Performance of the EO-BPM Prototype in the SPS

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T. Levens, T. Lefevre (CERN SY-BI)

14th HL-LHC Collaboration Meeting, 7–10 October 2024, Genoa

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- Introduction
- EO-BPM History
- Assembly and Installation
- Results
- Conclusion and Outlook

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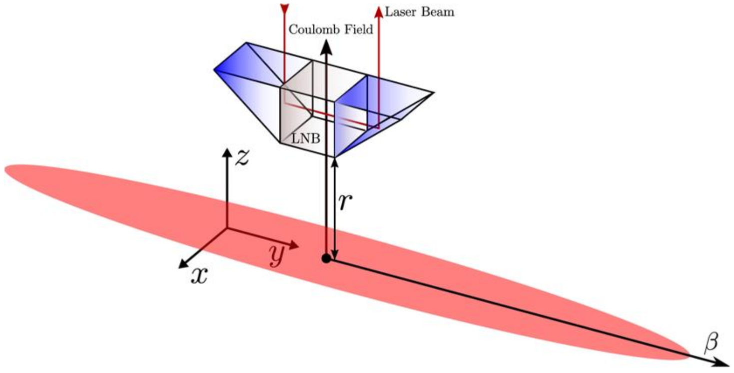
Introduction: EO-BPM

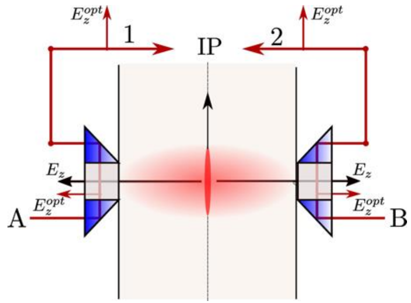
Definition

- The Electro-Optic Beam Position Monitor (EO-BPM) uses laser **interferometry** and the **Pockels effect** in a birefringent crystal to monitor a particle beam
- Upgrade of traditional BPM at higher bandwidth (GHz level)
- Collaboration between WP13 and RHUL



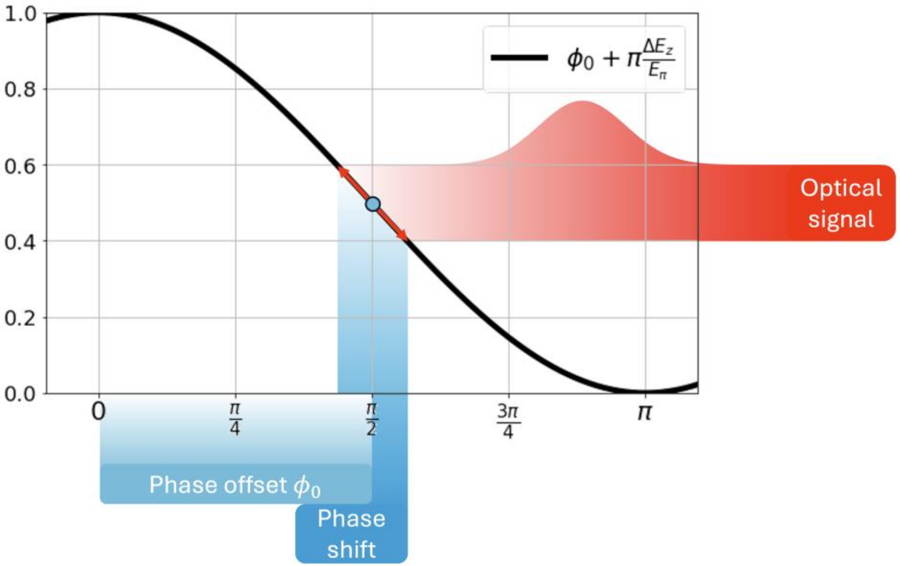
Mechanism

- The propagating electric field from the proton bunch interacts with the **LNB crystal** to change its **refractive index**
- **Mach-Zehnder interferometry** is used to determine the beam displacement



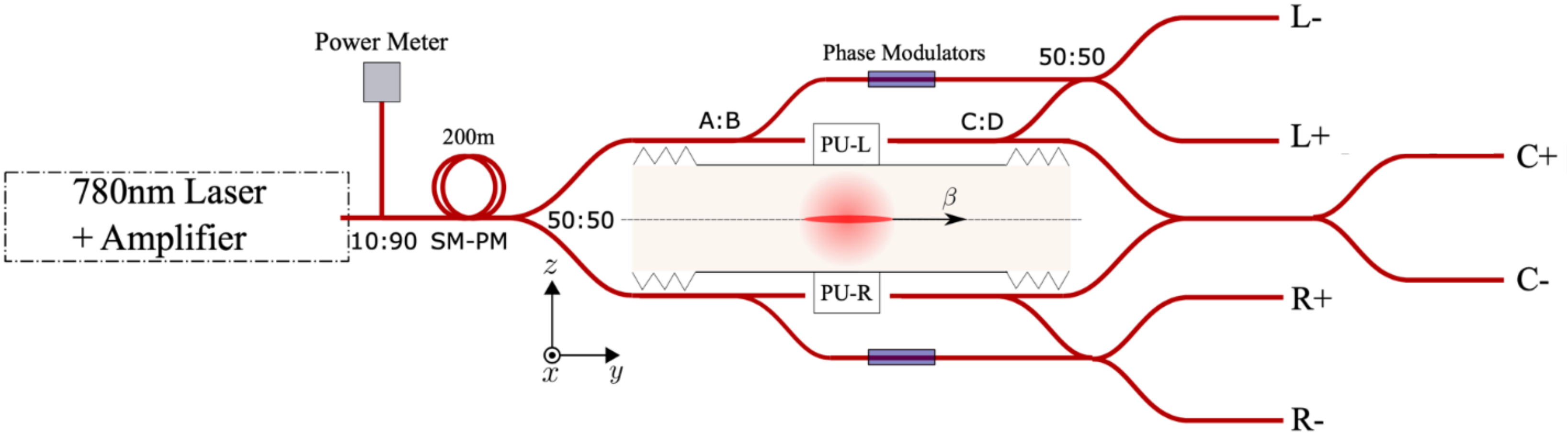
Introduction: interferometer setup

- **Phase offset is stabilised, beam field induces phase shift**
- Bunch charge, displacement, bunch type affect the overall shape
- One of three modes can be stabilised, we examine **common mode**



Introduction: interferometer

The EO-BPM consists of three separate Mach-Zender interferometers: a common mode (difference signal) and two side modes (sum signal).



