The study of high-frequency pick-ups for electron beam position measurements in the AWAKE common beamline

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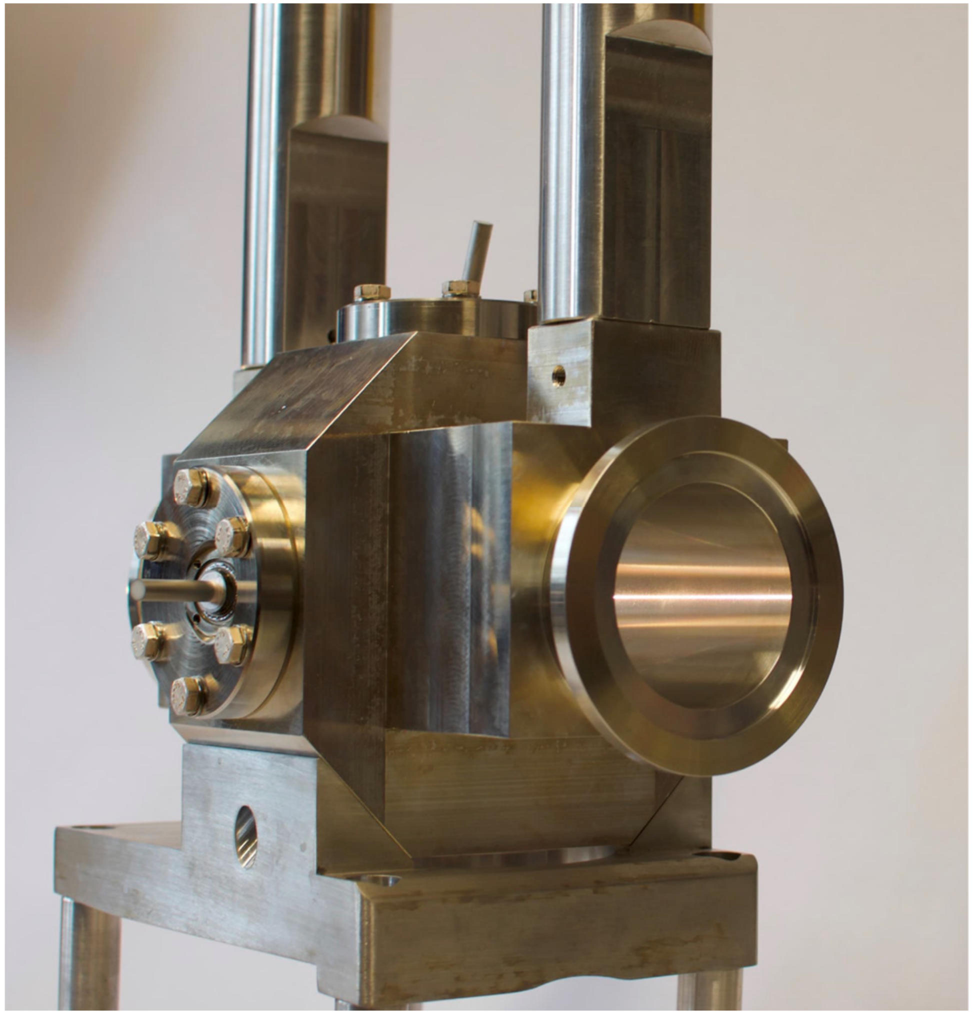
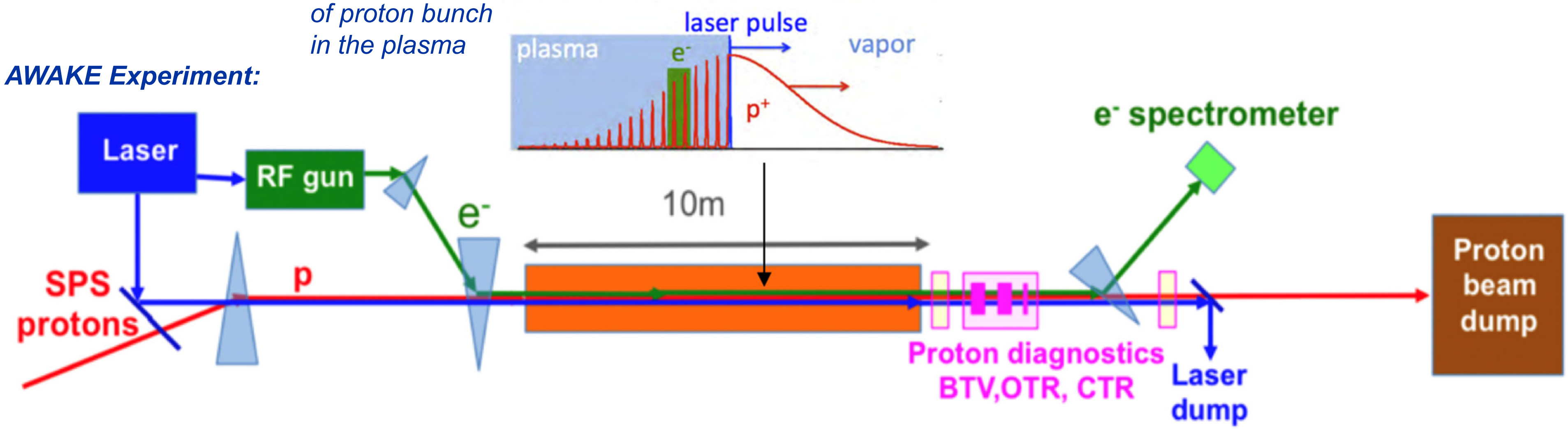


Motivation – the AWAKE Experiment

- The experiment uses 400 GeV/c proton bunches (RMS bunch length 6-8 cm) from the SPS to generate wakefields in a 10 m long rubidium vapor cell
- In the plasma cell, the long proton bunch is divided into a train of mm-long microbunches (@ plasma wavelength ~1mm) through a process called seeded self modulation (SSM) which is seeded by a short laser pulse
- Electron bunches from a linac are injected and captured in the plasma wakefields, and accelerated in the high-gradient E-field

Self modulation of proton bunch in the plasma

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 – measurement of co-propagating beams

