International Beam Instrumentation Conference
11-15 September 2022
Kraków

2022 IBIC

Electro-Optical BPM Development for High Luminosity LHC

Stephen Gibson, Alberto Arteche – RHUL

Thibaut Lefevre, Tom Levens – CERN

HiLumi HL-LHC PROJECT

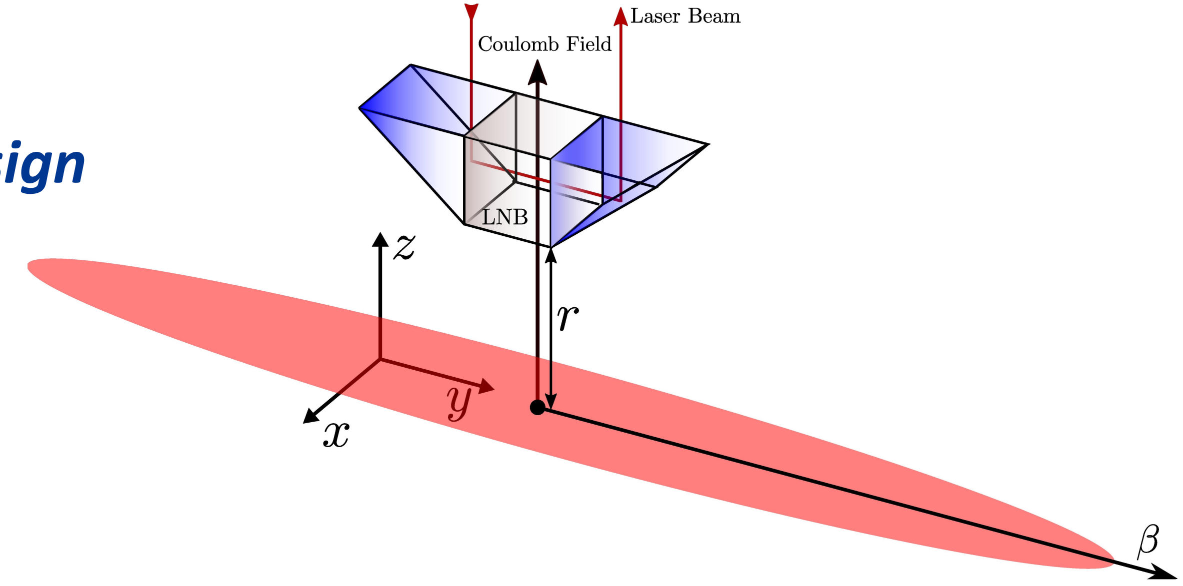
CERN

ROYAL HOLLOWAY UNIVERSITY OF LONDON

JAI John Adams Institute for Accelerator Science

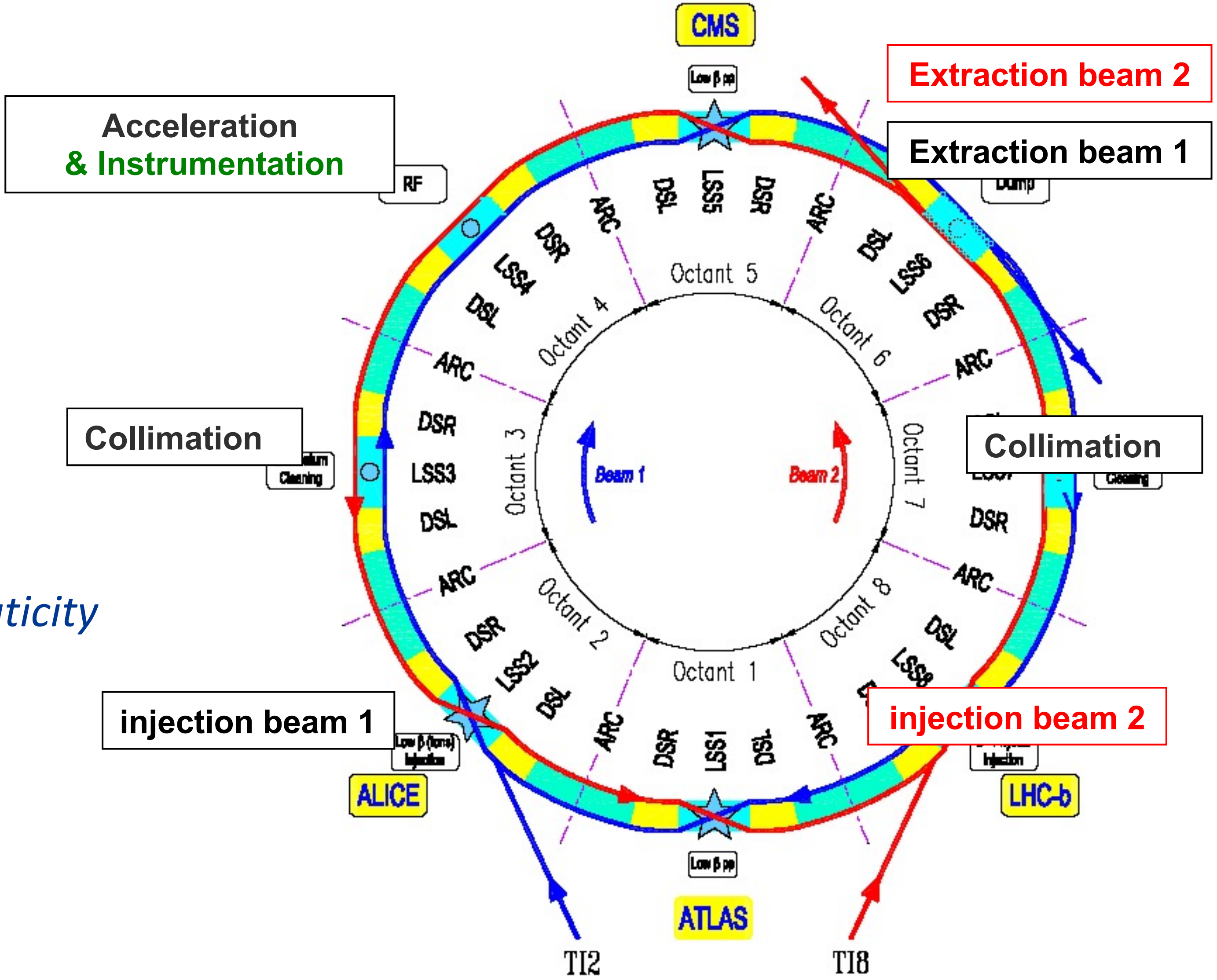
Overview

- ***Motivation for High-Luminosity LHC / fast diagnostics***
- ***Electro-optic Beam Position Monitors***
  - *Interferometric EOBPM concept*
  - *Historic development*
- ***Simulations of improved EO waveguide design***
- ***Validation with recent beam tests:***
  - *Transverse resolution at HiRadMat*
  - *Bandwidth resolution studies at CLEAR*
- ***Future developments***



Beam instrumentation at the LHC

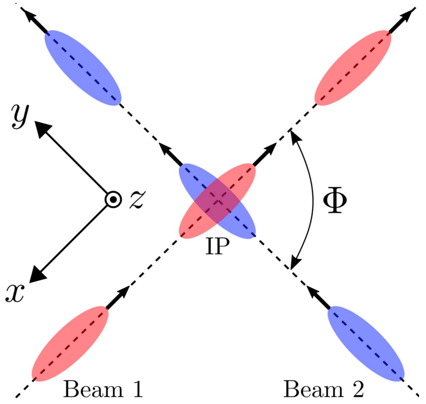
- *1182 beam position monitors*
- *>4000 beam loss monitors*
- *Screens at injection and extraction*
- *Wire scanners, synchrotron radiation monitors*
- *Monitors for current, tune and chromaticity*
- *Bunch instability monitors*
- *Luminosity monitors*

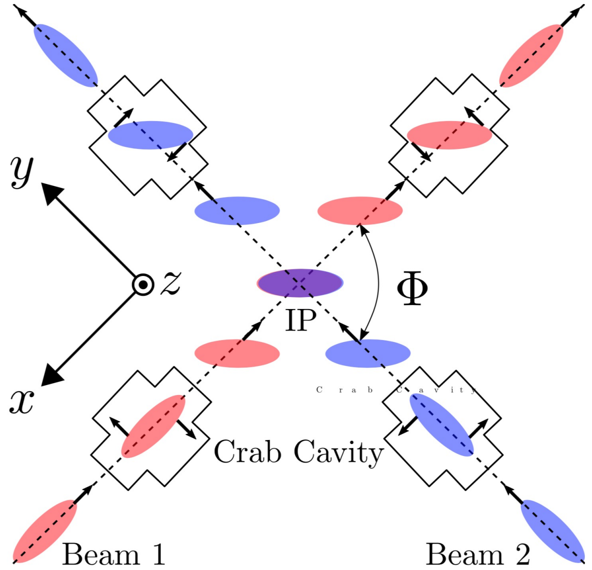


T. Lefevre

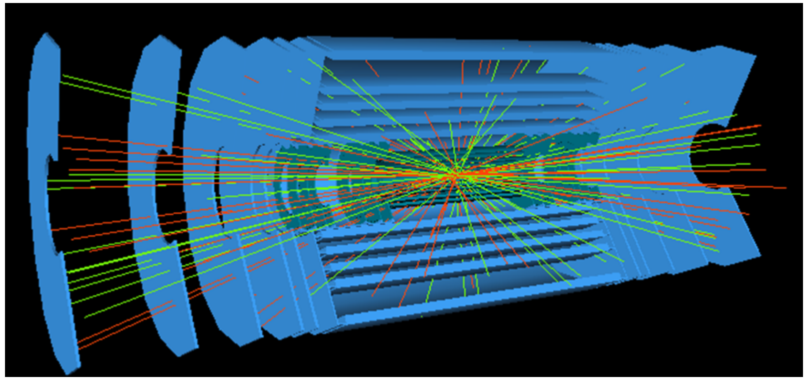
Motivation: Crab bunch rotation at HL-LHC

- *To optimize the performance of the crab-cavities for the High Luminosity LHC, a new, fast diagnostic tool is required to monitor the bunch rotation:*

