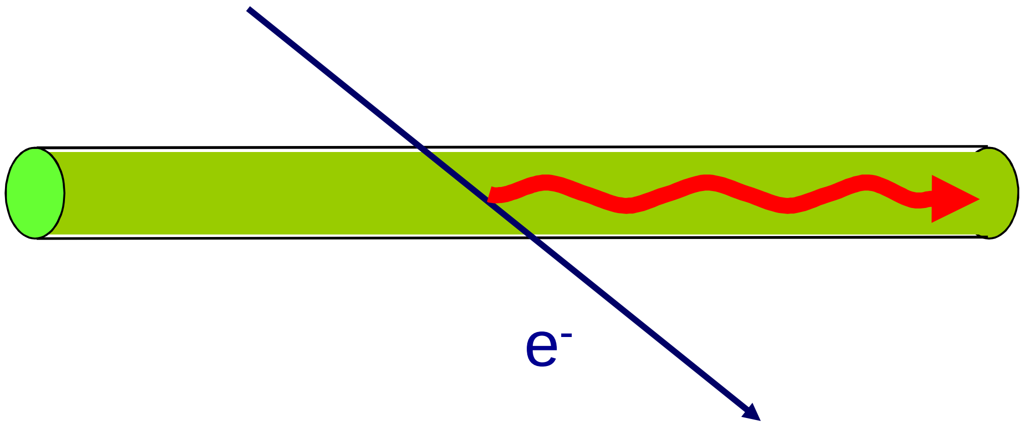
Channeling 2012, 23-28 September, Alghero

Radiation Induced by Charged Particles in Optical Fibers



X. Artru, C. Ray

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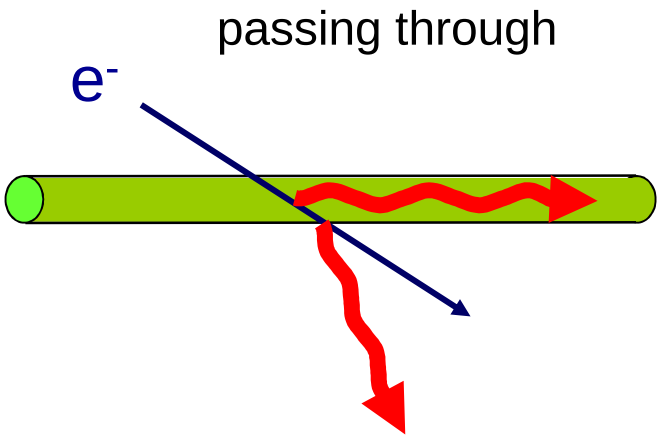
References

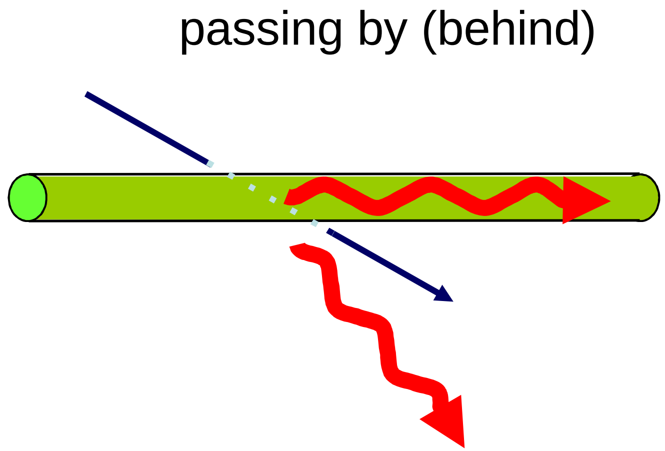
- *Photon production by charged particles in narrow optical fibers,* X. Artru, C. Ray Proceedings of Channeling 2006

- X. Artru, C. Ray, NIM B 266 (2008) 3725

- X. Artru, C. Ray, Chap.21 of book *"Selected Topics on Optical Fiber Technology"* (2012, InTech — Open Access Company)

Electron passing *through* or *by* an optical fiber





- Radiation is produced by the transient polarisation of the medium by the Coulomb field of the electron.
- Part of it is trapped in the fiber. We call it

  P*article* ***I****nduced* ***G****uided* ***L****ight* (PIGL).
- We take a *thin* fiber (radius *a* ~ λ) without clad.
- Guided light is decomposed in a few number of *modes*.

The fiber modes $\{m,\omega\}$

Electric field ≈ "*photon wave function*" of the mode

$$\mathbf{E}_{\{m,\omega\}}(\mathbf{X},t) = \mathbf{E}_{\{m,\omega\}}(\mathbf{r}) \exp(\, ipz - i\omega t\,)$$

$\mathbf{X} = (x,y,z)$; $\mathbf{r} = (x,y)$: transverse coordinate

ω = "frequency" = energy ; p = longitudinal momentum

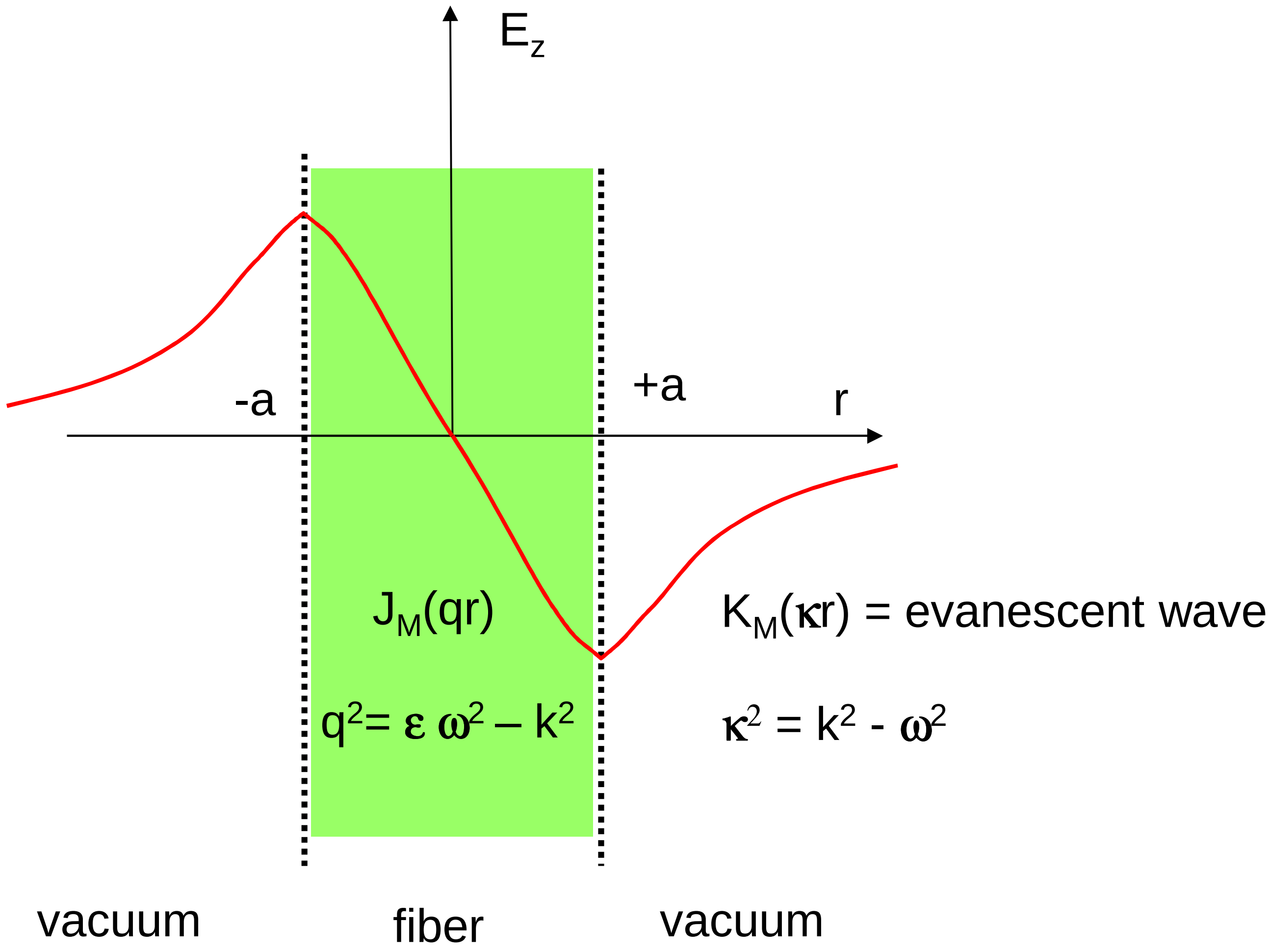
Mode type : $m = \{ M, n_r, \text{"TM"}, \sigma \}$ or $\{ M, n_r, \text{"TE"}, \sigma \}$

angular mom. J_z radial number "*Transverse Magnetic*"