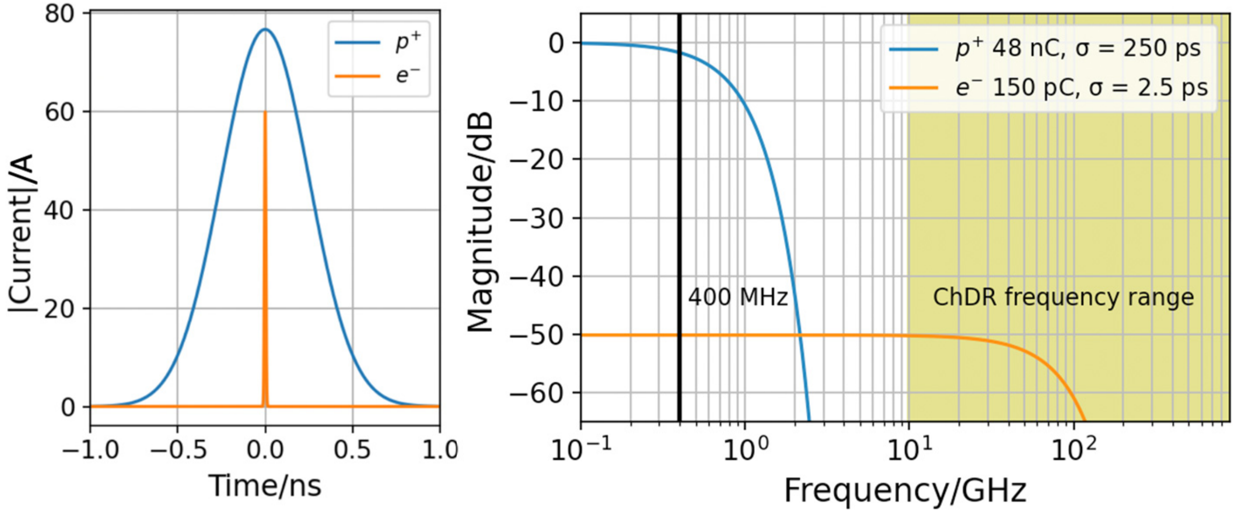
- In the common beamline, both electron and proton bunches propagate closely in time and space
- Beam parameters prior to entering plasma cell:

Particle beam	Charge/nC	σ
Proton	48	250 ps
Electron	0.1-0.6	Few ps

- The current electron BPMs in the common beam-line operate at $f_{readout} = 404$ 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

404 MHz – operating frequency of current electron BPMs

High-frequency pick-up should be designed to operate at higher frequencies



Beam distributions in time and frequency domain for perfect Gaussian longitudinal particle distributions

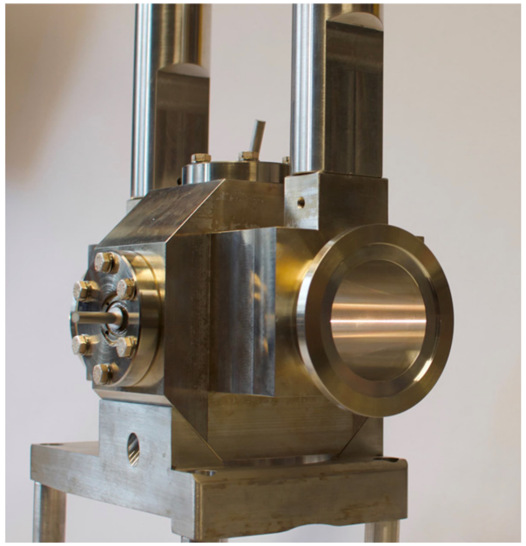
High-frequency pick-ups

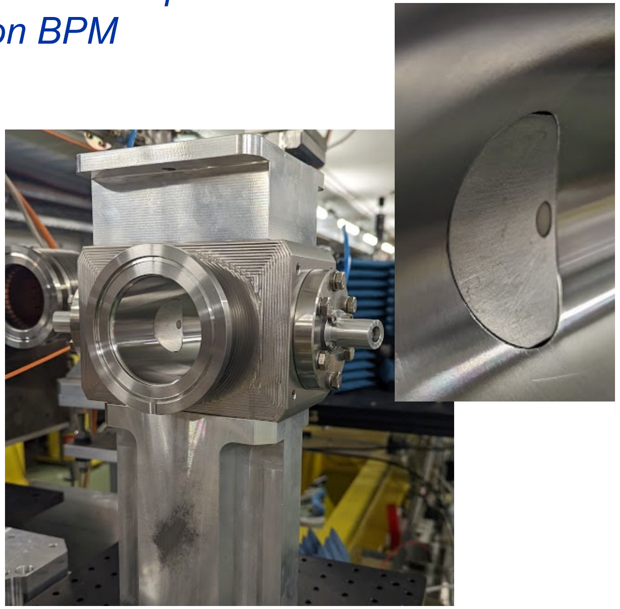
- Two options were studied:
  - Conical button BPM design inspired by DESY
    - Designed as part of a bunch arrival-time monitor
    - High bandwidth with cut-off frequency > 40 GHz

    [2] A. Angelovski et. al., *High bandwidth pickup design for bunch arrival-time monitors for free-electron laser*, Physical Review Special Topics – Accelerators and Beams, **15**, 112803 (2012)

  - ChDR-based BPM
    - Based on the generation of Cherenkov diffraction radiation
    - Very large bandwidth with high cutoff frequency defined by the bunch length and low cutoff frequency defined by the material and size

Conical button BPM comparison to LEP-type Button BPM

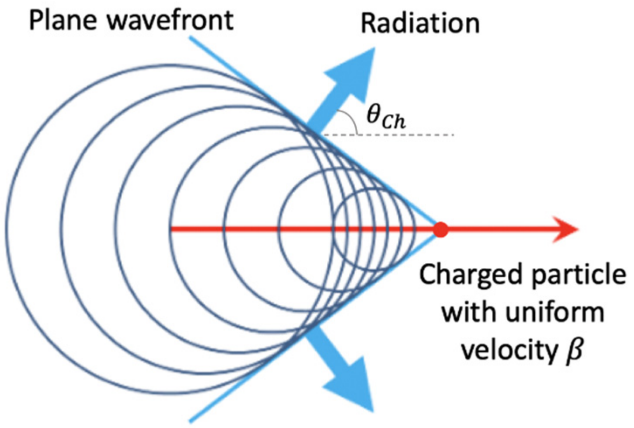




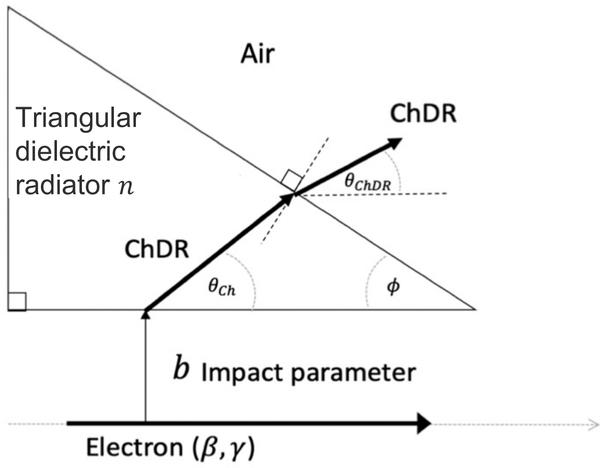
AWAKE ChDR BPM

Cherenkov diffraction radiation (ChDR)

