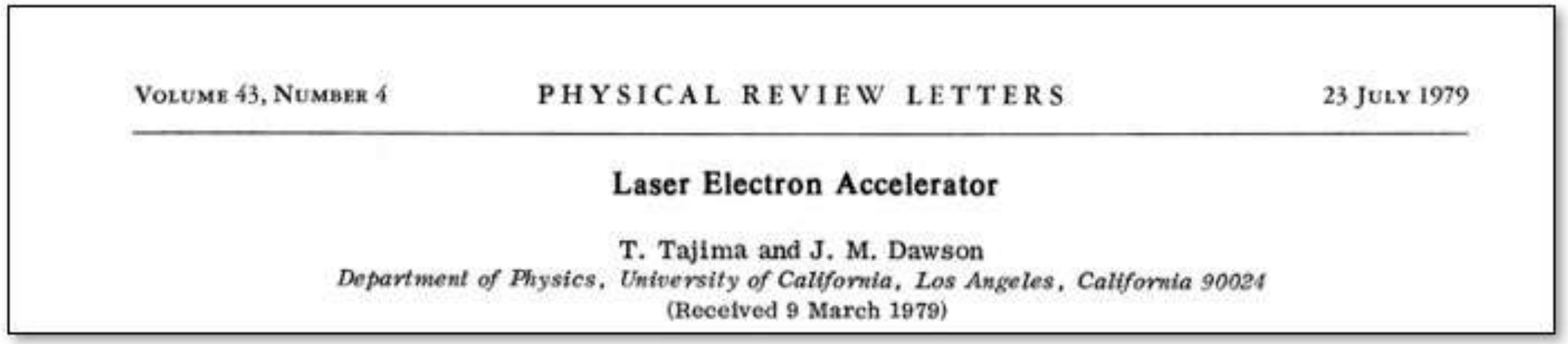
Nonlinear interaction between ultra-high-power ultra-short microwave pulses with gas/plasma

Yang Cao, John Leopold, Yury Bliokh,
and Yakov E. Krasik

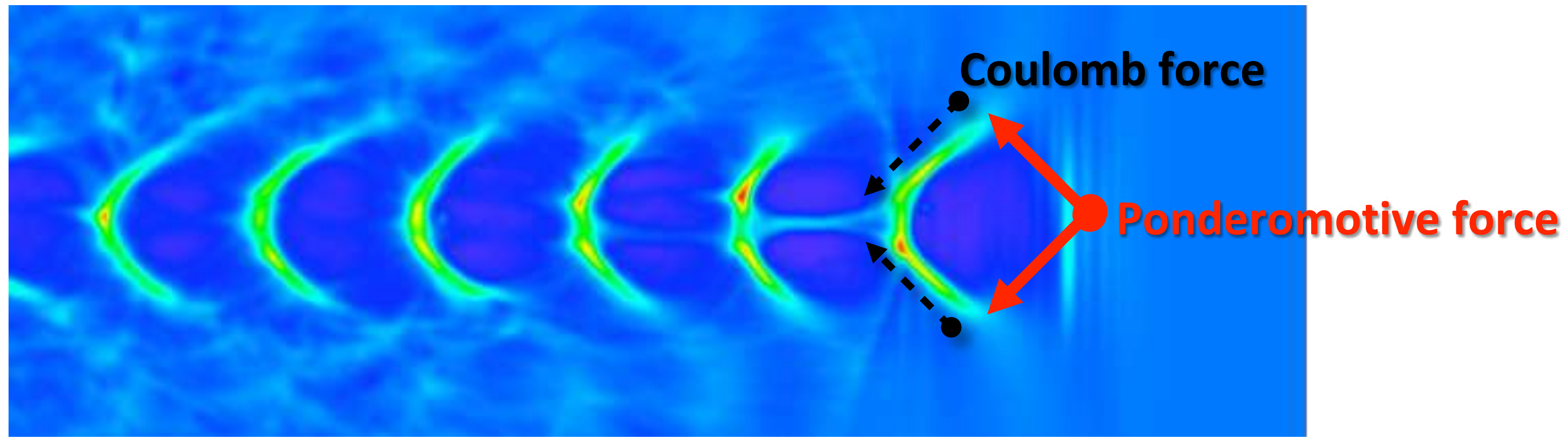
Physics Department, Technion – Israel Institute of Technology, Haifa 32000, Israel

Motivation


Volume 43, Number 4 PHYSICAL REVIEW LETTERS 23 July 1979

Laser Electron Accelerator

T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024
(Received 9 March 1979)

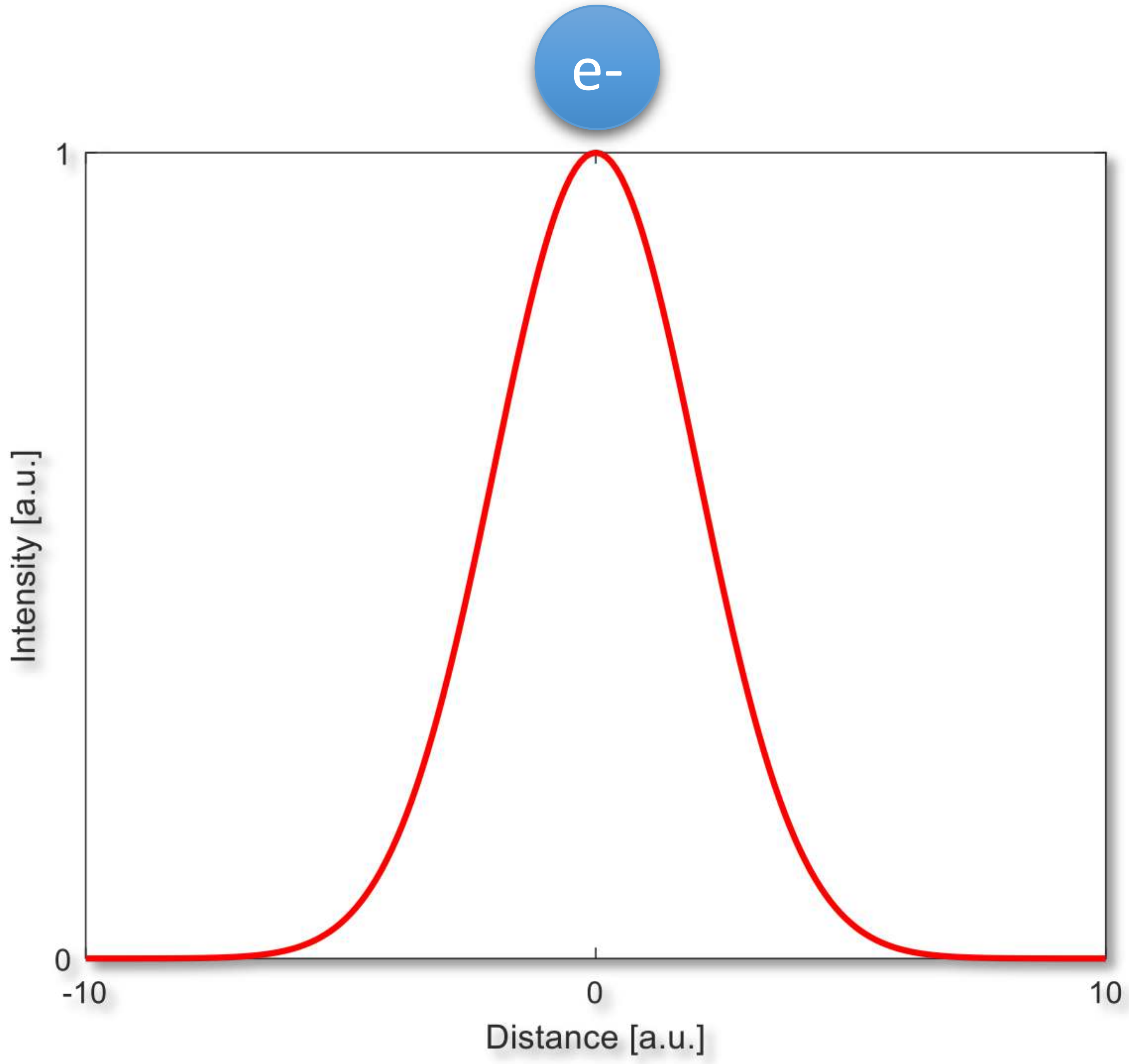


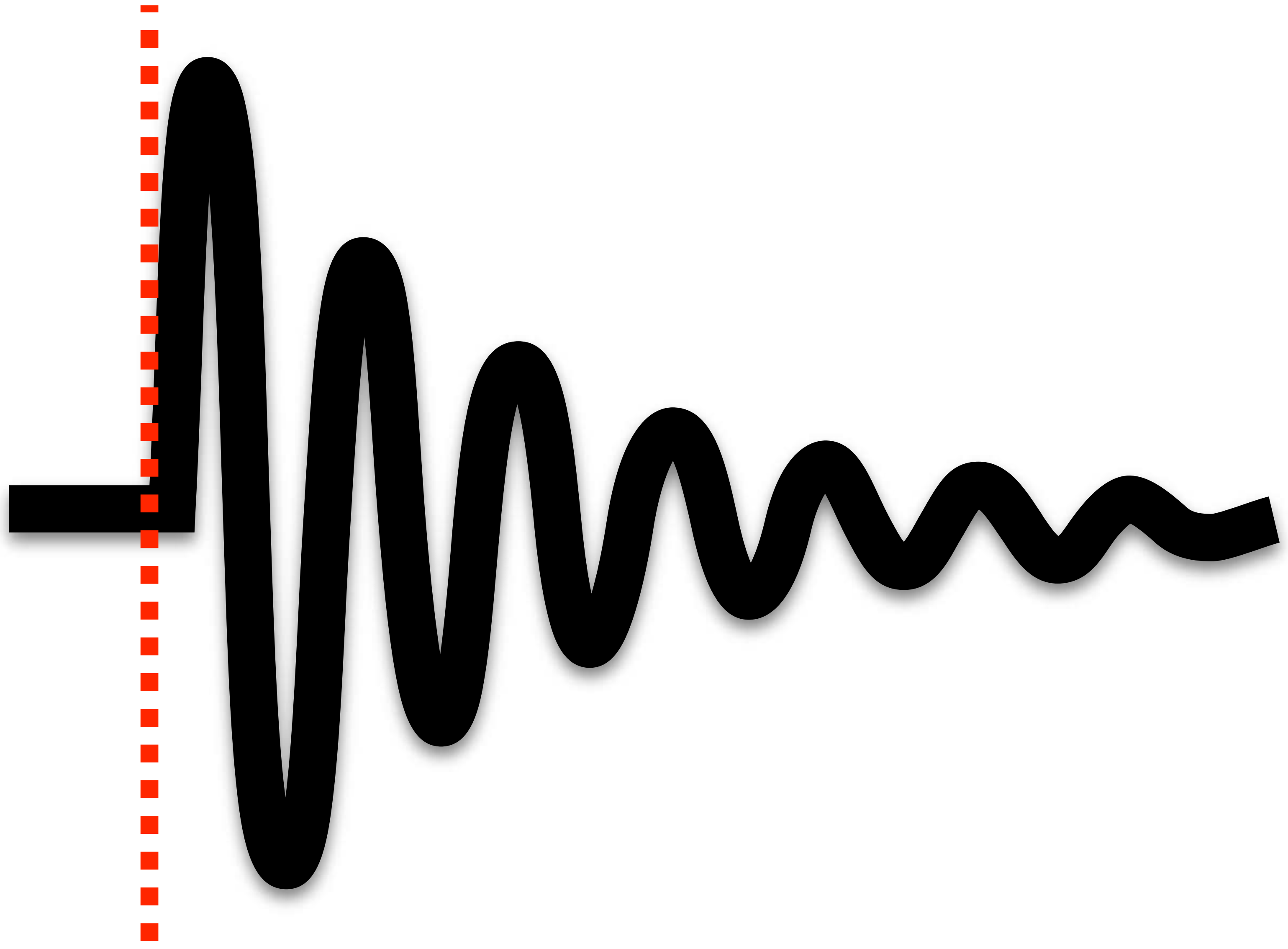
Plasma wave ~50 µm, ~100 GV/m*

➢ **Plasma wake** driven by an ultra-intense femtosecond laser pulse.

Ponderomotive Force

$$F_p = -\frac{e^2}{4m_e\omega^2}\nabla\left(E^2\right)$$



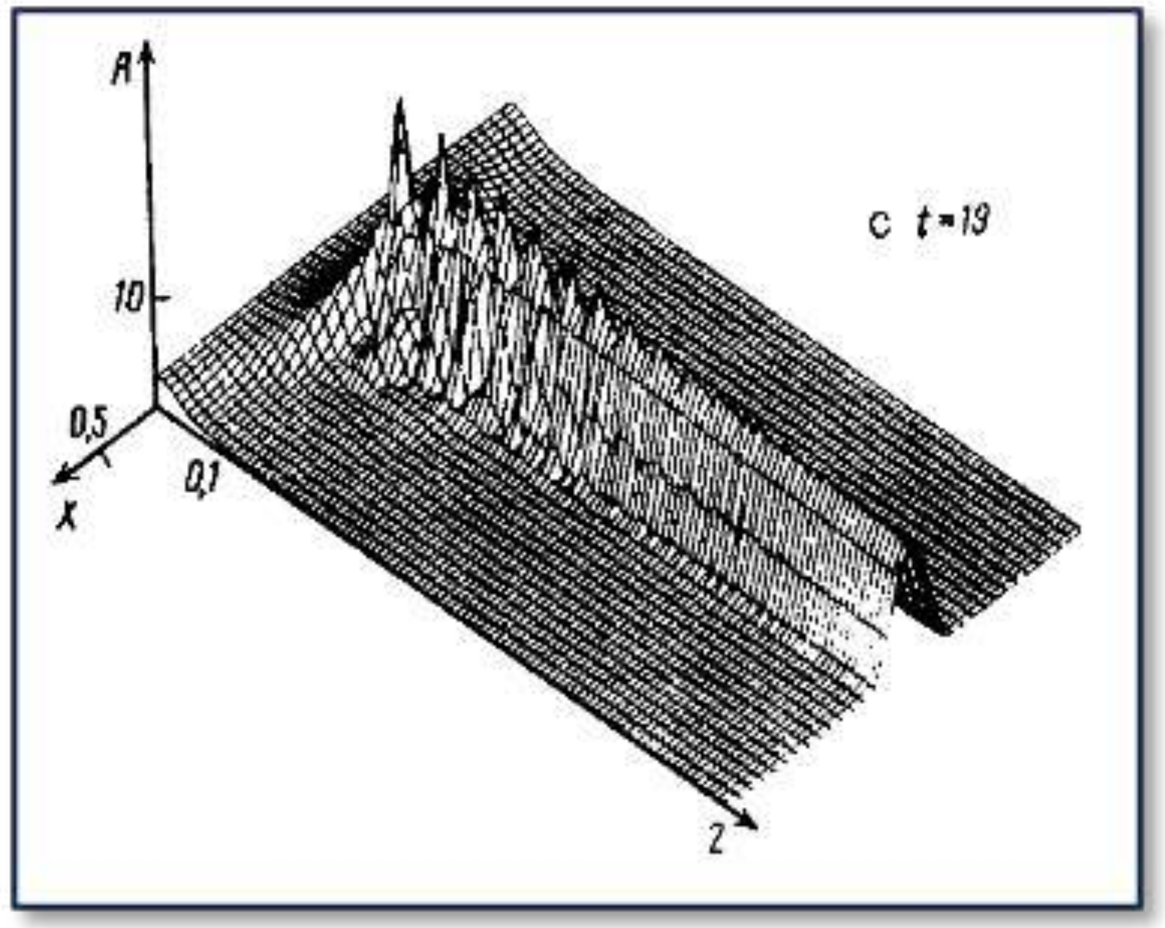


* Mangles, Stuart. "Introduction to plasma wakefield acceleration"
** Y. P. Bliokh, *et al.*, "Wakefield in a Waveguide", Phys. Plasmas 24, 063112 (2017).

Motivation

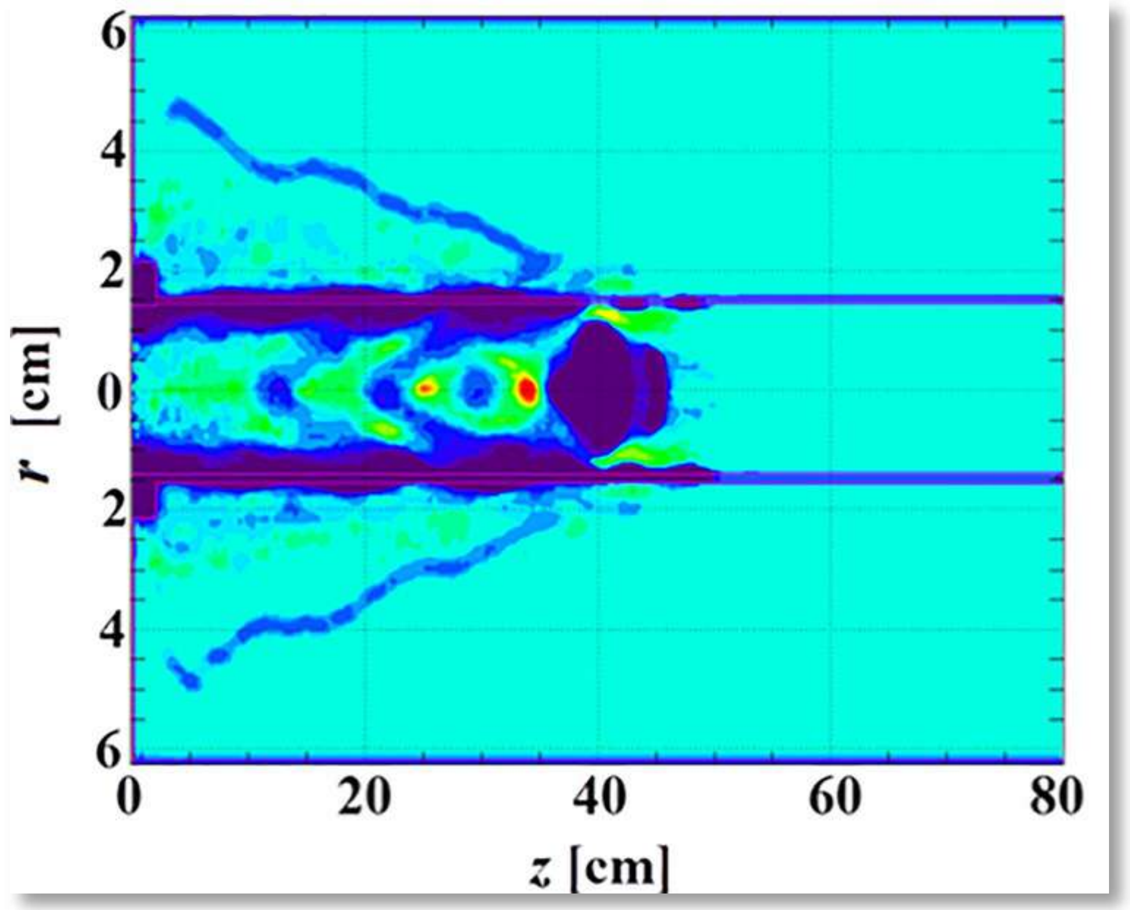
➢ Microwave-plasma interaction can be regarded as a scale down of laser-plasma interaction in terms of **power, plasma density** and the **intensity of wakefield** → <u>**can not**</u> use as accelerator.
➢ But it scales up the interaction with **Larger time-scale (fs → ns)** and **spatial-scale (μm → cm)**.

