Coherent Cherenkov Diffraction Radiation for Longitudinal Diagnostics of Short Bunches

Pavel Karataev
John Adams Institute for Accelerator Science at
Royal Holloway, University of London

Content:

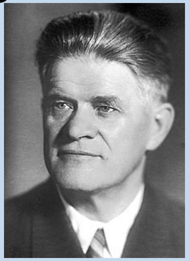
- *Cherenkov radiation and its spinout – Cherenkov Diffraction Radiation*
- *Theory and fundamental spectral angular characteristics*
- *Coherent ChDR and its applications in particle accelerators*
- *Conclusion and prospective*

History of Cherenkov Radiation

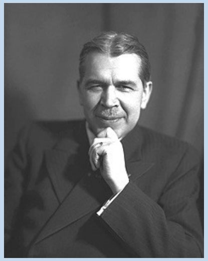
Vavilov-Cherenkov radiation

- Back in the 30s, in the prestigious Lebedev Physics institute in Moscow, a young scientist is working as a Ph.D student in the group of Professor Vavilov studying of the properties of charged particles induced luminescence in liquids

Pavel Cherenkov



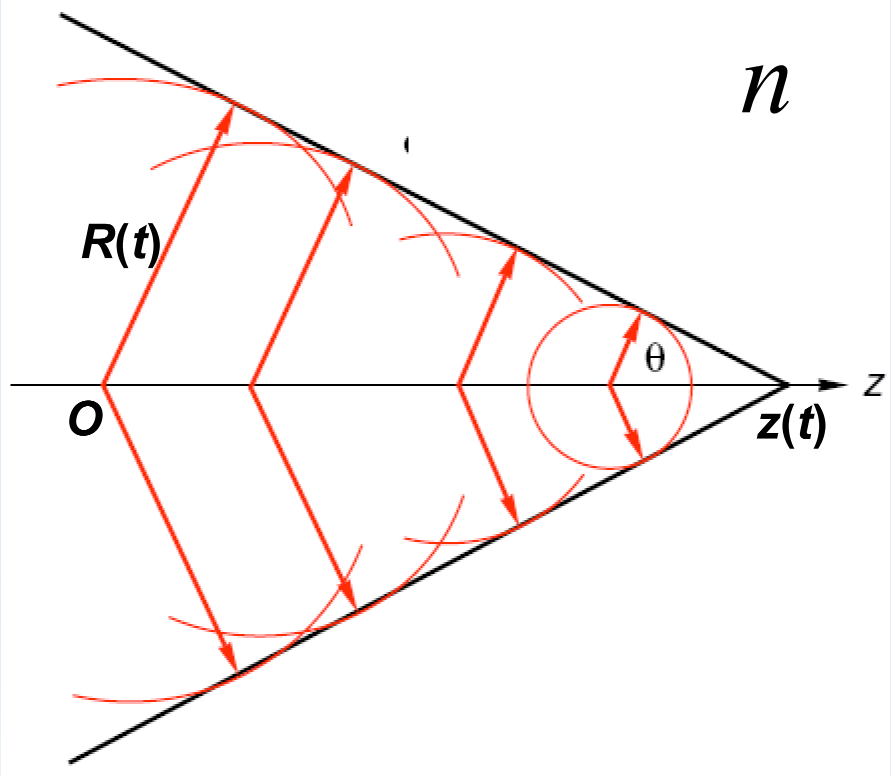
Sergey Vavilov



- They actually found out that, the presence of charged particles was producing light in water even in the absence of luminescent doping material : first observation in 1934

- Papers in Russian were published by the group but only one name was mentioned in the paper sent to American journal Physical review

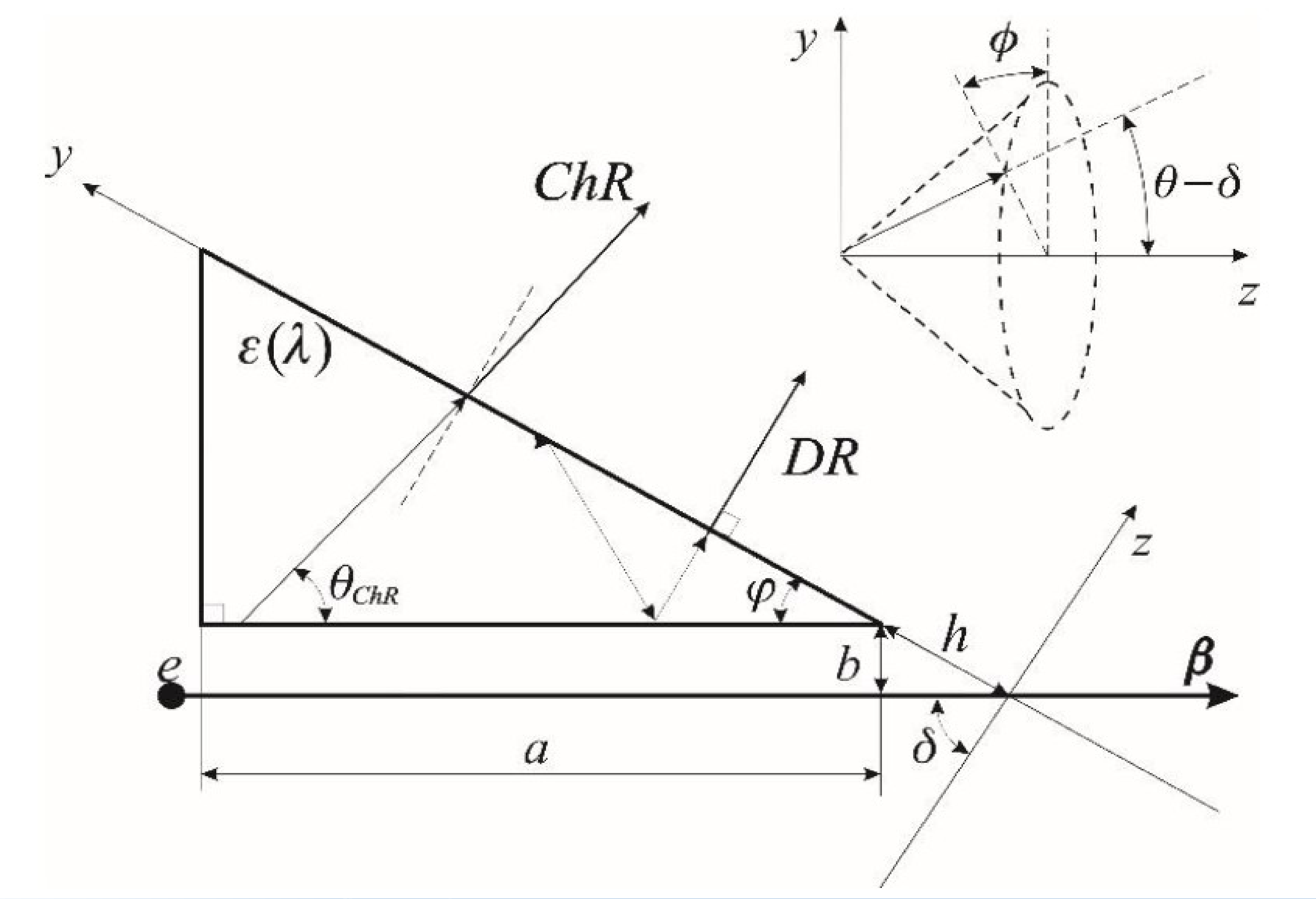
Cherenkov radiation



Cherenkov Radiation is generated whenever the charged particle velocity is larger than the phase velocity of light

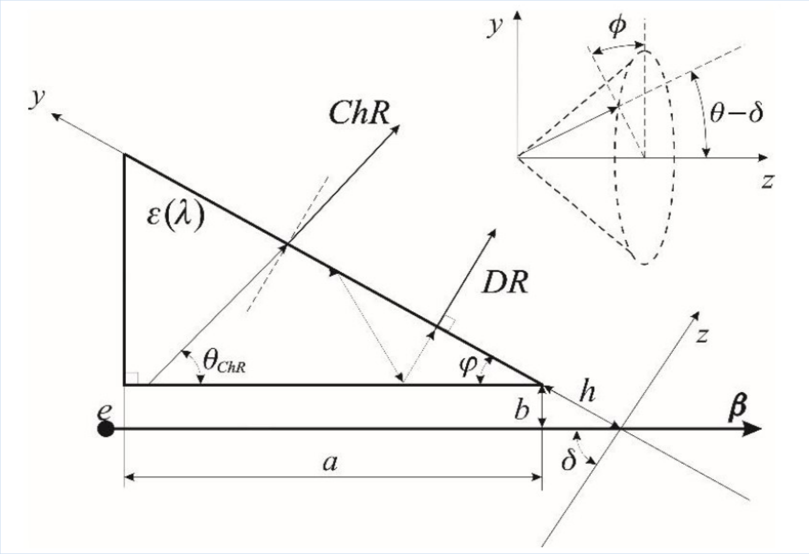
$$\cos\theta = \frac{R(t)}{z(t)} = \frac{(c/n)t}{vt} = \frac{1}{\beta n}$$

Cherenkov Diffraction Radiation



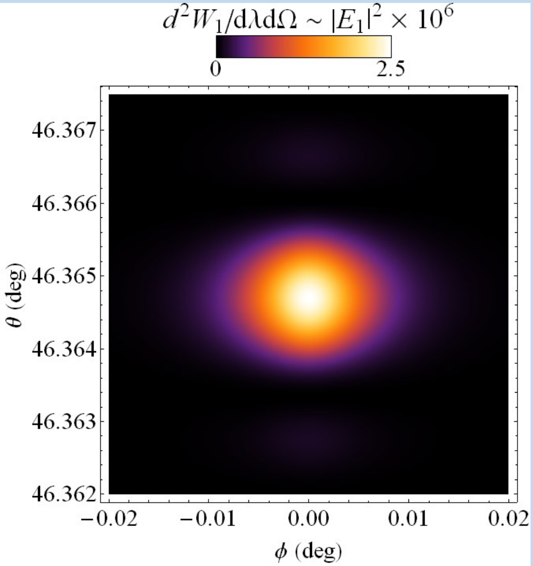
M.V. Shevelev and A.S. Konkov, JETP 118, 501 (2014)