- 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

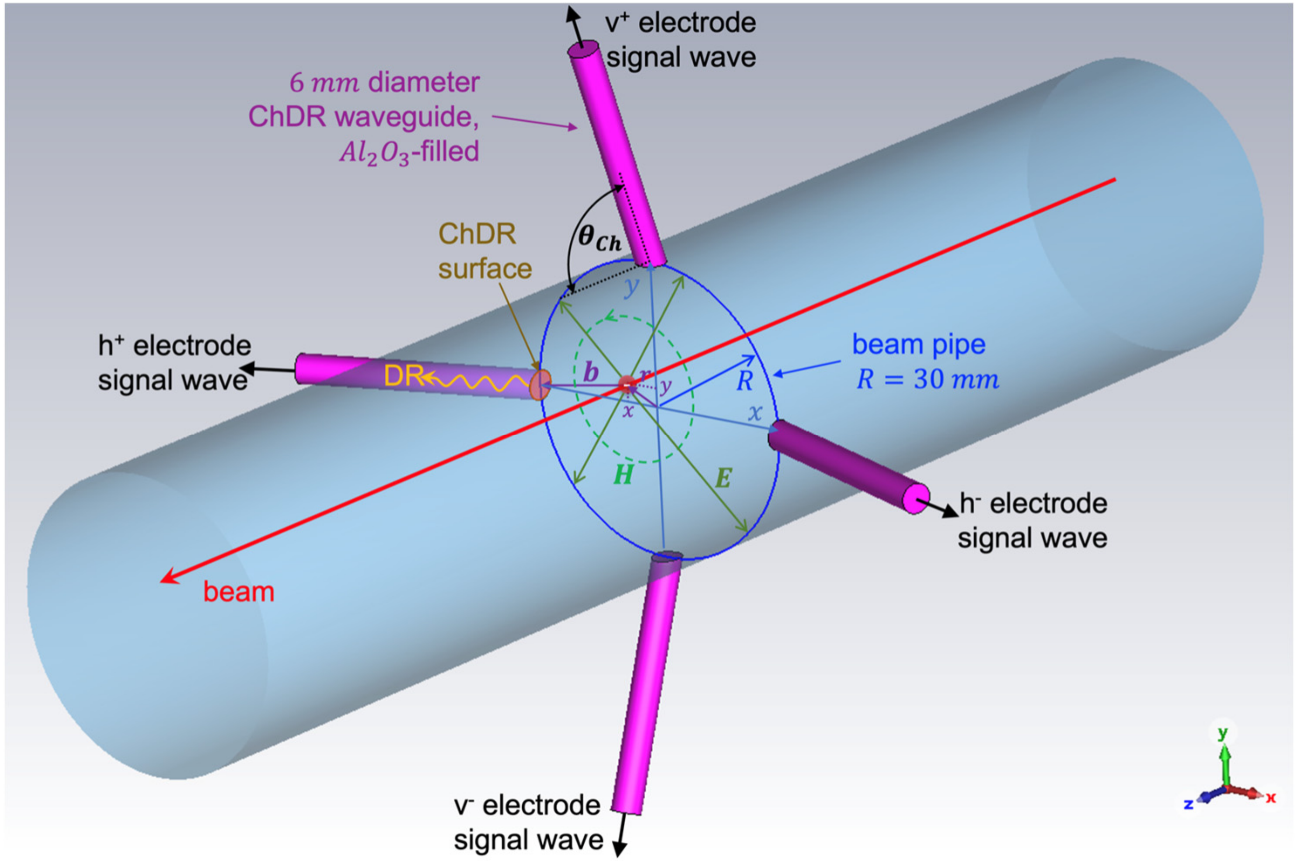
Useful technique:

✔ Provides **non-invasive** measurement

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

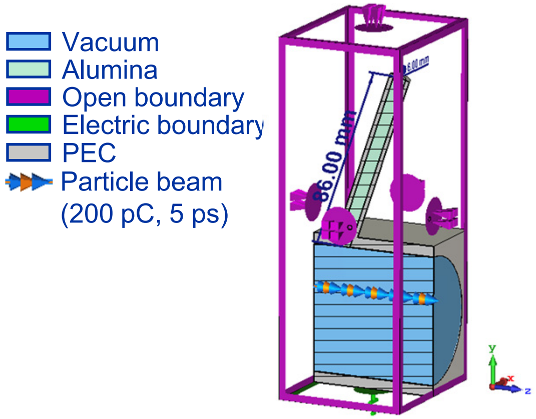
ChDR BPM conceptual design

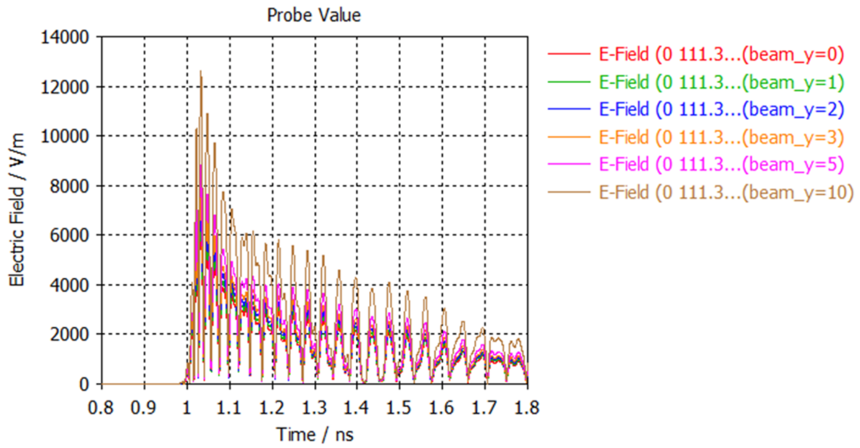
- 2+2 symmetric arrangement of radiators on the perimeter of beampipe
- Polarisation radiation (combination of ChDR and DR from radiator edge) is produced and propagates through the radiators
- Signal proportional to bunch charge and a function of the beam position
- Difference-over-sum of voltage signals provides charge-independent position measurement