$\sigma = sign(p) = \pm 1.$

Lowest mode : HE_{11} { |M|=1, n_r=1, "TM" }

Radial profile of a mode.
Example: E_z of the lowest mode, HE_{11}
m = { M=±1, n_r=1, "TM" }



The dispersion relation

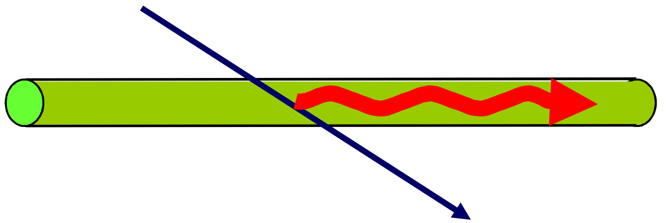
Continuity of **B**, $\mathbf{E}_T$ and $\varepsilon(r)\,E_r$:

$$\left[\frac{J_M'(qa)}{qa\,J_M(qa)}+\frac{K_M'(\kappa a)}{\kappa a\,K_M(\kappa a)}\right]\cdot\left[\frac{\varepsilon(r)\,J_M'(qa)}{qa\,J_M(qa)}+\frac{K_M'(\kappa a)}{\kappa a\,K_M(\kappa a)}\right]=$$

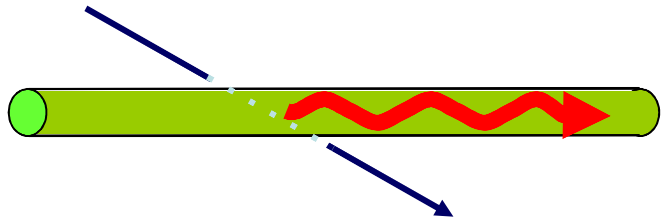
$$=M^2\left(\frac{1}{(qa)^2}+\frac{1}{(\kappa a)^2}\right)\cdot\left(\frac{\varepsilon(r)}{(qa)^2}+\frac{1}{(\kappa a)^2}\right)$$

$$\omega=\omega_m(p) \quad \text{or} \quad p=p_m(\omega)$$

The 2 types of ***P**article **I**nduced **G**uided **L**ight*

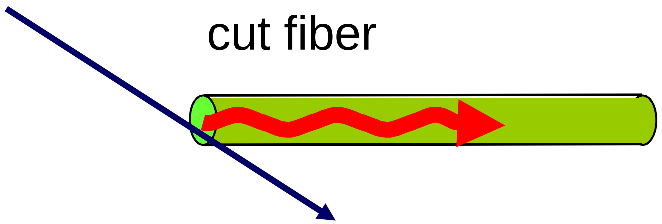


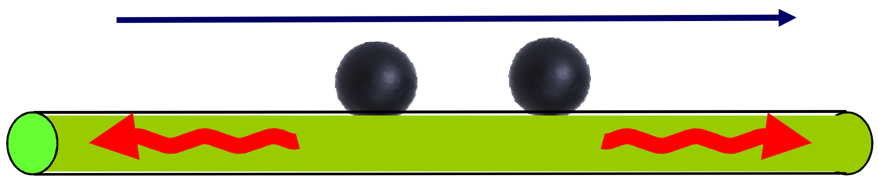
or



- Type-I PIGL (above) : the fiber is translation invariant

- Type-II PIGL (examples below) : translation invariance is broken

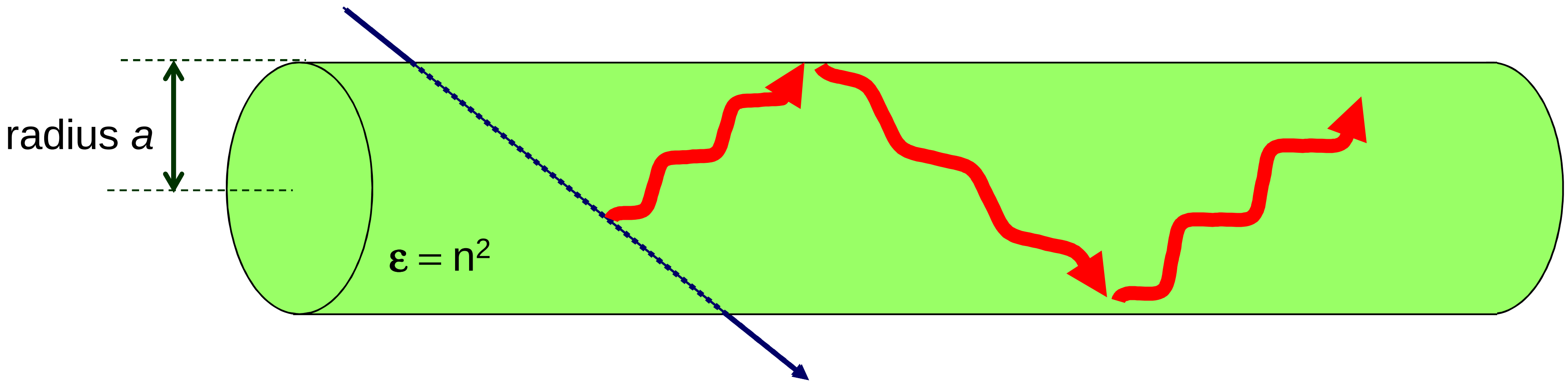




Light is first induced
in the metallic balls,
in the form of *plasmons*

Comparison with the *DIRC* Cherenkov detector

[P. Coyle et al, NIM A 343 (1994) 292]



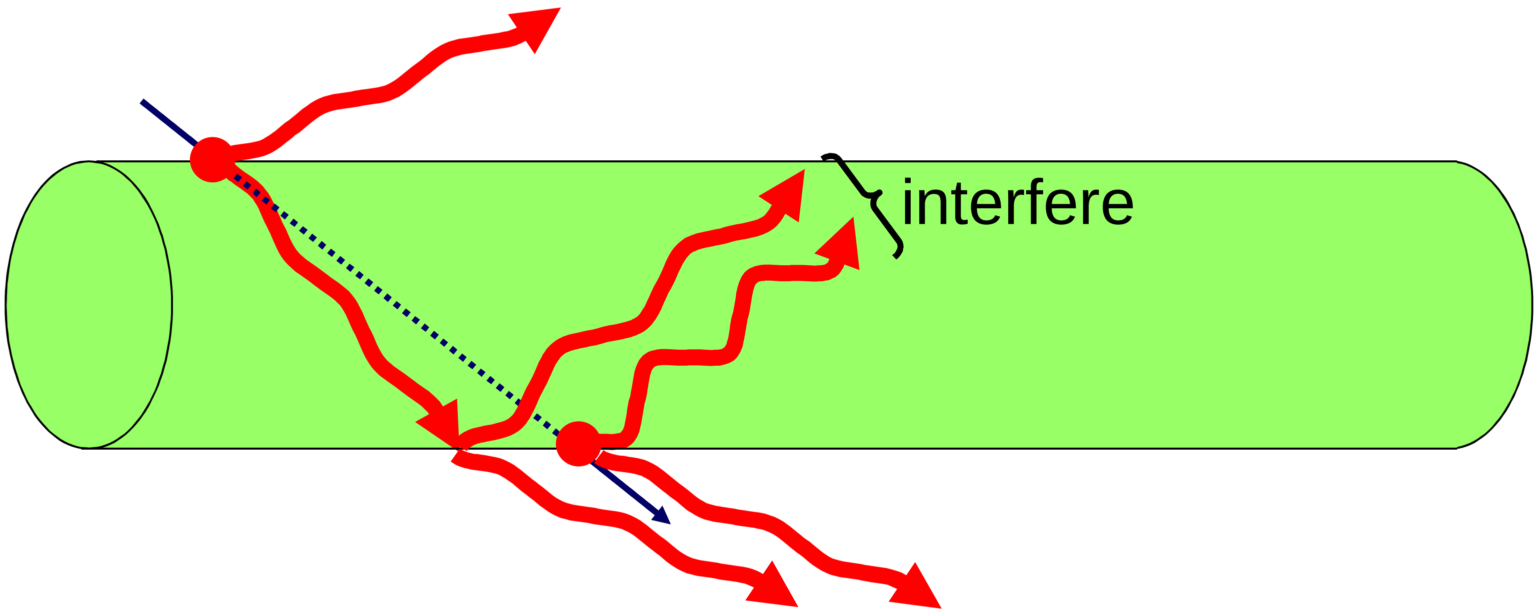
DIRC - *thick* guide : *a* ~1 cm >> λ $\rightarrow$ many modes.