The ionization-induced channeling



More than 30 years ago, the ionization-induced channeling (IIC) of an intense microwave beam propagating through neutral gas has been predicted theoretically*.

HPM-driven plasma wakefield

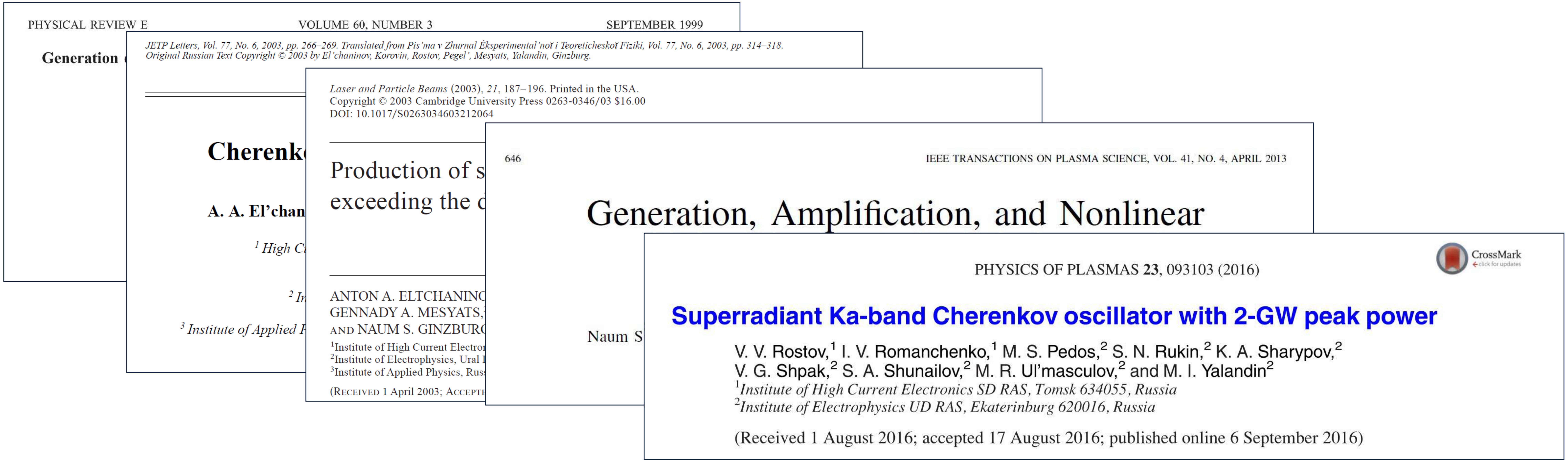


Recently, the feasibility of an experiment to study the effect of HPM-driven wakefield generation in plasma filled waveguide has been analyzed theoretically and simulated**.

* Y. L. Bogomolov, S. F. Lirin, V. E. Semenov, and A. M. Sergeev, JETP Lett. 45, 680 (1987).
** Bliokh, Y. P., Leopold, J. G., Shafir, G., Shlapakovski, A., & Krasik, Y. E. Physics of Plasmas, 24, 063112 (2017).

Motivation

➢ The development of the ultra-powerful sub-ns microwave source (2010s).



➢ This research allows to study the interaction of high-power microwave with plasma in the **nonlinear regime NEVER** studied before.

Outline

1. Ionization-induced **self-channeling** of a high-power microwave in plasma.

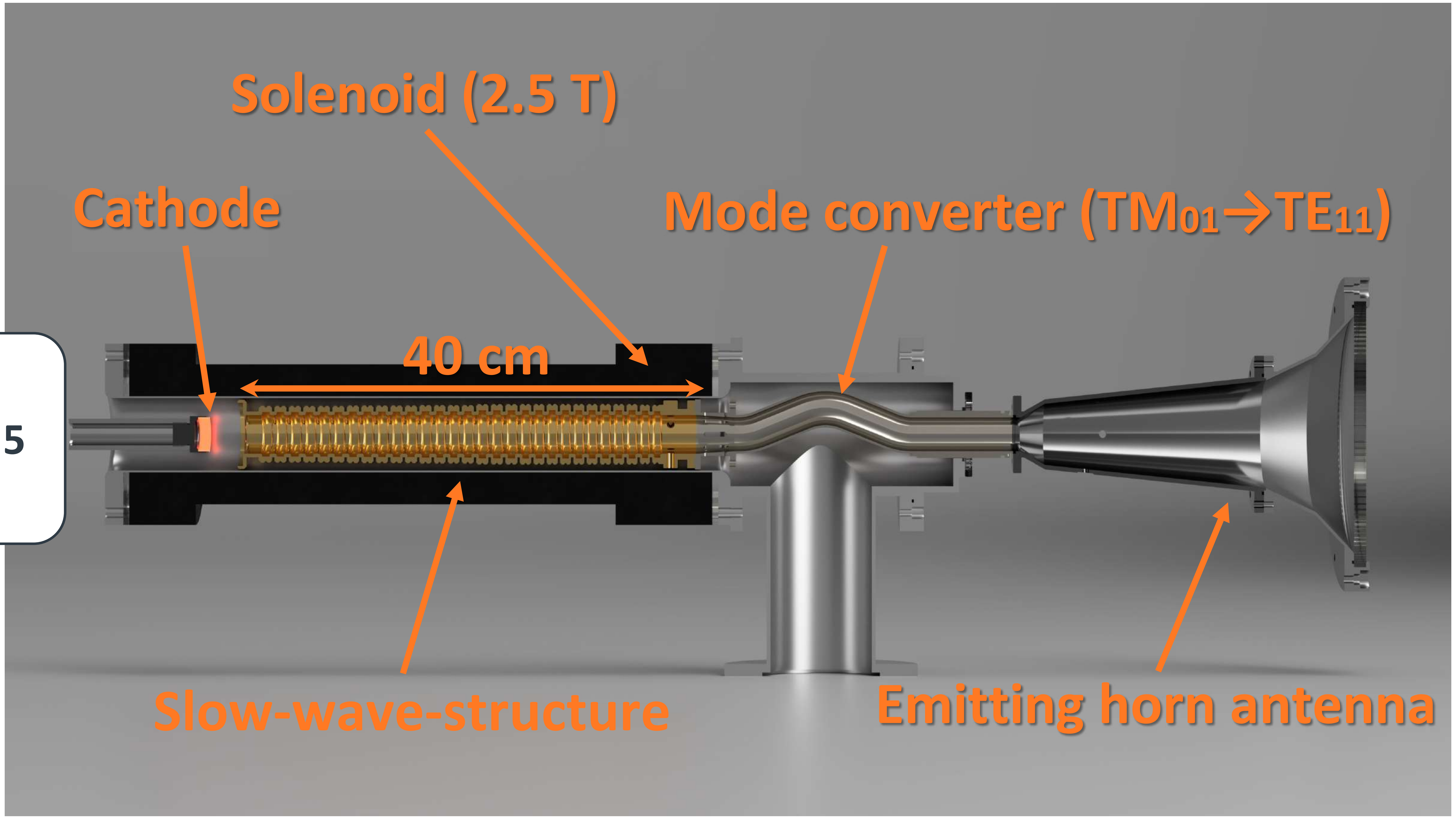
2. "**Superluminal**" propagation, and **compression** of high-power microwave pulse in propagating ionization front

3. High-power microwave driven **plasma wakefield** in a plasma-filled cylindrical waveguide.

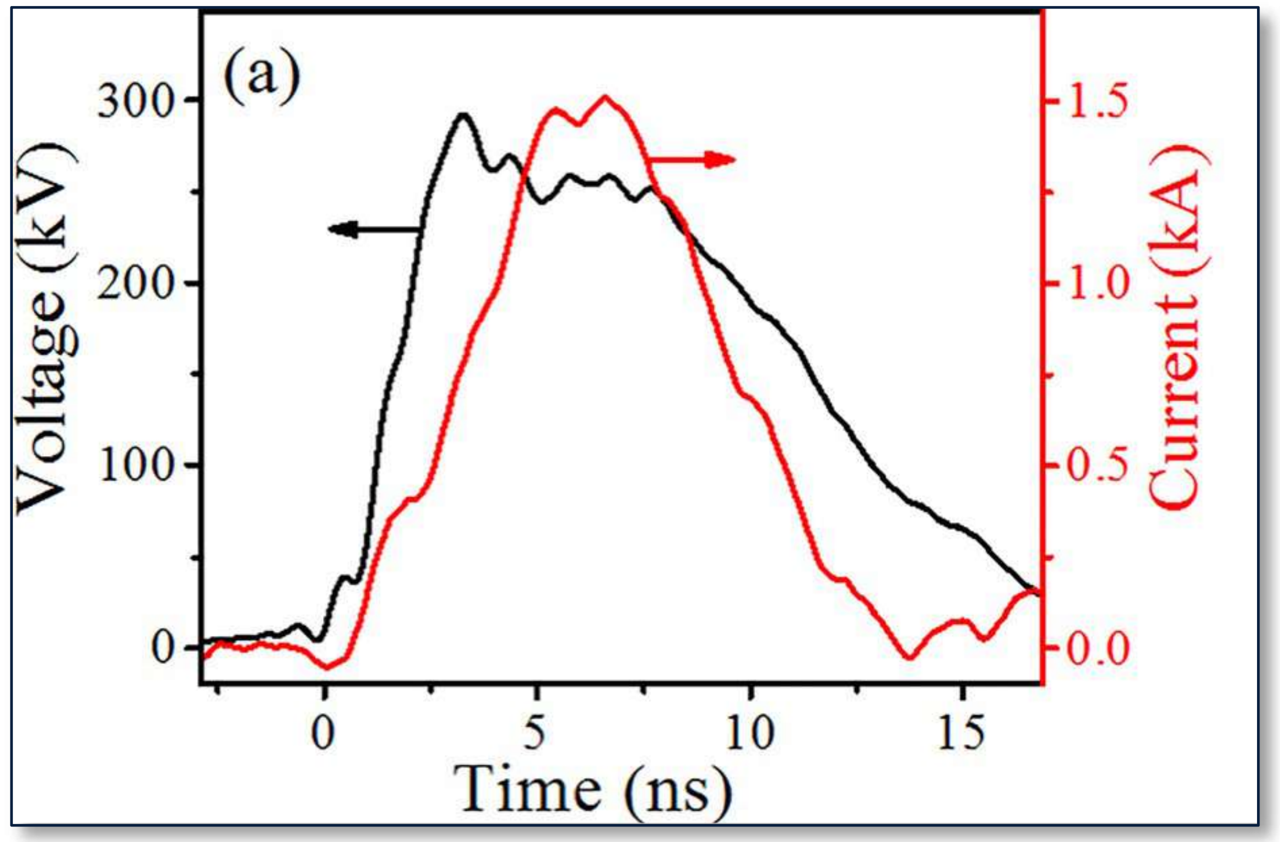
The High-Power Microwave Sources

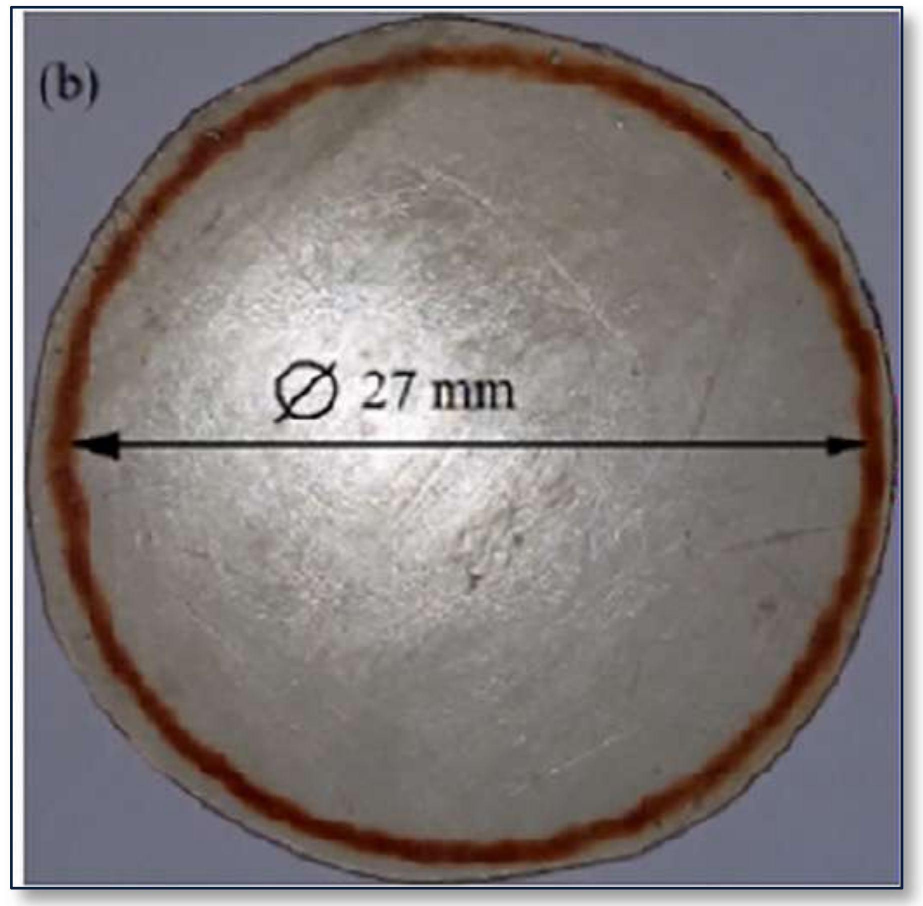
X-Band Microwave Source

Generator
350 kV, 2 kA, 5 ns



Typical waveforms of the voltage and electron beam current

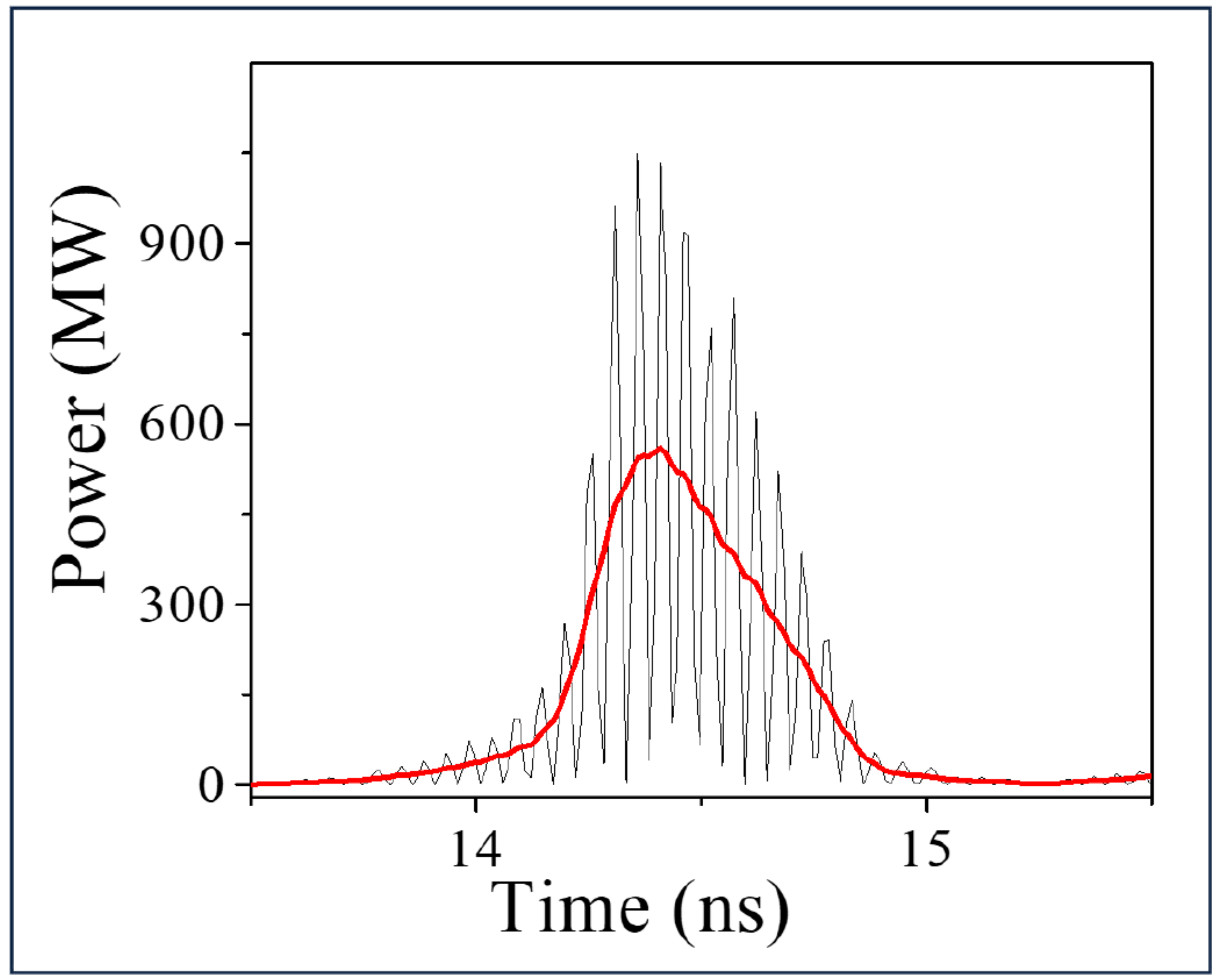




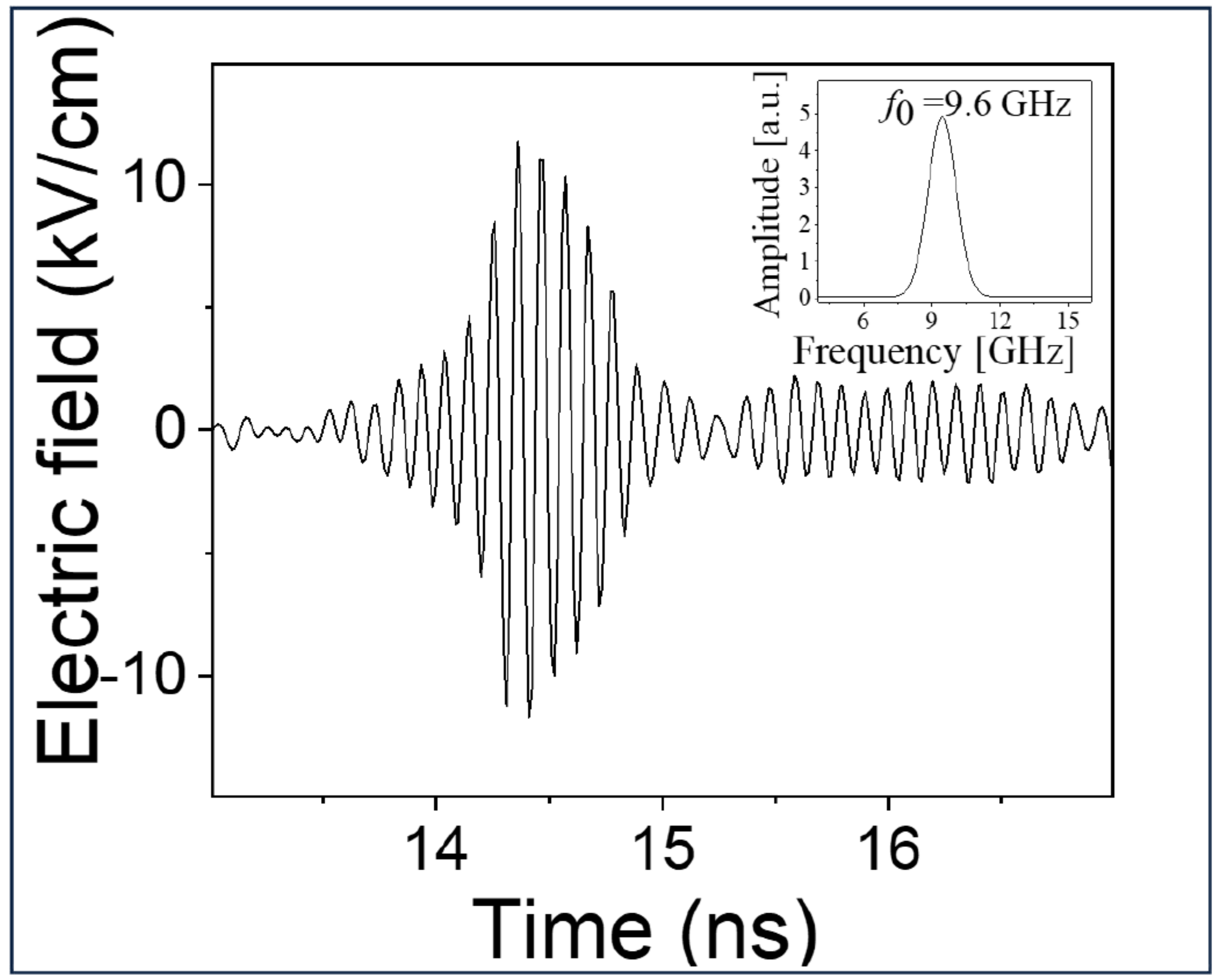
The pattern of the electron beam

 G. Shafir, A. Shlapakovski, M. Siman-Tov, Yu. Bliokh, J. G. Leopold, S. Gleizer, R. Gad, V. V. Rostov, and Ya. E. Krasik, J. Appl. Phys. 121, 033301 (2017).

