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Superradiant Transition and Diffraction radiation in the THz Region

A. Potylitsyn
Tomsk Polytechnic University (TPU)

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  - **Linac based THz sources**

- **Coherent Transition/ Diffraction radiation (CTR/ CDR)**
  - **Ginzburg-Frank formula (far-field zone approximation)**
  - **Pre-wave zone effect**
  - **Radiation from short bunches**

- **Focusing of CDR**

- **Superradiant CTR and CDR from a train of bunches**
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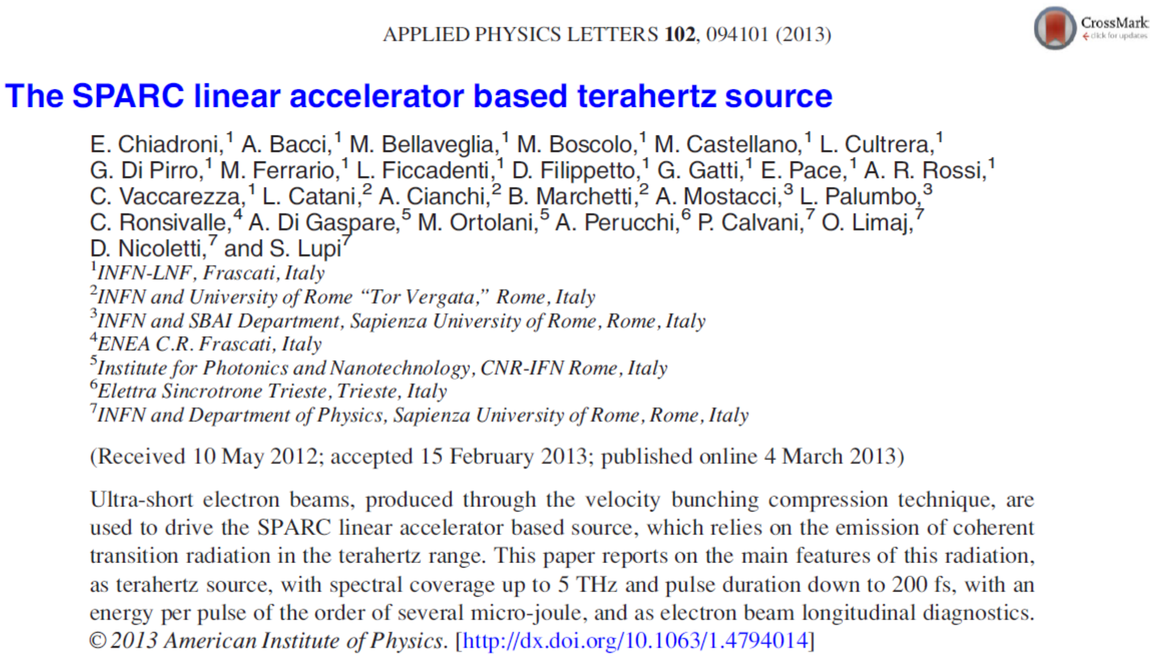
Linac based THz sources



APPLIED PHYSICS LETTERS **102**, 094101 (2013)

The SPARC linear accelerator based terahertz source

E. Chiadroni,[1] A. Bacci,[1] M. Bellaveglia,[1] M. Boscolo,[1] M. Castellano,[1] L. Cultrera,[1]
G. Di Pirro,[1] M. Ferrario,[1] L. Ficcadenti,[1] D. Filippetto,[1] G. Gatti,[1] E. Pace,[1] A. R. Rossi,[1]
C. Vaccarezza,[1] L. Catani,[2] A. Cianchi,[2] B. Marchetti,[2] A. Mostacci,[3] L. Palumbo,[3]
C. Ronsivalle,[4] A. Di Gaspare,[5] M. Ortolani,[5] A. Perucchi,[6] P. Calvani,[7] O. Limaj,[7]
D. Nicoletti,[7] and S. Lupi[7]
[1]*INFN-LNF, Frascati, Italy*
[2]*INFN and University of Rome "Tor Vergata," Rome, Italy*
[3]*INFN and SBAI Department, Sapienza University of Rome, Rome, Italy*
[4]*ENEA C.R. Frascati, Italy*
[5]*Institute for Photonics and Nanotechnology, CNR-IFN Rome, Italy*
[6]*Elettra Sincrotrone Trieste, Trieste, Italy*
[7]*INFN and Department of Physics, Sapienza University of Rome, Rome, Italy*

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Ultra-short electron beams, produced through the velocity bunching compression technique, are used to drive the SPARC linear accelerator based source, which relies on the emission of coherent transition radiation in the terahertz range. This paper reports on the main features of this radiation, as terahertz source, with spectral coverage up to 5 THz and pulse duration down to 200 fs, with an energy per pulse of the order of several micro-joule, and as electron beam longitudinal diagnostics.

[http://dx.doi.org/10.1063/1.4794014]

The finite size of the screen (i.e., 30 mm x 30 mm), the vacuum chamber geometry (i.e., 63 mm vacuum window clear aperture, at 70 mm distance from the target, and 60 mm beam pipe radius) and the optics acceptance introduce a low frequency cut-off estimated to be 100 GHz

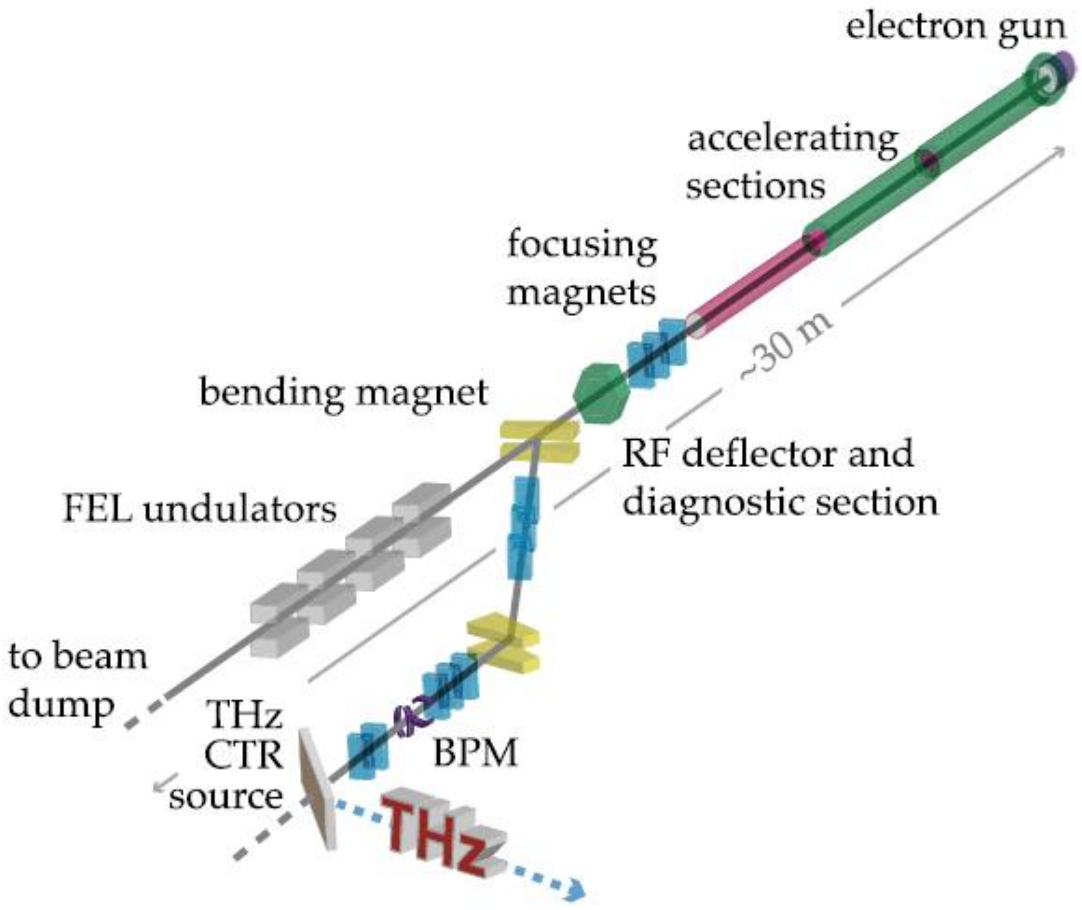

FIG. 1. Schematic layout of the SPARC test facility.

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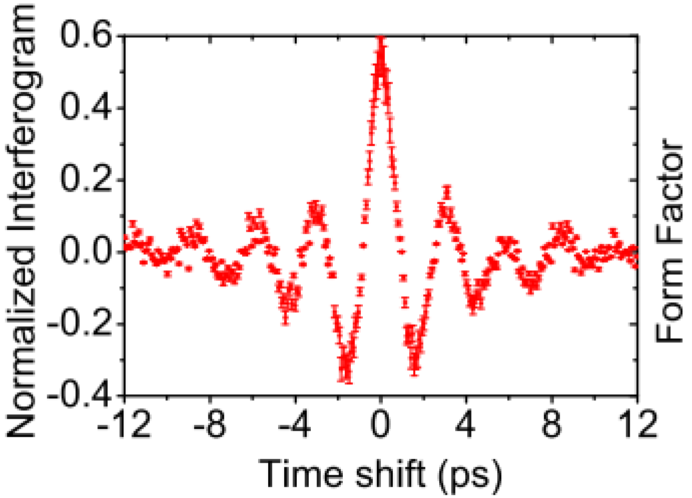
$$\sigma_t(Q) = AQ^B$$

$$S(t) = \frac{e^{-t^2/2\sigma_t^2}}{\sqrt{2\pi}\sigma_t} \leftrightarrow F(\omega) = e^{-\omega^2 A^2 Q^{2B}}$$

