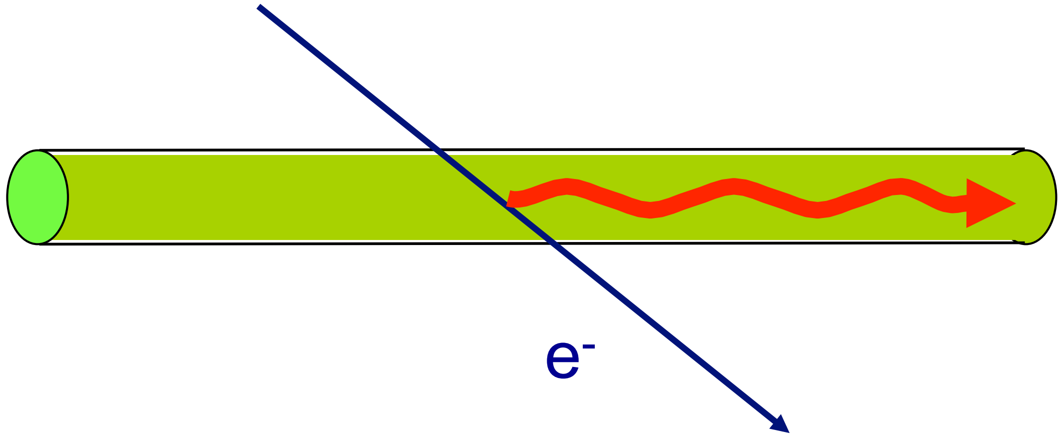
Orsay, 19 mars 2013

Lumière induite par une particule chargée dans une fibre optique. Application au diagnostic des faisceaux



X. Artru, C. Ray

Institut de Physique Nucléaire de Lyon,

References

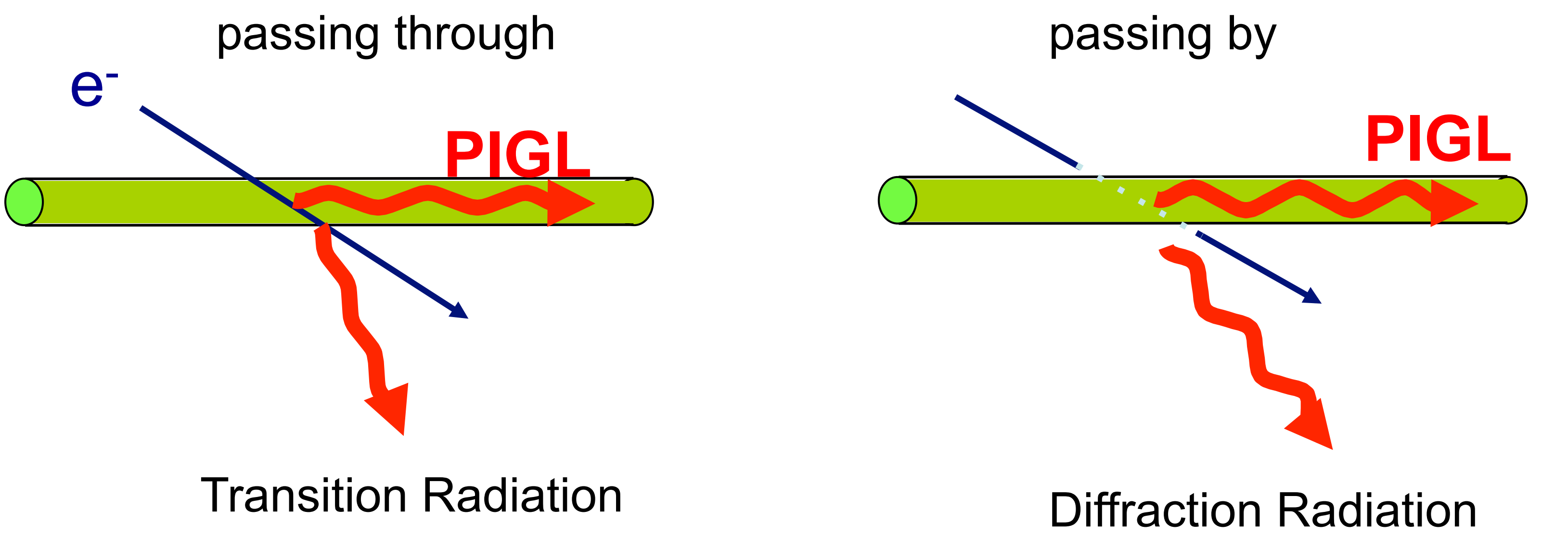
- *Photon production by charged particles in narrow optical fibers,* X. Artru, C. Ray Proceedings of Channeling 2006

- 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)

- X . Artru, C. Ray, Présentation à *Channeling 2002,* Alghero (Sardaigne) - à paraître dans NIM B

Electron passant *à travers* ou *à côté* d'une fibre



- **Mécanisme : polarisation transitoire** du milieu par le champ Coulombien de l'électron.
- **PIGL = *Particle Induced Guided Light***

- We take a *thin* fiber (radius *a* ~ λ), without clad.

The fiber modes $\mathbf{E}$_{m,ω}

"*photon wave function*"

longitudinal momentum

Electric field $\propto \mathbf{E}_{\{m,\omega\}}(\mathbf{r}) \exp(-i\omega t + ipz)$

transverse coordinate

2π × frequency

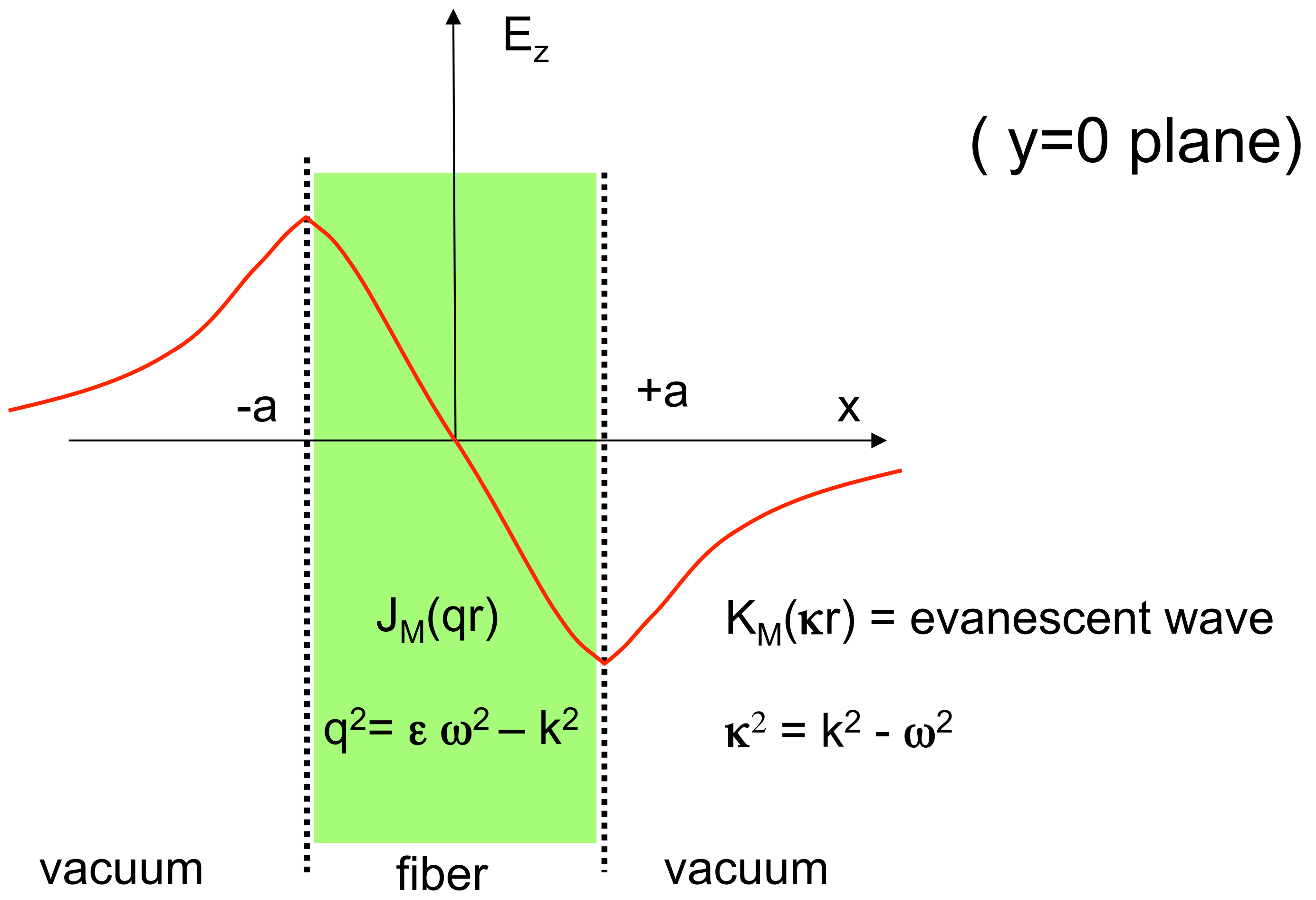
mode type = { M, n_r, "TM" } or { M, n_r, "TE" }