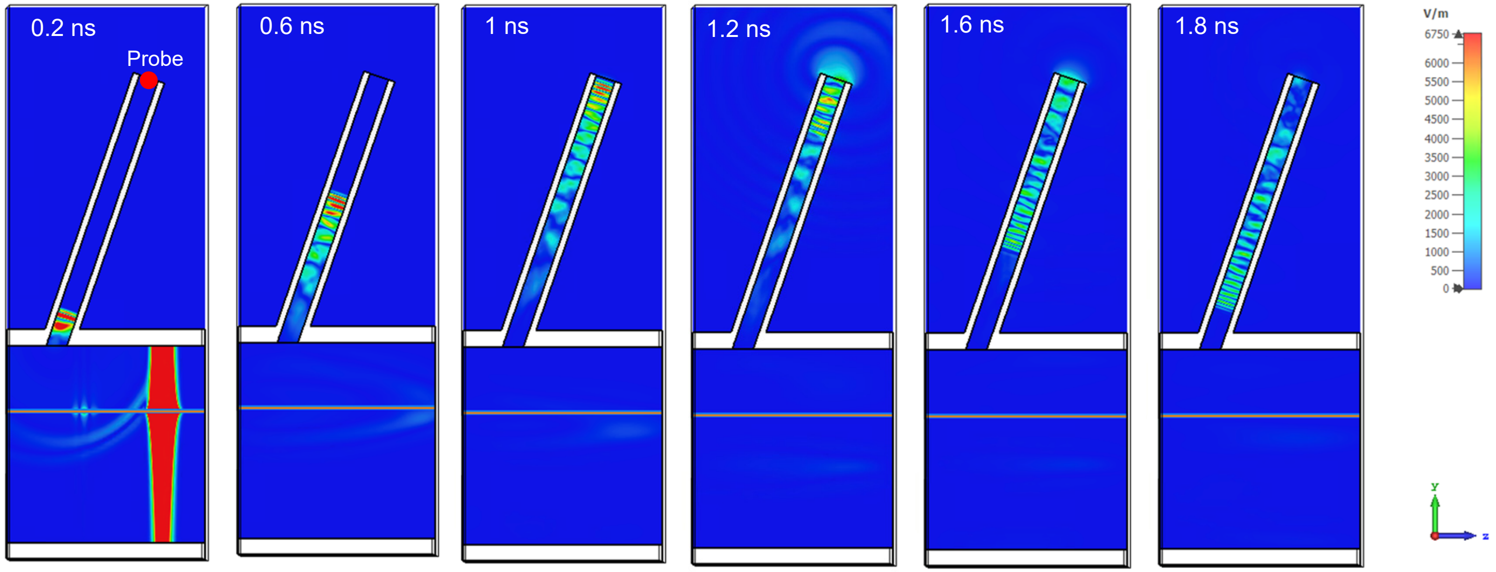


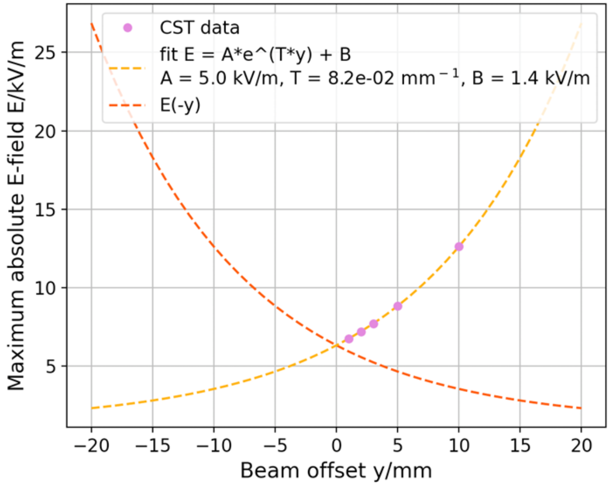
ChDR BPM numerical simulations

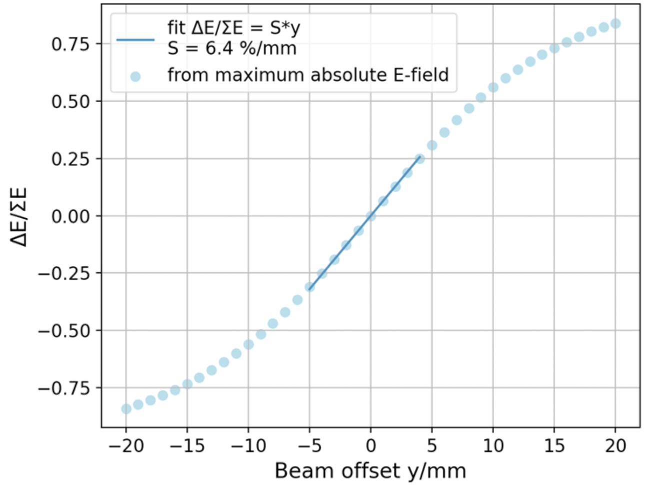
- Simulation in CST shows propagation of radiation in the dielectric and predicts the signal response of the BPM











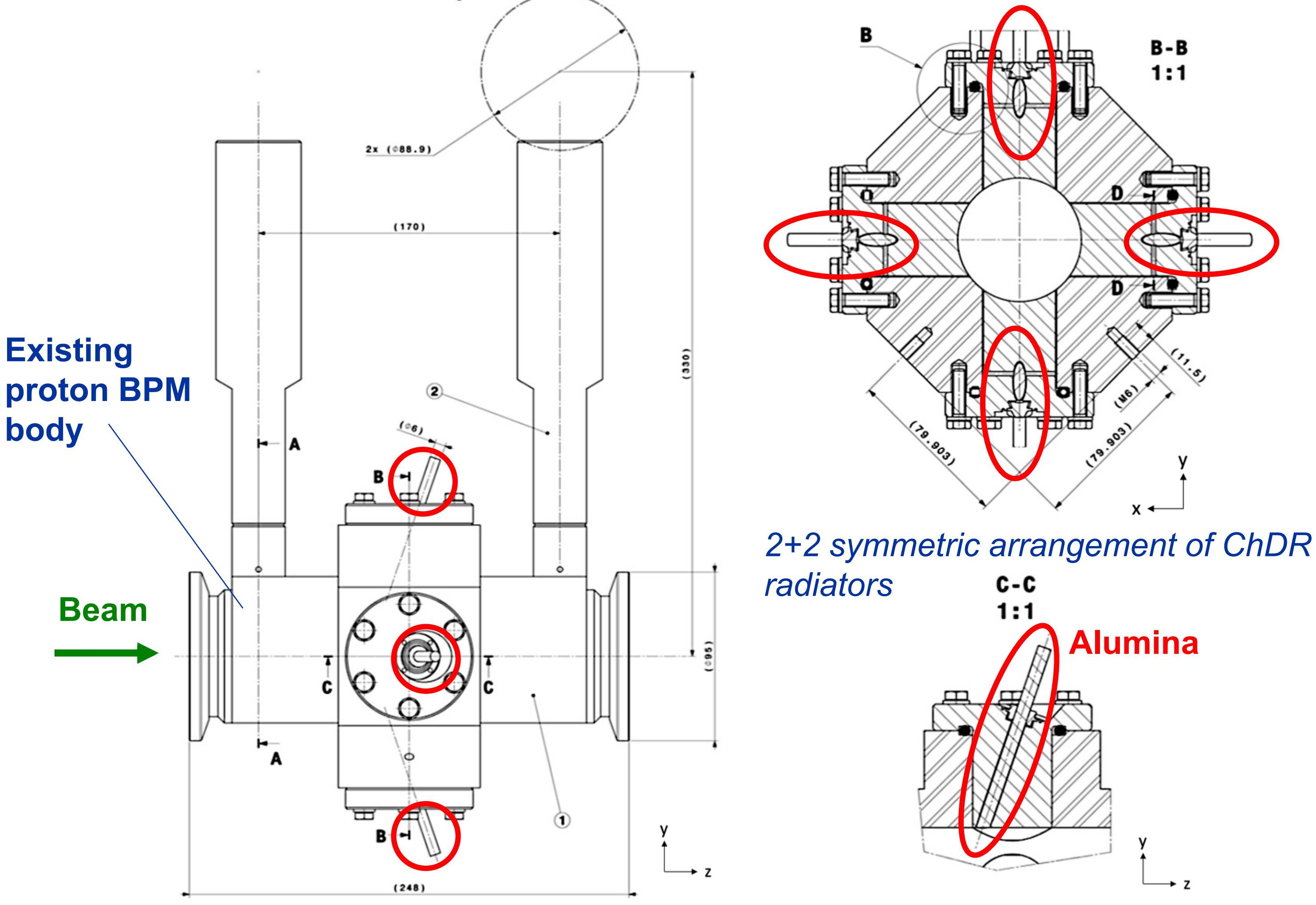
6.4 %/mm position sensitivity
Linear region ±5 mm
Image current model 6.7 %/mm

ChDR BPM mechanical design

- To have high-pass cut-off in the few GHz region, chose **⌀6 mm, 86 mm long alumina rods** angled at the Cherenkov angle (71°) to minimize internal reflections
- 9.6 GHz cut-off