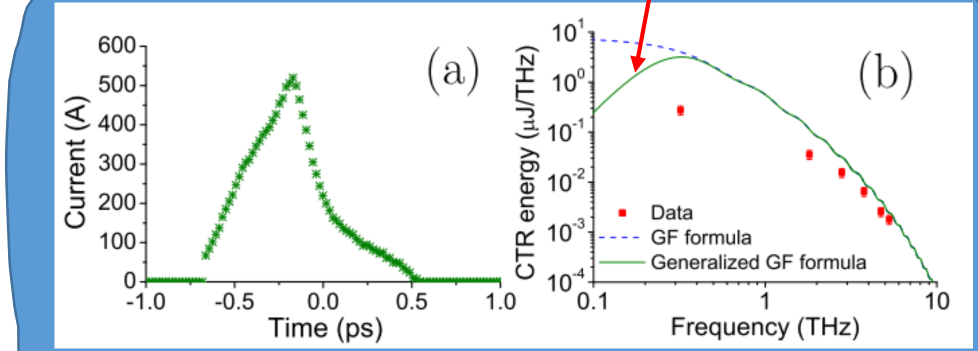
$$I_{CTR} = \int_{\Delta\Omega}\int_0^\infty \frac{d^2 I}{d\omega d\Omega} d\omega d\Omega \propto Q^{2-B}$$

τ_B	Q	I_{CTR}
2.52 ps	470 pC	211 nJ
0.5 ps	260 pC	4402 nJ

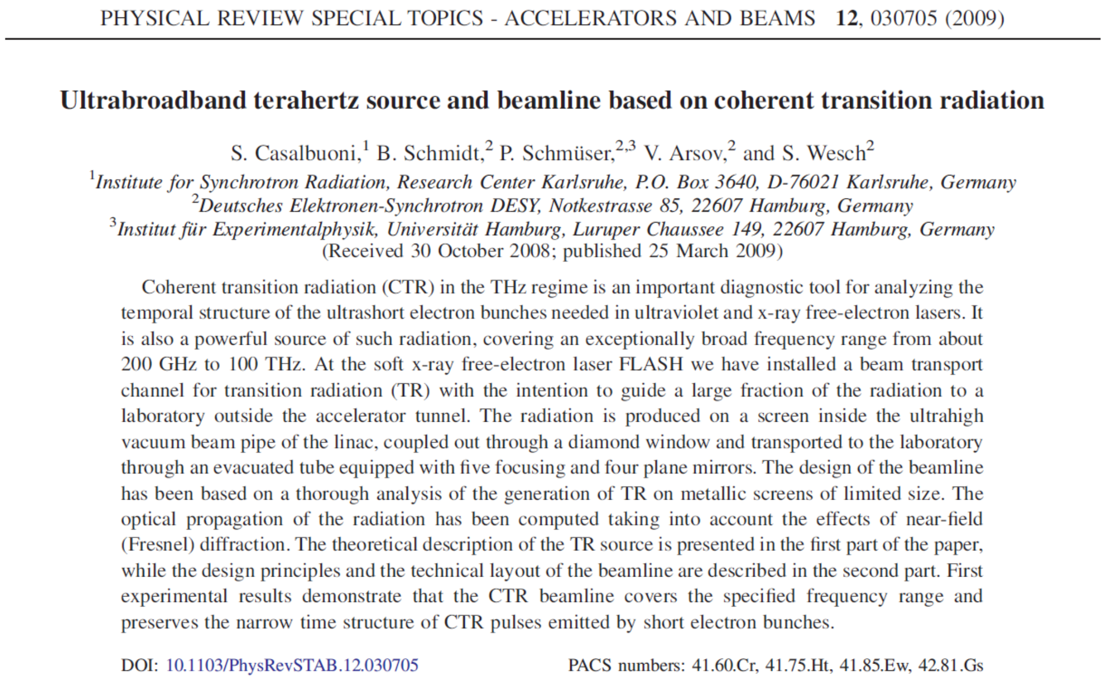


CTR autocorrelation function as measured through a Martin-Puplett interferometer.

Suppression due to prewave zone effect



(a) Longitudinal bunch profile measured with the RFD in case of a 260 fs RMS bunch duration with 260 pC charge. (b) Corresponding measured CTR pulse energy density in μJ/THz as function of frequency (red squares). Dashed blue and solid olive curves correspond to the CTR pulse energy density calculated from the ideal GF formula and the generalized one, respectively, taking into account the measured form factor.



PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **12**, 030705 (2009)

Ultrabroadband terahertz source and beamline based on coherent transition radiation

S. Casalbuoni,[1] B. Schmidt,[2] P. Schmüser,[2,3] V. Arsov,[2] and S. Wesch[2]
[1]*Institute for Synchrotron Radiation, Research Center Karlsruhe, P.O. Box 3640, D-76021 Karlsruhe, Germany*
[2]*Deutsches Elektronen-Synchrotron DESY, Notkestrasse 85, 22607 Hamburg, Germany*
[3]*Institut für Experimentalphysik, Universität Hamburg, Luruper Chaussee 149, 22607 Hamburg, Germany*

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Coherent transition radiation (CTR) in the THz regime is an important diagnostic tool for analyzing the temporal structure of the ultrashort electron bunches needed in ultraviolet and x-ray free-electron lasers. It is also a powerful source of such radiation, covering an exceptionally broad frequency range from about 200 GHz to 100 THz. At the soft x-ray free-electron laser FLASH we have installed a beam transport channel for transition radiation (TR) with the intention to guide a large fraction of the radiation to a laboratory outside the accelerator tunnel. The radiation is produced on a screen inside the ultrahigh vacuum beam pipe of the linac, coupled out through a diamond window and transported to the laboratory through an evacuated tube equipped with five focusing and four plane mirrors. The design of the beamline has been based on a thorough analysis of the generation of TR on metallic screens of limited size. The optical propagation of the radiation has been computed taking into account the effects of near-field (Fresnel) diffraction. The theoretical description of the TR source is presented in the first part of the paper, while the design principles and the technical layout of the beamline are described in the second part. First experimental results demonstrate that the CTR beamline covers the specified frequency range and preserves the narrow time structure of CTR pulses emitted by short electron bunches.

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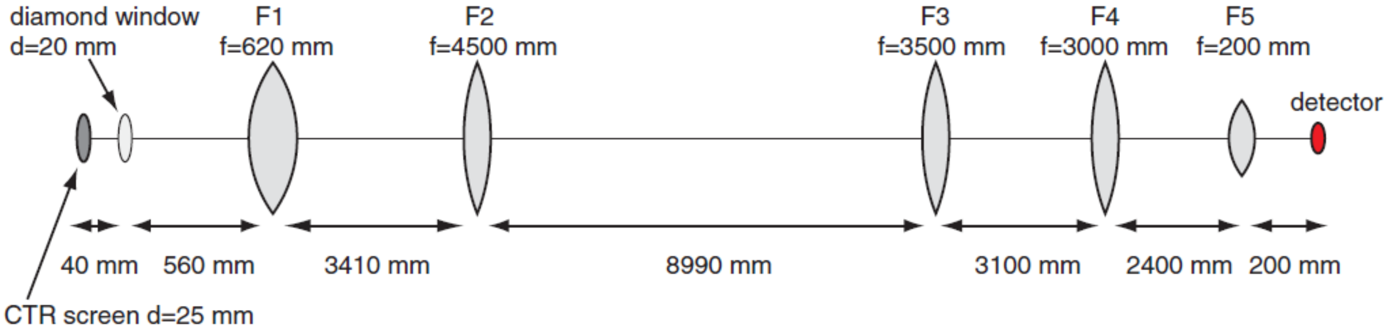

FIG. 7. Schematic optical design of the THz transfer line. The focusing elements F1 to F5 are shown as lenses with their respective positions and focal lengths.

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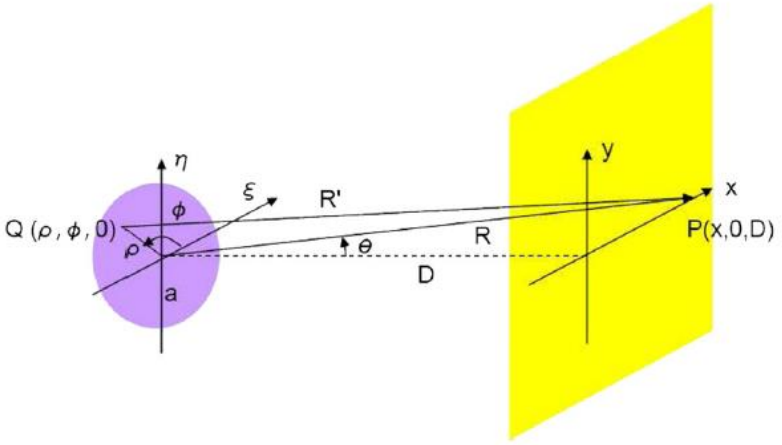
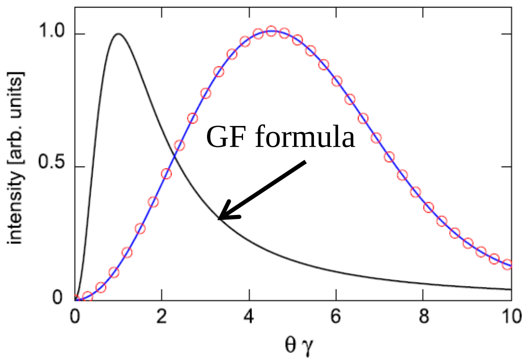
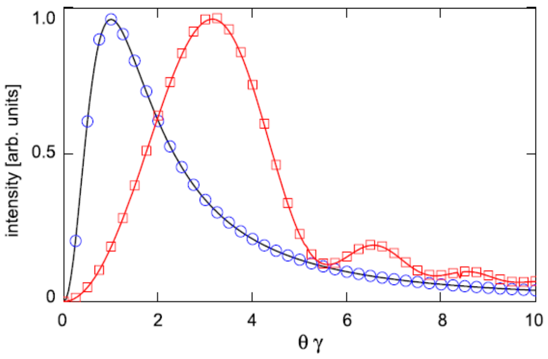


