wave heating experiments

Extreme ultraviolet lithography

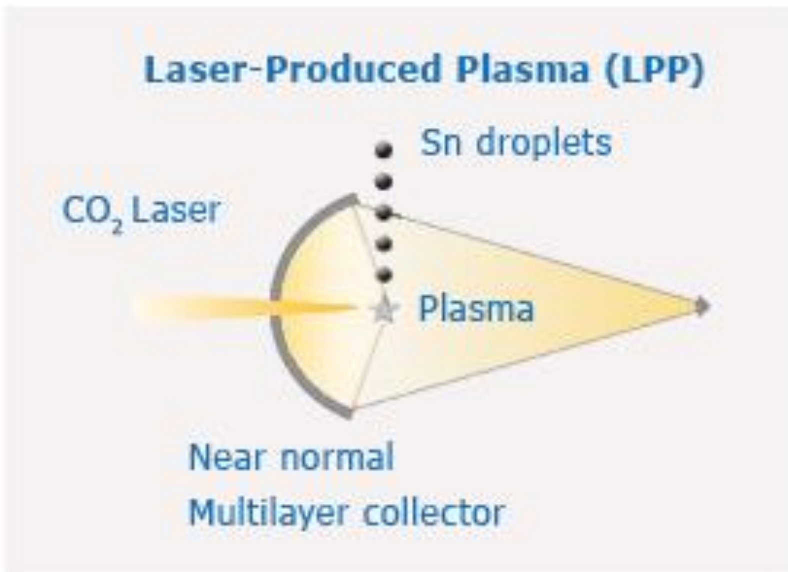
- Optics - Mo/Si Bragg multilayers
  R = 70%, Total 5%

↓

- Light source: 1 kW in 13.5 nm± 1 %
  – Emission of exited multicharged ions

  Xe^{10+} (CE 1%) Sn^{+7} – Sn^{+12} (CE 5%) Li^{3+} (CE 1%)

Introduction:
a point source of extreme ultraviolet radiation



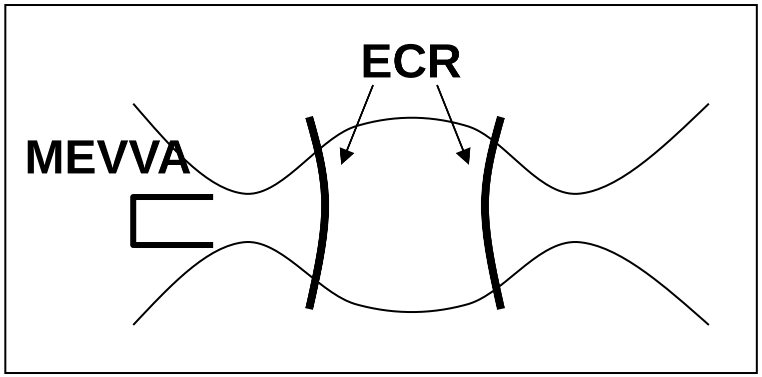
Requirements:
Wavelength: 13.5 ± 1 % nm
Size: less than 1 mm
Power in band: 1 kW

Shortcomings of LPP concept:
- Low power efficiency
- Short lifetime
- Mirror pollution

Non-equilibrium plasma

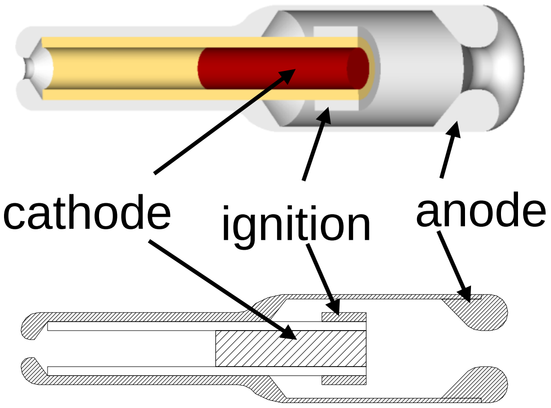
- More power to electron fraction $T_e \uparrow$
- Ions stay cold
- Higher excitation rates and light power

MEVVA + ECR discharge



Injection of vacuum arc plasma to ECR discharge

$Ne = 10^{12} - 10^{16}$ cm^{-3}
$Ne \sim I_{arc}$

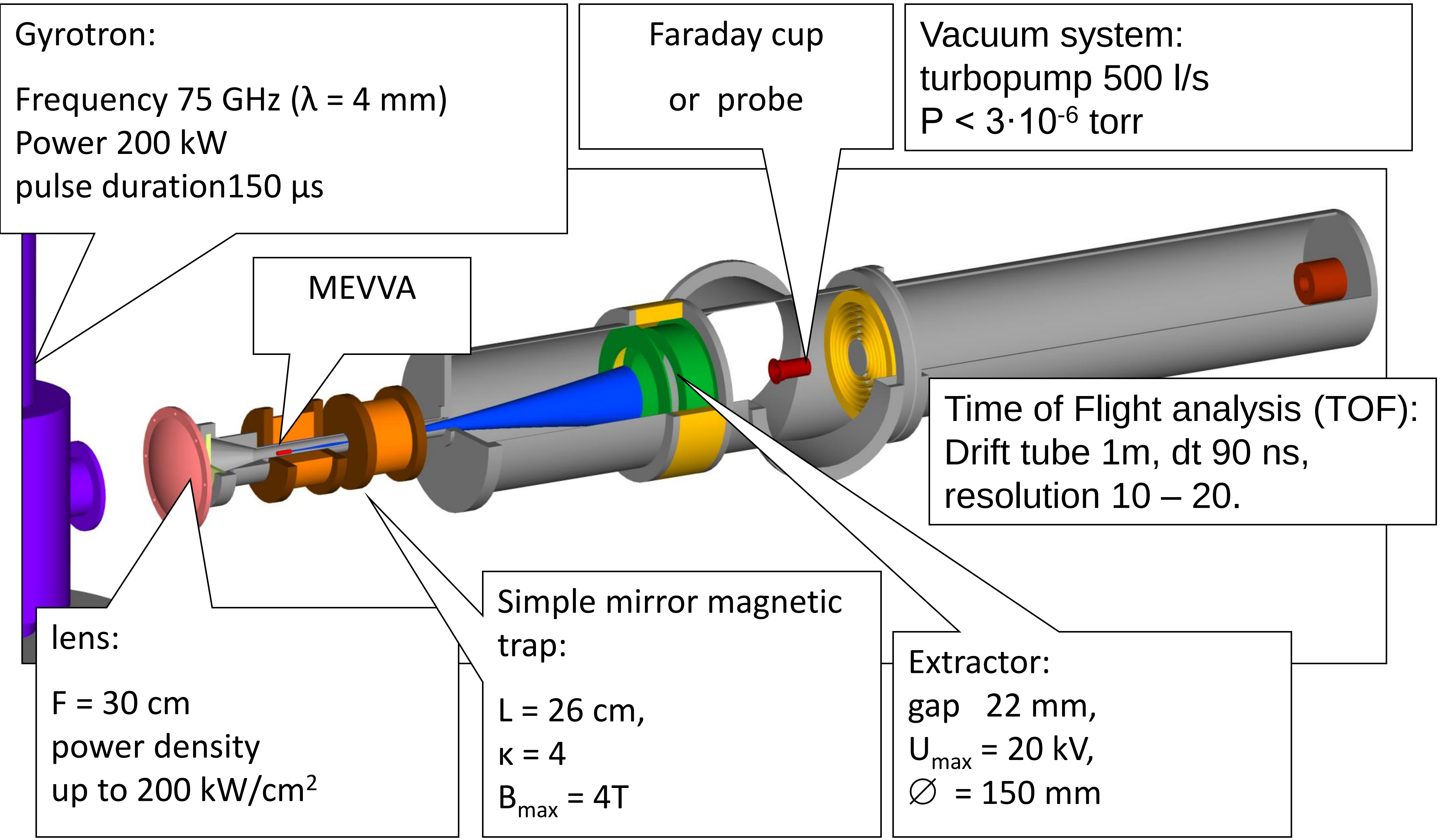


Plasma flow velocity
10^6 cm/s => $\tau = L/V$

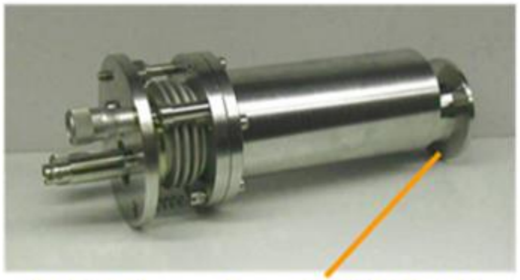
$N\tau \sim 10^9$ cm$^{-3}\cdot$s => $N \sim 5\cdot10^{13}$ cm^{-3}
=> f > 60 GHz

