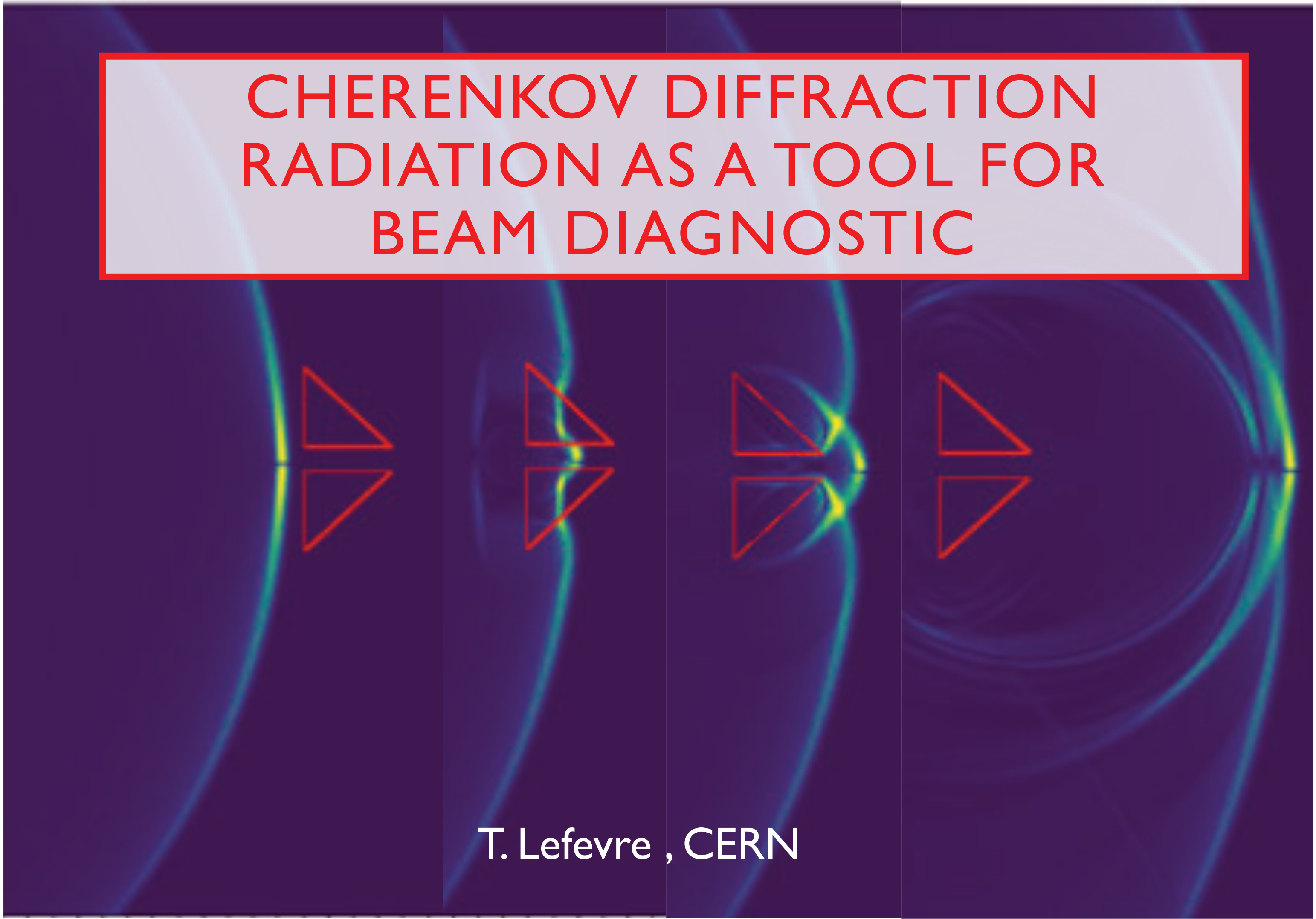
CHERENKOV DIFFRACTION RADIATION AS A TOOL FOR BEAM DIAGNOSTIC



T. Lefevre , CERN

D. Alves [1], A. Aryshev [6], M. Bergamaschi [1], V.V. Bleko [3], M. Billing [5], L. Bobb [7], J. Conway [5], A,.Curcio [1], K. Fedorov [2]. J. Gardelle [4], S.Y. Gogolev [3], D. Harryman [2], R.O. Jones [1], R. Kieffer [1], A.S. Konkov [3], P. Karataev [2], K. Lasocha [8], T. Lefevre [1], K. Lekomtsev [2], J.S. Markova [3], S. Mazzoni [1], N. Mounet [1], Y. Padilla Fuentes [5], A.P. Potylitsyn [3], E. Senes [1], A. Schloegelhofer [1], J. Shanks [5], D.A. Shkitov [3], N. Terunuma [6]

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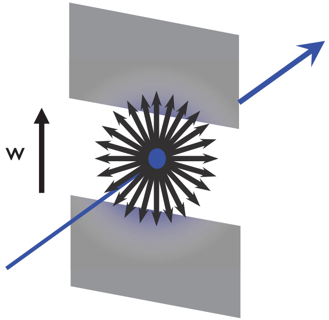
OUTLINE

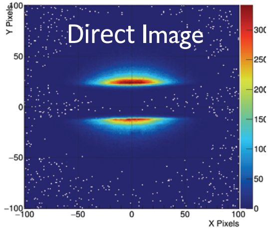
- Motivation
- Modelling and Simulations
- Experimental results
- Conclusions and Perspectives

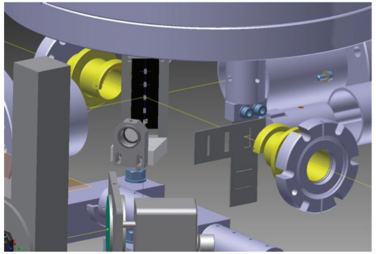
MOTIVATION

Studying non-invasive beam size monitor using Optical Diffraction radiation



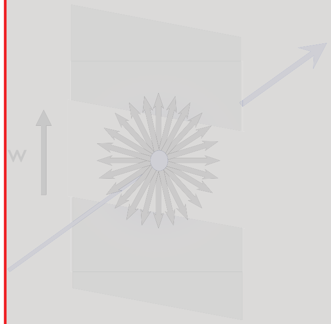
- Work started in 2011 at CESR and then ATF2 since 2015
- Few microns resolution recently demonstrated
- Limitations
  - ODR not emitting a lot of photons
  - Suffering from synchrotron radiation background
- **Motivation**
  - **Producing more photons**
  - **Emission at larger angles**





*T. Aumeyr et al., PRAB **18**, 042801 (2015) ; L. Bobb, PhD thesis, 2017 ; L. Bobb et al., PRAB **21**, 032801 (2018) ; M. Bergamaschi, PhD thesis, 2018*

Studying non-invasive beam size monitor using Optical Diffraction radiation

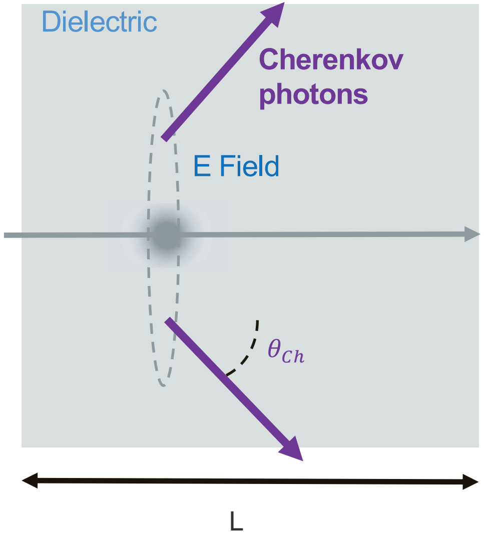


- Work started in 2011 at CESR and then ATF2 since 2015
- **Few microns resolution** recently **demonstrated** at ATF2
- **Larger aperture slits (>1mm)**

In 2016, we started investigating
Cherenkov diffraction radiation
in **longer dielectrics**

- DR and SR are emitted at similar angles
- Looking for a physical process emitted at larger angles

T. Aumeyr et al., PRAB ***18****, 042801 (2015) ; L. Bobb, PhD thesis, 2017 ; L. Bobb et al., PRAB* ***21****, 032801 (2018) ; M. Bergamaschi, PhD thesis, 2018*



In 1937

Cherenkov radiation

Emitted when a charge particle travels inside a medium at a speed faster than speed of light.

- Large emission angle: $\cos(\theta_{Ch}) = \frac{1}{\beta n}$
- Photons emitted along the target

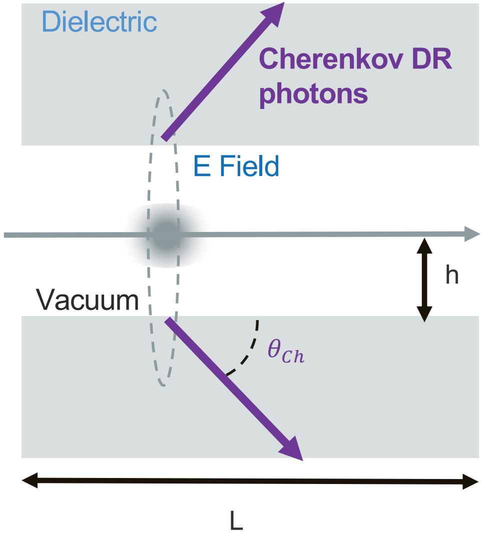
In 1934

For a cylindrical geometry

Cherenkov emission

$$\frac{d^2 N_{Dcph}}{d\Omega d\lambda} = \frac{\alpha n}{\lambda}\left(\frac{L}{\lambda}\right)^2 \left(\frac{\sin\left(\frac{\pi L}{\beta\lambda}(1-\beta n\cos\theta)\right)}{\frac{\pi L}{\beta\lambda}(1-\beta n\cos\theta)}\right) sin^2\theta$$

α, fine structure constant
β, normalised beam velocity
γ, beam relativistic factor
θ, angle of observation
L, radiator length
n, index of refraction



Cherenkov Diffraction Radiation (ChDR)

The electric field of ultra-relativistic charged particles passing in the vicinity of a dielectric radiator produces photons by the Cherenkov mechanism (polarization effect).

- Large emission angle: $\cos(\theta_{Ch}) = \frac{1}{\beta n}$
- Photons emitted along the target

For a cylindrical geometry

Cherenkov emission

Exponential decay of the particle field

$$\boxed{\frac{d^2N_{Dcph}}{d\Omega d\lambda} = \frac{\alpha n}{\lambda}\left(\frac{L}{\lambda}\right)^2 \left(\frac{\sin\left(\frac{\pi L}{\beta\lambda}(1-\beta n\cos\theta)\right)}{\frac{\pi L}{\beta\lambda}(1-\beta n\cos\theta)}\right) sin^2\theta} \,.\, \boxed{e^{\left(-4\pi\frac{h}{\gamma\beta\lambda}\right)}}$$

α, fine structure constant
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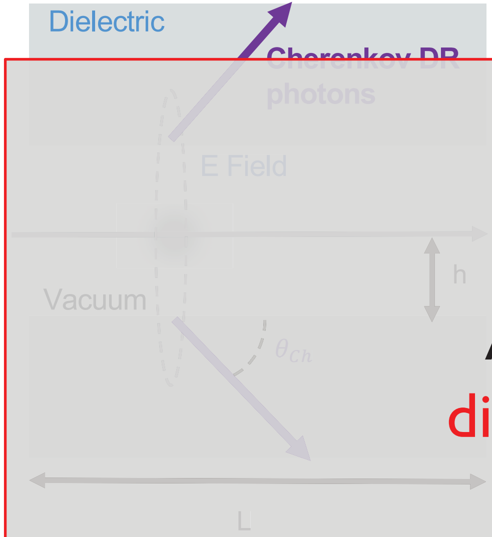
Cherenkov Diffraction Radiation (ChDR)



The electric field of ultra-relativistic charged particles passing in the vicinity of a dielectric radiator produces photons by the Cherenkov mechanism (polarization effect).

- Large emission angles
- Photons emitted along the target

Angular and spectral properties
different than Cherenkov radiation

For a cylindrical geometry

Cherenkov emission

Exponential decay of the particle field

$$\frac{d^2N_{Dcph}}{d\Omega d\lambda} = \frac{\alpha n}{\lambda}\left(\frac{L}{\lambda}\right)^2\left(\frac{\sin\left(\frac{\pi L}{\beta\lambda}(1-\beta n\cos\theta)\right)}{\frac{\pi L}{\beta\lambda}(1-\beta n\cos\theta)}\right) sin^2\theta \,.\, e^{\left(-4\pi\frac{h}{\gamma\beta\lambda}\right)}$$

