Coherent Cherenkov diffraction radiation studies at CLEAR

gratefully acknowledging:
Michael Benedikt, Candy Capelli, Nicolas Sebastien Chritin, Ashley Churchman, Can Davut, Morad Hamani, Lewis Hanson, Pavel Karataev, Kacper Lasocha, Thibaut Lefevre, Stefano Mazzoni, Collette Pakuza, Eugenio Senes,

the OP team at CLEAR

and Lionel Duvillaret from KATPEOS

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FCC-ee bunch length diagnostics

Synchrotron radiation (SR) in LEP

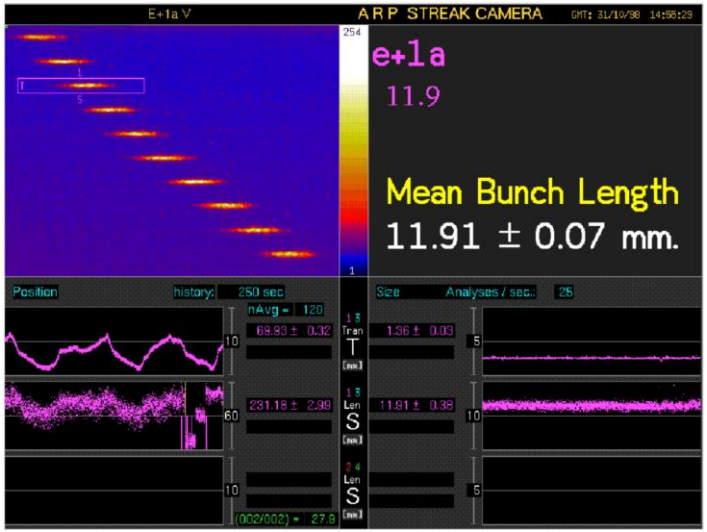
Bunch length measurements using SR on streak camera

SR in FCC-ee:

Distance of ~100 m necessary to separate the photon beam from the electron or positron beam[1] and X-rays dominating the spectrum

Cherenkov Diffraction Radiation (ChDR) at FCC-ee

- Non-invasive
- Simple geometries with small space requirements
- Photon emission at large and well-defined angle



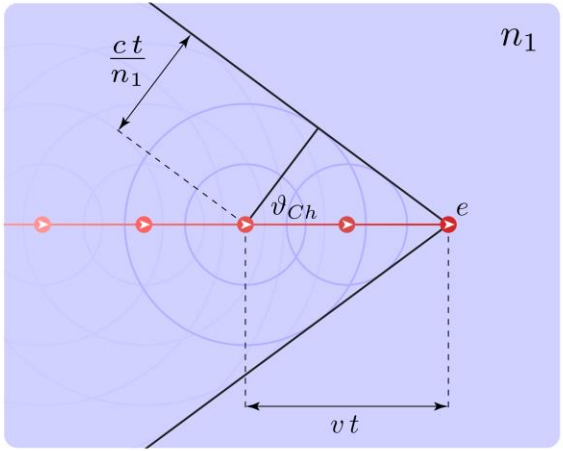
Bunch length measurement in LEP [2]

[1] Abada, A., Abbrescia, M., AbdusSalam, S.S. et al. FCC-ee: The Lepton Collider. Eur. Phys. J. Spec. Top. 228, 261–623 (2019). https://doi.org/10.1140/epjst/e2019-900045-4

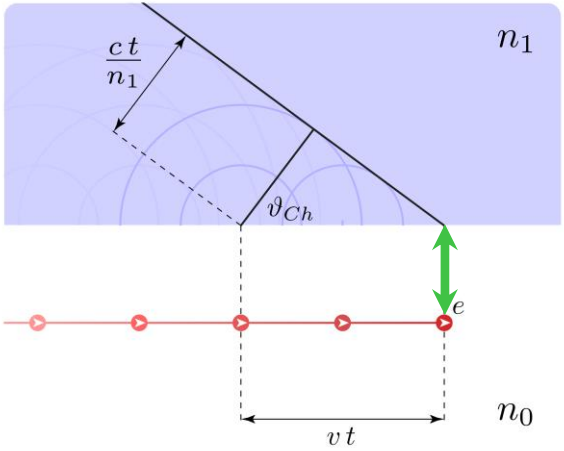
[2] A. J. Burns, H. Schmickler, Bunch length measurements in LEP, Proceedings DIPAC (1999) https://cds.cern.ch/record/398768

Cherenkov (Diffraction) Radiation

Cherenkov Radiation



Cherenkov Diffraction Radiation (ChDR)



Frank-Tamm

$$\frac{dW}{dl} = \frac{q^2}{4\pi}\,\mu_0 \int_0^\infty \omega \cdot \left(1 - \frac{1}{\beta^2 n^2(\omega)}\right) d\omega$$

$$cos(\vartheta_{Ch}) = \frac{1}{n\,\beta}$$

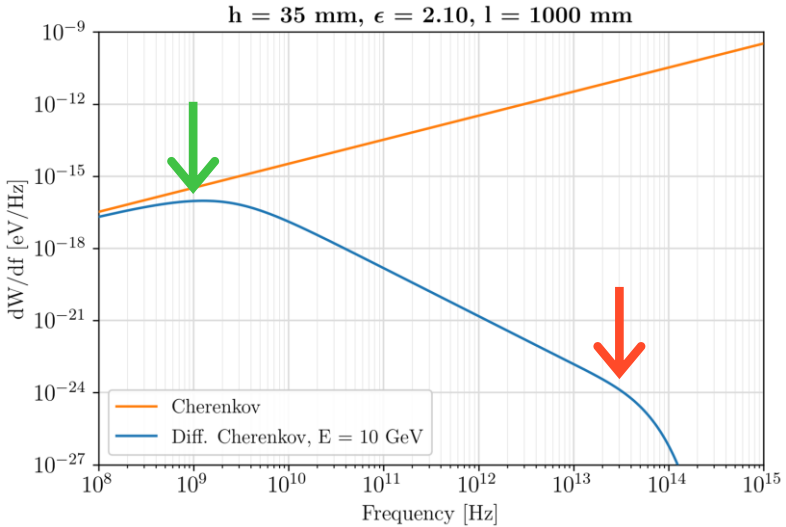
impact parameter

particle energy

I.M. Frank and I.E. Tamm. Coherent visible radiation of fast electrons passing through matter. *Compt. Rend. Acad. Sci. URSS*, 14(3):109– 114, 1937

