Beam position monitor based on Cherenkov diffraction radiation for the AWAKE experiment

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CERN AWAKE clear UNIVERSITY OF OXFORD JAI John Adams Institute for Accelerator Science

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- Results

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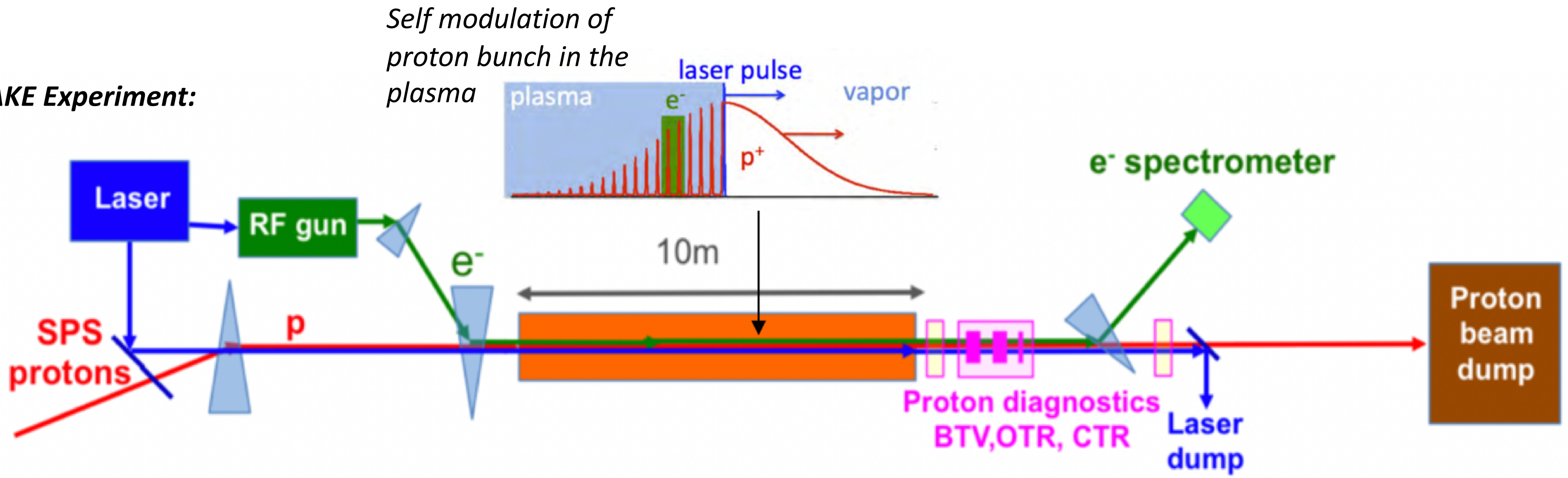
Introduction

The AWAKE Experiment

- A new type of beam position monitor based on Cherenkov diffraction radiation is being developed for application at the AWAKE experiment at CERN
- The experiment uses proton bunches (RMS bunch length 6-8 cm) from the SPS to generate wakefields in a 10 m long rubidium vapor cell for electron acceleration
- To effectively drive the wakefields, long proton bunch is divided into a train of microbunches (RMS longitudinal bunch size of the order of the plasma wavelength ~1mm) inside the plasma channel through a process of self modulation which is seeded by the laser pulse

The AWAKE Experiment:



[1] C. Bracco et. al., *Beam studies and experimental facility for the AWAKE experiment at CERN*, Nuclear Instruments and Methods, A, **740**, 48-53, 2014.

Motivation for a high-frequency beam position monitor

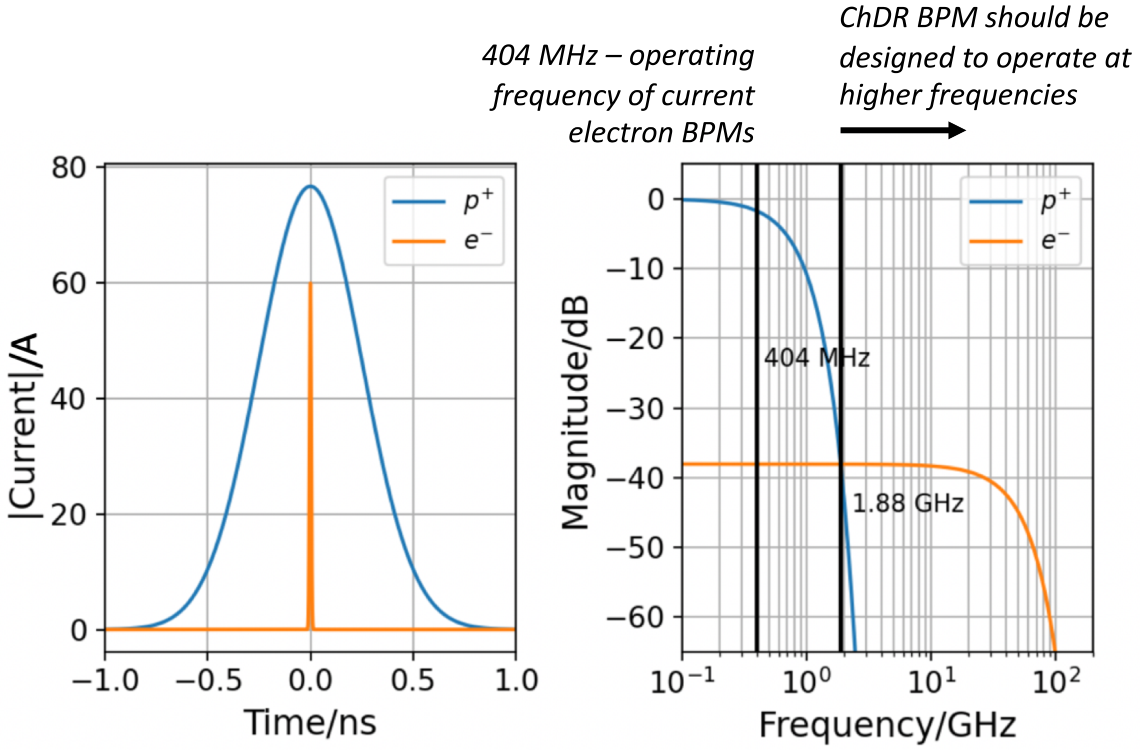
- In the common beam-line before the entrance of the plasma cell, both electron and proton bunches propagate together in time and space

- Beam parameters prior to entering plasma cell:

Particle beam	Charge/nC	σ/ps
Proton	48	250
Electron	0.6	4

- The current electron BPMs in the common beam-line operate at 404 MHz where the electron signal is overshadowed by the proton signal

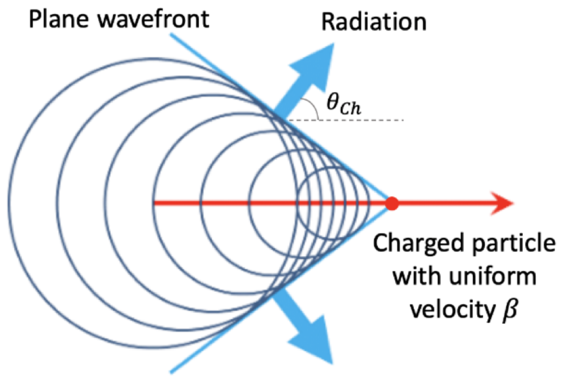
- To measure the electrons in the presence of the more-intense proton bunches, requires a BPM to have a pass-band at frequencies higher than a few GHz



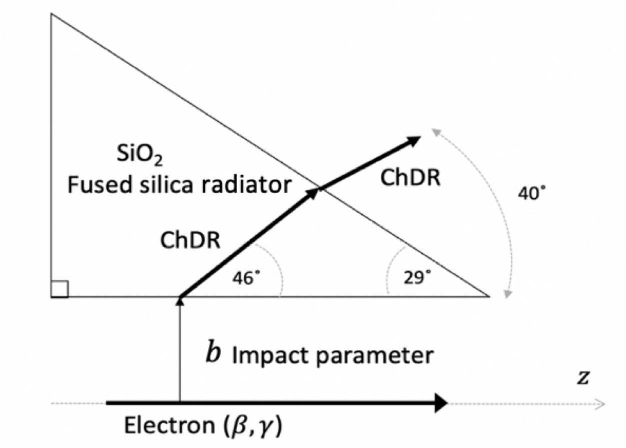
Beam distributions in time and frequency domain

Cherenkov diffraction radiation

- High frequency mechanically challenging for conventional BPMs
- Design a BPM based on Cherenkov diffraction radiation (ChDR) which is a type of **polarization radiation** produced when a charged particle passes in **close proximity** to a dielectric medium (radiator) with velocity greater than the phase velocity of light in that medium (Cherenkov condition $v_p > c/n$)
- Beam field interacts with the **surface** atoms of the radiator producing a polarization field that propagates through the medium at $\theta_{Ch} = \cos^{-1}\left(\frac{1}{n\beta}\right)$



*Generation of Cherenkov radiation **inside** a dielectric material*



Generation of ChDR for a triangular radiator

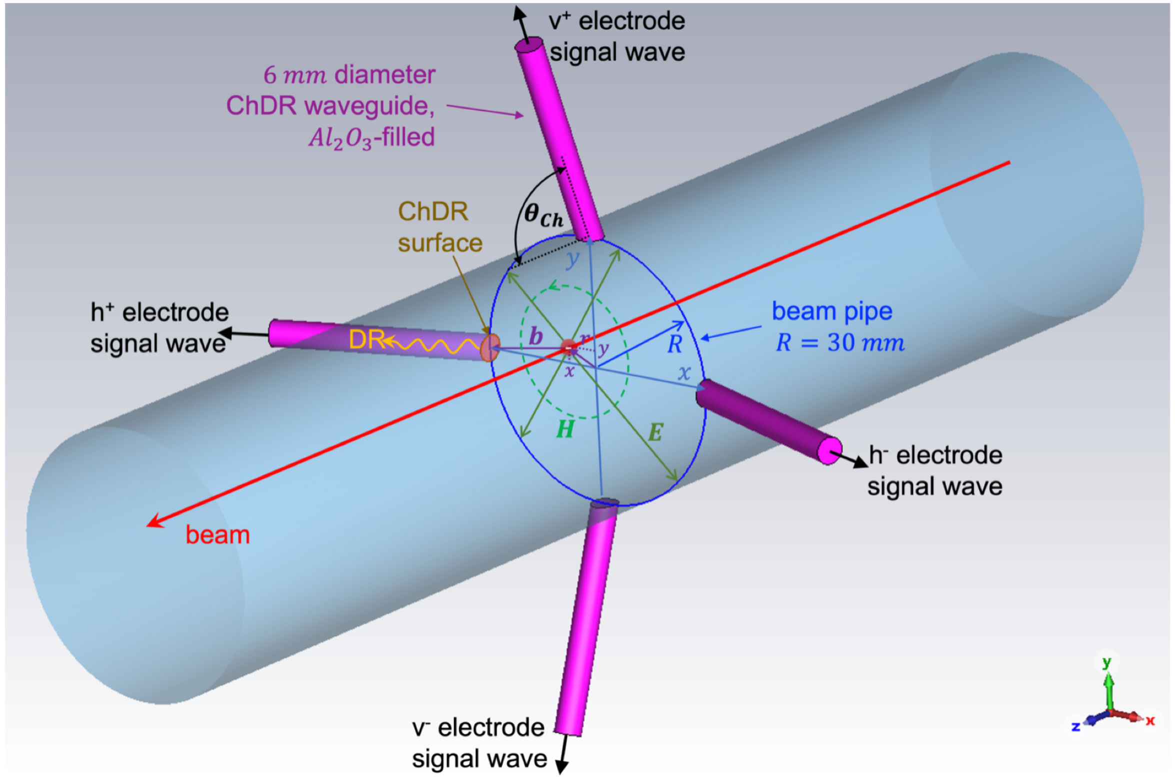
Useful technique:

✔ Provides **non-invasive** measurement

✔ Emission at a **well-defined angle**

Conceptual design

- 2+2 symmetric arrangement of radiators on perimeter of beampipe
- Polarisation radiation (combination of ChDR and DR from radiator edge) is produced and propagates through the radiators
- Signal proportional to bunch charge and function of beam position
- Capture the radiation from each radiator and take the difference-over-sum of the signals from each pair to obtain the intensity-independent position signal, like in "classical" BPMs



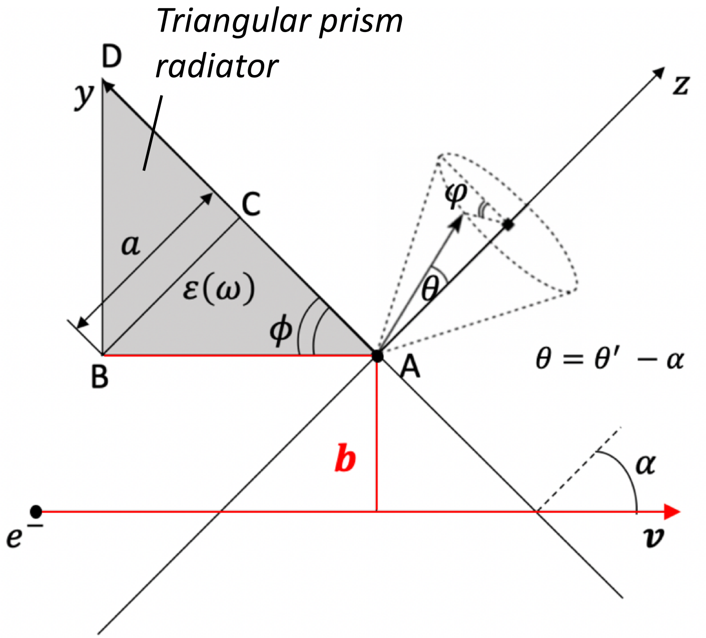
Theory and numerical simulations

[2] M. V. Shevelev and A. S. Konkov, *Peculiarities of the generation of Vavilov-Cherenkov radiation induced by a charged particle moving past a dielectric target*, J. Exp. Theor. Phys. 118, (2014).