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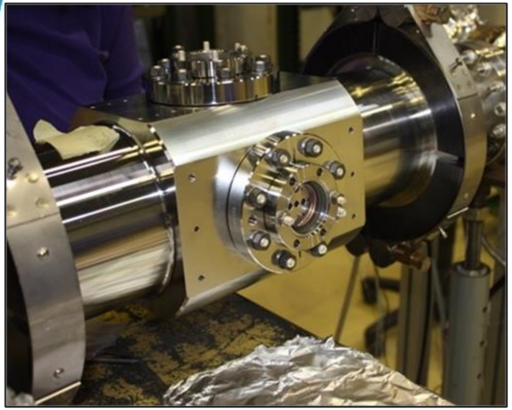
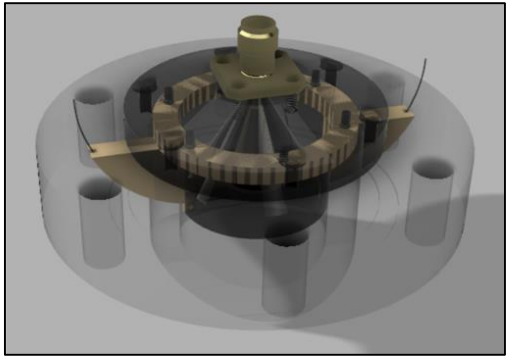
EO-BPM development history



1. **2016:** Original SPS design using bulky free-space optics with a polariser/analyser
2. **2018:** Installation of a compact interferometric design in SPS
3. **2021:** Optimised fully fiber-coupled waveguide design
4. **2021:** Beam tests in HiRadMat
5. **2022:** Beam tests in CLEAR
6. *2024: SPS installation*



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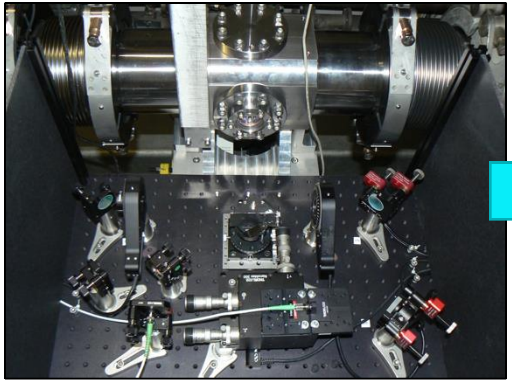
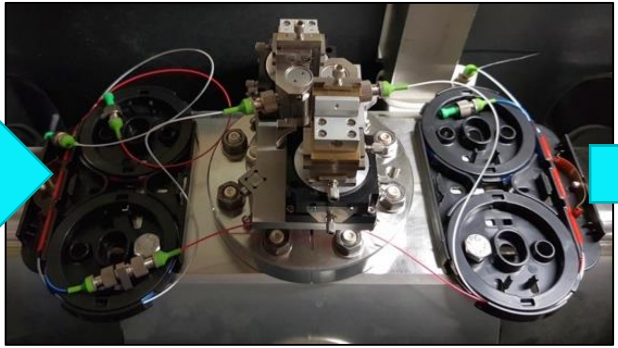
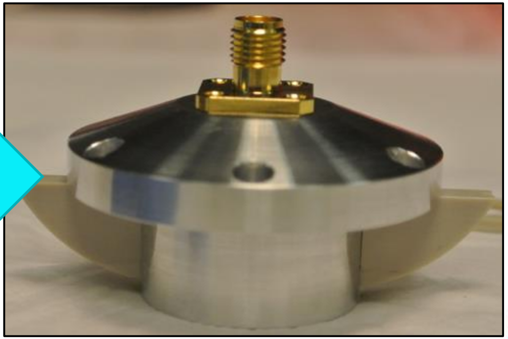


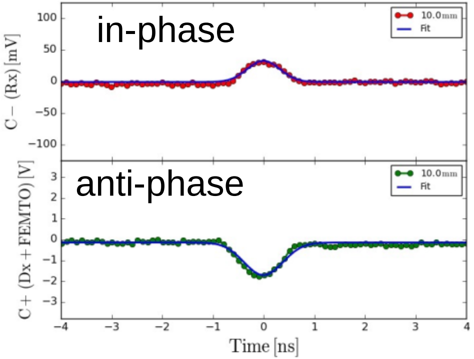




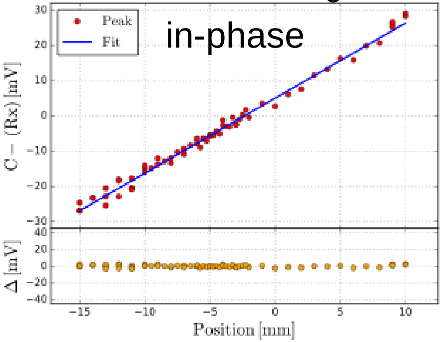
In-air EO-BPM tests at HiRadMat & Clear

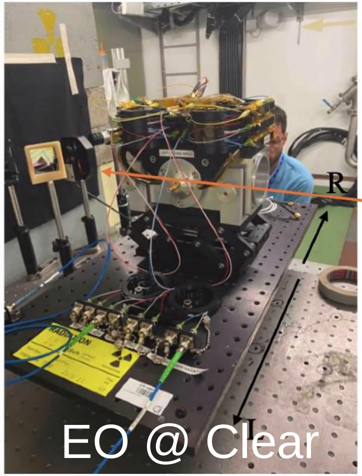
- **2021 HiRadMat: first EO-BPM single-shot measurements:**
  - **Bunch by bunch position measured as EO-BPM translated.**
- **2022 Clear:** measured fast **train of 5 *electron bunches***
- High bandwidth photodetector shows **time resolution** of EO pick-up is well **within the < *50 ps* specification** required for 1ns HL-LHC bunches

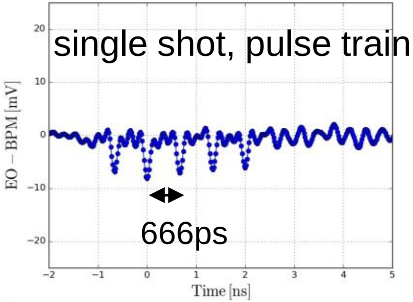
Typical single-shot signals:

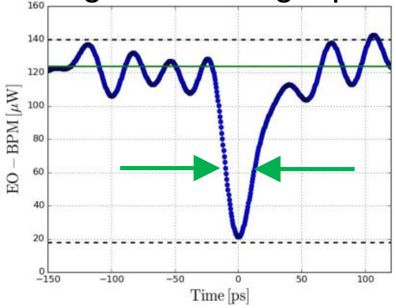


Beam position scan by moving EO-BPM on stage









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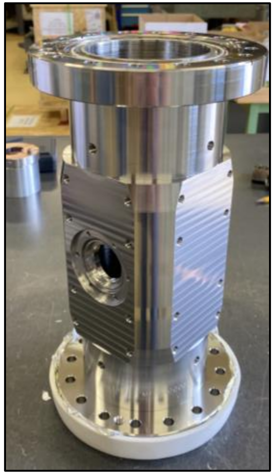
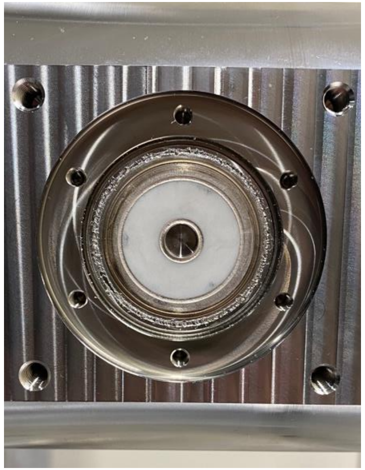
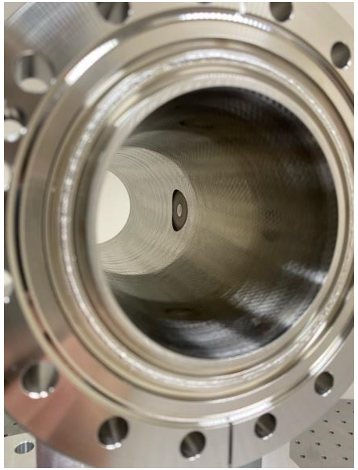
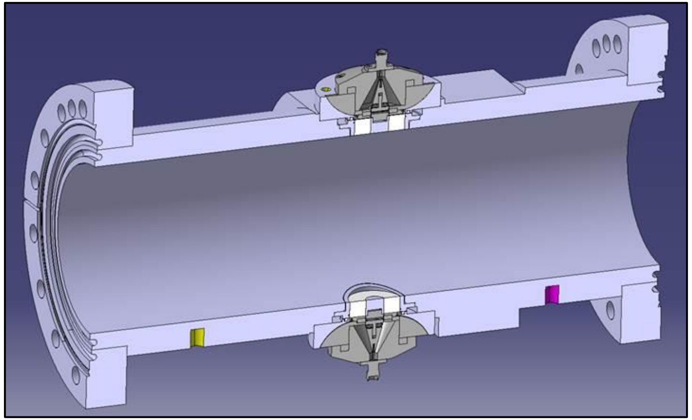
Vacuum compatible EO-BPM

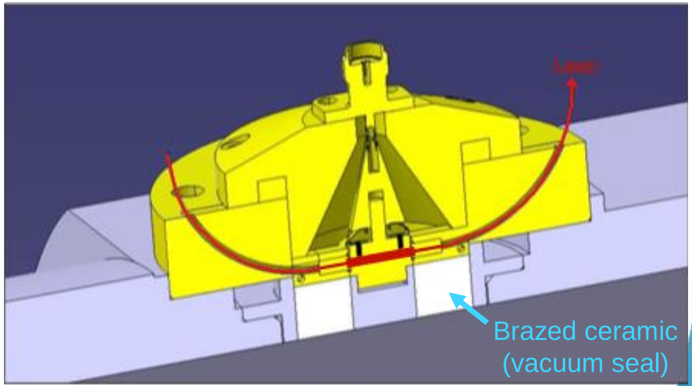
- EO-pick-up incorporated into in-vacuum design for beam tests at the SPS (ideally with crabbed bunches).
- A ceramic washer separates the EO-pickup from SPS vacuum
- 2022: the ceramic washer cracked during brazing, preventing installation in YETS22/23.
- 2023: ceramic washer **successfully brazed and welded** to the body with an airtight seal to be installed in beampipe.


EO body


Brazed button


Internal view





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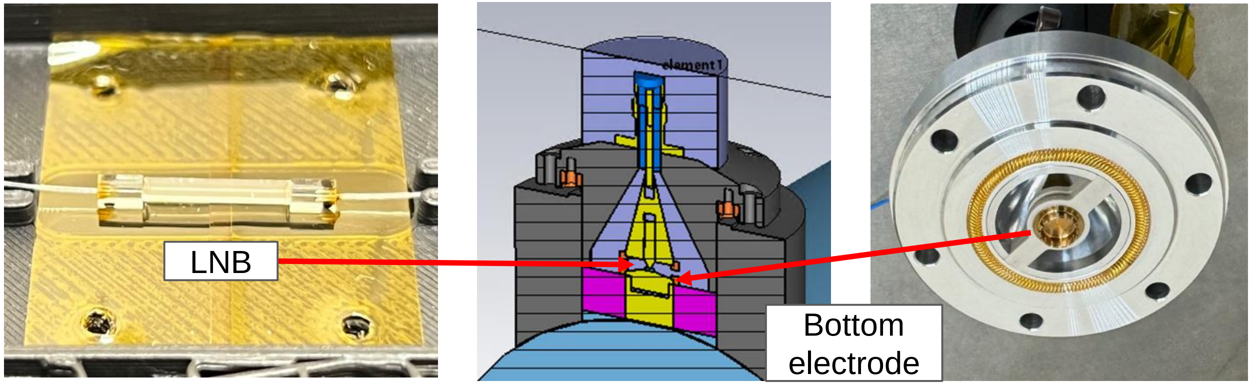
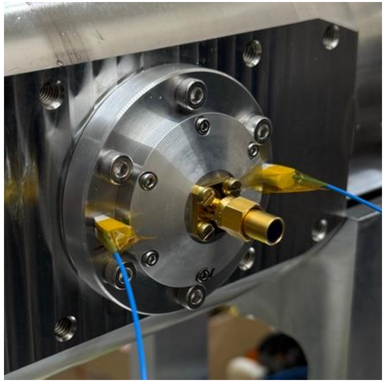
Button assembly

- Two buttons with waveguide LNB crystals connected to electrodes were assembled

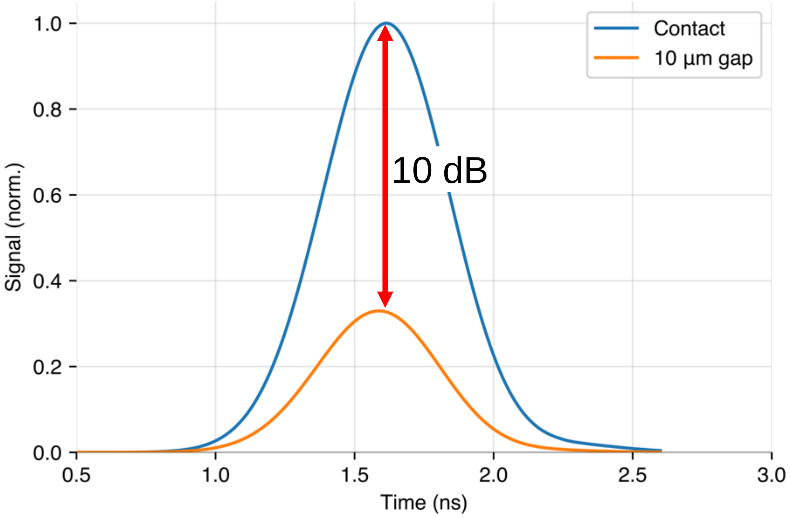




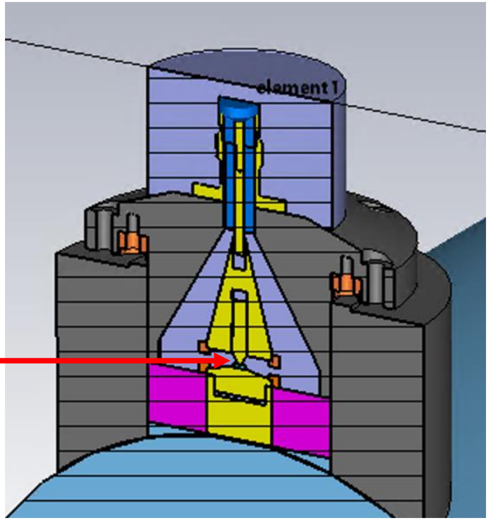
- Crystal measures 1x1x9 mm, waveguide 10 μm; many other very small parts mean **assembling the button** in a reproducible manner poses **significant challenge**

