Radiation of surface polaritons in cylindrical channels

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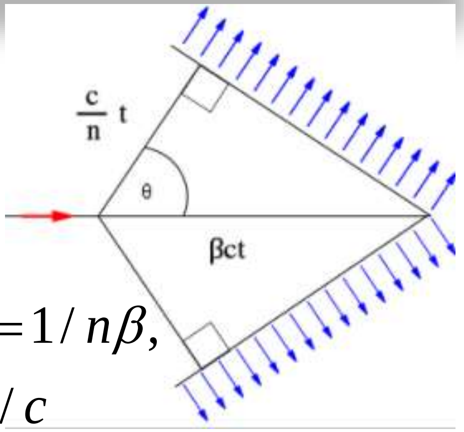
Outline

- ❖ Radiation processes in media
- ❖ Surface plasmon polaritons
- ❖ Radiation of SP in cylindrical waveguides
    - ❖ Circular motion around a cylinder
    - ❖ Rectilinear motion along the cylinder axis
- ❖ Conclusions

Radiation processes in media

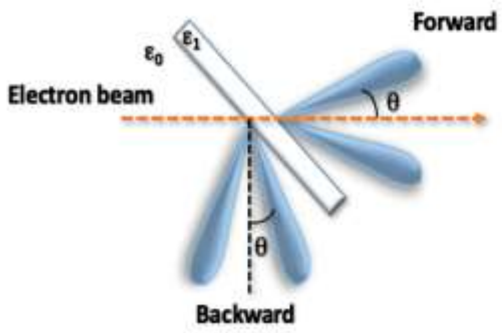
Interaction of charged particles with media gives rise to various types of radiation processes

- Cherenkov radiation: produced by charged particles when they pass through an optically transparent medium at speeds greater than the speed of light in that medium

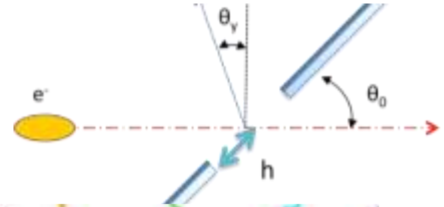


$$\cos\theta = 1/n\beta,$$
$$\beta = v/c$$

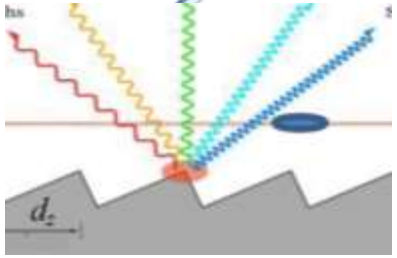
- Transition radiation: is emitted when a charged particle goes through the boundary between two media with different refractive index



- Diffraction radiation: is an emission phenomenon which occurs when a charged particle moves in the vicinity of a dielectric medium



- Smith-Purcell radiation/Resonance diffraction radiation Diffraction radiation on periodic structures

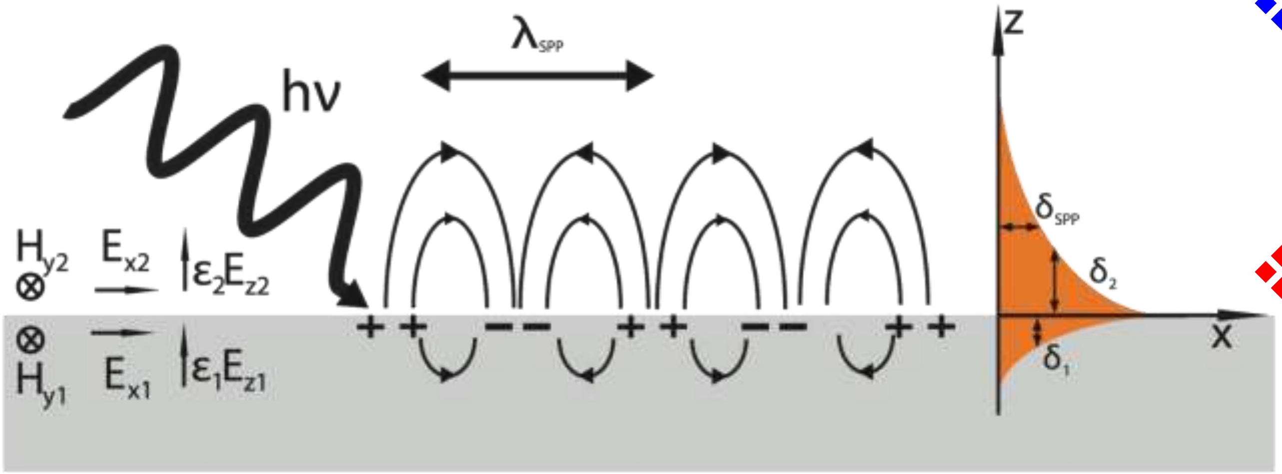


Surface Plasmon Polaritons

- Interfaces between two media with different electromagnetic characteristics give arise to new types of electromagnetic modes → Surface modes
- Surface modes depend on the geometry of the separating boundary and carry an important information on the electromagnetic properties of the contacting media
- Among the various types of surface waves, the surface plasmon polaritons (SPP) have been a powerful tool in the wide range of investigations including
  - Surface imaging
  - Surface-enhanced Raman spectroscopy
  - Data storage and Biosensors
  - Plasmonic waveguides
  - Light-emitting devices
  - Plasmonic solar cells, etc.

Surface Plasmon Polaritons

- SPPs are evanescent electromagnetic waves propagating along a metal-dielectric interface as a result of collective oscillations of electron subsystem coupled to electromagnetic field
- SPPs exist in frequency ranges where the real part of the permittivity undergoes a change of the sign at the interface
- Perpendicular to the interface SPPs have subwavelength-scale confinement



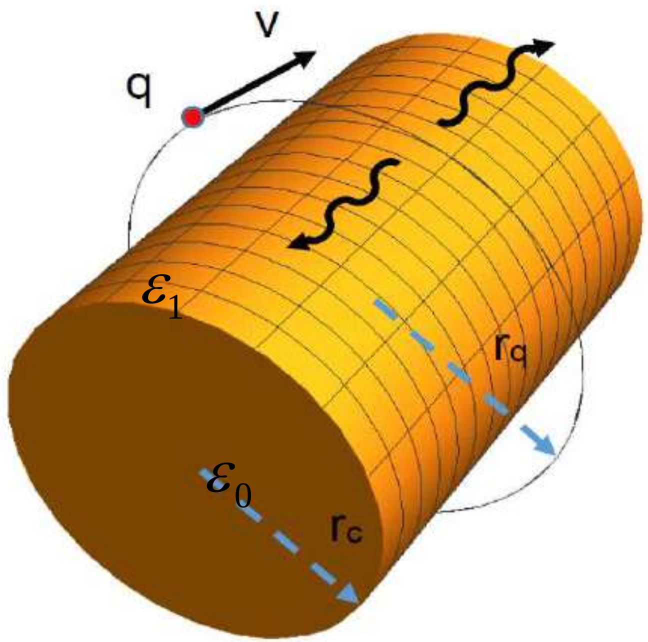
- Remarkable properties of SPPs include
  - Possibility of concentrating electromagnetic fields beyond the diffraction limit of light waves
  - Enhancing the local field strengths by orders of magnitude

Surface Polaritons

- Although SPPs are the most thoroughly investigated type of surface polaritons, depending on the dielectric properties of the active medium other forms of surface polaritons may exist.
- In particular, other materials besides metals, such as semiconductors, organic and inorganic dielectrics, ionic crystals, can support surface polariton type waves.
- An important direction of recent developments is the extension of plasmonics to the infrared and terahertz ranges of frequencies.
- This can be done by a suitable choice of the active medium such as doped semiconductors, superconductors, graphene, topological insulators and artificially constructed materials (metamaterials).

Radiation of SP in Cylindrical Waveguides by Charged Particles

Problem 1: Circular motion



- Cylindrical waveguide with permittivity ε_0 immersed into homogeneous medium with permittivity ε_1
- 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

Different types of radiations

- ❑ Radial dependence of the spectral components for electromagnetic fields

$$J_n(\lambda_0 r),\ \lambda_0 = \sqrt{\omega^2\varepsilon_0 / c^2 - k_z^2},\quad r < r_c$$ Bessel function

$$H_n(\lambda_1 r),\ \lambda_1 = \sqrt{\omega^2\varepsilon_1 / c^2 - k_z^2},\quad r > r_c$$ Hankel function of the first kind

Angular frequencies: $\omega = n\omega_0 = nv / r_q,\ m = 0, 1, 2, \ldots$

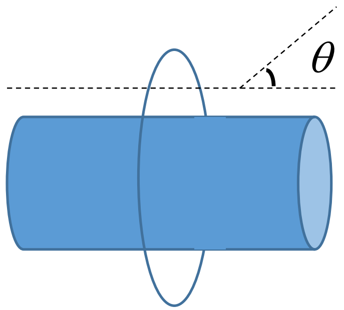
- ❑ Different types of radiations
  - ❑ Radiation at large distances from the cylinder (Synchrotron radiation in a medium influenced by the cylinder, Cherenkov radiation) ➡ $\lambda_1^2 > 0$
  - ❑ Radiation of guided modes ➡ $\lambda_1^2 < 0,\ \lambda_0^2 > 0$
  - ❑ Radiation of surface polaritons ➡ $\lambda_1^2 < 0,\ \lambda_0^2 < 0$

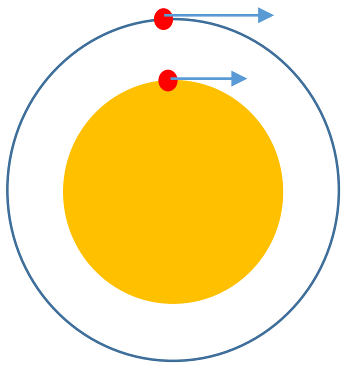
Radiation at large distances

- Under the Cherenkov condition for the material of the cylinder and the velocity of the particle projection 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 orders of magnitude
- Necessary condition for the appearance: $\varepsilon_0 > \varepsilon_1, \quad \tilde{v}\sqrt{\varepsilon_0}/c > 1$

Velocity of particle image on the cylinder surface

- Equation determining the angular locations of the peaks is obtained from the equation for eigenmodes of cylinder by the replacement