Analytical calculations

Cherenkov vs. Cherenkov Diffraction



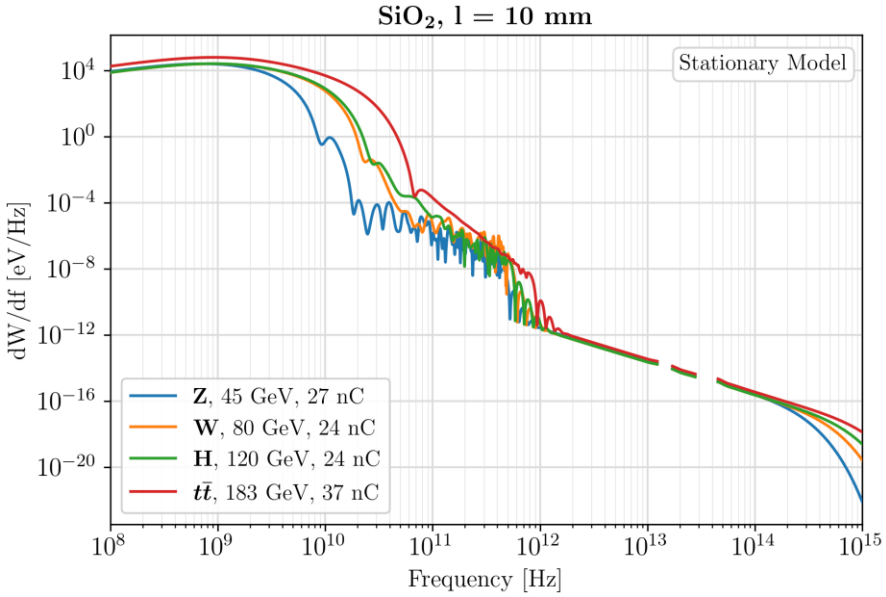
$\propto 1/h$ $\propto \gamma/h$

ChDR introduces turning points in the spectrum

Coherent and incoherent ChDR (FCC-ee)

$\lambda > \sigma_{bunch}$

$\propto N^2$



$\lambda << \sigma_{bunch}$

$\propto N$

$$\frac{dW}{d\omega} = \left(\frac{dW}{d\omega}\right)_1 \cdot \left(N + N(N-1)\cdot\left|F(\vec{k})\right|^2\right)$$

with $F(\vec{k}) = \int S(\vec{r}) \cdot e^{-i\vec{k}\,\vec{r}}\, d\vec{r}$

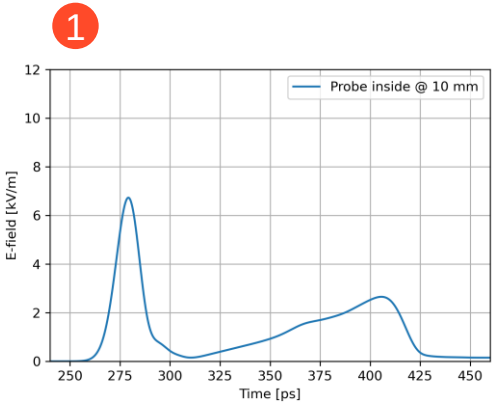
$F(\vec{k})$ … bunch form factor

$S(\vec{r})$ … particle density distribution

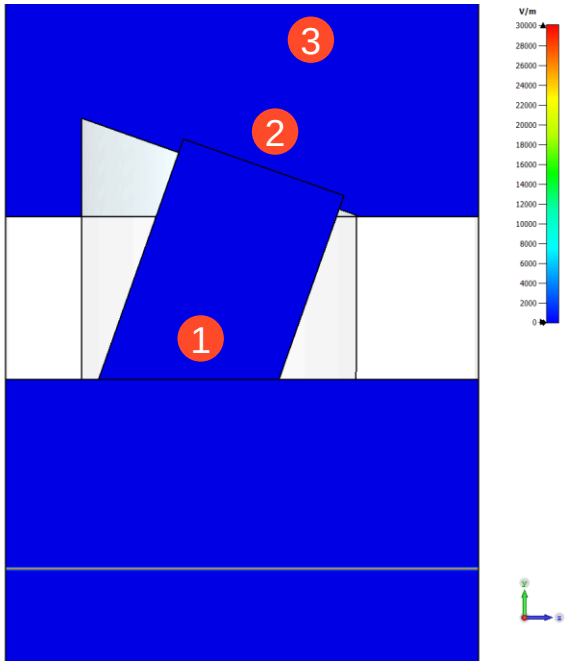
$\left(\frac{dW}{d\omega}\right)_1$ … energy spectrum of one particle

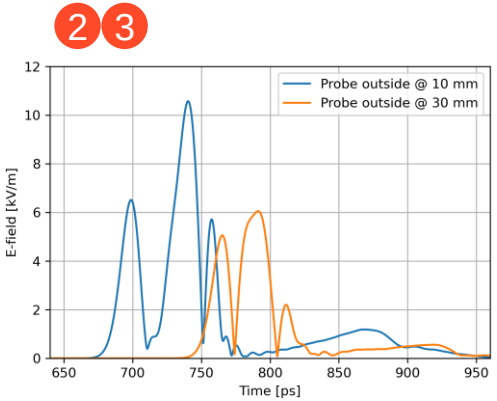
Coherent ChDR (CLEAR)

Numerical studies with CST



E-field, Median plane (yz-plane)