- Many photons per electron $\rightarrow$ *individual* particle detection.
- Velocity threshold : $v \geq 1/n$

PIGL - *thin* guide : *a* ~ λ $\rightarrow$ one or a few modes

- Less than 1 photon per electron $\rightarrow$ *beam* diagnostics
- No velocity threshold

PIGL as *channeled transition radiation*



… but the usual T.R. formula is not valid for surface of curvature radius $a \sim \lambda$

Channeled XTR in microcapillaries : Zhevago & Glebov, Phys. Lett. A 309 (2003) 31

For the *external* Transition Radiation on a cylinder: N. Shul'ga et al. (RREPS-01)

Photon spectrum in the type-I PIGL

Produced spectrum in the mode *m* :

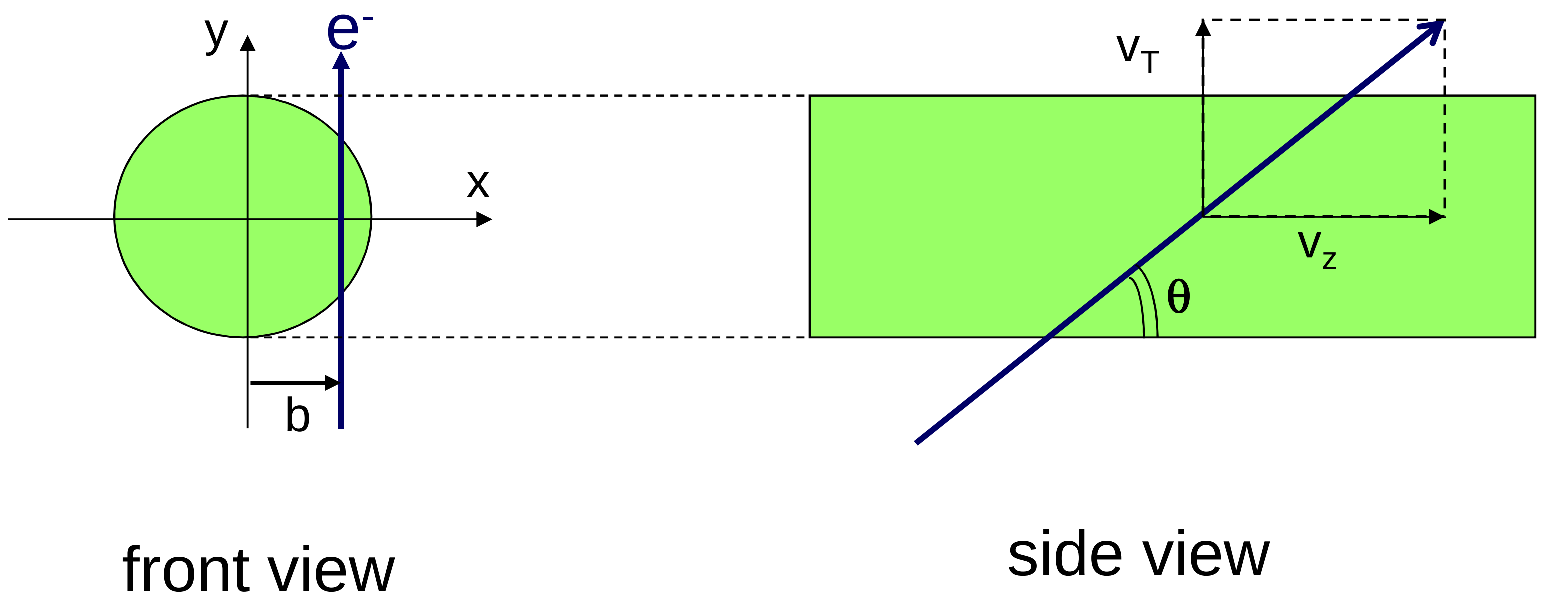
$$\omega \, dN / d\omega = (2\pi \, \Phi_{\{m,\omega\}})^{-1} \left| \, e \int d\mathbf{X}_e \, . \, \mathbf{E}^*_{\{m,\omega\}}(\mathbf{X},t) \right|^2$$

$\Phi_{\{m,\omega\}}$ = energy flux of the normalized mode

$$= 2 \, \mathrm{Re} \int d^2\mathbf{r} \, \left[\mathbf{E}^*_{\{m,\omega\}}(\mathbf{r}) \times \mathbf{B}_{\{m,\omega\}}(\mathbf{r}) \right]_z$$

