High Frequency Electro-Optic Beam Position Monitors for Intra-Bunch Diagnostics at the LHC

S.M. Gibson, A. Arteche, G. E. Boorman, A. Bosco – Royal Holloway*
P. Darmedru, T. Lefevre, T. Levens – CERN

Thanks *to R. Steinhagen, J. Doherty, S. Jamison, D. Walsch, R. Jones, L. Nevay, A. Lyapin, S. Boogert for helpful discussions*

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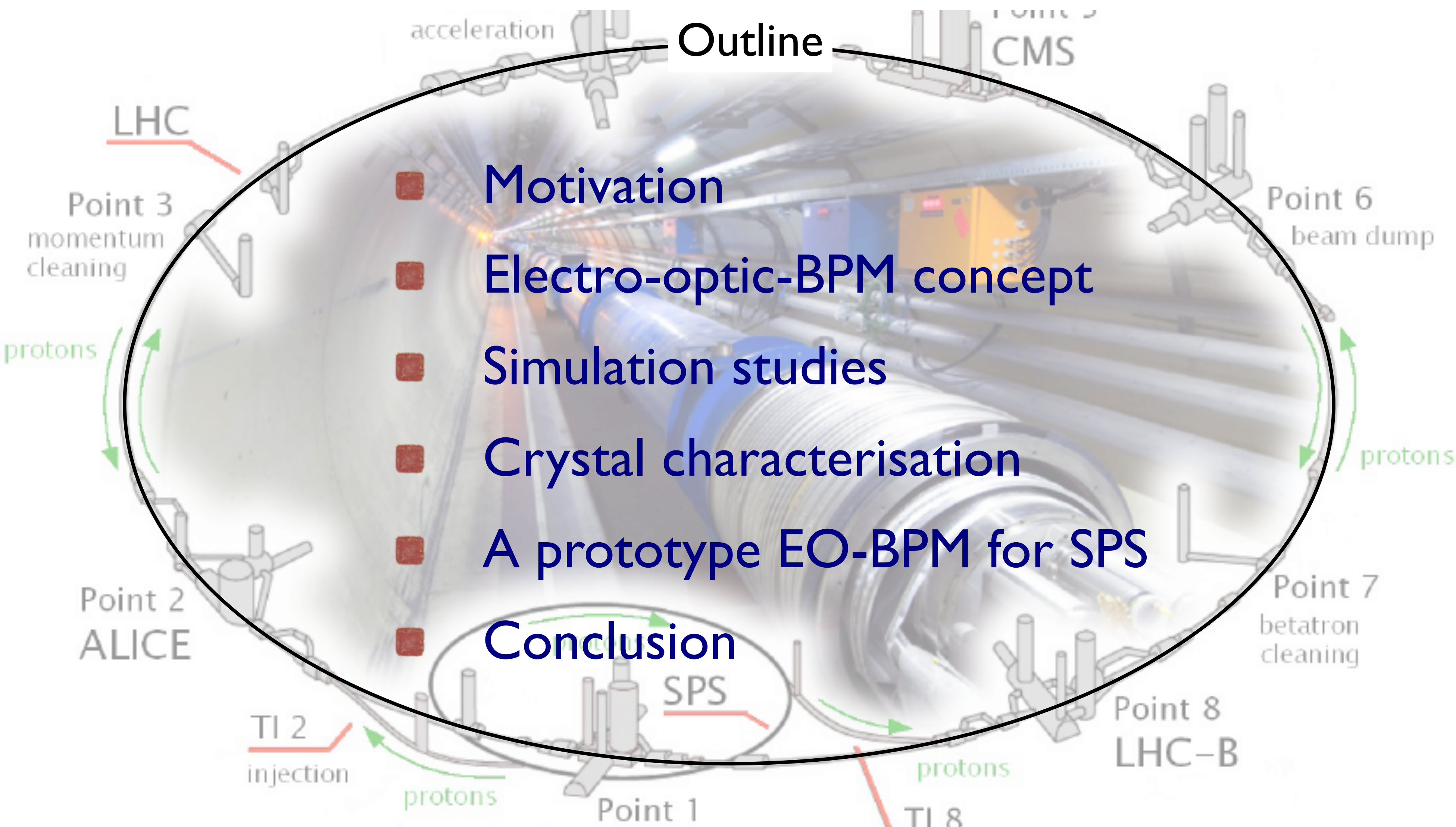


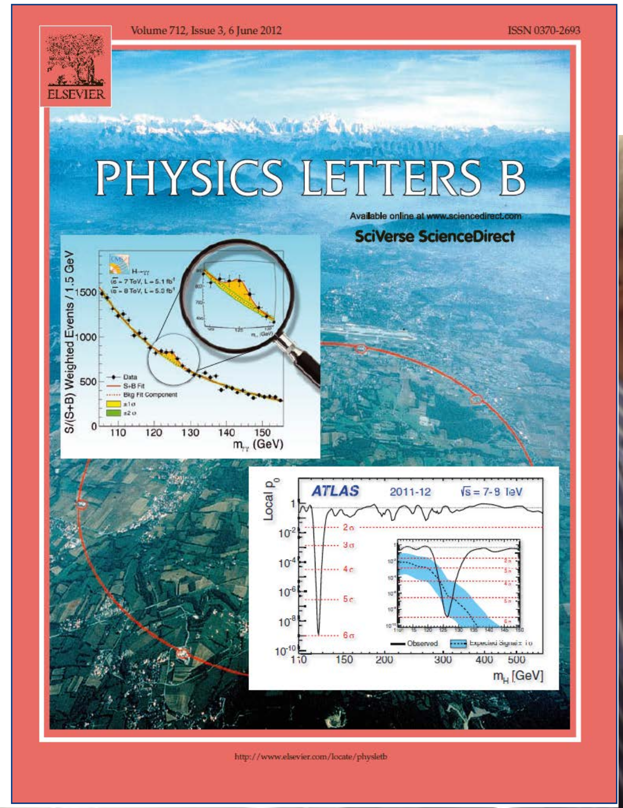
Outline

- Motivation
- Electro-optic-BPM concept
- Simulation studies
- Crystal characterisation
- A prototype EO-BPM for SPS
- Conclusion

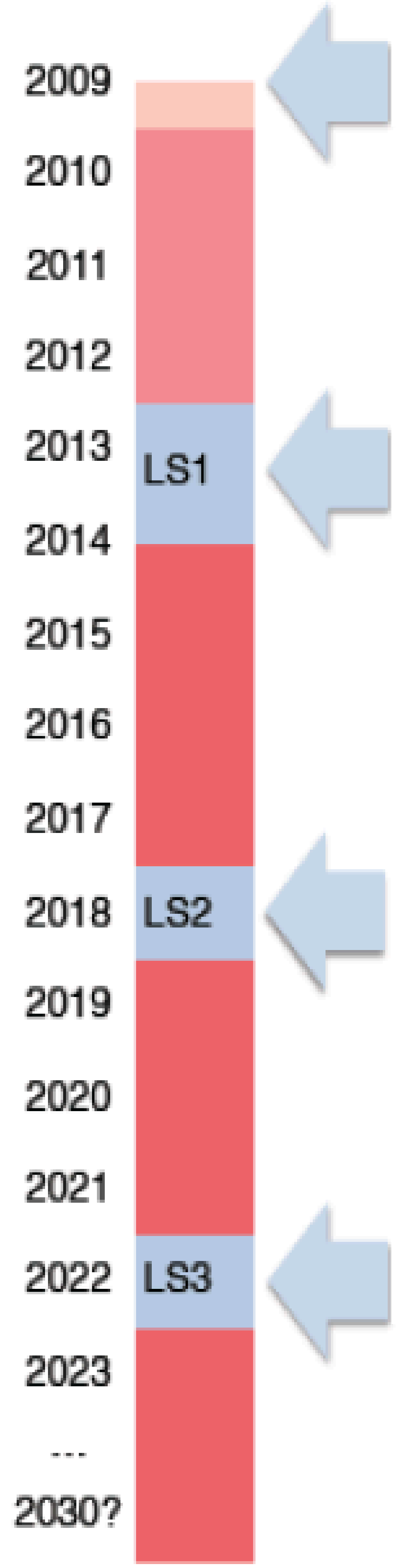
Motivation: the LHC so far…

- In only three years of 7~8 TeV operation:

4 July 2012:
5σ observation of a Higgs-like boson



Motivation: *more luminosity*



✧ LHC startup, √s = 900 GeV

√s=7~8 TeV, L=6x10^{33} cm^{-2} s^{-1}, bunch spacing 50 ns

Go to design energy, nominal luminosity

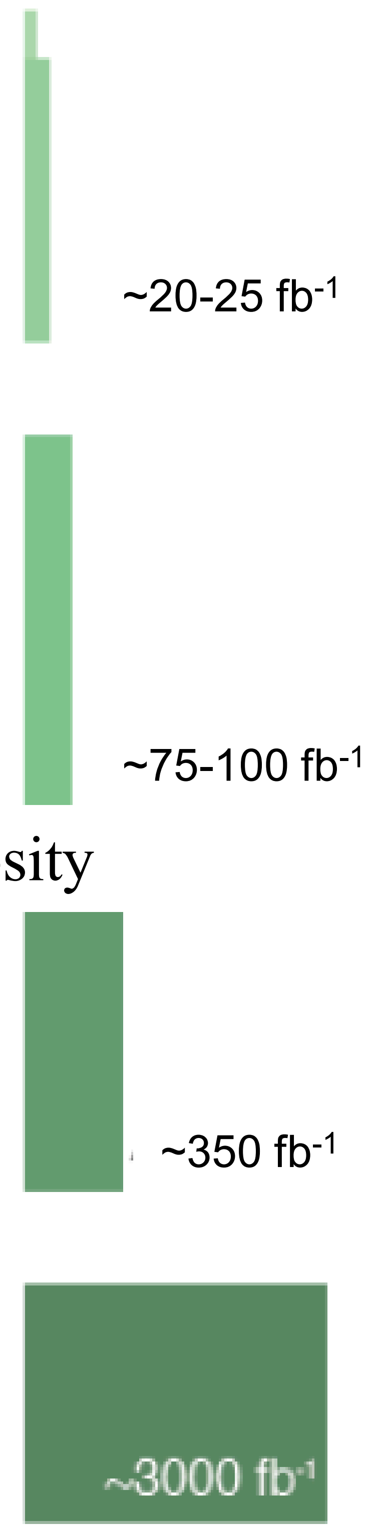
√s=13~14 TeV, L~1x10^{34} cm^{-2} s^{-1}, bunch spacing 25 ns

Injector and LHC Phase-1 upgrade to ultimate design luminosity

√s=14 TeV, L~2x10^{34} cm^{-2} s^{-1}, bunch spacing 25 ns

HL-LHC Phase-2 upgrade, IR, crab cavities?

√s=14 TeV, L=5x10^{34} cm^{-2} s^{-1}, luminosity leveling

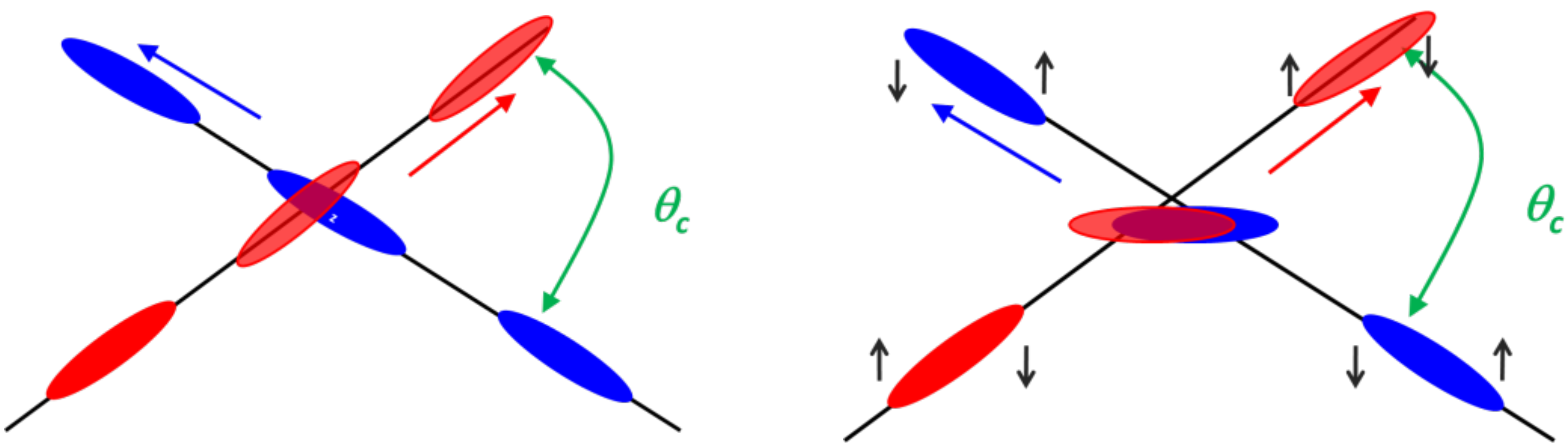


HL-LHC: crab cavities bunch rotation

- LHC luminosity is currently limited by geometrical overlap, due the crossing angle (285μrad) between beams.

$$\mathcal{L} = \frac{N_1 N_2 f N_b}{4\pi\sigma_x\sigma_y} \qquad R(\theta) = \frac{1}{\sqrt{1 + (\frac{\sigma_s}{\sigma_x} tan\frac{\theta}{2})^2}}$$

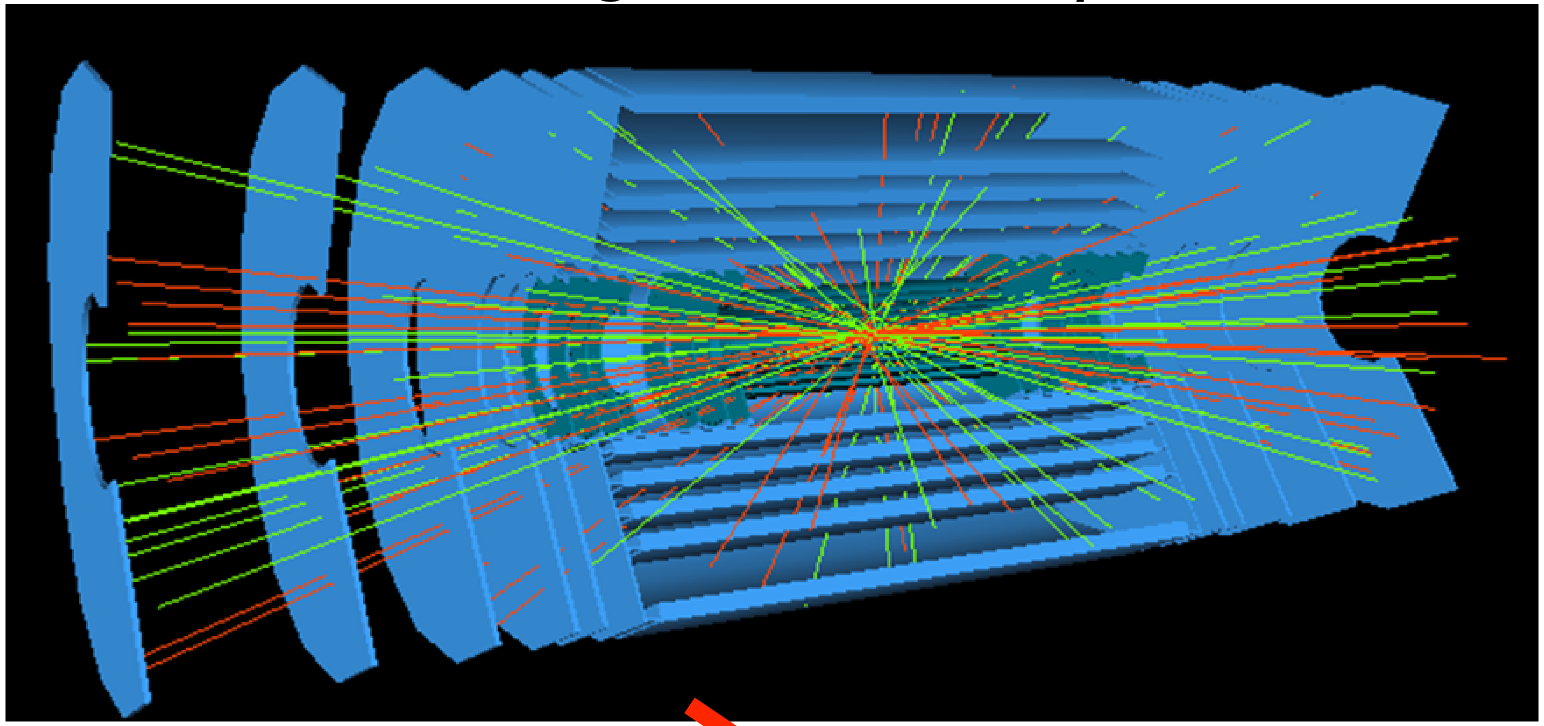
- The baseline HL-LHC will use RF ***crab cavities*** to ***rotate the bunches*** so that they collide head on:



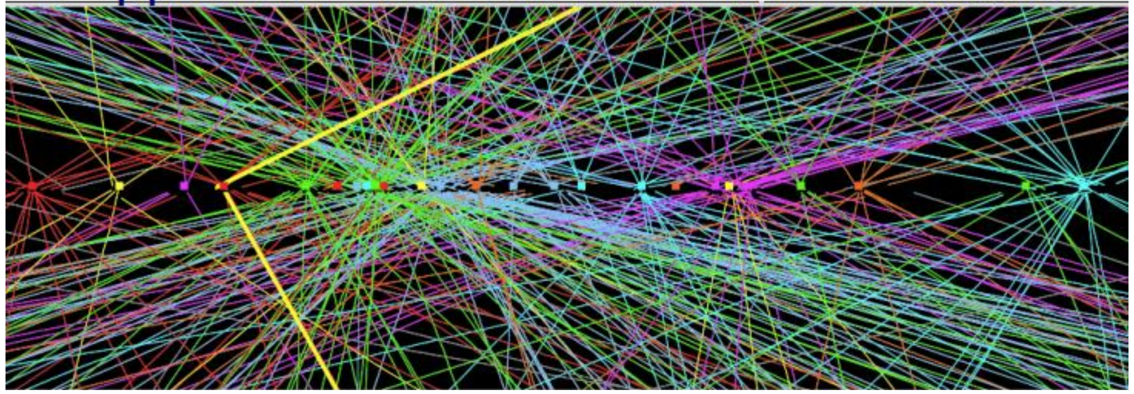
- Technique can also be used for luminosity leveling.

Living with 5x higher pile up

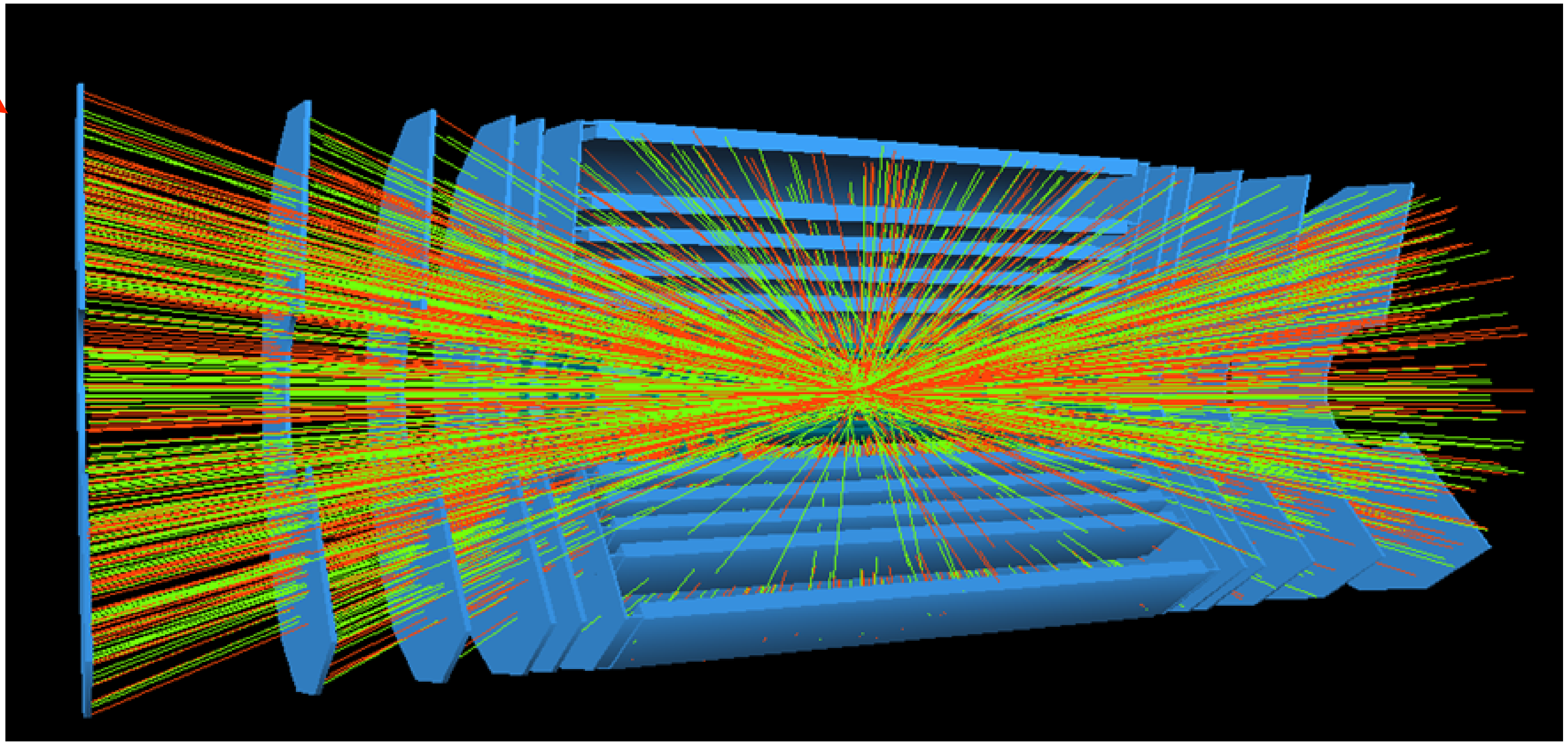
One bunch crossing in the ATLAS particle tracker:



Z→μμ event from 2012 data with 25 vertices

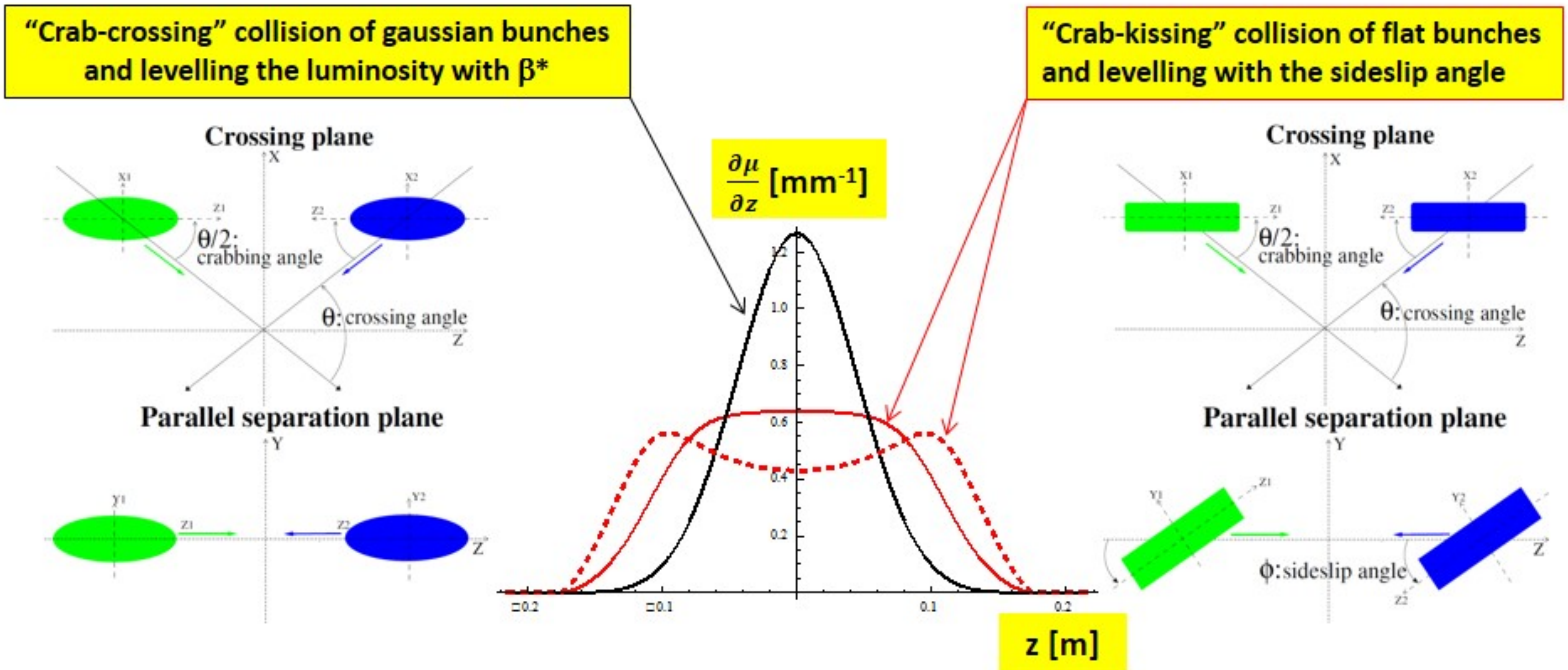


- Nominal LHC
  - ~23 primary interactions per bunch crossing.
- At High Luminosity
  - Pile up increases to ~140 vertices per bunch crossing.
  - Distribution along beam direction matters when identifying vertices



ATLAS, P.Vankov

Crab-crossing and crab-kissing

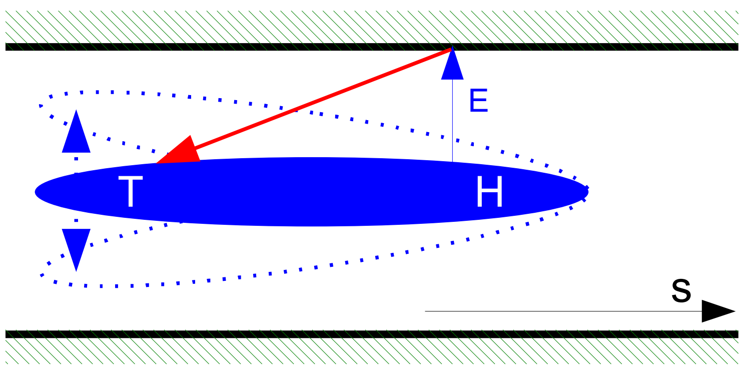


- Crab-kissing is a new approach for reducing, shaping and leveling the pile up line-density.
- 0.5-0.6 event /mm is within reach for the HL-LHC.

- ***To optimize the performance of the crab-cavities for HL-LHC, a new diagnostic tool is under development to monitor the bunch rotation.***

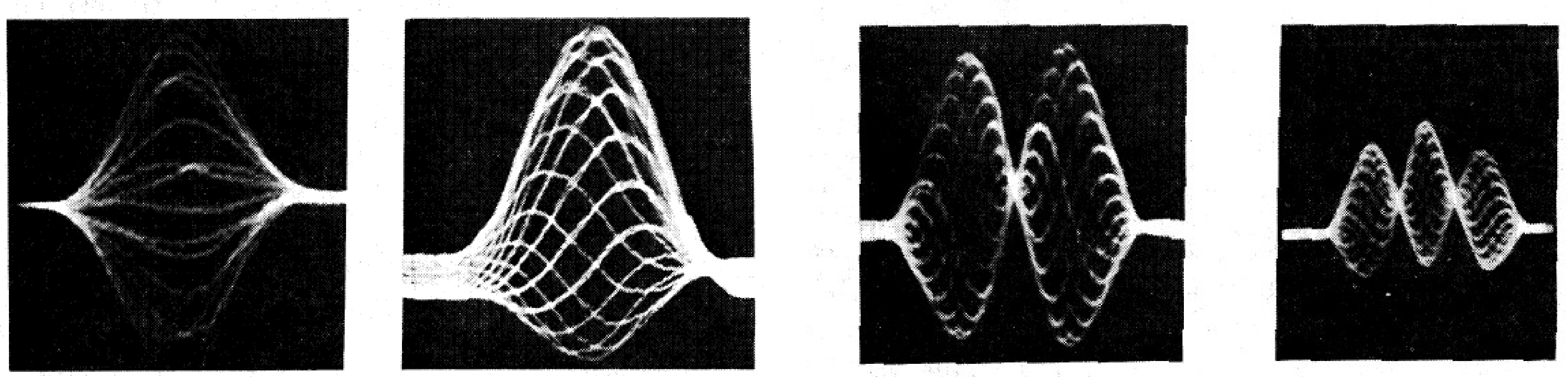
Intra-bunch diagnostics at the LHC

- The EO-BPM project started from an initiative to upgrade the CERN head-tail monitors for the SPS and LHC.
- Head-tail monitors are the main instruments to visualize and study beam instabilities as they occur.



transverse

e.g. J. Gareyte, "Head-Tail Type Instabilities in the PS and Booster", CERN, 1974

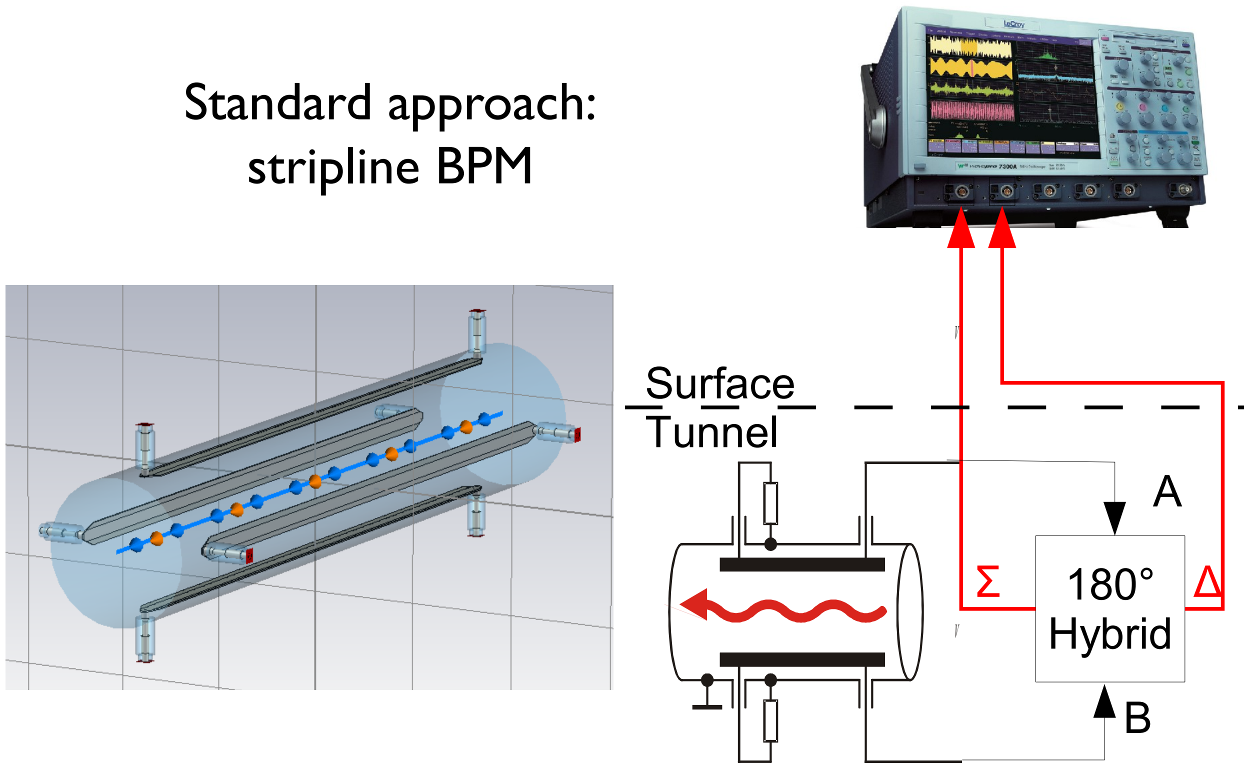


a) mode m = 0, χ = 0   b) m = 0, χ = 2.3 radians   b) m = 1, χ = 6.9 radians   d) m ≈ 2, χ = 6.9 radians

