Coherent radiation of relativistic electrons in dielectric fibers

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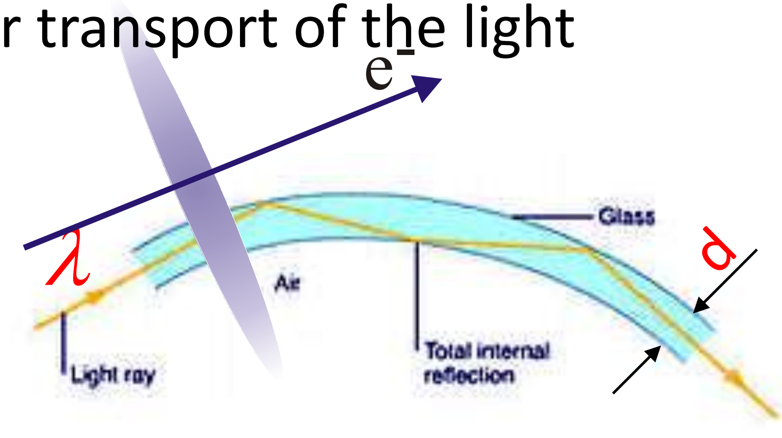
Optical fibers

Well known technique for transport of the light



based on the full internal reflection in fiber.

If λ is comparable to *d*, radiation propagates in several modes.

However, radiation in dielectric fibers may be generated by a Coulomb field of relativistic particles.

(This may be useful in beam diagnostics)

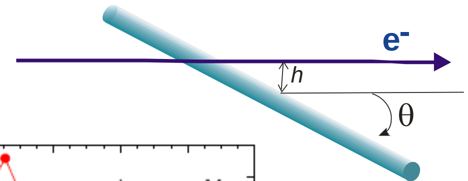
Theoretical background

Xavier Artru, Cédric Ray. Light induced by charged particles in optical fibers. NIM B 309 (2013)

Fiber → Low-loss dielectric waveguide

Two types of particle-induced guided light (PIGL):

Type-I PIGL: The particle passes near or through a straight (or weakly bent) part of the fibre, far from an extremity.



Specrum:

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

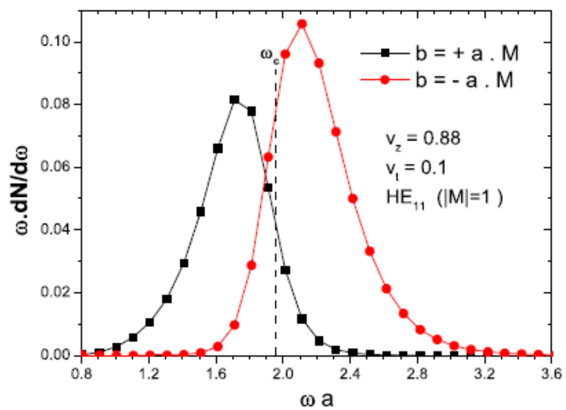
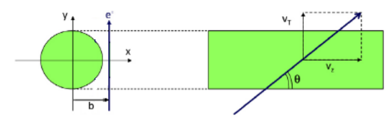


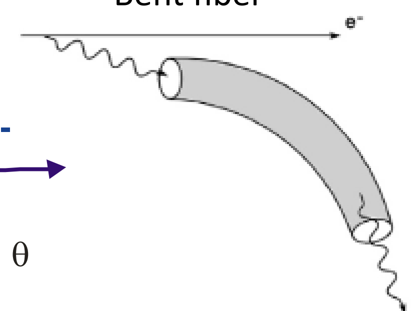
Fig. 3. Photon spectra in the HE_{11}, $M=\pm1$ modes, for a particle trajectory tangent to the fiber surface, v_z=0.88, v_T=0.1. Squares: bM positive; balls: bM negative. The vertical line is at ω_C defined by Eq. (5). The fiber index is $n = 1.41$.

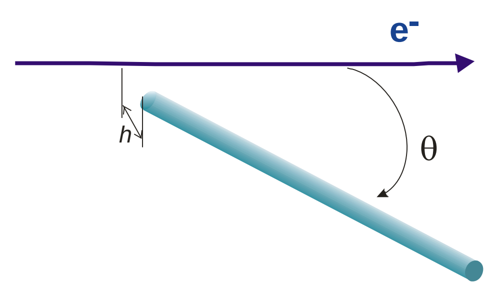


a is a fiber radius
b is imact-parameter

Type-II PIGL: The particle passes near or through an end of the fiber or an added structure (e.g., an indentation or a metallic ball stuck to the fiber).