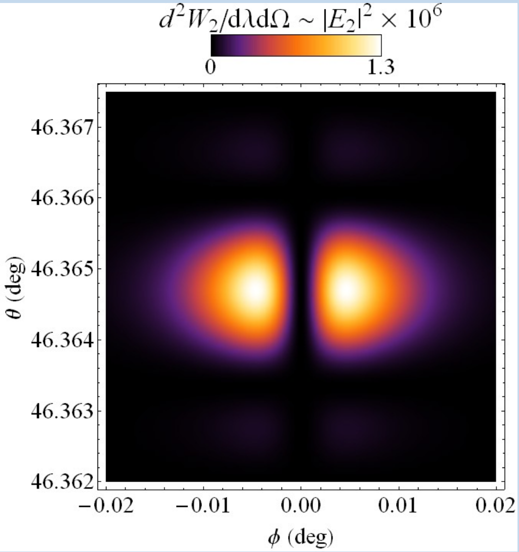
Cherenkov Diffraction Radiation



gamma = 10^4, λ = 600 nm, b = 0.8 mm, a = 11.5 mm

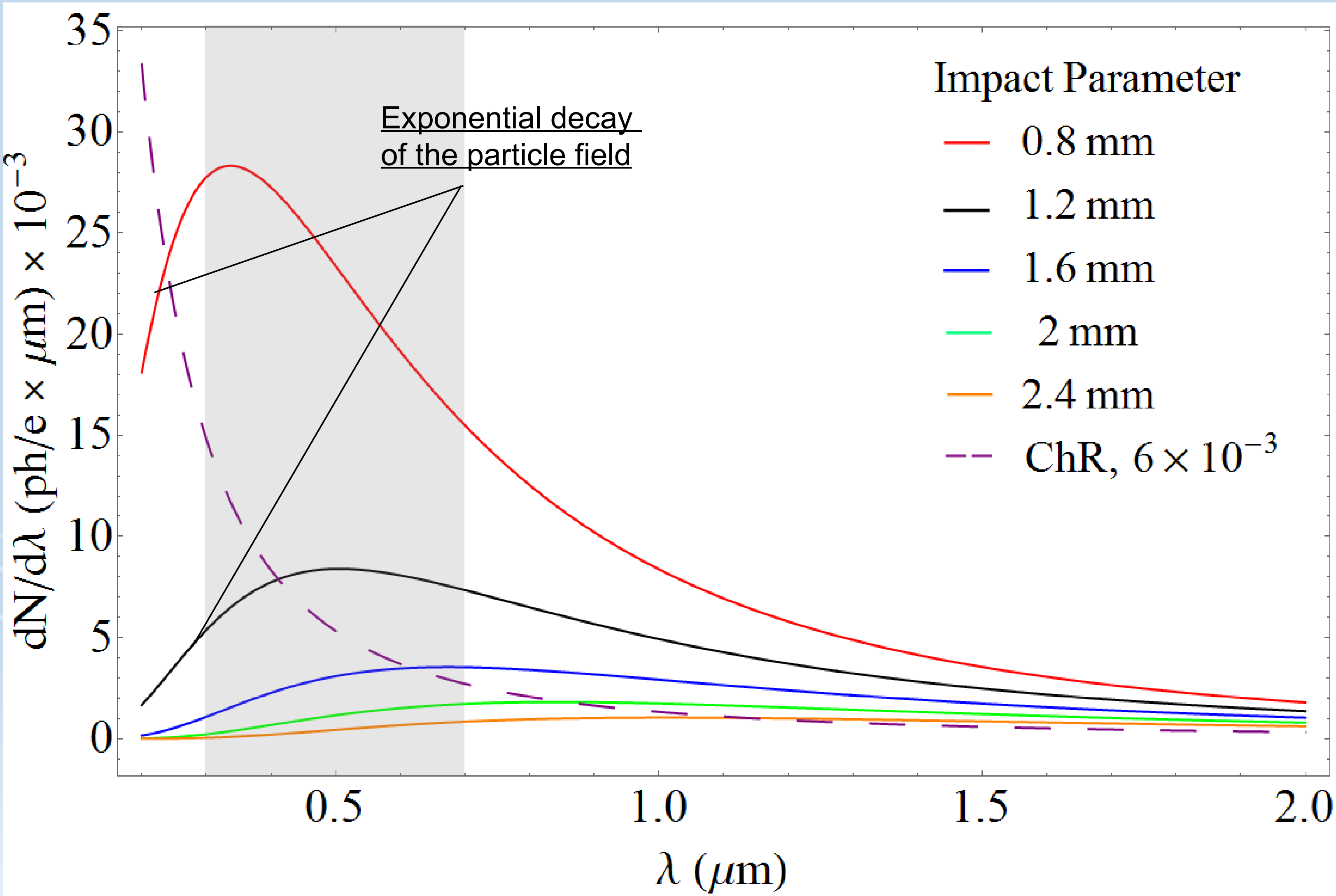
Vertical polarization **Horizontal polarization**





P. Karataev, G. Naumenko, A. Potylitsyn, and M. Shevelev, Cherenkov Diffraction Radiation from Relativistic Electrons, Monograph, Russian Academy of Science, Series of Radiation, Beams, Pasma N5, STT Publisher, Tomsk, 2021 (in Russian)

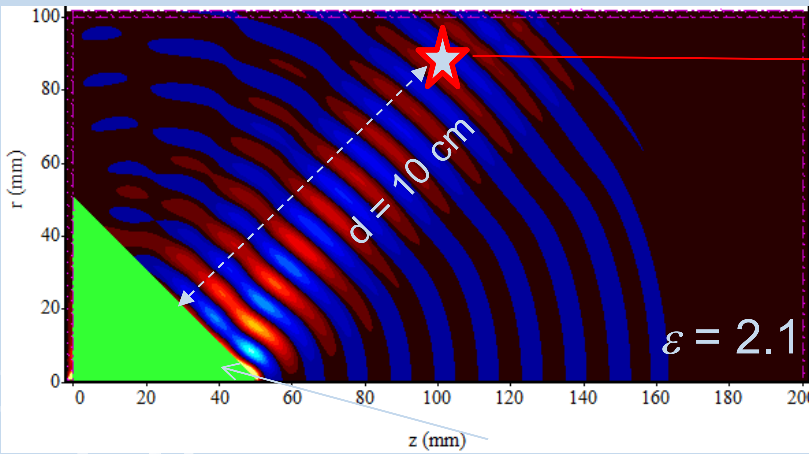
Cherenkov Diffraction Radiation

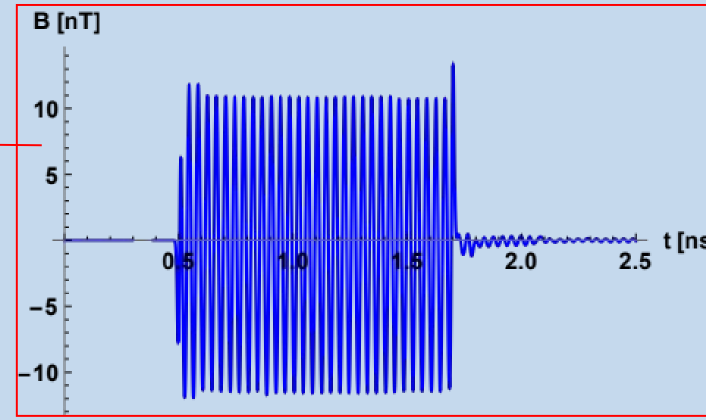


Cherenkov Diffraction Radiation

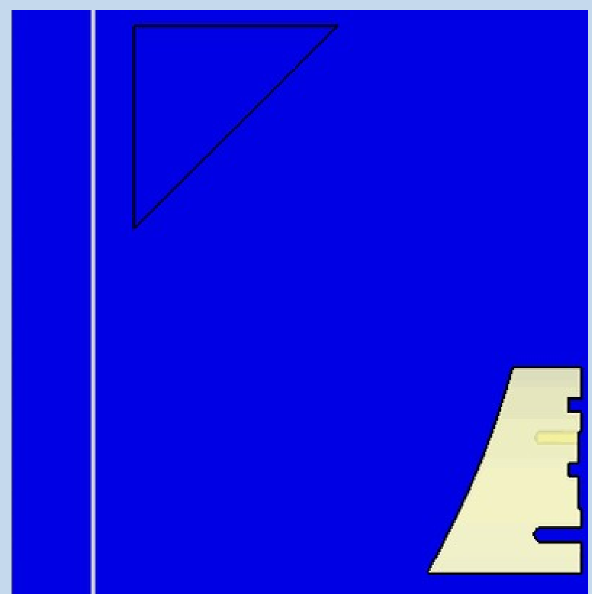
Simulations of Coherent ChDR using EM simulations codes

Using MAGIC and an electron beam current modulated at a 25GHz propagating at the vicinity of a Teflon cone