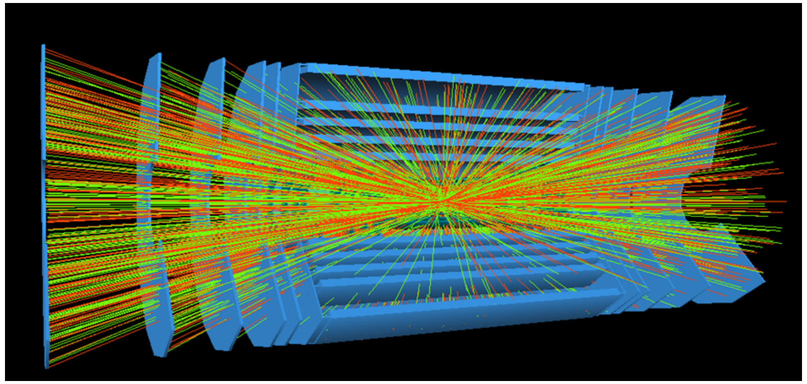


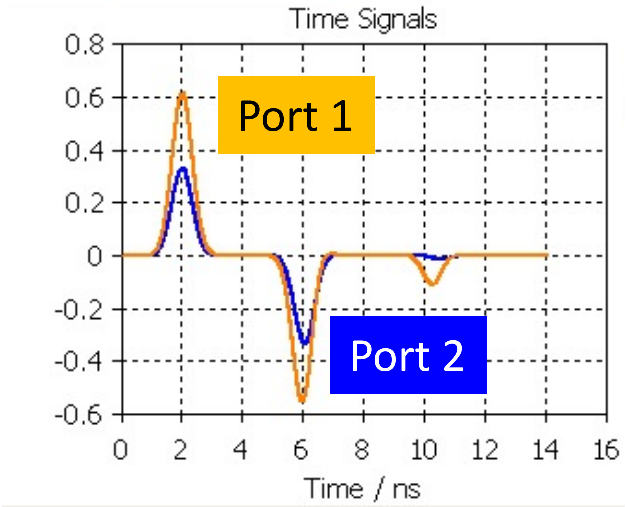


LHC: 23 interactions



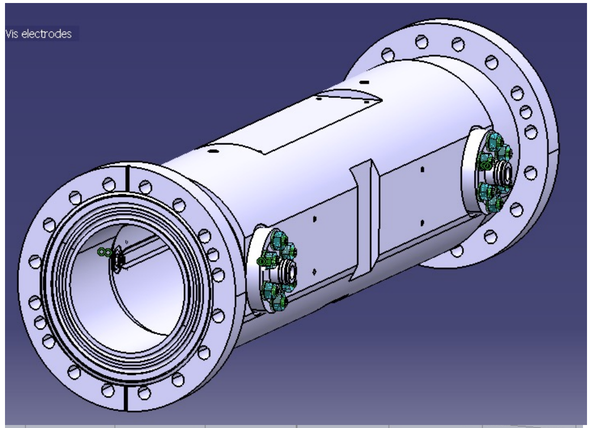
HL-LHC: 140 interactions

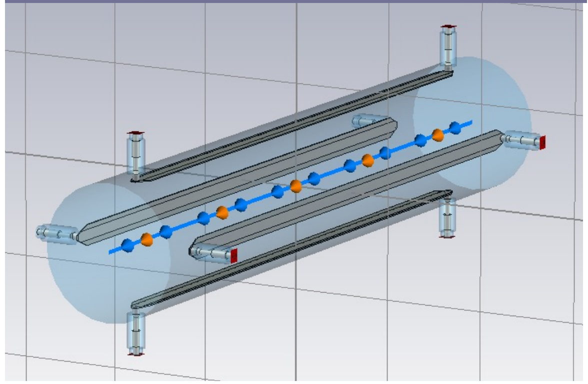


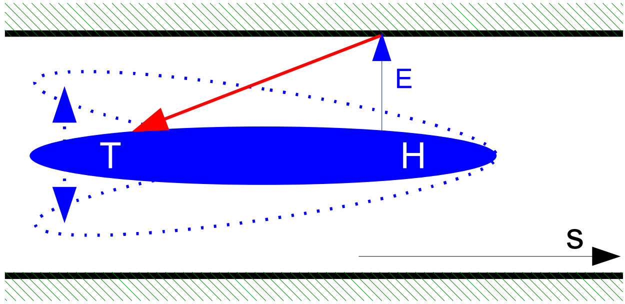


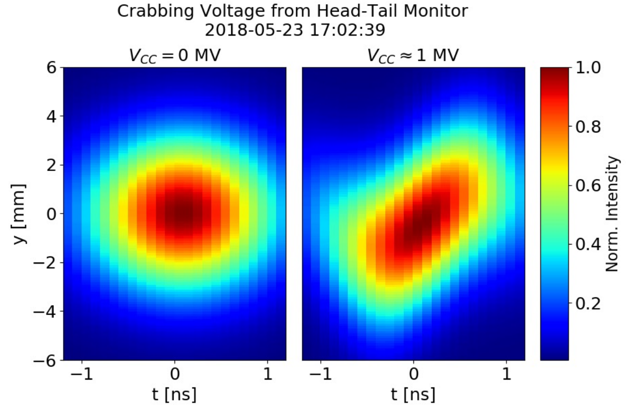
- *CERN's existing head-tail monitor is based on a stripline:*
- *Long enough that the signal and reflection do not mix*

→ Very clean time domain signal of the transverse position along the bunch







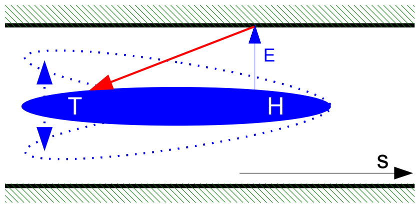


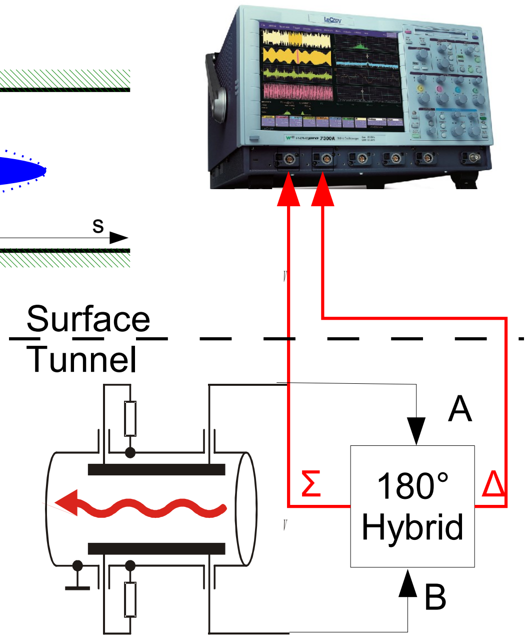
First detection of crabbed bunch in SPS

T. Levens et al

Motivation: rapid, intra-bunch diagnostics

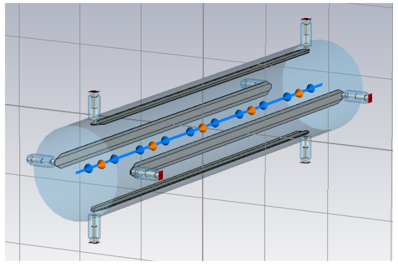
The EO-BPM project grew out of idea to upgrade the Head Tail monitor to visualize and study beam instabilities as they occur.





Bandwidth of conventional diagnostics is typically **limited** to a few GHz by the pick-ups, hybrid, cables and acquisition system.

New technology: fast electro-optics pickups:



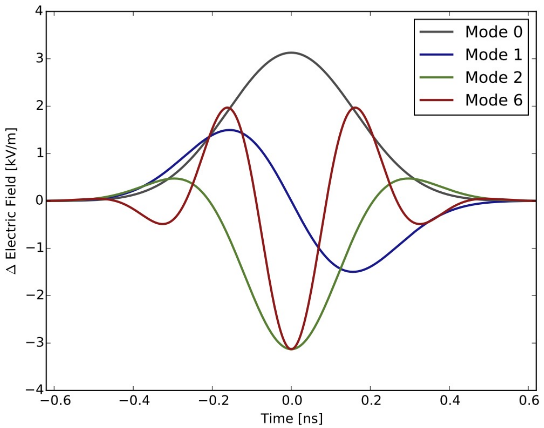
- replace capacitive pick-ups with fast electro-optic crystals
- replace electric cables by optical-fibre readout

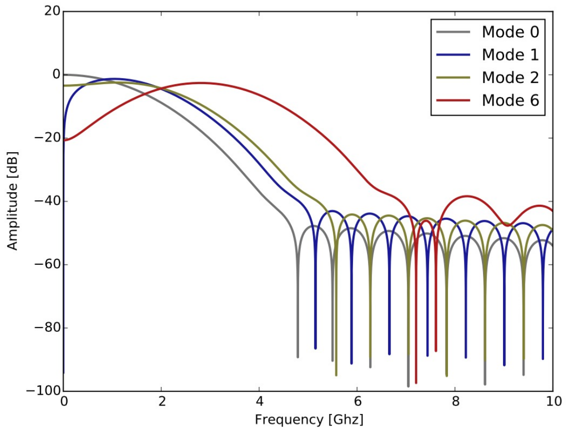
Aims:

Bandwidth: Mode 6 detection with a time resolution lower than 100ps.

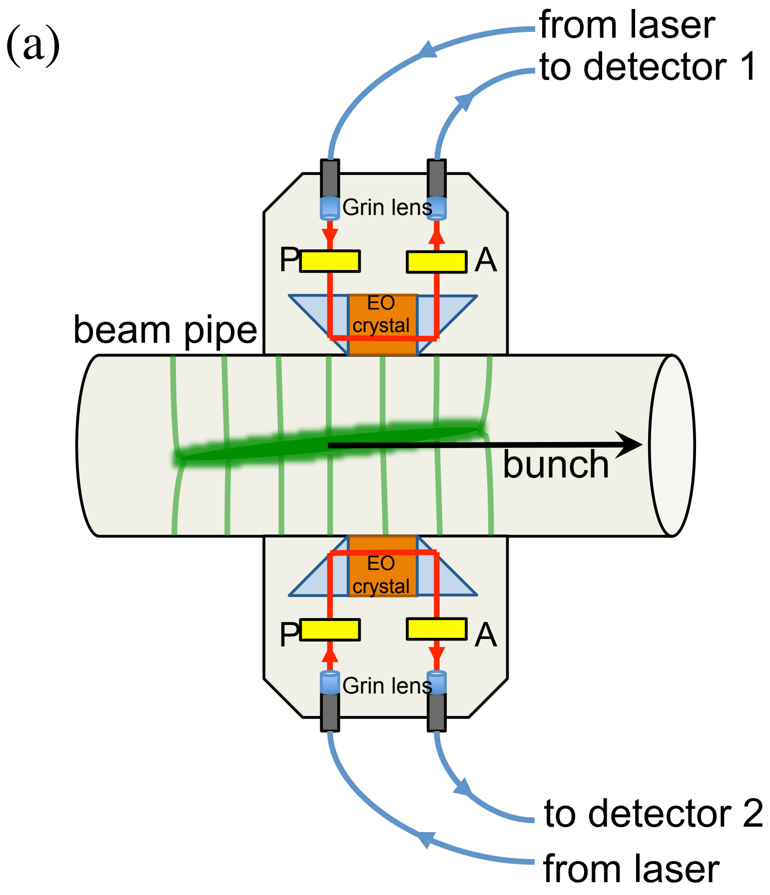
Higher bandwidth (>6GHz) required for the higher order modes.

Transverse resolution along 1ns proton bunch.





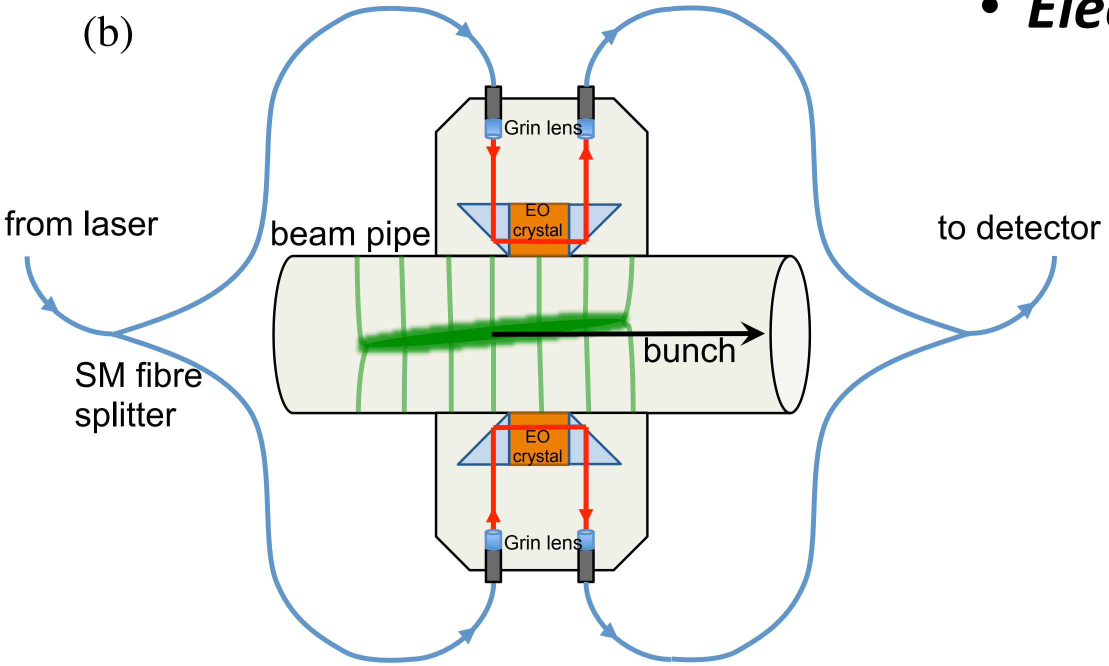
Basic principle of Electro-Optic BPM



- ***Electro-Optic BPM basic principle:***
  - ***Monitor the polarisation of light in birefringent crystals in response to the electric-field of a passing bunch***
  - *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*

High Frequency Electro-Optic Beam Position Monitors for Intra-Bunch Diagnostics at the LHC, WEDLA02, Gibson, S., et al, IBIC2015, https://doi.org/10.18429/JACoW-IBIC2015-WEDLA02

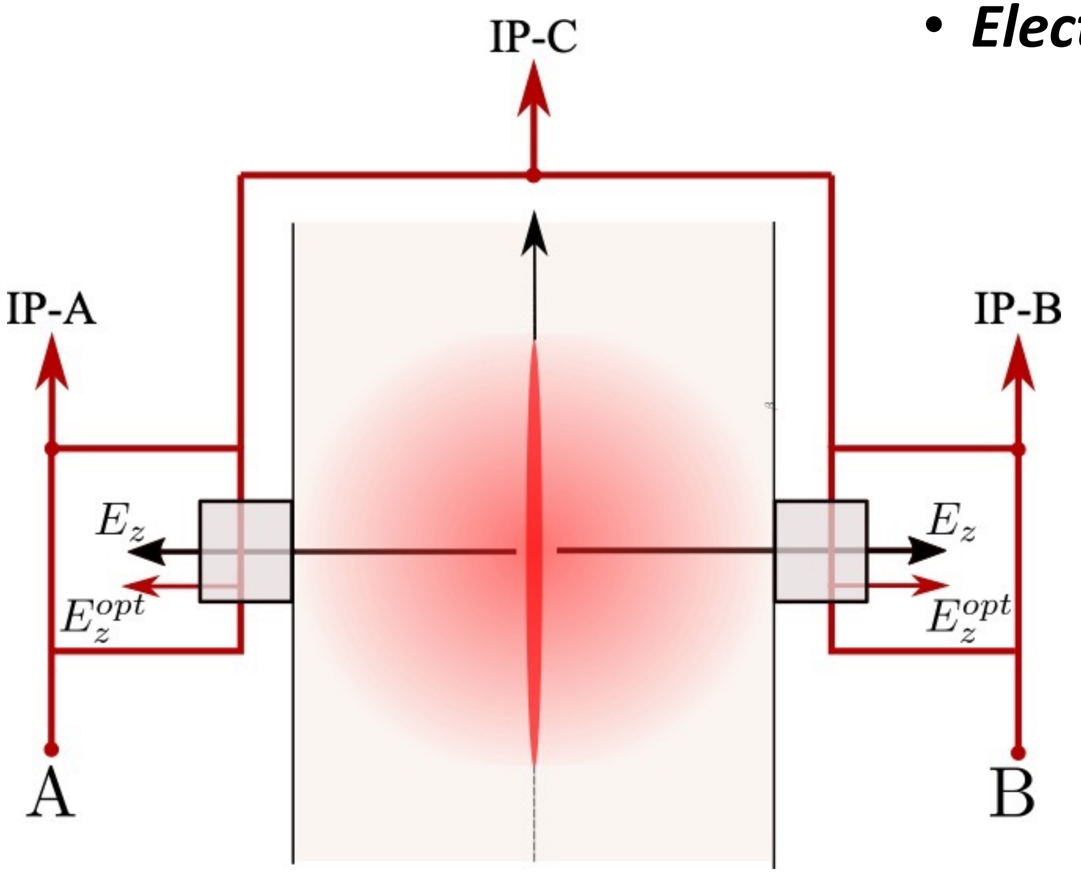
Interferometric principle of Electro-Optic BPM