Bent fiber





$$\omega\, d\mathcal{N}_{HE_{11}}/d\omega \sim (Z^2\alpha/\pi)\left(\langle \mathbf{r}^2\rangle / b^2\right)\Theta(\gamma - \omega b).$$

Bent fiber

Rulger W. Smink et.al. J. Opt. Soc. Am. B. Vol 24, No. 10. October 2007

Bending loss factor:

$$\alpha' = \frac{1}{2\omega}\sqrt{\frac{\pi}{\frac{2R}{d}w^3}} \cdot e^{-\frac{2w^3\frac{2R}{d}}{\left(\frac{3}{2}\omega\cdot d\right)^2}} \cdot \frac{u^2}{d\cdot\left(v\cdot K_1\left(w\right)\right)^2}$$

$u, \quad w, \quad v=\sqrt{u^2+w^2}$ the usual dimensionless kinematical variables.

For the investigated spectral interval $[\omega_1, \omega_2]$ $\alpha = \int\limits_{u=\hat{\omega}_1}^{\hat{\omega}_2} \int\limits_{w=\hat{\omega}_1}^{\hat{\omega}_2} \alpha' dw\, du,$

where $\omega = 2\pi k, \quad \hat{\omega} = ka,$ k is wave-number, a is fiber radius

Radiation intensity is reduced as $I = I_0 \cdot e^{-2\alpha\cdot\omega\cdot\Phi},$

where Φ is the bending angle in radians.

Evanescent waves problem

A. V. Kukushkin, A. A. Rukhadze, K. Z. Rukhadze.
On the existence conditions for a fast surface wave.
Physics-Uspekhi 55 11 (2012).

"Surface waves do not exist at the interface between the vacuum and a weakly absorbing dielectric."

On another hand, the evanescent waves are widely used in dielectric antennas technique
(V. M. Shibkov, A. P. Ershov, V. A. Chernikov, L. V. Shibkova. Microwave discharge on the surface of a dielectric antenna. Technical Physics 50 4 (2005))

Where is this contradiction from?

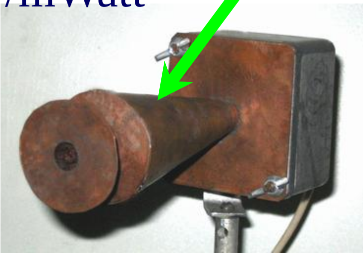
On our opinion, that is why, that usually are looking solutions, which are homogeneous along the fiber length (for the infinite fiber).

Experimental investigations

Detector parameters:

wavelength range: = 3 ~ 35 mm, ***Horn***

sensitivity = 0.3 V/mWatt



Broad bend detector

The detector efficiency is declared by the manufacturer in the wavelength region λ=3~35 mm

as a constant with accuracy ± 15%

Electron beam

Tomsk polytechnic university microtron

Beam parameters

Electron energy	6.1 MeV
Macro-pulse duration	2~6 ms
Pulse repetition rate	1~8 Hz
Micro-pulse length	≈ 6 mm
Electrons number per micro-pulse	$\approx 10^8$
Micro-pulses number per macro-pulse	$\approx 10^4$
Beam size at the output	4×2 mm^2
Emittance: horizontal	$3\cdot10^{-2}$ mm ×rad
vertical	$1.5\cdot10^{-2}$ mm ×rad

Coherency

$\gamma = 12,$

$\lambda = 9 - 35\ mm$

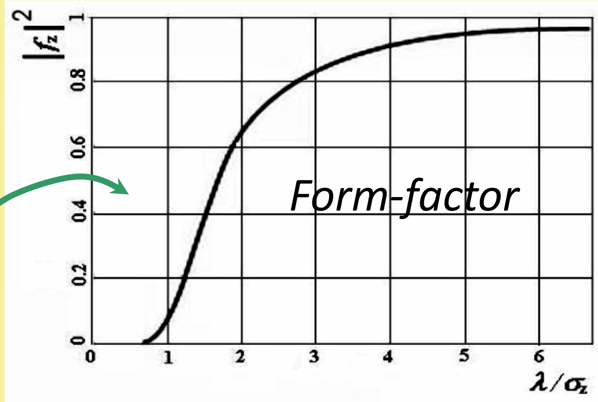


Fig.4 Dependence of the squared form-factor module on the radiation wavelength for the gaussian longitudinal distribution of electrons in a bunch.

