HT measurements & outlook for HL-LHC

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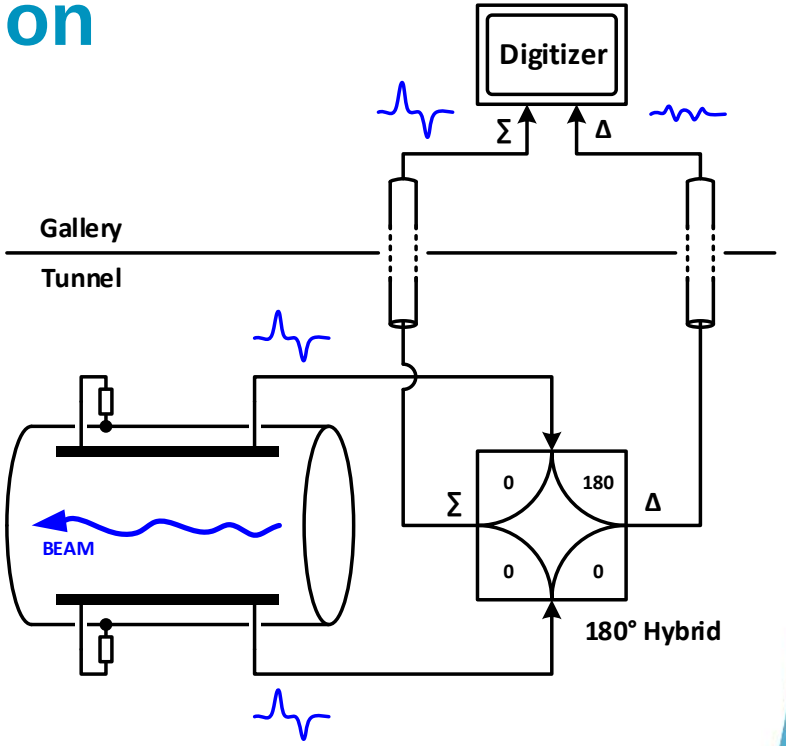
Introduction

- Existing high-bandwidth “Head-Tail” monitors installed in SPS + LHC
  - Measurement of transverse instabilities (LHC+SPS)
  - Measurement of crab-cavities (SPS)
- Limited in bandwidth & resolution by imperfections of pick-up, hybrid, cables and digitizers
- Existing LHC HT pick-ups generally at bad phase advances with respect to the future CC locations
  - Will need new pick-ups in optimal locations for CC diagnostics
  - Optimal locations studied by WP2…



HT diagnostic close to IP (APWL about 165 m from IP)

i.e. beside the CC

Amplitude of the ideal $0.03\sigma_{x,y}$ leakage (phase advance & ATS independent)

Round optics H crossing IP1, V crossing IP5

β* (cm)	x [IP1 L] (μm)	x [IP1 R] (μm)	y [IP5 L] (μm)	y [IP5 R] (μm)
15 (B1/B2)	**30.4**/19.0	20.8/**28.3**	20.7/**28.4**	**30.3**/19.1
50 (B1/B2)	**30.4**/18.8	20.8/**28.3**	20.7/**28.3**	**30.2**/19.0

Approx. 30um residual signal in all cases

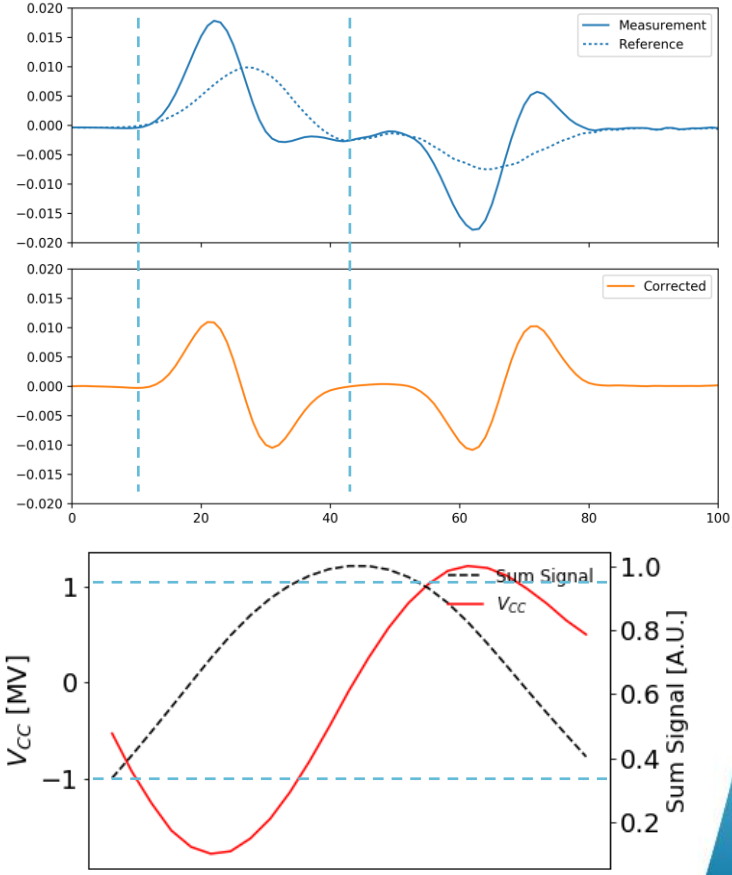
Flat optics with CC V crossing IP1, H crossing IP5