High Frequency Electro-Optic Beam Position Monitors for Intra-Bunch Diagnostics at the LHC, WEDLA02, Gibson, S., et al, IBIC2015, https://doi.org/10.18429/JACoW-IBIC2015-WEDLA02

- ***Electro-Optic BPM interferometric principle:***
  - ***A fibre-coupled interferometer which uses phase modulation rather than a polariser/analyser***
  - *Short, equal fibre lengths between the splitters improve tolerance to thermal instabilities and provide synchronization between pick-up*
  - ***Key advantage:***
    - The coherence of light is exploited to suppress the common mode signal.
    - The ***difference signal*** is directly measured by the photodetector.
    - Potential for enhanced positional resolution

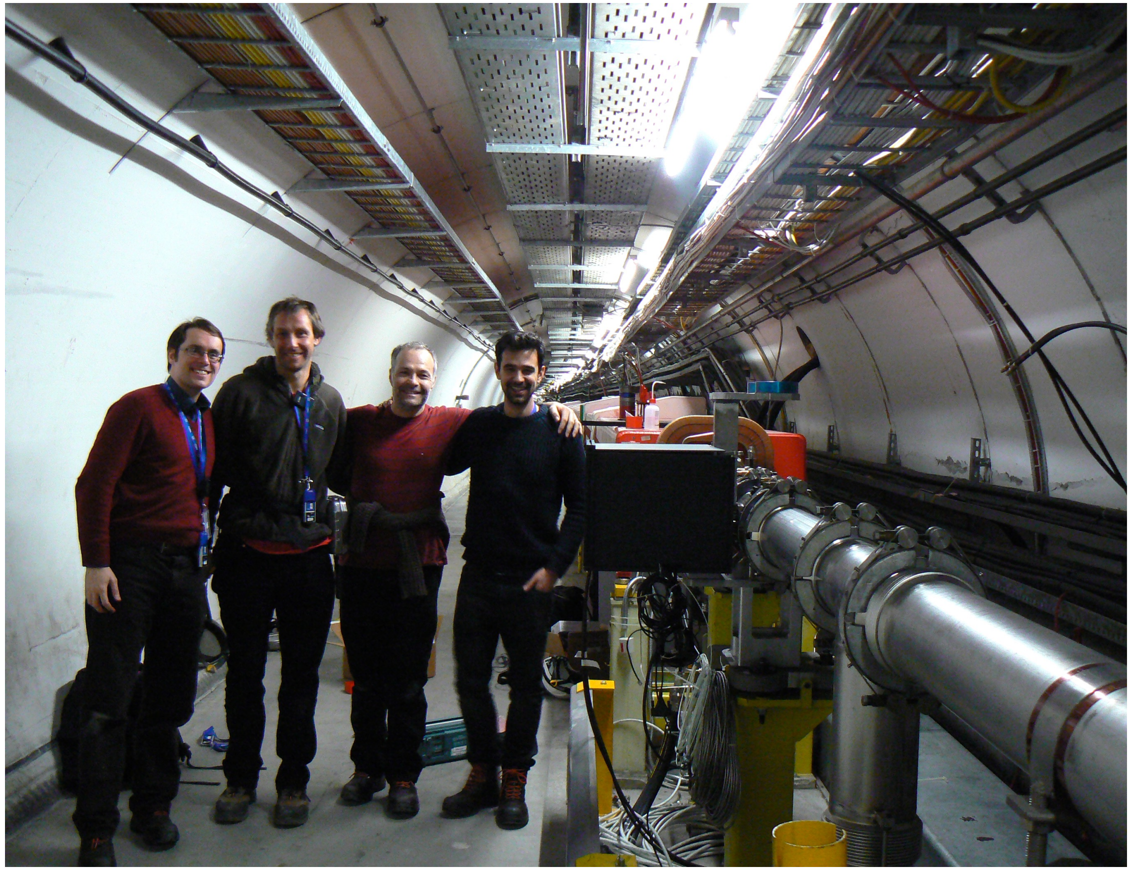
Triple interferometer used in these studies



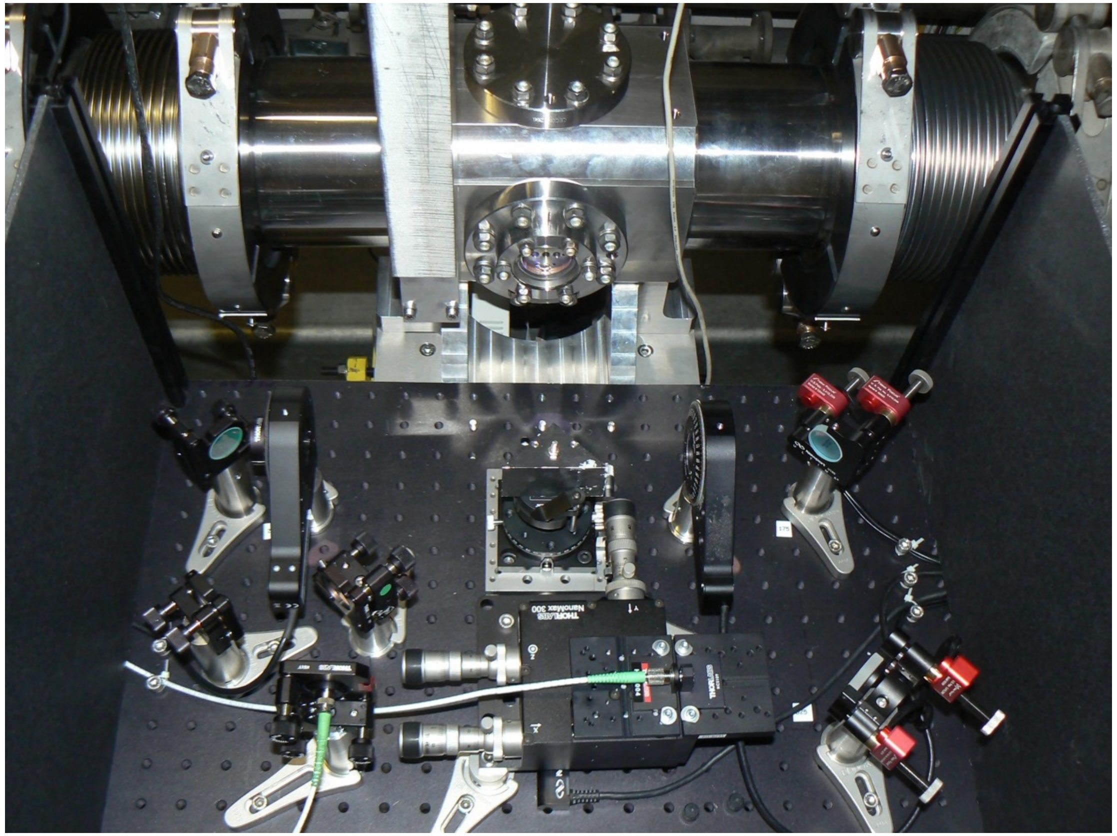
- ***Electro-Optic BPM triple interferometric principle:***
  - *The propagating Coulomb field from a passing bunch induces a phase change of a laser beam, split between both crystals.*
  - ***"Common mode" interferometer IP-C**: Optical modulation from opposite EO pickups is combined. **Difference signal** is produced when the beam is off-centre. **This optical difference signal has never been tested until now.***
  - ***Two "side mode" interferometers IP-A, and IP-B**: The optical modulation from each EO pickup is combined with a non-modulated arm, as in:*

Enhanced Bunch Monitoring by Interferometric Electro-Optic Methods, WEPAL073, Gibson, S. et al, IPAC May 2018. https://doi.org/10.18429/JACoW-IPAC2018-WEPAL073

Historic EO development at CERN SPS



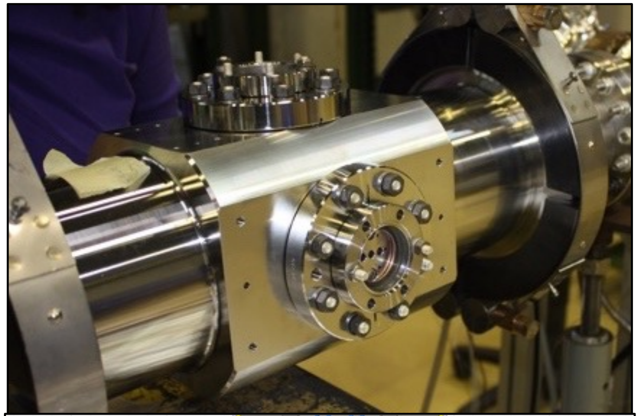
Original SPS prototype installed in 2015 used bulky free-space optics to sent light into the accelerator vacuum via a viewport. (Pickups still in use for AWAKE today!)

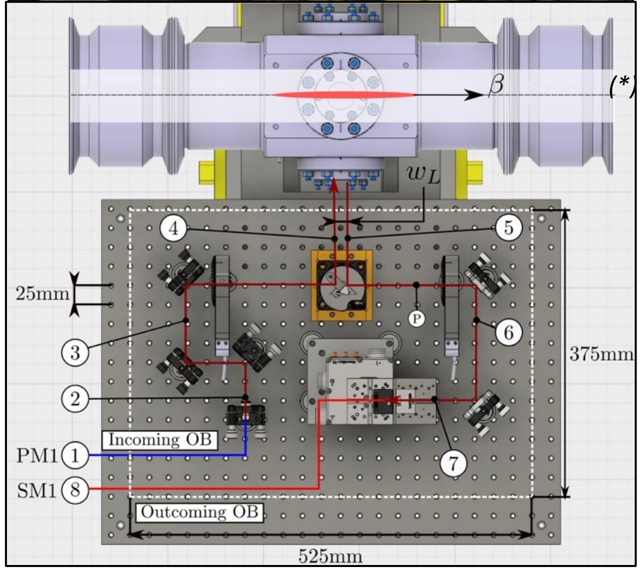


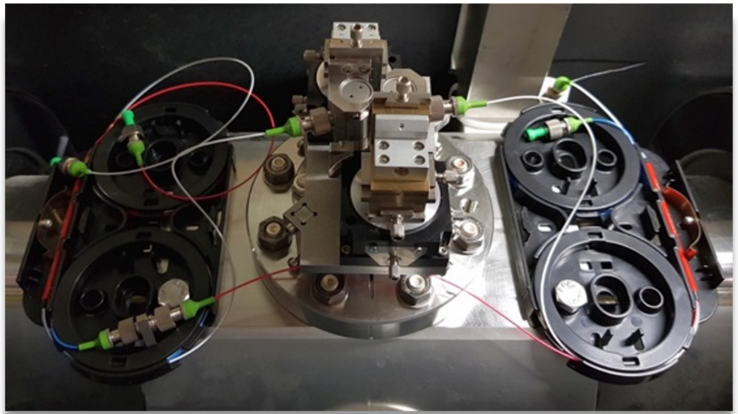
Arteche, A., RHUL PhD Thesis, June 2018, ***Studies of a prototype of an Electro-Optic Beam Position Monitor at the CERN Super Proton Synchrotron***, https://cds.cern.ch/record/2653351?ln=en

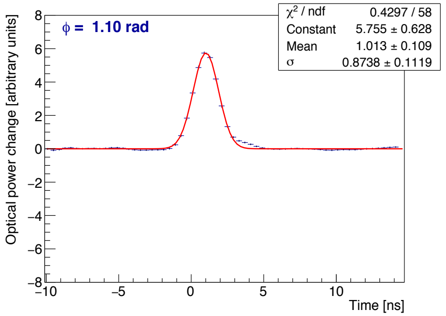
High-bandwidth EO-BPM development for HL-LHC

