Observation of Coherent Cherenkov Radiation of Electron Bunches from a Partially Dielectric Loaded Waveguide

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International collaboration

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Outline

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II. Experimental setup

III. Results of experiments

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I. Introduction and motivation

Modern accelerators generate:

- beams of relativistic monoenergetic electrons
- with very small sizes and
- with very large number of electrons $n_e = 10^9$

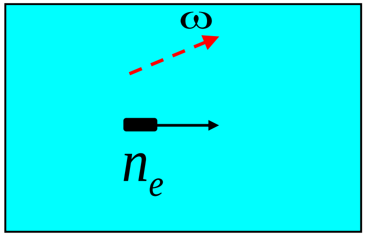


Fig.1

Radiated energy

$$I_{Non-coh}(\omega) = n_e I_1(\omega)$$ Noncoherent radiation

$$I_{Coh}(\omega) \approx n_e^2 I_1(\omega)$$ Quasi coherent radiation

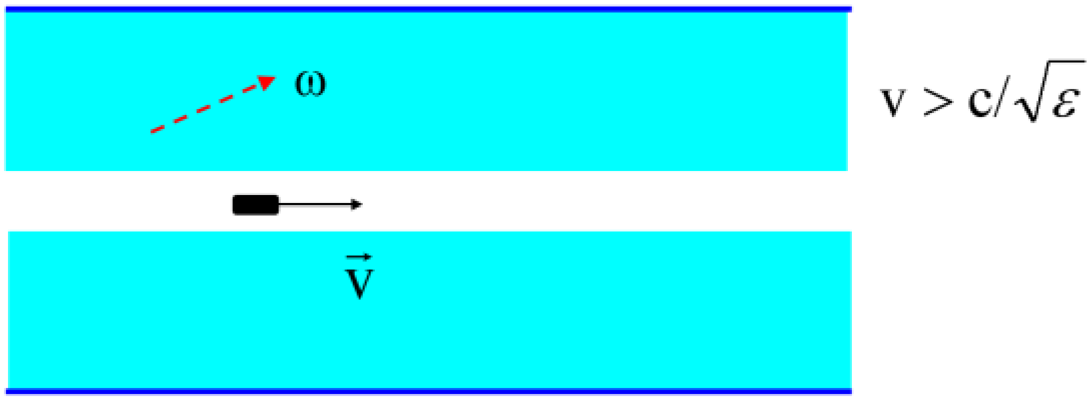
Amplification coefficient

$$I_{Coh}(\omega) / I_{Non-coh}(\omega) \approx n_e = 10^9$$

Quasi coherent radiation can be used for non destructive bunch diagnosis in accelerators (see e.g. [1])

I. Introduction and motivation

- The works A.M. Cook et. al., Phys. Rev. Lett. **103** (2009) 095003, G. Andonian et. al., Appl.Phys.Lett. **98** (2011) 202901 reported the direct observation of narrow-band terahertz coherent CR radiated by a subpicosecond electron bunch traveling along the axis of a hollow cylindrical dielectric-lined waveguide



- The radiation was generated on a selected waveguide mode

- Our group has shown that an electron bunch can generate coherent radiation simultaneously on several waveguide modes

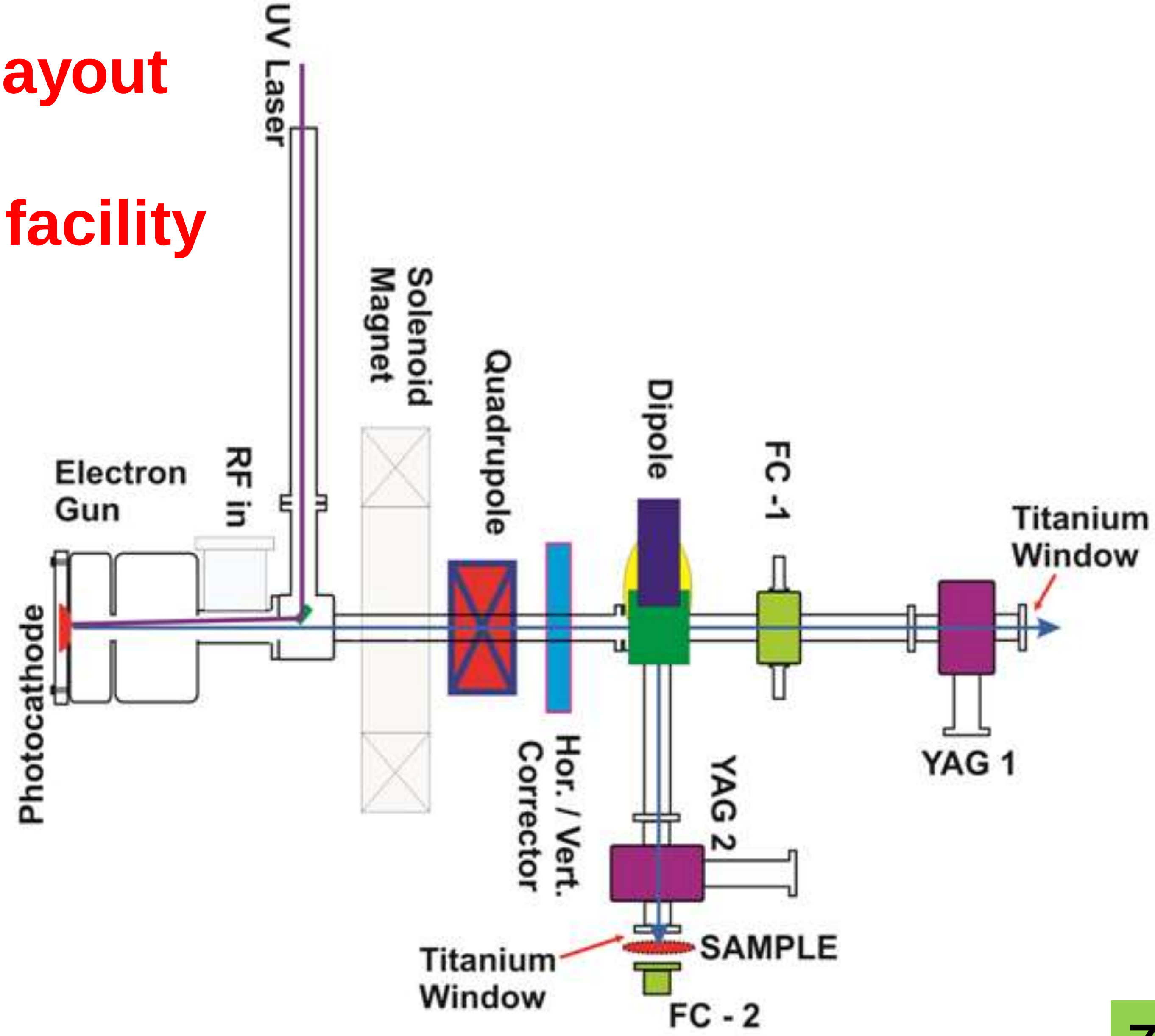
- For the confirmation of that feature experiments have been done on the linear accelerator AREAL of CANDLE laboratory in Yerevan.

