Experimental activity on radiation induced by charged particles in optical fibers

Xavier Artru, Iryna Chaikovska, Robert Chehab,
Nicolas Delerue

21 January 2015

Motivation

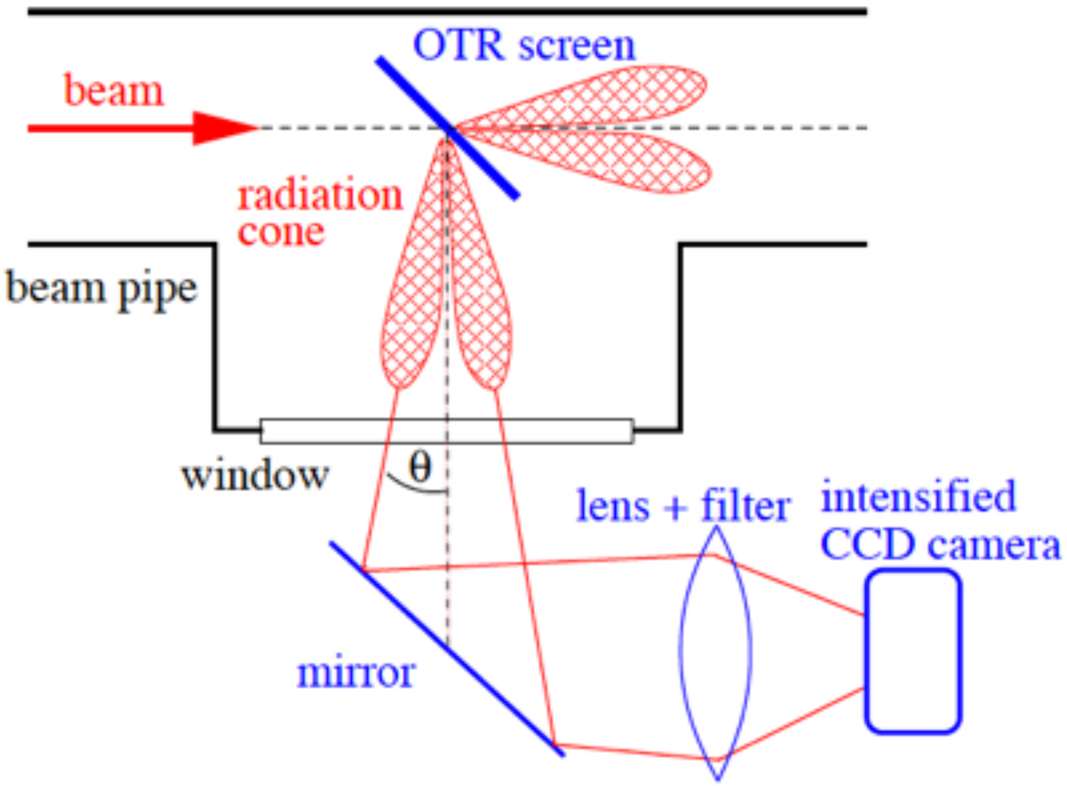
Particle Induced Guided Light (PIGL) is one type of the **polarization radiation.**
Polarization radiation: field of the moving charge induces currents changing in time on the surface or the volume of the target (time-dependent polarization at the target boundary) and it is these currents that eventually give rise to the radiation.

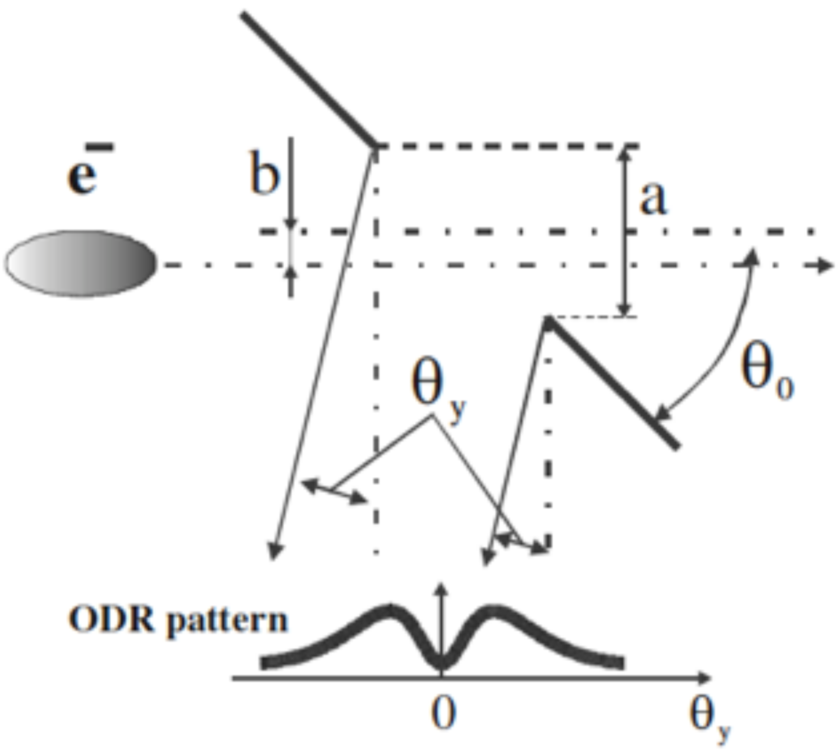
- New methods of diagnostics (especially for the small and intense beams). Non-invasive.
- There are already several papers about the generation and application of the polarization radiation (e.g. Transition Radiation, Diffraction Radiation, Smith-Purcell, Cherenkov radiation…). This is a very interesting and useful field as far as beam diagnostics and particle detectors are concerned.
- Theoretical support. The PIGL theory is developed by our colleague X. Artru (IPNL). Close collaboration.
- PHIL: we can perform the experiments using the PHIL beam.

Introduction

What happens if the charge particle passes from one medium into another (media with different dielectric constants) or moves in the vicinity of a medium?

☞ Production of Transition, Diffraction, Cherenkov, Smith-Purcell, Parametric X- ray radiation, etc..





$h = \gamma\lambda/2\pi$ - DR impact parameter. It measures the radial extension of the EM field of the particle (natural unit of measure for this phenomena).

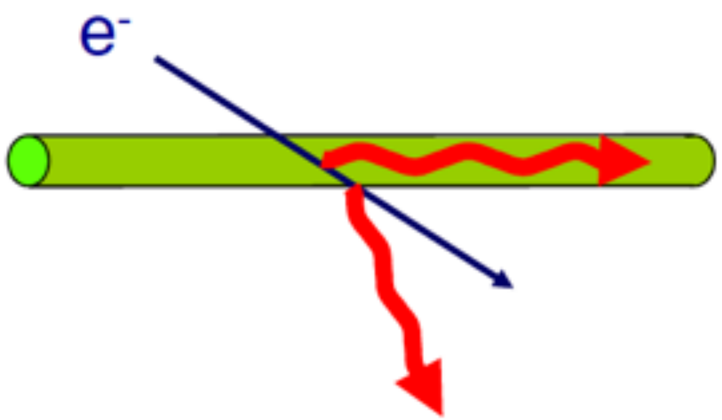
a $>> \gamma\lambda/2\pi$ - aperture is much larger than the extent of the particle EM field => **No radiation is produced.**

a $<< \gamma\lambda/2\pi$ - **Transition radiation.**

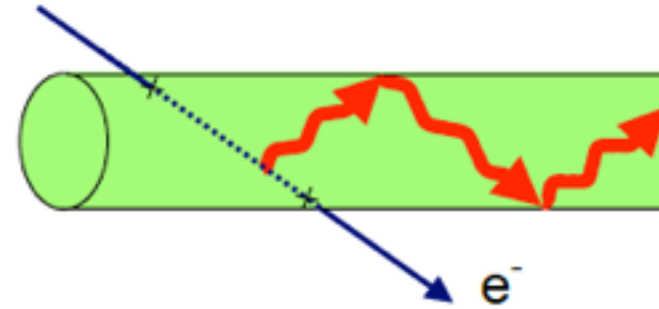
a $\leq$ $\gamma\lambda/2\pi$ - **Diffraction radiation.**