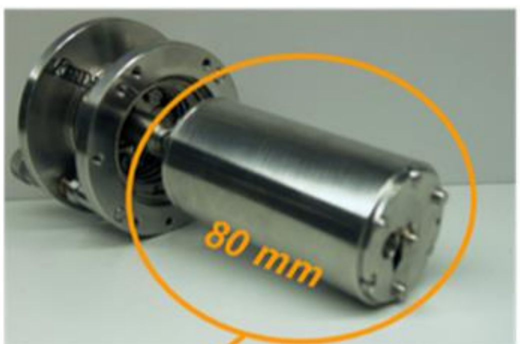
A.V.Vodopyanov, S.V. Golubev, S.V. Razin, V.G. Zorin, A.V. Vizir, A.G. Nikolaev, E.M. Oks, G.Yu. Yushkov.
Multiple ionization of metal ions by ECR heating of electrons in vacuum arc plasmas. Review of Scientific Instruments, v. 75, 2004 p. 1888

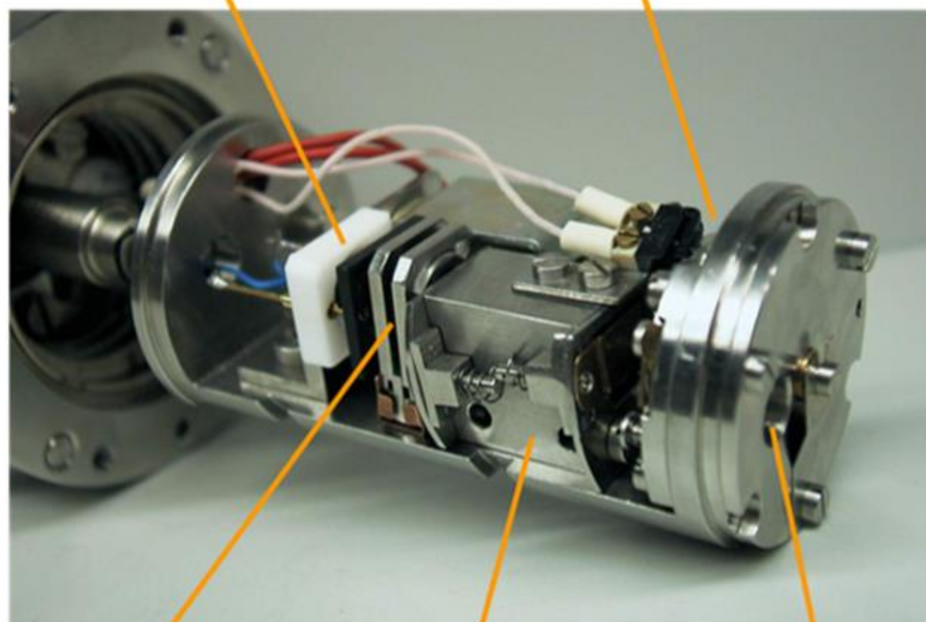
Experimental setup



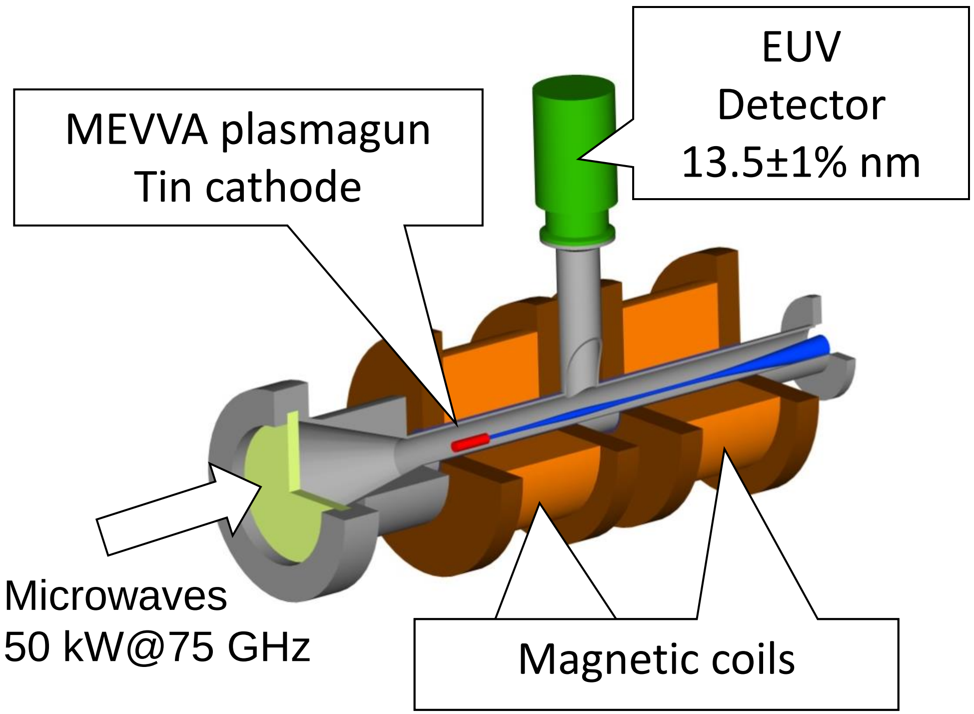
EUV energy monitor







ECR source of EUV light



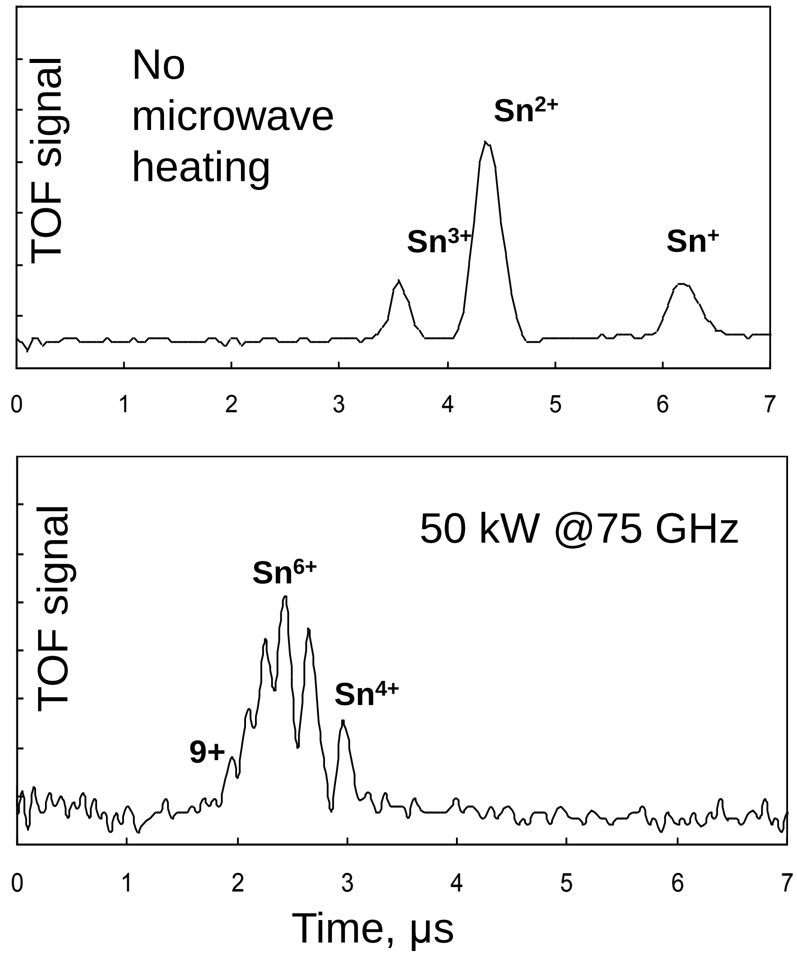
Experiment:

50 W to 4π to **13.5 nm** ± 1%

η ~ 1 %

Source size 3 x 3 x 50 mm

Ion charge state distribution



Simulation

$$
\begin{cases}
\dfrac{dN_0}{dt} = F_0 - k_0 \cdot N_0 \cdot N_e - \dfrac{N_0}{\tau} \\
\dfrac{dN_1}{dt} = F_1 + k_0 \cdot N_0 \cdot N_e - k_1 \cdot N_1 \cdot N_e - \dfrac{N_1}{\tau} \\
\ldots \\
\dfrac{dN_i}{dt} = F_i + k_{i-1} \cdot N_{i-1} \cdot N_e - k_i \cdot N_i \cdot N_e - \dfrac{N_i}{\tau} \\
N_e = \sum_{i=1} i \cdot N_i \qquad \tau = L/V
\end{cases}
$$

J. White et al. J. Appl. Phys, **98**, 113301

Experiment:

50 W in 4π in band **13.5 nm** ± 1%

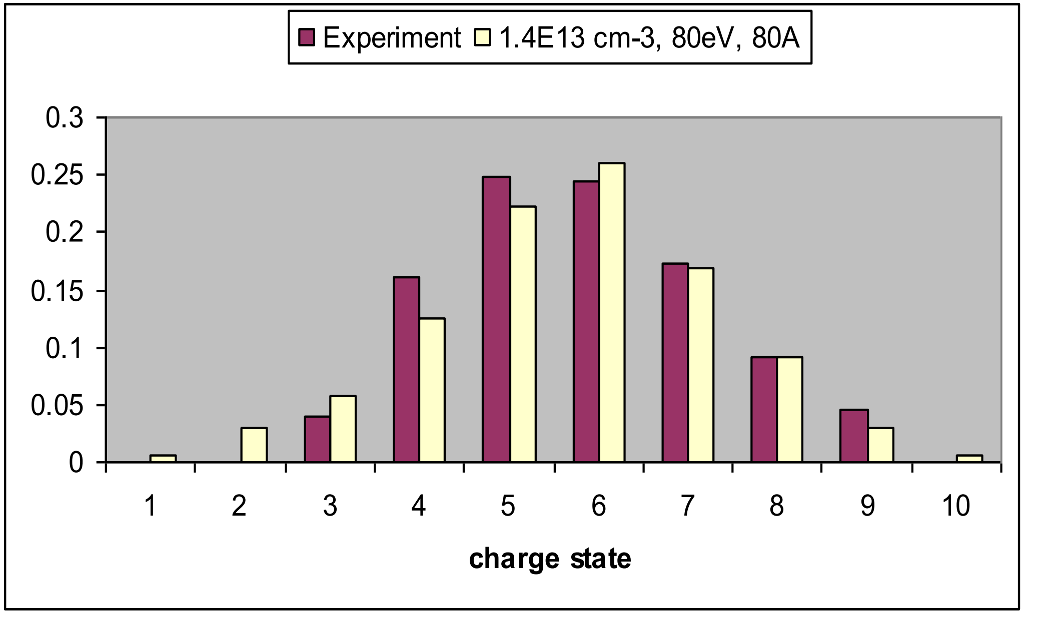
η ~ 0.5 %

Source size 3 x 3 x 50 mm

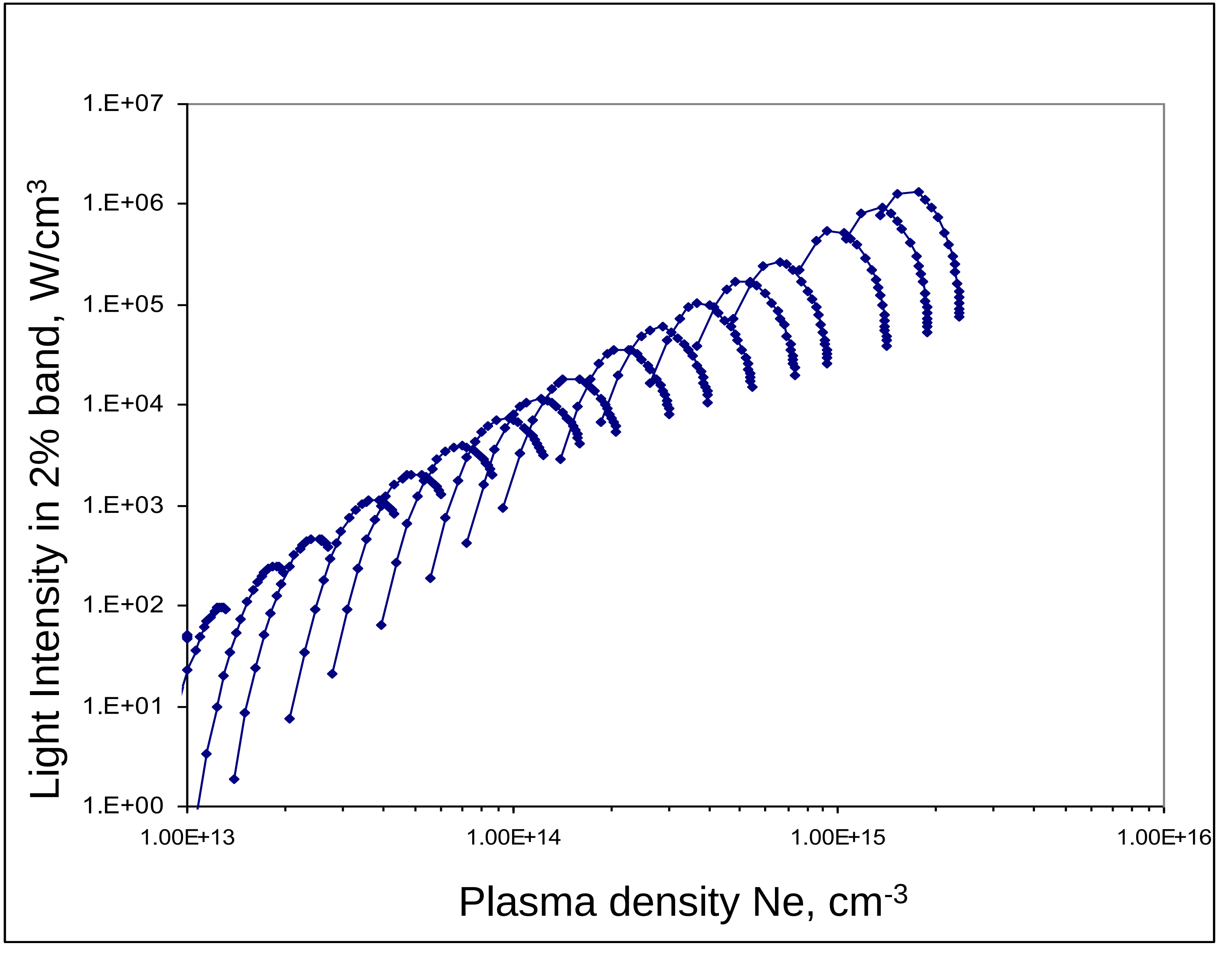
Conditions of experiment:

$N_e = 1.4 \cdot 10^{13}$ cm^{-3}
Te = 80 eV

P_{EUV} = 35 W

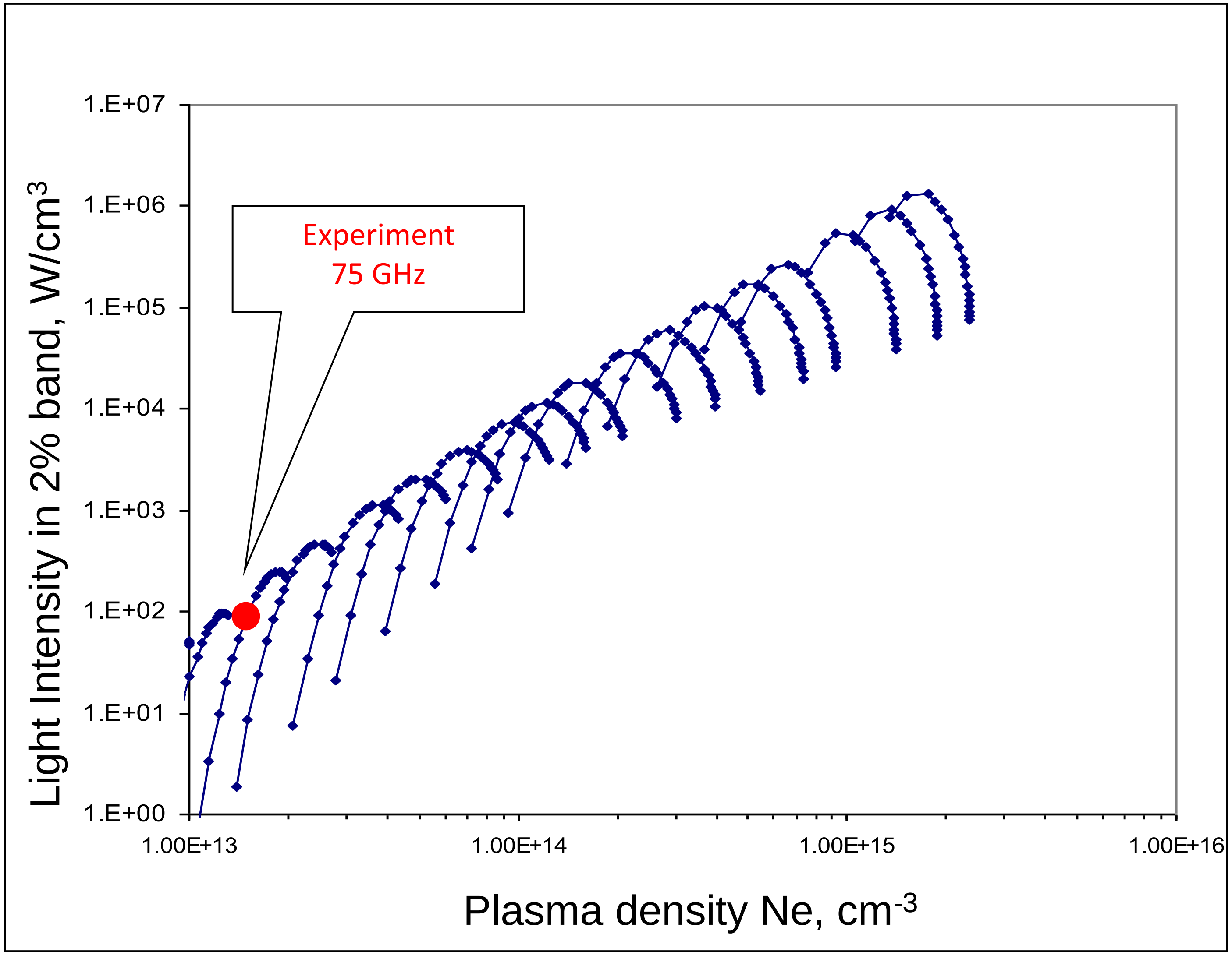


Simulation



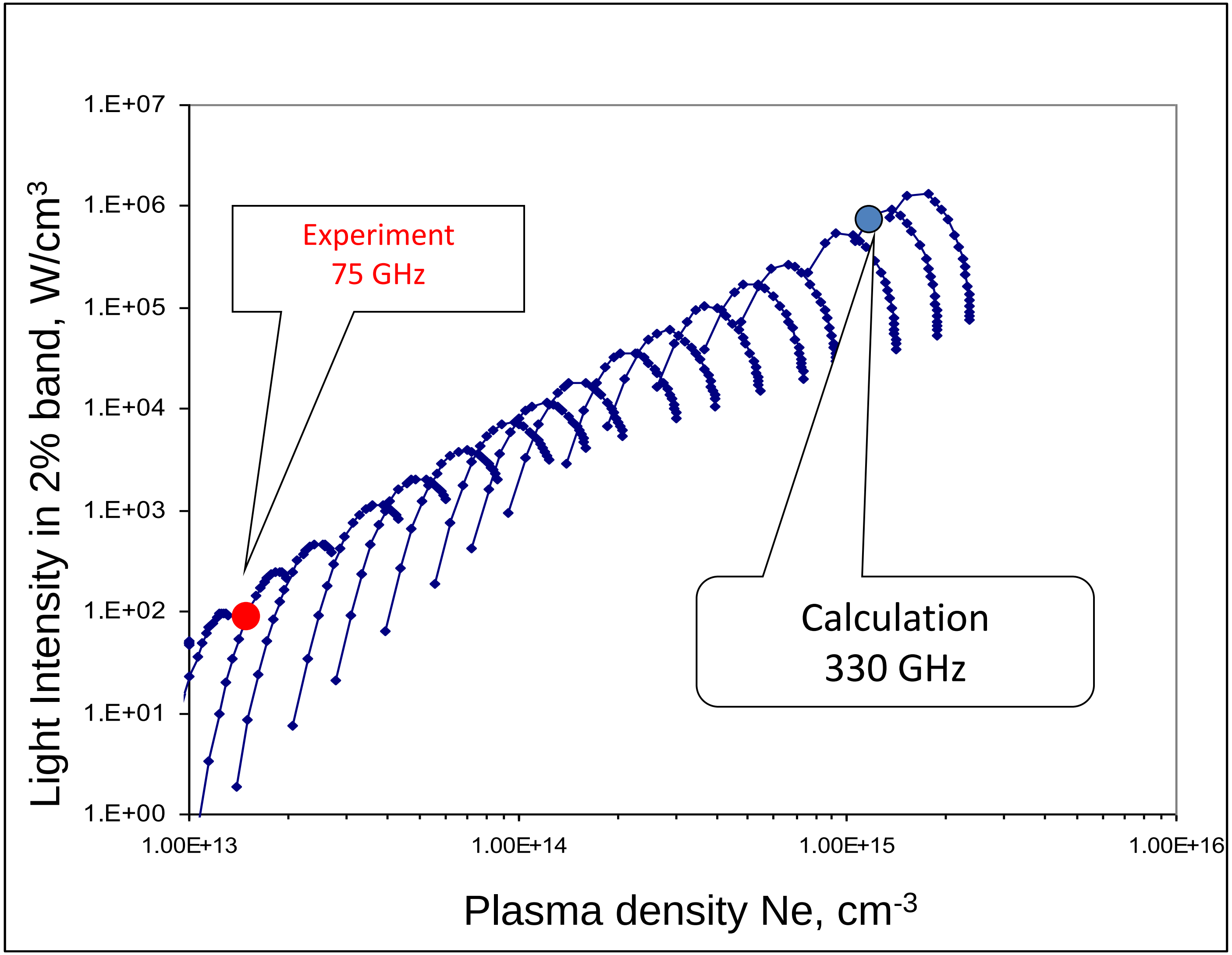
Light Intensity in 2% band, W/cm3
1.E+07
1.E+06
1.E+05
1.E+04
1.E+03
1.E+02
1.E+01
1.E+00
1.00E+13
1.00E+14
1.00E+15
1.00E+16
Plasma density Ne, cm-3