Distance between target and detector D = 4 m

$\gamma = 100$; $\lambda = 0.3$ mm; a = 30 mm



GF formula



D = 200 mm

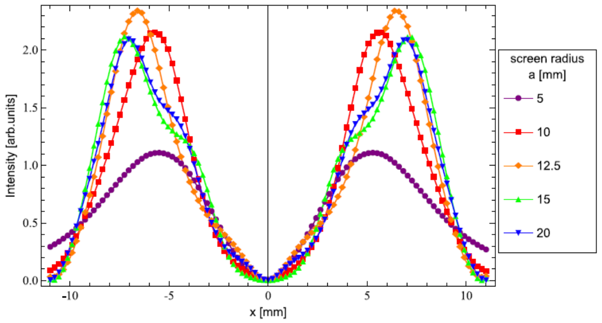
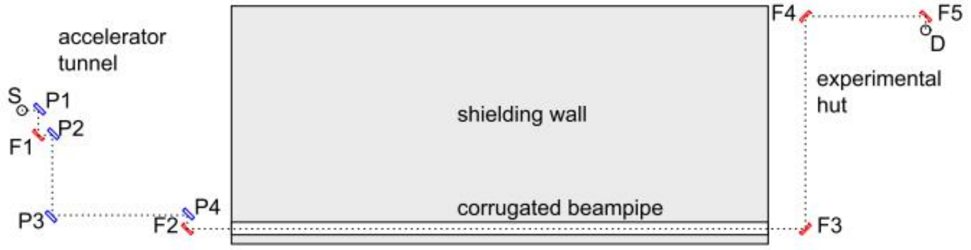
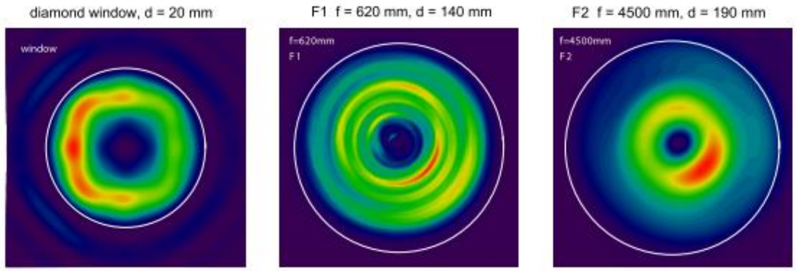


FIG. 10. (Color) Horizontal intensity distribution of 200 GHz transition radiation on the diamond window. The TR screen radius *a* is varied between 5 and 20 mm.





diamond window, d = 20 mm

F1 f = 620 mm, d = 140 mm

F2 f = 4500 mm, d = 190 mm

Diamond window

Since the price of CVD diamonds windows increases very rapidly with size, it was decided to use a small window with a radius r_w = 10 mm and place it at the CTR distribution is closed to TEM$_{10}$ mode

Coherent Transition radiation

Intensity of coherent transition radiation (CTR) from a bunch with population N_e:

$$\frac{d^2W_{CTR}}{d\omega\, d\Omega} = \frac{d^2W_{TR}}{d\omega\, d\Omega}[N_e + N_e(N_e - 1)]F(\omega)$$

$\frac{d^2W_{TR}}{d\omega\, d\Omega}$ - Spectral-angular distribution of TR from a single electron

Ginzburg-Frank formula for ultrarelativistic charge is valid for far-field zone:

$$\frac{d^2W_{TR}}{d\omega\, d\Omega} = \frac{e^2}{\pi^2 c}\frac{\theta_x^2 + \theta_y^2}{(\gamma^{-2} + \theta_x^2 + \theta_y^2)^2}$$

$\theta_x,\ \theta_y$ - projection angles

Formfactor:

$$F_L(\omega) = \left|\int S(\vec{r})\exp[-i\Delta\varphi]d\vec{r}\right|^2, \quad \Delta\varphi = \vec{k}\vec{r} - \omega\Delta t = \frac{2\pi}{\lambda}\left(x\theta_x + y\theta_y + z/\beta\right)$$

For ultrarelativistic case (neglecting by transverse formfactor):

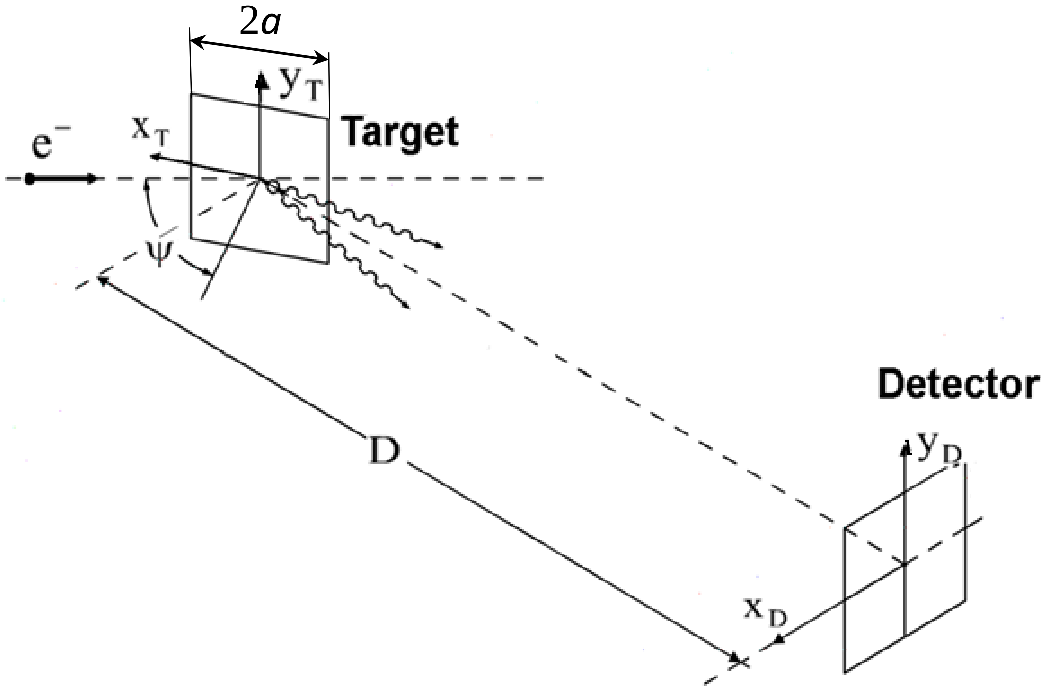
$$F_L(\omega) = \exp\left[-\frac{4\pi^2\sigma_z^2}{\lambda^2}\right] = \exp\left[-\left(\frac{2\pi\nu}{\nu_0}\right)^2\right], \quad \text{where } \nu_0 = c/\sigma_z$$

Pre-wave zone effect

Far-field zone $D \gg \gamma^2\lambda$.

Pre-wave zone $D < \gamma^2\lambda$, γ – Lorentz factor, λ – radiation wavelength

Finite target sizes effect: $a<\gamma\lambda$



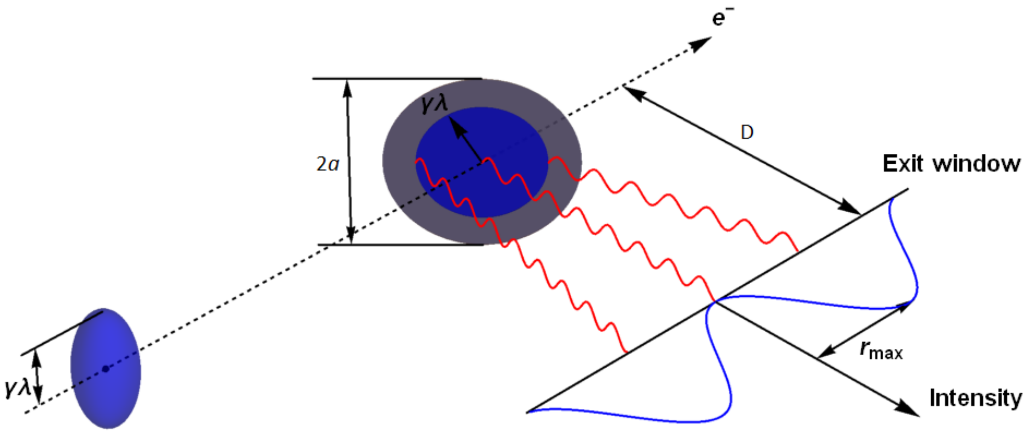
TR field distribution on the detector surface

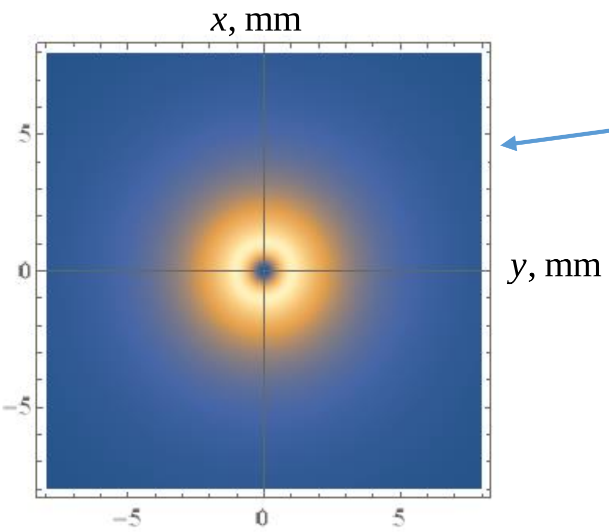
$$\boldsymbol{E}^{TR}_{x,y}(x_D,y_D)=const\iint_{S_T}dx_T\,dy_T\,\frac{\{x_T,y_T\}K_1\left(\frac{\omega\sqrt{x_T^2+y_T^2}}{\beta c\gamma}\right)}{\sqrt{x_T^2+y_T^2}}*\exp\left[i\frac{\pi\left(x_T^2+y_T^2\right)}{D\lambda}-i\frac{2\pi\left(x_Tx_D+y_Ty_D\right)}{D\lambda}\right],$$