Theory

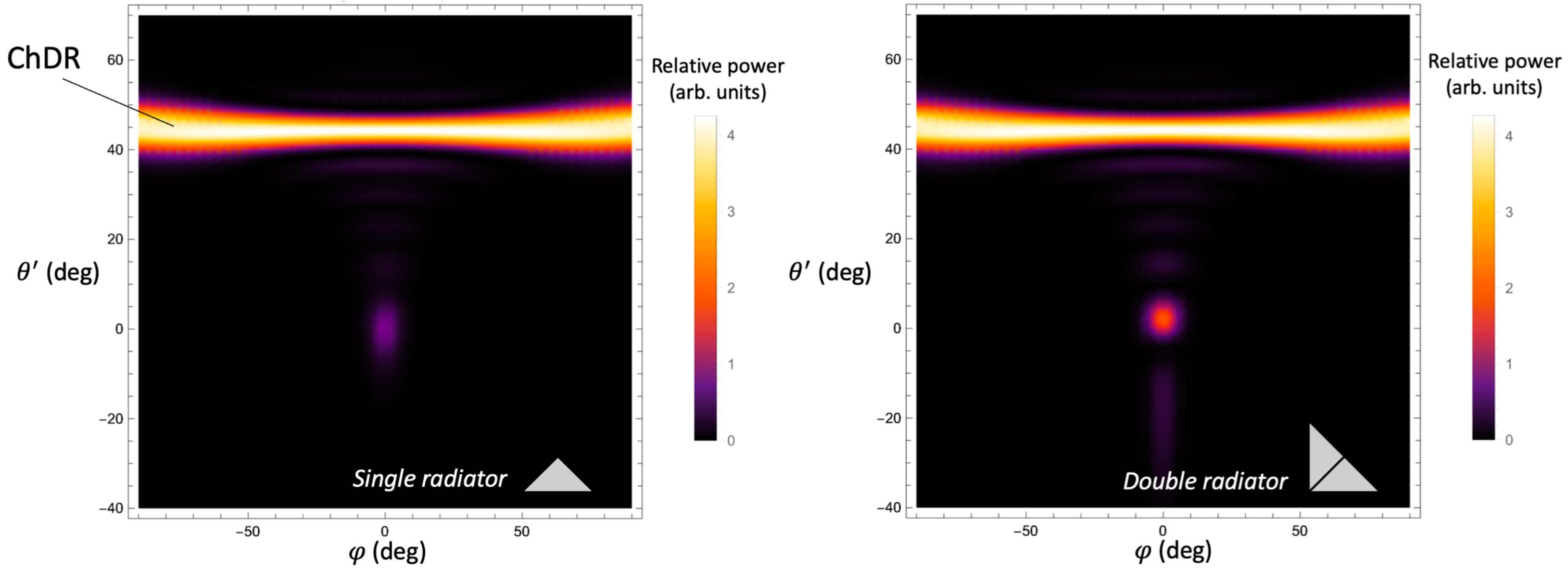
- Theoretical model describing the polarization radiation (PR) produced by a radiator is the Polarization Current Approach (PCA)

- Provides equations for the spectral-angular power distribution of emitted PR from simple radiator geometries



Spectral-angular power of polarization radiation leaving the radiator

$\sqrt{\varepsilon} = 1.41$, $b = 15$ mm, $\phi = \pi/4$, $\alpha = \pi/4$, $a = 45$ mm and wavelength $\lambda = 4$ mm



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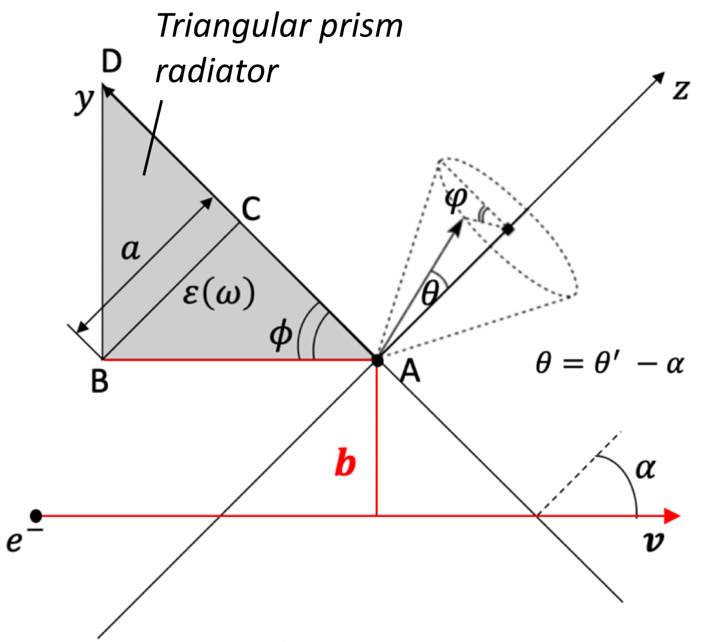

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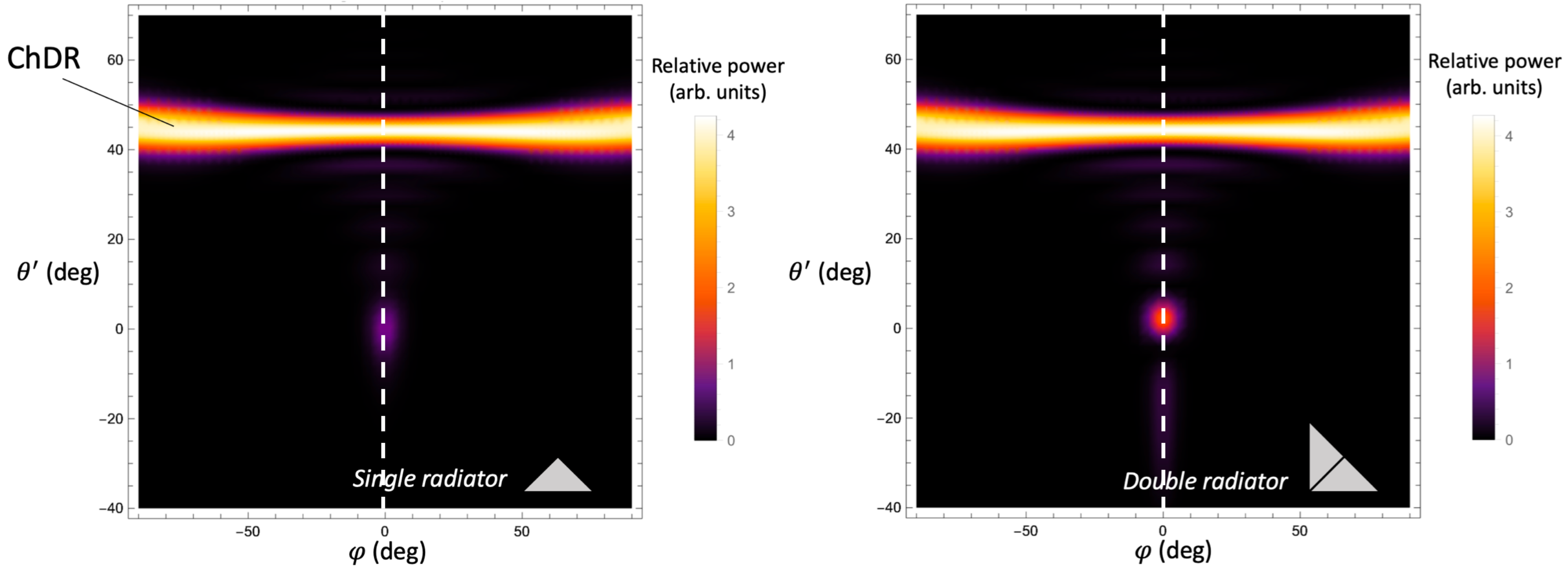
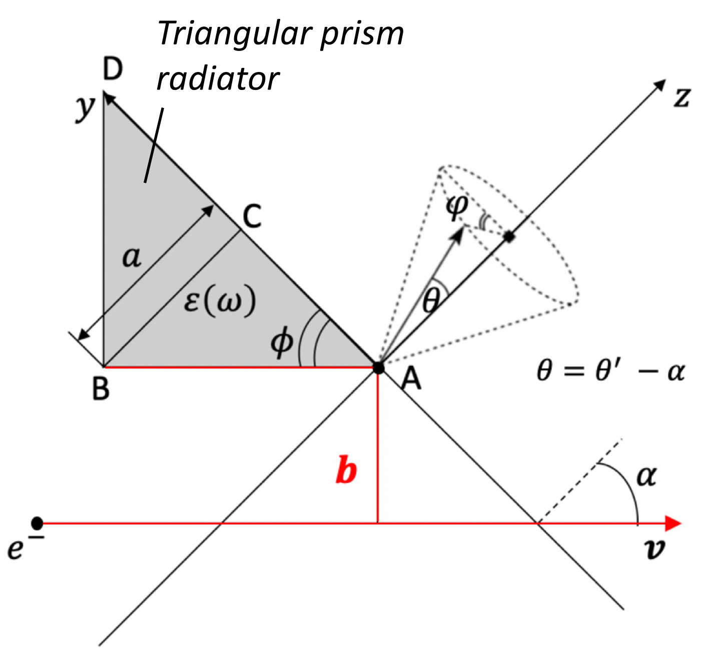
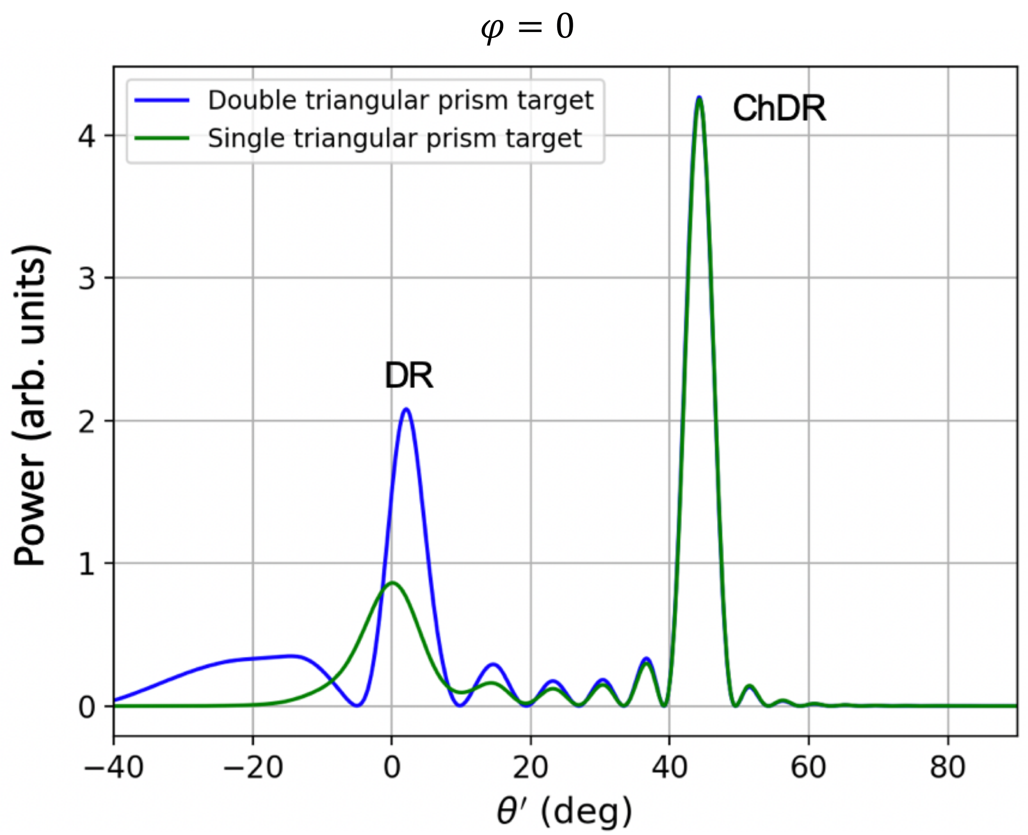


Theory

- ChDR peak doesn't change between the two radiators and more DR produced for double radiator

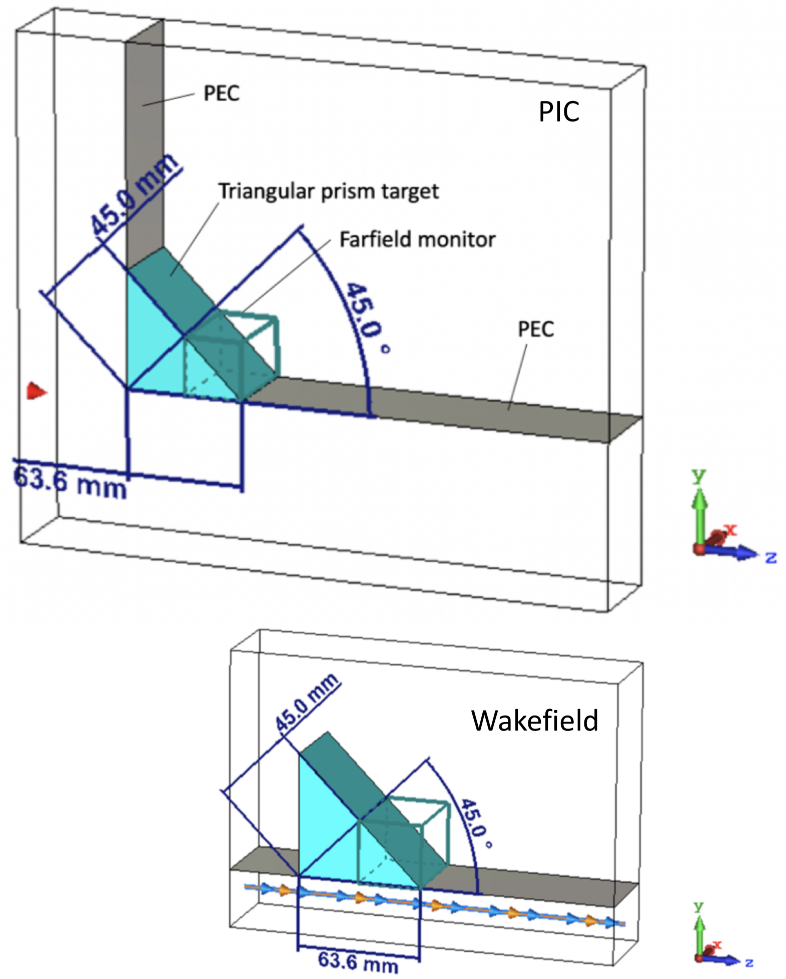
- ChDR only produced by face AB and exits at well-defined angle





Comparison to numerical simulations

- In view of studying more complex geometries for the radiator design of the AWAKE ChDR BPM, a comparison between theoretical and numerical model was made using CST with two solvers
- PIC solver:
  - Particles emitted from a circular source
  - All open space boundaries
- Wakefield solver:
  - Particle beam is represented by a line charge
  - Requires at least one electrical boundary
- Both models try to isolate the ChDR by only exposing the bottom face of the radiator to the beam field

