Generation of surface polaritons in dielectric cylindrical waveguides

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The 8th International conference "Charged & Neutral Particles Channeling Phenomena Channeling 2018", *ISCHIA (Naples, Italy)*, 23-28 September, 2018

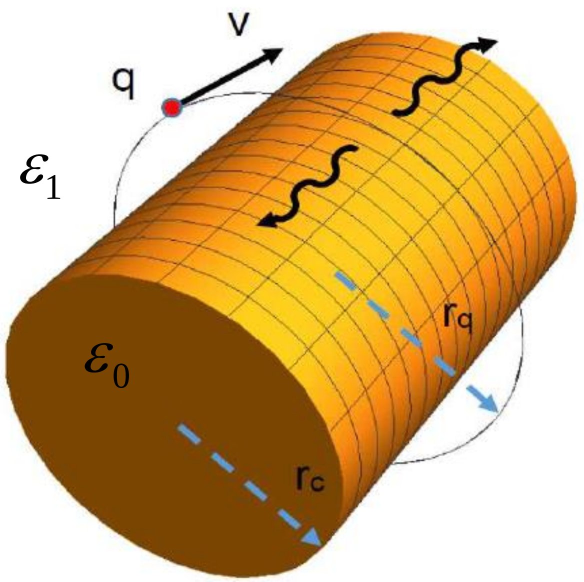
Outline

- Surface polaritons
- Problem setup
- Radiation at large distances
- Two types of modes inside the cylinder
- Radiation intensity for surface polaritons
- Conclusions

Surface polaritons

- Surface polaritons (SPs) (or surface plasmon polaritons (SPPs)) are electromagnetic waves that travel along a metal-dielectric interface
  - Perpendicular to the interface, they have subwavelength-scale confinement
- SPs are a type of surface wave, guided along the interface in much the same way that light can be guided by an optical fiber
- SPs are shorter in wavelength than the incident light (photons)
  - SPs can have tighter spatial confinement and higher local field intensity
- Applications include:
  - Subwavelength optics in microscopy and lithography beyond the diffraction limit
  - Micro-mechanical measurements of a fundamental properties of light
  - Photonic data storage
  - Light generation
  - Bio-photonics

Geometry of the problem



- Cylindrical waveguide immersed into homogeneous medium

- Charge rotates along a circular trajectory coaxial with the cylinder

- Types of the radiation present:
  - Radiation at large distances from the cylinder (synchrotron radiation in a medium influenced by the cylinder, Cherenkov radiation)
  - Radiation of guided modes
  - Radiation of surface polaritons

Radiation at large distances

- Under the Cherenkov condition for the material of the cylinder and the velocity of the particle image on the cylinder surface, strong narrow peaks appear in the angular distribution of the radiation intensity
- At the peaks the radiated energy exceeds the corresponding quantity in the case of a homogeneous medium by several orders of magnitude
- Necessary condition for the appearance: $\varepsilon_0 > \varepsilon_1 , \quad \tilde{v}\sqrt{\varepsilon_0}/c > 1$
- Angular range: $\cos^2\vartheta > \varepsilon_0/\varepsilon_1$ $\quad \vartheta \Leftarrow$ Radiation direction with respect to the cylinder axis
- Equation determining the angular locations of the peaks is obtained from the equation for eigenmodes of cylinder by the replacement

