A dielectric pickup for short bunches

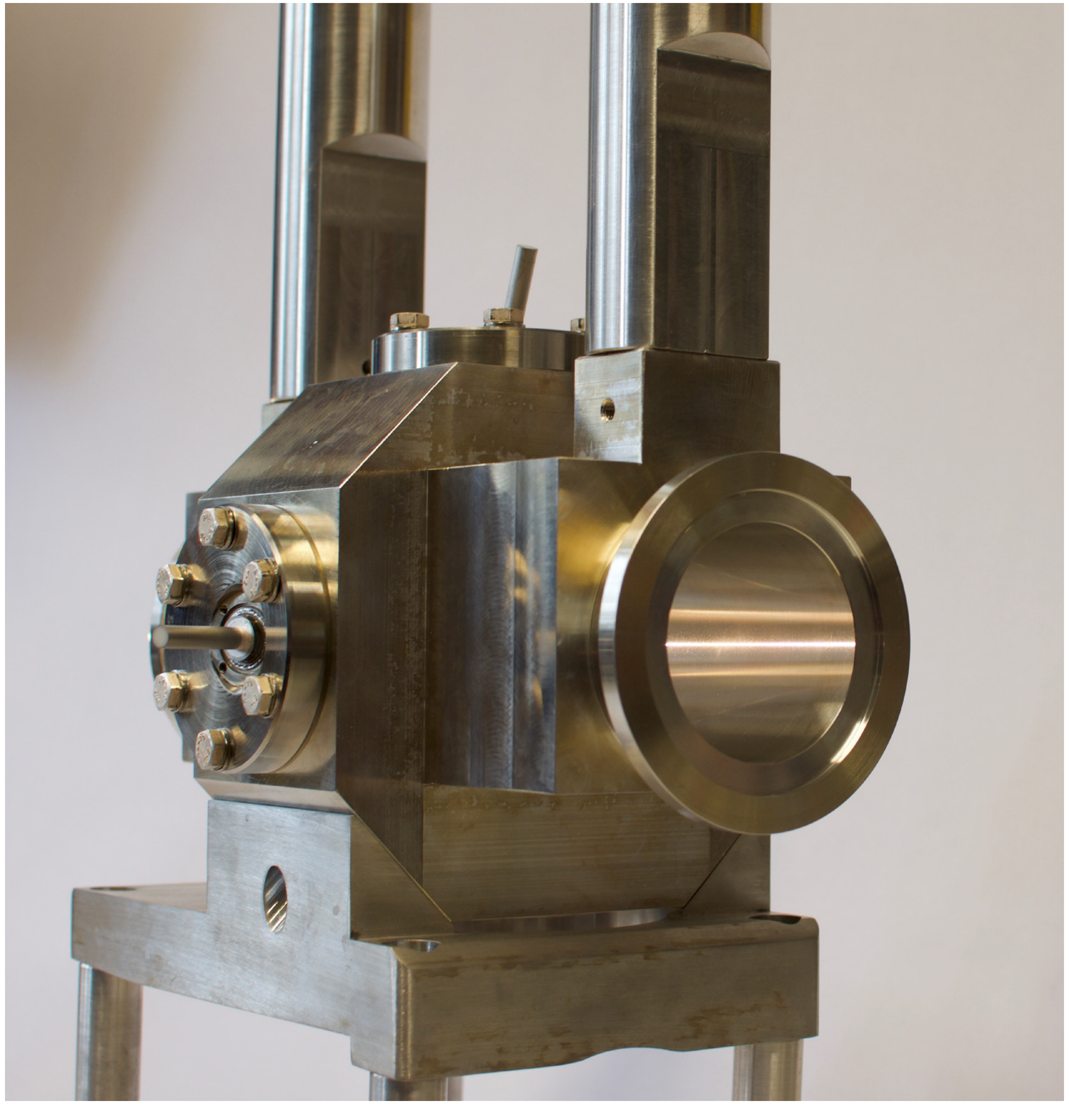
Eugenio Senes, V. Bencini, C. Davut, W. Farabolini, P. Karataev, P. Korysko, M. Krupa, K. Lasocha, S. Liu, T. Lefevre, T. Manson, S. Mazzoni, B. Moser, C. Pakuza, E. Poimenidou, A. Schloegelhofer, A. Topaloudis, B. Spear, L. Verra, V. Verzilov, M. Wendt, G. Zevi Della Porta

International Beam Instrumentation Conference IBIC 2023, Saskatoon, Canada

11 September 2023

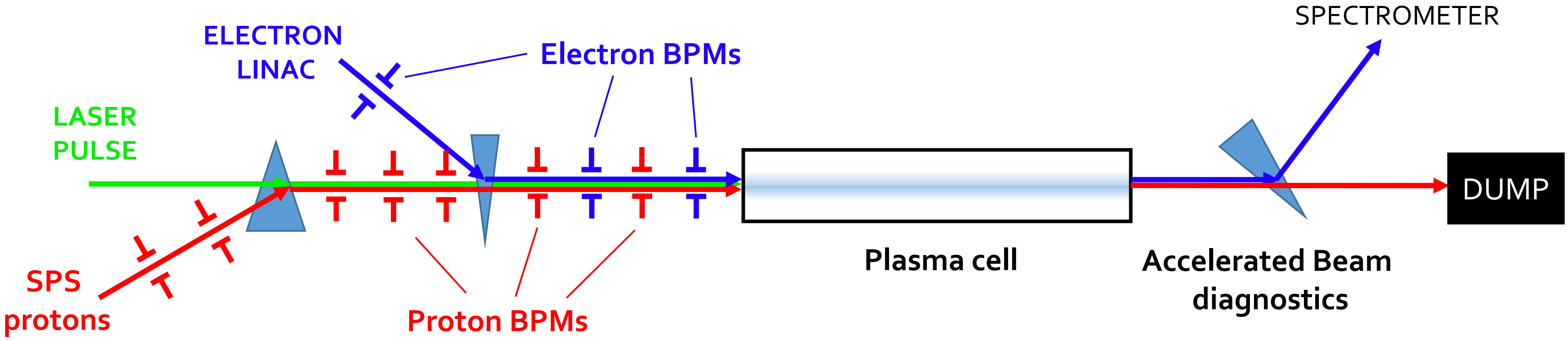
Outline

- Motivation
  - The AWAKE experiment
  - Co-propagating beams diagnostics
- Coherent Cherenkov diffraction radiation
- Pickup design
- Test results
- Operational electronics
- Future outlook



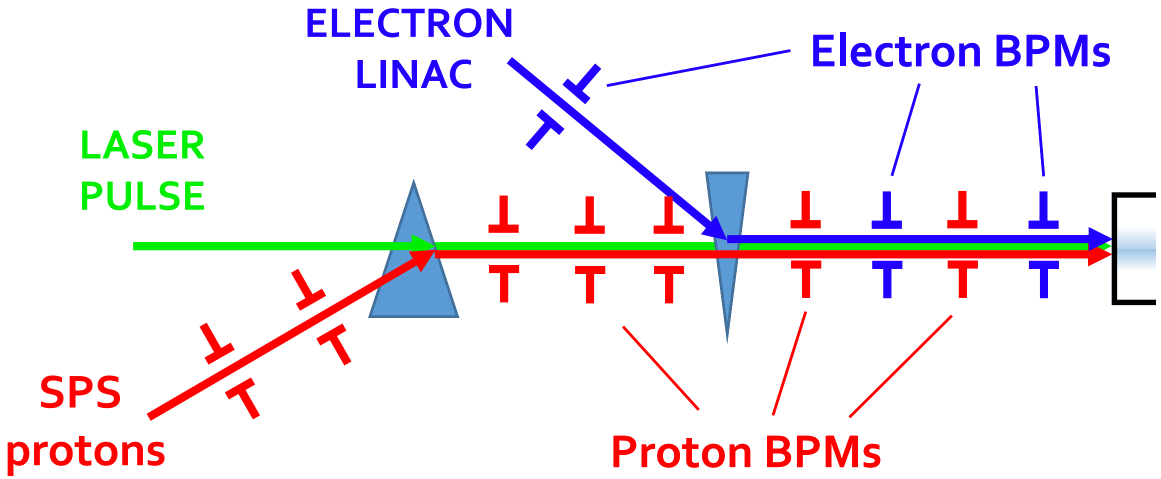
Motivation – AWAKE Experiment

AWAKE: Proton-driven plasma acceleration



Motivation – AWAKE Experiment

1 INJECTORS



The AWAKE ingredients

- **Proton beam** 48 nC, 250 ps-σ
- **Electron beam** 600 pC, 4 ps-σ
- **Laser beam** 120 fs, 450 mJ
- **Rb vapour**

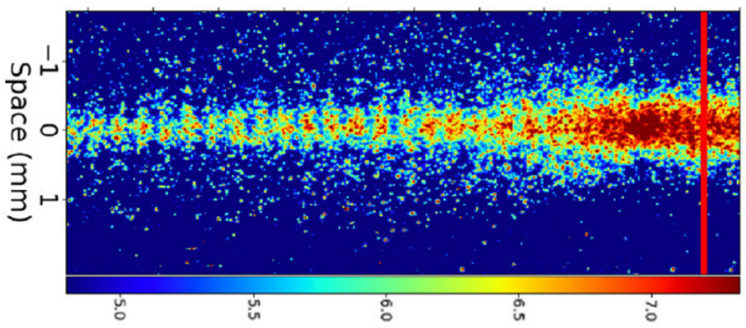
Motivation – AWAKE Experiment

2

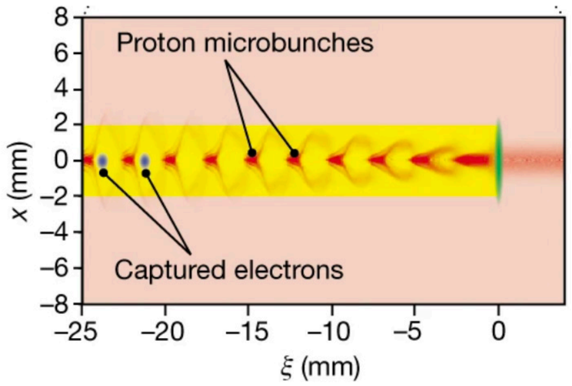
PROTON MICROBUNCHING AND ELECTRON ACCELERATION

The **proton** bunch is broken into a **train of microbunches** via the self modulation process in the plasma.

Captured electrons in the plasma wakefields are accelerated.

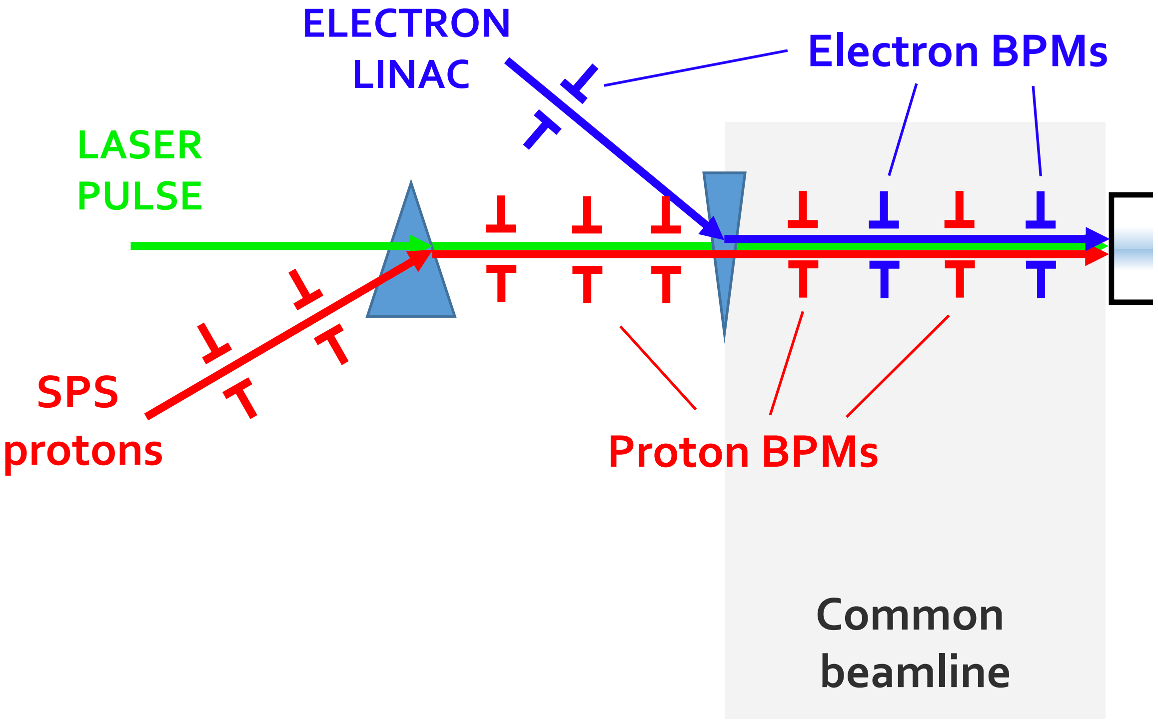


See AWAKE Collab., Phys. Rev. Lett. **122**, 054802 (2019)



See AWAKE Collab., Nature **561**, 363-367 (2018)

Motivation – Multiple beams



The trajectory control of the **laser**, **electron** and **proton** beam is essential to avoid instabilities and study reproducibility !