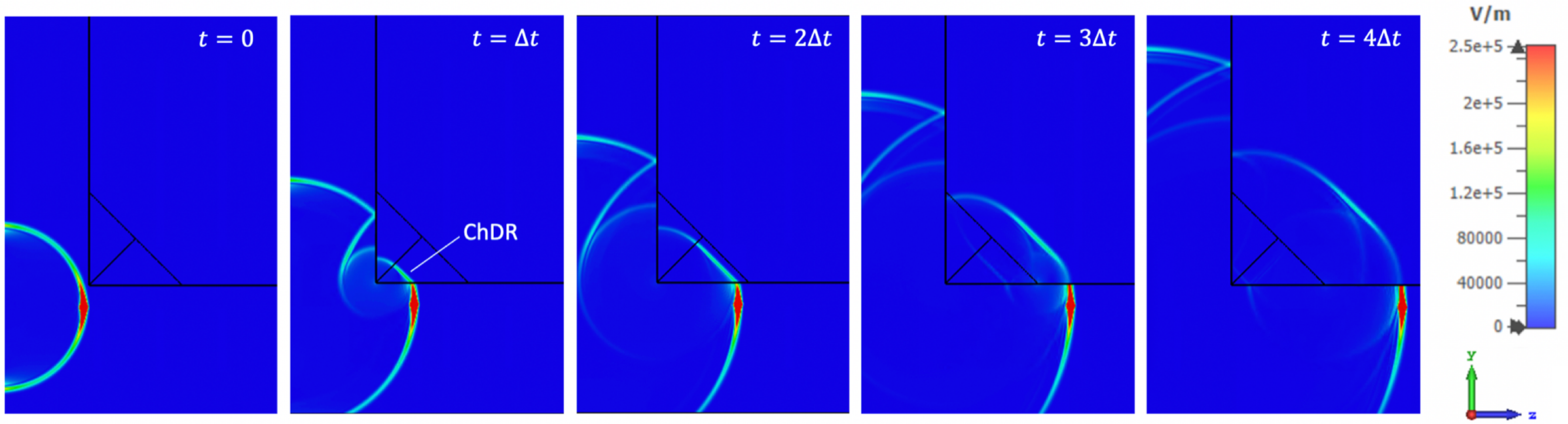


Calculation domain for double triangular radiator

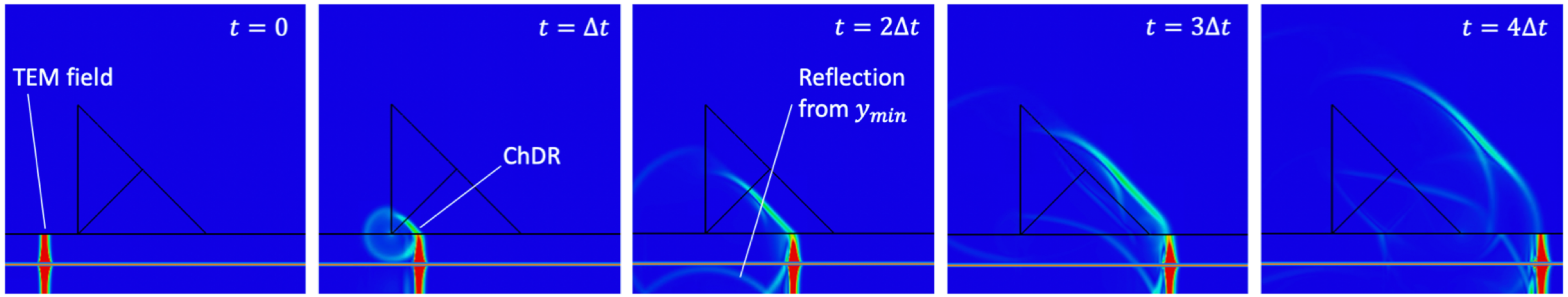
Comparison to numerical simulations

- PIC solver:
  - Beam field distribution given by geometry of emitting source
  - Beam field is not exact TEM field when entering the calculation domain

Time evolution of E-field, Δt = 0.1 ns

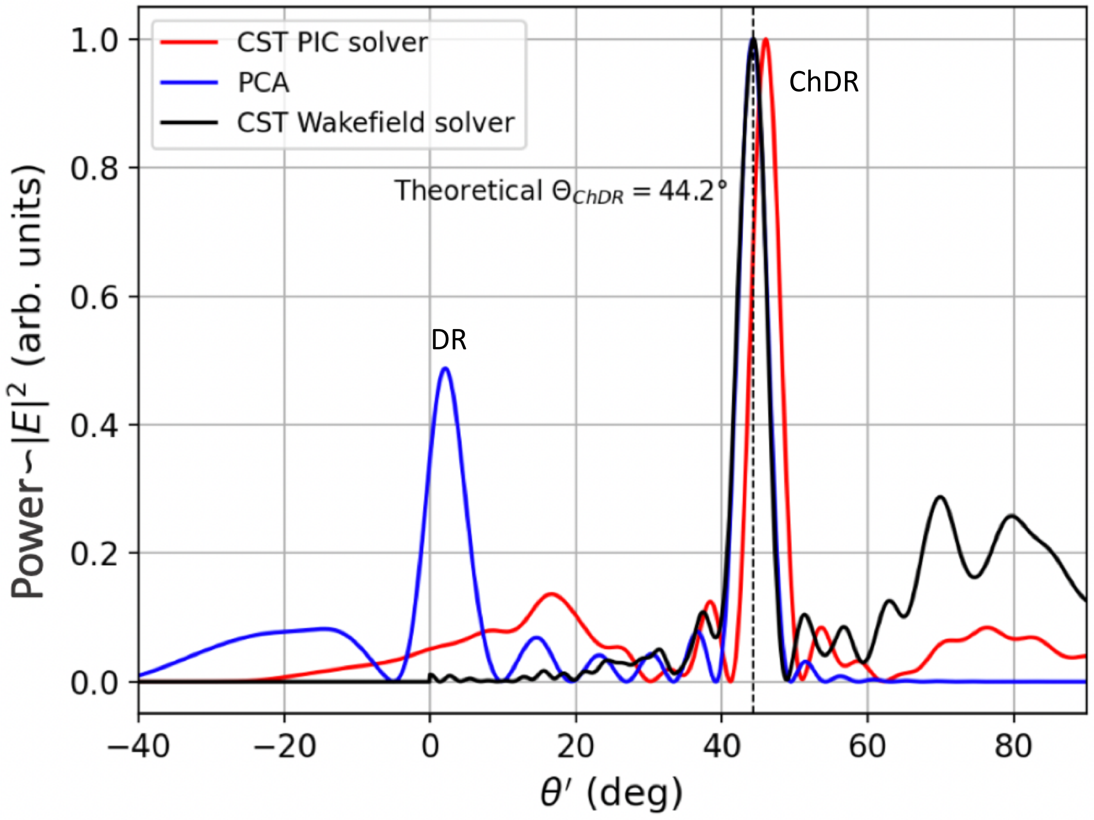


- Wakefield solver:
  - Beam field is TEM
  - Reflection artefacts from the boundary



Comparison to numerical simulations

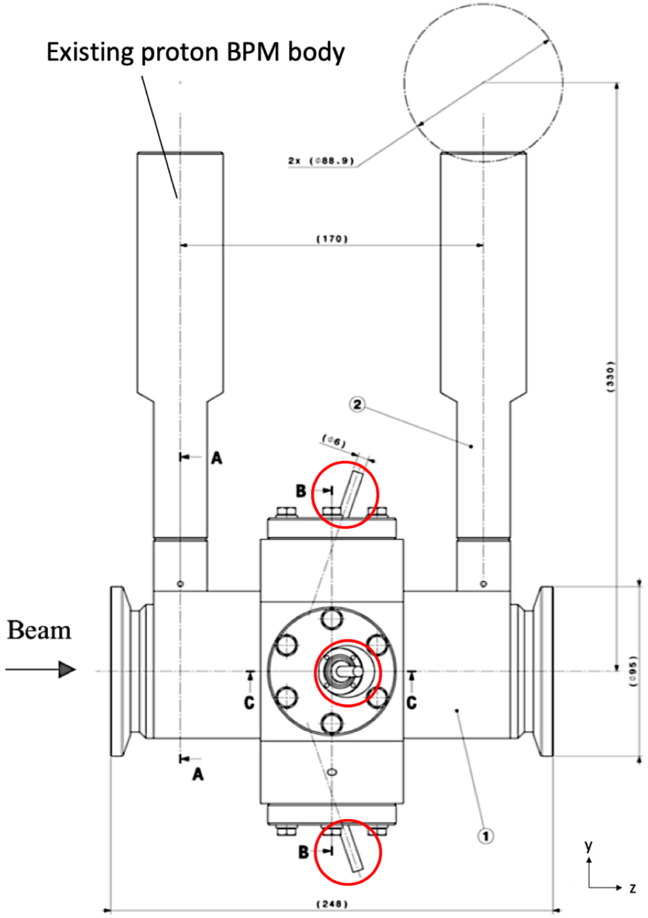
- Agreement of the angle of the ChDR peak between theory and simulations in the Wakefield solver
- Discrepancy of the angle of ChDR peak for the PIC solver due to non-perfect TEM beam field
- Continued to use the Wakefield solver for analysis of the ChDR radiator design for AWAKE

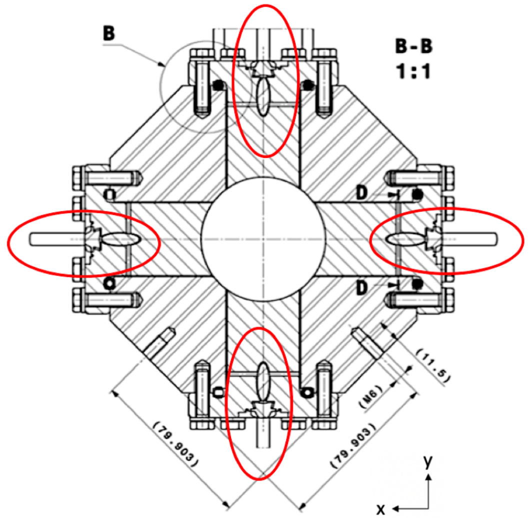


ChDR BPM design

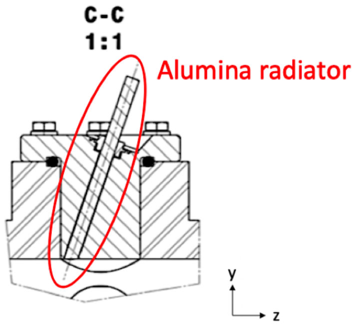
Mechanical design

- Limited space in the AWAKE common beamline, and to save on time and resources, made use of the existing pBPM bodies
- From simulations, reflections of the polarization radiation are reduced when the radiator is angled at θ_{Ch}
- Radiator length kept as short as possible
- Diameter and dielectric permittivity chosen to provide power transmission at frequencies higher than few GHz (acting as high-pass filter)
- Final design: **⌀6 mm, 86 mm long alumina rods** angled at the θ_{Ch} = 71° with f_{TE11}= 9.3 GHz





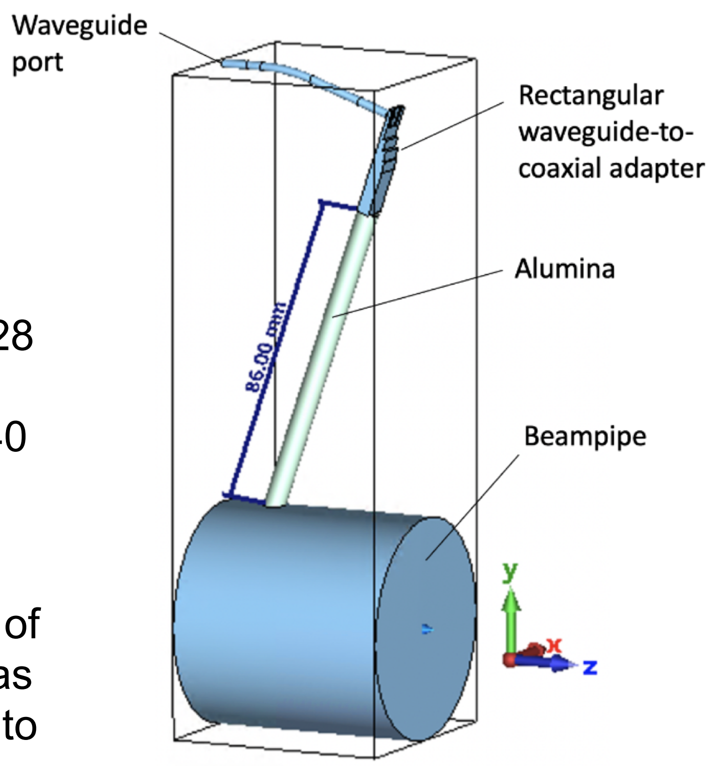
2+2 symmetric arrangement of ChDR radiators



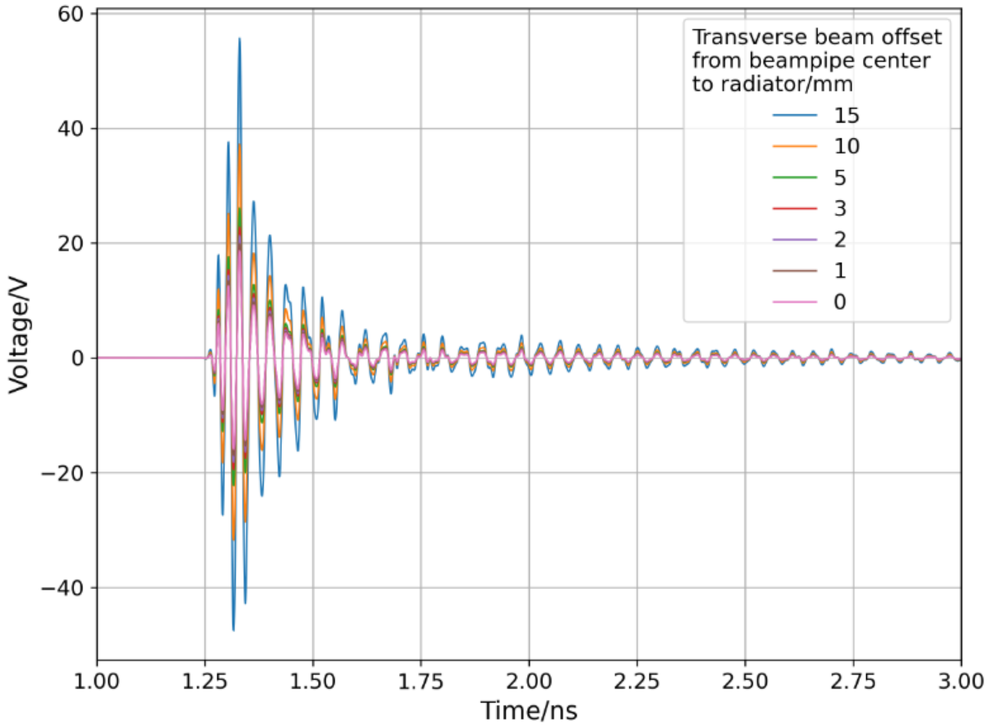
N. Chritin, CERN

Numerical analysis of final design

- A single radiator with read-out "arm” was simulated
- Several ways to transmit the radiation at the exit of the radiator to the detector
- Chose to use commercial WR28 rectangular waveguides that operate in the Ka-band (26.5-40 GHz) with f_{TE10}=21 GHz
- To estimate the time response of the radiator, 1 of 4 radiators was modelled in CST with a WR28 to coax adapter