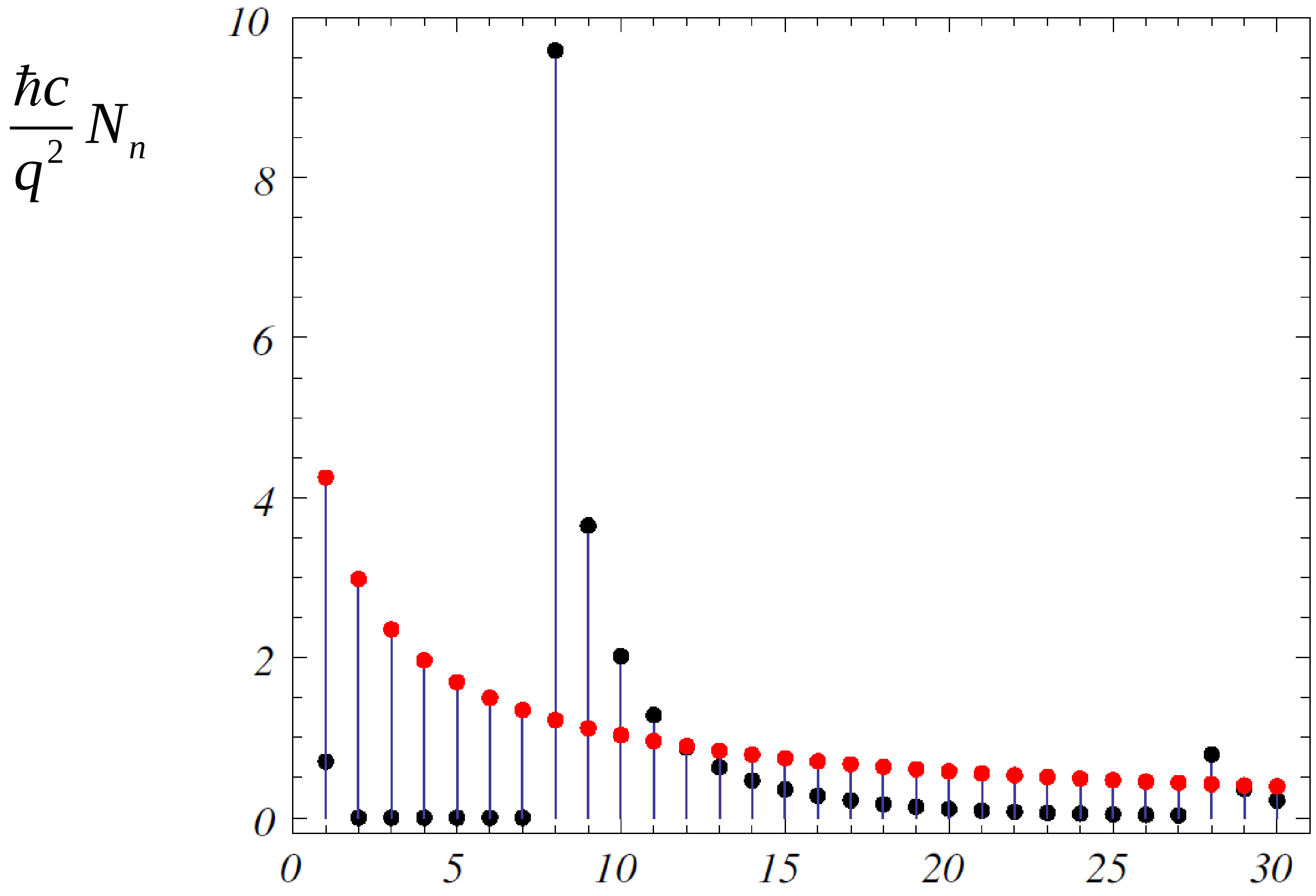
Hankel function $\Rightarrow$ $H_m \to Y_m$ $\Leftarrow$ Neumann function

Radiation fields inside the cylinder

- Radiation fields propagating inside the cylinder are radiated on the eigenmodes of the cylinder with the frequency $n\omega_0$ (ω_0 ⇐ angular velocity of the charged particle)
- For the corresponding modes $\lambda_1^2 < 0$, and the radial dependence is in the form of the function $K_{n+p}(|\lambda_1|r)$ $p = 0, \pm 1$ $\lambda_j^2 = n^2\omega_0^2\varepsilon_j/c^2 - k_z^2,$ $j = 0, 1$
- Dependence on the radial coordinate for a given mode is described by the function
$$J_{n+p}(\lambda_0 r)$$
- We assume that for surrounding medium $\varepsilon_1 > 0$
- Guiding modes (oscillating modes): $\lambda_0^2 > 0$
- Surface-type modes: $\lambda_0^2 < 0$ (radial dependence is in the form $I_{n+p}(|\lambda_0|r)$)
- Surface-type modes are present under the condition $\varepsilon_0 < 0$
- In the limit $r, r_c, r_q \to \infty$ with $r - r_c, r - r_q$ fixed, surface polaritons are obtained in the geometry of planar boundary