Coherent CR from dielectric prism is studied in [7]

II. Experimental setup

- AREAL-Advanced Research Electron Accelerator Laboratory is an electron linear accelerator facility based on photocathode RF gun.
- The facility is able to provide ultra-short electron bunches with about 0.5 ps bunch length with a particle charge up to 800 pC, and electron energies up to 5 MeV.
- Two experimental stations of AREAL facility provide a possibility to extract machine electrons (out of machine vacuum) and perform irradiation experiments in-air.
- We have used experimental station located at a straight arm of beam pipe which provides a mixture of nominal electron bunch, field emitted electrons.

Schematic layout of AREAL accelerator facility



Main parameters of AREAL electron bunch

Parameter		Value	
Bunch charge*	[pC]	10 – 800 (at straight) 15 – 100 (at 90 degree bend FC-2 Figure 1.)	
Bunch energy*	[MeV]	up to 5	
Bunch energy spread	[keV]	< 80 (1.6%)	
Particle distribution (x / y / t)		Gaussian / Gaussian / Gaussian	
Transverse rms size (x / y)	[mm]	2 / 2 1-20 / 1-20 15 / 5	(at photocathode) (adjustable at Exp. 1 – straight) (at experiment location 2 – bend)
Bunch length FWHM	[fs]	450	(adjustable up to 10000 fs)
Transv. norm. emittance	[mm-mrad]	< 1	
Pulse repetition rate	[Hz]	1 – 25	
Stability over 8 hours**	[%]	< 1.2	

* Minimal threshold values for some registering devices on accelerator.

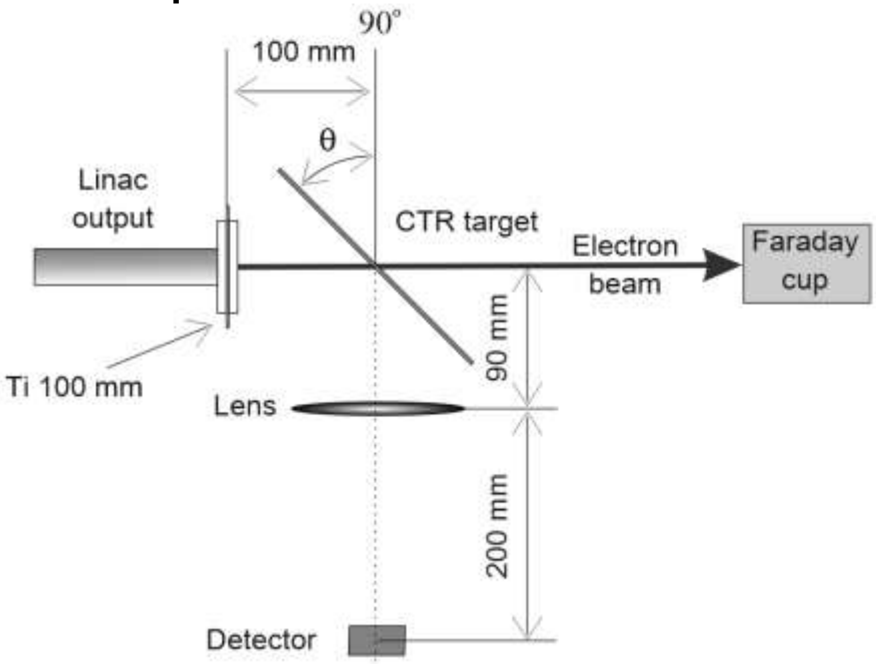
** The energy and the charge measured over 8 hours.

Table 2. Main parameters of AREAL UV laser

Parameter		Value	
Central wavelength	[nm]	258 ± 1	
Pulse energy	[μJ]	< 500	
Energy distribution (x / y / t)		Gaussian / Gaussian / Gaussian	
Transverse rms size (x / y)	[mm]	2 / 2	(at cathode)
Bunch length FWHM	[ps]	0.45 -10	(adjustable)
M^2 parameter		~ 1.1	
Pulse repetition rate	[Hz]	1 – 100000	
Energy stability over 8 hours	[%]	< 0.35	

Experiments on coherent transition radiation

Experimental Scheme



E_0=3.7 MeV, Q=400 pC,
CTR target – metal screen 100x200 mm

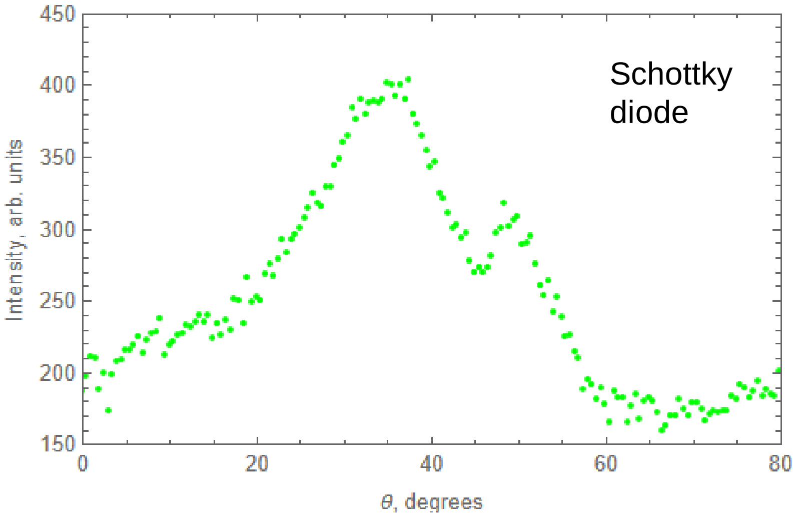
Schottky diode

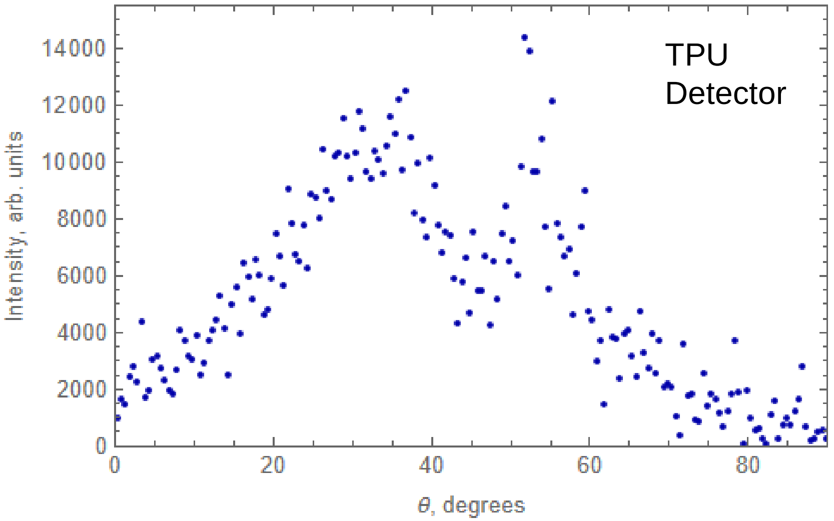
Spectral range: 100-700 GHz
Responsivity: 10 V/W.

TPU Detector

Spectral range: 6-100 GHz
Responsivity: 20 V/W.

