Coherent Cherenkov radiation from ultra-short electron bunch passing through vacuum channel in conical target

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RREPS_11, London, 2011, Sept.12-16

- Motivation
- Existing experimental results and discussion
- New theoretical model
- Experiment at Tomsk microtron
- Measurement of bunch length using «natural Cherenkov spectrometer»
- Conclusions

Few femtosecond, few kiloampere electron bunch produced by a laser–plasma accelerator

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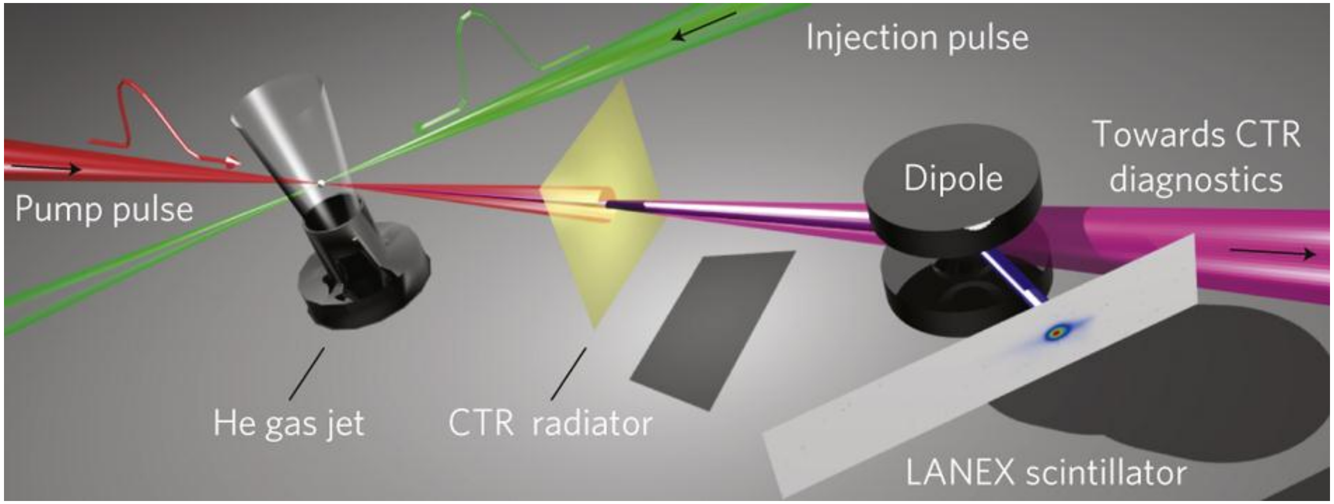
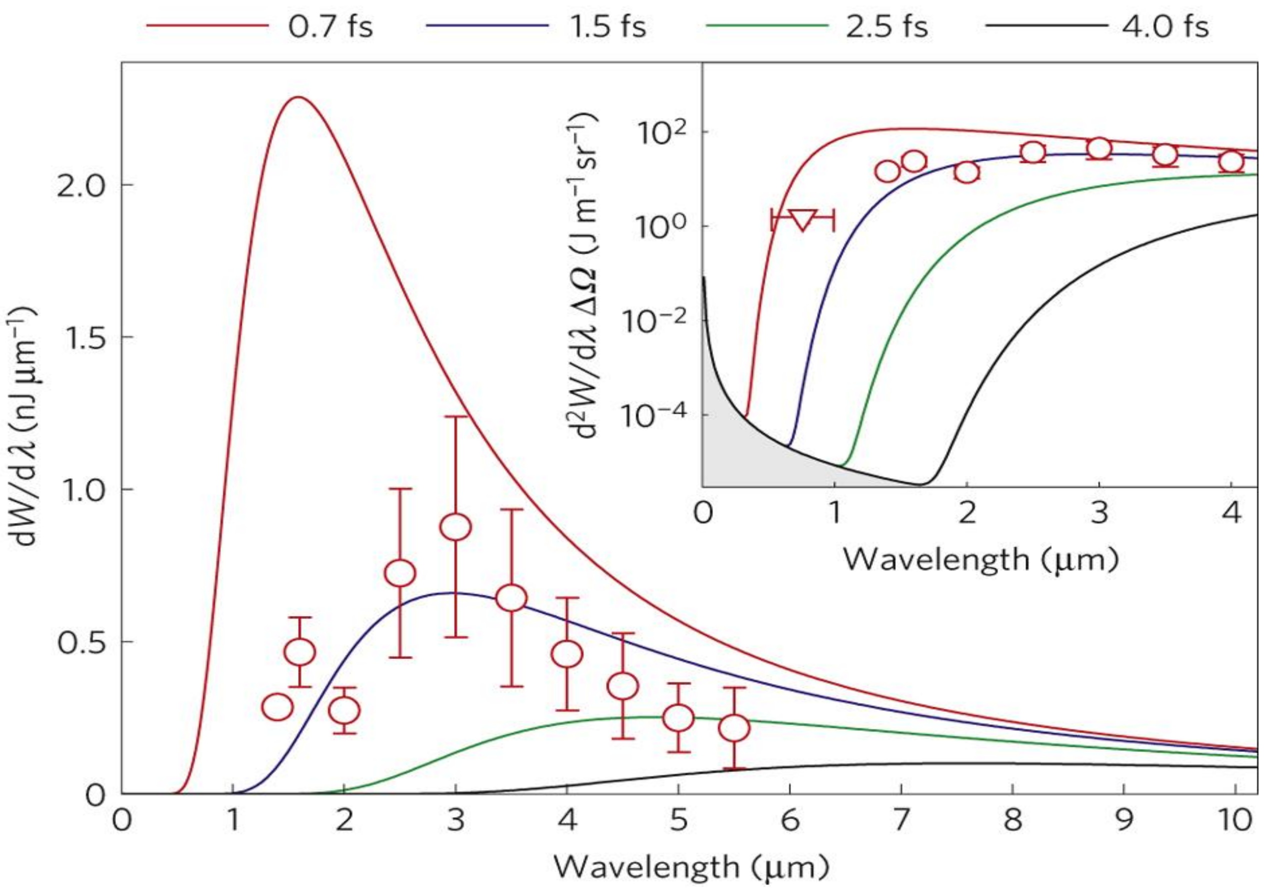
The 30 fs (full-width at half-maximum (FWHM)) pump pulse and injection pulse collide at an angle of 135° in the centre of a 3 mm helium gas jet. The geometry of this arrangement allows a 100 μm Al foil, used for generation of transition radiation, to intercept the electron beam 15 mm from the exit of the gas jet. The accelerated electron beam is highly relativistic, stable and quasi-monoenergetic (see Methods and Supplementary Fig. S1). On average, the peak charge and peak energy are 15 pC and 84 MeV respectively. We estimate that temporal stretching during transport to the radiator due to energy spread and divergence is negligible. The beam diameter on the radiator is estimated to 90 μm (FWHM)



The CTR spectrum is calculated for Gaussian bunch shapes, $f(t) \propto \exp[-t^2/2\sigma^2]$, with different root mean square (r.m.s.) durations σ. A good agreement, in intensity and wavelength of peak intensity, is found for a bunch duration of σ=1.5 fs. For a bunch charge of 15 pC, this leads to an inferred peak current of 4 kA (for a Gaussian pulse shape).



DESIGN OF A SINGLE-SHOT PRISM SPECTROMETER IN THE NEAR- AND MID-INFRARED WAVELENGTH RANGE FOR ULTRA-SHORT BUNCH LENGTH DIAGNOSTICS*