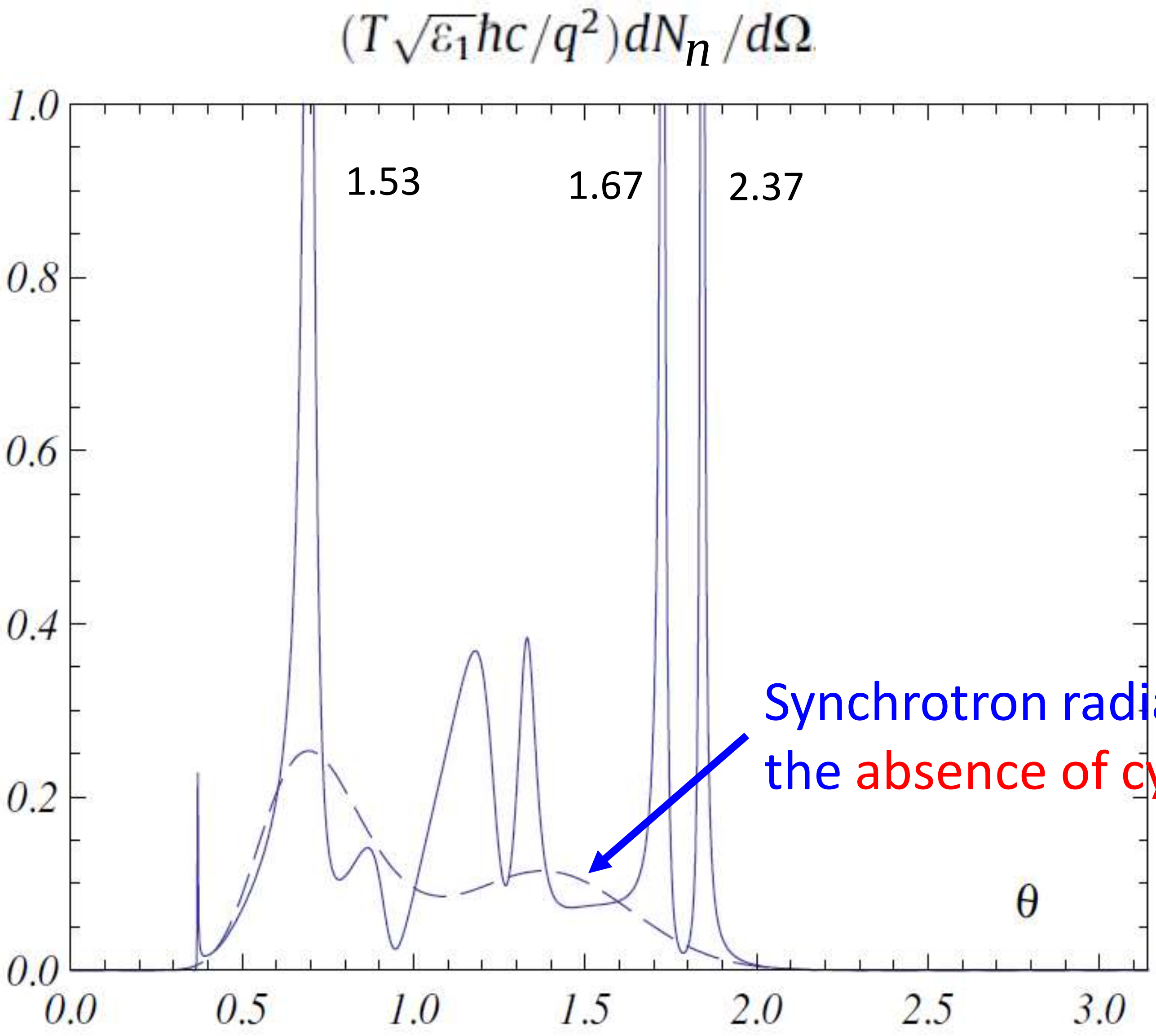




Hankel function $\Rightarrow$ $H_m \rightarrow Y_m$

Neumann function

Radiation at large distances (helical motion)



Radiation spectrum is discrete

$$\boxed{\omega = n\omega_0}$$

$$v_\perp / c = 0.9, \quad v_\parallel / c = 0.5,$$

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

$$r_c / r_q = 0.95,$$

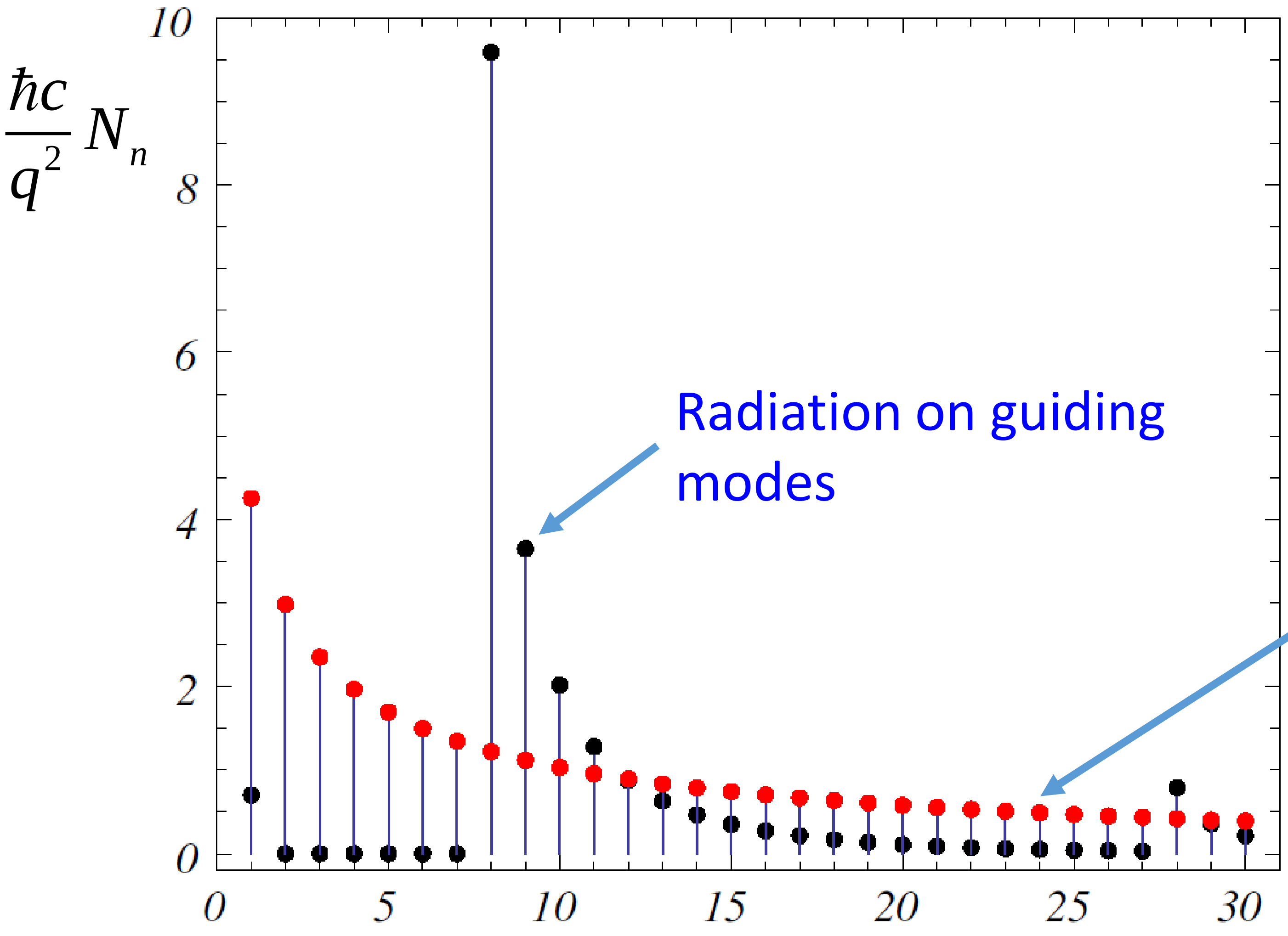
$n = 10$ ⇦ Radiation harmonic

Radiation fields inside the cylinder

- Waves 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: $p = 0, \pm 1$ (radial dependence is in the form $K_{n+p}(|\lambda_1| r)$)
- Surface-type modes are present under the condition $\boxed{\varepsilon_0 < 0}$
- 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



$n \Rightarrow$ harmonic number

Radiation spectrum is discrete $\boxed{\omega = n\omega_0}$

Electron energy 2 MeV

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

Black points $\Rightarrow$ Guiding modes propagating inside the cylinder

$$\frac{n\omega_0}{c}\sqrt{\varepsilon_1} < |k_z| < \frac{n\omega_0}{c}\sqrt{\varepsilon_0}$$

Red points $\Rightarrow$ Synchrotron radiation in the vacuum

$$\varepsilon_0 = \varepsilon_1 = 1$$

$$|k_z| < \frac{n\omega_0}{c}\sqrt{\varepsilon_1}$$

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: $k_z = k_{n,s}$

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

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

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

Surface-type modes

- Total radiation intensity = (-1) x work done by the radiation field on the charged particle

$$I = -\int dr d\phi dz r\, j_\phi E_\phi$$

- Radiation intensity

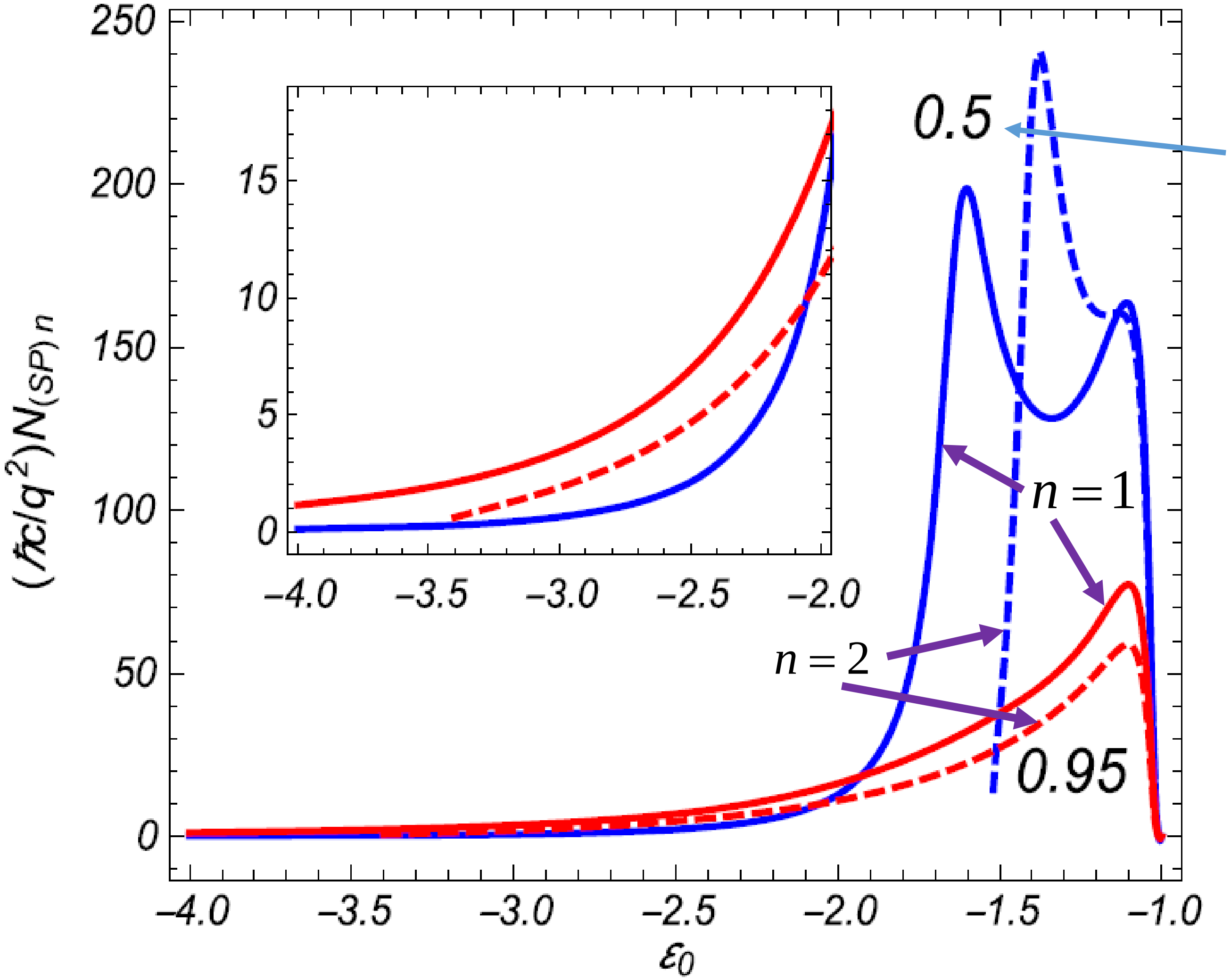
$$I = \frac{4q^2v^2(1-\varepsilon_0/\varepsilon_1)}{\omega_0}\sum_{n=1}^{\infty}\sum_s \frac{n\left(\lambda_{0n,s}I_n'/I_n - \lambda_{1n,s}K_n'/K_n\right)^2}{\lambda_{1n,s}K_nU_n'(k_{n,s})\left(V_n^{(s)2} - n^2u_n^{(s)2}\right)}$$