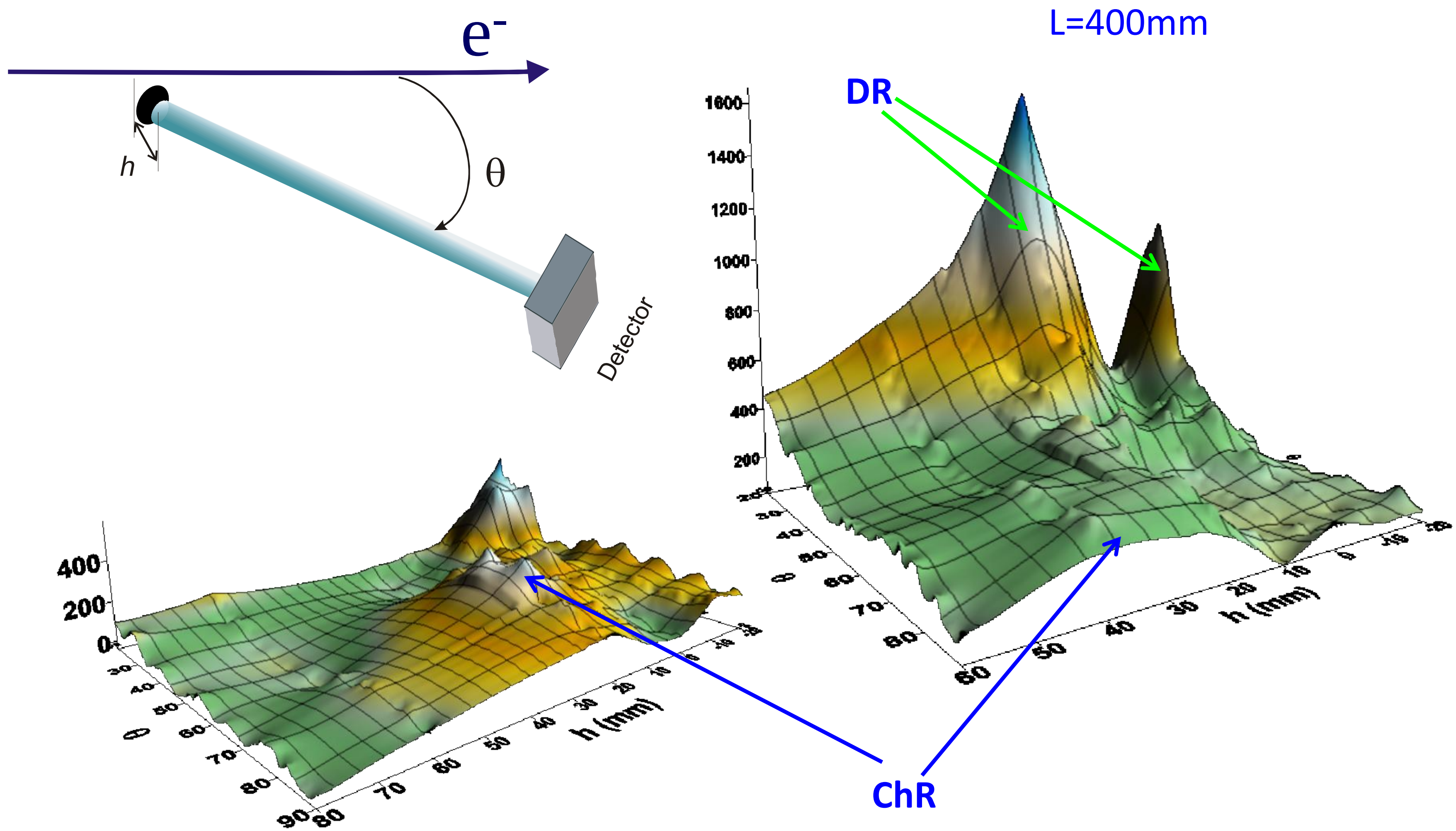
For λ≥ 8 mm the radiation is coherent

Dependence on the angle θ and impact-parameter h

in spectral region $\lambda = 9 - 35\, mm$

Teflon fiber
n=1.41
d=10mm
L=400mm

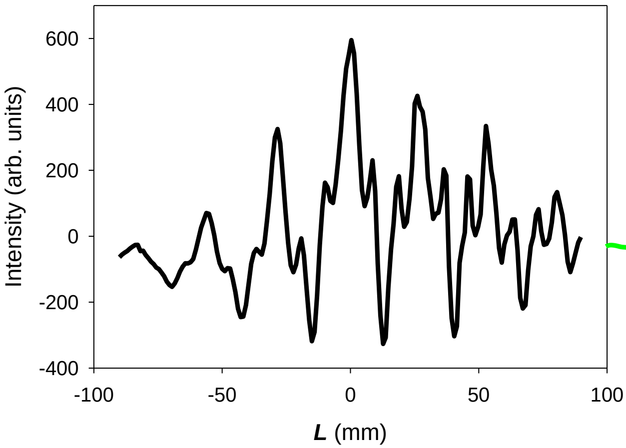
Type-II PIGL

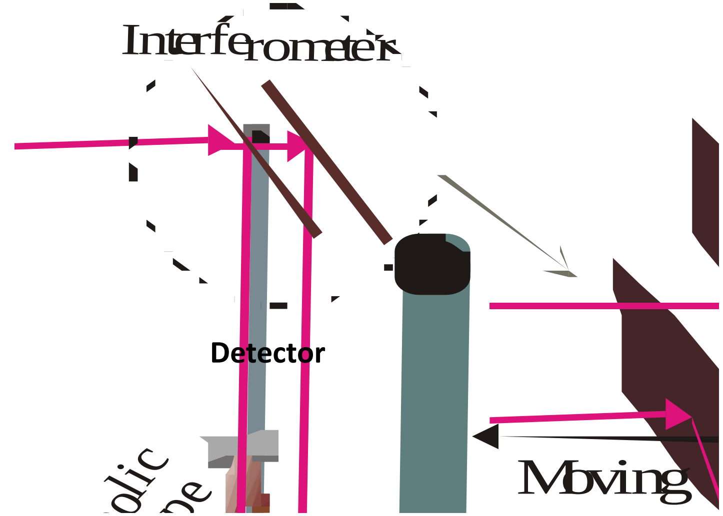


Spectral measurements

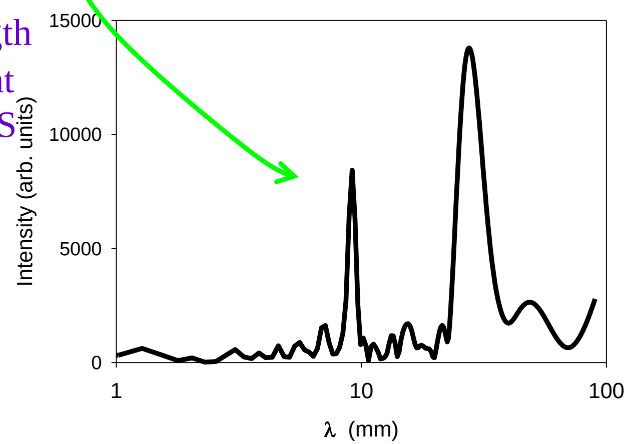
Interferometer with separation of the radiation flux at the two reflecting plates

Sample of interferogram from mm-emitter with two spectral lines





Spectrum recovered from interferogram

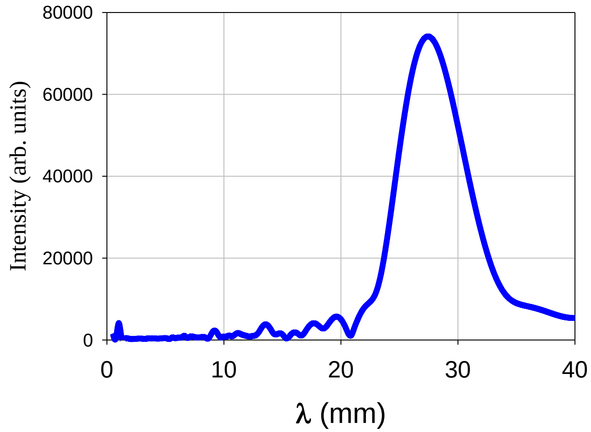


Spectra were recovered from interferogramms using technique from [Lars Froehlich. Bunch Length Measurements Using a Martin-Puplett Interferometer at the VUV-FEL. DESY-THESIS 2005-011, FEL-THESIS 2005-02 **] based on the inverse Fourier transforms of interferograms.**