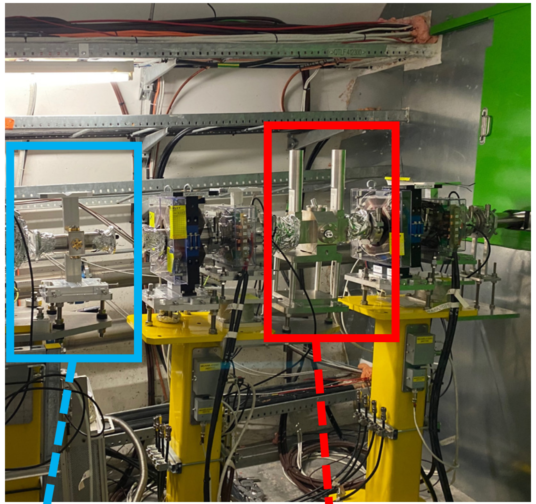
- Material and size also chosen to respect the geometry of existing LHC p-BPM body

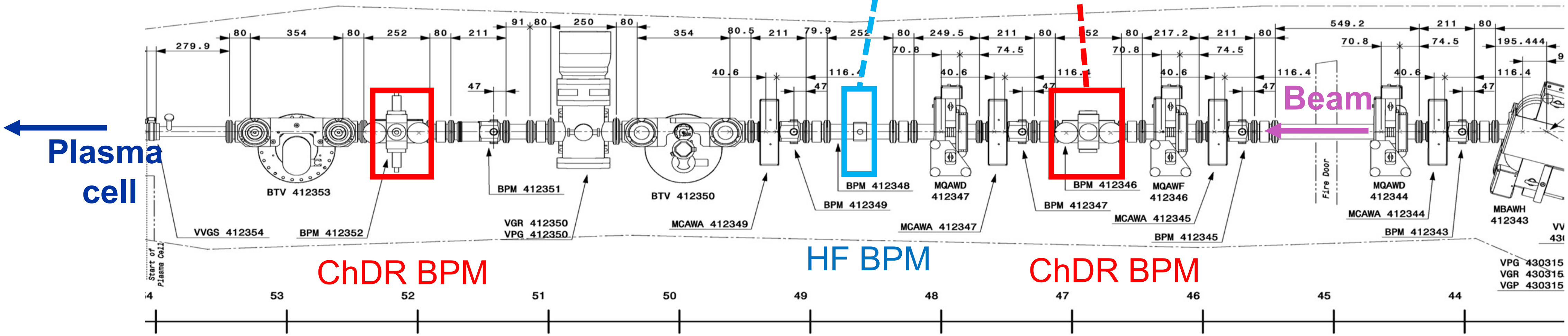
Mechanical representation of AWAKE ChDR BPM



Tests at AWAKE – Installations

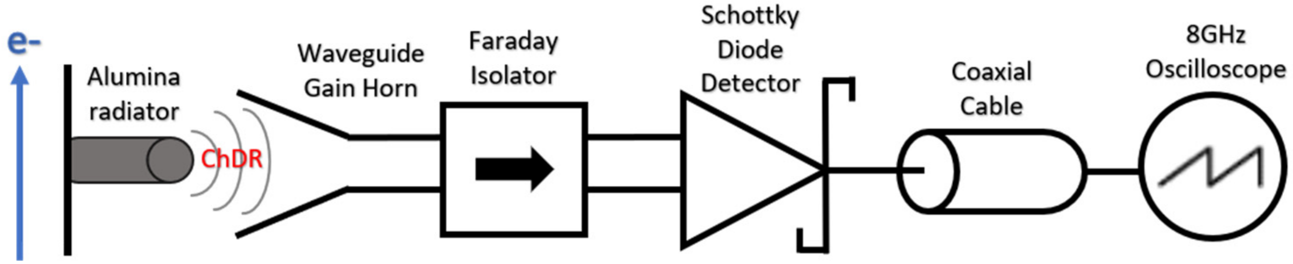
- 2 ChDR BPMs installed in the common beamline, one connected to TRIUMF electronics and one read out with horn antenna and diode detector to scope
- 1 HF BPM installed, less than 1 m from the upstream ChDR BPM, tested both with readout on scope and TRIUMF electronics





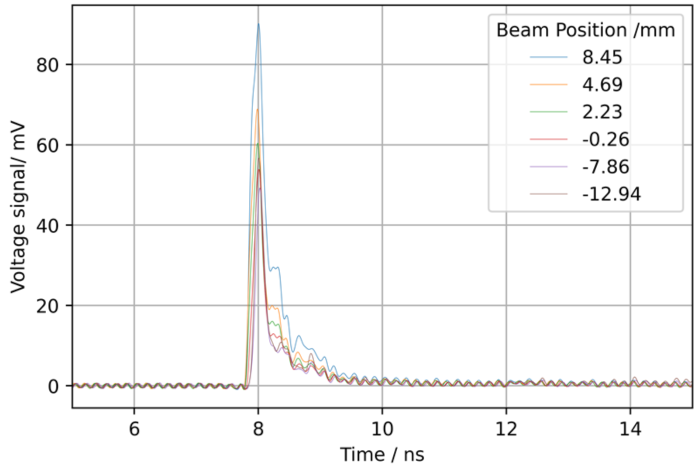
Beam tests at AWAKE – ChDR BPM, electrons only

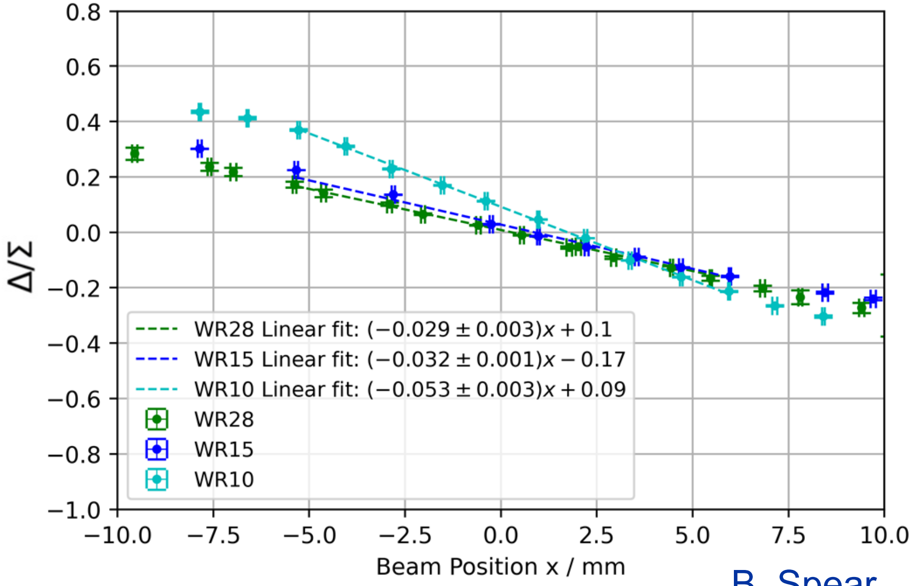
- For testing the position sensitivity of the ChDR pick-up, the read-out: waveguide horn, diode detector and scope



- Example time signal shown for WR15 (50-75 GHz), for one ChDR pick-up shows sensitivity to beam position
- Difference-over-sum shows linear response between ±5 mm
- Tested at 3 frequency bands: WR28 (26.5-40 GHz), WR15 (50-75 GHz), WR10 (75-110 GHz)
- Increased sensitivity with increased detection frequency 3%/mm to 5%/mm
- Measured sensitivity is lower than predicted by CST simulations
- But the increase in sensitivity with detection frequency is expected from ChDR theory