Due to the larger intensity, the **proton** beam **saturates** all the **other diagnostics** when present. Need for an electron position measurement in the common beamline.

Coherent Radiation

For any radiation mechanism, we know that the **radiation intensity spectrum** is

$$I(\omega) = I_{\mathrm{SP}}(\omega)\,\left[N + N\,(N-1)\,|f(\omega)|^2\right]$$

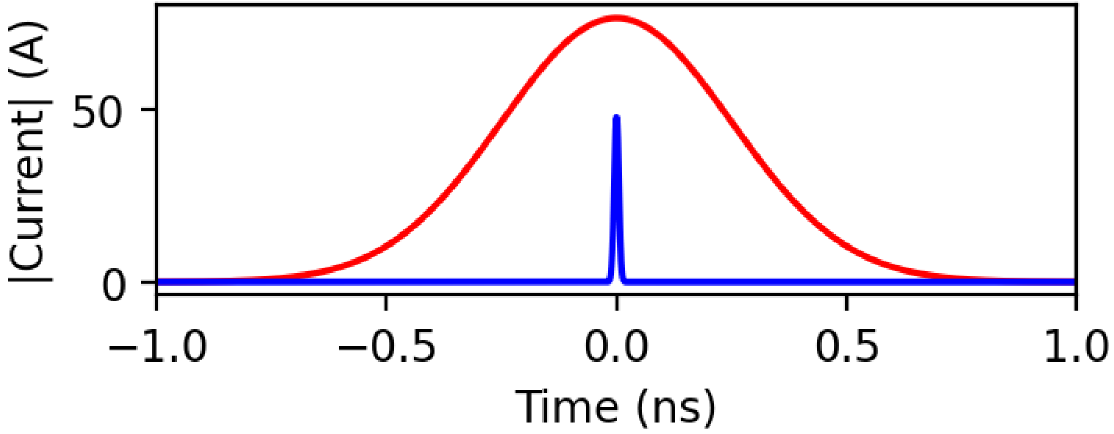
At low frequencies, **in the coherent region** of the spectrum, one can assume the single particle emission in quasi-phase, hence:

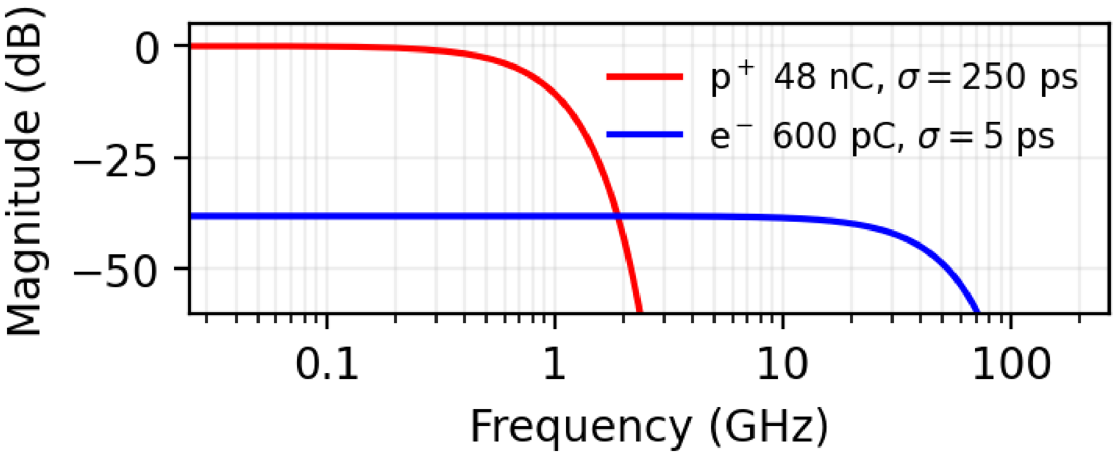
$$I_{\mathrm{Coh}}(\omega) \propto N^2 I_{\mathrm{SP}}(\omega)\,|f(\omega)|^2$$

Bunch intensity

Single particle term

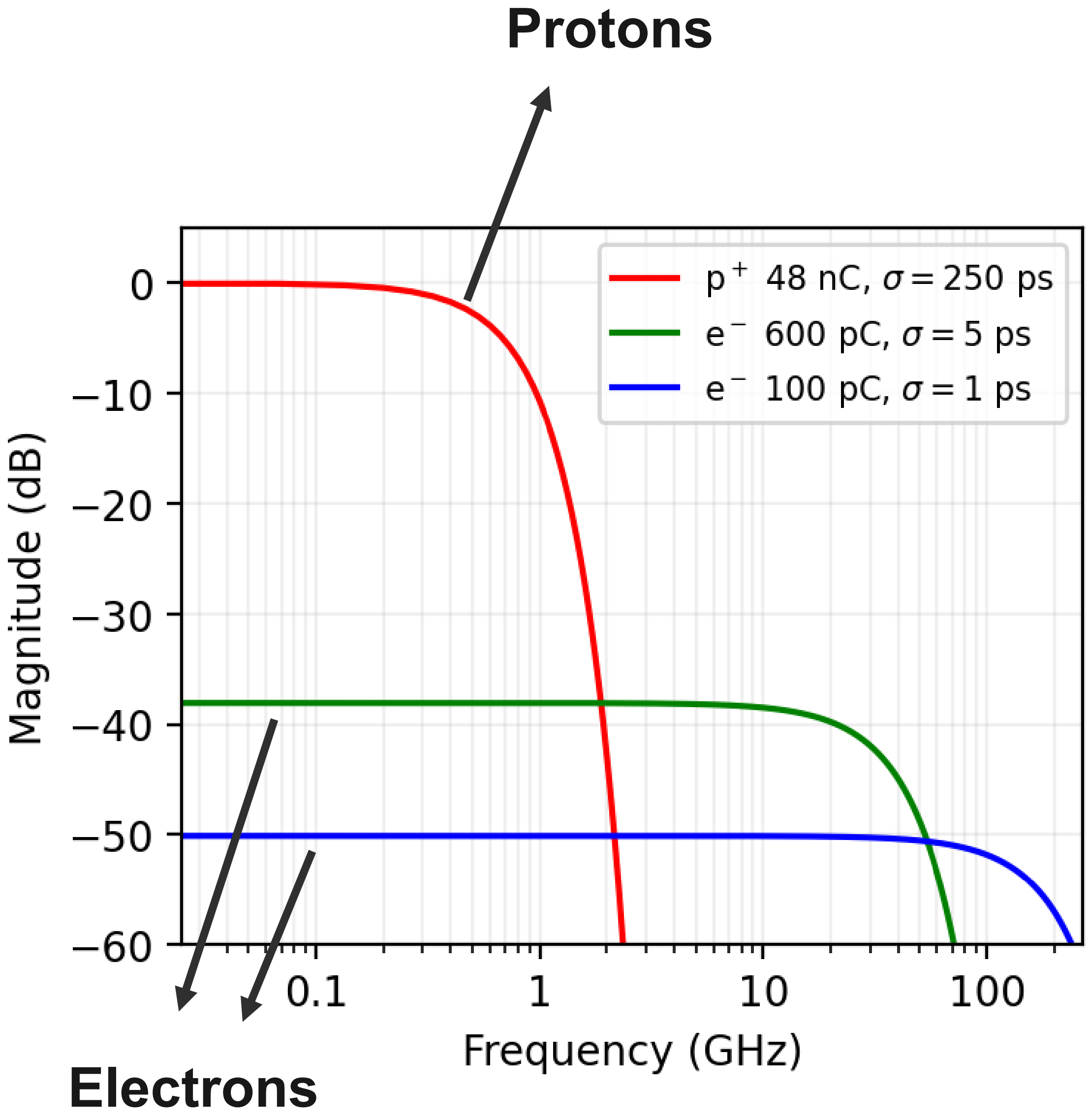
Bunch form factor (here Gaussian)





Coherent Radiation

Different beams feature different bunch form factors. For the AWAKE case:

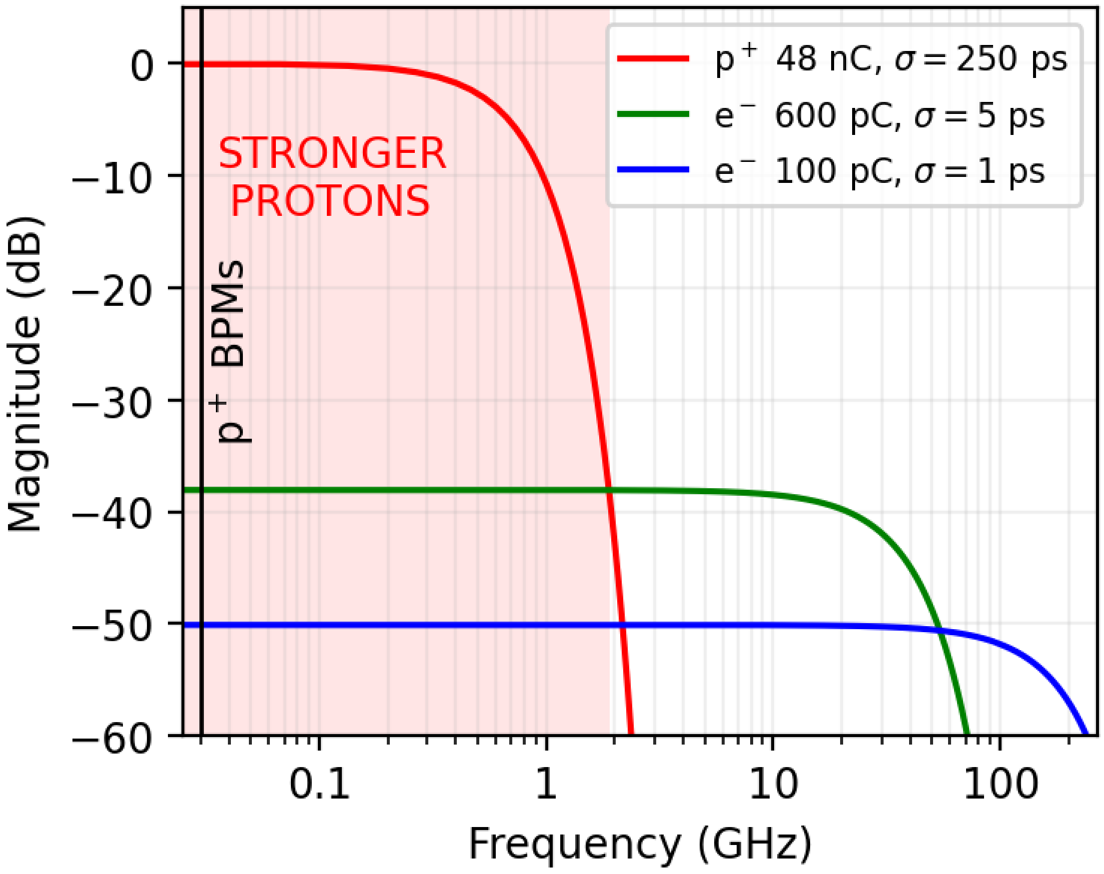


⚠ **Gaussian beams assumed here !**
Real life is not that simple !