- The standard head-tail monitors are based on stripline BPMs and fast sampling oscilloscopes.
- However they only offer a bandwidth up to a few GHz, limited by the pick-up, cables and acquisition system.
- A new technology is needed:

electro-optic crystal at the pick-up

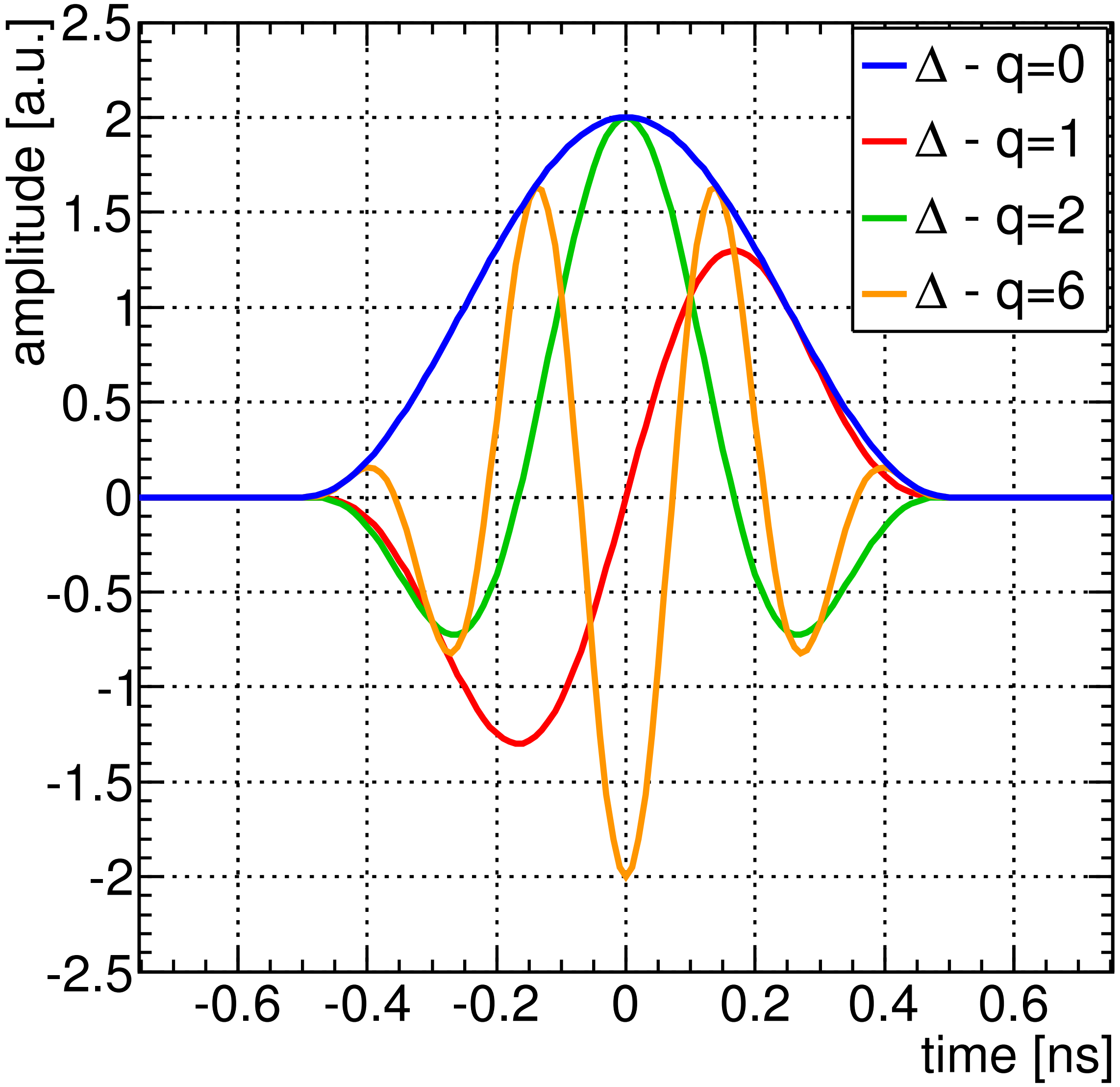
Standard approach: stripline BPM

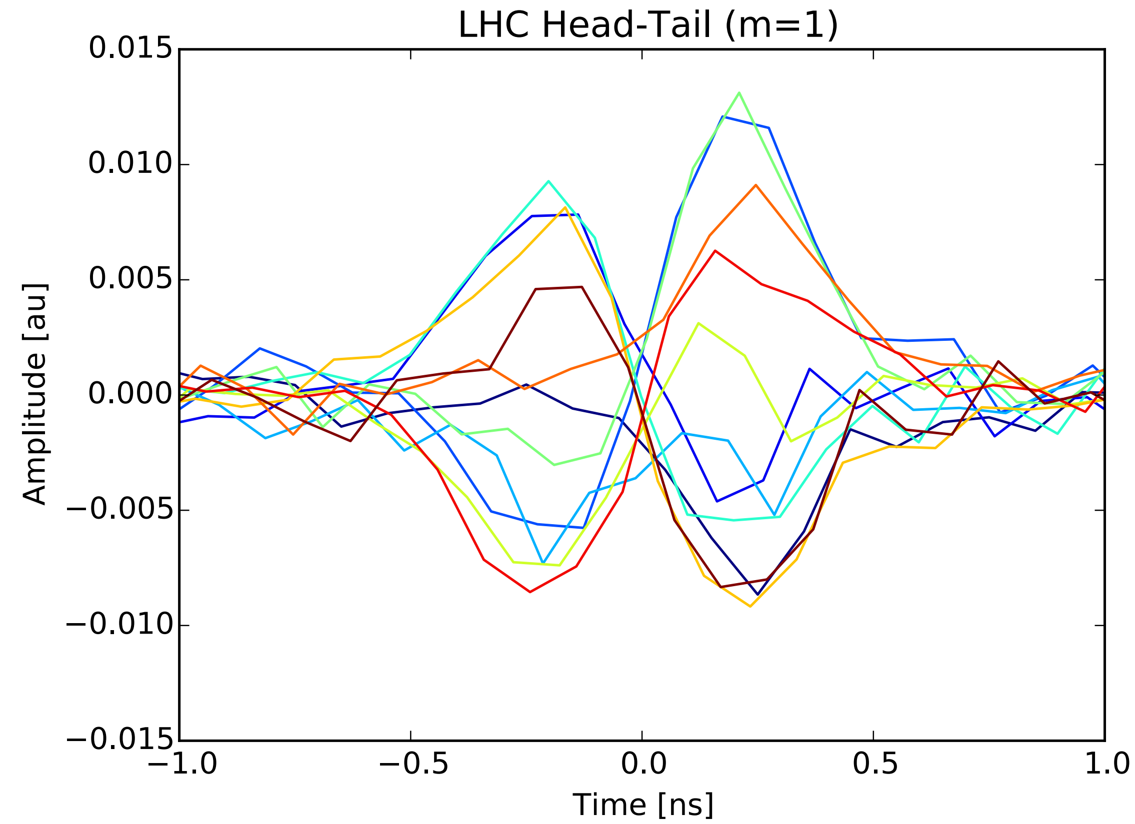