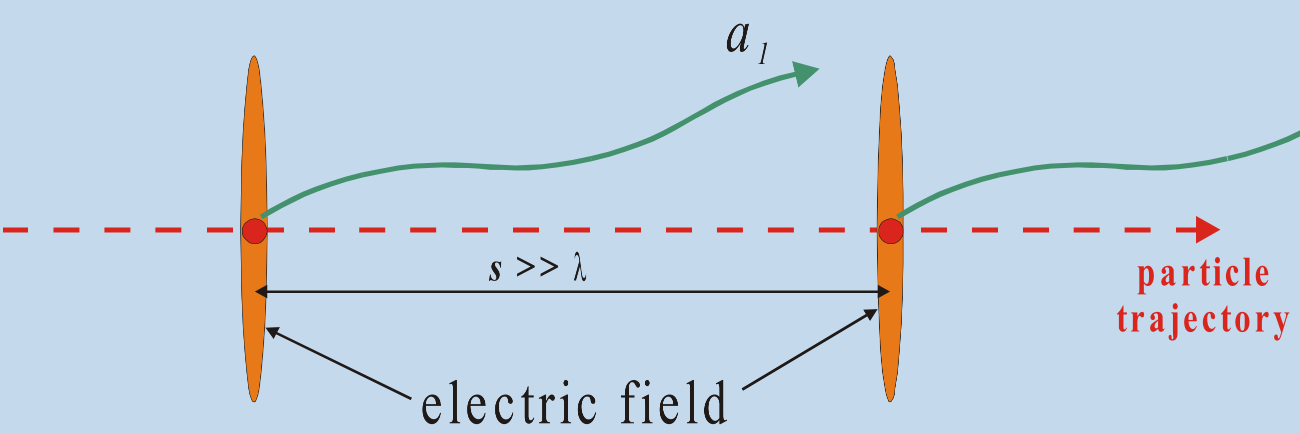
Broadband simulations using CST Studio Suite



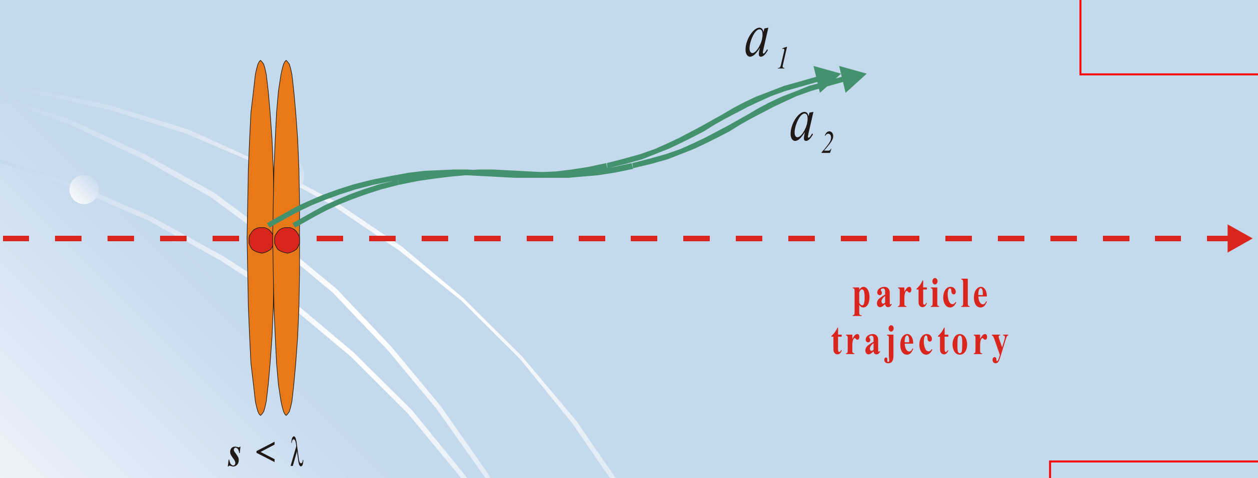
To detector

Coherent Radiation

Incoherent and Coherent radiation



$$I = |a_1|^2 + |a_2|^2 = 2|a|^2 \rightarrow N|a|^2$$



$$I = |a_1 + a_2|^2 = |2a|^2 = 4|a|^2 \rightarrow N^2|a|^2$$

Radiation spectrum

$$S(\omega) = S_e(\omega)\left[N + N(N-1)F(\omega)\right]$$

$S(\omega)$ – **radiation spectrum**

$S_e(\omega)$ – **single electron spectrum**

N – **number of electrons in a bunch**

$F(\omega)$ – **bunch form factor**

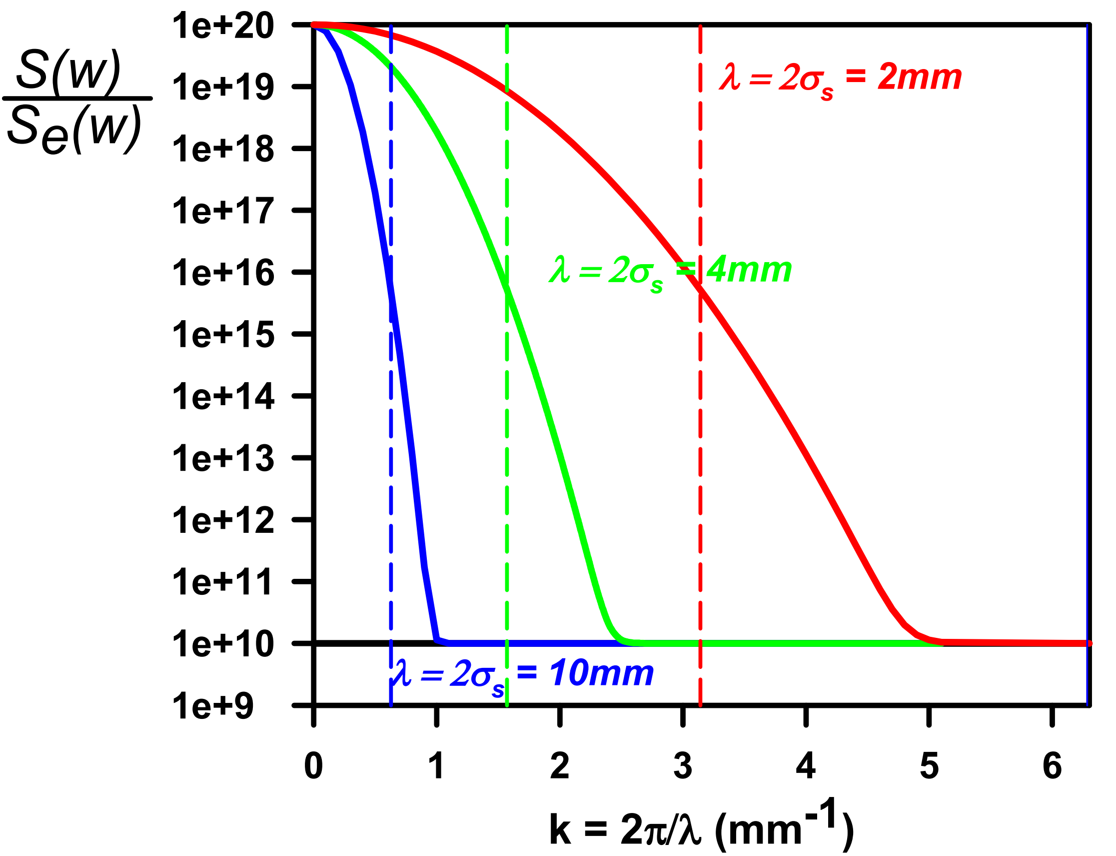
$$F(\omega) = \left| \int_{-\infty}^{\infty} \rho(s) e^{-i\frac{\omega}{c}s} ds \right|^2$$

$\rho\ (s)$ – **Longitudinal particle distribution in a bunch**

Gaussian beam

$$F(\omega) = \left| \frac{1}{\sigma_s \sqrt{2\pi}} \int_{-\infty}^{\infty} e^{-\frac{s^2}{2\sigma_s^2}} e^{-i\frac{\omega}{c}s} ds \right|^2 = e^{-\frac{\omega^2 \sigma_s^2}{c^2}} = e^{-k^2 \sigma_s^2}$$