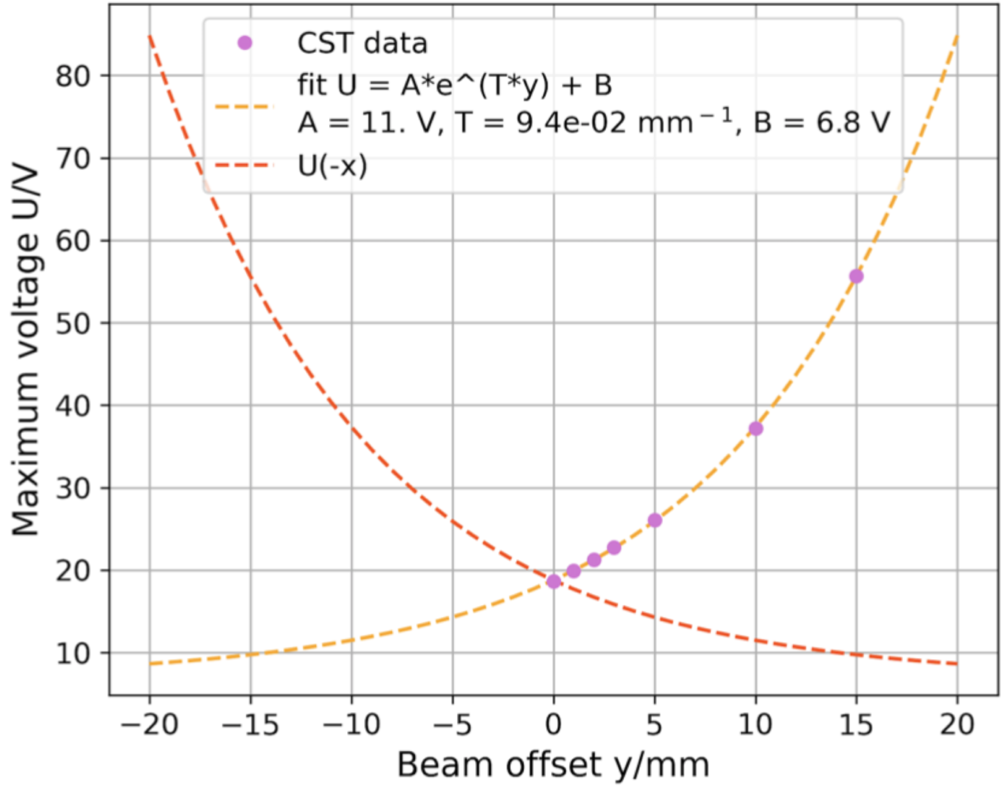


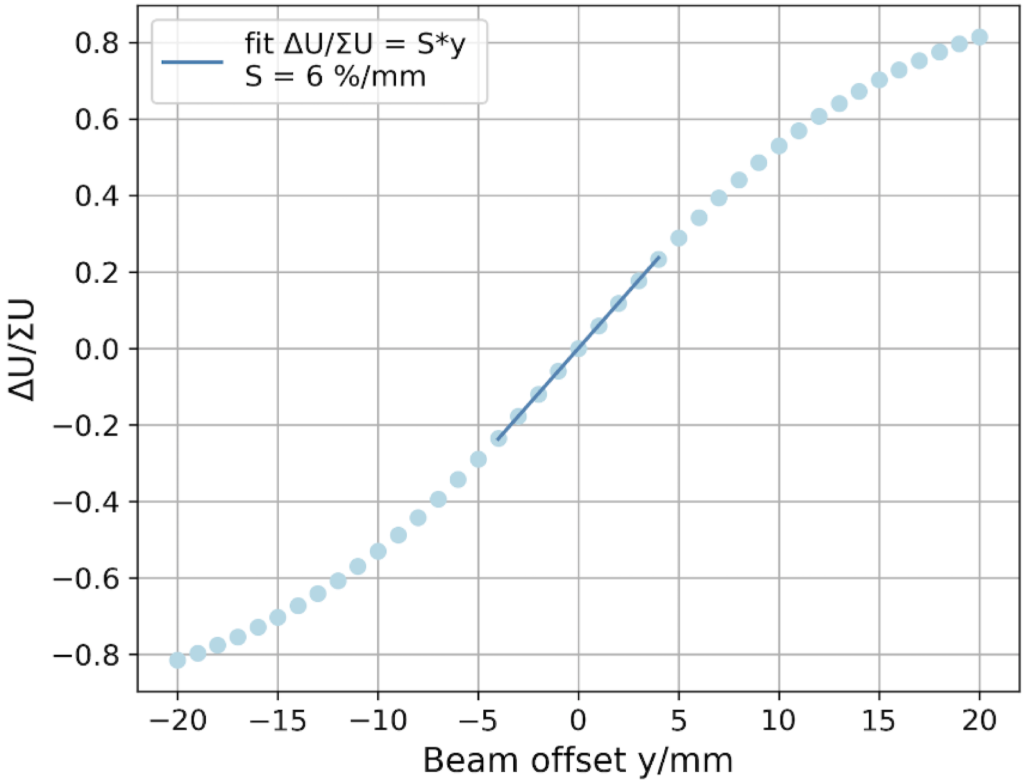
600 pC bunch charge, 4 ps RMS bunch length



Numerical analysis of final design

- Peak signal at every beam position, “mirrored” for an opposite read-out arm
- Difference-over-sum of the signals shows linear region ±4 mm and a position sensitivity of 6%/mm

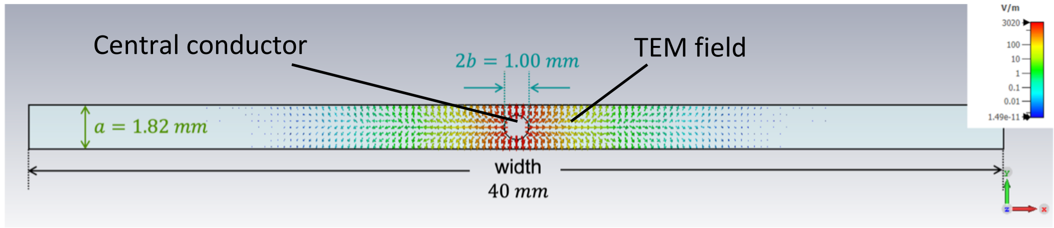


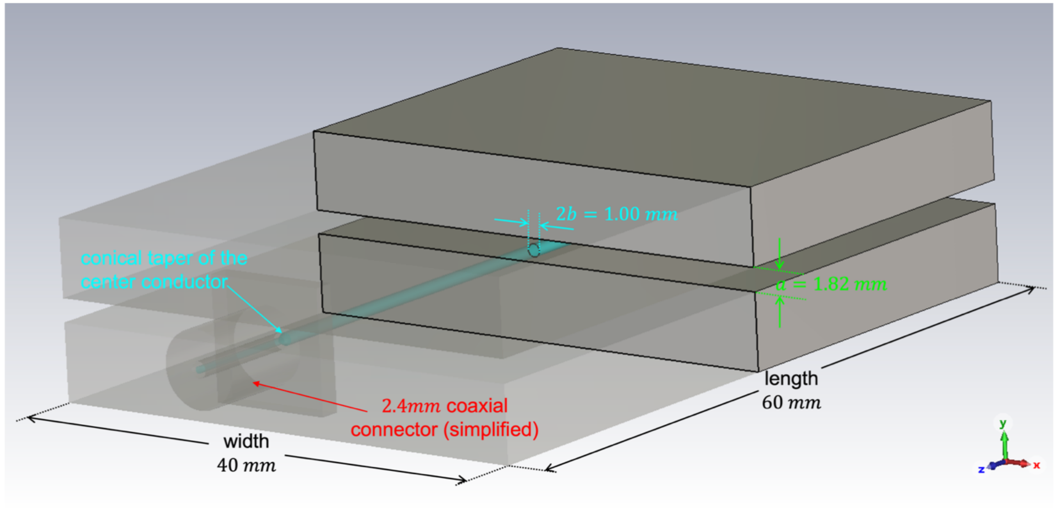


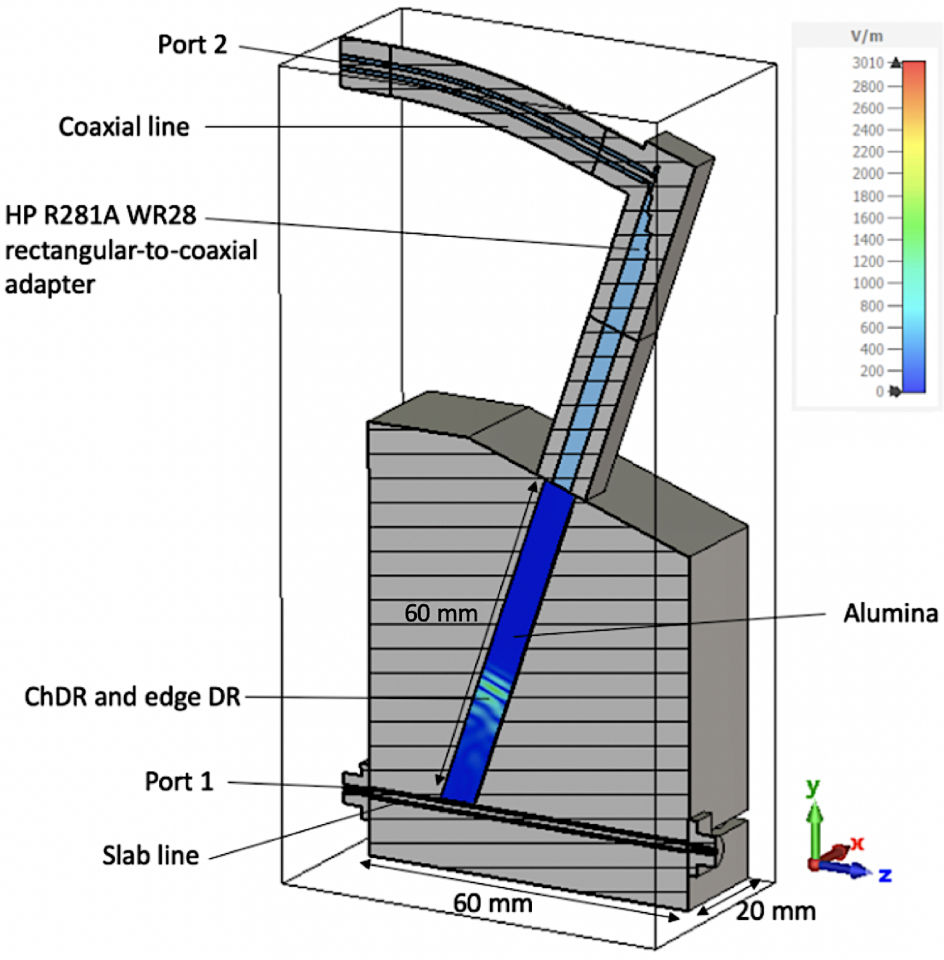
RF test-bench characterization of the radiator

Characterization in the laboratory

- Aimed at closing the gap between simulations and beam studies
- Requires a pure TEM-field to represent the bunched beam EM-field
- Used a slab-line to transmit excitation signal
- Central conductor with circular cross-section between two ground planes and the radiator is mounted on top

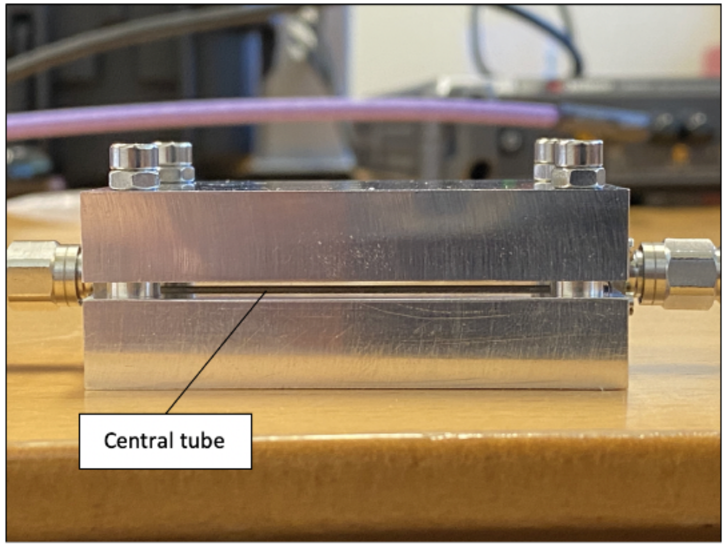


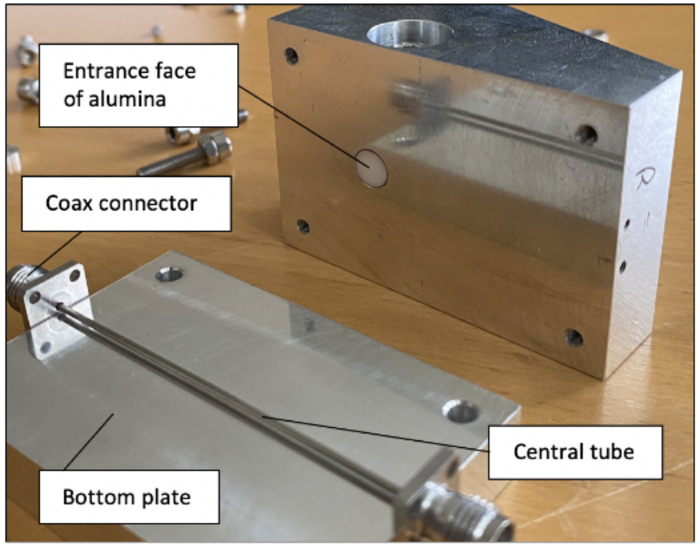


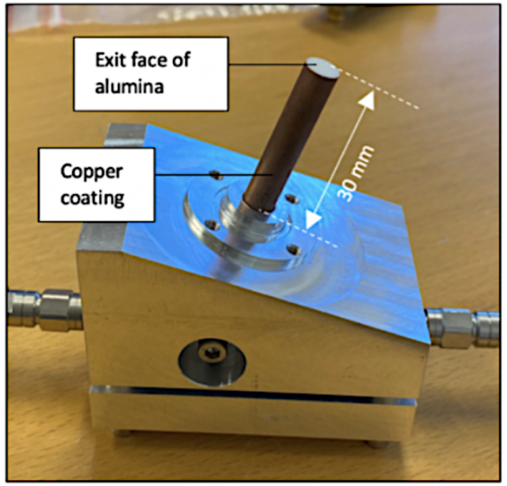


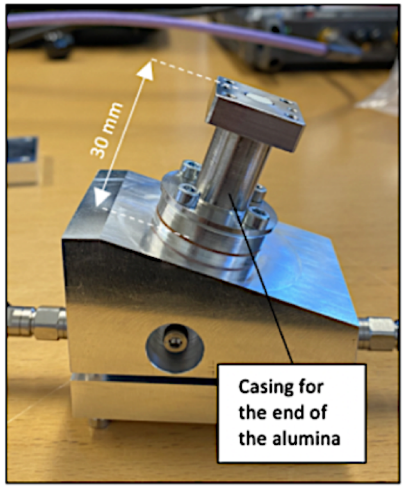
Set-up

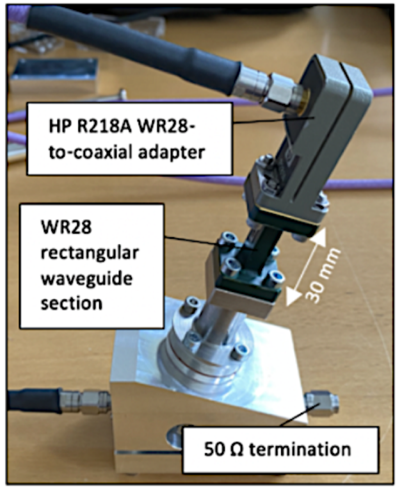
- Slab-line connected to VNA measuring between 10 MHz – 44 GHz
- Provided frequency response in this range under controlled conditions
- In-built iFFT function provided the time-domain response