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

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

Numerical results

Number of the radiated quanta in the form of surface polaritons on a given harmonic *n* per period of the charge rotation $\Rightarrow$ $N_{(\mathrm{SP})n} = T\dfrac{I_{(\mathrm{SP})n}}{\hbar\omega_n}$



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

$v/c = 0.5, 0.95$

Radiation of SP in Cylindrical Waveguides by Charged Particles

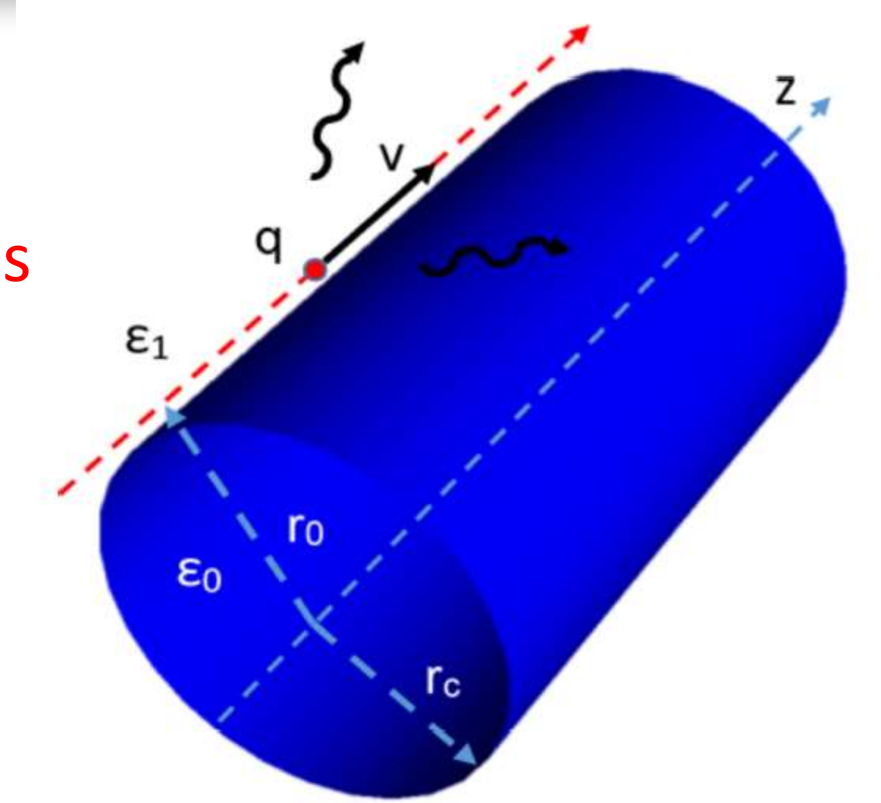
Problem 2: Rectilinear motion

- For the motion at hand $\boxed{\omega = k_z v}$
- Radial dependence of the spectral components for electromagnetic fields

$$J_n(\lambda_0 r),\ \lambda_0 = k_z\sqrt{\beta^2\varepsilon_0 - 1},\quad r < r_c$$

$$H_n(\lambda_1 r),\ \lambda_1 = k_z\sqrt{\beta^2\varepsilon_1 - 1},\quad r > r_c$$

$$\beta = \frac{v}{c}$$



- Different types of radiations
- Cherenkov radiation in the exterior medium

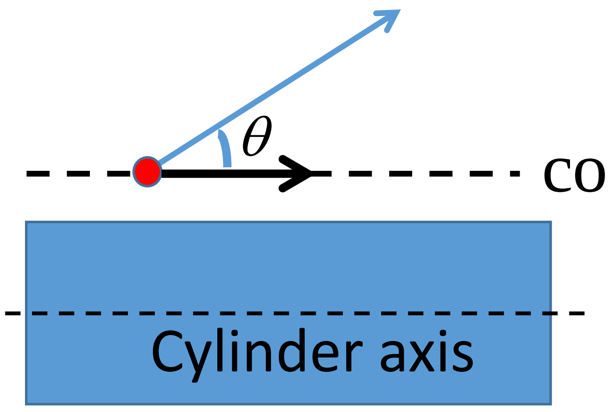
$$\lambda_1^2 > 0 \Rightarrow \boxed{\beta^2\varepsilon_1 > 1}$$ Cherenkov condition

- Radiation of guided modes ➡ $\lambda_1^2 < 0,\ \lambda_0^2 > 0$ ➡ $\boxed{\beta^2\varepsilon_1 < 1 < \beta^2\varepsilon_0}$
- Radiation of surface polaritons ➡ $\lambda_1^2 < 0,\ \lambda_0^2 < 0$ ➡ $\boxed{\beta^2\varepsilon_1, \beta^2\varepsilon_0 < 1}$

Cherenkov radiation

- Cherenkov radiation in the exterior medium is present under the condition

$$\beta_1 = \frac{v}{c}\sqrt{\varepsilon_1} > 1$$



$$\cos\theta = \frac{1}{\beta_1}$$

- Radiation propagates along the Cherenkov angle
- Two different ways have been used for the evaluation of the radiated energy
  - Energy flux per unit time through the cylindrical surface of radius *r*

$$I = \frac{c}{4\pi}\int_0^{2\pi} d\phi \int_{-\infty}^{\infty} dz\, r\mathbf{n}\cdot[\mathbf{E}\times\mathbf{H}]$$

Unit normal to the integration surface

  - Energy losses per unit of path length (work done by the electromagnetic field on the charge)

$$\frac{dW}{dz} = qE_3|_{r\to r_0, z\to vt, \phi\to\phi_0}$$

Cherenkov radiation intensity

- Spectral density for the Cherenkov radiation

$$\frac{dI}{d\omega} = \frac{q^2\omega}{2v\varepsilon_1}\sum_{n=0}^{\infty}{}' \left[\left| f_n^{(1)} + f_n^{(-1)} \right|^2 + \beta_1^2 \left| f_n^{(1)} - f_n^{(-1)} \right|^2 \right], \quad \beta_1 = \beta\sqrt{\varepsilon_1}$$

Notations

$$\begin{cases} f_n^{(p)} = -\sqrt{\beta_1^2 - 1}J_n(\lambda_1 r_0) + \dfrac{H_n(\lambda_1 r_0)}{V_n^H}\left[\sqrt{\beta_1^2 - 1}V_n^J + \dfrac{2ipk_z}{\pi}\dfrac{J_n(\lambda_0 r_c)}{r_c\alpha_n}\dfrac{J_{n+p}(\lambda_0 r_c)}{V_{n+p}^H}\right] \\ V_n^F = J_n(\lambda_0 r_c)\partial_{r_c}F_n(\lambda_1 r_c) - [\partial_{r_c}J_n(\lambda_0 r_c)]F_n(\lambda_1 r_c) \\ \alpha_n = \dfrac{\varepsilon_0}{\varepsilon_1 - \varepsilon_0} + \dfrac{1}{2}\sum_{l=\pm 1}\left[1 - \dfrac{\lambda_1}{\lambda_0}\dfrac{J_{n+l}(\lambda_0 r_c)H_n(\lambda_1 r_c)}{J_n(\lambda_0 r_c)H_{n+l}(\lambda_1 r_c)}\right]^{-1} \end{cases}$$

$\alpha_n = 0$ determines the cylinder eigenmodes

- Spectral density of the number of the radiated quanta per unit length of the trajectory

$$\frac{d^2N}{dz\,d\omega} = \frac{1}{\hbar\omega v}\frac{dI}{d\omega}$$

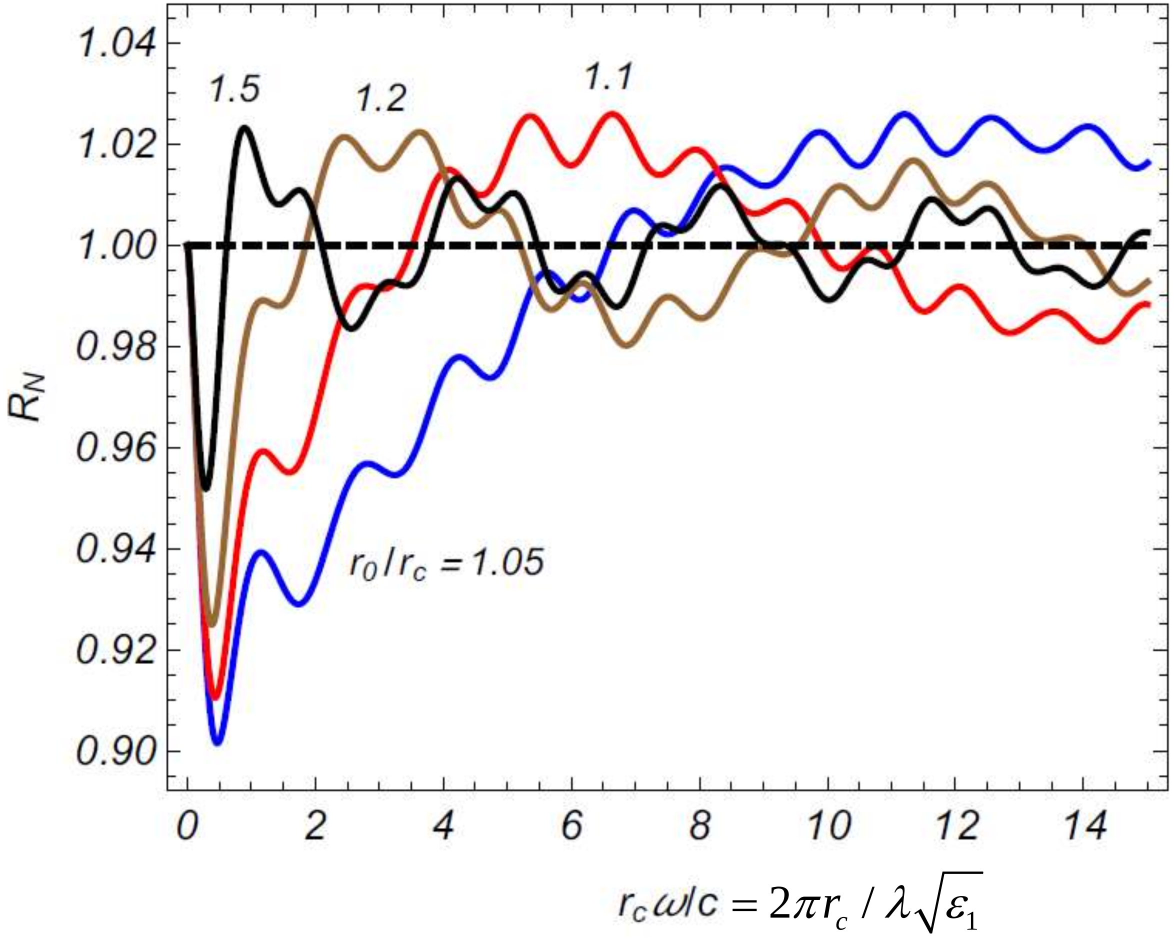
- Spectral density of the number of the radiated quanta per unit length of the trajectory in the absence of cylinder

$$\frac{d^2N_0}{dz\,d\omega} = \frac{q^2}{\hbar c^2}\left(1 - \frac{1}{\beta_1^2}\right)$$