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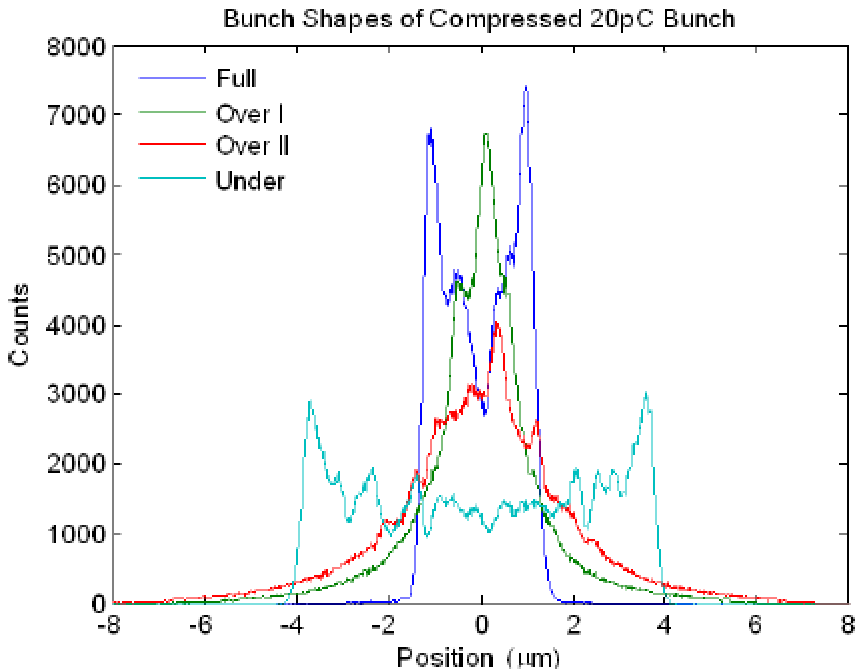
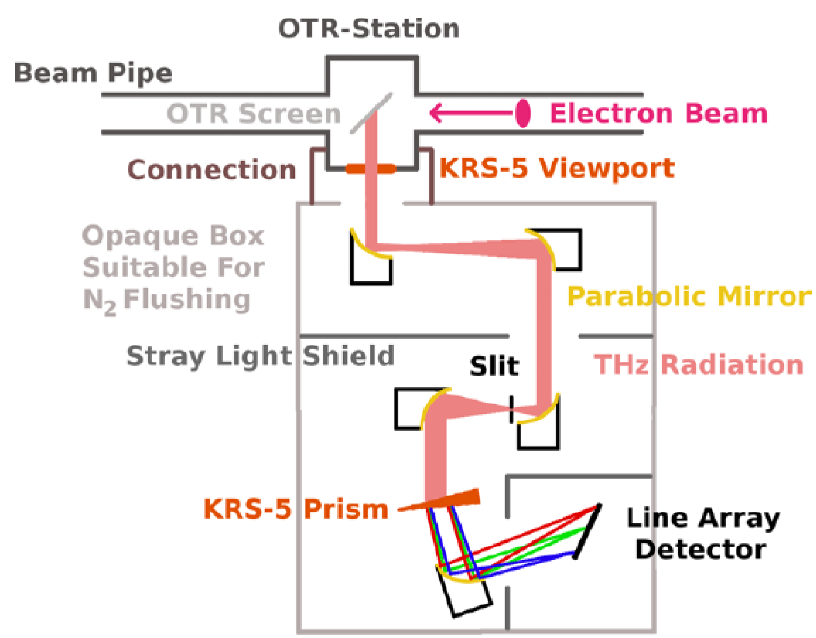
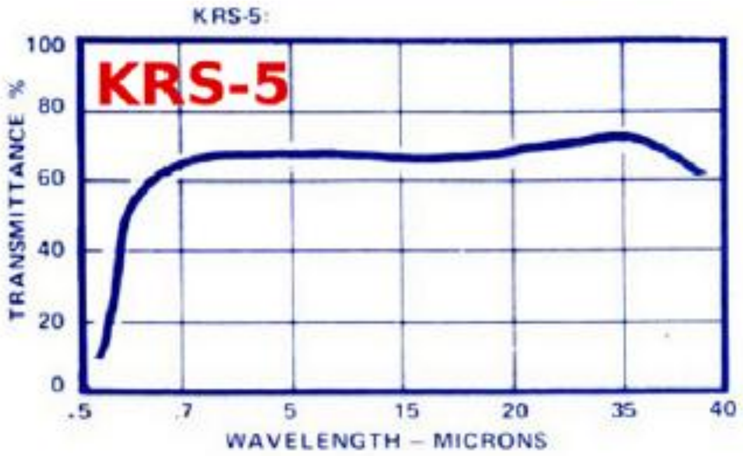
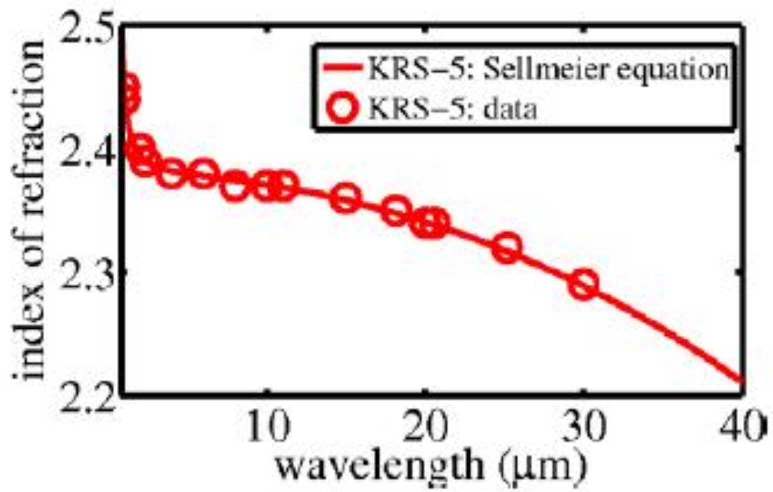




Thallium Bromiodide (KRS-5):

Optical Crystals KRS5 (TlBr-TlI) is a deep IR material with a high refractive index, KRS-5 is used extensively in spectroscopy for attenuated total reflectance(ATR) prisms, windows and lenses. In conjunction with Germanium, KRS-5 can also be used in thermally compensated IR imaging systems.





A design of a prism spectrometer for the operation in the near- and mid-infrared wavelength range dedicated for ultra-short bunch length diagnostics.

We showed the possibility to cover the broad wavelength range from 0*.8-39 µm using a KRS-5 prism.*

Sellmeyer's formula for wavelength range 0,5-40 µm:

$$\varepsilon(\lambda) = 1 + \frac{3,744239\,\lambda^2}{\lambda^2 - 0,2079603^2} + \frac{0,9189162\,\lambda^2}{\lambda^2 - 0,3765643^2} + \frac{12,5444602\,\lambda^2}{\lambda^2 - 165,6525518^2},$$

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Observation of coherent Čerenkov radiation from a solid dielectric with short bunches of electrons

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Short bunches of 150-MeV electrons of a linear accelerator passed along the surface of a crystal quartz or a teflon and coherent Čerenkov radiation from the solid dielectrics has been observed in the wavelength range from 0.5 to 4 mm. Properties of the radiation have been experimentally investigated. The angular distribution of the observed radiation showed a maximum peak in the direction of the Čerenkov angle with several satellite peaks. The intensity increased linearly with increasing the length of the medium and was proportional to the square of the number of electrons in the bunch. The spectral intensity was enhanced by almost five orders of magnitude in comparison with the theoretical calculation of incoherent radiation.

PACS number(s): 41.60.Bq, 07.57.Hm, 41.75.Ht, 52.75.Va

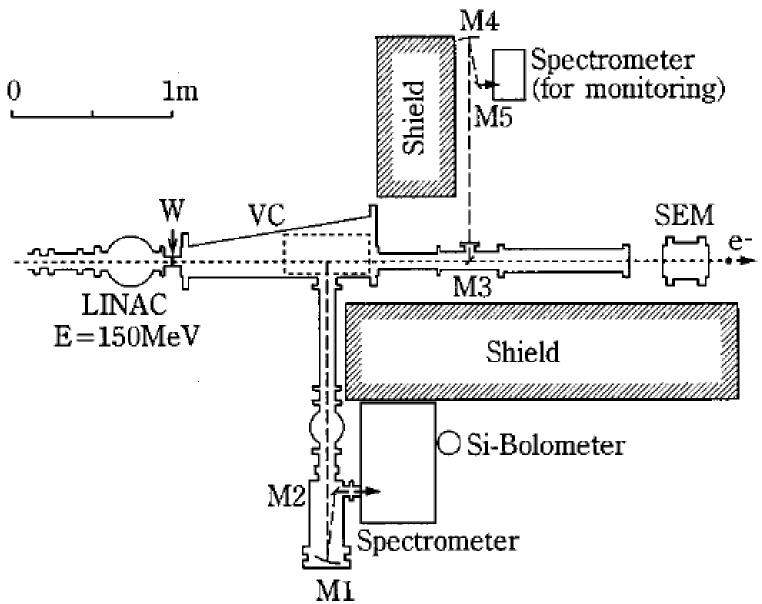


FIG. 1. The arrangement of the experiment. (VC) a vacuum chamber; (W) a titanium window 15 μm thick; (M2, M3, M5) plane mirrors; (M4) a spherical mirror; (SEM) a secondary emission monitor; and (e^-) electron beam.

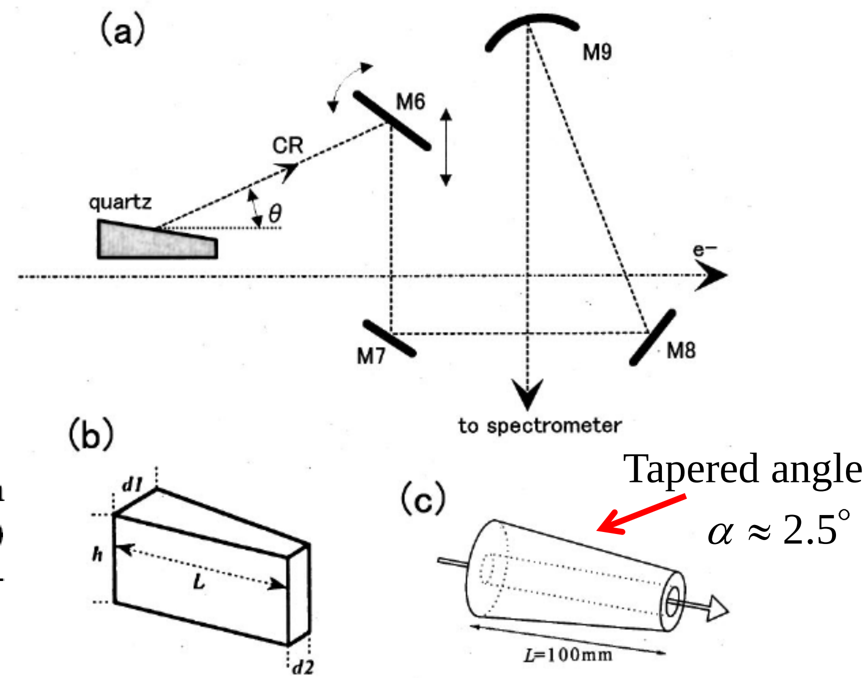
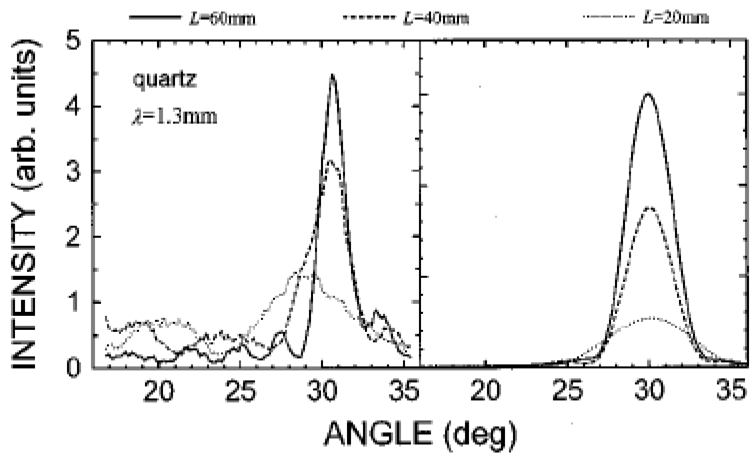
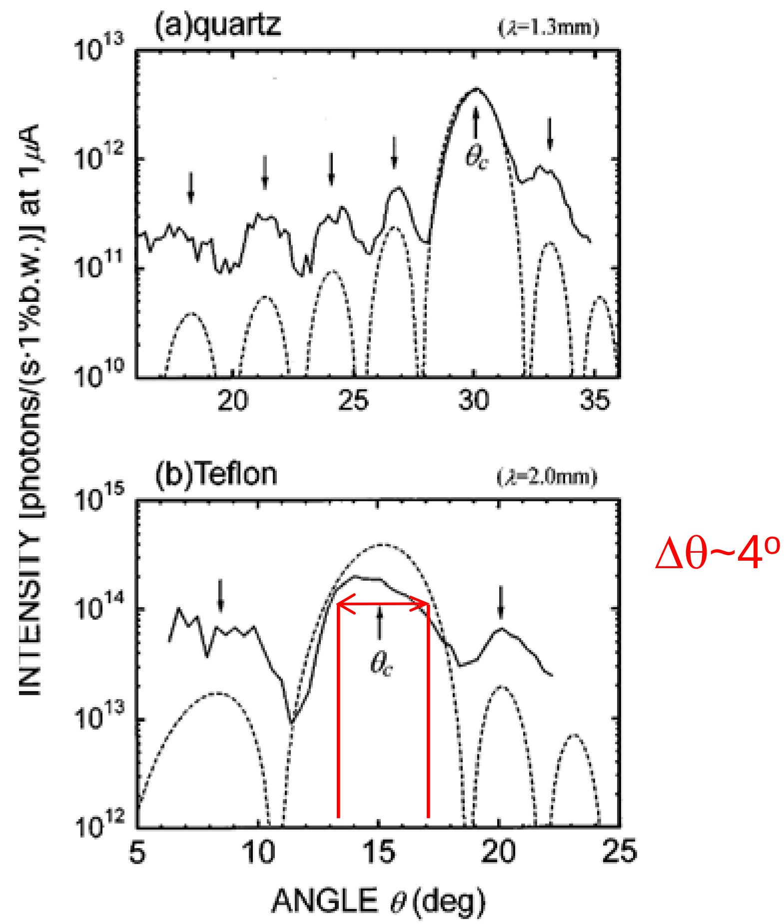