Particle Induced Guided Light (PIGL)

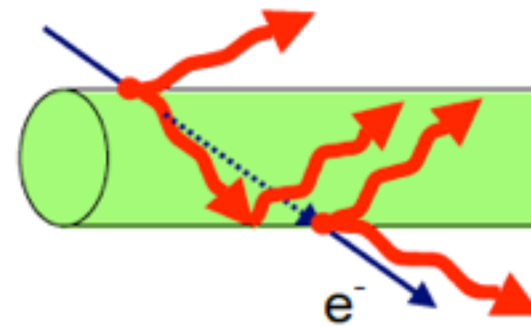
If the electron is passing though or by the dielectric waveguide (optical fiber) where $\lambda << R$: Transition Radiation (PIGL + outside radiation) or Diffraction Radiation This regime corresponds to usual quartz fiber operation.



Diffraction Radiation



Cherenkov Radiation



Transition Radiation

☞ 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.

☞ It is called the Particle Induced Guided Light (PIGL).

If λ is comparable to the effective size of the medium (R) the TR description is not appropriate => X. Artru theory.

Hereafter we will consider the “thin” fiber for which $\lambda \sim R$.

PIGL - Cherenkov difference

Cherenkov Radiation (used for DIRC detectors)

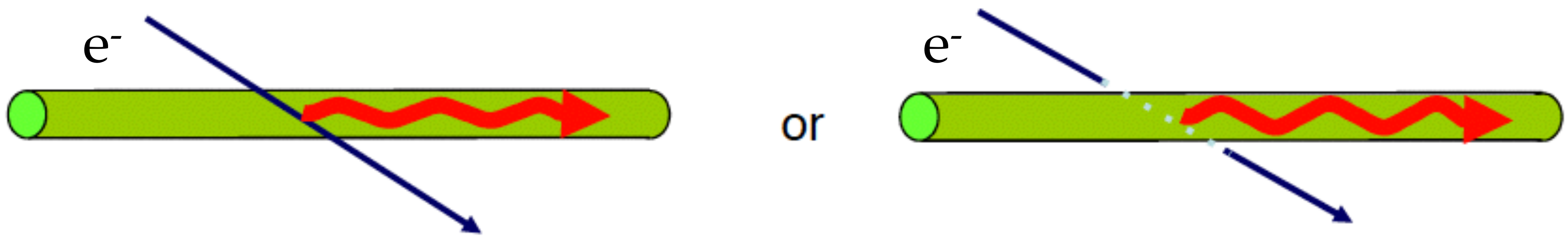
- Thick guide: R ~1 cm >> λ
- Radiation is decomposed in many modes
- Many photons per electron (individual particle detection is possible)
- Velocity threshold, $v > 1/n$.

PIGL

- Thin guide: R ~ λ
- Radiation is decomposed in one or a few modes
- Less than 1 photon per electron (beam diagnostics is envisaged)
- No velocity threshold.

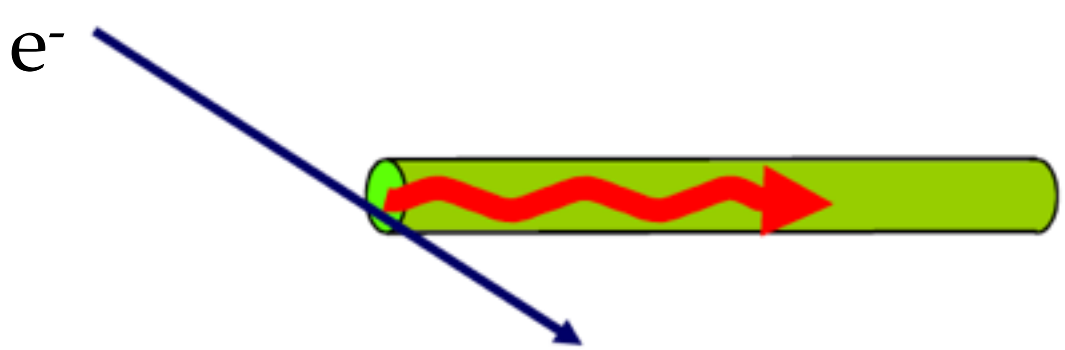
Types of the PIGL

- **Type-I PIGL**



Electron beam passes close or inside the fiber where it is assumed to be translationally symmetric (far from the extremity).

- **Type-II PIGL**



Electron beam passes close to the fiber termination.

Electron beam passes close to the added structures (metallic balls, rings, etc.). In this case, radiation is first induced in the metallic balls in the form of plasmons.

Theoretical background (PIGL - I)

- We consider a narrow and non-scintillating fiber without clad (R ~ λ => one or a few number of modes).
- Guided radiation is decomposed in modes (the lowest is HE_{11}, then TM and TE).

Produced spectrum in the mode *m* by a particle charge *Ze* and trajectory **X**(*t*) :

$$\frac{\omega d\mathcal{N}_m}{d\omega} = \frac{1}{2\pi |P_m(\omega)|} \left| Ze \int_{\text{trajectory}} d\mathbf{X} \cdot \vec{\mathcal{E}}^*_{\{m,\omega\}}(\mathbf{X}, t) \right|^2$$

$$P_m(\omega) = 2 \int d^2\mathbf{r} \, \mathrm{Re}\left\{ \mathbf{E}^*_{\{m,\omega\}}(\mathbf{r}) \times \mathbf{B}_{\{m,\omega\}}(\mathbf{r}) \right\}_z$$ - energy flow of the proper fields of the mode.

Small angle limit:

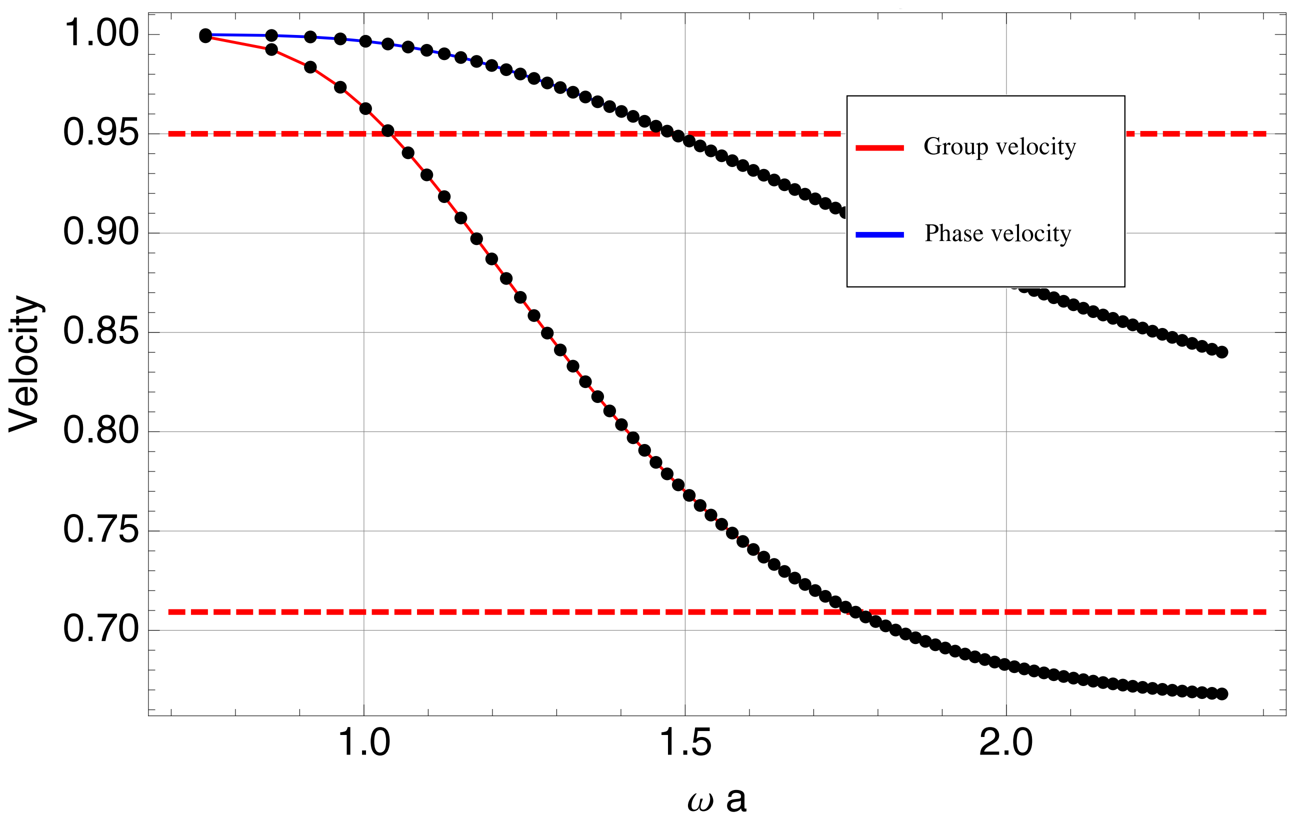
Radiation becomes nearly *monochromatic*. At the peak frequency w_c, the phase velocity $v_{ph} \equiv w/p$ of the wave is equal to the longitudinal velocity of the electron v_z.

$$v_{\text{ph}}(m, \omega_C) = v_z(\text{particle})$$

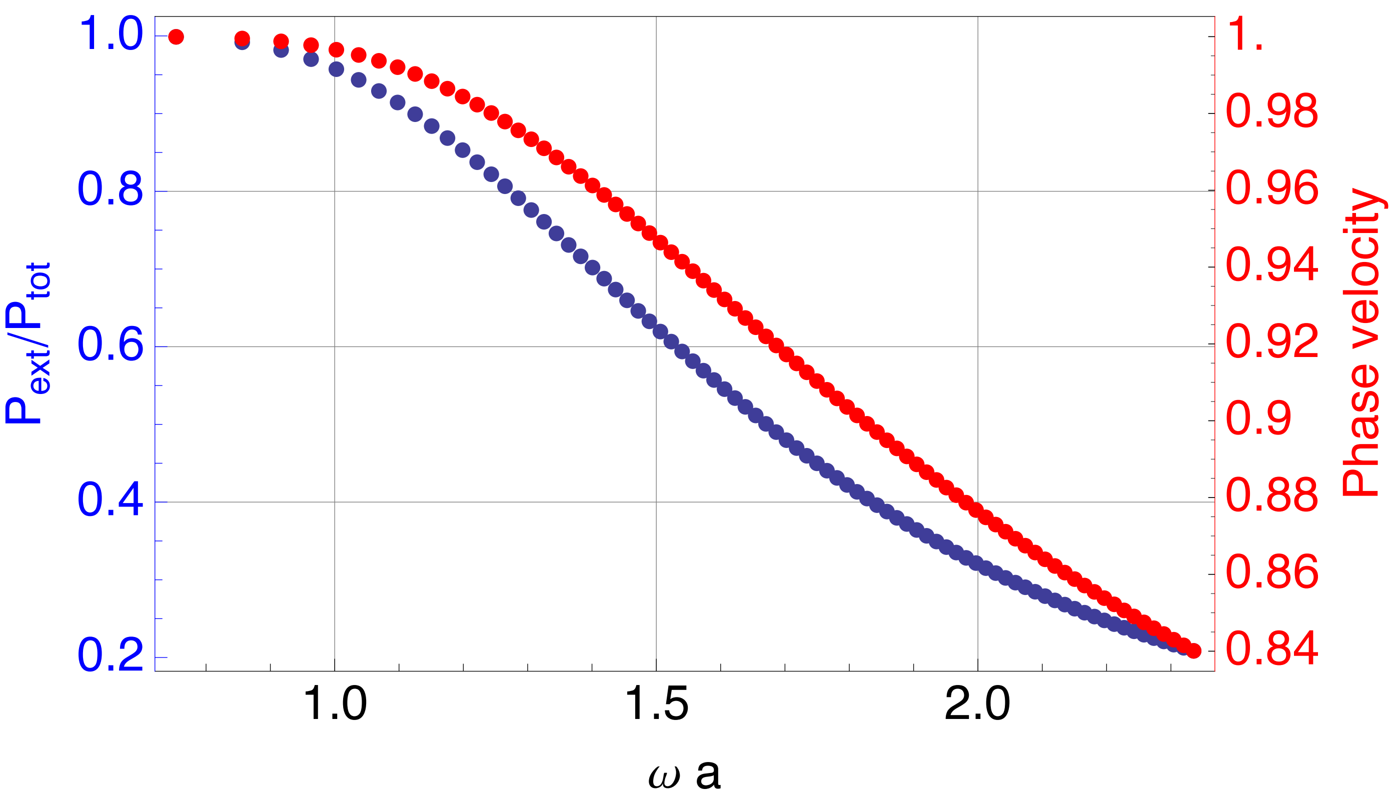
$$\mathcal{N}_m \simeq \frac{4\pi Z^2 \alpha}{\omega_C P_m(\omega_C)} \left| 1/v_g(\omega_C) - 1/v_z \right|^{-1} \times \int_{\text{traj.}} dz(t) \left| E_{\{m,\omega_C\},z}(\mathbf{r}(t)) \right|^2.$$

Theoretical background (PIGL - I)

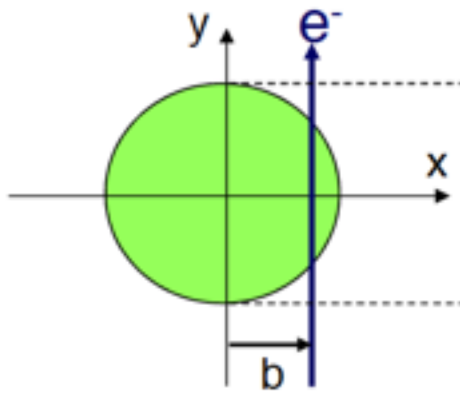
Phase and group velocity of the HE_{11} mode.



