Non-invasive beam measurement using polarization radiation

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On Behalf of the Collaboration

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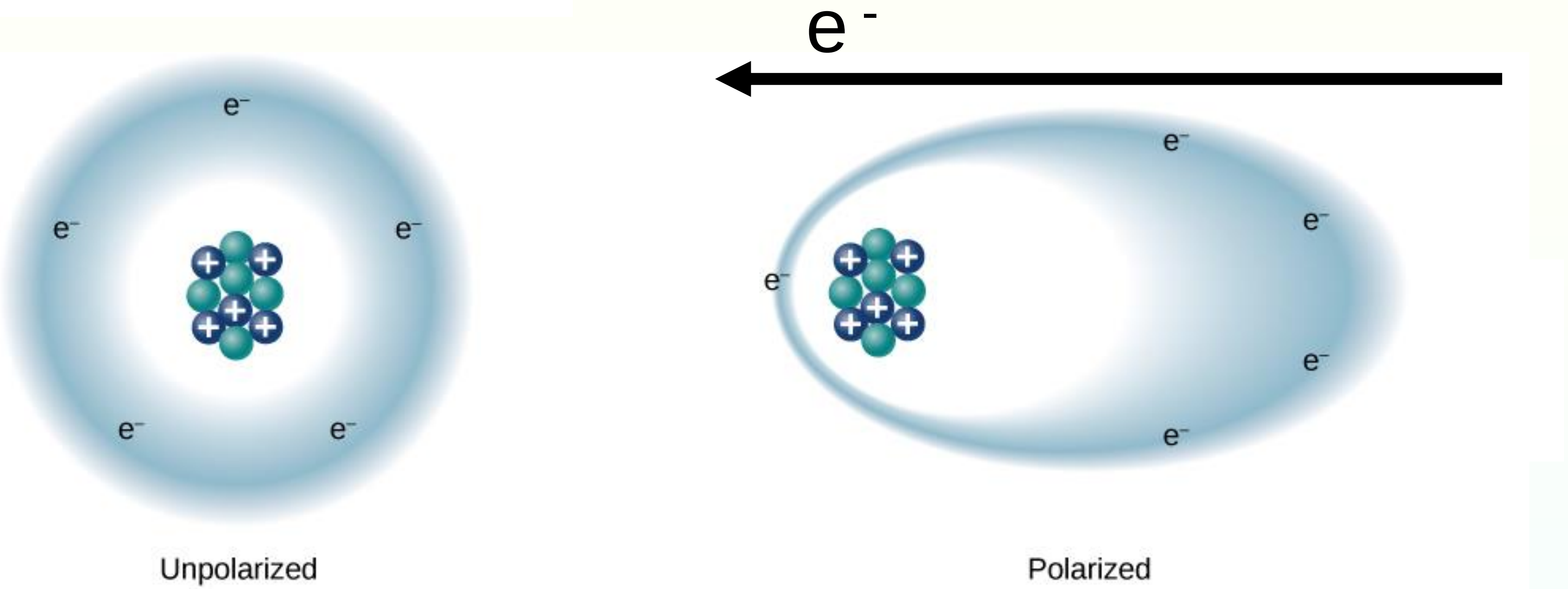
What is Polarization Radiation?



- **a fast charged particle passes by creating a dipole;**
- **the dipole oscillates around the nucleus emitting EM radiation;**
- **depending on the target composition and geometry, this mechanism is responsible for the entire family of polarization radiation**

Polarization Radiation Family

- **Transition Radiation**
- **Diffraction Radiation**
- **Smith-Purcell Radiation**
- **Cherenkov Radiation**
- **Cherenkov Diffraction Radiation**
- **Parametric X-ray Radiation**
- **Wakefield radiation**

Polarization Current Approach (PCA)

The theoretical approach is based on the method of polarization currents. For a non-magnetic medium the density of the polarization currents in the right-hand side of Maxwell equations

$$\mathbf{j}_{pol} = \sigma(\omega)\left(\mathbf{E}^0 + \mathbf{E}^{pol}(\mathbf{j}_{pol})\right)$$

where conductivity is

$$\sigma(\omega) = \frac{i\omega}{4\pi}\left(1 - \varepsilon(\omega)\right)$$

The field of the Polarization Radiation (PR) emitted by medium atoms excited (polarized) by the external field of the passing particle moving rectilinearly and with constant velocity in a substance (or in its vicinity) can be represented as a solution of Maxwell equations

$$\mathbf{H}^{pol}(\mathbf{r},\omega) = \mathrm{curl}\frac{1}{c}\int_{V_T}\sigma(\omega)\mathbf{E}^0(\mathbf{r}',\omega)\frac{\exp\left(i\sqrt{\varepsilon(\omega)}\left|\mathbf{r}'-\mathbf{r}\right|\omega/c\right)}{\left|\mathbf{r}'-\mathbf{r}\right|}d^3r'$$

Two mechanisms we concentrate on

- Transition Radiation
- **Diffraction Radiation**
- Smith-Purcell Radiation
- Cherenkov Radiation
- **Cherenkov Diffraction Radiation**
- Parametric X-ray Radiation
- Wakefield radiation

Two mechanisms we concentrate on

- Transition Radiation
- **Diffraction Radiation**
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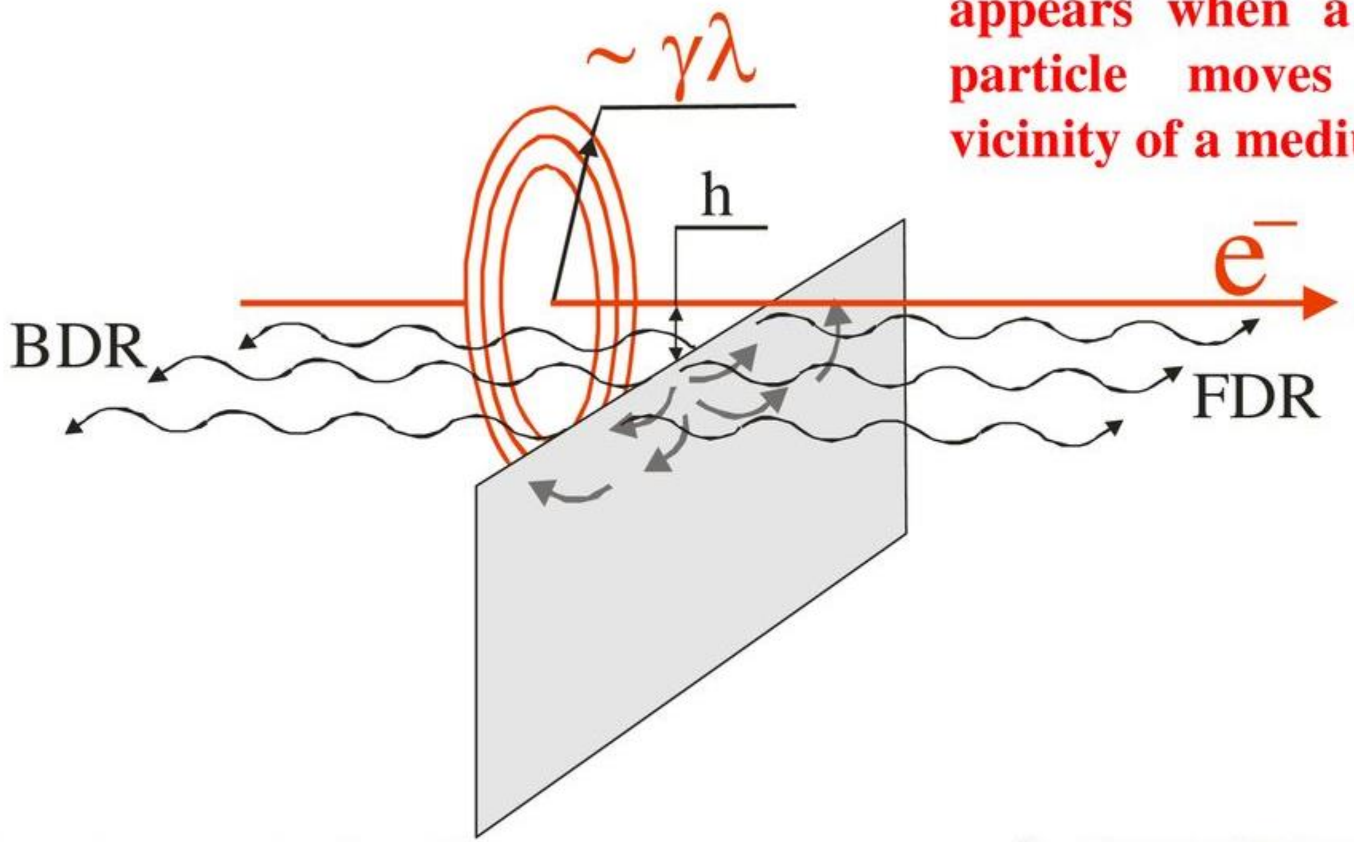
- Cherenkov Radiation
- **Cherenkov Diffraction Radiation**
- Parametric X-ray Radiation
- Wakefield radiation

Diffraction Radiation



Diffraction radiation (DR) appears when a charged particle moves in the vicinity of a medium

Impact parameter, h, – the shortest distance between the target and the particle trajectory

$$h \leq \gamma\lambda$$

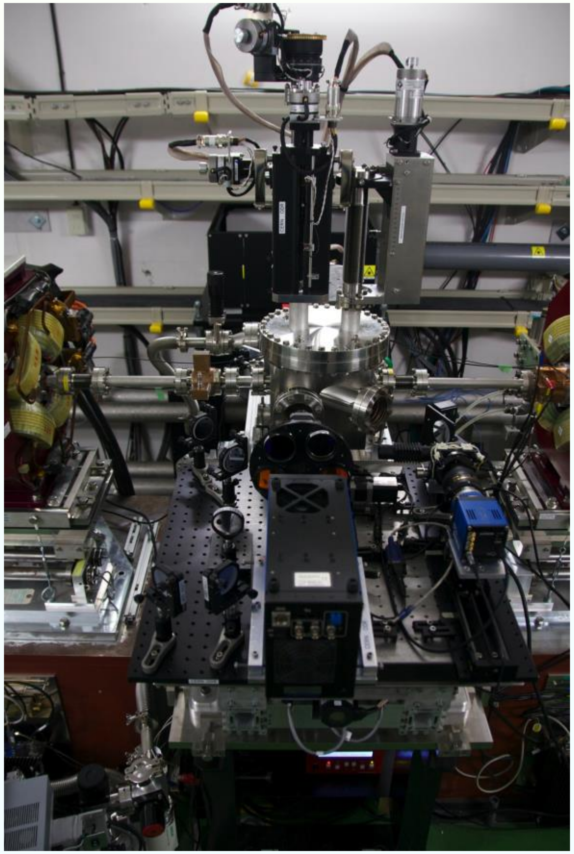
λ - observation wavelength

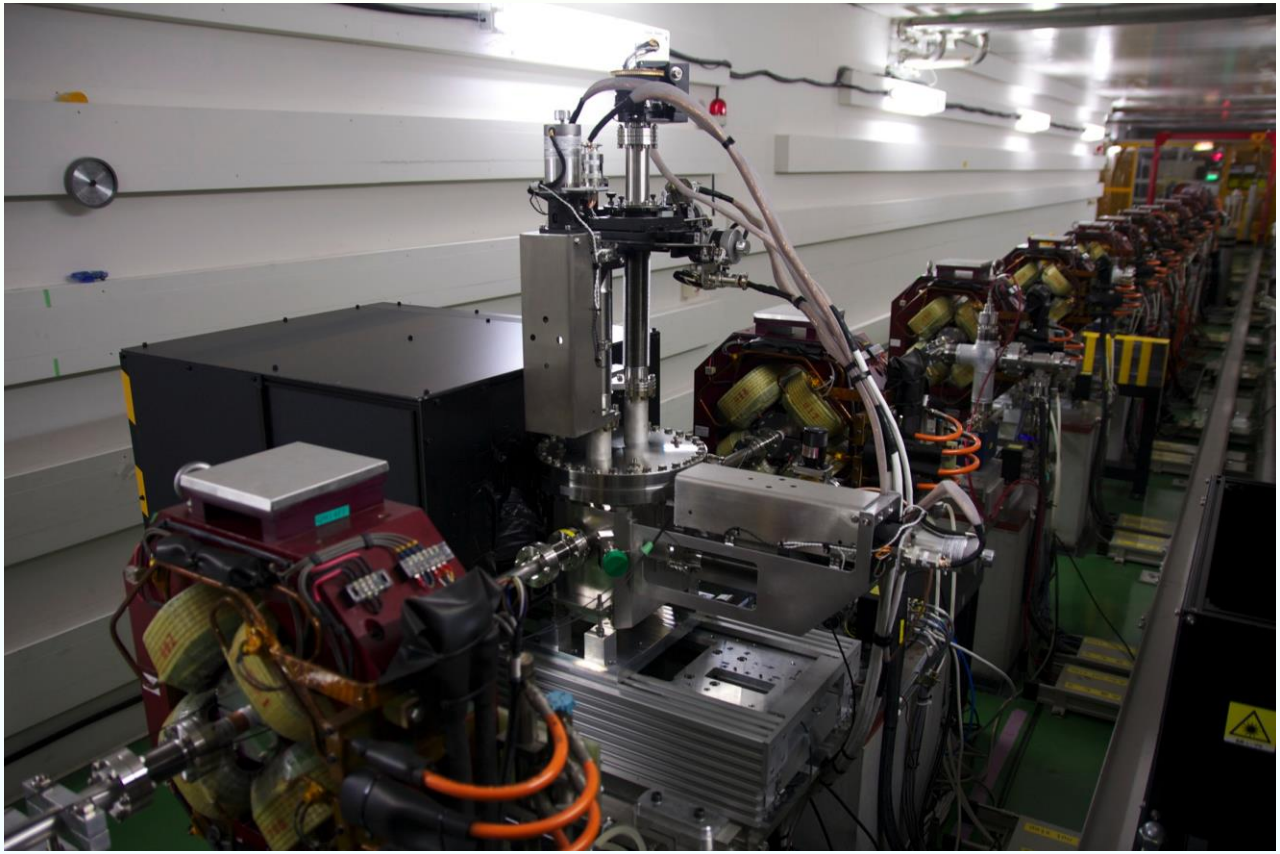
$\gamma = E/mc^2$ – Lorentz - factor

T. Muto, et al., Observation of incoherent diffraction radiation from a single edge target in the visible light region, Physical Review Letters, 90 (10), p. 104801 , 2003