β* (cm)	y [IP1 L] (μm)	y [IP1 R] (μm)	x [IP5 L] (μm)	x [IP5 R] (μm)
18/7.5 (B1/B2)	20.8 /**28.3**	**30.4**/19.0	**30.2** /19.1	20.7/**28.4**

N.B. there is another flat optics with H, V crossing not shown here.

Head-Tail correction for CC

- Well phased CC results in a static intra-bunch position offset at the HT pick-up
- Residual HT baseline signal from beam position offset plus systematic effects from hybrids, etc
- In SPS, baseline correction has been performed by taking a reference measurement in each cycle with the cavities un-phased (or off)
  - Works well in SPS but is not technique that is easy to implement in long fills in HL
  - Hoped to study stability of baseline during 2023 LHC run… maybe in 2024 ☺

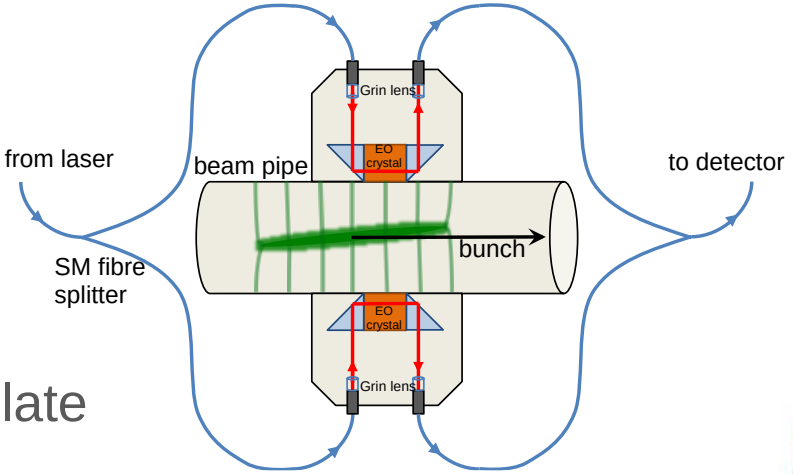


Limits of traditional Head-Tail

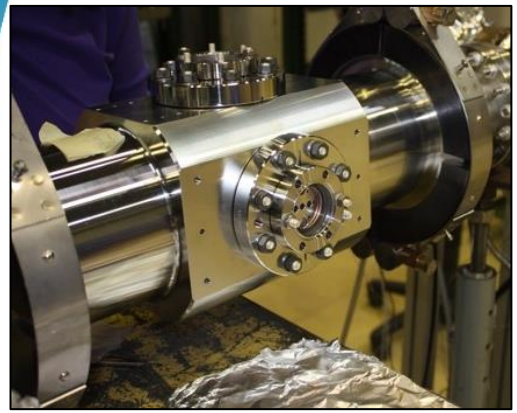
- With optimal BPM locations (IP1/5) need to measure ~30um signal
  - **Note:** we are still missing a spec from WP2/WP4 on resolution requirement!
- Given existing HT, 30um corresponds to a ~3mV signal
- Baseline signals of ~20mV from hybrid imperfections
  - Current HT scopes have ~175uVrms noise for these signal levels
  - **~10% of signal level**
- **Reminder:** no FRAS foreseen for these BPMs, can expect mm offset between beam and BPM electrical center!
  - Resulting in an additional ~200mV baseline from the beam offset
  - Current HT scopes have ~750uVrms noise for these signal levels
  - **~25% of signal level**
- There is possibly some improvement from newer high-speed ADCs
  - But cannot expect an orders of magnitude improvement
- Electro-Optical (EO) techniques are under study for potential of further improvements

