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I.FAST WP10.7
Development of Electro-optical Waveguide Sensors

I.FAST WP10 meeting, April 20th 2023

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for the Task 10.7 team:

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T. Levens, T. Lefevre – CERN BI group

with thanks to

P. Simon, N. Charitonidis & HiRadMat team

A. Schloegelhofer, C. Pakuza & CLEAR team.

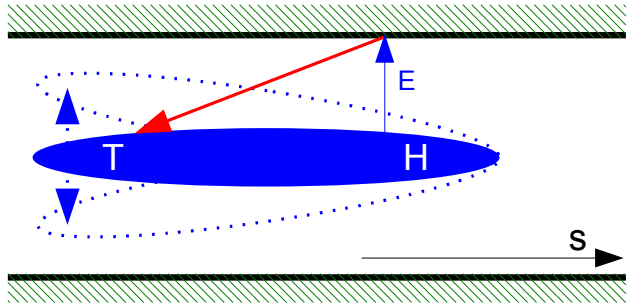
iFAST

Task objectives

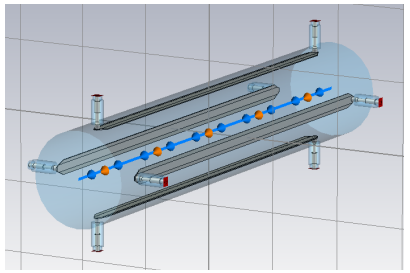
- **Task 10.7: Development of electro-optical waveguide sensors as beam electric field sensors.** M1 – M24 by RHUL & CERN + industry.
- Develop **novel electric-field sensors** based on electro-optic waveguides to address new challenges in fast time response (<50ps) beam instrumentation.
- **Demonstrate the capability** to optically measure the intra-bunch transverse displacement of a passing relativistic bunch, with a bandwidth that is beyond state-of-the-art.

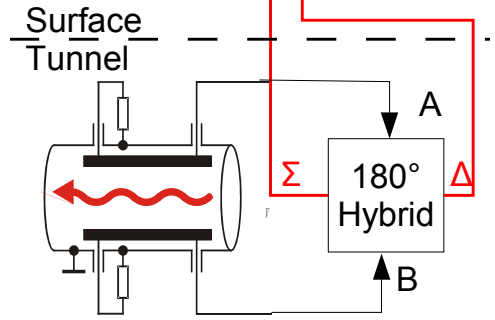
How to make beam Instrumentation FASTer?

- ***Challenge of rapid diagnostics***
  - Beam instrumentation at current and future particle accelerators would **benefit from an improved time response** in multiple areas:
    - Bunch arrival time/ ToF; crabbed bunch rotation; temporal longitudinal profiles; measuring rapid, intra-bunch transverse instabilities…
  - **Bandwidth** of conventional diagnostics is typically **limited** to a few GHz by the pick-ups, hybrid, cables and acquisition system.



Standard approach: stripline BPM

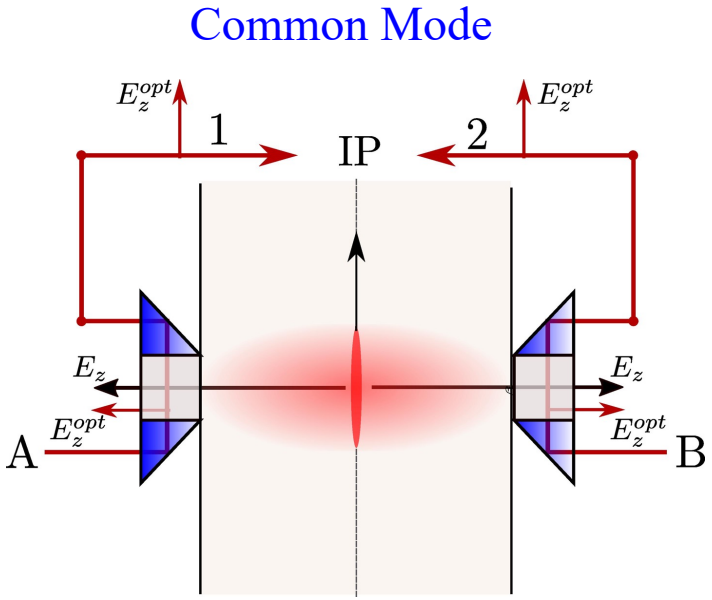




- ***A new technology is needed***
  - replace capacitive pick-ups with fast electro-optic crystals
  - replace electric cables by optical-fibre readout

Electro-optic BPM

- ***Basic principle:***
  - Monitor the polarisation of light in birefringent crystals in response to the electric-field of a passing bunch



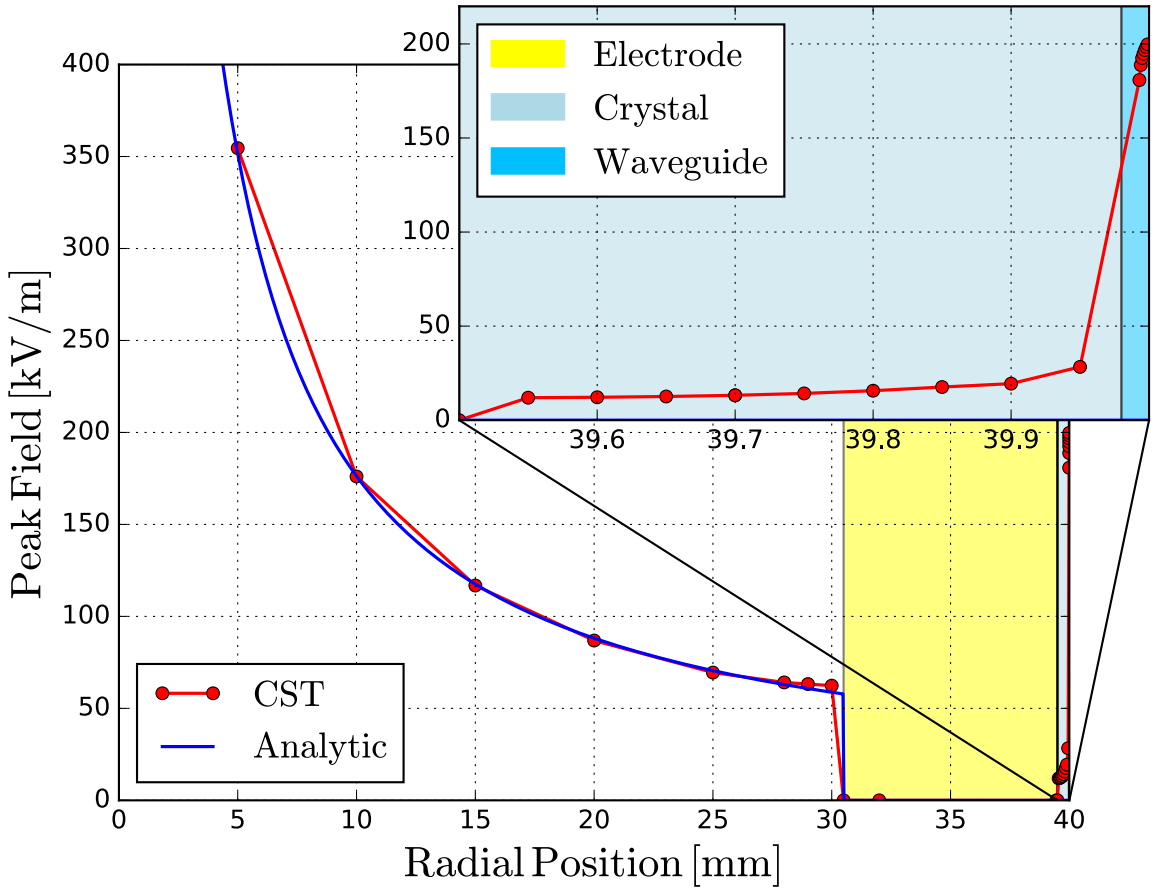
- Effectively a BPM in which the electrodes are replaced by eo-crystals
- Transverse position along passing bunch is measured
- A fibre coupled laser source and photodetector read-out are housed away from the accelerator tunnel.
- As polarised light passes through the crystal, the electric field of the bunch induces a change in polarisation state by the linear Pockels effect.