Poynting vector

Geometrical parameters

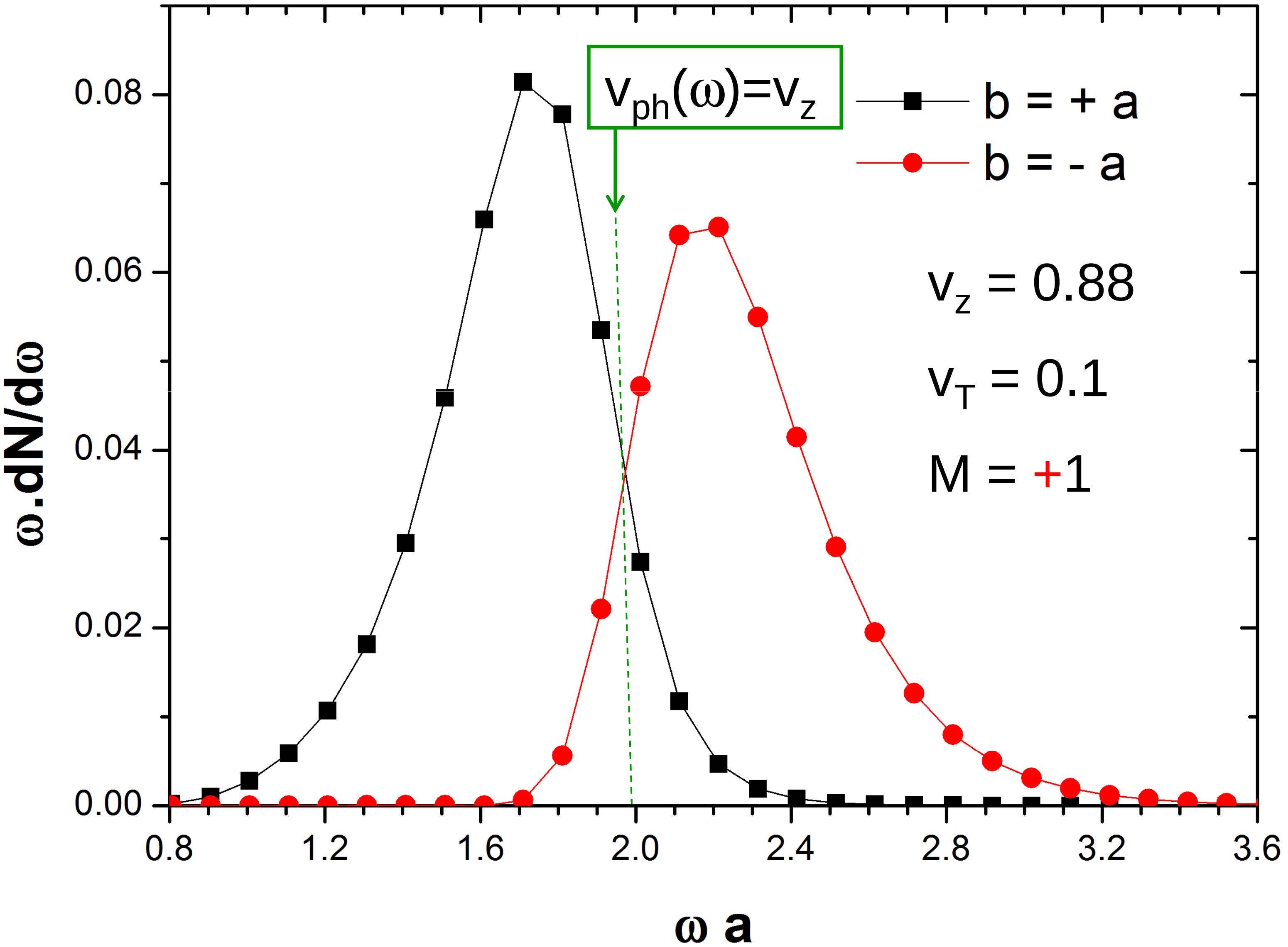


b : impact parameter

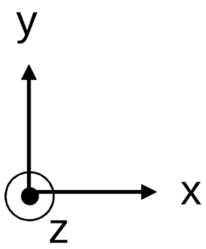
$v = (0, v_T, v_z)$: electron velocity

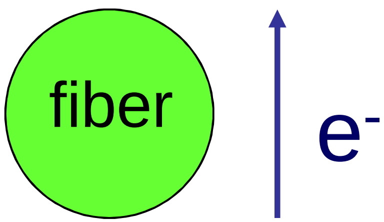
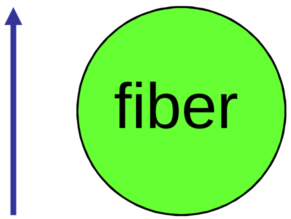
θ : crossing angle. $\tan\theta = v_T / v_z$

Example of type-I PIGL spectrum

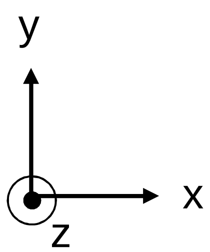
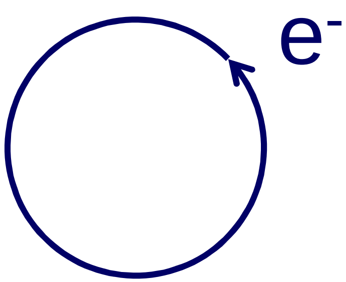
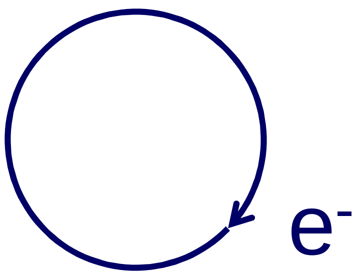


Correlation between the electron *side* and the photon *helicity*
(difference between the red and black curves in the last slide)

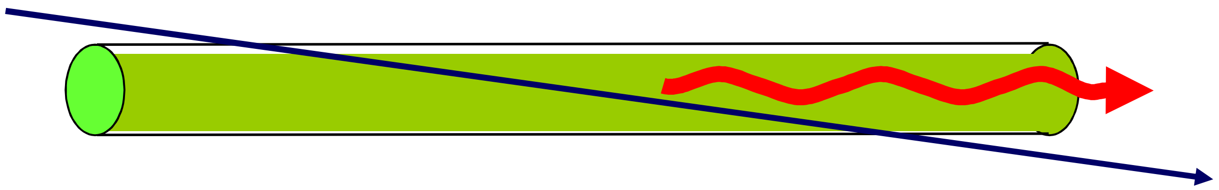


	$v_{ph} > v_z$ (small ω)	$v_{ph} < v_z$ (large ω)
side *b>0* 	favored M = +1	favored M = -1
side *b<0* 	favored M = -1	favored M = +1

There is an analogous correlation in the helical undulator

	$v_{z\ photon} > v_{z\ electron}$ ($\theta<1/\gamma$, large ω)	$v_{z\ photon} < v_{z\ electron}$ ($\theta>1/\gamma$, small ω)
	favored M = +1	favored M = -1
	favored M = -1	favored M = +1

Type-I PIGL : case of small crossing angle



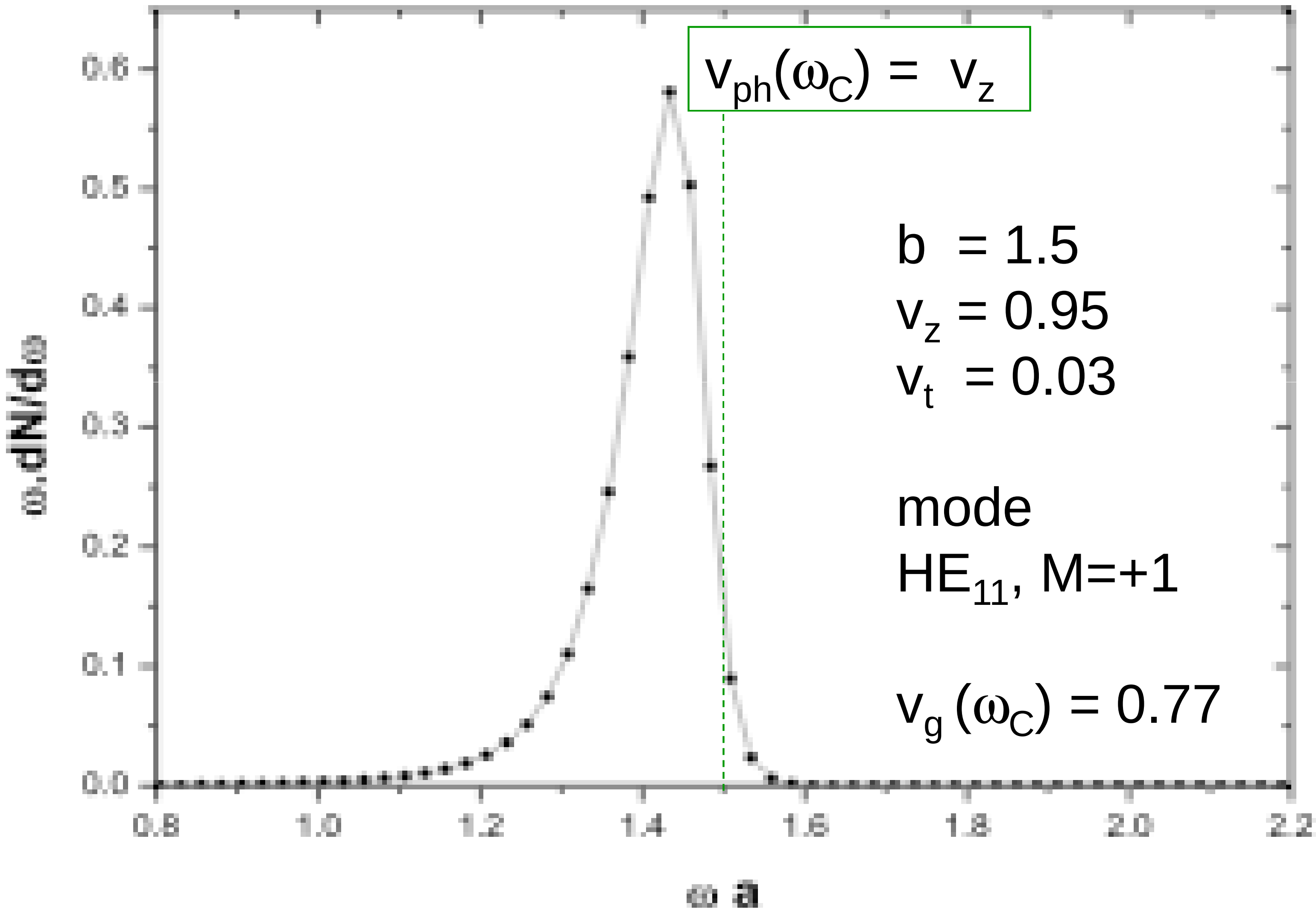
The radiation becomes nearly *monochromatic*. At the peak frequency ω_C , the phase velocity $v_{ph} \equiv \omega/p$ of the wave is equal to the longitudinal velocity of the electron :