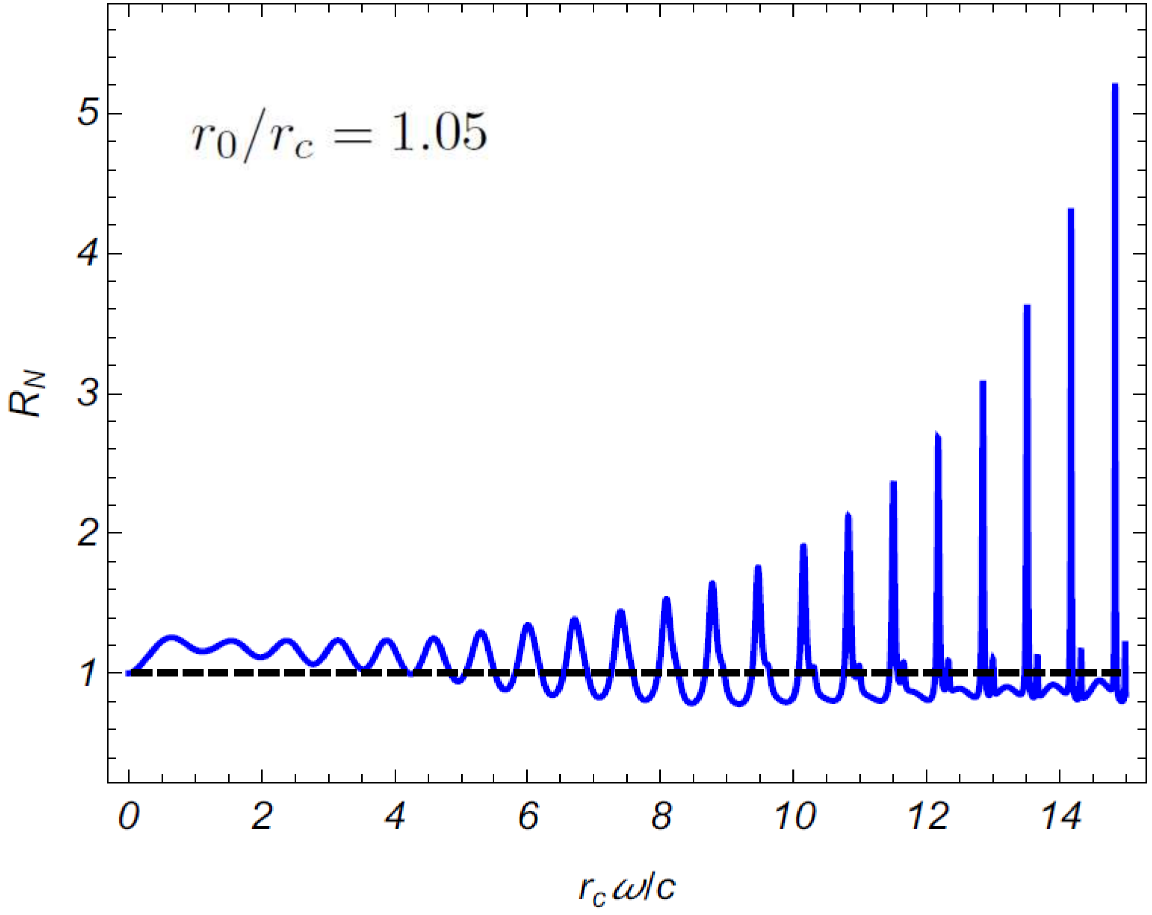
Cherenkov Radiation in the Exterior Medium

$$R_N = \frac{d^2N/dzd\omega}{d^2N_0/dzd\omega} \qquad \mathcal{E}_e = 2\,\mathrm{MeV}$$

$\varepsilon_0 = 1 \quad \varepsilon_1 = 3.8$



$\varepsilon_0 = 3.8,\ \varepsilon_1 = 2.2$



Radiation of guided modes

- Guided modes are radiated in the range $\beta^2\varepsilon_1 < 1 < \beta^2\varepsilon_0$ ⬅ Velocity threshold
- The modes are roots of the equation

$$\alpha_n = \frac{\varepsilon_0}{\varepsilon_1 - \varepsilon_0} + \frac{1}{2}\sum_{l=\pm1}\left[1 + l\frac{|\lambda_1|}{\lambda_0}\frac{J_{n+l}(\lambda_0 r_c)K_n(|\lambda_1| r_c)}{J_n(\lambda_0 r_c)K_{n+l}(|\lambda_1| r_c)}\right]^{-1} = 0$$

$$\lambda_0 = k_z\sqrt{\beta^2\varepsilon_0 - 1}$$

$$|\lambda_1| = k_z\sqrt{1 - \beta^2\varepsilon_1}$$

$$\boxed{k_{n,s} r_c = f(\varepsilon_0/\varepsilon_1, \beta_1)}$$

- Radiation intensity on the angular frequency $\omega_{n.s} = v k_{n,s}$

$$I_{n,s} = -2\delta_n q^2 \frac{v}{\varepsilon_1}\sqrt{1 - \beta_1^2} k_z^2 \frac{K_n^2(|\lambda_1| r_0)}{V_n^{J,K}} \frac{J_n(\lambda_0 r_c)}{r_c |\alpha_n'(k_z)|} \sum_{p=\pm1} \frac{J_{n+p}(\lambda_0 r_c)}{V_{n+p}^{J,K}}\bigg|_{k_z = k_{n,s}}$$

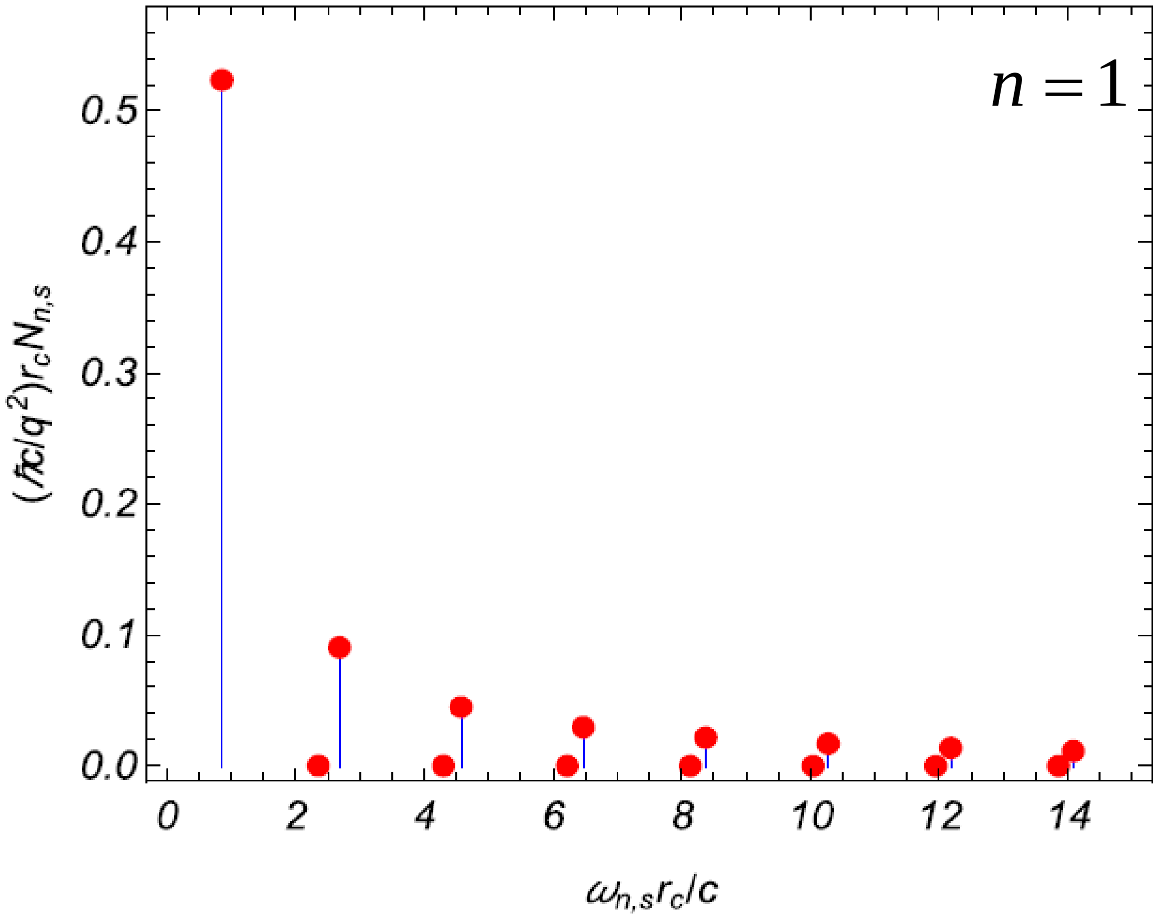
$$V_n^{J,F} = J_n(\lambda_0 r_c)\partial_{r_c} F_n(|\lambda_1| r_c) - F_n(|\lambda_1| r_c)\partial_{r_c} J_n(\lambda_0 r_c)$$