J_z radial number "*Transverse Magnetic*"

Lowest mode is { M=±1, n_r=1, "TM" } called HE_{11}

Another mode is {|M=0, n_r=1, "TE" } called TM_{01}

Example of radial profile of a mode : E_z of the lowest mode, HE_{11}



The dispersion relation

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

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

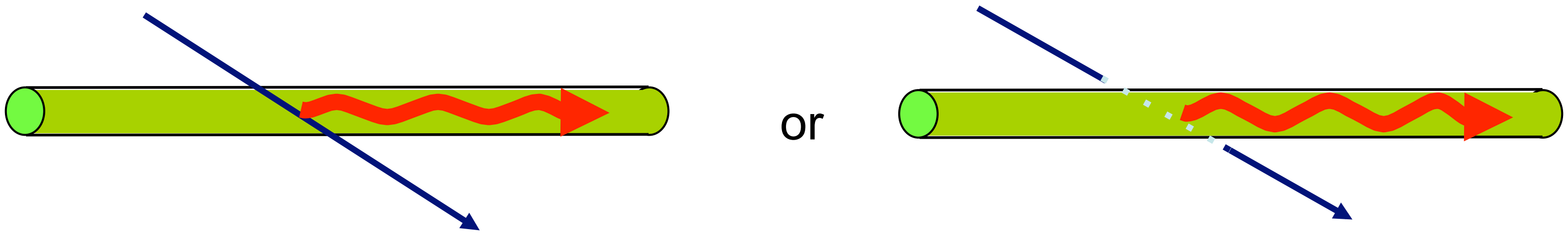
$$=M^2\left(\frac{1}{(qa)^2}+\frac{1}{(\kappa a)^2}\right)\cdot\left(\frac{\varepsilon(r)}{(qa)^2}+\frac{1}{(\kappa a)^2}\right)$$

$$\Downarrow$$

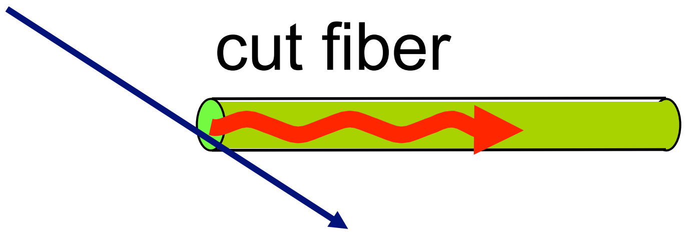
$$\omega=\omega_m(p)\quad\Leftrightarrow\quad p=p_m(\omega)$$

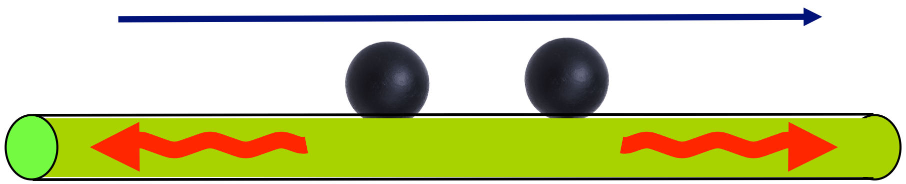
2 types of "***P**article **I**nduced **G**uided **L**ight*"

- Type-I : the fiber is translation invariant



- Type-II : translation invariance is broken. Two examples :

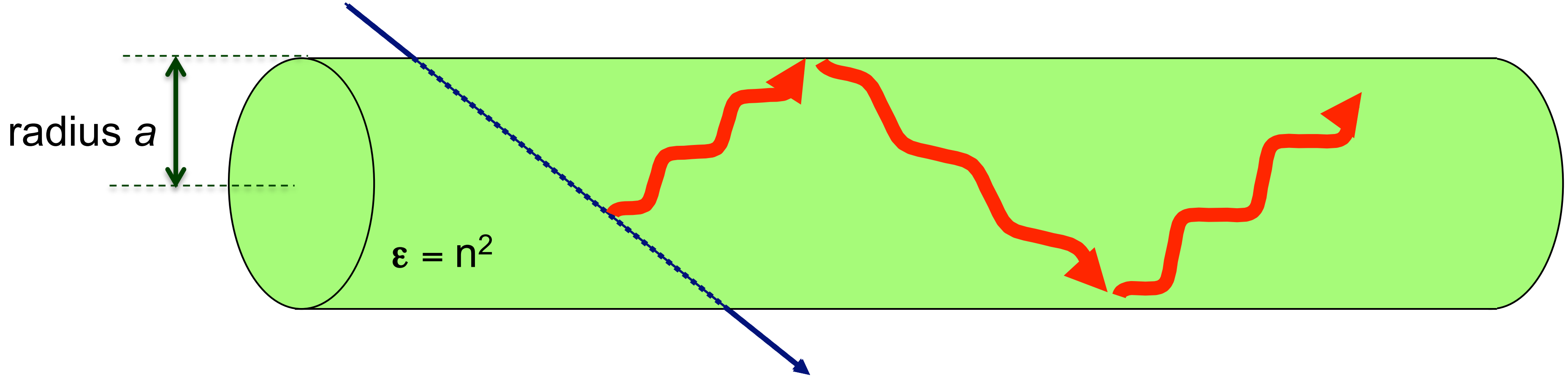




plasmons are formed
in the metallic balls

Comparison with *DIRC* Cherenkov detector

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



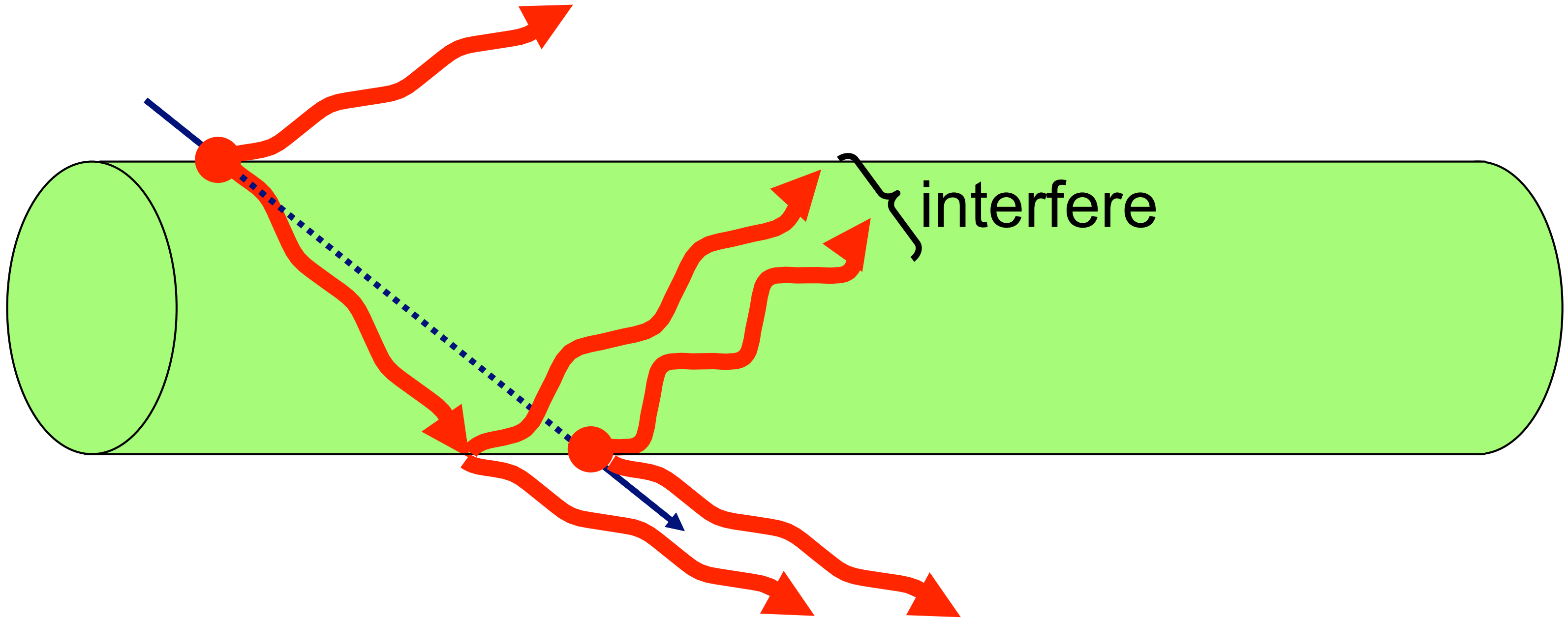
DIRC - *thick* guide : *a* ~1 mm >> λ → many modes.