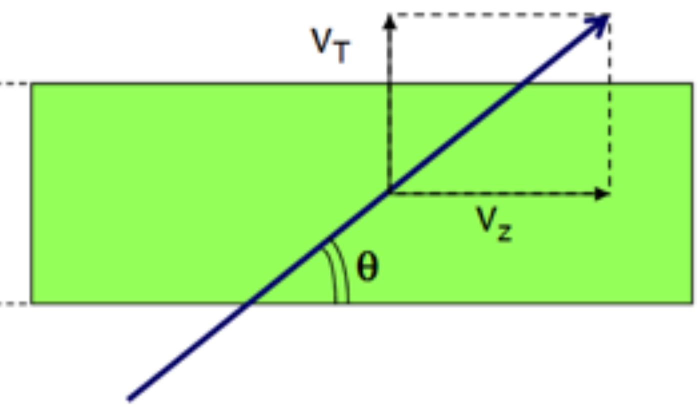
External fraction of power for the HE_{11} mode.



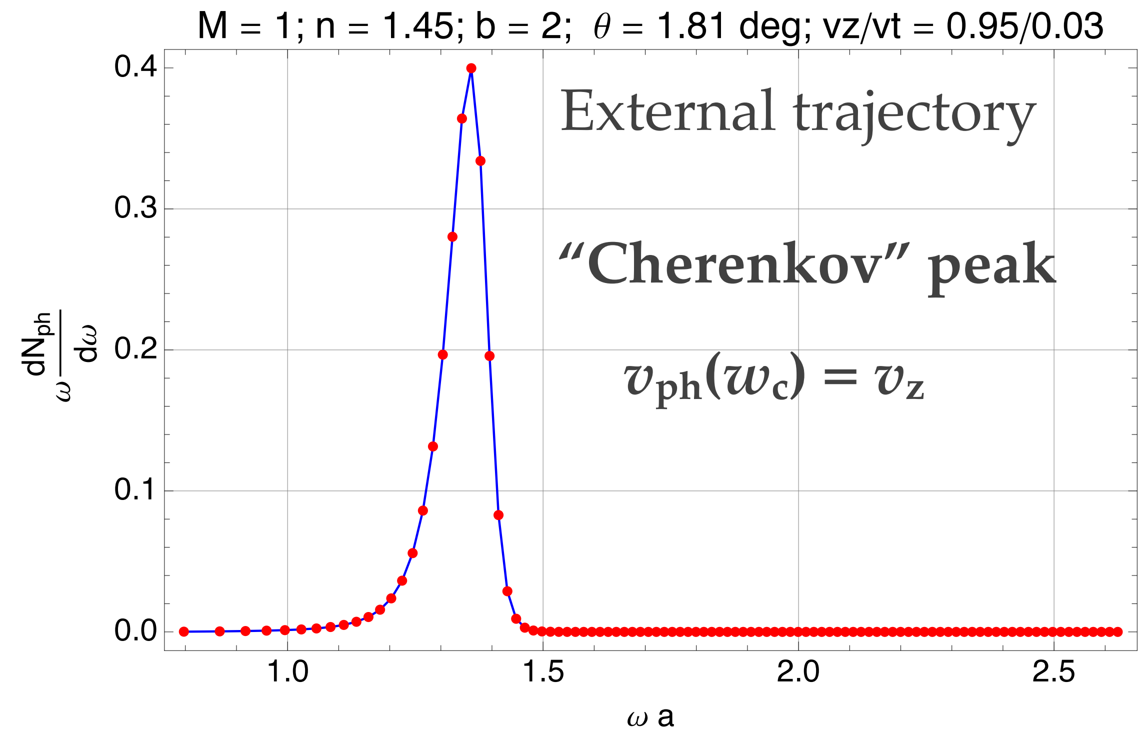
Calculated spectrum (HE_{11} mode)