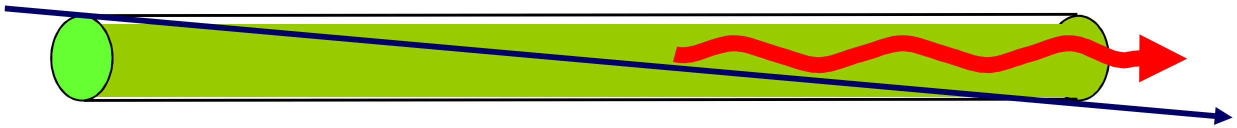
$v_{ph}(\omega_C) = v_z$ $\rightarrow$ the electron "surfes" on the wave

We call it the "Cherenkov peak"

The case of *parallel* trajectory was treated by Bogdankevich & Bolotovskii (1957), N. Zhevago & Glebov (1990, 1993).

Example of Cherenkov peak





Small θ : number of produced photons

$$N = (4\pi/137\omega)\,(\Phi_{\{m,\omega\}})^{-1}\;[\,1/v_g - 1/v_{ph}\,]^{-1}$$
$$\times \int dz\,.\,\left|\mathbf{E}_{z\{m,\omega\}}(\mathbf{r})\right|^2$$

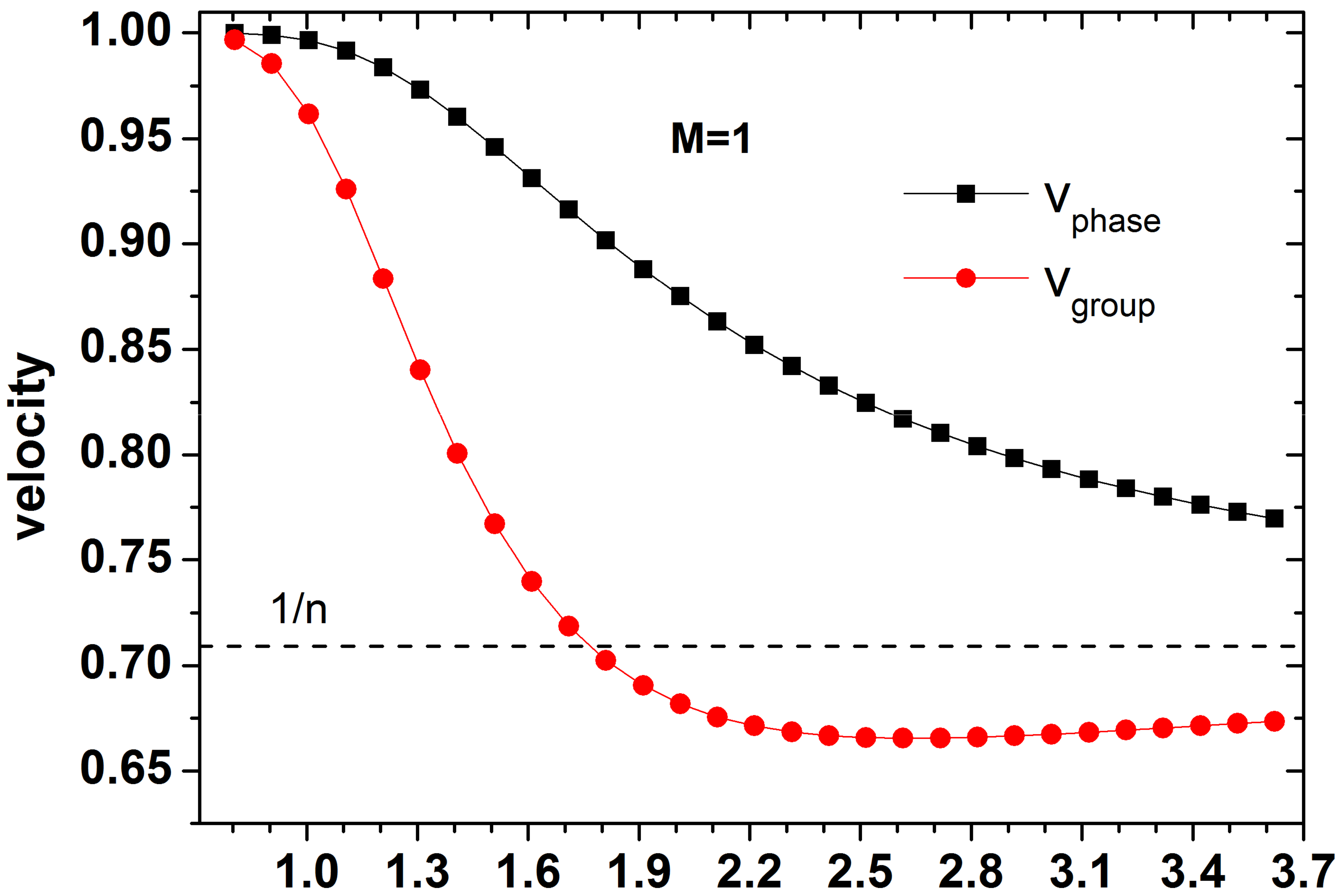
v_g = group velocity

Here $\omega = \omega_C$ such that $v_{ph}(\omega_C) = v_z$

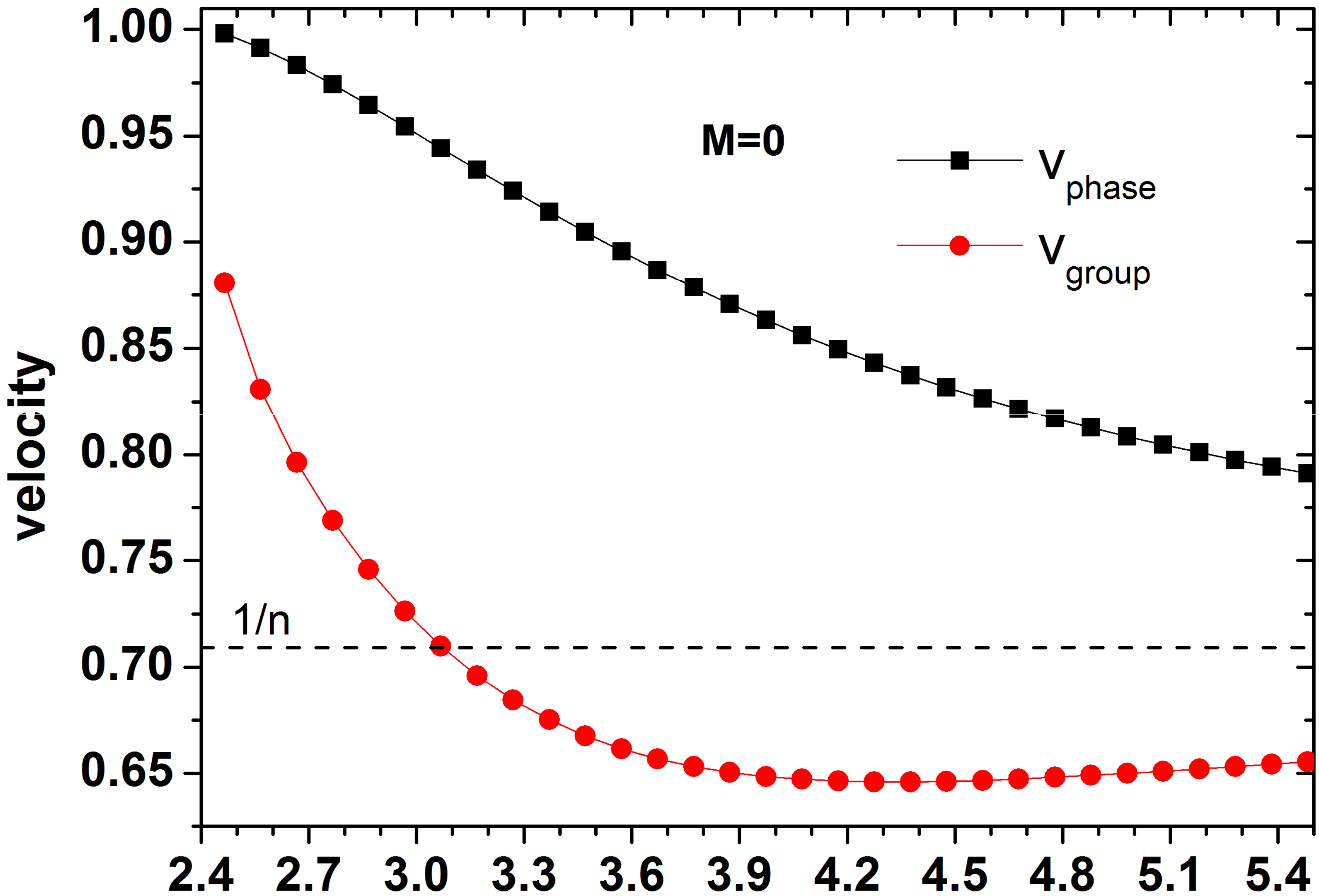
$\Phi_{\{m,\omega\}}$ = normalized energy flux of the mode