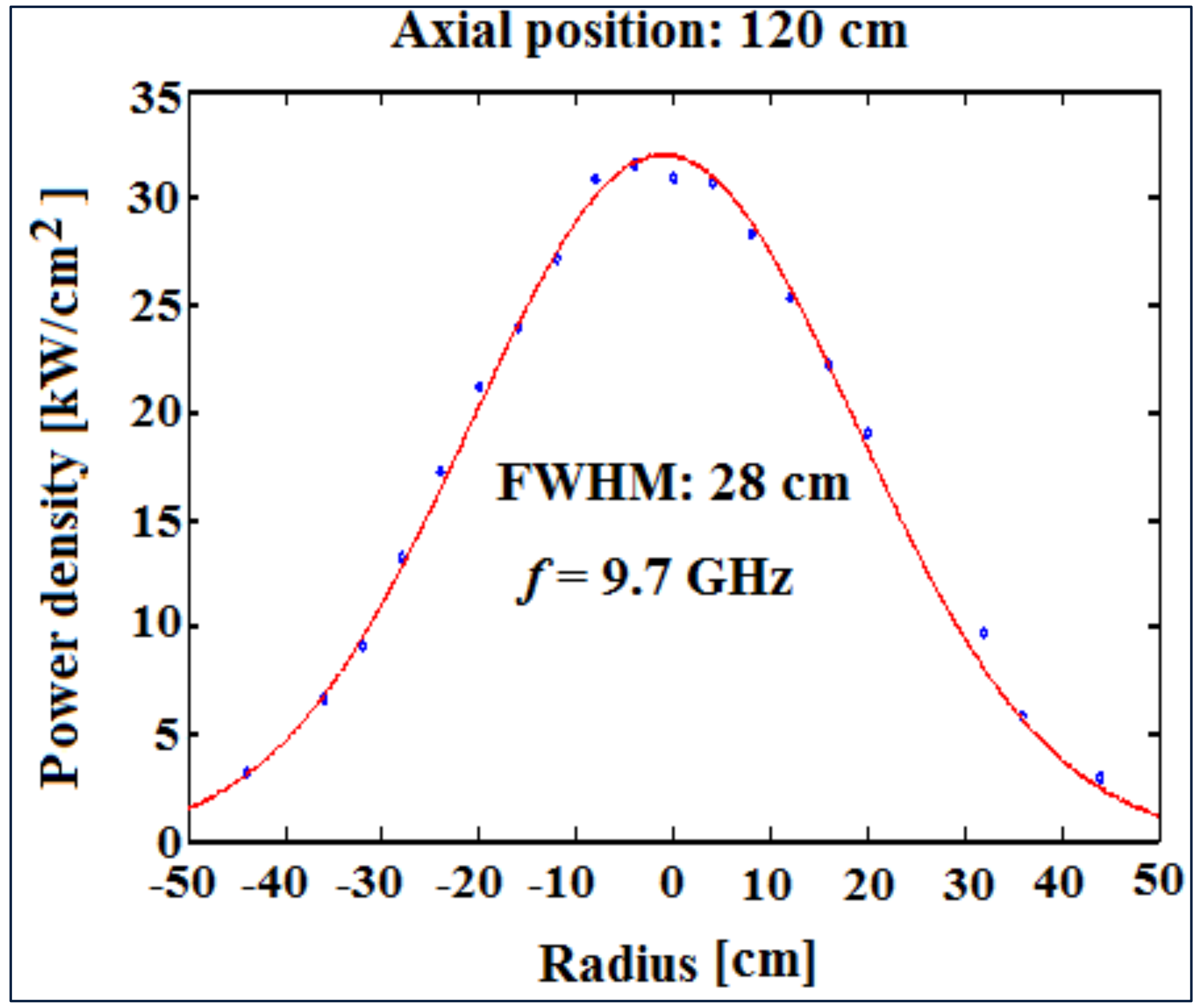
X-Band Microwave Source



Microwave instantaneous and averaged power



Electric field at the aperture of receiving antenna (Z = 120 cm) and frequency of the microwave signal (insert)



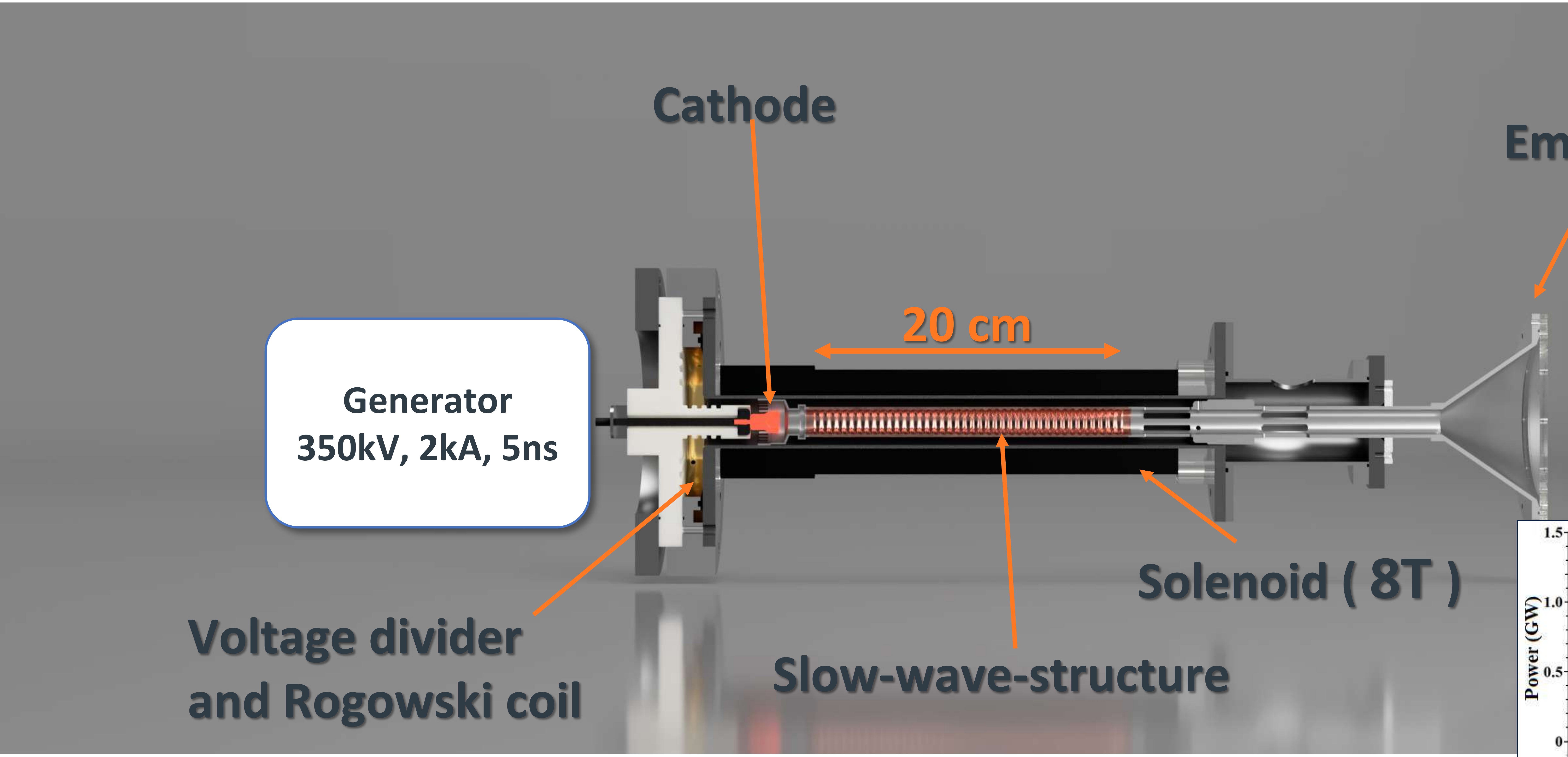
Microwave power density radial distributions at z = 120 cm

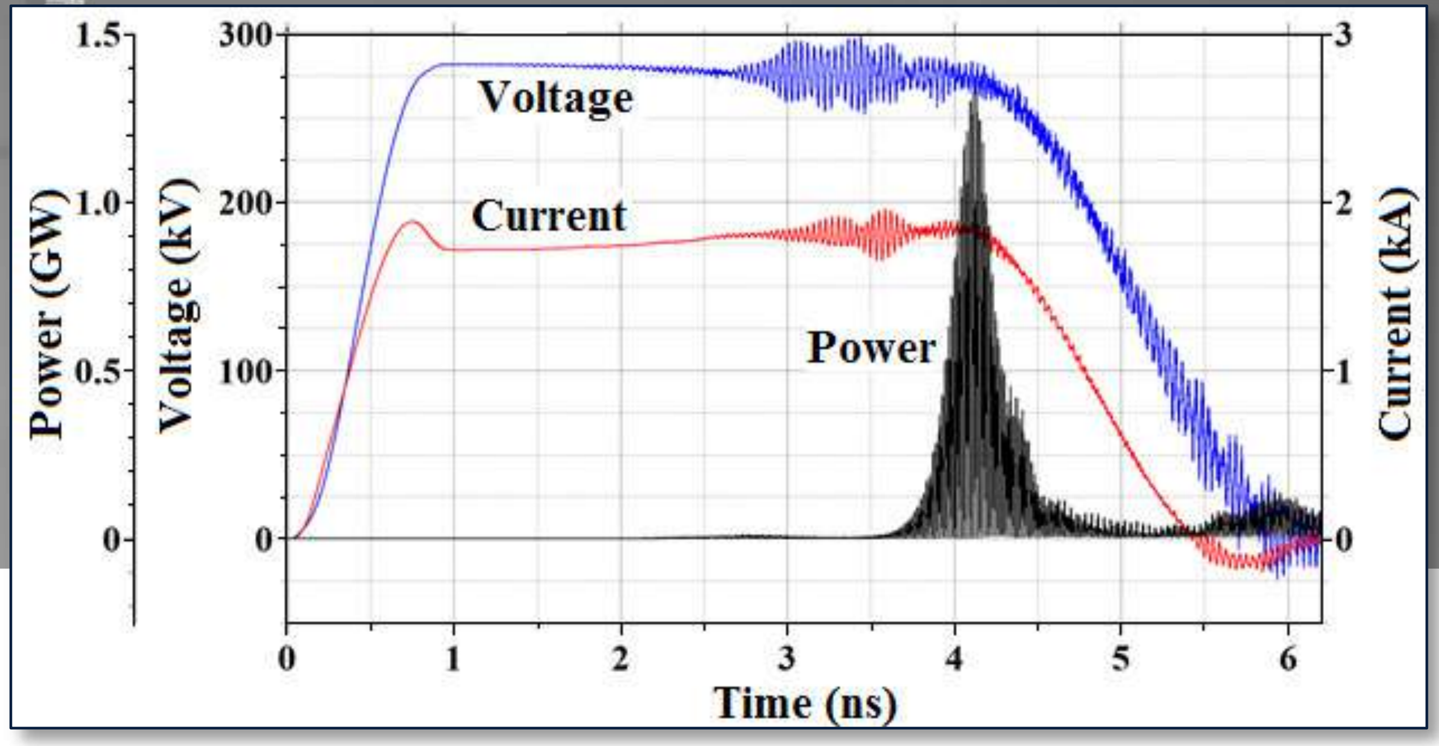
Microwave beam output:

$P_{MW} < 500$ MW, $\tau \sim 0.7$ ns, $f \sim 9.7$ GHz

G. Shafir, A. Shlapakovski, M. Siman-Tov, Yu. Bliokh, J. G. Leopold, S. Gleizer, R. Gad, V. V. Rostov, and Ya. E. Krasik, J. Appl. Phys. 121, 033301 (2017).

K-Band Microwave Source



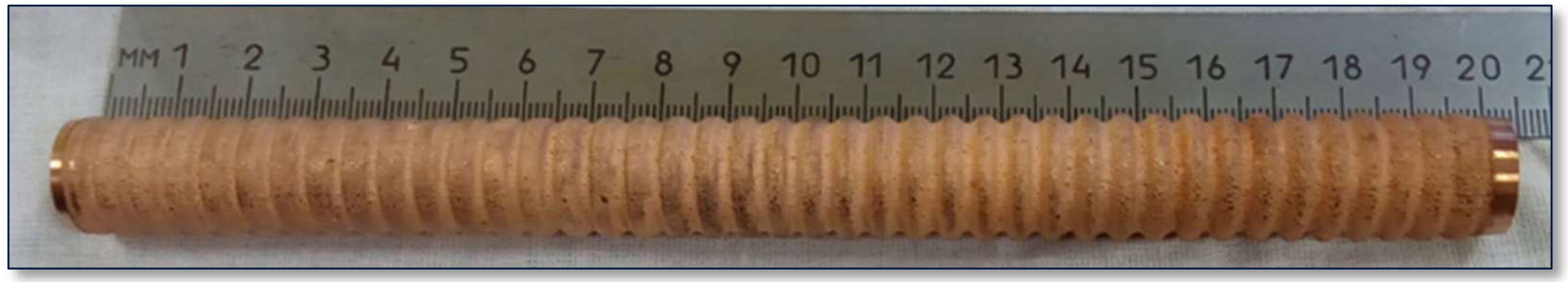


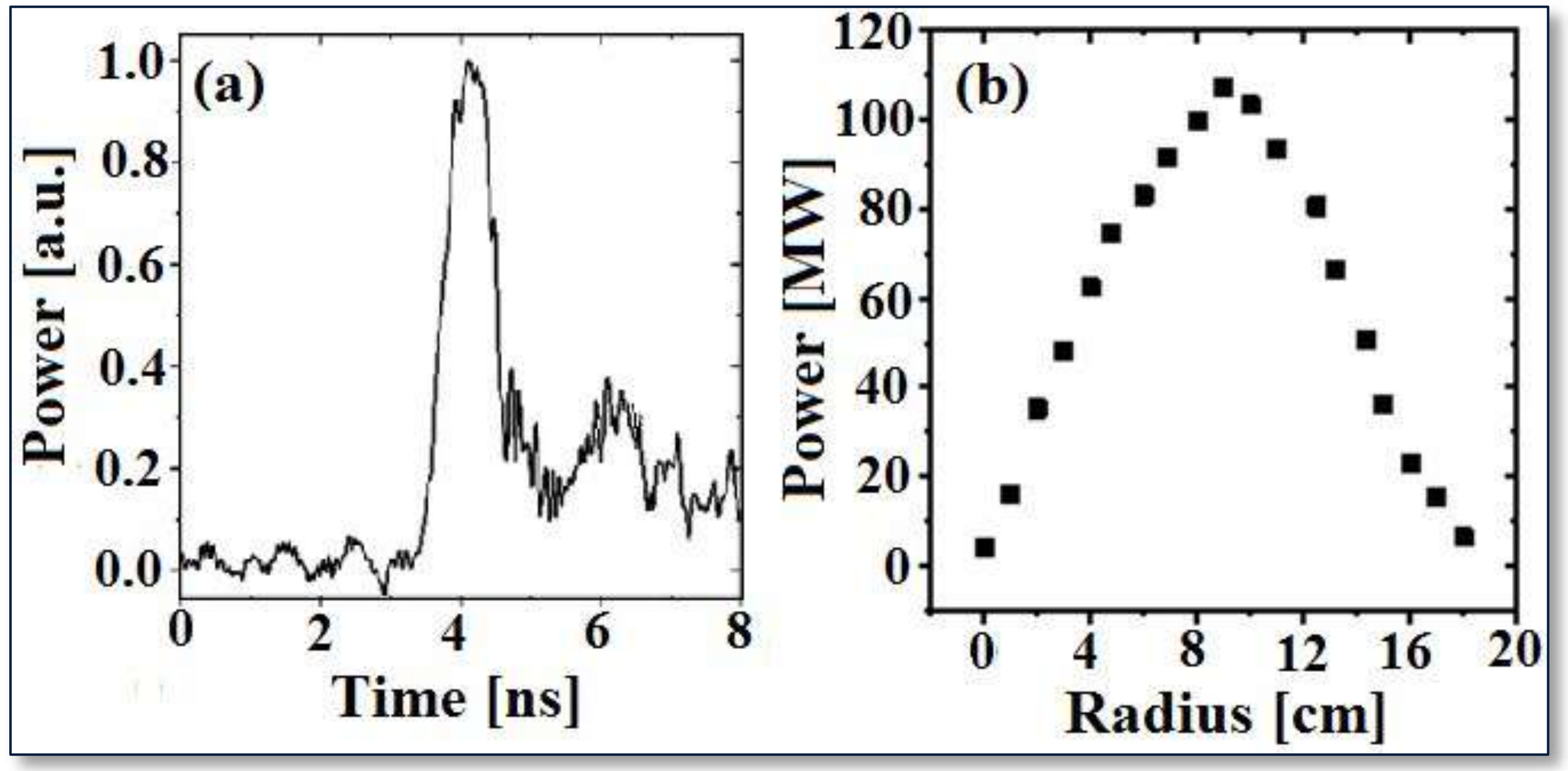
3D MAGIC-PIC simulations: The input voltage, the beam current and the output microwave power