ODR experiment at KEK-ATF2 facility

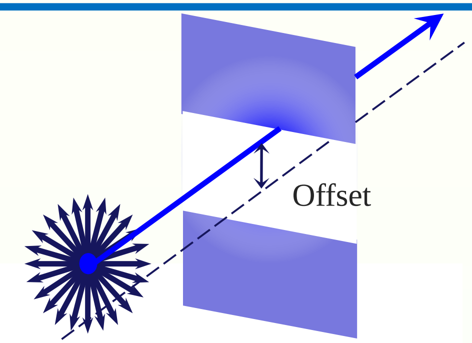
- **The tank is installed at the virtual interaction point of ATF2 vertical beam can be focused to < 1um .**

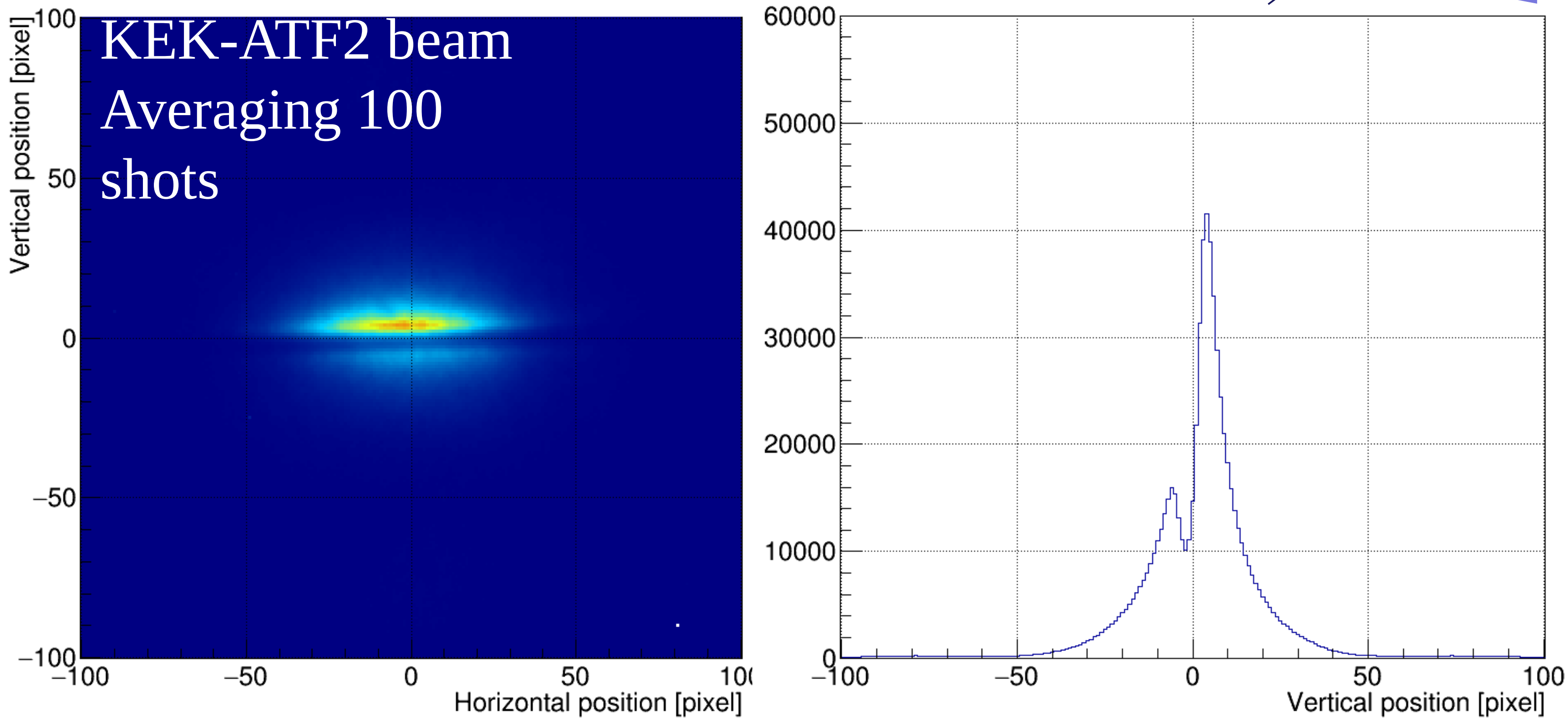




ODR imaging as an Optical BPM

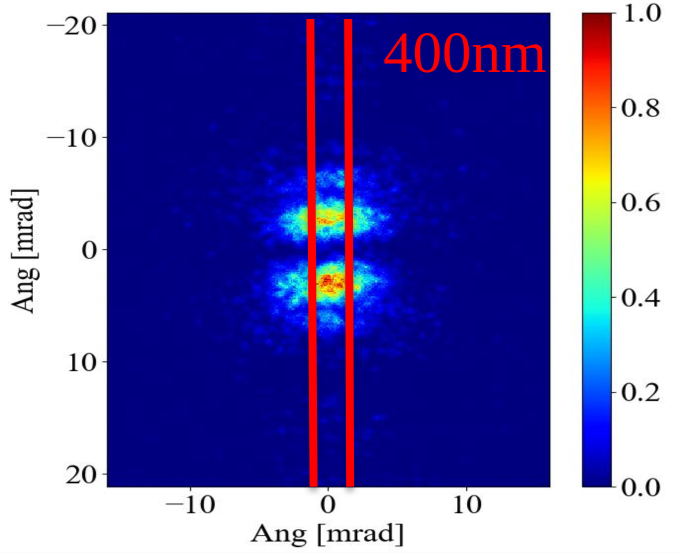
There is **no visible beam size dependency** off the pattern in **imaging**.
But the **vertical position** into the slit change the profile **asymmetry** => **Optical Beam Position Monitor (BPM)**

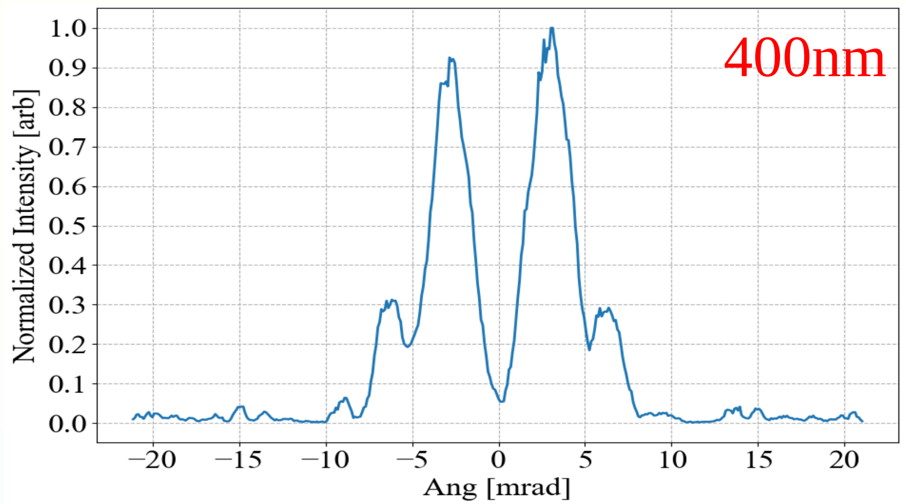


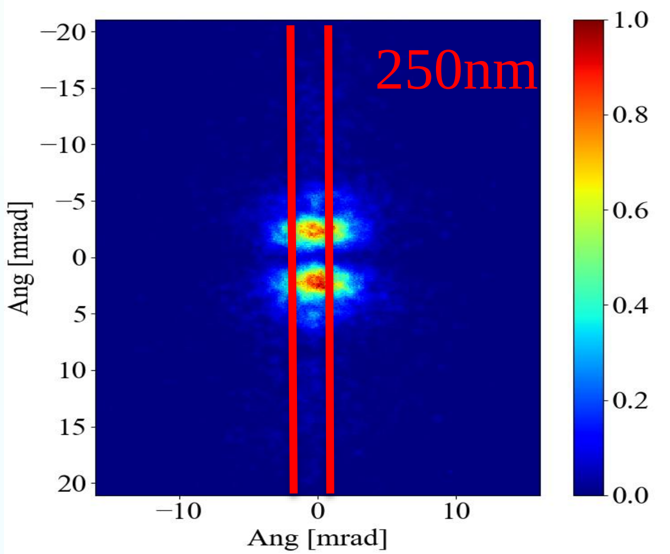


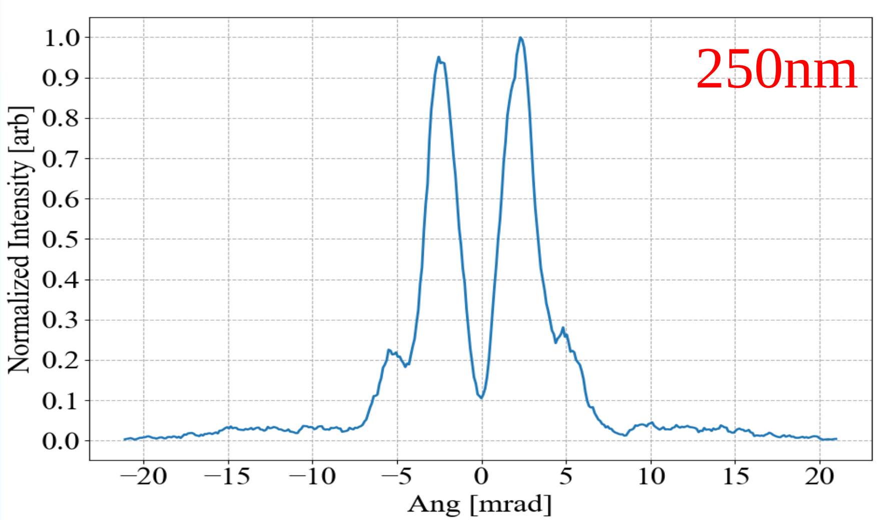
R. Kieffer, et al., Optical diffraction radiation for position monitoring of charged particle beams, NIMB 402 (2017) 88-91