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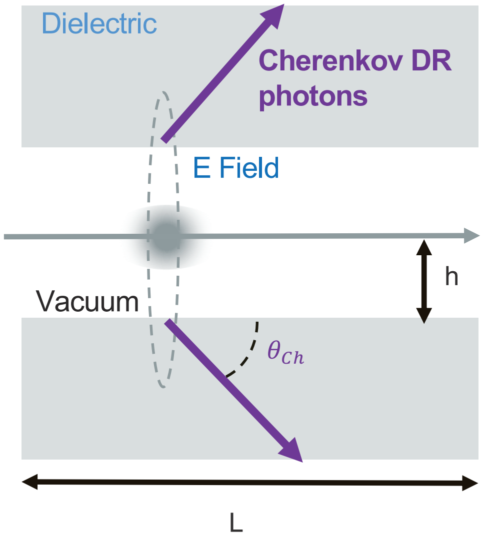
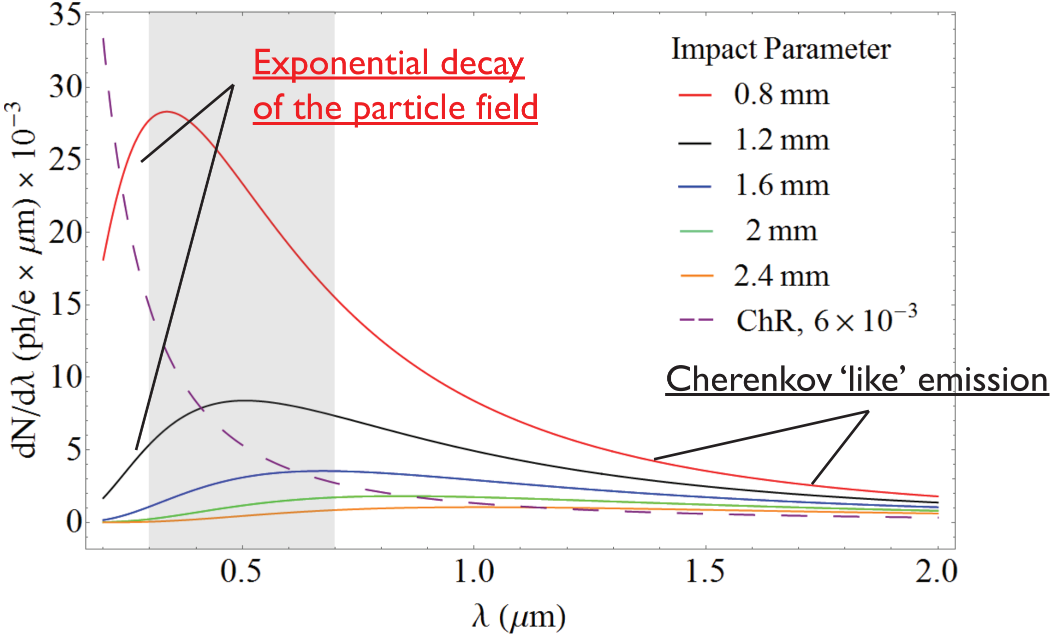


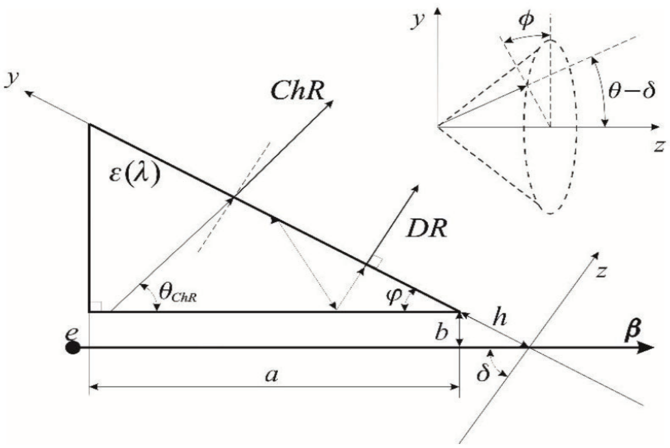
ChDR Spectrum



MODELLING AND SIMULATIONS

Polarization Current Approach – a model developed at Tomsk Univ.

D.V. Karlovets and A.P. Potylitsyn, JETP letters 90, 326 (2009)
M.V. Shevelev and A.S. Konkov, JETP 118, 501 (2014)



Spectral-Angular density of the radiation

$$\frac{d^2W_1}{d\lambda d\Omega} = D \cdot \left|\frac{\varepsilon(\lambda)}{\varepsilon(\lambda)\cos(\theta-\delta)+U}\right|^2 \Big|\cos\delta\left(\gamma^{-1}\sin(\theta-\delta) - iKU\cos\phi\right) + \sin\delta\left(iK\sin(\theta-\delta)+\gamma^{-1}U\cos\phi\right) - \gamma\beta U\sin(\theta-\delta)\sin^2\phi\Big|^2$$

$$\frac{d^2W_2}{d\lambda d\Omega} = D\cdot\gamma^2\sin^2\phi\left|\frac{\sqrt{\varepsilon(\lambda)}}{\cos(\theta-\delta)+U}\right|^2\left(\sin^2(\theta-\delta)+|U|^2\right)\times \left[1-\beta^2\cos^2(\theta-\delta)+2\beta\gamma^{-2}\sin\delta\sin(\theta-\delta)\cos\phi-\gamma^{-2}\sin^2\delta\left(K^2-\gamma^{-2}\right)\right]$$

$$D = \frac{\alpha}{2\pi^2}\frac{\hbar c}{\lambda^2}\frac{\beta^2\cos^2(\theta-\delta)}{K^2|P|^2}\left|\frac{\varepsilon(\lambda)-1}{\varepsilon(\lambda)}\right|^2\left|1-\exp\left[-ia\frac{2\pi}{\beta\lambda}(P+\Sigma\cdot\cot\varphi)\sin\varphi\right]\right|^2\times \\ \times\frac{\exp\left[-2\frac{2\pi}{\gamma\beta\lambda}(h+a\cdot\cos\varphi)K\cos\delta\right]}{1-\beta^2\cos^2(\theta-\delta)+\beta^2\sin^2\delta\left(1-\sin^2(\theta-\delta)\sin^2\phi\right)+2\beta\sin\delta\sin(\theta-\delta)\cos\phi}$$

$$U=\sqrt{\varepsilon(\lambda)-\sin^2(\theta-\delta)},\qquad K=\sqrt{1+(\gamma\beta\sin(\theta-\delta)\sin\phi)^2},$$
$$P=\cos\delta-\beta U+i\gamma^{-1}K\sin\delta,\qquad \Sigma=\sin\delta+\beta\sin(\theta-\delta)\cos\phi-i\gamma^{-1}K\cos\delta$$

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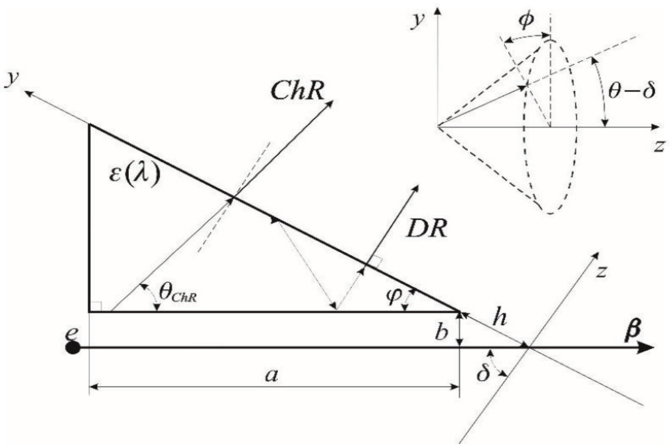
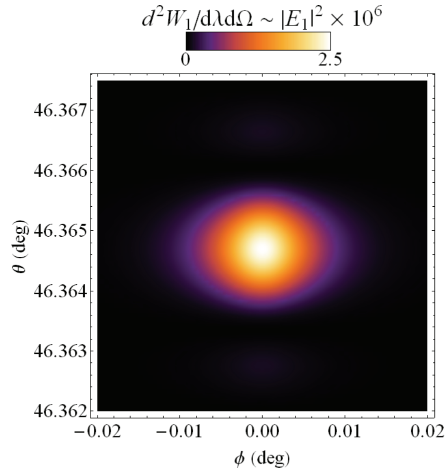
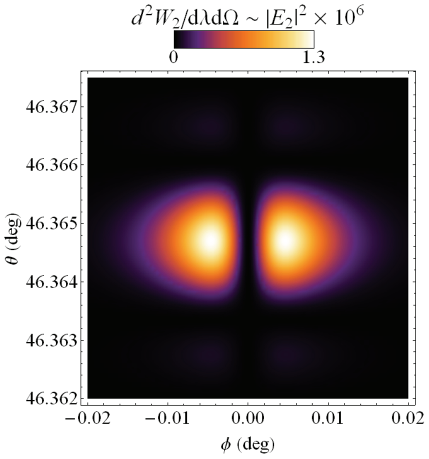


$\gamma = 10^4, \lambda = 600\,nm, b = 0.8\,mm, a = 11.5\,mm$

Vertical polarization



Horizontal polarization



MODELLING AND SIMULATIONS

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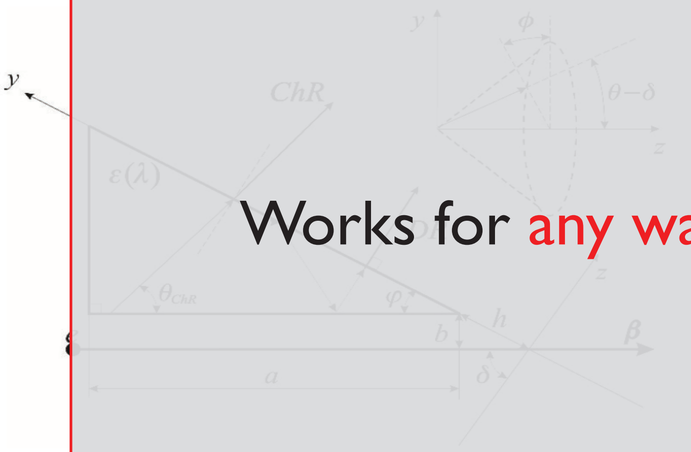
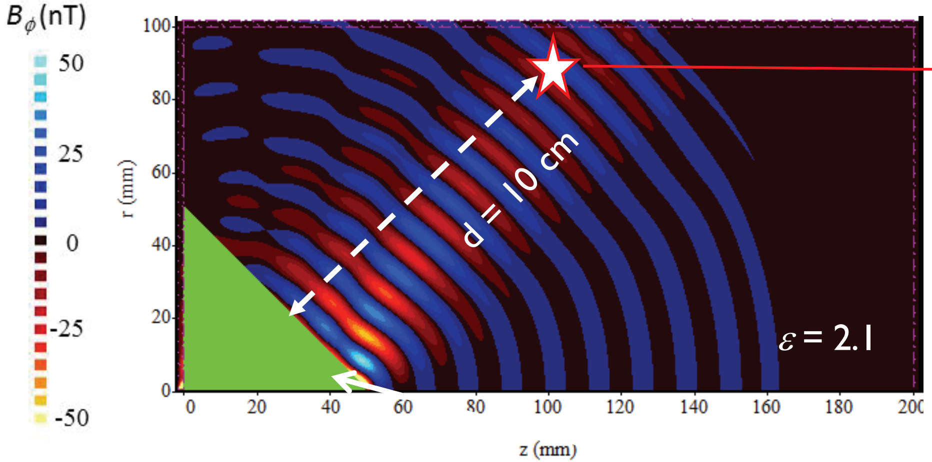


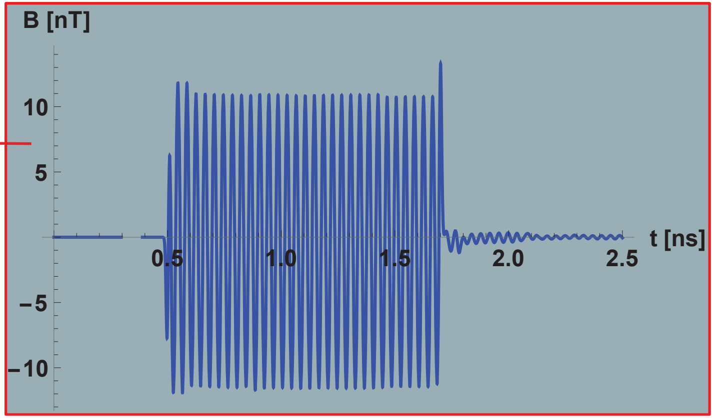
Works for any wavelengths but only for few geometries

$\gamma = 10^4, \lambda = 600\ nm, b = 0.8\ mm, a = 11.5\ mm$

Emission of Coherent ChDR at longer wavelength from short bunches simulated using EM simulations codes

Using MAGIC to simulate an electron beam modulated at a 25GHz propagating in the vicinity of a Teflon cone





from J. Gardelle

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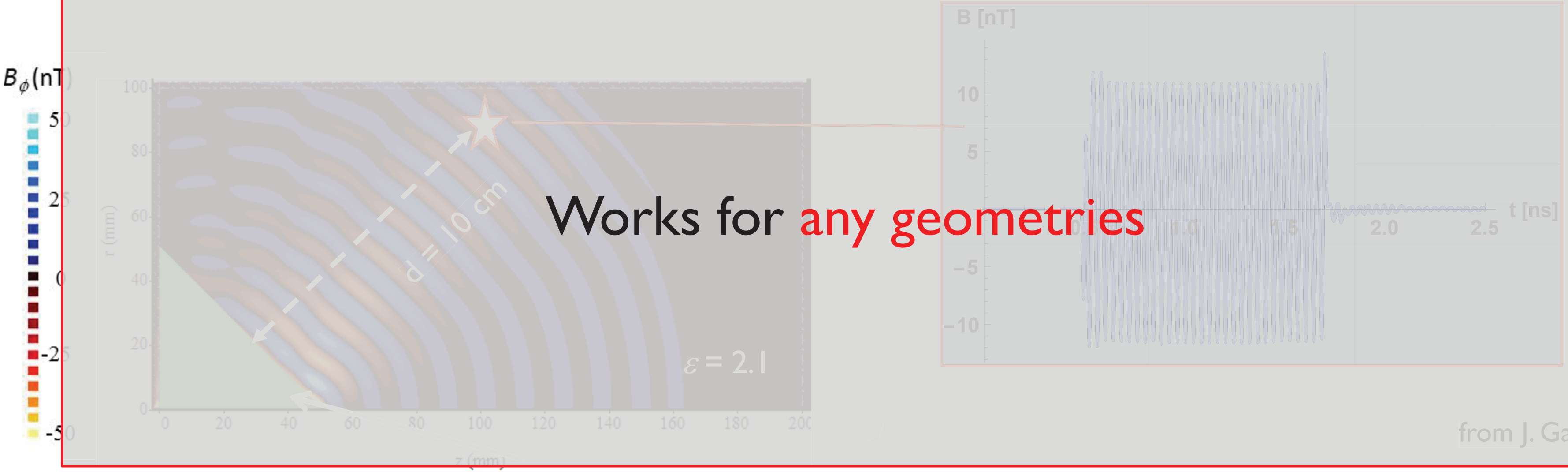
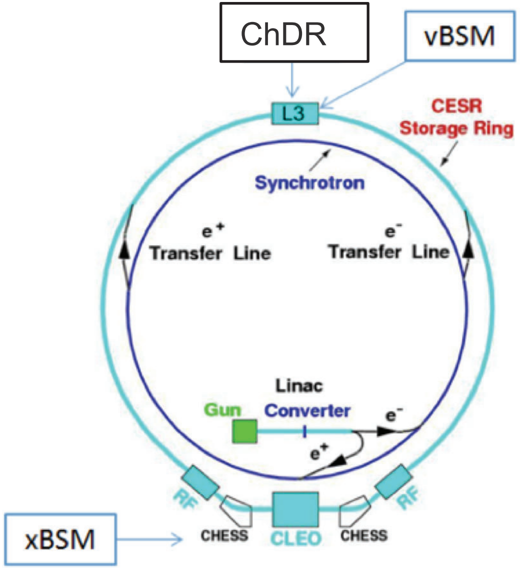
Using MAGIC to simulate an electron beam modulated at a 25GHz propagating in the vicinity of a Teflon cone