$\rightarrow$ N grows like θ^{-1}

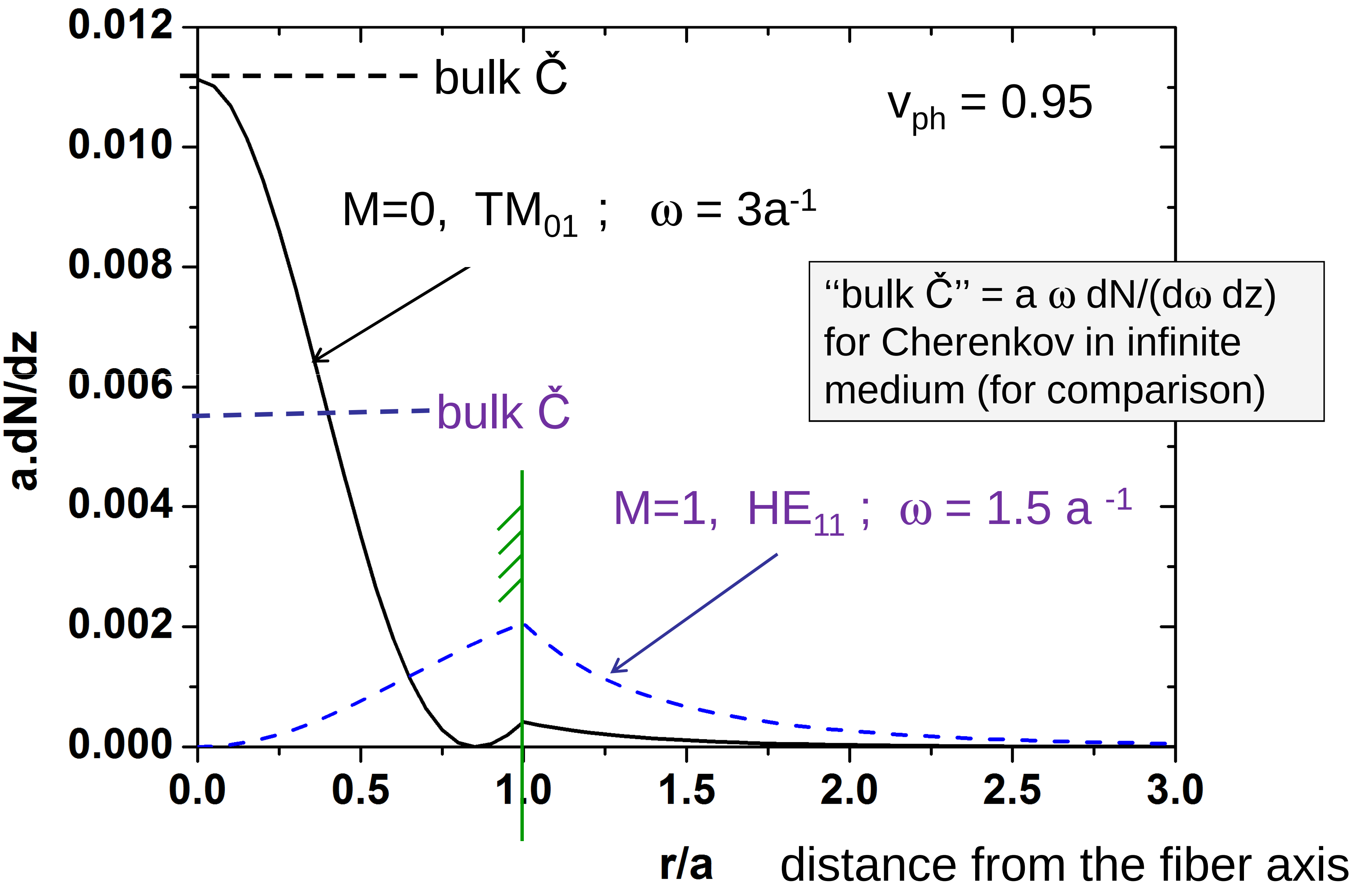
Phase and group velocity (HE_{11} mode)



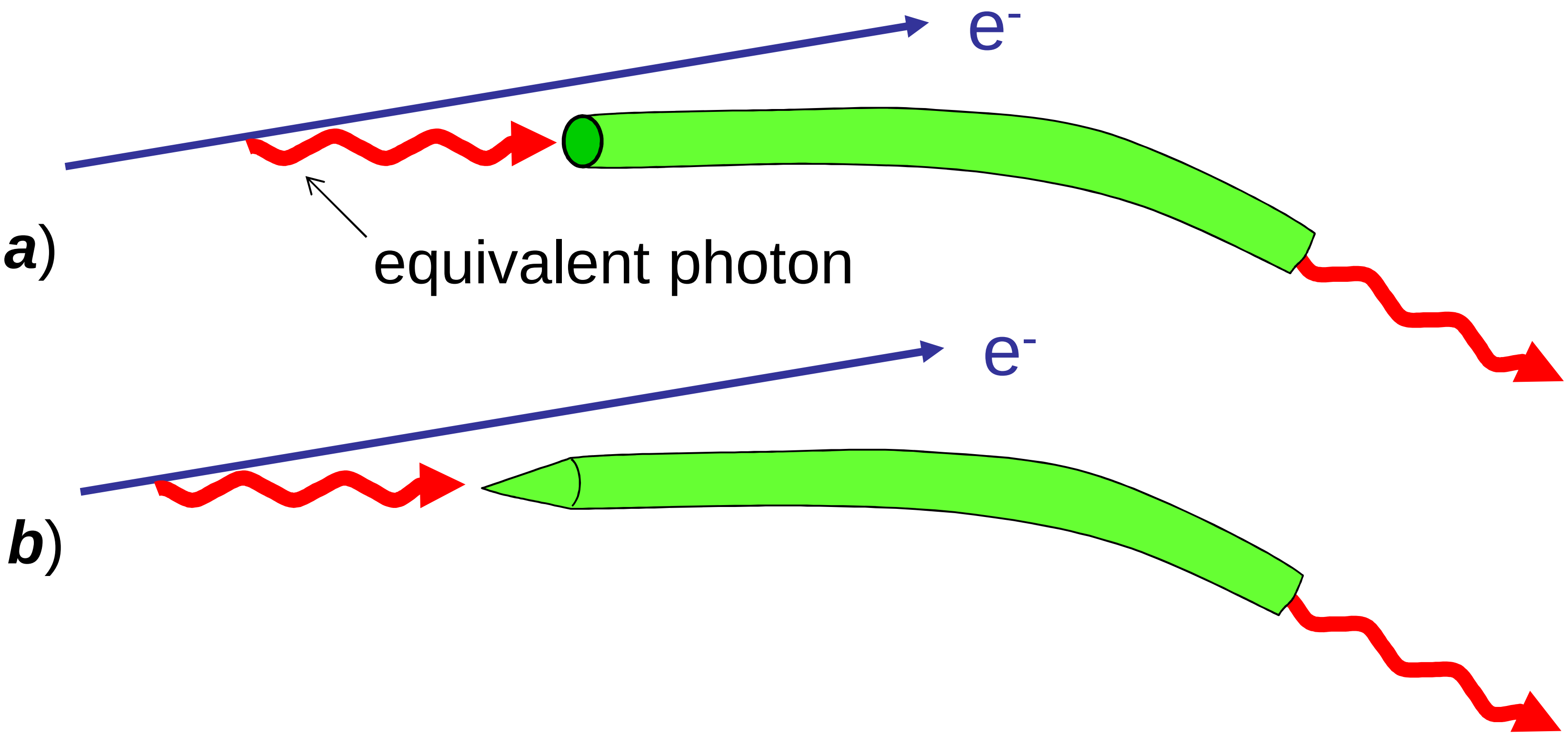
Phase and group velocity (M=0, TM_{01} mode)