ODR angular distribution



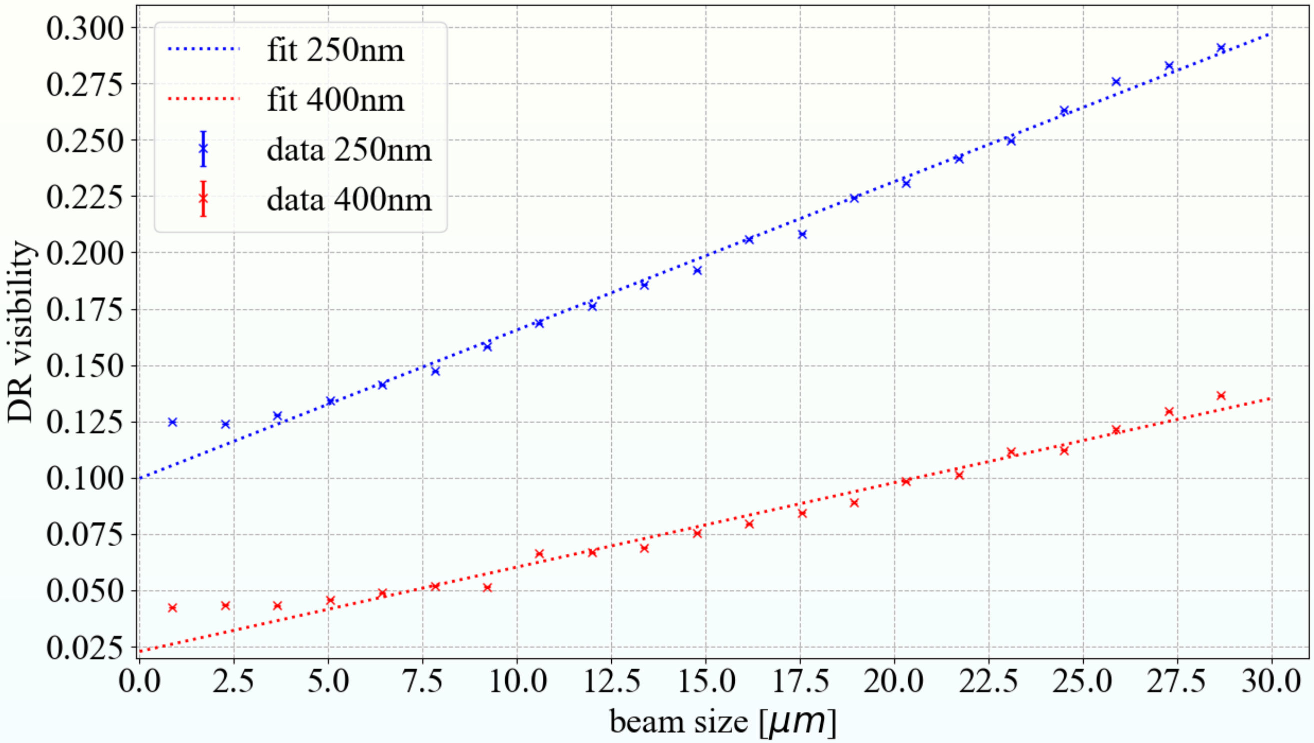






Visibility vs beam size measured with OTR

target $= 49.7\ \mu m$



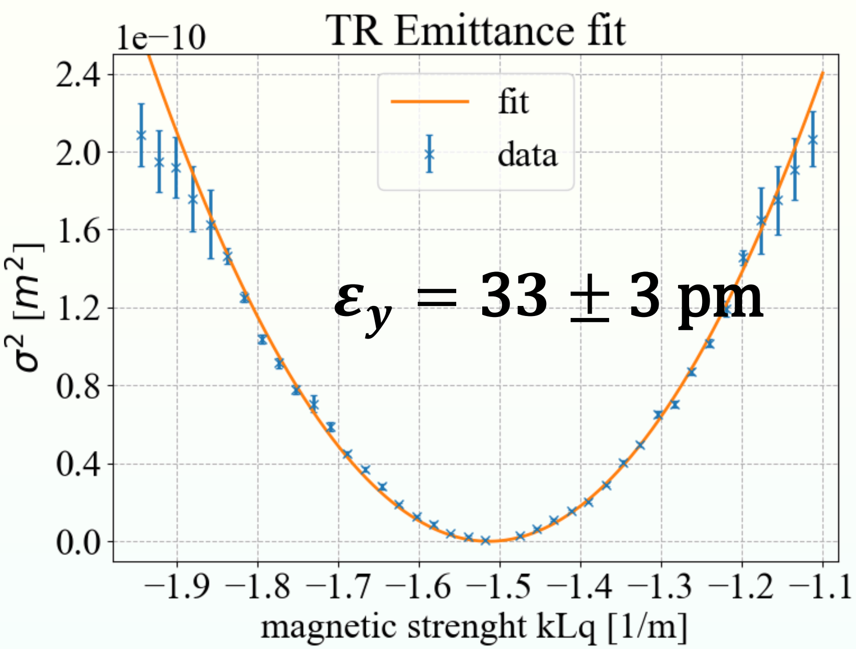
As expected sensitivity increase with decreasing wavelength, good sensitivity for UV down to 4-5 micrometers.

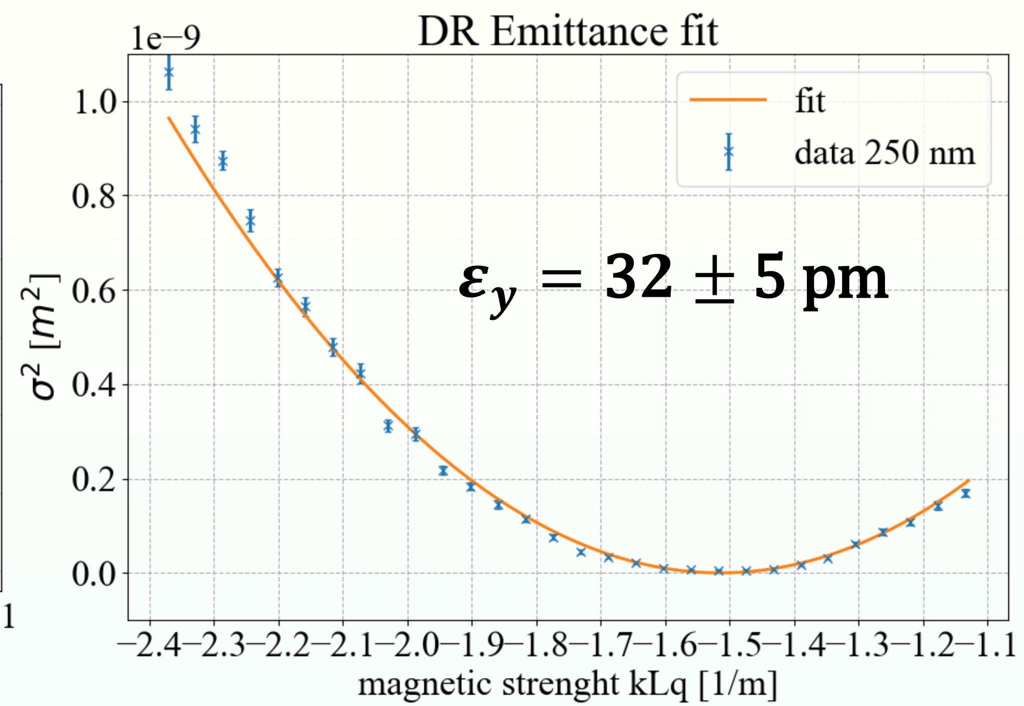
Previous measurements minimum was 14 μm*

$$\text{Visibility} = \frac{I_{min}}{I_{max}}$$

- M. Bergamaschi, et al., Non-invasive micron-scale particle beam size measurement using Optical Diffraction Radiation in the ultra violet wavelength range, Physical Review Applied 13, 014041 (2020)
- *P. Karataev, et al., Beam-Size Measurement with Optical Diffraction Radiation at KEK Accelerator Test Facility, Physical Review Letters 93 (2004) 244802.

Vertical Emittance measurements

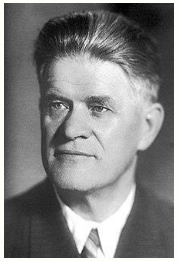




- Good agreement with simulated SAD emittance
- Optical background creates difficulties
- The slit is very small

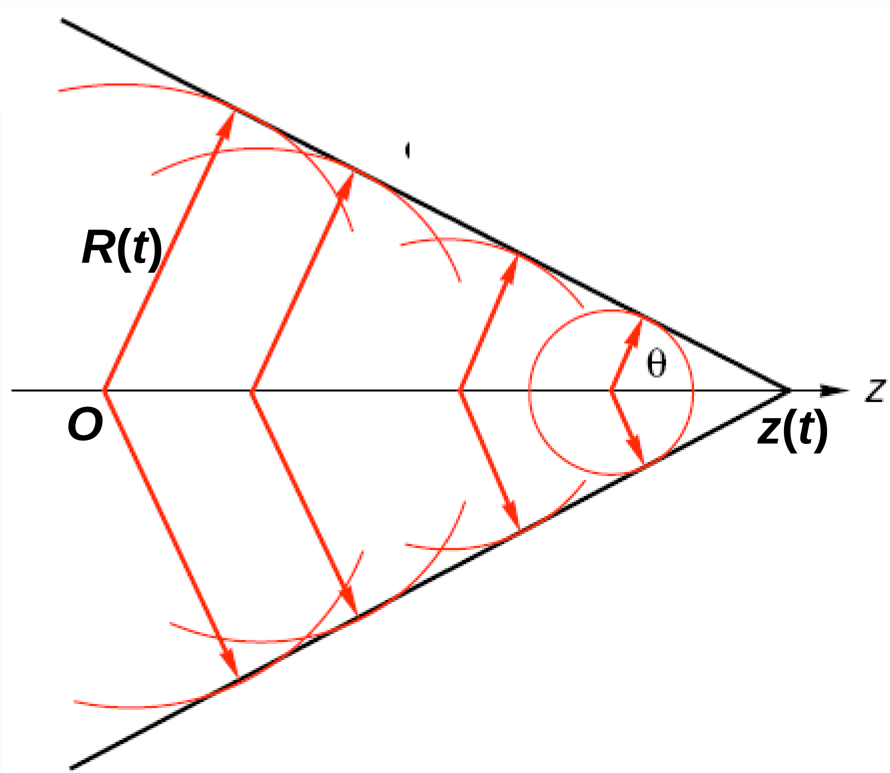
Vavilov-Cherenkov Radiation

Pavel Cherenkov



Sergey Vavilov

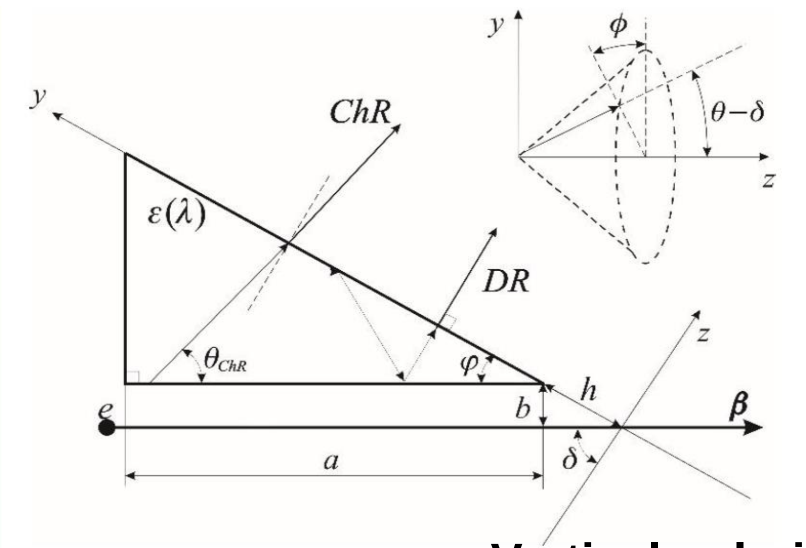
- **First observation in 1934**
- **Nobel prize in 1958**



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

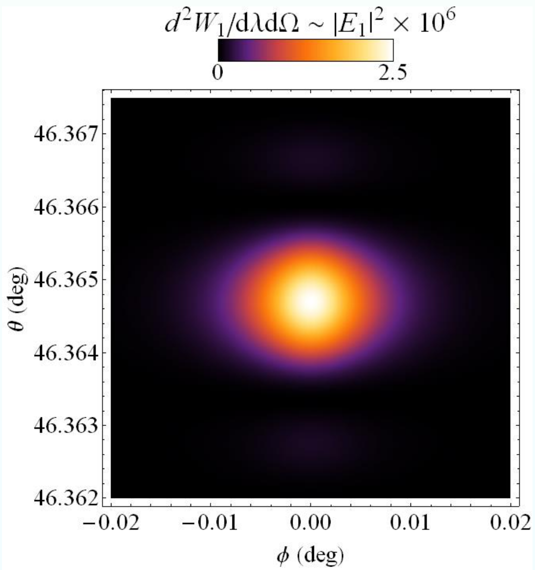
$$\cos\theta = \frac{R(t)}{z(t)} = \frac{(c/n)t}{vt} = \frac{1}{\beta n}$$

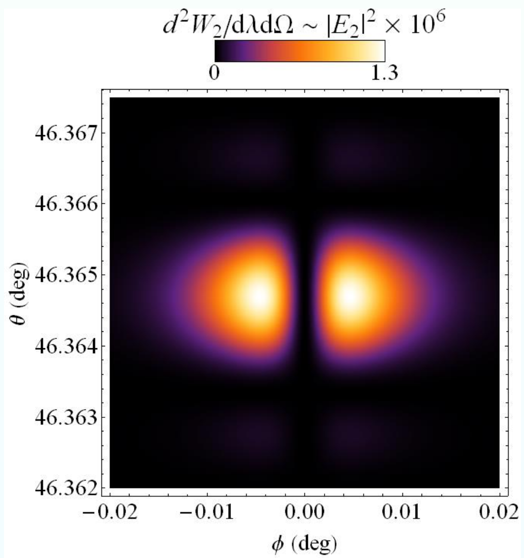
Cherenkov Diffraction Radiation



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

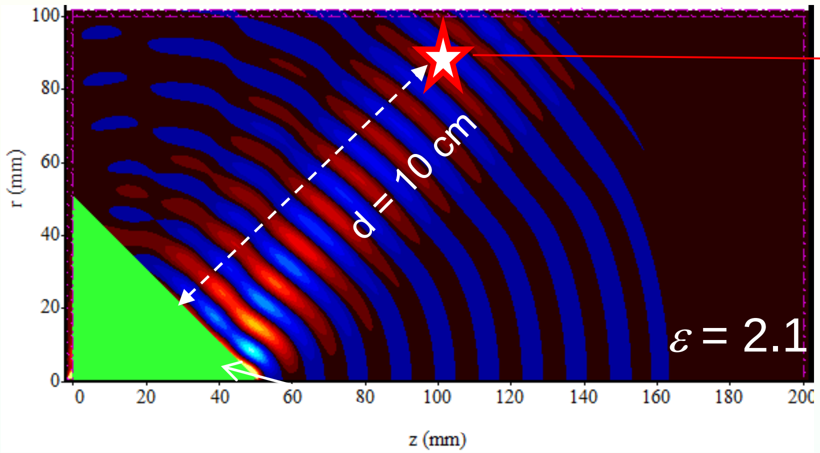
Vertical polarization **Horizontal polarization**

