Non-invasive beam diagnostic using Cherenkov diffraction radiation

M. Bergamaschi[1], V.V. Bleko[2], M. Billing[3], L. Bobb[4], J. Conway[3], R. Kieffer[1], A.S. Konkov[2] P. Karataev[5], R.O. Jones[1], **T. Lefevre[1]**, J.S. Markova[2], S. Mazzoni[1], Y. Padilla Fuentes[3], A.P. Potylitsyn[2], J. Shanks[3]
1. CERN, Geneva, Switzerland
2. Tomsk Polytechnic University, Tomsk, Russia
3. Cornell University, Ithaca, New York, USA
4. Diamond Light Source, Oxfordshire, United Kingdom
5. John Adams Institute at Royal Holloway, University of London, Egham, United Kingdom

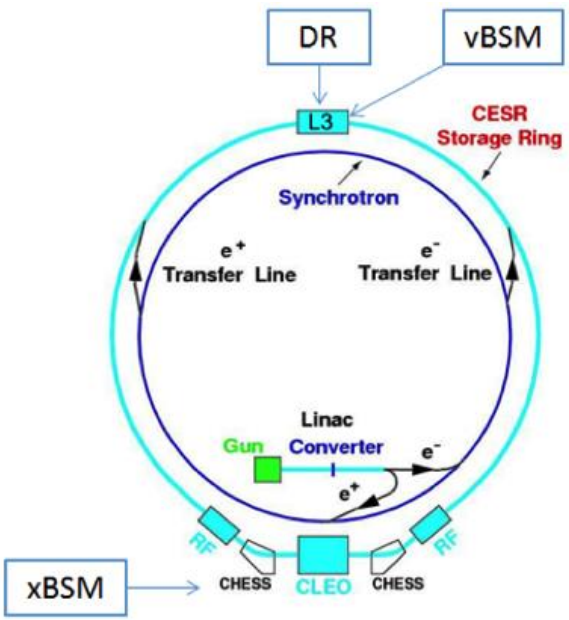
CLIC workshop, 22-26 January 2018, CERN

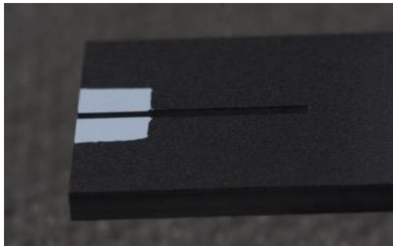
Outline

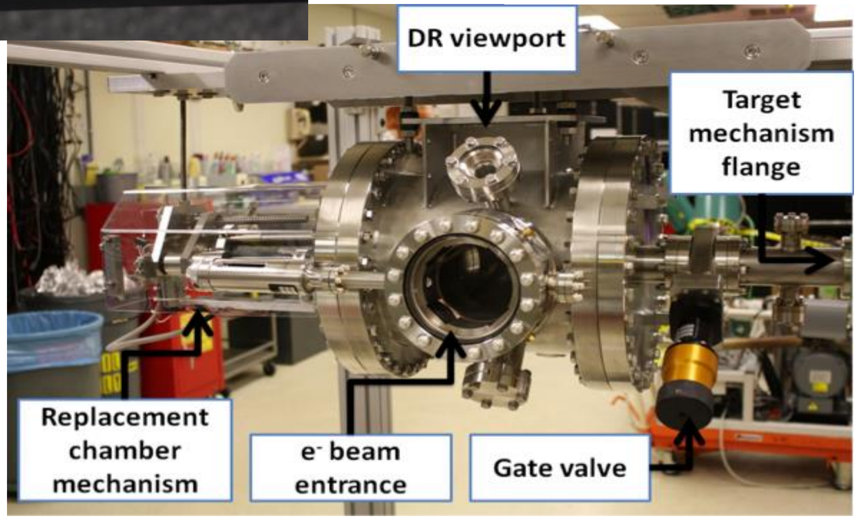
- Development of non-invasive beam size monitor for CLIC
  - From the emission of Diffraction radiation in Slits to Cherenkov Diffraction Radiation (ChDR) in longer dielectric
- Experimental validation of ChDR on CESR in 2017
- Possible applications in the context of novel acceleration techniques

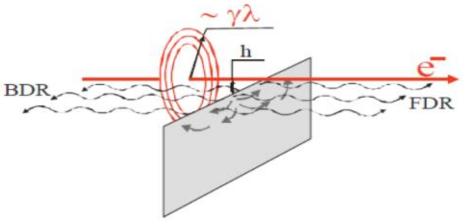
Incoherent Diffraction Radiation on CESR (1/3)

- Experimental program since 2011 at Cornell (electrons@2.1GeV) measuring DR for non-interceptive beam size monitoring using thin (0.5mm aperture) slits



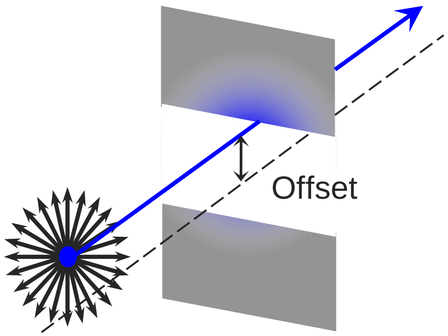


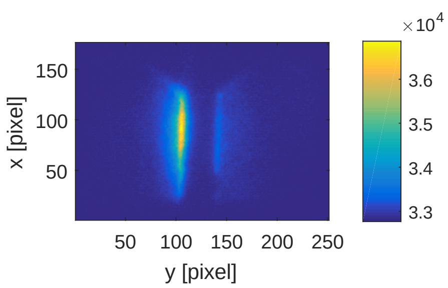




Incoherent Diffraction Radiation on CESR (2/3)

- Imaging the slit for Beam centering
  - The light emitted by each edge of the slit changes depending on the beam centering





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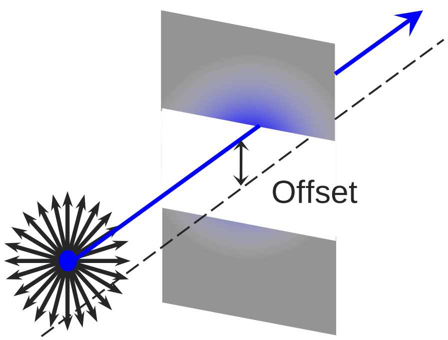
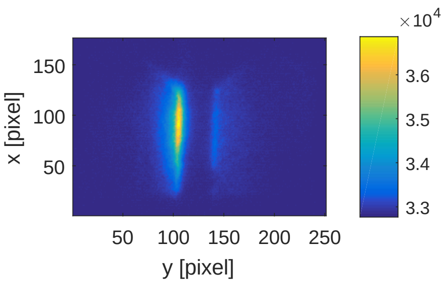
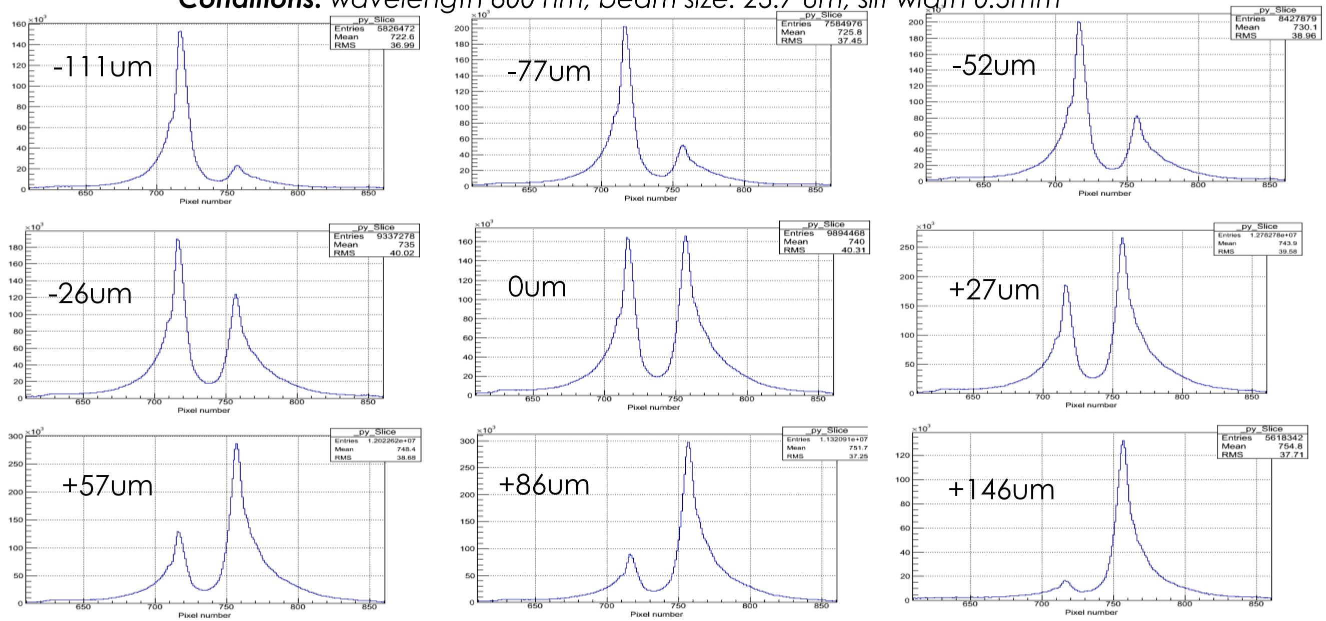




Conditions: *wavelength 600 nm, beam size: 23.7 um, slit width 0.5mm*

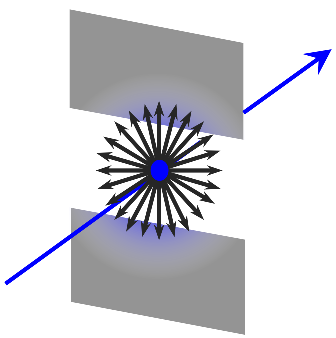


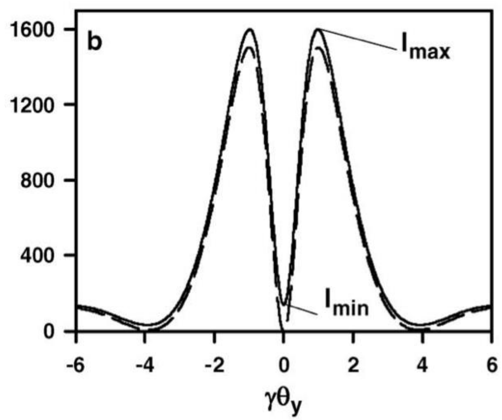
From the profile asymmetry we get **Optical Beam Position Monitor (BPM)** with a sensitivity: 1.52 %/um

T. Lefevre, CLIC workshop 2018, CERN

Incoherent Diffraction Radiation on CESR (3/3)

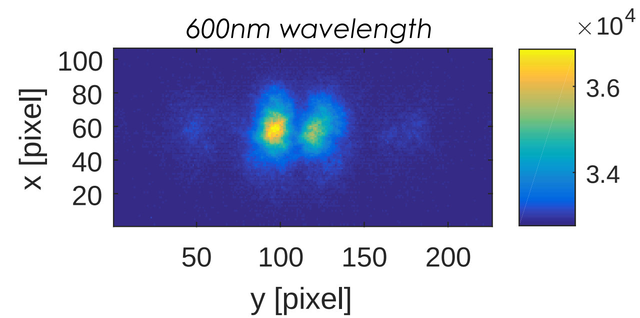
- Measuring the **beam size** from the **visibility I_{min}/I_{max}** of the projected vertical polarization component of the ODR **angular distribution**

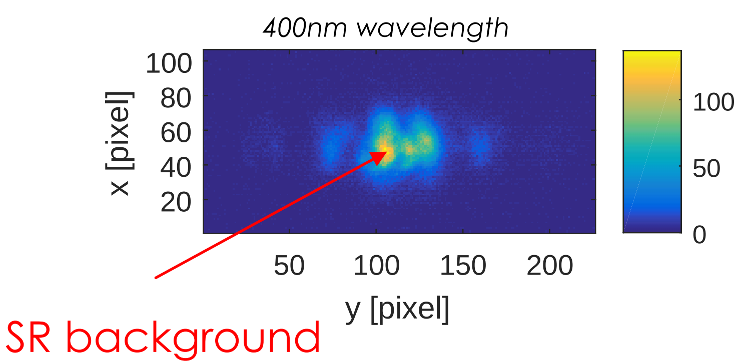




An **horizontal slit** is used to measure a **vertical beam size**.