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

PIGL - *thin* guide : *a* ~ λ → one or a few modes

- few photons per electron. But sufficient for beam diagnostics
- No velocity threshold

PIGL as *channeled transition radiation*



- Caution : usual T.R. formula is not valid for such mall radius of curvature ($a \sim \lambda$)
- T.R. does not explain PIGL in the "*passing by*" case

THEORY
Photon spectrum in type-I PIGL

Produced spectrum in the mode *m* :

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

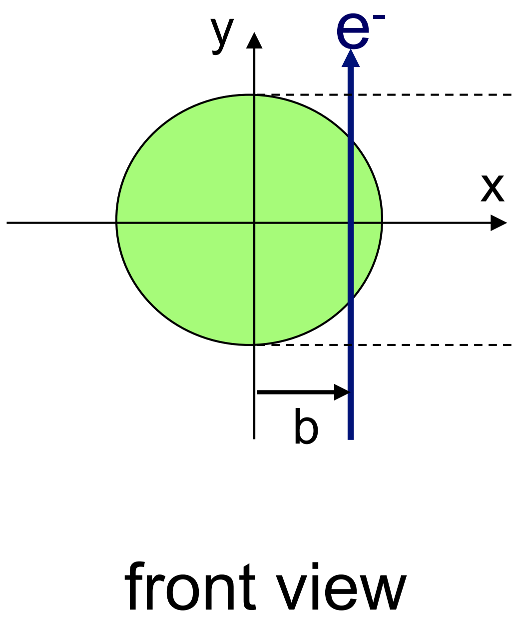
"work" of the electric force

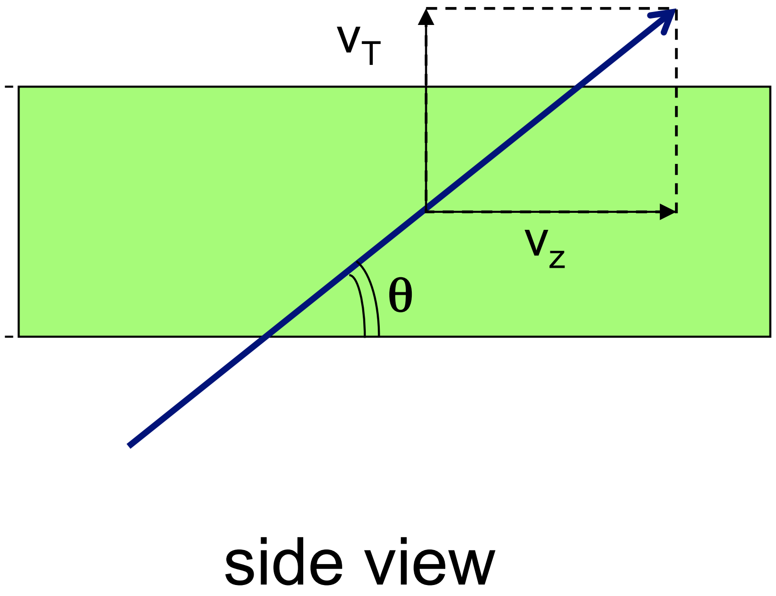
$\Phi_{\{m,\omega\}}$ = energy flux of the normalized mode

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

Poynting vector

Geometrical parameters



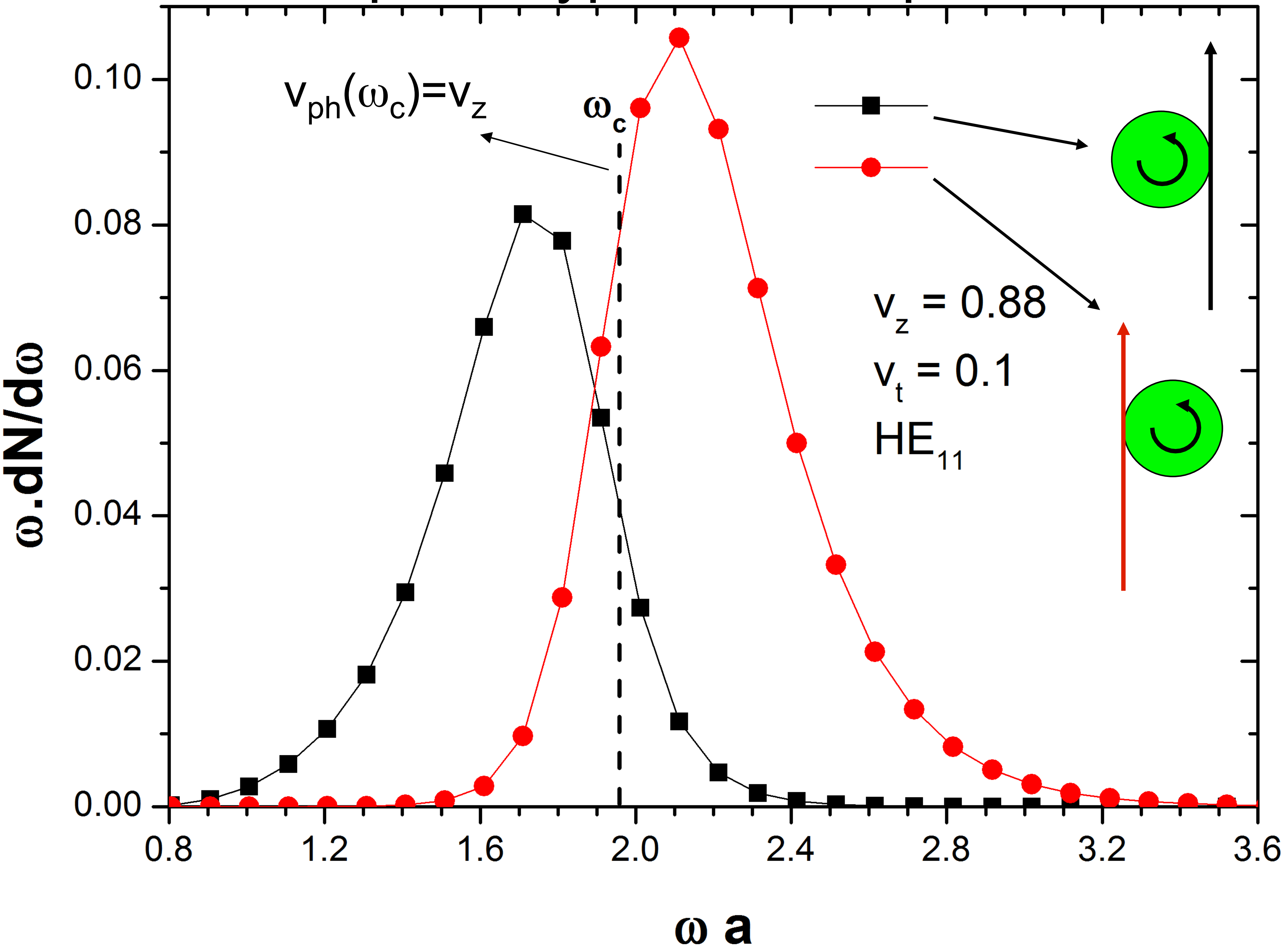


b : impact parameter

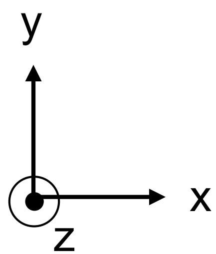
$v = (0, v_T, v_z)$: electron velocity

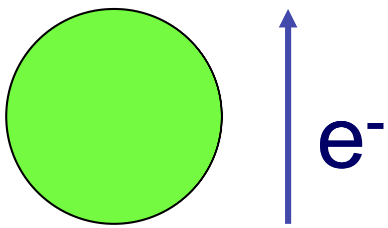
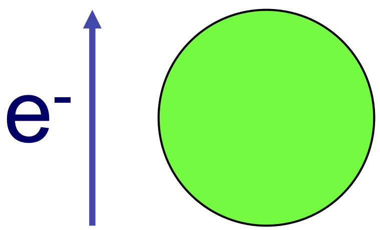
θ : crossing angle. $\tan\theta = v_T / v_z$

Example of type-I PIGL spectrum

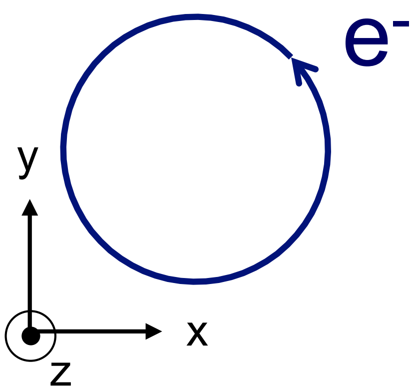


Correlation between electron *side* and photon *helicity*

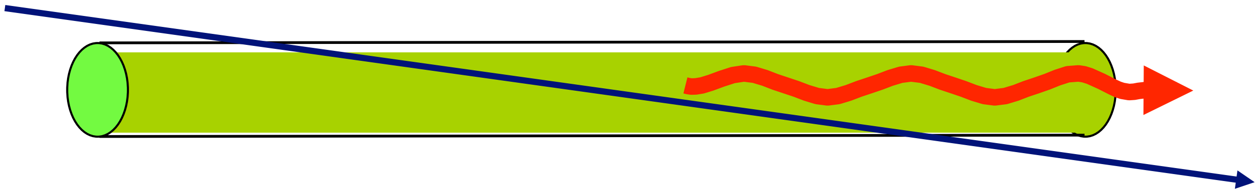


	small ω	large ω
	$v_{ph} > v_e$	$v_{ph} < v_e$
side *b>0* 	favored M = +1	favored M = -1
side *b<0* 	favored M = -1	favored M = +1