Electro-Optical BPMs

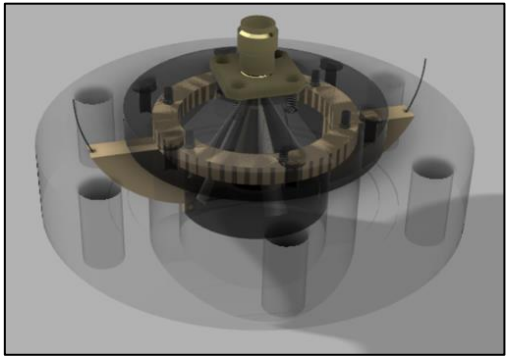
- Electro-Optical (EO) BPMs are being studied by WP13, in collaboration with RHUL, as a potential upgrade for higher bandwidth
  - Using birefringent crystals to modulate a laser signal in response to the bunch's EM field
  - Fiber coupled interferometer utilises the coherence of light to suppress common mode signal
  - Difference signal measured directly at photodetector



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



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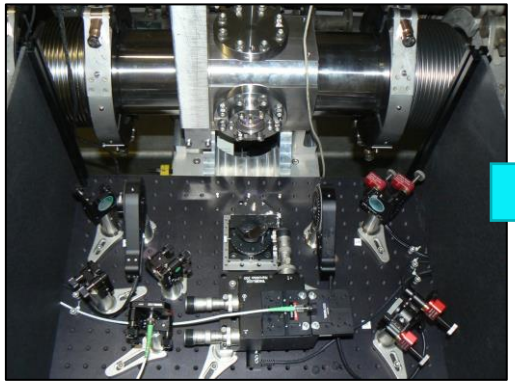
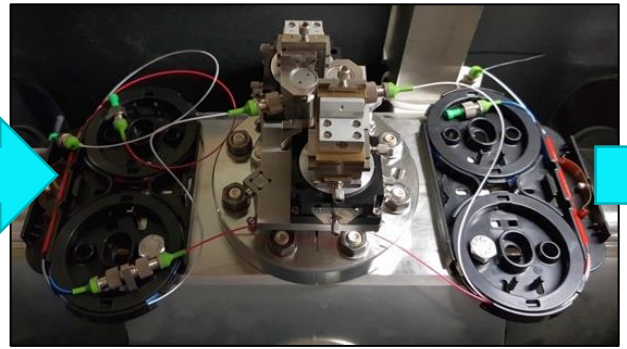
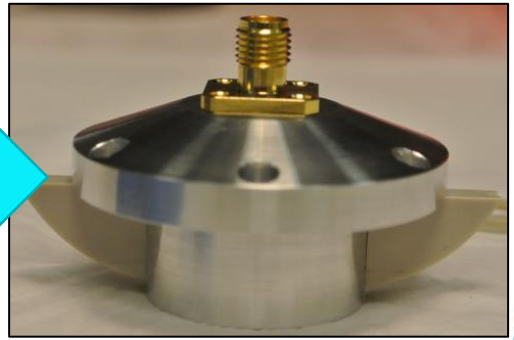