FIG. 2. The schematic view in the vacuum chamber. (a) The sectional diagram of the optical components, (b) the block of quartz, and (c) the cone of teflon with the cylindrical hole of 7 mm. (M6, M7, M8) plane mirrors; (M9) a spherical mirror; and (e^-) electron beam. The values of dimensions in (c) are listed in Table II.



The dependence of the angular distribution on the length of quartz. The solid, broken, and dotted curves represent the data for quartz of 60, 40, and 20 mm long, respectively. The curves at the right-hand side show the theoretical calculation.



The angular distribution of radiation from the quartz of 60 mm long at λ = 1.3 mm and the teflon of 100 mm long at λ = 2.0 mm. The data are plotted on a logarithmic scale in order to visualize satellite peaks in the angular distribution.

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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.

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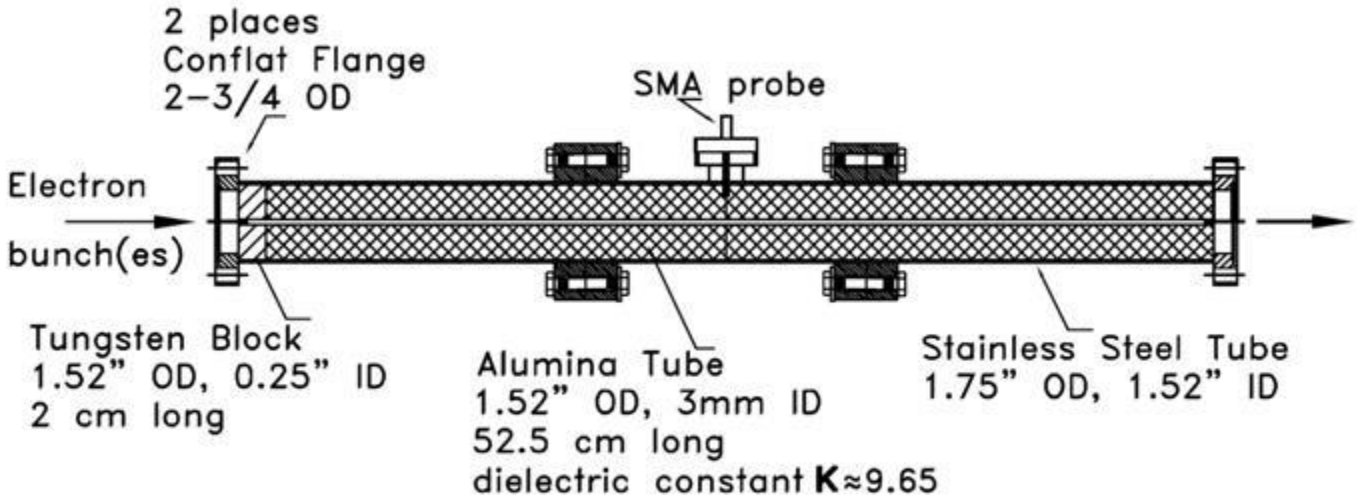
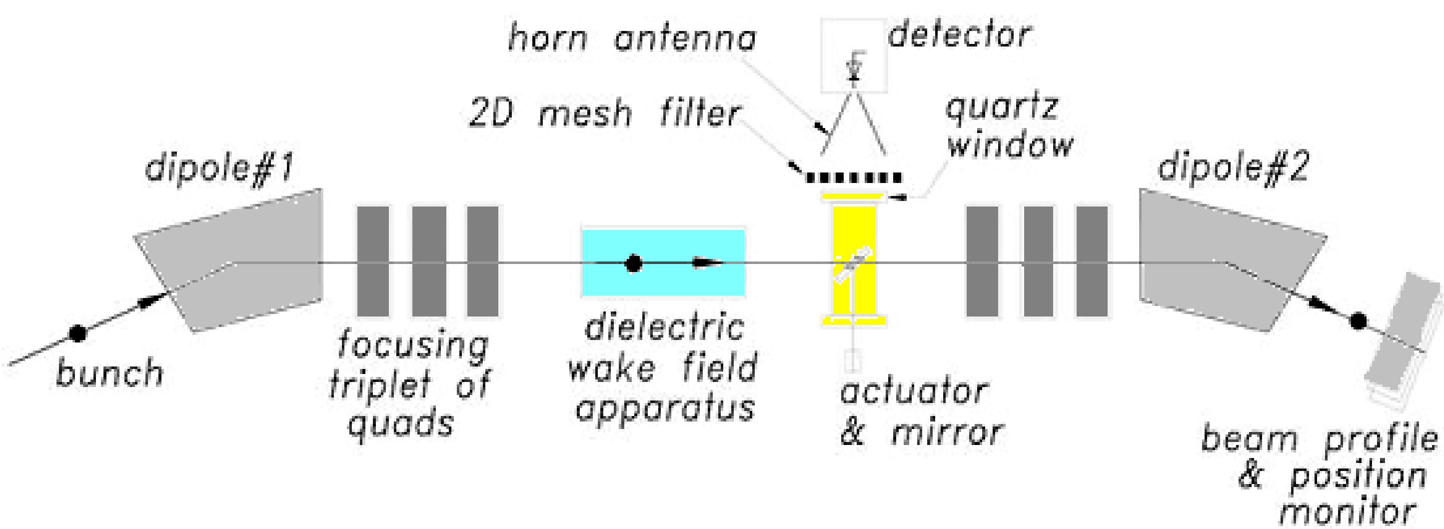
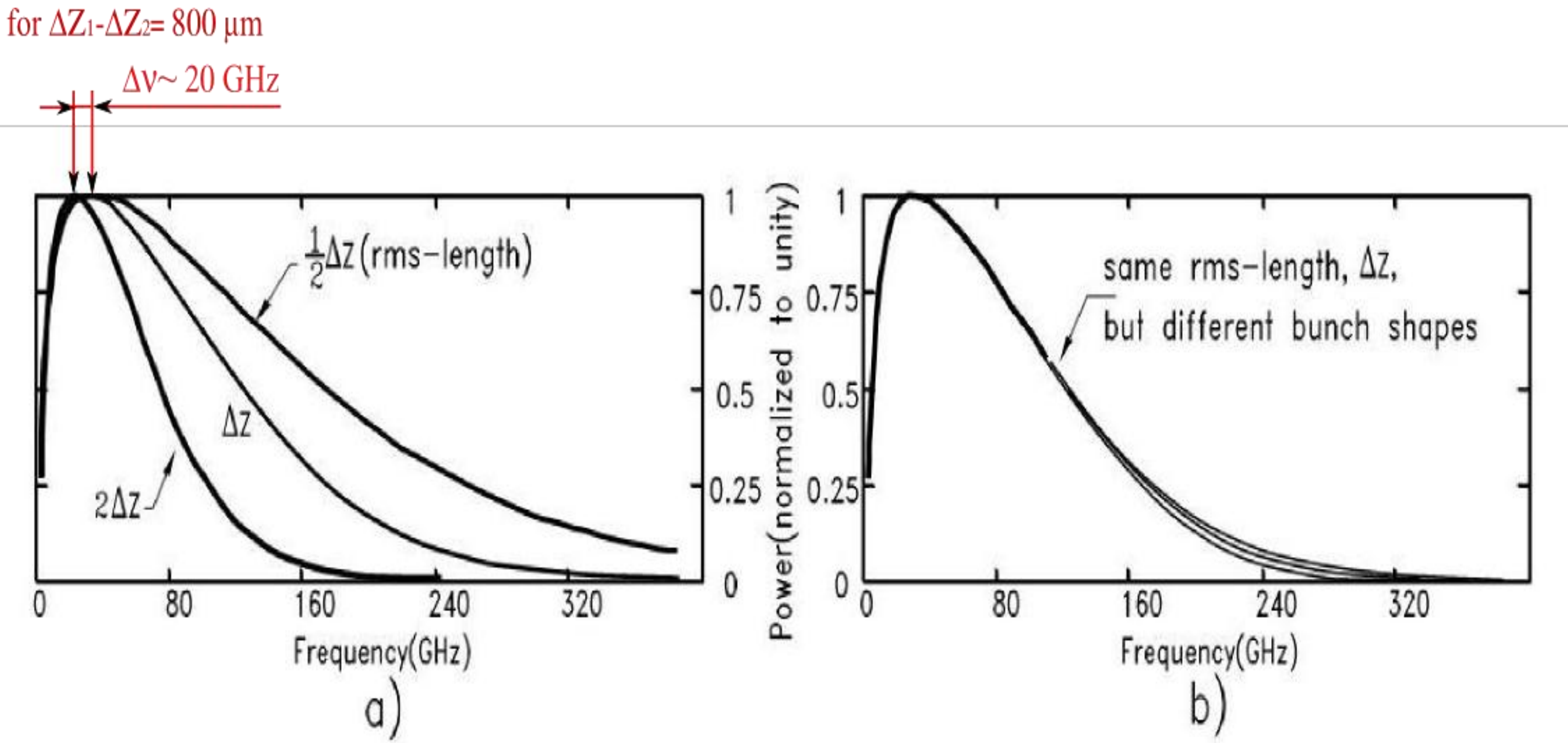