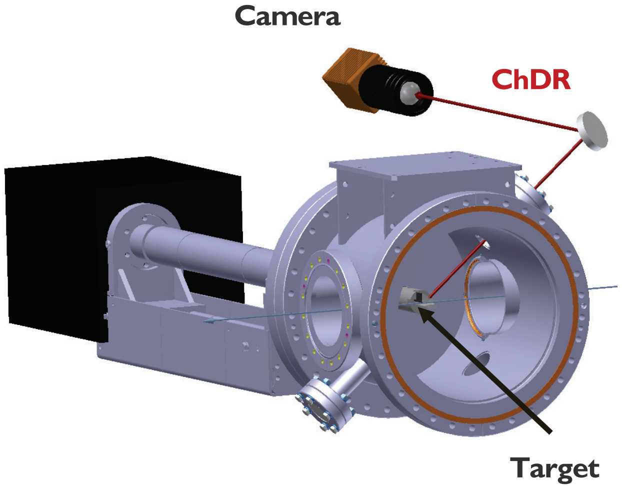
Works for any geometries

from J. Gardelle

First tests of incoherent ChDR on Cornell Electron Storage Ring



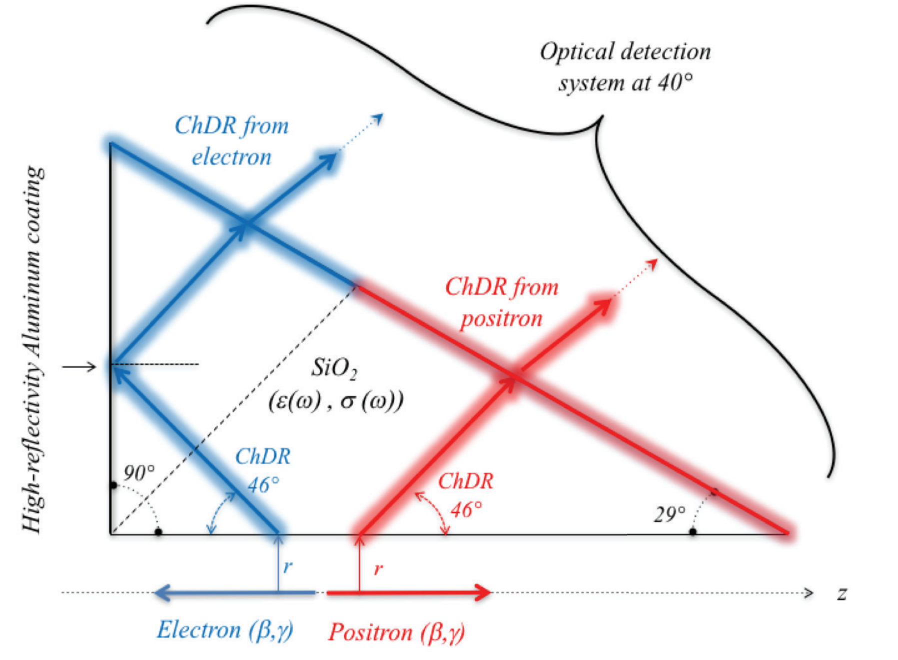
CESR Ring Circumference	768.4m
Revolution Time	2.563 µs
Beam Energy	2.1 and 5.3GeV
Beam Species	**e^- and e^+**
Particles per bunch	$1.6\ 10^{10}$

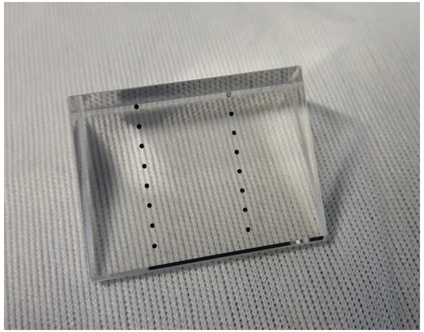


R. Kieffer et al., *"Direct Observation of Incoherent Cherenkov Diffraction Radiation in the Visible Range", PRL* ***121*** *(2018) 054802*

EXPERIMENTS AT CESR

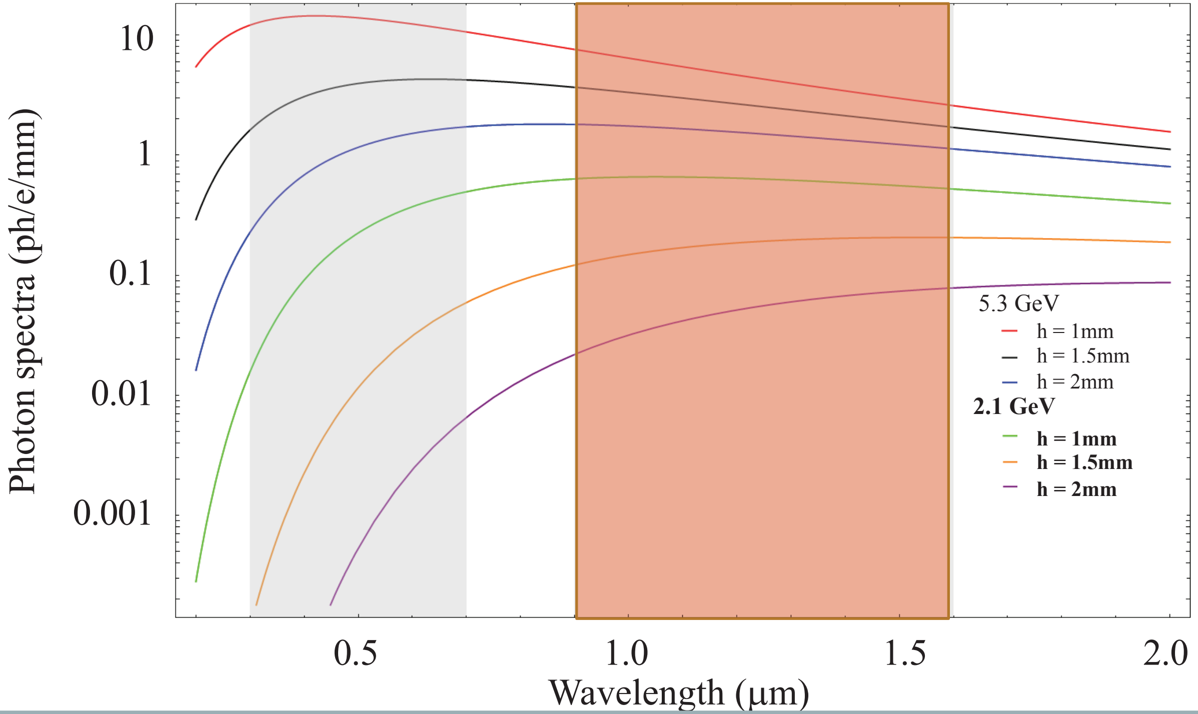
Using a 2cm long SiO_2 (n=1.46) ChDR target



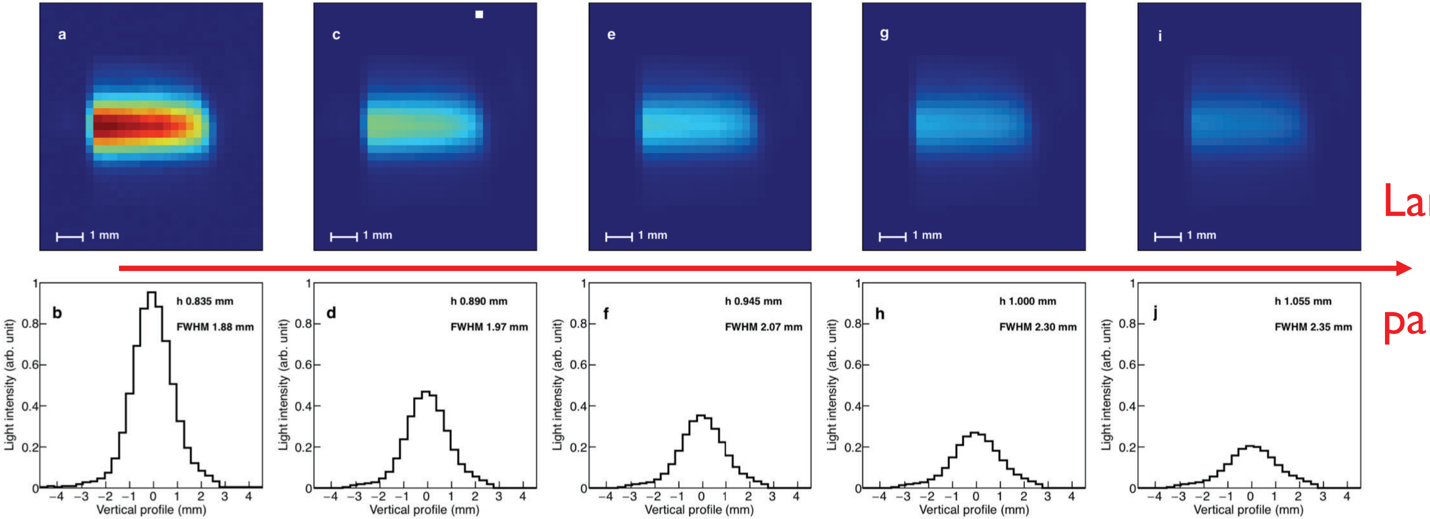


EXPERIMENTS AT CESR

Testing with 2.1GeV e⁻ and measuring in IR (0.9-1.7um) – April 2017



Light intensity vs Impact parameter – imaging conditions

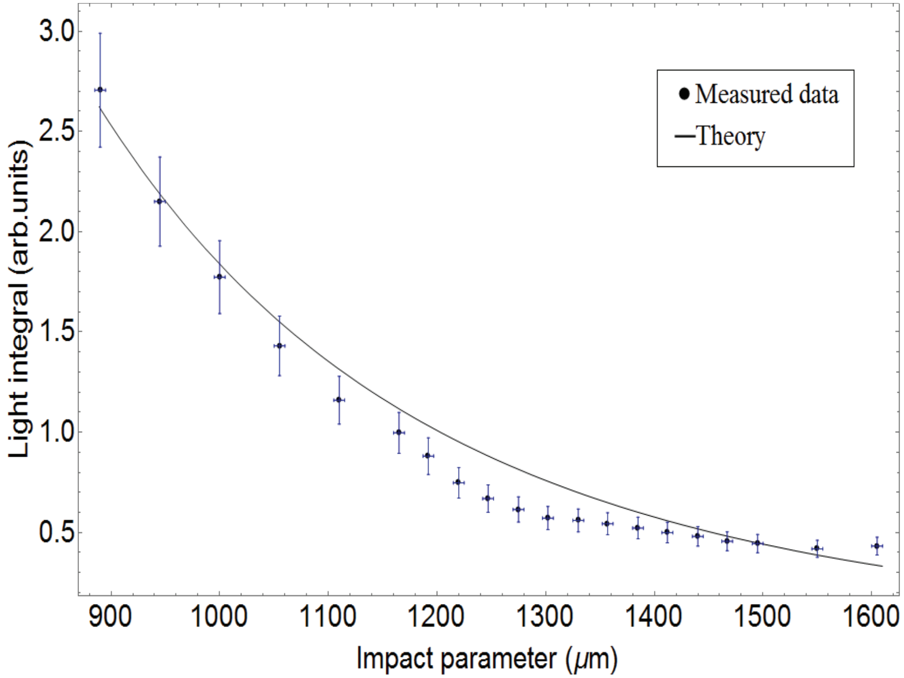


Larger impact parameters

'Cherenkov photons yield increasing strongly for smaller impact parameter'

EXPERIMENTS AT CESR

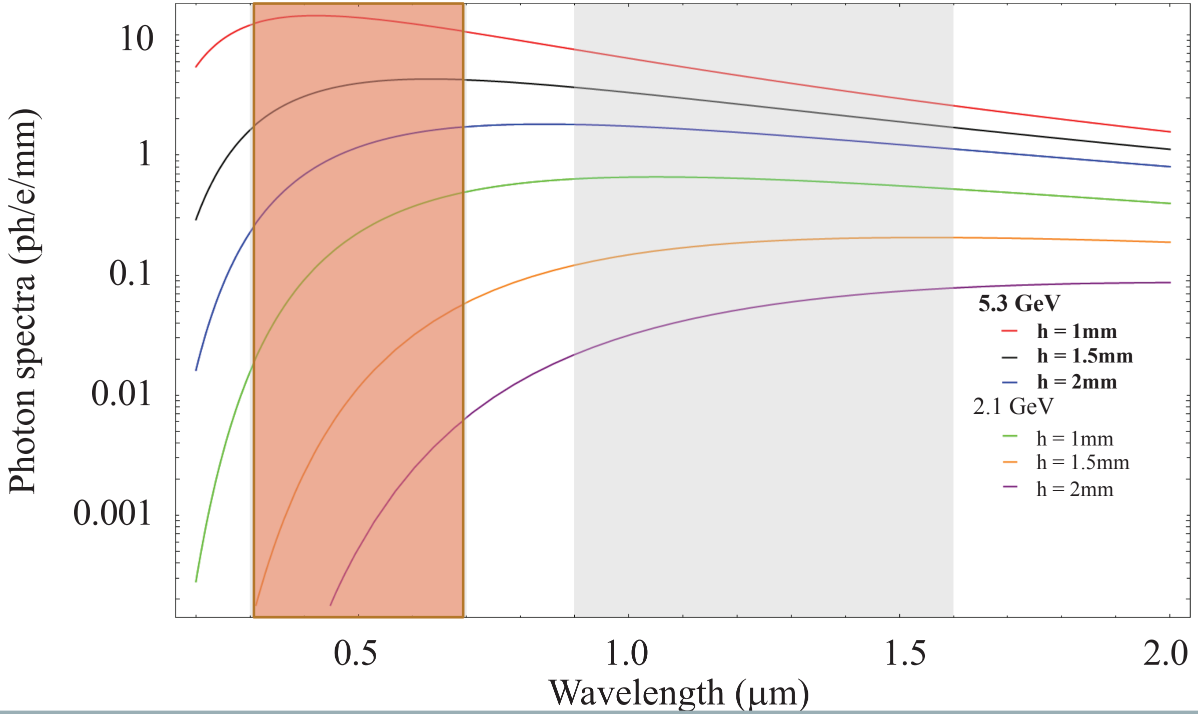
Light intensity vs Impact parameter – imaging conditions