K-Band Microwave Source

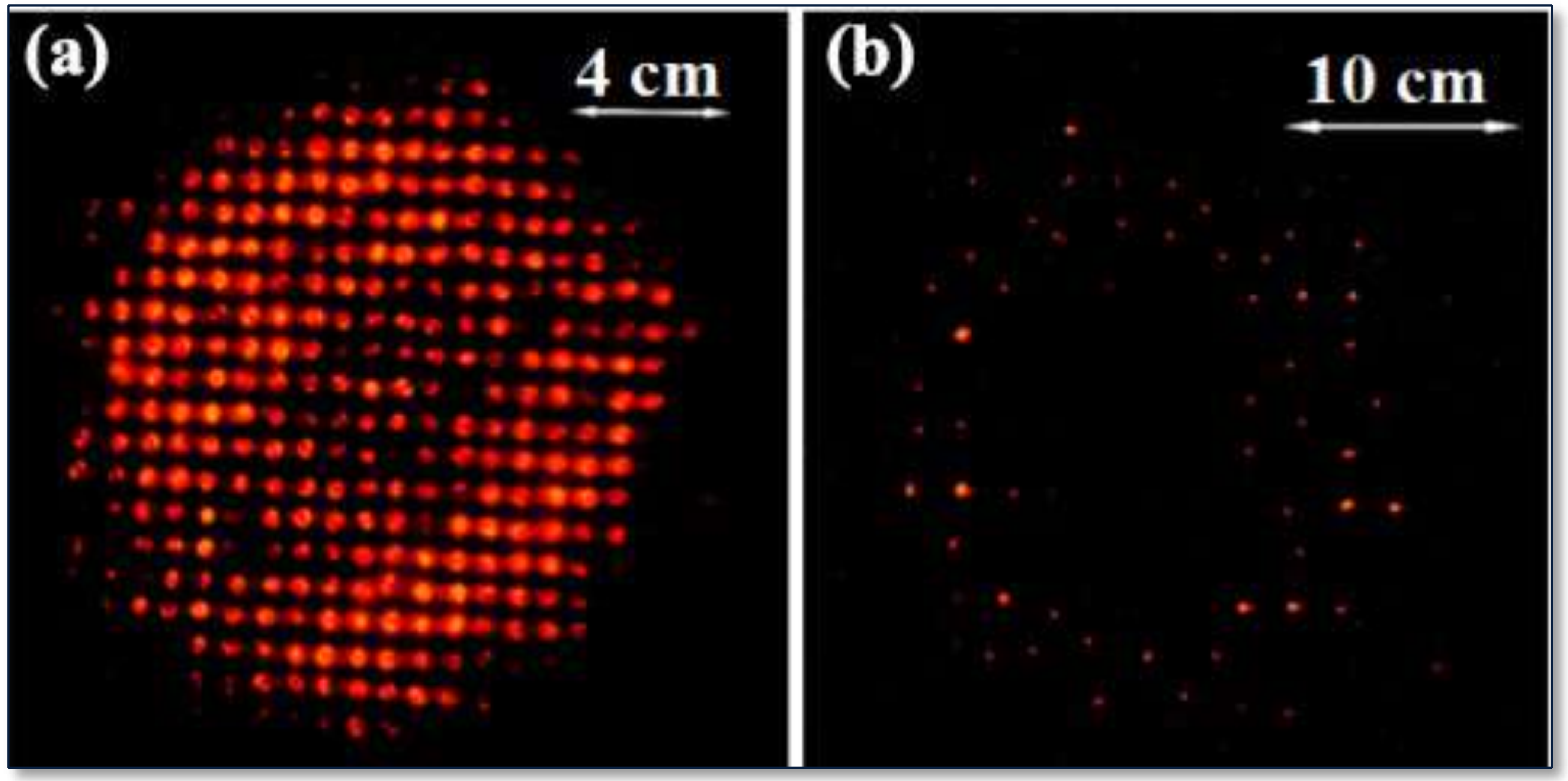
The electron beam pattern on CR-39 plastic target (radius 0.7 cm)

External view of the 25.5 GHz slow wave structure.





(a) Typical waveform of the microwave beam power and (b) Microwave power radial distribution measured at z=20 cm.



Microwave spatial distribution by Neon-lamp matrix at distance of 4 cm and 20 cm. (TM_{01} mode)

Microwave beam output:

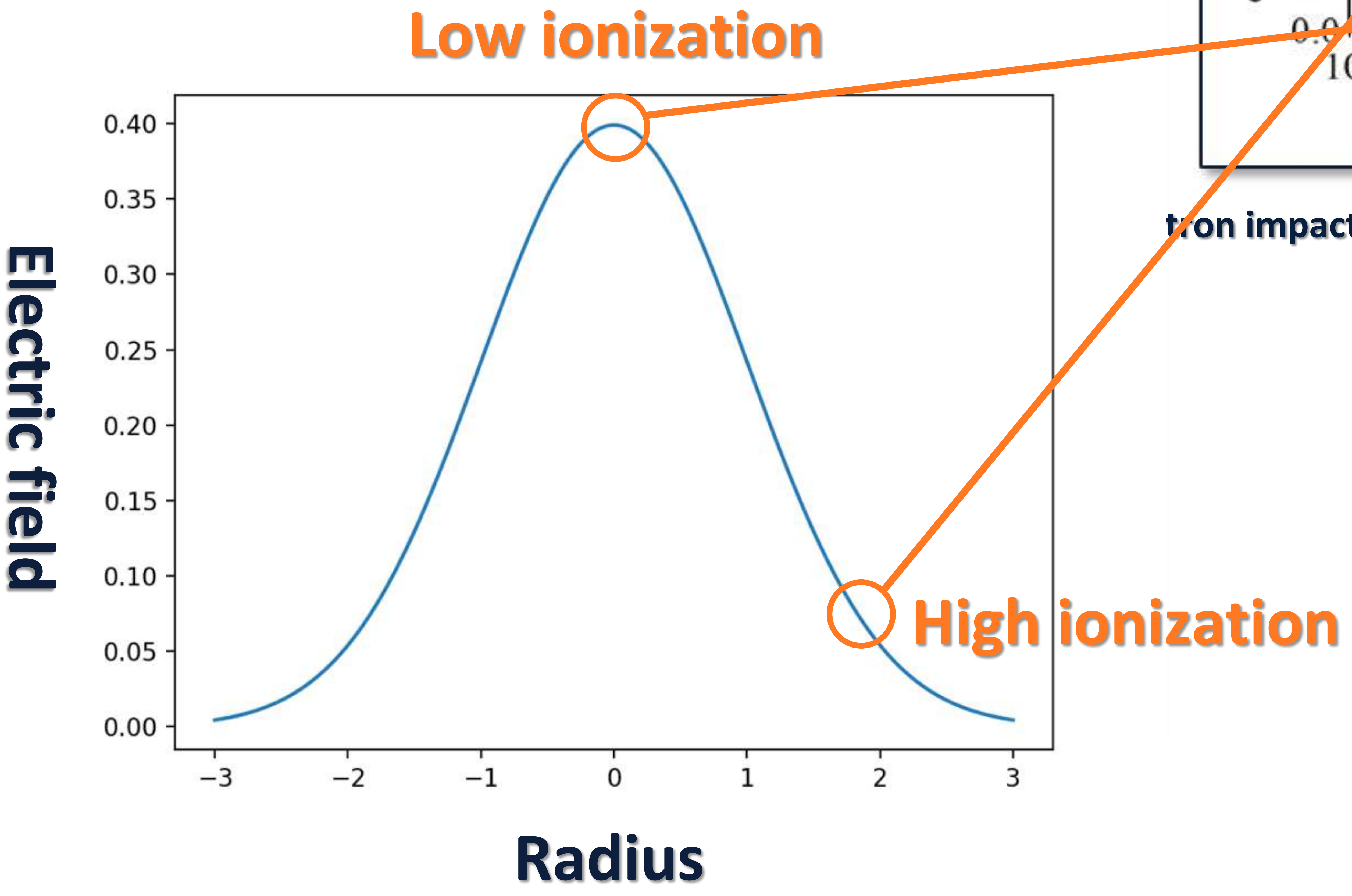
- P_{MW} ~ 1.2 GW,
- τ ~ 0.4 ns,
- f ~ 25.5 GHz.

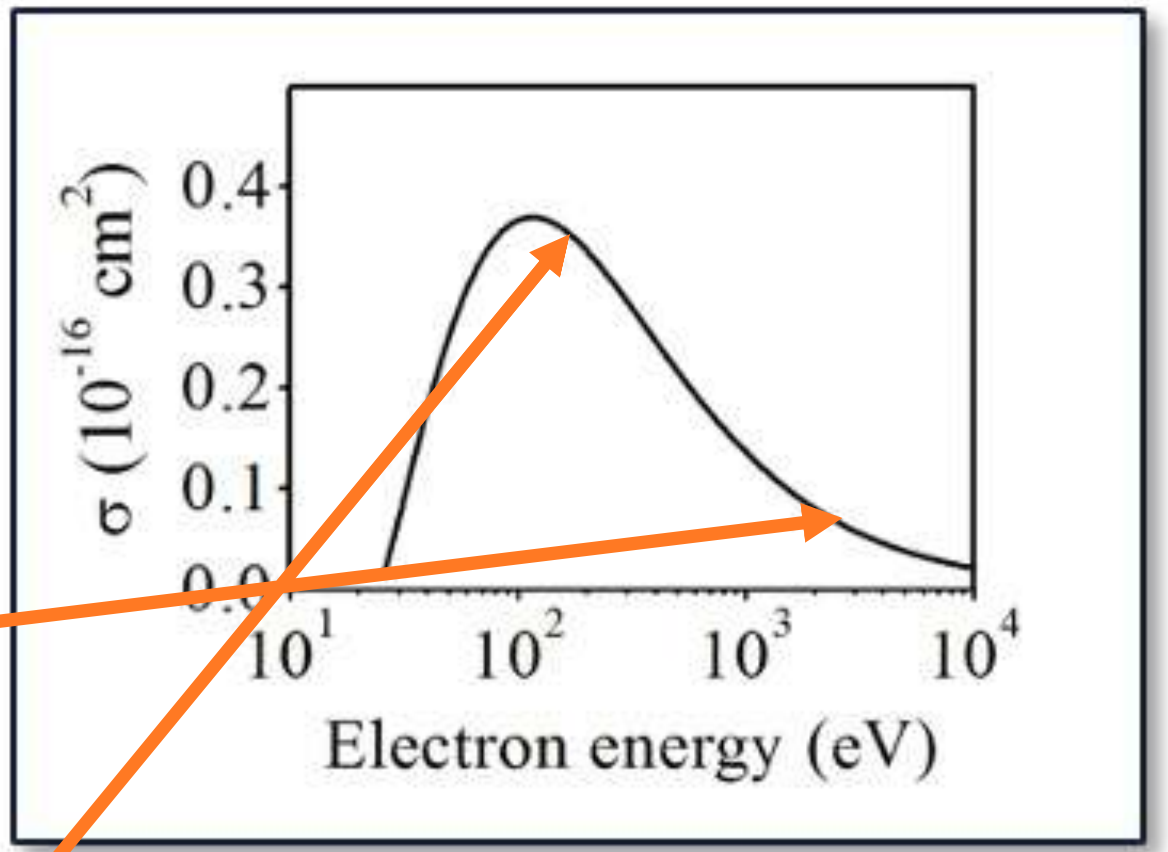
 Y. Cao, Y. Bliokh, J. G. Leopold, V. Rostov, Y. Slutsker, and Y. E. Krasik, Phys. Plasmas 26, 023102 (2019).

Ionization-induced self-channeling of a high-power microwave in plasma

Mechanism

Ionization-induced self-channeling of a HPM pulse*





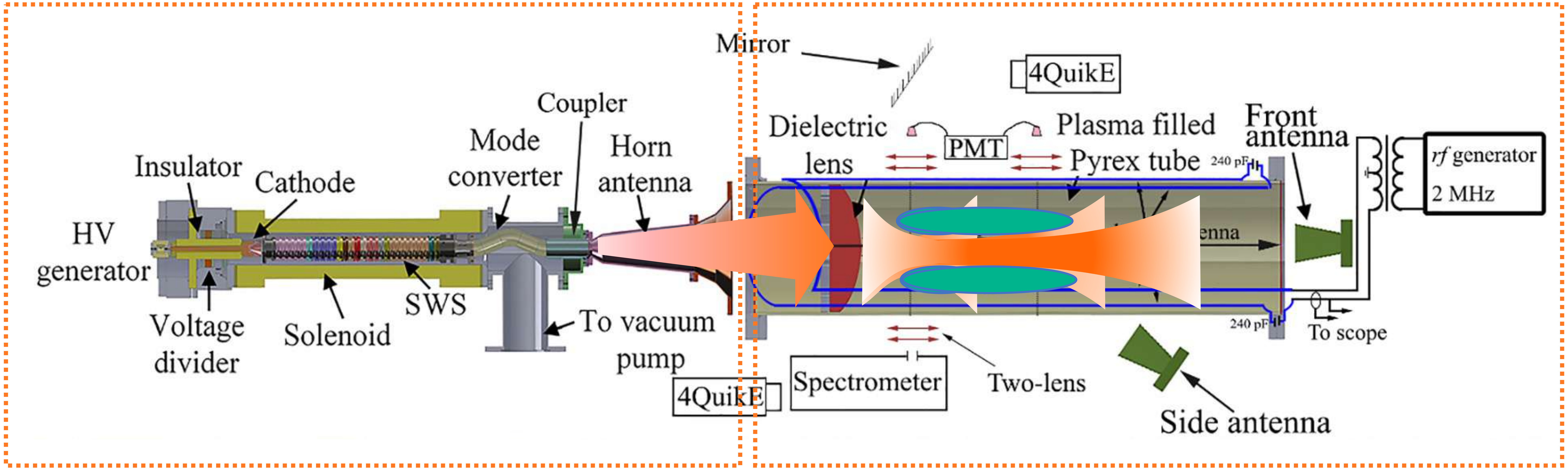
tron impact ionization cross-section for varies electron energies

* Y. L. Bogomolov, S. F. Lirin, V. E. Semenov, and A. M. Sergeev, JETP Lett. 45, 680 (1987).