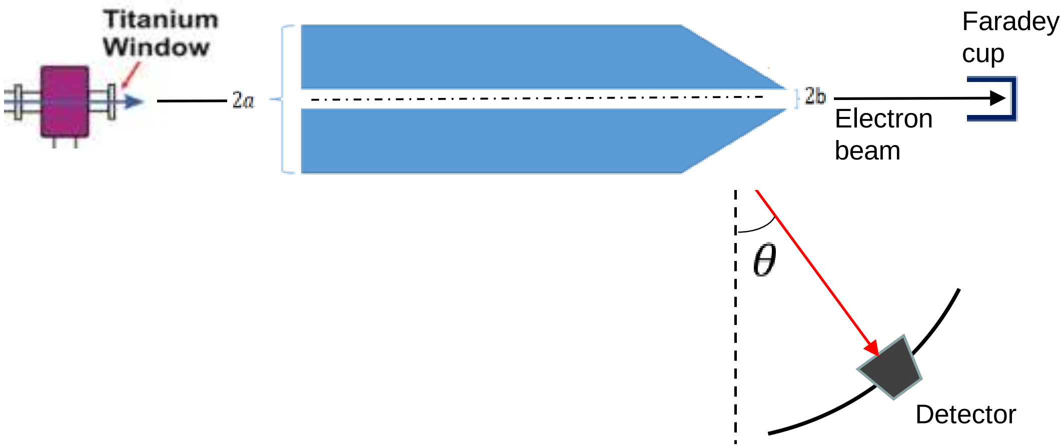
Results of experiment





Experimental Scheme for CR

For the generation of CR radiation we have used hollow cylindrical target from fused quartz



Experimental scheme for measurement of angular dependence

Parameters of target and electron bunch

a – 10 mm
b – 2,5 mm;
L – 100 mm

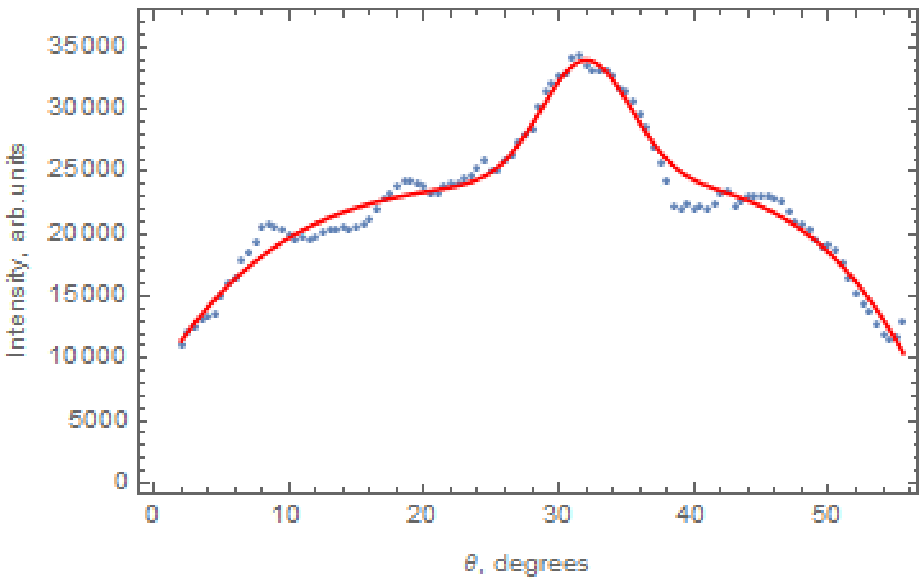
E – 3,7 MeV
Q – 400 pC
Bunch size -2x2x2 mm

TPU Detector

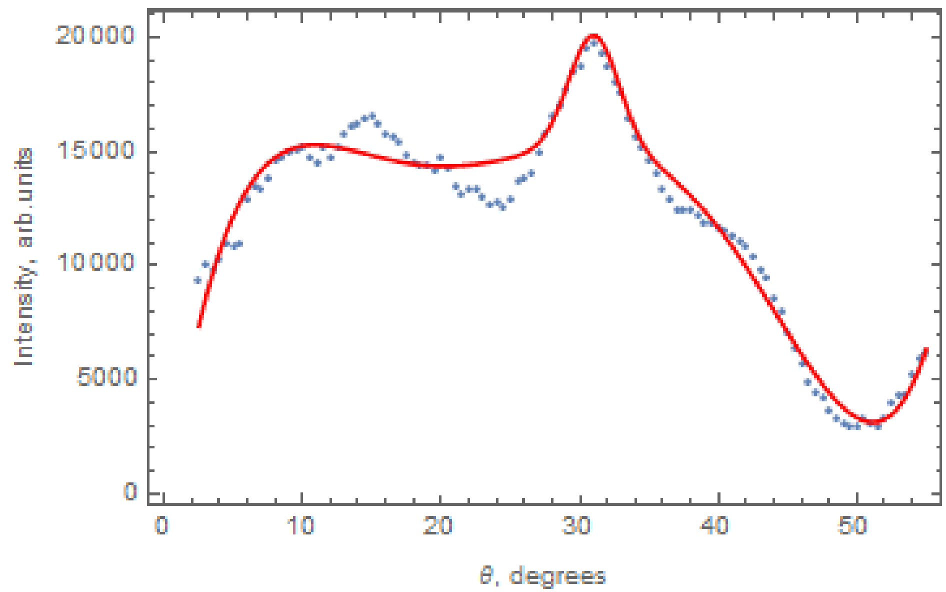
Spectral range: 6-100 GHz
Responsivity: 20 V/W.