We use a polarizer to select only the **vertically polarized ODR photons** and 40nm BW **filters** to select the **wavelength**





Motivation to develop Incoherent Cherenkov Diffraction Radiation

- Larger aperture slits
  - Difficult as DR will provide less photons
  - Looking for a physical process providing more photons

- Suppress Synchrotron radiation → cleaner signal
  - DR and SR are emitted at similar angles
  - Looking for a physical process emitted at larger angles

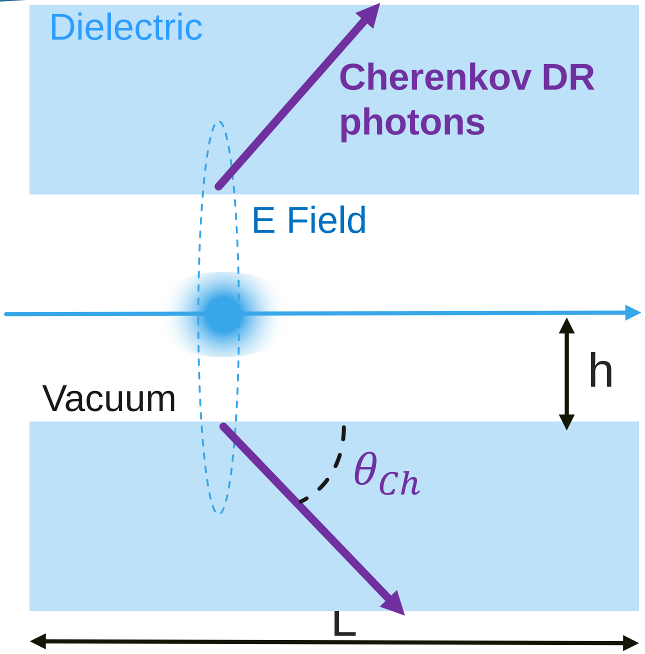
⇨ 'Generating Cherenkov diffraction radiation in longer dielectric'

Incoherent Cherenkov Diffraction Radiation

Incoherent Cherenkov Diffraction Radiation (ChDR)

The electric field of ultra-relativistic charged particles passing in the vicinity of a dielectric radiator produce photons by 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

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

α, fine structure constant
β, normalised beam velocity
γ, beam relativistic factor
θ, angle of observation

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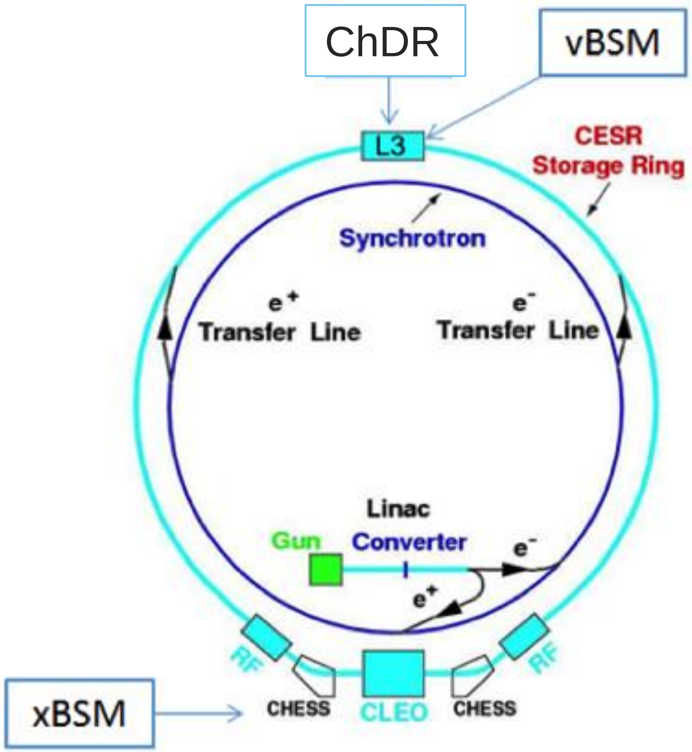
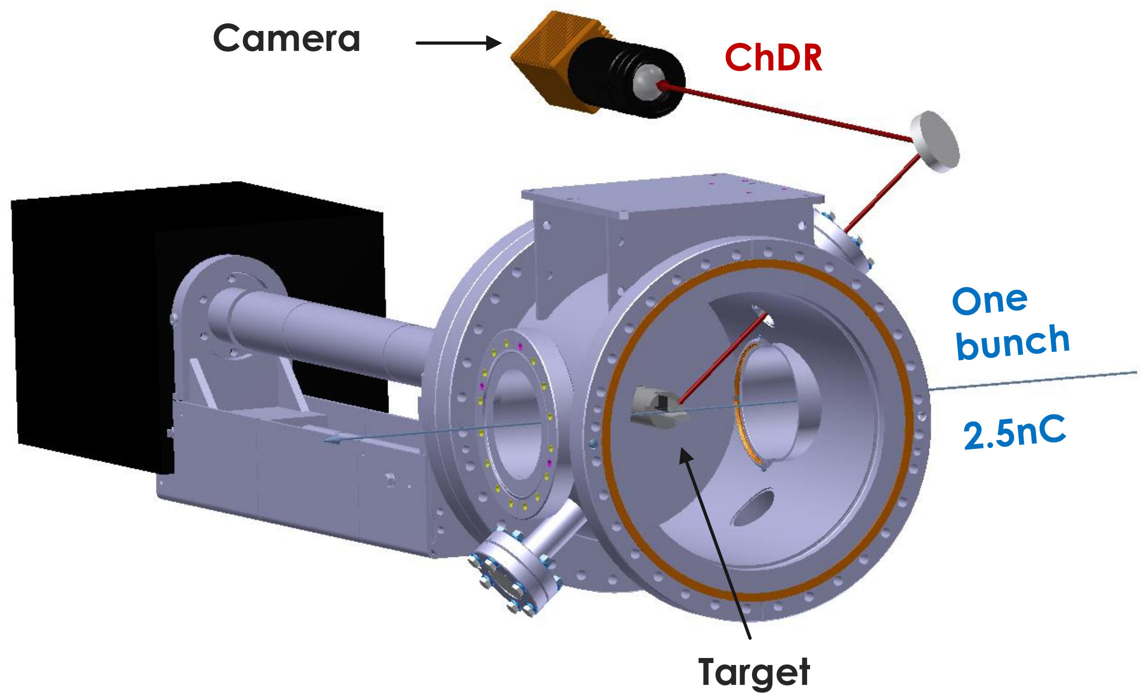
Experimental set-up on CESR (1/3)

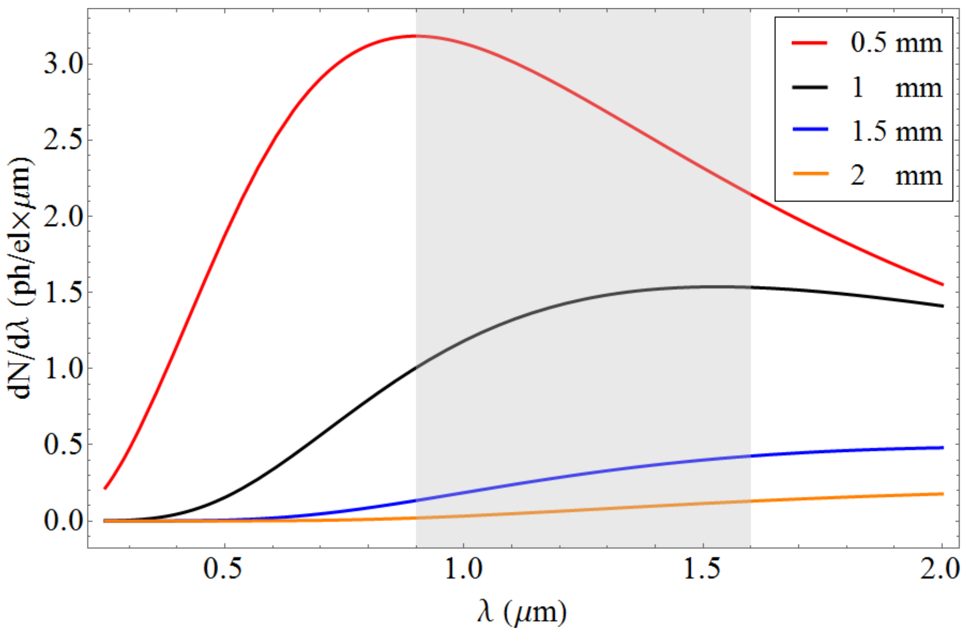
- Re-using the DR vacuum chamber and optical system





Experimental set-up on CESR (2/3)

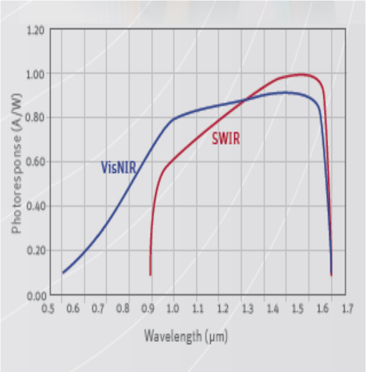
- Design a 2cm long SiO_2 (n=1.46) Cherenkov Diffraction Radiation target
  - Testing with 2.1GeV e^- and measuring in IR (0.9-1.7um) – April 2017



'The red curve as been scaled down by 1/3 for better presentation

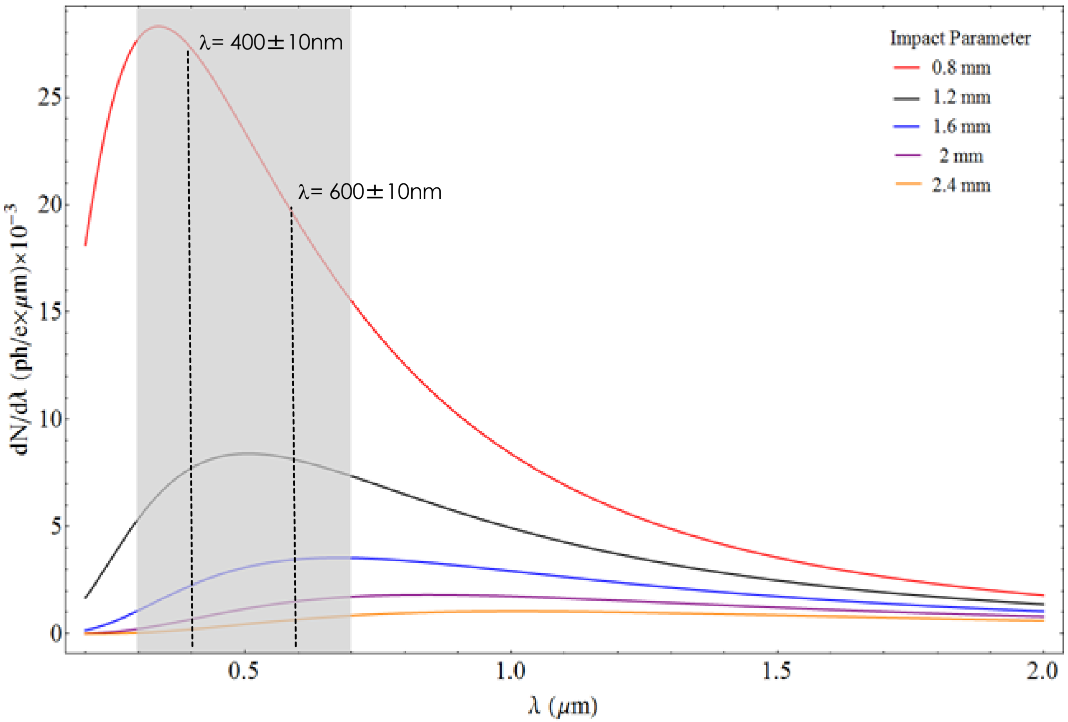
Xenics Bobcat 640 GigE

- Cooled InGaAs 640x512 pixels : 20um pixel pitch
- QE up to 80% at 1.6um
- 14bit ADC
- 1us-40ms integration window

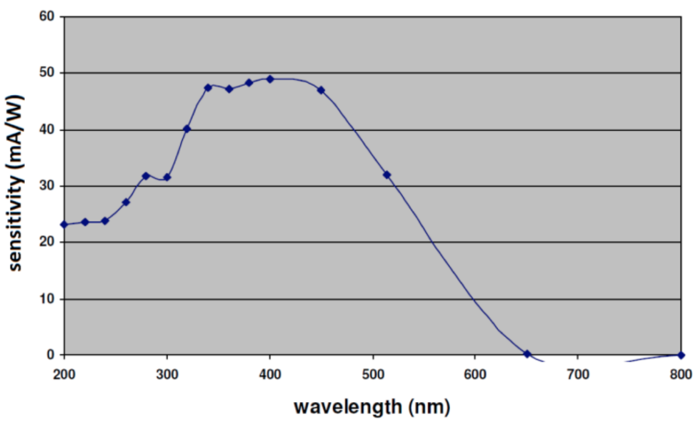


Experimental set-up on CESR (3/3)

- Design a 2cm long SiO_2 (n=1.46) Cherenkov Diffraction Radiation target
  - Testing with 5.3GeV e^- / e^+ and measuring in visible (0.3-0.7um) – October 2017