- **I.FAST Task 10.7 focuses on developing miniaturised e-field sensors based on *electro-optic waveguides***

Optimization of electric-field at waveguide:

Electromagnetic simulations of pick-up performed in CST to optimise field strength at waveguide.

- The EO-BPM prototype previously tested at the SPS successfully delivered a weak proof-of-concept signal, while operating at a radial position of 66.5mm from the bunch (<1kV/m).
- Optimisation work focused on an improved pickup design capable of generating a highly magnified image field replica of the Coulomb field within an optical waveguide.
- Therefore, the result is a highly optimised opto-mechanical design, fully fibred-coupled, capable to enhance the field up to ~200kV/m.



Partners fabrication & test facilities

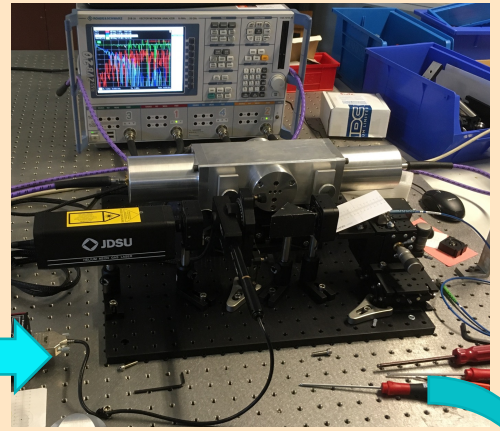
- **Pickup development and bench tests at RHUL**

ROYAL HOLLOWAY UNIVERSITY OF LONDON

Waveguide fabrication in photonics industry

Inspection in new nanofabrication clean-room facility at RHUL

Precision manufacture & waveguide integration



Bench tests on RF coaxial line / laser labs

- **Beam tests of waveguides at CERN**

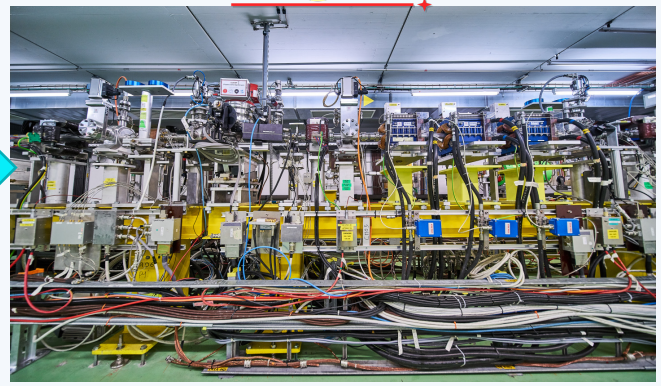
In collaboration with CERN BI, T. Lefevre et al

CERN

HiRadMat
High-Radiation to Materials

Beam test of waveguide signal

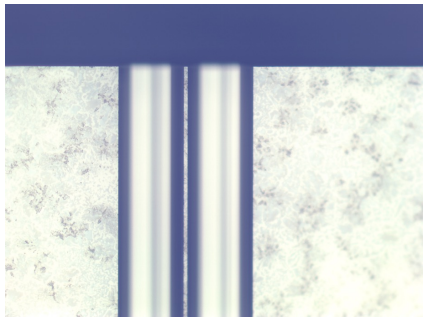
clear



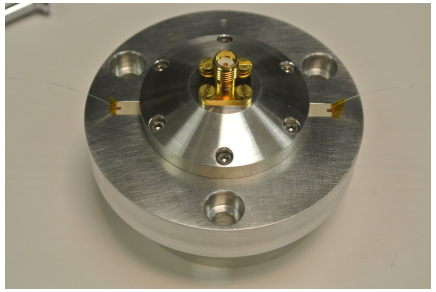
Beam test of waveguide bandwidth

EO waveguide design shipped to CERN for beam tests

- Partnered with UK industry to produce waveguides suitable for our custom design:

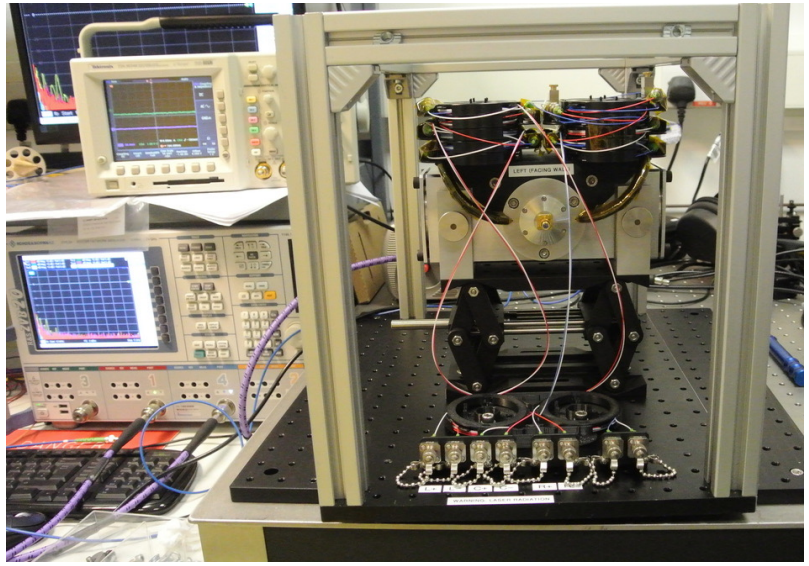


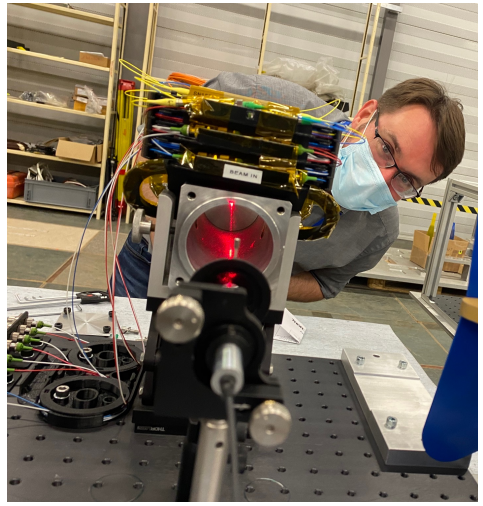
Optical inspection of waveguide in RHUL clean room