WR15



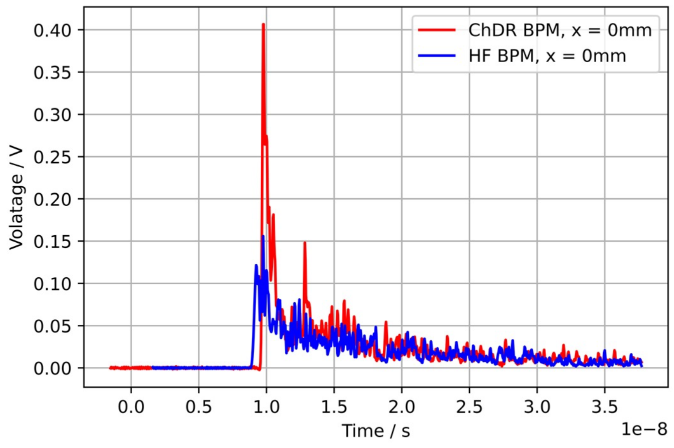


B. Spear

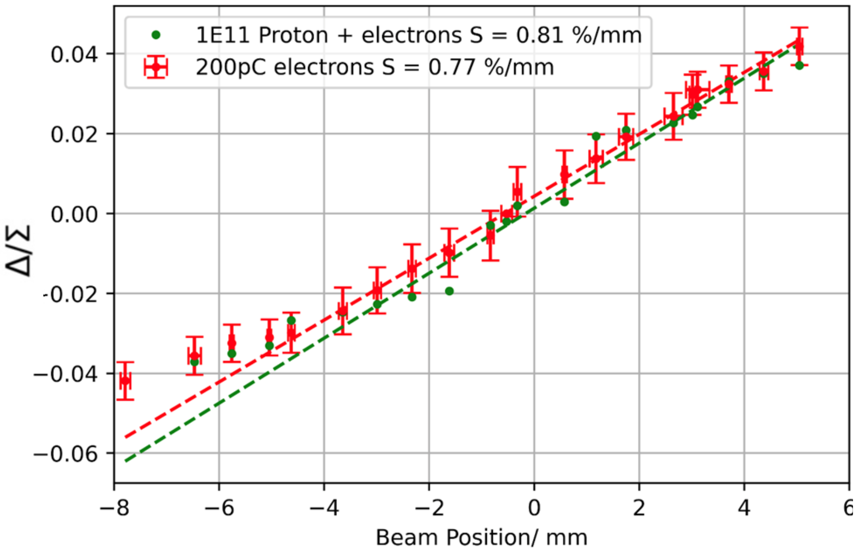
Beam tests at AWAKE – HF and ChDR BPM, electrons only, and electrons + protons

- For comparison between both pick-ups: direct WR28 waveguide connection and diode detectors set-up for both
- Time signals of both show larger signal produced by ChDR pick-up