- Good agreement with Theory
- BUT
  - No polarization studies
  - No angular measurements

EXPERIMENTS AT CESR

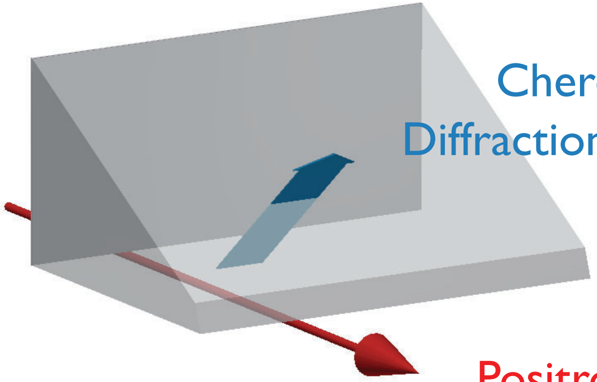
Testing with 5.3GeV e^- / e^+ and measuring in visible (0.3-0.7um) – Oct. 2017

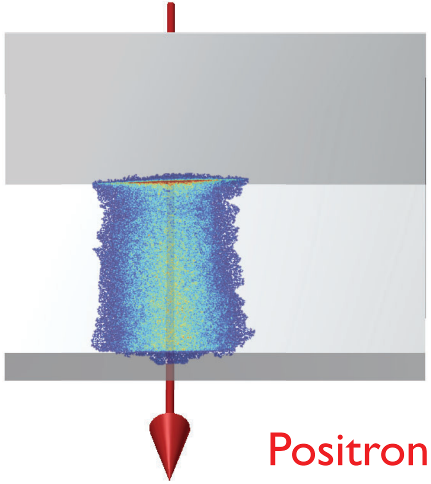


- Both imaging and angular measurements
- Polarization studies
- Narrow-band wavelength filters

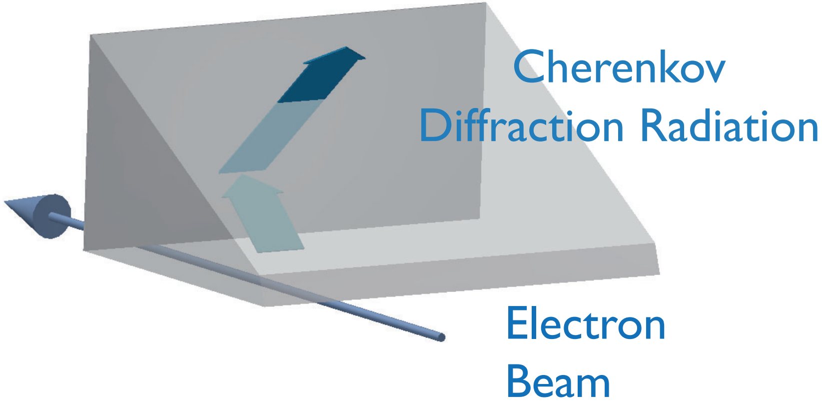
EXPERIMENTS AT CESR

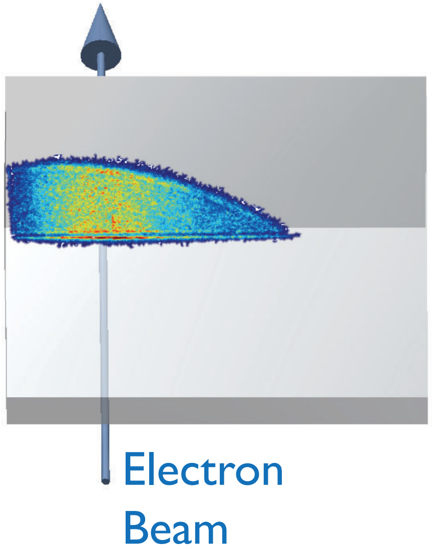
Imaging Positrons





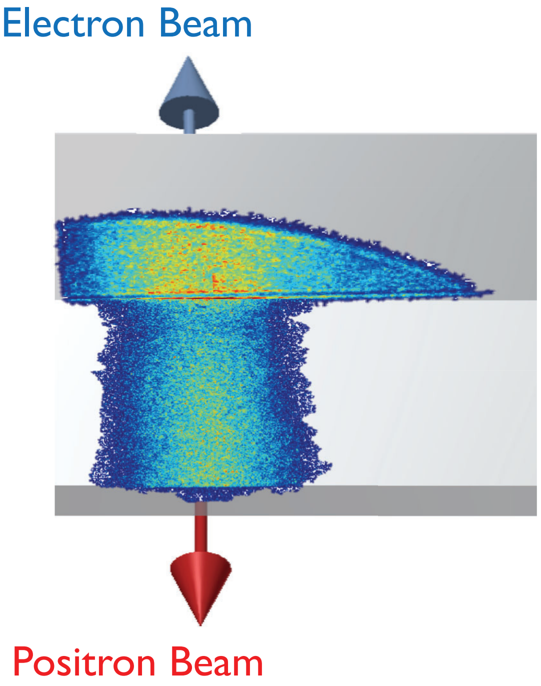
Imaging Electrons





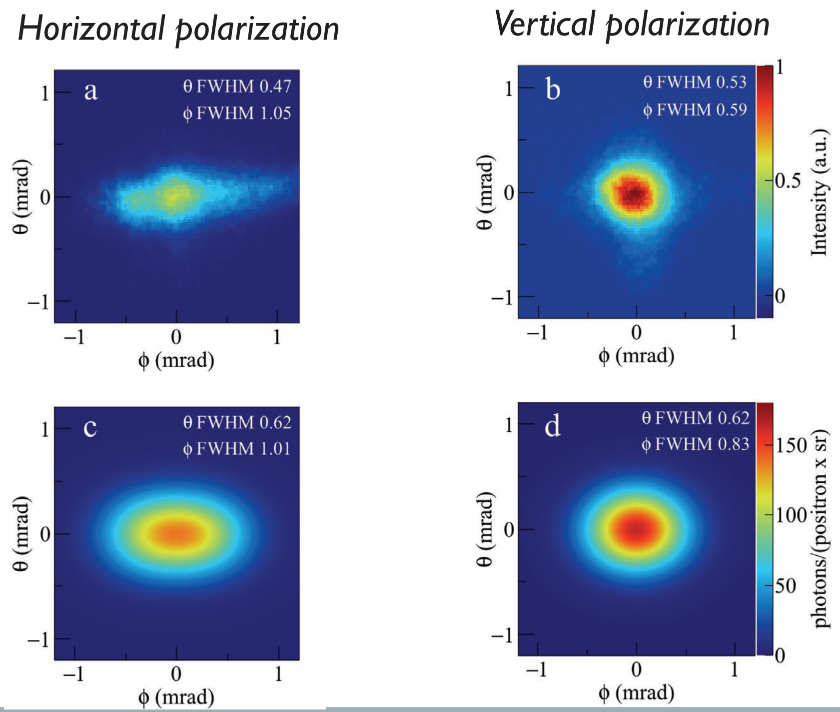
Images from e⁻ is truncated due to the limited aperture of the current detection system

EXPERIMENTS AT CESR



The photons produced by electrons and positrons appear on a different zone of the image as expected

Angular distributions



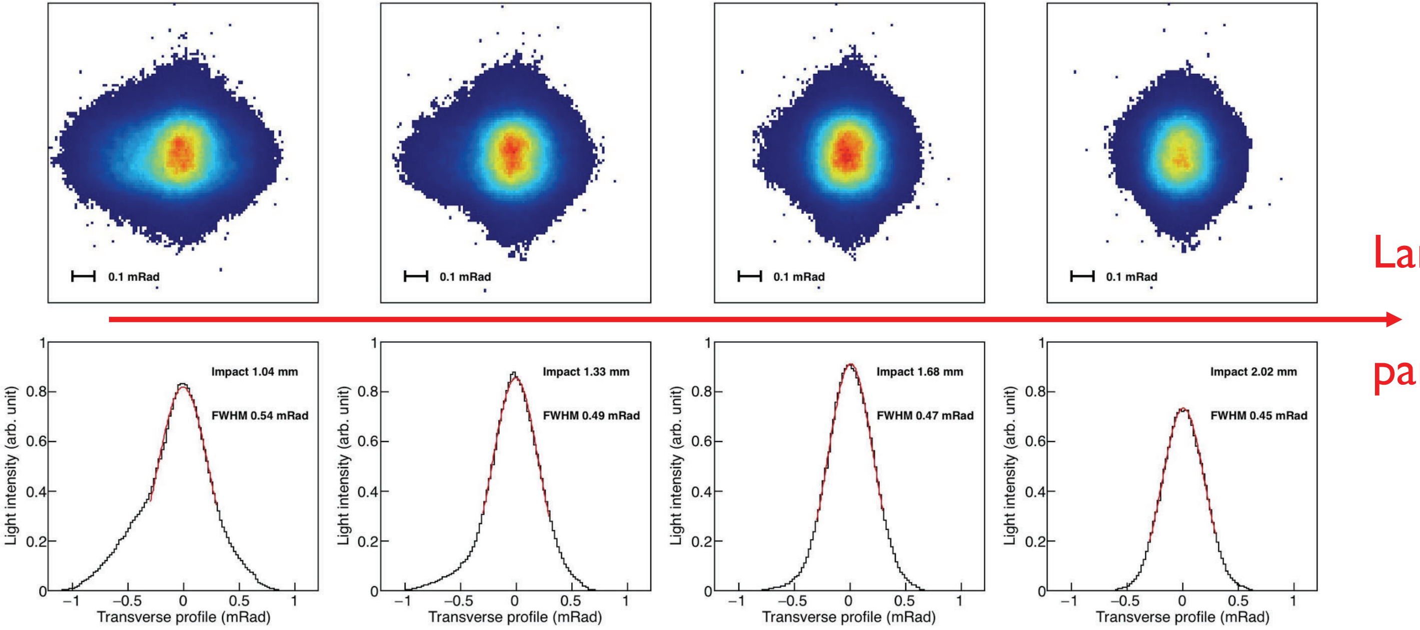
Measurements with Positrons

Ang. divergence: ±200urad

Simulations from PCA

Angular distributions as function of impact parameter

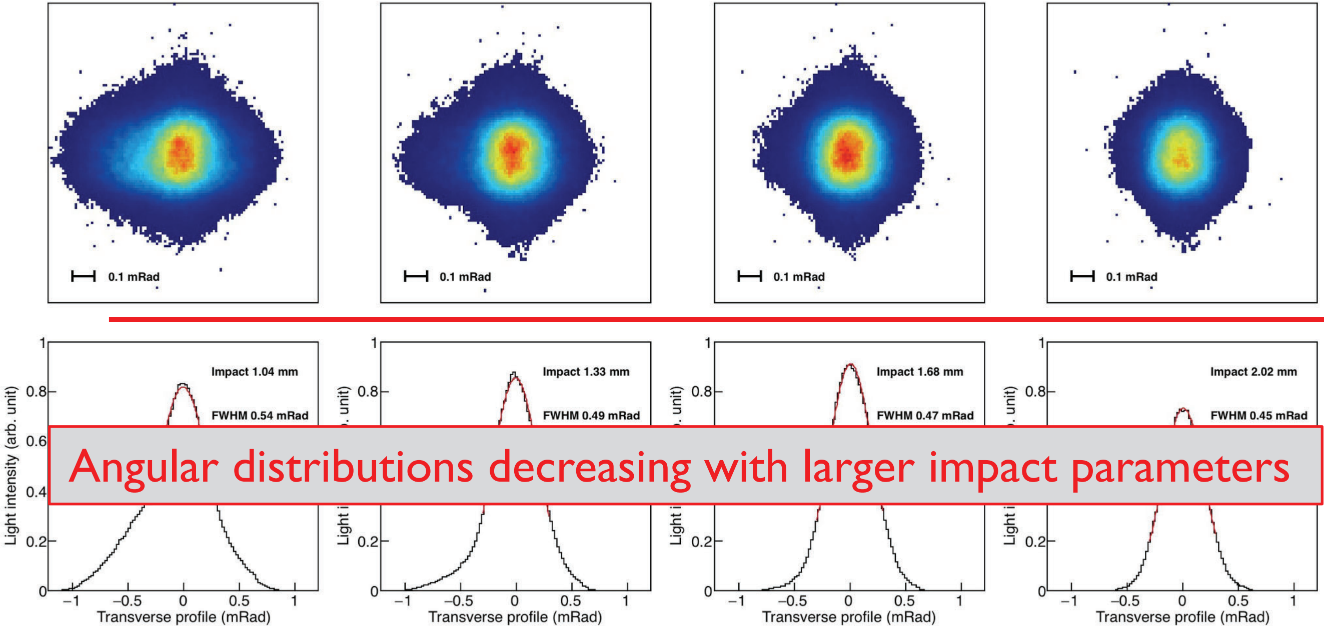
5.3 GeV positrons - 600nm+/-10nm filter – Vertical polarizer