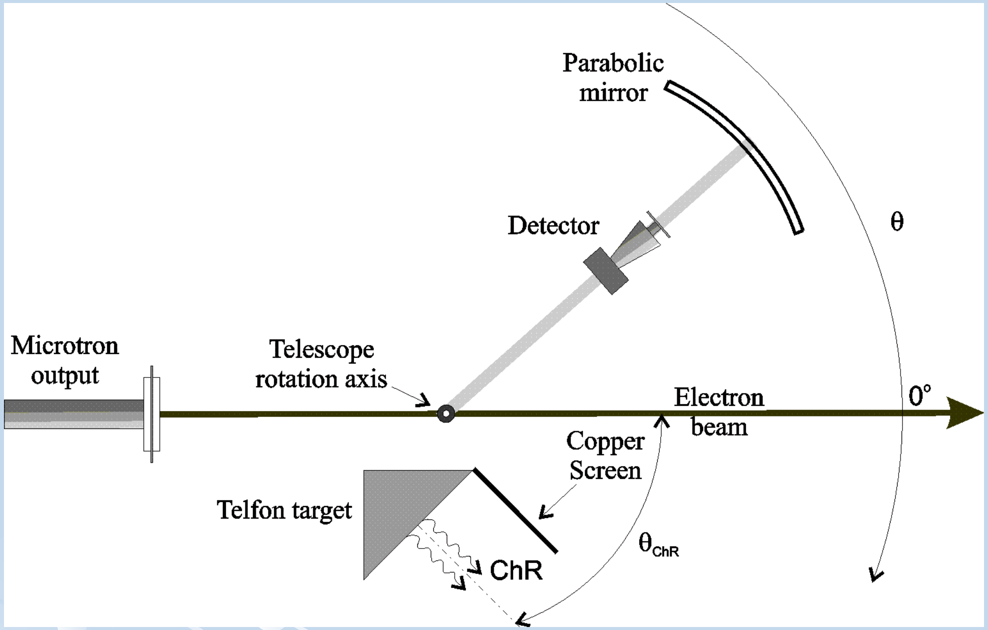
Assume $N = 10^{10}$ e/bunch

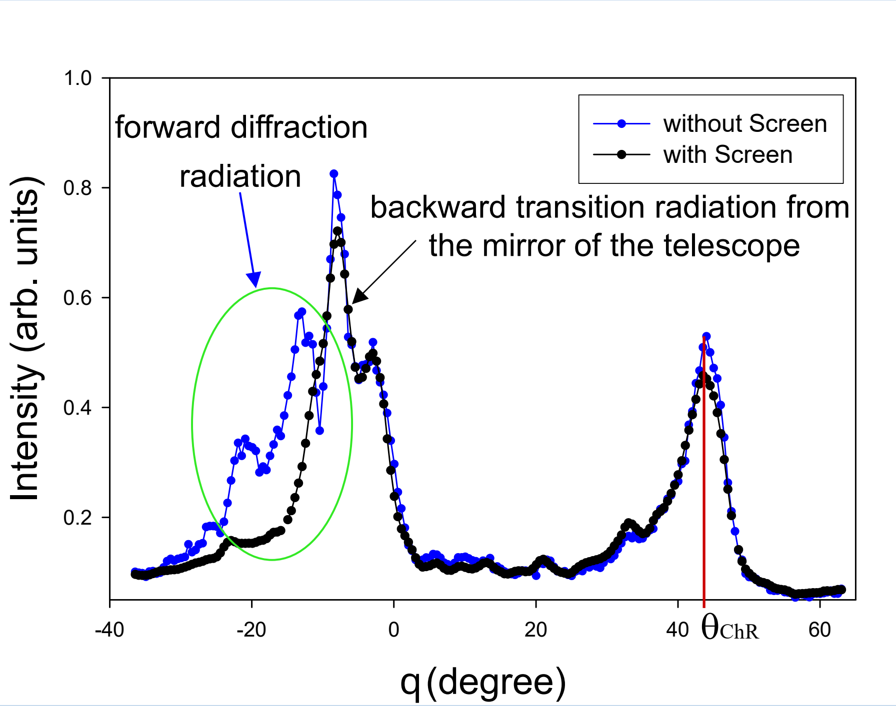


Coherent radiation appears when the bunch length is comparable to or shorter than the emitted radiation wavelength

Coherent Cherenkov Diffraction Radiation TPU microtron, CLEAR, CLARA

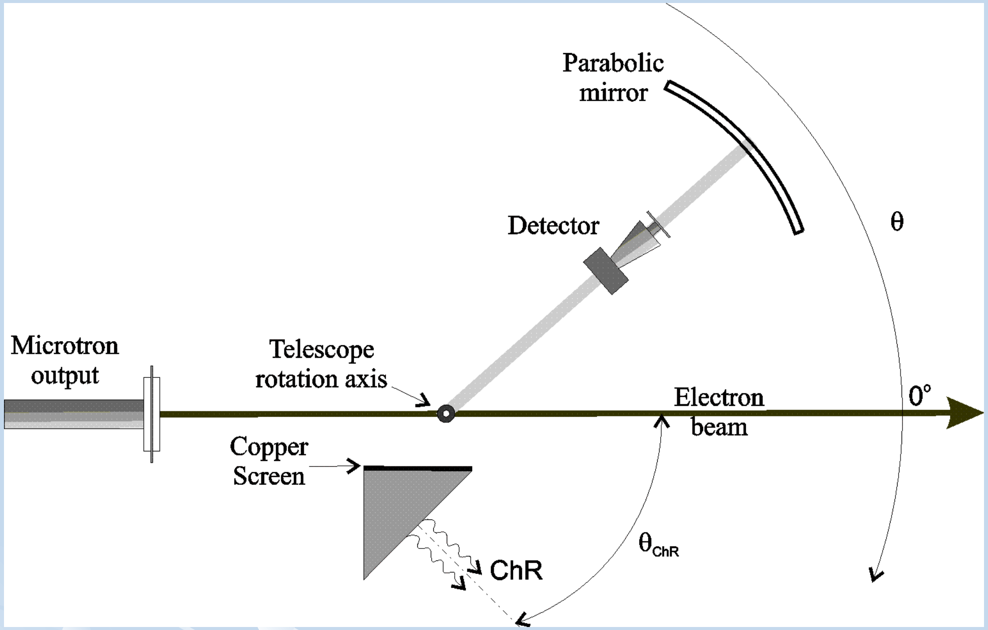
Experimental Results at TPU 6 MeV microtron

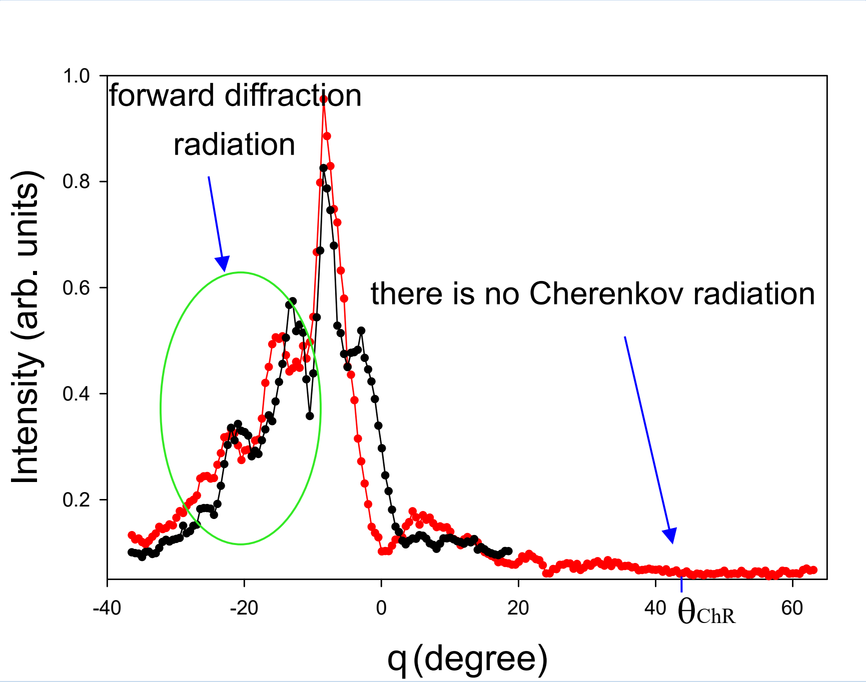




$$\cos[\theta_{ChR}] = \frac{1}{n \cdot \beta}$$

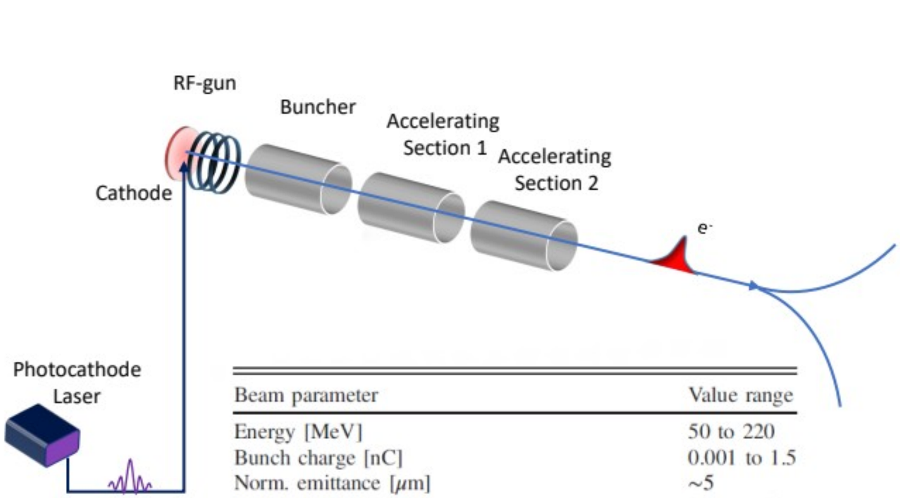
Experimental Results at TPU 6 MeV microtron



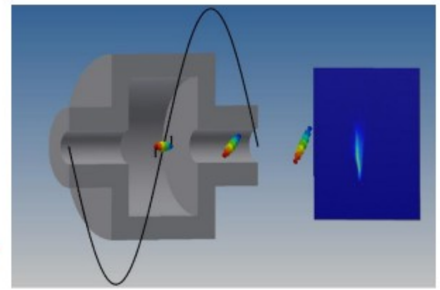


Coherent ChDR experiment at CLEAR in CERN

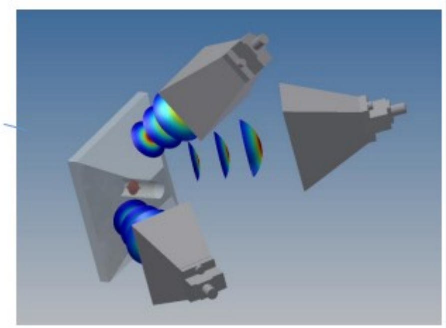
Development of Coherent ChDR for bunch length monitoring



Beam parameter	Value range
Energy [MeV]	50 to 220
Bunch charge [nC]	0.001 to 1.5
Norm. emittance [μm]	~5
Bunch length rms [ps]	0.5 to ~10
Relative energy spread rms	< 0.2%
Frequency of the train of bunches [GHz]	1.5
Number of bunches in a train	Up to ~200
Repetition rate [Hz]	0.833 to 10



- Cross calibrating using RF deflector



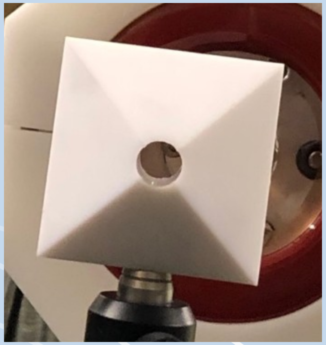
- Measuring beam power spectrum in 3 frequency bands

A. Curcio et al, Beam-based sub-THz source at the CERN Linac Electron Accelerator for Research facility, PRAB 22, 020402 (2019)