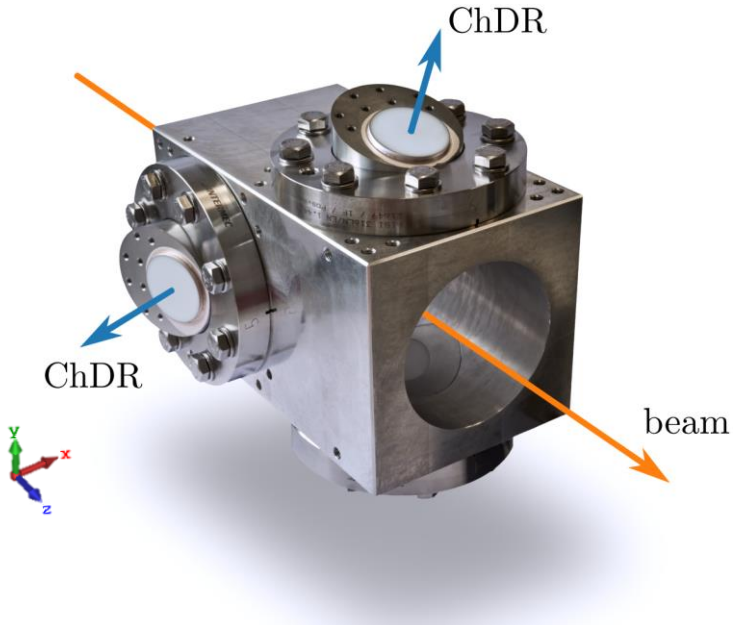




$\varepsilon = 9$, $\theta_{Ch} = 70.5°$

Electron bunch
5 ps Gaussian, 300 pC, 200 MeV

Radiatior Design

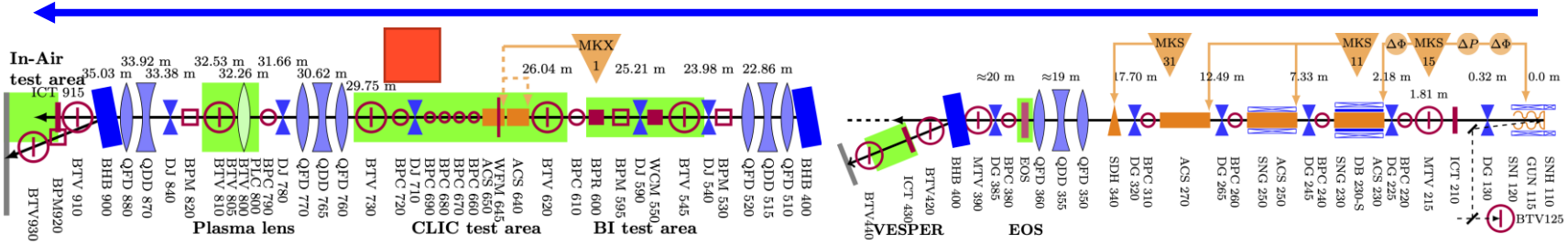


36 mm diameter Alumina rods

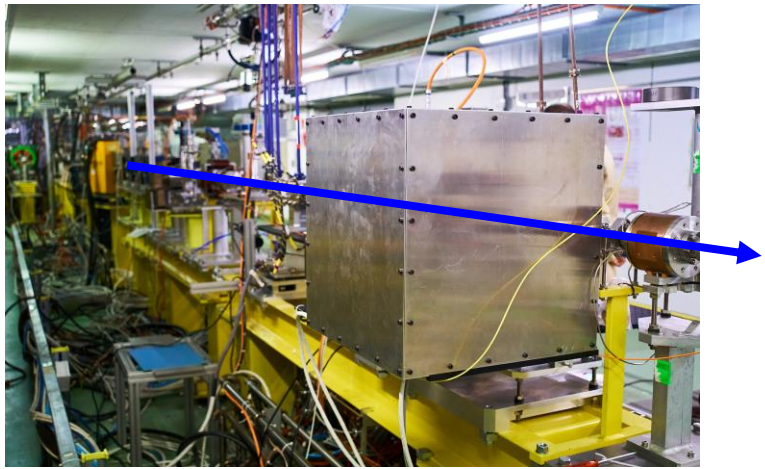
brazed to DN 60 flange, vacuum tight

curvature for Ø 80 mm beam pipe

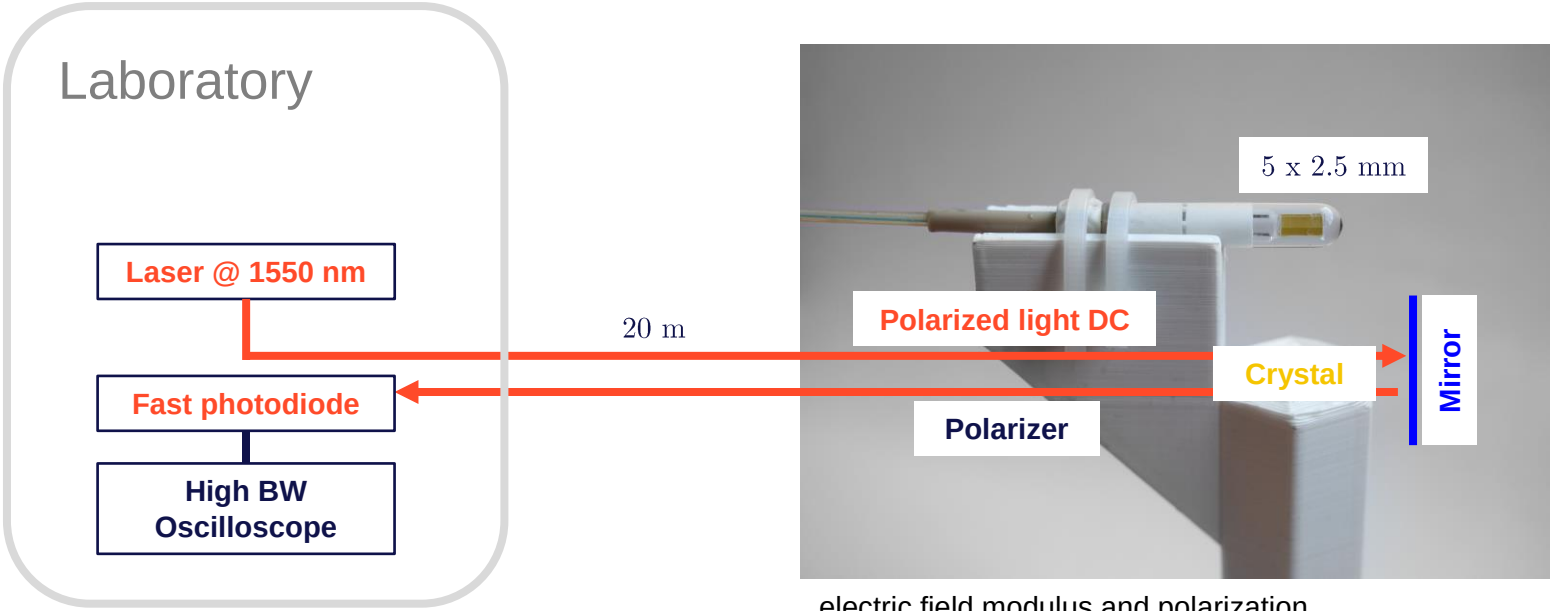
CLEAR



Beam parameter (end of linac)	Value range
Energy	60 - 220 MeV
Bunch charge	0.01 - 0.5 nC
Normalized emittances	3 um for 0.05 nC per bunch 20 um for 0.4 nC per bunch (in both planes)
Bunch length	~100 um -1.2 mm
Relative energy spread	< 0.2 % rms (< 1 MeV FWHM)
Repetition rate	1 - 5 Hz (25 Hz with upgrade)
Number of micro-bunches in train	1 and more than 100
Micro-bunch spacing	1.5 GHz