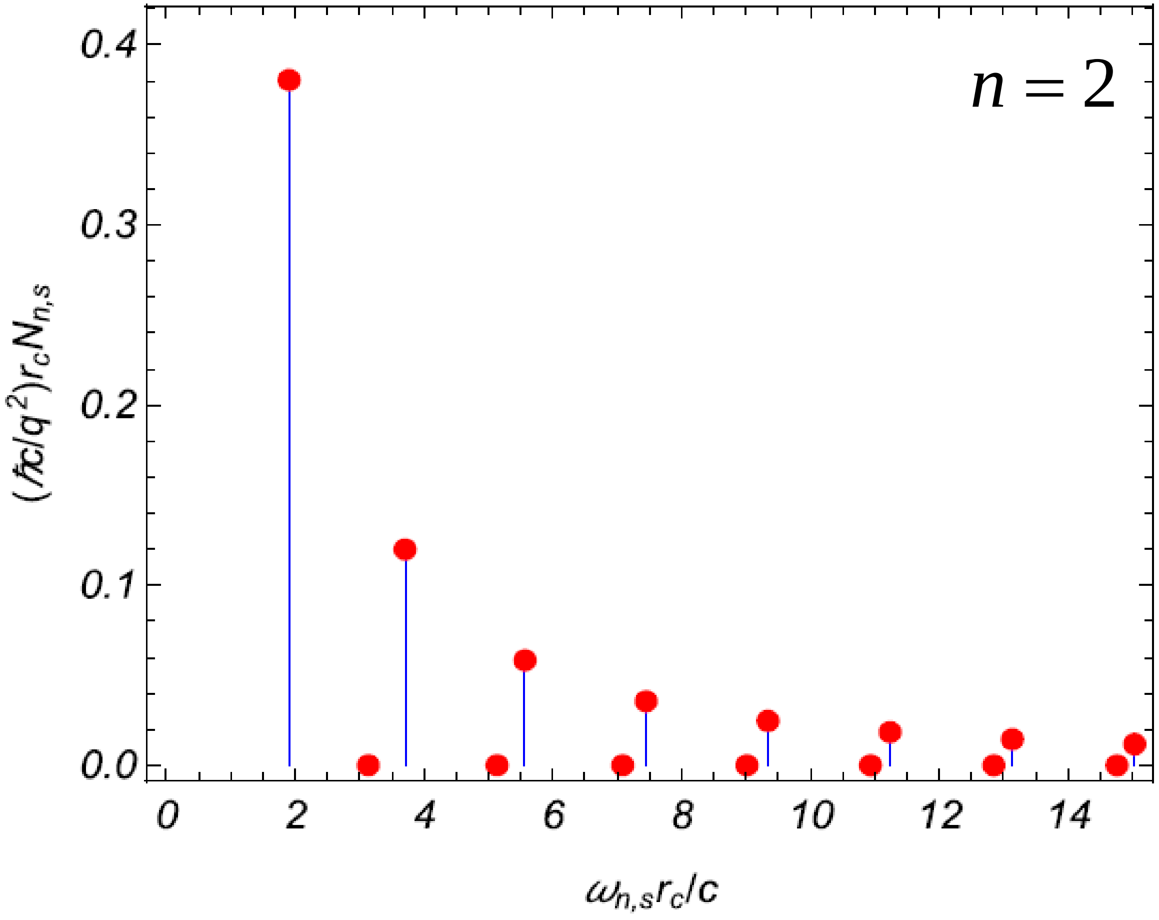
- Guided modes of the waveguide are mainly radiated on the frequencies $\omega_{n,s} \lesssim \dfrac{v}{\sqrt{1 - \beta_1^2}(r_0 - r_c)}$

Radiation of guided modes

$$N_{n,s} = \frac{I_{n,s}}{\hbar\omega_{n,s} v}$$

Number of quanta radiated on a given mode per unit length of the charge trajectory



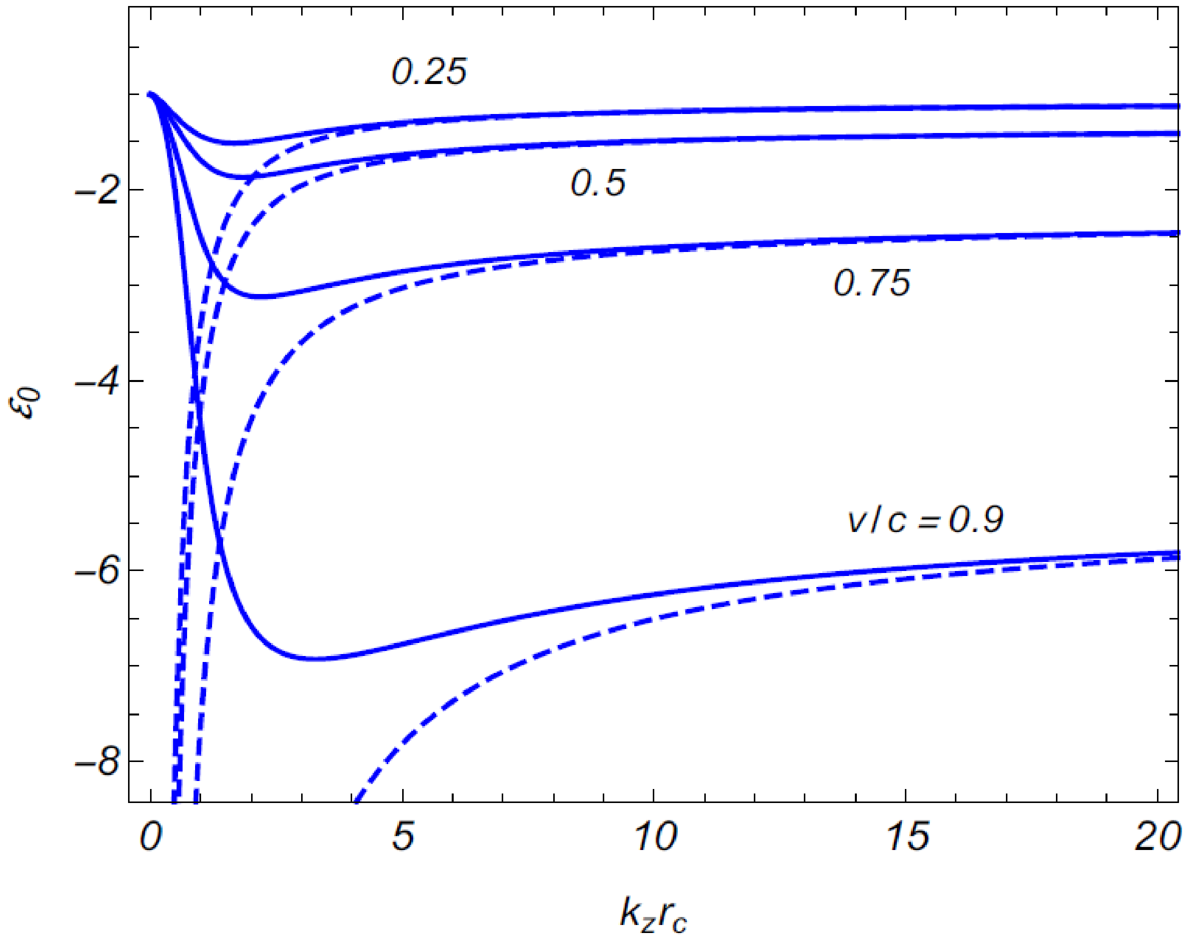


$$\mathcal{E}_e = 2\ \mathrm{MeV},\ \varepsilon_0 = 3.8,\ \varepsilon_1 = 1,\ r_0/r_c = 1.05$$

Electromagnetic modes corresponding to SP

SP modes are roots of the equation

$$\alpha_n = \frac{\varepsilon_0}{\varepsilon_1 - \varepsilon_0} + \frac{1}{2}\sum_{l=\pm 1}\left[1 + \frac{|\lambda_1|}{|\lambda_0|}\frac{I_{n+l}(|\lambda_0|r_c)K_n(|\lambda_1|r_c)}{I_n(|\lambda_0|r_c)K_{n+l}(|\lambda_1|r_c)}\right]^{-1} = 0 \Rightarrow k_z = k_{n,s}$$



$$\lambda_0^2 = k_z^2(v^2\varepsilon_0/c^2 - 1) < 0,\ \varepsilon_0 < 0 < \varepsilon_1$$

$$\lambda_1^2 = k_z^2(v^2\varepsilon_1/c^2 - 1) < 0$$

$n = 0$ ⬅ Dashed curves

$n = 1$ ⬅ Full curves

$\varepsilon_1 = 1$

$$\varepsilon_0 \to \varepsilon_0^{(\infty)} \equiv -\varepsilon_1/(1 - \beta_1^2)$$

Radiation of Surface Polaritons

- Radiation intensity on a given angular frequency $\omega_{n,s} = vk_{n,s}$

$$I_{n,s} = 2\delta_n q^2 \frac{v}{\varepsilon_1}\sqrt{1-\beta_1^2}k_z^2 \frac{K_n^2(|\lambda_1|r_0)}{V_n^K}\frac{I_n(|\lambda_0|r_c)}{r_c|\alpha_n'(k_z)|}\sum_{p=\pm 1}\frac{I_{n+p}(|\lambda_0|r_c)}{V_{n+p}^K}\Bigg|_{k_z=k_{n,s}}$$

$$|\lambda_j| = k_z\sqrt{1-\beta_j^2}, \quad V_n^F = I_n(|\lambda_0|r_c)\partial_{r_c}F_n(|\lambda_1|r_c) - F_n(|\lambda_1|r_c)\partial_{r_c}I_n(|\lambda_0|r_c)$$

- Unlike the guided modes, there is no velocity threshold for the generation of surface polaritons