Correlation analogue pour un undulateur hélicoïdal

	$v_{z\ photon} > v_{z\ electron}$	$v_{z\ photon} < v_{z\ electron}$
	⇕	⇕
	$\theta < 1/\gamma$, grand ω	$\theta > 1/\gamma$, petit ω
	favorise M = +1	favorise M = -1

Type-I PIGL - Case of small crossing angle θ



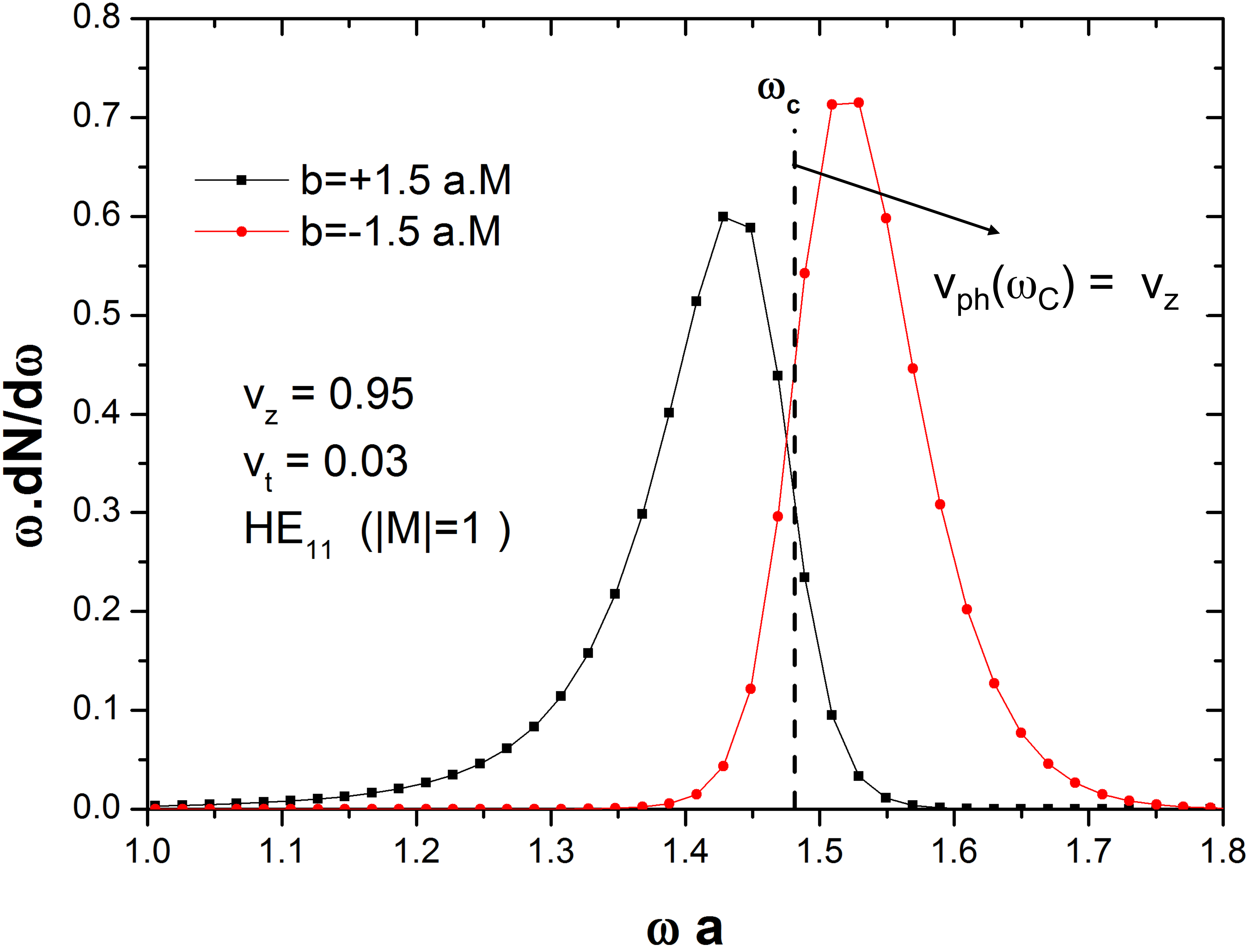
Nearly *monochromatic* at frequency ω_C such that the phase velocity $v_{ph} \equiv \omega/p$ of the wave is equal to the longitudinal velocity of the electron :

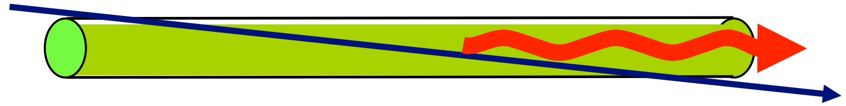
$$v_{ph}(\omega_C) = v_z$$

$\rightarrow$ the electron "surfes" on the wave (call it "Cherenkov peak")

Case of *parallel* trajectory : Bogdankevich & Bolotovskii (1957), Zhevago & Glebov (1990, 1993)

Example of Cherenkov peak





Small θ : integrated spectrum.