Mechanical assembly

- Crystal is electrically connected to electrodes
- Simulations show adding a **10 µm gap** (representing assembly inconsistencies) a **signal drop of 10 dB**



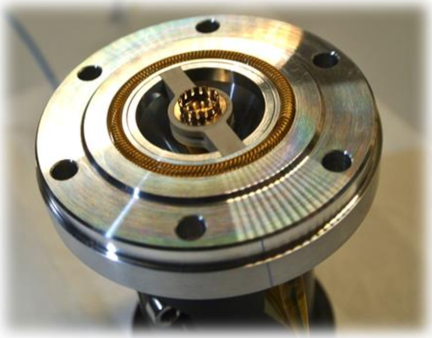
LNB



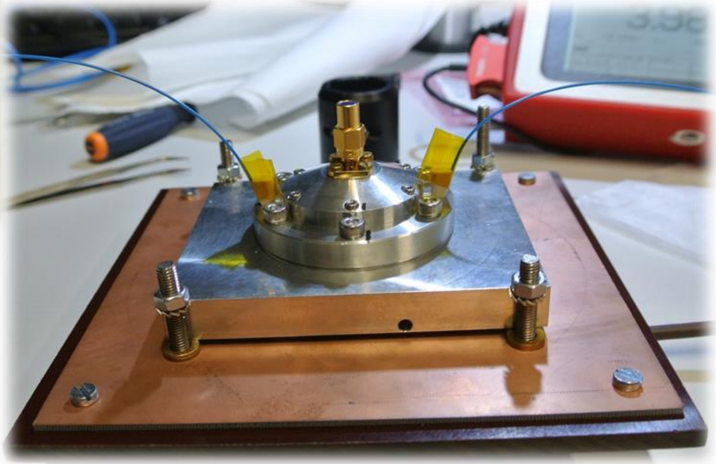
Delivery to CERN of EO-BPM for beam tests at SPS

- EO waveguide pickups built, tested and installed onto brazed-button EOBPM for CERN SPS tests.

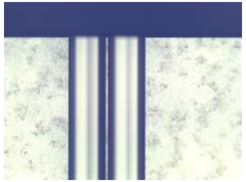
EO waveguide built into pickup



EO pickup test prior to BPM assembly



Optical inspection of waveguide in RHUL clean room



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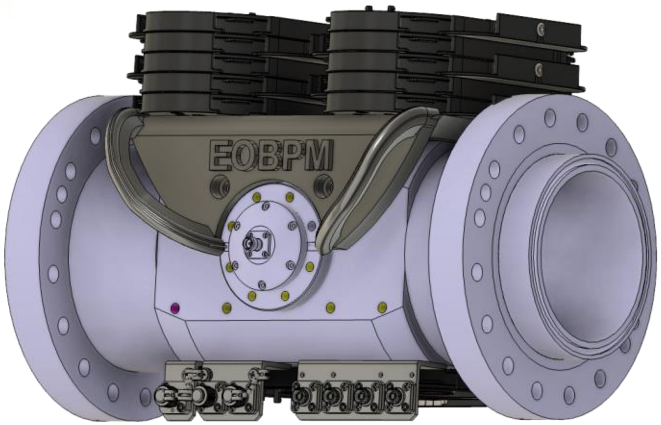
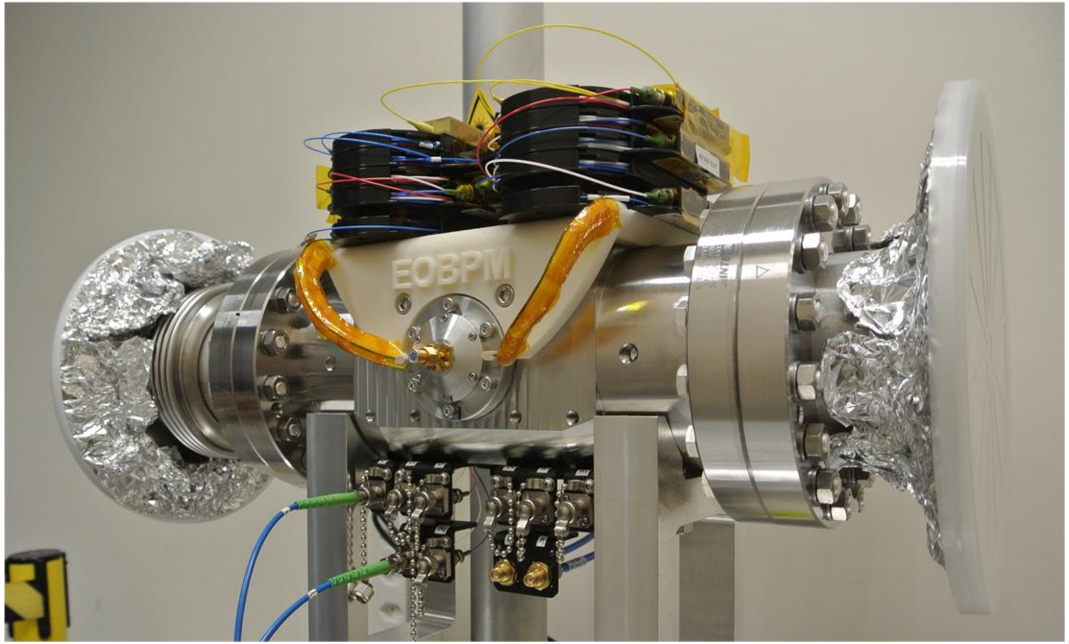
Complete, Dec 2023

Delivery to CERN of EO-BPM for beam tests at SPS

- **EO-BPM demonstrator** assembled and ready for installation in **SPS** for operation in Run 3