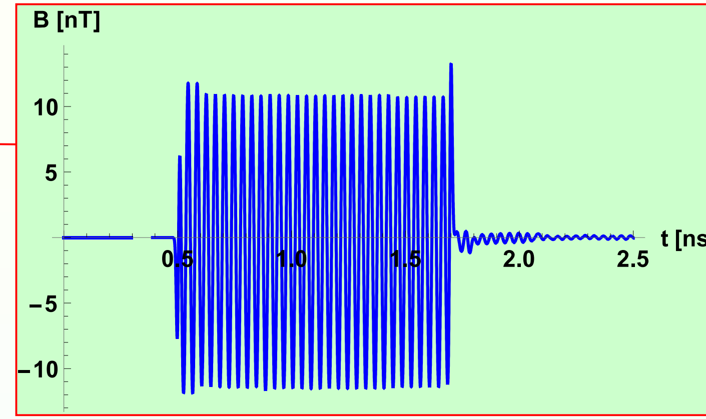


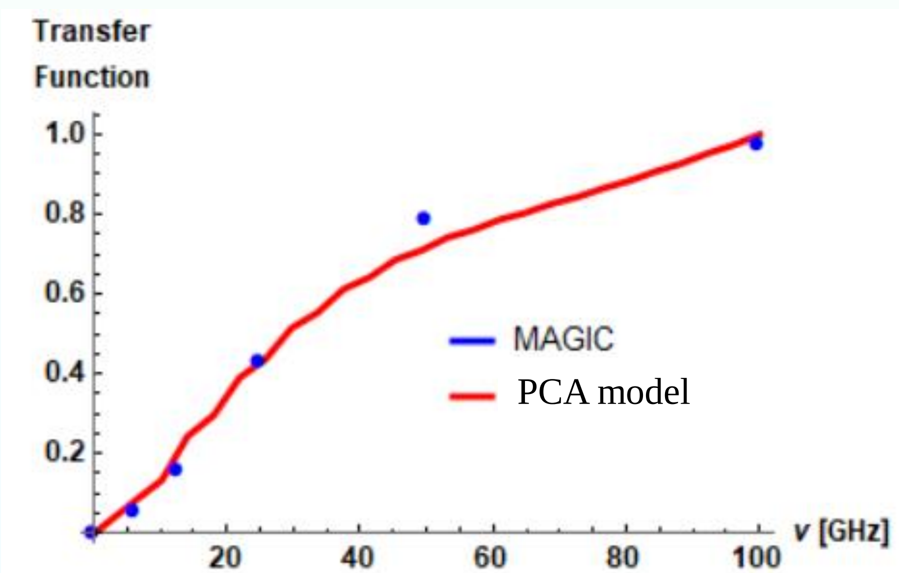


Simulations with 'Magic' code

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

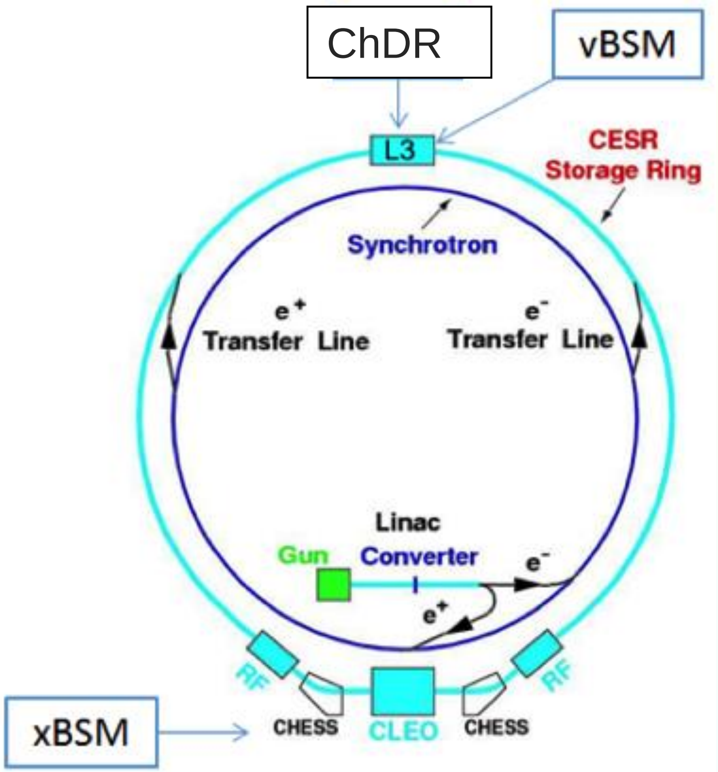






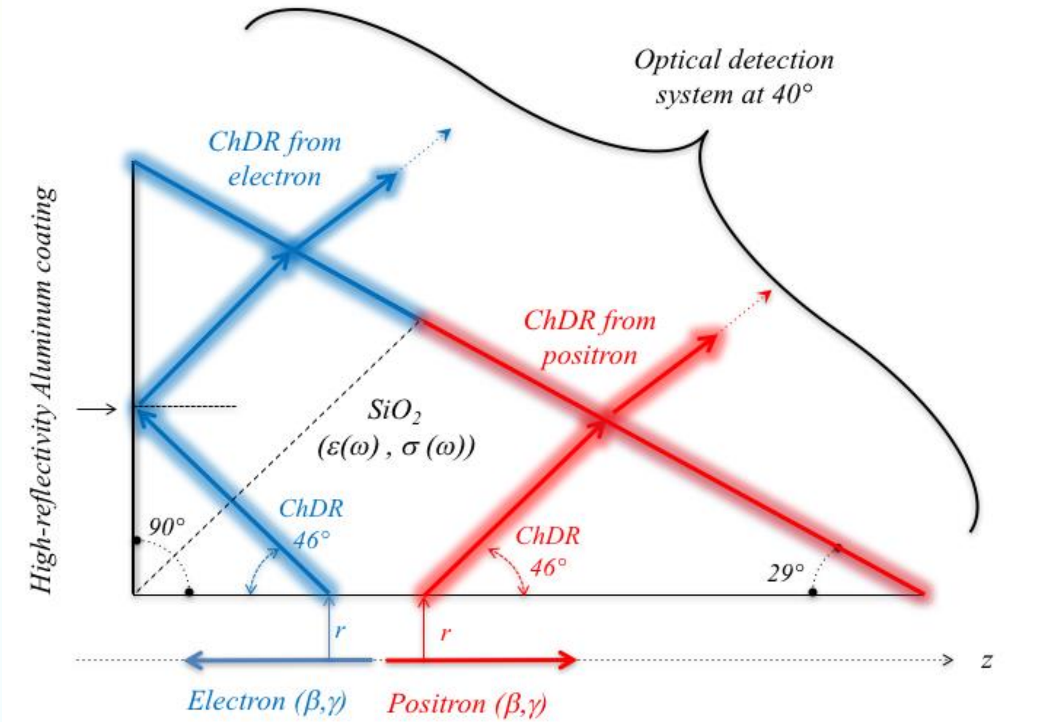
A. Curcio, et al., *Noninvasive bunch length measurements exploiting Cherenkov diffraction radiation*, Phys. Rev. AB **23**, 022802 (2020)

Optical/IR ChDR experiment at Cornell



CESR Ring Circumference	768.4m
Revolution Time	2.563 μs
Beam Energy	2.1 and 5.3GeV
Beam Species	e^- and e^+
Particles per bunch	$1.6\ 10^{10}$

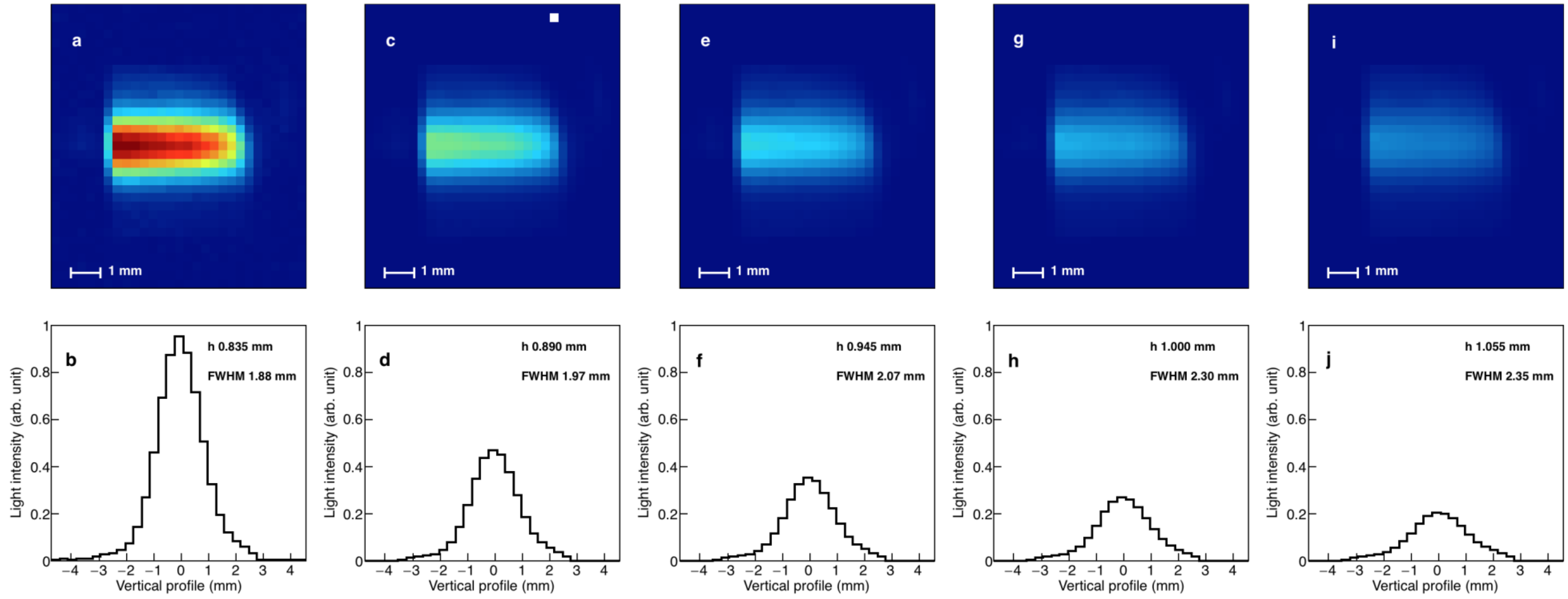
Using a 2cm long SiO_2 (n=1.46) ChDR target



R. Kieffer et al., "Direct Observation of Incoherent Cherenkov Diffraction Radiation in the Visible Range", PRL ***121*** *(2018) 054802*

Dependence on impact parameter

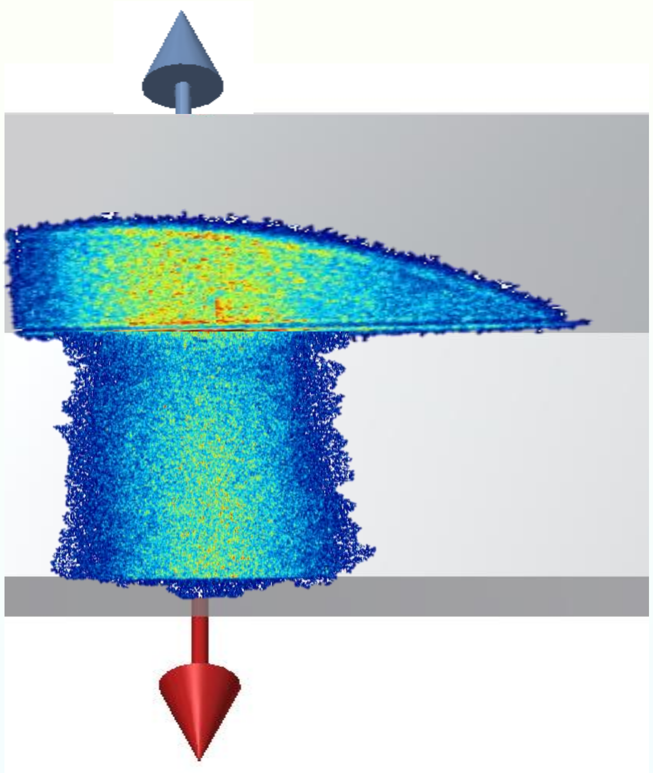
Imaging conditions and Radiation power vs Impact parameter