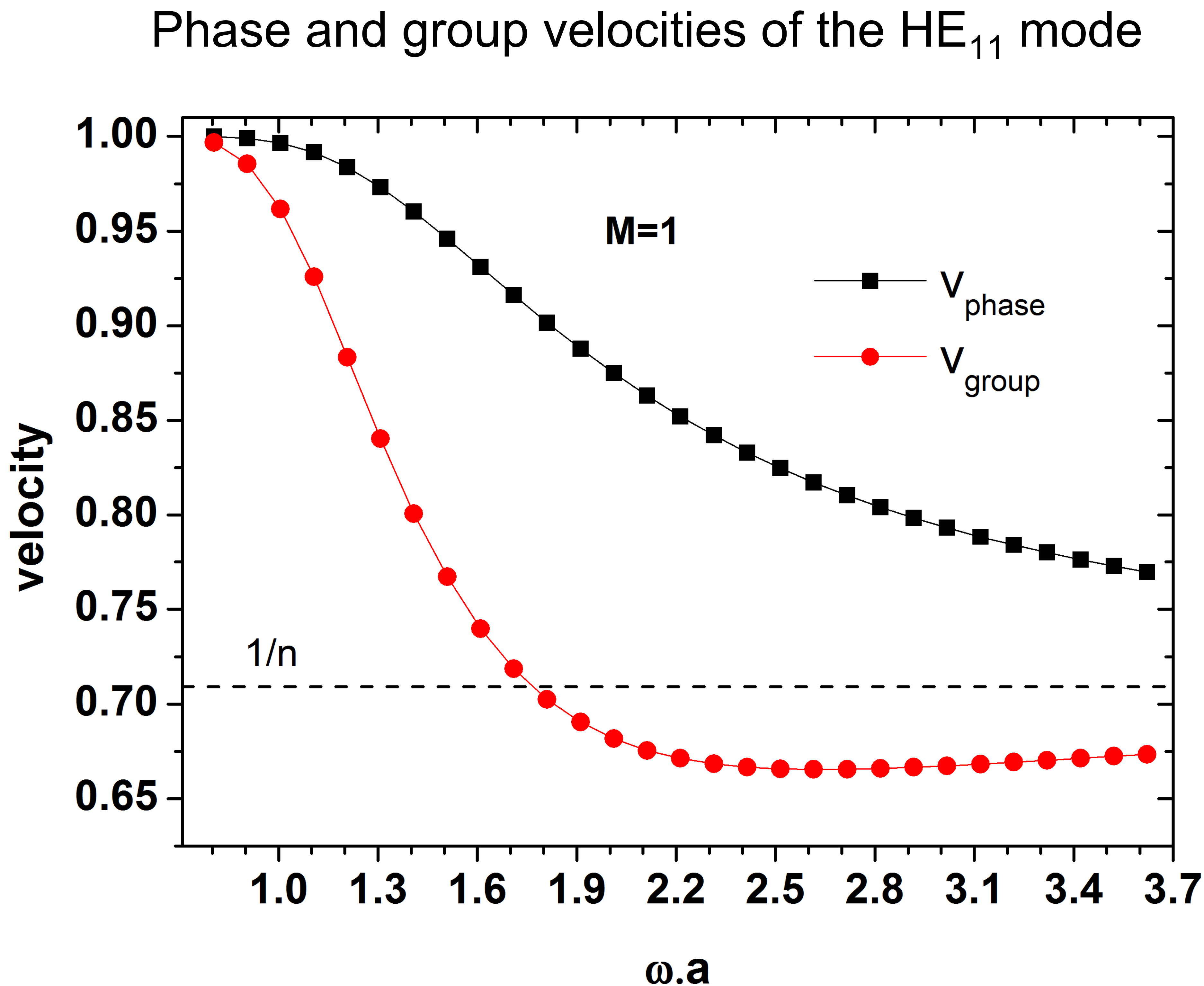
Number of produced photons

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

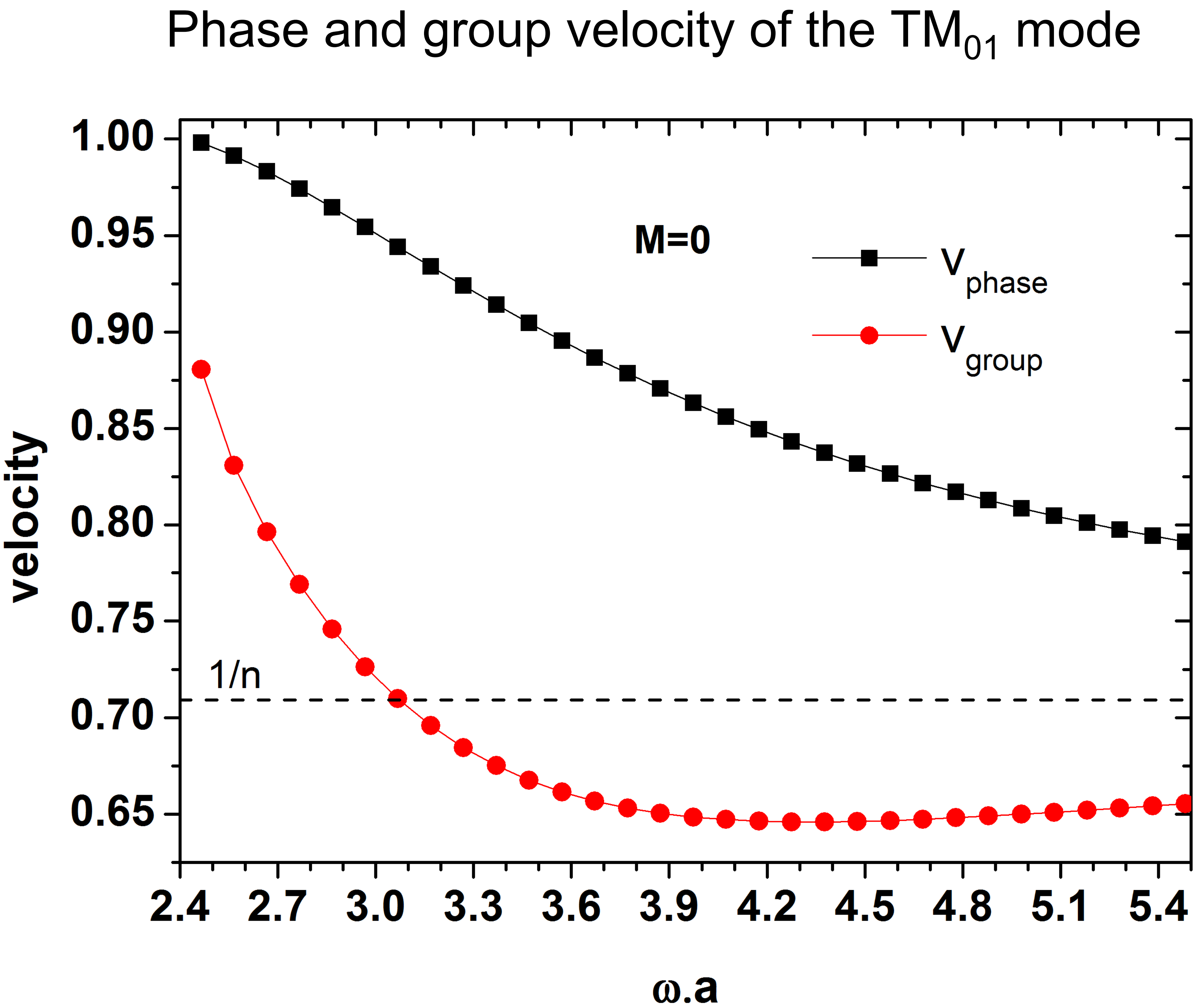
(with $\omega = \omega_C$)

v_g: group velocity — v_{ph}: phase velocity

- N grows like θ^{-1} ; it can reach values >> 1

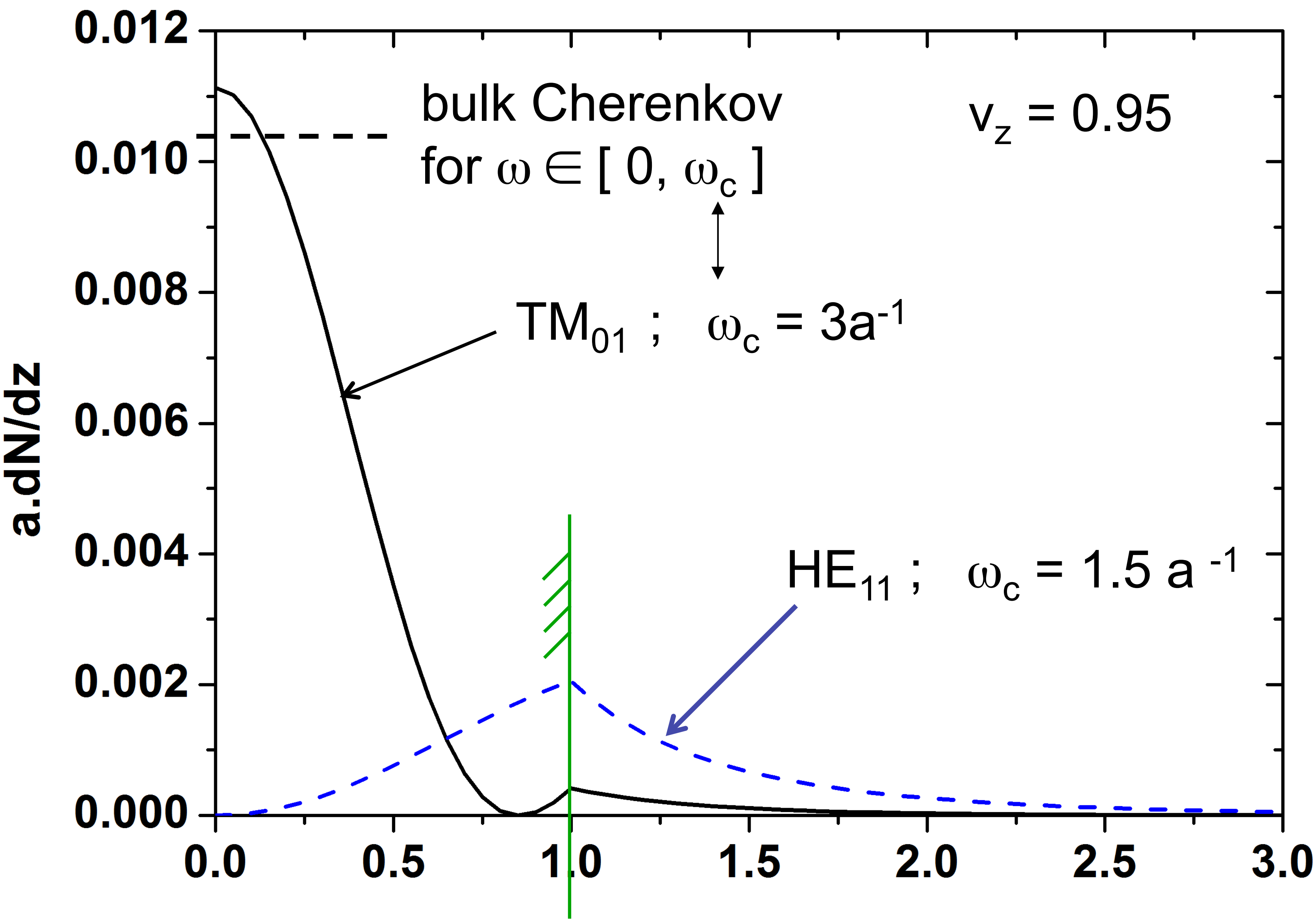


Phase and group velocities of the HE11 mode
M=1
V phase
V group
1/n
velocity
ω.a
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
1.0
1.3
1.6
1.9
2.2
2.5
2.8
3.1
3.4
3.7