Coherent Radiation

DOMINANT PROTON AREA < 2 GHz

- **BPMs for p^+** detect at 20 MHz



Gaussian beams assumed here !
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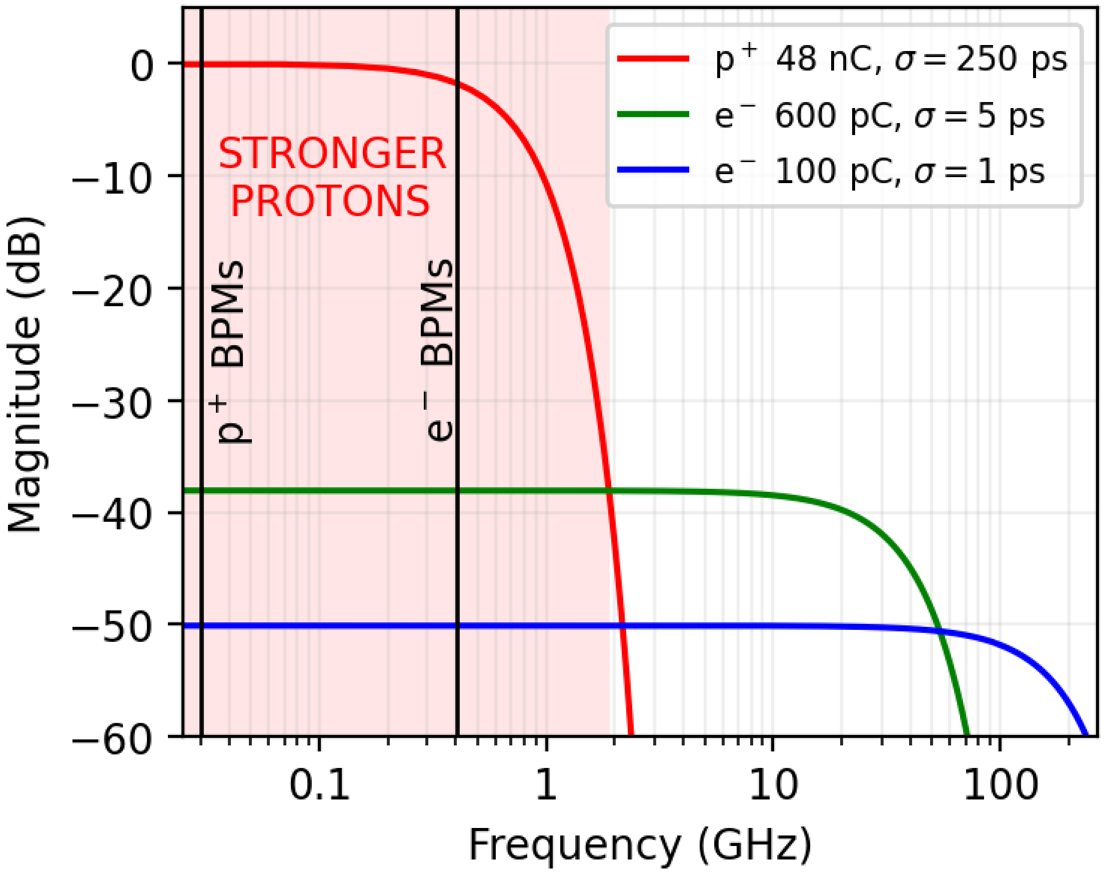
Coherent Radiation

DOMINANT PROTON AREA < 2 GHz

- **BPMs for p^+** detect at 20 MHz
- **BPMs for e^-** detect at 404 MHz



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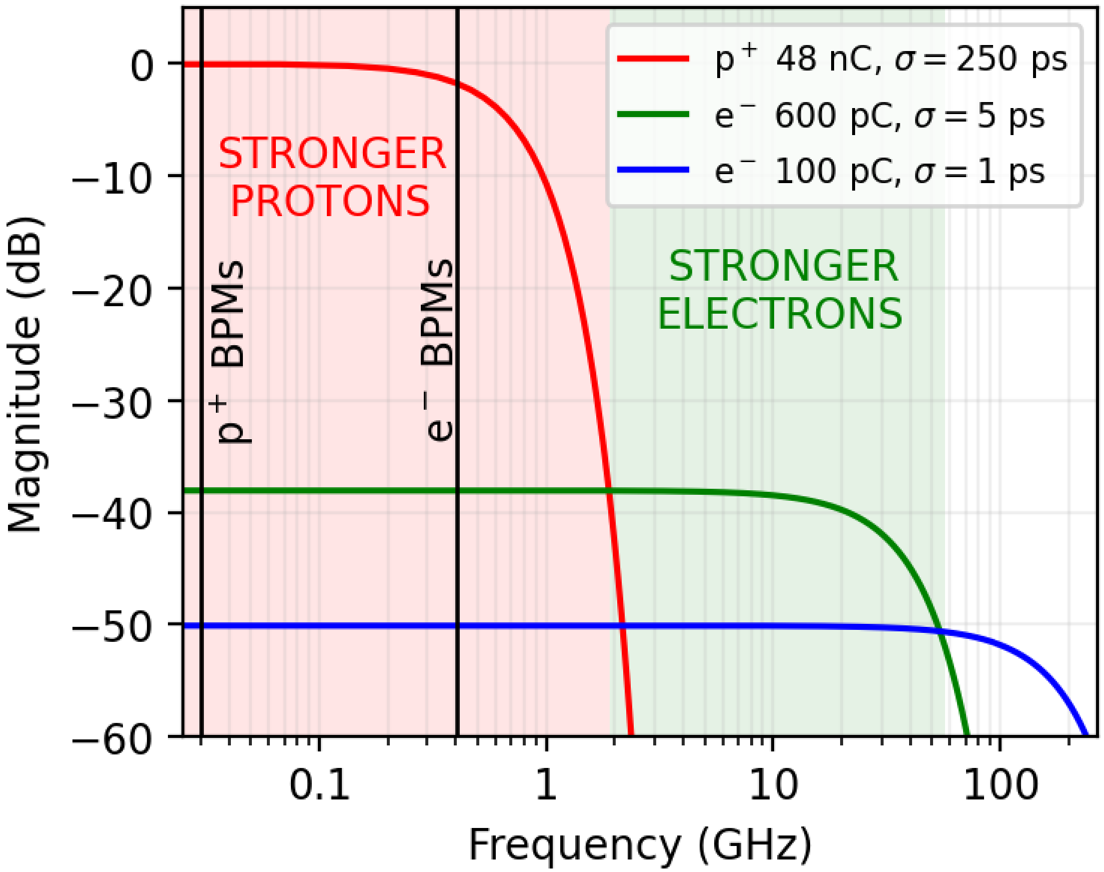
Coherent Radiation

DOMINANT PROTON AREA < 2 GHz

- **BPMs for p^+** detect at 20 MHz
- **BPMs for e^-** detect at 404 MHz

DOMINANT ELECTRON AREA > 2 GHz



Gaussian beams assumed here !
Real life is not that simple !

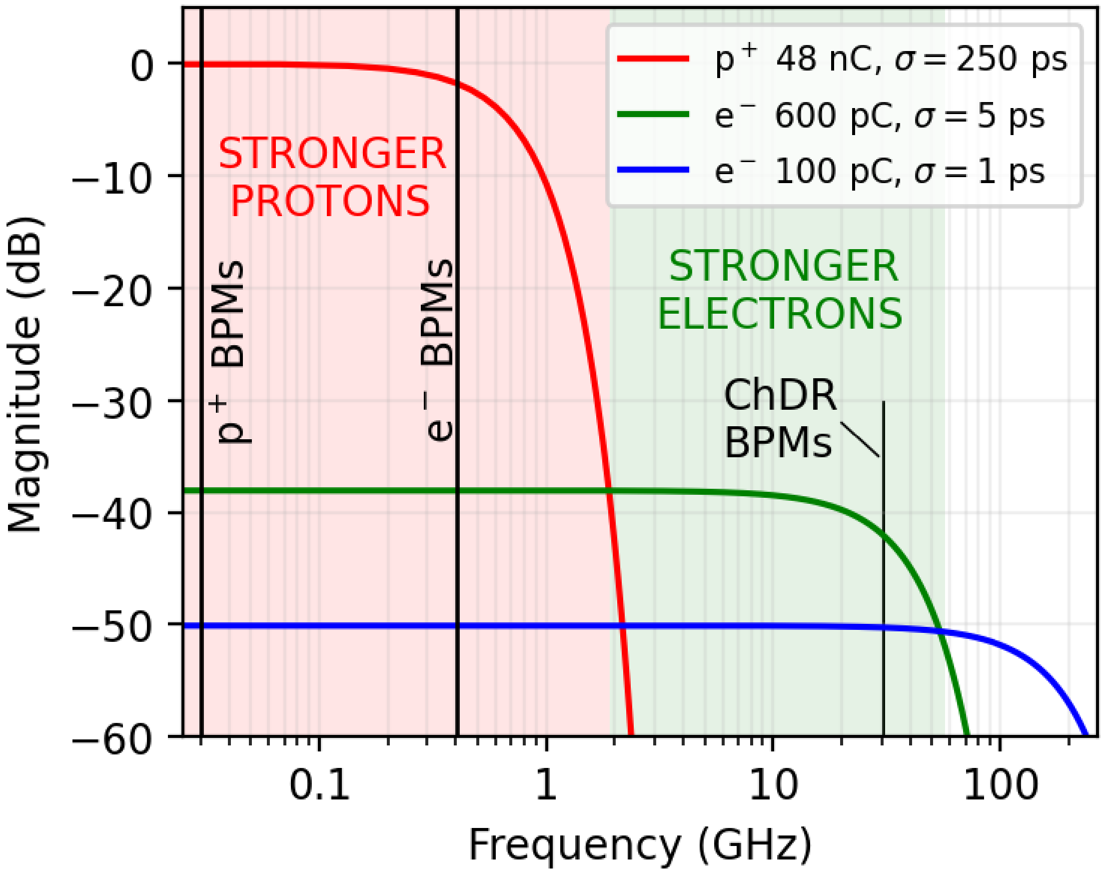
Coherent Radiation

DOMINANT PROTON AREA < 2 GHz

- **BPMs for p⁺** detect at 20 MHz
- **BPMs for e⁻** detect at 404 MHz

DOMINANT ELECTRON AREA > 2 GHz

- **Ideal BPMs for e⁻** detect at 20-30 GHz



Gaussian beams assumed here !
Real life is not that simple !

Coherent Radiation

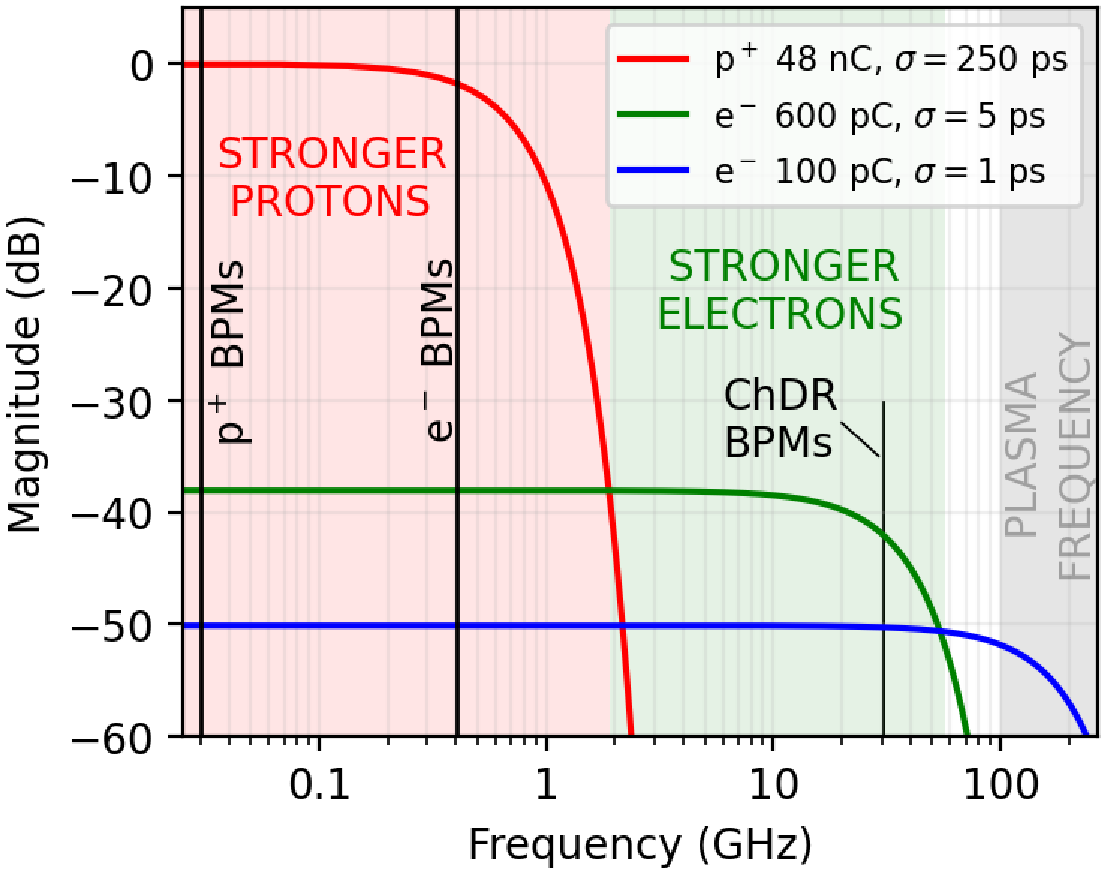
DOMINANT PROTON AREA < 2 GHz

- **BPMs for p⁺** detect at 20 MHz
- **BPMs for e⁻** detect at 404 MHz

DOMINANT ELECTRON AREA > 2 GHz

- **Ideal BPMs for e⁻** detect at 20-30 GHz

PLASMA FREQUENCY > 100 GHz



Gaussian beams assumed here !
Real life is not that simple !