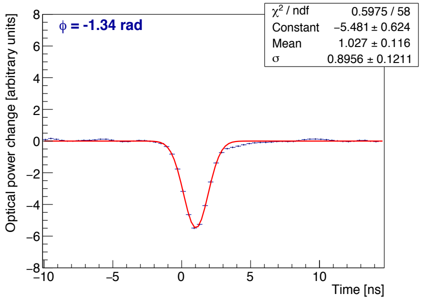
SPS Prototype → Miniaturisation → HL-LHC compatible waveguide design



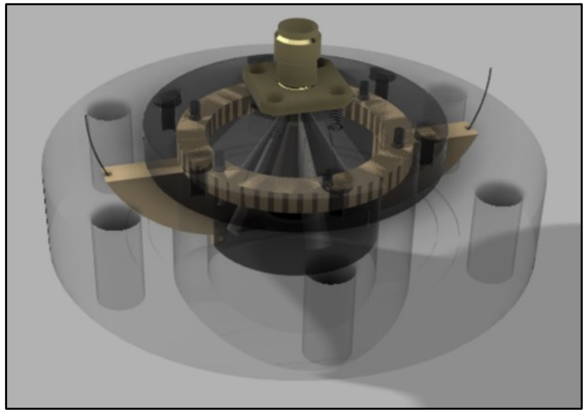


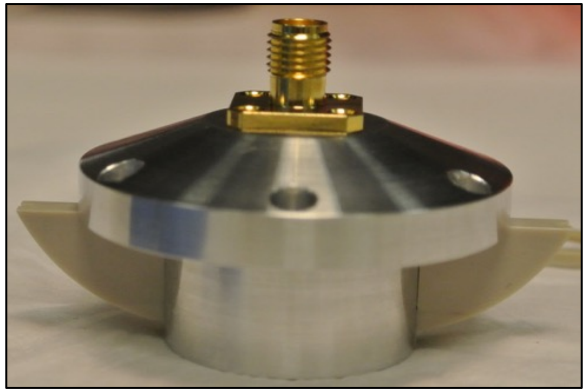






- Bulky side boxes replaced by more compact fibre-optic design and finally became totally fibre-coupled for the waveguide design.





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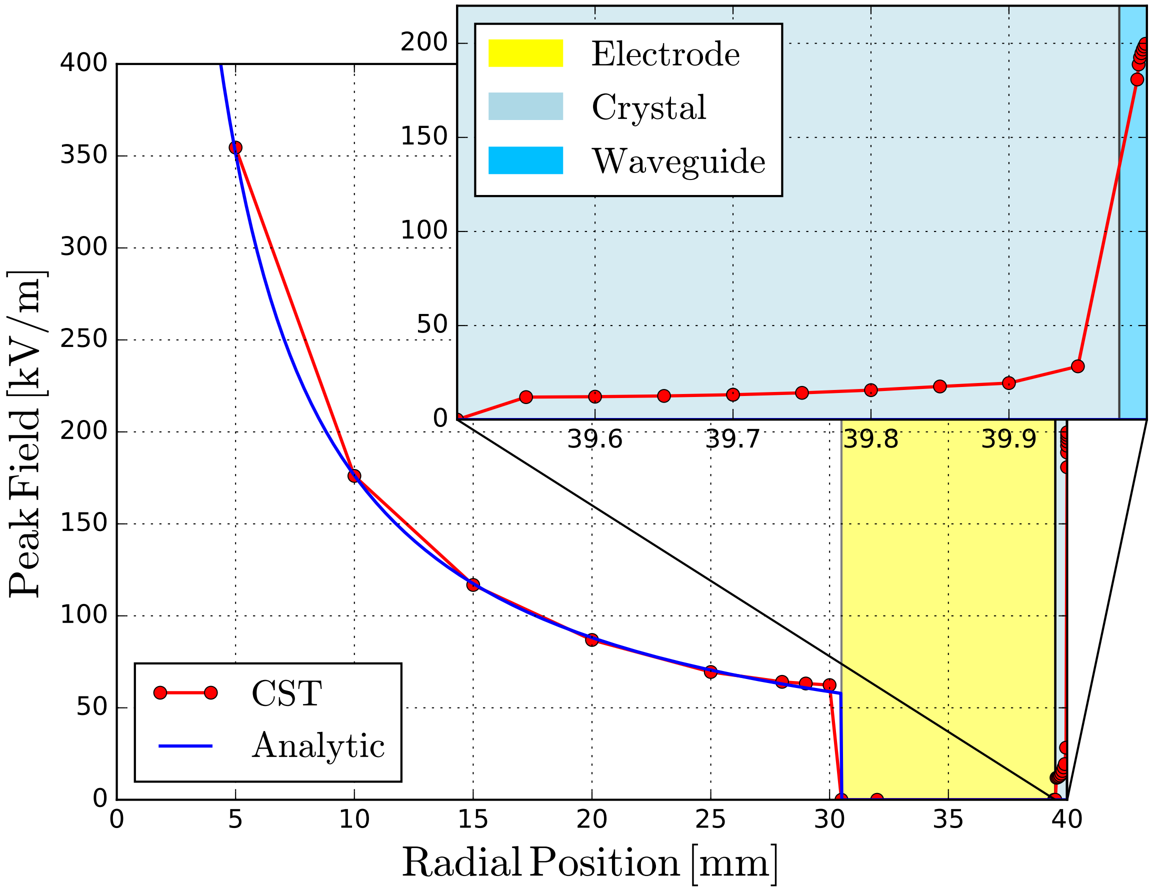
Simulated upgraded pick-up performance

- *The EO-BPM prototype tested at the SPS (2016-2018) successfully delivered a weak proof-of-concept signal, while operating at a radial position of 66.5mm from the bunch (<1kV/m).*
- *The optimisation work (2018-2020) 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.*



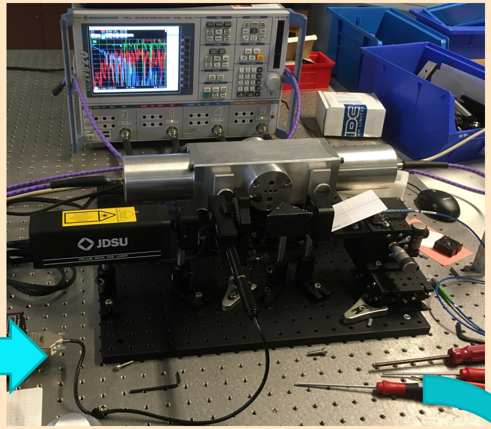
New design EO waveguide fabrication for beam tests

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

Waveguide fabrication in photonics industry

Inspection in new nanofabrication clean-room facility at RHUL

Precision manufacture & waveguide integration

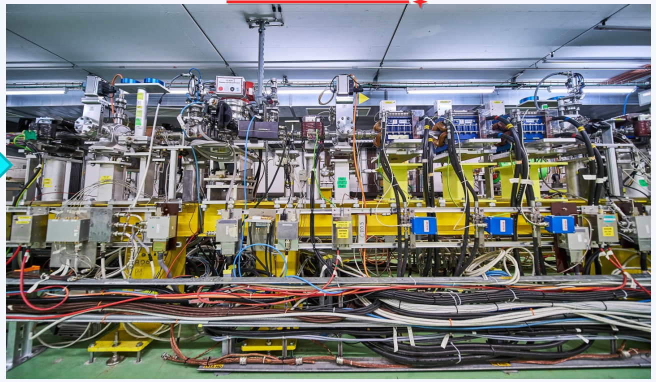


Bench tests on RF coaxial line / laser labs

- **Beam tests of waveguides at CERN**

In collaboration with CERN BI, T. Lefevre et al

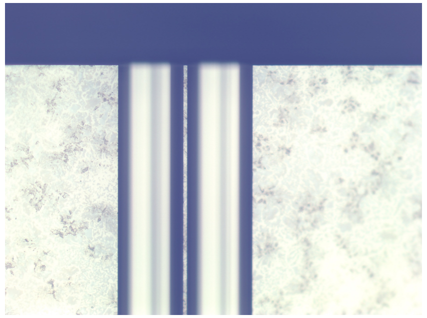
Beam test of waveguide signal



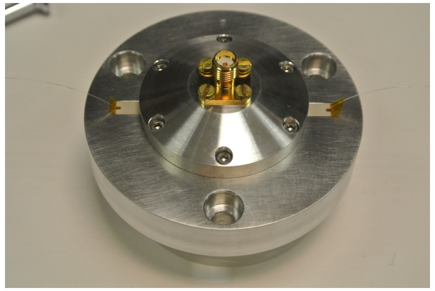
Beam test of waveguide bandwidth

New EO waveguide design shipped to CERN for beam tests

- EM simulations of pick-up performed in CST to optimise field strength at waveguide.
- Partnered with UK industry to produce waveguides suitable for our custom design:

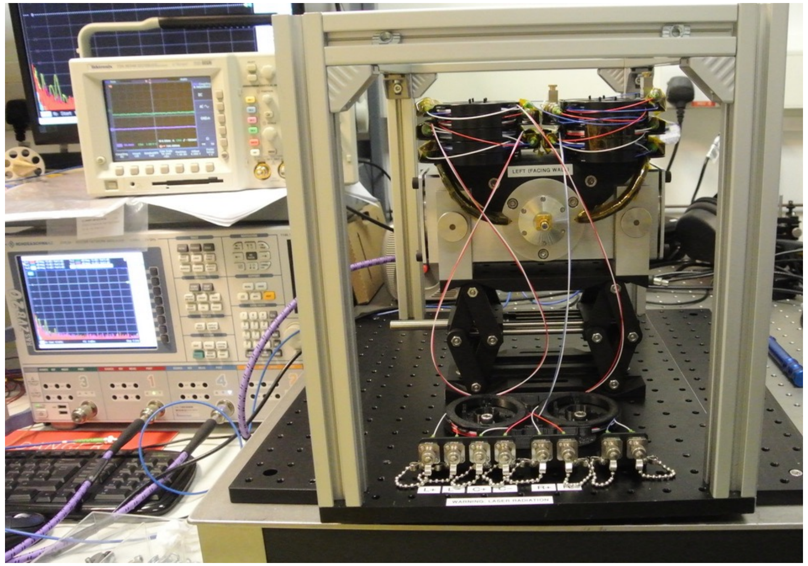


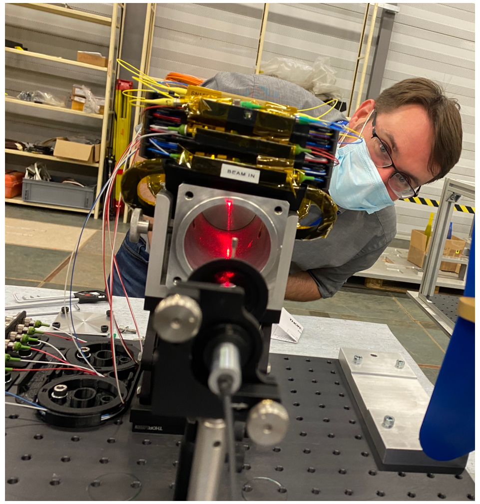
Optical inspection of waveguide in RHUL clean room