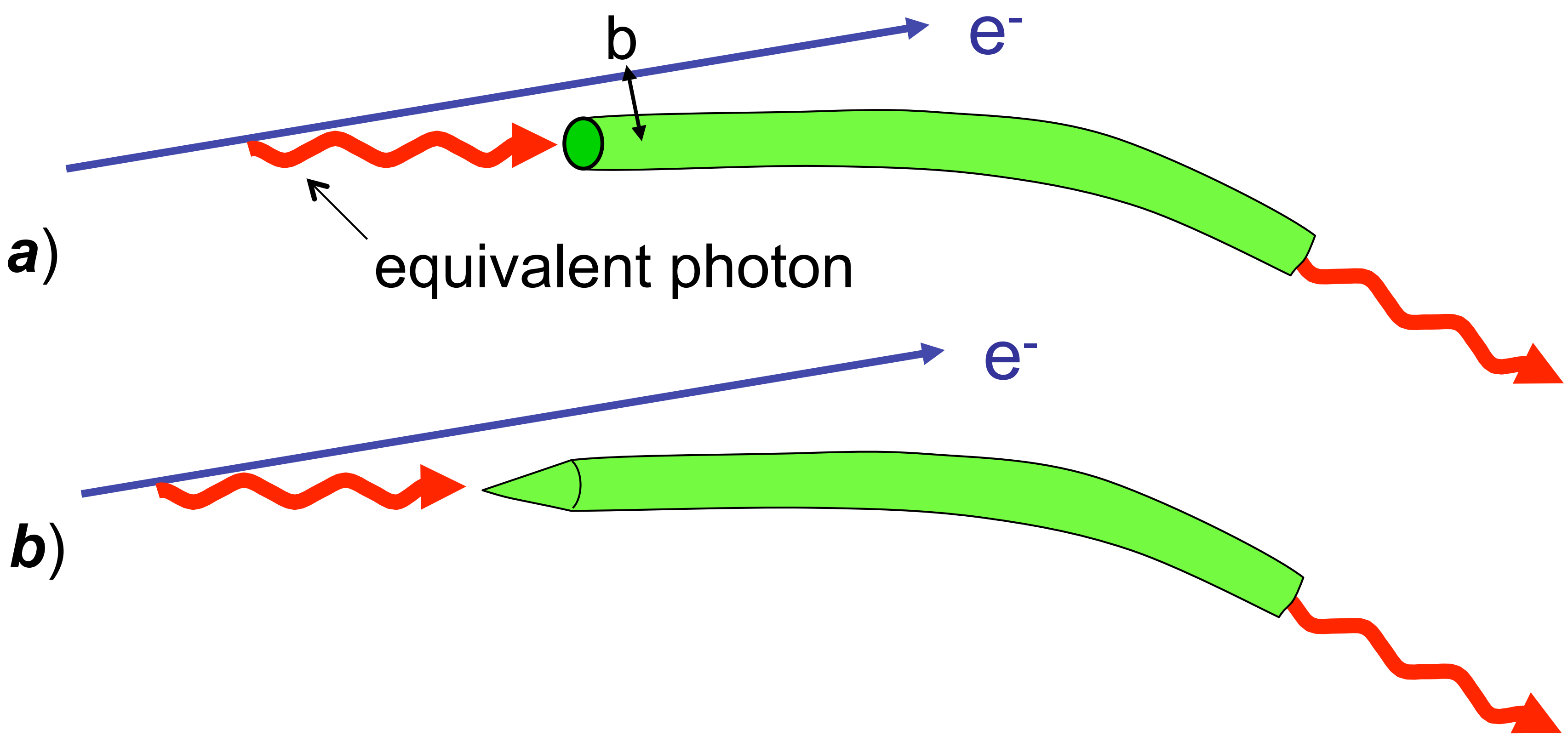
Phase and group velocity of the TM01 mode
M=0
V phase
V group
1/n
velocity
ω.a
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
2.4
2.7
3.0
3.3
3.6
3.9
4.2
4.5
4.8
5.1
5.4

Small θ : Photon yield per unit of length



r = distance from axis

Type-II PIGL with a cut fiber

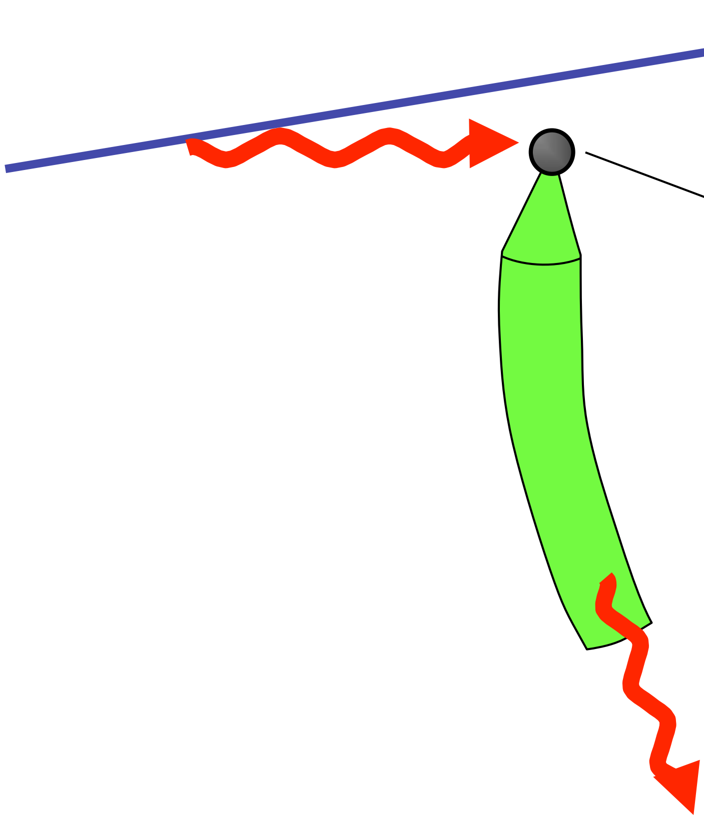


• Scheme ***a***), for a relativistic electron :

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

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

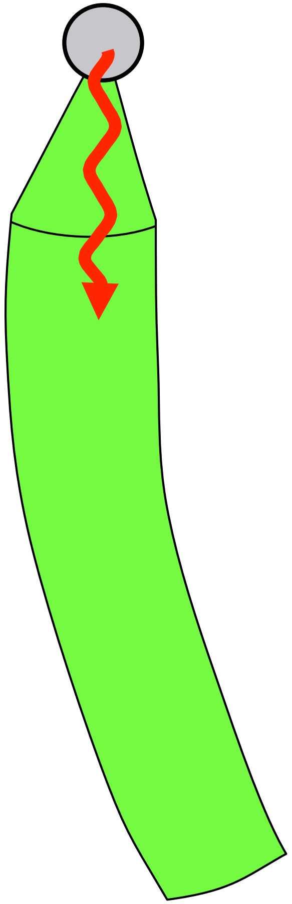
Type-II PIGL through a metallic ball



e^-

metallic ball of radius R

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

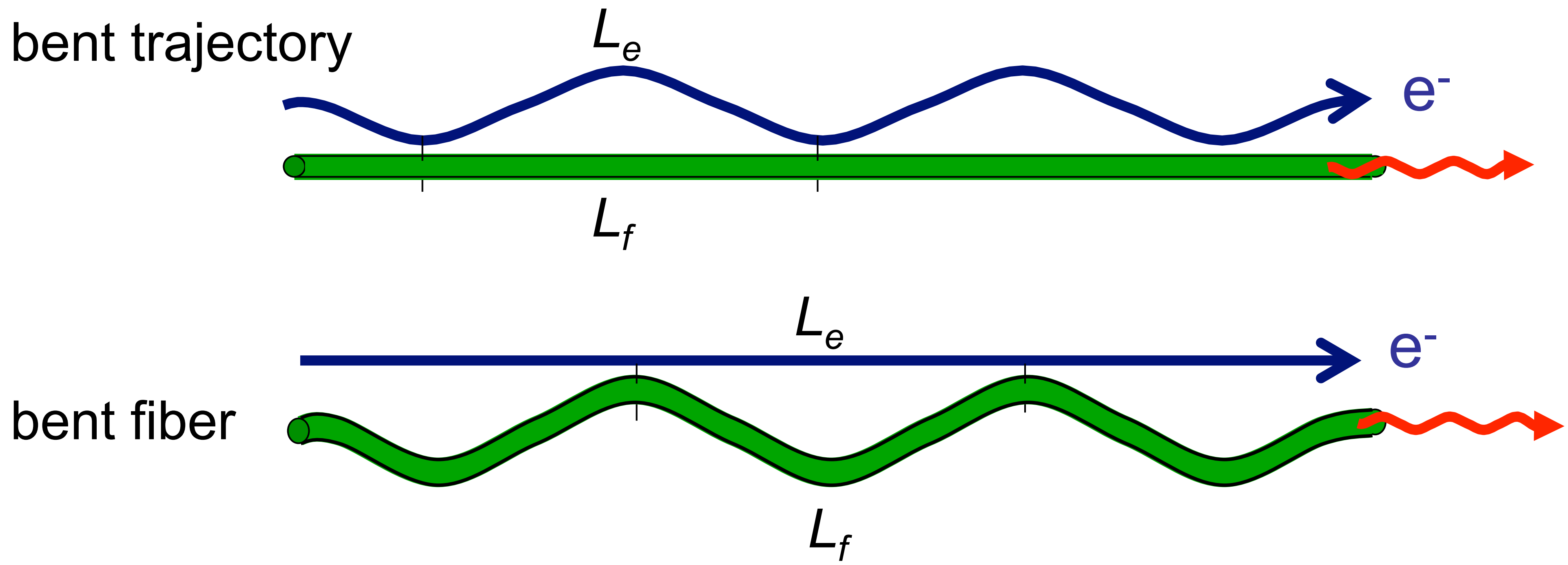


Number of photons :