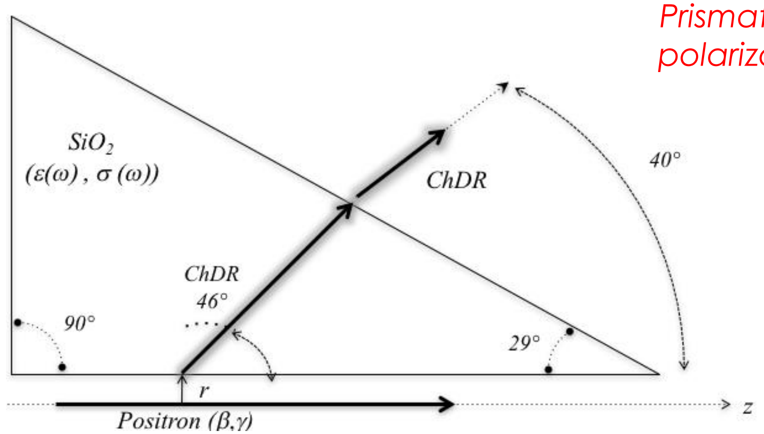
Gated and intensified camera



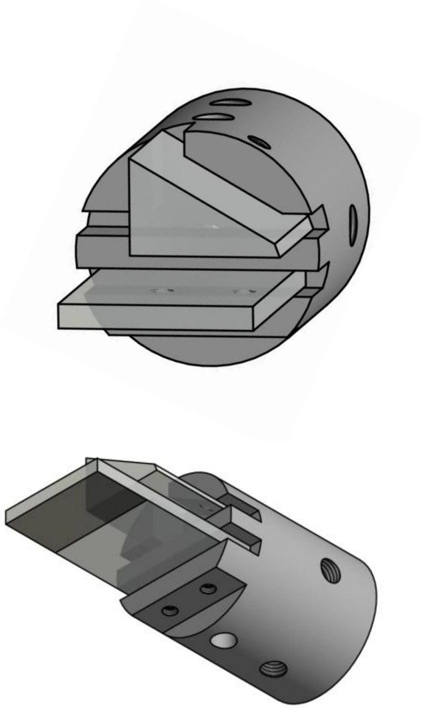
*M.V. Shevelev and A.S. Konkov, JETP **118,** 501 (2014)*

Cherenkov radiators (1/2)

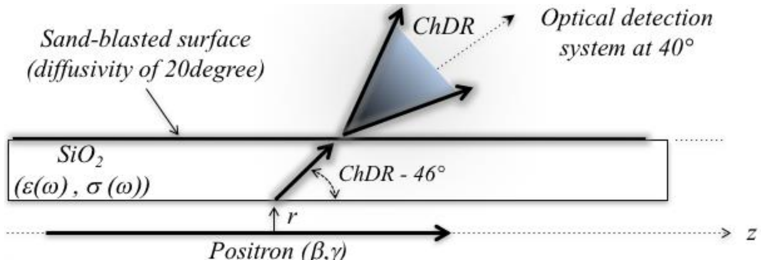
- Two different geometries have been tested
  - **Prismatic radiator**



Prismatic target for polarization studies



  - **Flat radiator** (simpler and cheaper)



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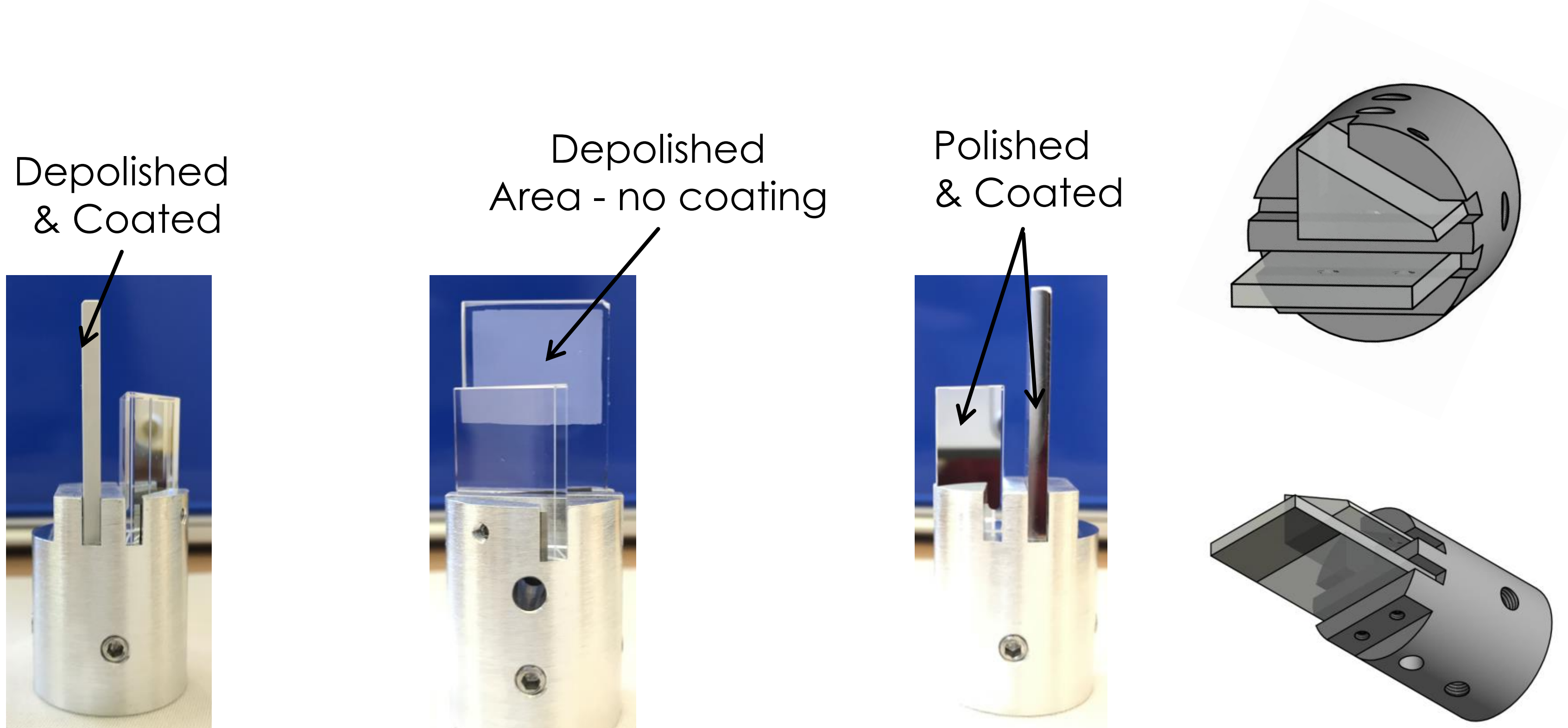
Cherenkov radiators (2/2)

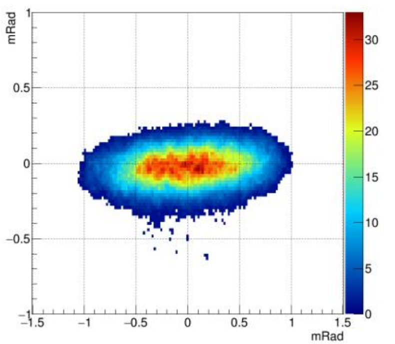
- Pictures of the radiators

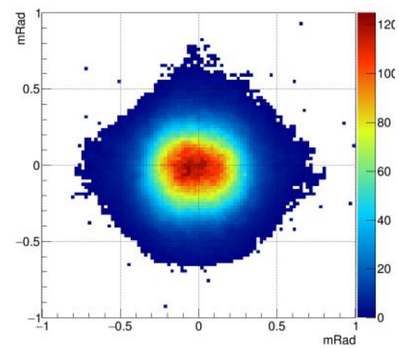


Experimental data : Positron at 5.3GeV

- Angular distributions with Prismatic radiator : Comparison with simulations

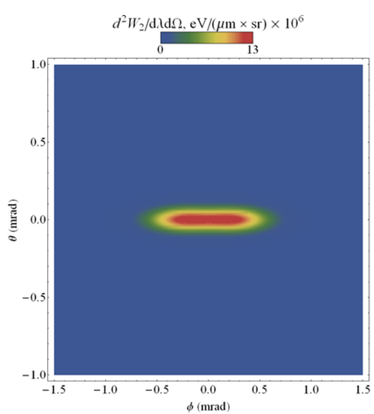
Horizontal polarization | *Vertical polarization*

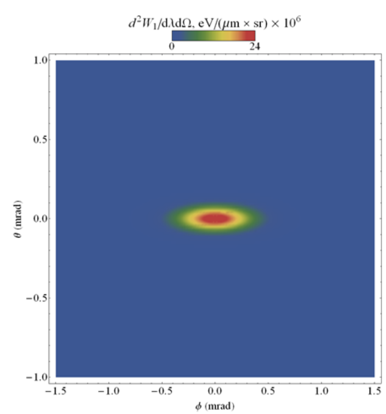




Measurements

Ang. divergence: ±200urad





Simulations

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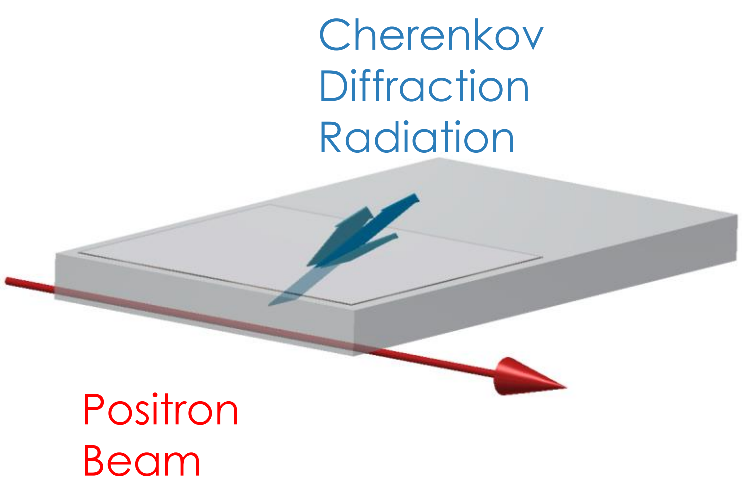
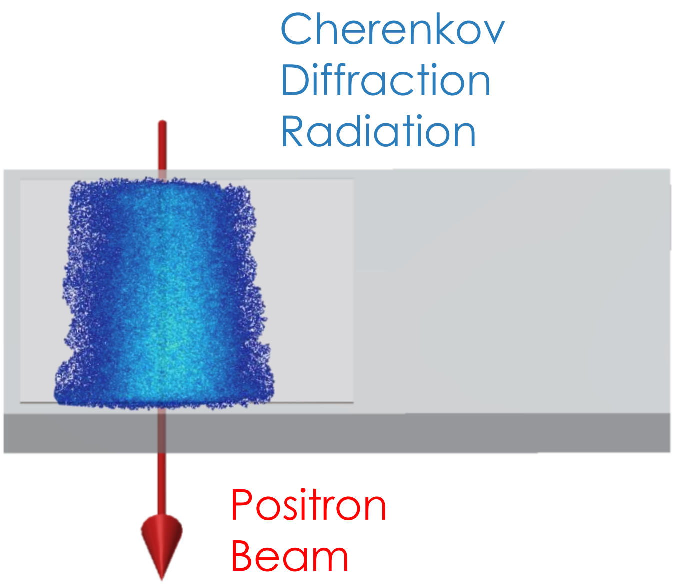
Experimental data : Positron at 5.3GeV

- Imaging the Flat radiator (diffusive coating to extract the photons out of the target)





'Cherenkov photons emitted all along the target surface'