Simulation



Experiment
75 GHz
1.E+07
1.E+06
1.E+05
1.E+04
1.E+03
1.E+02
1.E+01
1.E+00
1.00E+13
1.00E+14
1.00E+15
1.00E+16
Light Intensity in 2% band, W/cm3
Plasma density Ne, cm-3

Simulation

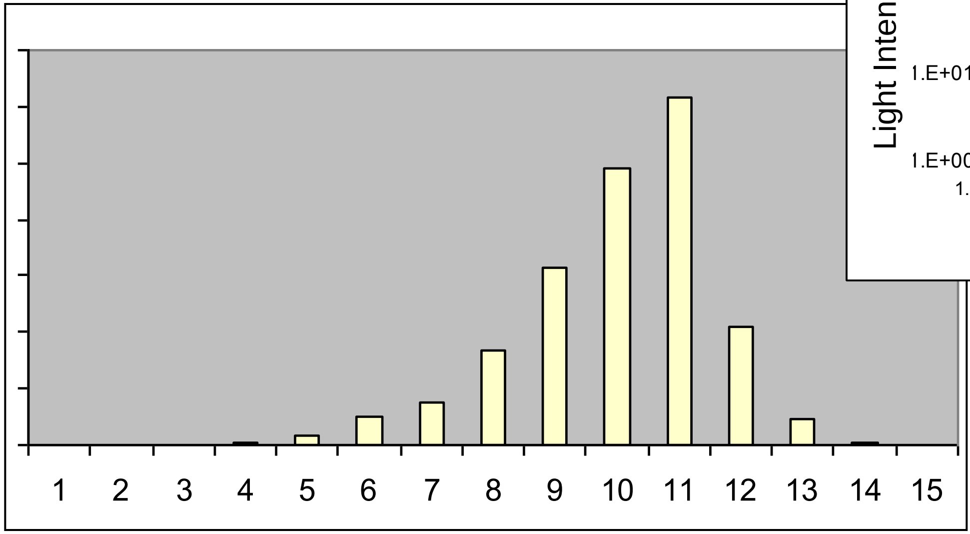


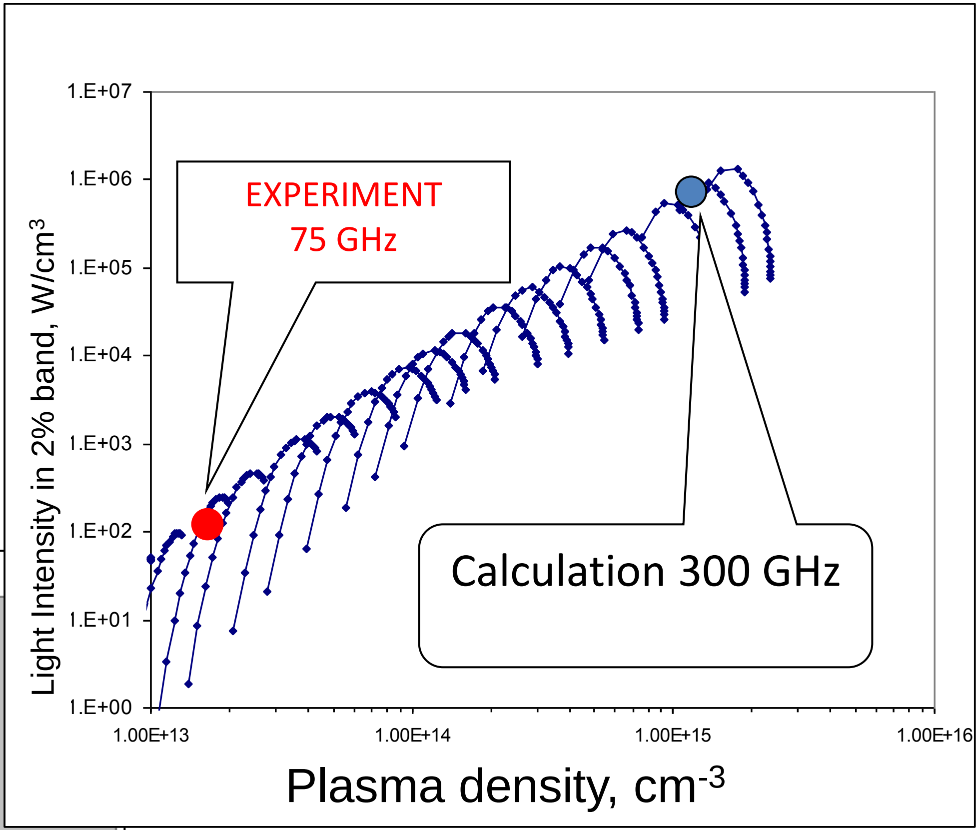
Experiment
75 GHz
Calculation
330 GHz
Light Intensity in 2% band, W/cm^3
1.E+07
1.E+06
1.E+05
1.E+04
1.E+03
1.E+02
1.E+01
1.E+00
1.00E+13
1.00E+14
1.00E+15
1.00E+16
Plasma density Ne, cm^{-3}

Simulation

1 kW/mm³ (13.5±1%) :

$N_e = 1.3 \cdot 10^{15}$ cm^{-3}
T_e = 50 - 60 eV
P = 20 kW/mm³ @ 300 GHz
4-5% efficiency





Prospects of EUV light source

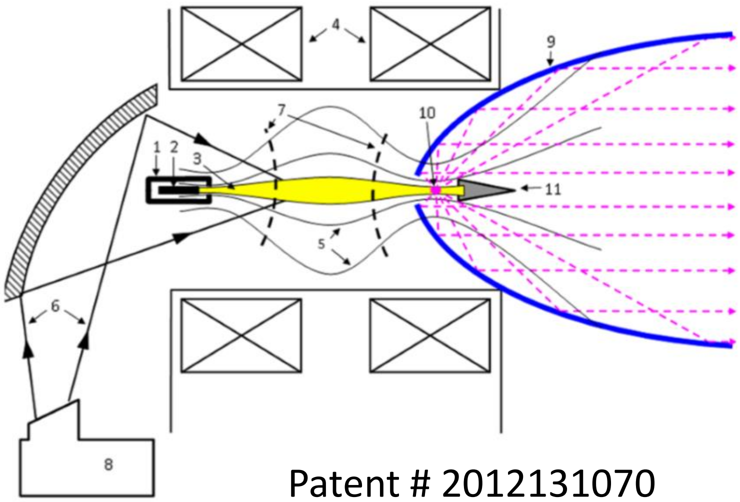
I

Gyrotron
Power - 20 kW
Frequency - 300 GHz
CW operation

$N_e = 1.3*10^{15}$ cm^{-3} $T_e = 50$ eV

1 kW в 4π st.rad. in **13.5 nm** ± 1%

η ~ 4 %. Source size ~ λ = **1** mm



Patent # 2012131070

Fig. 10 Schematic view of the proposed source of EUV light.