III. Results of experiments

Characteristic angular distribution of the radiation



Horizontally polarized part of radiation



Angular dependence of radiation intensity in arbitrary units

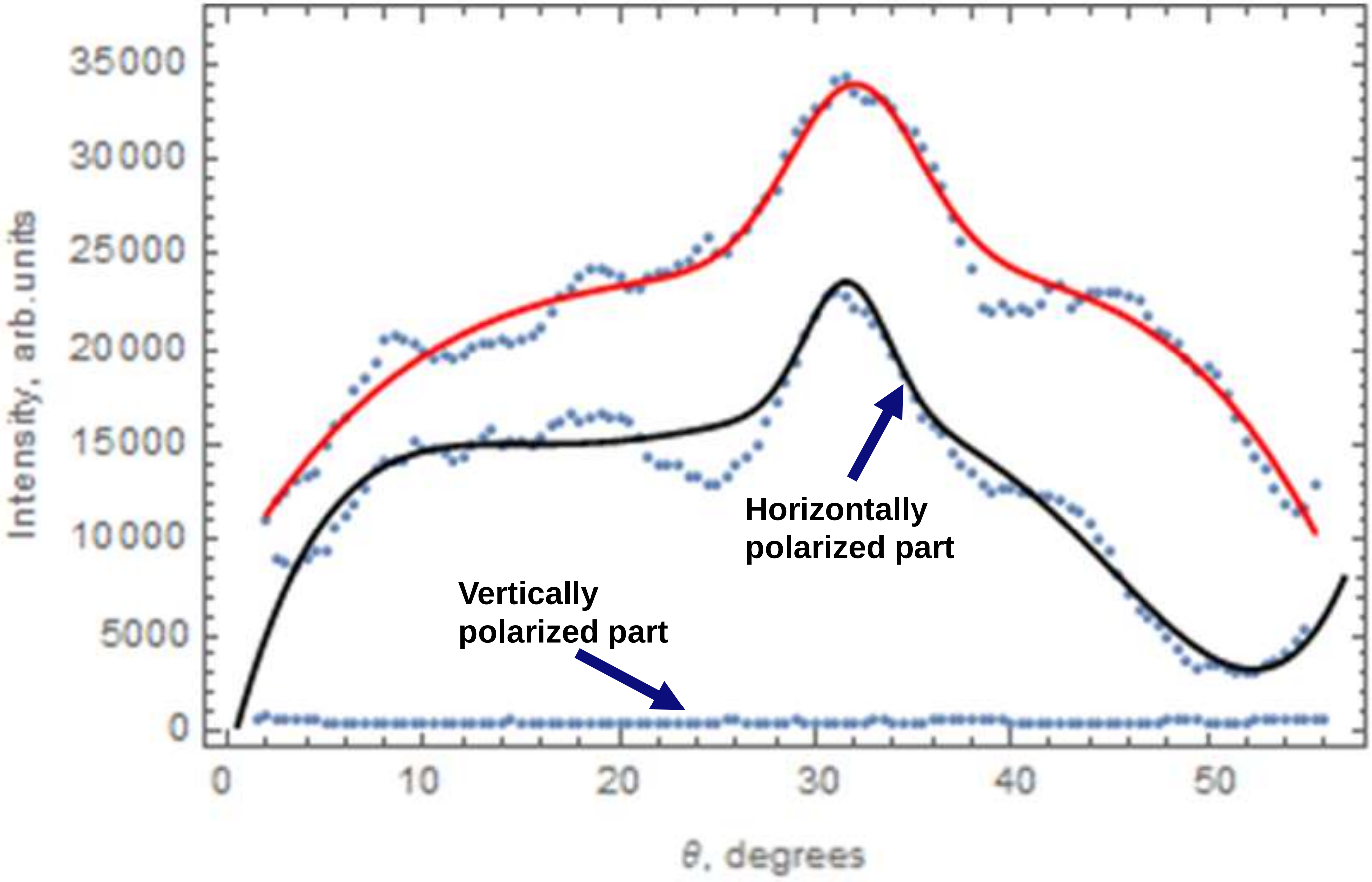
θ - azimuthal angle of radiation

$$\theta_{ch} = arccos\frac{c}{v\sqrt{\varepsilon}} = 57{,}2°$$

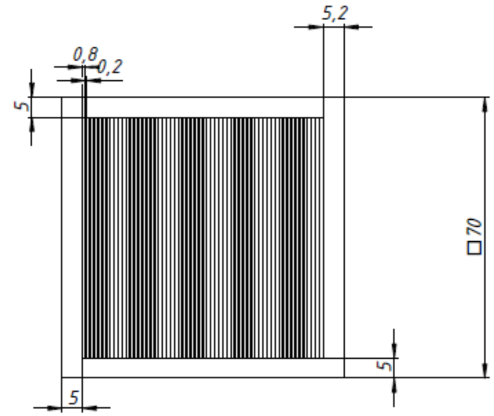
$$\theta_{max} \approx 90 - \theta_{ch} = 32{,}8$$

III. Results of experiments

Polarization of the radiation

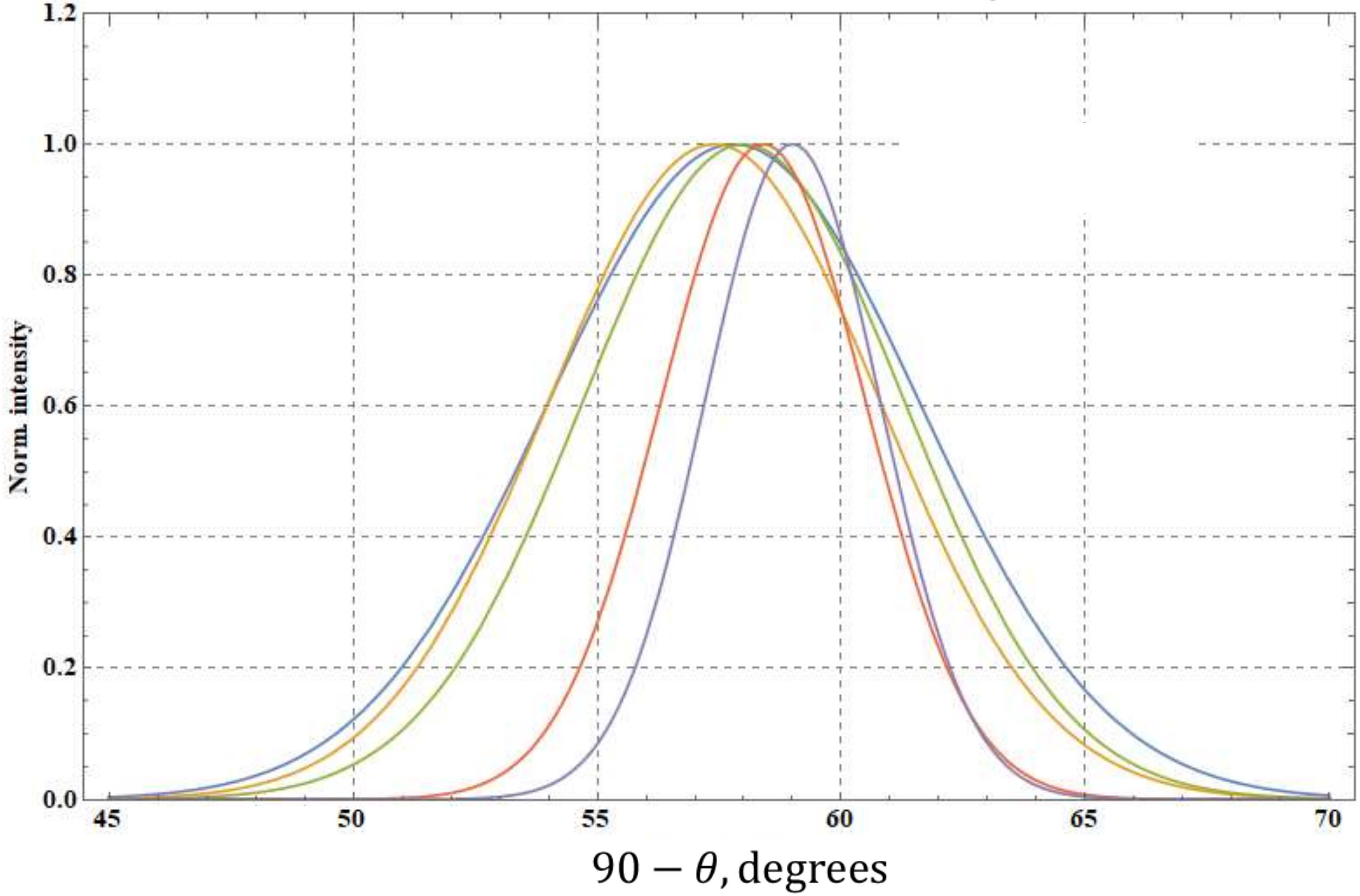


Polarizer was made as a steel frame (70x70 mm) with a 0.8 mm strip spacing and 0.2 mm strip.