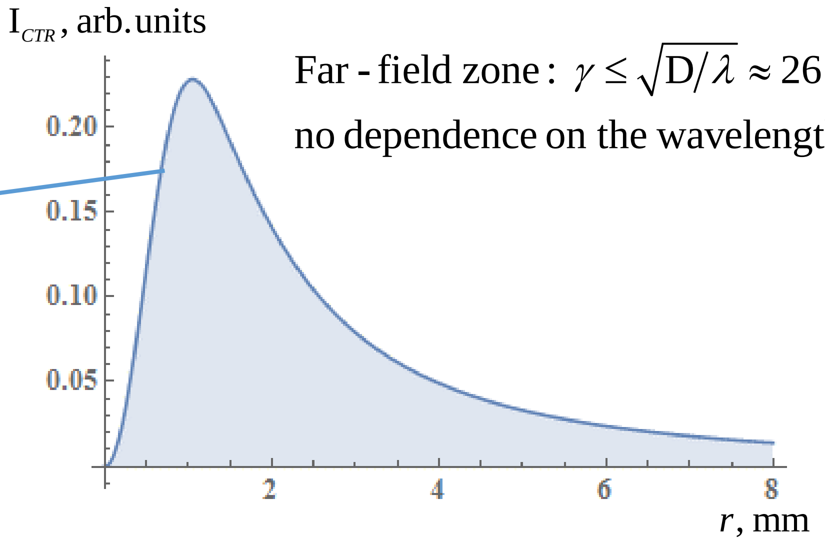
S_T – target surface

TR in the pre-wave zone

D = 200 mm, a=30 mm





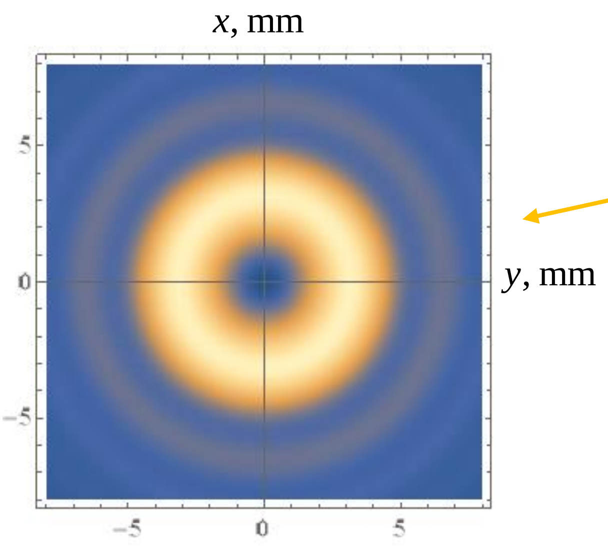


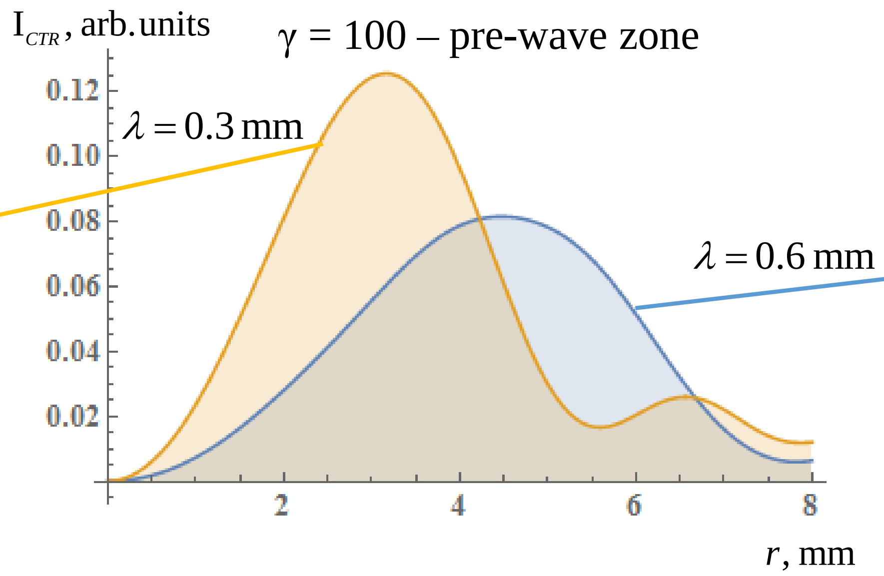
Far-field zone: $\gamma \leq \sqrt{D/\lambda} \approx 26$

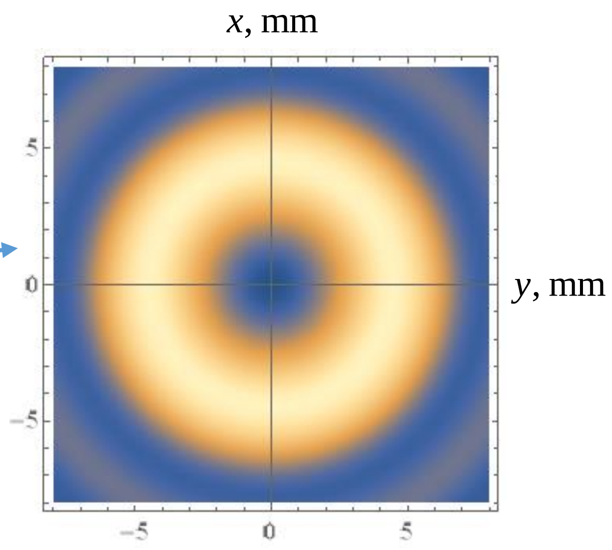
no dependence on the wavelength

$r_{\max} \sim D/\gamma$ for far-field zone

$\gamma = 100$ – pre-wave zone







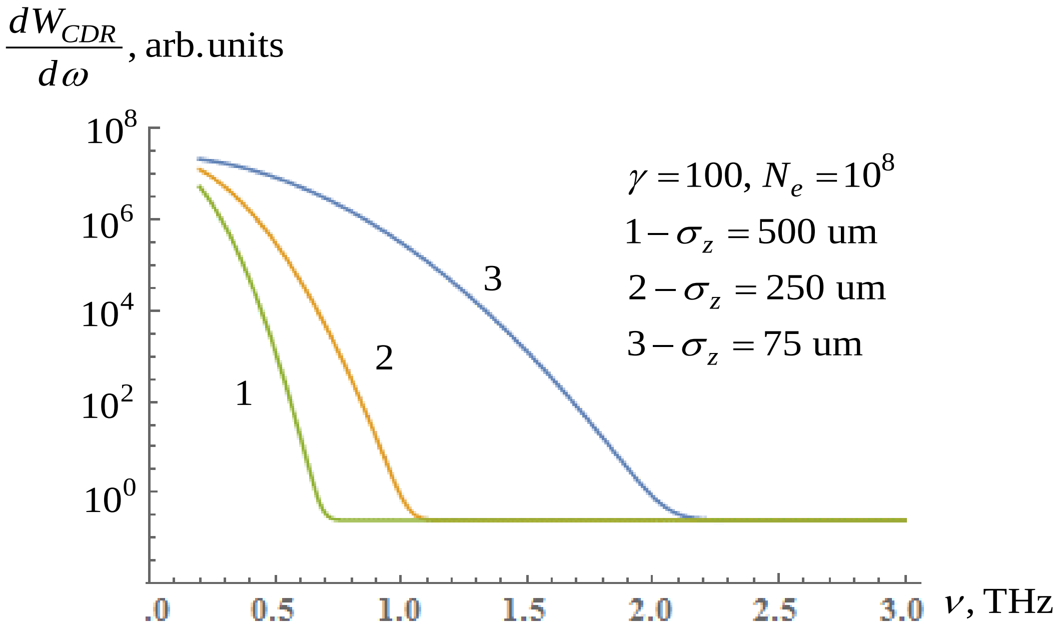
For pre-wave zone $r_{\max} \sim \sqrt{a\lambda}$, no dependence on γ

Spectrum of the coherent transition radiation

Far-field zone:

$$\frac{dW_{\mathrm{CTR}}}{d\omega} = 2\pi \int_0^{\theta_{\max}} \theta\, d\theta \frac{d^2 W_{\mathrm{CTR}}}{d\omega\, d\Omega} \approx N_e^2 F(\omega) \cdot \frac{\alpha h}{\pi}\left[\log\left(1+\gamma^2\theta_{\max}^2\right) + \frac{1}{1+\gamma^2\theta_{\max}^2} - 1\right], \quad \theta_{\max} - \text{aperture}$$

Pre-wave zone: $$\frac{dW_{\mathrm{CTR}}}{d\omega} = c\,\mathrm{D}^2 \int_{\Delta S_{aperture}} \left|\vec{E}\left(x_d, y_d\right)\right|^2 dx_d\, dy_d$$



CTR radiation losses

$$\Delta W_{\mathrm{CTR}} : \int \frac{dW_{\mathrm{CTR}}}{d\omega} d\omega$$

Losses per bunch for $\theta_{\max}$: $2/\gamma$

$$\Delta W_{\mathrm{CTR}} : N_e^2 \alpha \frac{hc}{\sigma_z}$$

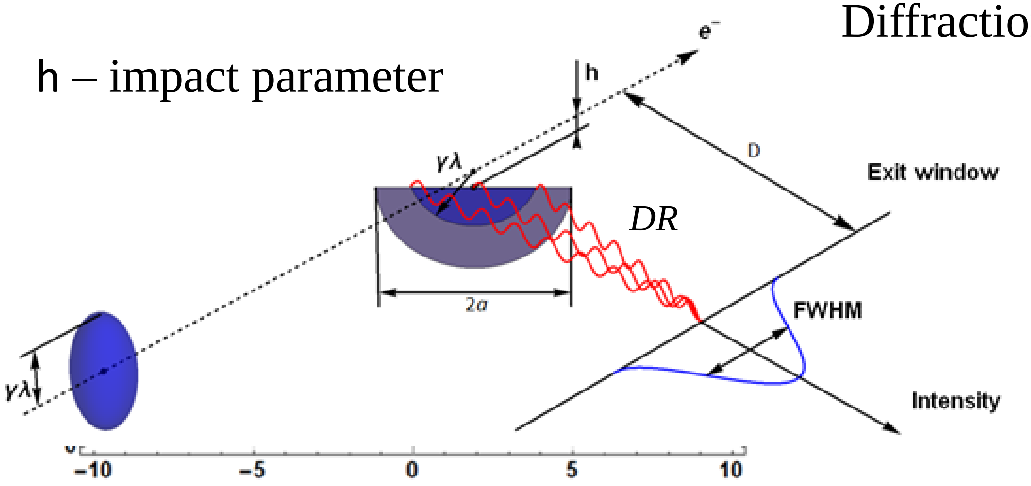
For Q=0.5 nC,

$$\begin{cases} \sigma_z = 500\ \mu m, \Delta W_{CTR} \sim 1200\ nJ,\ \nu < 0.05\ THZ \\ \sigma_z = 100\ \mu m, \Delta W_{CTR} \sim 6000\ nJ,\ \nu < 0.4\ THZ \end{cases}$$