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

Prototype
en granit

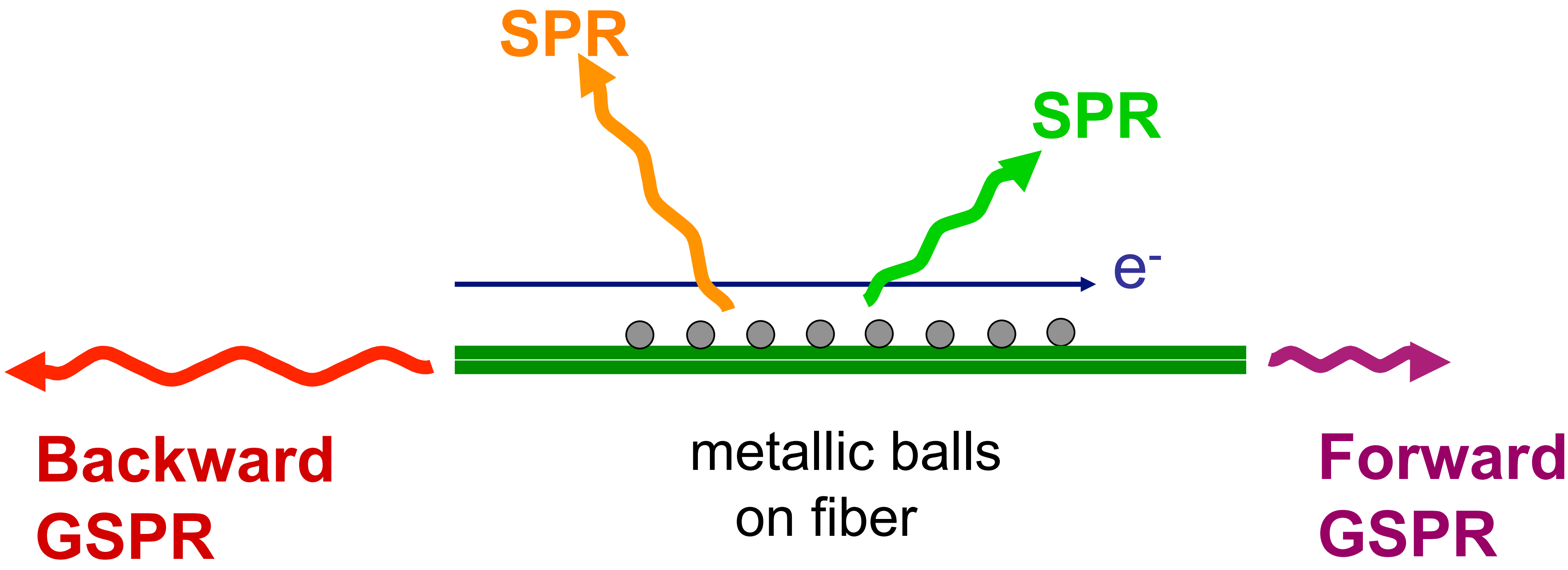
Interference effects for type-I PIGL : the *"fiber undulator"*



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

$\rightarrow$ discrete spectrum

Interference effects in type-II : the *Guided Smith-Purcell Radiation*



Resonance condition :

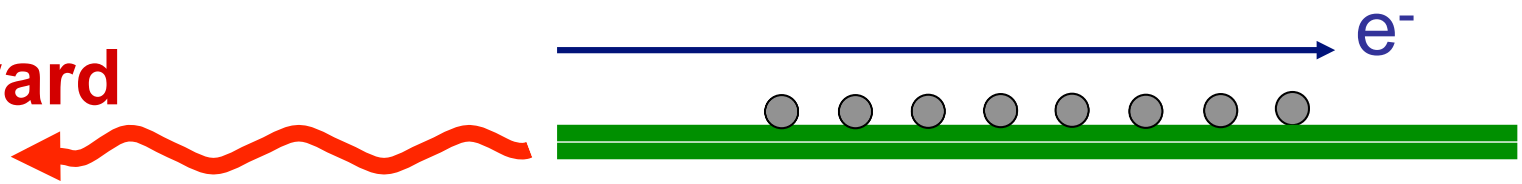
$(1/v_{ph} \pm 1/v)\ \omega L = 2\pi \times$ integer (L=ball spacing)

Specially intense GSPR if the plasmon frequency matches this resonance condition.

Guided Smith-Purcell Radiation (continued)

If L . $\omega_{plasmon}$ is small enough :

backward GSPR



no external SPR, no forward GSPR → more efficiency in **backward** GSPR

However GSPR is reduced by shadowing* : each ball **screens** the electron field for the next ball. A *dynamical* theory like in Garcia et al** is needed.

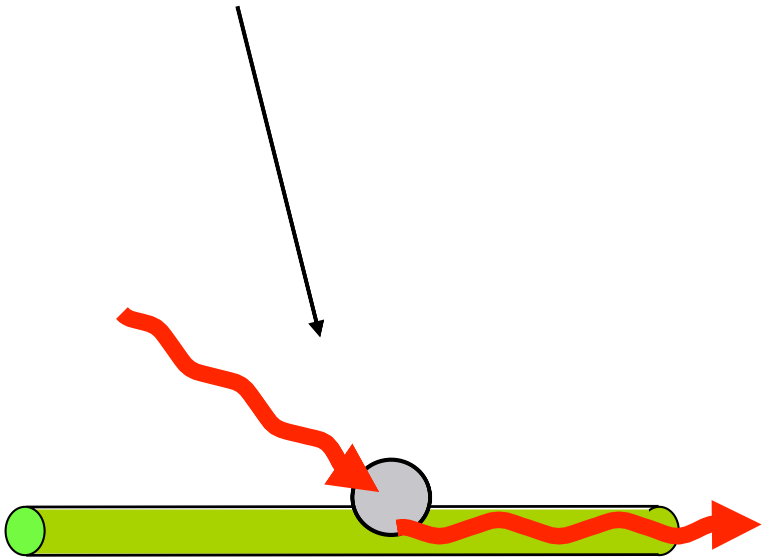
[*] shadowing was checked in Diffraction Radiation [Naumenko et al, J. Phys. Conf. Series 236, (2010)]
[**] Garcia de Abajo, PRL 82 (1999) 2776 (Smith-Purcell on balls)

Background of upstream radiation

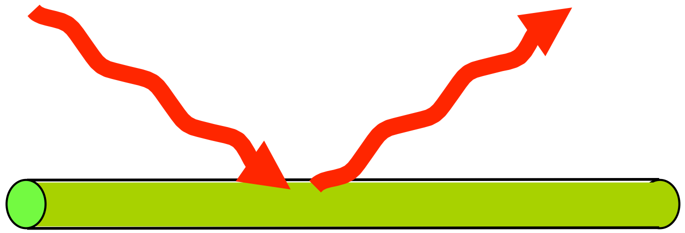
A PIGL target of **type-II** (cut fiber or metallic balls) can capture real photons emitted upstream, e.g. by synchrotron radiation.

= **background** (like in OTR or ODR).

In the case of **type-I**, upstream photons are not captured by the fiber, but only *scattered*.



type-II



type-I

Conclusion

- Particle-Induced Guided Light may be used for beam diagnostics, more specially for **micro-beams**

⊕ flexibility of fiber optics

⊕ little effect on the beam emittance if a ~ λ

- PIGL can measure the transverse beam profile. Type-I can even tell on which side a microbeams passes by.

- At small crossing angle PIGL grows like $1/\theta$ and becomes monochromatic. The peak frequency measures the beam velocity.

Conclusion (continued)

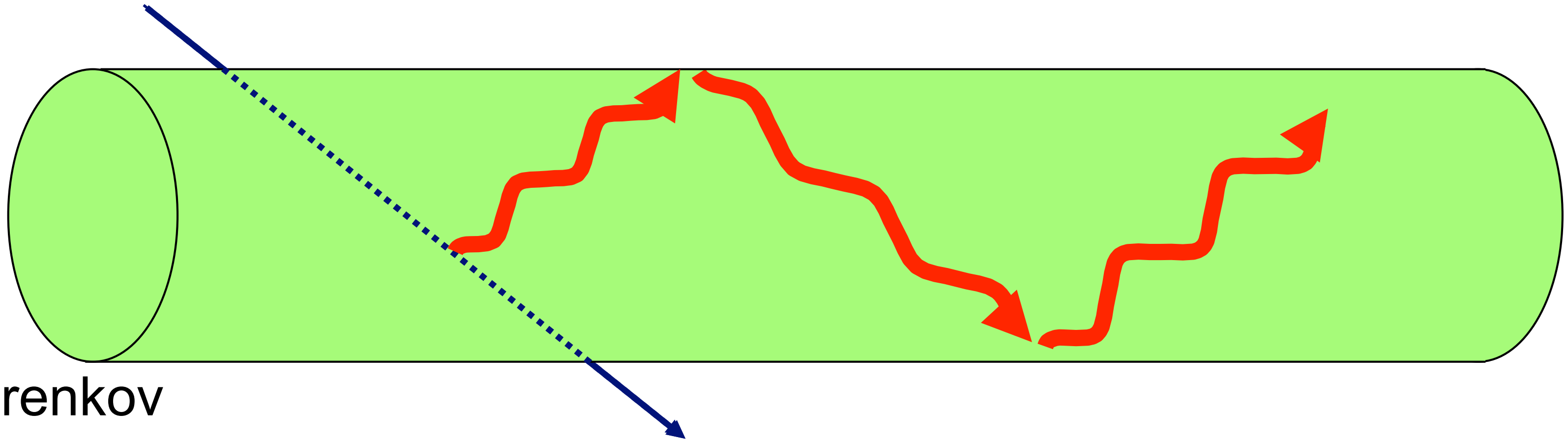
-Thanks to the one-mode field, interferences can take place and build resonance peaks.