Diagram of the dielectric-lined beam line element installed in the Omega-P/Yale/Columbia experiment at ATF, Brookhaven for studying wakefields.

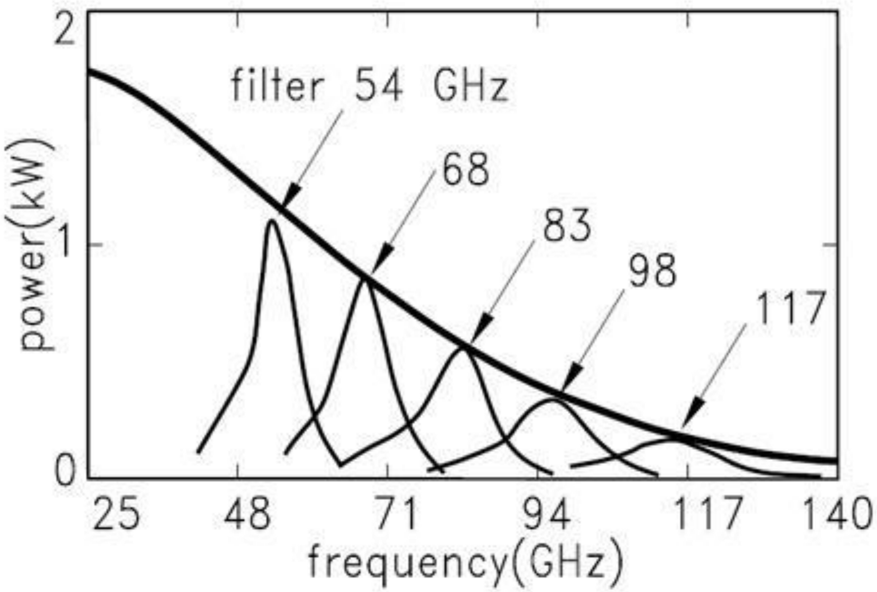
This is to insure that Cerenkov wakefield radiation dominates the transition radiation that is emitted as the bunch enters or leaves the structure. Furthermore, experience has



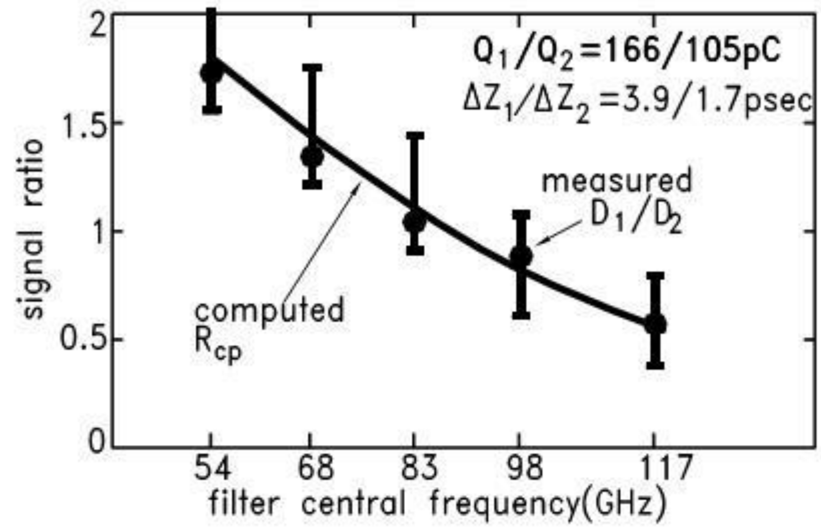
Schematic of portion of the beam line, showing transverse radiation output by use of 45° deflecting mirror



Power spectrum that we predict to be emitted from a typical well-focused bunch obtained at ATF-BNL. (a) Radiation from a Gaussian charge distribution having different rms length (here Δz = 1.8 psec, and for the sake of convenience, we measure the rms length in units of time, i.e., Δz = 1.8 psec corresponds to $c \times 1.8$ psec ≈ 540 μm); (b) spectrum generated by three different bunch shapes: a Gaussian, an asymmetrical triangular (tail/head = 4/1), and a rectangular charge distribution along the bunch-length axis.



Filters break the spectrum of wakefield radiation into five channels. The solid line is the theoretical emitted spectrum from a single bunch having rms length of 4.2 psec and charge 310 pC.



Comparison of the computed R_{cp} with the measured D_1/D_2 for each channel (fixed wavelength) for two different bunch lengths (3.9 and 1.7 psec) and charges (166 and 105 pC). The solid black line is the computed R_{cp} after one has measured bunch charges, and rms lengths by an independent technique. The dots represent the measured D_1/D_2. The variation in charge from one shot to another is measured by calculating the charge variation from the signal variation of the detector.

The minimum rms length one can resolve with this technique is

$$\Delta Z_{\mathrm{Min}} = \sqrt{C_{\Delta Z} \times (\Delta D / 2D)}.$$

For the ATF experimental setup and $(\Delta D / 2D) \approx 1.5\%,$

$$C_{\Delta Z} \approx 13.8\,\mathrm{psec}^2\,(\mathrm{f}_{\mathrm{max}} = 120\,\mathrm{GHz}),$$

one may expect to resolve the rms length $\Delta Z \geq 450\mathrm{fsec}\ \ (\square\ 150\mu\mathrm{m})$

Using the same dielectric-lined structure but changing to the range

of filtered frequencies up to 300 GHz, one reduces $C_{\Delta Z} \approx 2.4\,\mathrm{psec}^2.$

With $(\Delta D / 2D) \approx 1.5\%,$ one could resolve the rms length $\Delta Z \geq 190\mathrm{fsec}\,(\square\ 60\mu\mathrm{m})$

A Coherent Cherenkov radiation spectrum is defined by geometry of dielectric wave guide also.

PRL 103, 095003 (2009) PHYSICAL REVIEW LETTERS week ending 28 AUGUST 2009

Observation of Narrow-Band Terahertz Coherent Cherenkov Radiation from a Cylindrical Dielectric-Lined Waveguide