Larger impact parameters

Angular distributions as function of impact parameter

5.3 GeV positrons - 600nm+/-10nm filter – Vertical polarizer

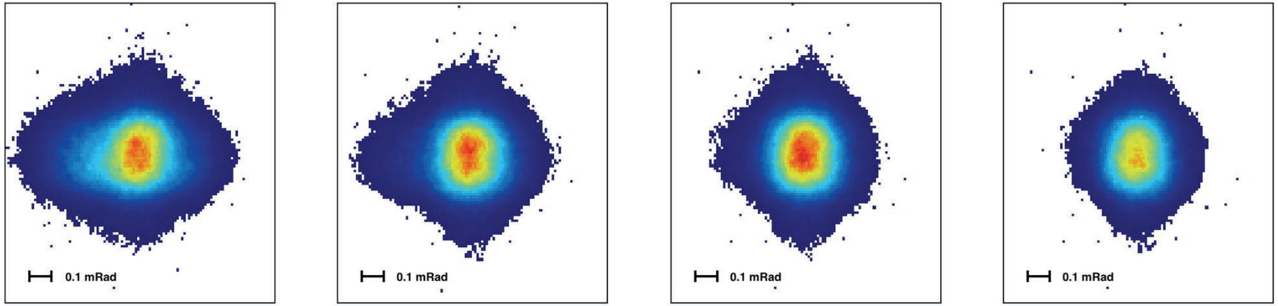


Larger impact parameters

Angular distributions decreasing with larger impact parameters

Angular distributions as function of impact parameter

5.3 GeV positrons - 600nm+/-10nm filter – Vertical polarizer

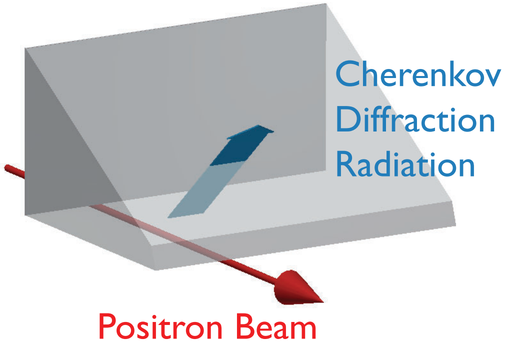


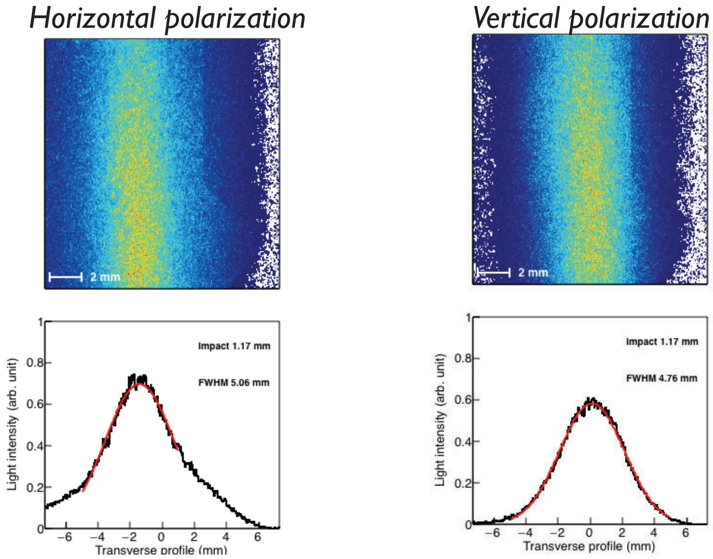
Impact parameter (mm)	1.04	1.33	1.68	2.02	2.46
$FWHM_{exp}$ (mrad)	0.54	0.49	0.47	0.45	0.43
$FWHM_{est}$ (mrad)	0.56	0.49	0.46	0.44	0.40

Good agreement with theory

Beam imaging - Polarization studies

5.3 GeV positrons - 600nm+/-10nm

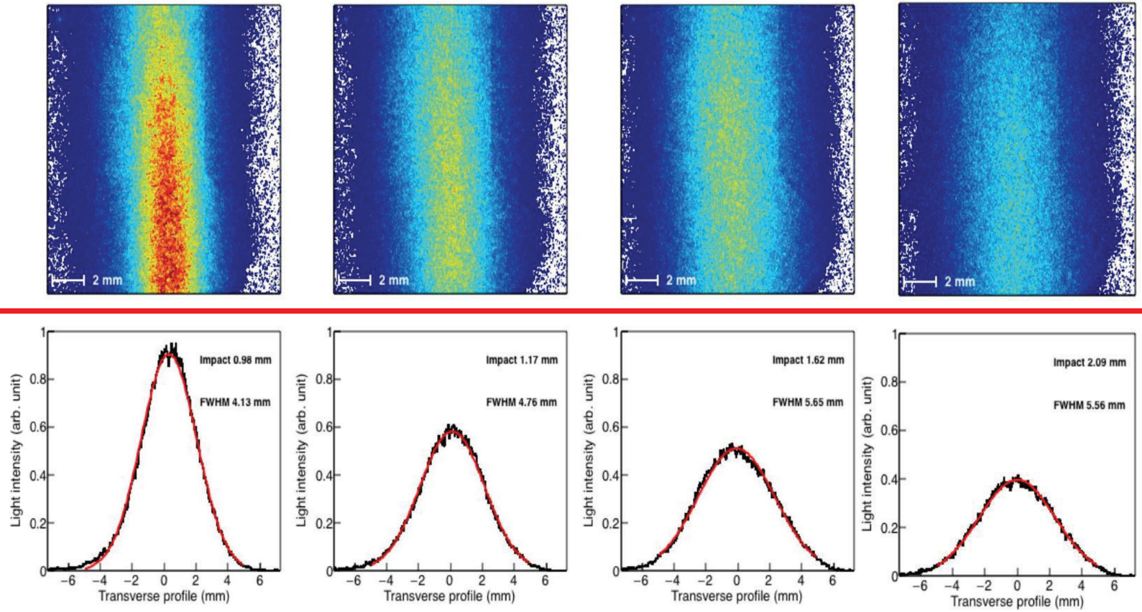




Vertically polarized photons give the best spatial resolution (here for σ_y=2mm)

Beam imaging as function of impact parameter

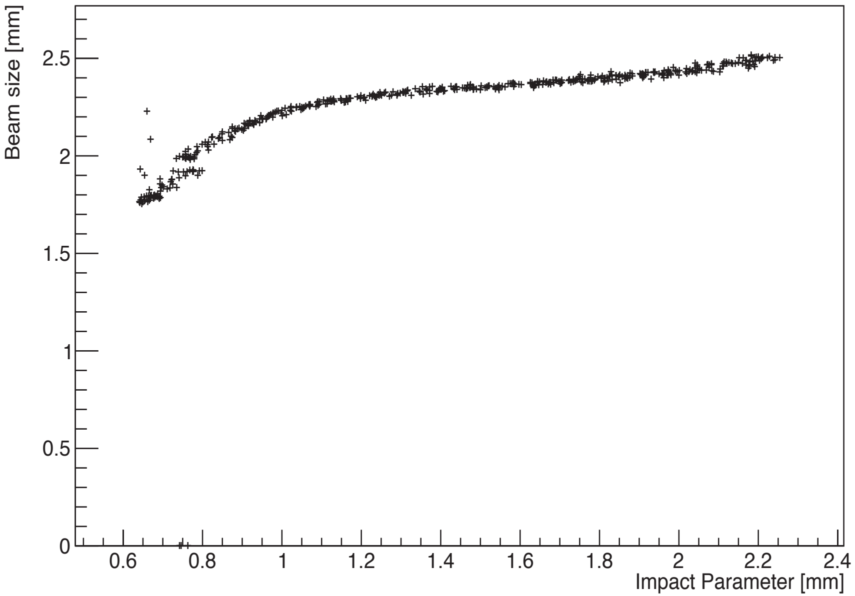
5.3 GeV positrons 600nm+/-10nm filter – Vertical polarizer



Larger impact parameters

Beam imaging as function of impact parameter

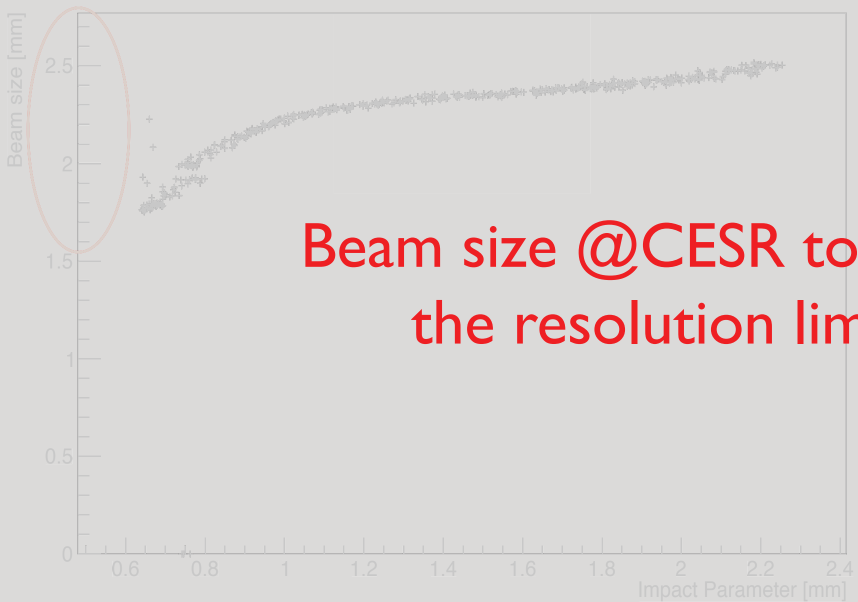
5.3 GeV positrons 600nm+/-10nm filter – Vertical polarizer



- Measured beam size increasing for larger impact parameters
- Theoretical model being developed to investigate how Line Spread Function would vary with impact parameter

Beam imaging as function of impact parameter

5.3 GeV positrons, 600nm+/-10nm filter, Vertical polarizer



Measured beam size increasing for larger impact parameter

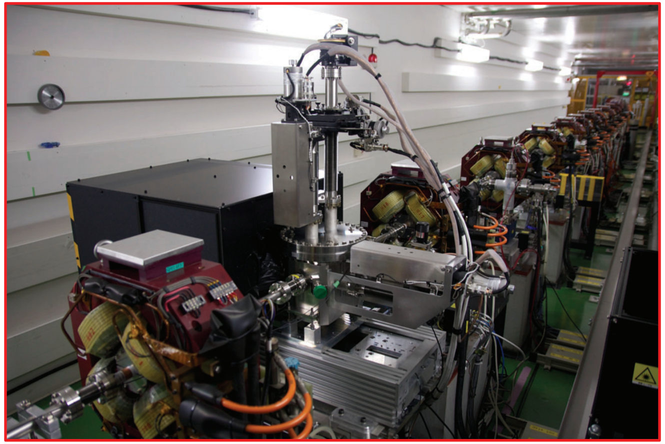
Theoretical model being developed to investigate Line Spread Function as function of impact parameter

Beam size @CESR too large to study the resolution limit of ChDR

EXPERIMENTS AT ATF2/KEK

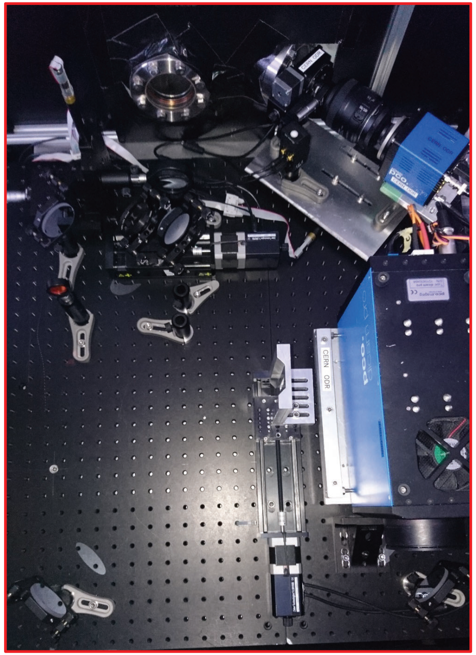
Studying the spatial resolution of ChDR at ATF2/KEK - 2018

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



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

- Vacuum target manipulator and Optical system in the visible



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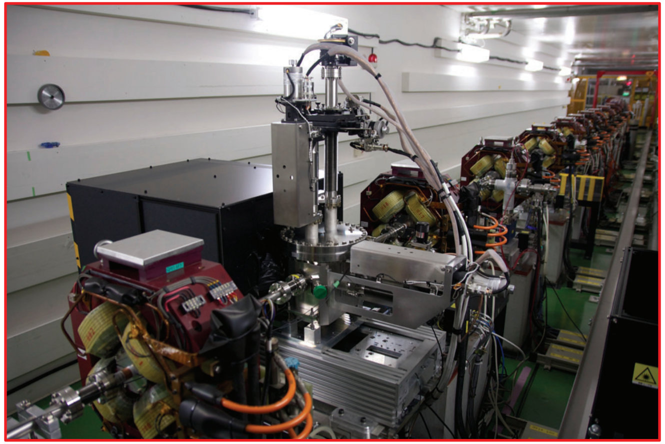
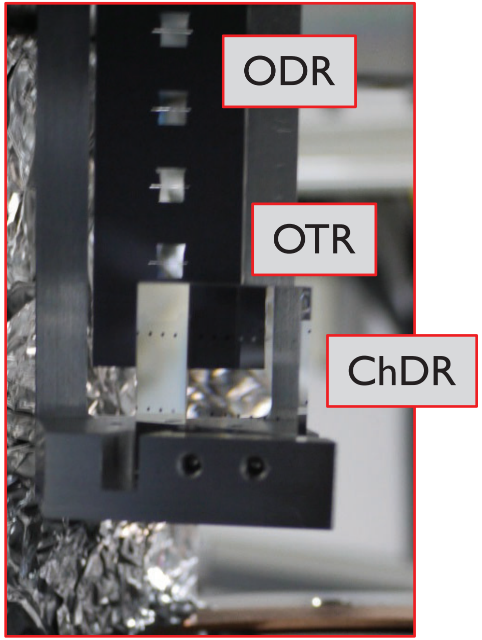
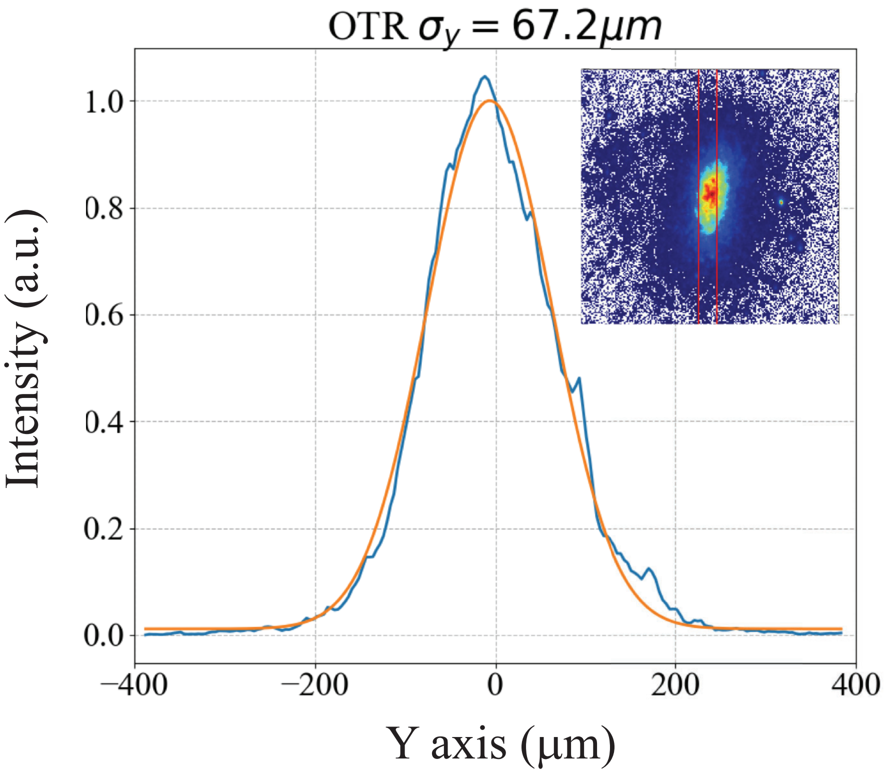