III. Results of experiments

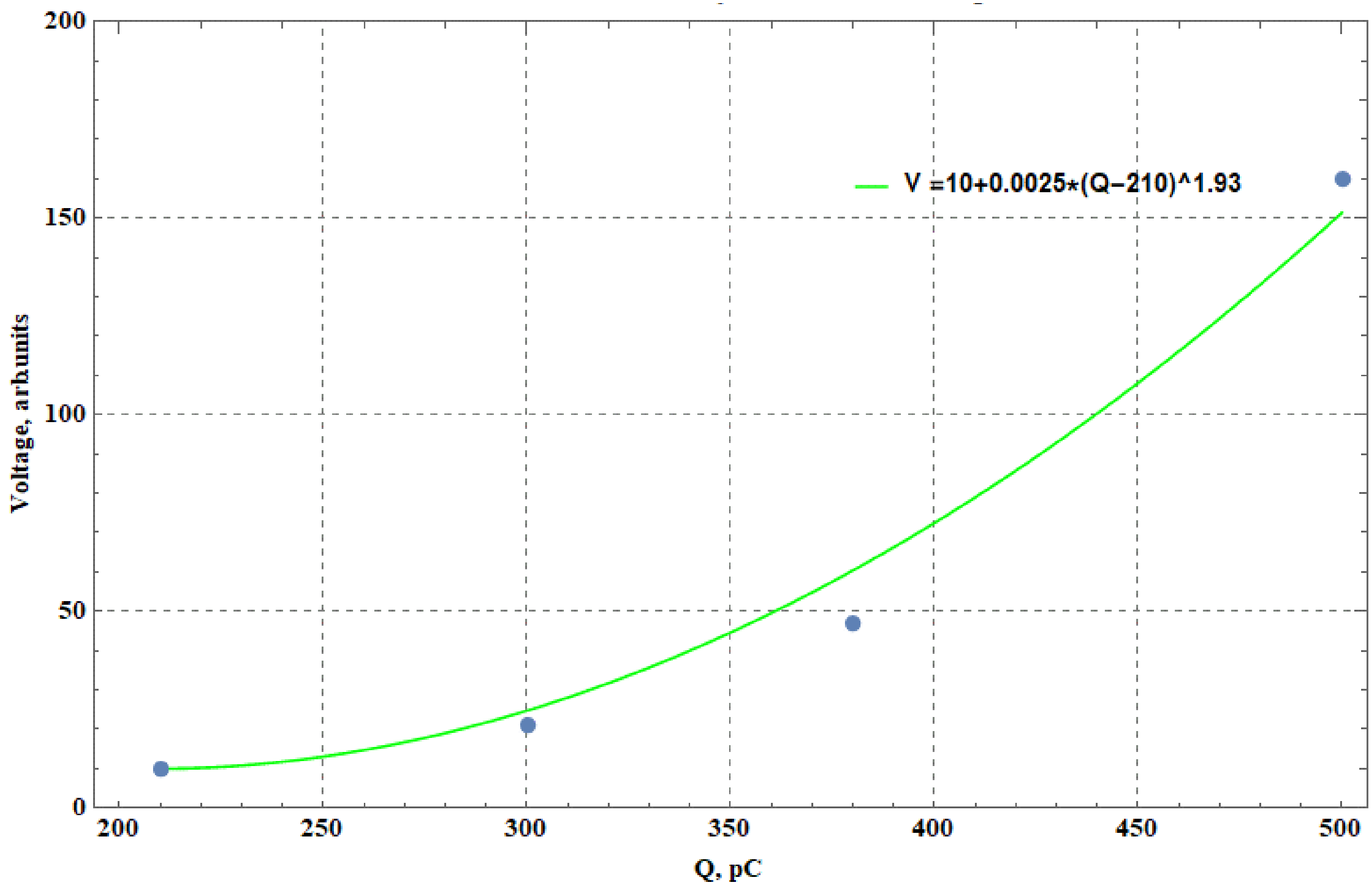
Normalized useful signal



Normalized intensity of radiation (normal-Gaussian distribution)

III. Results of experiments

Coherence of radiation



Dependence of signal amplitude from charge of bunch

III. Results of experiments

Summary of the results of the experiment and further plans

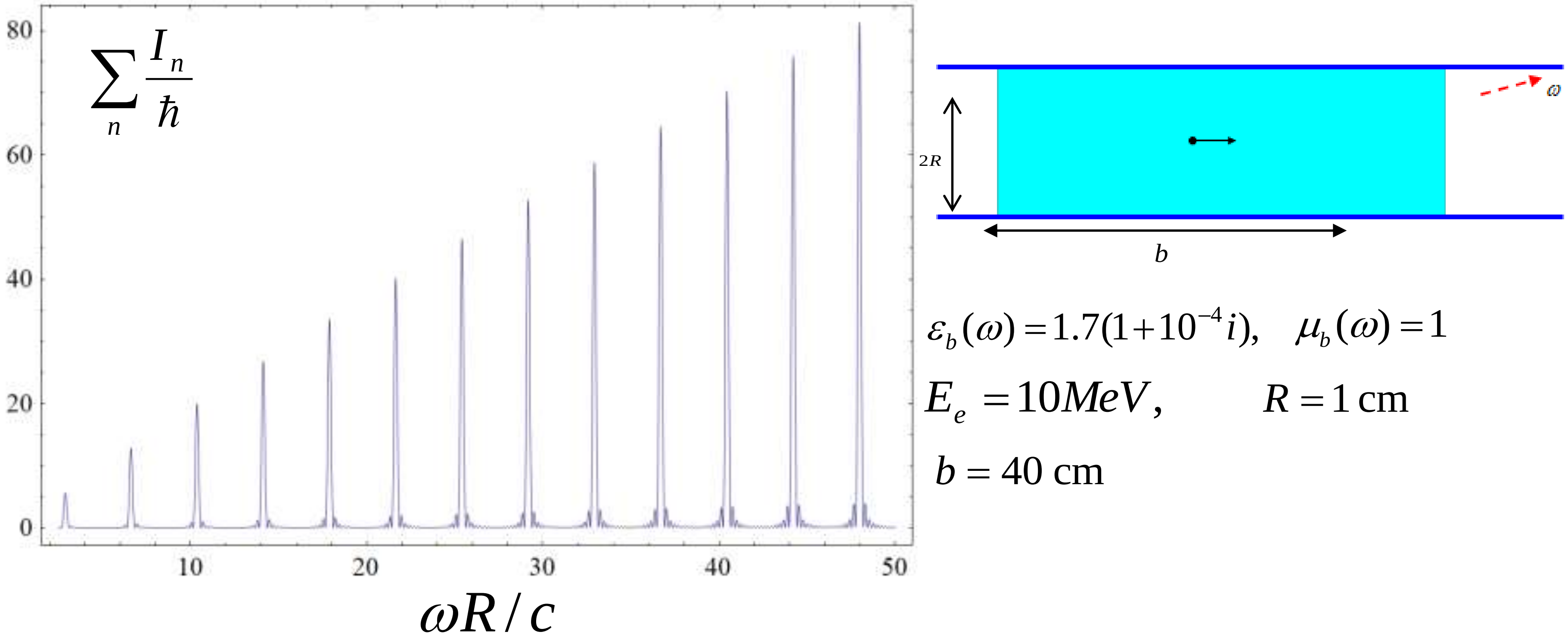
- We have registered coherent Cherenkov radiation of a picosecond electron bunch at the AREAL accelerator (in the frequency range 10-60 GHz) and measured its angular distribution.

- We plan to investigate the spectral-angular distribution of radiation of chains of electron bunches in cylindrical dielectric target.

- In this regard, we have theoretically investigated the radiation of a chain of relativistic electron bunches flying through a waveguide partially filled with a dielectric.