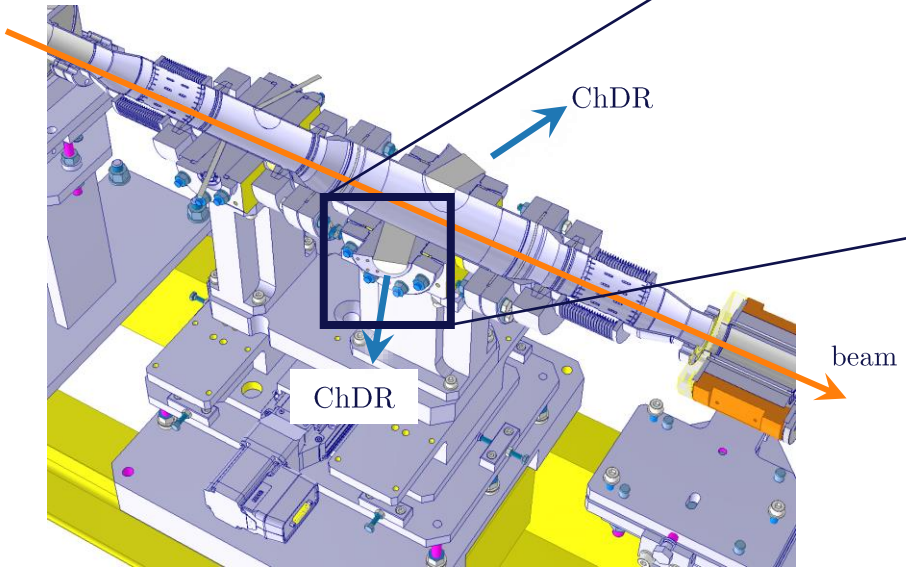


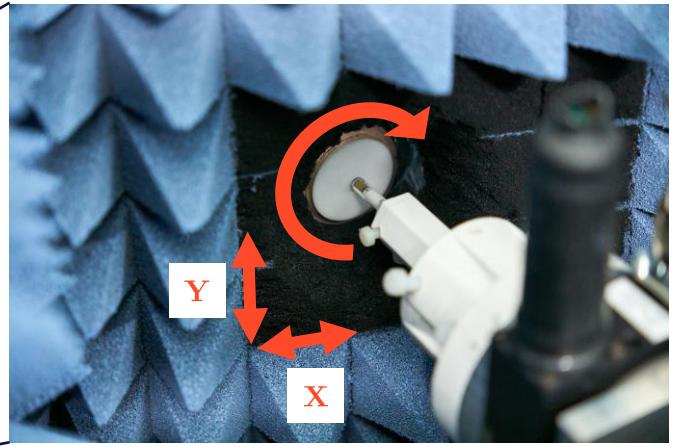
EO probe from Kapteos

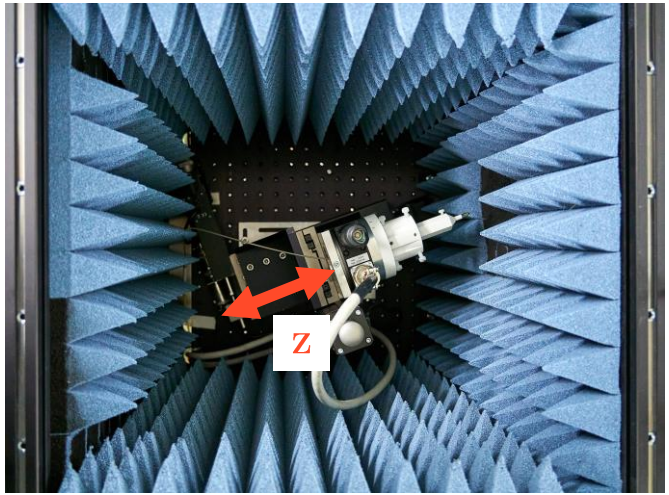


electric field modulus and polarization
bandwidth of 1 – 10 GHz

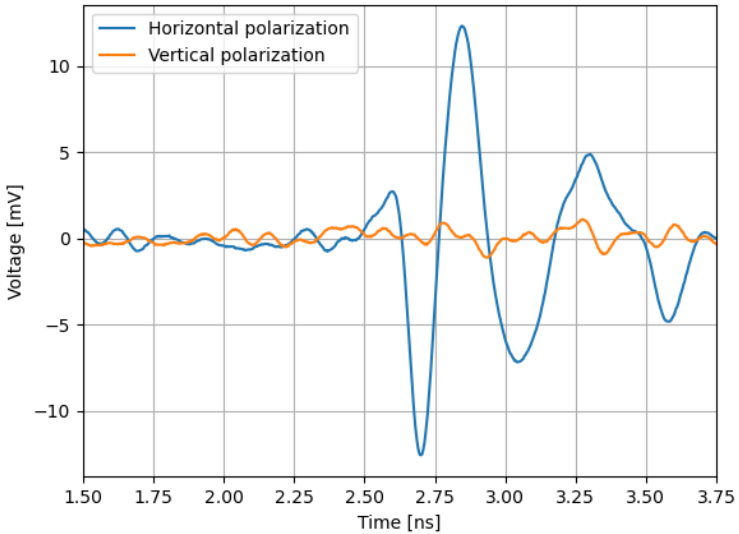
Vacuum setup at CLEAR

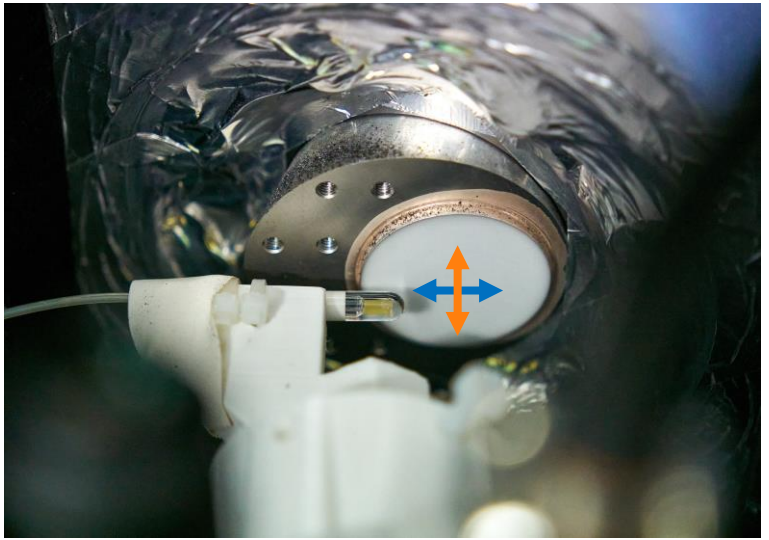






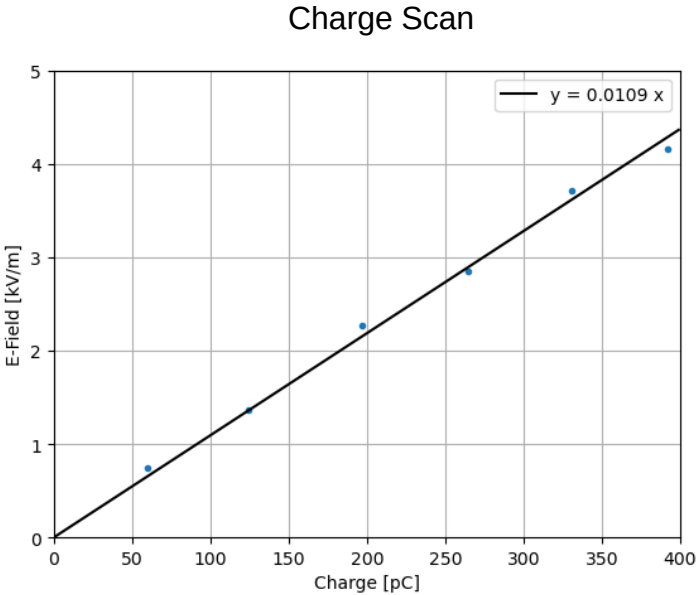
Preliminary results at CLEAR

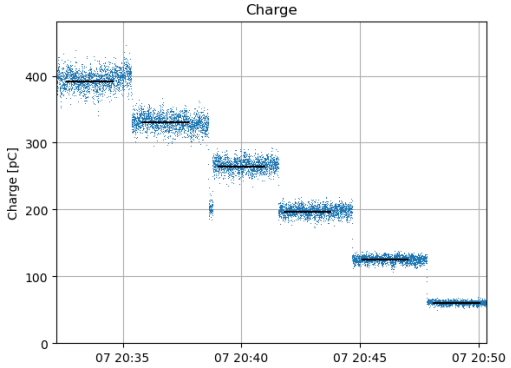