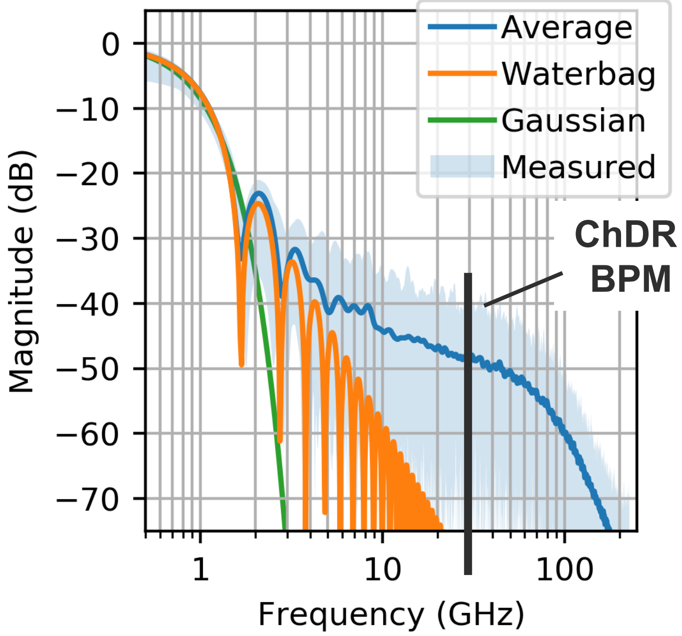
Non-Gaussian Beams

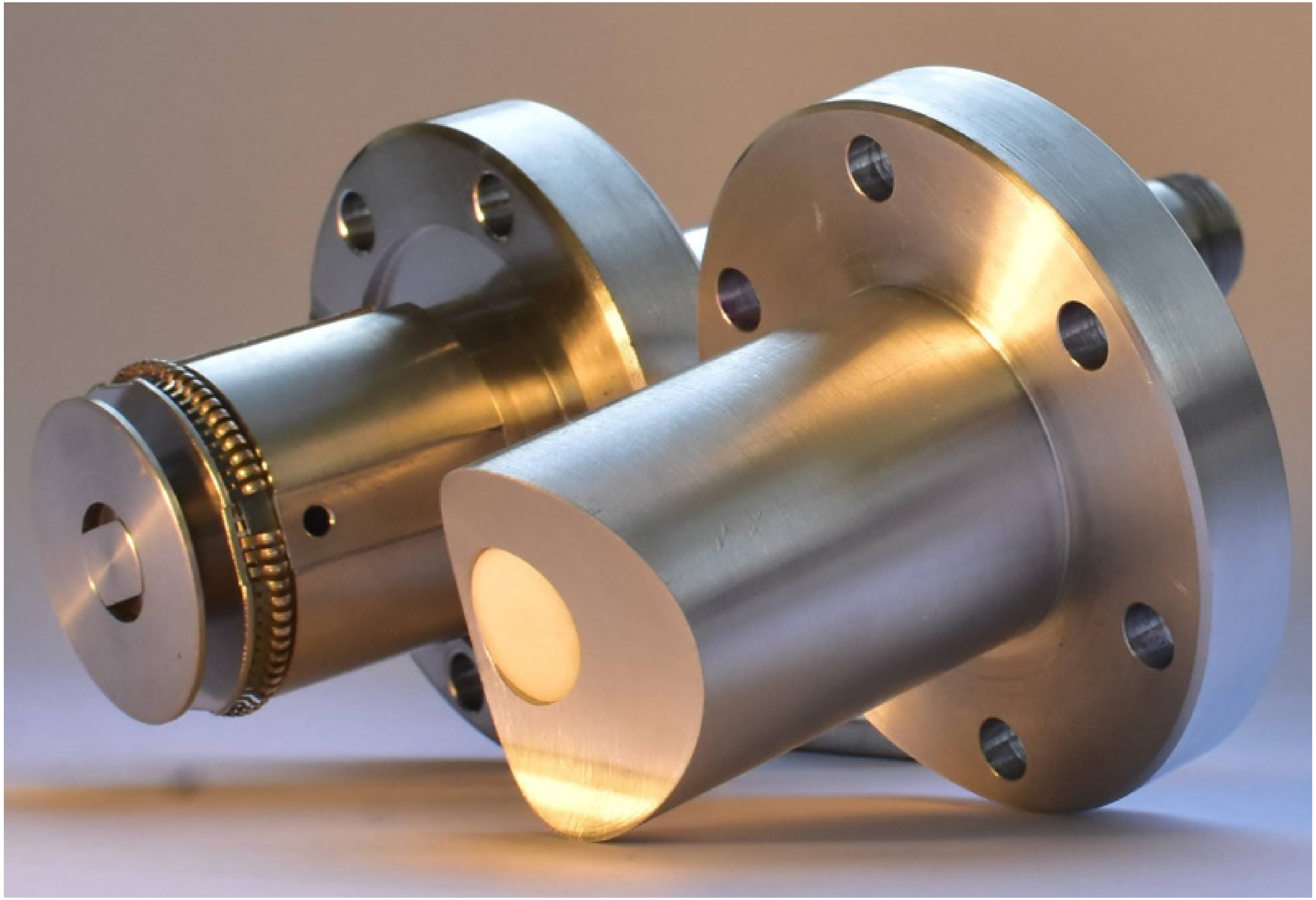
p$^+$ average
Waterbag fit
Gaussian fit

- The **Gaussianity of the beam profile** determines the **extension at high frequency** of the beam **spectrum**.
- For the **AWAKE** case, a **low-tailed distribution** such a **waterbag fits** better the **p$^+$ beam** profile measured with a streak camera analysing the OTR light.
  This has a longer extension in the frequency spectrum.
- To select the detection frequency for the electrons, **some margin must be accounted for to accommodate proton non-Gaussianity.**

WATERBAG FUNCTION

$$f_{\mathrm{WB}}(t, t_b, A) = \begin{cases} A\left(1-\left(\frac{2t}{t_b}\right)^2\right)^{\frac{3}{2}} & |t| < \frac{t_b}{2} \\ 0 & |t| \geq \frac{t_b}{2} \end{cases}$$





Cherenkov Diffraction radiation

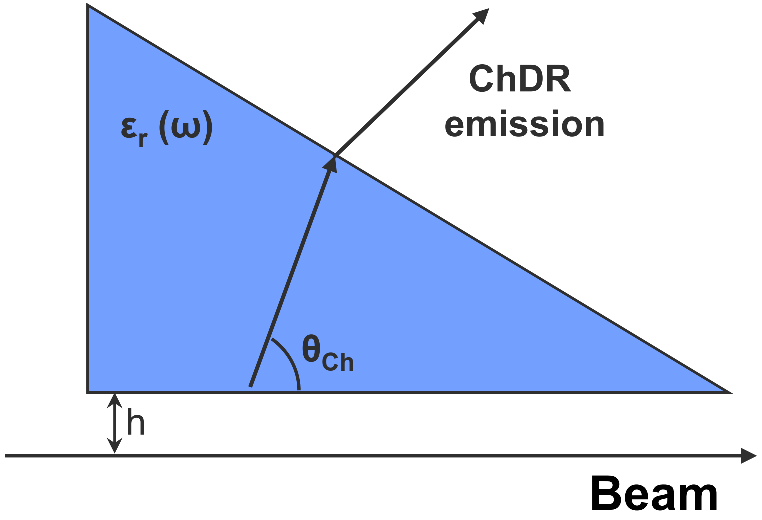
- Cherenkov Diffraction Radiation is a type of polarization **radiation induced in dielectrics** when a charged particle passes in proximity to the surface

- Very well-defined properties, including the radiation front direction at the Cherenkov angle θ_{Ch}

  See: M. V. Shevelev and A. S. Konkov, JETP **118**, 501-511 (2014)

- Recent interest to realise non-intercepting diagnostics

  See: A. Curcio et al., *Phys. Rev. Accel. Beams* **23** (2020) 022802
  R. Kieffer et al., *Phys. Rev. Lett.* **121** (2018) 0548802
  T. Lefevre et al., *Cherenkov Diffraction Radiation as a tool for beam diagnostics*, Conf. Proc. IBIC 2019 (2019), Malmo, Sweden

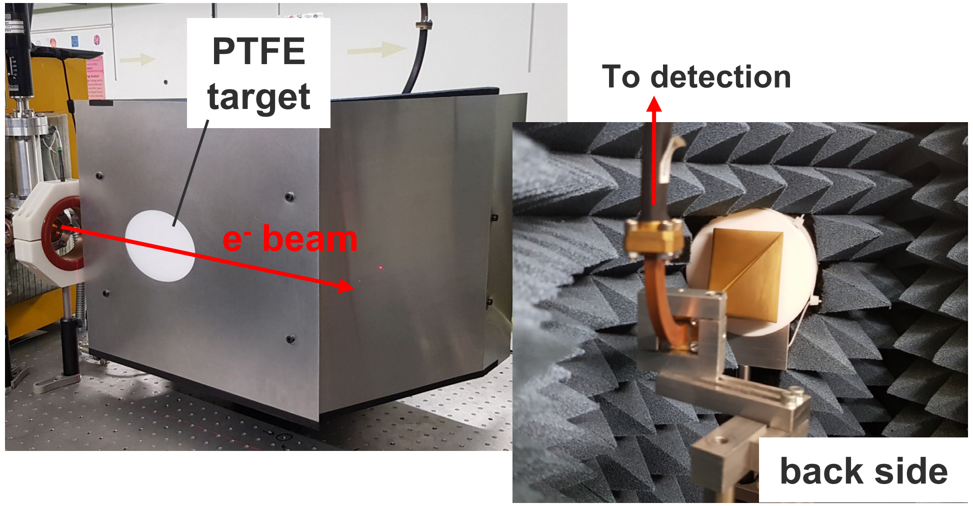


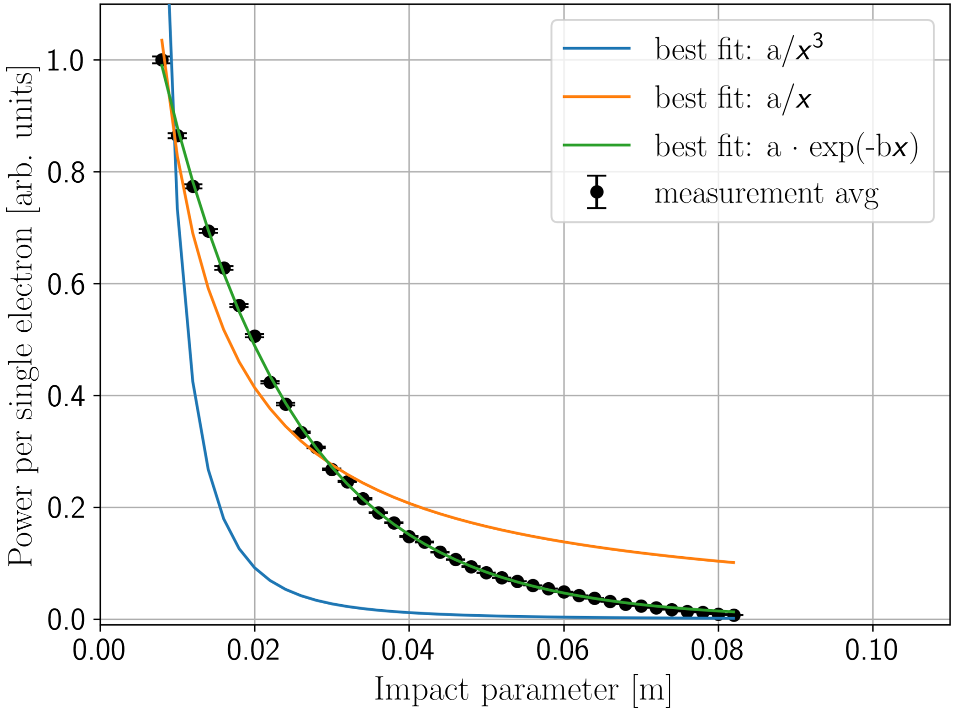
ChDR position dependence

- The **position dependence** was tested with a large PTFE radiator in air at the CLEAR facility to compare different theoretical models.
- The radiation was coupled with a horn antenna, and measured with a Schottky diode at 30 GHz with 300 MHz bandwidth.
- Details were presented in IPAC’22

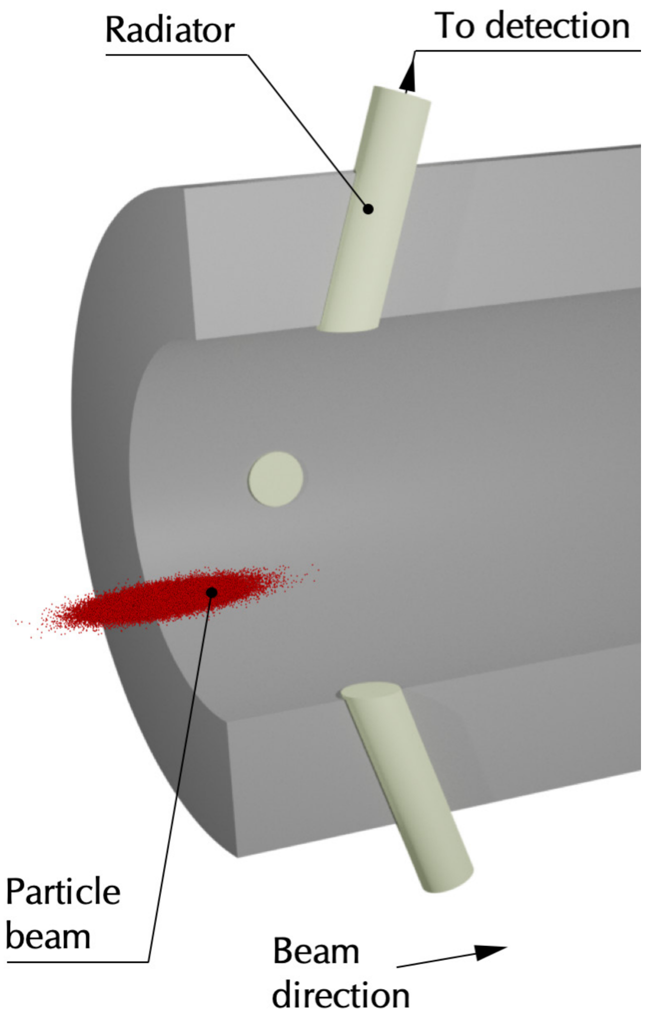
  See: K. Lasocha et al., *Experimental Verification of Several Theoretical Models for ChDR Description*, Conf. Proc. IPAC’22 (2022), Bangkok, Thailand

For the latest results with direct E-field measurement with EO techniques check out the **poster TUP022** !