Experimental Setup

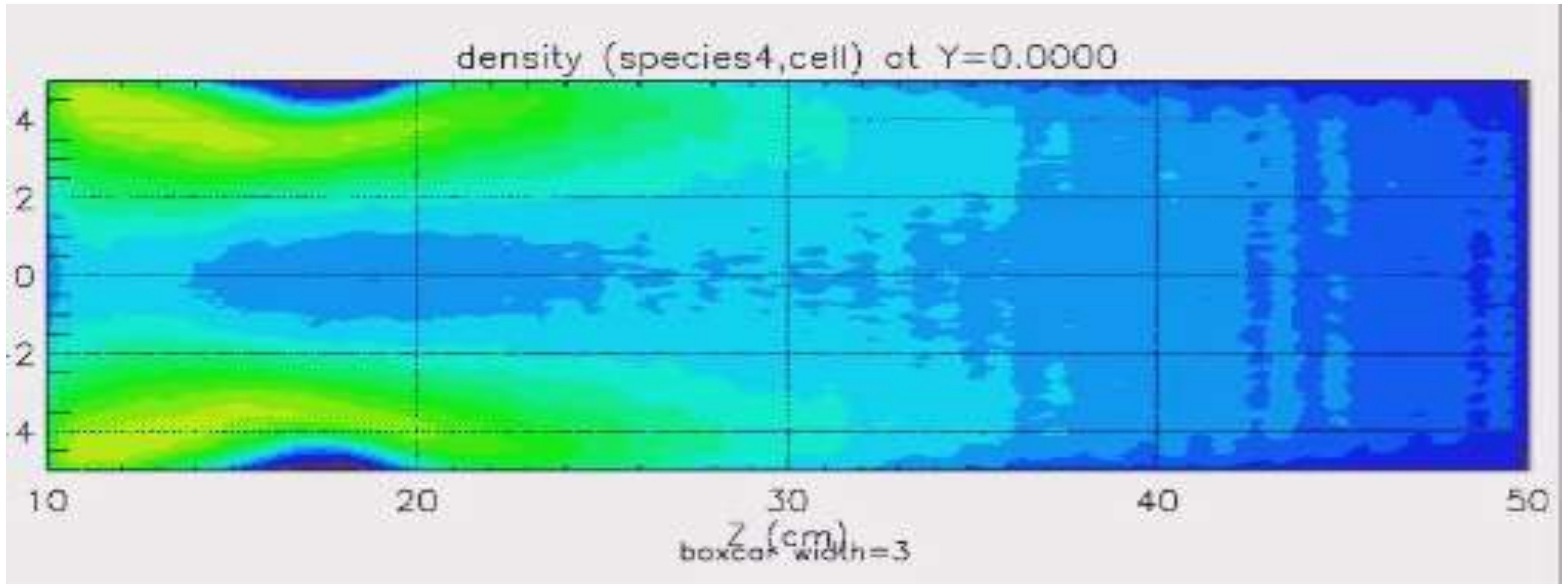
X-band Microwave Source

Pyrex Tube Plasma Source

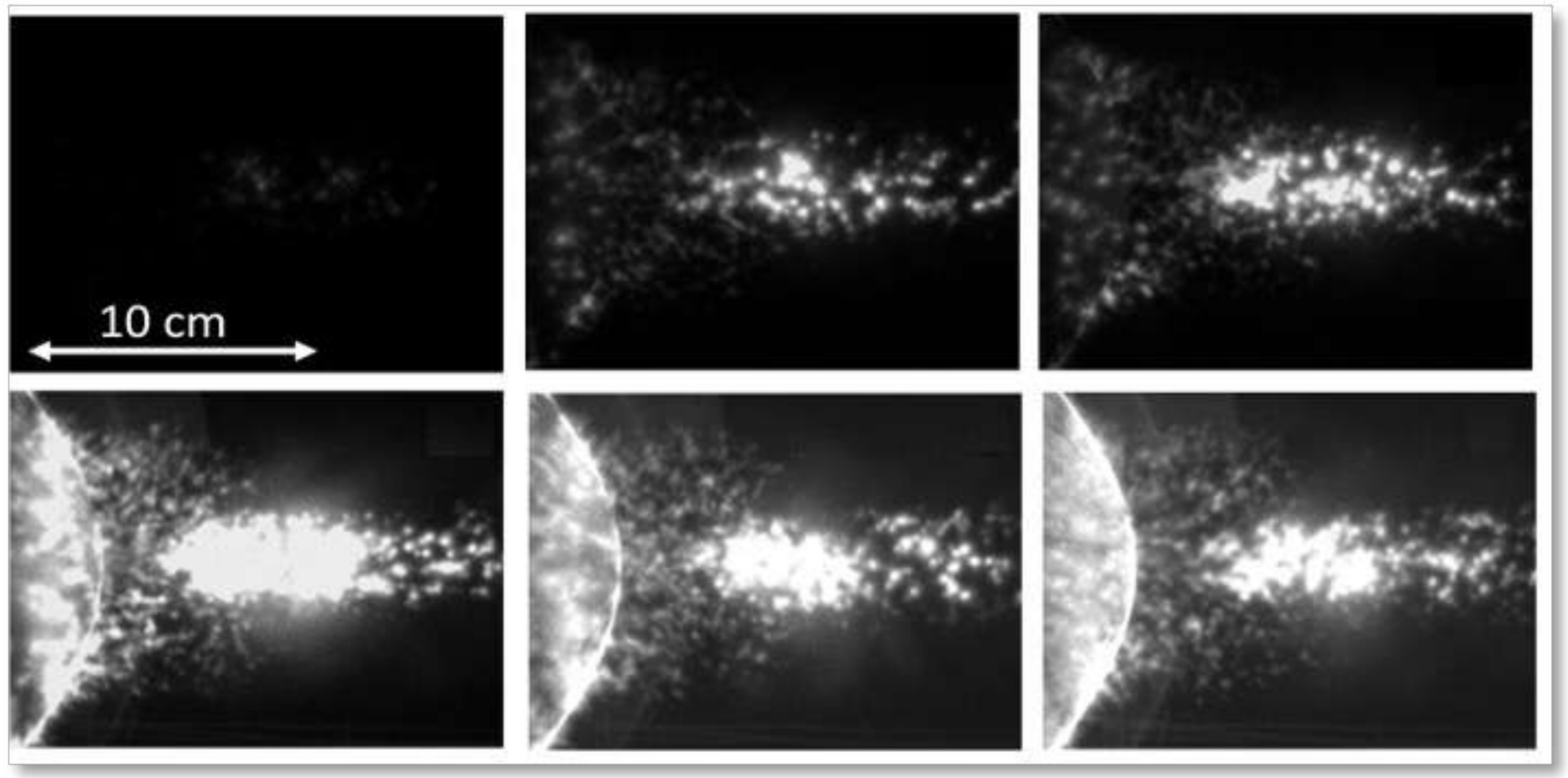


 Y. Cao, J. G. Leopold, Y. P. Bliokh, and Y. E. Krasik, Phys. Plasmas 25, 103101 (2018).

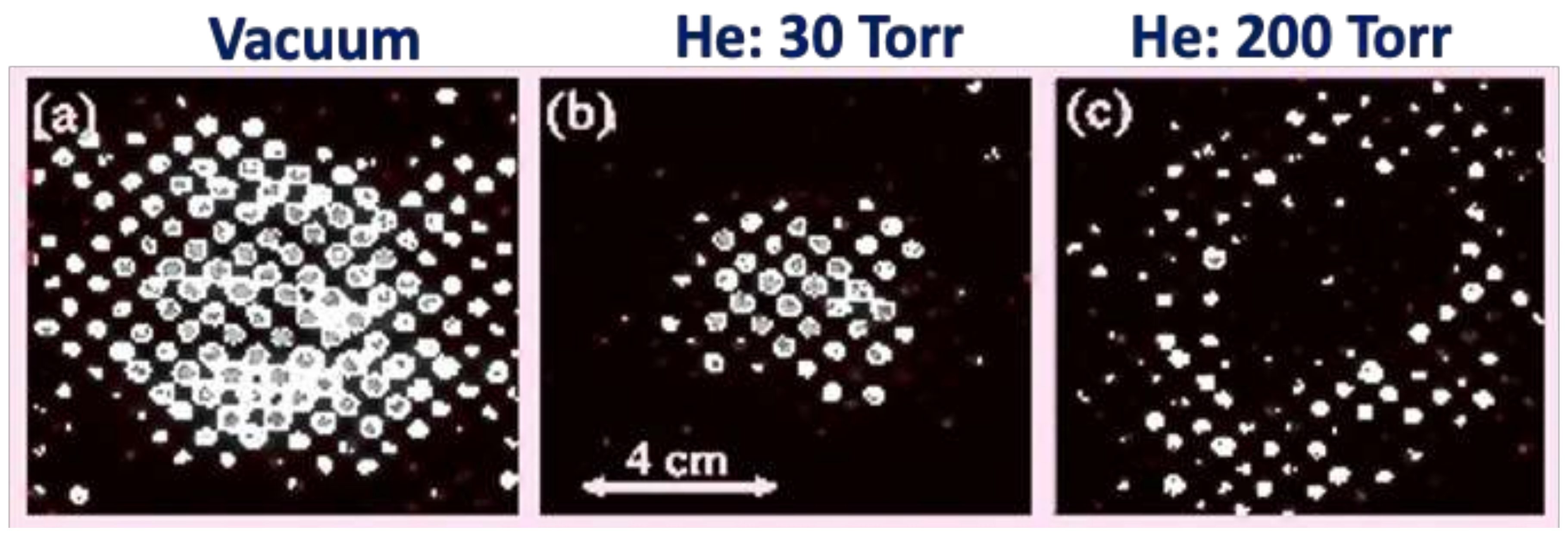
Simulation and Experimental Result

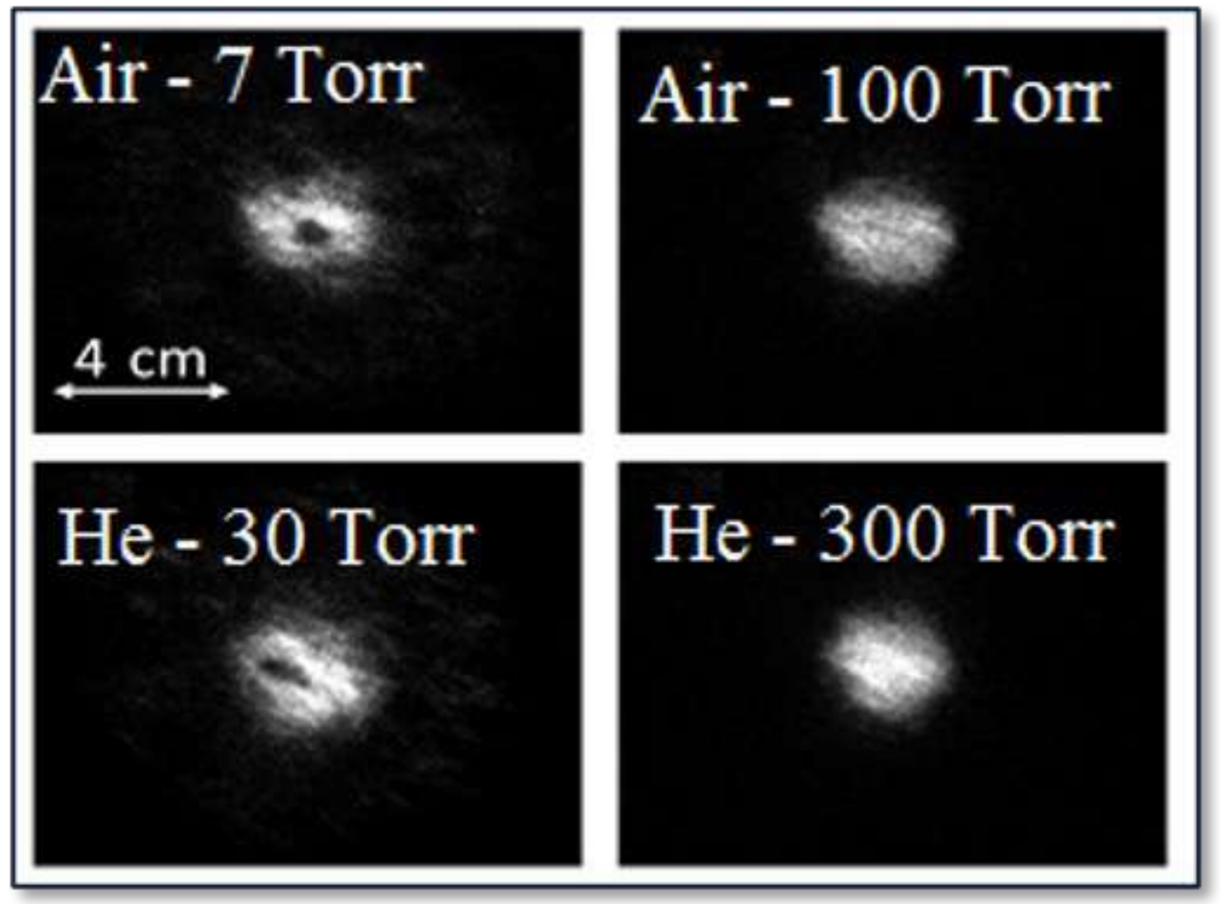


3D PIC simulation of self-channeling for a HPM pulse



Plasma formation, Air 7 Torr. Time delay of 1 ns between frames each of 1.2 ns duration





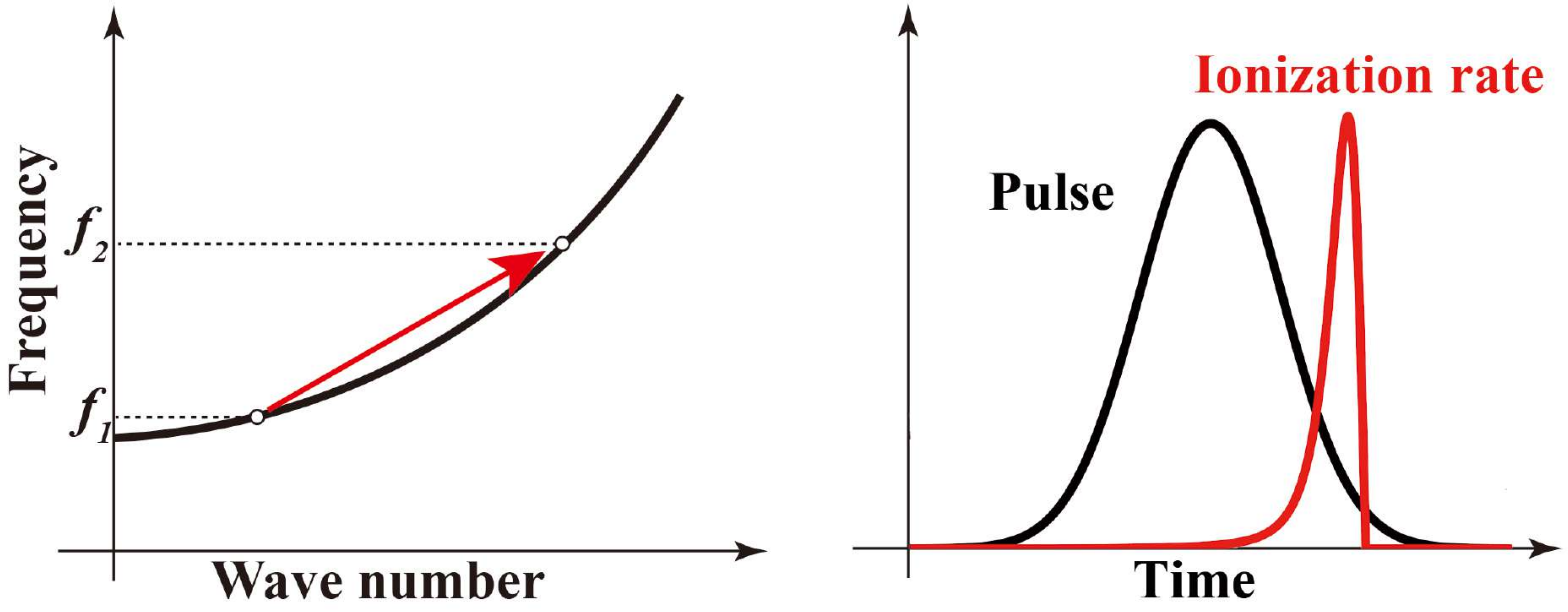
Hollow plasma channel was observed by fast (0.5 ns) framing camera

Conclusions

Impact ionization-induced self-channeling of a sub-nanosecond, high-power microwave pulse in plasma was observed **experimentally**, and confirmed **numerically**.

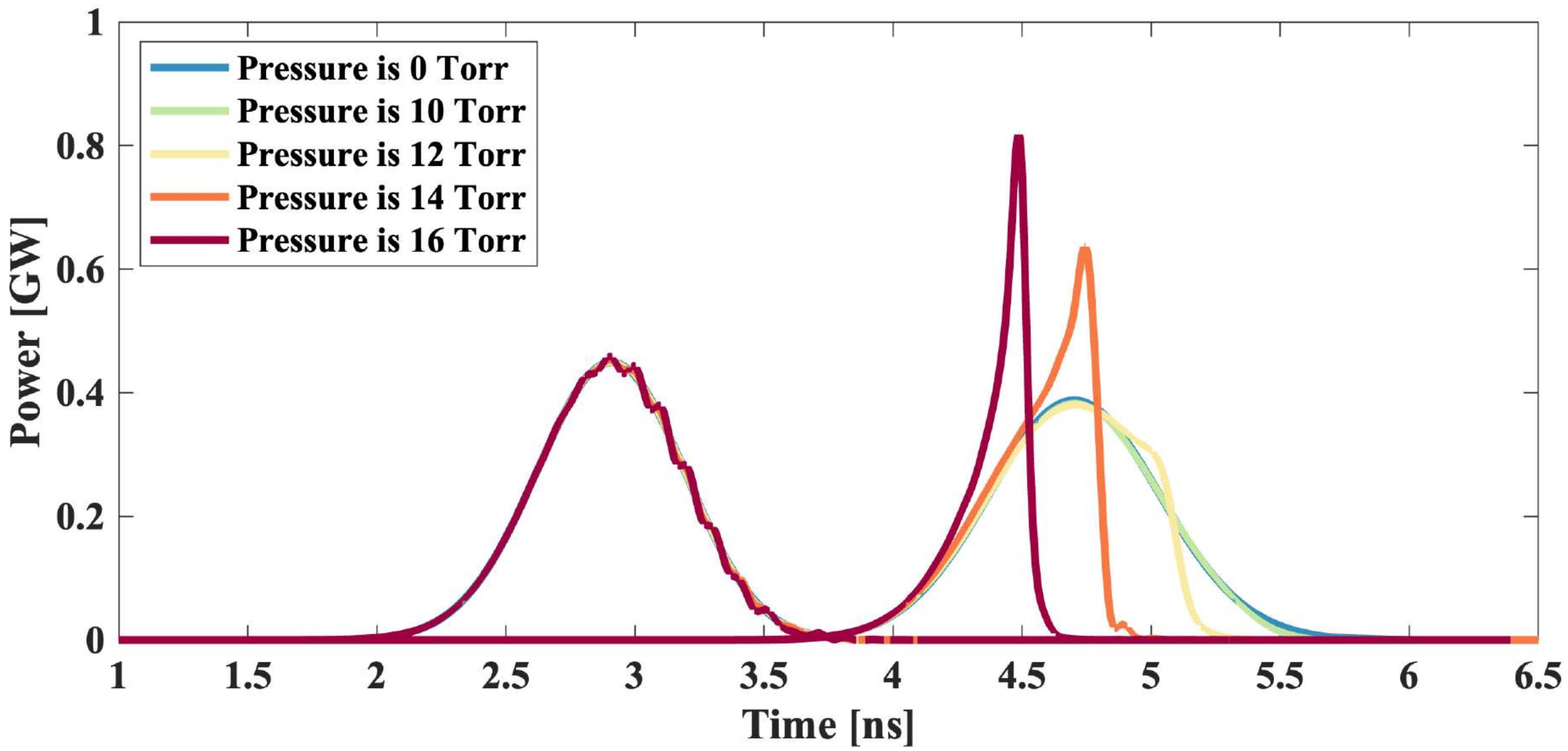
Phys. Rev. Lett. **120**, 135003 (2018).
Phys. Plasmas **25**,103101 (2018)
Phys. Plasmas **25**, 032308 (2018).

“Superluminal” propagation, and compression of high-power microwave pulse in propagating ionization front



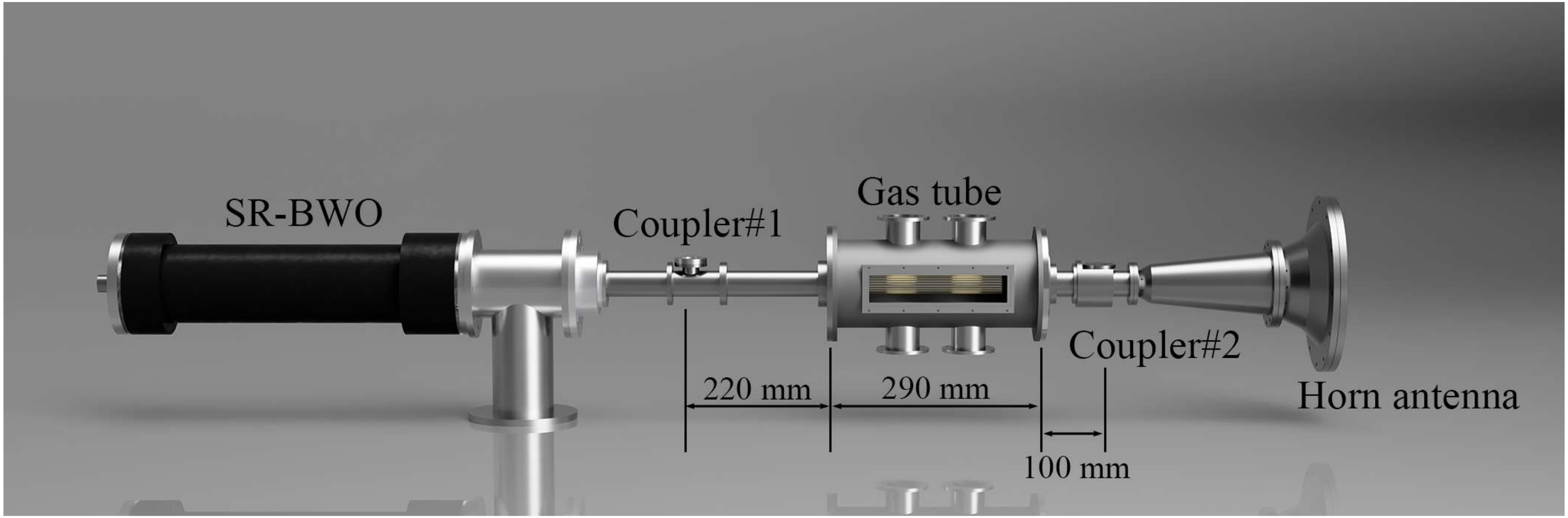
(left) The dispersion relation of the MW pulse in a time-varying medium and (right) the ionization rate within the pulse.

3D Lsp simulation results of the incident and transmitted microwave pulse in various helium pressure.