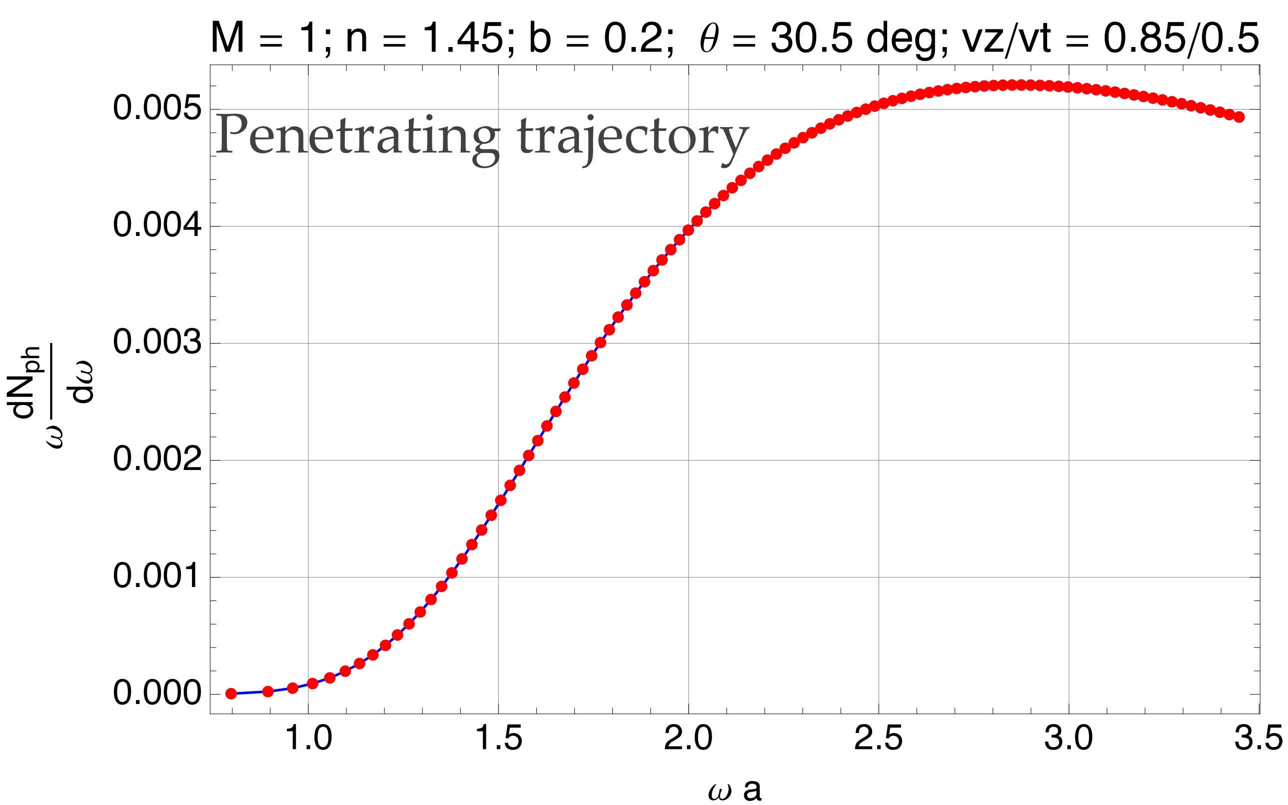


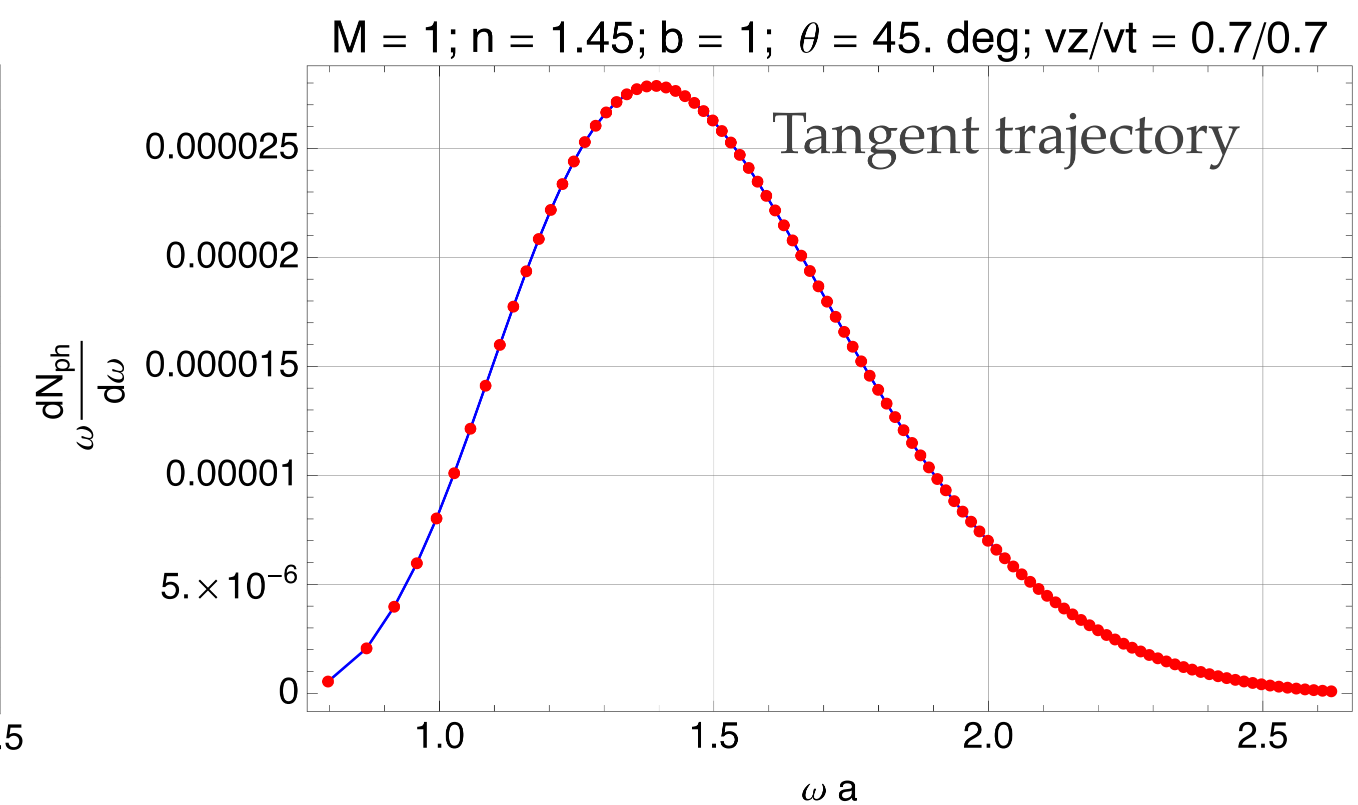
Impact parameter



Crossing angle



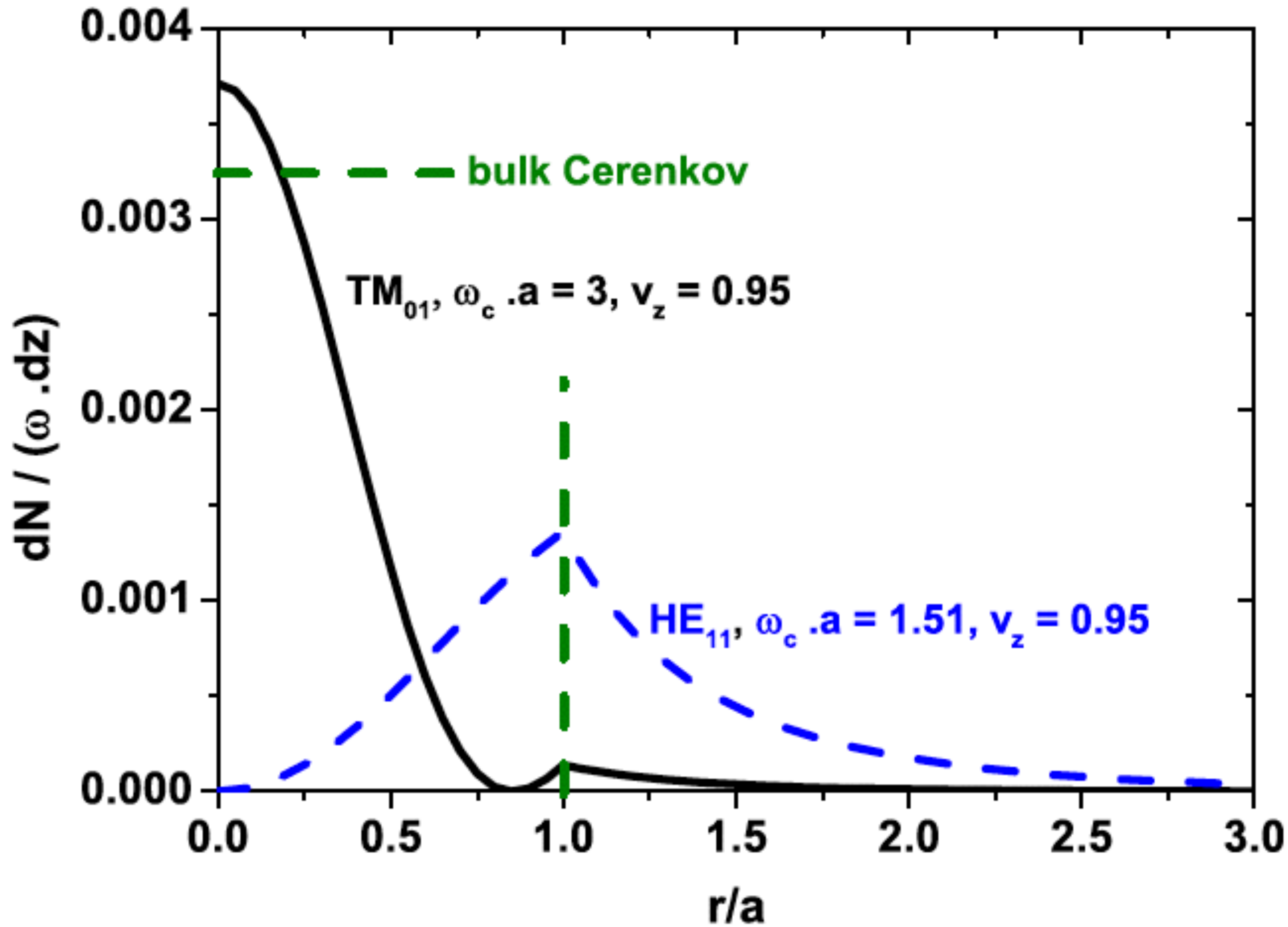




Calculated number of photons (small θ)

Small crossing angles approximation

$$dN/d\omega/dz\,(\text{bulk Cherenkov}) = Z^2\,\alpha\left[1-(nv)^{-2}\right]$$



PIGL possible applications

- PIGL is quite promising for the beam diagnostics.
- Fiber and its flexibility offers the more simple signal transport (no need to employ the mirrors, lenses, etc.).
- Advantage of dealing with "optical" signal over the electronic one (if the fiber diameter ~ μm).
- The thin dielectric fiber (~ μm) should not, in principle, perturb much the beam.
- No background is generated by real photons coming from the upstream sources (advantage over OTR and ODR).
- There are no well-understood experimental studies done on the PIGL up to now. Only Tomsk group (G. Naumenko, A. Potylitsyn et al.) is working on the radiation induced by the charged particles in the dielectric rods.
- First step to practical applications: investigation of spectral distribution and intensity of the PIGL in the dielectric rod.