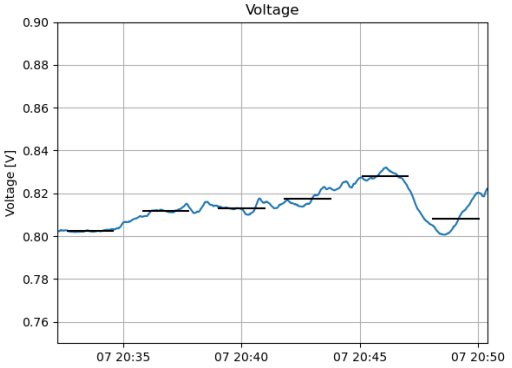


probe ←→ radiator: 9 mm distance
beam ←→ radiator: 10 mm distance
average over 2400 traces (4 minutes @ 10 Hz)

Preliminary results at CLEAR

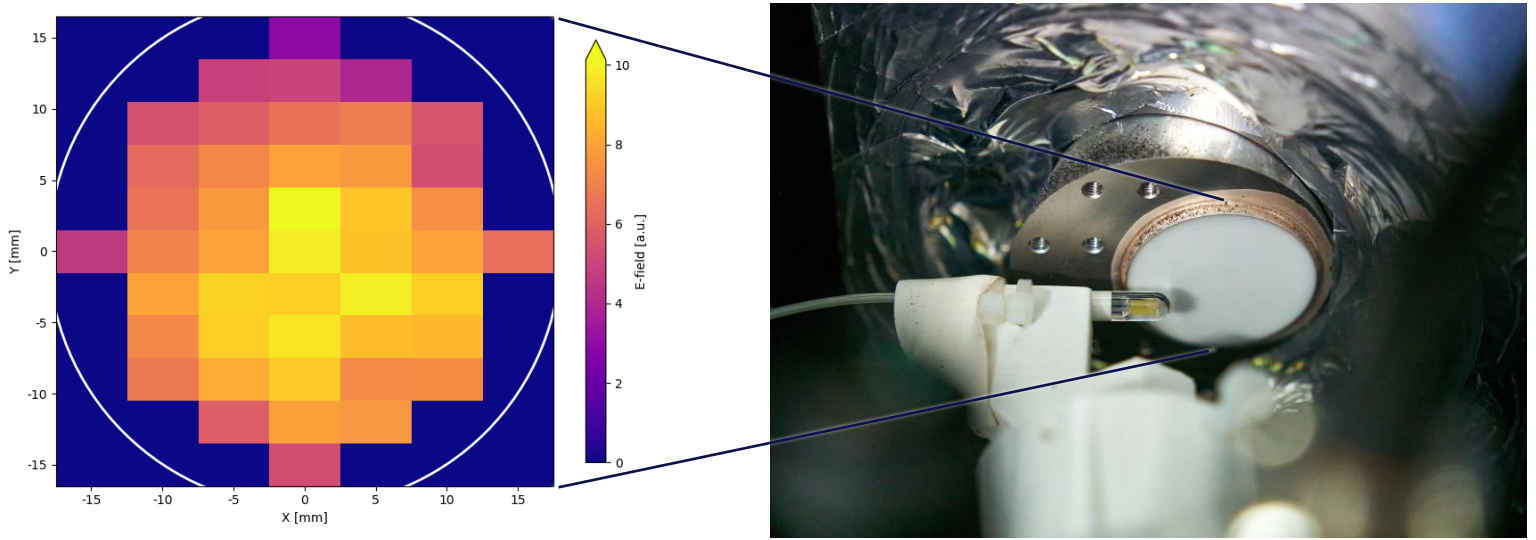






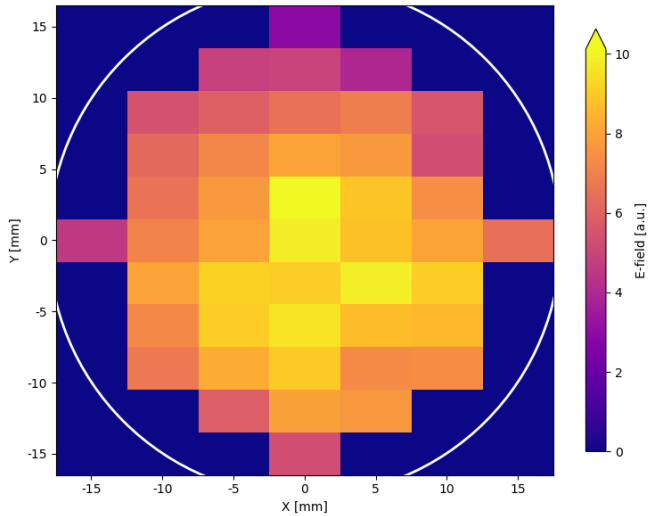
probe ←→ radiator: 9 mm distance
beam ←→ radiator: 20 mm distance
average over 1200 traces, absolute value of negative peak