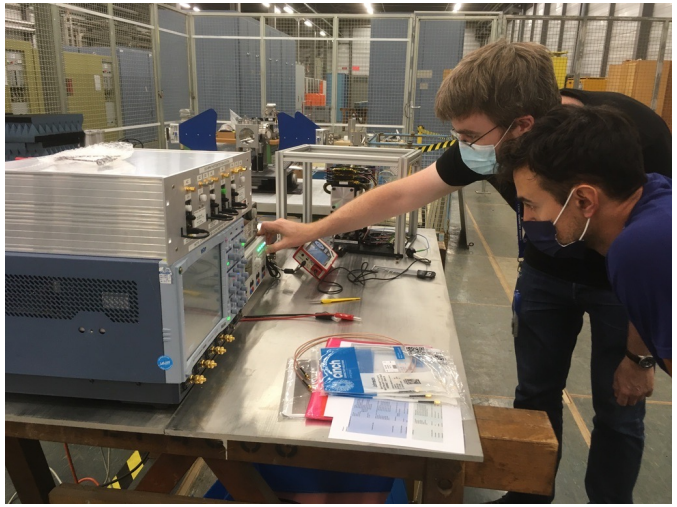


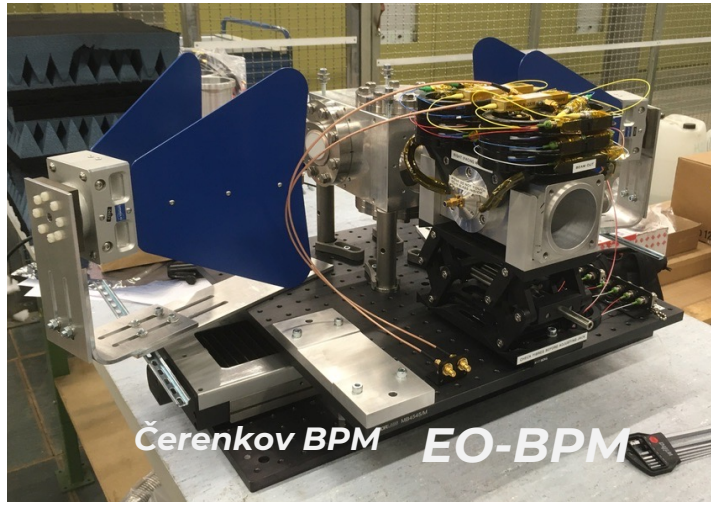
Compact fibre-coupled waveguide pick-up

EO-BPM manufacture & VNA tests at RHUL



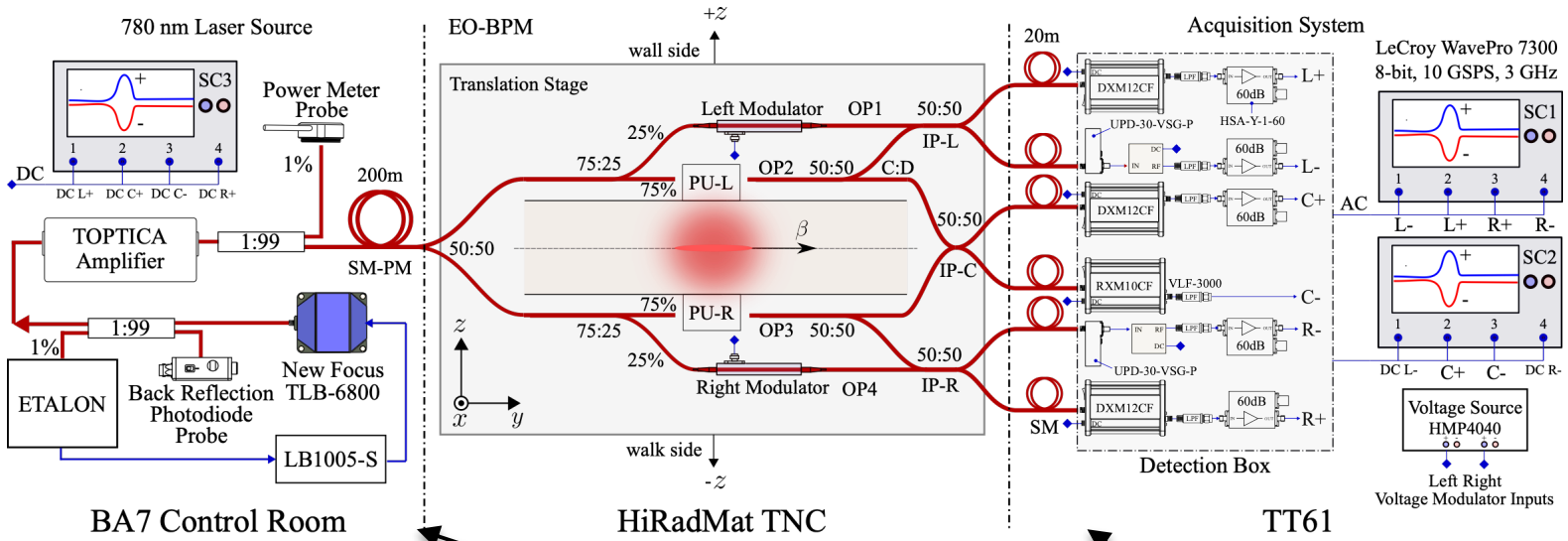