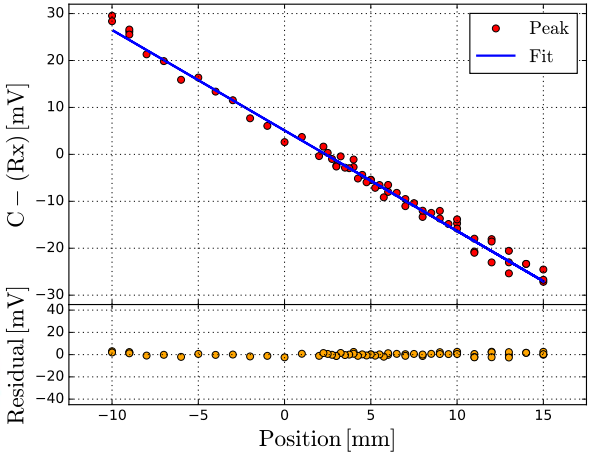




EO-BPM tests summary

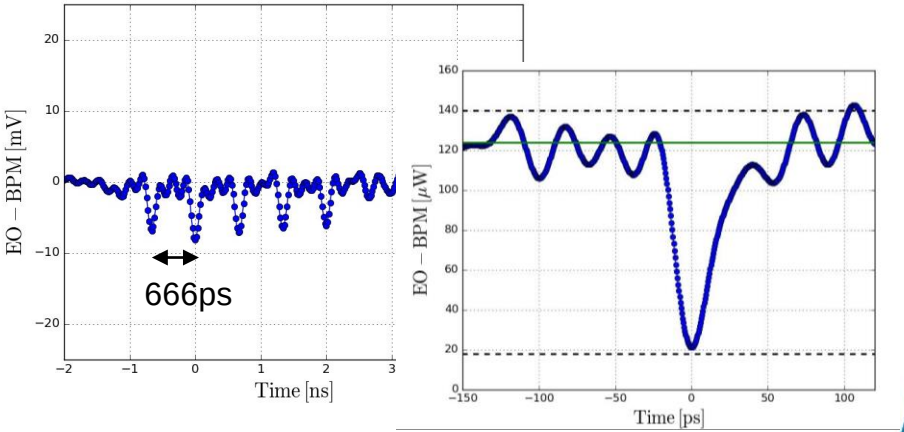
HiRadMat (2021)

- First single shot measurements with proton beams with in-air prototype and EO interferometer
- Mechanical translation of BPM body to allow “beam position” scans



CLEAR (2022)

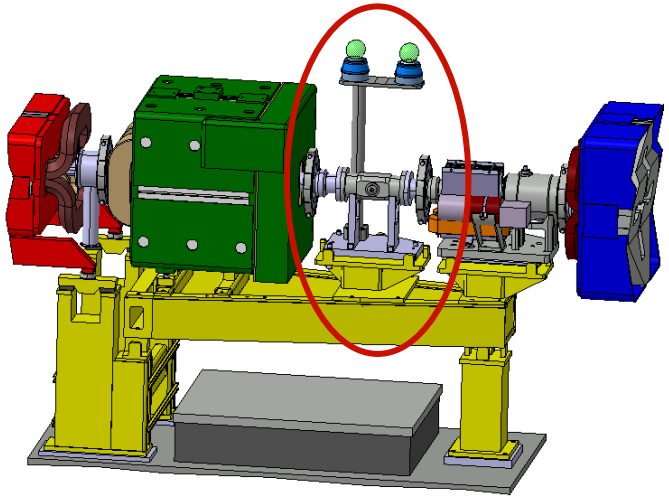
- Test of time resolution with short (5ps) electron bunches, acquisition with 33 GHz oscilloscope and optical probe
- Preliminary results show time resolution is within the required <50ps specification.



2nd SPS EO-BPM test installation

(As presented at the 2022 meeting)

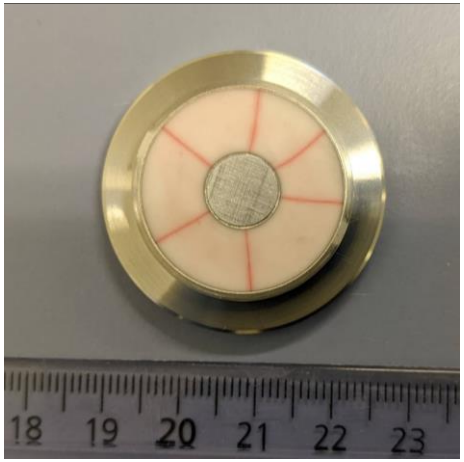
- HL-LHC EO-BPM prototype will be installed in SPS
  - Benefit from reuse of existing fiber infrastructure in SPS LSS4
- Beam tests planned during ~~2023~~
  - Focusing on resolution and long-term stability of the EO-BPM
  - Benefit from possible 2023 crab-cavity tests as a validation step
- Technical review at end of ~~2023~~
  - Decision to install EO-BPMs or “traditional” strip-lines in HL-LHC

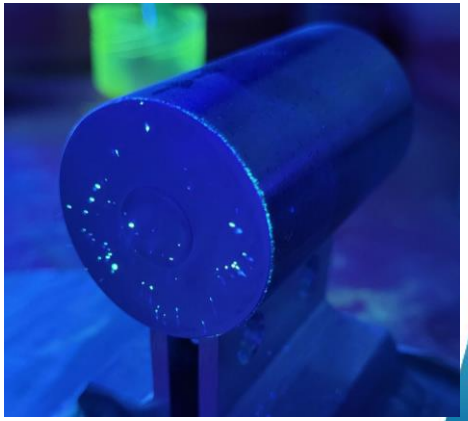


Integration of EO-BPM on SPS girder GHY.42101 (EN-ACE)