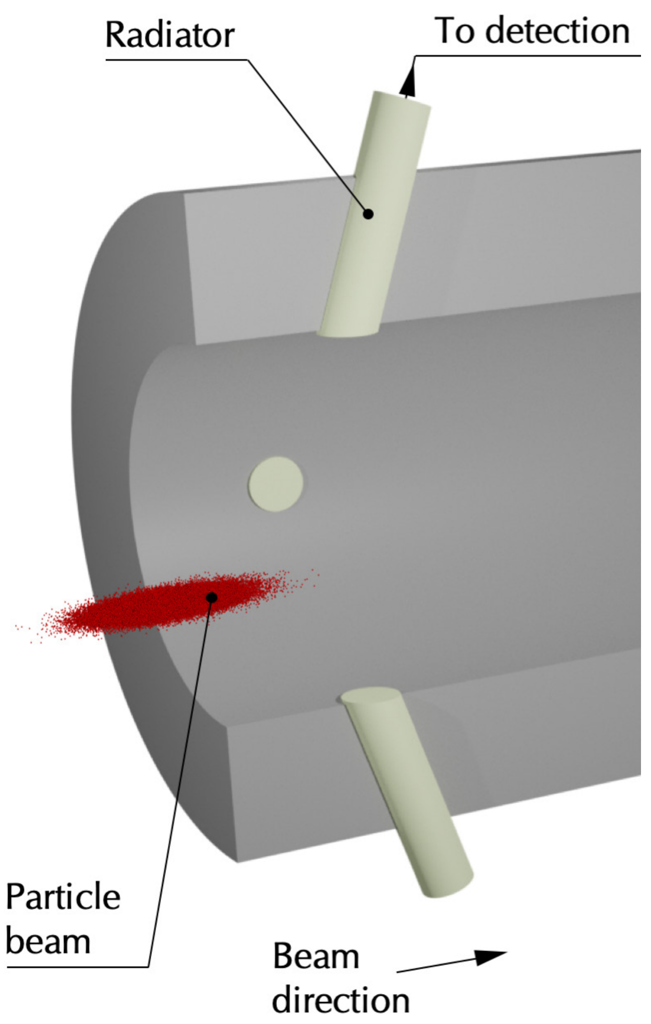


Pickup design – Mechanical description



- **Cylindrical Radiators** are inserted in a vacuum chamber.
- A brazed collar assure them to be vacuum tight.
- The dielectric bar is left protruding outside, to ease the transition into waveguides.

Pickup design – Radiation propagation

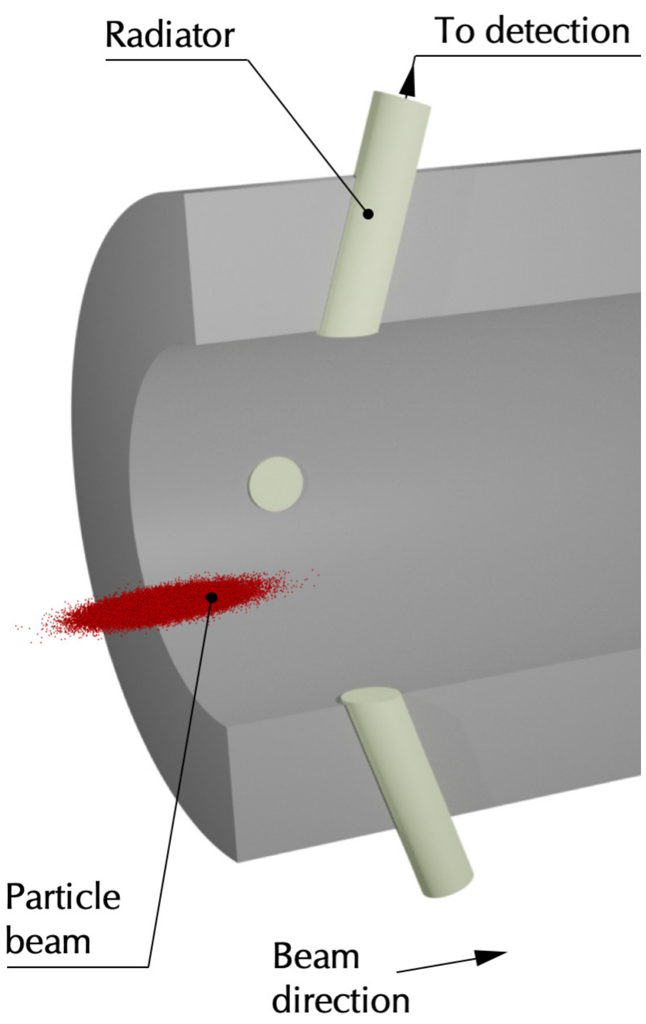


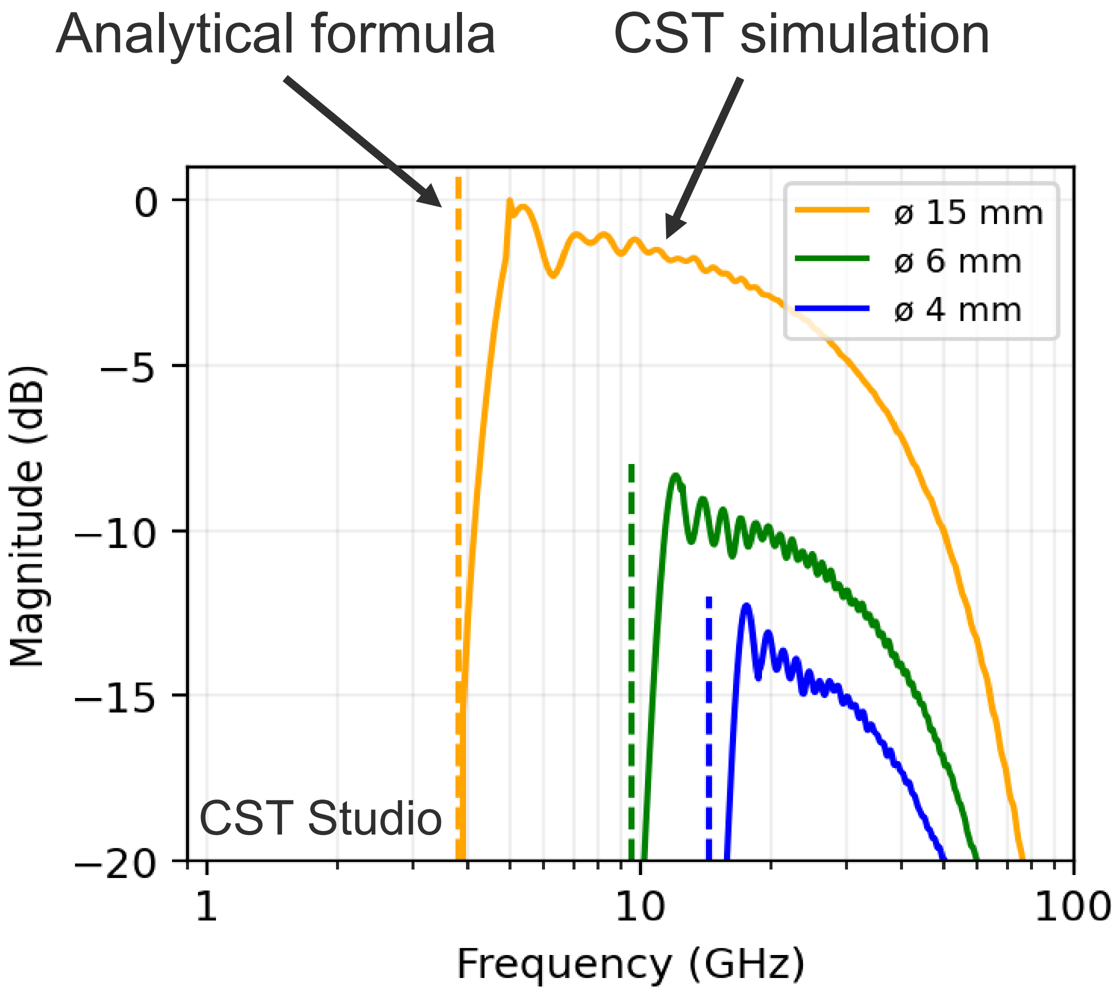
- Although broadband radiation is generated at the surface, the radiator dimensions determine the output radiation properties.
- For cylindrical radiators surrounded by metallic walls, the **base mode cutoff frequency** is

$$f_{c,TE11} = 1.8412 \underbrace{\frac{c}{2\pi r}}_{\text{Radiator radius}} \underbrace{\frac{1}{\sqrt{\epsilon_r}}}_{\text{Material selection}}$$

- Below cutoff, the electric field propagation is exponentially damped.

Pickup design – Radiation propagation simulation



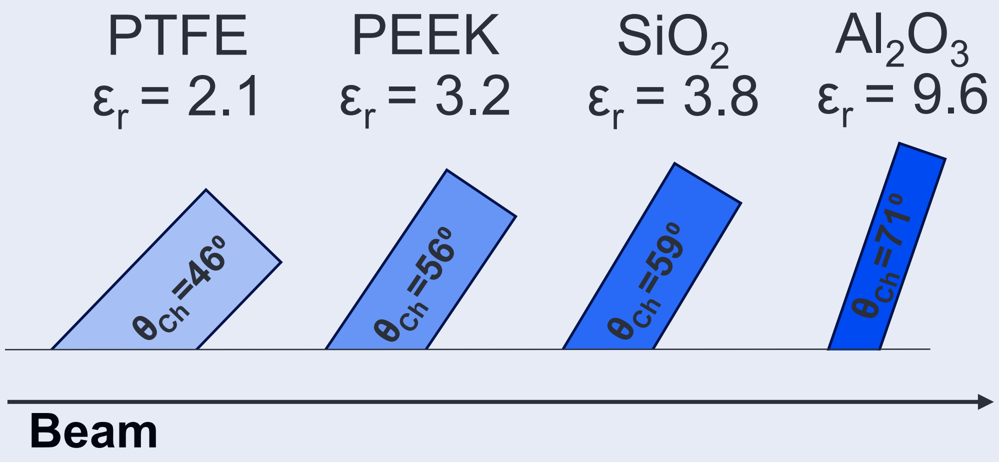


Pickup design – Material selection

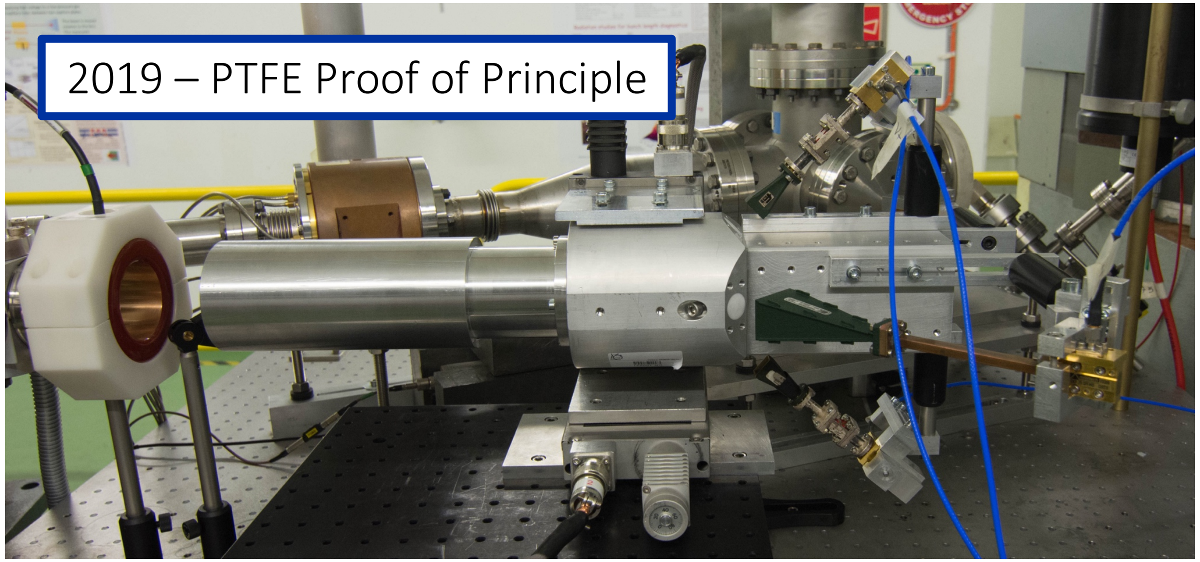
- A large choice of dielectric materials can be used as radiators, such as PTFE, PEEK, Fused silica, Alumina, …