IV. Theoretical estimates

Figure below presents the results of theoretical investigation of spectral distribution of radiation energy of a single electron passing through a dielectric plate in waveguide (L.Sh. Grigoryan, et. al., IL Nuovo Cimento **34C** (2011) 317), L.Sh. Grigoryan, et. al., J. Phys.: Conf. Ser. **357** (2012) 012004, A.R. Mkrtchyan et. al., JINST **15** (2020) C06019)



$\varepsilon_b(\omega) = 1.7(1+10^{-4} i), \quad \mu_b(\omega) = 1$

$E_e = 10 MeV, \quad R = 1\text{ cm}$

$b = 40\text{ cm}$

Radiation energy from electron crossing a dielectric plate in cylindrical waveguide

IV. Theoretical estimates

The radiation energy W of a chain of bunches passing through a plate in a cylindrical waveguide:

$$W = \sum_n W_n = \sum_{n=1}^{\infty} \int_{\omega_n}^{\infty} F(\omega) I_n(\omega)\, d\omega$$

$W_n \Leftarrow$ radiation energy on the n-th mode of the waveguide

$I_n \Leftarrow$ spectral density of the radiation energy of a single particle

$\omega_n \Leftarrow$ boundary frequency of the n-th mode.

Structure factor of a chain $\quad F = n_q (1 - f_q f_{tr}) n_b + n_q^2 f_q n_b^2 f_{tr}$

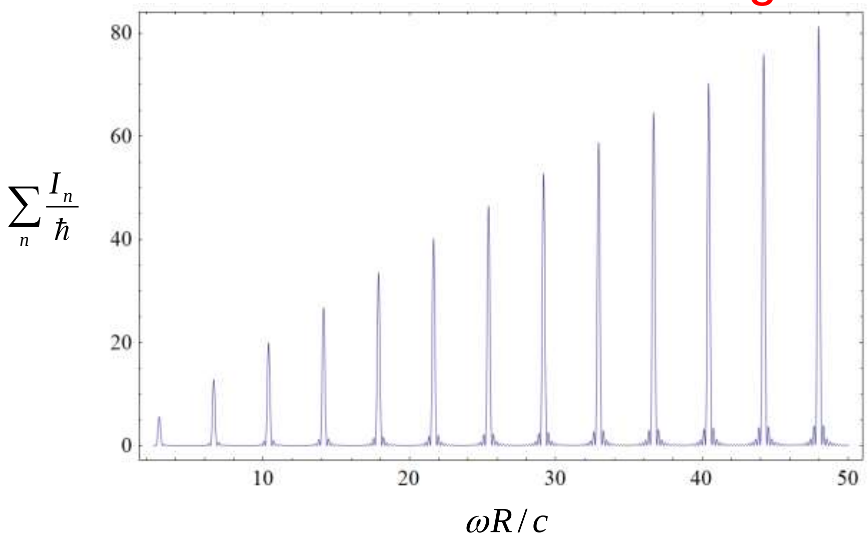
where $\quad f_q = \exp(-\omega^2 \sigma^2 / \mathrm{v}^2) \qquad f_{tr} = \dfrac{\sin^2(\omega d\, n_b / 2\mathrm{v})}{n_b^2 \sin^2(\omega d / 2\mathrm{v})}$

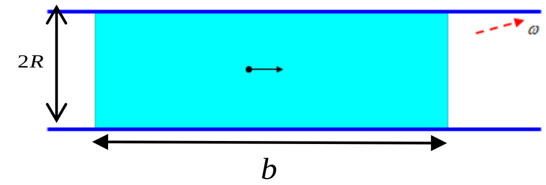
d - distance between bunches

IV. Theoretical estimates

Case of single electron

Fig. 8.





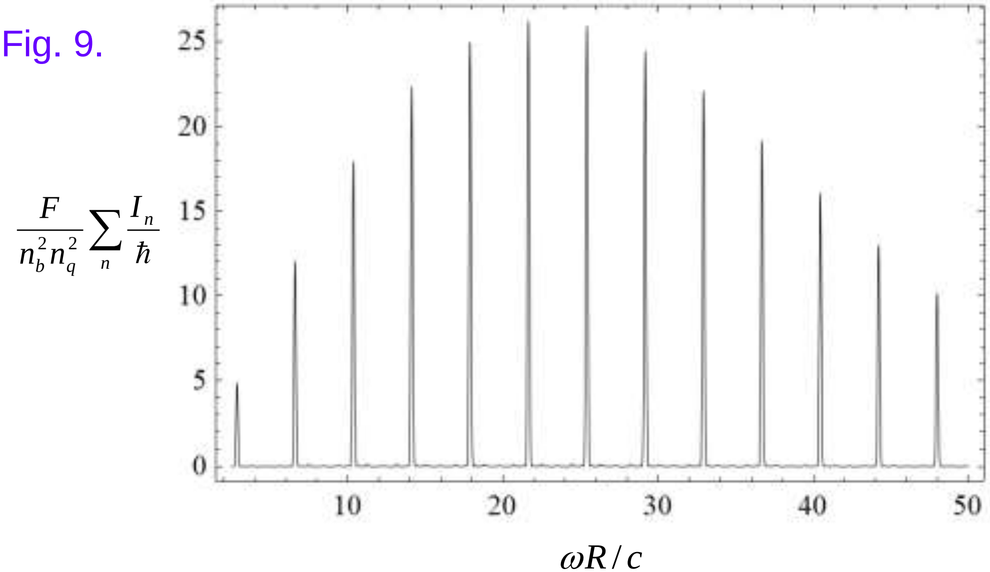
$$\varepsilon_b(\omega) = 1.7(1+10^{-4} i), \quad \mu_b(\omega) = 1$$

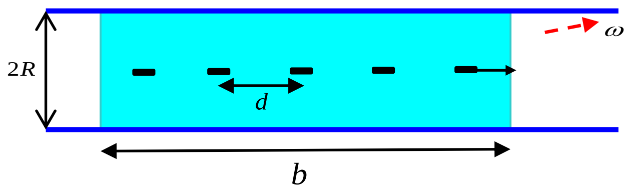
$$E_e = 10 MeV, \qquad R = 1\text{ cm}$$

$$b = 40\text{ cm}$$

Case of chain of bunches

Fig. 9.