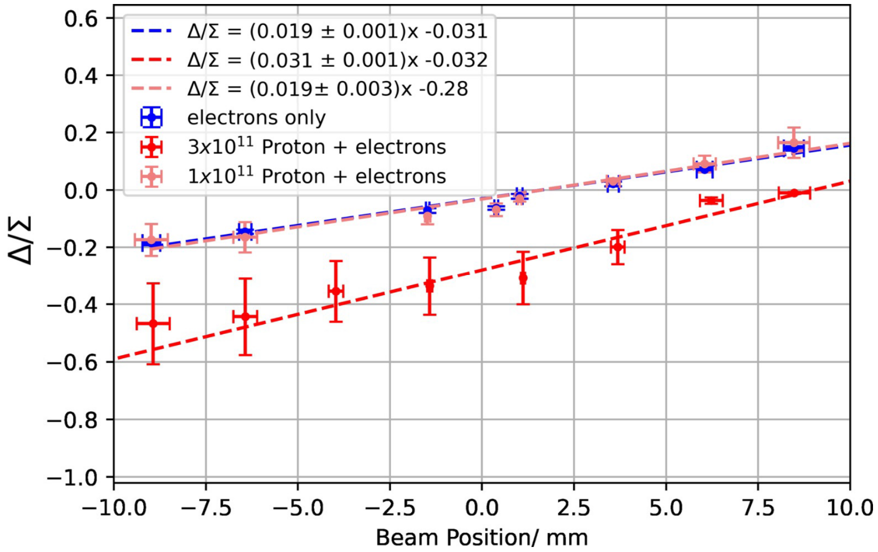
Example time signals



HF



ChDR

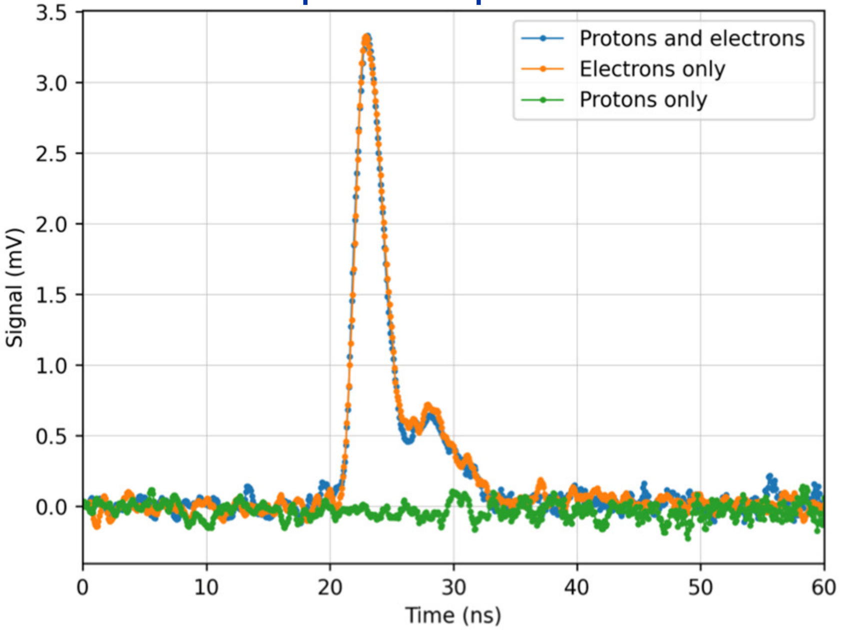


B. Spear

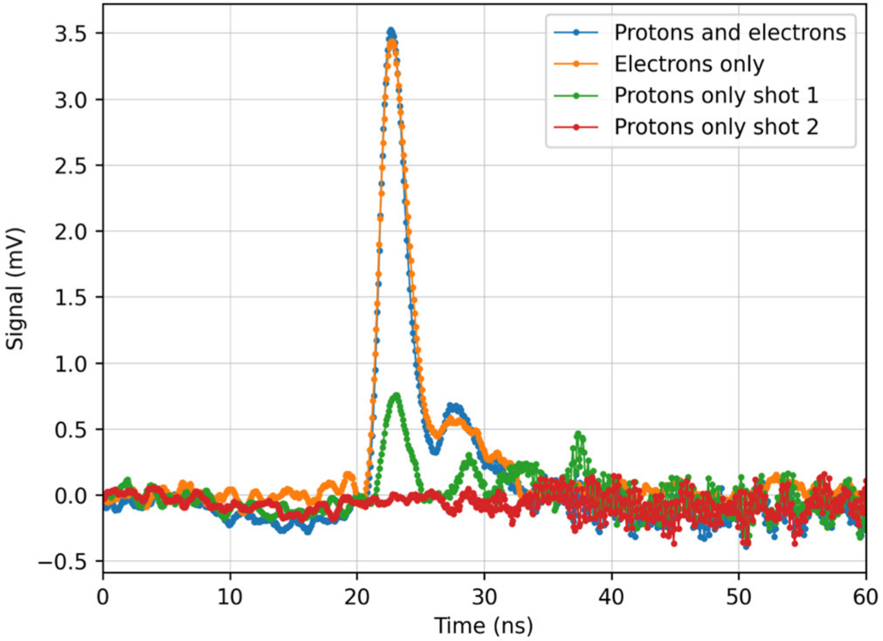
- Performed position scans, electron only shots taken before & after electron + proton shot
- Demonstrated that sensitivity is not affected by 1e11 protons per bunch (ppb)
- But it is affected by the 3e11 ppb so there is some contribution to the signal from protons
- Sensitivity is lower for the HF BPM than the ChDR BPM with the same detection set-up, 1%/mm vs 2%/mm

Beam tests at AWAKE – proton signal rejection

1e11 protons per bunch



3e11 protons per bunch



- Examples of the time signals of the ChDR BPM with 30 GHz detection
- Shows that proton signal at 1e11 ppb is below the noise level
- No change of the signal shape for simultaneous protons + electrons
- For 3e11 ppb, some signal perturbation present with a large shot-to-shot variability but depressed w.r.t. the electrons
- Hints that the proton spectrum extends to frequencies higher than what we expect, under investigation

[3] E. Senes, Ph.D. thesis, University of Oxford, Oxford, UK
[4] B. Spear, in proceedings IPAC24, Nashville, Tennessee, USA (2024)
[5] B. Spear, in proceedings IBIC24, Beijing, China, (2024)

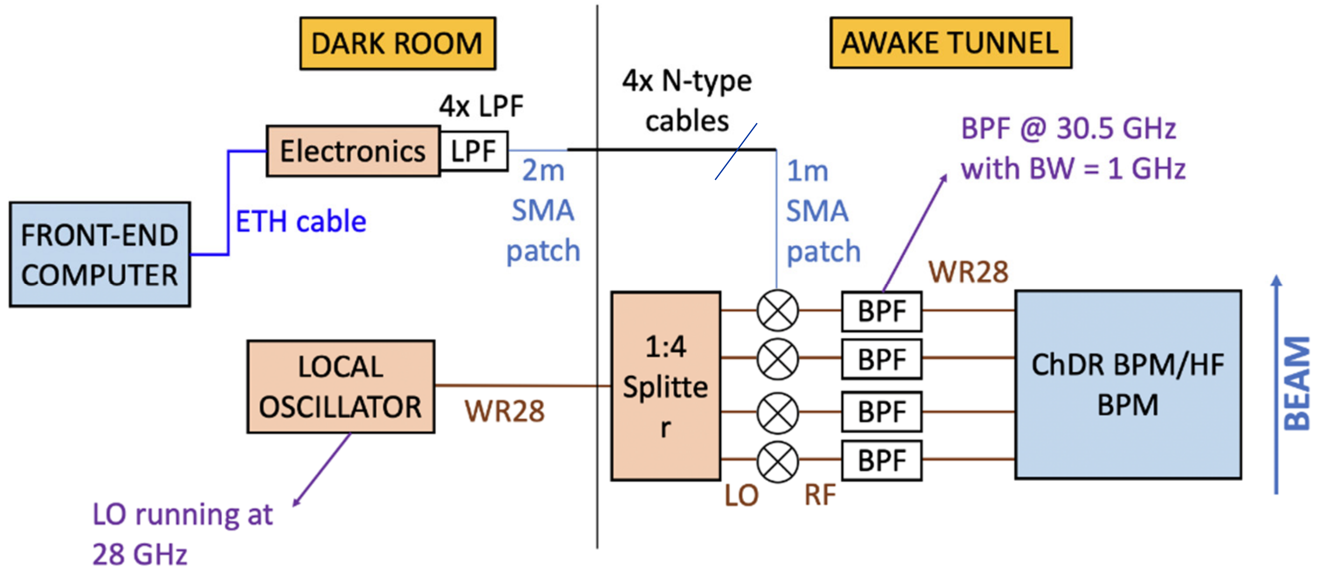
- ChDR BPM operation for 1e11 ppb is feasible as it shows good rejection of 1e11 ppb

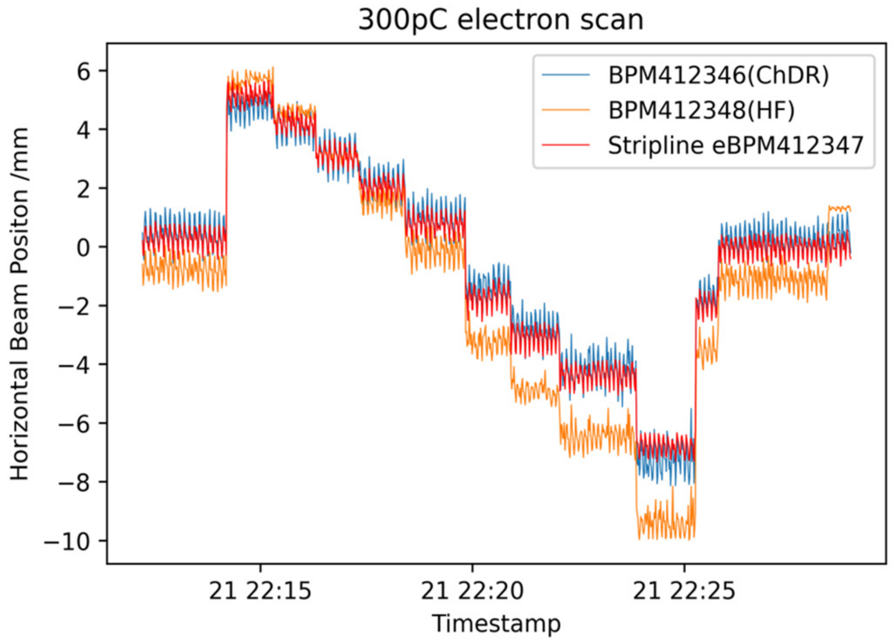
Beam tests with TRIUMF read-out systems

- Both, HF and ChDR BPMs were connected to a pair of read-out electronics designed by TRIUMF
- Detection chain – frequency downmixing, etc.
- Preliminary tests done showing that both the ChDR and HF BPMs are sensitive to beam position following closely the response of the neighboring electron BPMs
- Calibration was performed on both read-out electronics to remove the non-linear response of the diode detectors

[6] C. Pakuza, in proceedings IBIC24, Beijing, China, 2024.