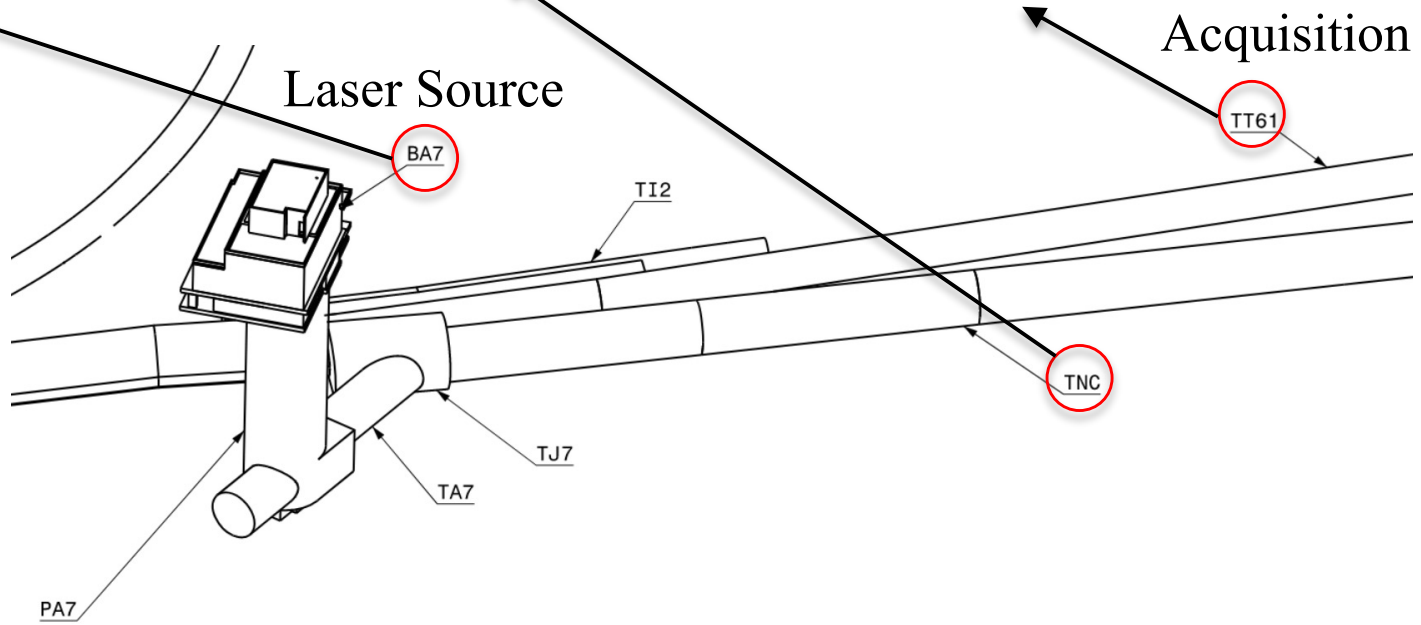




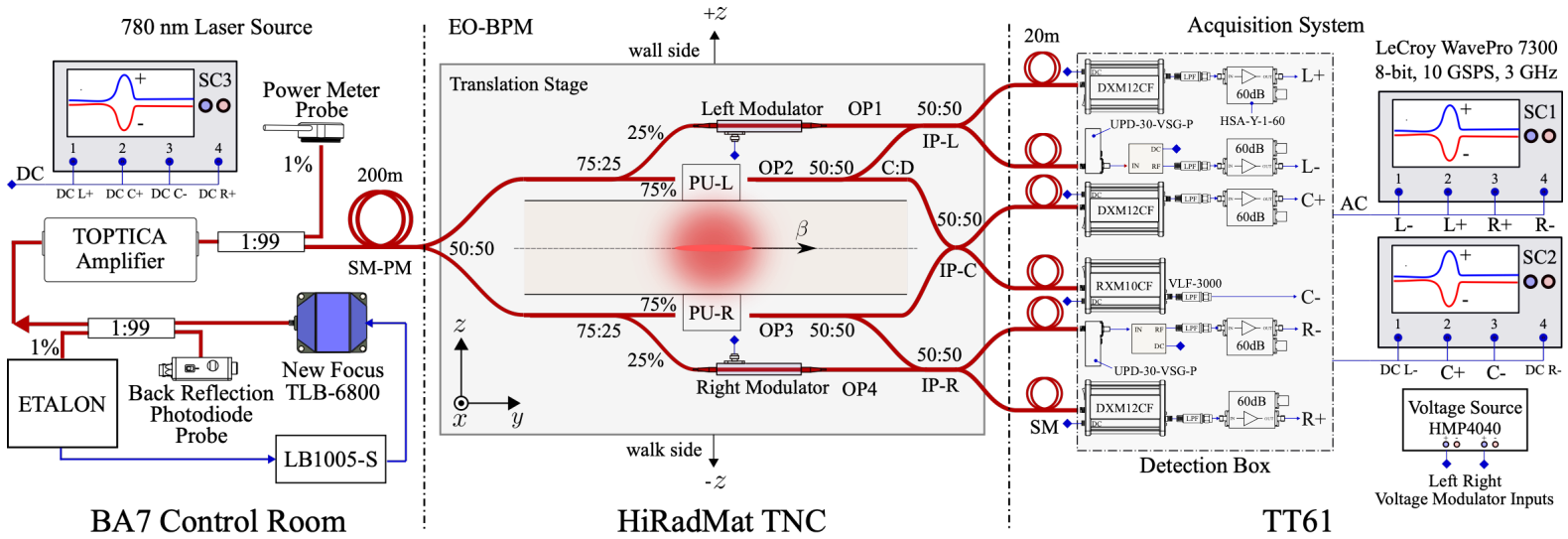
EO-BPM reception tested at CERN and laser-aligned with dielectric BPM on shared translation table