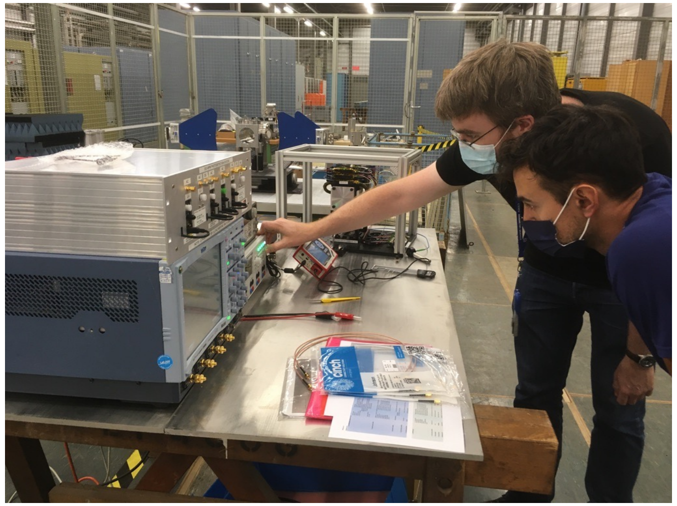


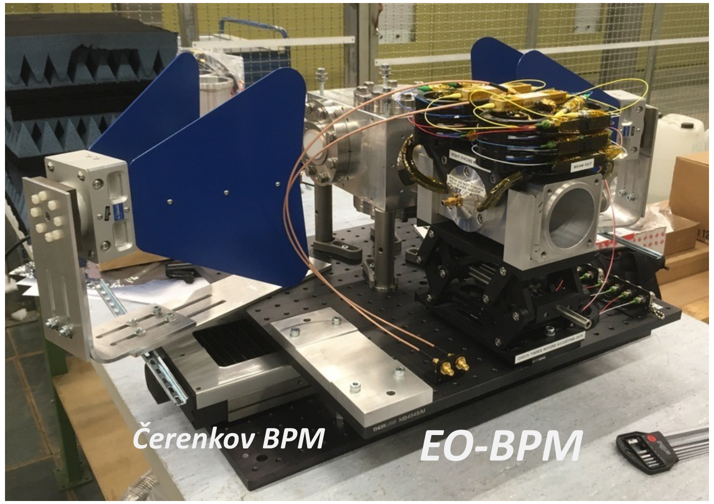
Compact fibre-coupled waveguide pick-up

EO-BPM manufacture & VNA tests at RHUL



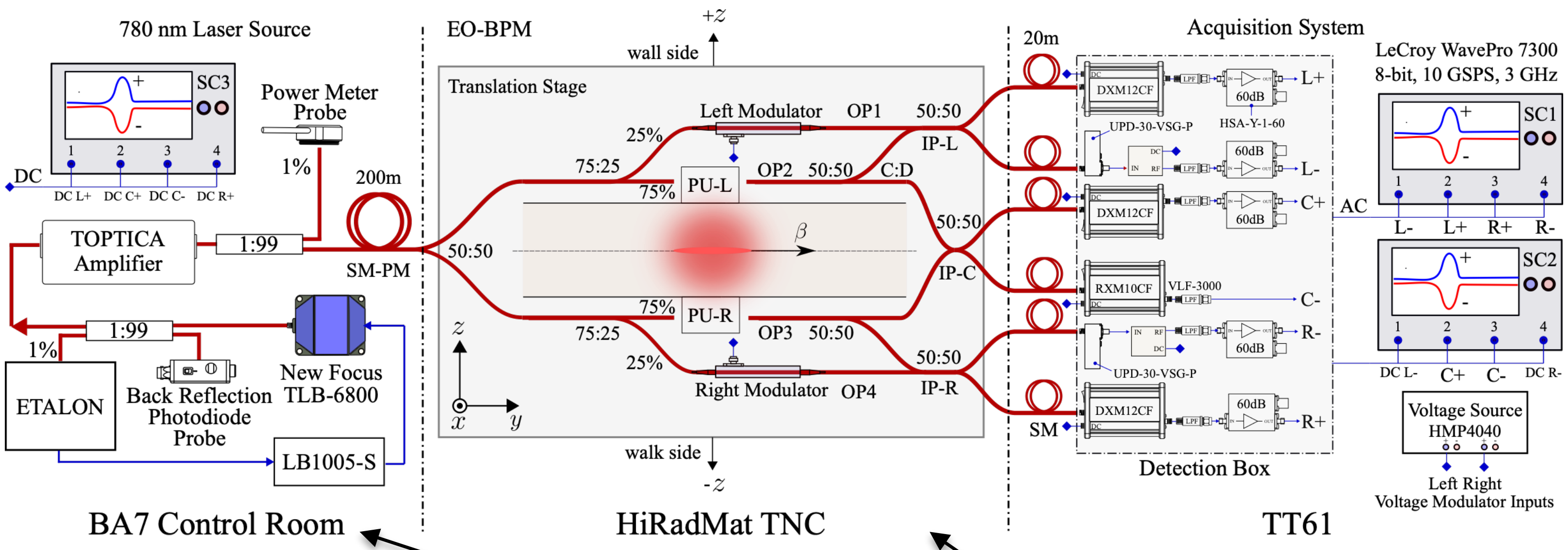


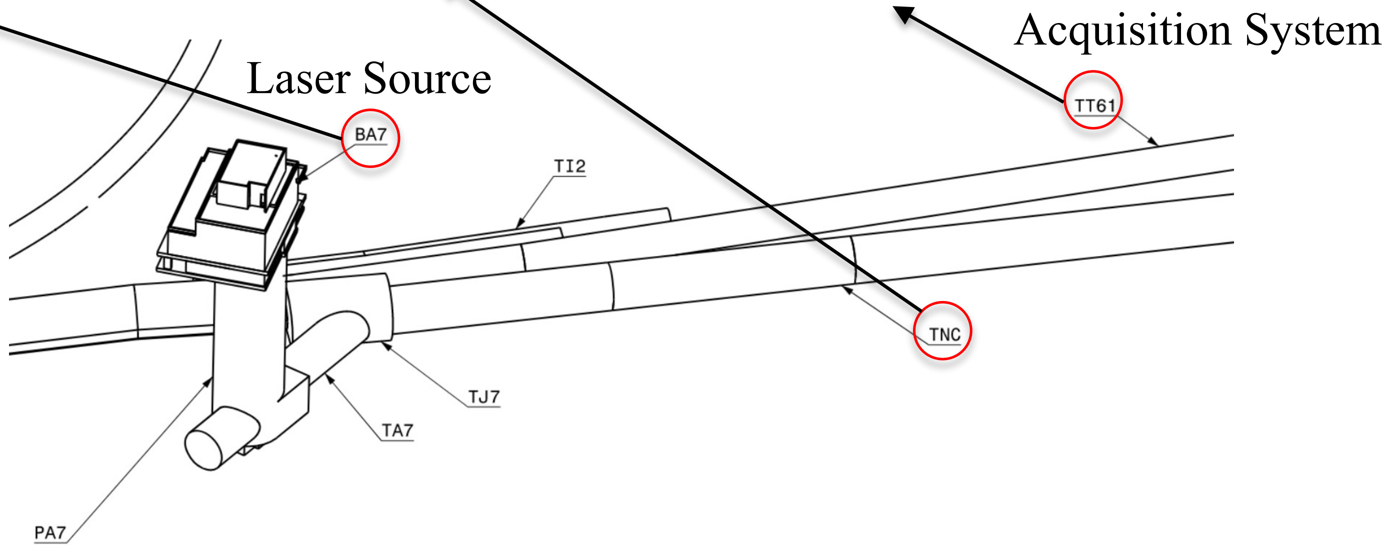




EO-BPM reception tested at CERN and laser-aligned with dielectric BPM on shared translation table

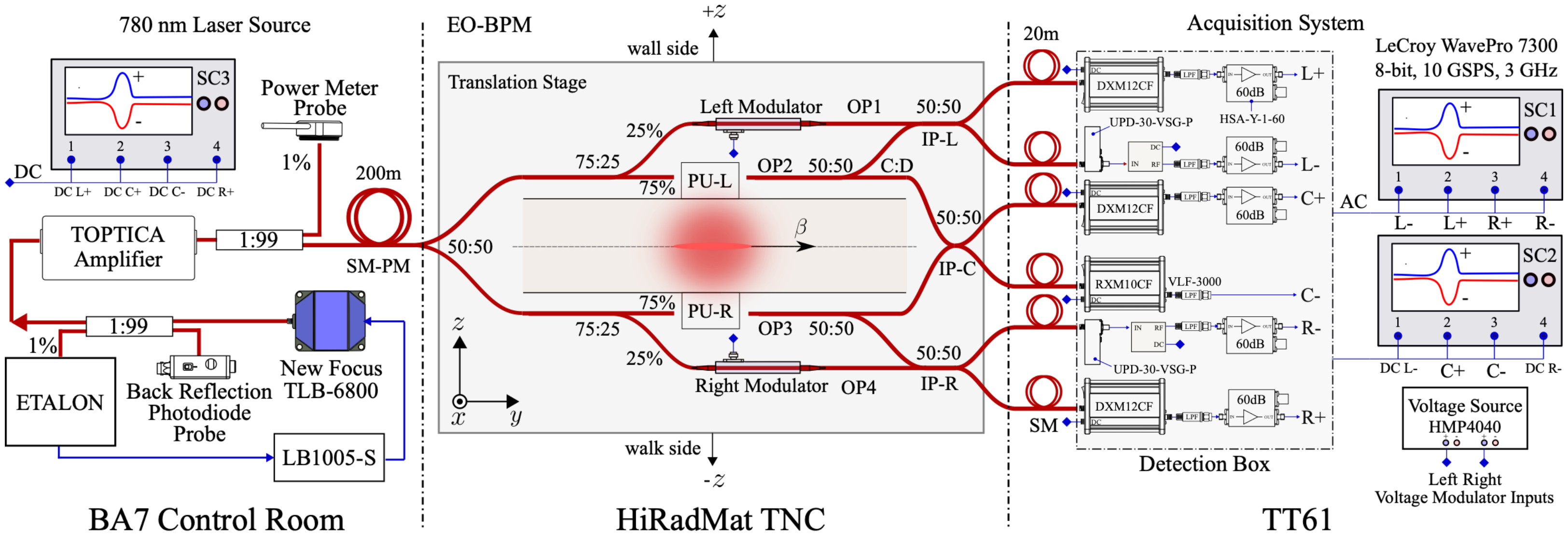
EO-BPM installation in HiRadMat facility



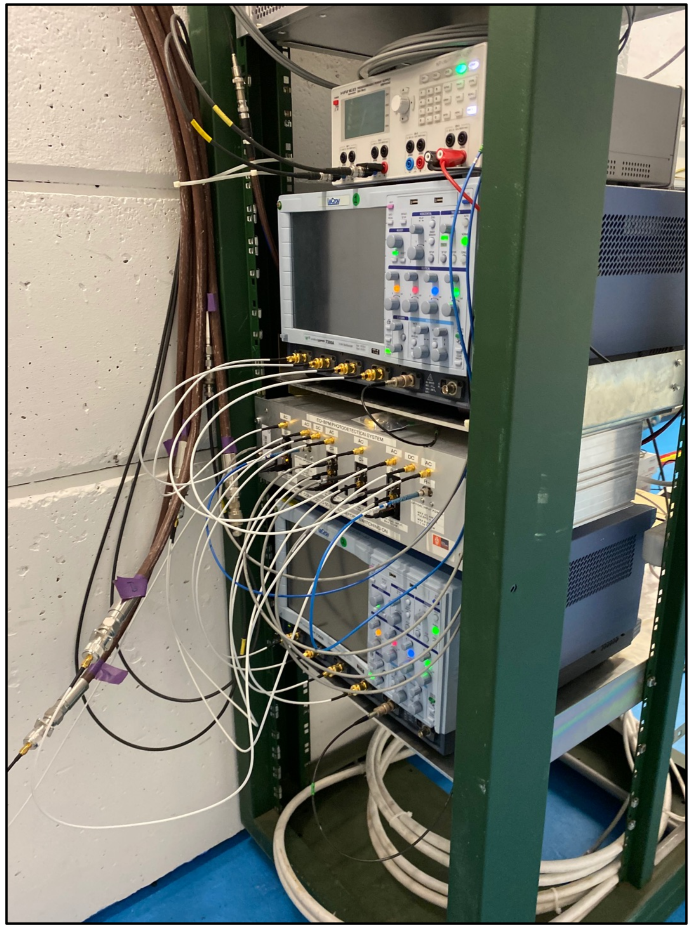


- SPS extraction line:
  - 1.5ns proton bunches.

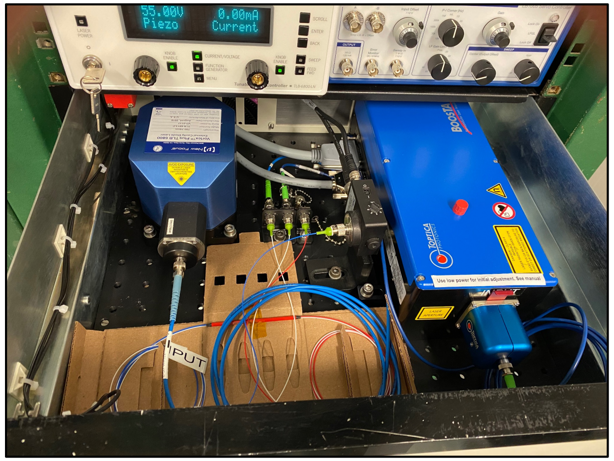
EO-BPM installation in HiRadMat facility



Acquisition system:

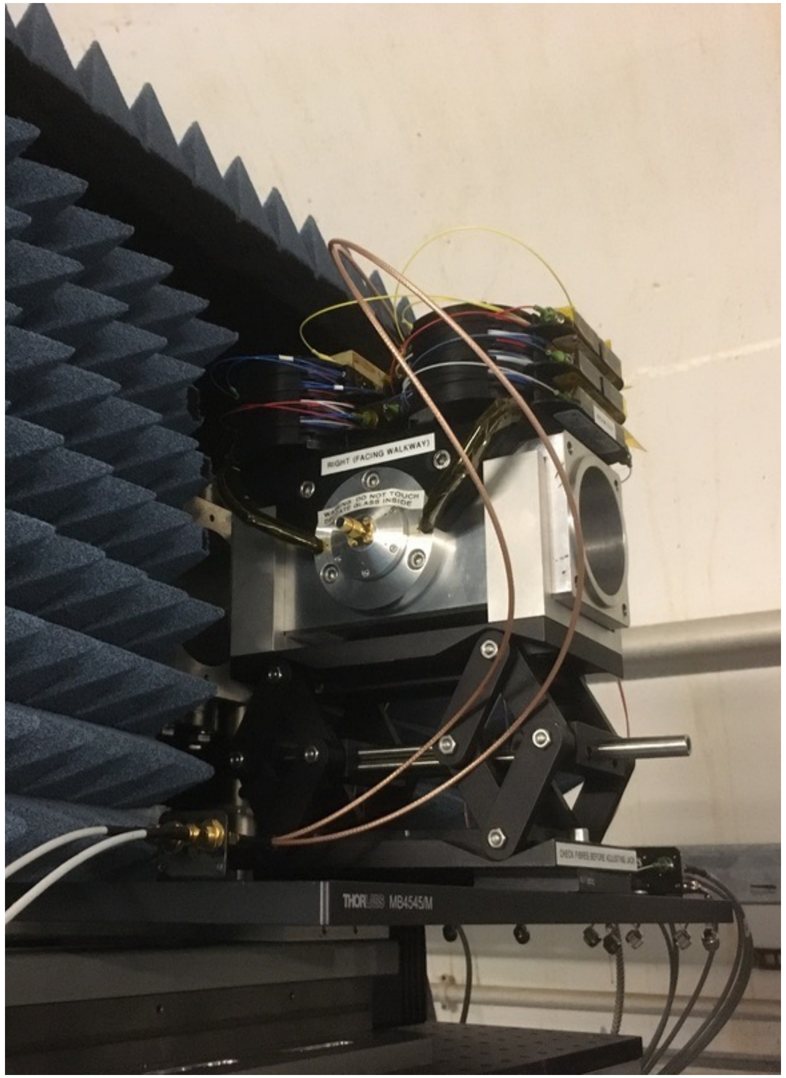


780nm laser source in BA7

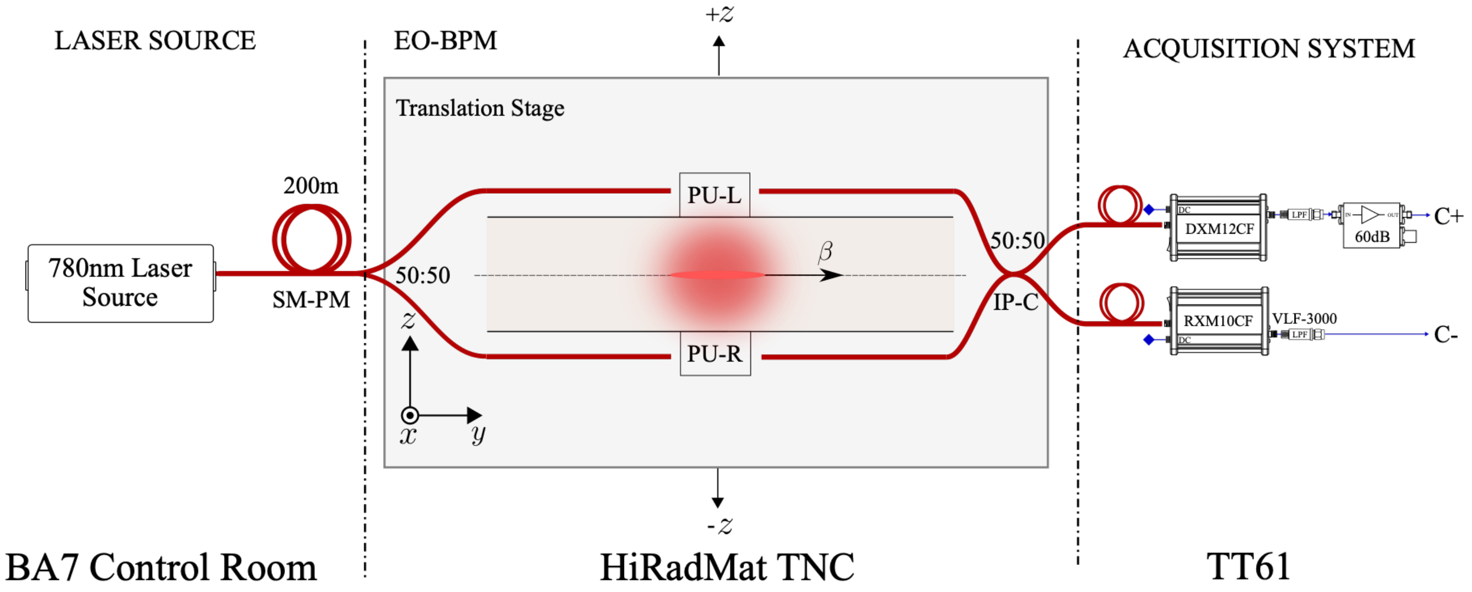


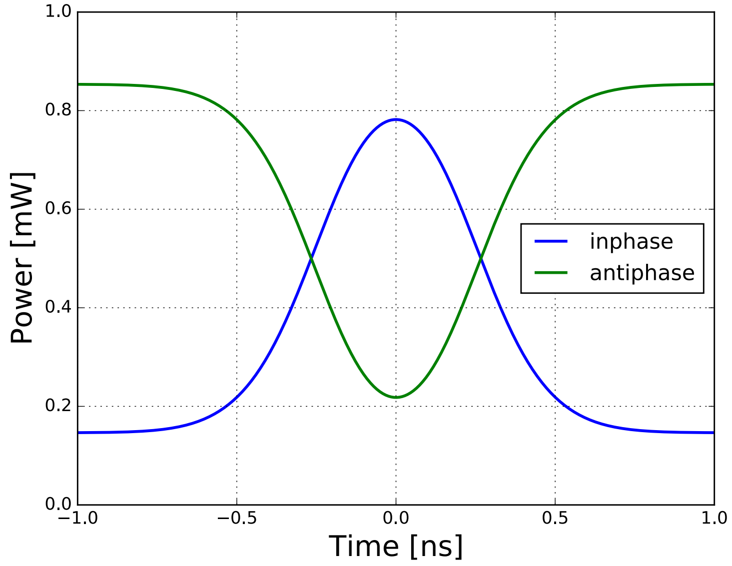
EO-BPM at HiRadMat extraction line

EO-BPM installation in HiRadMat facility

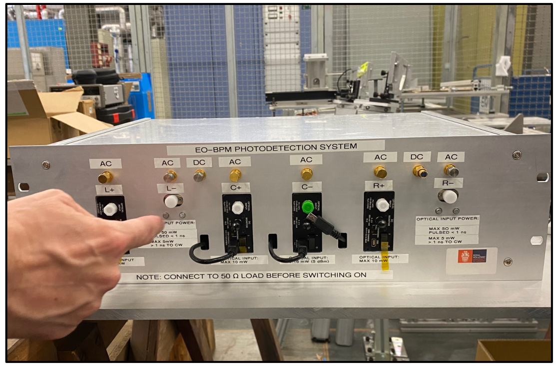


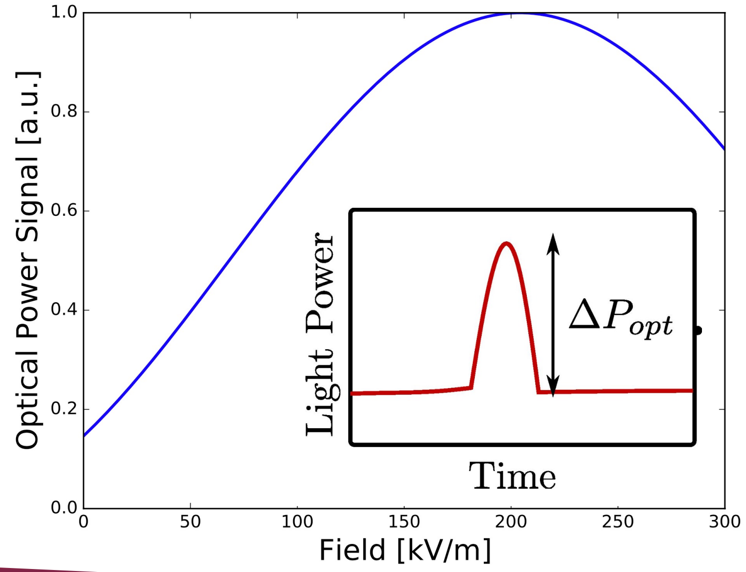
Transverse resolution studies at HiRadMat





- x3 8-bit LeCroy scope
- x3 DXM12CF + 1GHz-60dB FEMTO HSA-Y-1-60
- x1 RXM10CF + 3GHz Filter
- x2 Alphalas UPD-30-VSG-P

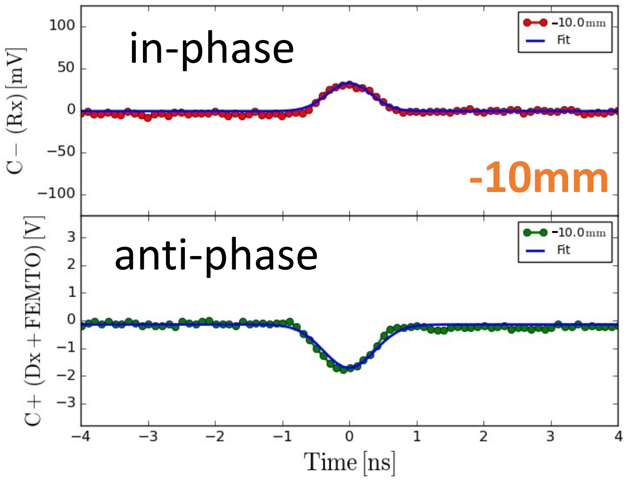




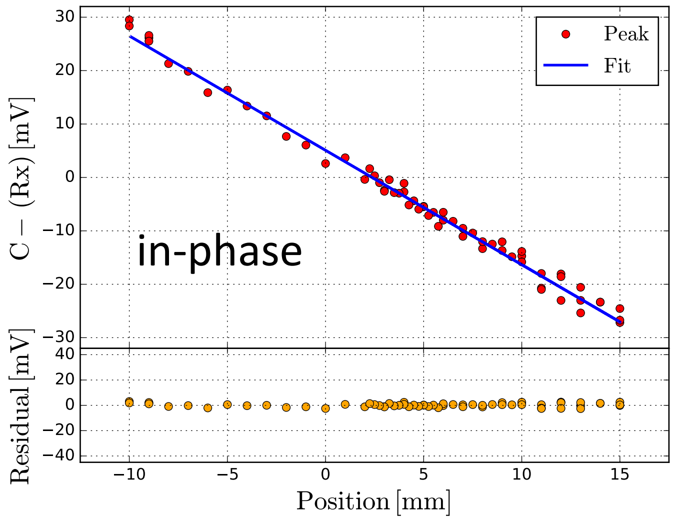
Successful first beam test at HiRadMat

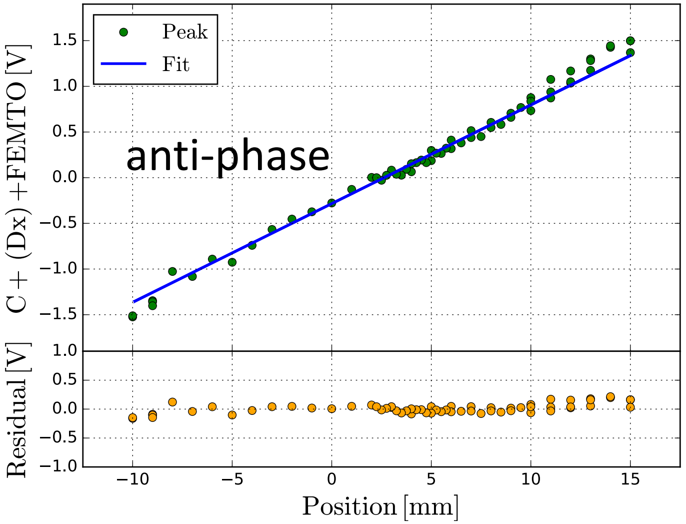
- **Waveguide design** enabled **first single-shot measurements of each passing bunch**.
- EO-BPM also **sensitive to low intensity bunches**.
- Laser scanning technique developed to **automate operation** of electro-optic interferometer.
- Translation of EO-BPM across the HiRadMat extraction line: ***first bunch by bunch position measurements:***
- *Campaign extended to 3 run periods.*