Radiation intensity of guiding modes

Number of the radiated quanta on a given harmonic per period of charge rotation



n ⟶ harmonic number

Electron energy 2 MeV

$\varepsilon_0 = 3,\ \varepsilon_1 = 1,\ r_c / r_q = 0.95$

Black points ⟶ Guiding modes propagating inside the cylinder

Red points ⟶ Sinchrotron radiation in the vacuum

$\varepsilon_0 = \varepsilon_1 = 1$

Surface-type modes

- Surface-type modes are present under the conditions

$$\varepsilon_0 < 0, \quad k_z^2 \geqslant \frac{n^2\omega_0^2}{c^2}\varepsilon_1$$

- Equation determining the eigenvalues for the projection of wave vector on the cylinder axis for a given radiation harmonic: $k_z = k_{n,s}$

$$U_n = -V_n^{(s)}\left(\varepsilon_0\lambda_{1n,s}\frac{I_n'}{I_n} - \varepsilon_1\lambda_{0n,s}\frac{K_n'}{K_n}\right) + n^2\frac{\lambda_{1n,s}^2 - \lambda_{0n,s}^2}{\lambda_{0n,s}^2\lambda_{1n,s}^2}\left(\varepsilon_0\lambda_{1n,s}^2 - \varepsilon_1\lambda_{0n,s}^2\right) = 0$$

$$\lambda_{0n,s} = r_c\sqrt{\frac{n^2\omega_0^2}{c^2}|\varepsilon_0| + k_{n,s}^2}, \quad \lambda_{1n,s} = r_c\sqrt{k_{n,s}^2 - \frac{n^2\omega_0^2}{c^2}\varepsilon_1}, \qquad I_n = I_n(\lambda_{0n,s}), \quad K_n = K_n(\lambda_{1n,s}),$$

$$V_n^{(s)} = \lambda_{1n,s}\frac{I_n'}{I_n} - \lambda_{0n,s}\frac{K_n'}{K_n},$$

- For numerical examples we have considered the equation has solution for the harmonic *n*=1 only

Radiation of surface-type modes

- Total radiation intensity =- work done by the radiation field on the charged particle

$$I=-\int drd\phi dzr\, j_\phi E_\phi$$

- Radiation intensity

$$I = \frac{4q^2v^2(1-\varepsilon_0/\varepsilon_1)}{\omega_0}\sum_{n=1}^{\infty}\sum_s \frac{n\left(\lambda_{0n,s}I_n'/I_n-\lambda_{1n,s}K_n'/K_n\right)^2}{\lambda_{1n,s}K_nU_n'(k_{n,s})\left(V_n^{(s)2}-n^2u_n^{(s)2}\right)}$$

$$\times\left[\frac{k_{n,s}^2}{r_q/r_c}K_n(\lambda_{1n,s}r_q/r_c)\frac{V_n^{(s)}I_n'/I_n+n^2u_n^{(s)}/\lambda_{0n,s}}{\lambda_{0n,s}I_n'/I_n-\lambda_{1n,s}K_n'/K_n}+\frac{n^2\omega_0^2}{c^2}\varepsilon_1K_n'(\lambda_{1n,s}r_q/r_c)\right]$$

$$u^{(s)}=\frac{\lambda_{0n,s}}{\lambda_{1n,s}}-\frac{\lambda_{1n,s}}{\lambda_{0n,s}}$$

Numerical example

- Numerical example is considered for $\varepsilon_1 = 1, \;\; \varepsilon_0 = -3$ and for electron energy 2 MeV