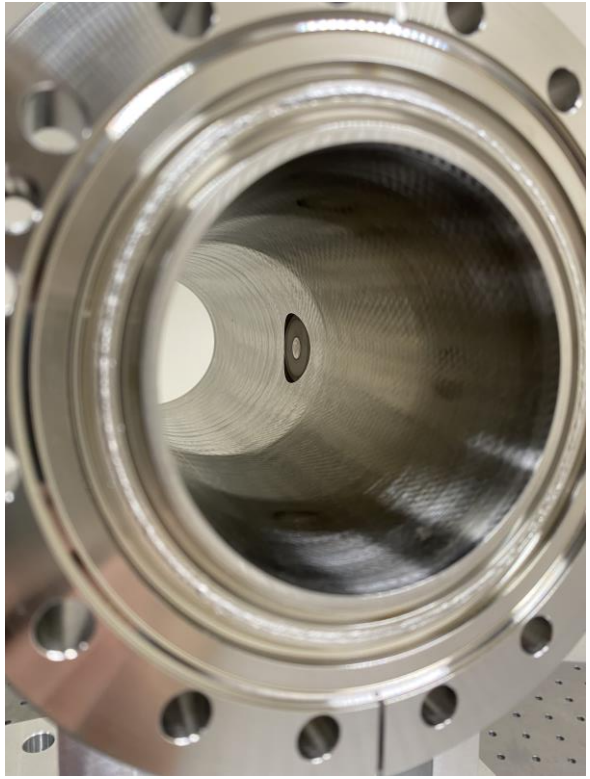
Issues with EO-BPM production

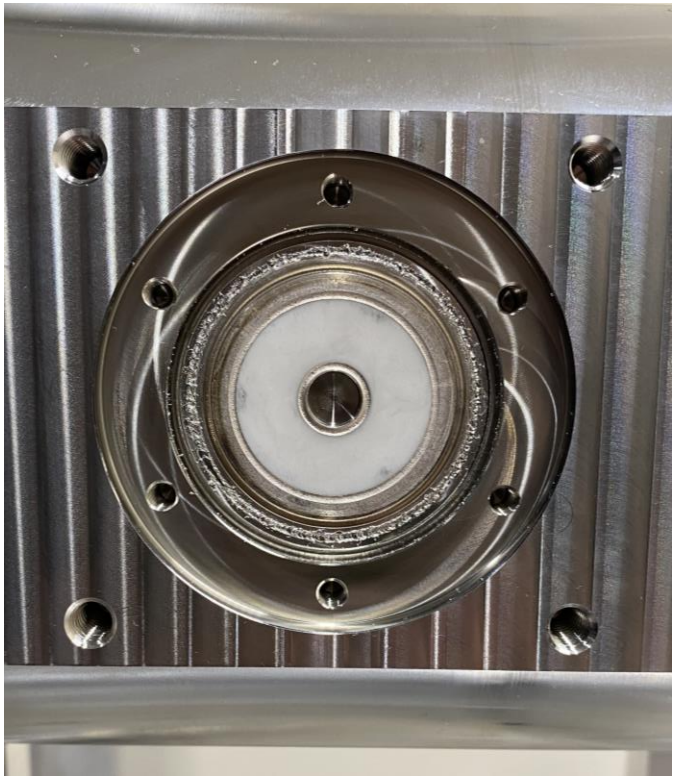
- Long lead time on ceramic washers and delays lead to delivery only in late 2022
- First brazing attempt: cracked ceramics
  - Minor adaptation of geometry of Kovar parts to improve the situation
- In addition, defects (pores) were found in Kovar stock at CERN
  - Again, long lead time of replacement material
- Successfully (?) brazed parts finished in mid-2023 and welded to the body…