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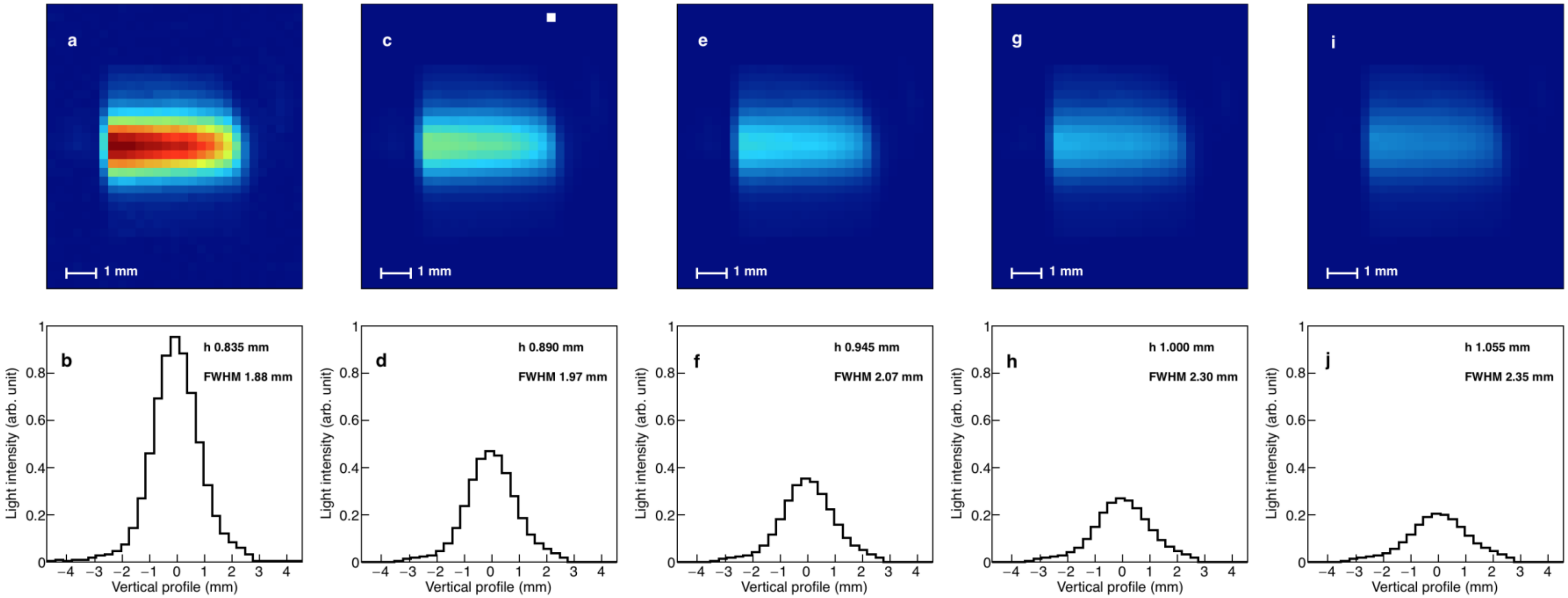
Experimental data : Electron at 2.1GeV

- Steering the beam vertically
  - No wavelength filter – no polarizer



‘Cherenkov photons yield increasing strongly for smaller impact parameter’

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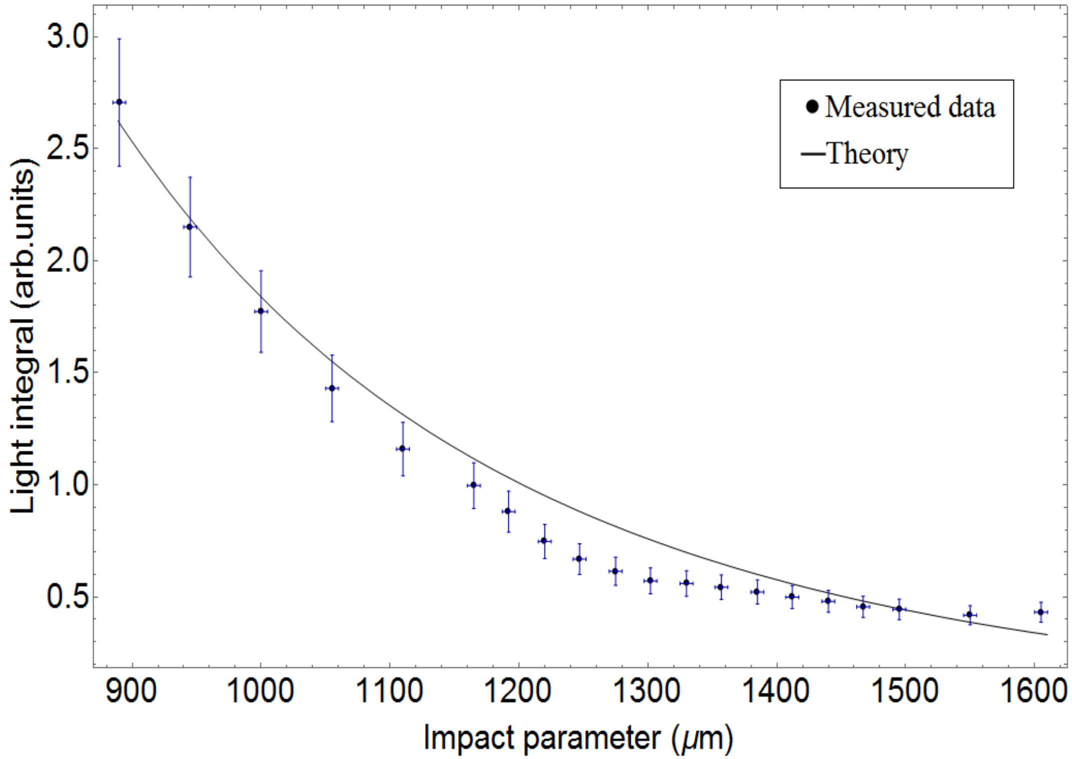
Experimental data : Electron at 2.1GeV

- Steering the beam vertically : comparison with simulations

No wavelength filter – No polarizer



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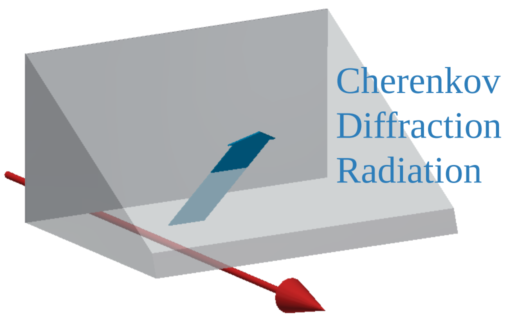
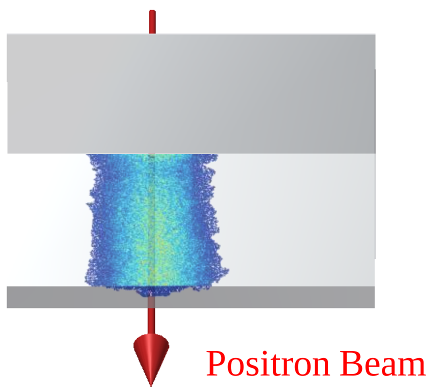
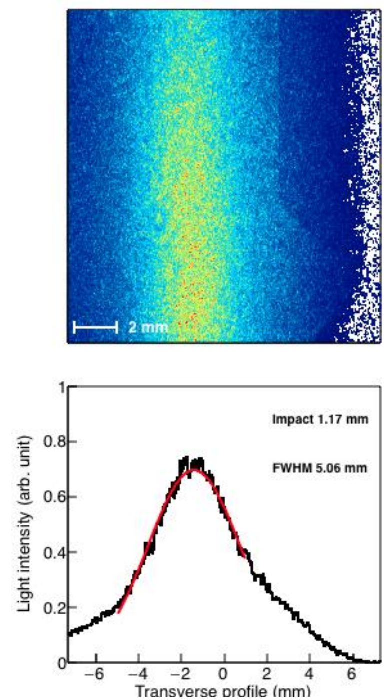
Experimental data : Positron at 5.3GeV

- Measuring the horizontal Beam size :

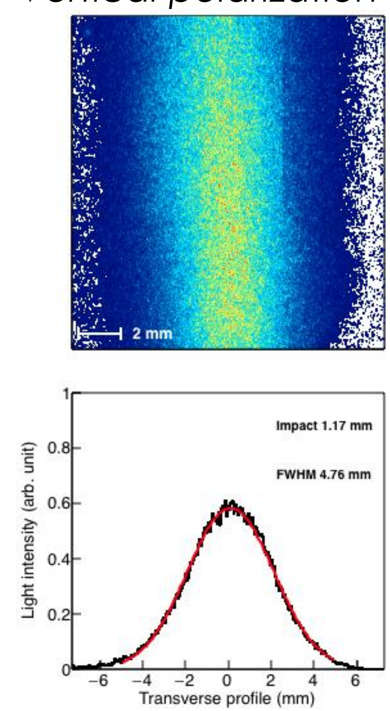




Horizontal polarization



Vertical polarization



‘Vertically polarized photons give the best spatial resolution (here for σ_y=2mm)
Expected resolution should be much better – possibly microns’

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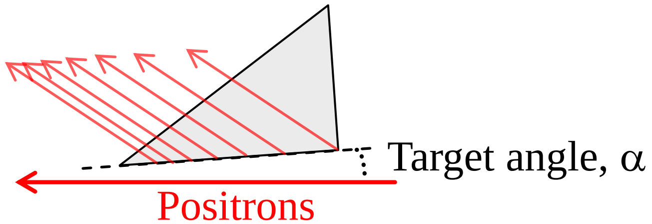
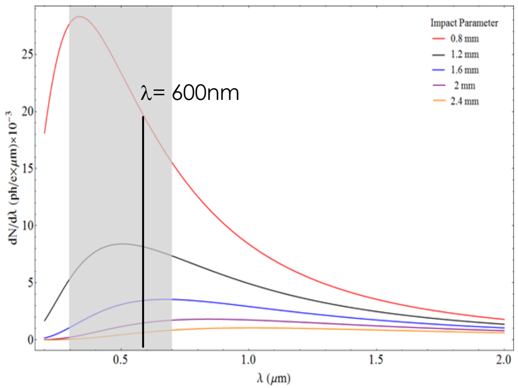
Experimental data : Positron at 5.3GeV

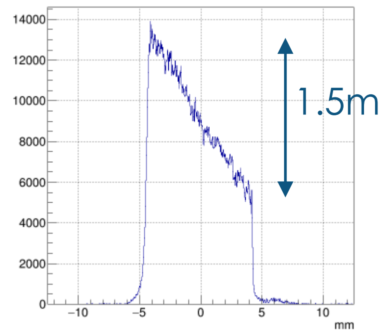
- Rotating the target :



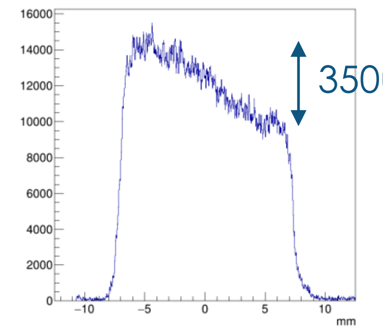


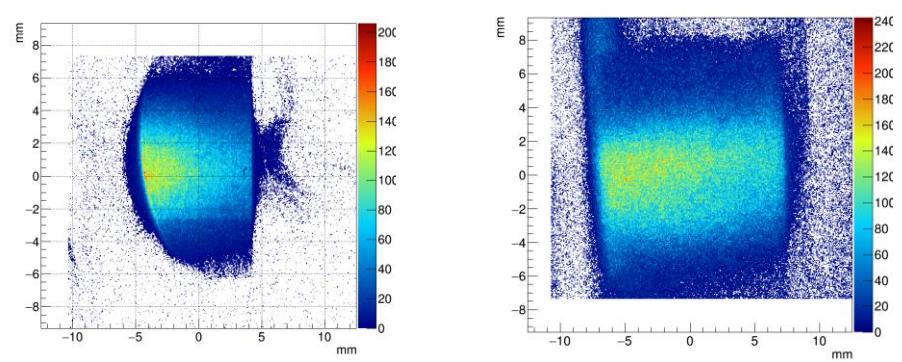
ChDR @600±10nm ; h_{mean} = 1.5mm

α = 4.28 deg (74mrad)



α = 0.98 deg (17mrad)





'Measuring the Beam tilt angle with respect to the surface of dielectric as the light intensity strongly depends on the impact parameter'

T. Lefevre, CLIC workshop 2018, CERN

Applications to new accelerating techniques

nature COMMUNICATIONS

ARTICLE

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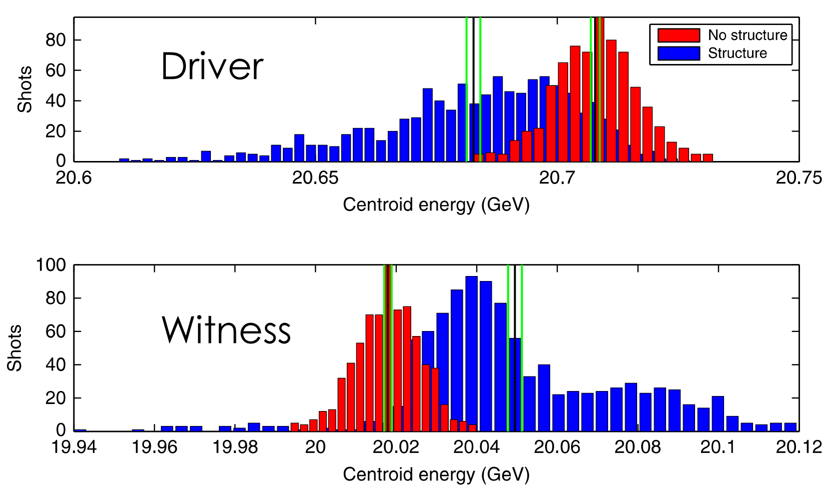
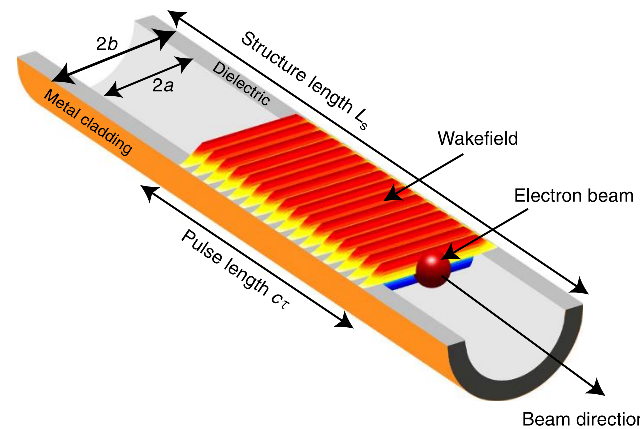
Observation of acceleration and deceleration in gigaelectron-volt-per-metre gradient dielectric wakefield accelerators