DR in the far-field zone

Diffraction radiation is concentrated along beam axes.

h – impact parameter

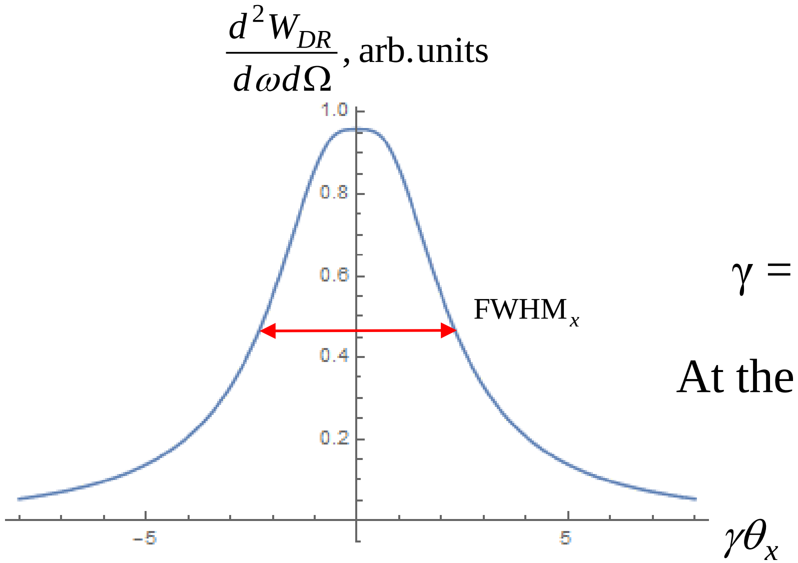


$$\frac{d^2W_{CDR}}{d\omega\, d\Omega} = \frac{d^2W_{DR}}{d\omega\, d\Omega}[N_e + N_e(N_e - 1)]F(\omega)$$

Far-field zone:

$$\frac{d^2W_{DR}}{d\omega\, d\Omega} = \frac{e^2}{4\pi^2 c}\exp\left[\frac{-4\pi h}{\gamma\lambda}\sqrt{1+(\gamma\theta_x)^2}\right]\frac{(\gamma^{-2}+2\theta_x^2)}{(\gamma^{-2}+\theta_x^2)(\gamma^{-2}+\theta_x^2)+\theta_y^2}$$

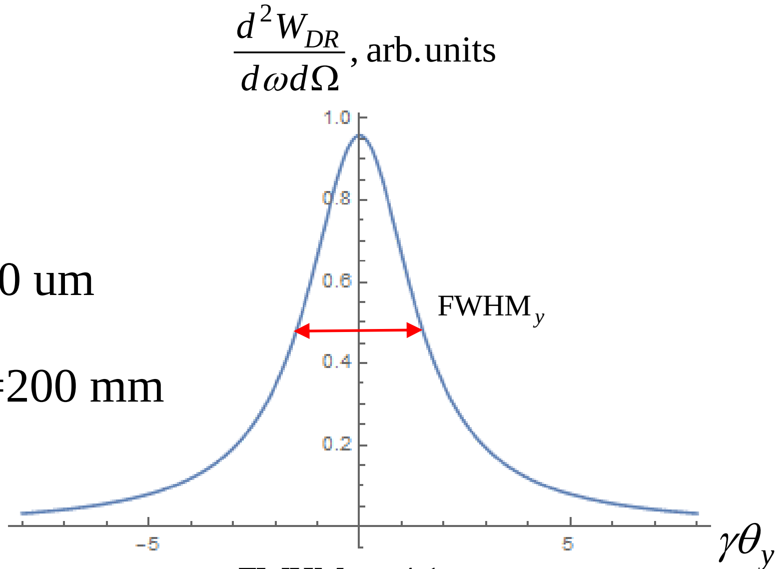
FWHM : $2D/\gamma$ for far - field zone



$\text{FWHM}_x = 5.5$ mm

γ = 300; λ = 500 um

At the distance D=200 mm



$\text{FWHM}_y = 4.1$ mm

DR in the pre-wave zone [A. Potylitsyn, NATO Science Series, V.199, 2009]

DR distribution on the windows surface

$$\boldsymbol{E}_{x,y}^{DR}(x_D, y_D) = const\iint_{S_T} dx_T dy_T \frac{\{x_T, y_T\}\left(1+0.57\sqrt{x_T^2+y_T^2}-0.04\left(x_T^2+y_T^2\right)\right)\exp\left[-\sqrt{x_T^2+y_T^2}\right]}{x_T^2+y_T^2} * \exp\left[i\frac{\left(x_T^2+y_T^2\right)}{4\pi \mathrm{R}} - i\left(x_T x_D + y_T y_D\right)\right],$$

where $R = \frac{\mathrm{D}}{\gamma^2\lambda}, \quad x_T\left(y_T\right) = \frac{2\pi X_T\left(Y_T\right)}{\gamma\lambda}, \quad x\left(y\right) = \frac{\gamma}{\mathrm{D}} X\left(Y\right)$

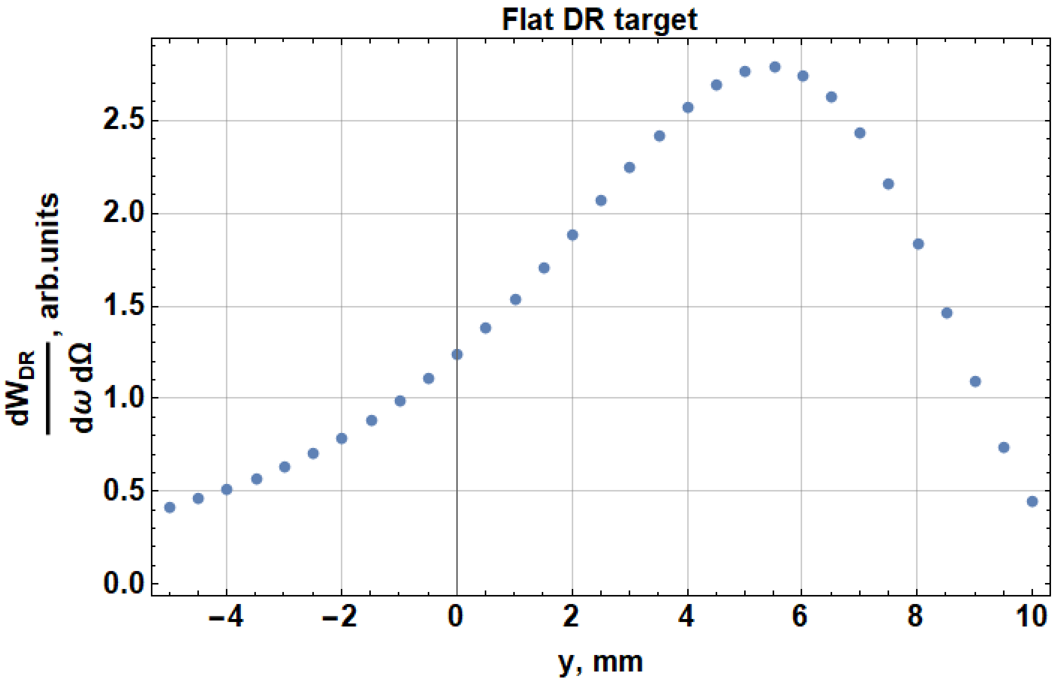
ΔS_T- target area,

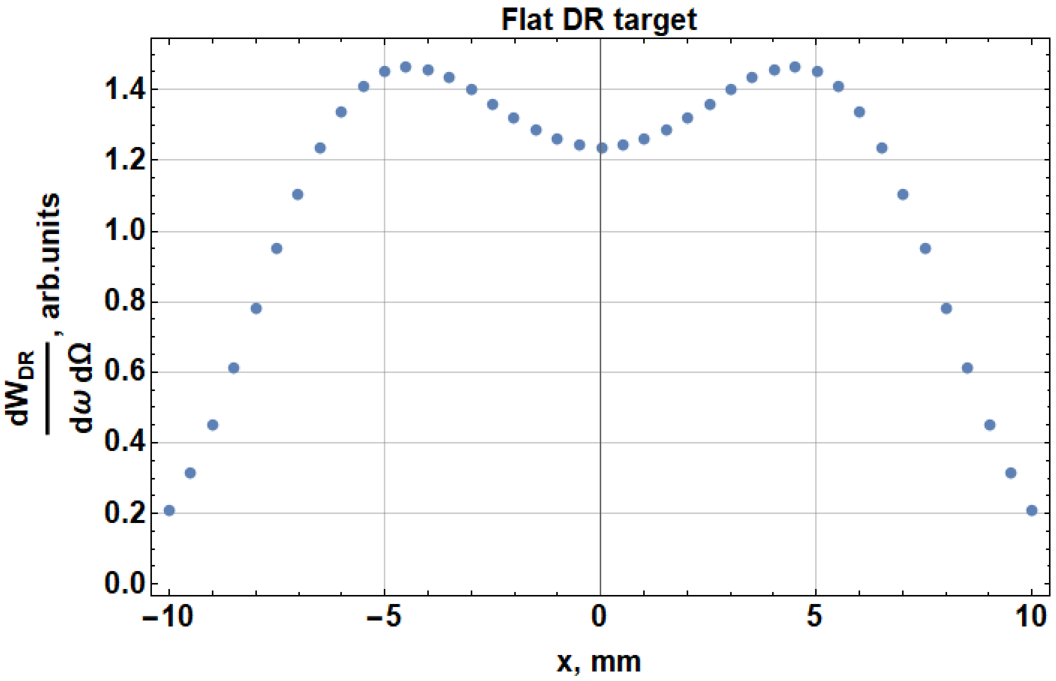
X_T ,Y_T- coordinate on the target surface,