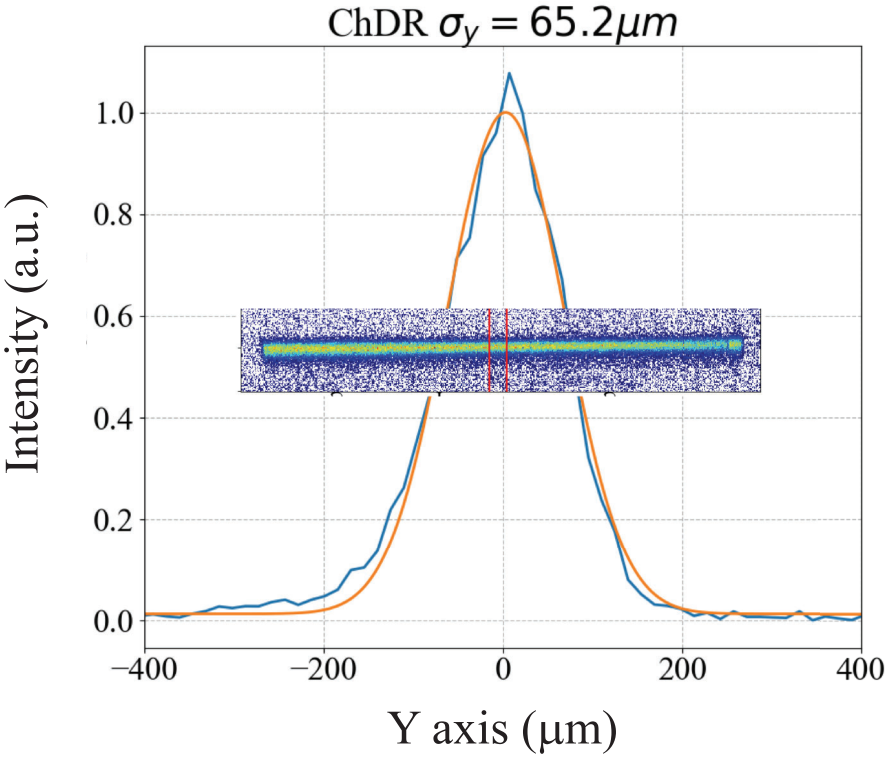
Re-using and modifying the hardware used for Diffraction radiation studies

- Vacuum target manipulator and Optical system in the visible
- OTR for cross calibration



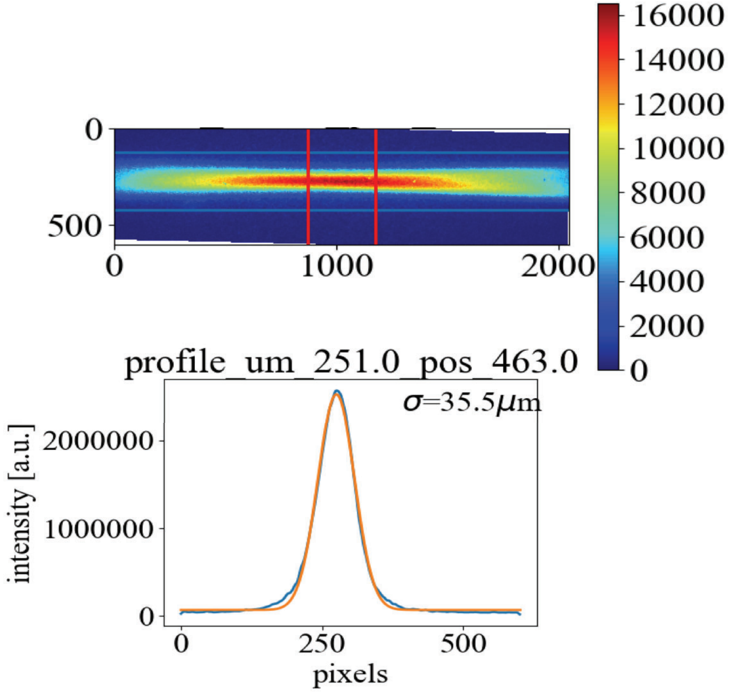
EXPERIMENTS AT ATF2/KEK





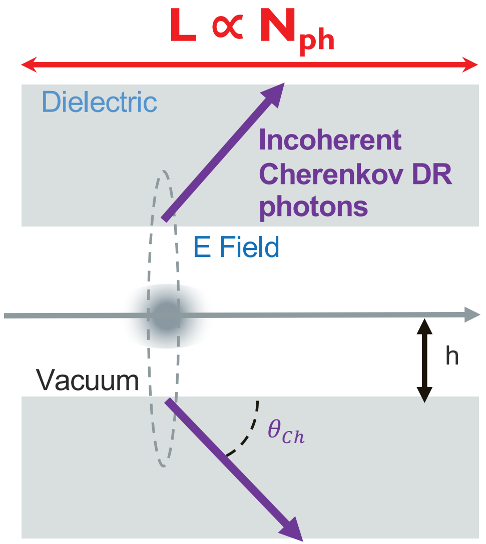
EXPERIMENTS AT ATF2/KEK

Work in progress ….



- *Smallest beam size measured around 35 μm*
- Next shift in Nov-Dec 2019 : Measuring the line spread function of ChDR

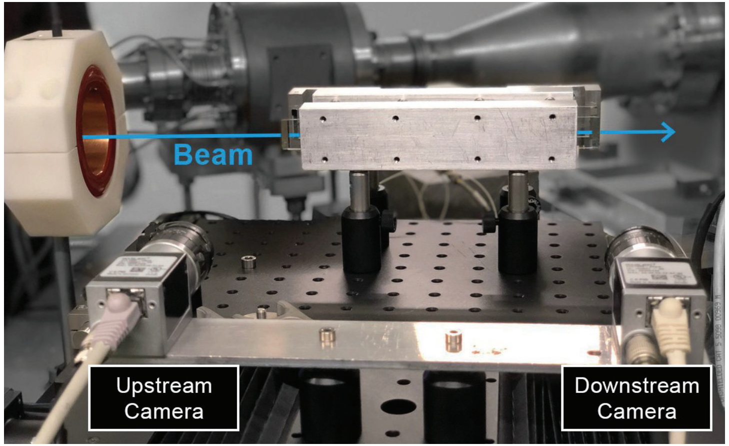
Incoherent ChDR in long(er) dielectrics to increase sensitivity

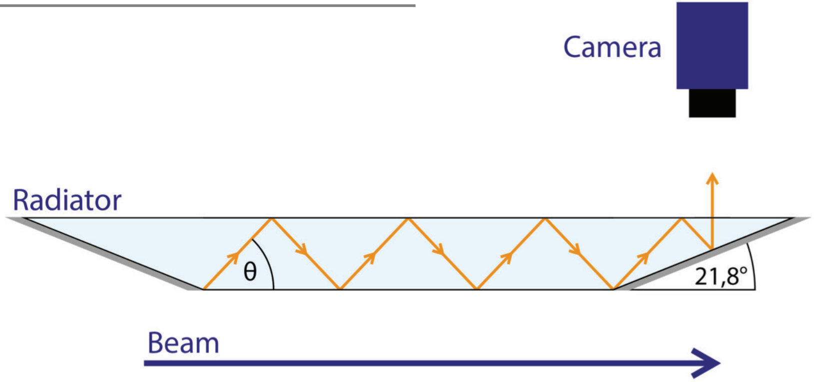


- L > 10cm
- Allow the detection of particles sitting at **larger distances (h ~ several cm)**
- Allow the detection of **low(er) beam energies** (e^-@200MeV or H^+@400GeV)

EXPERIMENTS AT CLEAR/CERN

CLEAR facility at CERN	
Beam Energy	200 MeV
Particles per bunch	$3\ 10^9$
Typical beam size H/V (mm)	> 0.1 / > 0.1

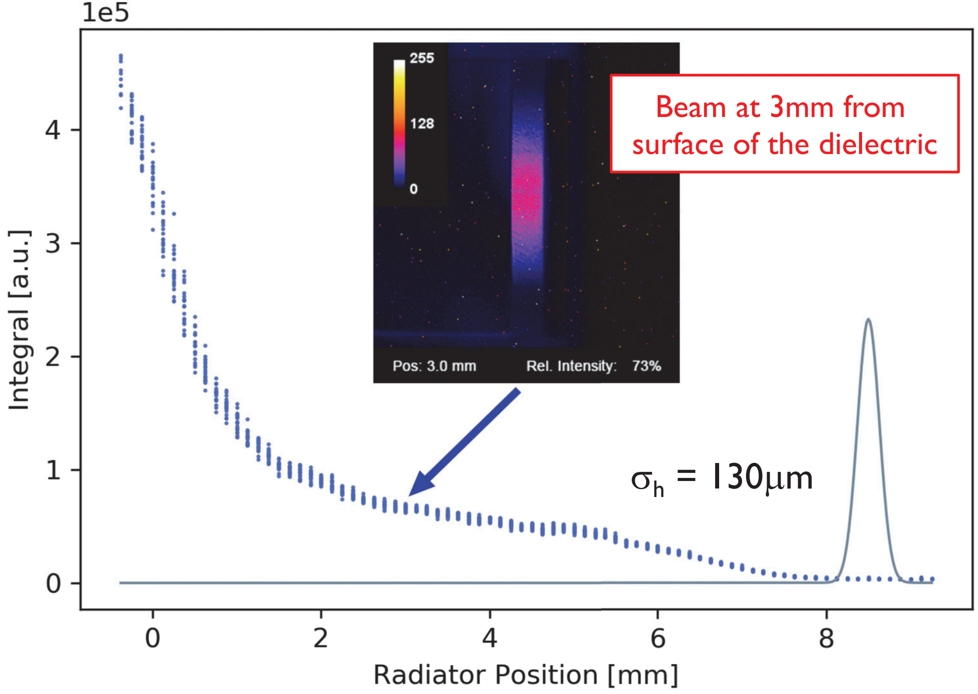




'2mm thick, 20cm long stripline in fused Silica'

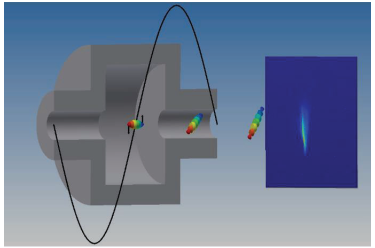
In-air test-stand for fast prototyping

Impact parameter scan - 200MeV 500pC e⁻ bunch – measuring at 600 ± 10 nm

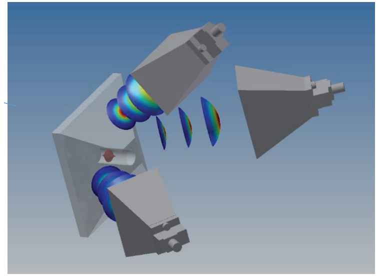


- **Still signal at h > 7mm**
- Next shift in Nov-Dec 2019

Coherent ChDR for bunch length monitoring of short bunches



CLEAR facility at CERN	
Beam Energy	200 MeV
Particles per bunch	3 10^9
Typical bunch length (ps)	0.5 - 5



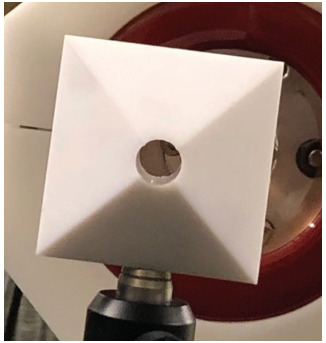
- Longitudinal profiles using RF deflector for cross calibrator
- Bunch spectrum measurements using Coherent ChDR at mm wavelength

Similar studies at CLARA – talk from K. Fedorov on Tuesday

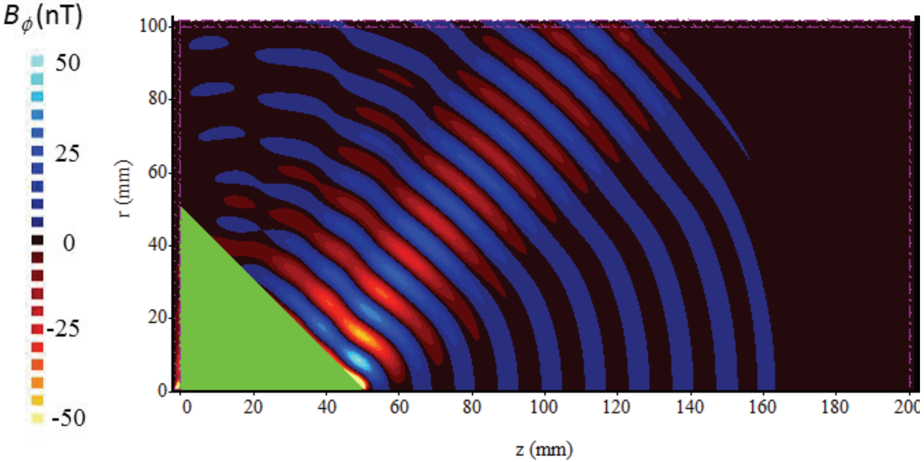
CChDR radiator installed in the in-air test-stand