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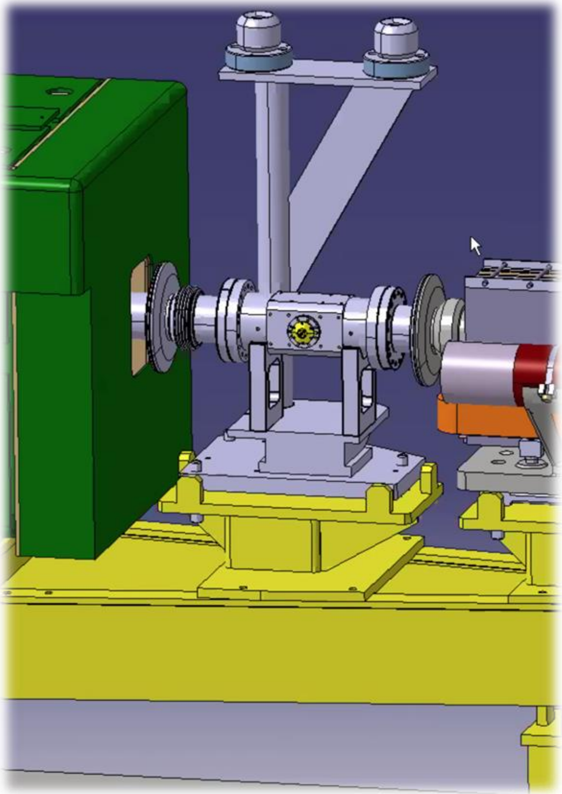
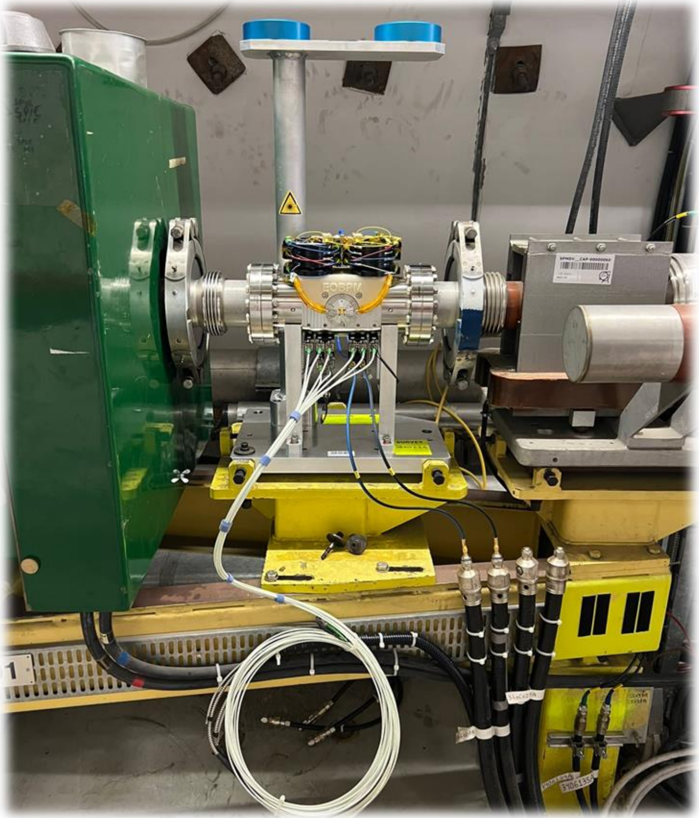
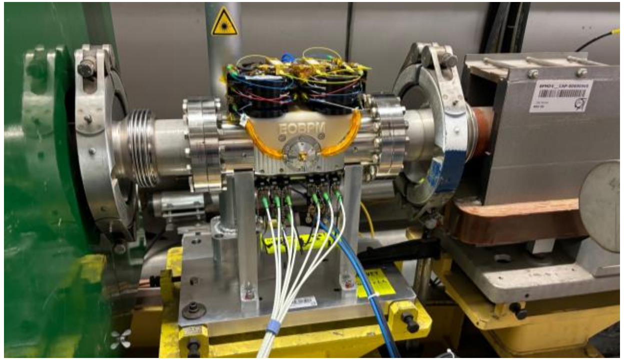
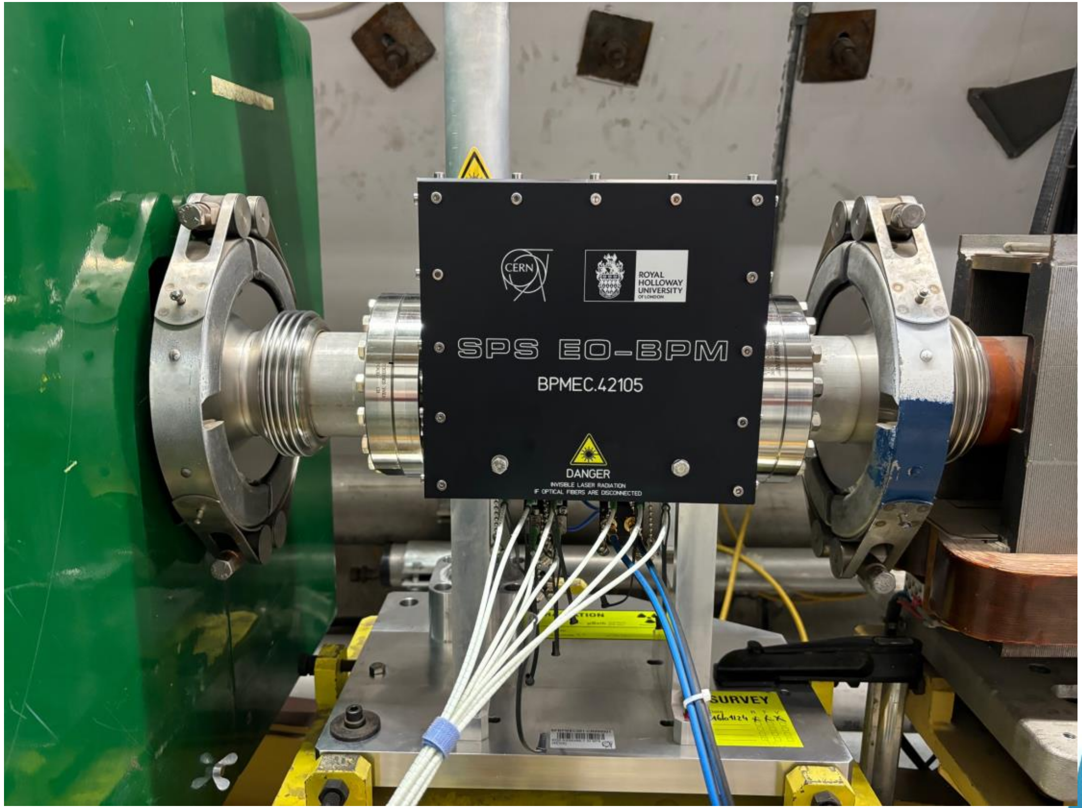
EO-BPM demonstrator installed & ready for beam