'Cherenkov photons yield increasing strongly for smaller impact parameter'

Electron and positron trajectory control

Electron Beam



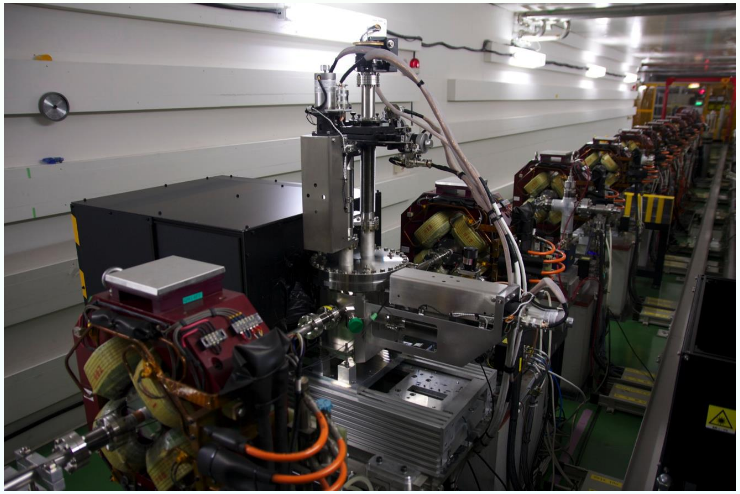
Positron Beam

The photons produced by electrons and positrons appear on a different zone of the image and give the possibility to high directivity beam measurements

Optical ChDR experiment at KEK-ATF2

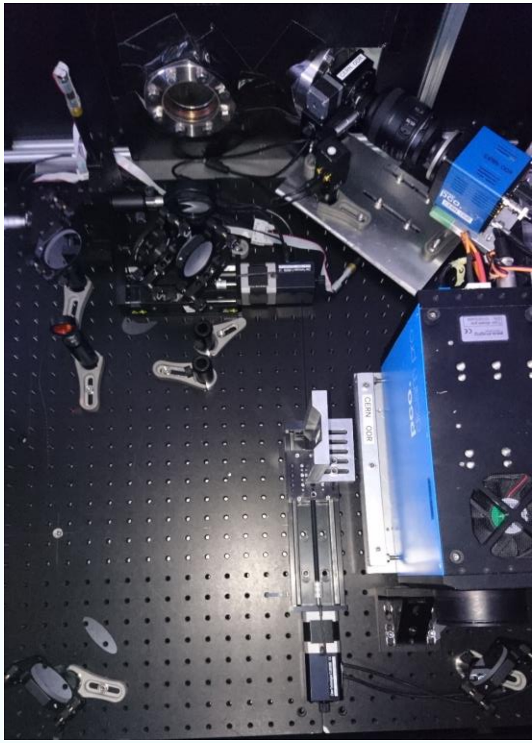
Studying the spatial resolution of ChDR at ATF2/KEK - 2018

ATF2 extraction line	
Beam Energy	1.25 GeV
Particles per bunch	1.6 10^{10}
Achievable beam size H/V (microns)	100 / 1



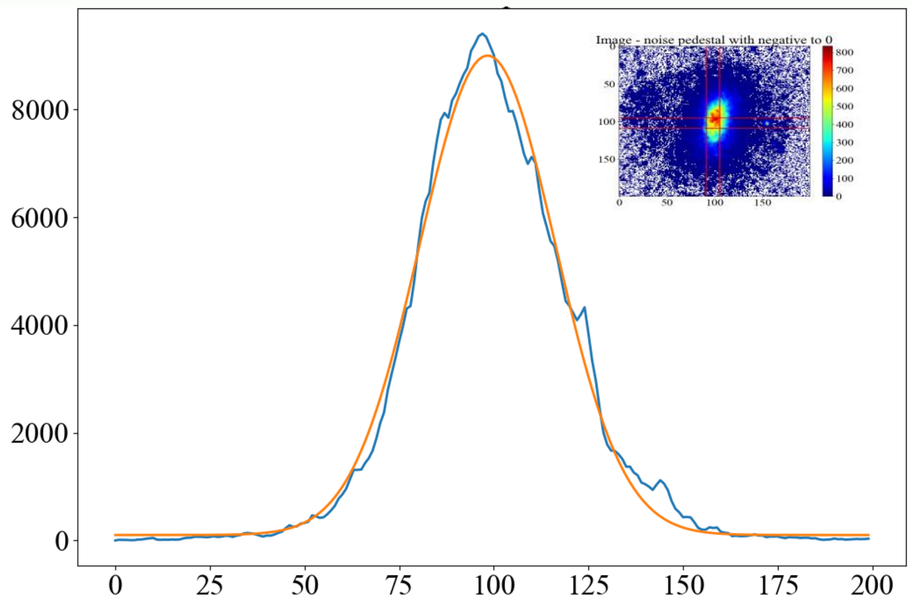
Re-using and modifying the hardware used for Diffraction radiation studies

- Optical system in the visible
- OTR for cross calibration



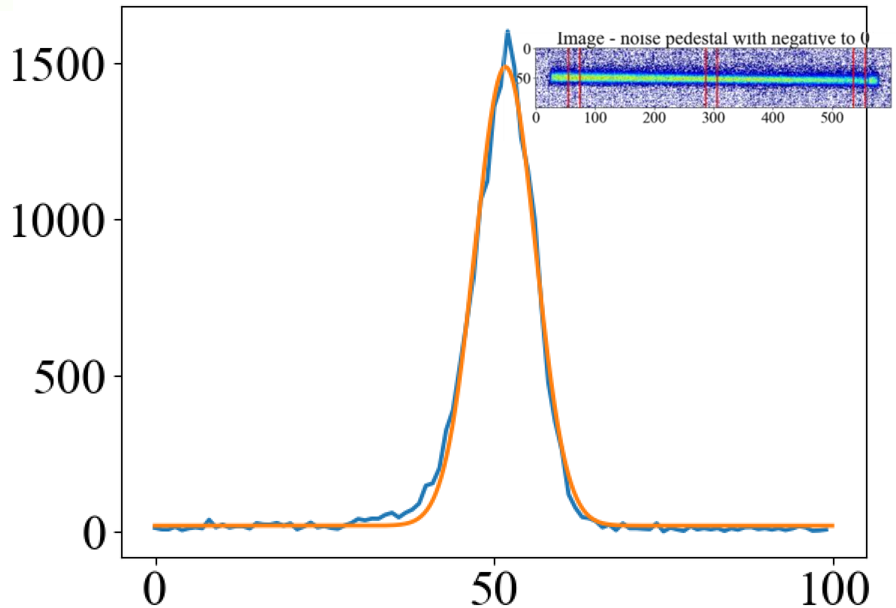
Beam profile

OTR Vertical beam profile



Vertical rms is: 67.2 um

ChDR Vertical beam profile



Vertical rms: 63.5 um

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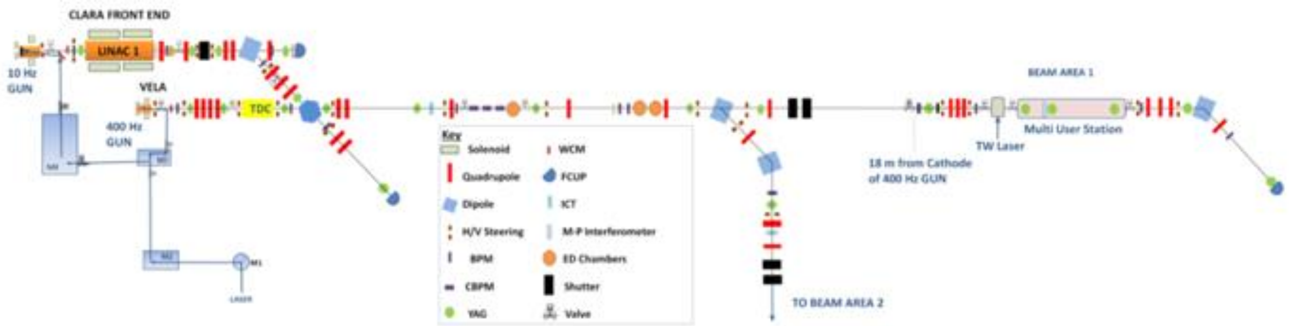
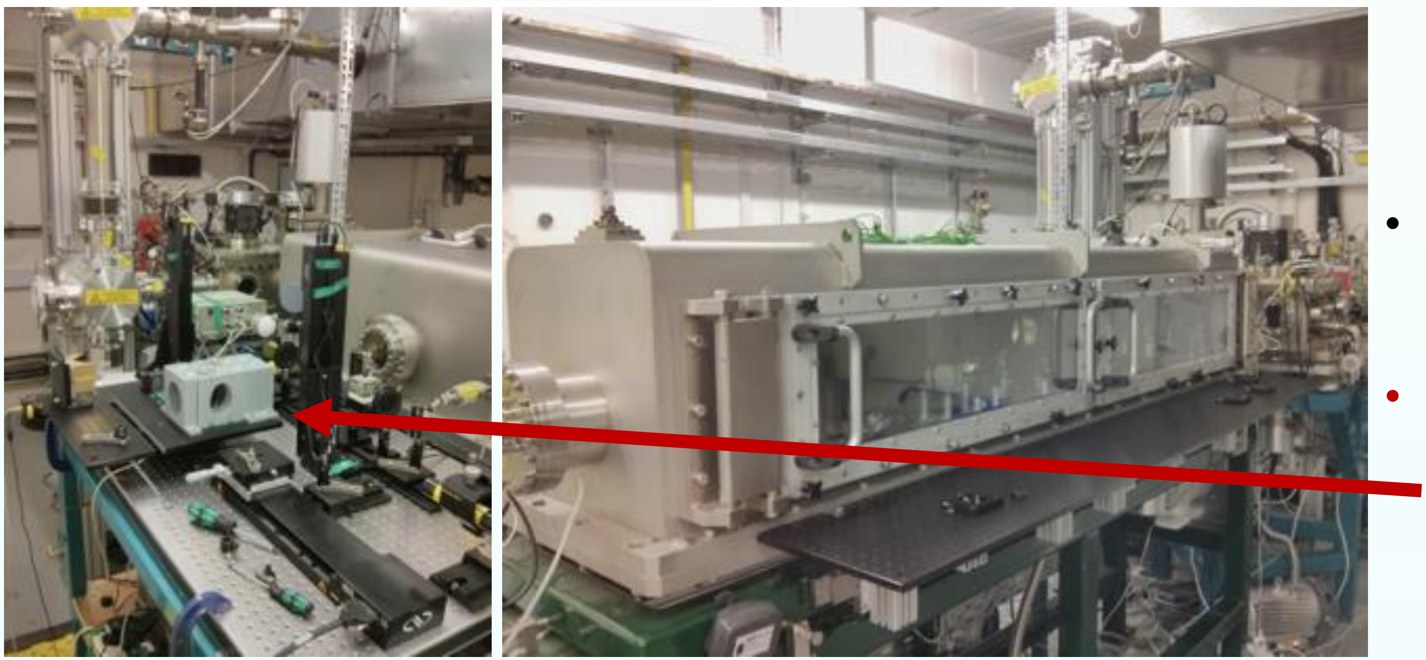
Coherent ChDR experiment at CLARA in Daresbury

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

$S(\omega)$ – radiation spectrum
$S_e(\omega)$ – single electron spectrum
N – electrons in a bunch
$F(\omega)$ – bunch form factor



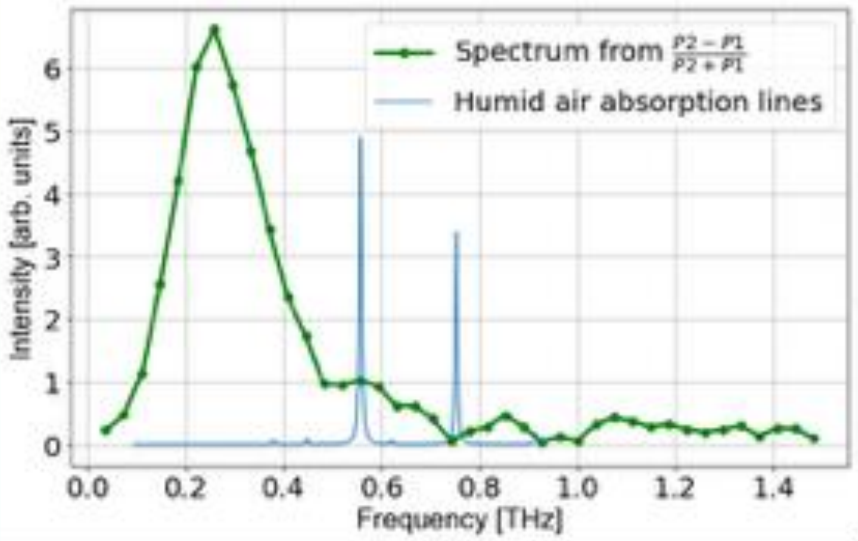


- f = 10Hz
- E = 35 MeV
- Longitudinal beam size was about 0.6 ps with charge ranging within 70 - 100 pC
- 200 microns RMS transversal bunch size
- Martin-Puplett interferometer for spectral measurements