PIGL possible applications

Longitudinal beam profile / Bunch length

- Non-invasive beam diagnostics.
- Using coherent mechanism (when $\lambda > 2\pi\,\sigma_z$ the coherent effect occurs inside the bunch) => the longitudinal form factor of the bunch.
- Pulse duration using the streak camera.

Transverse beam profile / beam sizes

- Similar to wire scanner (one should probe the beam with the fiber)
- In principle non-invasive (the fiber R ~ 1 μm)
- The resolution ~ 2 R (a few μm)
- No background unlike the wire scanner case
- Critical points: radiation damages, robustness, mechanics.

☞ Another scheme: fiber is placed at a certain distance from beam => fully non-invasive.

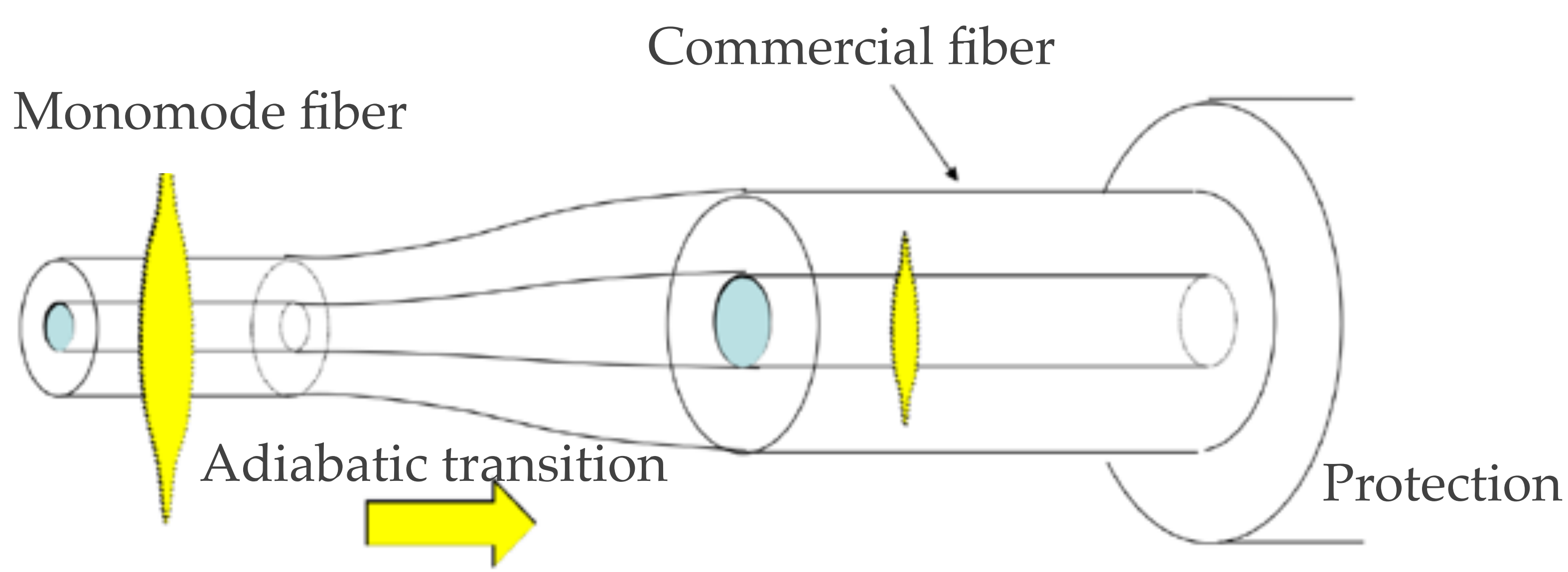
One can imaging to measure:

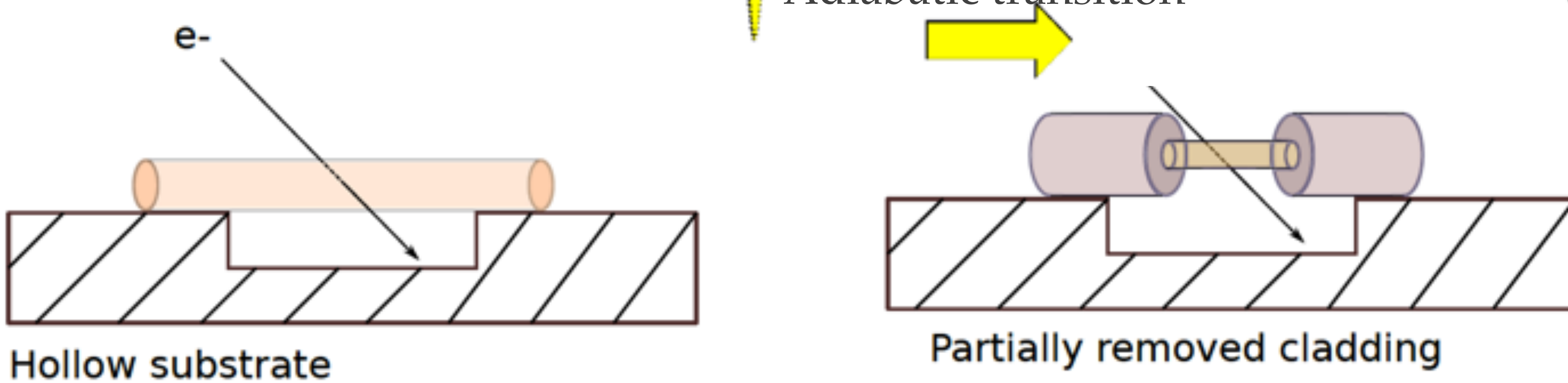
- Energy spread (for semi-relativistic particles by using the dependence v_{ph} on ω at at small crossing angle)…

Experiment with optical fiber

- First, we thought to perform the proof-of-principle experiment with the monomode optical fiber.
- Since $R \sim \lambda/2\pi$, for the $R = 1$ μm fiber, the produced radiation lies in the ~ 6 μm range (infrared domain).
- Zirconium Fluoride Glass fiber (ZBLAN glass group) can guide 0.3 - 7 μm in the infrared, refractive index $n = 1.50$.
- Development and production of the fiber assembly is quite expensive. Many difficulties.