EO-BPM demonstrator installed & ready for beam





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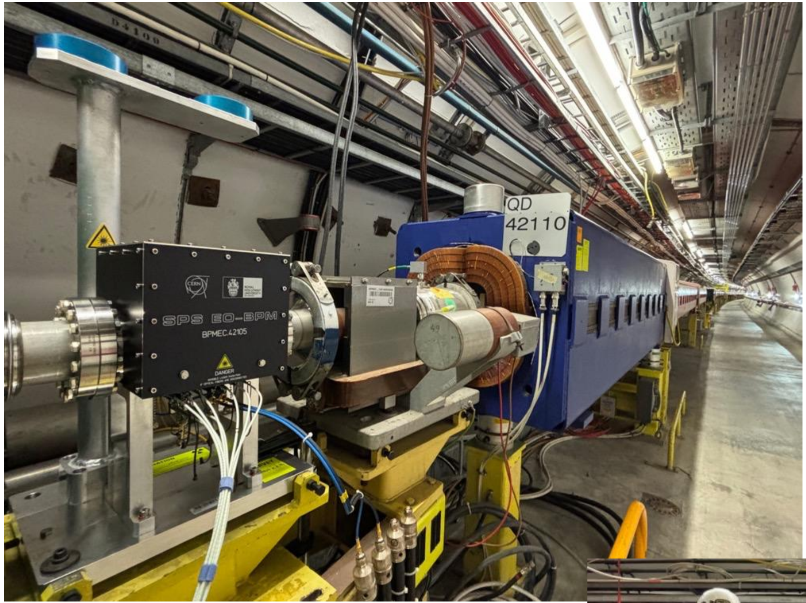
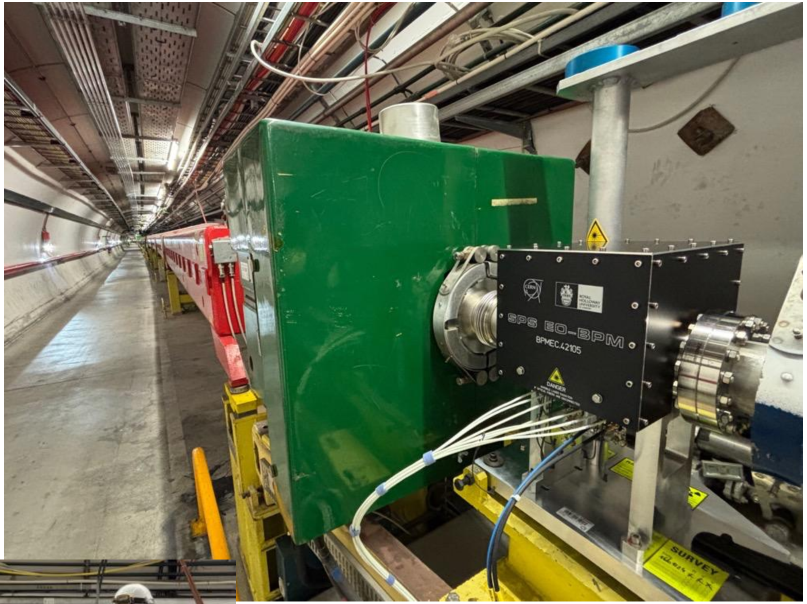
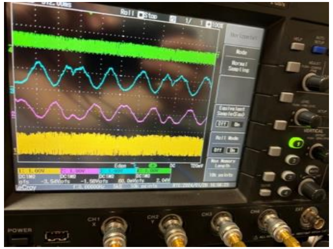
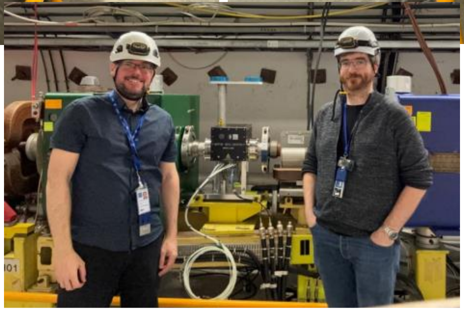
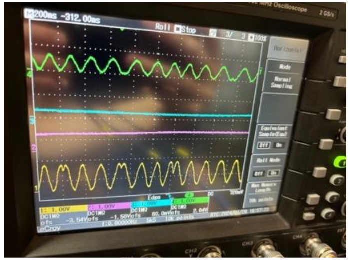




C+/-
interferometers







L / R
interferometers

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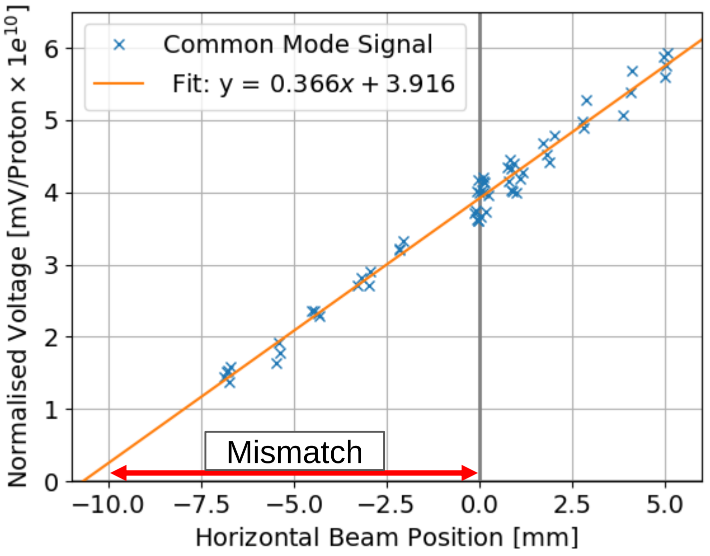
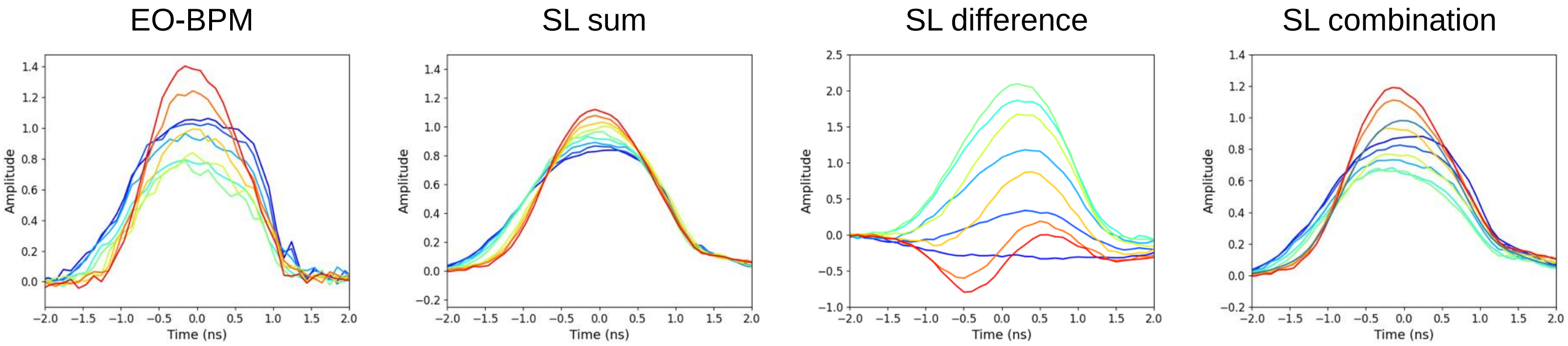
Position sensitivity