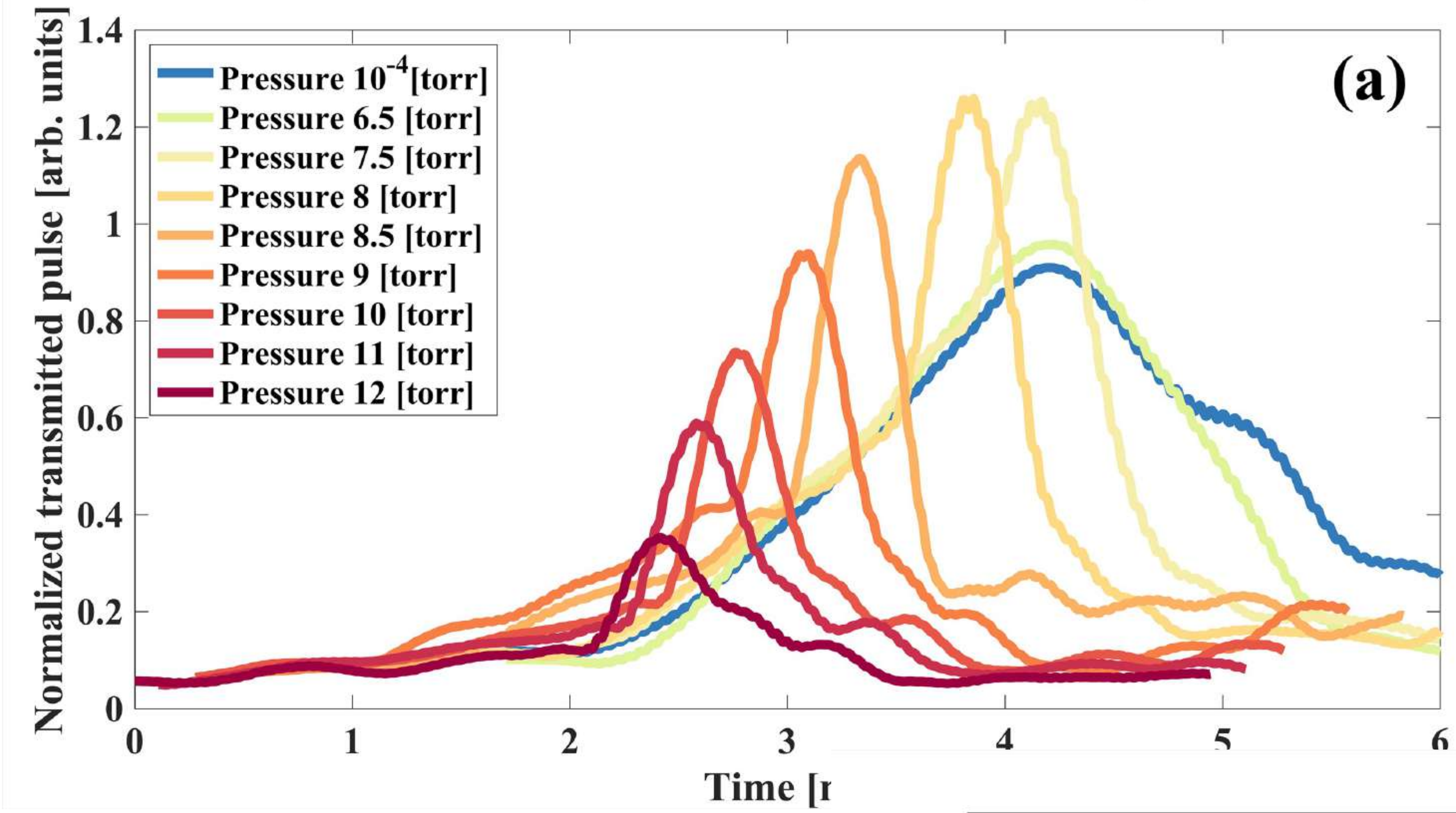


 Cao, Y. and Bliokh, Y. P. and Maksimov, V. and Leopold, J. G. and Krasik, Ya. E., Phys. Rev. E, 107 (045203), 2023

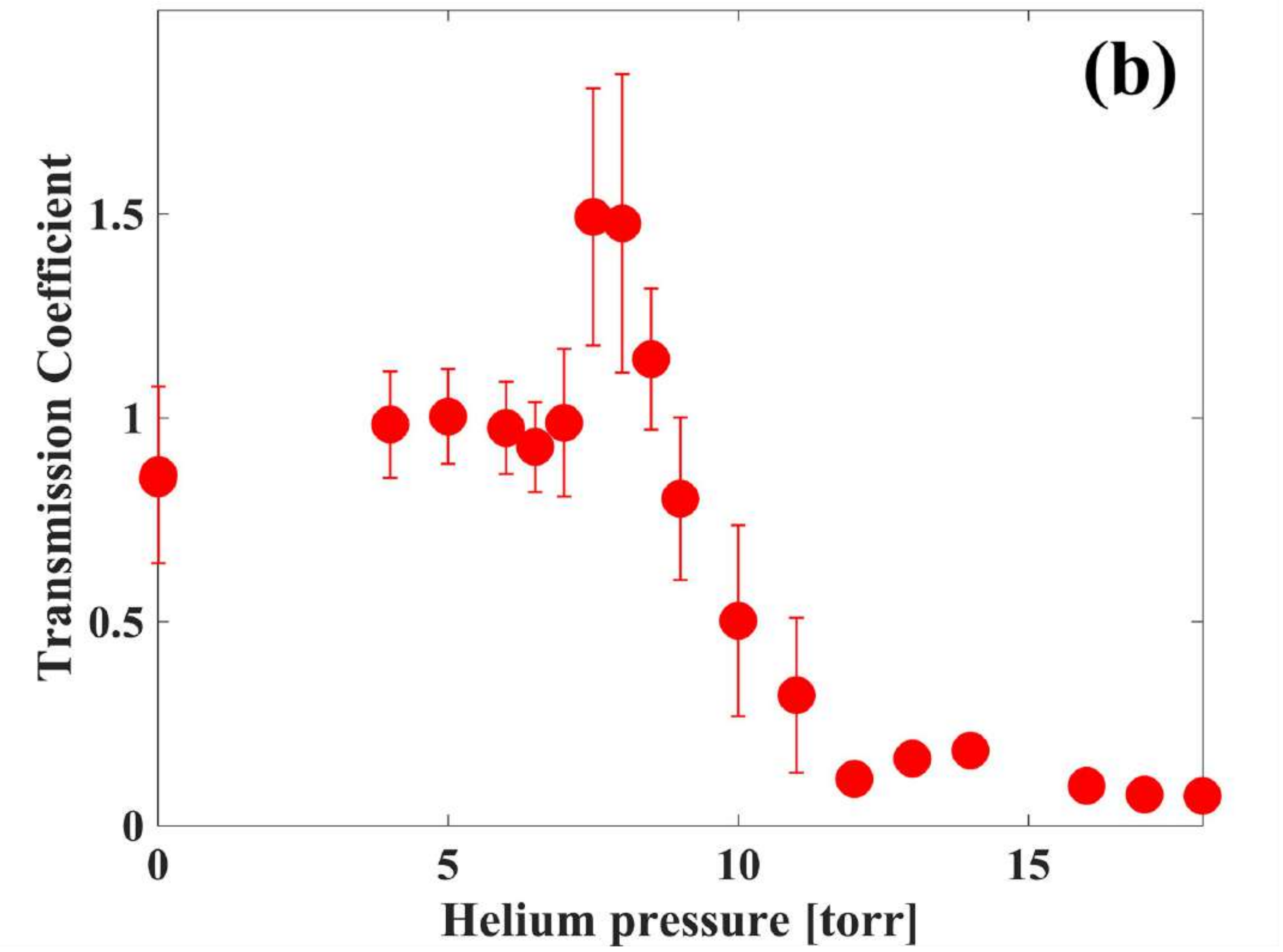
Experimental Setup

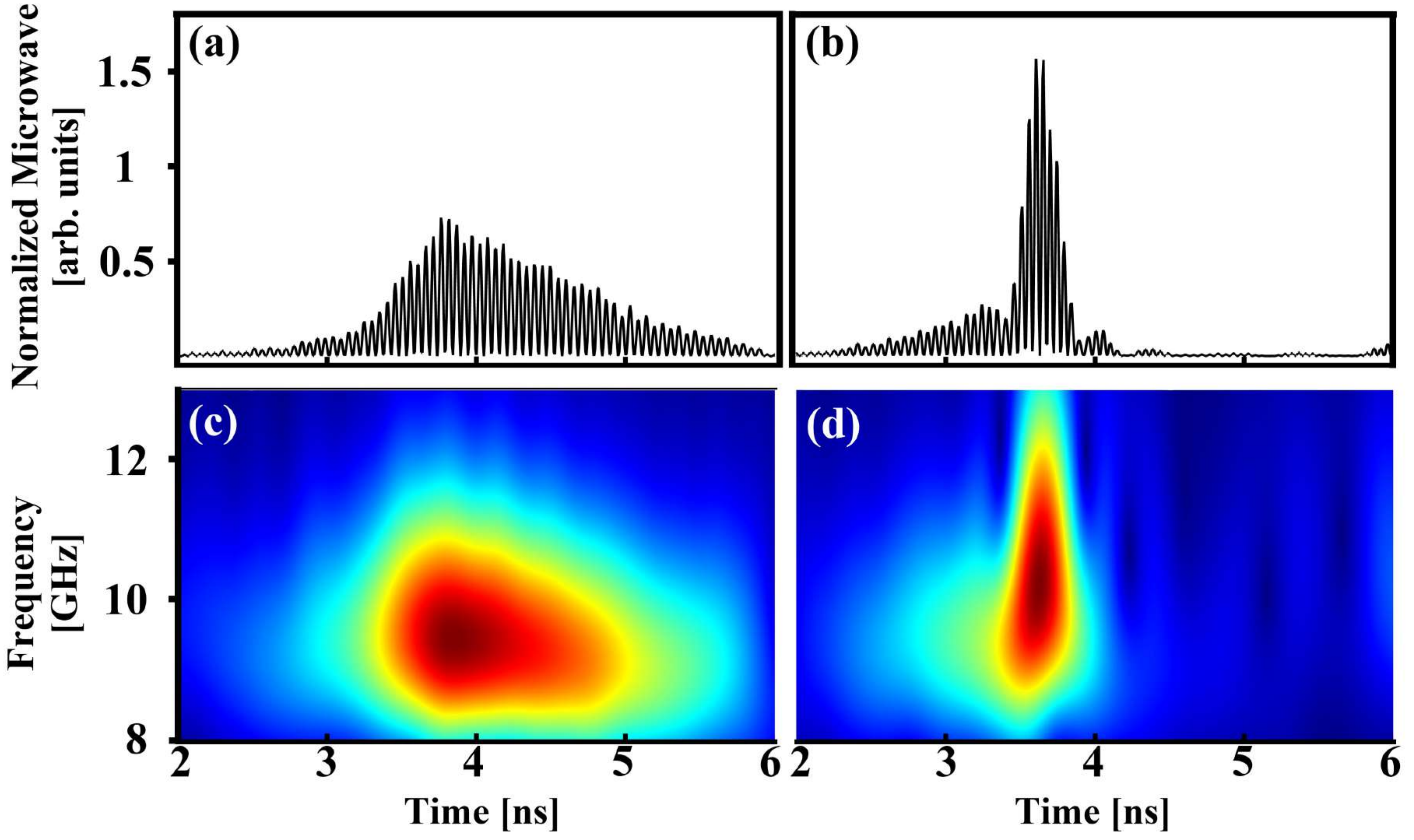


The transmitted microwave pulse



The microwave transmission coefficient at various helium pressure.





The (left) incident and (right) transmitted (upper panel) microwave pulse with its (lower panel) time-frequency spectrum.

Conclusions

- Propagation of a powerful short microwave pulse in a nonstationary and nonuniform medium with time varying parameters is studied both experimentally and theoretically.

- The resulting specific phenomena, that is, frequency conversion and pulse compression have been demonstrated experimentally.

  - ✓ Observed the relative frequency shift of ~ 10%.
  - ✓ Observed the relative power enhancement of ~ 150%.
  - ✓ Observed the faster propagation than vacuum system (superluminal).

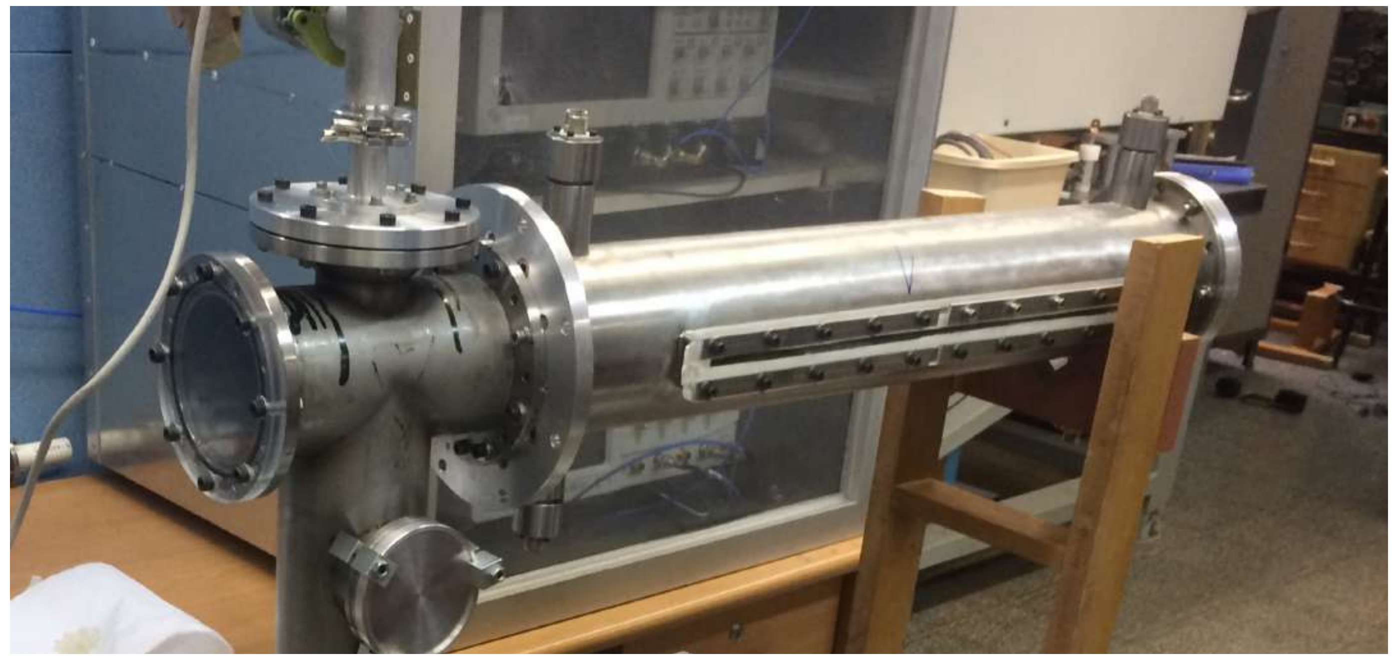
Phys. Rev. E, **107** (045203), 2023

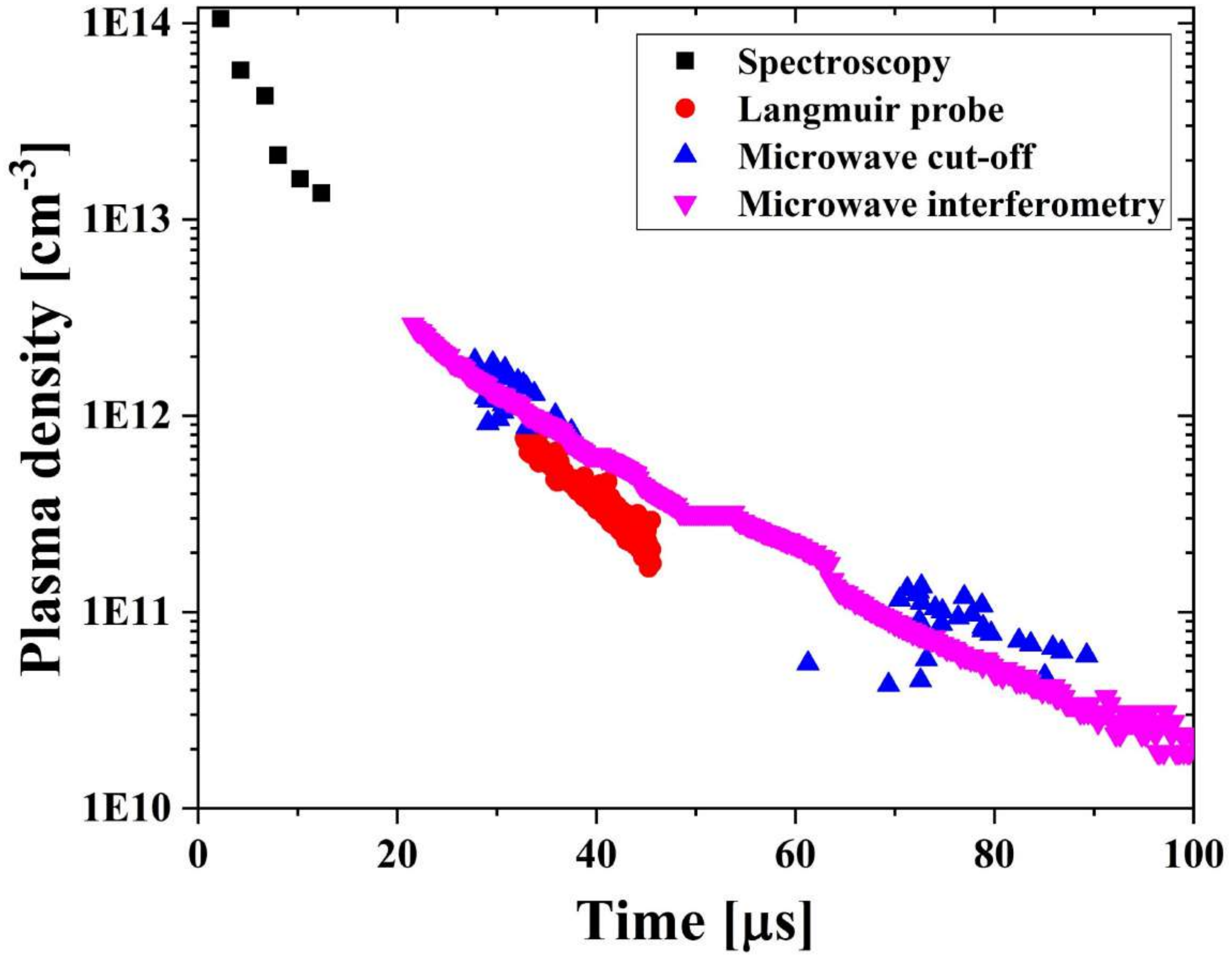
High-power microwave driven plasma **wakefield** in a plasma-filled cylindrical waveguide.