A. Curcio et al, PRAB 22, 020402 (2019)

Pyramid in Teflon



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



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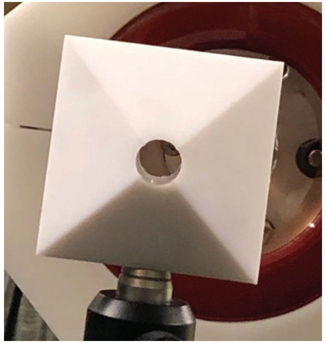

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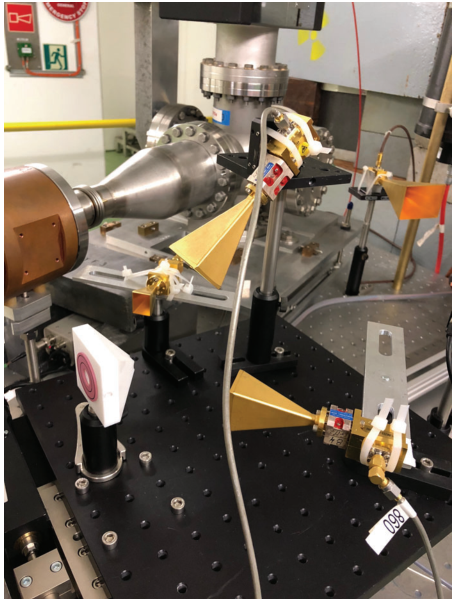
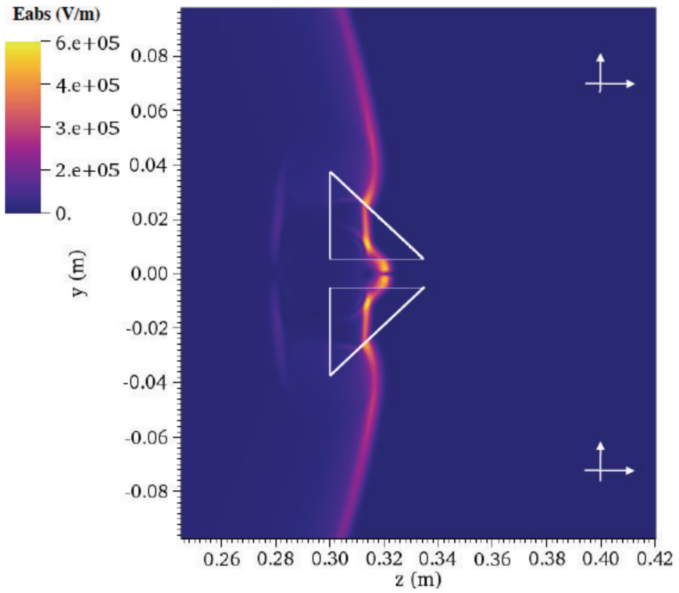
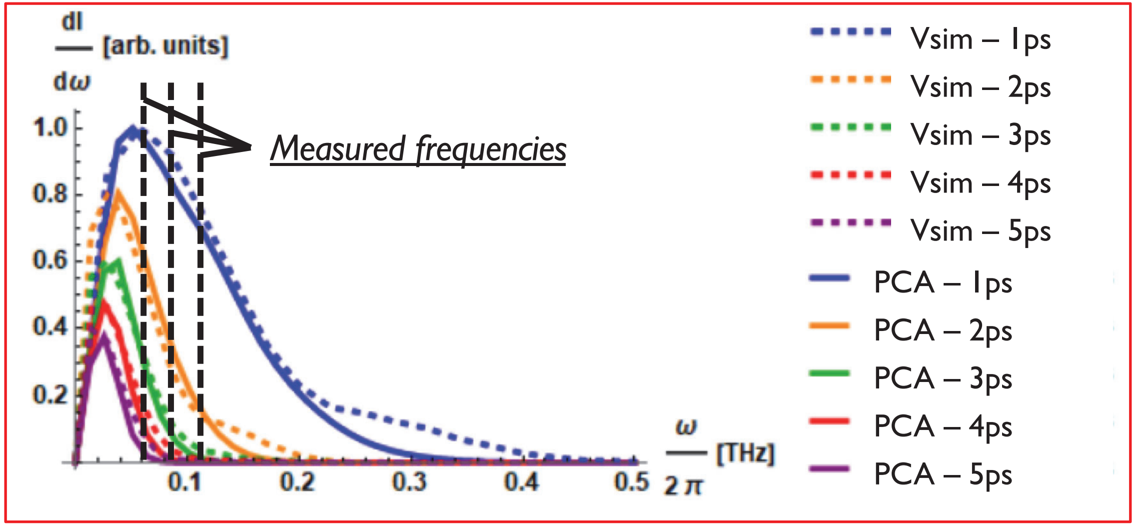


- Measuring in 3 bands (60-84-113.5GHz)
- Scintillating screen on the radiator's input face for beam tuning
- Typical beam size (H/V) < 500microns
- All set-up mounted on remotely controlled table to allow hor/ver centering

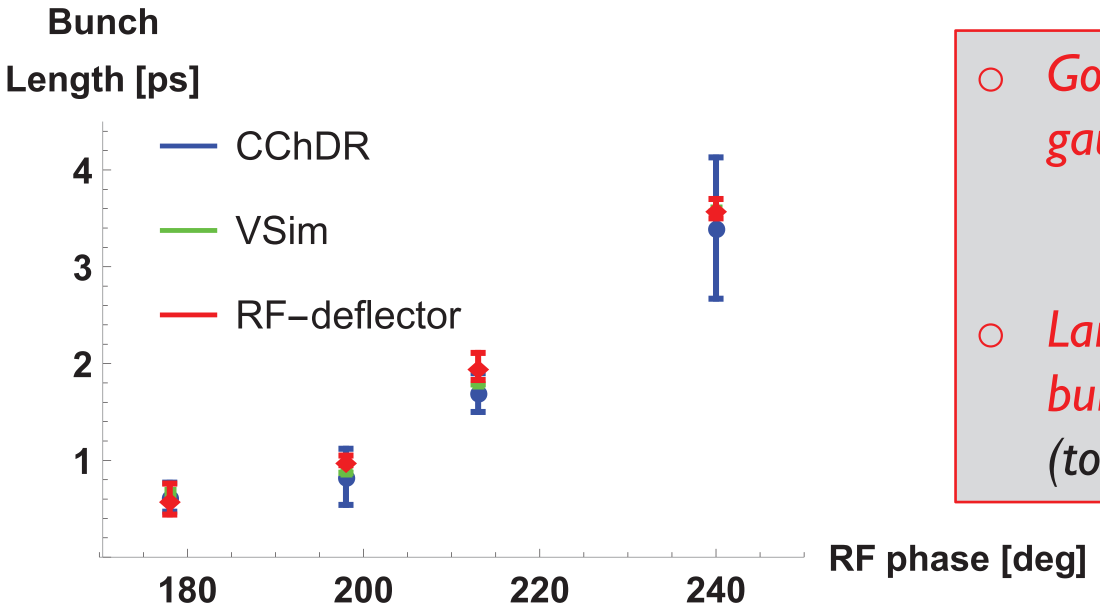
CChDR power spectrum simulated by VSIM





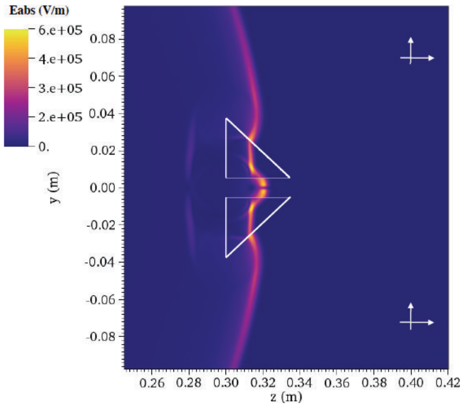
from K. Lekomtsev

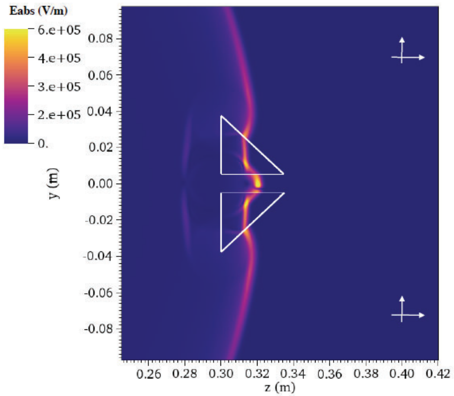
Comparison between CChDR, RF deflector and Vsim

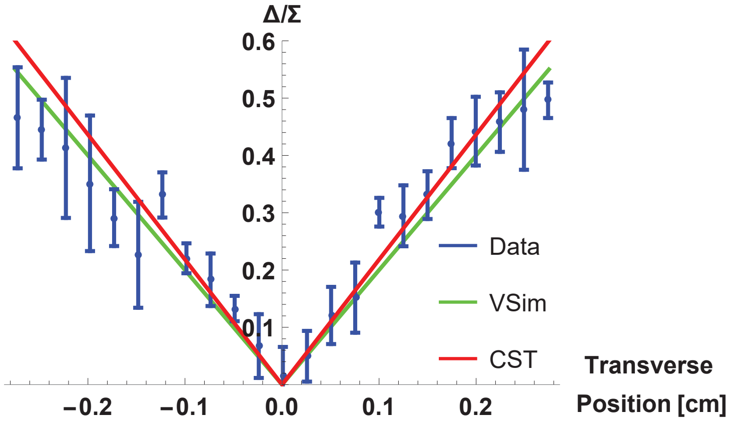


- *Good agreement using gaussian bunches*
- *Larger noise* for *longer bunches as we measured at (too) high frequencies*

Alignment of the beam going through the radiator's hole



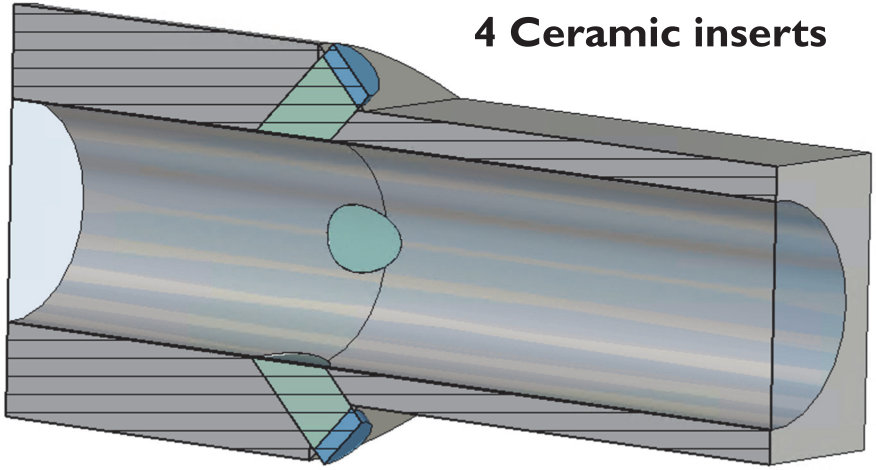




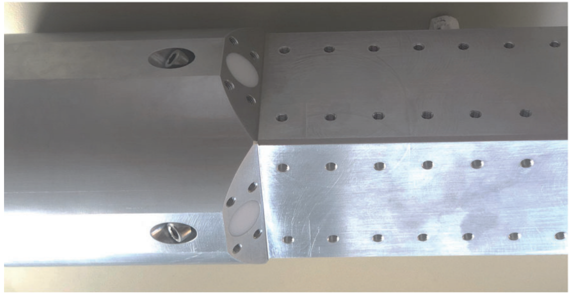
Using the CChDR for beam centering as BPM

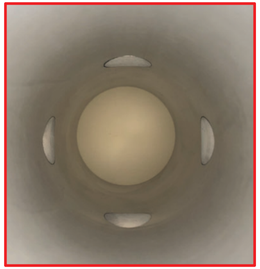
EXPERIMENTS AT CLEAR/CERN

Test of an ‘better’ engineered version of ChDR on CLEAR later this year



Detection foressen at 30GHz





CONCLUSIONS

- Both experimental and theoretical studies are investigating the use ChDR for non-invasive beam diagnostics
  - *Still a lot of work to fully understand its potential (imaging resolution, sensitivity)*
  - *How to optimise such a system i.e. material, shape / length, detection system (visible, NIR, THz, .)*
  - *Impedance calculations started using a code developed at CERN, IW2D by N. Mounet*