- At small wavelengths the radiation intensity is suppressed by the factor

$$e^{-2|\lambda_1|(r_0-r_c)} \text{ for the modes with } |\lambda_1|r_c \gg 1$$

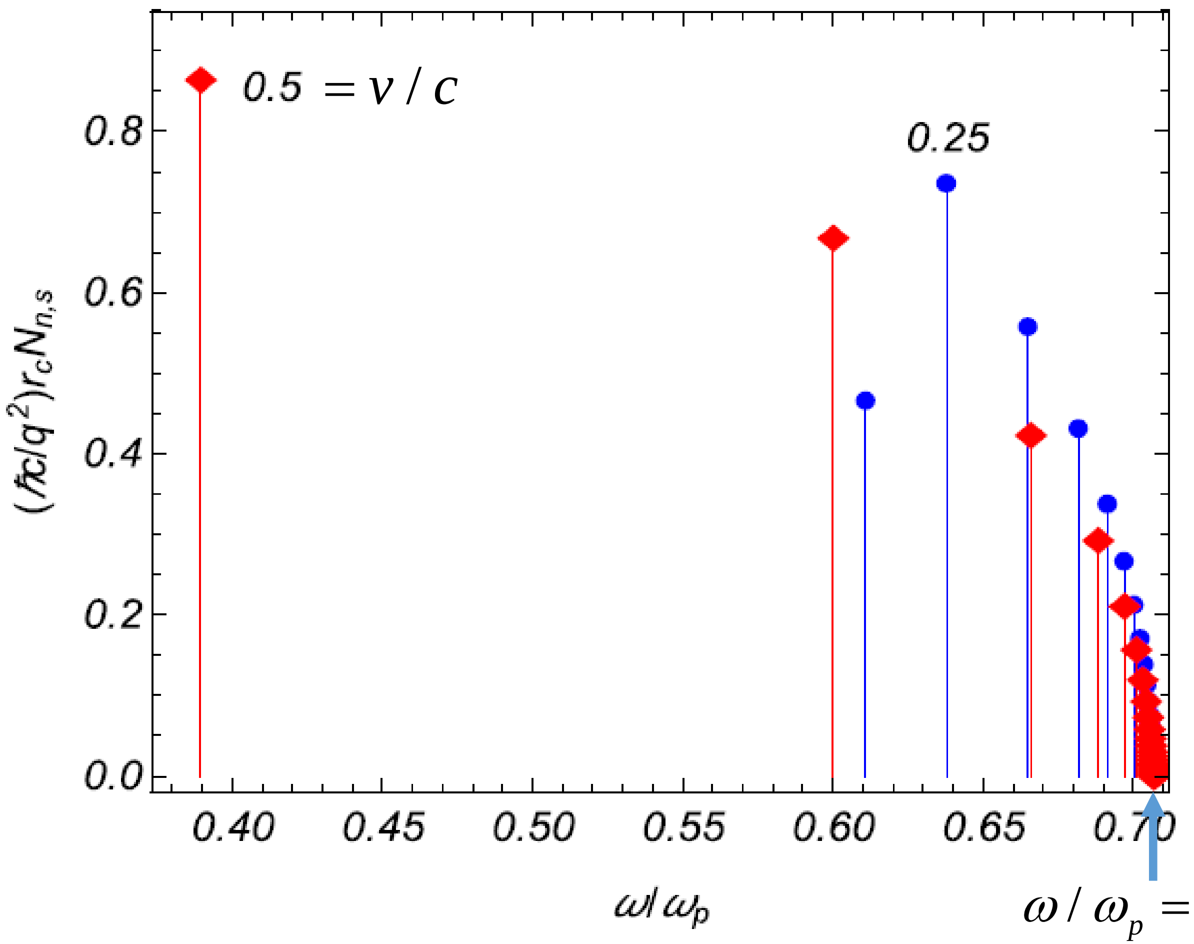
- Among the most popular models used in surface plasmonics is the Drude type dispersion

$$\varepsilon_0(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 + i\gamma\omega}$$

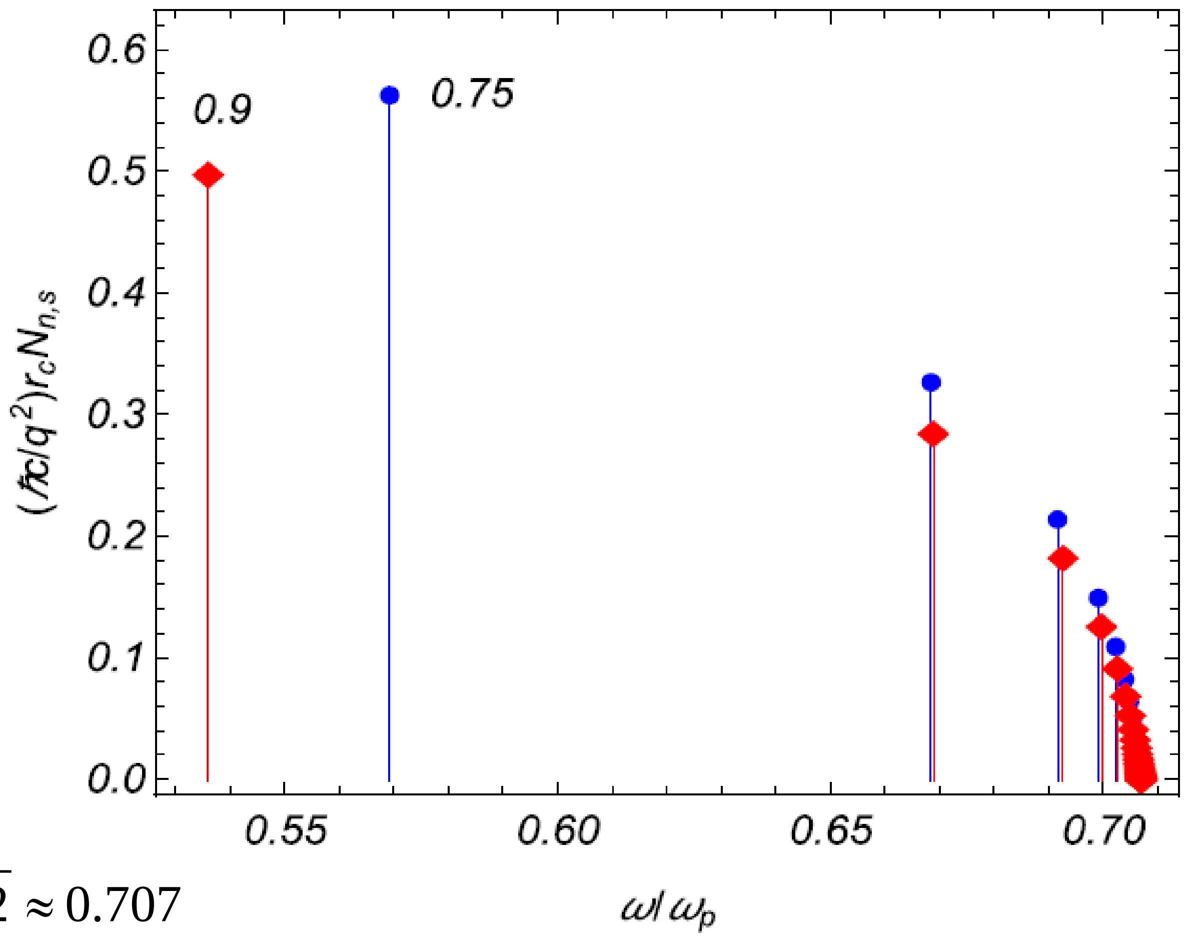
Background dielectric constant

Number of the radiated quanta in the form of surface polaritons, as a function of the frequency, for different values of $n \in [0, 20]$

$$\varepsilon_\infty = \varepsilon_1 = 1,\ r_0 / r_c = 1.05,\ \omega_p r_c / c = 1$$