X_D ,Y_D- coordinate on the exit window surface,

DR from a flat target (pre-wave zone):

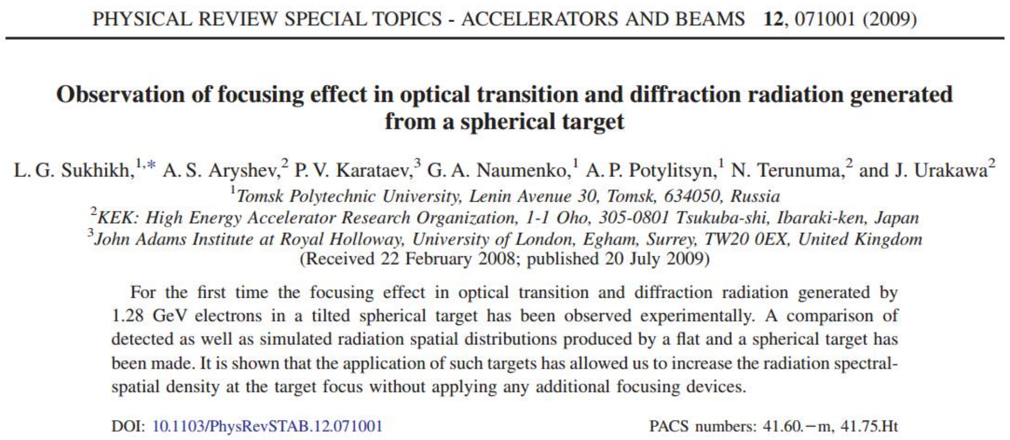
$\gamma = 300$, $a = 30$ mm, $\lambda = 0.3$ mm, D= 200 mm





DR distribution in the pre-wave zone is much broader in comparison with far-field zone

Focusing of the DR



PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **12**, 071001 (2009)

Observation of focusing effect in optical transition and diffraction radiation generated from a spherical target

L. G. Sukhikh,[1,*] A. S. Aryshev,[2] P. V. Karataev,[3] G. A. Naumenko,[1] A. P. Potylitsyn,[1] N. Terunuma,[2] and J. Urakawa[2]
[1]*Tomsk Polytechnic University, Lenin Avenue 30, Tomsk, 634050, Russia*
[2]*KEK: High Energy Accelerator Research Organization, 1-1 Oho, 305-0801 Tsukuba-shi, Ibaraki-ken, Japan*
[3]*John Adams Institute at Royal Holloway, University of London, Egham, Surrey, TW20 0EX, United Kingdom*

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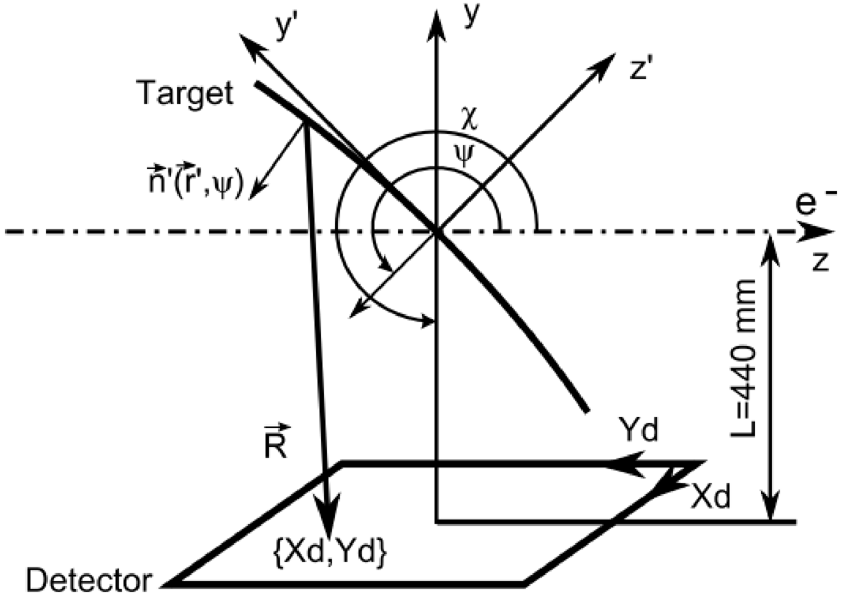
For the first time the focusing effect in optical transition and diffraction radiation generated by 1.28 GeV electrons in a tilted spherical target has been observed experimentally. A comparison of detected as well as simulated radiation spatial distributions produced by a flat and a spherical target has been made. It is shown that the application of such targets has allowed us to increase the radiation spectral-spatial density at the target focus without applying any additional focusing devices.

DOI: 10.1103/PhysRevSTAB.12.071001 PACS numbers: 41.60.−m, 41.75.Ht

The pre-wave zone effect (broadening of the DR cone) can be eliminated using a parabolic focusing DR target



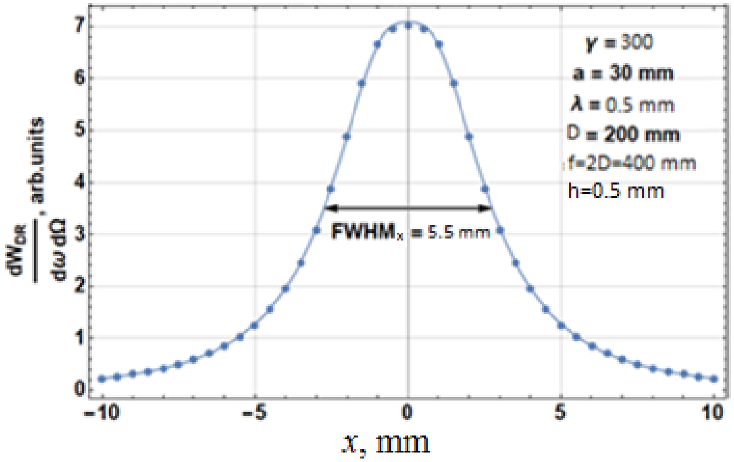
The simulation scheme and some definitions.

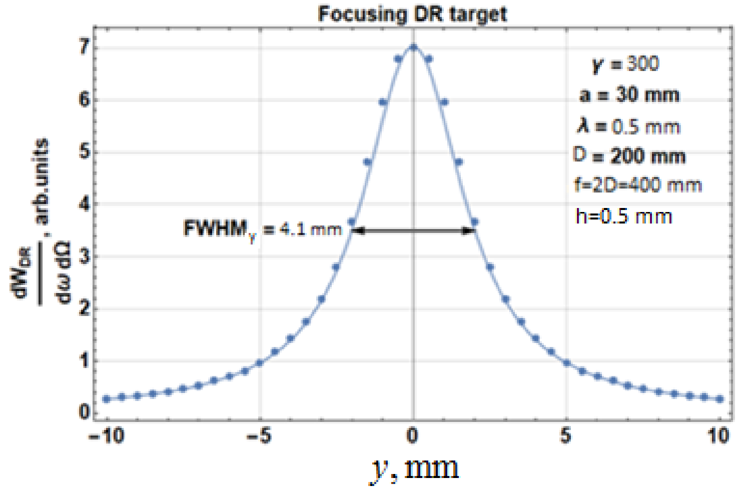
Calculations are performed using the same formula with the target surface element