B.D. O'Shea[1,2], G. Andonian[1], S.K. Barber[1], K.L. Fitzmorris[1], S. Hakimi[1], J. Harrison[1], P.D. Hoang[1], M.J. Hogan[2], B. Naranjo[1], O.B. Williams[1], V. Yakimenko[2] & J.B. Rosenzweig[1]





SiO_2 - 15cm long dielectric

Outer diameter : 2b-400um

Inner diameter : 2a-300um

Beam size 30um

Bunch length 25um (W) and 55um (D)

Δt (D-W) = 250um – 833fs

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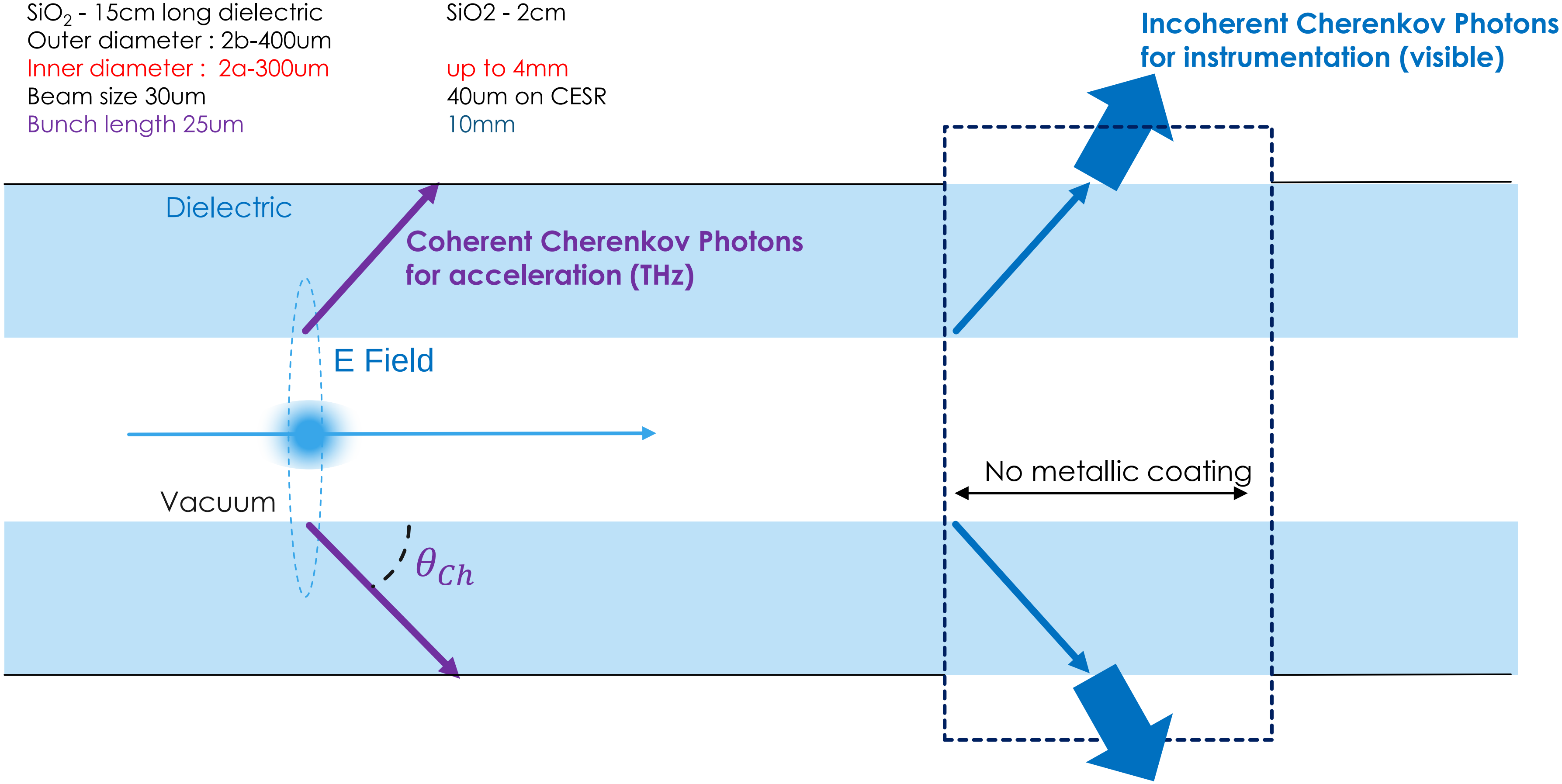
Applications to new accelerating techniques

SLAC/Facet	CESR
SiO_2 - 15cm long dielectric	SiO2 - 2cm
Outer diameter : 2b-400um	
Inner diameter : 2a-300um	up to 4mm
Beam size 30um	40um on CESR
Bunch length 25um	10mm



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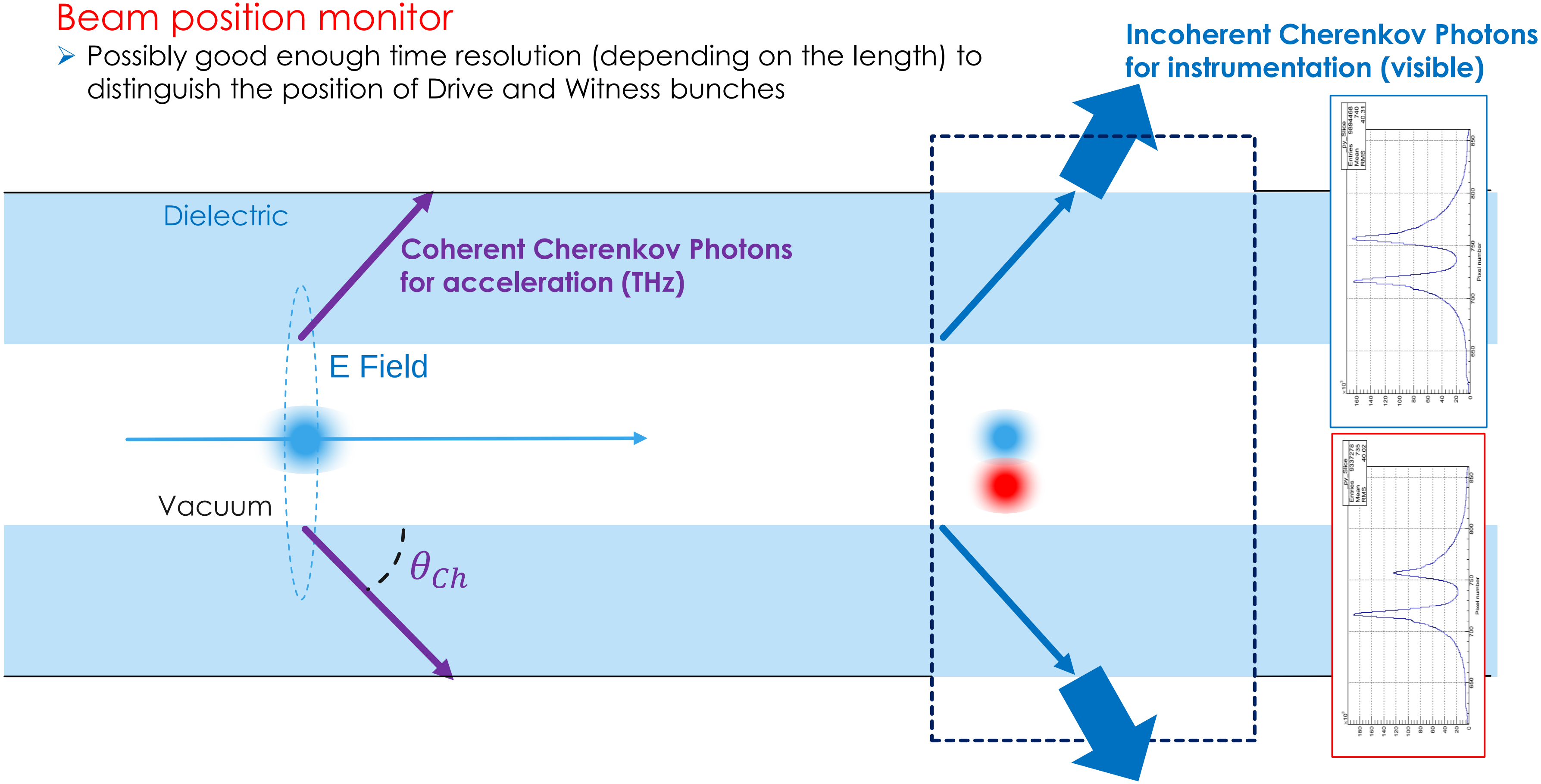
Applications to new accelerating techniques

Beam position monitor

- Possibly good enough time resolution (depending on the length) to distinguish the position of Drive and Witness bunches



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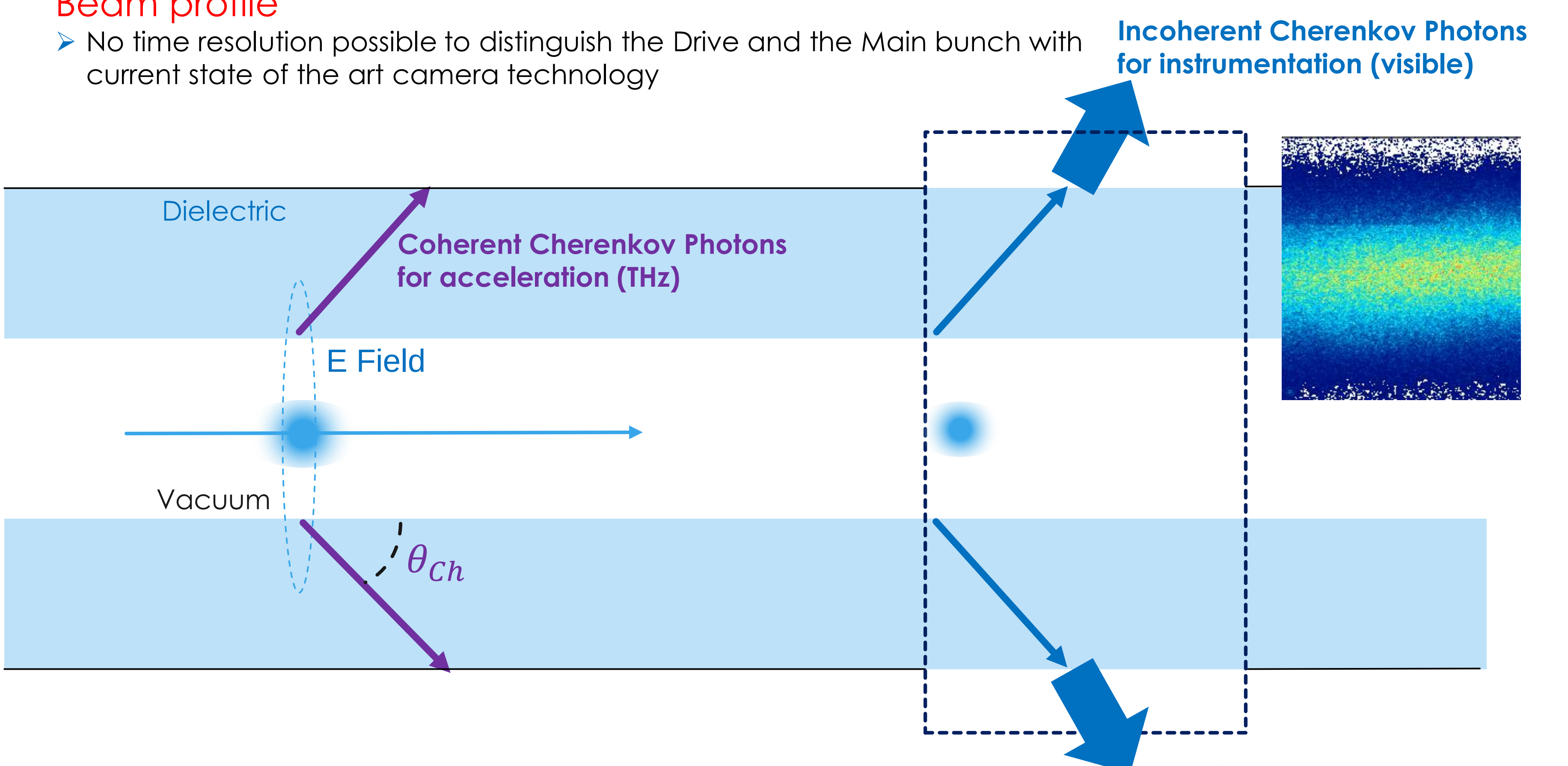
Applications to new accelerating techniques