II

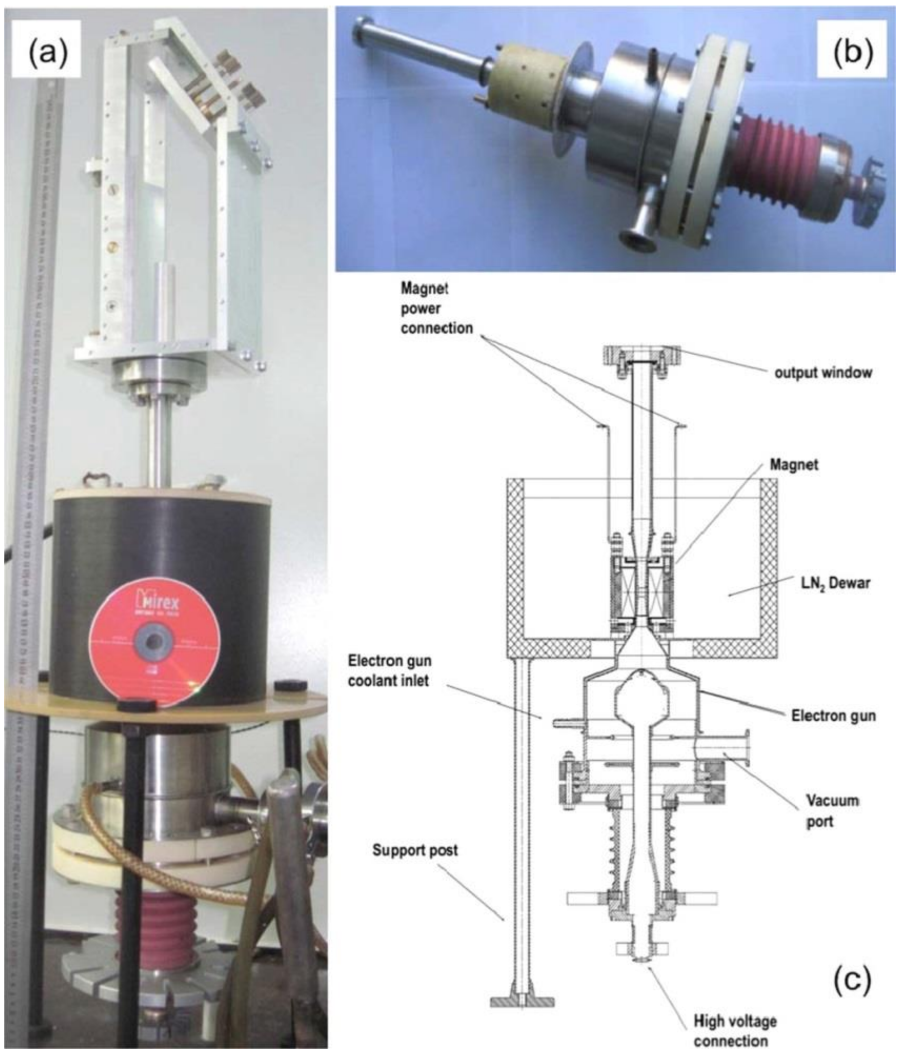
Gyrotron
Power - 20 kW
Частота - 1 THz
CW operation

$N_e \sim 1*10^{16}$ cm^{-3} $T_e \sim 30$ eV

1 kW in 4π st.rad. in **13.5 nm** ± 1%

η ~ 4 %. Source size ~ λ = **0.3** mm

Experimental setup: gyrotron



Parameters:

Frequency:
f = 0.67 THz

Power:

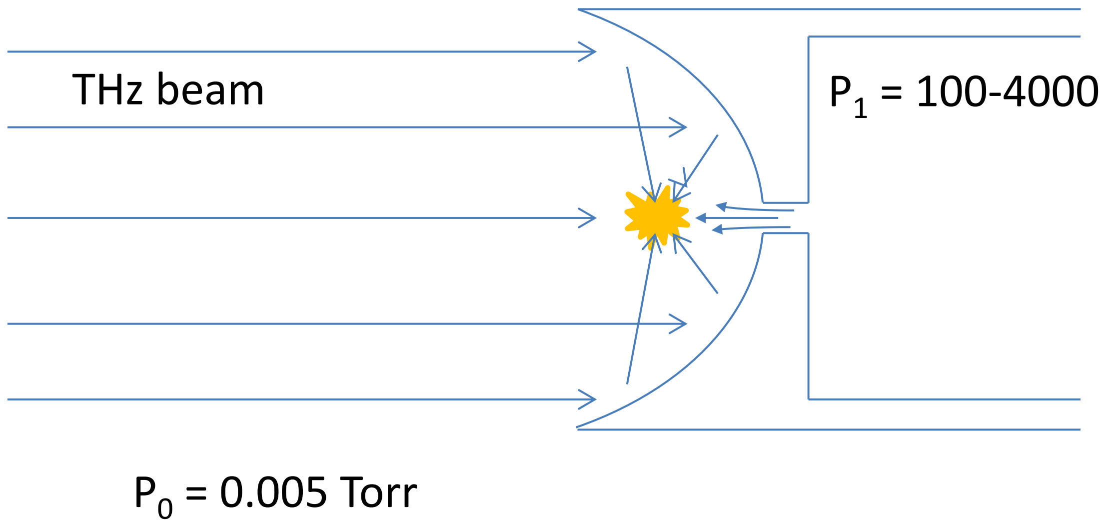
up to 200 kW

Pulse length:

20 μs

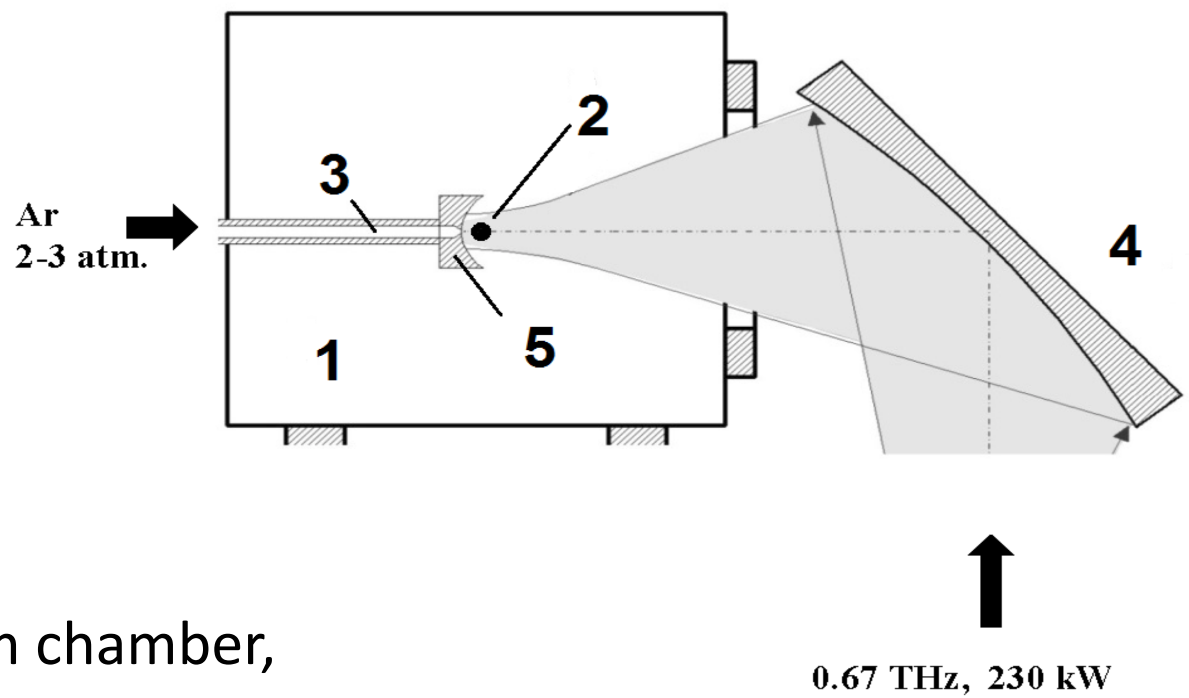
Linear polarization

Plasma discharge sustained by strong terahertz powerful radiation in inhomogeneous gas flow