EO-BPM installation at HiRadMat facility

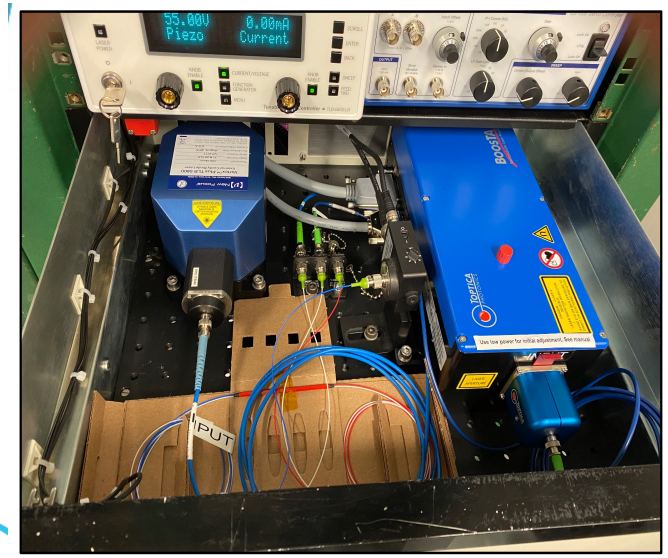




EO-BPM installation at HiRadMat facility

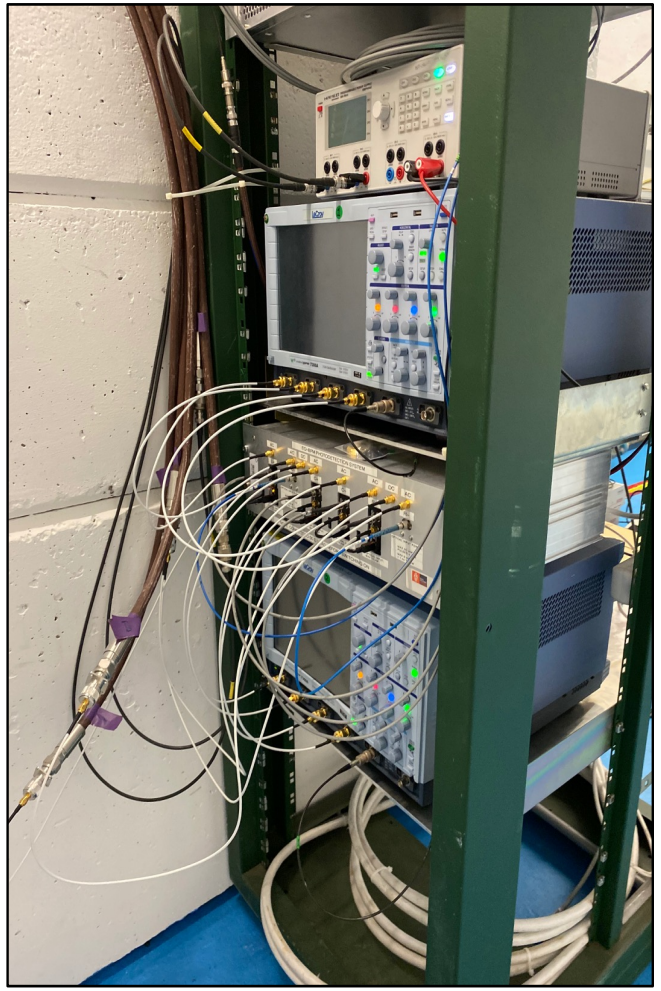


780nm laser source in BA7

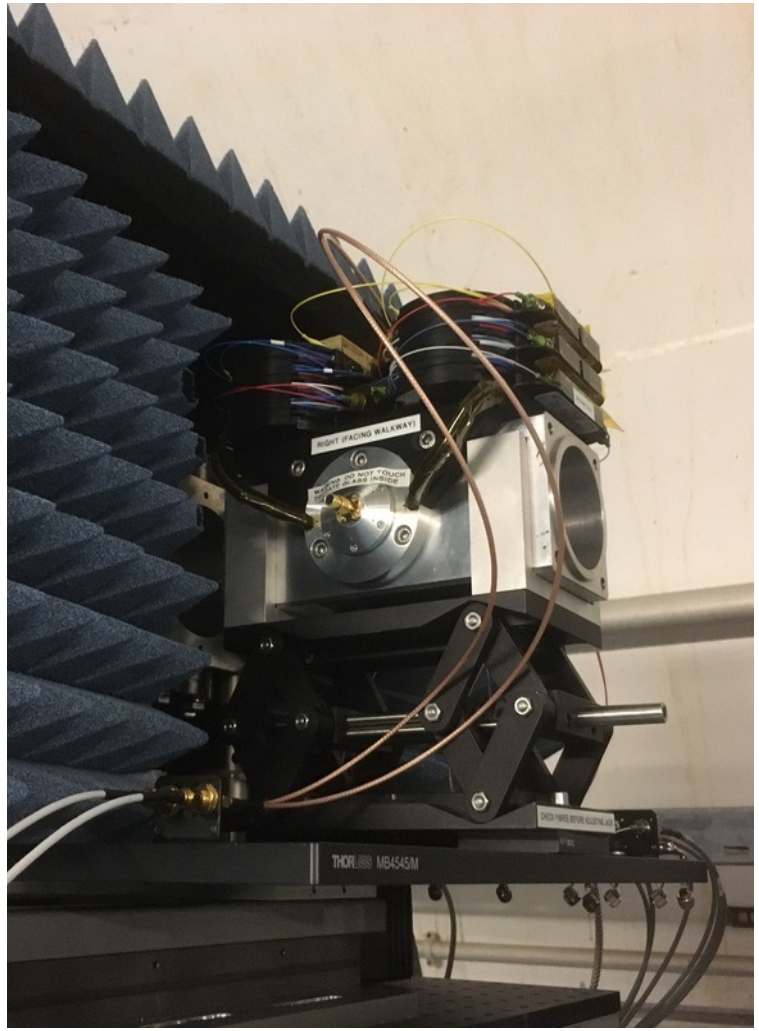


EO-BPM at HiRadMat extraction line

Acquisition system:



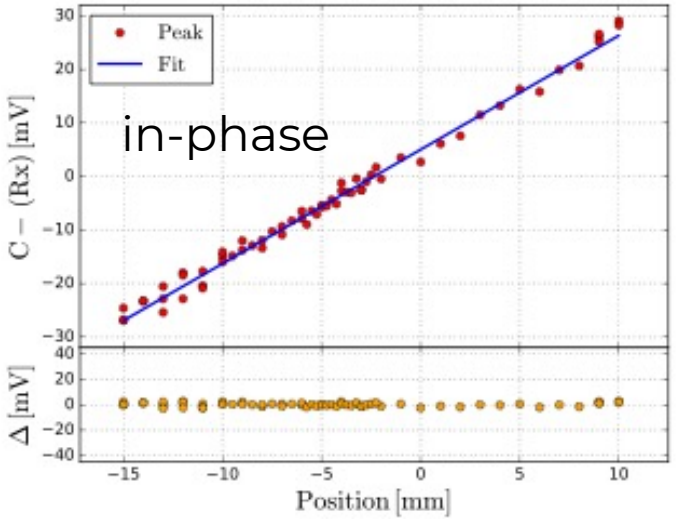
Installation at HiRadMat facility



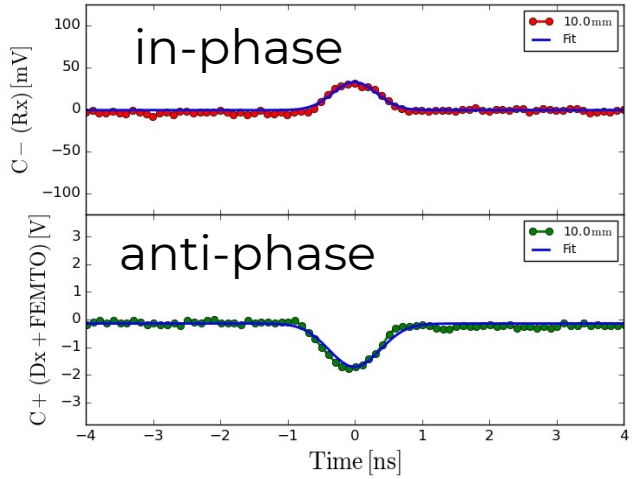
Successful first beam test at HiRadMat

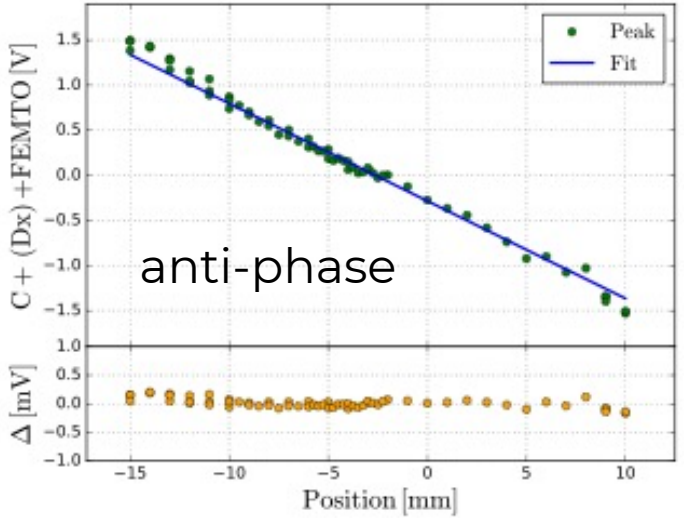
- **Waveguide design** enabled **first single-shot measurements of each passing bunch**.
- EO-BPM also **sensitive to low intensity bunches**.
- Laser scanning technique developed to **automate operation** of electro-optic interferometer.
- Translation of EO-BPM across the HiRadMat extraction line: ***first bunch by bunch position measurements.***
- ***Test campaign extended to 3 runs;*** ***see invited talk at IBIC2022***