EO-BPM prototype assembly



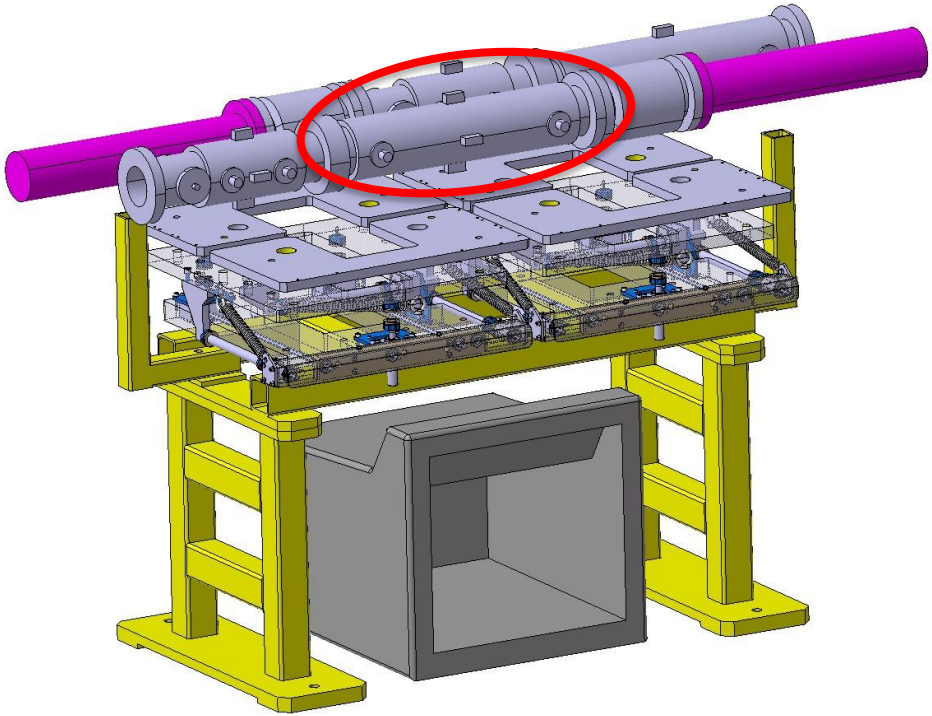


Issues with EO-BPM production (pt. 2)

- **Last week:** leaks were found on both buttons during vacuum acceptance tests
- Work ongoing now to understand the source of the leaks
  - Seems to be localised to brazing
- Additional parts are available:
  - 3 brazed buttons
  - 1 body
- Still some possibility for installation in YETS 23-24 but schedule is very tight
- Need to make a go/no-go decision soon for EO-BPM installation
  - Ideally should be done *after* the SPS tests
  - Any further installation delays make this difficult