- For **type-I** there is no background from upstream radiation (advantage over OTR and ODR)

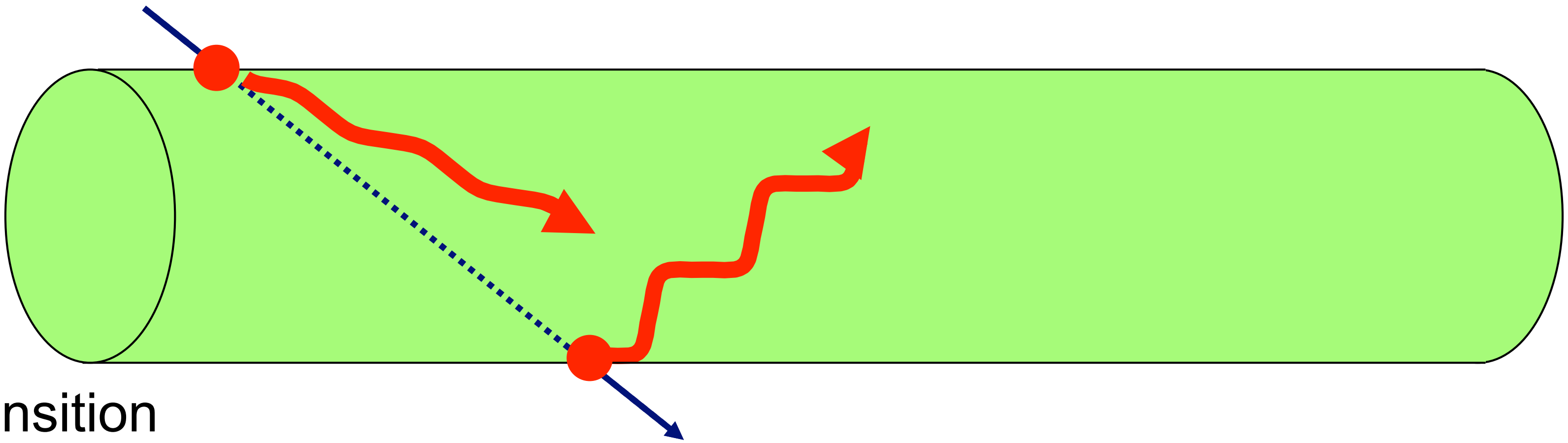
Work to be done and open questions :

- Calculate - or measure - the probability *K* that a fiber takes the plasmon off a metallic ball.
- Thermal problem: what beam flux a fiber can sustain ?
- Make experiments

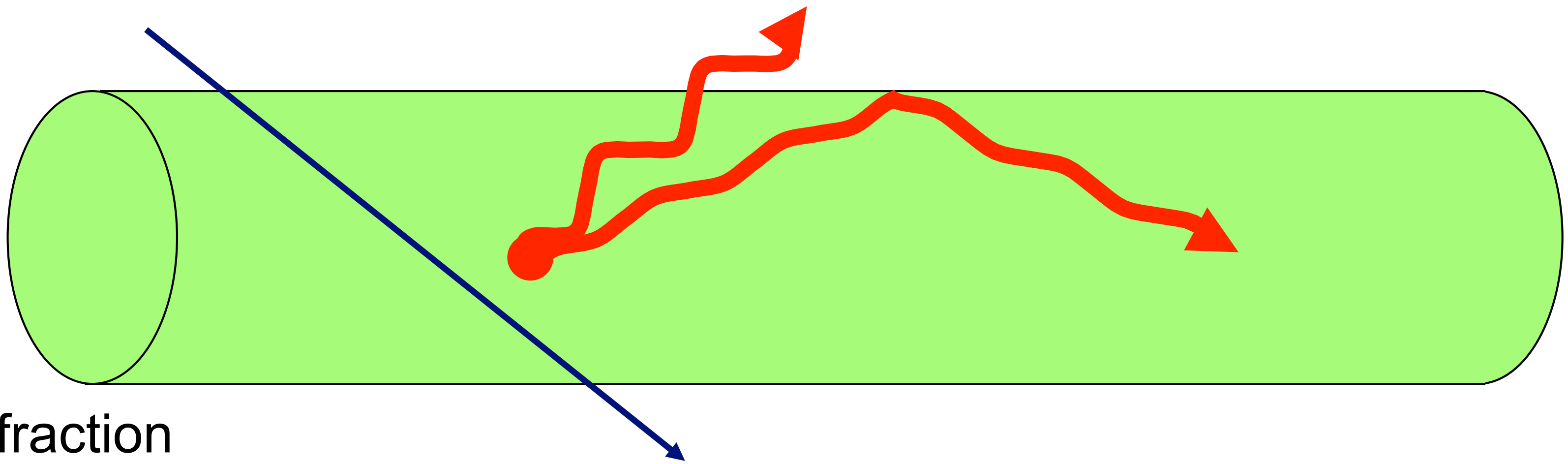
Merci pour votre attention !



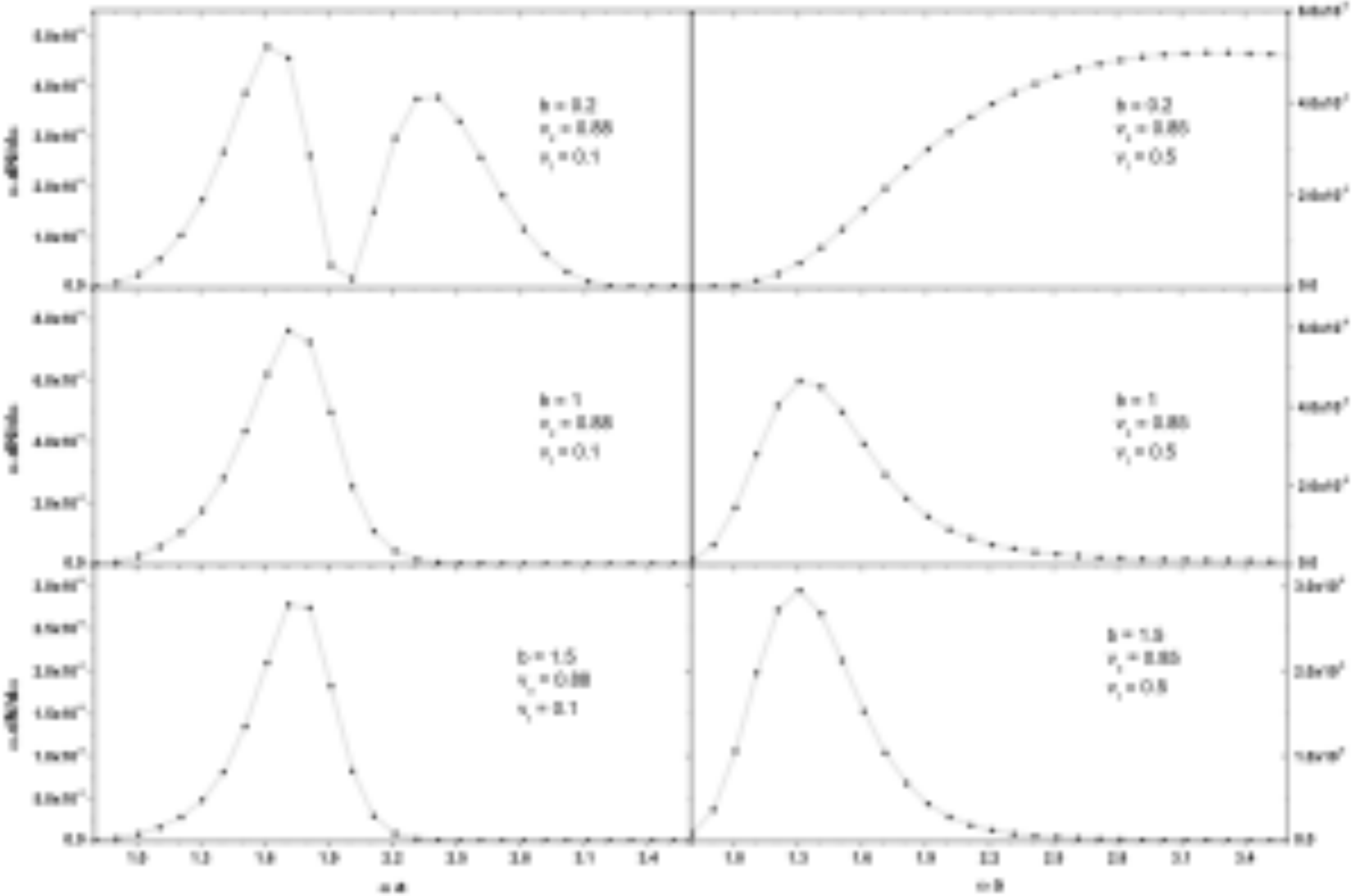
Cherenkov



Transition



Diffraction



b = 0.2
b = 1
b = 1.5