Beam profile

- No time resolution possible to distinguish the Drive and the Main bunch with current state of the art camera technology



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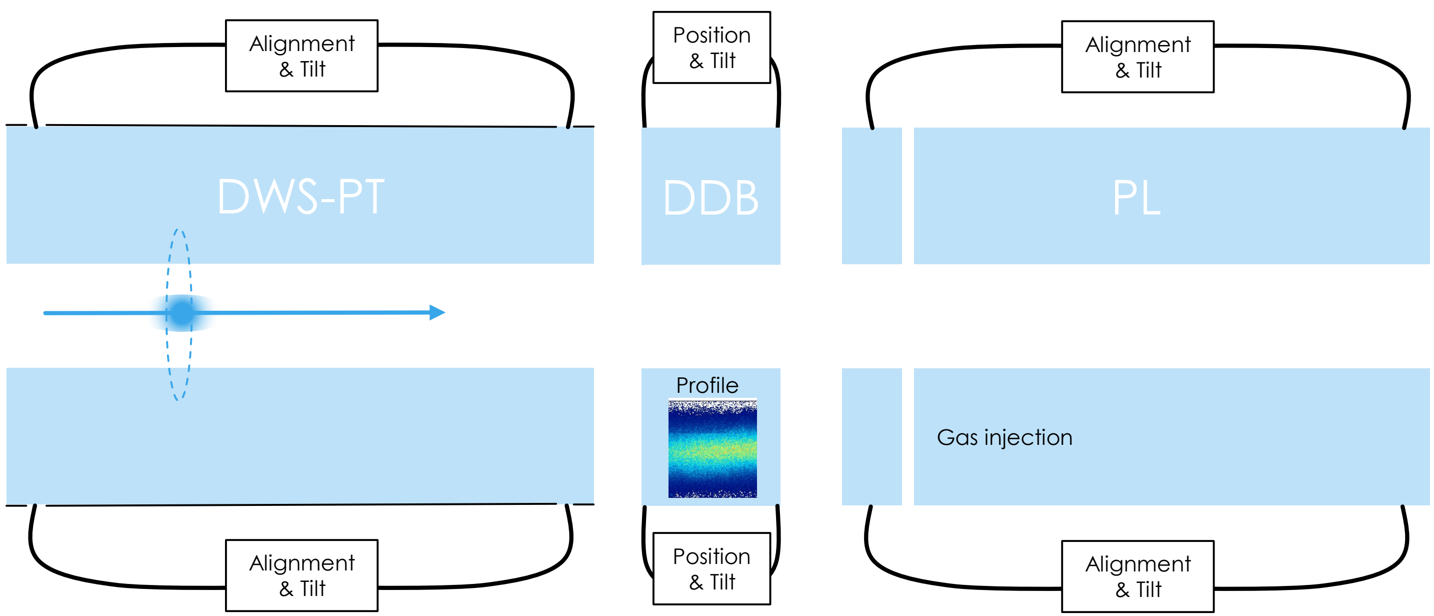
Applications to new accelerating techniques

➢ Dielectric based components: Acceleration – Diagnostic - Focusing



DWS-PT = Dielectric Wakefield Structure with Position and tilt diagnostics
DDB = Dielectric Diagnostic Box for beam position, tilt and profile measurements
PL = Plasma lens with position and tilt diagnostics

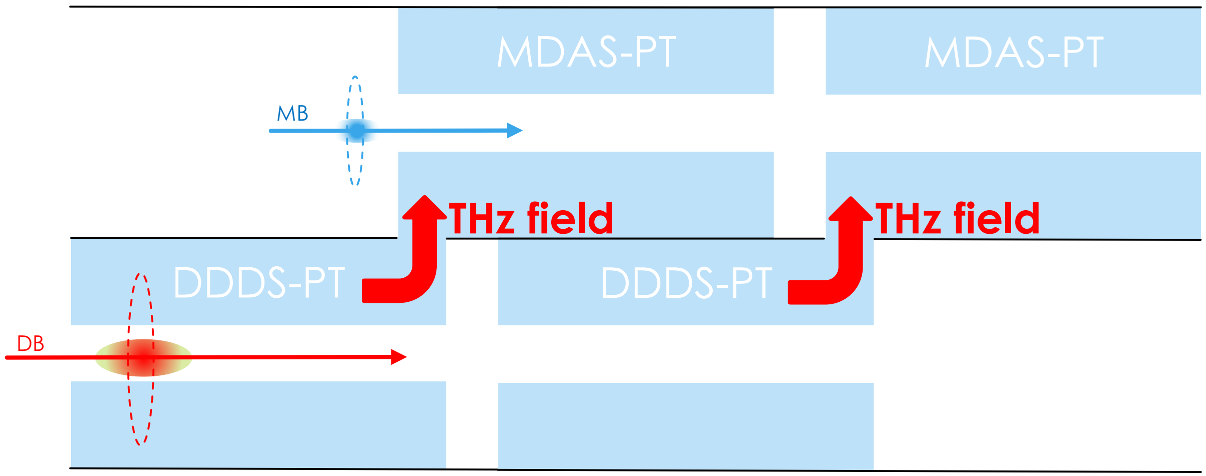
Can we regroup all functionalities in a long dielectric structure ?

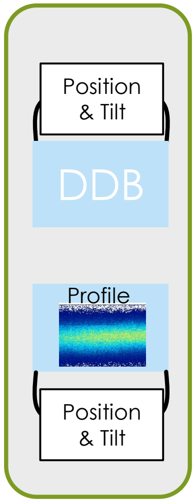
Applications to new accelerating techniques

- Challenge to identify the Drive and the Main bunches in the same capillary
- For high energy applications – after which distance do we need to get fresh drive bunches and how do we get rid of it ?

Applications to new accelerating techniques

- Dielectric acceleration with different capillaries for drive and main bunches





Diagnostic boxes on each beam

MDAS-PT = MB Dielectric accelerating Structure with Position and tilt diagnostic
DDDS-PT = DB Dielectric Decelerating Structure

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Conclusions

- Incoherent Cherenkov Diffraction Radiation looks promising for Beam diagnostic applications

- After the tests at CESR, several beam tests to continue the R&D are prepared at CERN/CLEAR and also at KEK/ATF2 and Diamond.

- Some synergies with hardware & technologies used for dielectric acceleration and plasma lenses (possibly plasma acceleration in capillary)
  - Having two beams in the same structure makes diagnostics difficult
  - If using very short bunches (1fs and shorter), then the radiation becomes coherent in the visible range and ChDR cannot be used anymore for beam profile measurements

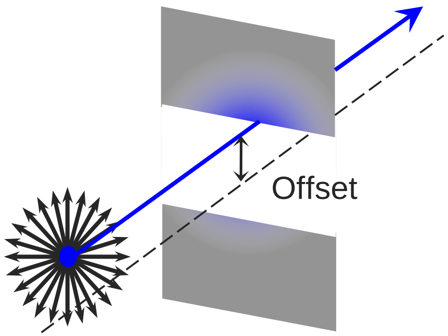
Thanks for your attention

M. Bergamaschi[1], V.V. Bleko[2], M. Billing[3], L. Bobb[4], J. Conway[3], R. Kieffer[1], A.S. Konkov[2] P. Karataev[5], R.O. Jones[1], T. Lefevre[1], J.S. Markova[2], S. Mazzoni[1], Y. Padilla Fuentes[3], A.P. Potylitsyn[2], J. Shanks[3]

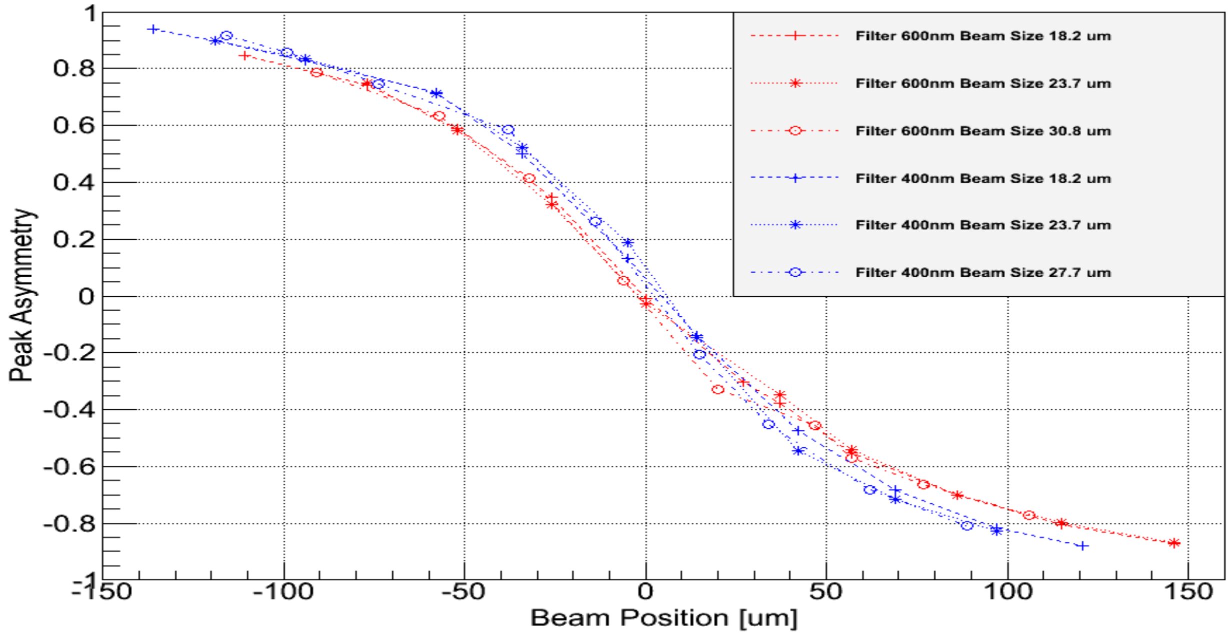
1. CERN, Geneva, Switzerland
2. Tomsk Polytechnic University, Tomsk, Russia
3. Cornell University, Ithaca, New York, USA
4. Diamond Light Source, Oxfordshire, United Kingdom
5. John Adams Institute at Royal Holloway, University of London, Egham, United Kingdom

Incoherent Diffraction Radiation on CESR (4/6)

- Steering the beam through the slit



Conditions: *wavelength 400/600 nm, beam size: 16.2/23.7 um, slit width 0.5mm*

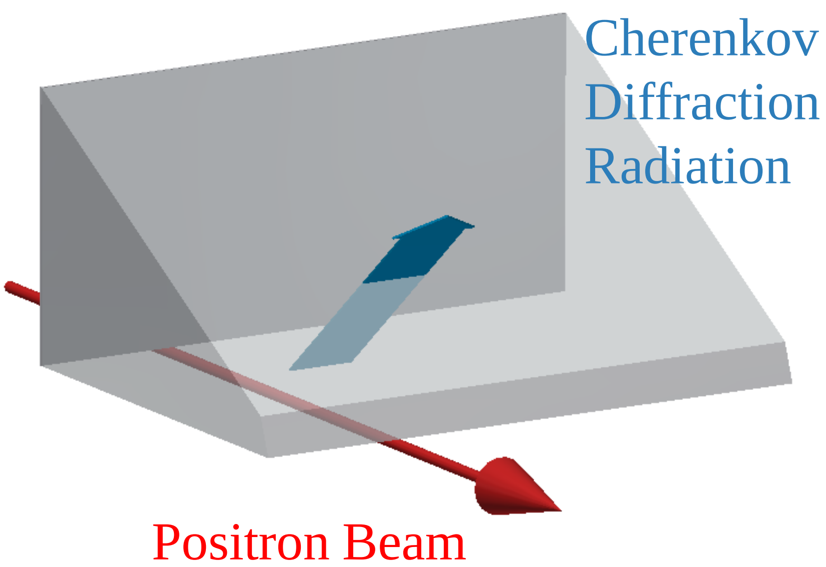


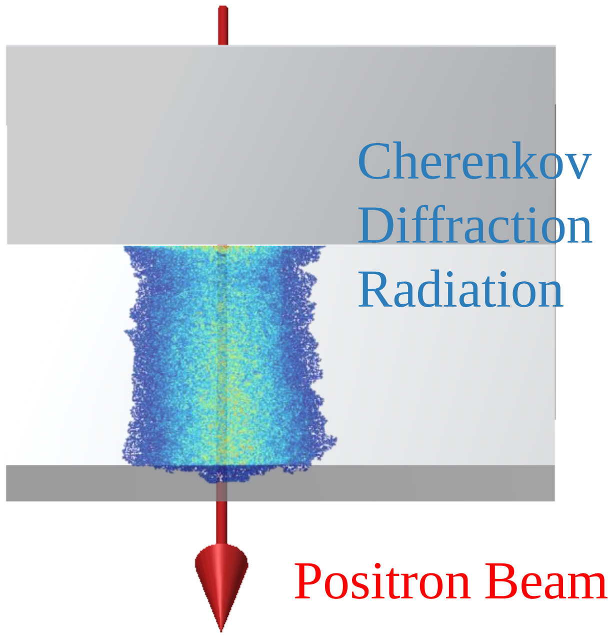
Different sensitivity depending on the wavelength