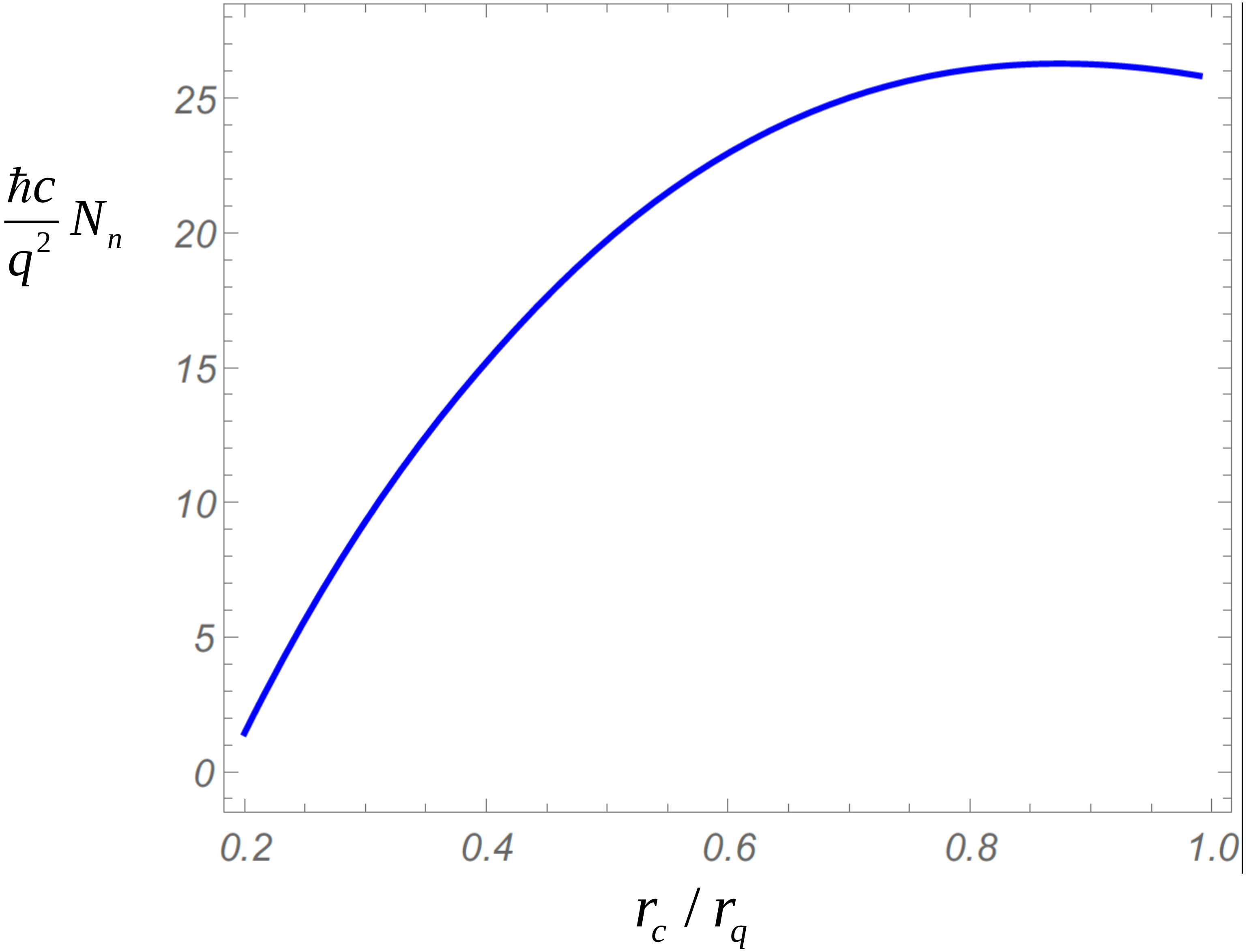
- Surface-type modes are present for *n*=1 only

- Number of the radiated quanta on the harmonic *n*=1 per period of the charge rotation

$$N_n \approx 26.1 \frac{q^2}{\hbar c}$$

Numerical example

$$\varepsilon_1 = 1, \quad \varepsilon_0 = -3$$



Conclusions

- Presence of cylindrical waveguide may essentially change the spectral-angular distribution of the synchrotron radiation in the exterior medium
- Two types of modes are radiated propagating inside the cylinder with an exponential damping in the exterior region: Guided modes and Surface-type modes (Surface polaritons)
- Radiation fields and the radiation intensities for both these type of modes are evaluated
- We have also evaluated the separate parts of the radiation intensities propagating inside and outside the cylinder

Thank You!