Ultrashort-Pulse High-Power Microwave Source for a Wakefield Formation in Plasma

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**Motivation:** Wake-field formation by high-power microwave pulse interaction with plasma

**Ponderomotive repulsion force of the plasma electrons by the gradient of the amplitude of the microwave beam electric field generates plasma waves**

**Example:**
Microwave: \( f = 10 \text{ GHz}, P = 160 \text{ MW}, \tau = 0.5 \text{ ns}, r = 2 \text{ cm}, E_{mw} = 14 \text{ MV/m} \)
Plasma: \( n_e = 10^{10} \text{ cm}^{-3} \)

Ponderomotive repulsion force: \( F_p = \left( \frac{e^2}{4m\omega^2} \right) \nabla \left( E_{mw}^2 \right) \)

Plasma density modulation \( \frac{\delta n}{n_0} = 2 \left( \frac{eE_{mw}}{r_s m\omega \omega_p} \right)^2 > 0.2 \)
A uniform, large scale and low-density plasma source

**RF generated plasma**

- 2MHz, 0.5-5kW RF generator
- Quadruple antenna with matching elements
- Uniform plasma in 80 cm long and 25 cm in diameter gas-filled (Ar, He) Pyrex tube
- Plasma parameters diagnostics:
  - MW 26 GHz interferometer; MW cutoff at different frequencies
  - Moveable Langmuir probe
  - Visible spectroscopy
  - Density range: $1 \times 10^{10} - 5 \times 10^{12}$ cm$^{-3}$, $T_e = 1 – 3$ eV

Axial and radial distribution of the plasma density $P \approx 0.9$ Pa. RF power of 600 W.

High-current electron beam for microwave source

**HV generator**
- Magnetically compression stages + SOS
  - Voltage - 350 kV
  - Current - 1.7 kA
  - Duration at FWHM - 5 ns
  - Rise time after additional spark gap switch: 0.6 ns

**Explosive emission and surface plasma cathodes**

**Current and voltage waveforms**

Electron beam power $P_b \approx 350$ MW
Electron energy $E_e \approx 250$ keV
Electron beam current $I_e \approx 1.4$ kA

Microwave beam parameters

BWO

Mode converter: TM$_{01}$ $\Rightarrow$ TE$_{11}$

Antenna

Electric field at the aperture of receiving antenna (Z = 120 cm)

Insert: FFT of the microwave signal

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Microwave beam pattern

$P_t = 2\pi P_0 \int_{0}^{\infty} \exp \left( -\frac{2r^2}{\rho^2} \right) rdr$

$= \frac{\pi \rho^2}{2} P_0$;

$\rho$ – Gaussian beam width

$P_0$ – Power density at r = 0

Microwave instantaneous and averaged power over period

$P_{MW} \approx 550$ MW, $\tau \approx 0.5$ ns, $f \approx 9.6$ GHz

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Microwave beam propagation and focusing

Radial distributions of the microwave beam electric field

Expansion of a Gaussian beam

$$\rho(z)^2 = \rho_0^2 + \frac{(z - z_0)^2 \lambda^2}{\pi^2 \rho_0^2}$$

$z_0$ is the waist location

$\rho_0$ is the beam radius at the waist

- In free space FWHM of the beam at $Z = 120$ cm from antenna:
  
  $\sim 70$ cm (network analyzer) and $\sim 80$ cm (BWO microwave beam)

- Dielectric lens: beam FWHM decreases to 13 cm at $Z = 60$ cm from the lens
Microwave beam electric field along the axis of the antenna

Lens was placed at the distance of ~20 cm from the horn antenna

**Without lens**: decrease in the E-field fits Gaussian beam expansion: \( E(z) = E_0 \rho_0 / \rho(z) \)

**The application of the lens** results in focusing of the microwave beam at \( Z \sim 40 \) cm

Focusing of the Gaussian microwave beam (9.6 GHz, \( \sim 550 \) MW, \( \sim 0.5 \) ns) with dielectric lens results in \( E \sim 6 \) MV/m at the focus
Feasibility of wake-field experiment – numerical simulations

FWHM of spot size of 6 cm

**Long focus**: Rayleigh length of 40 cm

**Short focus**: Rayleigh length of 20 cm

\[ E_{\text{max}} \leq 10 \text{ MV/m} \]

Interaction length with plasma: \( \sim 40 \text{ cm} \)

\[ E_{\text{max}} \leq 16 \text{ MV/m} \]

Interaction length with plasma: \( \sim 15 \text{ cm} \)
Microwave focusing and interaction with plasma

Gaussian microwave beam \((f = 10 \text{ GHz}, \sim 700 \text{ MW}, \sim 0.5 \text{ ns})\) is applied at \(Z = -10 \text{ cm}\) and focused to \(Z = 0 \text{ cm}\) where beam “spot-size” is of 3.8 cm FWHM. Plasma density: \(10^{10} \text{ cm}^{-3}\).

**Instantaneous microwave power vs time** \((x = y = z = 0)\)

**Snapshot of the electric field** \(E_x\) at \(t = 1 \text{ ns}, y = z = 0\)

**Snapshot of the electric field** \(E_x\) at \(t = 1 \text{ ns}, x = y = 0\)

**Plasma particle energy**

Electrons are “heated” up to 4 keV

Ions are “heated up to 1.6 eV
Ponderomotive force of microwave beam pushes out electrons forming positively charged bubble of the order of waist.

This bubble attracts electrons toward it, forming a localized wake (≤0.5 MV/m) oscillating with plasma electron frequency, until this process dampens when microwave pulse has left the focal region.
• Application of the SR-BWO powered by high-current electron beam (~1.5 kA, ~250 keV, 5 ns) results in generation of high-power microwave beam (~550 MW, 0.5 ns, ~9.6 GHz).

• Focusing of this microwave beam by dielectric lens should be suitable for wake-field generation in under-dense plasma producing density modulation of ~100%, and longitudinal and transverse electric field of few of kV/cm in a localized wake.

• These results indicate that direct measurement of the wake are possible using time- and space-resolved diagnostics.