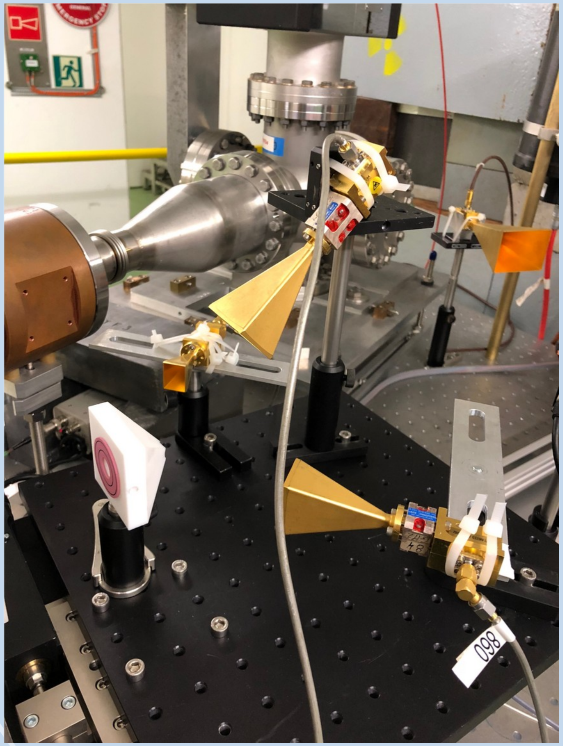
Coherent ChDR experiment at CLEAR in CERN

CChDR radiator installed in the in-air test-stand

<u>Pyramid in Teflon</u>



- 5x5cm base
- 45° output angle
- ∅ 1cm hole

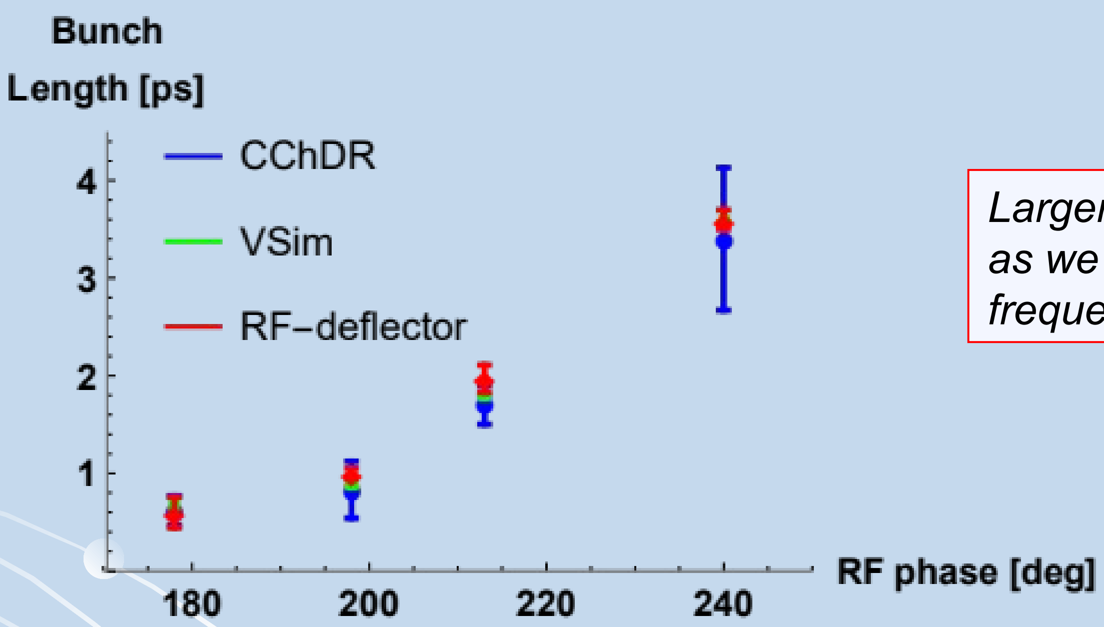


- Measuring in 3 bands (60-90-110GHz)
- Scintillating screen on the radiator's input face for beam tuning
- Typical beam size (H/V) < 500microns
- All set-up mounted on remotely controlled table to allow hor/ver centering

A. Curcio et al, Beam-based sub-THz source at the CERN Linac Electron Accelerator for Research facility, PRAB 22, 020402 (2019)

Coherent ChDR experiment at CLEAR in CERN

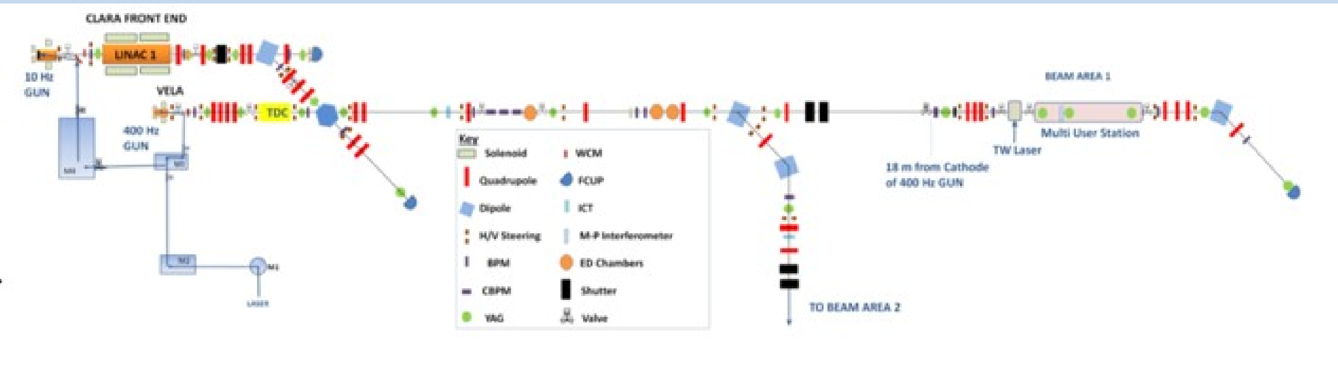
Comparison between CChDR and RF deflector



Larger noise for longer bunches as we measured at (too) high frequencies

A. Curcio et al, Beam-based sub-THz source at the CERN Linac Electron Accelerator for Research facility, PRAB 22, 020402 (2019)

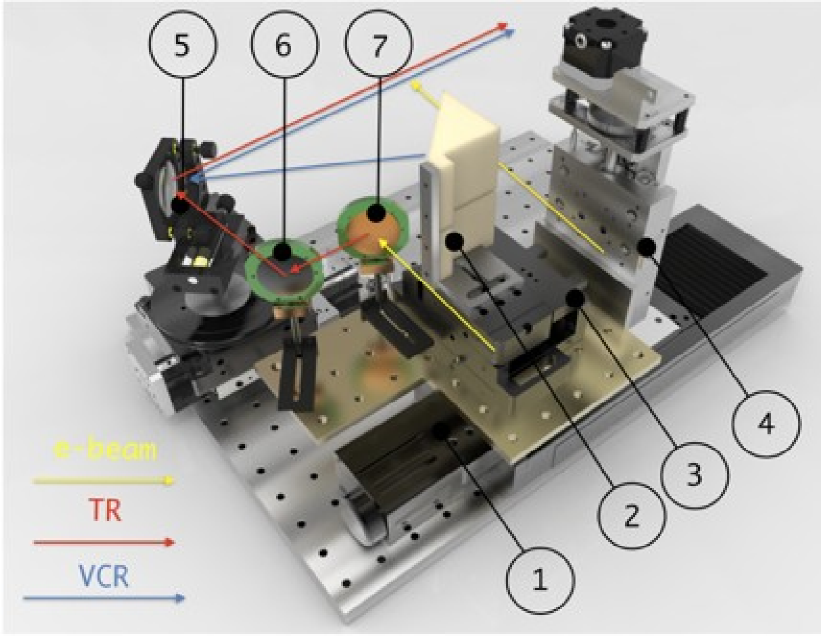
Coherent ChDR experiment at CLARA in Daresbury

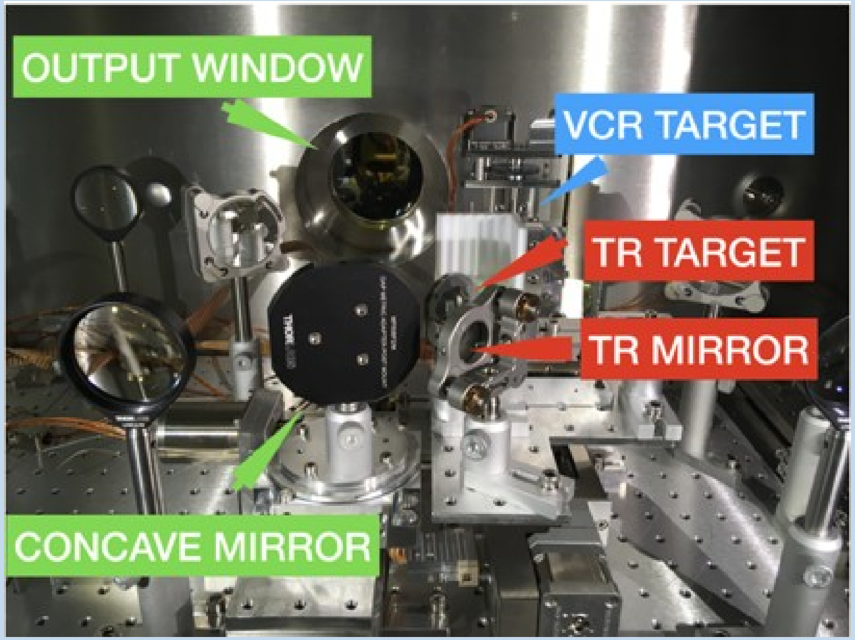


- f = 10Hz
- E = 35 MeV
- Longitudinal beam size was about 0.2-0.3 ps with charge ranging within 70 - 100 pC
- 200 microns RMS transversal bunch size

A. Curcio et al, Beam-based sub-THz source at the CERN Linac Electron Accelerator for Research facility, PRAB 22, 020402 (2019)