$$dS = dx_T dy_T \sqrt{x_T^2 + y_T^2 + 4f^2} \Big/ 2f$$

Where f is the target focal distance, f=2D

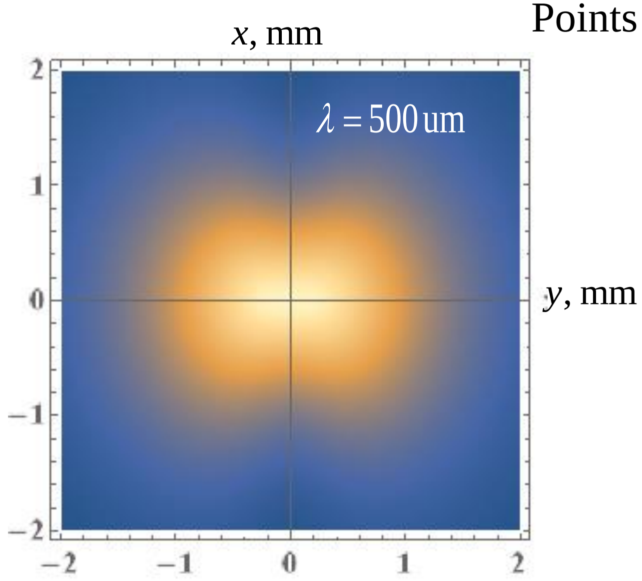
DR from a focusing target

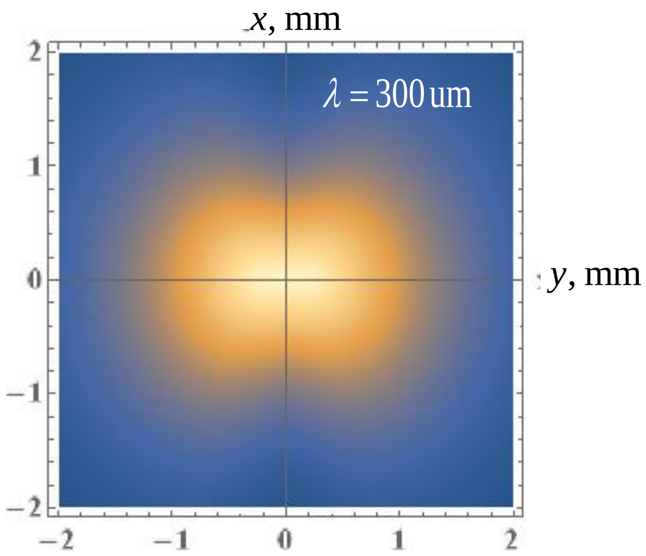




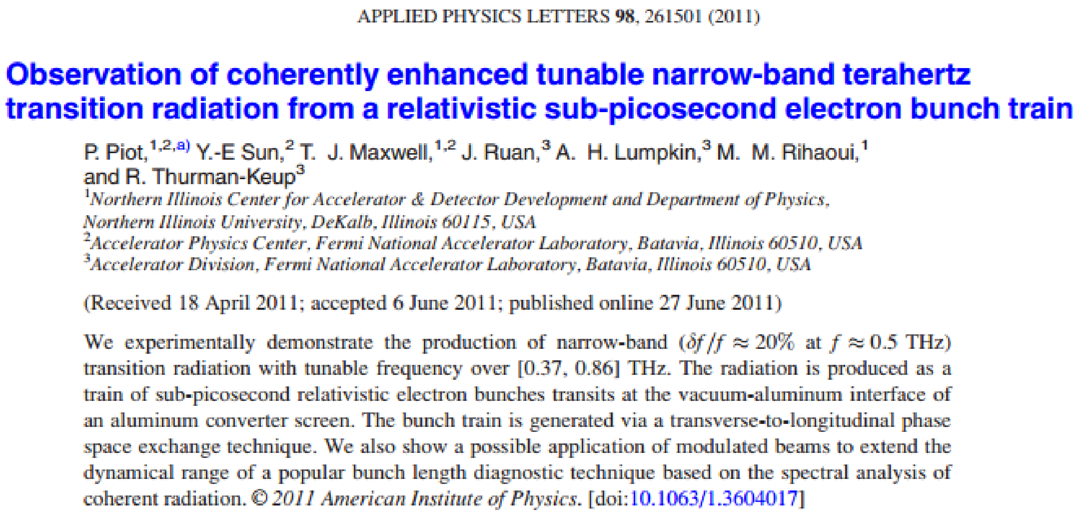
Solid curve – far-field distribution

Points – focused distribution





DR angular distribution on the exit window is closed to the TEM$_{00}$ mode distribution and can be focused by the optical system to a spot with a waist comparable with radiation wavelength



APPLIED PHYSICS LETTERS **98**, 261501 (2011)

Observation of coherently enhanced tunable narrow-band terahertz transition radiation from a relativistic sub-picosecond electron bunch train

P. Piot,[1,2,a)] Y.-E Sun,[2] T. J. Maxwell,[1,2] J. Ruan,[3] A. H. Lumpkin,[3] M. M. Rihaoui,[1] and R. Thurman-Keup[3]

[1]*Northern Illinois Center for Accelerator & Detector Development and Department of Physics, Northern Illinois University, DeKalb, Illinois 60115, USA*
[2]*Accelerator Physics Center, Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*
[3]*Accelerator Division, Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*

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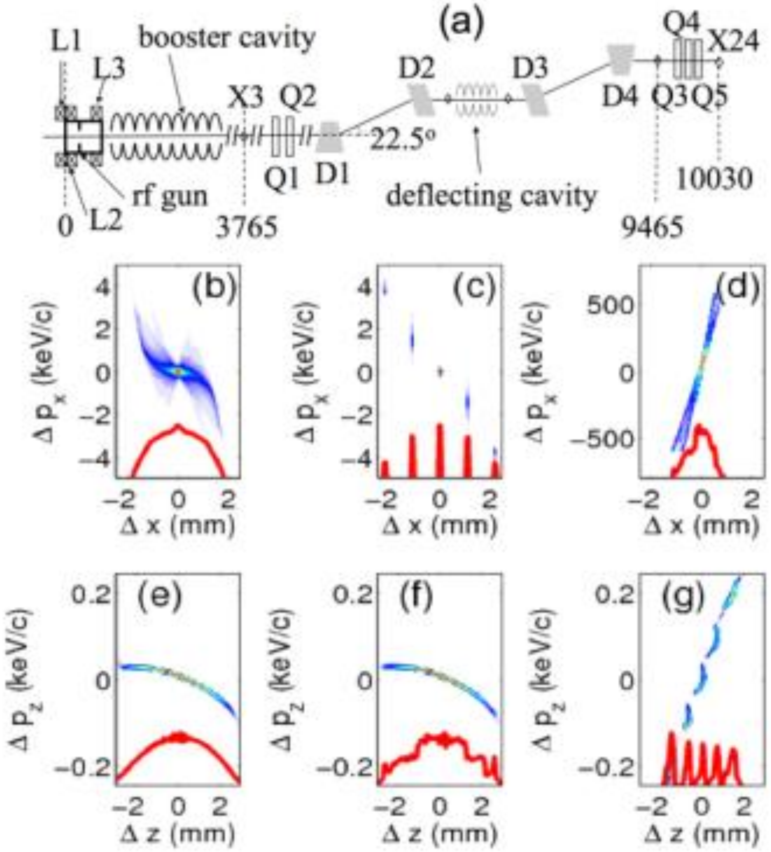
We experimentally demonstrate the production of narrow-band ($\delta f/f \approx 20\%$ at $f \approx 0.5$ THz) transition radiation with tunable frequency over [0.37, 0.86] THz. The radiation is produced as a train of sub-picosecond relativistic electron bunches transits at the vacuum-aluminum interface of an aluminum converter screen. The bunch train is generated via a transverse-to-longitudinal phase space exchange technique. We also show a possible application of modulated beams to extend the dynamical range of a popular bunch length diagnostic technique based on the spectral analysis of coherent radiation. © *2011 American Institute of Physics*. [doi:10.1063/1.3604017]



The rf gun is surrounded by three solenoidal lenses (L1, L2, and L3) that control the beam's transverse size and divergence. The beam is then accelerated in a 1.3-GHz superconducting rf cavity (the booster cavity) to ~14 MeV. Downstream of the booster cavity, the 500-pC bunch is intercepted by a multislit mask consisting of 48-μm wide slits with 1-mm spacing thereby producing a transversely segmented beam with total charge of ~15 pC. The beam is transported, with a set of quadrupole magnets, to the phase space exchange (PEX) beamline which consists of a liquid-nitrogen-cooled deflecting cavity operating on the TM110-like π-mode at 3.9 GHz.

Superradiant CTR and CDR from a train of bunches

$$S_L(z)=\frac{1}{N_b\sqrt{\pi}\sigma_z}\sum_{n=1}^{N_b}\exp\left[-\frac{(z-n\lambda_0)^2}{\sigma_z^2}\right],$$

σ_z is the length of a microbunch, λ_0 is the distance between microbunch, N_b is the number of bunch in a train

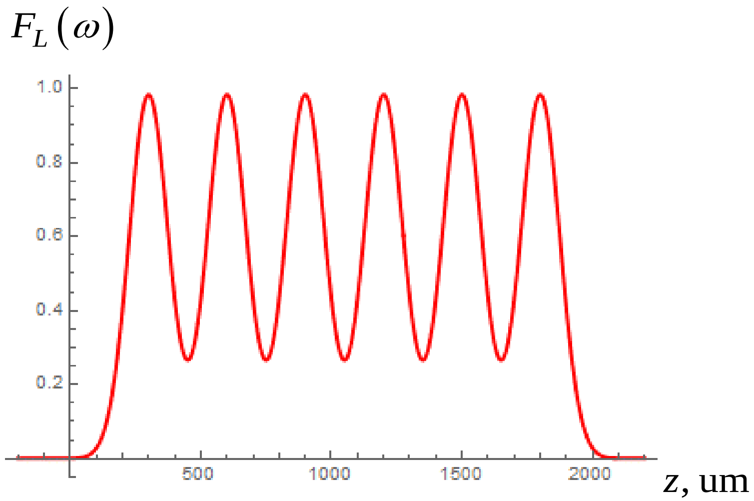
$$F_L(\omega)=\exp\left[-\sigma_z^2\,\omega^2/c^2\right]\frac{1}{N_b^2}\frac{\sin^2(N_b\lambda_0\omega/2c)}{\sin^2(\lambda_0\omega/2c)},$$

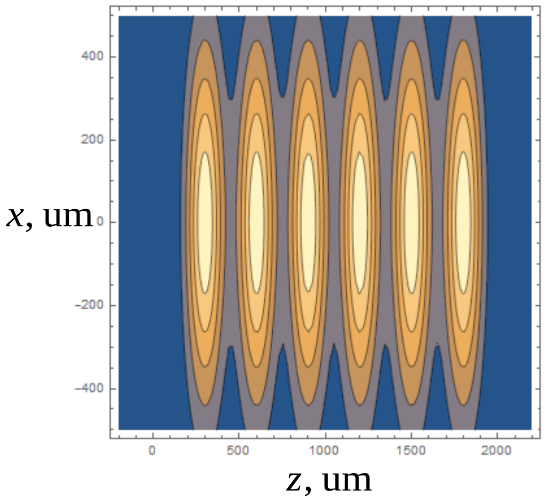
The fundamental frequency in the SCTR spectrum is determined by the last factor: $\nu_0=\lambda_0/c$
Monochromaticity is defined by the number of bunches N_b : $\Delta\nu/\nu=1/N_b$

$$\frac{d^2W_{\mathrm{SCTR}}}{d\omega d\Omega}=\left[N_e+N_e\left(N_e-1\right)\right]N_b{}^2F_L(\omega)\frac{d^2W_{\mathrm{TR}}}{d\omega d\Omega}\approx N_e{}^2N_b{}^2F_L(\omega)\frac{d^2W_{\mathrm{TR}}}{d\omega d\Omega}$$