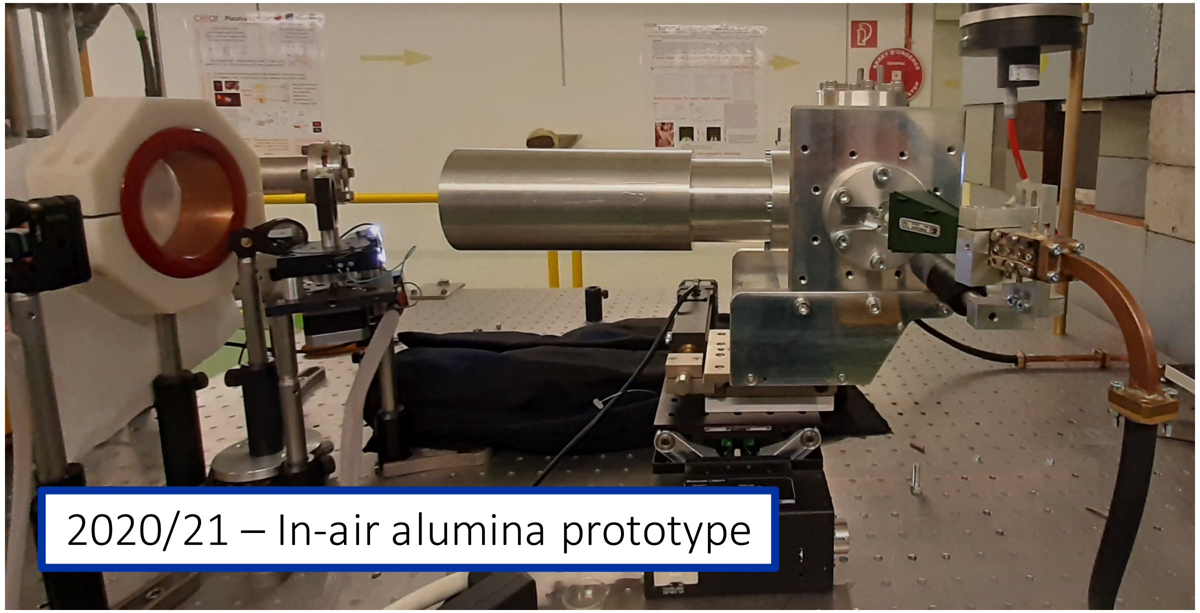
- As ε_r increases:
  - Larger Cherenkov angles
  - The low cutoff frequency decreases

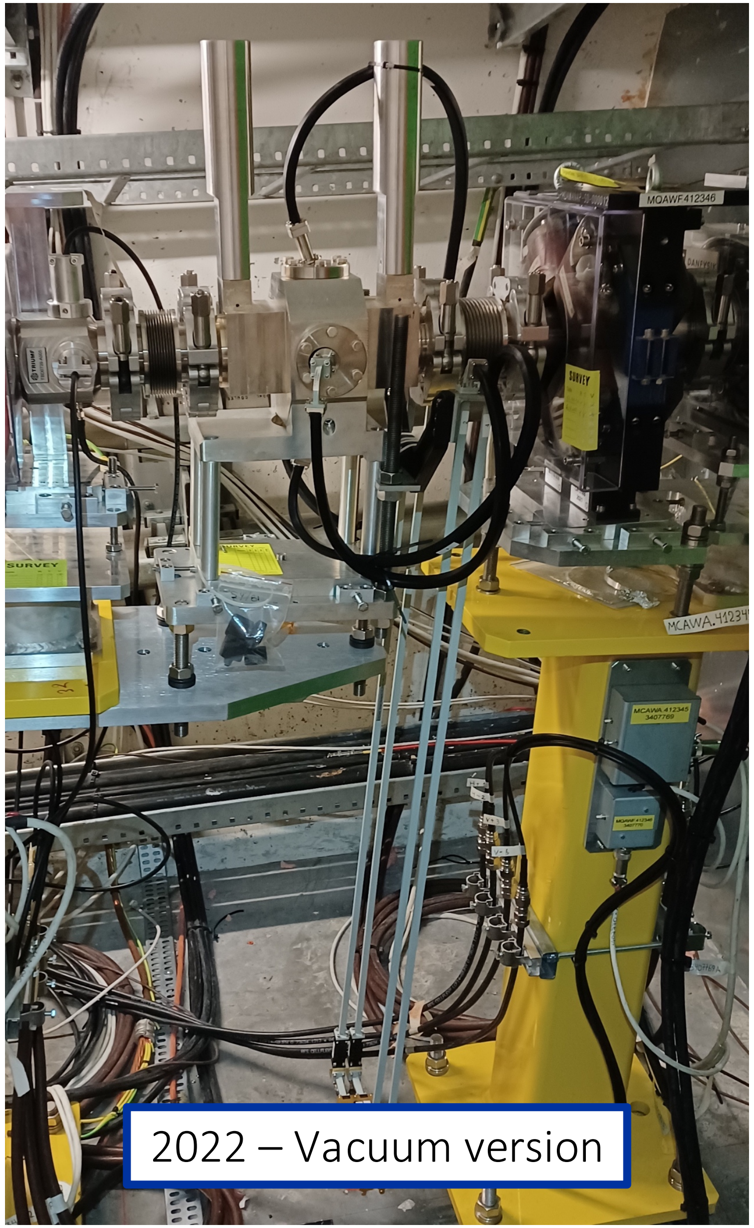
Material	PTFE	PEEK	Fused Silica	Alumina
Relative permittivity ϵ_r	2.1	3.2	3.8	9.6
Cherenkov angle θ_{Ch}	46°	56°	59°	71°
Relative cutoff to vacuum $f_c/f_{c,vac}$	0.69	0.55	0.51	0.32



Comparison of **different dielectric materials** for cylindrical ChDR radiators. The **radiator radius is scaled** to maintain the same cutoff frequency.


2019 – PTFE Proof of Principle

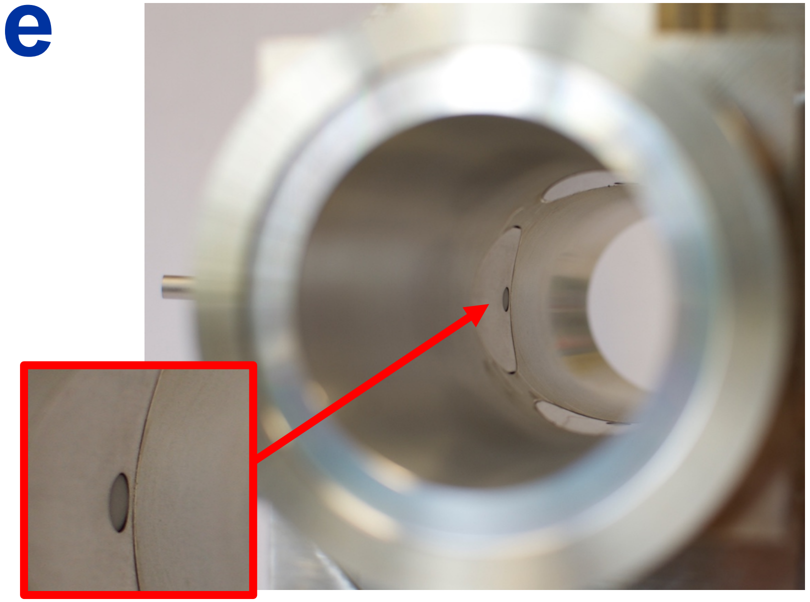

2020/21 – In-air alumina prototype

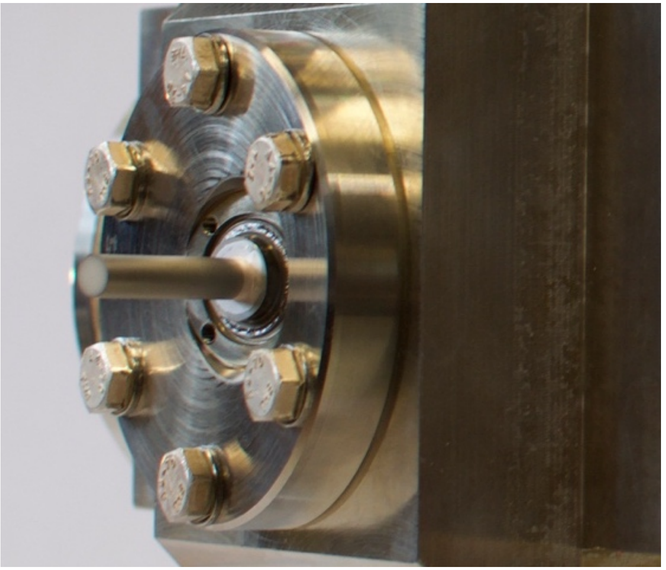

2022 – Vacuum version

Pickup design – Real case

- Beampipe diameter 60 mm
- Alumina 99.5% pure ($\varepsilon_r = 9.4$)
- Cylindrical rods 90 mm x Ø 6 mm
- Metallic coating ~10 μm thick
- Low cutoff frequency choice
  $f_{c,TE11}$ = 9.7 GHz

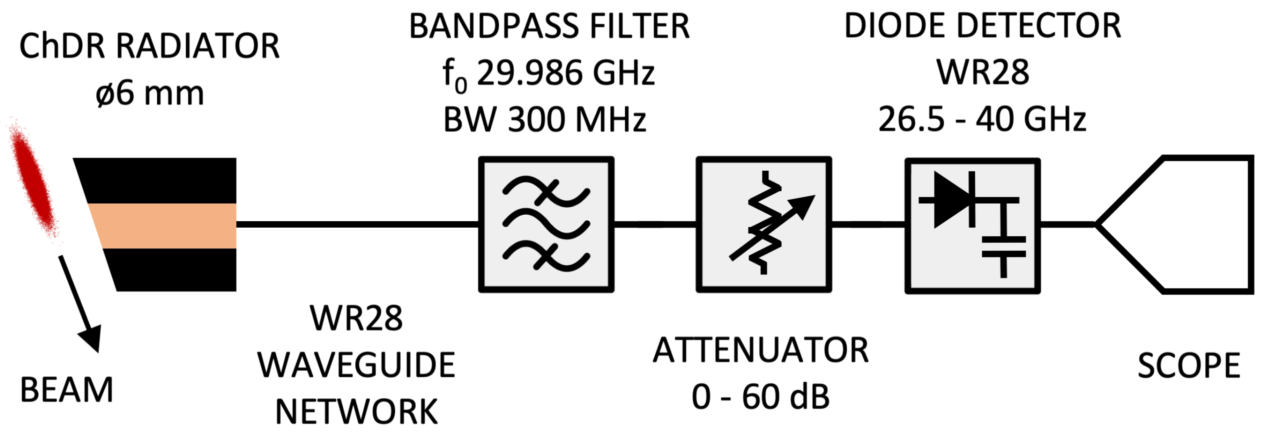
Diameter (mm)	f cutoff (GHz)
2	29
4	14.5
5	11.6
6	9.7
10	5.8
15	3.9