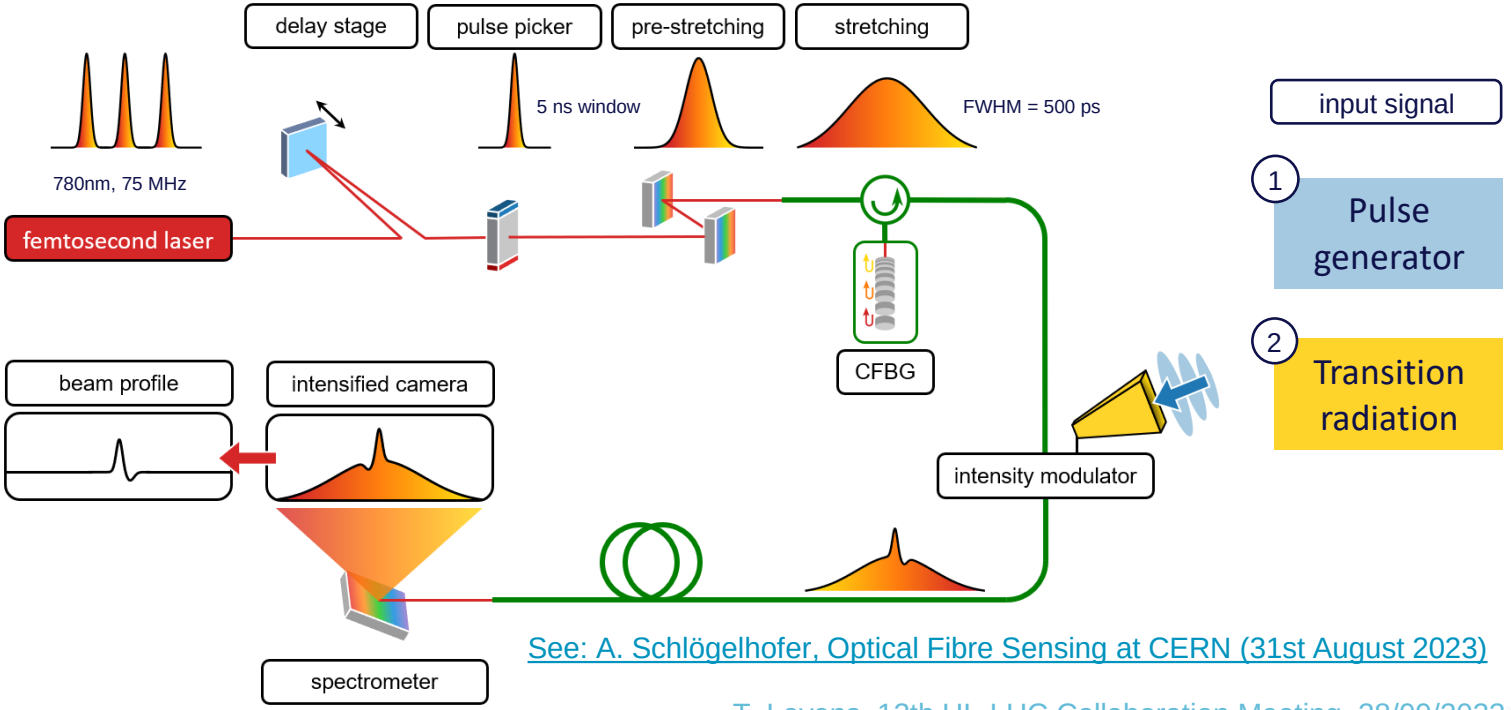
Stripline for CC

- Design of a traditional strip-line BPM is being done in parallel to the EO-BPM
- Backup in case the EO-BPM is not a viable option
- Space reservation and integration proceeding with this design as it has a longer length
  - Possibility to substitute it by a shorter EO-BPM
- More details in the next talk by M.Krupa



BI R&D into EO spectral decoding techniques

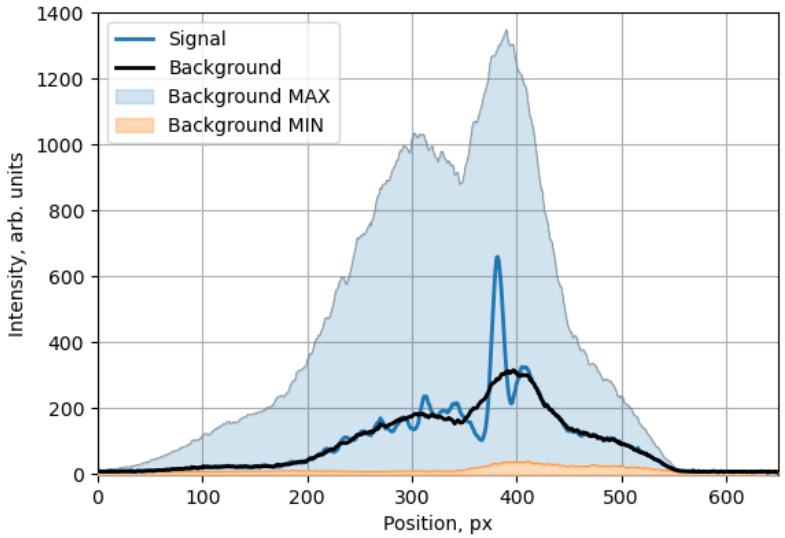
- Study in BI for FCC using EO intensity modulators with spectral decoding techniques using commercial EO-modulators

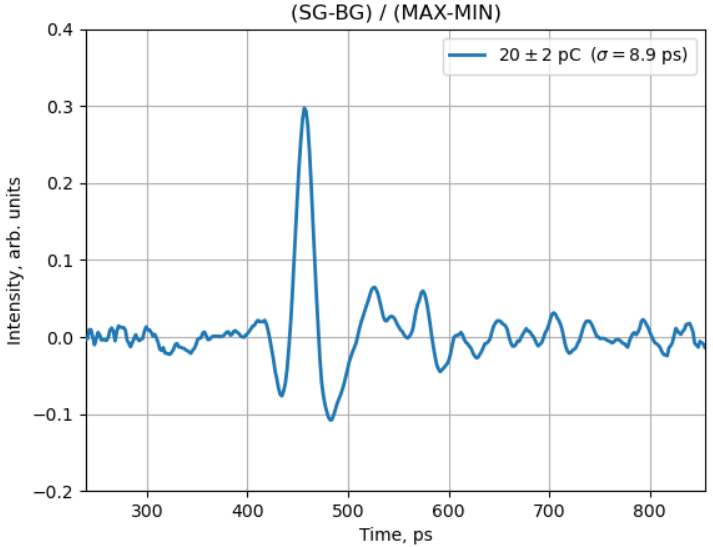


See: A. Schlögelhofer, Optical Fibre Sensing at CERN (31st August 2023)

BI R&D into EO spectral decoding techniques

- Initial results at CLEAR show very high potential with pulse response **< σ = 10 ps**