Beam position scan by moving EO-BPM on stage

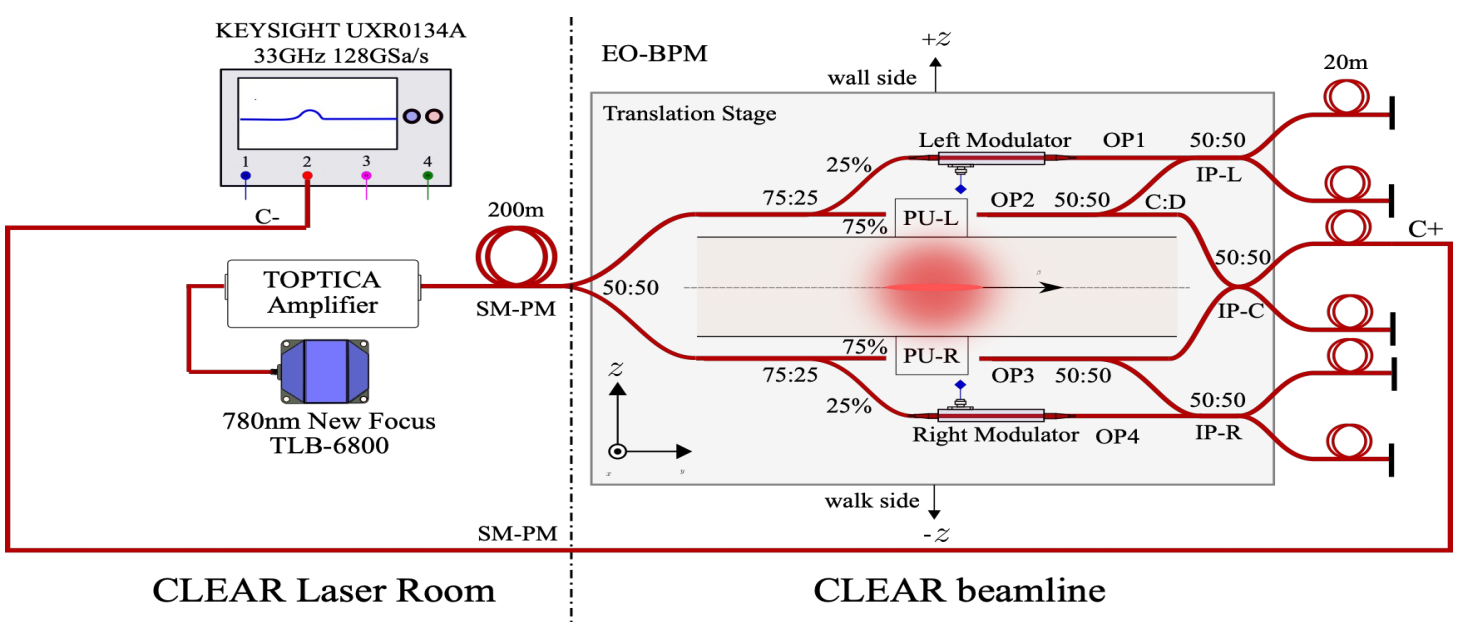


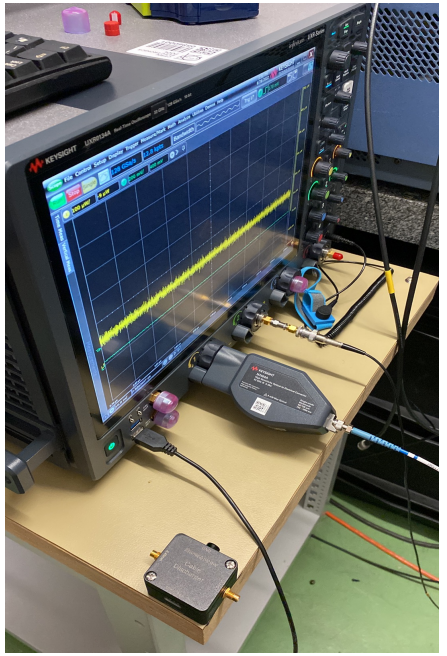
Typical single-shot signals

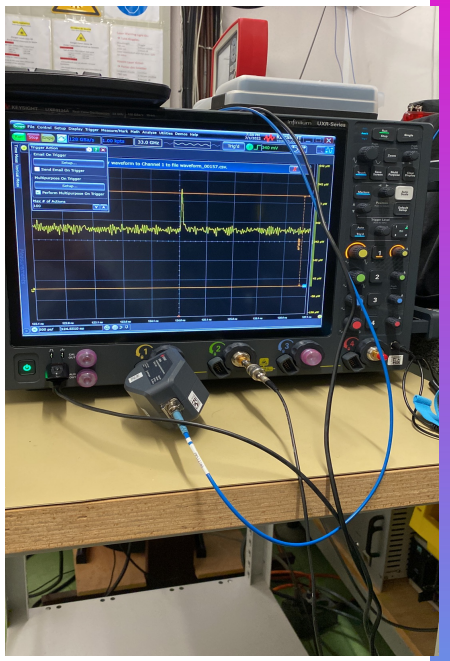




Bandwidth tests at CLEAR facility



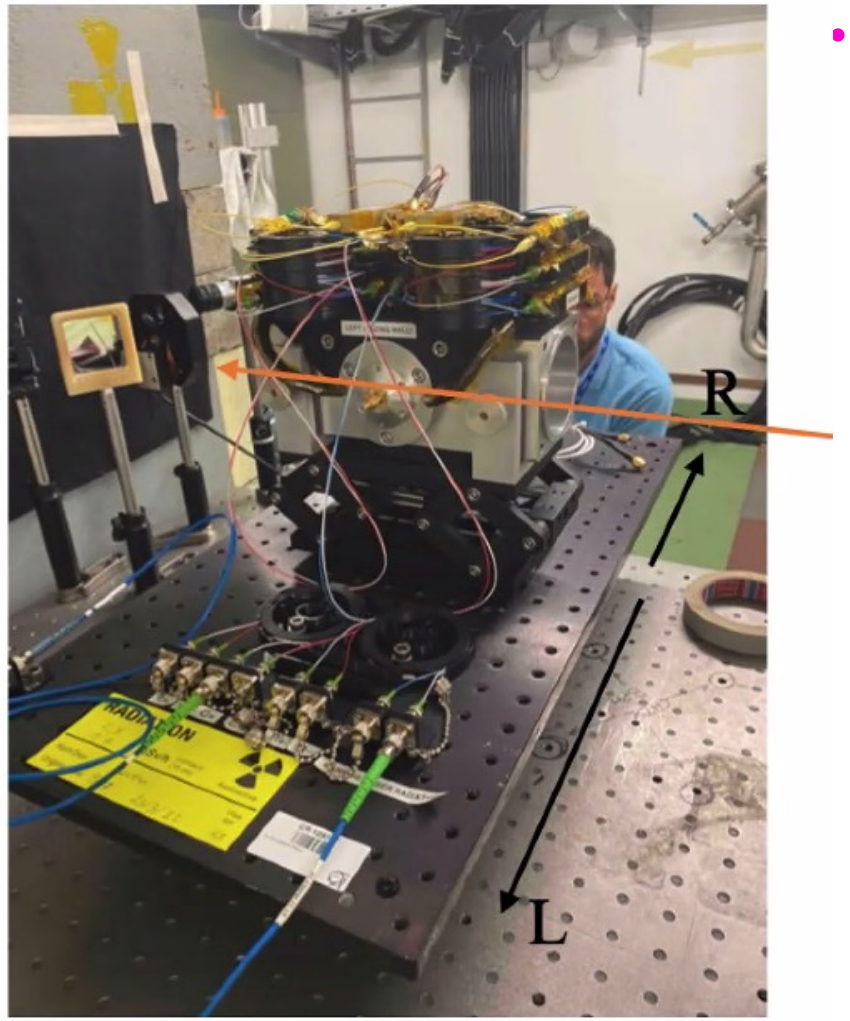




- 5ps electron bunches
- Interferometric Common Mode measured at a single C+ channel using a 33GHz optical probe directly attached to a Keysight UXR series 33GHz scope.
- This scope allowed simultaneous detection of the DC working point baseline and the AC optical modulation on top.
- EOBPM installed in the in-air section of the beamline on a translation stage to perform transverse beam measurements.