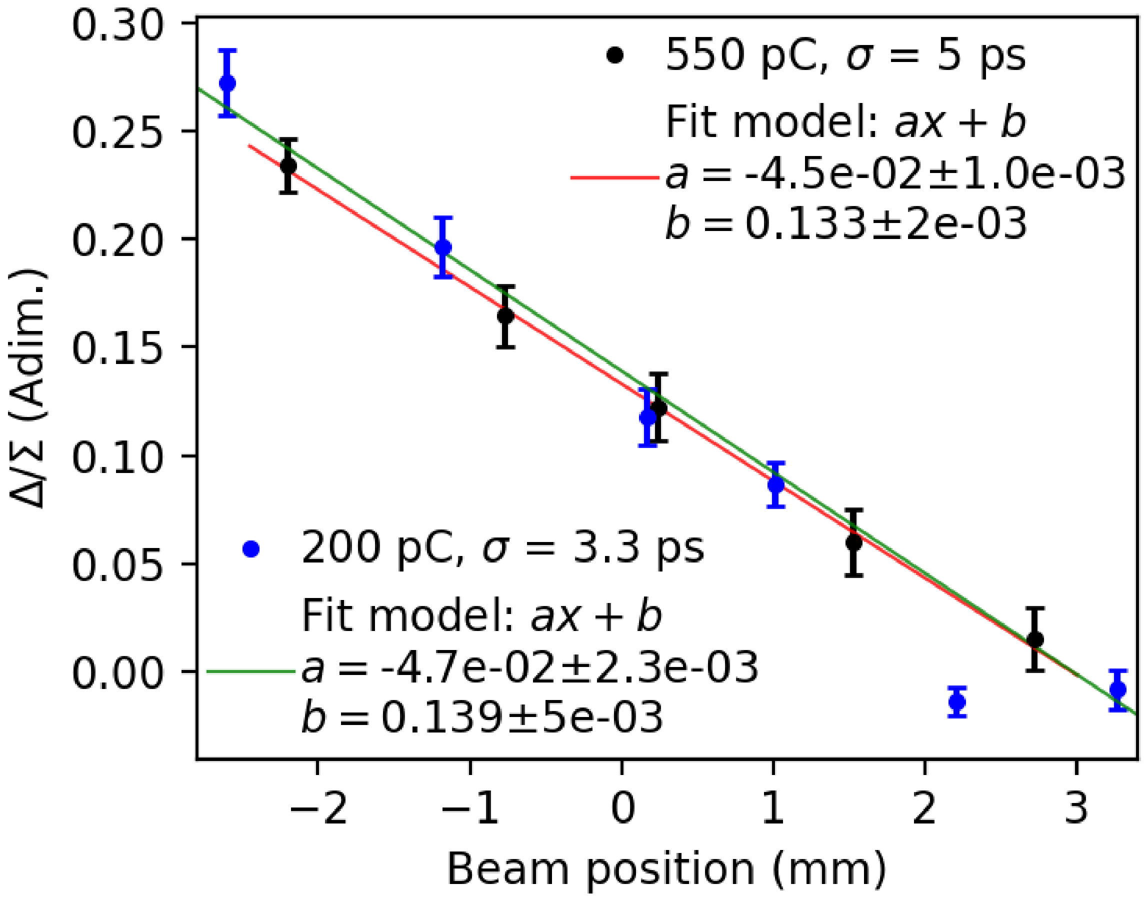


Test setup

- **Beam-based test** with 100-600 pC single-bunch electron.
- **Multi-shot measurement**, using the remote-controlled attenuator to keep a constant diode input power and limit non-linear response effects.
- Data recorded with a 6 GHz scope in the alcove ~20 m away.



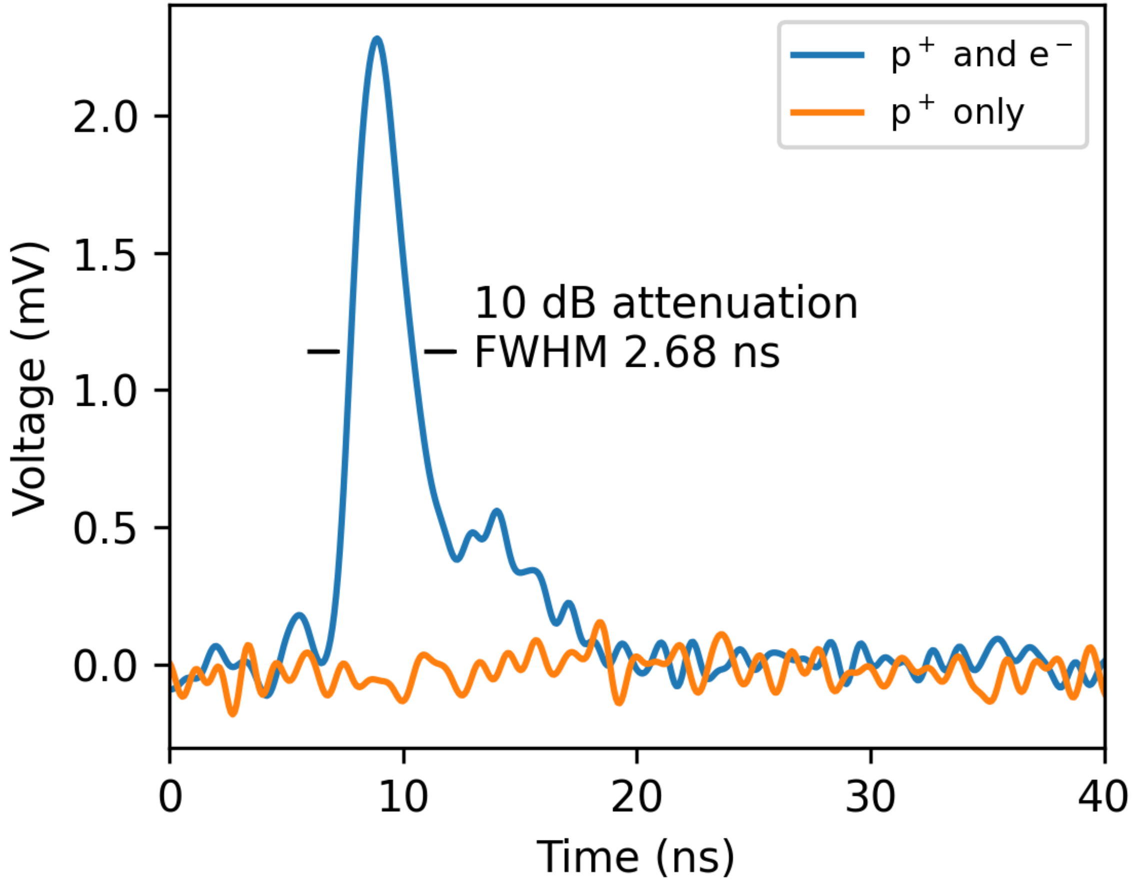
Test results (1)



Sensitivity to electrons only

- Similar response to high and low charge with AWAKE parameters
- **Linear response** in a 5 mm range
- Limited test time in AWAKE, preliminary test for the operational electronics

Test results (2)

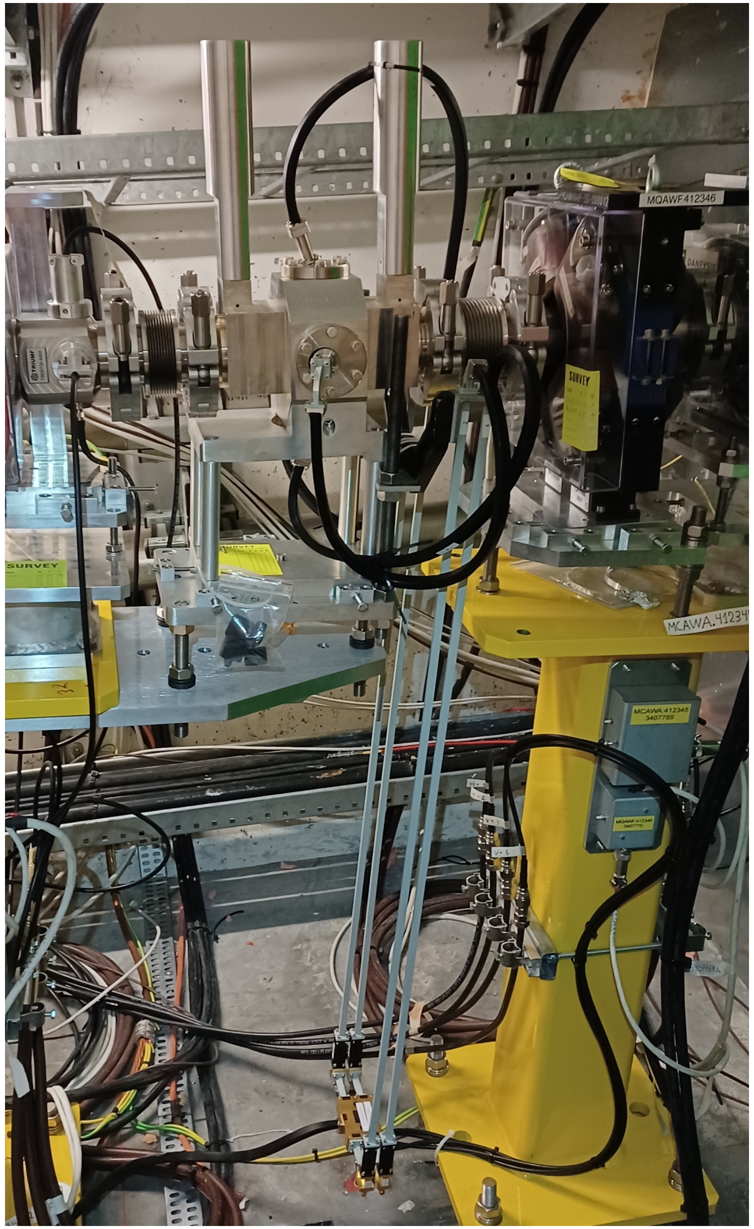


Proton signal rejection

- **Proton-only signals below noise** level for 1e11 protons per bunch
- **No signal** shape change for simultaneous **protons + electrons**
- Some signal with 3e11 protons per bunch, however depressed with respect to the electrons. Under investigation.

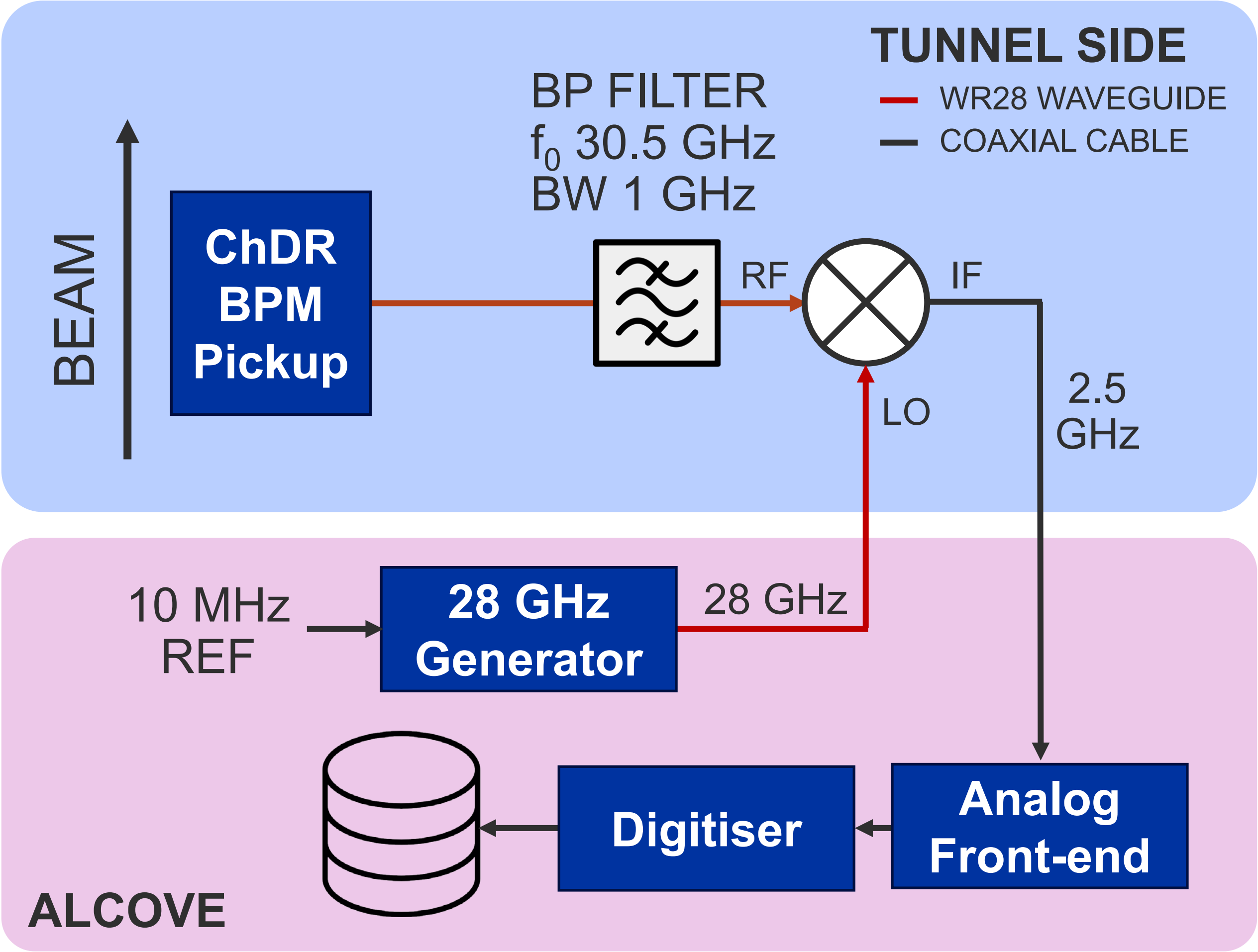
Operational electronics

- A collaboration with **TRIUMF** was started to realise **high-frequency BPM electronics.**
- The elected **operation frequency** is **30.5 GHz** with a bandwidth of 1 GHz.
- The system was realised on the model of the existing electron BPMs, to ease integration.
- First module installed for tests in 2022.



Operational electronics

- Initial tests in 2022 currently ongoing.