Spectral resolution is $\approx 9\%$

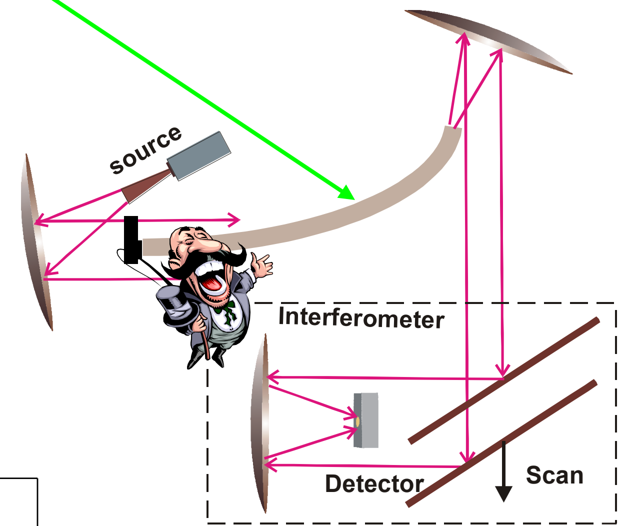
Spectral measurements using radiation from emitter

Spectrum of emitter

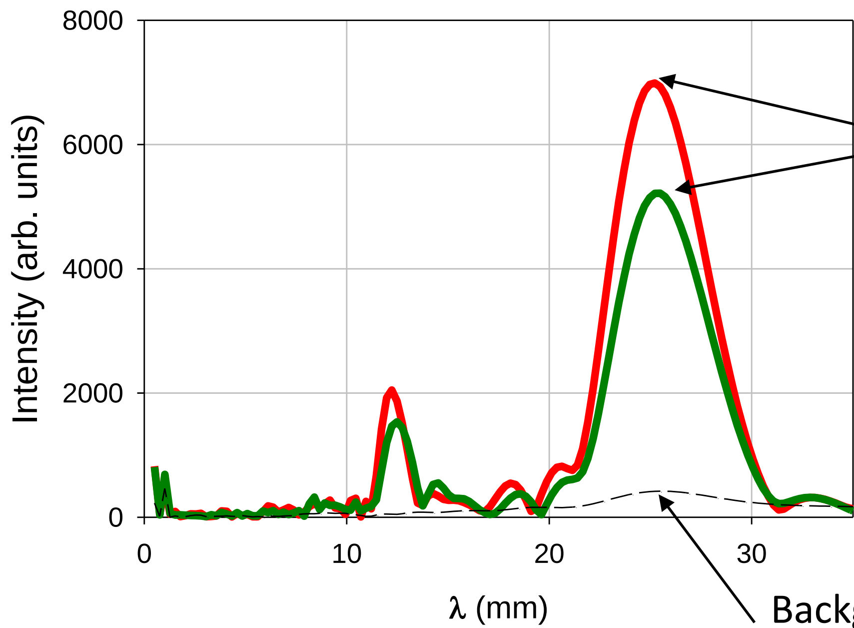


Polymer fiber
L=600mm
d=11 mm
n=1.5

Experimental setup



Spectra from fiber



Most part of radiation is expanded by walls of fiber.

We may expect surface waves on the fiber walls

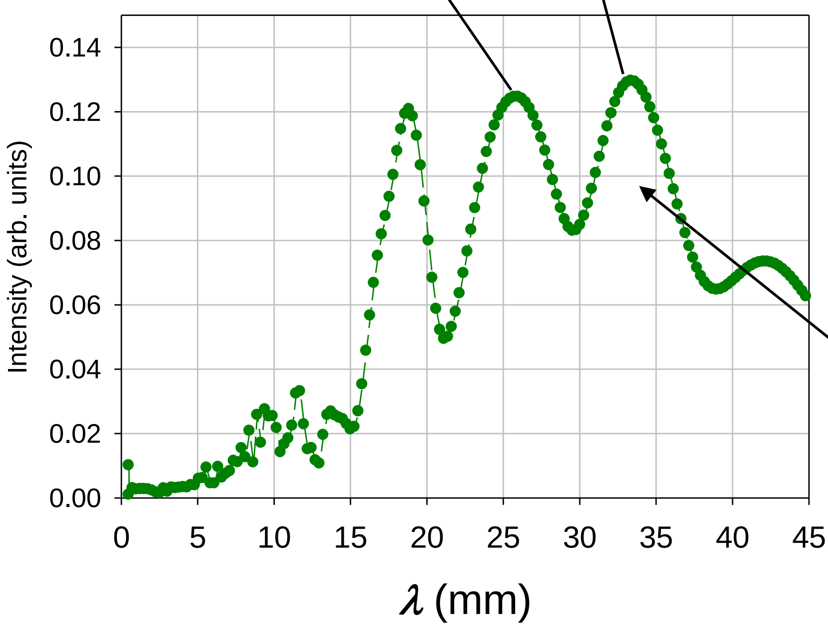
Background (fiber is removed)

Spectrum of radiation generated by electron beam in rectilinear dielectric fiber

HE$_{11}$ mode

?