Typical single-shot signals

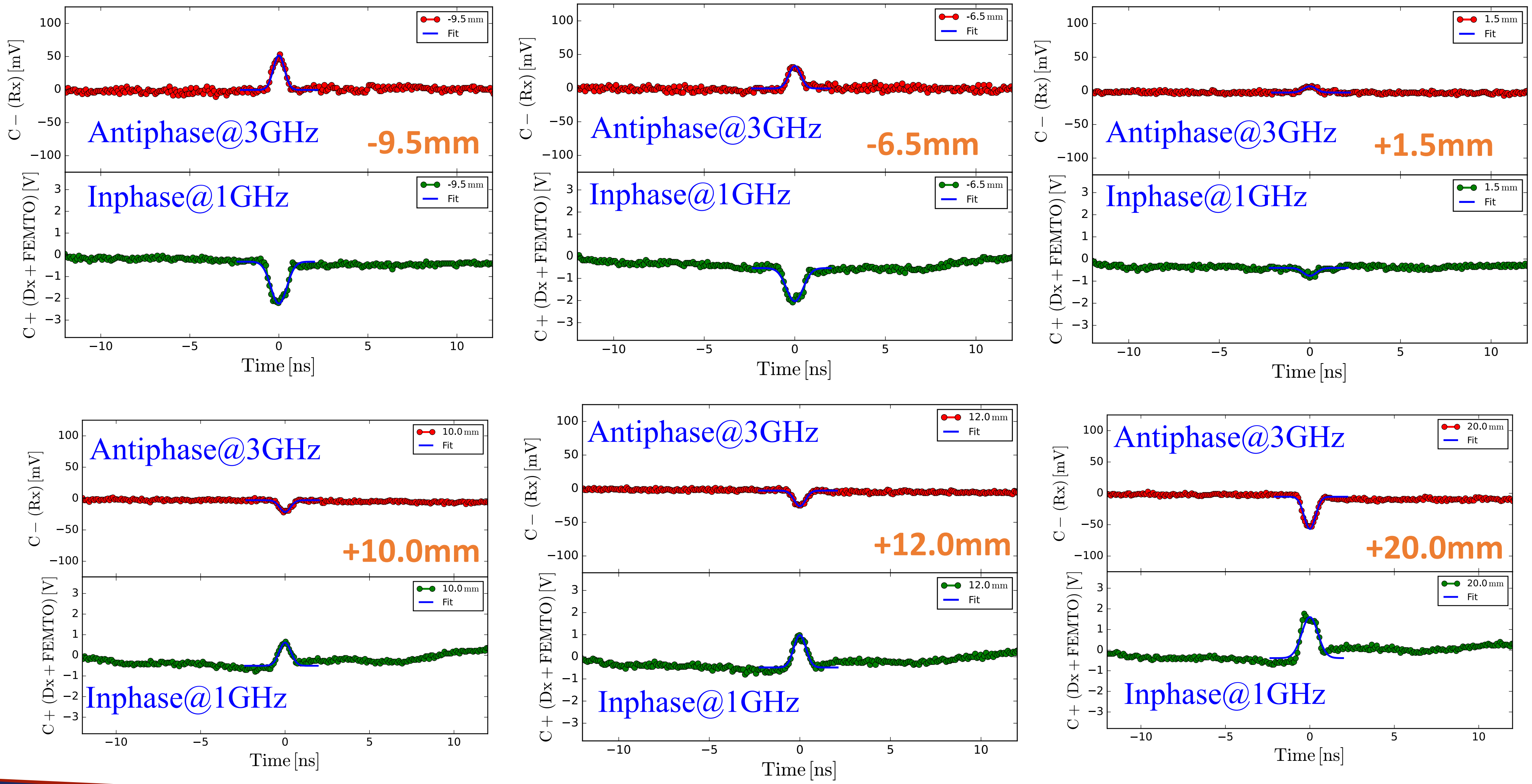


Measured at relatively low proton bunch charge: $7.7\text{x}10^{10}$



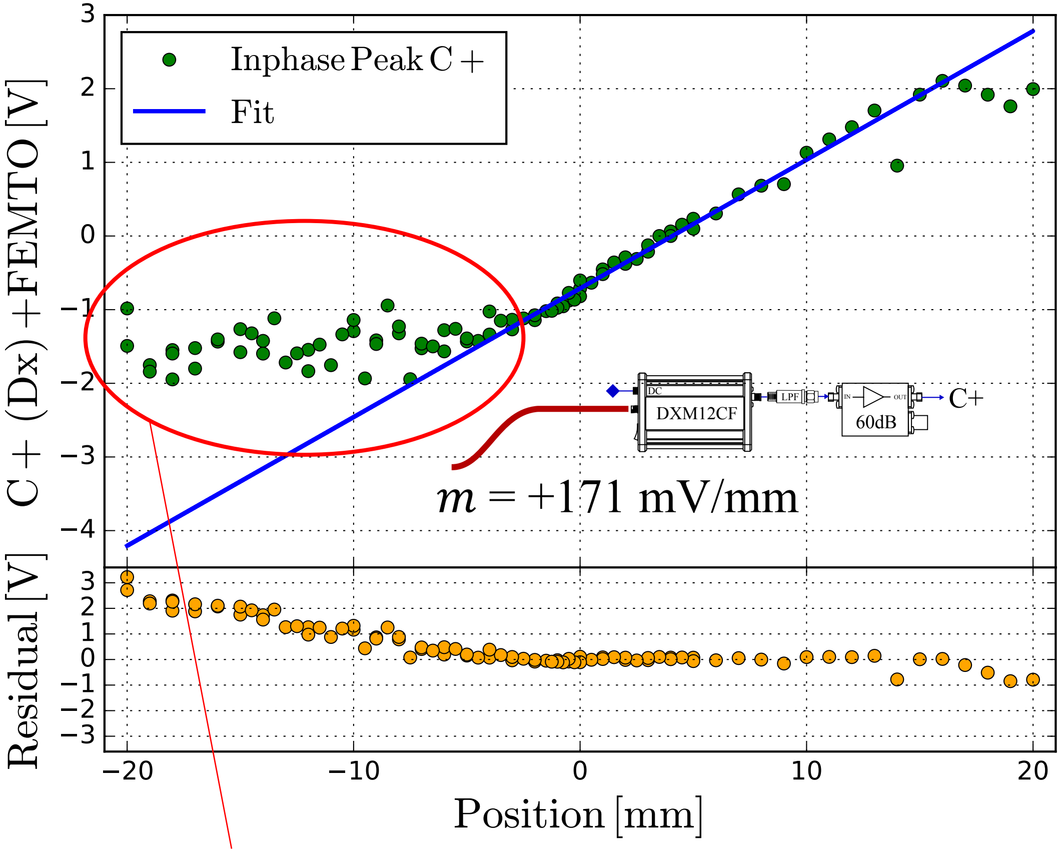


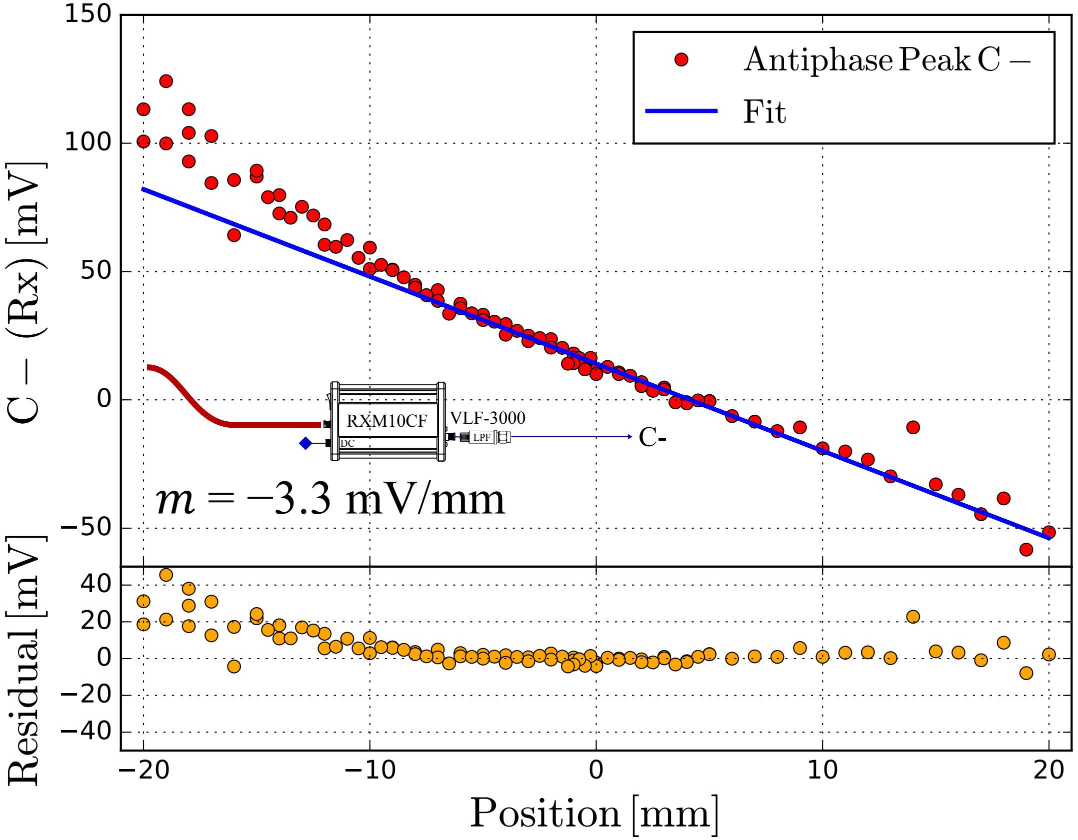
Transverse displacement, single-shots



Measured at close to nominal proton bunch charge: $1.05x10^{11}$

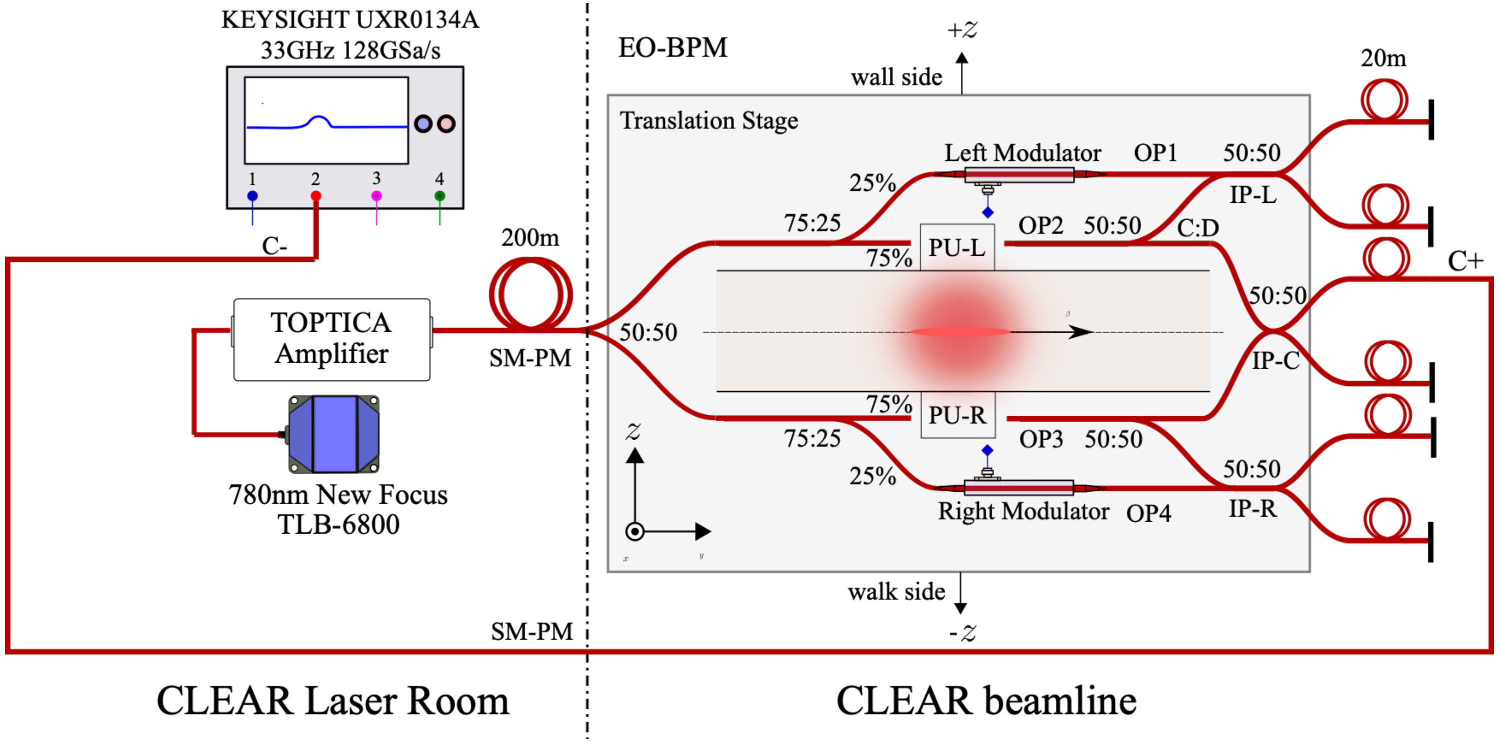
Transverse single-shot bunch resolution

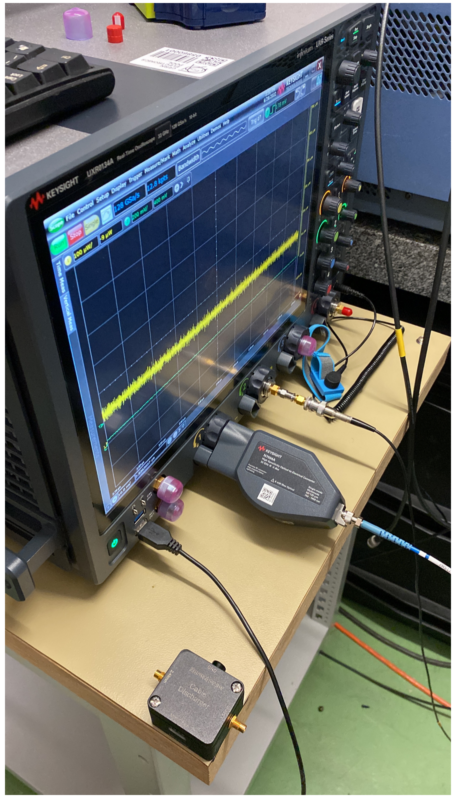


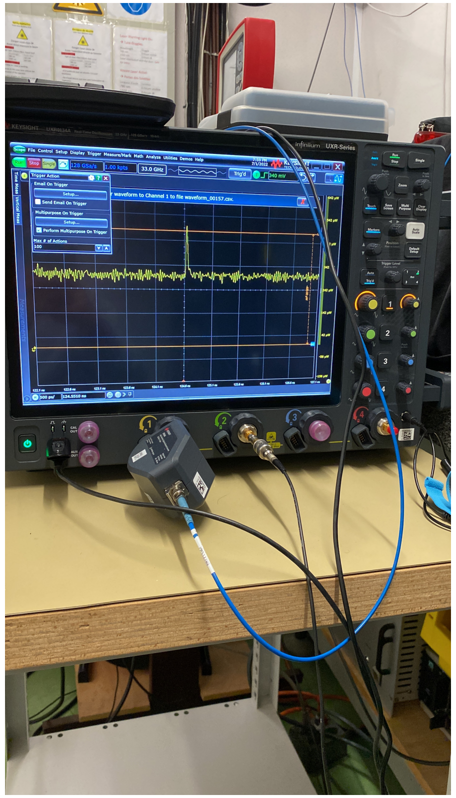


- *Dx + FEMTO saturates for large signals, < -2V.*
- *Opposite sign gradients for in-phase and anti-phase, as expected*