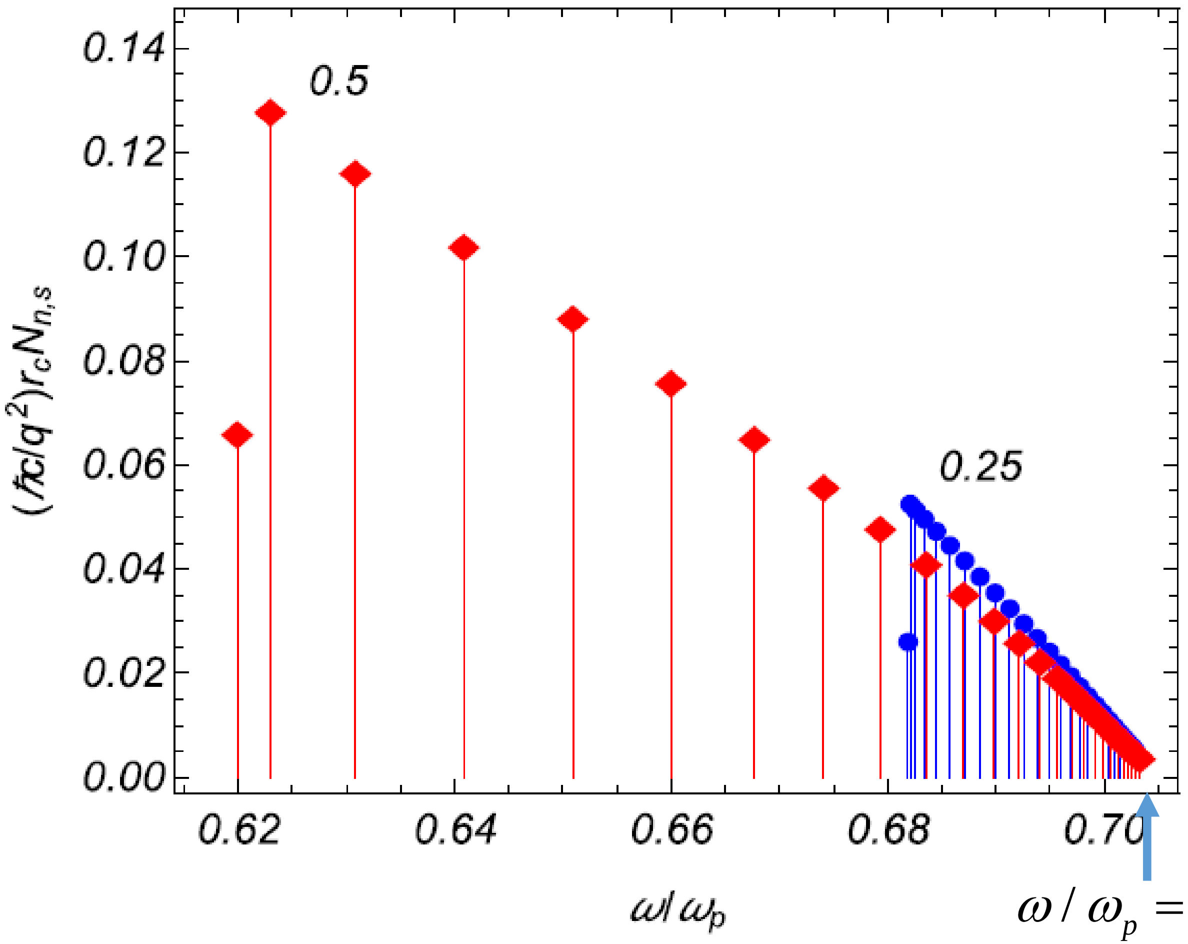


$\omega / \omega_p = 1/\sqrt{2} \approx 0.707$

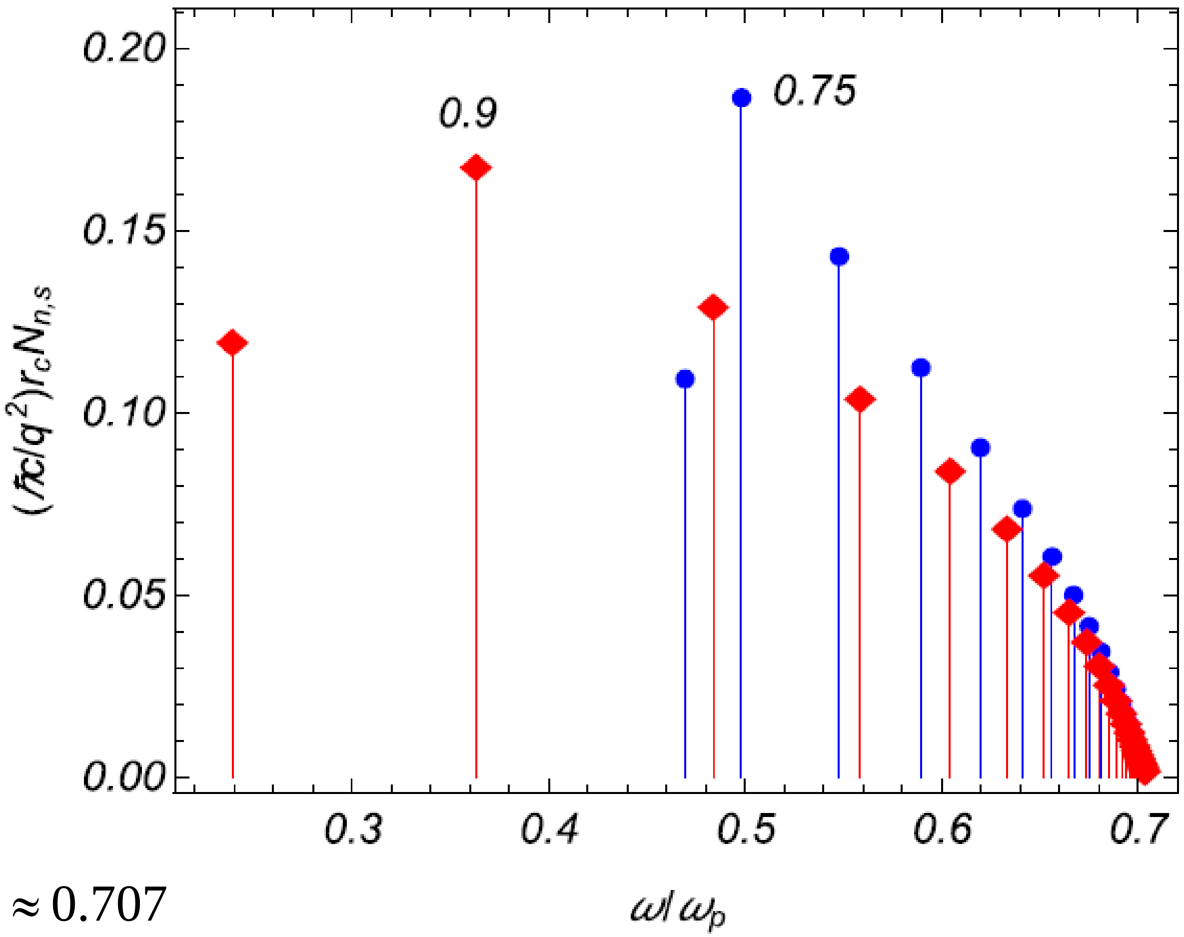


Number of the radiated quanta in the form of surface polaritons, as a function of the frequency, for different values of $n \in [0, 20]$

$$\varepsilon_\infty = \varepsilon_1 = 1,\ r_0 / r_c = 1.05,\ \omega_p r_c / c = 5$$

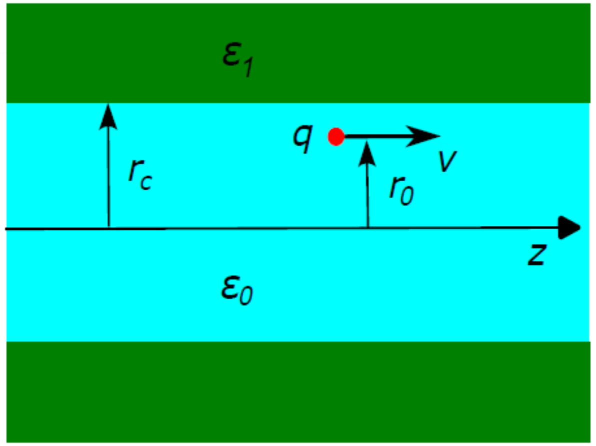


$\omega / \omega_p = 1/\sqrt{2} \approx 0.707$



Energy fluxes for surface polaritons

- Interesting features appear in the distributions of the energy fluxes for surface polaritons
- Charged particle moving inside a cylindrical waveguide



$$\varepsilon_1 < 0 < \varepsilon_0$$

- Energy flux through the plane perpendicular to the waveguide axis (z=const)

$$I^{(f)} = \frac{c}{4\pi}\int_0^{2\pi} d\phi \int_0^{\infty} dr\, r \left[\mathbf{E}^{(\mathrm{P})} \times \mathbf{H}^{(\mathrm{P})}\right] \cdot \mathbf{n}_z$$

- We evaluate the energy fluxes inside and outside the cylinder separately

Energy fluxes for surface polaritons

- Energy fluxes on a given mode inside and outside the cylinder

$$
\left.
\begin{aligned}
I^{(f)}_{\mathrm{i},n,s} &= \delta_n \frac{q^2 v}{4r_c^2}\frac{Q_n^2(u)}{\varepsilon_0}\sum_{p,p'=\pm1}\left(1+pp'\beta^2\varepsilon_0\right)\frac{K_{n+p'}(\gamma_1 u)}{W^I_{n+p'}} \\
&\times \frac{K_{n+p}(\gamma_1 u)}{W^I_{n+p}}\left[I^2_{n+p}(\gamma_0 u) - I_{n+2p}(\gamma_0 u) I_n(\gamma_0 u)\right]\big|_{u=u_{n,s}}
\end{aligned}
\right\} \quad r < r_c
$$

$$
\left.
\begin{aligned}
I^{(f)}_{\mathrm{e},n,s} &= \delta_n \frac{q^2 v}{4r_c^2}\frac{Q_n^2(u)}{\varepsilon_1}\sum_{p,p'=\pm1}\left(1+pp'\beta^2\varepsilon_1\right)\frac{I_{n+p'}(\gamma_0 u)}{W^I_{n+p'}} \\
&\times \frac{I_{n+p}(\gamma_0 u)}{W^I_{n+p}}\left[K_{n+2p}(\gamma_1 u) K_n(\gamma_1 u) - K^2_{n+p}(\gamma_1 u)\right]\big|_{u=u_{n,s}}
\end{aligned}
\right\} \quad r > r_c
$$

Notations: $u = k_z r_c = \omega r_c / v$

$$\gamma_j = \sqrt{1-\beta^2\varepsilon_j},\ \beta = v/c,$$

$$Q_n(u) = \frac{K_n(\gamma_1 u)}{W^I_n \bar{\alpha}_n(u)} I_n(\gamma_0 u r_0 / r_c)$$

$$
\begin{aligned}
W^I_n &= -\gamma_1 I_n(\gamma_0 u) K_{n+1}(\gamma_1 u) \\
&\quad - \gamma_0 I_{n+1}(\gamma_0 u) K_n(\gamma_1 u)
\end{aligned}
$$

- Special case of axial motion (n=0 mode contributes only)

$$I^{(f)}_{\mathrm{i},0} = \frac{q^2 v}{2r_c^2\varepsilon_0}\frac{\varepsilon_0^2}{\varepsilon_1^2}\frac{\left[\frac{I_1(\gamma_0 u)}{I_0(\gamma_0 u)} + \frac{1}{\gamma_0 u}\right]^2 - \frac{1}{\gamma_0^2 u^2} - 1}{\left(1-\varepsilon_0/\varepsilon_1\right)^4 I_1^2(\gamma_0 u)\bar{\alpha}_0^2(u)},\quad I^{(f)}_{\mathrm{e},0} = -\frac{q^2 v}{2r_c^2\varepsilon_1}\frac{\gamma_0^2}{\gamma_1^2}\frac{\left[\frac{K_1(\gamma_1 u)}{K_0(\gamma_1 u)} - \frac{1}{\gamma_1 u}\right]^2 - \frac{1}{\gamma_1^2 u^2} - 1}{\left(1-\varepsilon_0/\varepsilon_1\right)^4 I_1^2(\gamma_0 u)\bar{\alpha}_0^2(u)},$$

$$\boxed{I^{(f)}_{\mathrm{e},0} < 0 < I^{(f)}_{\mathrm{i},0}}$$

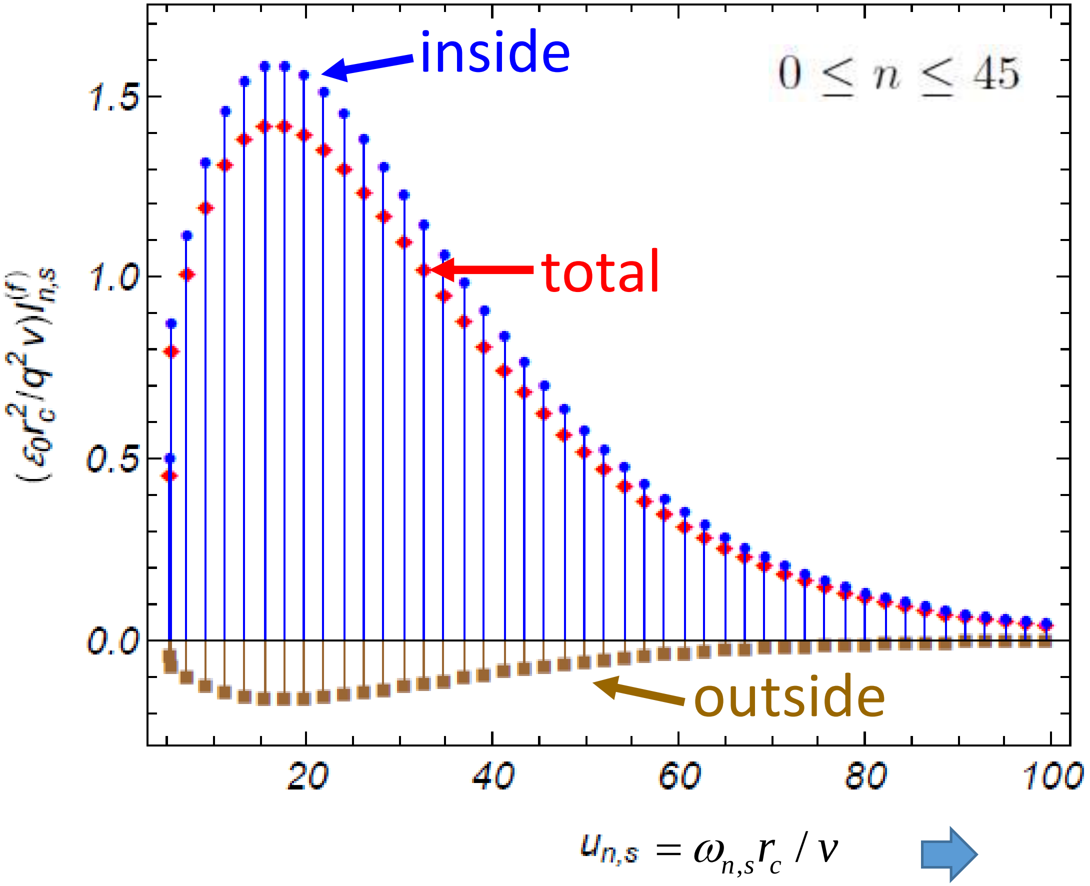
The energy flux is directed towards the charge motion inside the cylinder and towards the opposite direction in the exterior region