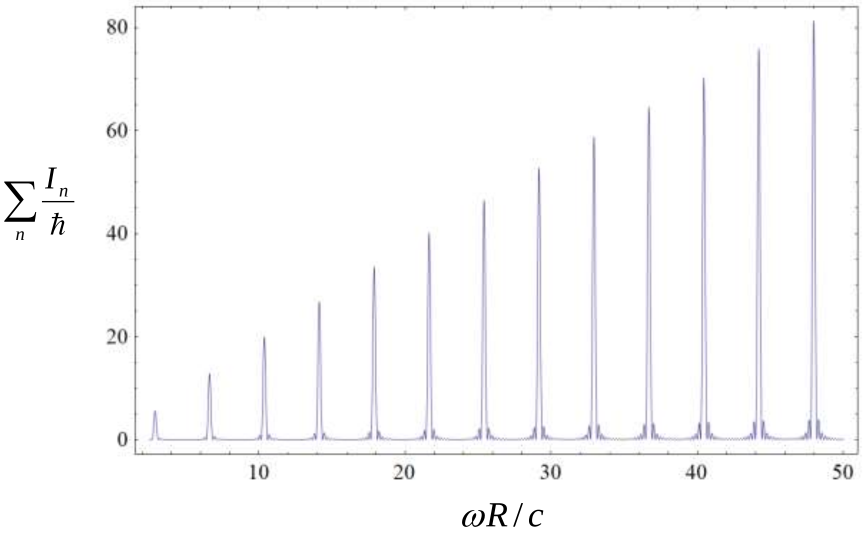


$$n_q = 10^9, \quad n_b = 5, \quad \sigma = 0.03\text{ cm}$$

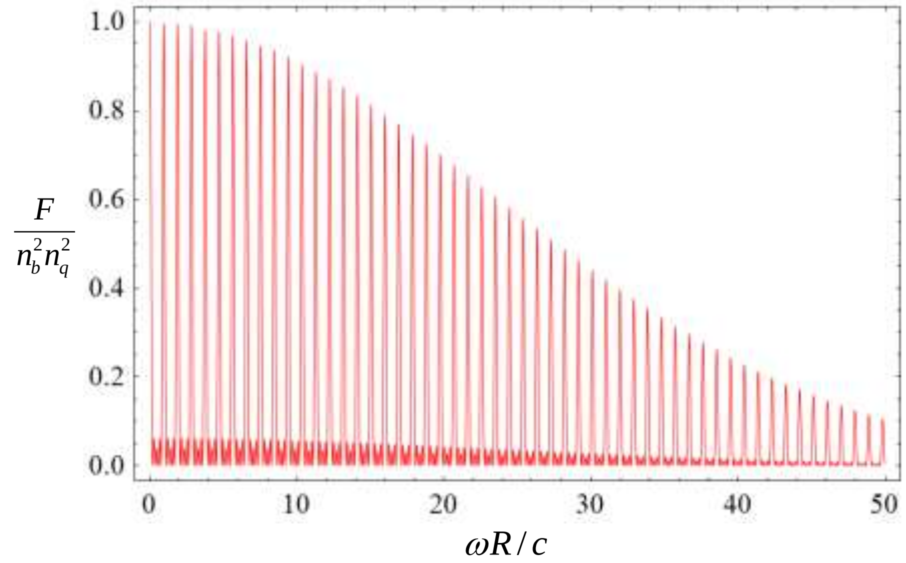
$$d = 8R\sqrt{\varepsilon v^2 / c^2 - 1} = 6.67\text{ cm}$$

IV. Theoretical estimates

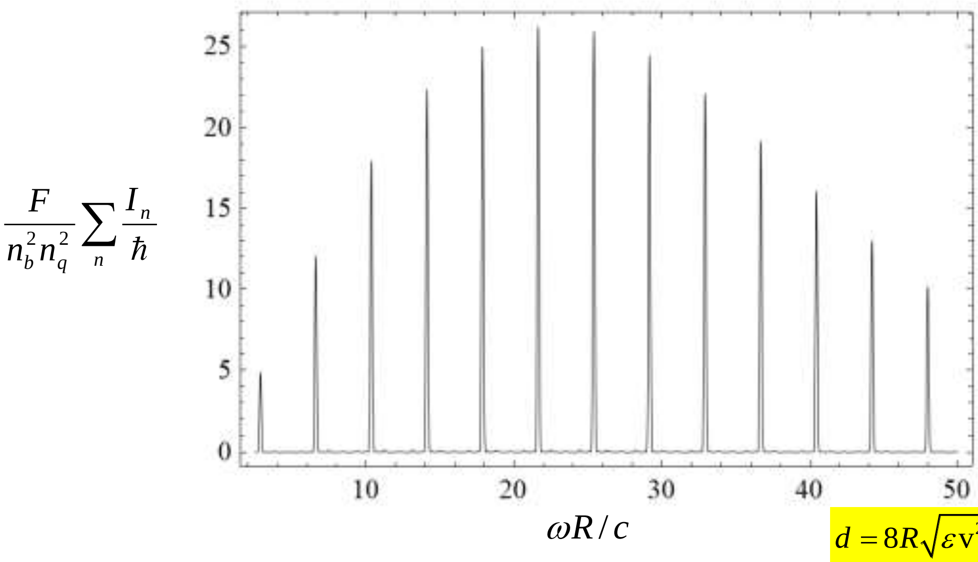
Case of single electron

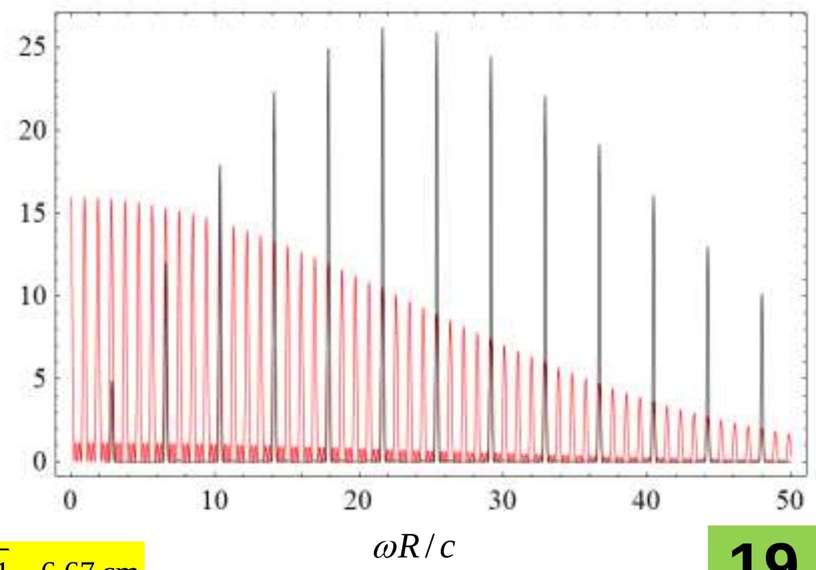


Structure factor



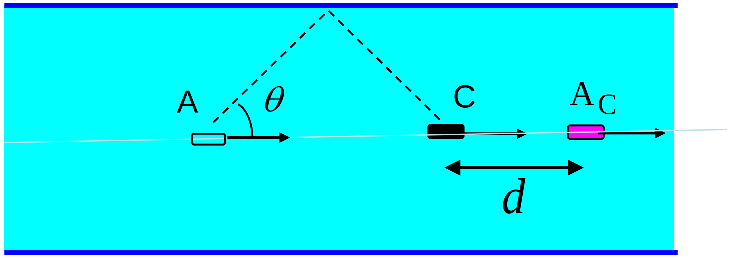
Case of chain of bunches





$d = 8R\sqrt{\varepsilon \mathrm{v}^2/c^2 - 1} = 6.67\ \mathrm{cm}$

V. Visual explanation



Consider the Cherenkov wave (dotted line) emitted by the first bunch at point A. While propagating, at some time moment the wave will approach the bunch trajectory at point C.