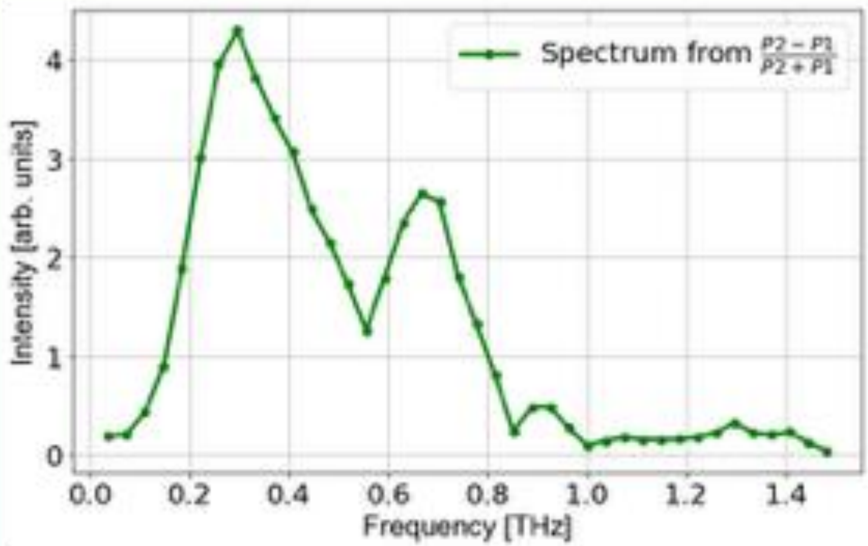
A. Curcio, et al., *Noninvasive bunch length measurements exploiting Cherenkov diffraction radiation*, Phys. Rev. AB **23**, 022802 (2020)

CTR and CChDR spectra

(a)



(b)

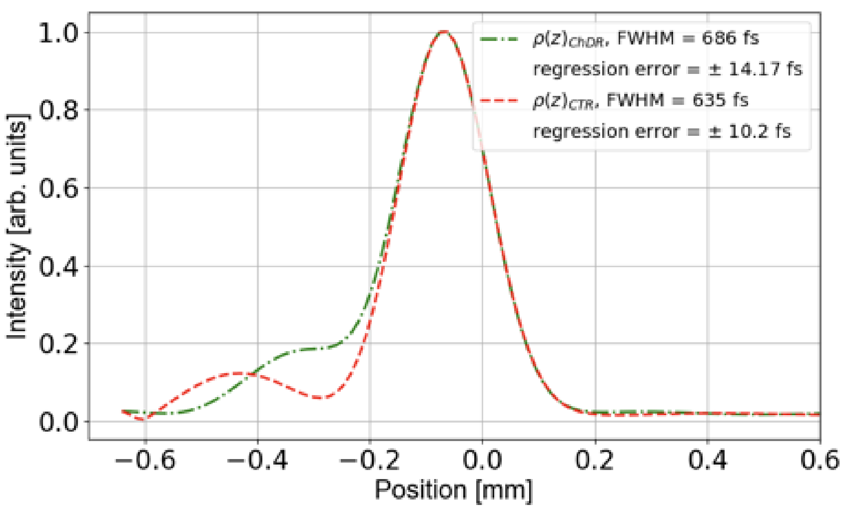


Spectrum of coherent ChDR diffraction radiation (a) and coherent TR (b)

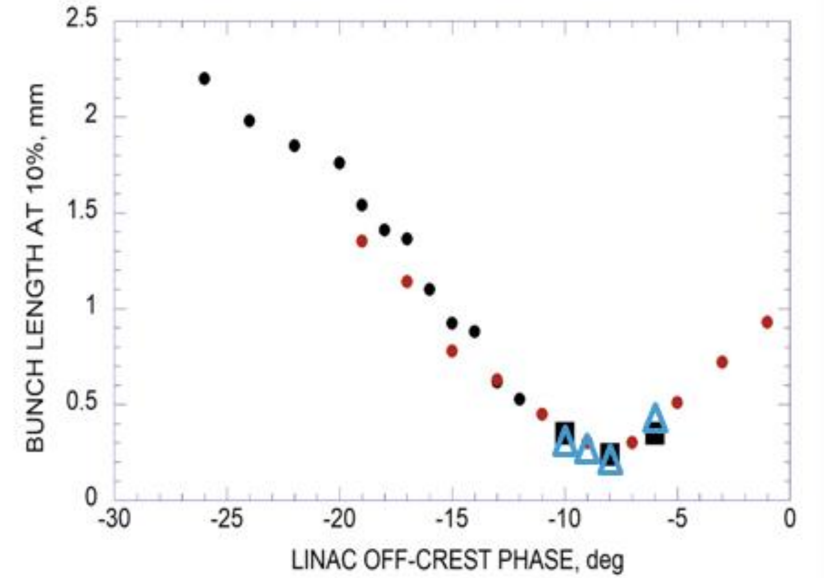
A. Curcio, et al., *Noninvasive bunch length measurements exploiting Cherenkov diffraction radiation*, Phys. Rev. AB **23**, 022802 (2020)

CTR and CChDR spectra

Kramers-Knronig method



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



△ CChDR scan

■ CTR scan

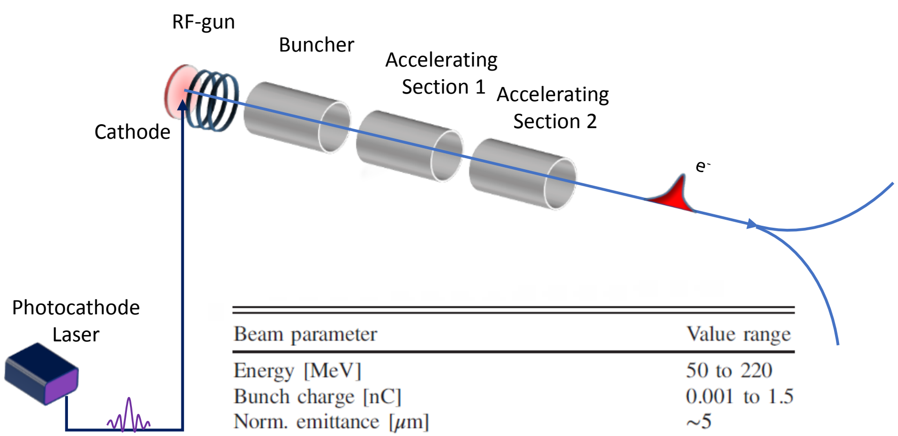
● Energy spread measurement method

● elegant code beam simulation

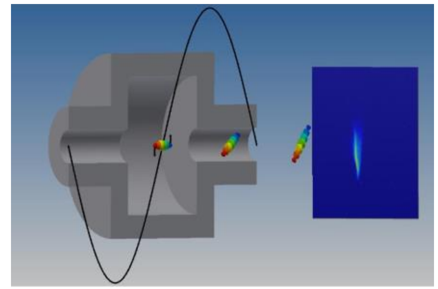
A. Curcio, et al., *Noninvasive bunch length measurements exploiting Cherenkov diffraction radiation*, Phys. Rev. AB **23**, 022802 (2020)

Coherent ChDR experiment at CLEAR in CERN

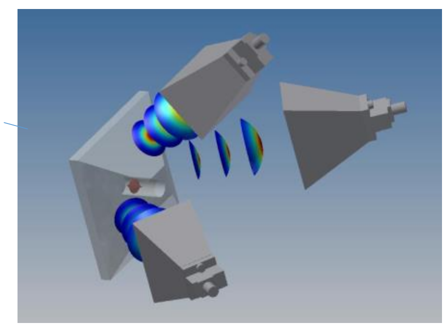
Development of Coherent ChDR for bunch length monitoring



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



- Cross calibrating using RF deflector

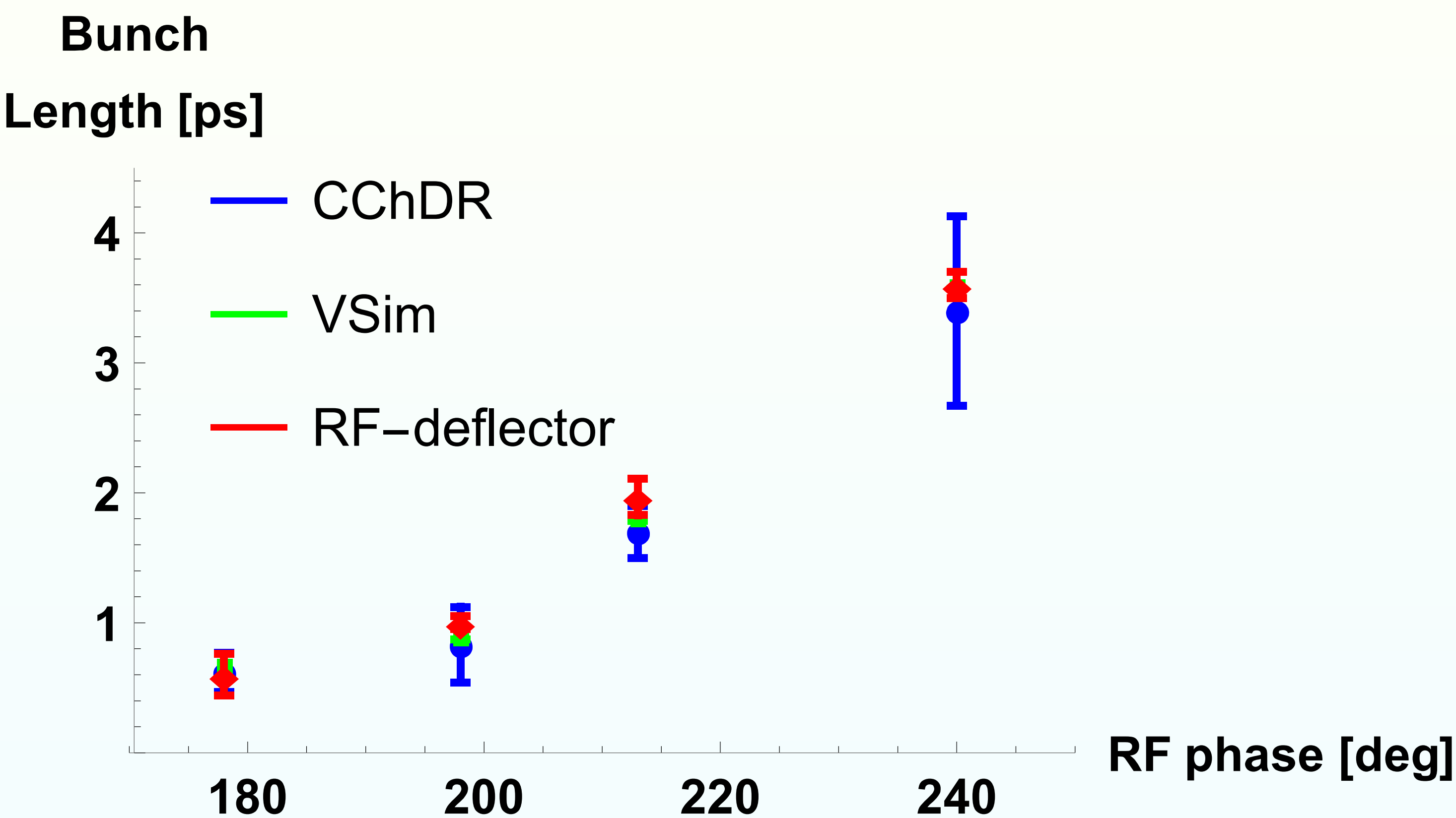


- Measuring beam power spectrum in 3 frequency bands

A. Curcio, et al., *Noninvasive bunch length measurements exploiting Cherenkov diffraction radiation*, Phys. Rev. AB **23**, 022802 (2020)