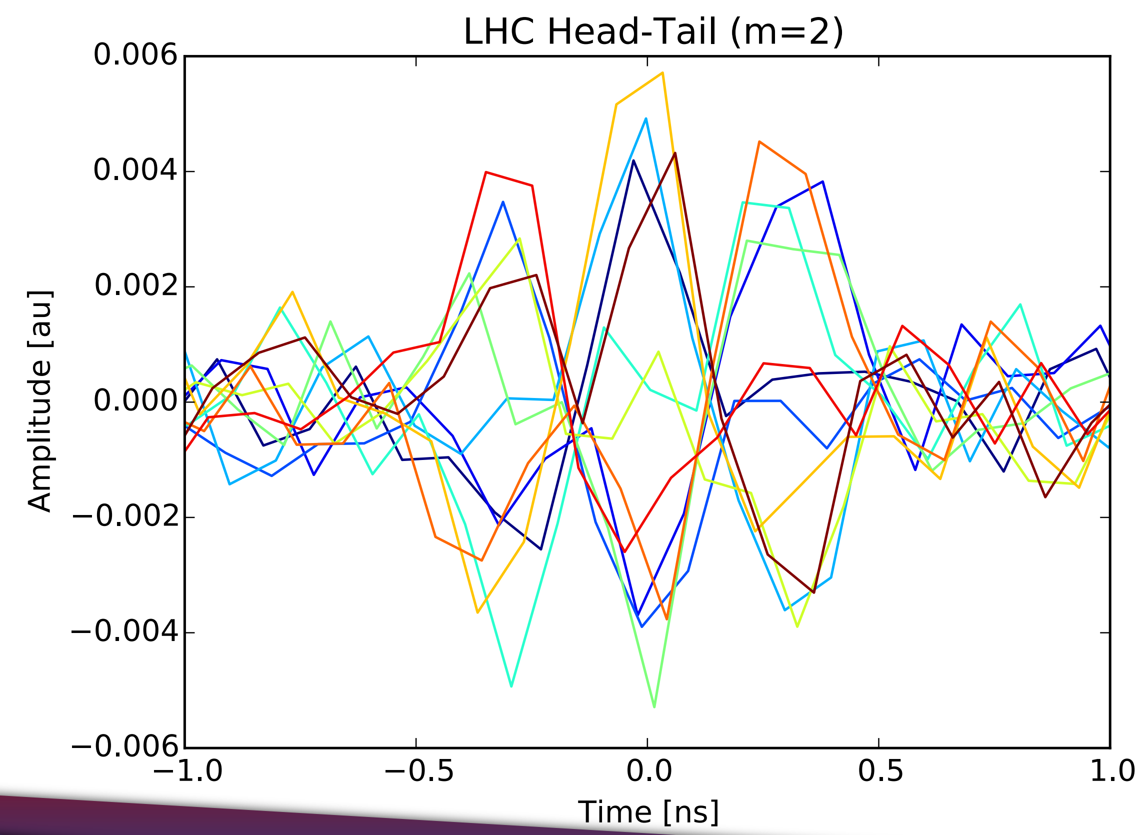
Instability modes at the LHC

August 2015 LHC measurements by T. Levens

- The present HT monitors reveal low order instability modes at the LHC:



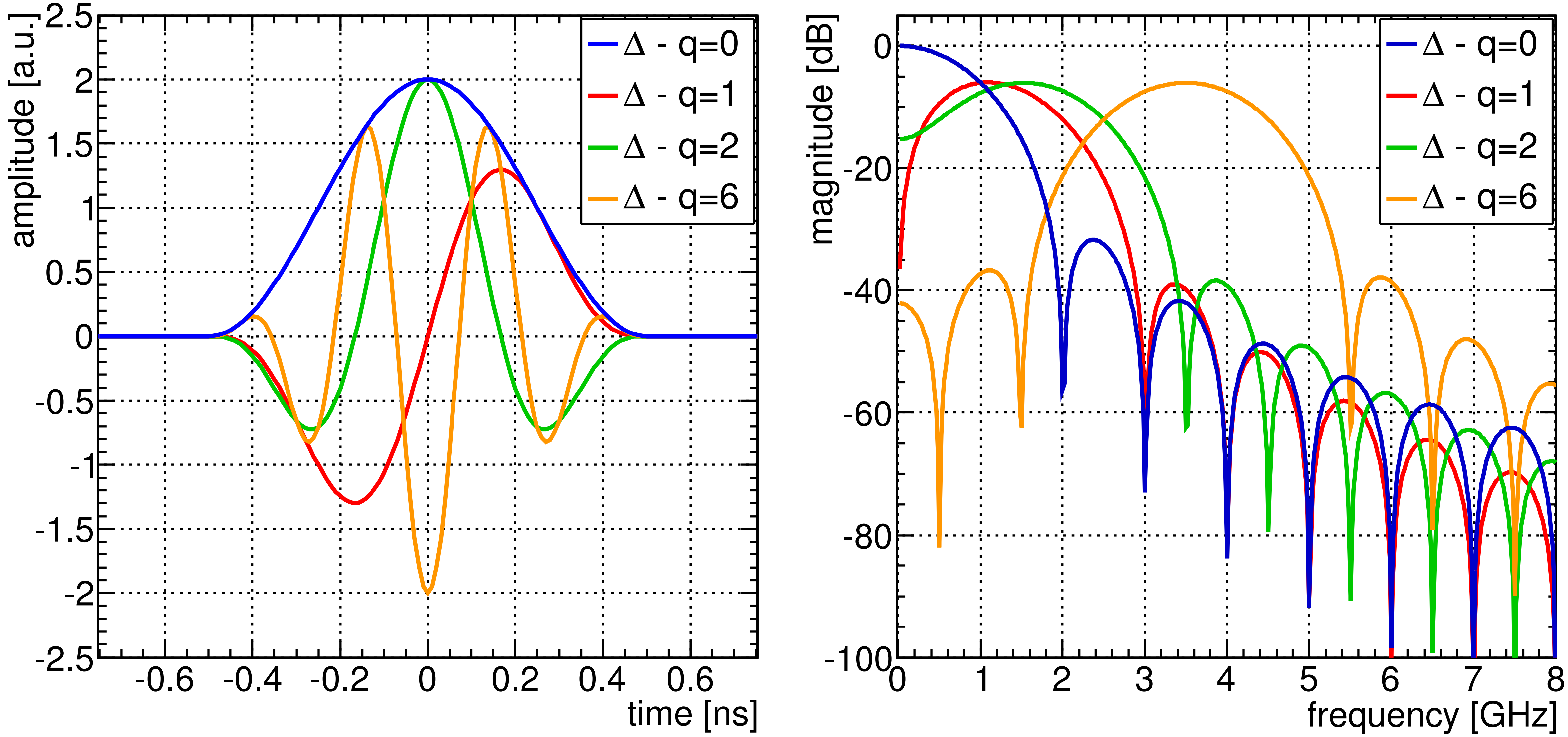




Courtesy of Ralph Steinhagen,
Multiband instability monitor, IBIC2013 TUBL3

Instability modes at the LHC

- However, higher bandwidths are required for the highest order modes:

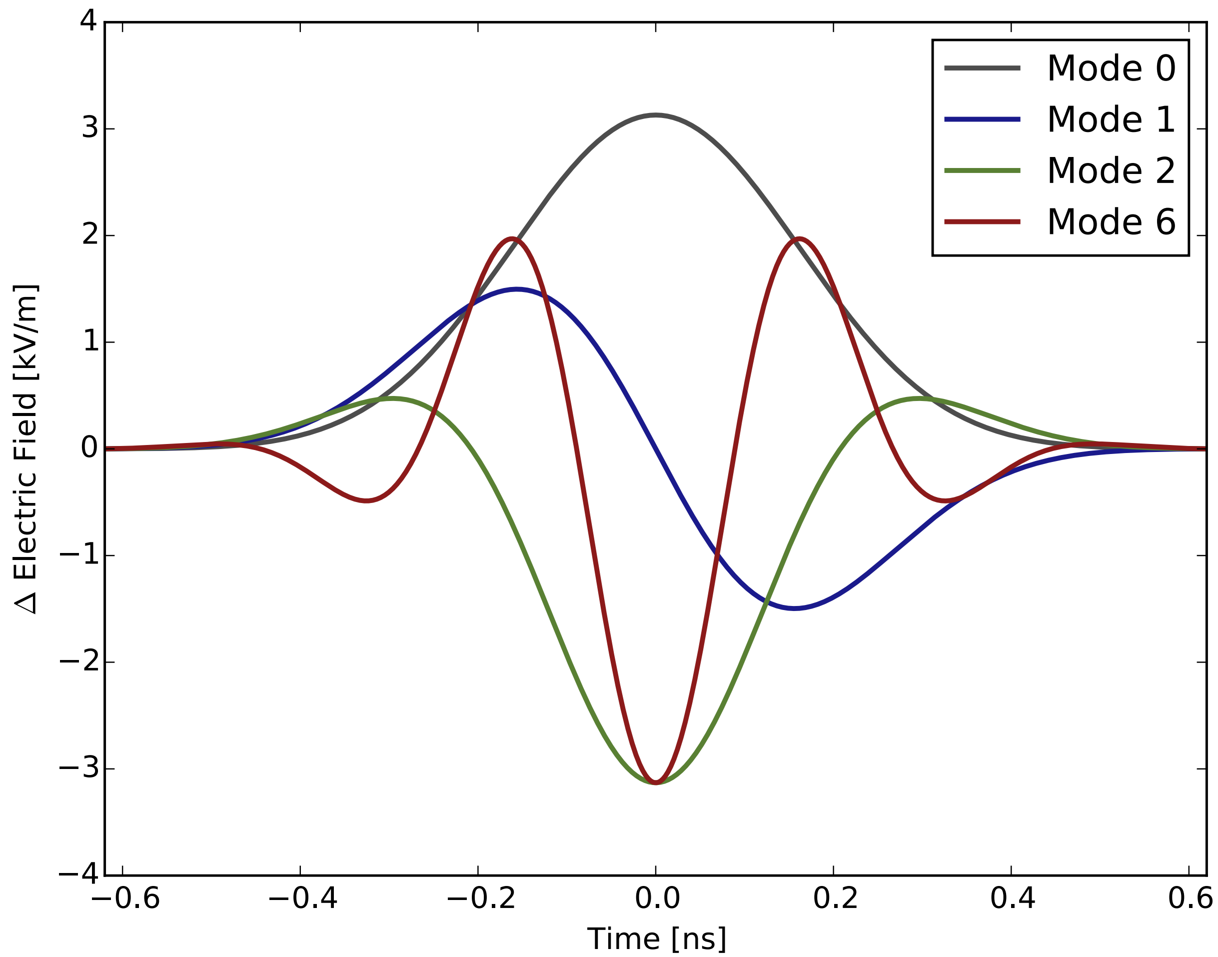


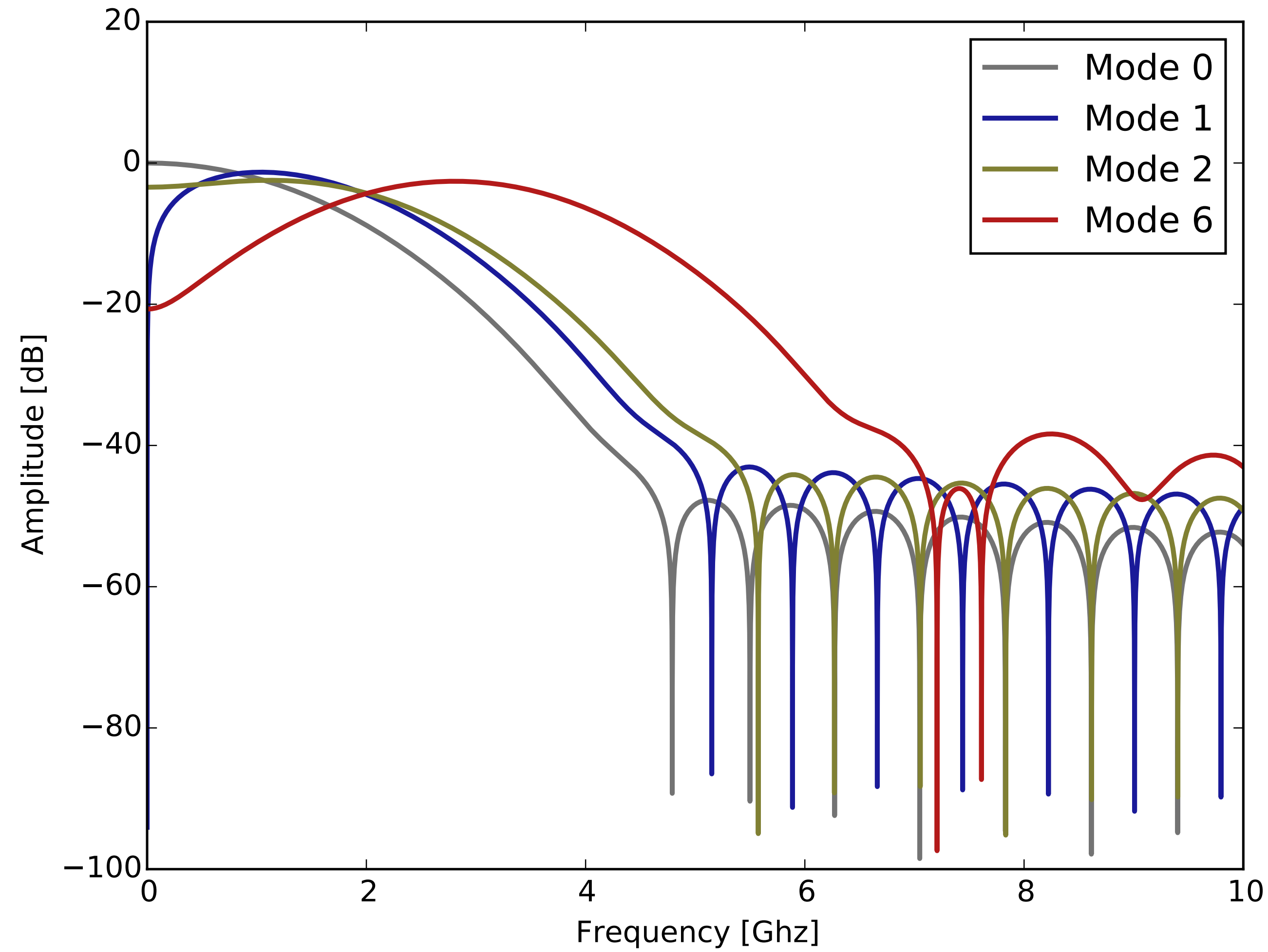
Courtesy of Ralph Steinhagen,
Multiband instability monitor, IBIC2013 TUBL3

Aim for 6 - 12 GHz bandwidth:
Electro-optic pick-ups offer
response times in the picosecond range

Instability modes at the LHC

- Synchrotron damping is overcome by RF excitation to maintain the bunch length at 1.0 – 1.2 ns.
- New bandwidth calculation assuming a Gaussian charge distribution, 4σ = 1.0 ns.