TUNNEL SIDE

🟥 WR28 WAVEGUIDE

⬛ COAXIAL CABLE

BEAM

ChDR BPM Pickup

BP FILTER
f_0 30.5 GHz
BW 1 GHz

RF

IF

LO

2.5 GHz

10 MHz REF

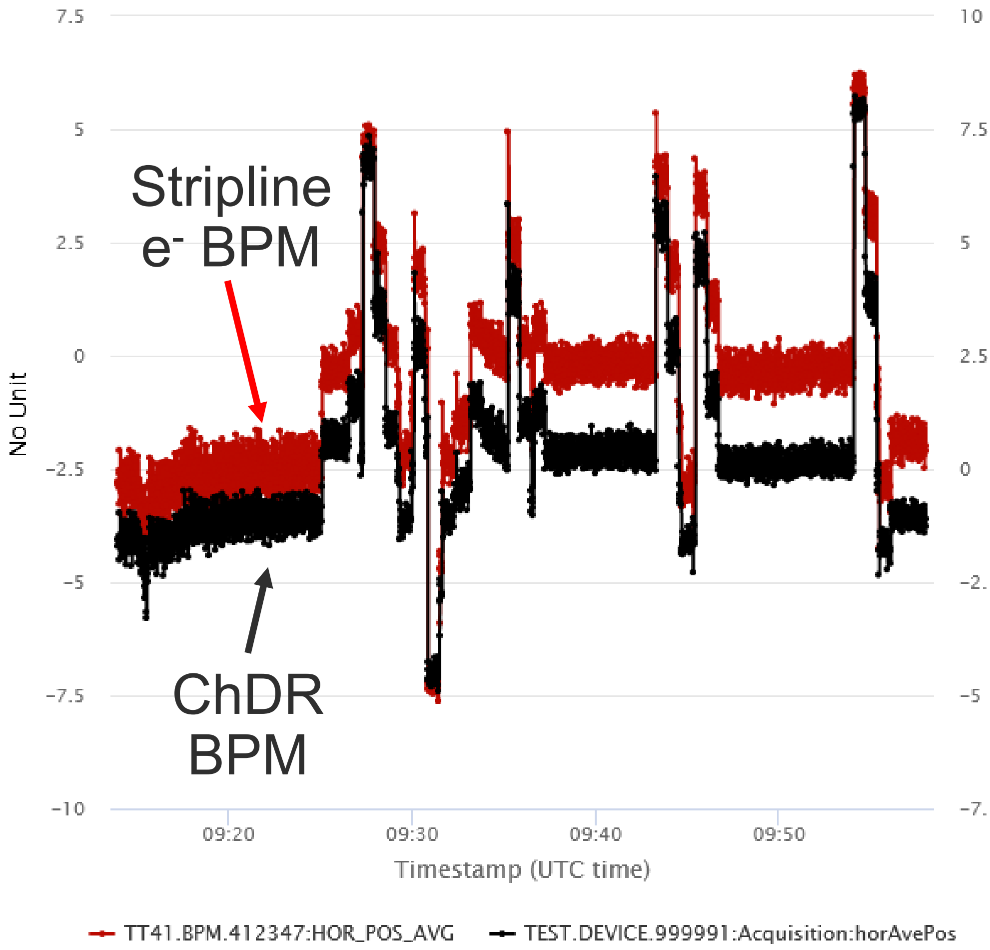
28 GHz Generator

28 GHz

Digitiser

Analog Front-end

ALCOVE



Stripline e^- BPM

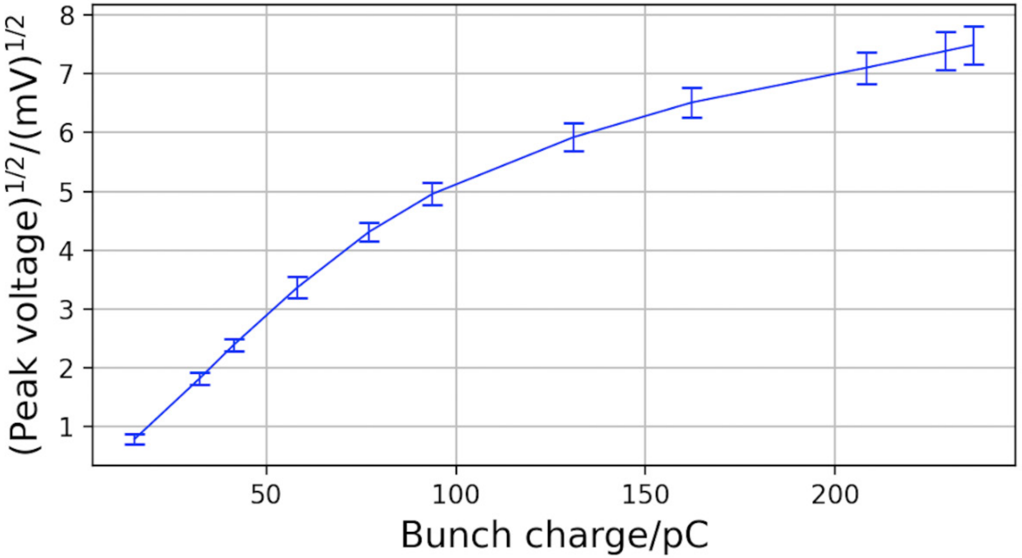
ChDR BPM

Future outlook

ChDR pickups are a **promising but young technology !**

PROs:

- Large signal output. Can measure **charges** as **low** as **few pC.**



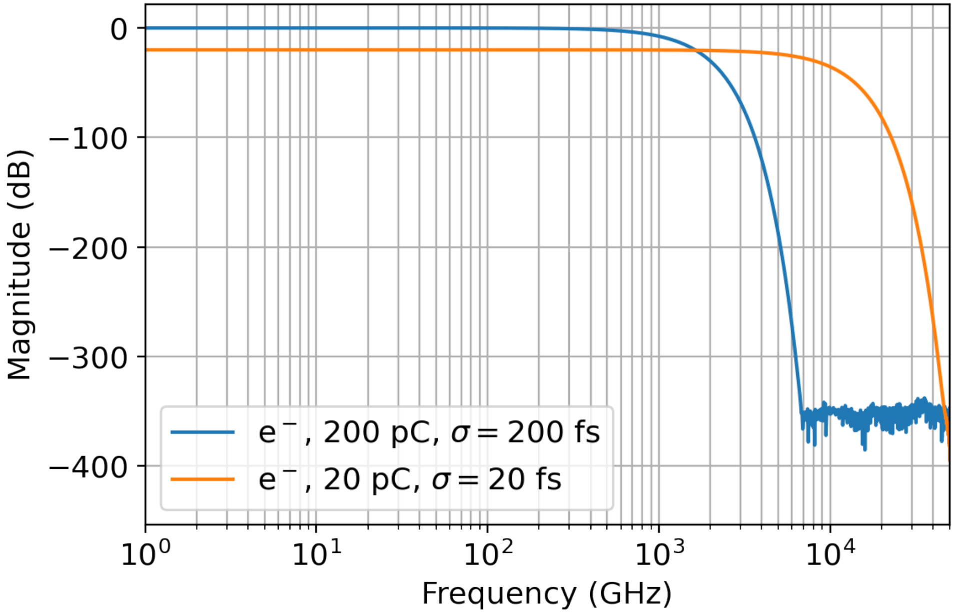
See: C. Pakuza et al., *Electron Beam studies on a Beam Position Monitor based on Cherenkov Diffraction radiation*, Conf. Proc. IPAC'23 (2023), Venice, Italy

Future outlook

ChDR pickups are a **promising but young technology !**

PROs:

- Large signal output. Can measure **charges** as **low** as **few pC.**
- **Very large bandwidth**.
  - **High cutoff frequency** defined only by the bunch length. Potential for **optical detection** with short bunches.
  - **Low cutoff frequency** defined by construction.
- Allow for **beam distinction** based on frequency discrimination.



Example for driver + witness bunch with beam parameters from Pompili et al., Nature Vol 605, 659 (2022)

Future outlook

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  - **Low cutoff frequency** defined by construction.
- Allow for beam distinction based on frequency discrimination.

CONs:

- **Difficult to test** in the GHz regime.
  - Pickup **quality control** and pairing.
  - No lab setup to find the electrical centre.

Future outlook

ChDR pickups are a **promising but young technology !**

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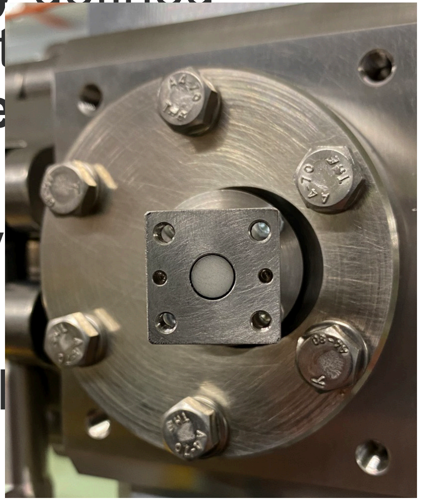


CONs:

- **Difficult to test** in the GHz regime.
- **Complicated RF front-end design.**
  - Need careful front-end design with **waveguide hardware** and broadband emission.
  - A broadband **transition** between **radiator** and standard **waveguide** must be engineered.

Future outlook

ChDR pickups are a **promising but young technology !**

PROs:

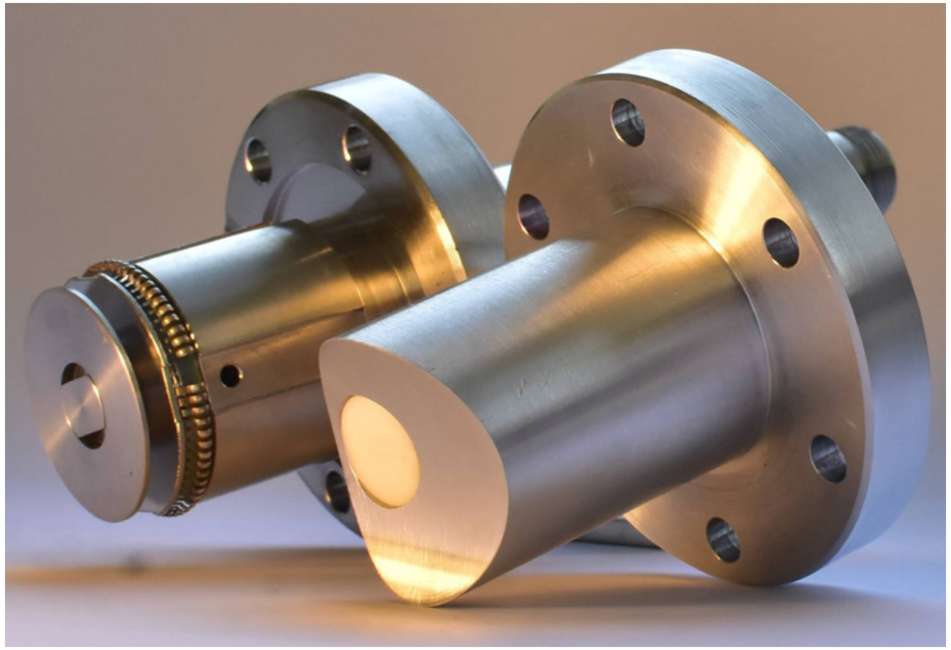
- Large signal output. Can measure **charges** as **low** as **few pC.**
- **Very large bandwidth**.
  - **High cutoff frequency** defined only by the bunch length. Potential for **optical detection** with short bunches.
  - **Low cutoff frequency** defined by construction.
- Allow for beam distinction based on frequency discrimination.

CONs:

- **Difficult to test** in the GHz regime.
- **Complicated RF front-end design.**
- **Impedance control**: so far tests with single bunch single pass beamlines. To be assessed for rings.

Conclusions

- **Cherenkov Diffraction Radiation** is a useful tool for building non-interceptive beam diagnostics, and it is increasingly gaining relevance in the community in recent years.
- **Dielectric pickups are a promising** young technology, as they can achieve a larger bandwidth than other pickup types, even with large beampipe apertures.
- **Potential impact for** any accelerator with **short bunches**, including new acceleration technologies (PWFA, LWFA, xFELs, …).



Thanks for your attention

Acknowledgements: V. Bencini, P. Bestmann, P. Burrows, A. Cherif, N. Chritin, V. Clerc, C. Davut, W. Farabolini, F. Galleazzi, E. Gschwendtner, E. Guran, P. Karataev, J. Kortesmaa, P. Korysko, M. Krupa, K. Lasocha, S. Liu, T. Lefevre, T. Manson, S. Mazzoni, B. Moser, C. Pakuza, E. Poimenidou, P. Muggli, A. Pardons, C. Pasquino, C. Saury, A. Schloegelhofer, P. Schwartz, E. Senes, A. Topaloudis, B. Spear, L. Verra, F. M. Velotti, C. Vendeuvre, V. Verzilov, M. Wendt, B. Woolley, G. Zevi Della Porta

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