Coherent ChDR experiment at CLEAR in CERN

Comparison between CChDR and RF deflector

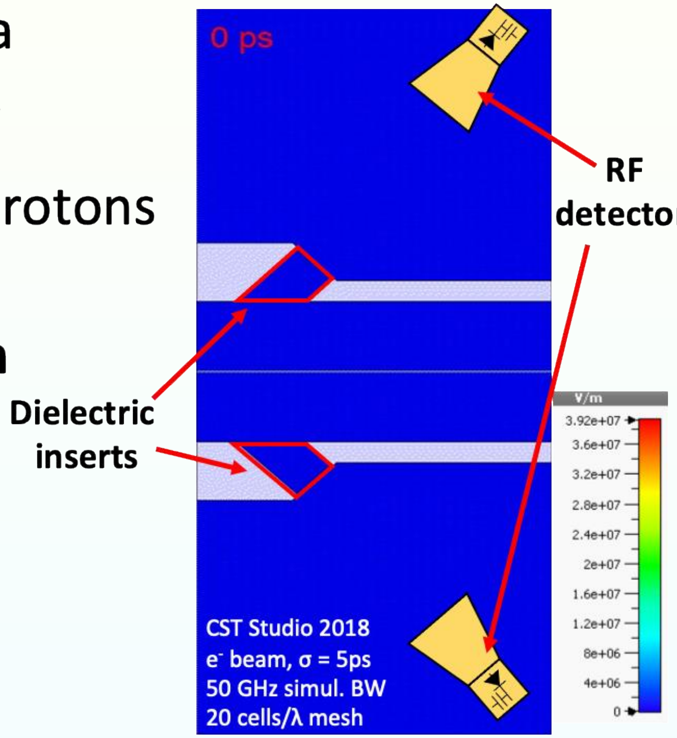


A. Curcio, et al., *Noninvasive bunch length measurements exploiting Cherenkov diffraction radiation*, Phys. Rev. AB **23**, 022802 (2020)

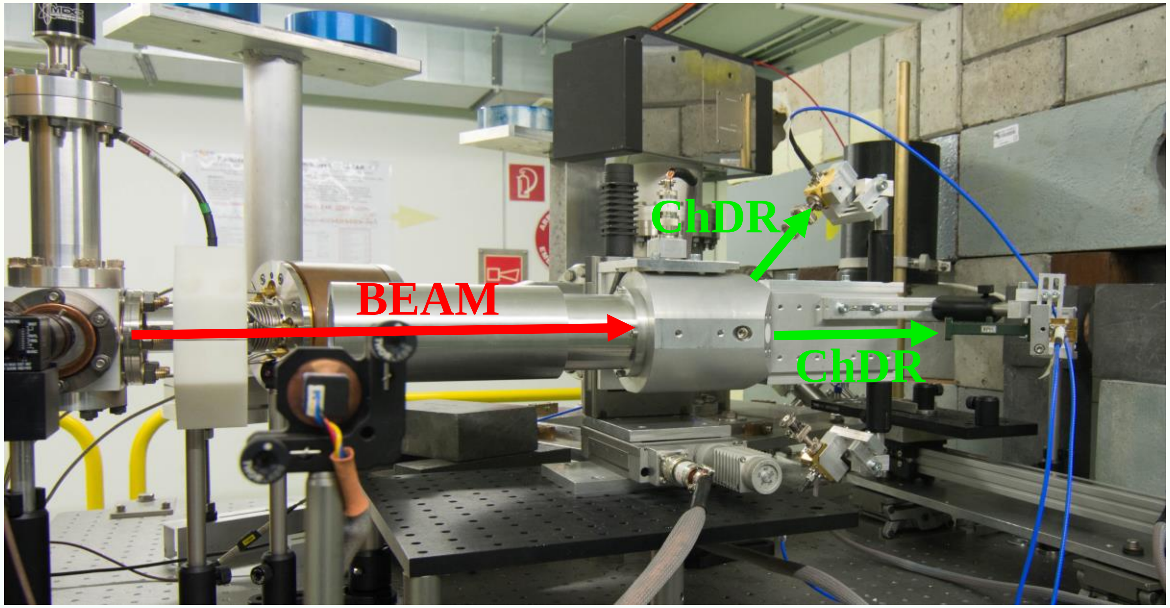
Coherent ChDR BPM for AWAKE

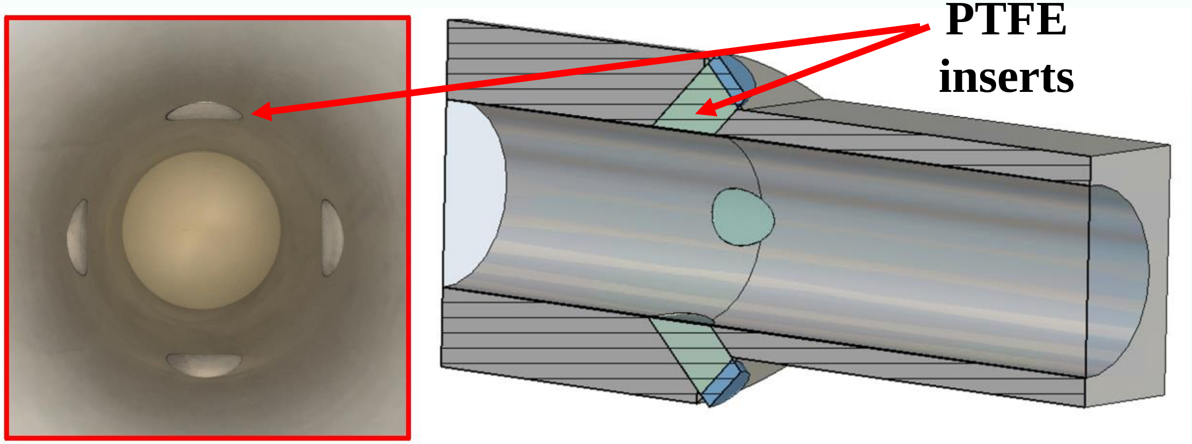
- The **A**dvanced **Wak**efield **E**xperiment (**AWAKE**) at CERN uses a long, intense proton bunch, and a short electron bunch for **proton-driven PWFA**
- 'Normal' instrumentation dominated by the protons
- **The electron position can be detected at high frequency exploiting the bunch length difference**

Need for a very high-bandwidth beam position monitor (>20 GHz)



Coherent ChDR BPM test at CLEAR

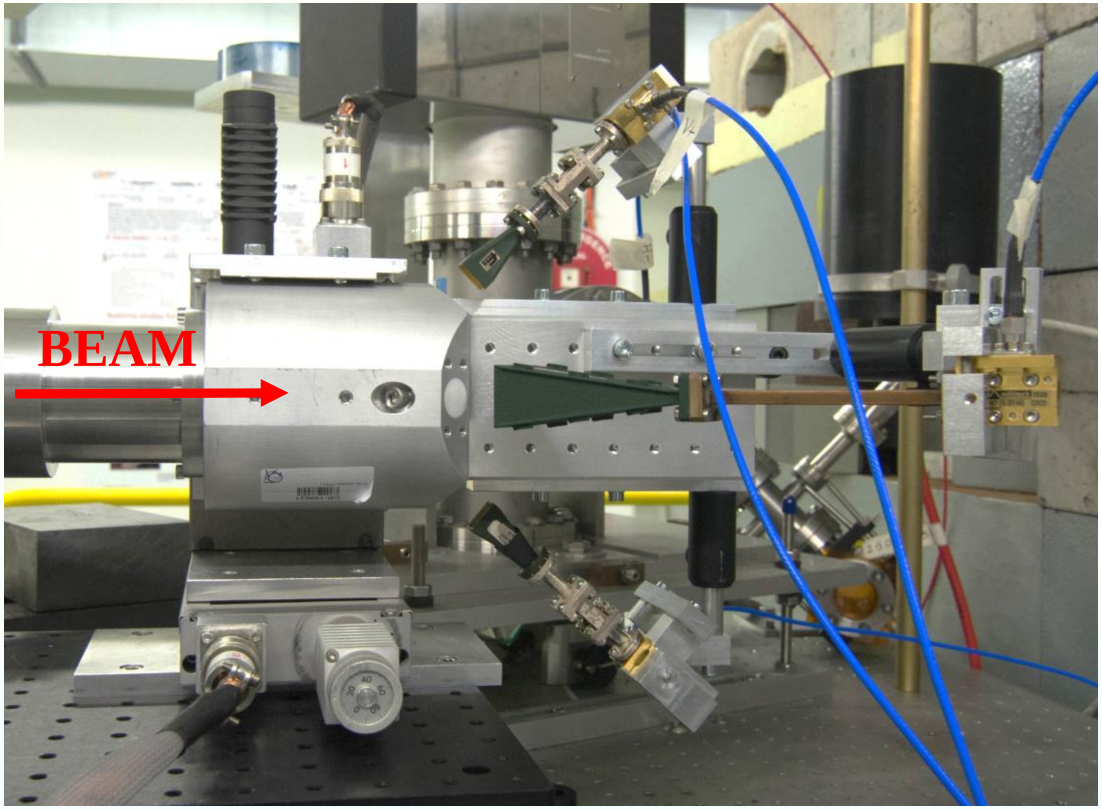


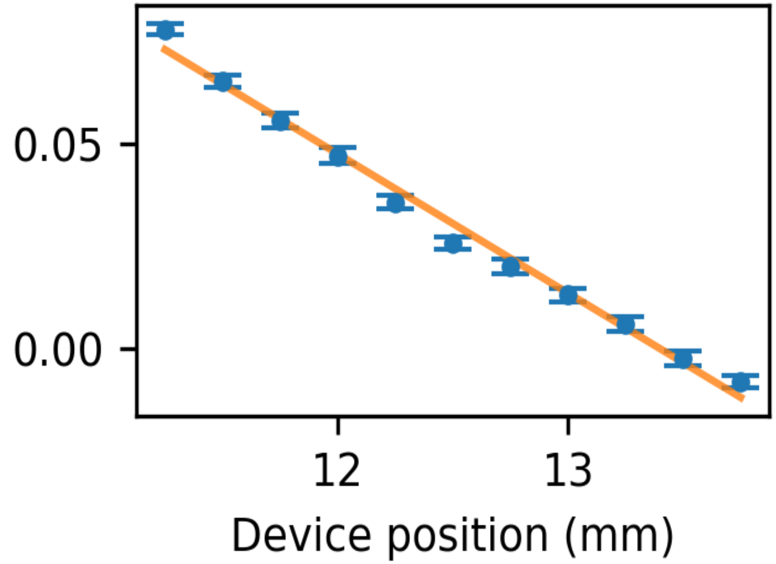


Prototype in-air test:

- 60 mm diameter aperture (AWAKE)
- PTFE radiators
- Emission at 45º
- In-air detection for flexibility
- Zero-bias RF schottky diode detectors in the Ka-band
- Motorised support, move the device, not the beam

Coherent ChDR BPM test at CLEAR





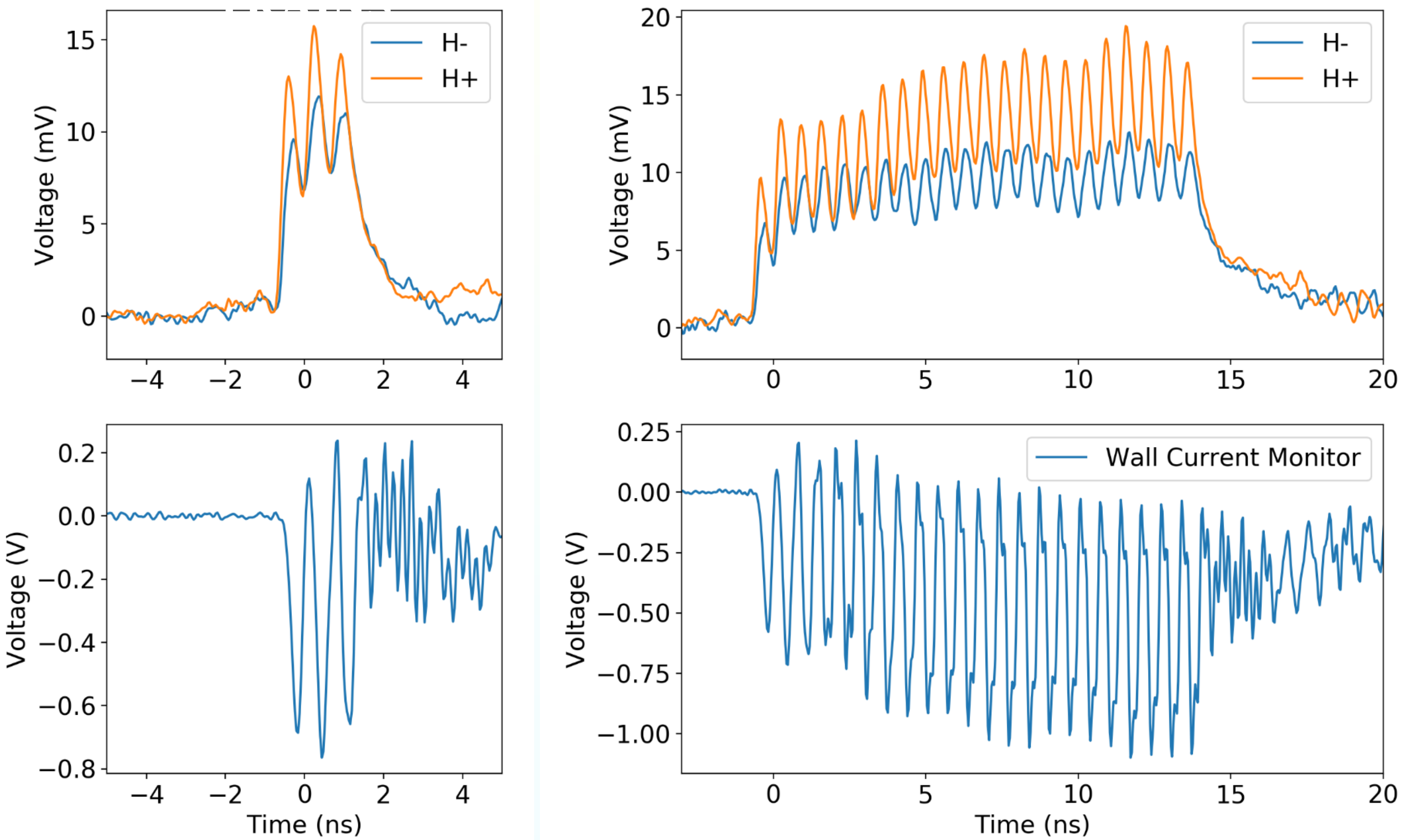
- Sensing the **power emitted** by **opposite radiators** to calculate **the position**
- **Linear response around the centre**