(*) https://www.keysight.com/zz/en/products/oscilloscopes/infiniium-real-time-oscilloscopes/infiniium-uxr-series-oscilloscopes.html

2022 EO-BPM beam test at CLEAR:

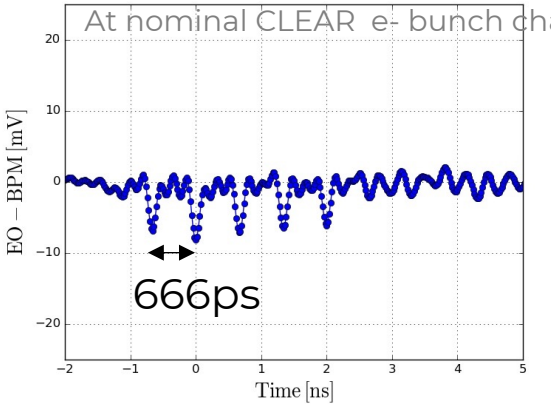


- EO-BPM installed in the CLEAR beamline to check sensitivity and ***time resolution*** to short electron bunches.

Preliminary analysis:

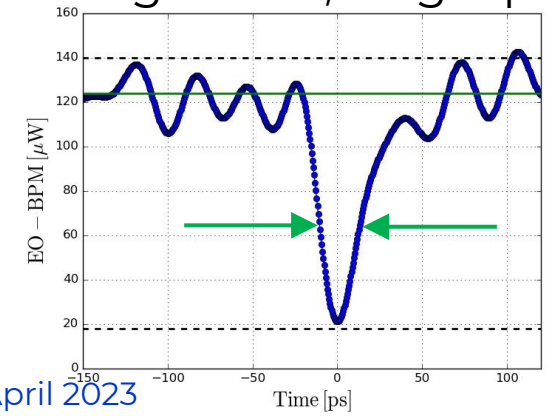
- Initial measurements of a train of 5 ***electron bunch pulses spaced by 666ps (1.5GHz) were observable*** at the photodetector, where the pulse width was limited by the bandwidth of the photodetection system.

single shot, pulse train



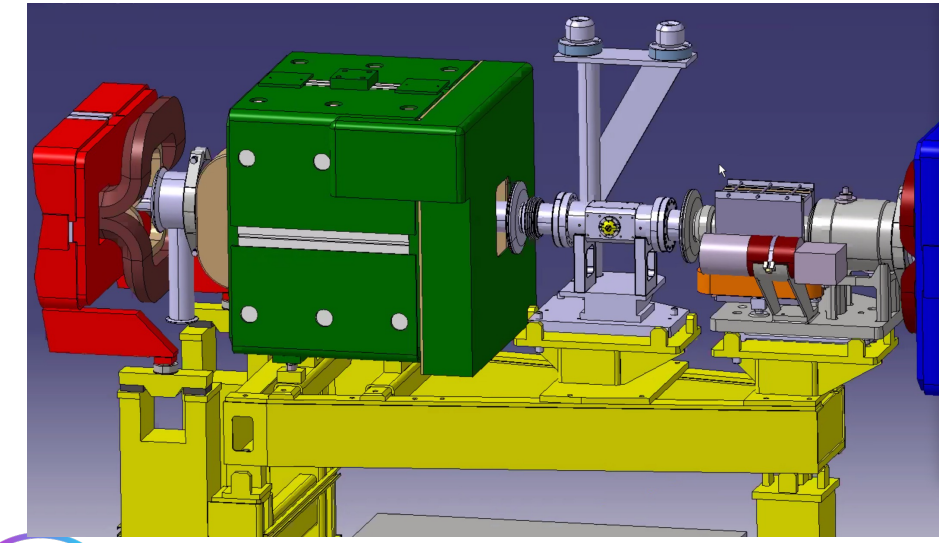
- With an upgraded detector, the pulse width indicates the time resolution of EO pick-up is well **within the < *50 ps* specification** required for the HL-LHC measurement of 1ns bunches.

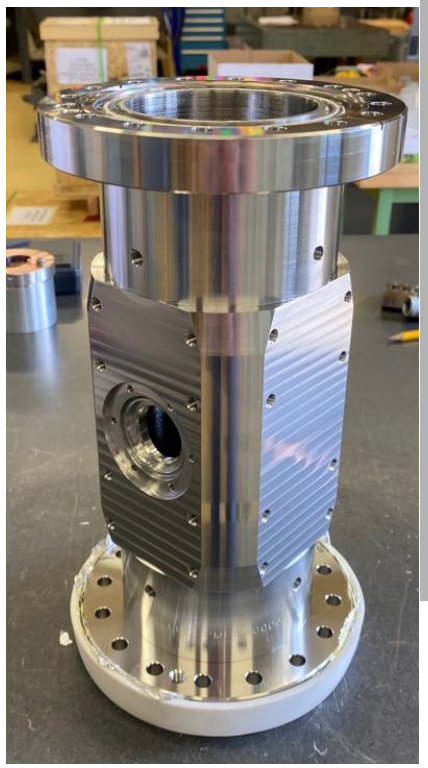
single shot, single pulse

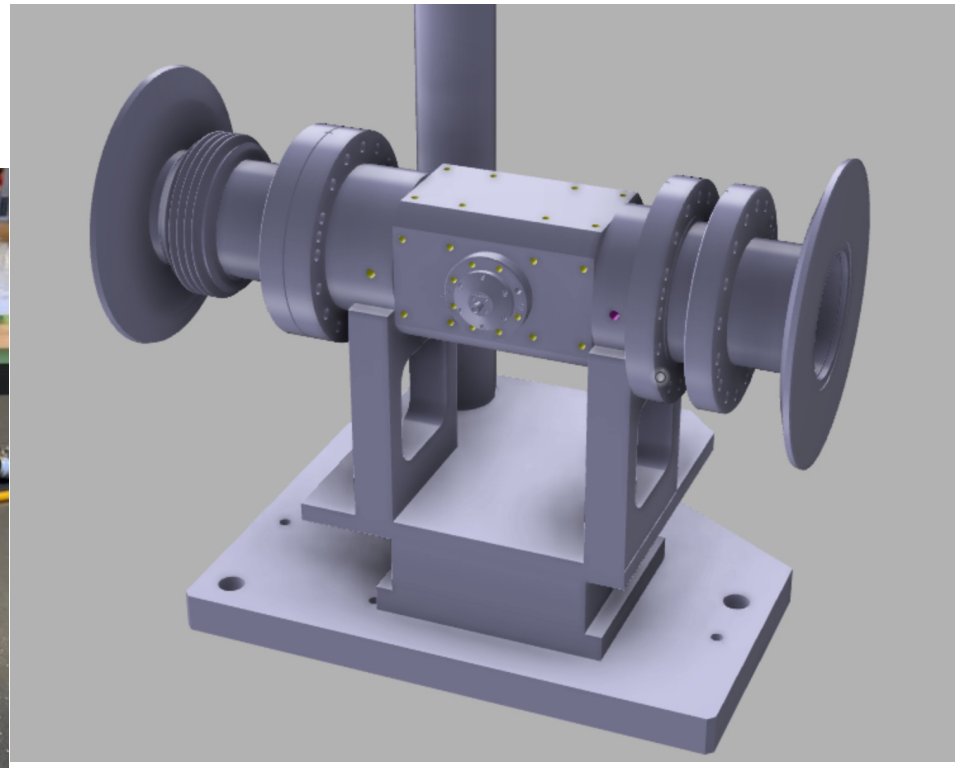


Future: waveguide EO-BPM demonstrator for beam tests at SPS

- HiRadMat EO-pick-up design incorporated into an in-vacuum design.
- Excellent progress in recent months on CERN engineering drawings and vacuum brazing.
- **EO-BPM demonstrator** will be built and installed in **SPS**, for operation in Run 3.