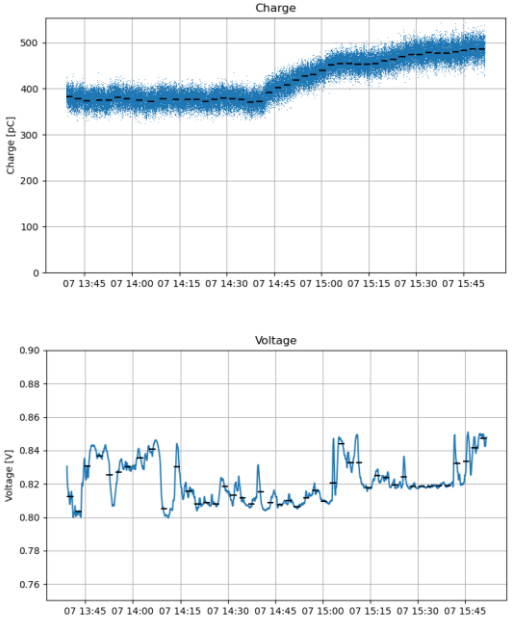
Preliminary results at CLEAR



probe ←→ radiator: 9 mm distance
beam ←→ radiator: 20 mm distance
average over 1200 traces (2 min per point), total measurement takes roughly two hours

Preliminary results at CLEAR





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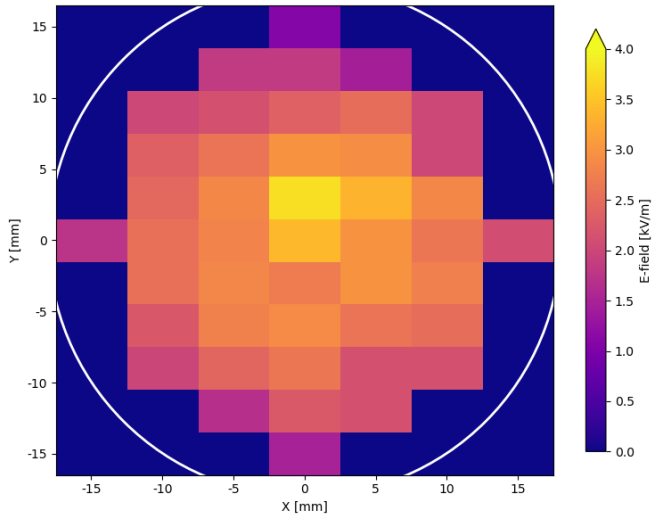

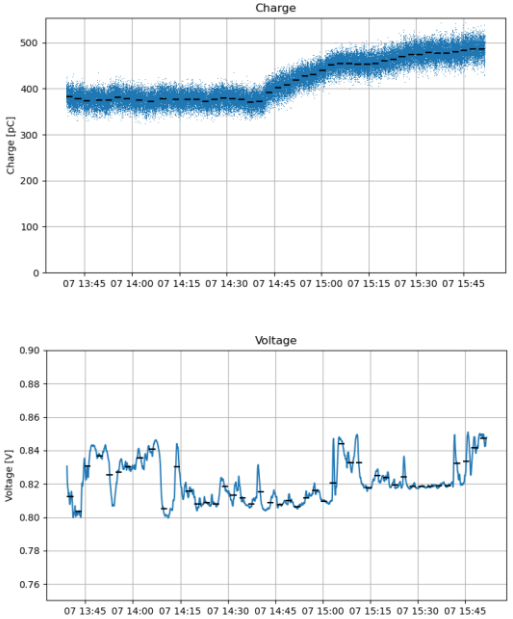

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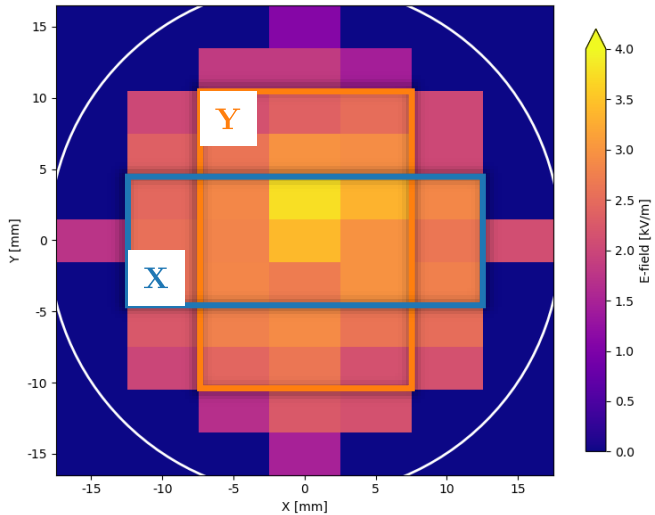
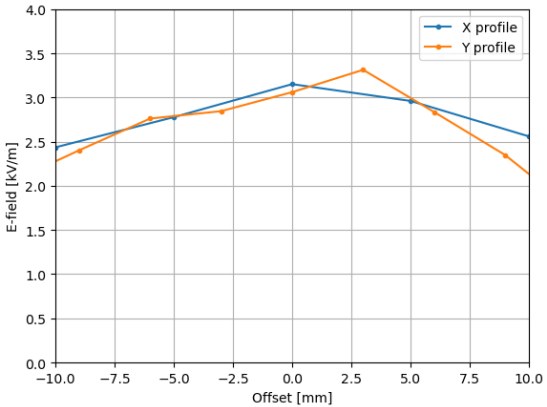




probe ←→ radiator: 9 mm distance
beam ←→ radiator: 20 mm distance
average over 1200 traces (2 min per point), total measurement takes roughly two hours

Conclusions

Coherent ChDR

First measurement of absolute value of e-field

- *sets lower limit for e-field strength*
- *surface distribution on radiator*

First quantified measurement of e-field polarization

CST suitable tool for numerical simulation of ChDR

→ EO methods prove to be a versatile tool to investigate ChDR

→ Coherent ChDR remains a promising candidate for FCC-ee diagnostics

Outlook

Coherent ChDR

Detailed analysis of the acquired data still to be done:

- *jitter, arrival time, signal shape for different positions*
- *impact parameter scan in-air and in-vacuum*
- *probe distance from radiator*

Refined CST simulations for actual measurement values

- *benchmark simulations up to 10 GHz*

New EO measurement setup being finalized

- *modulation of chirped pulse and readout with spectrometer*
- *aim for improved temporal profile without the need of a fast oscilloscope*

Incoherent ChDR

Continue experimental path for coherent ChDR

- *high energies required* → *North Area @ CERN (100 GeV)*
  → *ATF 2 @ KEK (2 GeV)*

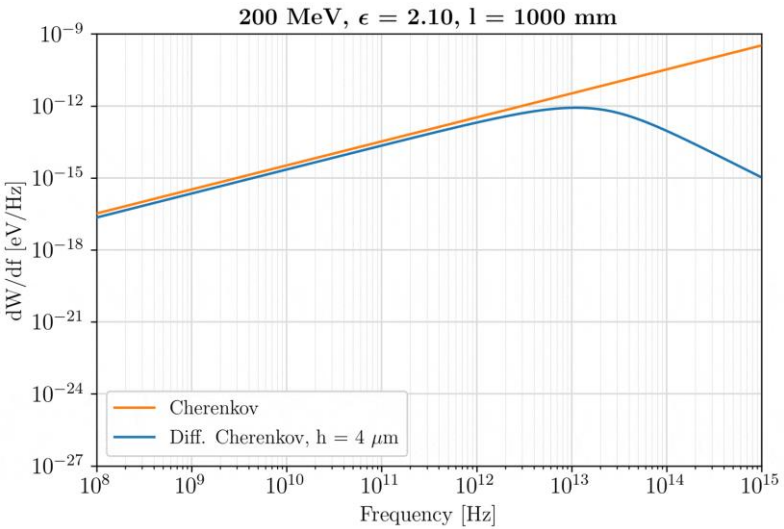
→ **under investigation**

FCC

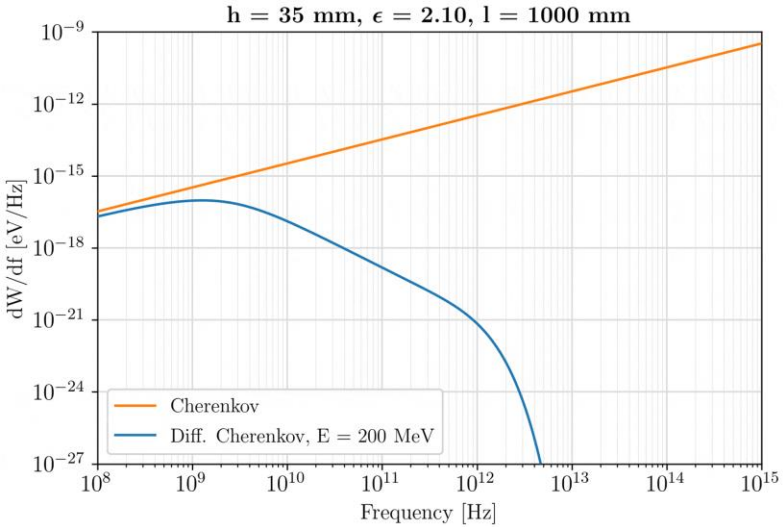
Thank you
for your attention.