Small crossing angle : Photon yield per unit of length



Type-II PIGL : cut fiber

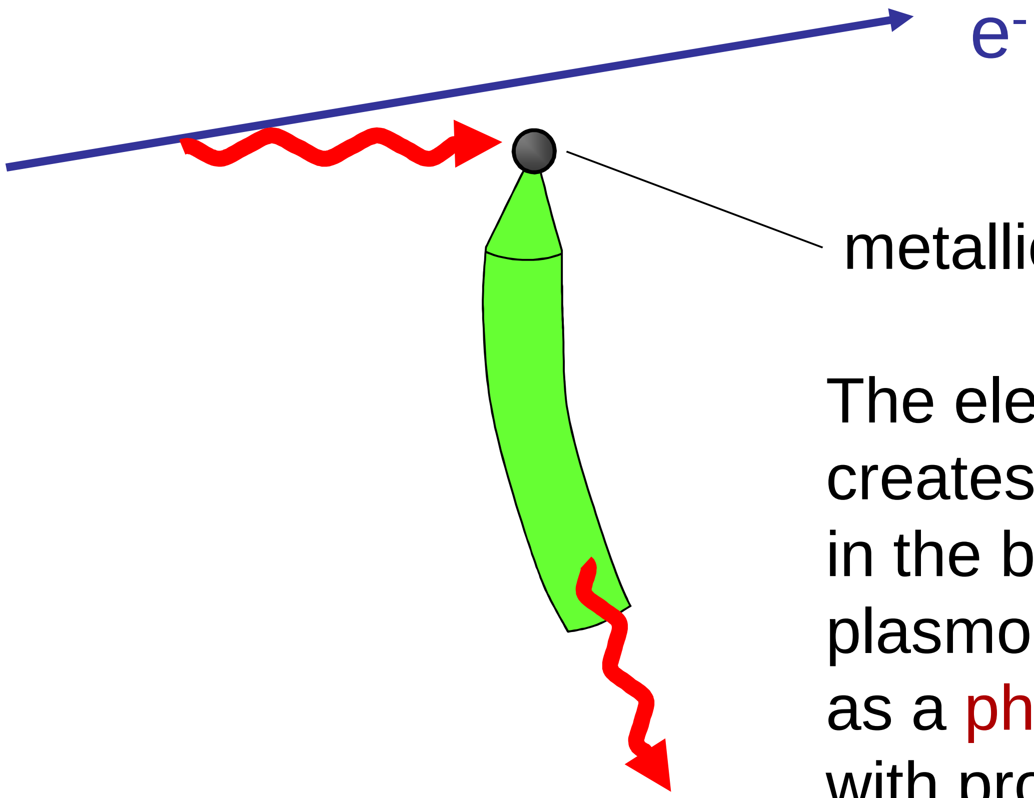


- In scheme ***a***), for a relativistic electron :

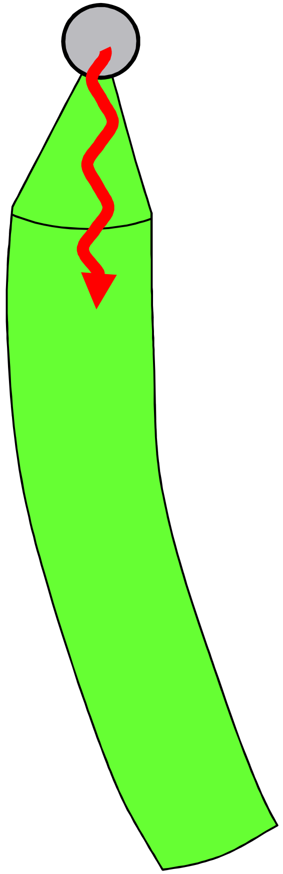
$dW/d\omega \sim (1/\ 137\ \pi)\ \langle r^2 \rangle_{mode} / b^2$,   with a cutoff at $\omega_{max} \sim \gamma/b$

- Scheme ***b***) is more efficient (the capture is more “adiabatic”)

Type-II PIGL : through a metallic ball



The electron field creates a plasmon in the ball. Then the plasmon is evacuated as a photon in the fiber, with probability ***K***

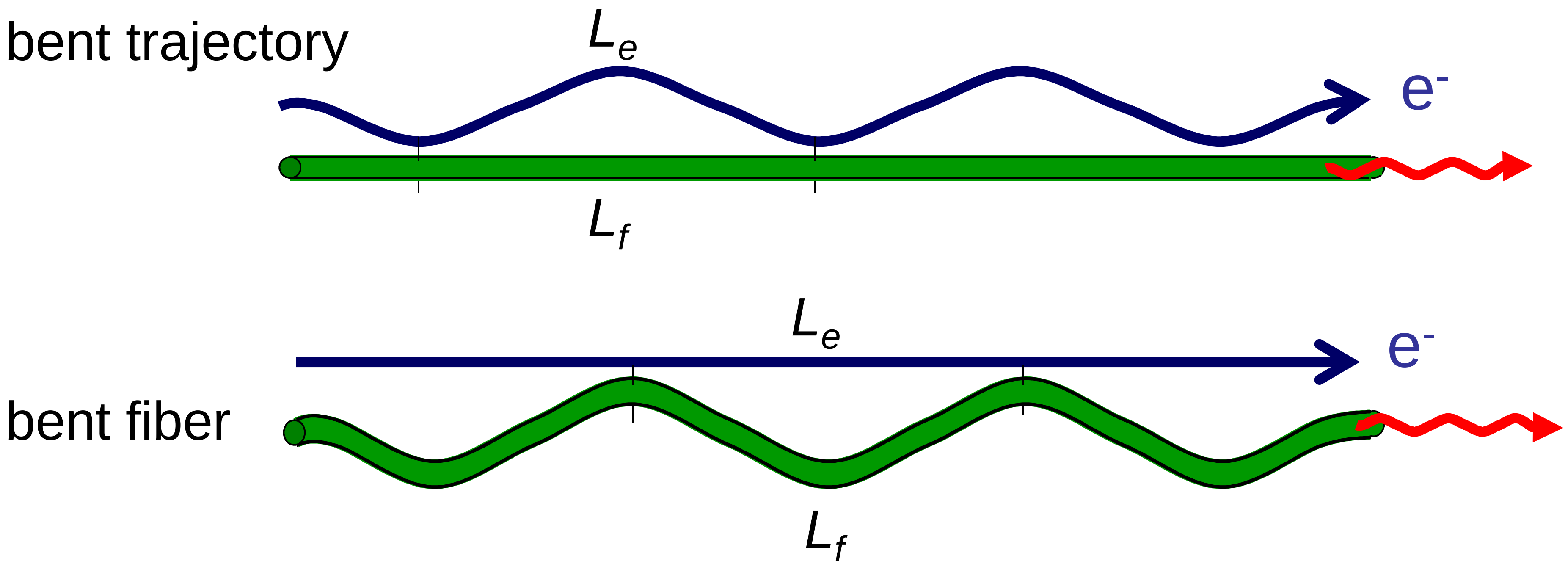


Number of photons :

$$N \sim \boldsymbol{K} \; (2/137) \; \omega_{plasmon} \; R^3/v^2b^2 \; , \qquad b < b_{max} \sim \gamma / \omega_{pl}$$

a prototype :