Coherent ChDR experiment at CLARA in Daresbury



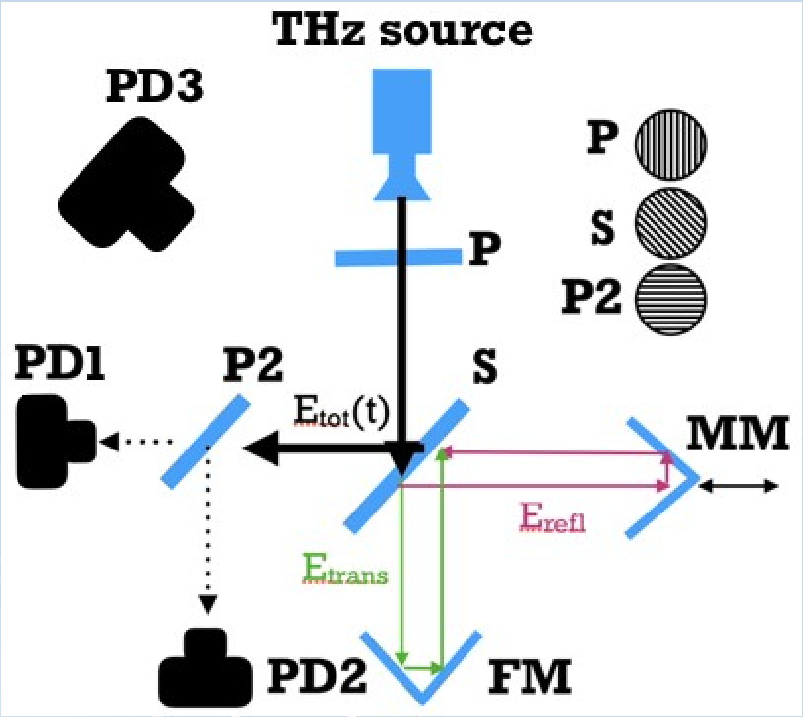


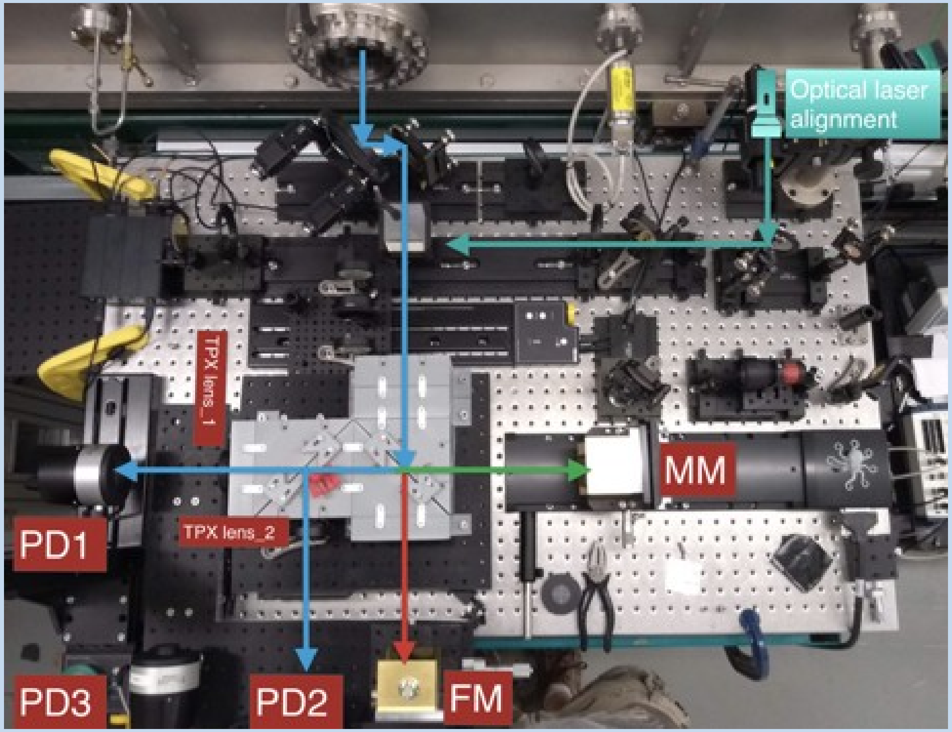
1 — Horizontal positioning stage
2 — Teflon (VCR) target
3 — Tip-Tilt stage
4 — Vertical positioning stage
5 — Concave mirror
6 — Mirror for TR
7 — Foil (TR) target

Both TR and ChDR scans were conducted during same accelerator run

A. Curcio et al, Beam-based sub-THz source at the CERN Linac Electron Accelerator for Research facility, PRAB 22, 020402 (2019)

Coherent ChDR experiment at CLARA in Daresbury

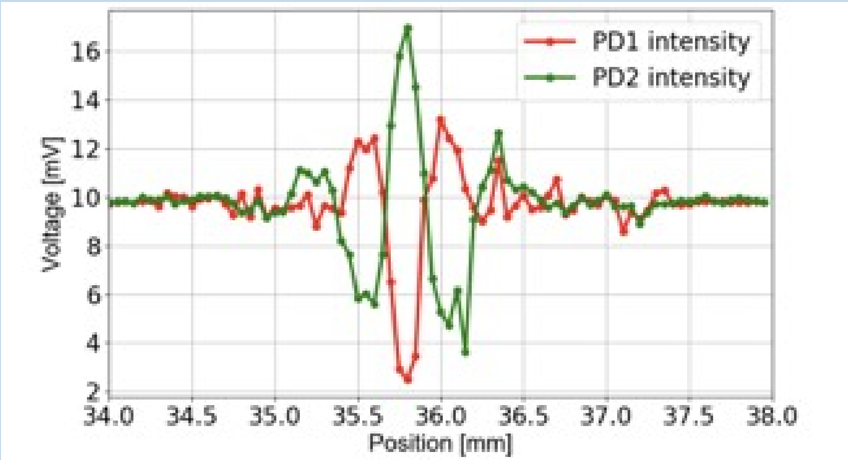


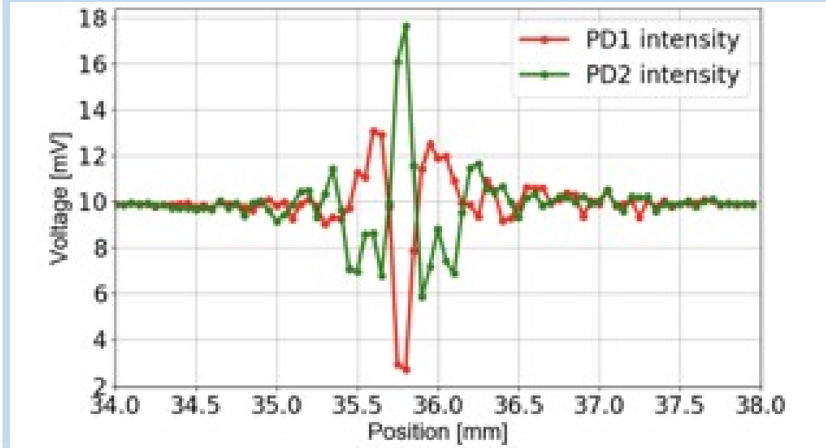


$$I(x) = \frac{PD2 - PD1}{PD2 + PD1}$$

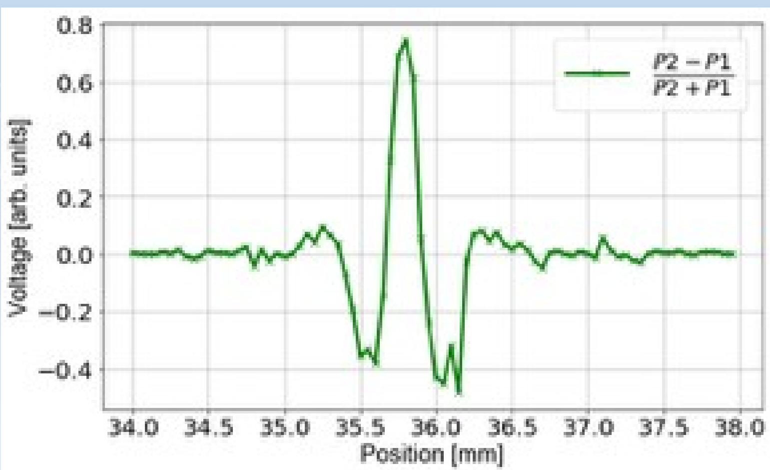
A. Curcio et al, Beam-based sub-THz source at the CERN Linac Electron Accelerator for Research facility, PRAB 22, 020402 (2019)

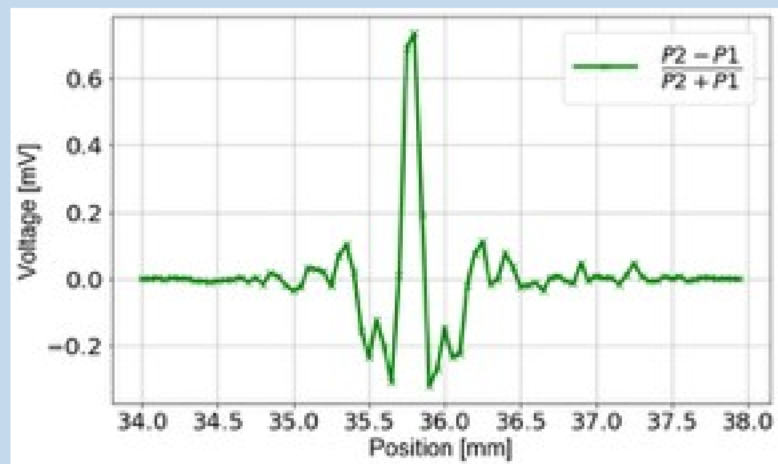
Coherent ChDR experiment at CLARA in Daresbury





Interferograms of coherent ChDR diffraction radiation (a) and coherent TR (b)