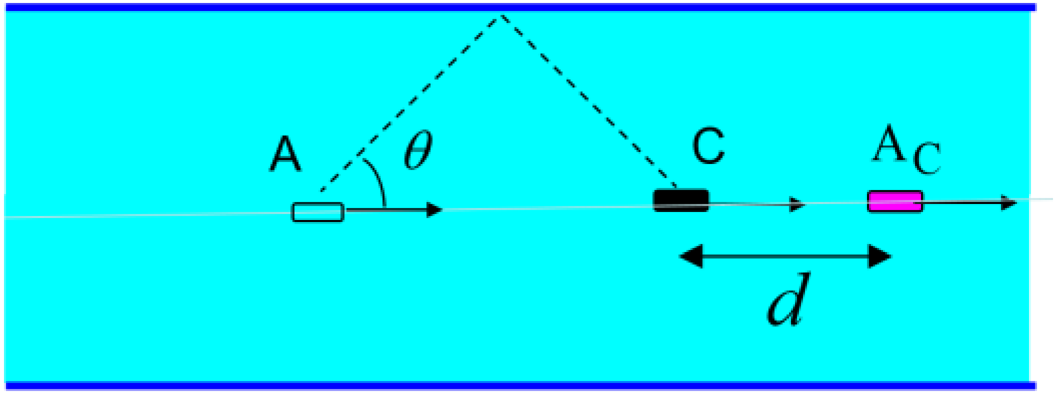
By this point in time, it will lag behind its source (the first bunch), which, moving at superluminal speed, will be at the point A_C. In this case, the second bunch of the chain is to the left at a distance *d* from the first one, and if

$$d_0 = CA_C \qquad CA_C = 2R\sqrt{\varepsilon v^2/c^2 - 1} \qquad (8)$$

then it will be in the vicinity of point C simultaneously with the wave.

Thus, in the areas directly adjacent to each of the bunches (with the exception of the first), two processes will simultaneously occur: emission and interference of waves.

V. Visual explanation



The in-phase superposition ($d = 4d_0$) of electromagnetic oscillations would go with an amplification of field in the zone of radiation formation. As a result, the force retarding the motion of bunches also increases, and an additional work performed by the external force constraining the uniform motion of bunches shall be used for formation of higher power resonant CR stimulated on the large number of neighboring modes.

This explains the resonant increase (stimulation) of the quasi-coherent CR on a large number of waveguide modes.

$$d = 4 \times 2R\sqrt{\varepsilon \mathrm{v}^2 / c^2 - 1}$$

VI. Conclusions

1) The results of experimental observation of angular distribution of coherent CR from picosecond electron bunches traveling along the axis of a hollow cylindrical dielectric loaded waveguide are presented.
2) Polarization measurements confirmed observation of coherent CR with horizontal polarization.
3) Theoretically it was shown that with a special choice of the distance between bunches excitation of quasi coherent CR from a train of bunches passing a plate in waveguide may be stimulated on the large number of neighboring waveguide modes.
4) A visual explanation of this effect was given.
5) It is proposed to use the effect of stimulated excitation of the quasi coherent CR on the large number of neighboring modes for an additional increase of the power of experimentally observed resonant and coherent THz radiation ([2,3]).

References

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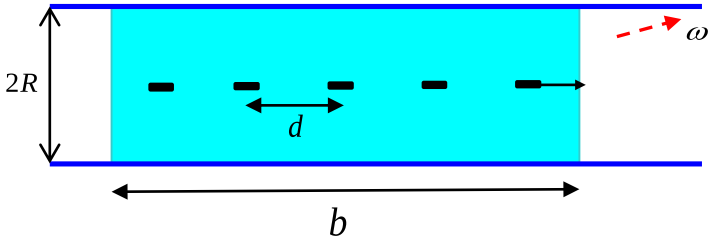

$$d \neq 2\pi \mathrm{v}/\omega_s \qquad \boxed{d \simeq 8R\sqrt{\varepsilon \mathrm{v}^2/c^2 - 1}}$$

Thank you for attention

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Nondestructive diagnostic for electron bunch length in accelerators using the wakefield radiation spectrum

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We report the development of a nondestructive technique to measure bunch rms length in the psec range and below, and eventually in the fsec range, by measuring the high-frequency spectrum of wakefield radiation which is caused by the passage of a relativistic electron bunch through a channel surrounded by a dielectric. We demonstrate numerically that the generated spectrum is determined by the rms bunch length, while the specific axial and longitudinal charge distribution is not important. Measurement of the millimeter-wave spectrum will determine the rms bunch length in the psec range. This has been done using a series of calibrated mesh filters and the charge bunches produced by the 50 MeV rf linac system at ATF (Accelerator Test Facility), Brookhaven. We have developed the analysis of the factors crucial for achieving good accuracy in this measurement, and find the experimental data are fully understood by the theory. We point out that this technique also may be used for measuring fsec bunch lengths, using a prepared planar wakefield microstructure.

DOI: 10.1103/PhysRevSTAB.8.062801 PACS numbers: 41.85.Qg, 41.75.Ht, 41.60.Bq, 84.40.−x

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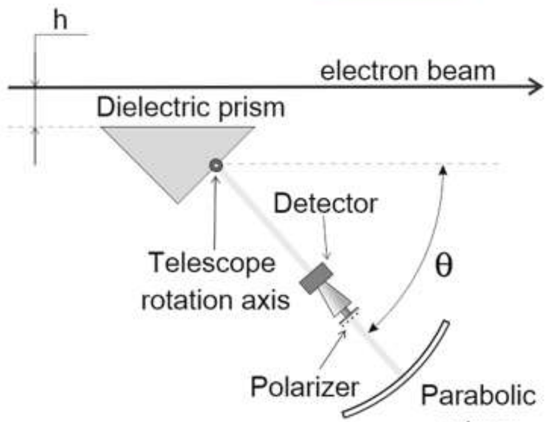
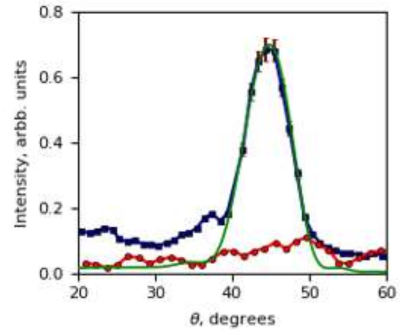
Journal of Physics: Conference Series **236** (2010) 012025 doi:10.1088/1742-6596/236/1/012025

Investigation of coherent Cherenkov radiation generated by 6.1 MeV electron beam passing near the dielectric target

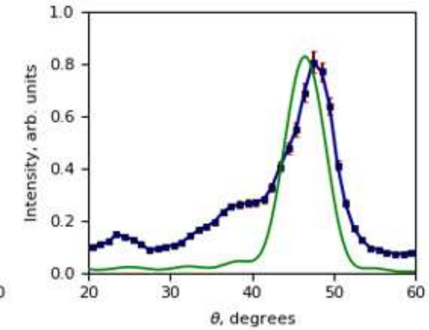
A. Potylitsyn, Yu. Popov, L. Shukhikh, G. Naumenko, M. Shevelev



Teflon prism, n=1.41



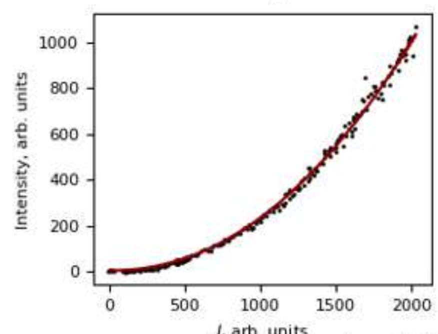
Paraffin prism, n=1.49



TPU Detector

Spectral range: 6-100 GHz (3-50 mm);
Responsivity: 20 V/W.

Current dependence



$$y = 4.53 + 10^{-4} \cdot I^{2.12}$$

Impact-parameter dependence