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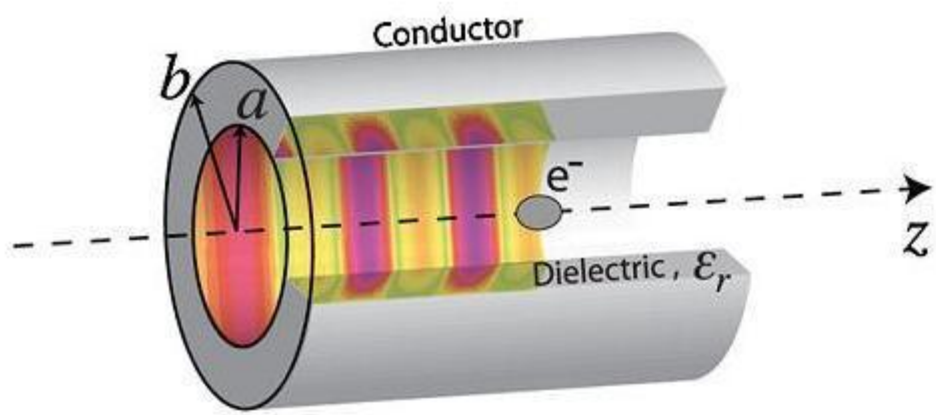
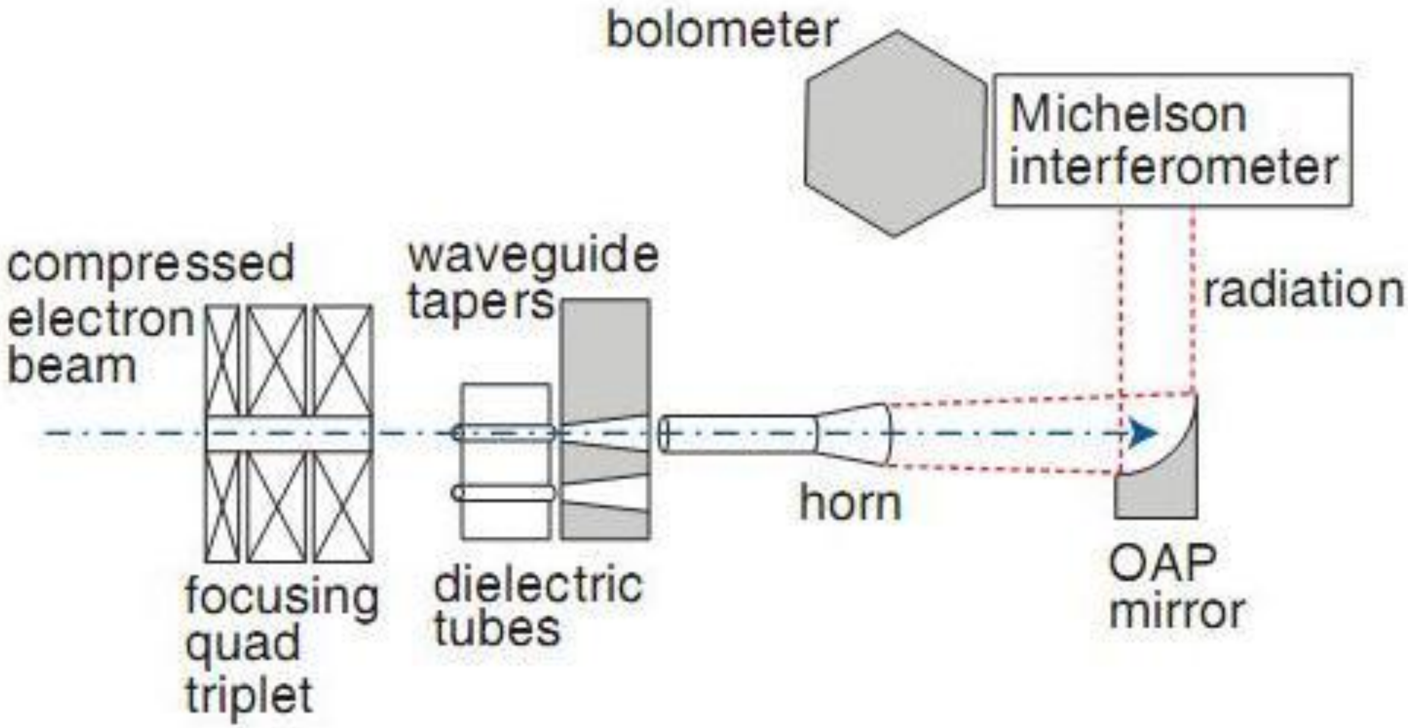
We report experimental observation of narrow-band coherent Cherenkov radiation driven by a subpicosecond electron bunch traveling along the axis of a hollow cylindrical dielectric-lined waveguide. For an appropriate choice of dielectric wall thickness, a short-pulse beam current profile excites only the fundamental mode of the structure, producing energetic pulses in the terahertz range. We present detailed measurements showing a narrow emission spectrum peaked at 367 ± 3 GHz from a 1 cm long fused silica capillary tube with submillimeter transverse dimensions, closely matching predictions. We demonstrate a 100 GHz shift in the emitted central frequency when the tube wall thickness is changed by 50 μm. Calibrated measurements of the radiated energy indicate up to 10 μJ per 60 ps pulse for an incident beam charge of 200 pC, corresponding to a peak power of approximately 150 kW.

TABLE I. Experimental parameters.

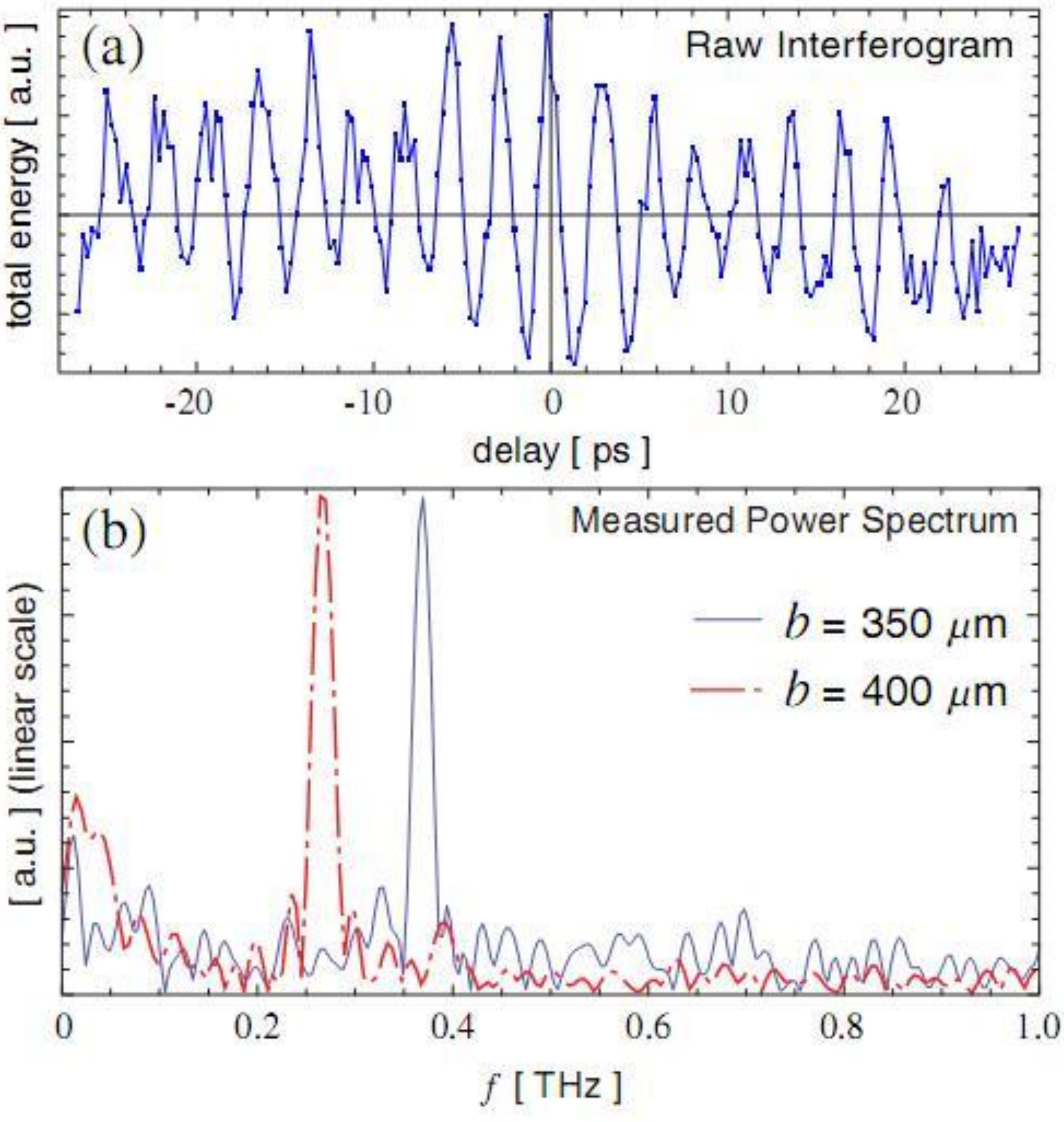
Bunch charge	Q	200 pC
rms bunch length	σ_z	200 μm
rms bunch radius	σ_r	80 μm
β function		1 cm
Beam energy		10–11 MeV
Dielectric inner radius	a	250 μm
Dielectric outer radius	b	350, 400 μm
Dielectric tube length	L	1 cm
Dielectric constant	ε_r	3.8



Cutaway diagram of beam-driven cylindrical dielectric-lined waveguide.
Color map illustrates longitudinal wakefield.



Schematic of experimental setup.



(a)
Raw Interferogram
total energy [a.u.]
-20
-10
0
10
20
delay [ps]
(b)
Measured Power Spectrum
[a.u.] (linear scale)
b = 350 μm
b = 400 μm
0
0.2
0.4
0.6
0.8
1.0
f [THz]

A charged particle moving nearby a spatially inhomogeneous condensed medium (target) may produce different types of so-called polarization radiation (PR): Cherenkov radiation (CR), transition radiation (TR), diffraction radiation (DR), Smith-Purcell radiation (SPR).

From the macroscopic point of view all these types of radiation arise due to polarization of medium by the external field of the moving charge and may be classified as the manifestation of the so-called polarization radiation (PR).

A source of PR is the polarization current density linearly depending upon external field of a moving particle $\mathbf{E}^0$ PR field $\mathbf{E}^R$ itself (the medium is non-magnetic):

$$\mathbf{j}_{pol} = \sigma(\omega)(\mathbf{E}^0 + \mathbf{E}^R(\mathbf{j}_{pol})), \quad \sigma(\omega) - \text{conductivity}$$

The solution of Maxwell equation written as following [D.V. Karlovets, A.P. Potylitsyn, Pis'ma v ZhETP 90(5), 368 (2009).]