Bunch-by-bunch measurements

3 BUNCH | **20 BUNCH TRAINS**

CHERENKOV RESPONSE

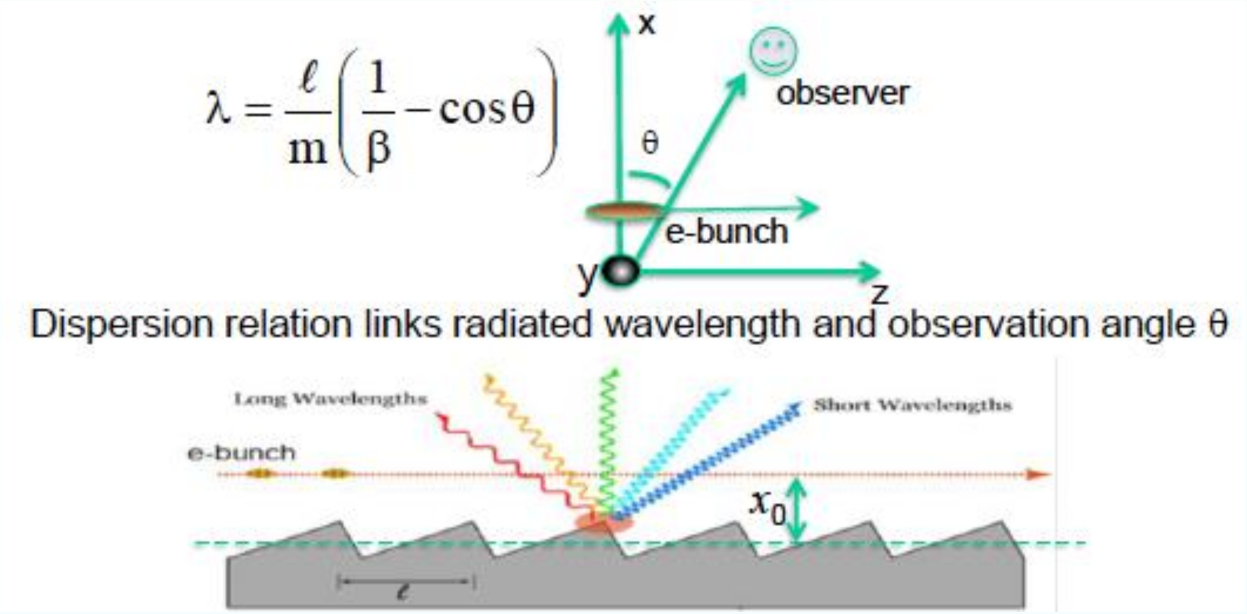
WALL CURRENT MONITOR



Coherent Smith-Purcell Radiation

Micro-bunched beam monitoring and bunch profiling using coherent radiation spectrum analysis

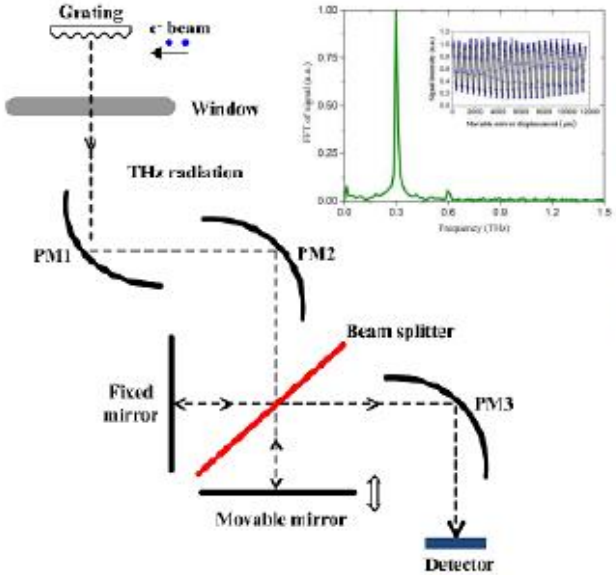
I.V. Konoplev , G. Doucas , H. Harrison, A. J. Lancaster
JAI at University of Oxford



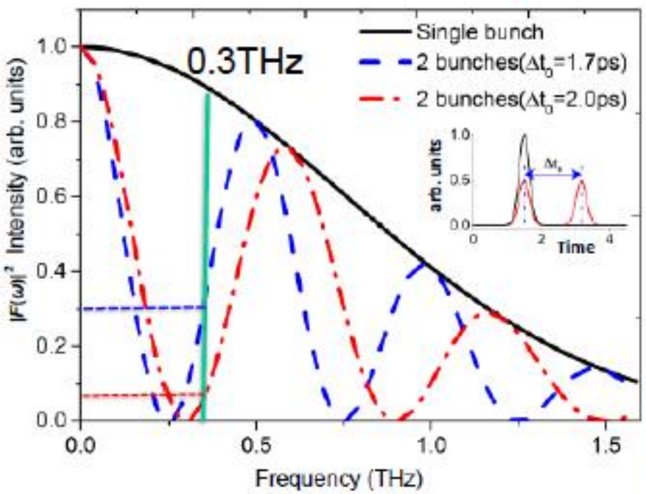
Single Shot CSPR

Signal Amplitude Modulations to monitor distance between 2 micro-bunches

Experimental set-up

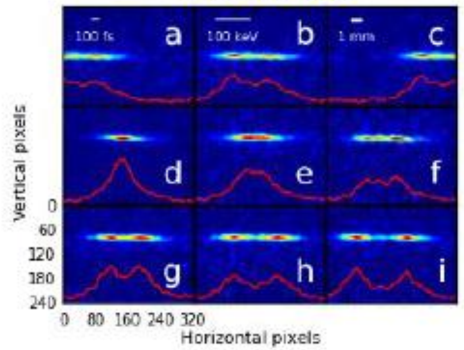


Theoretical concept

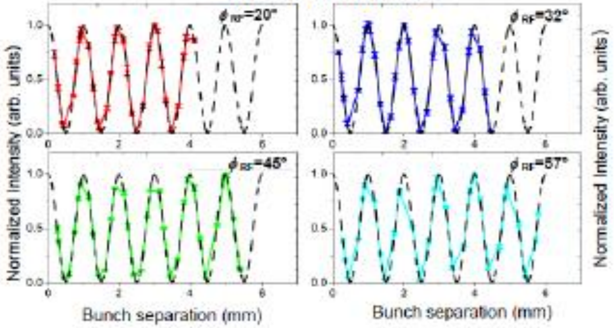


$$|F(\omega)|^2 = |F_1(\omega)|^2 \frac{sin^2(M\omega\Delta t/2)}{M^2 sin^2(\omega\Delta t/2)} = |F_1(\omega)|^2 G(\omega, \Delta t)$$

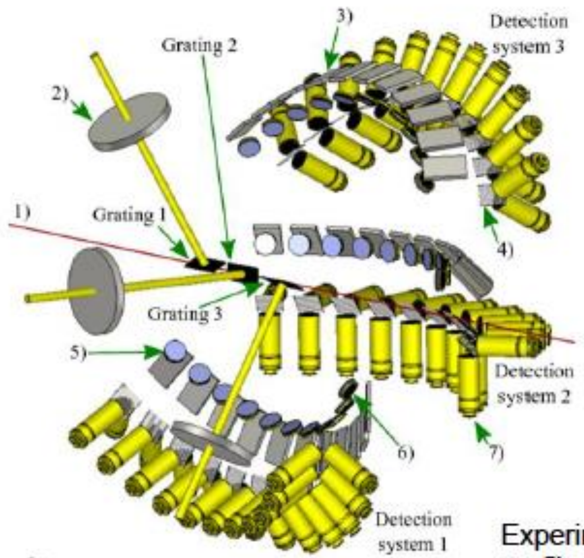
Experimental measurements at LUCX KEK

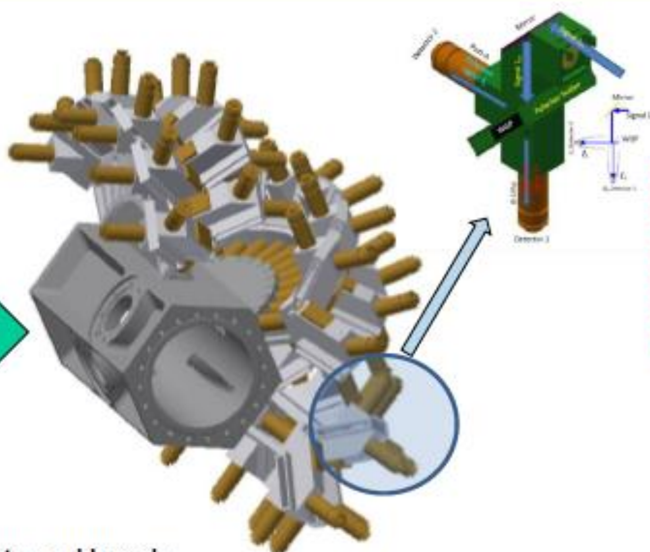


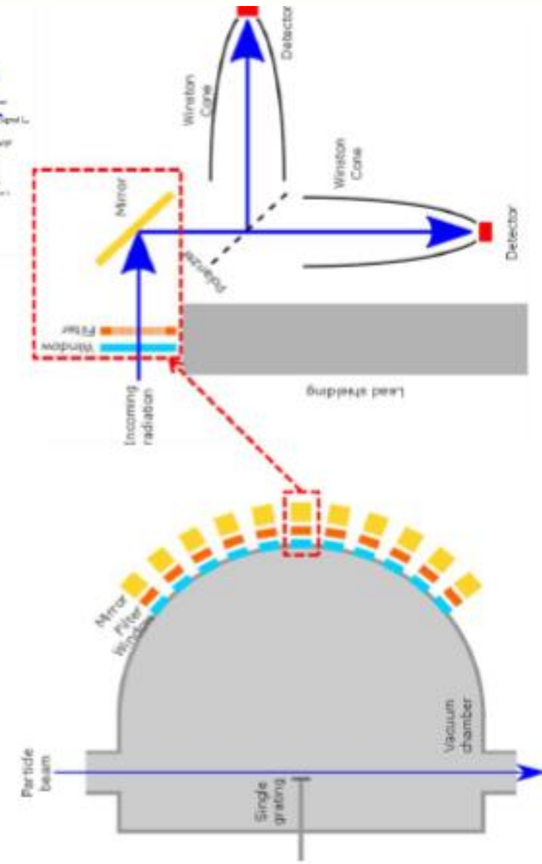
Black dashed line is theory, the red line is the experimental data.

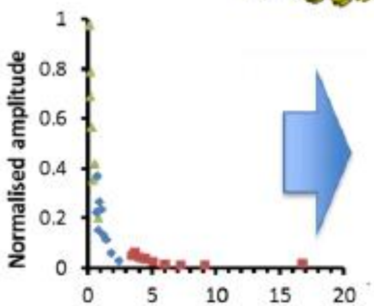


Single shot CSPR bunch length diagnostics concept

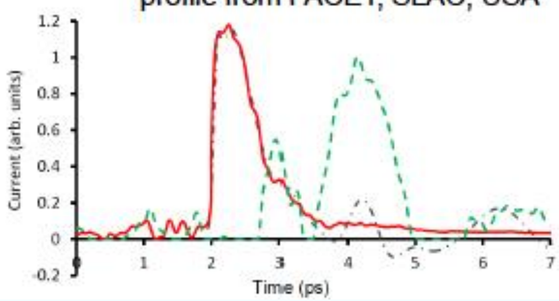








Experimental data and bunch profile from FACET, SLAC, USA



Conclusion

- **Polarization radiation is an efficient mechanism**
  - Low particle energy loss
  - Non-invasive nature of generation
  - Large emission angles
  - Low coherent radiation background for ChDR
  - Multi-parameter monitoring
- **Beam position, trajectory, transverse and longitudinal profile measurements**
  - Resolution still has to be understood
  - PCA model and EM simulations have to be verified to be able to optimize instruments for different accelerators
  - Designs for CLIC, AWAKE and Light Sources

Conclusion

- **Short bunch length measurement needs to be verified**
  - **Limited access to the facilities with short enough bunch**
- **Potentially can be applied for**
  - **THz radiation generation**
  - **Particle acceleration**
  - **Energy spread manipulation**
  - **Beam cooling**

Thank you for your time