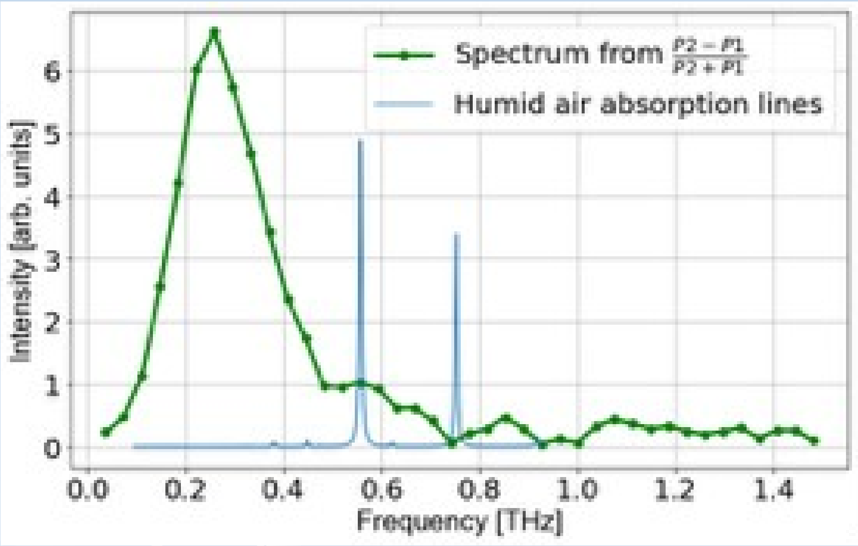


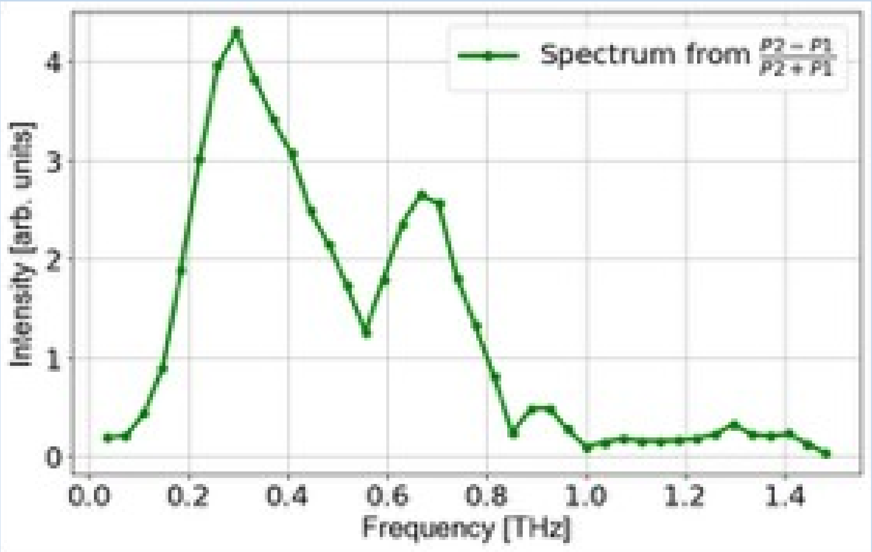


Normalised interferograms of coherent ChDR diffraction radiation (a) and coherent TR (b)

A. Curcio et al, Beam-based sub-THz source at the CERN Linac Electron Accelerator for Research facility, PRAB 22, 020402 (2019)

Coherent ChDR experiment at CLARA in Daresbury

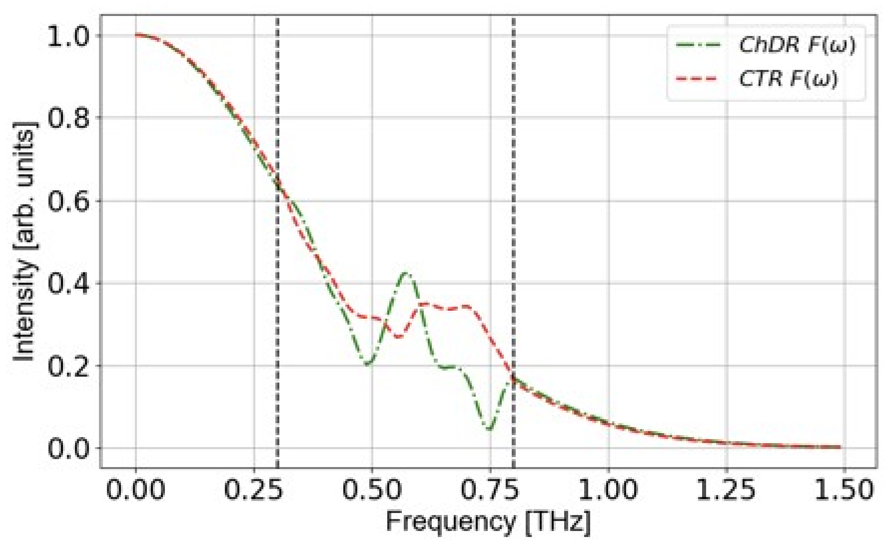




Spectrum of coherent ChDR diffraction radiation (a) and coherent TR (b)

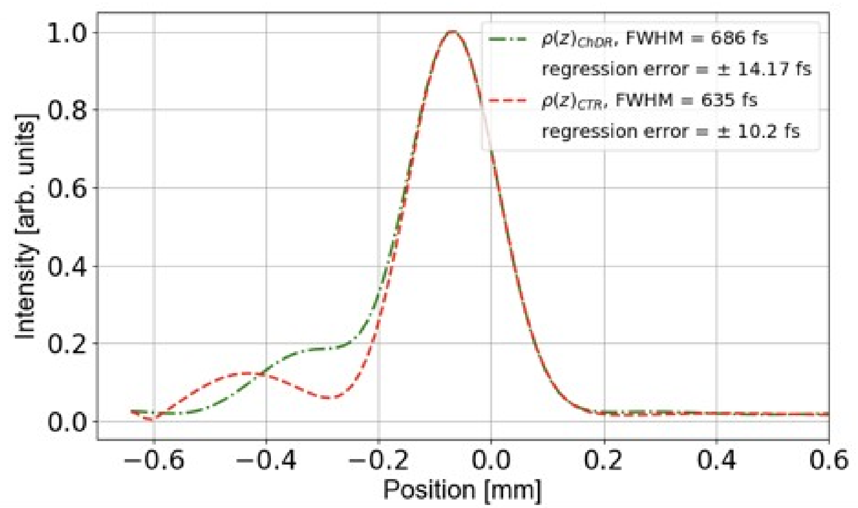
A. Curcio et al, Beam-based sub-THz source at the CERN Linac Electron Accelerator for Research facility, PRAB 22, 020402 (2019)

Coherent ChDR experiment at CLARA in Daresbury



Extrapolated form-factor for both ChDR (green) and TR (red). Extrapolation according to:

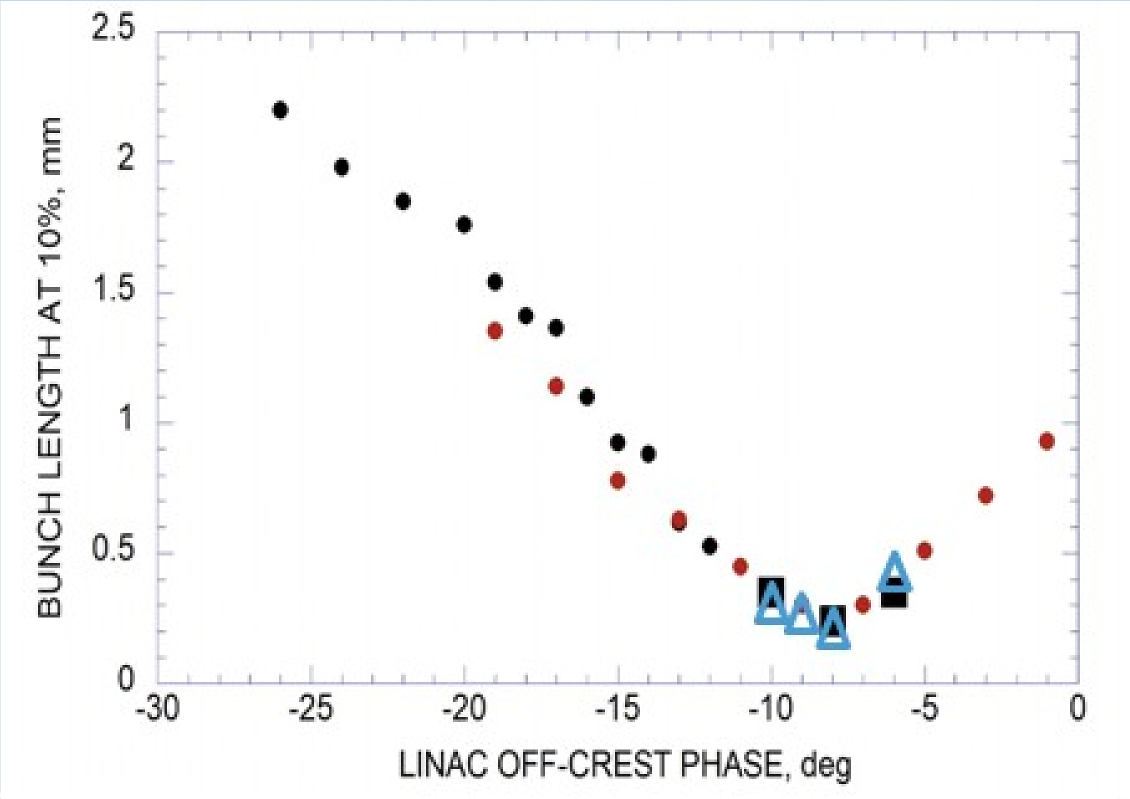
M Micheler et al. "Longitudinal beam profile monitor at CTF3 based on Coherent Diffraction Radiation." In: *Journal of Physics: Conference Series* 236 (June 2010), p. 012021.