- **Clear response in output voltage**
- 10 mm **mismatch** between optical centre and beampipe
- Assembly inconsistencies cause stronger **electro-optic response** of the left crystal
- Analysis show 3.5 dB difference; 10 µm displacement was 10 dB
- EO-BPM exhibits characteristics of **both sum and difference signal**



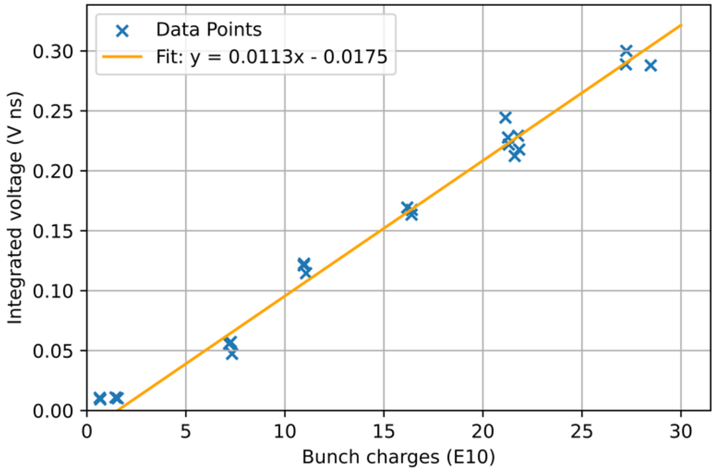
Position sensitivity: resolution



- EO-BPM results compared to stripline BPM 18 m downstream
- Typical **noise** generated by **detection chain** equivalent **250 µm uncertainty**
- The stripline BPM uncertainty is approximately **25 µm**
- EO-BPM shows **turn by turn data comparable to current standards**

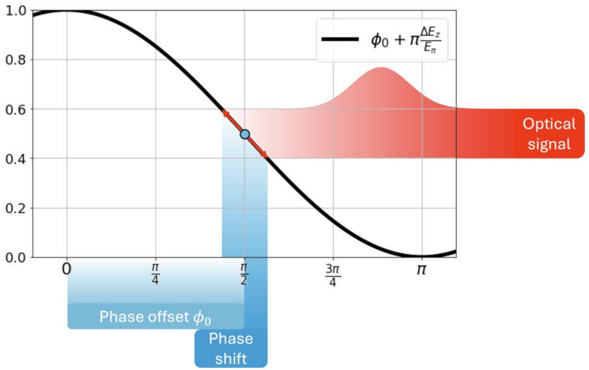
Dynamic range

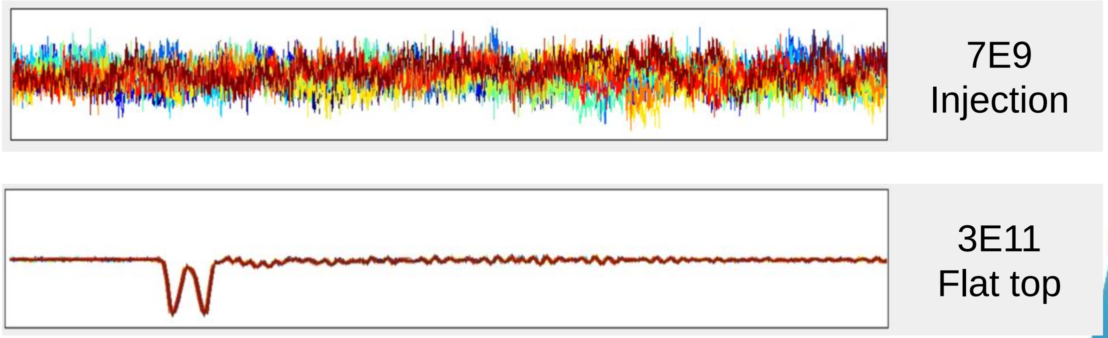
- Variability of bunch types requires the EO-BPM to cover the dynamic range of the SPS (5E9 – 3E11 protons)
- Each data point is 100 averaged turns of a bunch taken at injection
- Data shows a **clear linear response in output voltage**
- Trendline intersects x axis at 1.5 E10: no signal below this bunch charge



Dynamic range: over- and underrotation

- Left: electro-optic signal is a sum of phase offset and optical signal
- Right: if the signal is **very low**, it does **not exceed noise levels**. If the peak signal is **very high**, it **overrotates**
- At flat top, peak signal is significantly higher and overrotation becomes a larger problem





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Conclusion and Outlook

Achievements:

- Vacuum compatible design successfully installed in SPS
- Good signal response to beam position and bunch charge variation
- Intra bunch turn-by-turn measurements comparable to stripline BPMs

Conclusion and Outlook

Summary of improvements:

- Optical centre matching
  - Can be improved by streamlining button production as well as standardised bench top testing
- Dynamic range
  - Amplify optical signal, increase laser power
  - Phase extraction algorithm
- Ability to read out three modes simultaneously

Performance of the EO-BPM Prototype in the SPS

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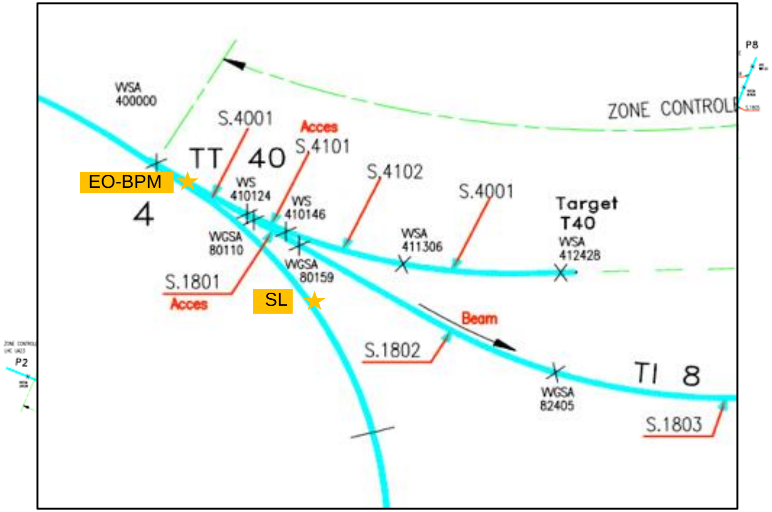
Appendix

SPS installation



Laser → EO-BPM → Photo-diode → Scope

Laser

TLB 6800 Vortex Plus
- Continuous wave
- 780 nm
- Tuneable

EO-BPM

3 inter-ferometers

Photo-diode

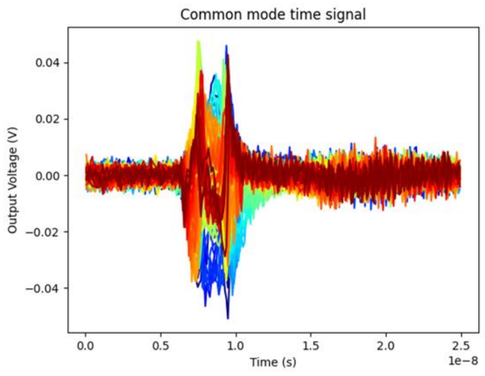
Thorlabs RXM10CF
- 240 V/W (at 780 nm)
- Max BW: 10 GHz
- Introduces noise