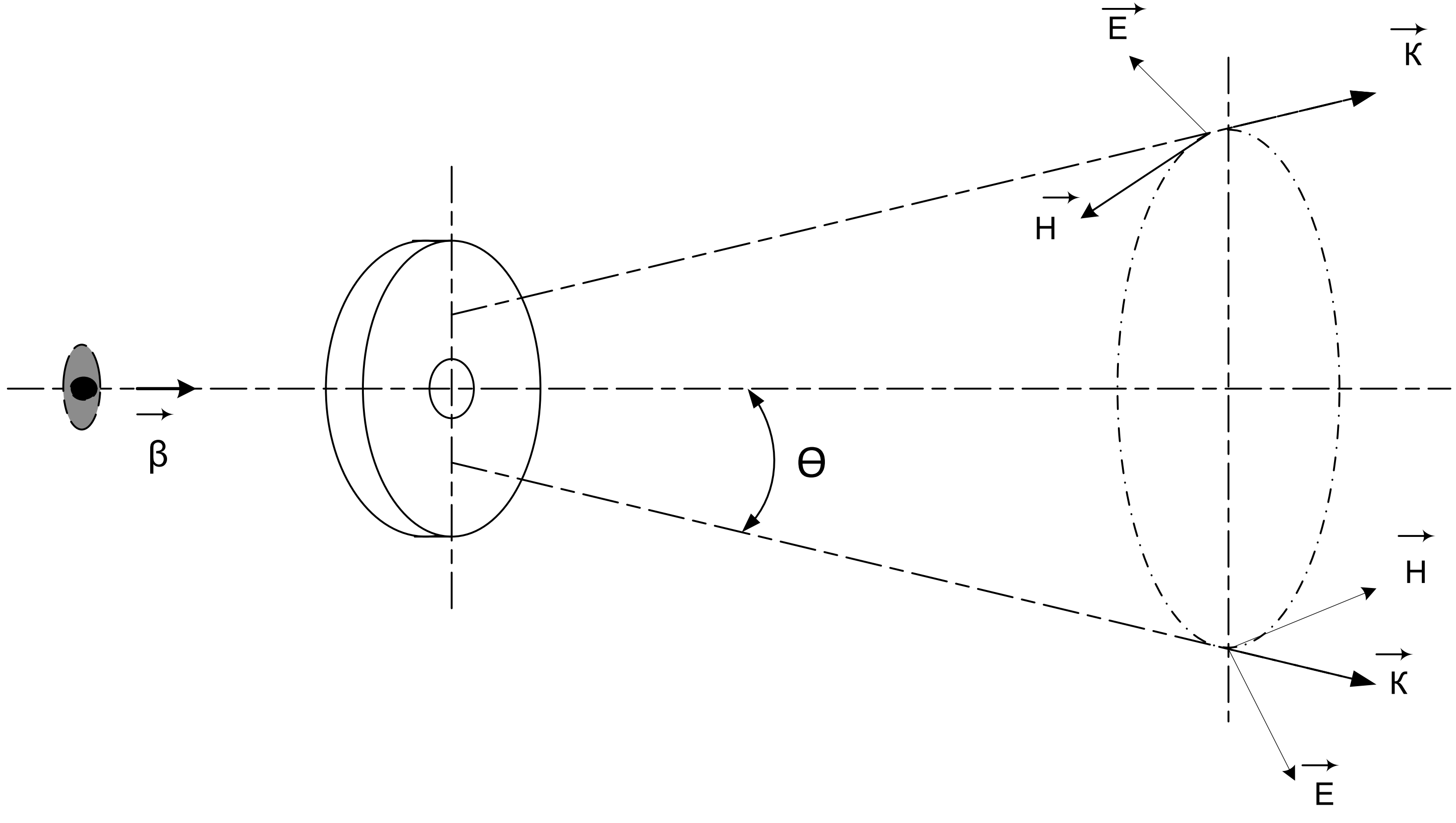
$$\mathbf{H}^R(\mathbf{r},\omega) = \text{curl}\frac{1}{c}\int_{V_T} \sigma(\omega)\mathbf{E}^0(r',\omega)\frac{e^{i\sqrt{\varepsilon(\omega)}\omega|\mathbf{r}-\mathbf{r}'|}}{|\mathbf{r}-\mathbf{r}'|}d^3\mathrm{r}'$$

Where integration is performed only over the volume of the target V_T.

Field of an initial relativistic charge:

$$\mathbf{E}^0(\mathbf{r},\omega) = \frac{e\omega}{\pi v^2\gamma}\left\{\left(\frac{\boldsymbol{\rho}'}{\rho'}K_1\left[\frac{\omega\rho'}{v\gamma}\right] - \frac{i}{\gamma}\frac{\mathbf{v}'}{v'}K_0\left[\frac{\omega\rho'}{v\gamma}\right]\right)\right\}e^{i\frac{\omega}{v}z'}, \qquad \boldsymbol{\rho}' = \left\{\mathrm{x}',\mathrm{y}'\right\}$$

Scheme of Cherenkov radiation generation



PR field in the wave zone is found as:

$$\mathbf{H}^{R}(\mathbf{r},\omega)=\frac{e\,\omega^{2}(\varepsilon-1)}{4\pi^{2}v^{2}c\gamma}\frac{e^{ir\sqrt{\varepsilon(\omega)}\omega}}{r}\mathbf{k}\times\int\limits_{a}^{\infty}\rho' d\rho'\int\limits_{0}^{2\pi}d\varphi'\int\limits_{-d_1}^{d_2}\left(\frac{\boldsymbol{\rho}'}{\rho'}K_1[\frac{\omega\rho'}{v\gamma}]-\frac{i}{\gamma}\frac{\mathbf{v}'}{v'}K_0[\frac{\omega\rho'}{v\gamma}]\right)e^{-i\mathbf{k}\mathbf{r}'+i\frac{\omega}{v}z'}dz'$$

For an azimuthal symmetry of target
(disc with thickness D, inner and outer radius- a, b)

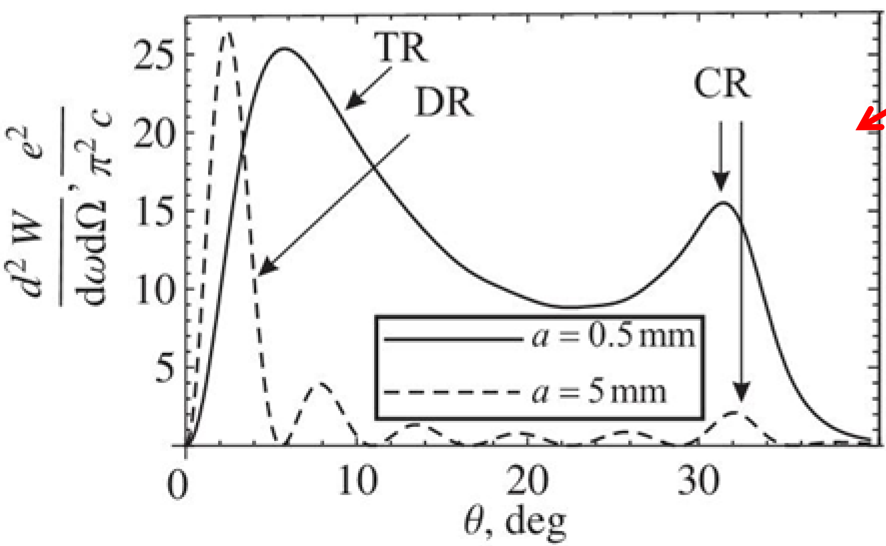
$$\mathbf{H}^{R}(\mathbf{r},\omega)=\{sin\phi,-cos\phi,0\}\frac{e\omega\sqrt{\varepsilon}(\varepsilon-1)}{2\pi c v\gamma^{2}}\frac{e^{ir\sqrt{\varepsilon(\lambda)}\omega/c}}{r}\frac{\left(e^{-i\frac{D}{2}\frac{\omega}{v}(1-\beta\sqrt{\varepsilon(\lambda)}\cos\Theta)}-e^{i\frac{D}{2}\frac{\omega}{v}(1-\beta\sqrt{\varepsilon}\cos\Theta)}\right)}{(\beta^{-1}-\sqrt{\varepsilon}\cos\Theta)(1-\beta^{2}+(\beta\sqrt{\varepsilon}sin\Theta)^{2})}$$

$$\left[\left(\frac{v\gamma}{\omega}-bJ_0[\frac{\omega}{c}b\sqrt{\varepsilon}sin\Theta)]K_1[\frac{\omega b}{v\gamma}]\right)sin\Theta\left(\gamma^{-1}-\beta\gamma\sqrt{\varepsilon}\cos\Theta\right)+\right.$$

$$\left.+bJ_1[\frac{\omega}{c}b\sqrt{\varepsilon}sin\Theta)]K_0[\frac{\omega b}{v\gamma}(\cos\Theta+\beta\sqrt{\varepsilon}sin^{2}\Theta)\right] \qquad (*)$$

In the first approximation introducing the target «effective thickness» $z' = D/2$ one may use formula for spectral-angular distribution of Cherenkov radiation

$$\frac{d^2W}{\hbar d\omega d\Omega} = \frac{e^2\beta^2\sqrt{\varepsilon(\omega)}}{\pi^2 c}\frac{\sin^2\left(\frac{\omega}{v}\frac{D}{2}(1-\beta\sqrt{\varepsilon(\omega)}\cos\Theta)\right)}{(1-\beta\sqrt{\varepsilon(\omega)}\cos\Theta)^2}\left[\frac{(\varepsilon-1)(1-\beta^2-\beta\sqrt{\varepsilon(\omega)}\cos\Theta)}{(1-\beta^2+(\beta\sqrt{\varepsilon(\omega)}\sin\Theta)^2)}\right]^2\sin^2\Theta$$



Angular distributions total polarization radiation in vacuum calculated using the formula (*) . Parameters: $\gamma = 10$, $\lambda = 1$mm, $b \to \infty$, $D = 40mm$, $\varepsilon = 1.3 + i\,0.05$ (dashed curve is multiplied by the factor 60). The angle of Cherenkov radiation reflected into vacuum is determined from the condition