Task WP10.7 activities & status

1. ***Waveguide design and optimisation***
   - Electromagnetic simulation of waveguide response.
   - Optimisation of design in collaboration with photonics industry.
2. ***Development and manufacture***
   - Collaboration with photonics industry to produce highly-efficient fibre-coupled EO waveguides.
   - Manufacture and integration into EO pick-ups in RHUL clean rooms.
   - **Milestone MS49: "Delivery of an electro-optic waveguide prototype for demonstration at RHUL test bench"** M12 ***complete***
3. ***Test and validation***
   - Bench tests of waveguide pick-ups at RHUL & design optimisation.
   - Two successful beam tests at CERN facilities: Transverse beam position at HiRadMat & time response characterisation at CLEAR.
   - ➢ **Deliverable 10.6: Electro-optic performance report M24: *Final report on the performance of the electro-optic pick-up prototype with beam:* *complete***

Development of a High-Bandwidth Interferometric Electro-Optic Beam Position Monitor

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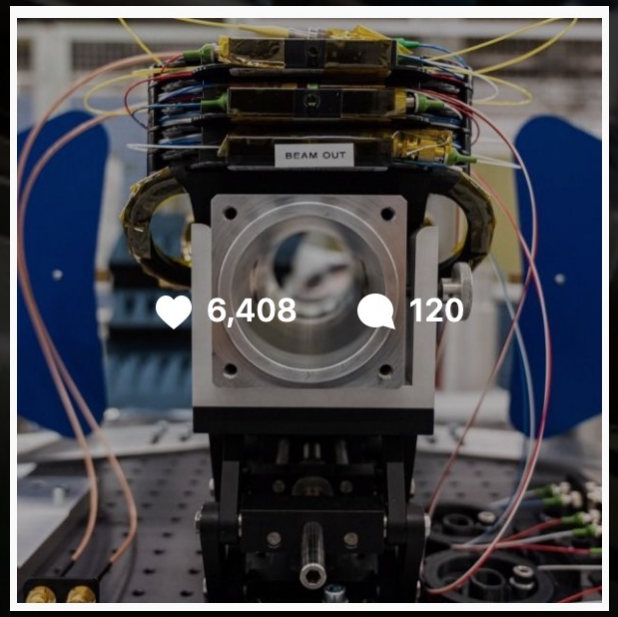
Thanks for your attention!

CERN social media



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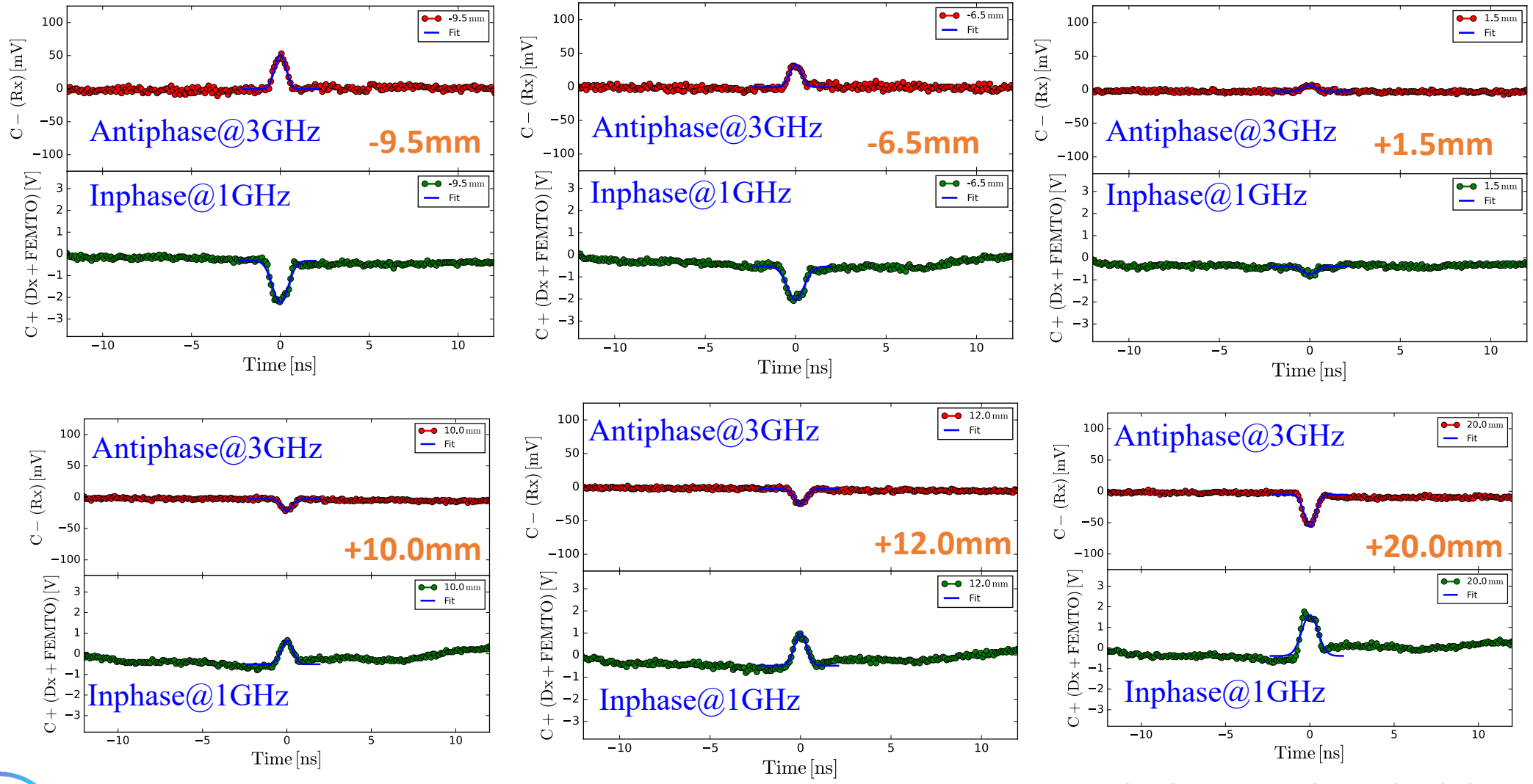
Transverse displacements, single shots



Measured at close to nominal proton bunch charge: 1.05×10^{11}