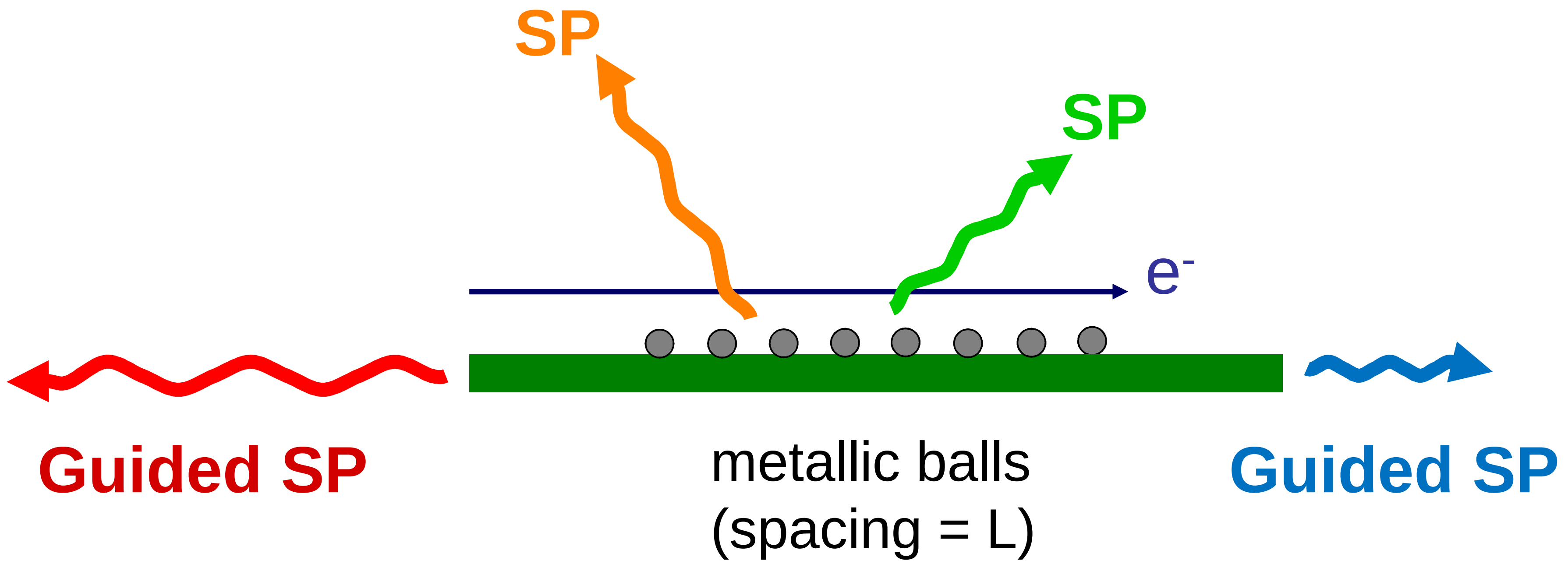
Interference effects for type-I PIGL : the *“fiber undulator”*



Resonance condition: $pL_f - \omega L_e / v = 2\pi \times$ integer

$\rightarrow$ discrete spectrum

Interference effects in type-II : the *guided Smith-Purcell* radiation

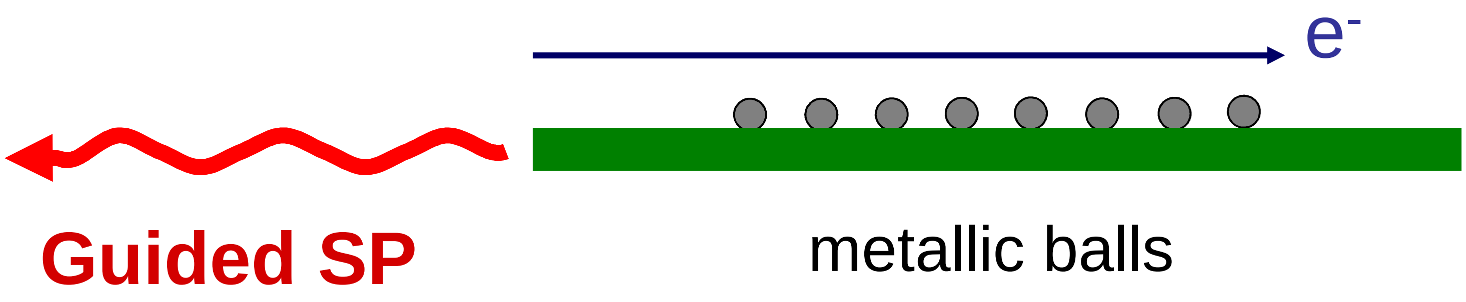


Resonance condition for Guided SP :

$$(p \pm \omega/v)\, L \;\equiv\; (1/v_{ph} \pm 1/v)\, \omega L \;=\; 2\pi \times \text{integer}$$

Intense Guided SP is expected if the plasmon frequency matches the resonance condition.

Guided Smith-Purcell radiation (continued)



For small enough L, no external SP and only backward GSP is emitted at $\omega = \omega_{pl}$ $\rightarrow$ still more intense GSP.

However GSP is reduced by shadowing [*]: each ball **screens** the electron field for the following balls. A *dynamical* theory like in [**] is needed.

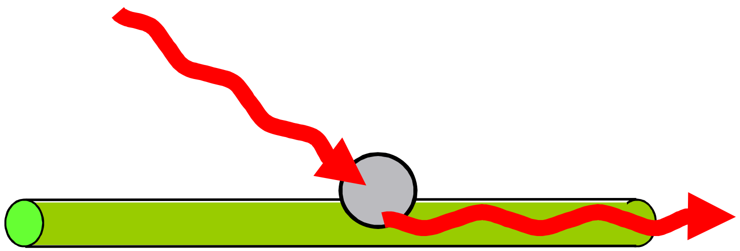
[*] Shadowing was checked in Diffraction Radiation [Naumenko et al, *J. Phys. Conf. Series* 236, (2010)]

[**] Garcia de Abajo, PRL 82 (1999) 2776 (Smith-Purcell on balls)

Background of upstream radiation

A *PIGL* target of type-II (cut fiber, metallic balls) captures not only the virtual photons of the Coulomb field, but also real photons, like synchrotron radiation from upstream magnets. This background is the same as for Optical TR.

In the case of type-I, upstream radiation is not captured by the fiber, but only *scattered*. Type-I PIGL is a pure *near-field* sensor.



type-II

type-I

Conclusion (1)

-Particle-Induced Guided Light may be used for beam diagnostics, more specially for micro-beams. It posses the flexibility of fiber optics and has little effect on the beam emittance.

-Type-I (at large θ) and type-II PIGL can measure the transverse beam profile. Type-I can even tell on which side of the fiber a microbeams passes by.

- At small crossing angle PIGL grows like θ^{-1} and becomes monochromatic. The peak frequency depends on the beam velocity.

Conclusion (2)

- For type-I PIGL there is no background from upstream radiation.
- In a monomode (or few mode) fiber, PIGL can take advantage of interference effects.

Work to be done :

- Calculate or measure the probability ***K*** that a fiber takes a plasmon off a metallic ball.
- Estimate the maximum beam flux that a fiber can sustain without melting.
-Make experiments.

Thanks for your attention!