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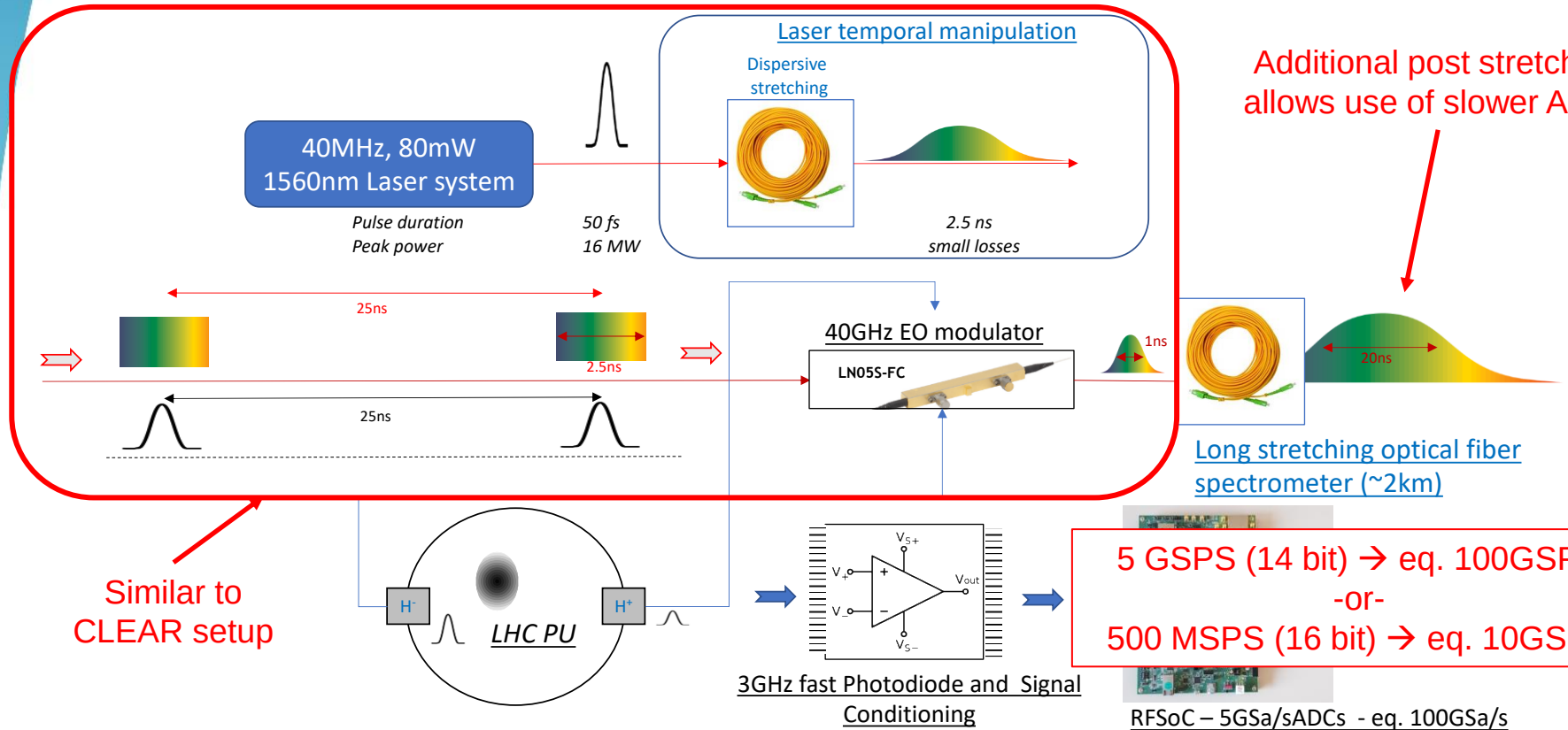
Applicability to HL-LHC

- Initial proposal to test these techniques for HL-LHC:



Summary

- Traditional Head-Tail techniques on the limit for HL-LHC
  - Measurement of 30um residual crabbing is very challenging!
- EO-BPMs under development with RHUL as potential upgrade
  - Issues during manufacturing → installation in SPS was not possible in YETS 22-23
  - Further vacuum leaks were recently discovered → not yet clear if installation in YETS 23-24 is possible
  - Any futher delay will make the go-no decision for installation in HL-LHC too late
- Novel new EO techniques are also being investigated to overcome limits of traditional HT
  - Allowing slower (higher resolution) ADCs for the same equivalent resolution
  - Possibility for continuous data acquisition (not possible with current HT)
  - Procurement of suitable laser for test with LHC beam conditions started
  - Early stage of R&D

HiLumi
HL-LHC PROJECT

Thank you…

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