Bandwidth tests at CLEAR facility



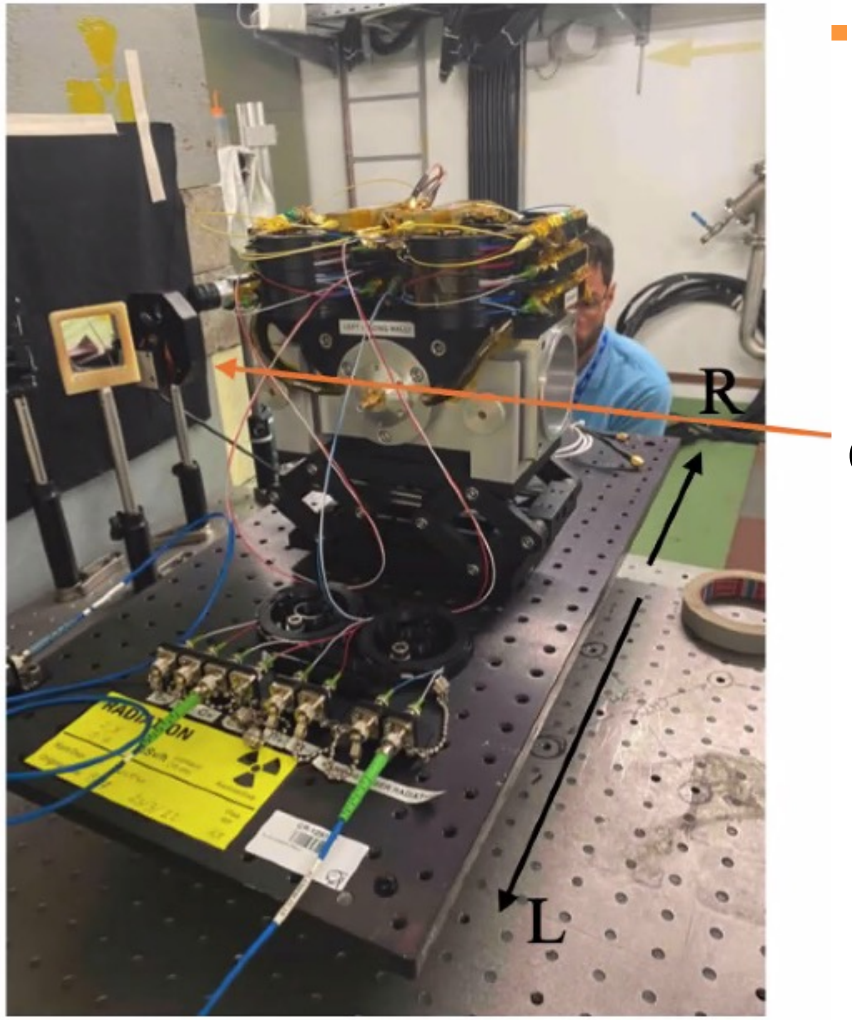




- 5ps electron bunches
- Interferometric Common Mode measured at a single C+ channel using a 33GHz optical probe directly attached to a Keysight UXR series 33GHz scope.
- This scope allowed simultaneous detection of the DC working point baseline and the AC optical modulation on top.
- EOBPM installed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

July 2022 EO-BPM beam test at CLEAR:

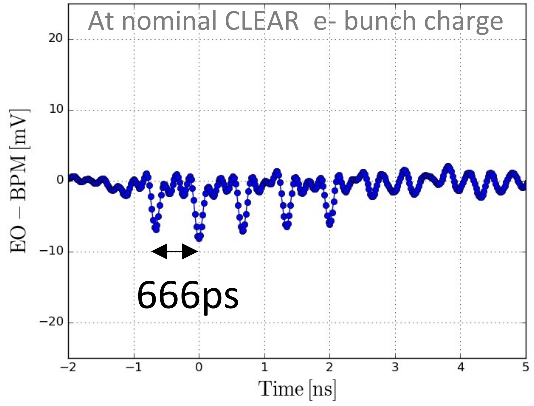


- EO-BPM installed in the CLEAR beamline to check sensitivity and ***time resolution*** to short electron bunches.

Preliminary analysis:

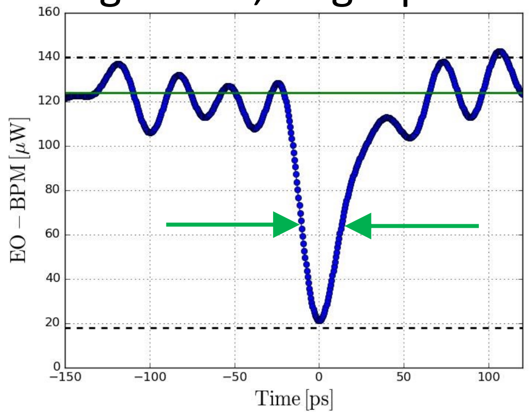
- Initial measurements of a train of 5 ***electron bunch pulses spaced by 666ps (1.5GHz) were observable*** at the photodetector, where the pulse width was limited by the bandwidth of the photodetection system.

single shot, pulse train



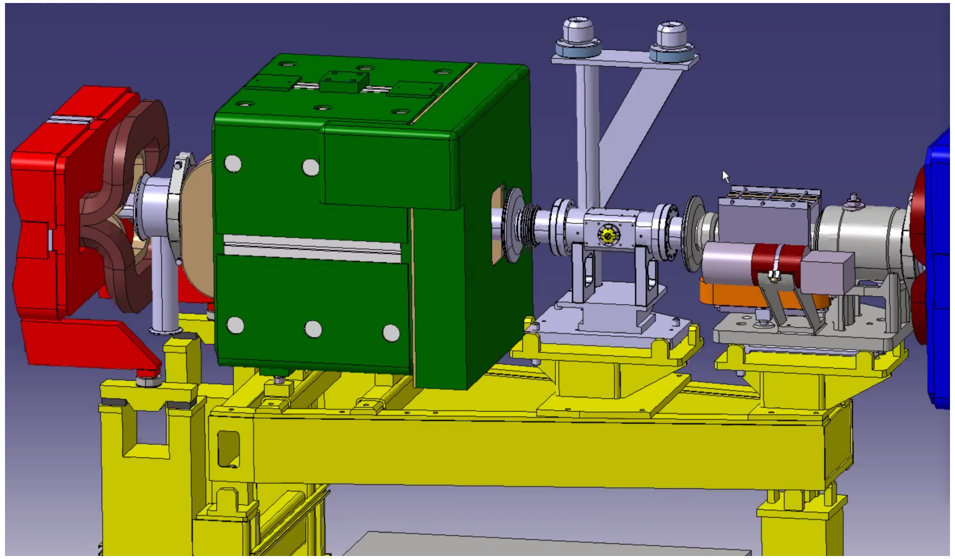
- With an upgraded detector, the pulse width indicates the time resolution of EO pick-up is well **within the < 50 ps specification** required for the HL-LHC measurement of 1ns bunches.

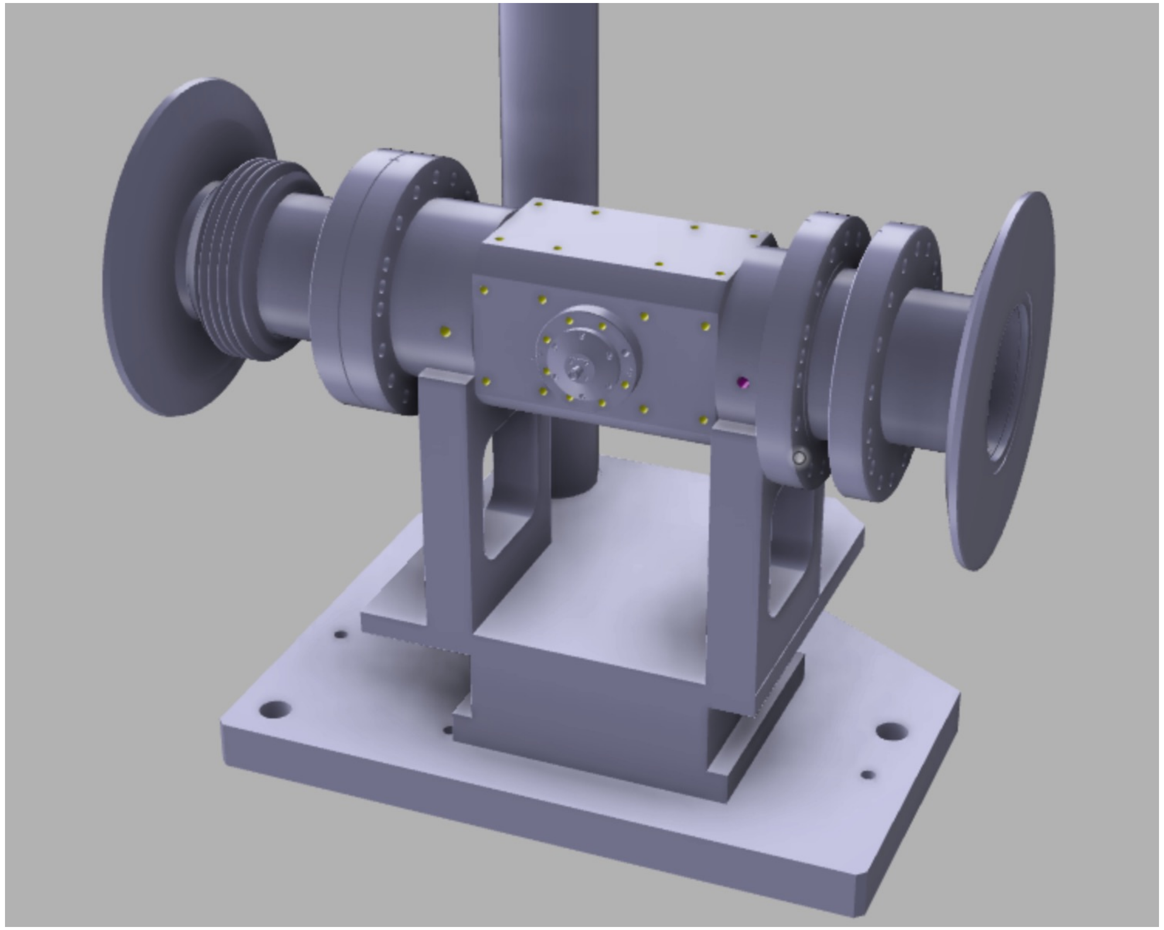
single shot, single pulse



EO-BPM future HL-LHC demonstrator in SPS

- HiRadMat EO-pick-up design incorporated into an in-vacuum design for the next phase of project.
- Excellent recent progress on CERN engineering drawings and vacuum brazing.
- **EO-BPM demonstrator** now being built for installation in **SPS** and operation in Run 3.





Summary

- First successful electro-optic transverse displacement measurements of **single-shot bunches**, using for first time the novel “common mode” **optical *difference detection.***
- **Signal strength** has been **significantly enhanced** by an **in-fibre, EO waveguide design**, which shows promise for further improvements in the transverse resolution.
- The new electro-optical button, incorporating the waveguide, shows a time response <50ps, which is at the expected limit of the design and acquisition system.
- Further improvements in the bandwidth of the detection system are anticipated for the future prototype in SPS.
- A fully vacuum compatible design is in production for beam tests at the SPS.

Thank you!

Thanks for your attention…and GO EO!

With thanks to Pascal Simon and the HiRadMat team

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under GA No 101004730.

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