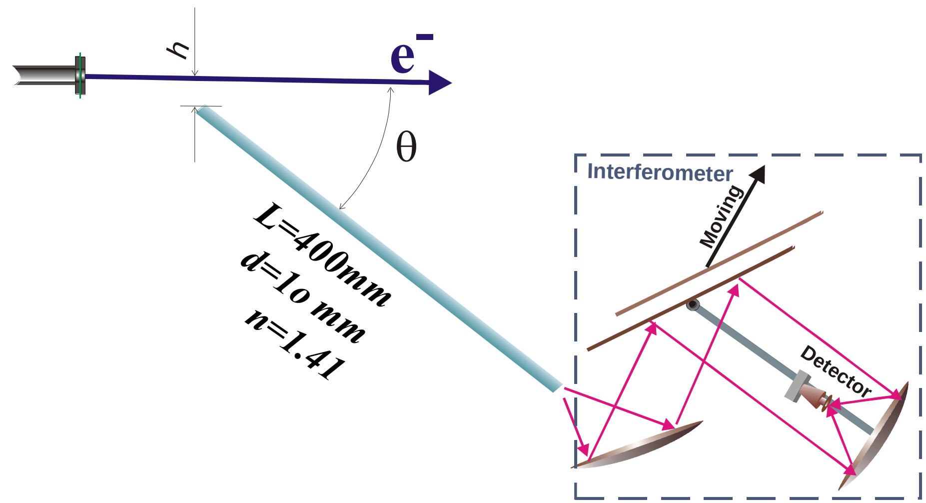
Spectrum



Subwavelength area for fiber

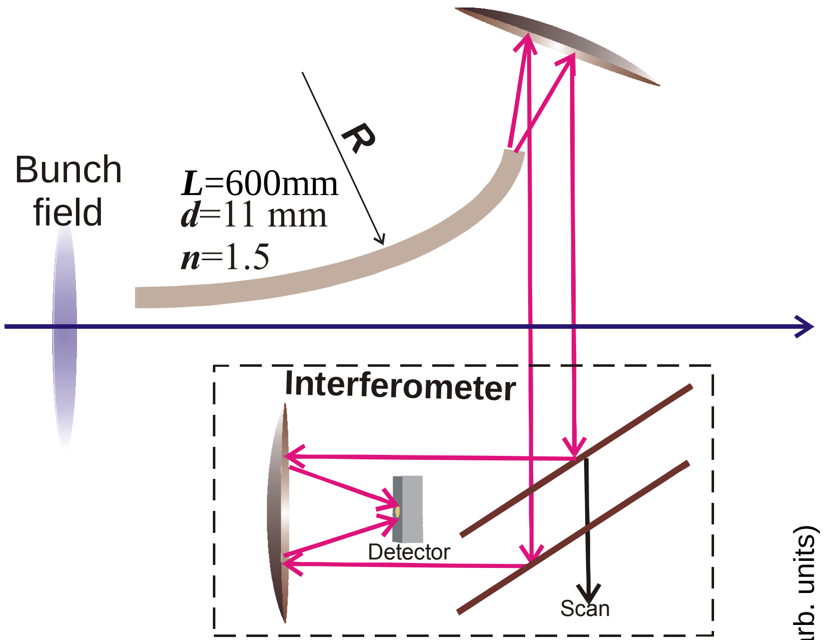
Scheme of spectra measurement

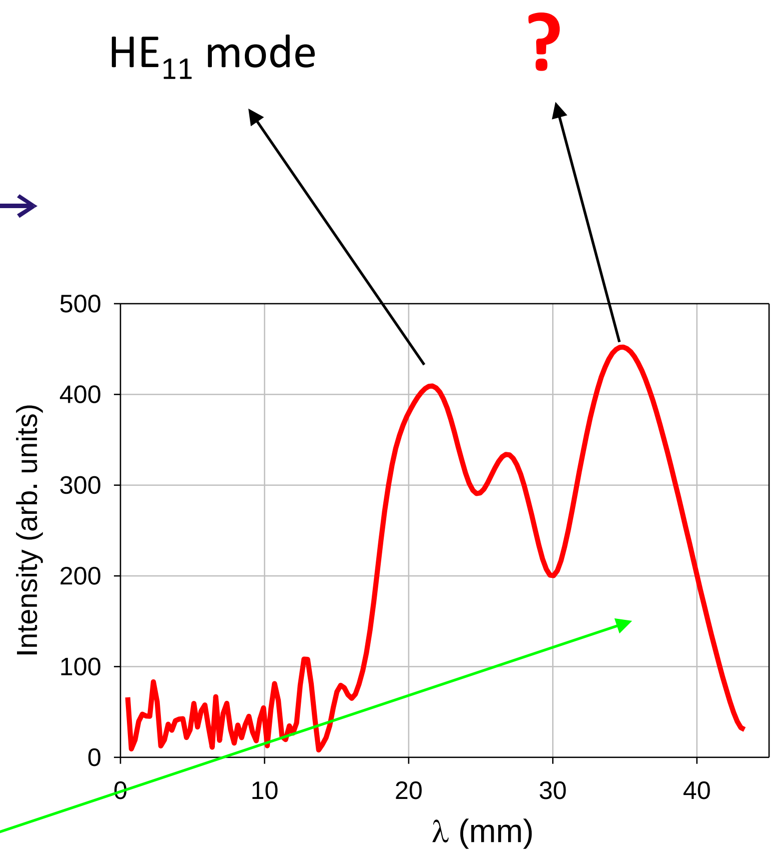
(Type-II PIGL)