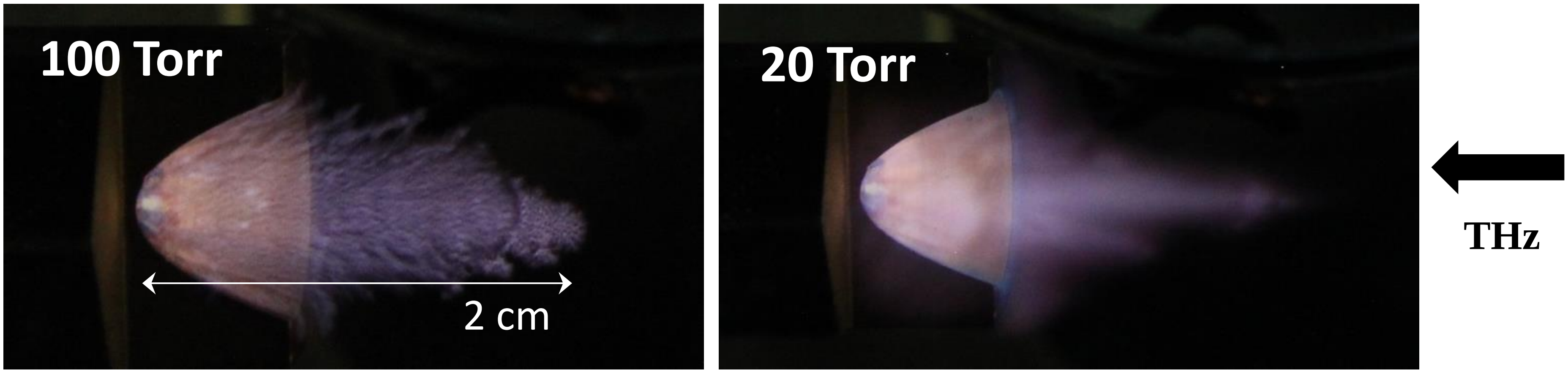
THz beam power : 200 kW @ 0.67 THz
Nozzle diameter: 0.3, 0.15, 0.05 mm
Power density: 40 MW/cm^2
Electric field: 120 kV/cm

Experimental setup



1- vacuum chamber,
2 – plasma,
3 – gas inlet tube,
4 – THz wave mirror,
5 – short-focus mirror with nozzle

Results of experiments: discharge photo (200kW @ 0.67 THz)