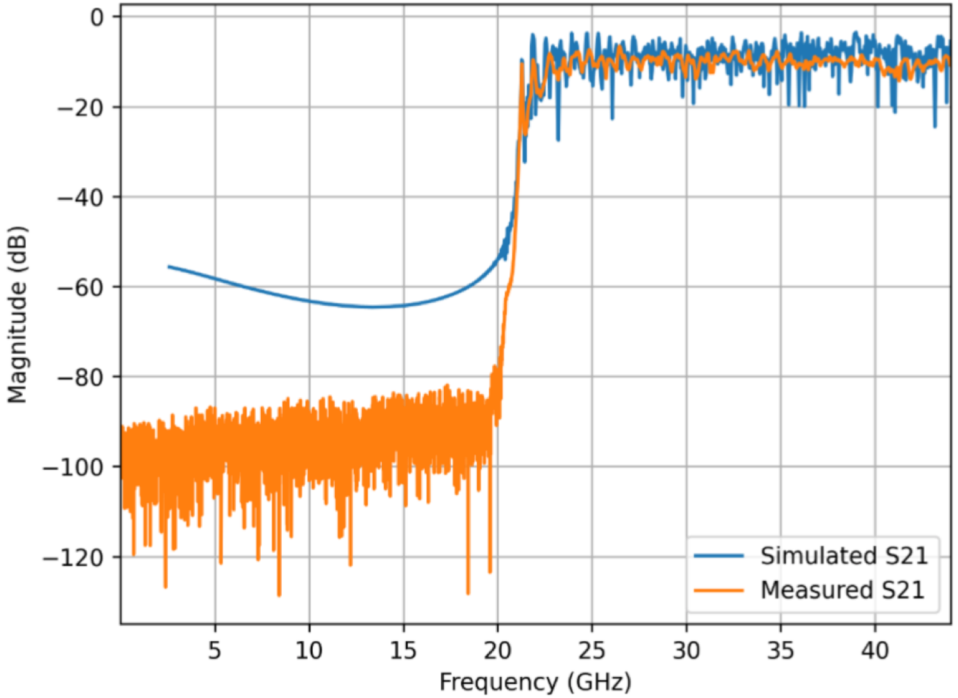


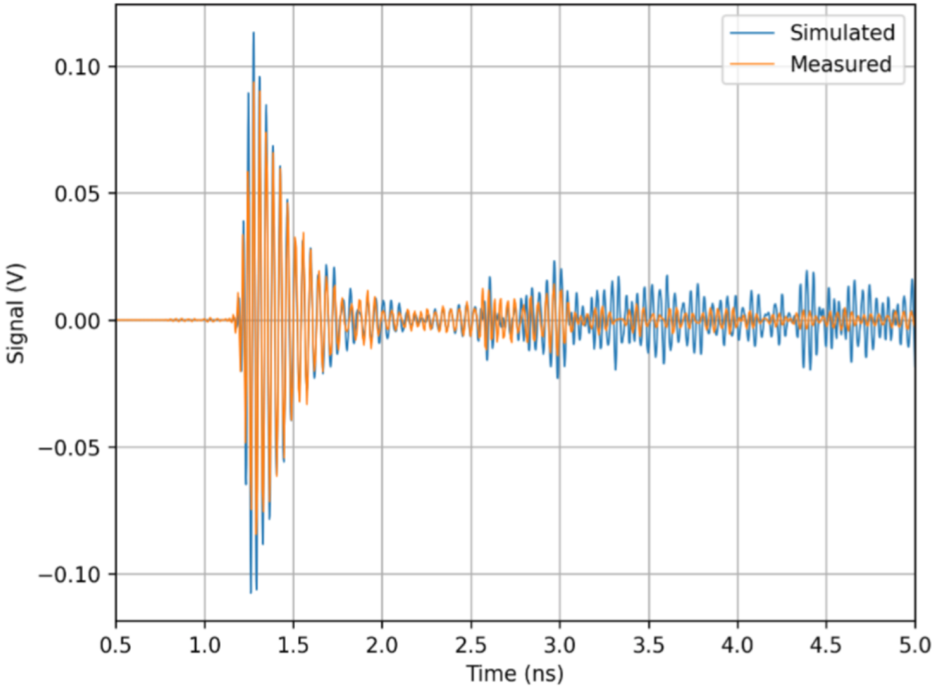
[3] C. Pakuza and M. Wendt, *Cherenkov diffraction radiation dielectric button characterization via a slab-line*, IPAC 2023, Venice, Italy, May 2023, paper THPL084.

Results

- Numerical and measured results agree well with signal transmission above 21 GHz as expected

- More ringing in the simulated case partly due to numerical noise and lack of surface impedance and roughness of materials in the simulation

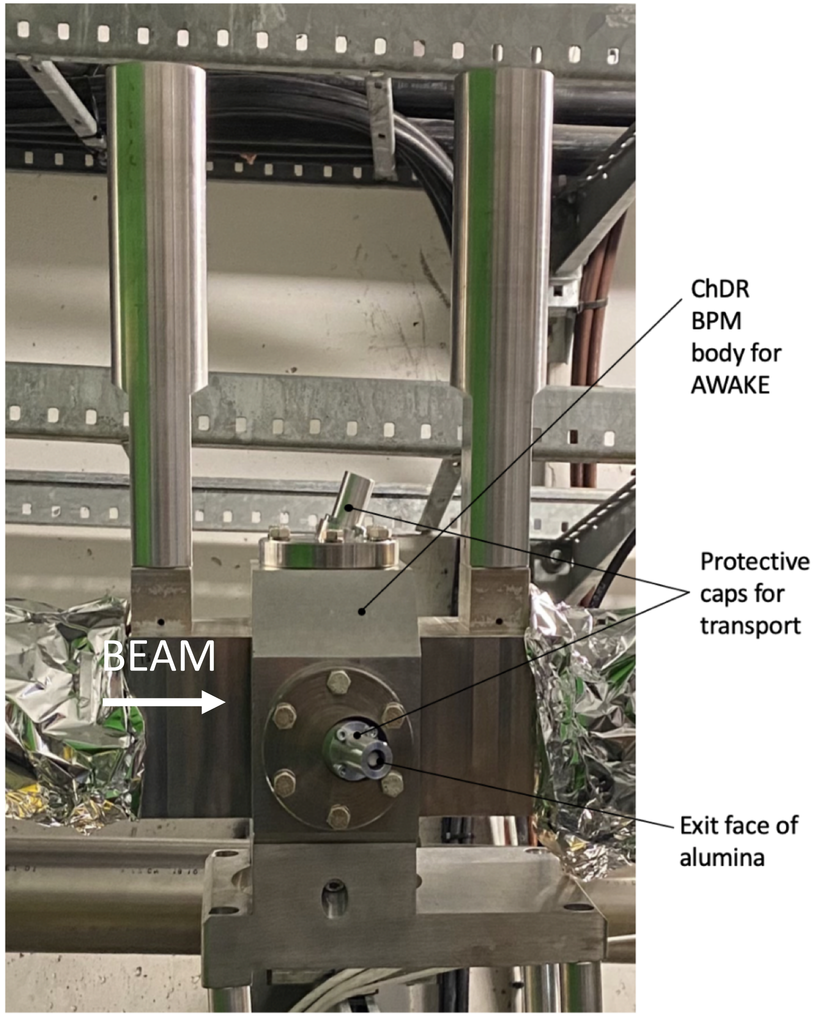




- Useful tool for radiator characterization and simulation verification but no position response, ultimate goal is beam studies

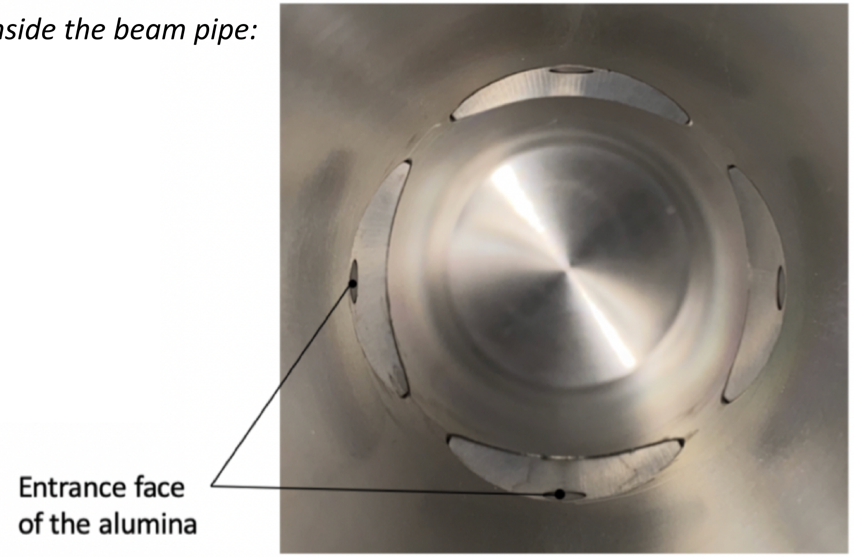
Beam studies at AWAKE and CLEAR

Set-up at AWAKE

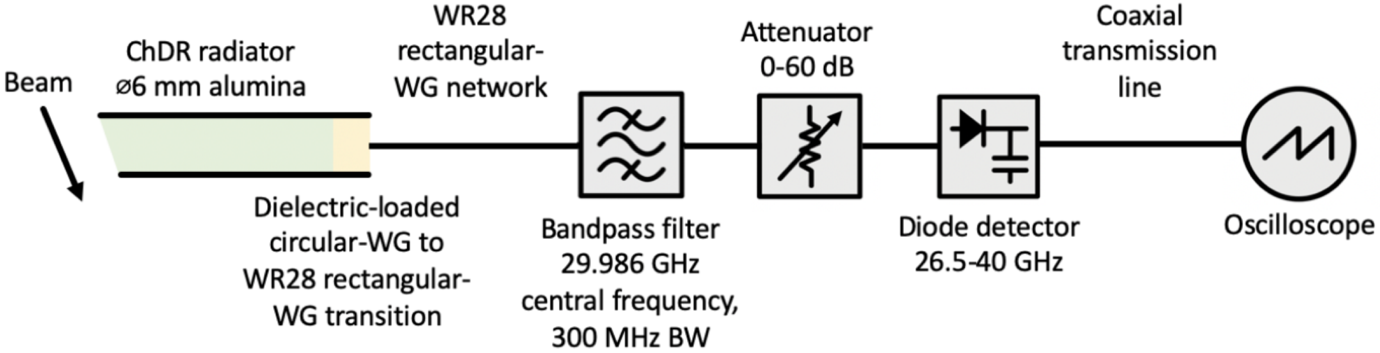


- One proton BPM close to plasma cell converted to ChDR BPM and another installed ~2.64 m upstream

Inside the beam pipe:



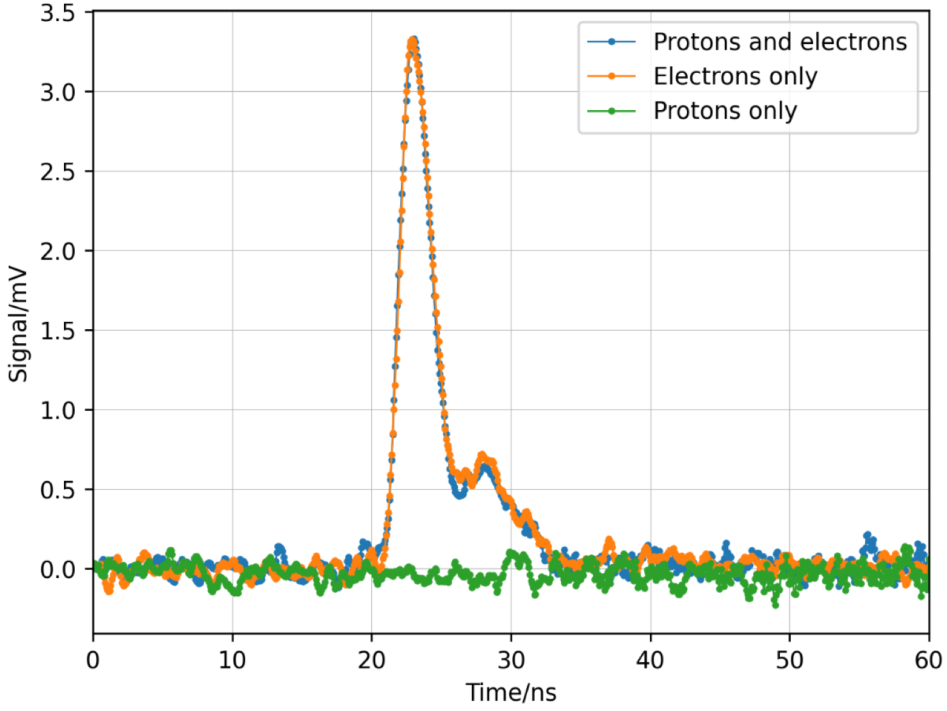
Detection chain:



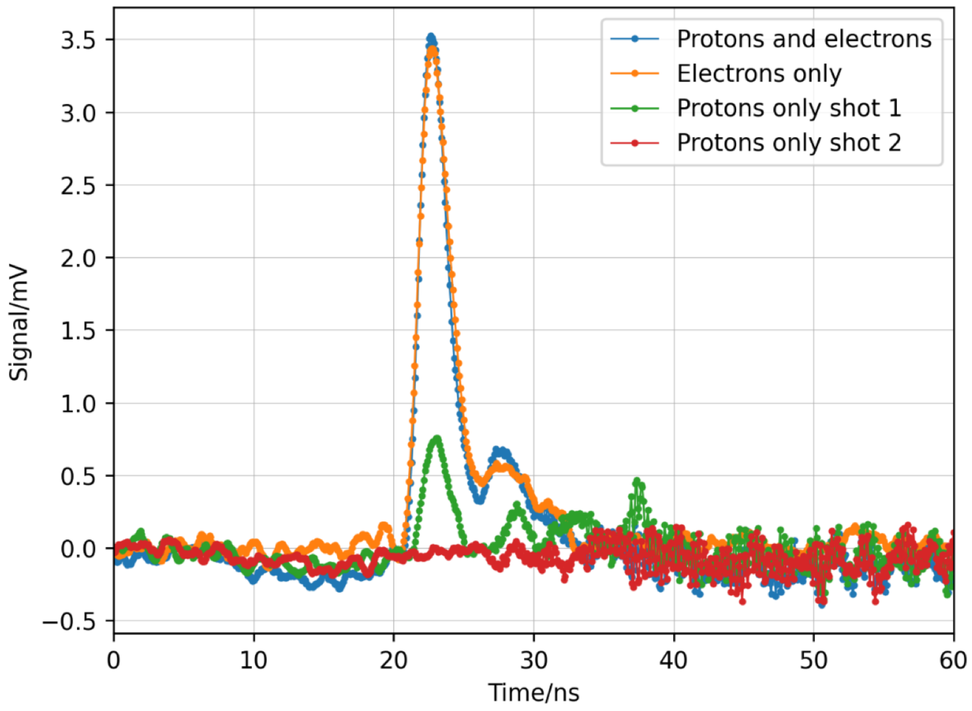
Results

- Parasitic measurements taken in April 2022 with 16 nC and 48 nC proton bunch charge and 250 pC electron bunch charge

16 nC proton bunch charge



48 nC proton bunch charge

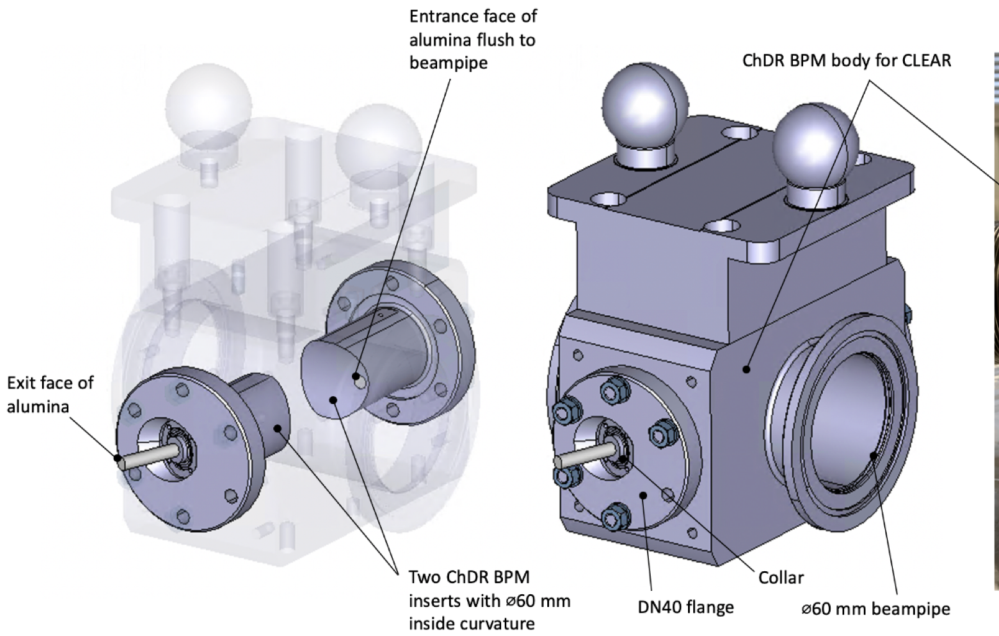


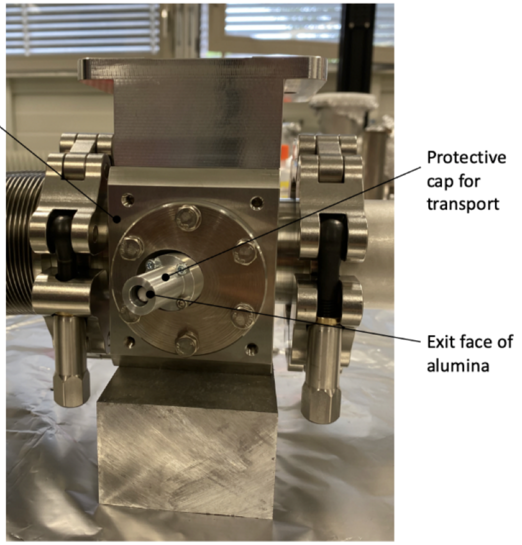
- ChDR BPM insensitive to protons at 16 nC bunch charge
- Signal measured at high proton charge with large shot-to-shot variability, hints the proton bunch spectrum extends beyond 30 GHz

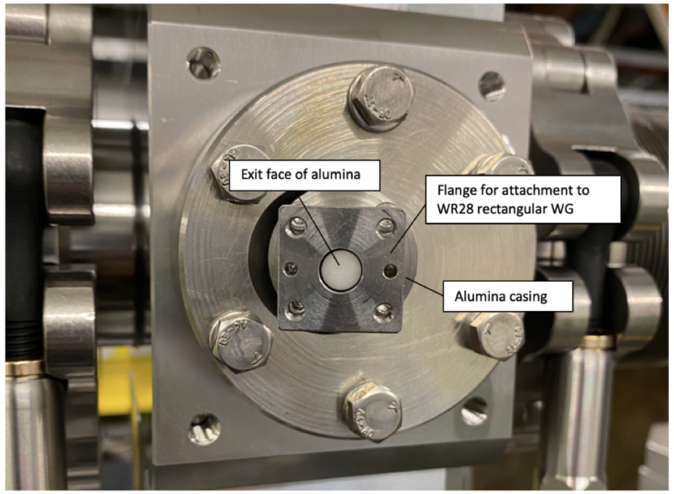
Set-up at CLEAR

- Since proton signal was still being measured at 30 GHz, the detection frequency of the ChDR BPM had to be revisited and possible higher frequency detection chains had to be considered

- One plane of the ChDR BPM was manufactured and tested systematically with electron beam at the CERN Linear Electron Accelerator for Research (CLEAR) test facility



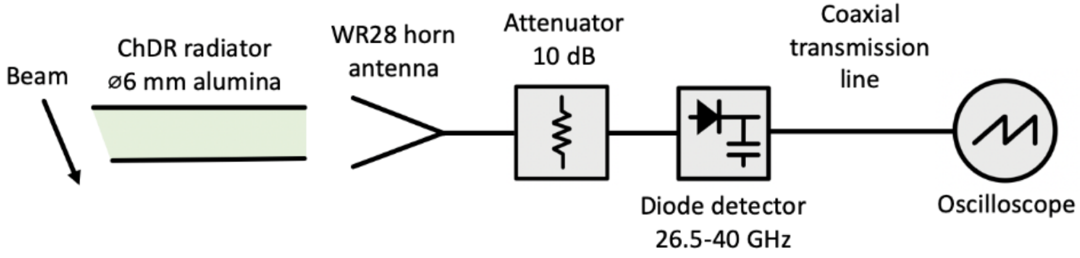


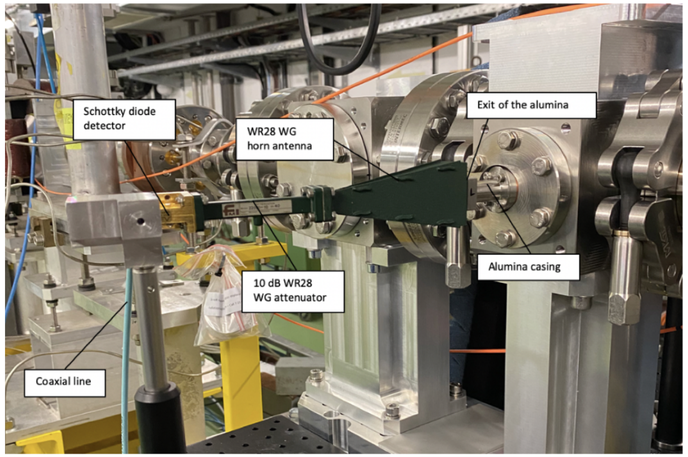


Set-up at CLEAR

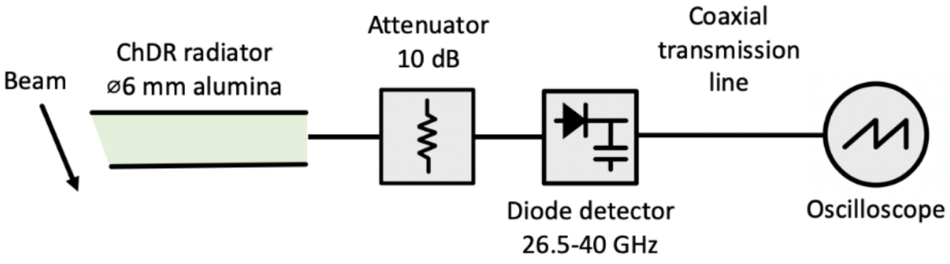
- Installed ~7 m upstream of in-air test stand
- Different detection frequencies measured using horn antennas to couple the radiation to the detector: Ka-band (26.5-40 GHz), V-band (50-75 GHz) and W-band (75-110 GHz)
- For Ka-band, enough components for symmetric set-up and also tested with direct waveguide connection

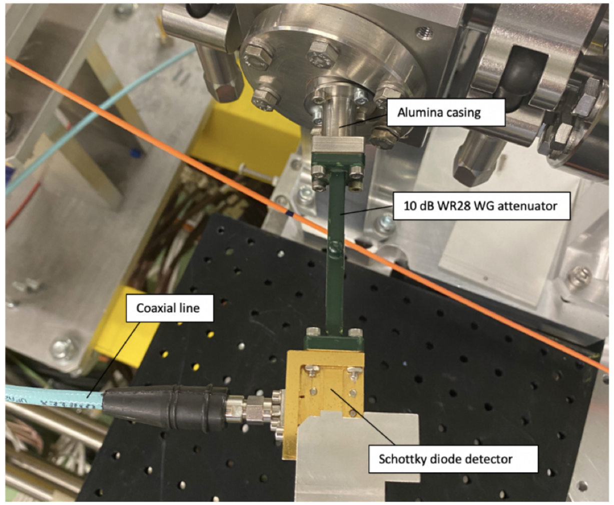
3 frequency ranges tested with horn antennas





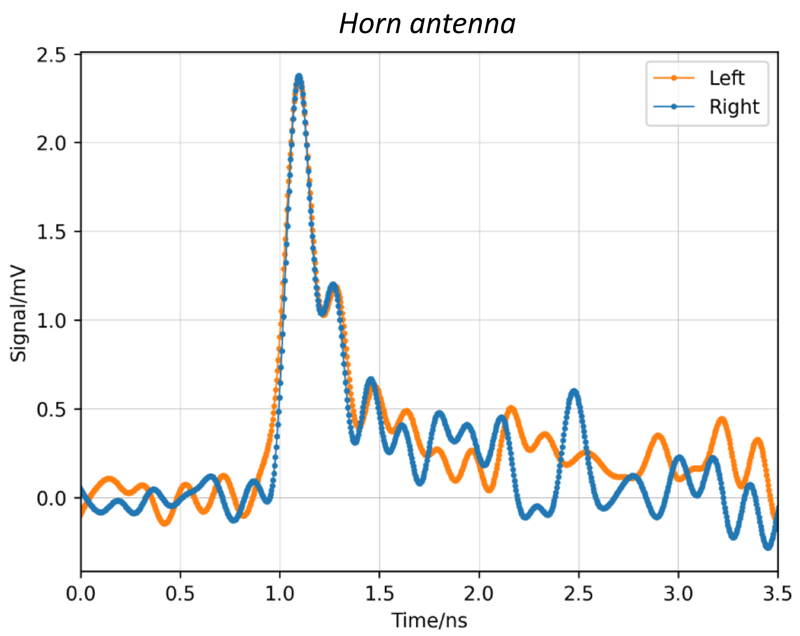
Ka-band was also tested with direct waveguide connection

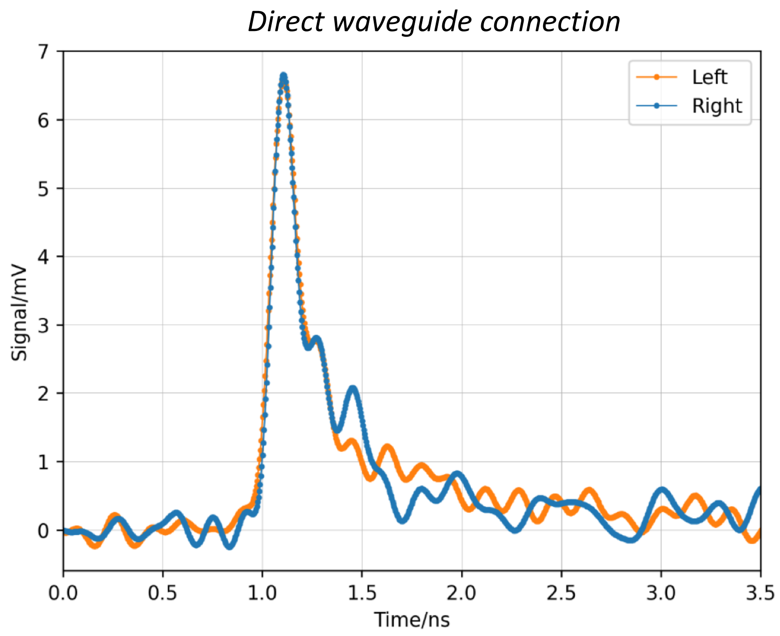




Results

- Signals from left and right arm in Ka-band with horn antennas and direct waveguide connection for 1 ps bunch length and 45 pC bunch charge