LSP simulation: Wakefield and Flashboard

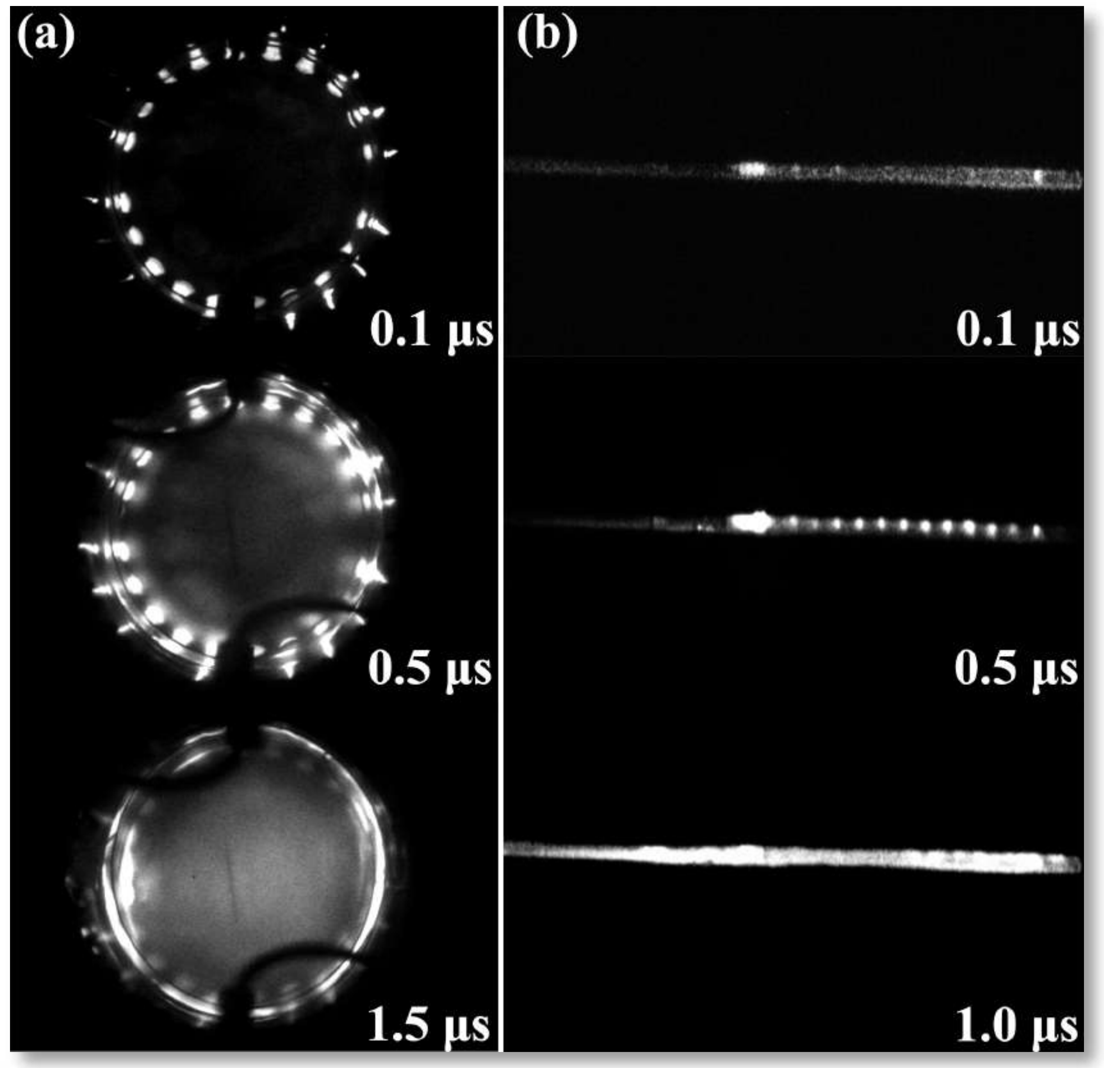
The (left) side view and (right) front view of LSP™ simulation of HPM-driven wakefield generation animation in preliminary plasma density $n_e=3\times10^{10}$ cm^{-3} with MW pulse power P=500 MW, duration (FWHM) τ=0.4 ns and central frequency f = 9.7 GHz.

Flashboard Plasma Source





Plasma density characterization by varies diagnostic methods.



Fast-frame images of plasma light emission from front and side taken by 4QuikE camera with exposure time of 50 ns.

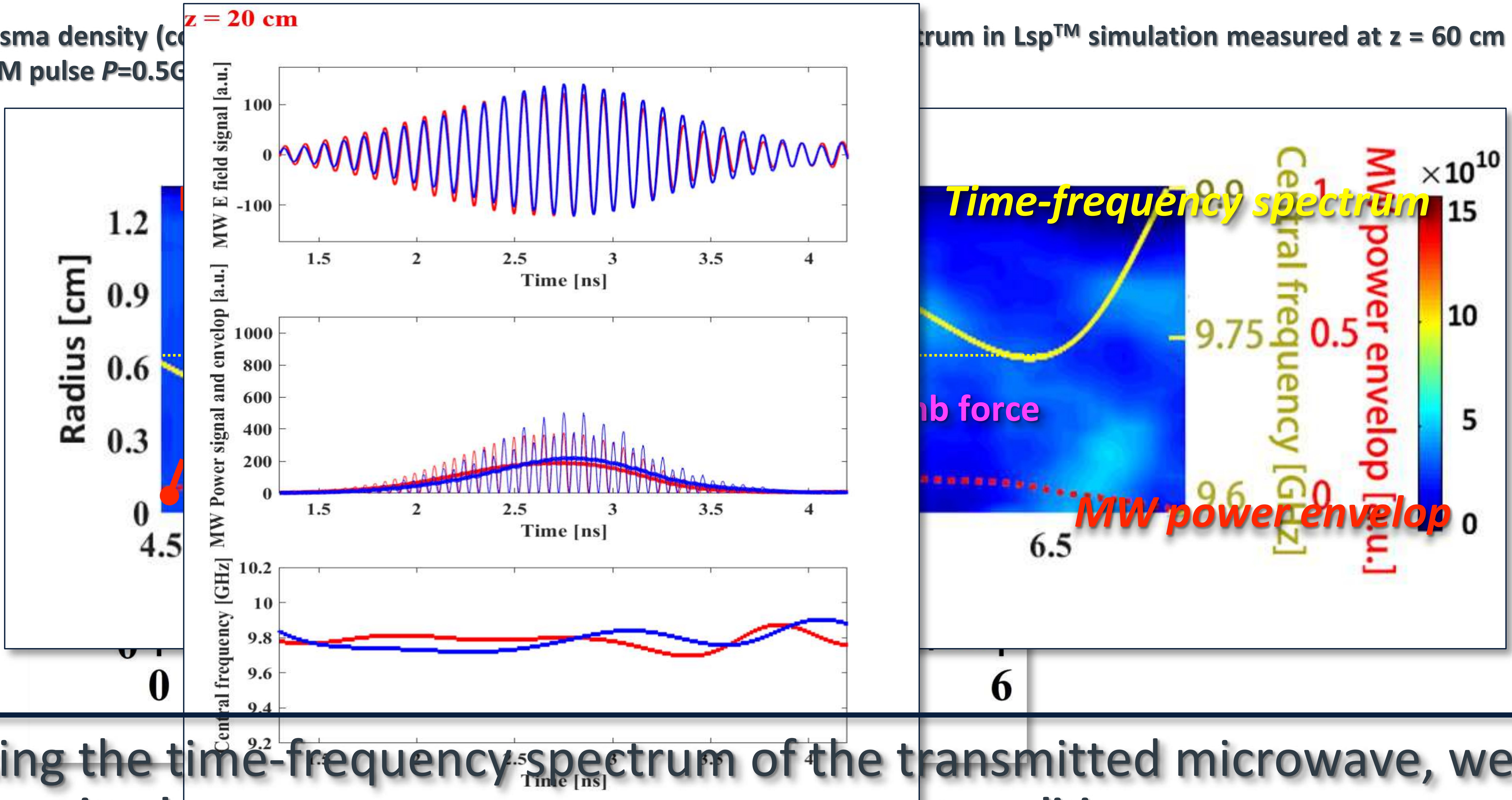
Experimental Setup

Experimental Results

LSP simulation for P = 0.5 GW, $n_e^0 = 3\times10^{10}$ cm^{-3}

Plasma density (c
HPM pulse *P*=0.5G

trum in Lsp™ simulation measured at z = 60 cm for



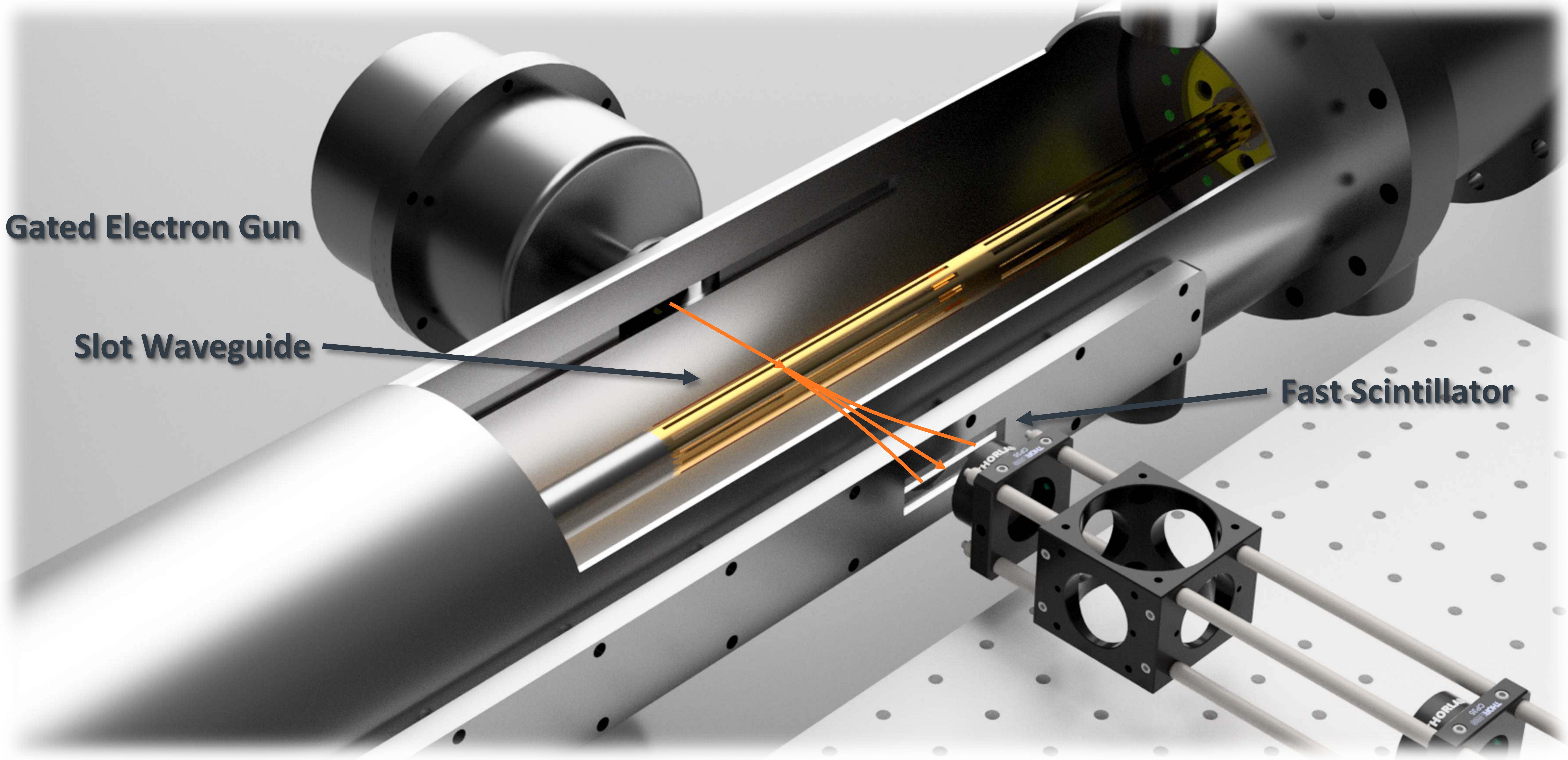
Using the time-frequency spectrum of the transmitted microwave, we could **reconstruct the plasma dynamics** of plasma **wake** formation.

Transmitted ... t conditions

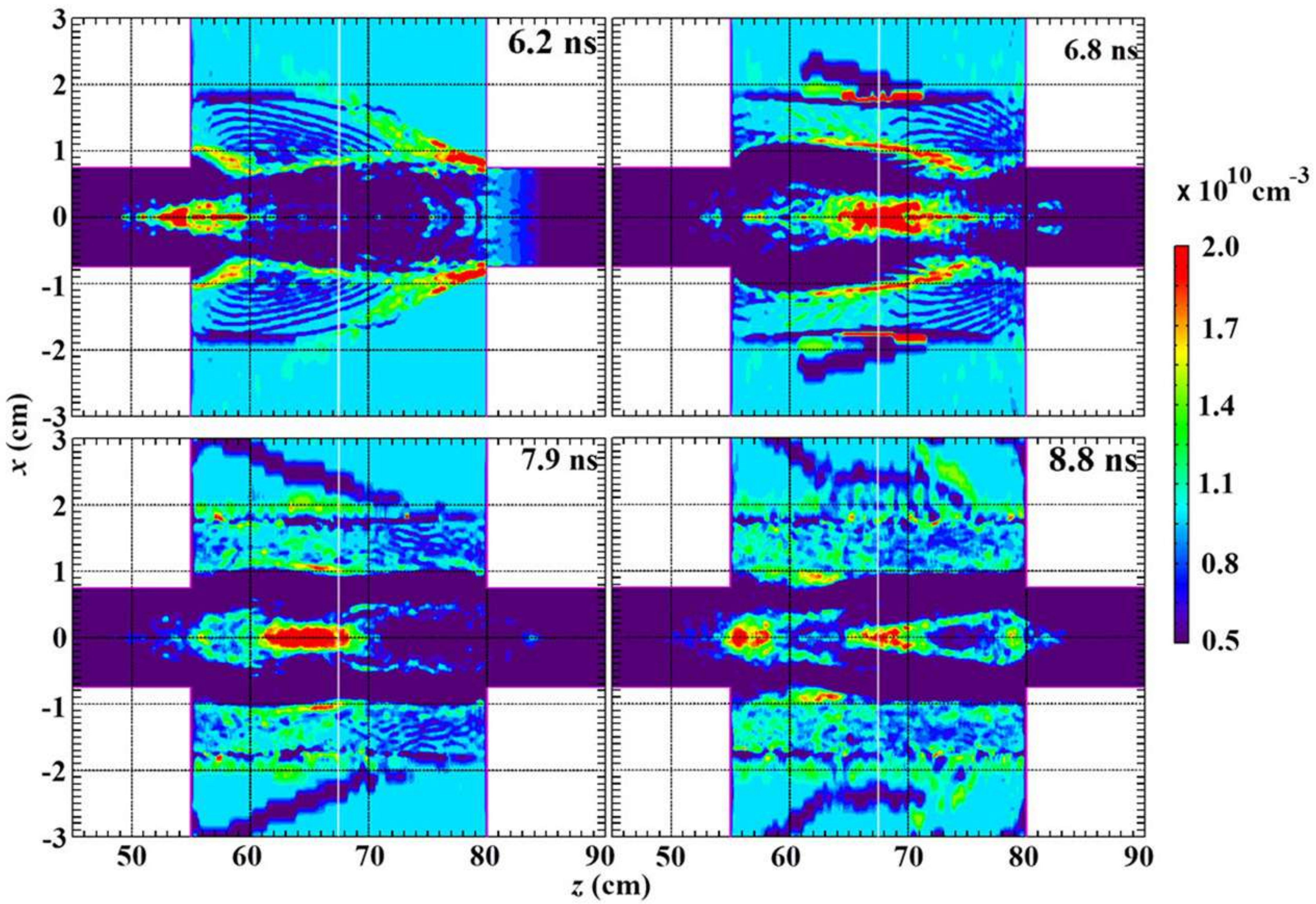
HPM pulse dynamics during propagation in plasma:
(a) electric field, (b) power and (c) time-frequency spectrum

 Cao, Y., Leopold, J. G., Bliokh, Y. P., Li, A., Shafir, G., Fisher, A., Leibovitch, G., Rostov, V. V, & Krasik, Y. E. IEEE TPS, 48(4) (2020).

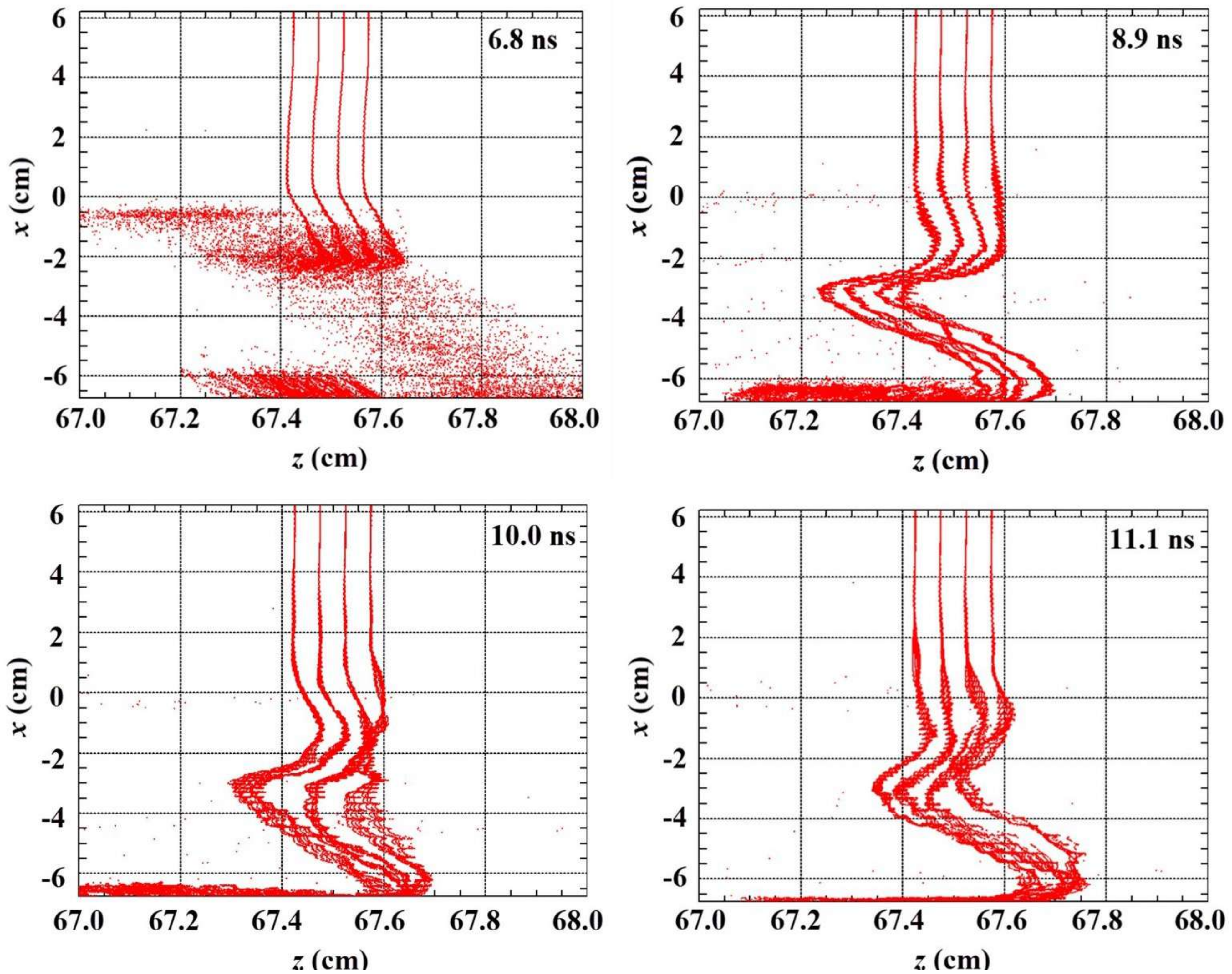
eBeam: Experimental Setup



LSP: Probing electron and wakefield

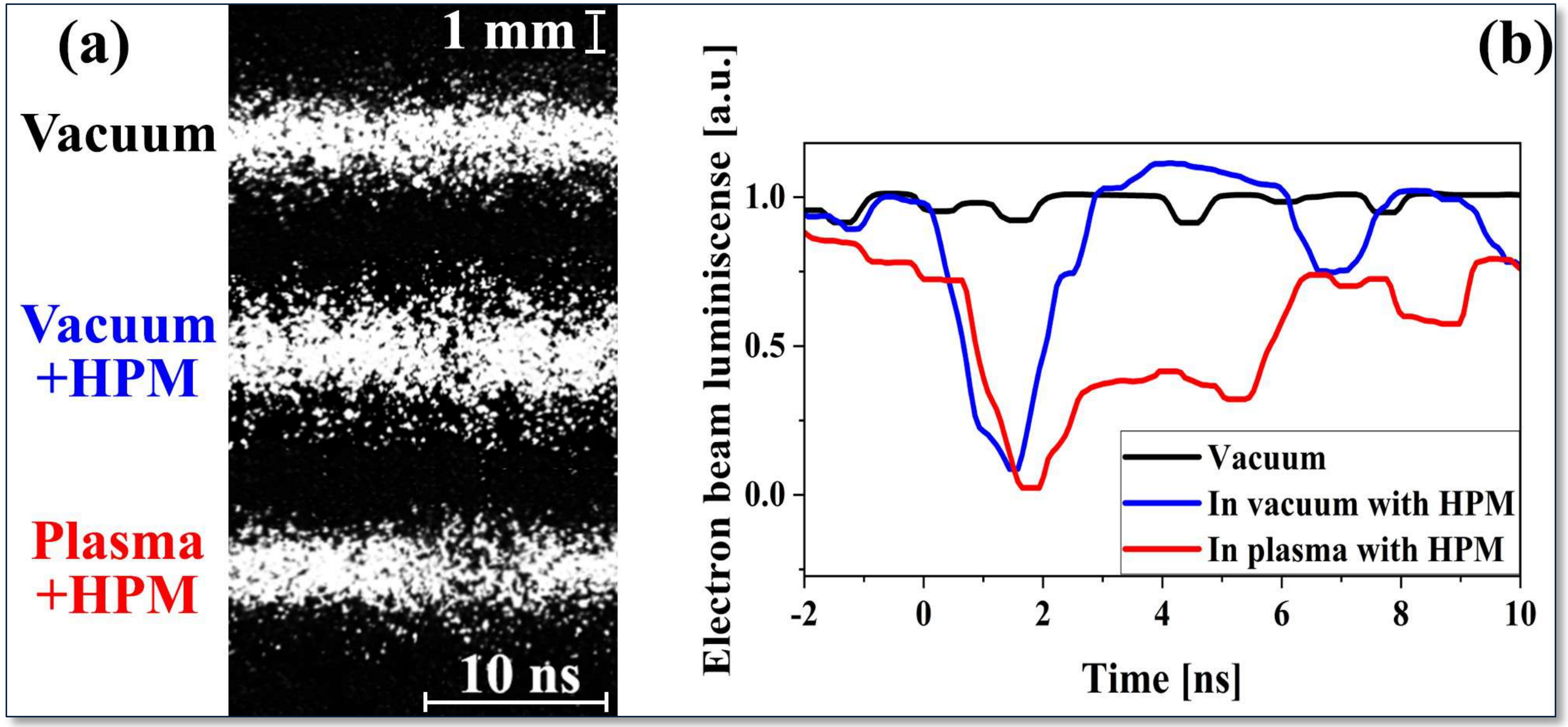


Snapshots of plasma density contours in the *y* = 0 cross section at three consecutive times obtained in the LSP simulations.