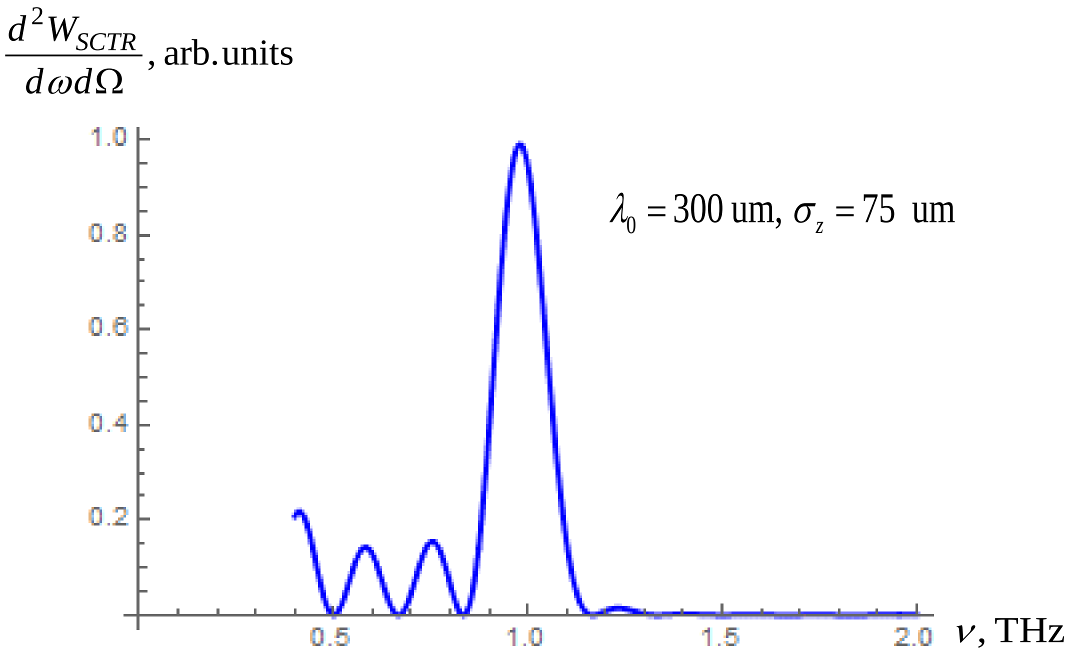
The charge $e*N_e*N_b$ is the charge of segmented initial bunch passed trough a slit mask

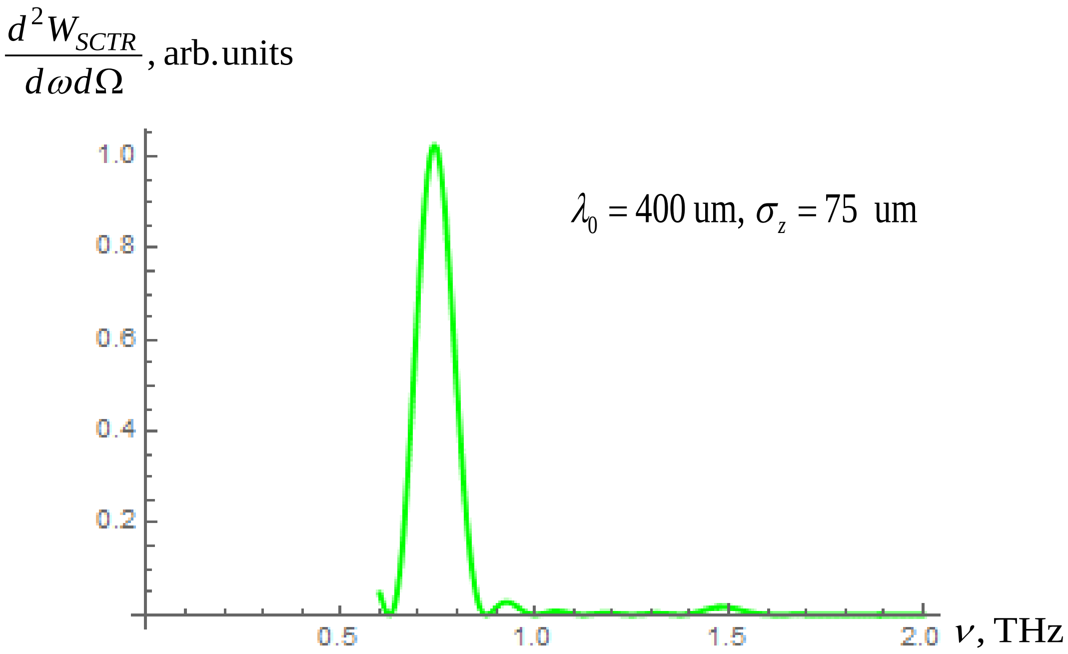
A mask with spacing 300 um and the slit width 75 um can provide transparency ~ 20% (for instance N_b=6, N_e ~ 20 pC)



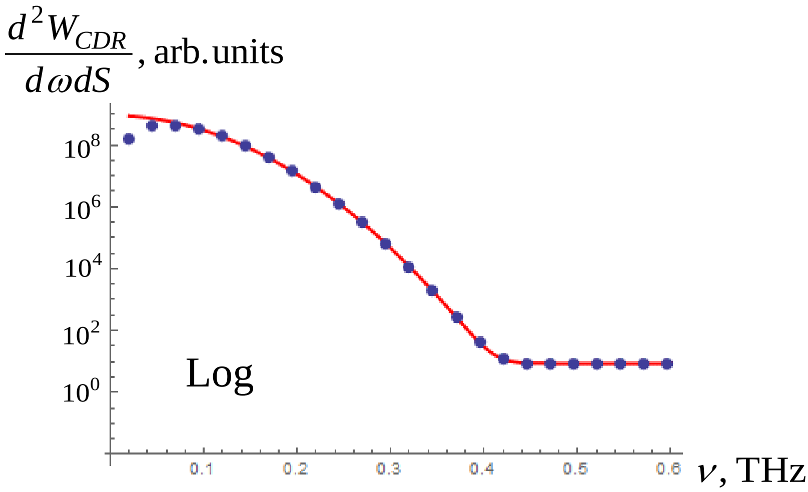


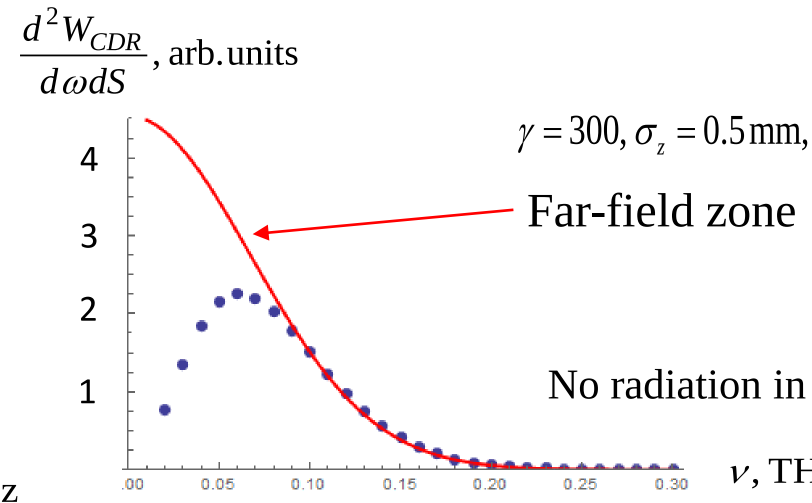
Superradiant CTR spectra from a train of bunches





Focused CDR spectrum





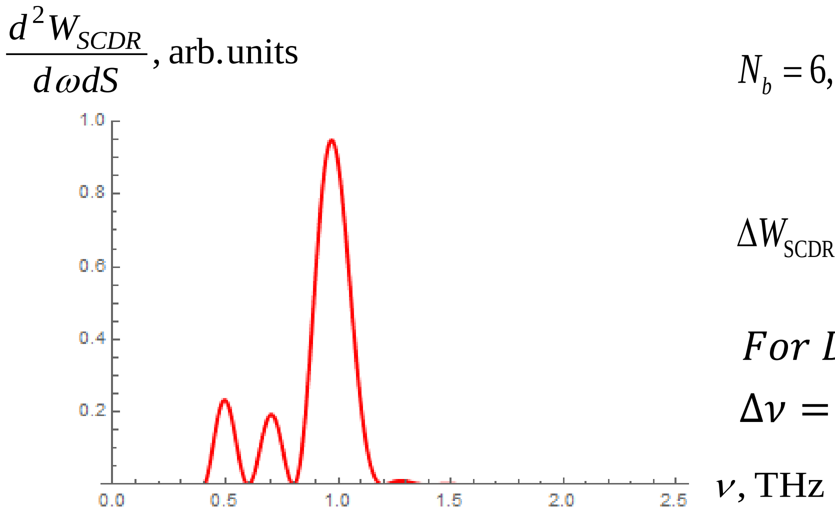
$\gamma = 300, \sigma_z = 0.5\,\mathrm{mm}, N_e = 10^8, D = 200\,\mathrm{mm}$, x = y = 0

No radiation in the range ν>0.2 THz

ν, THz

Superradiant CDR spectrum from a train of bunches

$$\frac{d^2W_{\mathrm{SCDR}}}{d\omega dS} \approx N_e^{\,2} N_b^{\,2} F_L(\omega) \frac{d^2W_{\mathrm{DR}}}{d\omega dS}$$



$N_b = 6, N_e :\ 20\,\mathrm{pC}, \lambda_0 = 300\,\mathrm{um}, \sigma_z = 75\ \mathrm{um}$

$$\Delta W_{\mathrm{SCDR}} :\ \int d\omega \int_{\Delta S} \frac{dW_{\mathrm{SCDR}}}{d\omega dS} dS$$

$For\ D = 200\ mm, \Delta S = 10\ mm^2, \Delta W_{SCDR} = 6\ nJ,$
$\Delta\nu = 0.15\ THz, \frac{\Delta W}{\Delta\nu} = 0.04\ \mu J/THz$

Summary

- **Focused CDR provides transverse distribution similar to TEM_{00} mode**
- **TR/ DR generated by a train of short electron bunches becomes monochromatic with the fundamental frequency defined by the distance between bunches**
- **Monochromaticity of the radiation is defined by the number of bunches in a train $(\Delta\nu/\nu_0=1/N_b)$**
- **Intensity of the radiation is proportional squared number of bunches and squared charge of each microbunch (superradiant radiation)**
- **For $N_b=6$ and $Q_b\approx20$ pC SCDR monochromatic pulse energy density can achieve the $\Delta W/\Delta\nu \sim 0.04$ μJ/THz at $\nu\sim1$ THz (for the broadband SPARC source $\Delta W/\Delta\nu\sim0.1$ μJ/THz)**

THANK FOR YOUR ATTENTION!