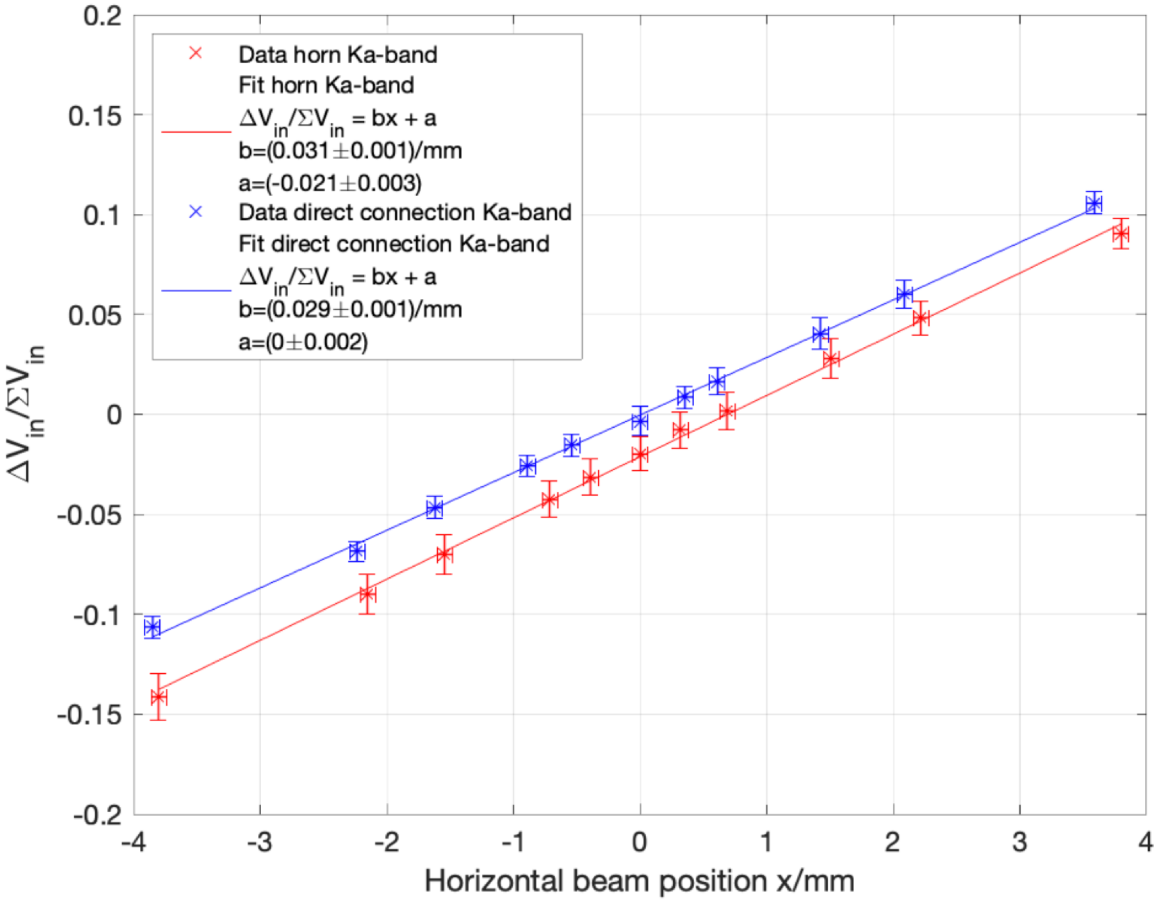


- Shows good symmetry between the two arms, cleaner signal when waveguide is connected directly and less attenuation

- Exact cause of reflection at 165 ps after the initial peak is not understood but is not from the environment or the round trip time of radiation inside the radiator and the other components in the detection chain

Results

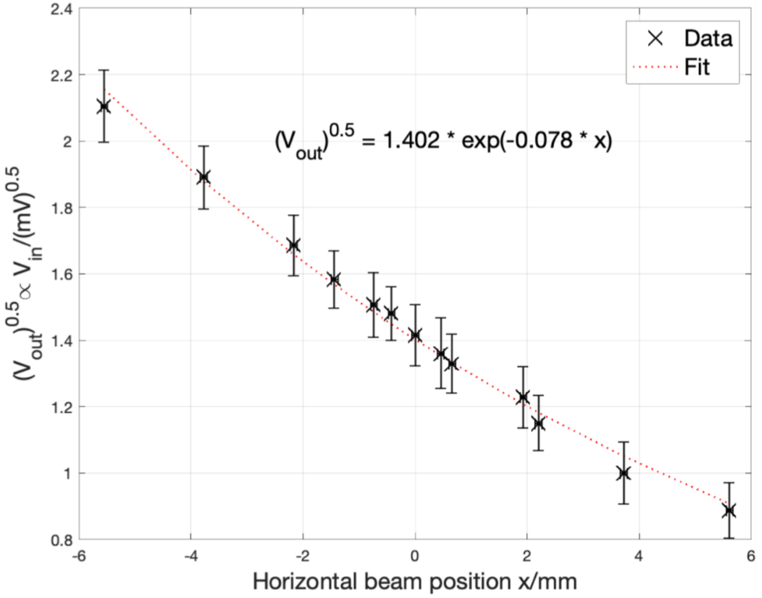
- Beam position scans, difference-over-sum of the peak signals taken
- Shows linear response as expected from simulations
- Larger offset when the horn antennas are used due to asymmetry of detection chain i.e. alignment of horn antennas
- Position sensitivity (3.1±0.1)%/mm (horn antenna), (2.9±0.1)%/mm (direct waveguide connection)



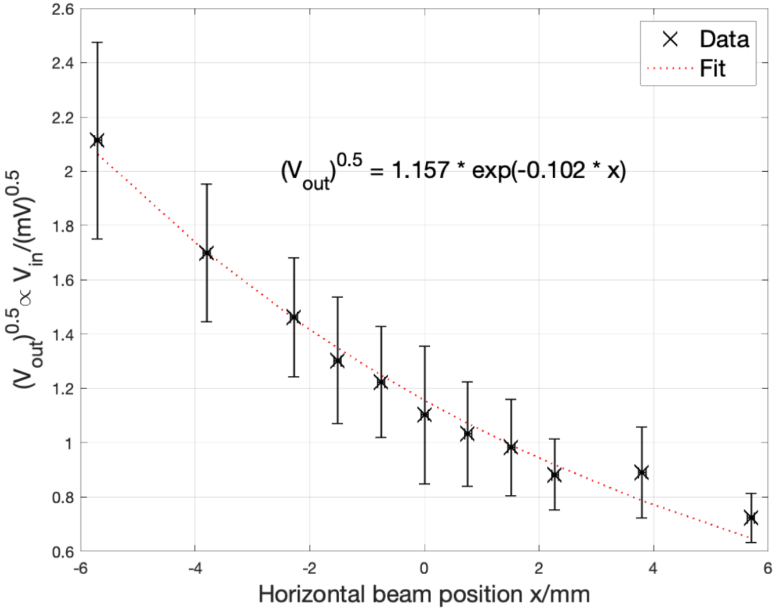
Results

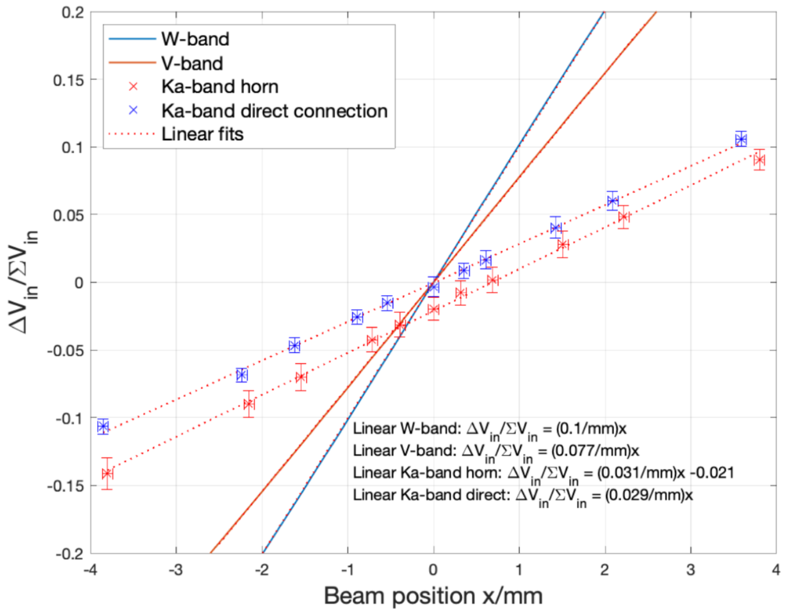
- One arm measured with the V-band and W-band detection chains, again peak signal response to changing beam position recorded
- Assuming symmetric system, position sensitivity estimated to be 7.7%/mm (V-band) and 10.0%/mm (W-band)
- Sensitivity increases with increasing detection frequency not predicted by simulations, needs to be further studied

V-band



W-band





Conclusions and future work

Conclusions

- Large simulation campaign performed to better understand the ChDR propagation inside the radiators, comparison made with theoretical PCA model, informed the design of the radiator for application at AWAKE

- The RF-test bench characterisation bridged the gap between numerical simulations and experimental studies, showed very good agreement and verified the simulations, provides useful tool for radiator characterisation

- Beam studies at AWAKE showed that the system is insensitive to low charge proton bunches but residual proton signals are sometimes still detected for high charge proton bunches

- Detection chains with different frequency ranges were tested at CLEAR, position response was measured and showed increasing sensitivity with increasing detection frequency

Future work

- Ongoing tests of ChDR BPM at CLEAR and AWAKE with both proton and electron beams – Bethany Spear, JAI, Oxford University
- Will better inform the choice of operating frequency of the ChDR BPM
- The core characteristics of the ChDR BPM i.e. the sensitivity, resolution and accuracy, still need to be studied and measured directly with beam

Thank you for your attention!

Additional references:

[4] AWAKE Collaboration, Acceleration of electrons in the plasma wakefield of a proton bunch, Nature **561**, 363-367 (2018).

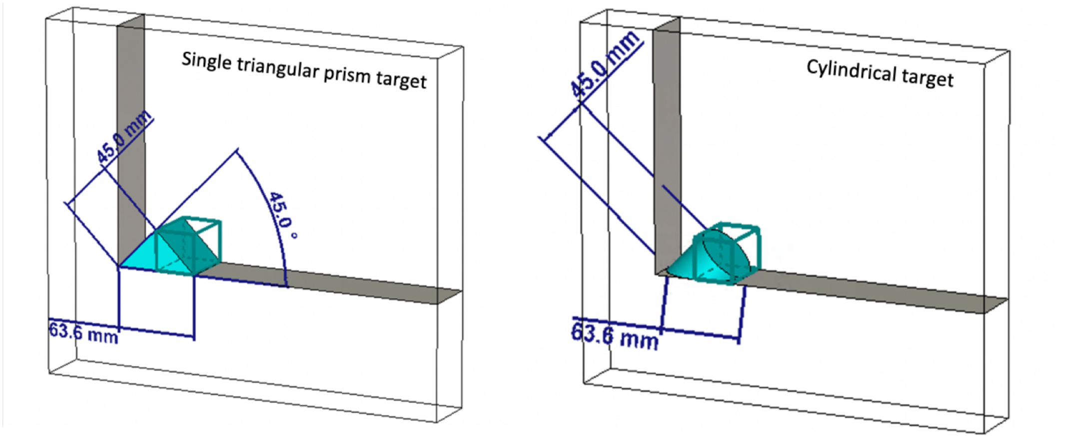
[5] C. Pakuza, et.al., A beam position monitor for electron bunch detection in the presence of a more intense proton bunch for the AWAKE experiment, IPAC 2022, Bangkok, Thailand, Jun 2022, pp.381-384.

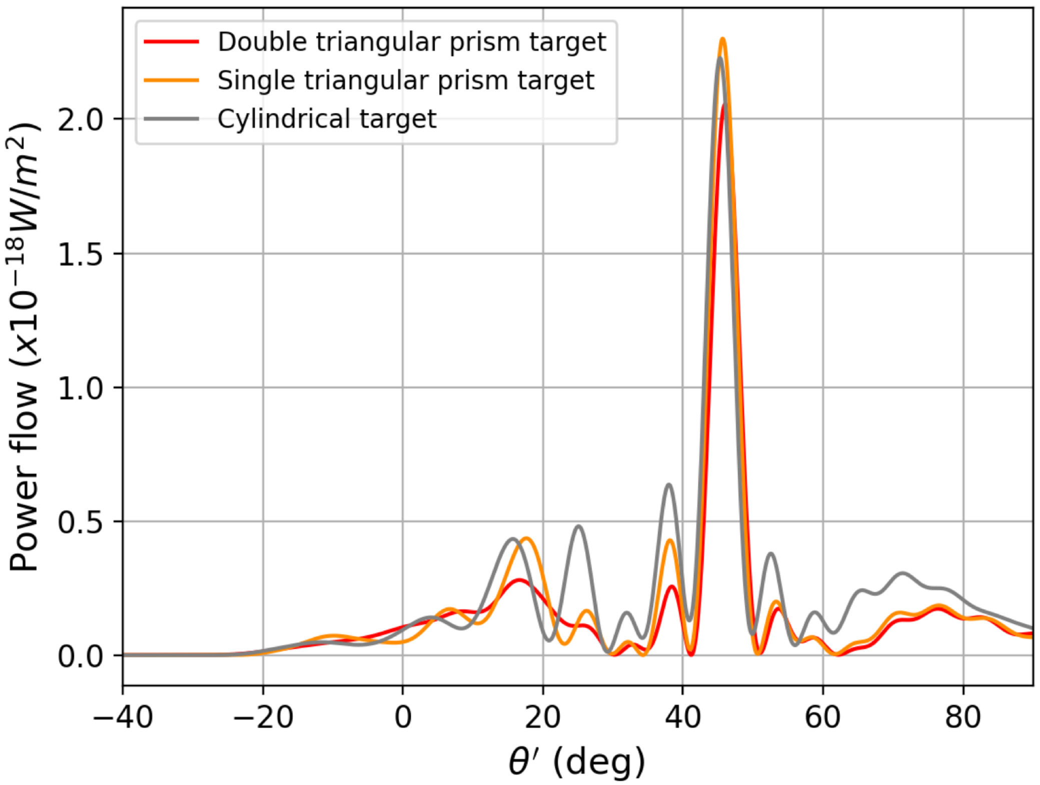
[6] C. Pakuza, et.al., Electron Beam Studies on a Beam Position Monitor based on Cherenkov Diffraction radiation, IPAC 2023, Venice, Italy, May 7 - 12, 2023.

