**Introduction**

It is experimentally found that during the propagation of an electron beam through a thin plasma column immersed in external magnetic field the powerful electromagnetic radiation is observed. What is the mechanism? How does the efficiency of radiation depend on plasma parameters?

**Formulation of the Problem**

- An electron beam (density $n_0$, speed $v_0$) and the relativistic factor $\gamma_0$ excite an unstable longitudinal wave.
- The frequency and growth rate of this wave are $\omega = \omega_0 = (m_0 / m) \gamma_0 v_0 / c$ and $\frac{d\omega}{dt} = \frac{\gamma_0}{\gamma_0 - 1} \alpha_0 \frac{d\gamma_0}{dt}$, where $\alpha_0 = \gamma_0 v_0 / c$.
- The electric field of the wave $E_0(\mathbf{x}, t) = E_0 \exp(i\mathbf{k} \cdot \mathbf{x} - i\omega t)$, where $E_0 = \gamma_0 / (\gamma_0 - 1)$. The wave vector $\mathbf{k} = \mathbf{e}_z$.
- If such a wave scatters on harmonic density perturbation ($\delta n = \delta n_0 \cos(qz - wt)$) it can radiate EM waves with frequency $\omega$ and wave vector $\mathbf{k}_0 = \gamma_0 / (\gamma_0 - 1)$. 
- Generation is possible when $1 - \gamma_0 < 0 < 1 + \gamma_0$.
- The direction of the radiation $\theta = \arctan \left( \frac{\gamma_0 - 1}{\gamma_0 + 1} \right)$.

**The Particular Case**

The factor $J_1$ as a function of plasma thickness for $\omega = 0.9\epsilon_0$.

- When the modulation period coincides with the wavelength of the beam-driven mode ($Q = 1$) the radiation angle $\theta = 90^\circ$.
- Dispersion relations of eigenmodes:
  - $\alpha_0^2 = \eta$ and $\alpha_0^2 = (c^2 - \omega^2 / \epsilon)^{1/2}$.
  - $F_2 = 0$: this mode has X-polarization, can propagate inside the plasma but cannot interact with the longitudinal current.
  - The first mode has C-polarization and penetrates into the plasma only to the skin-depth ($\alpha_0 = \omega$).
  - The power density depends on $1 + \frac{3}{2}$.

**Cylindrical Antenna**

- $J_1[1] \propto \frac{\text{area} \times \text{radius}}{\text{plasma}}$.
- Efficiency of such radiation can be raised to the level of $5-10\%$.

**Plane Beam-Plasma Antenna**

Outside the plasma, electromagnetic fields $E = E_0 \exp(i\mathbf{k} \cdot \mathbf{x} - i\omega t) + \cdots$ c.c. obey

$$\frac{\partial^2 \phi_1}{\partial t^2} - \frac{\phi_1 - \phi_2}{\epsilon_0} = \frac{\omega^2}{\epsilon_0} \left( 1 - \frac{\mathbf{k}_0^2}{\epsilon_0} \right),$$

where $\omega = \sqrt{\epsilon_0 \mu_0}$. The current $\mathbf{J} = \epsilon_0 \frac{\omega^2}{\epsilon_0} \mathbf{k}_0^2$. The radiation angle $\theta = \arctan \left( \frac{\gamma_0 - 1}{\gamma_0 + 1} \right)$.

**Summary**

- The region of transparency for both modes is bounded by $\alpha_0^2 = 0$, $\alpha_0^2 = (c^2 - \omega^2 / \epsilon)^{1/2}$.
- Solutions for $Q$:
  - $Q_1^2 = 1 + \gamma_0^2 / \gamma_0^2$.
  - $Q_2^2 = 1 + \gamma_0^2$.
- $L = \frac{\gamma_0 (\eta + 2)}{\epsilon_0 (\eta - 2)}$.
- Both plasma modes penetrate into the plasma in regions $Q_2^2 < 0 < Q_2^2$ and $Q_2^2 < Q_2^2 < Q_2^2$.
- These modes have X-polarisation with different angles to the magnetic field.

**Fig. 1** The factor $J_1[1]$ as a function of plasma thickness for $\omega = 0.9\epsilon_0$.

**Fig. 2** Radiation efficiency as a function of the modulation period and radius of plasma column for the cylindrical antenna.

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**About the Author**

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**Theory of electromagnetic wave generation via a beam-plasma antenna**

**Volchok E. P., Timofeev I. V., Annenkov V. V.**

**BINF SB RAS, Russia**

**11th International Conference on Open Magnetic Systems for Plasma Confinement, Novosibirsk, 8-12 August 2016**

**Plane Beam-Plasma Antenna**

Inside the plasma, electromagnetic fields $E = E_0 \exp(i\mathbf{k} \cdot \mathbf{x} - i\omega t)$ + c.c. obey

$$\frac{\partial^2 \phi_1}{\partial t^2} - \frac{\phi_1 - \phi_2}{\epsilon_0} = \frac{\omega^2}{\epsilon_0} \left( 1 - \frac{\mathbf{k}_0^2}{\epsilon_0} \right),$$

where $\omega = \sqrt{\epsilon_0 \mu_0}$. The current $\mathbf{J} = \epsilon_0 \frac{\omega^2}{\epsilon_0} \mathbf{k}_0^2$. The radiation angle $\theta = \arctan \left( \frac{\gamma_0 - 1}{\gamma_0 + 1} \right)$.

**Fig. 3** Geometry of the problem.

**Fig. 4** Window of plasma transparency to the generated EM waves ($\nu_0 = \nu_0$, $\delta n = 0.1m_0$, $\nu_0 = 0.2m_0$, $\nu_0 = 0.3m_0$).

**Fig. 5** (a) Radiation efficiency as a function of the modulation period and plasma thickness for the plane antenna (for the parameters $n_0 = 0.2m_0$, $n_0 = 0.2m_0$, $L = 0.2m_0$, $\delta n = 0.3m_0$), (b) Transverse structure of electric fields for plasma eigenmodes at the point of the global maximum of $\eta$: $\mathbf{E}_1$, $\mathbf{E}_2$, $\mathbf{E}_3$.

- The theory of EM emission generated in a thin magnetised plasma with the longitudinal density modulation under the injection of an electron beam has been formulated in terms of plasma antenna.
- It has been predicted that, at certain emission angles, plasma becomes transparent to radiation and the whole plasma volume may be involved in generation of EM waves.
- The relative power remains enough high even for relativistic thick plasma ($\sim 10 - 15\%$).
- The proposed method can be generalised to the turbulent regime in which random fluctuations of plasma density are represented by a set of periodic perturbations of the type $L = \sum_{n} a_n e^{i\omega n}$.