Analytical calculations

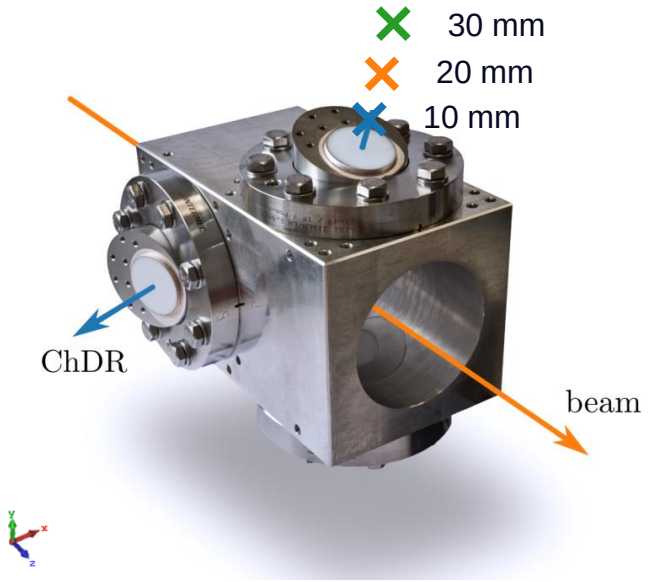
Dependency on impact parameter

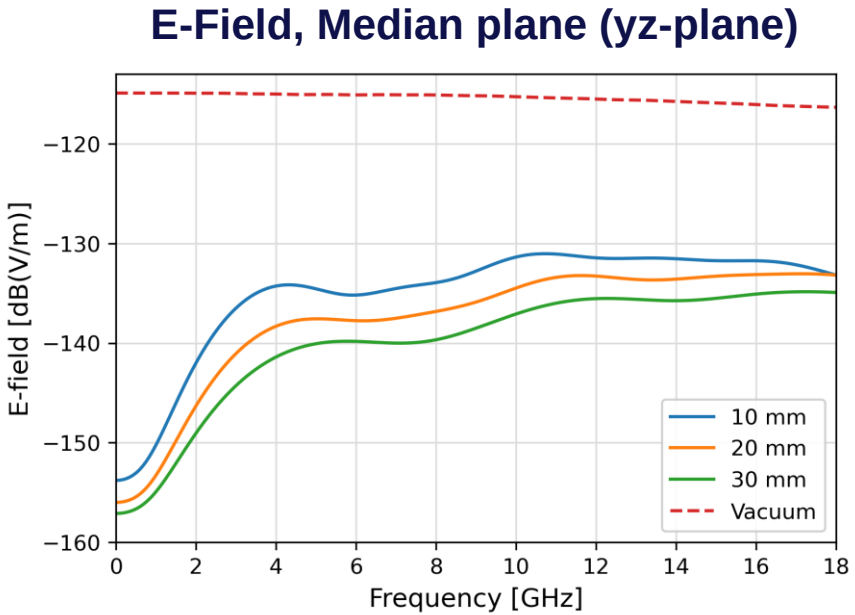


Dependency on particle energy



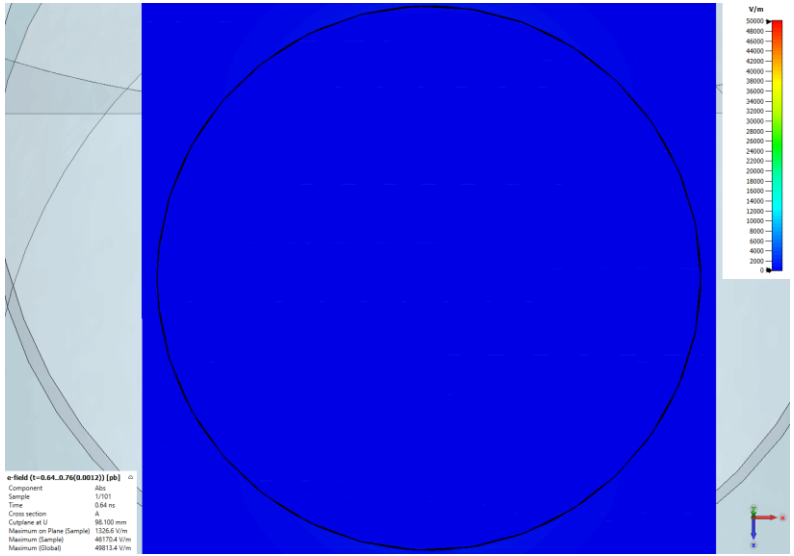
Coherent ChDR



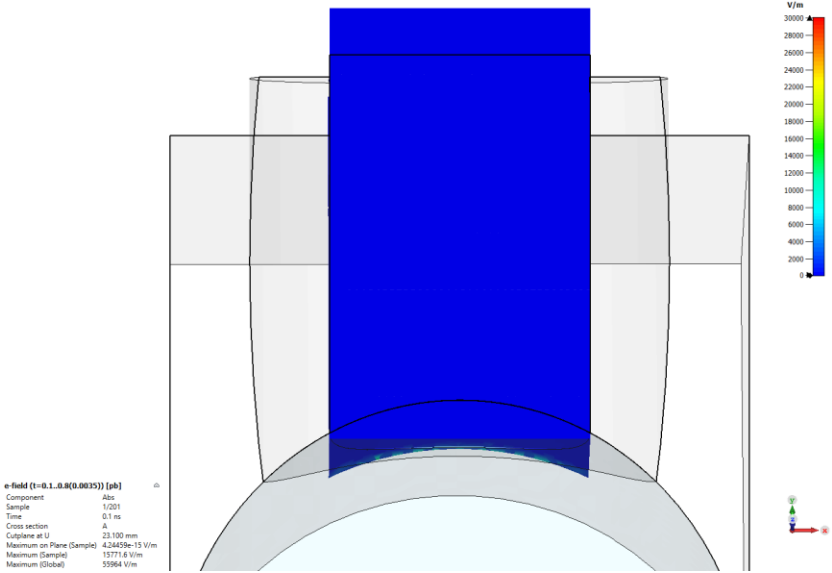


Coherent ChDR

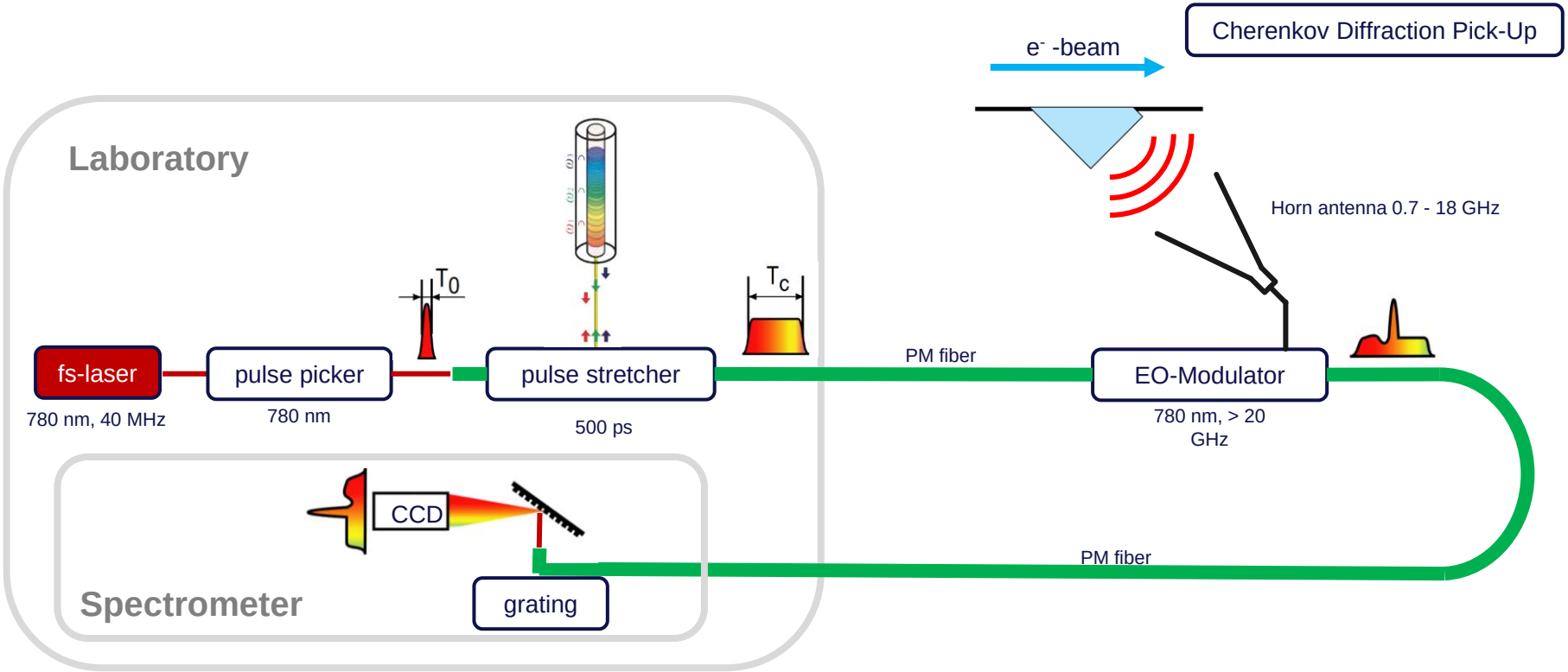
E-field, exit surface



E-field, transverse plane (xy-plane tilted)



Electro Optical Spectral Decoding



Pictures: First electro-optical bunch length measurements at European XFEL, B. Steffen et al., DOI 10.18429 (2019), Time delay signature elimination of chaos in a semiconductor laser by dispersive feedback from a chirped FBG, Daming Wang et. al., Opt. Express 25, 10911-10924 (2017)