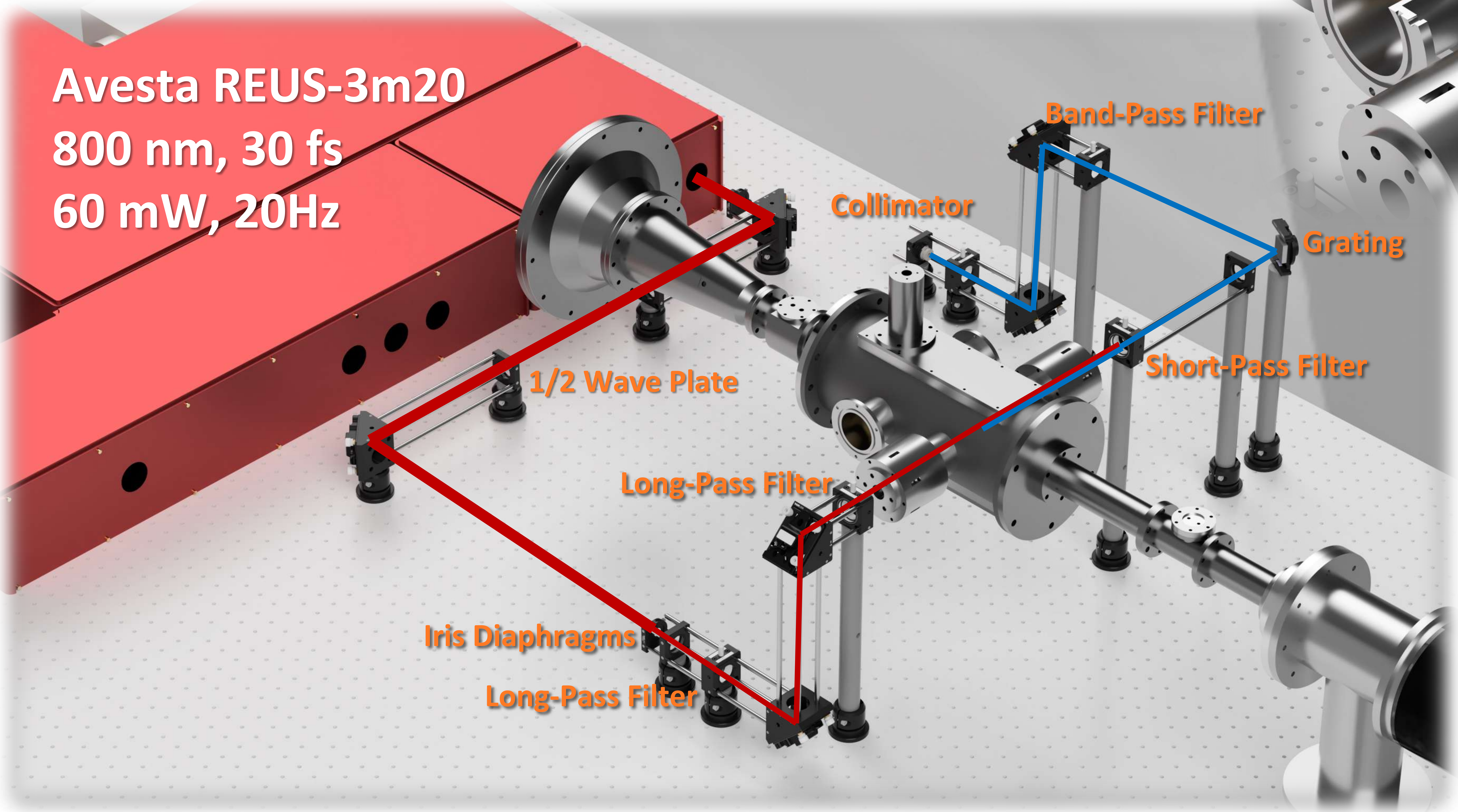
Snapshots of the probing electron beam at increasing points in time.

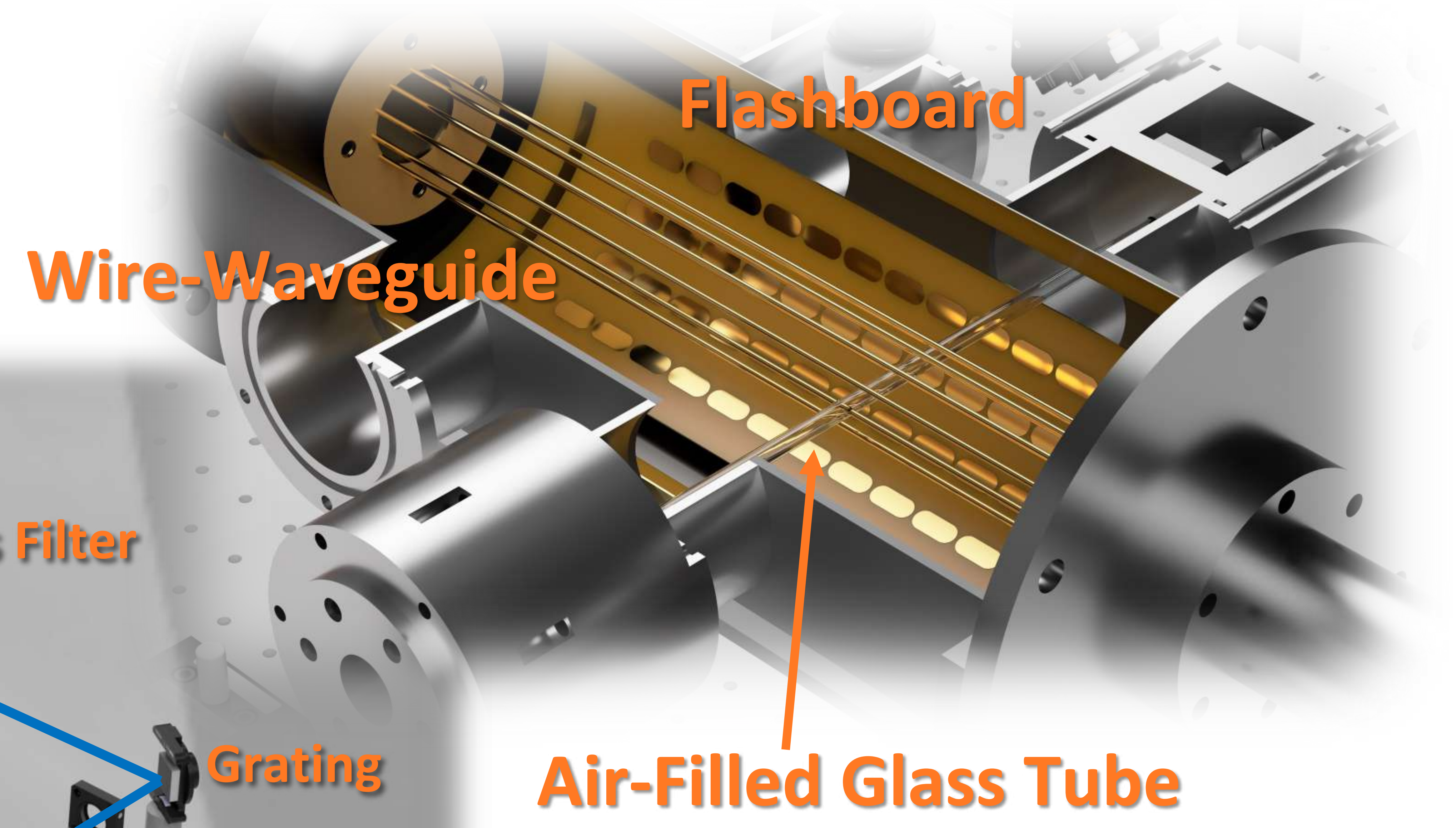
Experimental Results

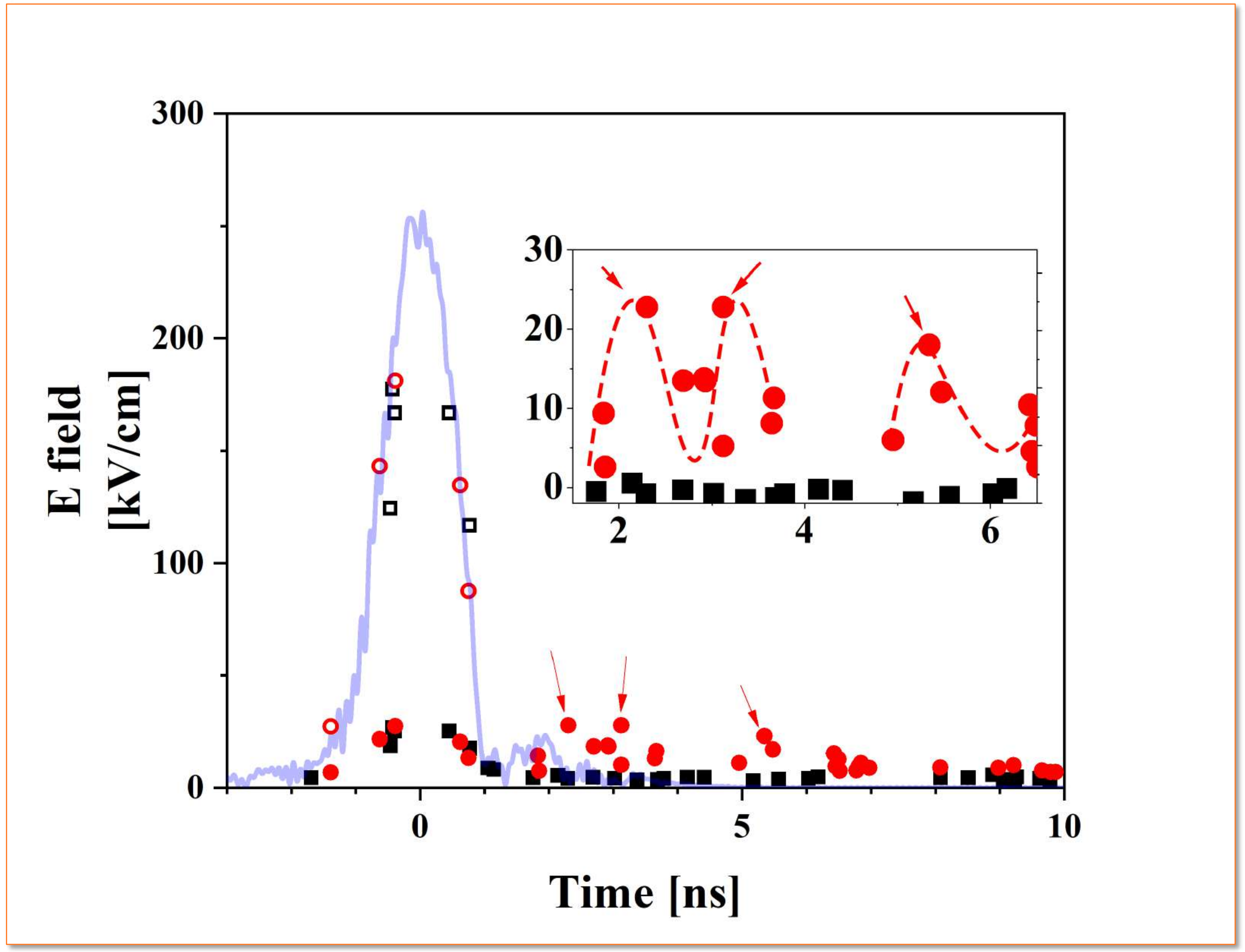


(a) Overlaid multiple (4 - 6) streak images for the same experimental conditions resulting in the time dependent light bands concentrated over $\Delta z \cong 2$ mm obtained in vacuum without and with the HPM pulse and in plasma (~3×10^{10} cm^{-3}). (b) Time dependence of the averaged luminescence intensity seen in (a) in vacuum in the absence of the HPM pulse (black) with the HPM pulse (blue) and when the HPM pulse traverses the plasma filled waveguide (red).

EFISH: Experimental Setup

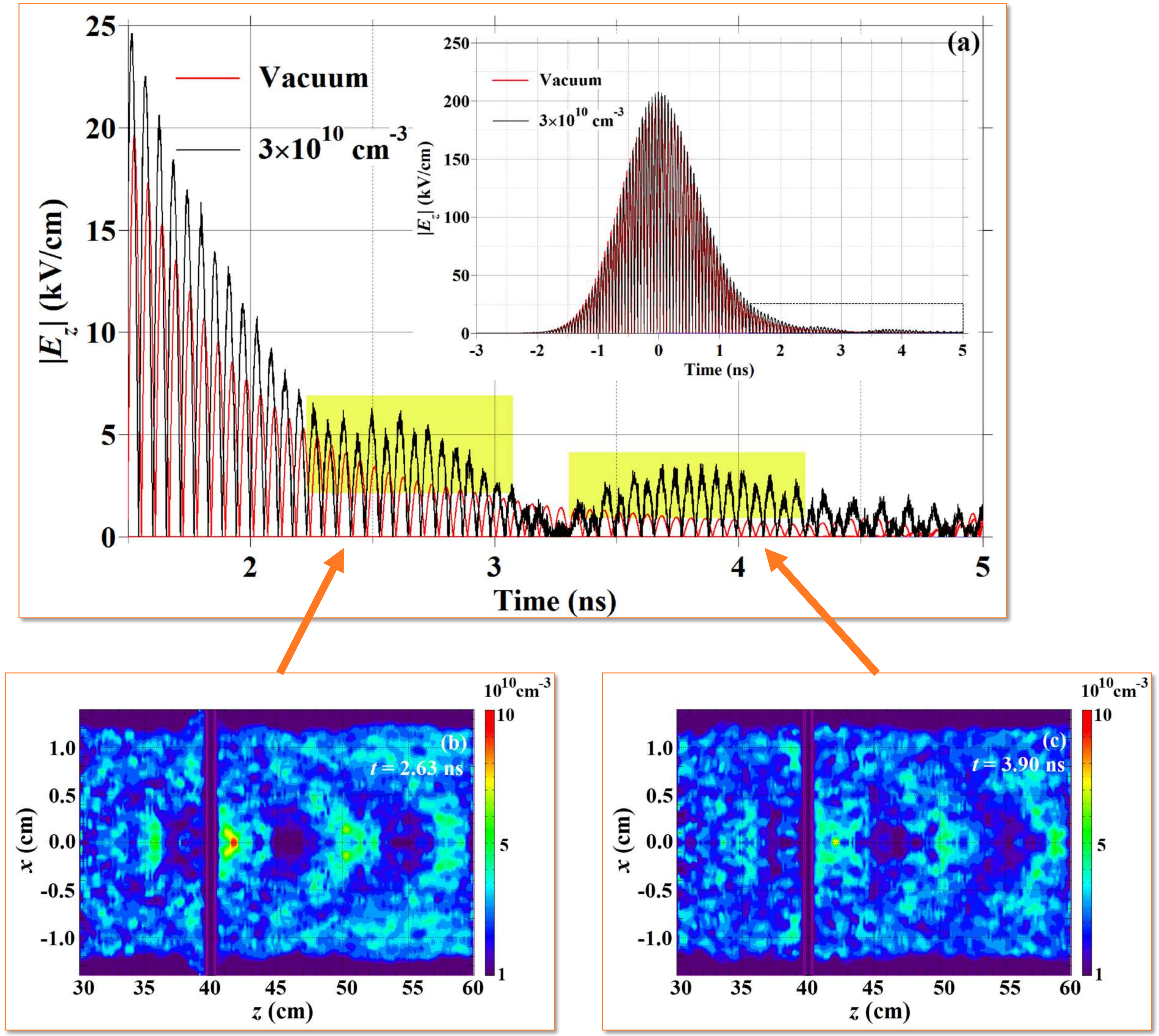






Temporal variation of EFISH generation intensity

Results of LSP simulations



Conclusions

Plasma wakefield driven by a high-power microwave pulse in plasma-filled cylindrical waveguide has been **demonstrated**, **observed** and **directly measured** for the **first time**.

- Experimental result:
  - ✓ Observation of the transmitted **microwave compression**, which can be used **reconstruct** the **plasma dynamics** when plasma wake formation.
  - ✓ Observation of **energetic electrons** ejected perpendicularly to the microwave beam, indicates the formation of the wake.
  - ✓ Observation of l**ong-duration disturbance** of the probing electron beam is the evidence of the wake long after the microwave pulse.
  - ✓ Directly measured the plasma wake for the first time.

- Numerical **particle-in-cell** simulations:
  - ✓ Confirmed the experimental observation of the plasma wake.

IEEE TPS, vol. 50, no. 10, pp. 3536-3538 (2022).
Phys. Plasmas. **27**, 053103 (2020). (Featured)
Phys. Plasmas. **26**, 023102 (2019).

Thank you for your attention.