T. Lefevre, LER 2018, CERN

Experimental data : Positron at 5.3GeV

- Imaging the prismatic target at wavelength of 600±10nm

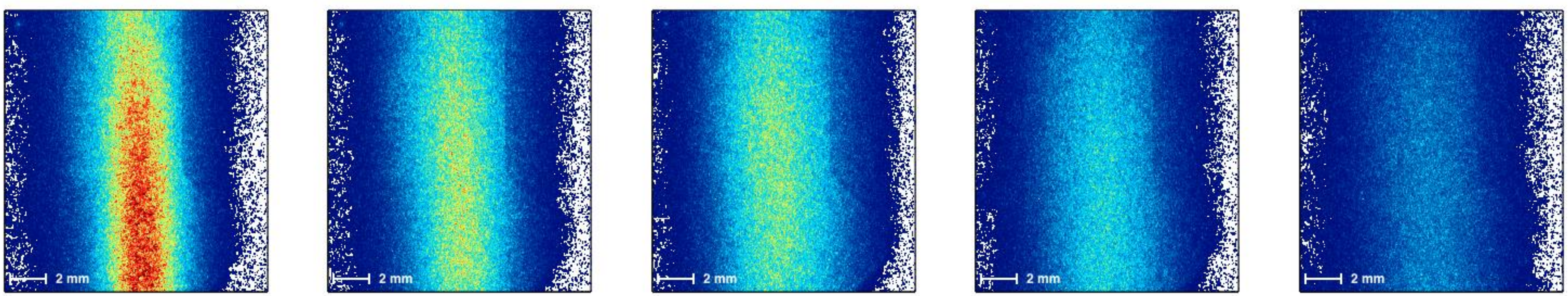




Experimental data : Positron at 5.3GeV

- Steering the beam vertically
  - Wavelength 600±10nm
  - Vertical Polarization component

h= 0.96mm 1.17mm 1.52mm 2.09mm 2.43mm

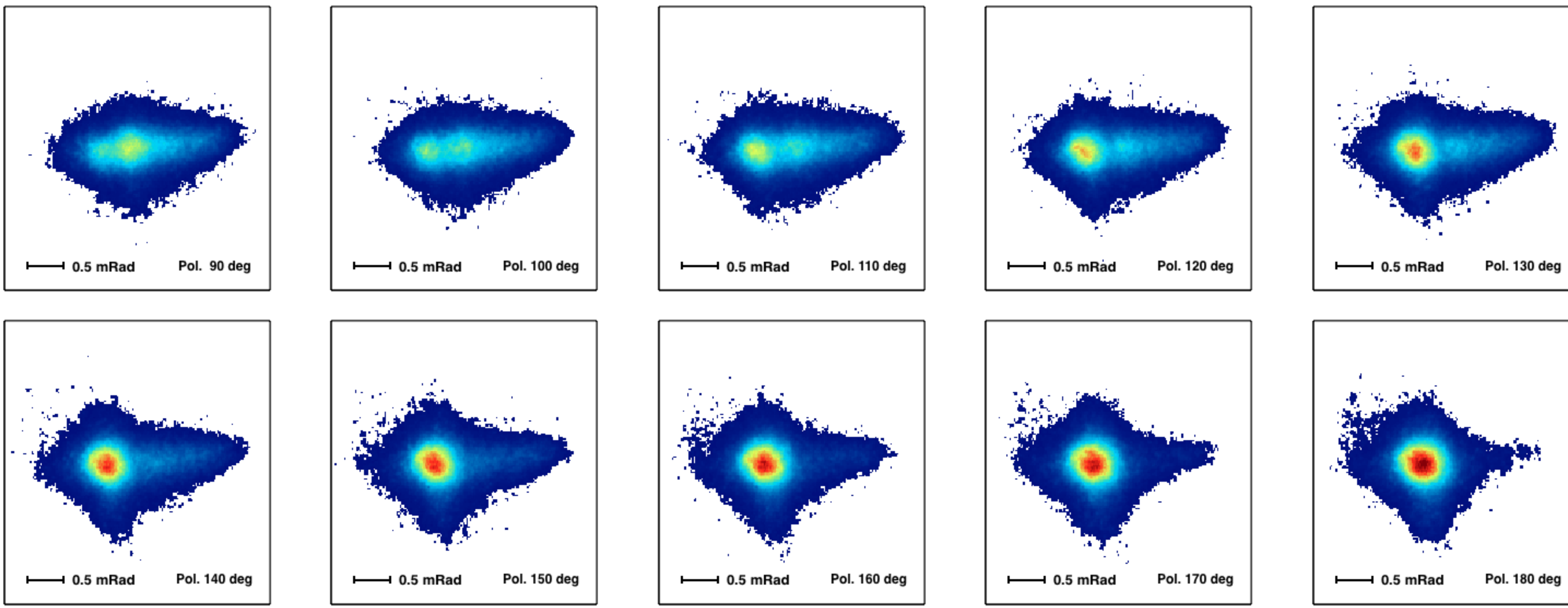


Cherenkov photons yield increasing strongly for smaller impact parameter

Experimental data : Positron at 5.3GeV

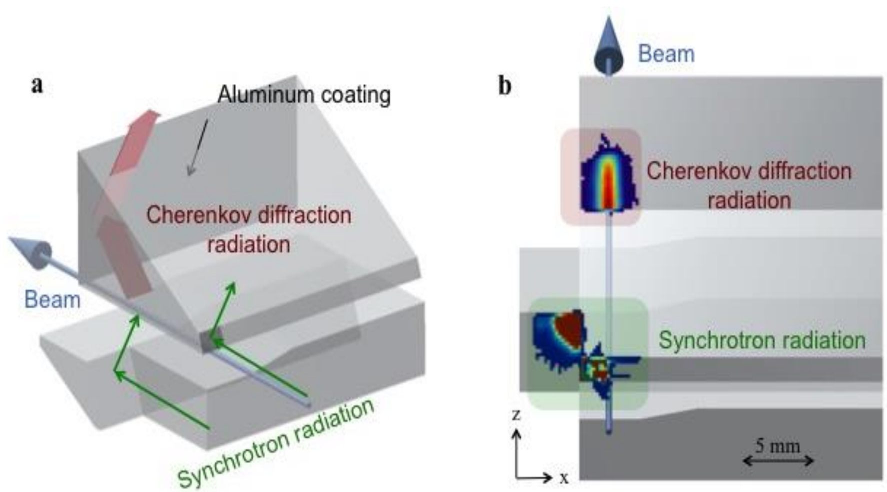
- Prismatic target : Angular distribution and polarization study

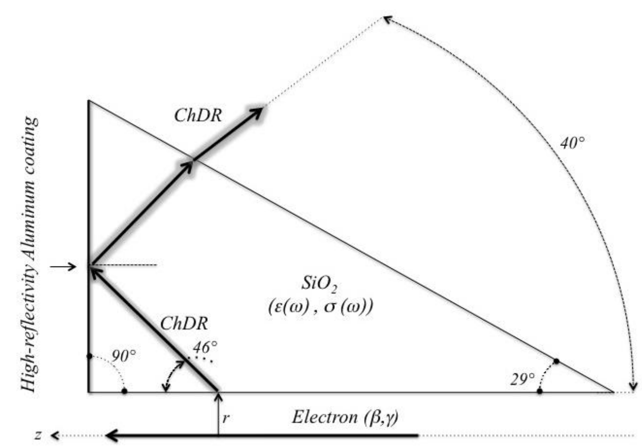
Impact parameter fixed , 600±10nm wavelength, Polarization Scan



Experimental data : electron at 2.1GeV

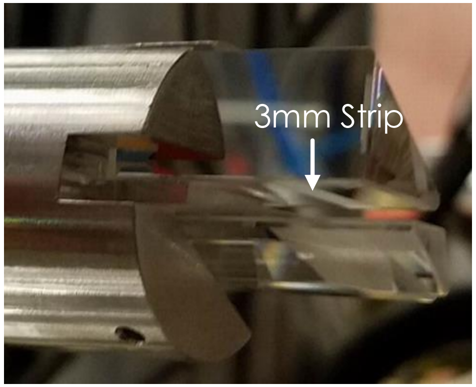
- Prismatic target for the detection of electrons



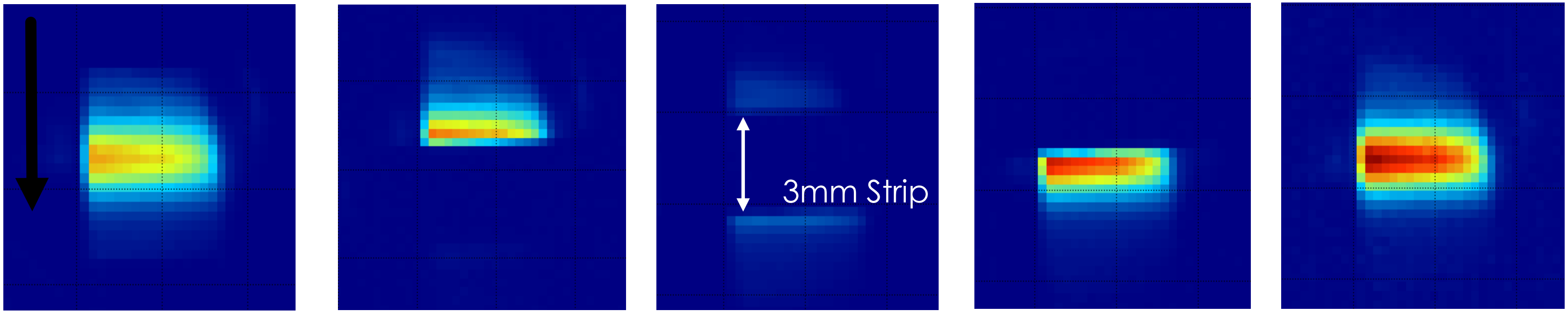


Experimental data : electron at 2.1GeV

- Optically polished ChDR target insertion passing over a 3mm de-polished strip on the surface.
- Diffusive surface =>We loose the highly directional ChDR emission.

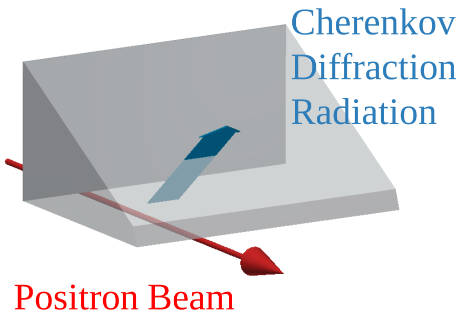


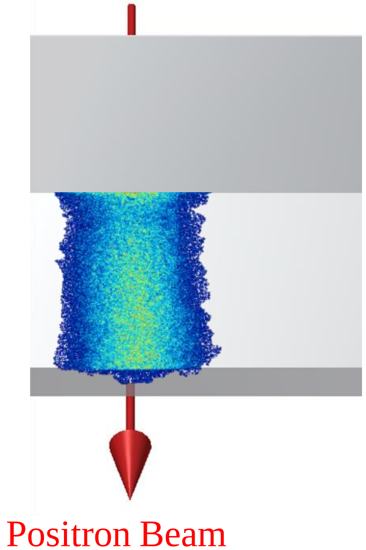
Target Movement



Experimental data : Measuring counter-propagating beams

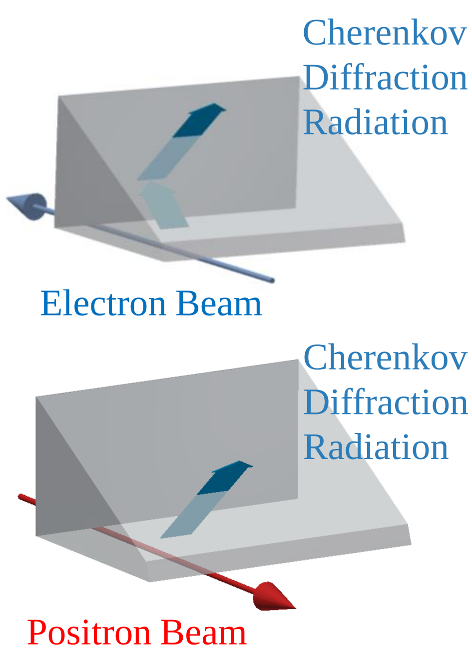
- Imaging both beams with the prismatic target