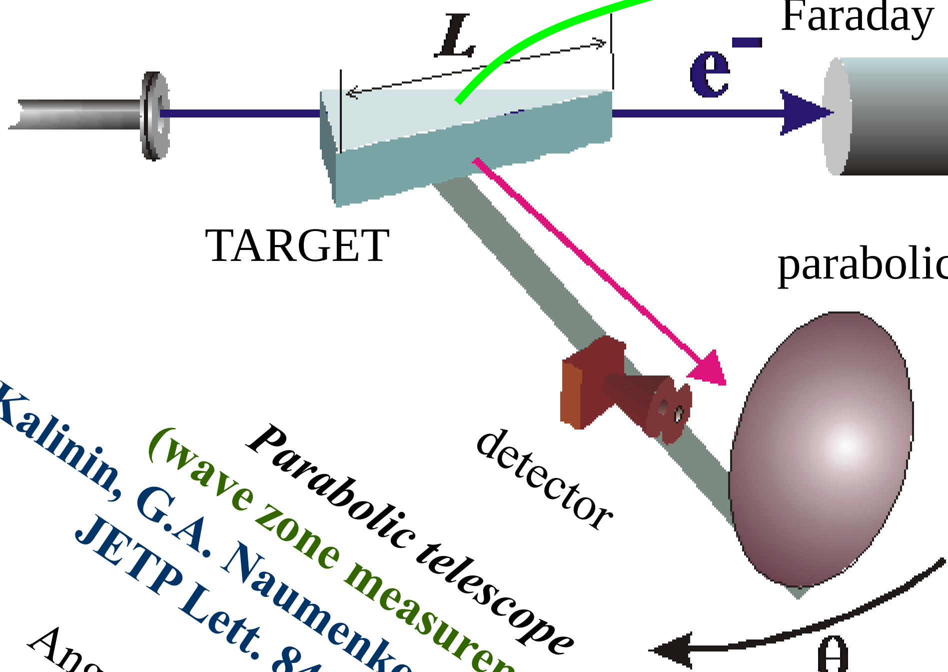
$$\beta\sqrt{\varepsilon - \sin^2(\theta)} = 1$$

EXPERIMENT AT TOMSK MICROTRON

Wave zone condition

$R > L/\delta\theta \approx 3$ m.

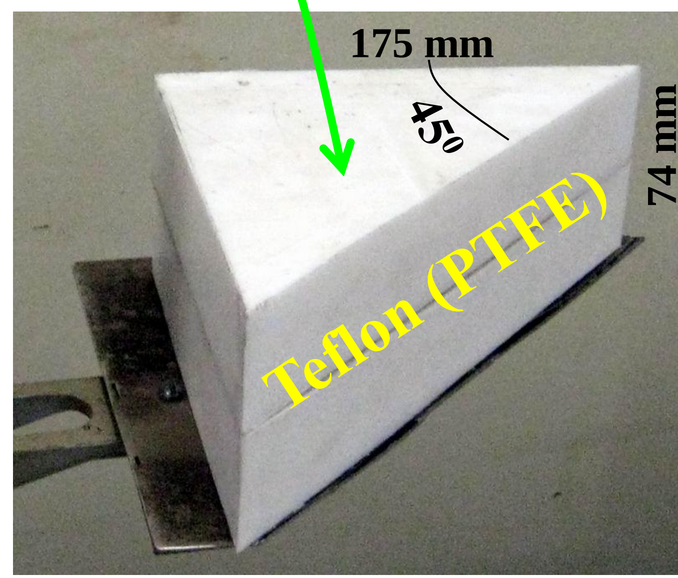
Cherenkov angle



(wave zone measurements)

B.N. Kalinin, G.A. Naumenko, A.P. Potylitsyn et al.,
JETP Lett. 84 (3), 110 (2006

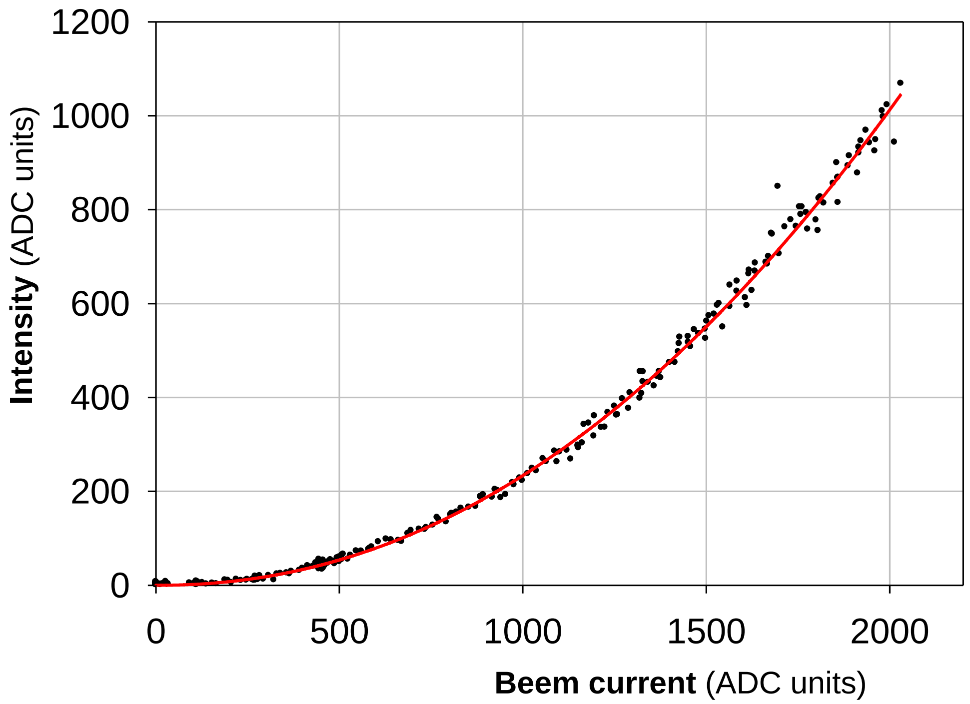
Angular resolution $\delta\theta = 3^o$



9 mm < λ < 25 mm **n=1.45±0.05**

Beam current dependence

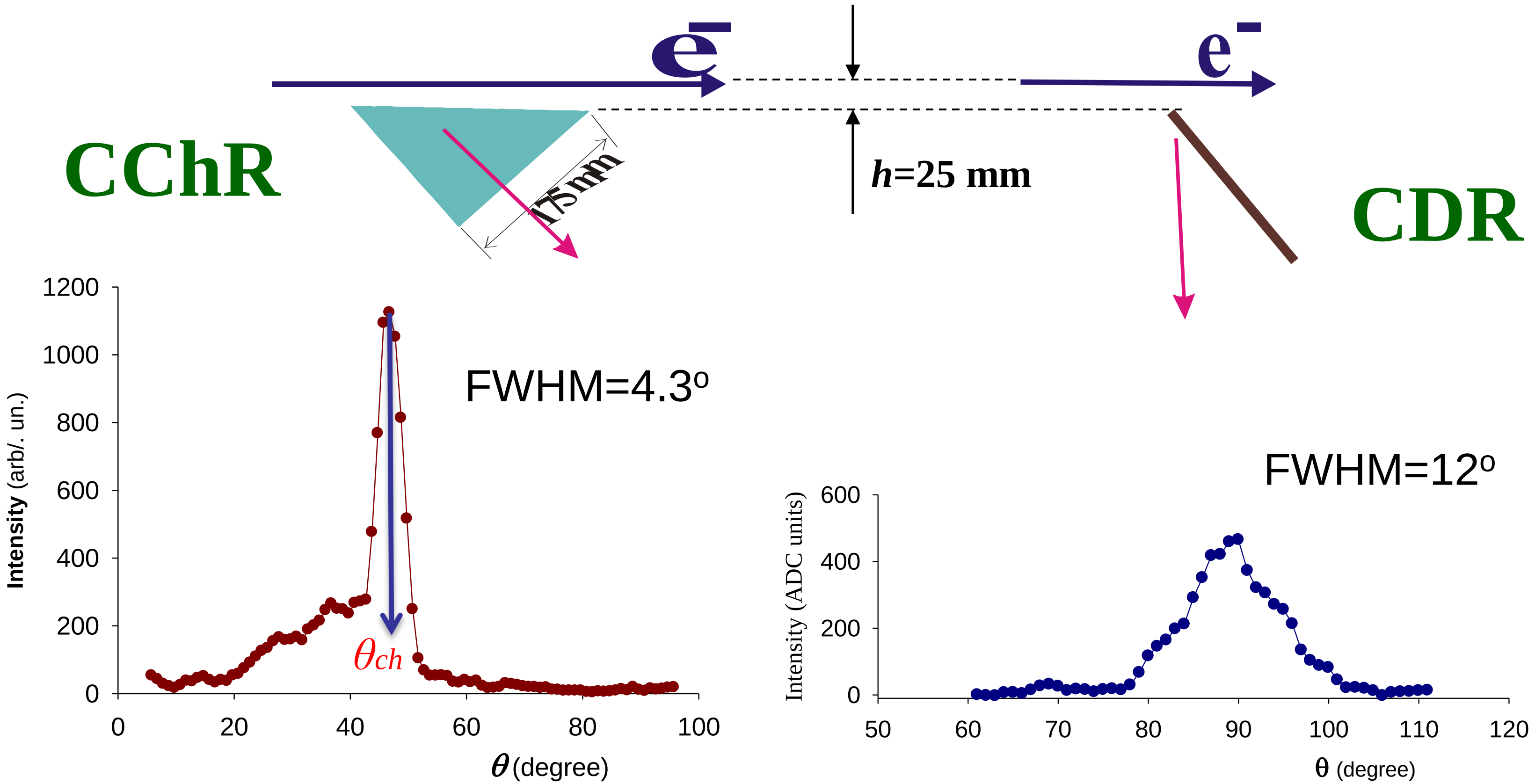
(*To show that measured radiation is coherent one*)



Approximation:

$$y = a \cdot x^{b} \quad \Rightarrow \quad y = 1.05 \cdot 10^{-4} \cdot x^{2.11 \pm 0.1}$$