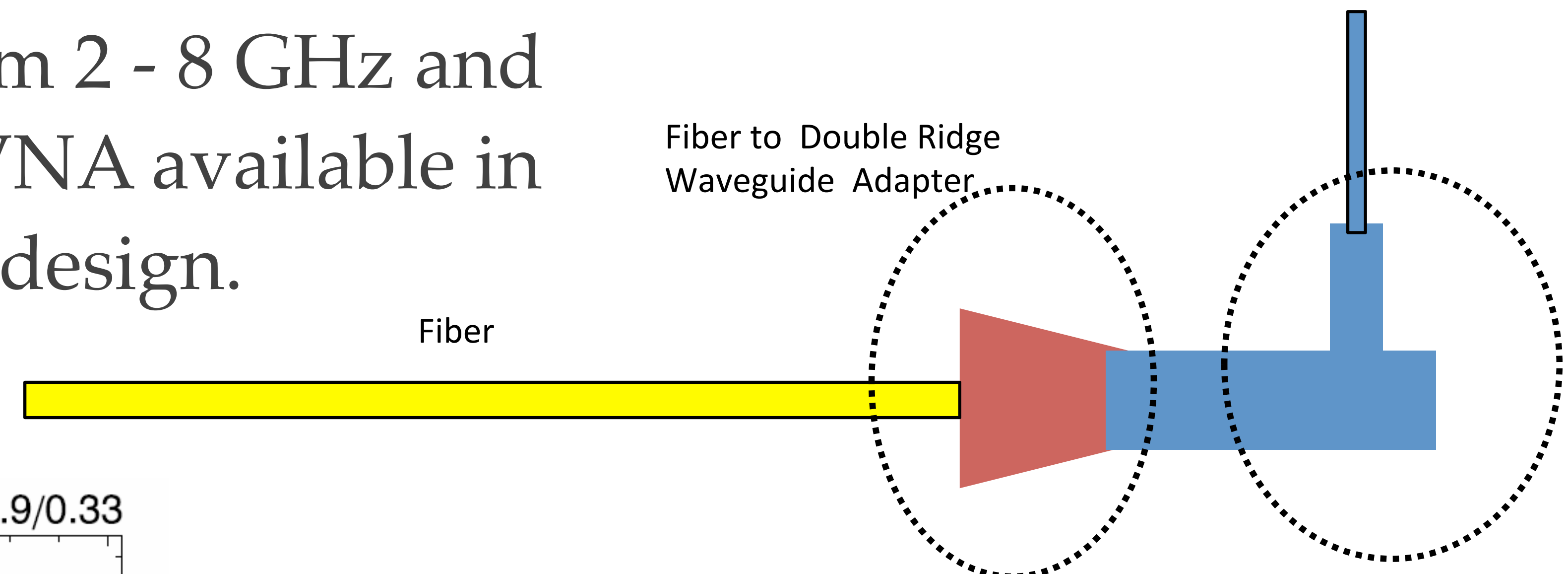
☞ **<u>Solution:</u>** to go to a bigger scale ($R \sim$ mm/cm).

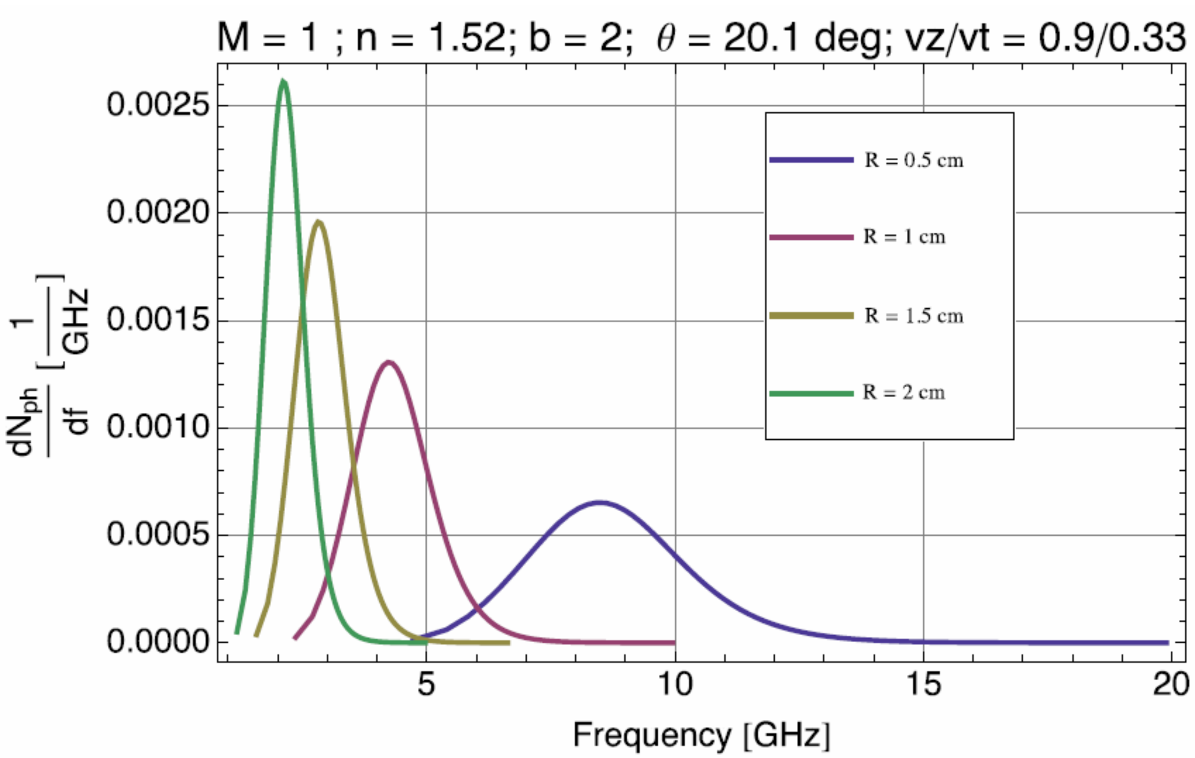




Experiment with dielectric rod

- Proof-of-principle experiment using the dielectric rod.
- Since R ~ $\lambda/2\pi$, for the R = 1 cm fiber, the produced radiation lies in the ~ 60 mm range (microwave domain).
- R = 1 cm => PIGL spectrum 2 - 8 GHz and therefore we can use the VNA available in the lab to characterise the design.