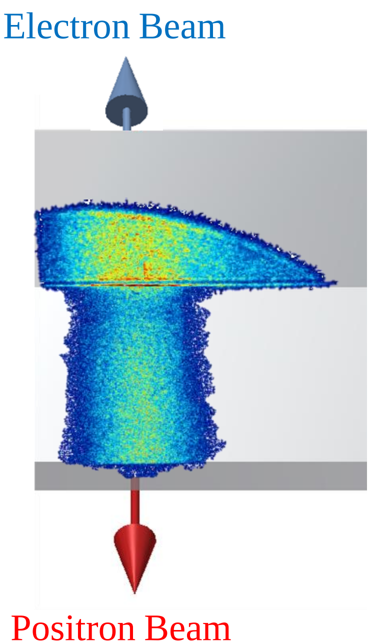




Experimental data : Measuring counter-propagating beams

- Imaging both beams with the prismatic target





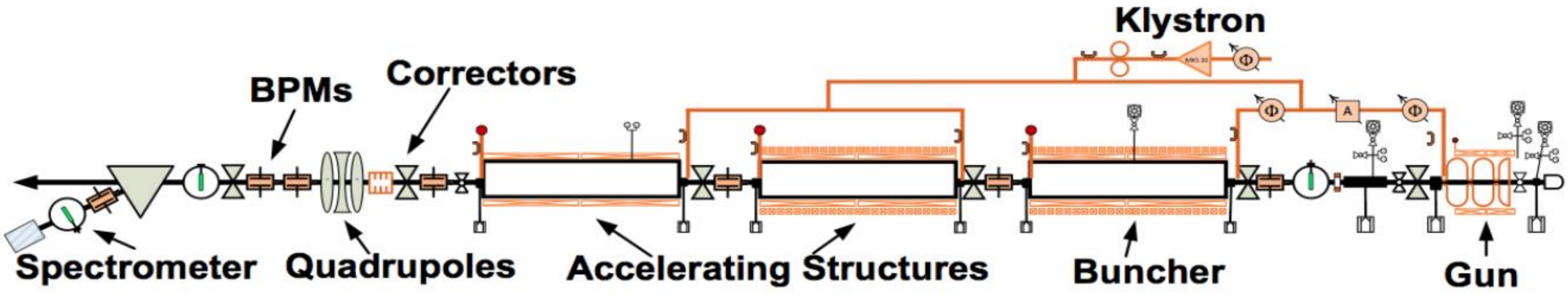
Images from e^- is truncated due to the limited aperture of the current detection system

The photons produced by electrons and positrons appear on a different part of the target and give the possibility to high directivity beam measurements (measured more than 60dB)

T. Lefevre, LER 2018, CERN

ChDR measurements at CERN

- Previously named CTF3-**CALIFES**, the new CERN electron beam test facility **CLEAR** is being commissioned at present.
- Beam: **130-220MeV** electrons
- **Up to 0.5nC per bunch**, trains available 1-100 bunches.
- CLEAR Proposal online: https://clear.web.cern.ch/sites/clear.web.cern.ch/files/documents/CLEAR_proposal.pdf

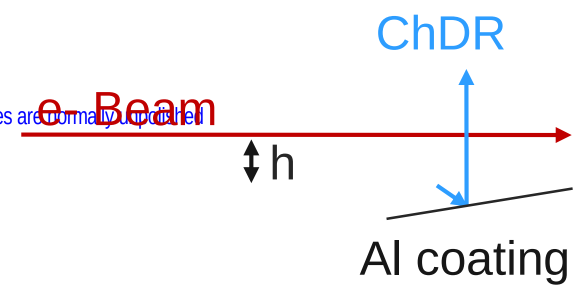


End of 2017 two **ChDR** experiments foreseen, in the infrared range:

1. Under vacuum, using **CVD diamond** radiator.
2. In-air, using crystalline **silicon** radiator.

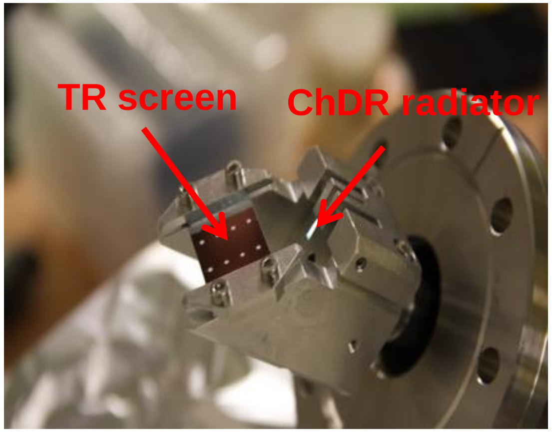
1. Diamond ChDR on CLEAR at CERN

CVD diamond radiator under vacuum.
<u>Goal:</u> Comparison between OTR, Cherenkov, and ChDR light emission.



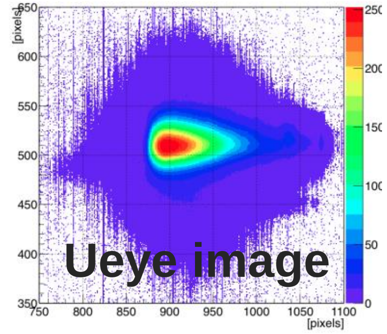
<u>Already tested cameras on that setup:</u>

- **Ueye** (visible range) =>*Nice images, but inappropriate wavelength for diffraction radiation studies at 200 MeV*
- **Onca-MWIR-InSb** (2-5um) =>Bad SNR
- **Gobi-LWIR**(8-15um) =>Bad SNR (bolometer)



<u>To be tested soon:</u>

- **Bobcat-SWIR**(0.8-1.6um) Might be the right one for this measurement.




Ueye

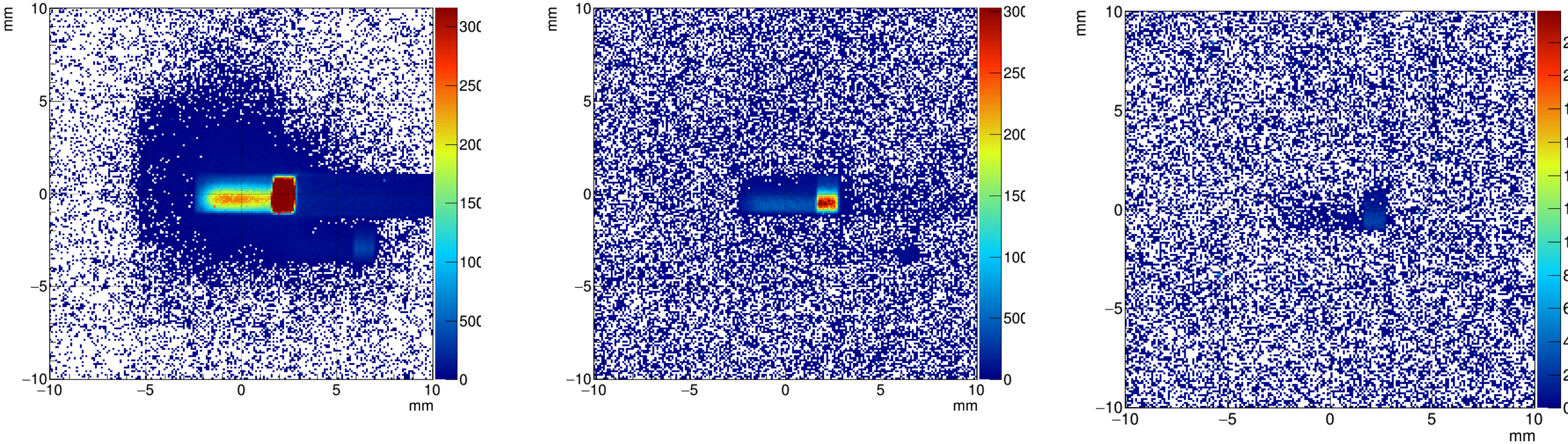

Onca


Gobi


Bobcat

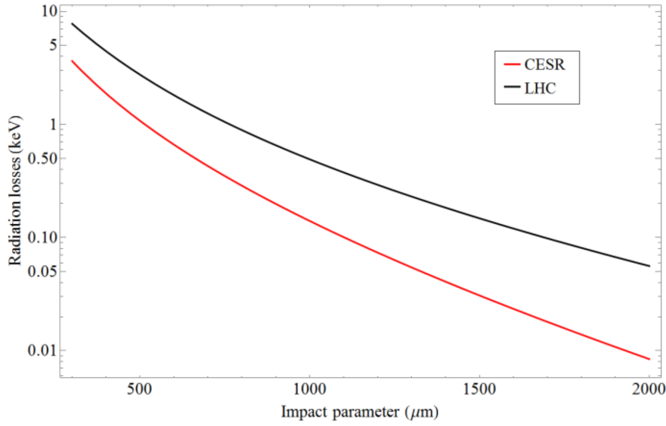
Experimental set-up at Califes@CERN

- CALIFES : 200MeV electrons – up to 15nC per bunch train
- 15x2x1.2mm Diamond crystal with one face cut and Al Coated to reflect the ChDR photons on a FIR Camera (microbolometer, 16bit, 8-14um)
- Measuring and comparing Transition, Cherenkov and Cherenkov Diffraction radiation

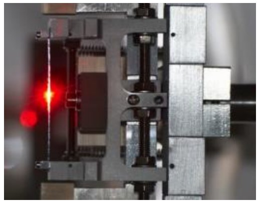


Perspectives for beam instrumentation

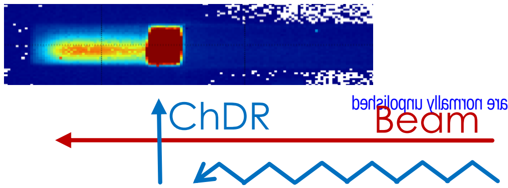
- Imaging system for relativistic beam
  - What is the the smallest beam size measurable ?
    - The Cherenkov diffraction PSF should be smaller than transition radiation PSF
      → possible tests in 2018 with micron beam sizes on ATF2



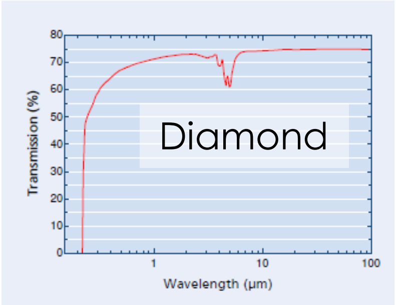
- What is the smallest the beam tilt angle measurable ?
  - A non linear response depending on wavelength, beam energy and impact parameter
- Measuring counter-propagating beams with very high directivity : BPM for FCC, HE-LHC, …
- A Beam Position Monitor for Crystal collimator on LHC

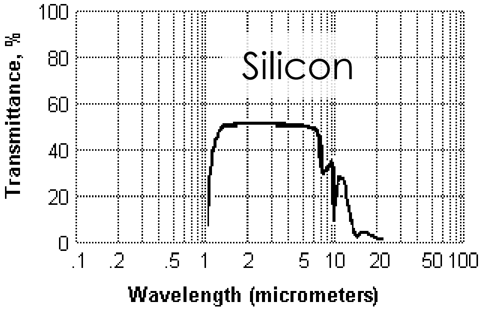


Perspectives on radiator's shapes and material



- Prismatic or flat targets ? Something else ?
  - BPM using flat target – possibly using long(er) target
  - Imaging system requiring to select the appropriate polarization
- How thick should a target be ? cm/mm/um ?
  - ChDR is mainly emitted within the first atomic layer of the dielectric since the beam field decreases as it penetrates inside the material.
- Testing different materials for different applications / wavelength



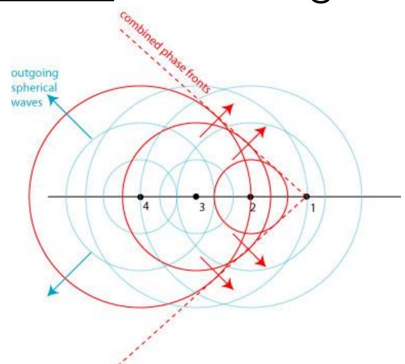


Cherenkov radiation (1/2)

'Equivalent to the supersonic boom but for photons'

<u>Threshold process:</u> Particles go faster than light $\beta > 1/n$

- n is the index of refraction
- β is the relative particle velocity



- θ_c is the Cherenkov light emission angle

$$\cos(\theta_c) = \frac{1}{\beta n}$$

- d the length of the cherenkov radiator

- The total number of photons proportional to the thickness of the Cherenkov radiator

$$N_{ph} = 2\pi\alpha \cdot d \cdot \left(\frac{1}{\lambda_a} - \frac{1}{\lambda_b}\right)\left(1 - \frac{1}{(\beta n)^2}\right)$$

- Almost no dependency on beam energy

Cherenkov radiation (2/2)

- Emitted (measurable) power spectrum depends on the materiel transparency (*Tr*(λ))