Flexibility is the important advantage of fibers

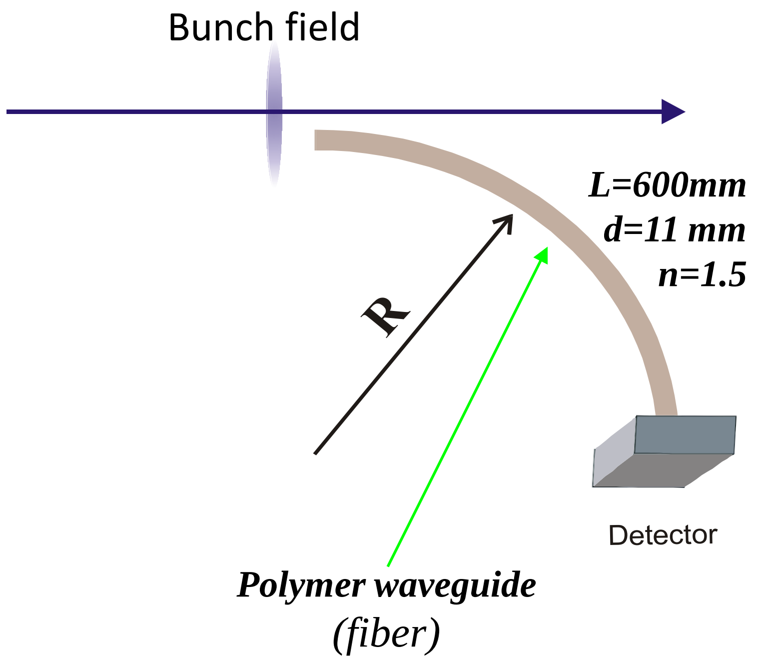
Spectrum from bent fiber



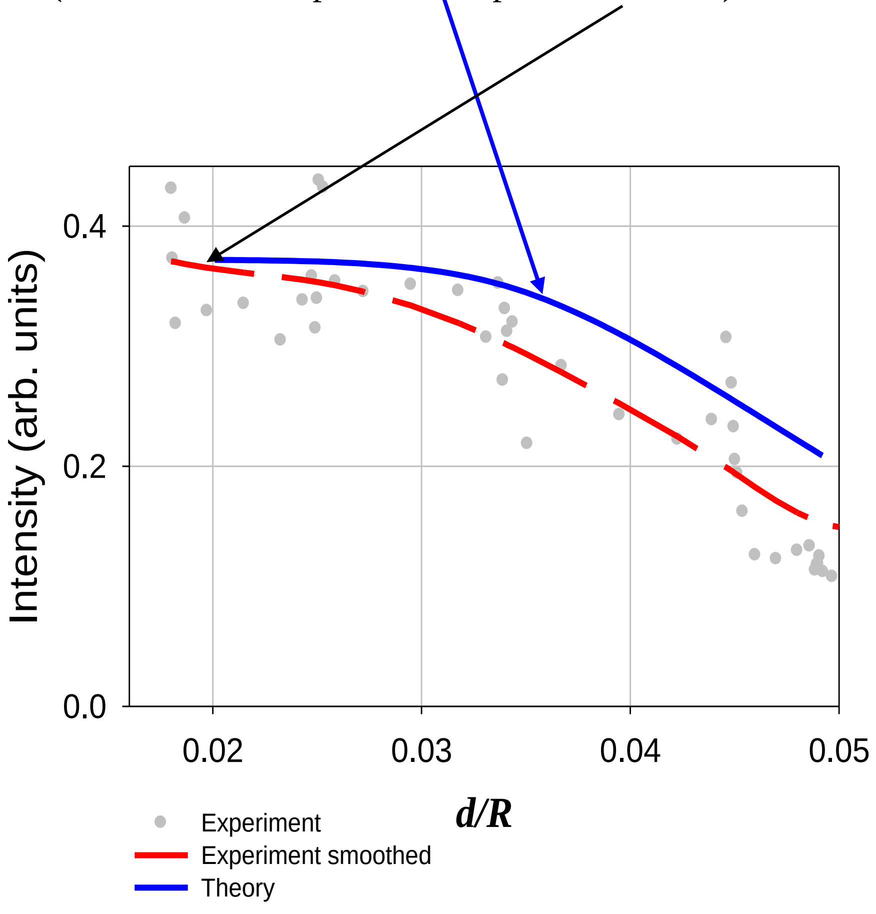


The same problem in long-wave region

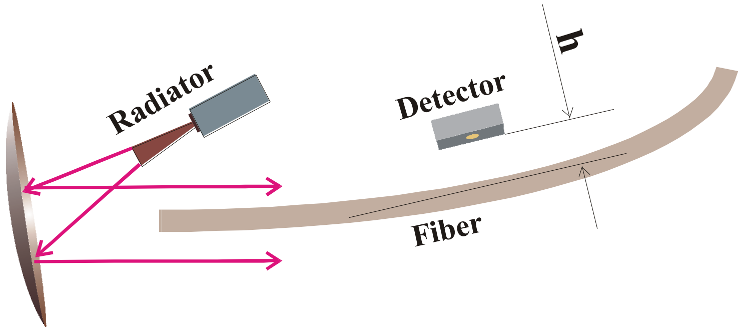
Measurement of the R-dependence



Theory using Rulger W. Smink formula (above mentioned) averaged above the spectral region.
(normalized to experiment in point *d/R=0.02*)

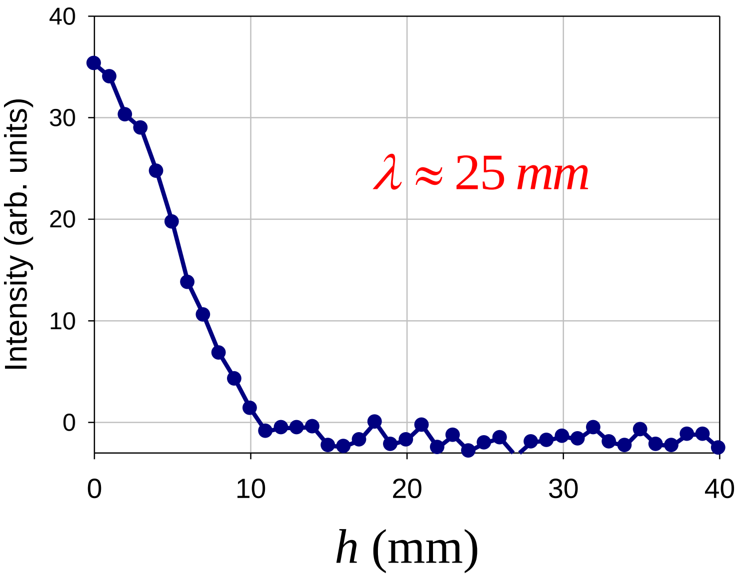


Evanescent waves measurement



The measured dependence is typical for surface waves

Dependence of the field intensity on a distance to the fiber wall



Background has been measured without a fiber

Summary

- Diffraction and Cherenkov radiation are generated in fibers (dielectric waveguide) by a field of relativistic particles without its interaction with matter.

- Radiation is generated by charged particles both at end face and on a wall of fibers (both PIGL-I and PIGL-II can be realized).

- In millimeter wavelength region a fiber can’t be considered as an infinite waveguide. Evanescent waves should be taken into account.
- Dielectric waveguides (fibers) with length up to 1 m can be used for beam diagnostics in sub-mm range (losses are small).

Thank you for attention