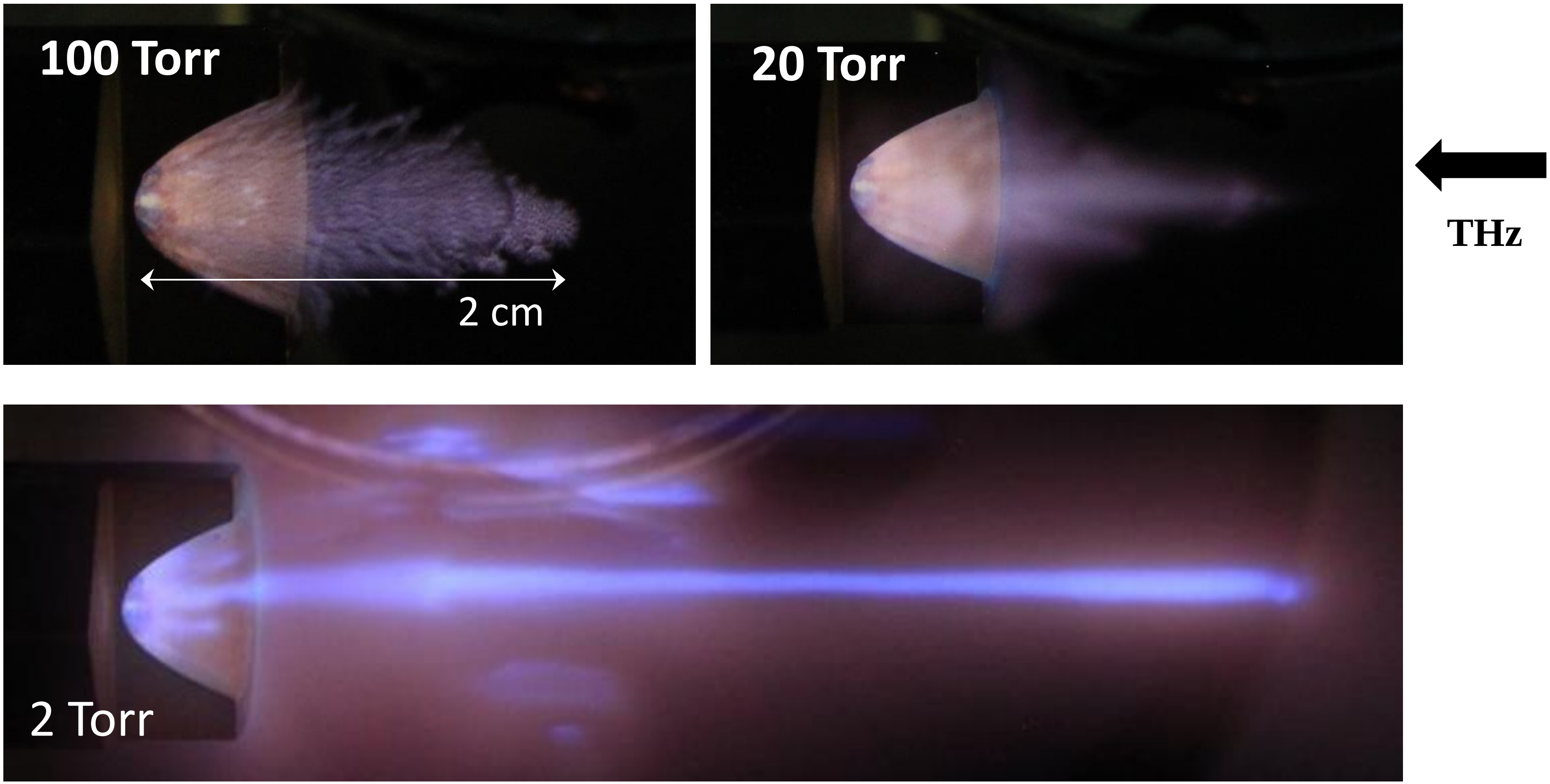


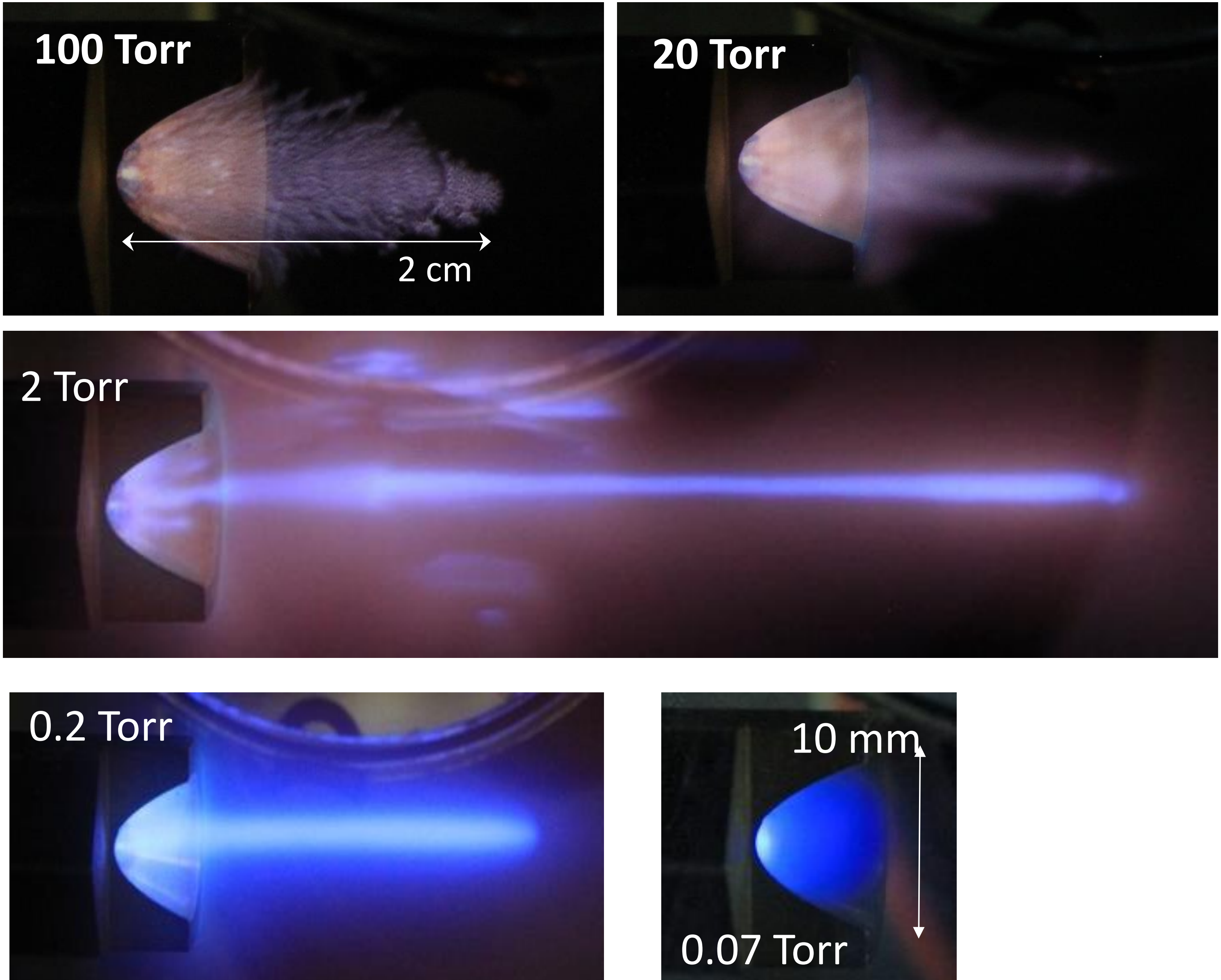
Ambipolar diffusion $D_A=10^4/(p[Torr])$ [cm^2/s]

P > 80 Torr => $\Lambda_a < \lambda$

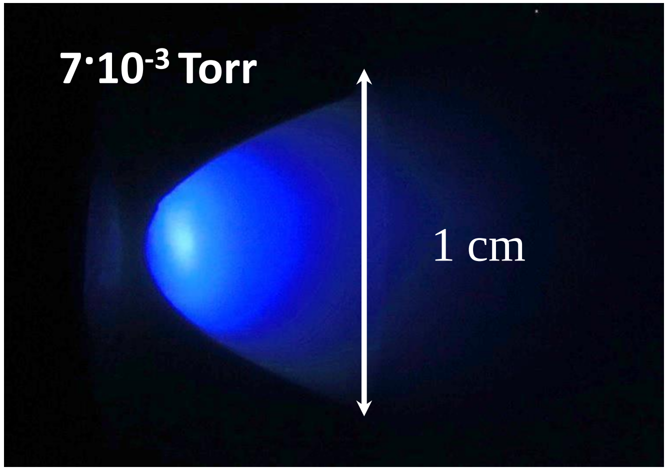
P < 80 Torr => $\Lambda_a > \lambda$

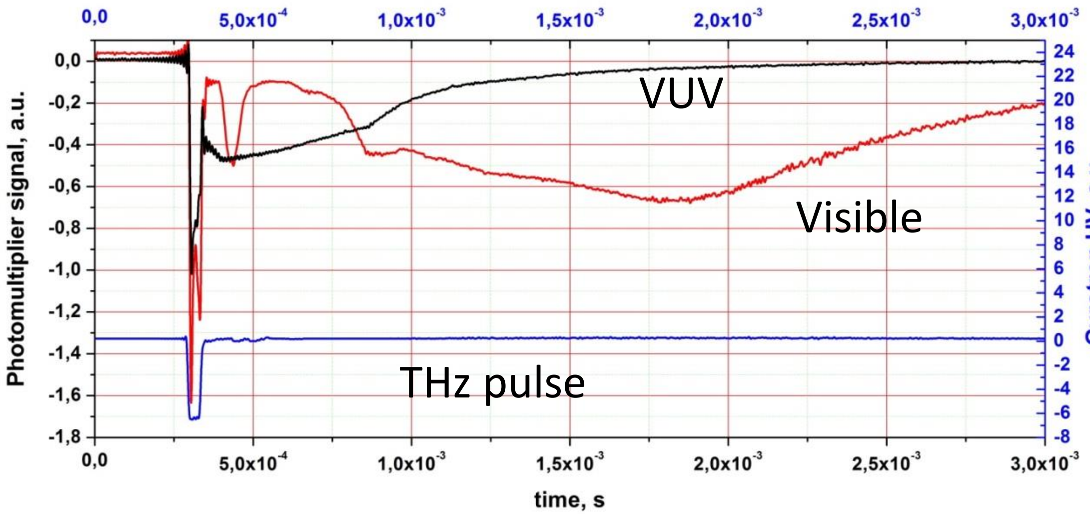
Results of experiments: discharge photo (200kW @ 0.67 THz)



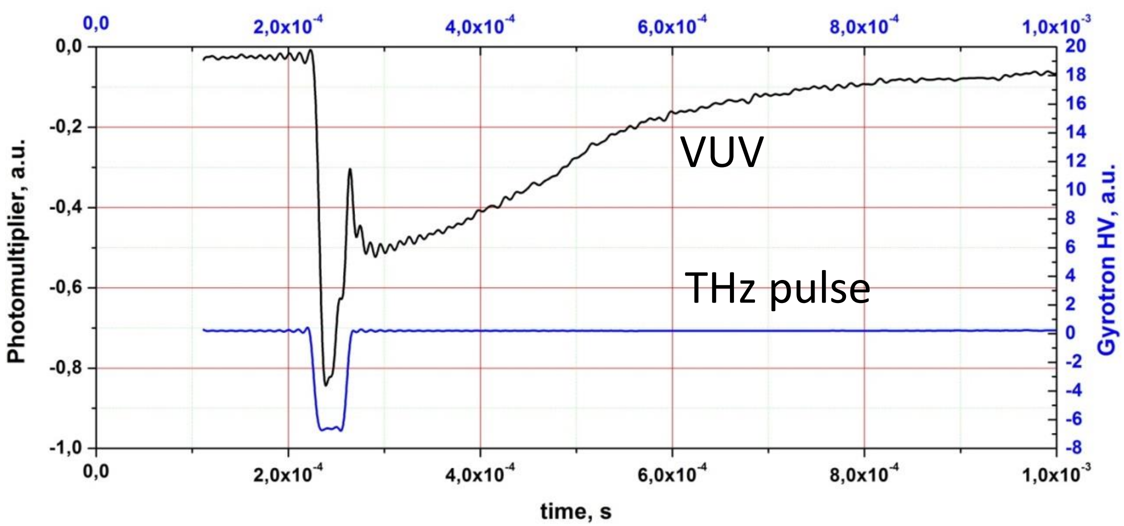

100 Torr
2 cm
20 Torr
2 Torr
0.2 Torr
10 mm
0.07 Torr

Pointed source of UV





112-180 nm emission of the “point-like” THz- discharge reaches level of 10 kW



Summary

- Source of extreme ultraviolet radiation based on ECR discharge is demonstrated
- Scaling calculation shows the prospects to use THz waves to sustain point plasma emitting extreme ultraviolet radiation
- Point discharge emitting ultraviolet radiation sustained by the THz waves is demonstrated