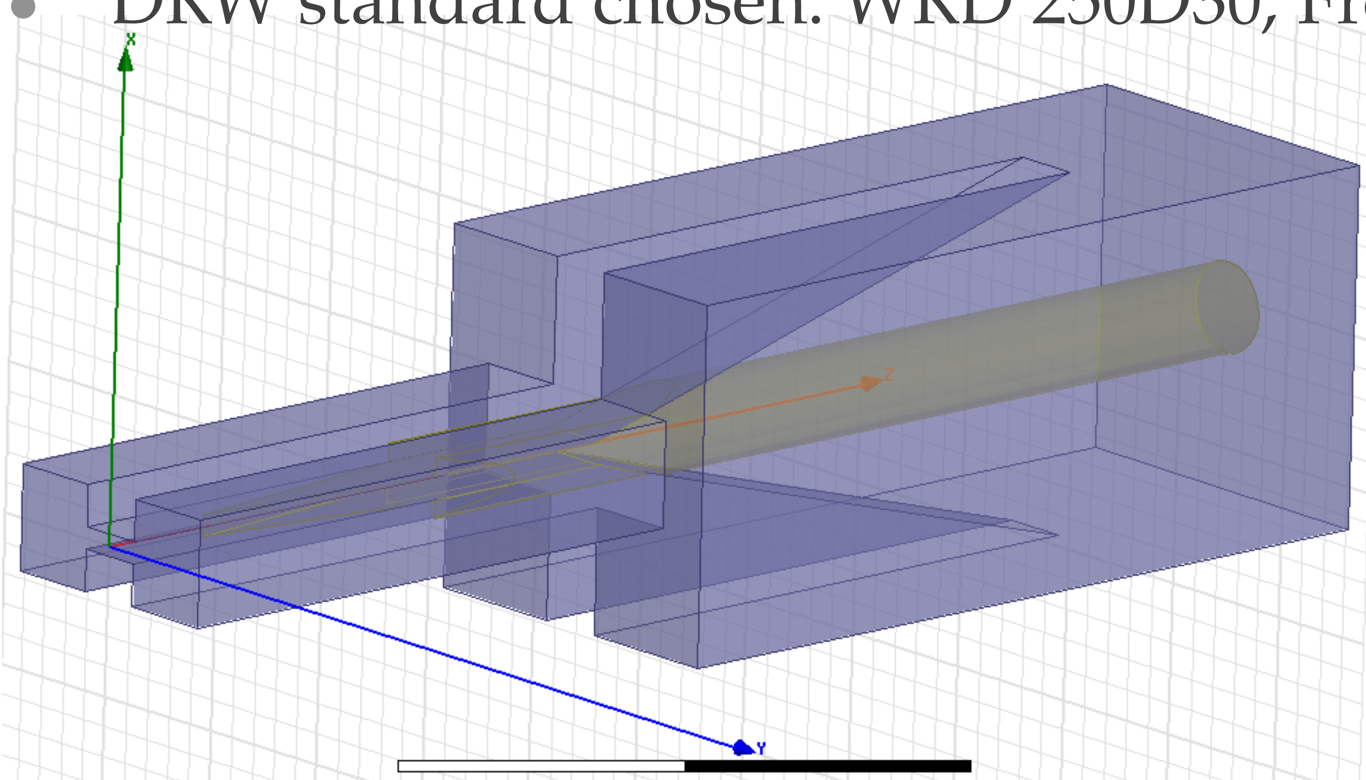


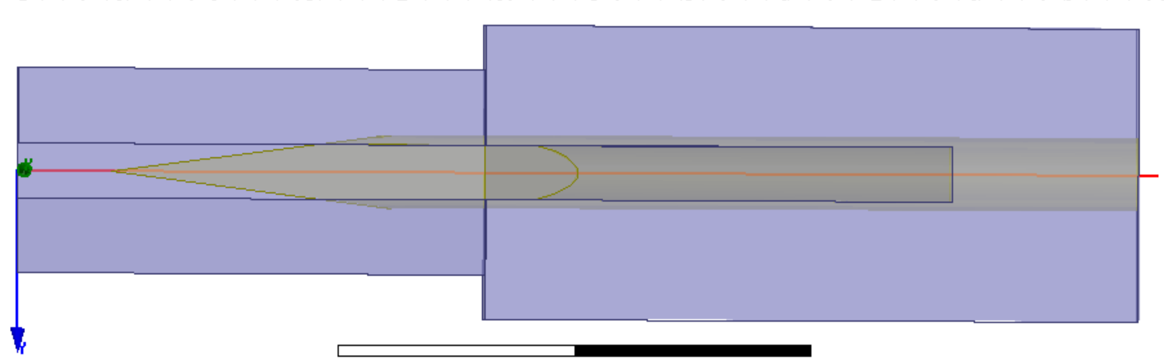
Design (together with colleagues from Telecom Paristech):

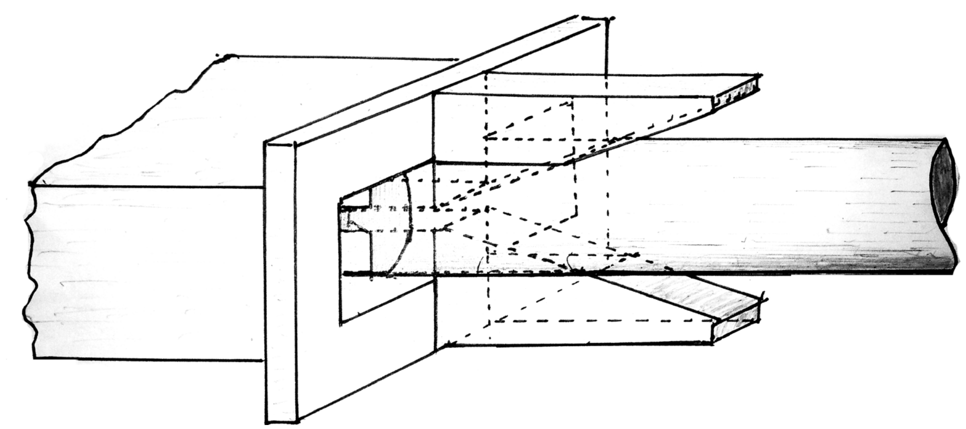
- Dielectric rod + Transition section to extract the radiation (rod-waveguide-coax adapter)
- Spectrum analyzer to measure the PIGL spectrum.

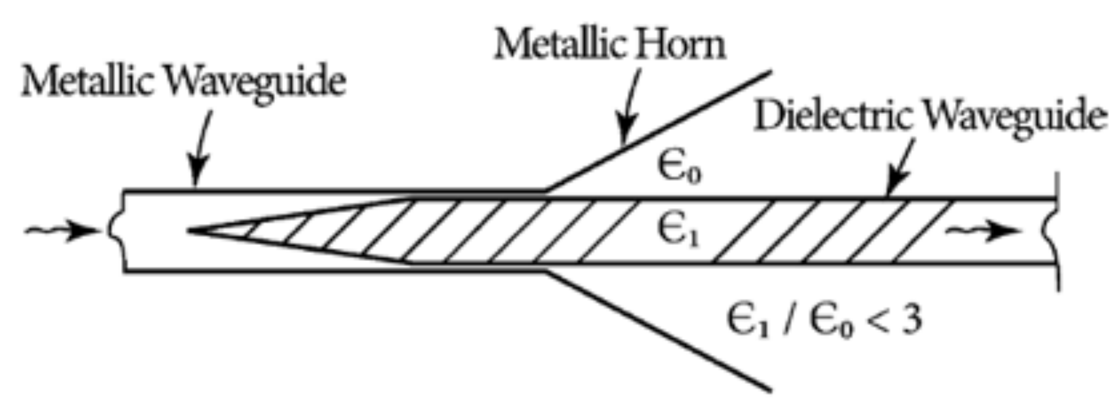
Practical realization

- Given the large bandwidth of the PIGL spectrum (2 - 8 GHz) a broadband extraction adapter is needed.
- To achieve maximum coupling efficiency the PIGL collector can be designed by a combination of a tapered rod, horn, Double Ridge Waveguide (DRW) transition followed by the DRW to Coax adapter.
- DRW standard chosen: WRD 250D30, Freq. Range: 2.6 - 7.8 GHz, Material: AL.









Coupling efficiency of ~98%

Work to be done

Realize and test the design proposed => we should have injection and extraction adapters.

- Mechanical fabrication of the another waveguide section and horns.
- Mechanical help to give shape to the dielectric rod (tapered rod).
- Characterise the set-up with the VNA (measure the transmutation and reflection parameters, estimate the coupling efficiency).
- To find/rent the Spectrum Analyzer (perhaps Schottky Barrier Diode for the first tests).
- Experiment with the electron beam at the PHIL facility.

Summary and Perspectives

- The PIGL is a very interesting physical phenomena and it can be studied and confirmed experimentally.
- The theory of the PIGL is well-developed and can be used to analyse the experimental results.
- PIGL can be considered as the innovative detection method for non-destructive beam diagnostics even though practical realization is very raw and hardly feasible at the moment. The further studies are needed in this context.
- This is an attractive activity which is useful and important from both fundamental and practical point of view.