Backup slides

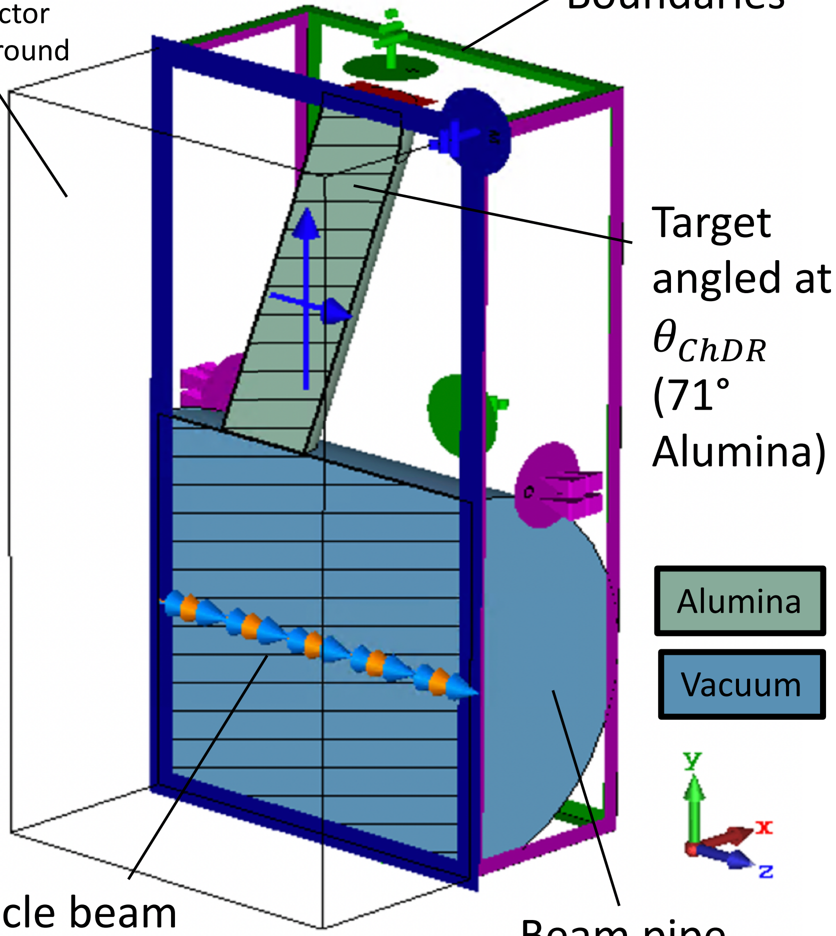
Radiator shape

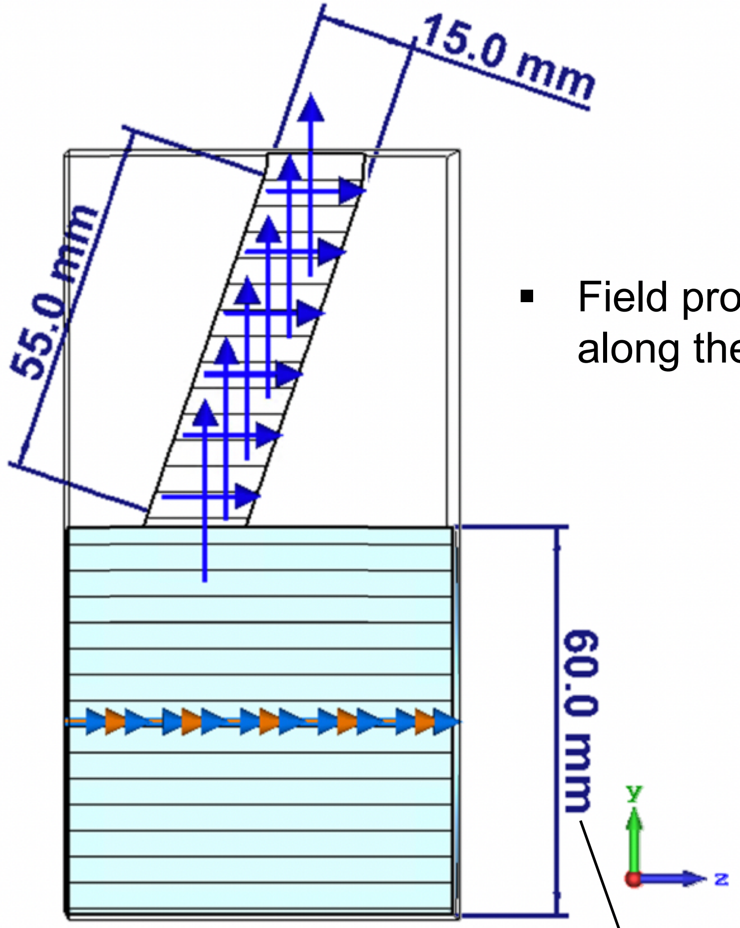
- Does cylindrical target face change the ChDR characteristics exiting the radiator?
- Similar radiation distribution for all target geometries where the face exposed is similar in area
- Cylindrical target, easier to manufacture and metalize





Radiator length

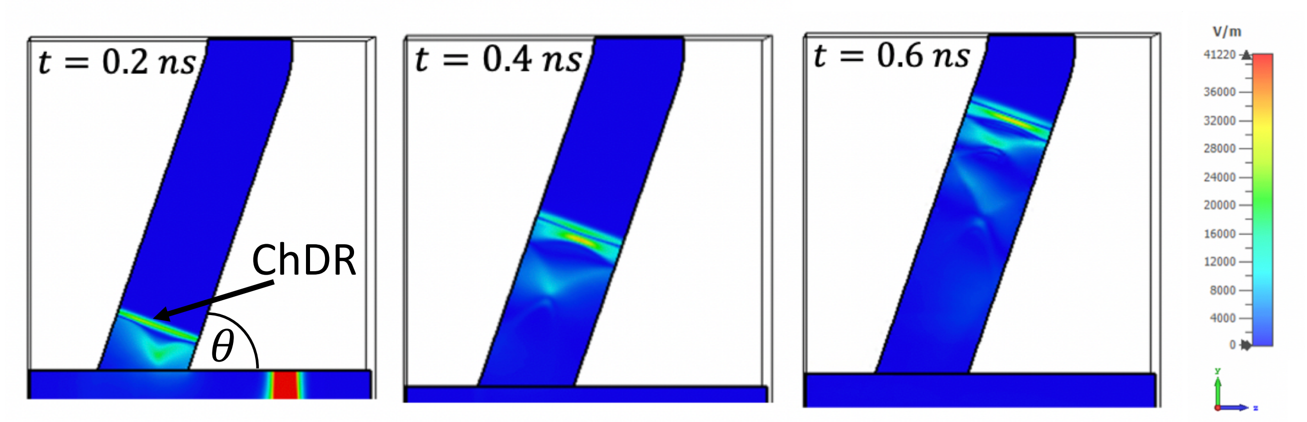




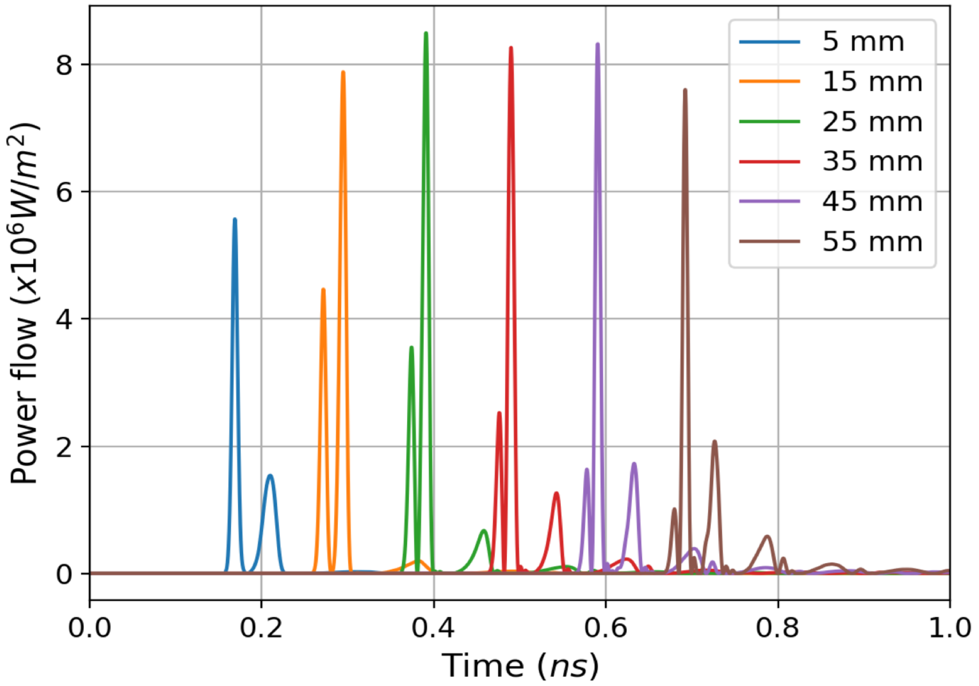
- Field probes every 5 mm along the target

Radiator length

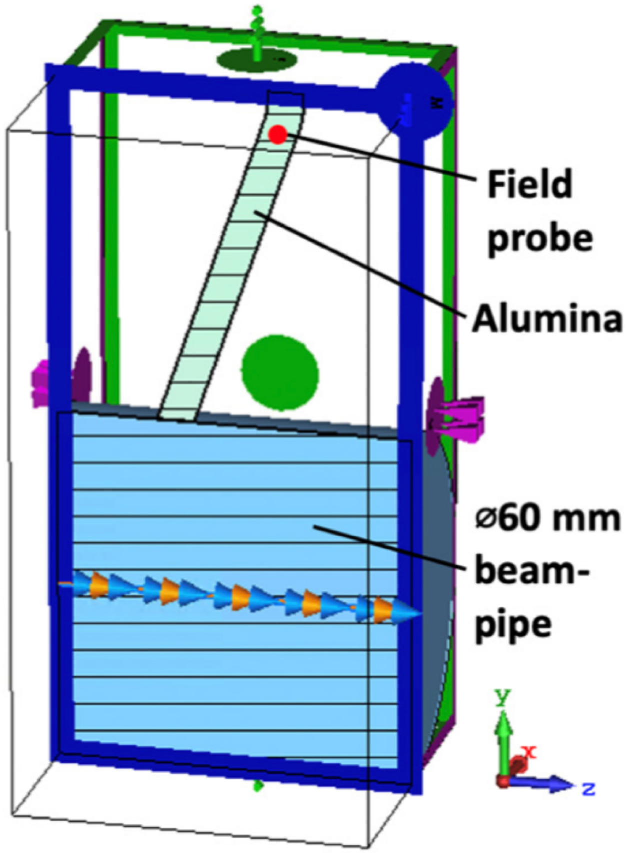
- t=0.2 ns, field passing probe 1 shows first peak is ChDR and second is DR from the edges
- As length increases, the various peaks become harder to distinguish as you have multiple reflections of the DR
- **Short as possible** to minimize these effects and make it as clean as possible



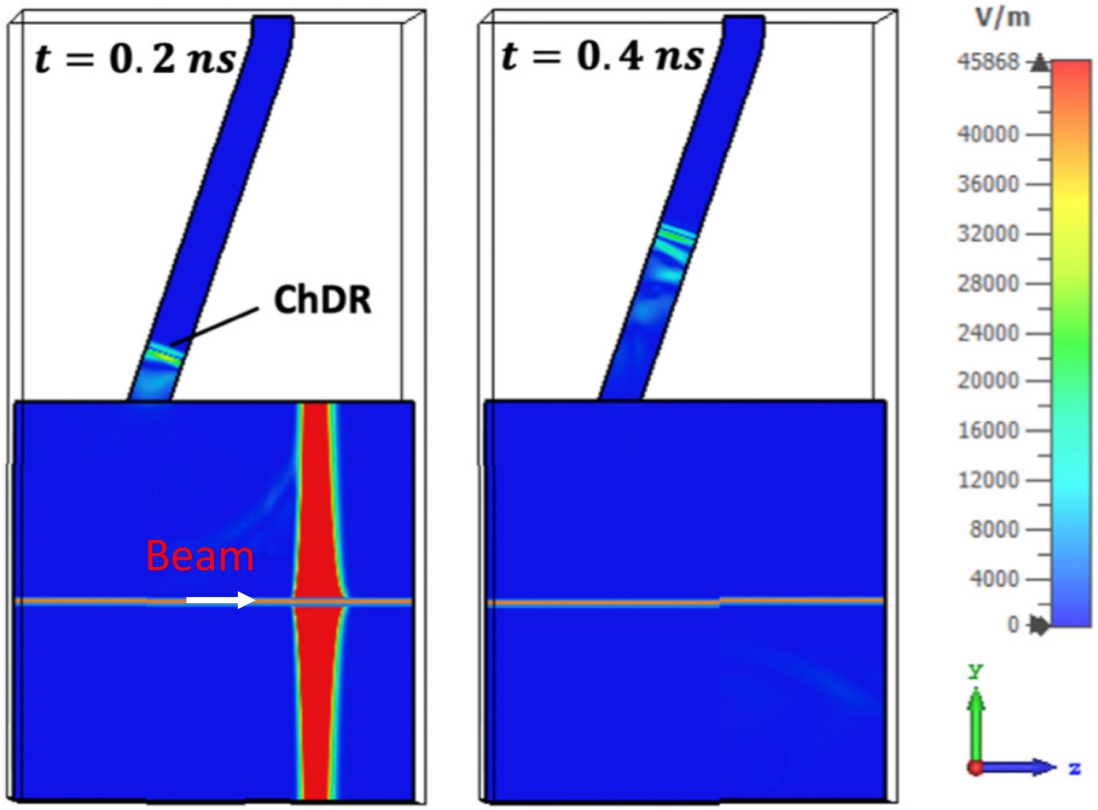
Time evolution of abs. E-field in one arm of the BPM



3D simulation of final design



3D model of final design



Time evolution of E-field

Slab-line

- HOMs exist at low frequencies for beampipe of 60 mm diameter when using the stretched wire technique for radiator characterization
- Slab-line used to avoid HOMs
- Dimensions chosen to create a 50 Ω line for impedance matching to the coax
- Impedance along the line was measured and simulated

$$Z_{SL} = \eta_0 \left[\frac{1}{2\pi} \ln\left(\frac{2a}{\pi b}\right) - \frac{0.2153R^2}{1 + 5.682R^2} \right]$$

with: $R = \left(\frac{b}{a}\right)^2, \qquad \eta_0 \cong 120\pi\Omega$

$$2a = 1.00\ mm, b = 1.82\ mm \implies Z_{SL} \cong 50\ \Omega$$