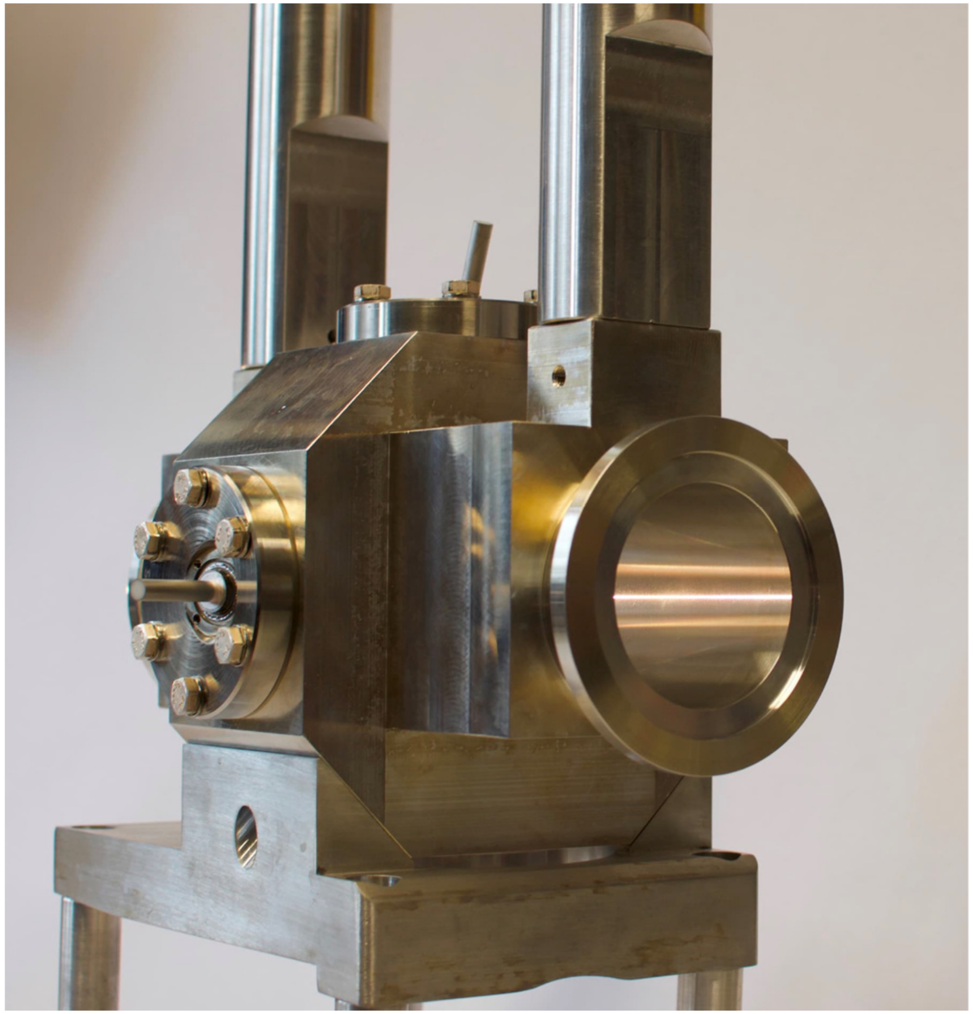
- More beam tests are required for the calibrated electronics and compared with beam trajectory





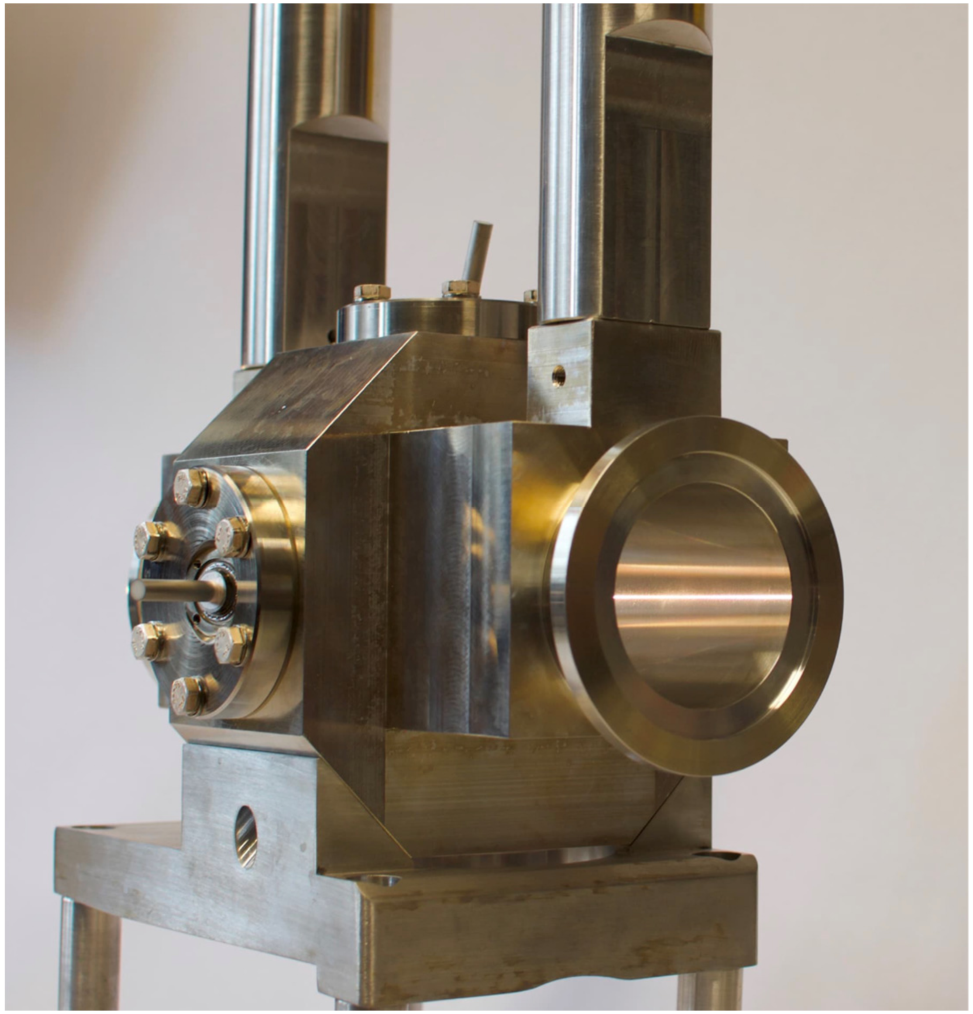
Future outlook

- Some **challenges** still need to be studied
- Broadband **matching** between the **radiator** and the **standard waveguide** is more difficult for the ChDR PU than the HF PU needs to be further studied
- **Time response** of the PU should also be measured and possibly further optimized
  - *Please refer to talk by Andreas Schloegelhofer on Wednesday on how this measurement can be achieved*
- Further testing required to better understand the systems and better optimize the detection
  - The proton bunches still have a frequency content at 30 GHz
  - The electron detection systems would benefit from **operating at a higher frequency** to further **reduce the contribution from the proton signal**



Conclusions

- ChDR pick-ups are a **young and promising technology** for non-invasive beam position measurements
- Both HF and ChDR pick-ups have **large bandwidth** which may also have impact for accelerators with short bunches
- Specifically at AWAKE, these could allow for **beam distinction** based on frequency discrimination



Thank you for listening!

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