Energy fluxes for surface polaritons

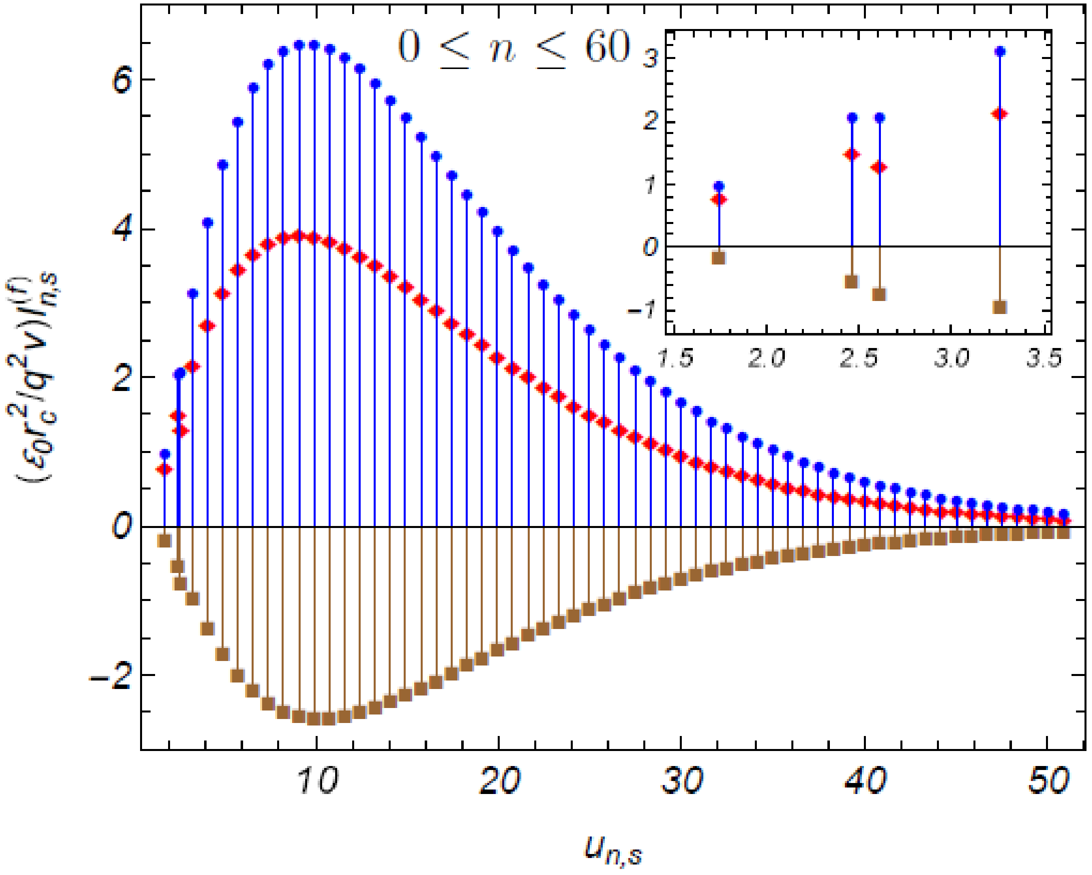
Energy fluxes of the radiated SPs inside (circles) and outside (squares) the cylinder

$$\beta_0 = 0.9,\ r_0/r_c = 0.95,$$

$\varepsilon_1/\varepsilon_0 = -3$



$\varepsilon_1/\varepsilon_0 = -1.5$

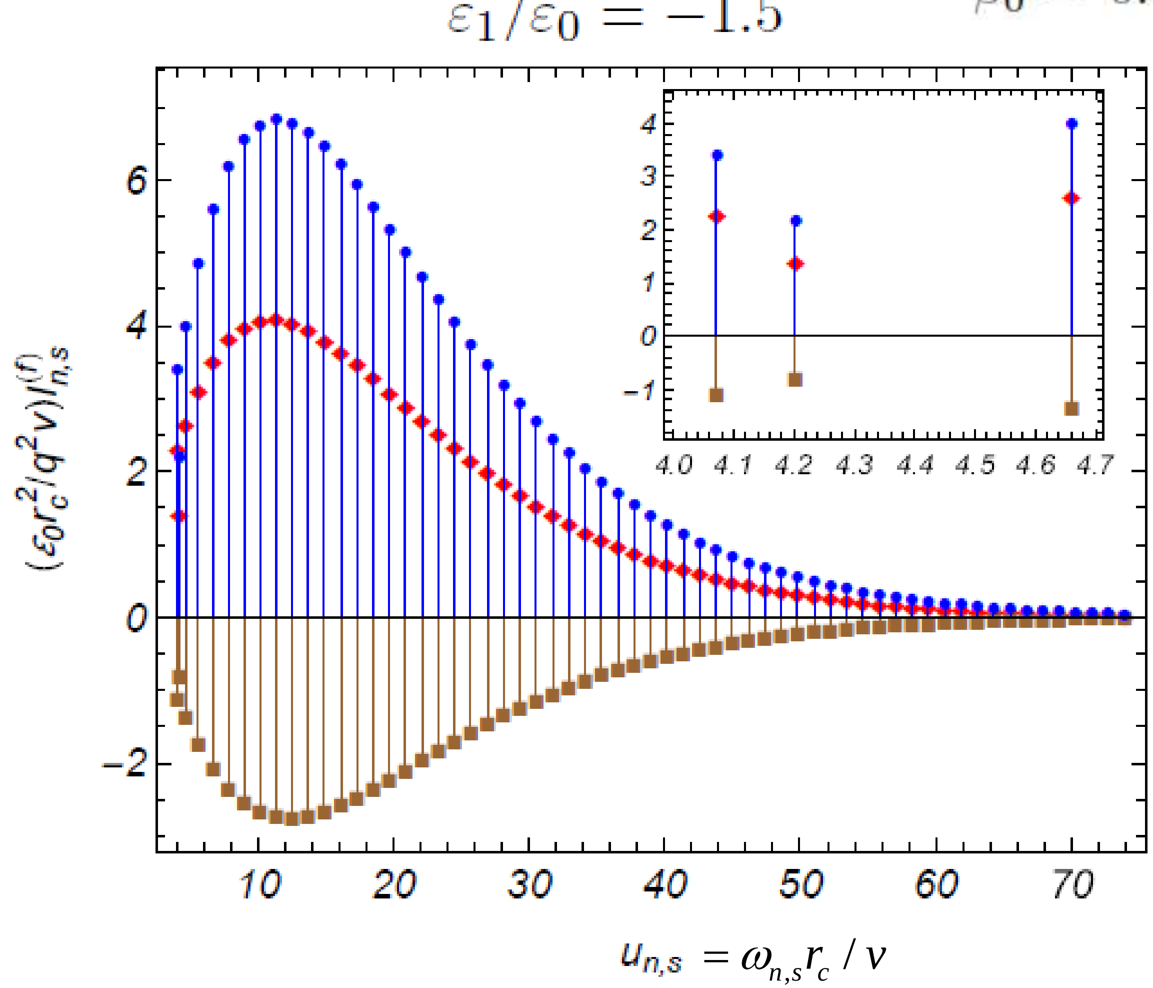


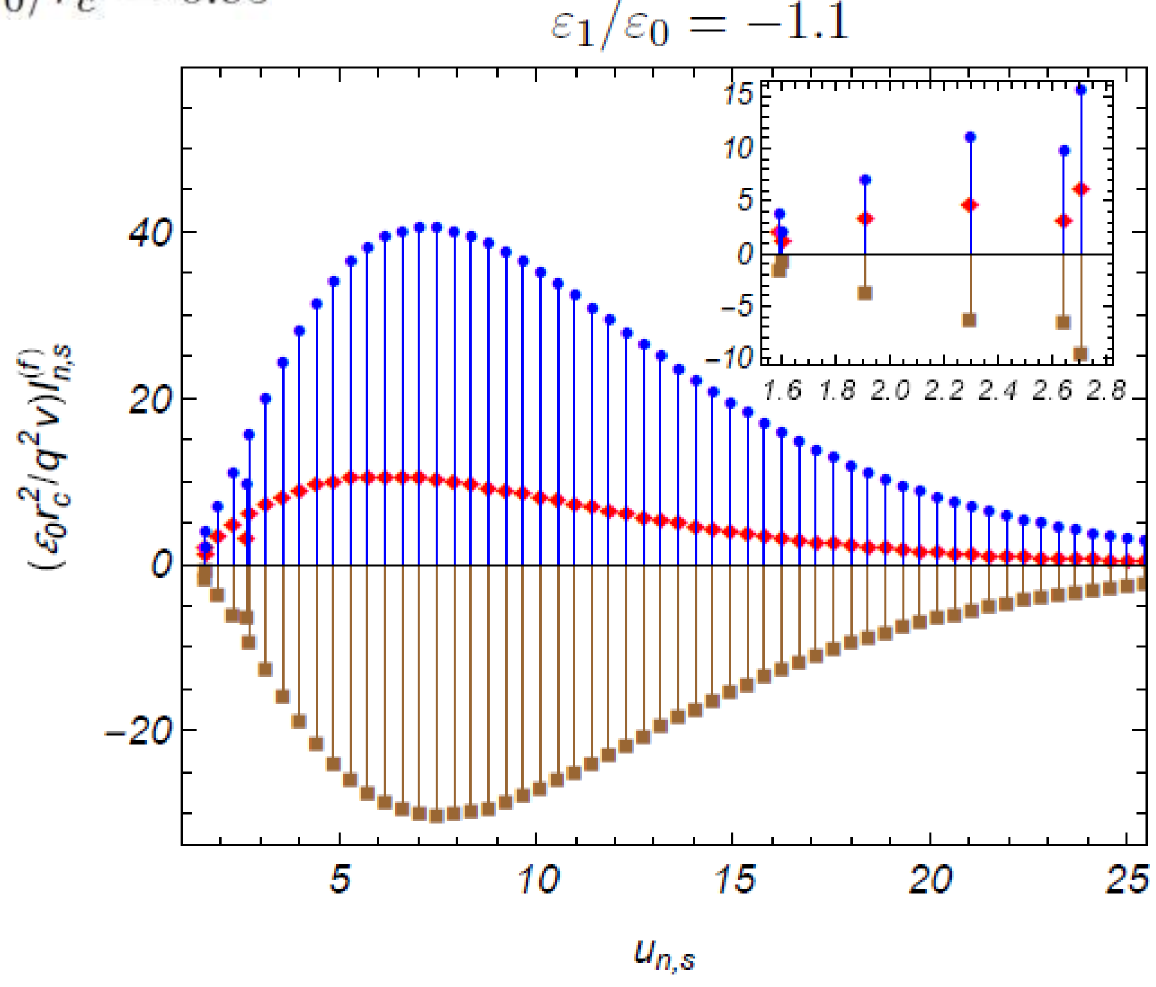
Frequency of radiated surface polaritons

Energy fluxes for surface polaritons

Energy fluxes of the radiated SPs inside (circles) and outside (squares) the cylinder

$\beta_0 = 0.75,\ r_0/r_c = 0.95$





Summary

- Presence of cylindrical waveguide may essentially change the spectral-angular distribution of the Synchrotron and Cherenkov radiations 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
- Depending on the waveguide radius one can have radiation in the spectral range from microwaves to optics

Summary

- For the motion parallel to the cylinder axis the energy flux is directed towards the charge motion in the passive medium and towards the opposite direction in the active medium

- Important features of relativistic effects include:

  - Possibility of essential increase of the radiated energy
  - Narrowing the confinement region of the SP fields near the cylinder surface in the active medium
  - Enlarging the frequency range for radiated SPs
  - Decrease of the cutoff factor for radiation at small wavelengths compared with the waveguide radius

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Thank you for your attention!