Bunch profile reconstruction via ChDR (green) and TR (red)

A. Curcio et al, Beam-based sub-THz source at the CERN Linac Electron Accelerator for Research facility, PRAB 22, 020402 (2019)

Comparison of the bunch length measured with different techniques at CLARA facility in Daresbury



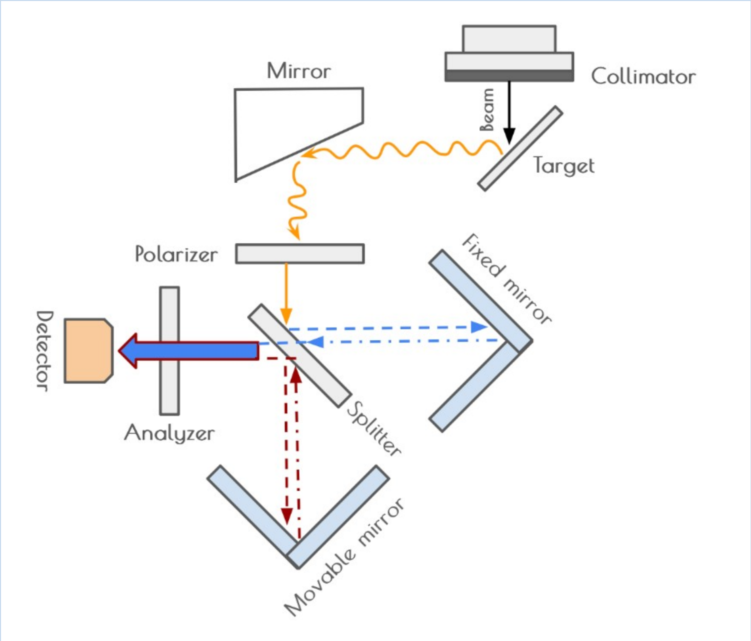
CChDR scan

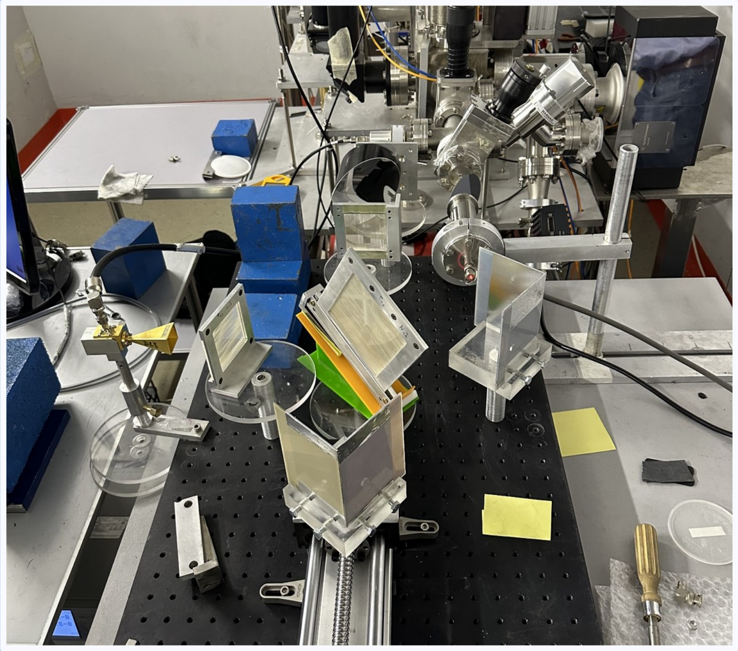
CTR scan

CTR scan during DWA experiment

elegant code beam simulation

AREAL experiment

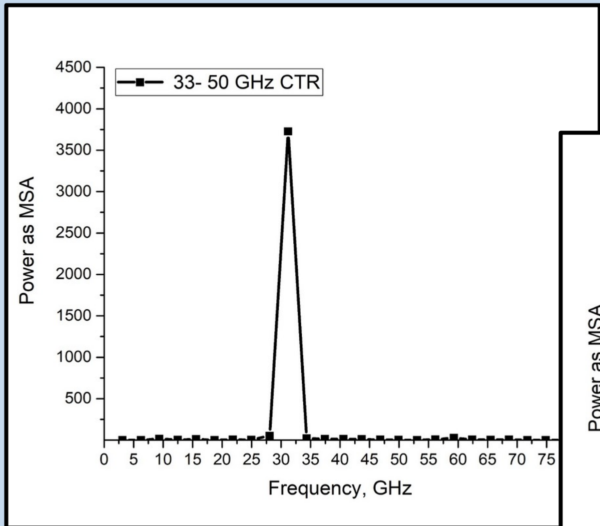


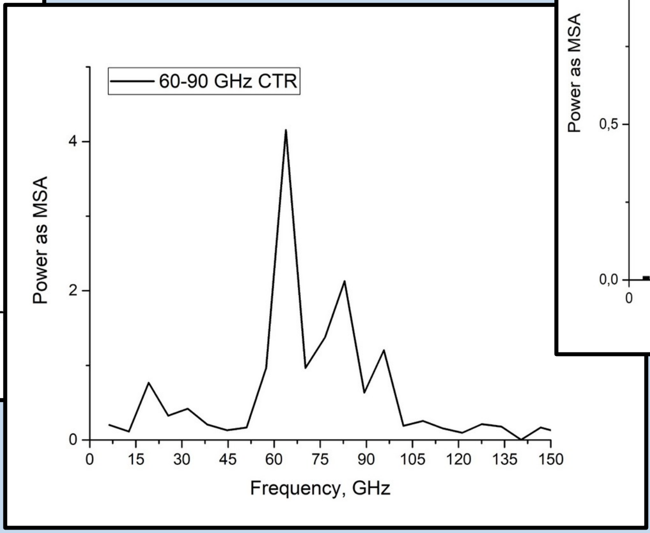


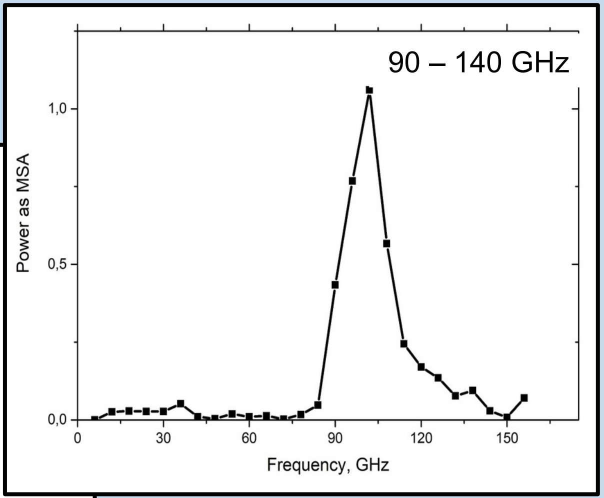
Key experimental parameters:

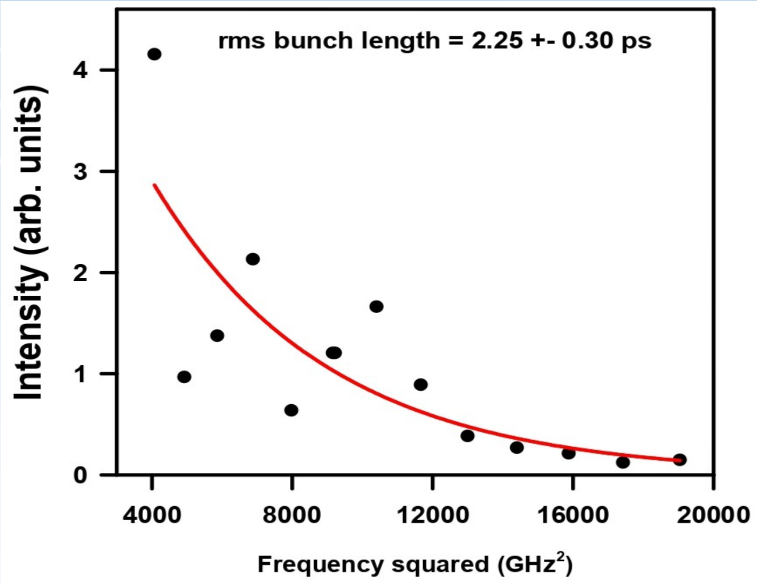
- Charge per bunch 12 pC
- Beam energy 3.6 MeV
- Repetition rate 20 Hz
- Laser duration on photo-cathode 550 fs

Coherent Transition Radiation









$$F(\omega) = a \cdot exp(-4\pi^2 f^2 \sigma^2)$$

Conclusion and prospective

- Our studies both experimental and theoretical have been dedicated to coherent ChDR characteristics
  - *Still a lot of work to fully understand its potential (resolution, sensitivity, intensity amplification, dynamic range, etc.)*
  - *How to optimise such a system i.e. material, shape / length, detection system, …*
  - *Impedance calculations started using a code developed at CERN*

- Coherent ChDR would find applications in short bunches beam instrumentation
  - *Bunch length monitor for short bunches (electrons or protons)*
  - *Beam position monitor of short bunches*
  - *High frequency BPM (>30GHz) for AWAKE – proton driven plasma acceleration: separate electrons from protons*
  - *Intense EM radiation beams in THz frequency range*

Thanks to all members of the international collaboration!

Science & Technology Facilities Council
Daresbury Laboratory

JAI
John Adams Institute for Accelerator Science

The Cockcroft Institute of Accelerator Science and Technology

JINR

НИУ БелГУ
BELGOROD NATIONAL RESEARCH UNIVERSITY

CANDLE

MANCHESTER 1824
The University of Manchester

CERN

ROYAL HOLLOWAY UNIVERSITY OF LONDON

TOMSK POLYTECHNIC UNIVERSITY

CORNELL UNIVERSITY FOUNDED A.D. 1865

cea

diamond
www.diamond.ac.uk