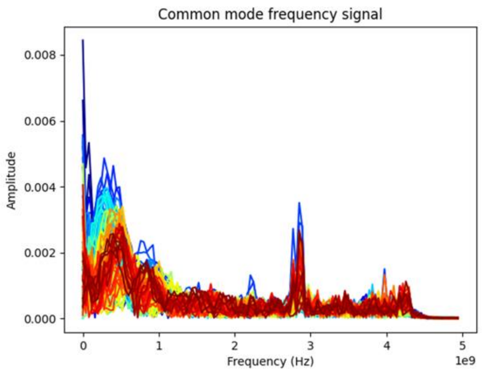
Scope

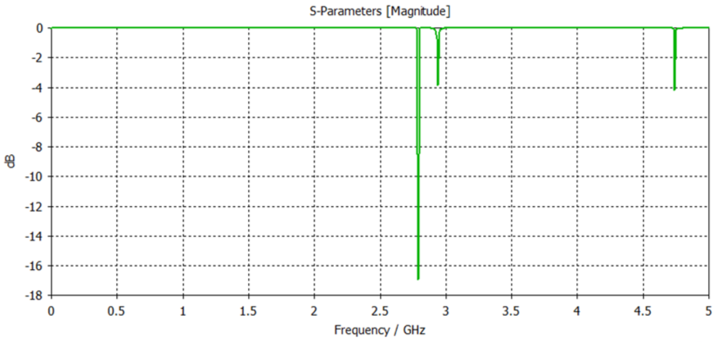
KeySight DSOS404A
- Max BW: 4 GHz
- Introduces noise

Resonance

- Nominal bunch data with base signal subtracted shows a resonant peak around 2.9 GHz; this is consistent with CST simulations

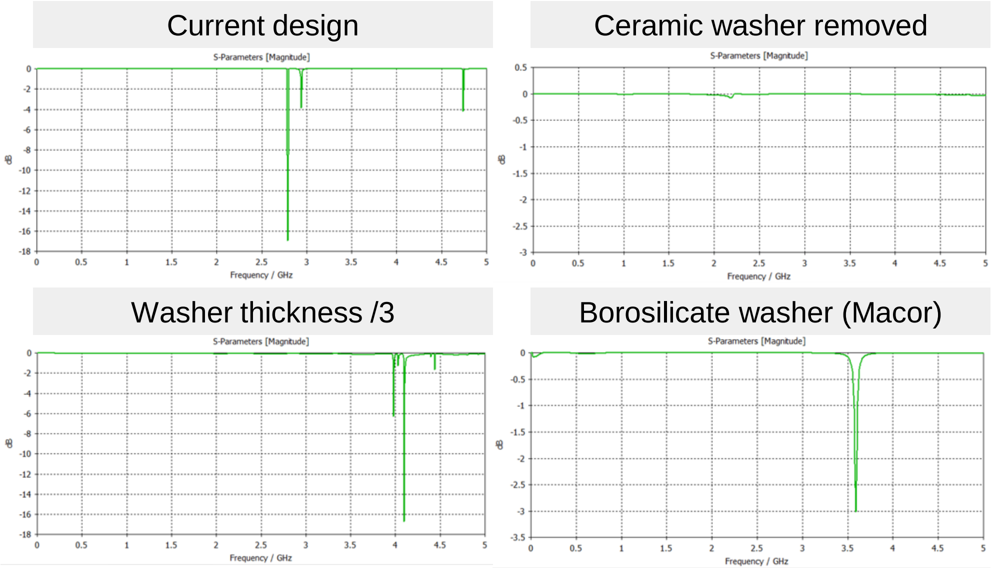






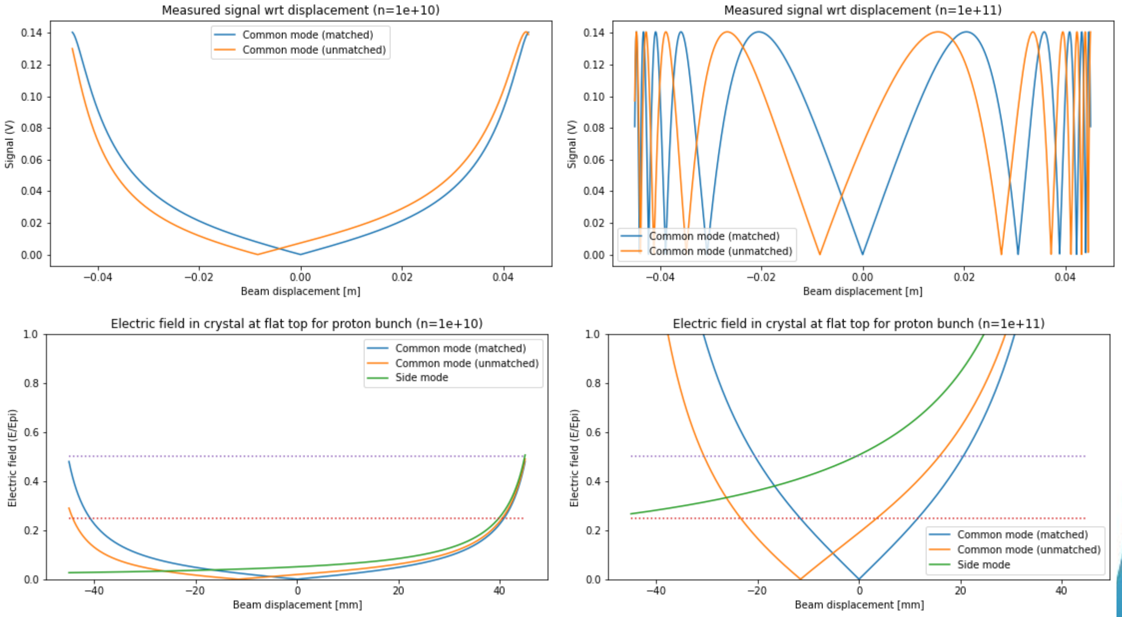
Resonance

- Simulations show that the resonance is greatly influenced by changing the ceramic washer
- The ceramic washer creates a discontinuity in impedance and material, generating a resonance
- Thinner or lower electric transmittivity material increases resonant frequency



Overrotation occurs when the electric field strength causes phase response to lose linearity

- Top: expected signal for different beam intensities
- Bottom: corresponding electric field in crystal as fraction of E_{π}
- Linearity is lost at $\frac{E_{\pi}}{4}$ and overrotation occurs at $\frac{E_{\pi}}{2}$.
- Note: these are at **flat top**, not injection



Future

- Splitter design – Say how we can use these PLC splitter boards to effectively put the splitter tree on a circuit board.
- Lifetime testing – We can say that someone lifetime testing of the buttons can be done at CERN. But we need a benchtop tester first.
- Overrotation – IQ demodulation and phase extraction (Carré) algorithm