CONCLUSIONS

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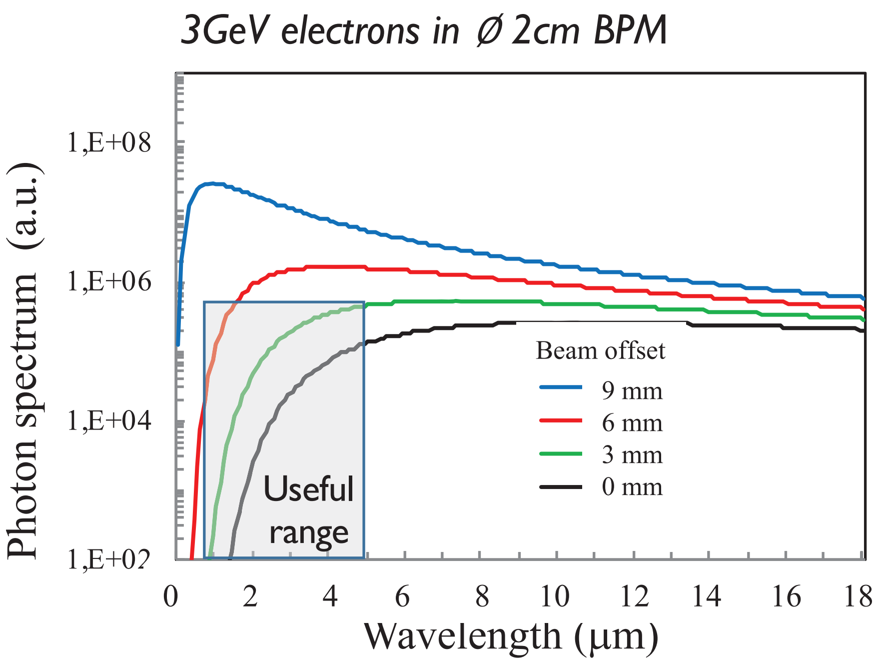
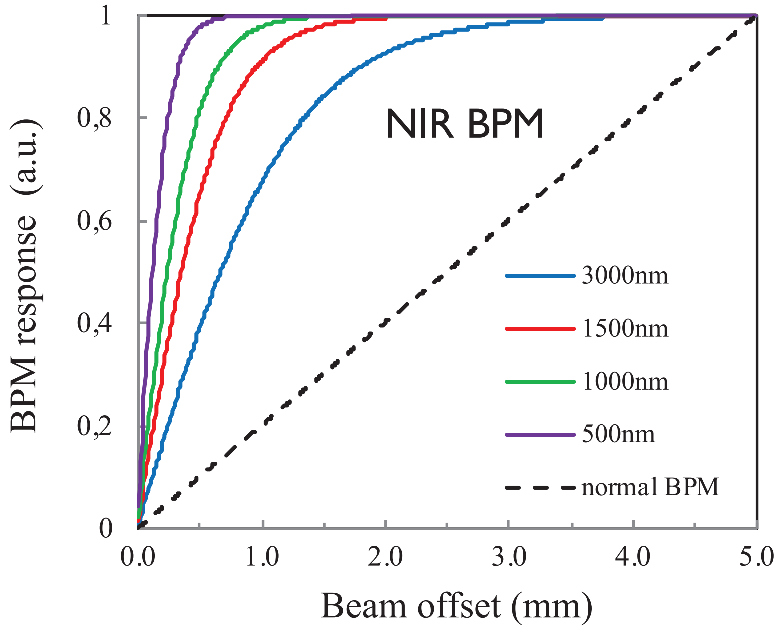
  - *How to optimise such a system i.e. material, shape / length, detection system (visible, NIR, THz, .)*
  - *Impedance calculations started using a code developed at CERN, IW2D by N. Mounet*

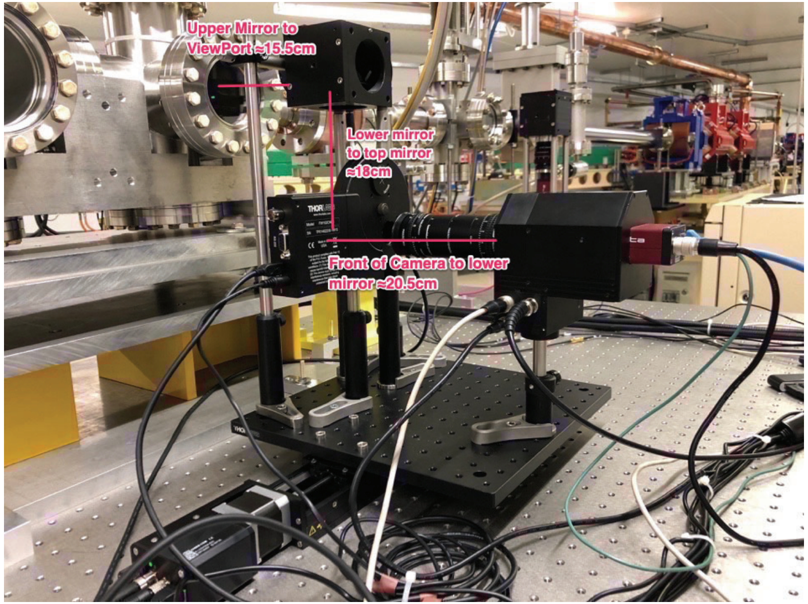
- Coherent and incoherent ChDR would find **applications** for short bunches or highly relativistic particles respectively
  - *Non-invasive transverse profile for high-energy colliders (ILC, CLIC, $FCC_{ee\,/\,hh}$)*
  - *High sensitivity (optical / NIR) beam position monitor for the centering of LHC crystal collimator, for DC beams*
  - *High frequency BPM for AWAKE – Proton driven plasma acceleration at CERN*
  - *Bunch length monitor for short bunches (electrons or protons) : ESS ?*

Incoherent ChDR as a compact BPM for Sync. light sources





Incoherent ChDR studies at Diamond Light Source

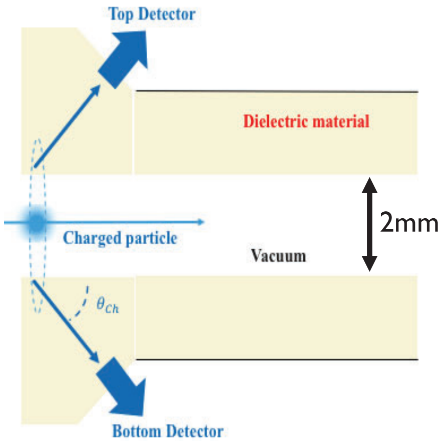


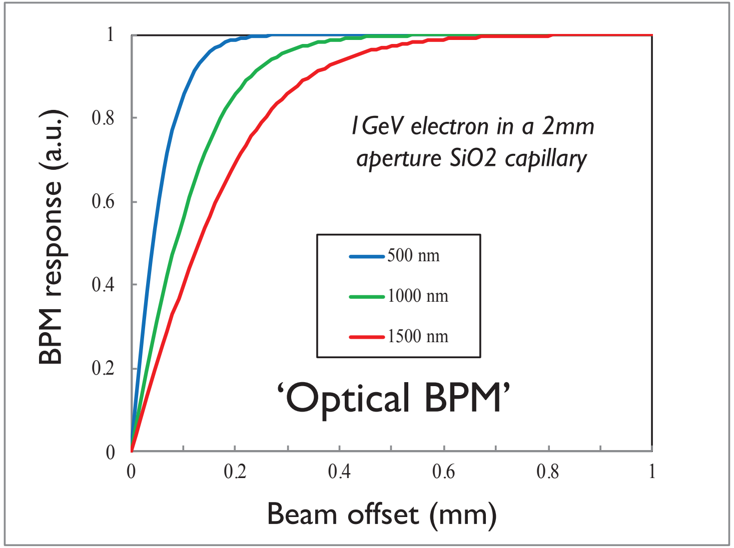
Poster by D. Harryman on Wednesday

Test-stand installed on the transfer line from the booster to main ring

PERSPECTIVES

Very compact BPM for centering beams in dielectric capillaries (Ø < 2mm)



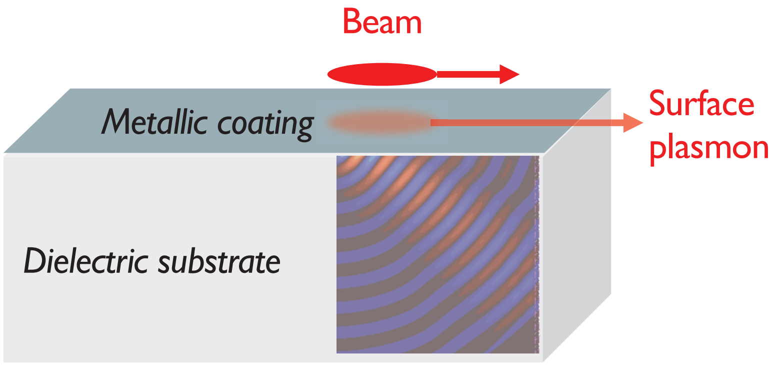


T. Lefevre et al, IPAC 2018, p.2005

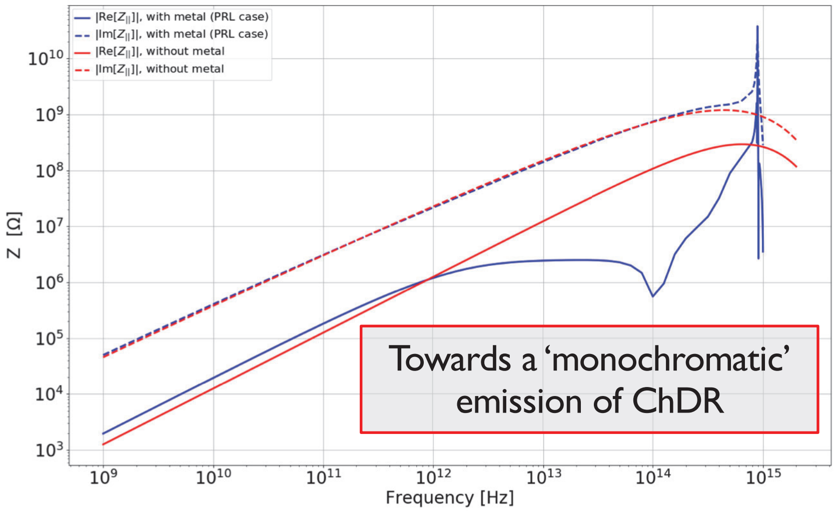
- Dielectric wakefield acceleration
- Plasma lens
- Plasma wakefield acceleration

Similar studies at Tohoku Univ – Talk by K. Nanbu on Wednesday

Can we make use of plasmonic resonance induced in thin metallic layer coated on the dielectric surface ?



IW2D simulations

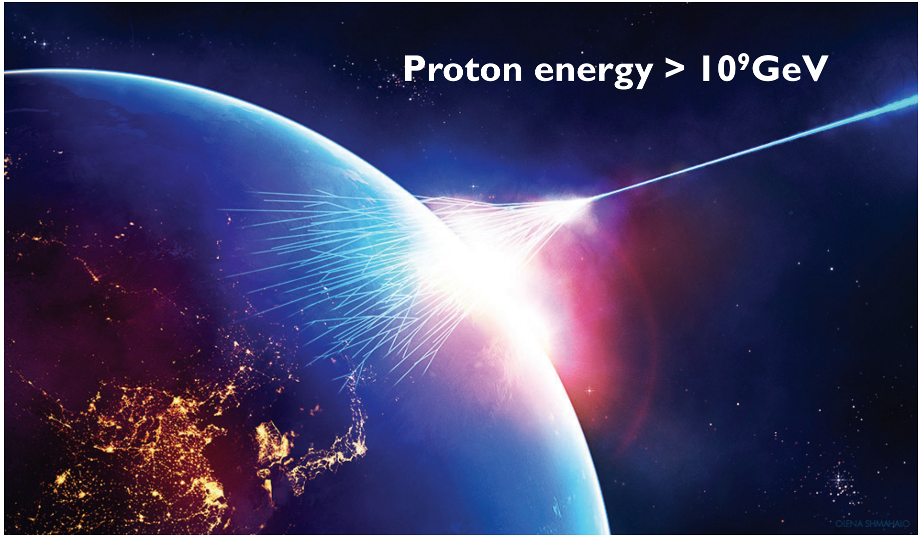


S. Liu et al., "Surface Polariton Cherenkov Light Radiation Source", PRL ***109*** *(2012) 153902*

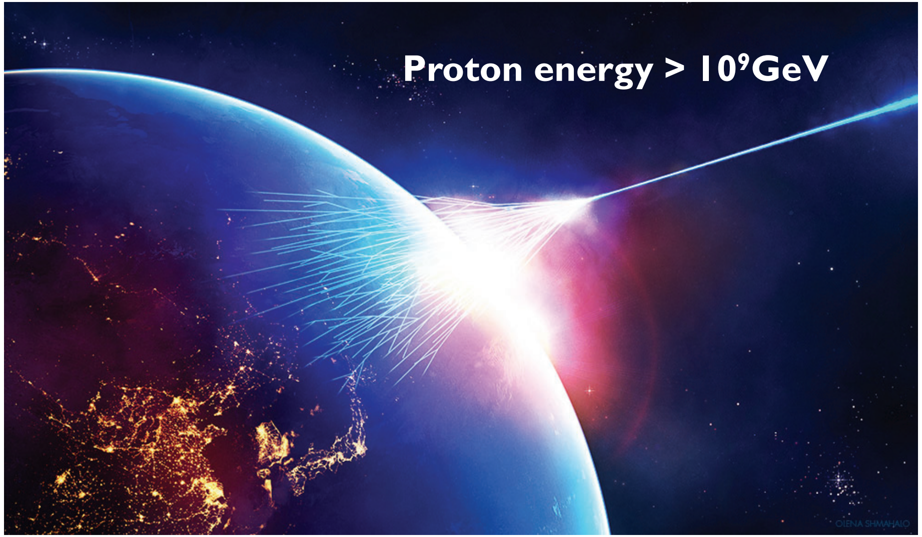
From N. Mounet

PERSPECTIVES

Following the success of Cherenkov radiation in the detection of high energy cosmic rays generating Cherenkov showers ..



Can we measure non-invasively very high energy cosmic rays using optical fibre based ChDR technology ?



Thanks for your attention

D. Alves [1], A. Aryshev[6], M. Bergamaschi[1], V.V. Bleko[3], M. Billing[5], L. Bobb[7], J. Conway[5], A,.Curcio[1], K. Fedorov[2]. J. Gardelle[4], S.Y. Gogolev[3], D. Harryman[2], R.O. Jones[1], R. Kieffer[1], A.S. Konkov[3], P. Karataev[2], K. Lasocha[8], T. Lefevre[1], K. Lekomtsev[2], J.S. Markova[3], S. Mazzoni[1], N. Mounet[1], Y. Padilla Fuentes[5], A.P. Potylitsyn[3], E. Senes[1], A. Schloegelhofer[1], J. Shanks[5], D.A. Shkitov[3], N. Terunuma[6]

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5. Cornell University, Ithaca, USA
6. KEK, High energy Accelerator Organization, Japan
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