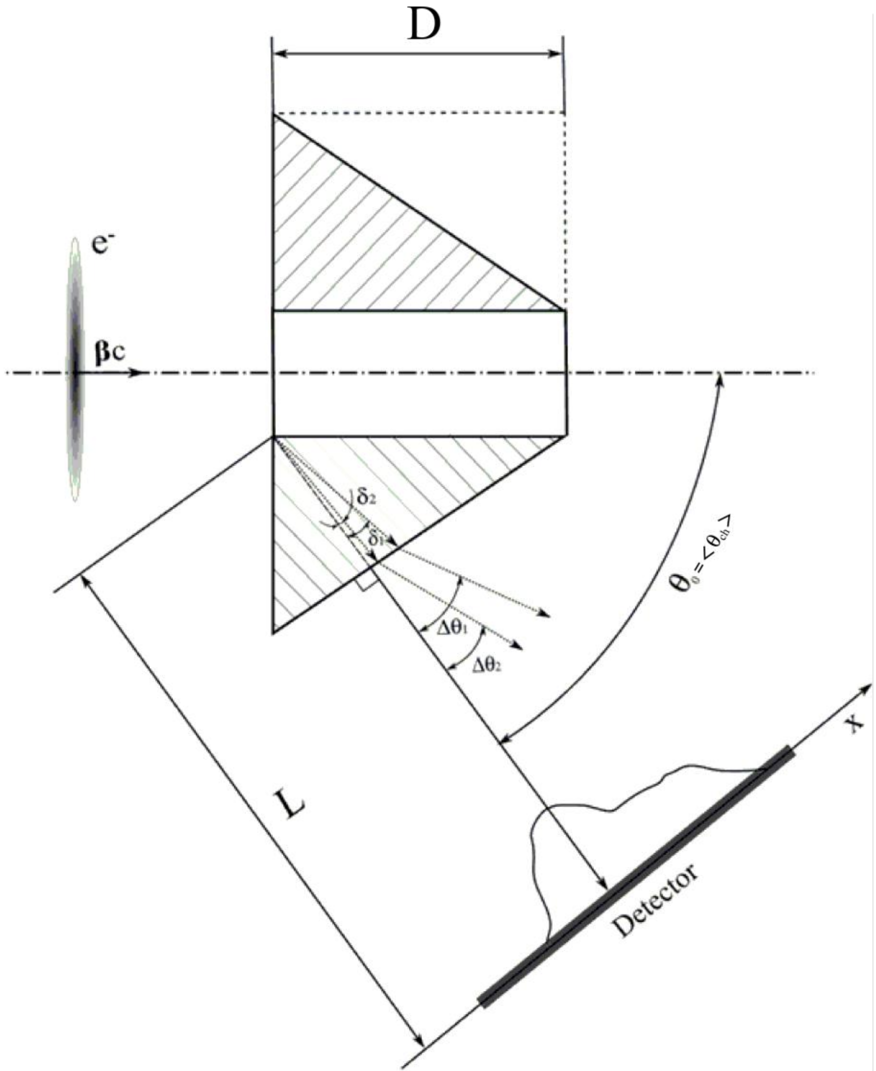
Comparison of coherent ChR and coherent DR in similar condition

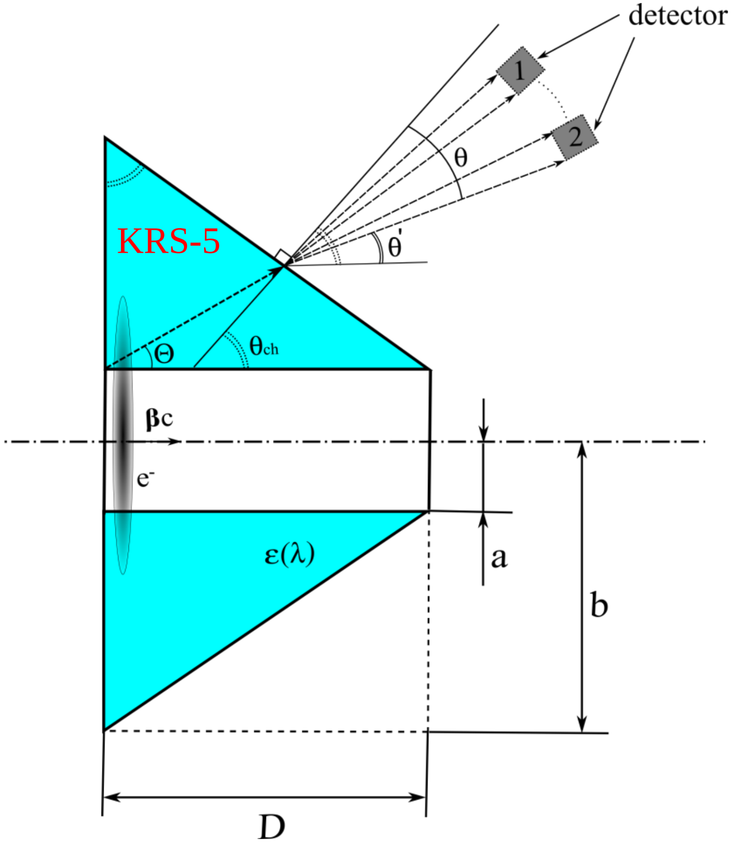


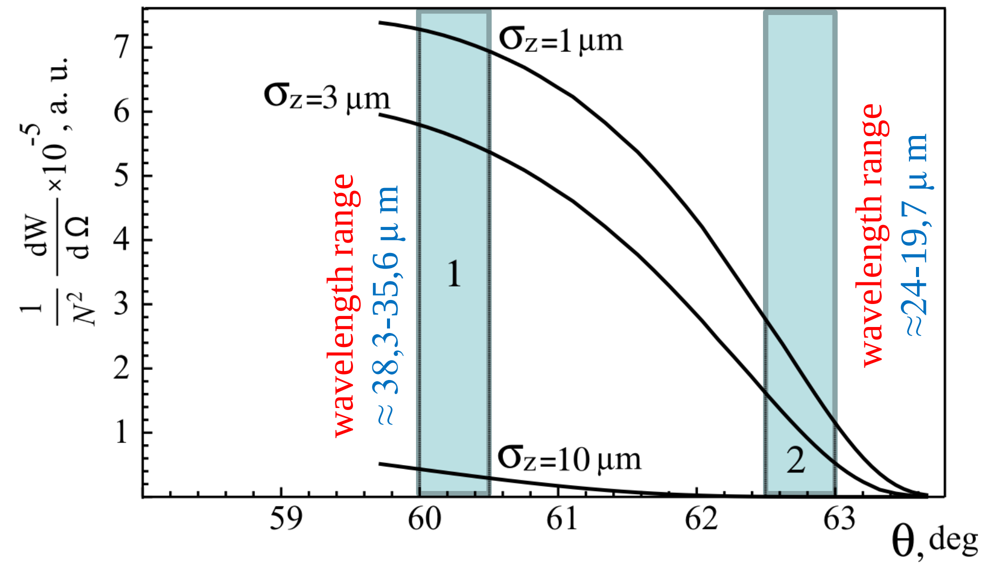
FWHM$_{th}$=2.72° FWHM$_{th}$=8.3°

Coherent ChR may be used for beam diagnostics

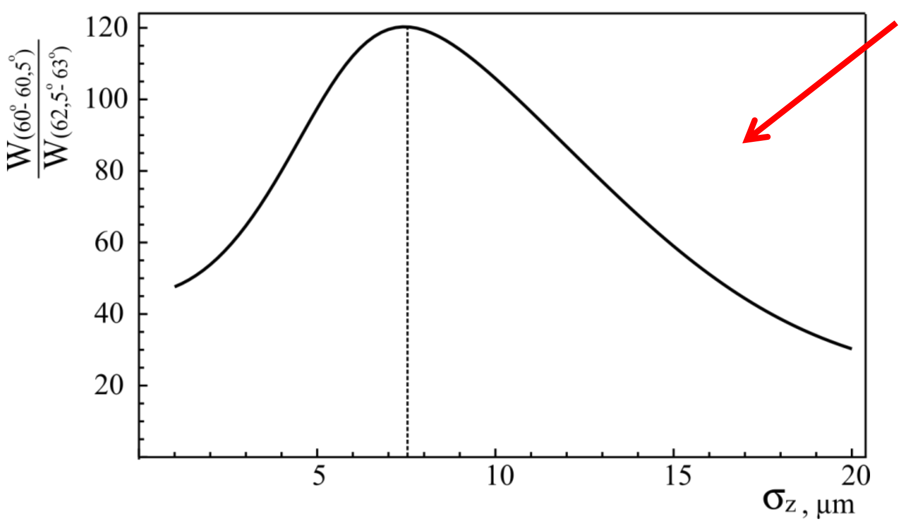
A conical target with hole may be considered as a «natural Cherenkov spectrometer» if a dispersion of cone matter is not so small [A.P. Potylitsyn, et al., Coherent Cherenkov Radiation from a Short Bunch Passing Near a Target and Possibility of a Bunch Length Diagnostics, *MOPE046 IPAC'10*, http://ipac10.org]







Angular distribution of coherent radiation of Vavilov-Cherenkova with following parametres of a conic target: a=3 mm, $b \approx$ 20,8 mm, D=40 mm (θ_{ch}=66 °) for Lorentz-factor γ =*200.*



The relation of signals from detectors 1 and 2 (the relation of losses of energy on coherent radiation in a various angular range) depending on the longitudinal sizes of ultrarelativistic bunch. Modelling parametres: a=3 mm, $b \approx$ 20,8 mm, D=40 mm (θ_{ch}=66 °), γ =200. Integration was spent on all range of lengths of waves (0.5 – 40 microns)

Conclusions:

• Intensity of coherent ChR (CChR) from relativistic electrons passing near a target is comparable with intensity of coherent diffraction radiation

• Direct measurement of CChR spectrum is possible if a target geometry is chosen according it's refractive index

• Using dielectric conical target with properties defined by estimated bunch length it is possible to design the «natural Cherenkov spectrometer» allowing to measure a bunch length via noninvasive technique with a good accuracy

• For instance, KRS-5 (TlBr-TlI) target is appropriate to measure a bunch length in interval σ_z=8-20 μm

Thank you for your attention