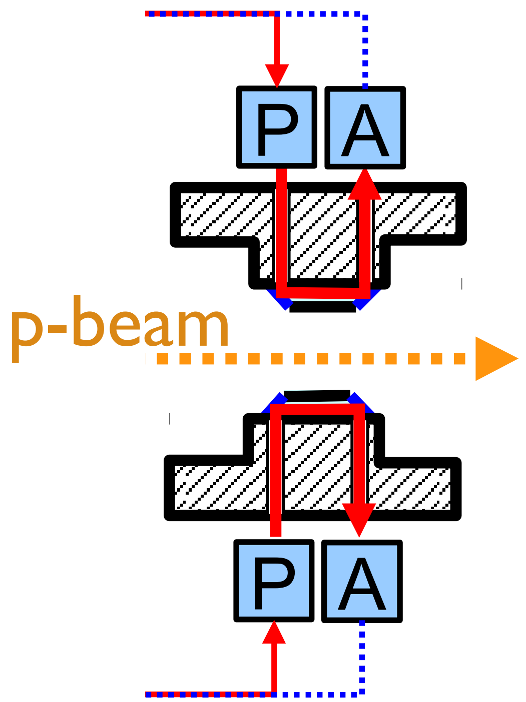


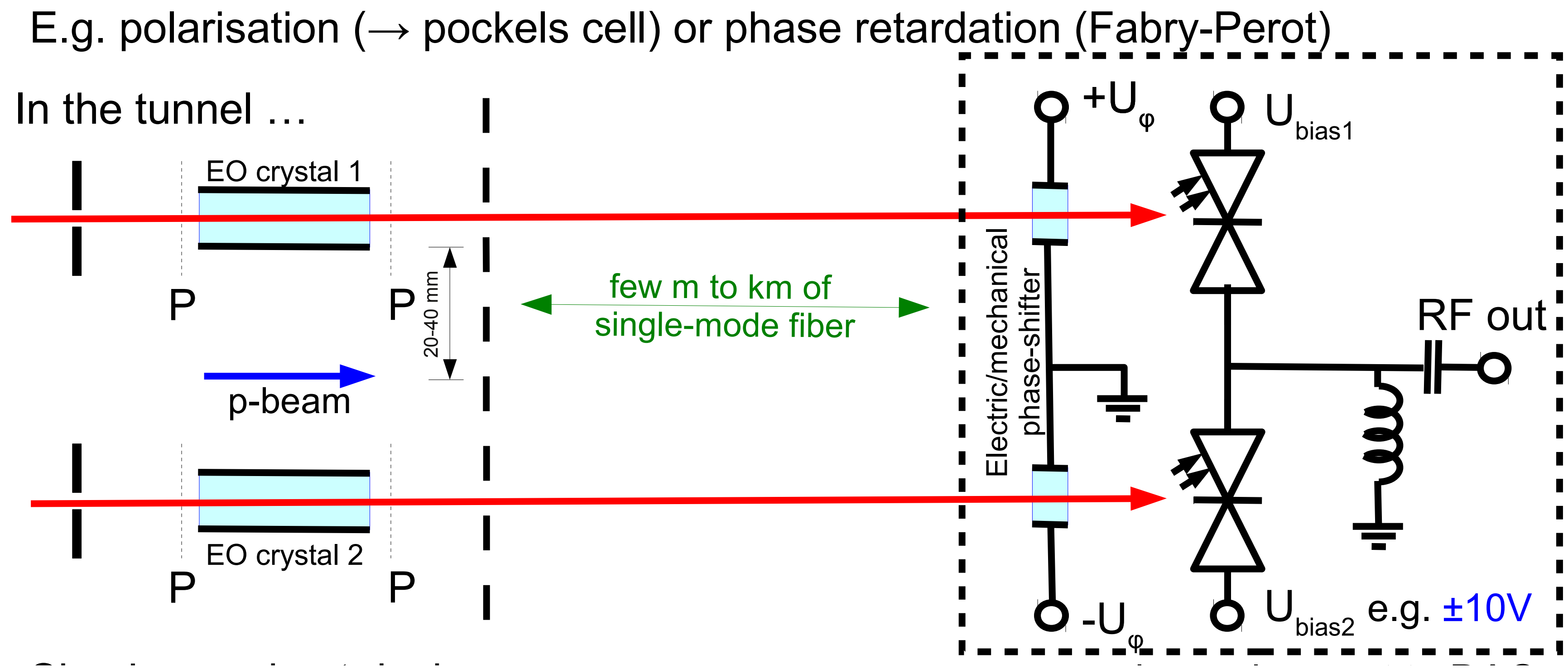
Simulations of A. Arteche

Electro-optic Beam Position Monitor

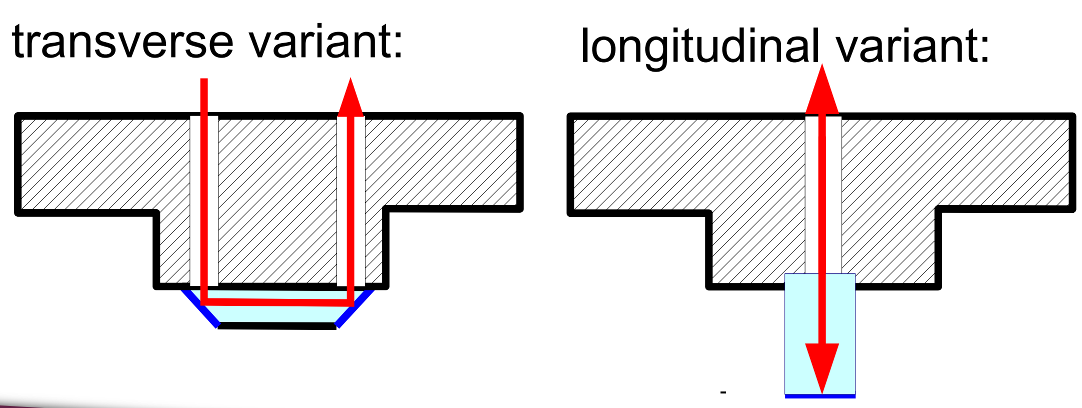
Original concept for HT monitor

R. Steinhagen



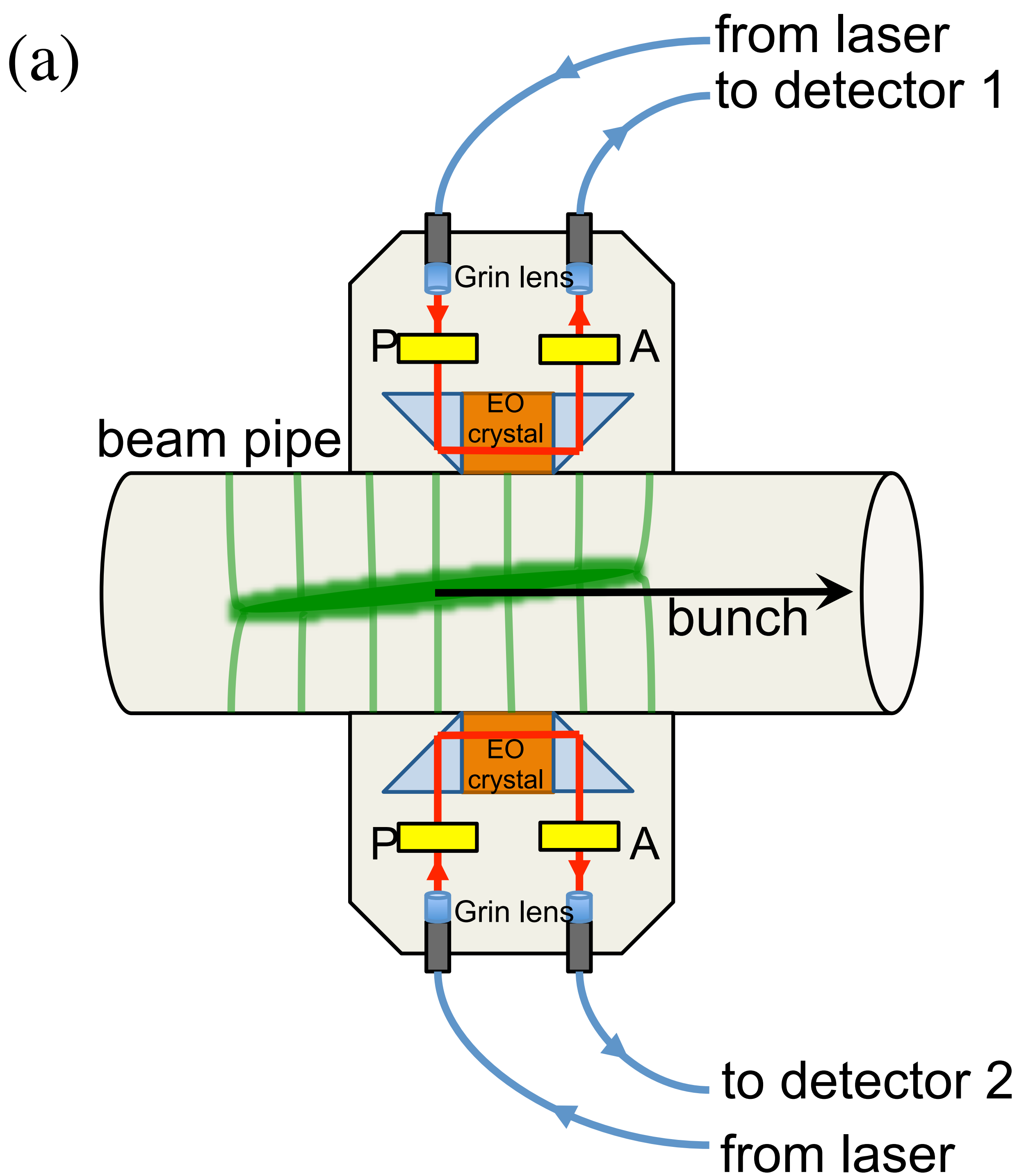


- Electro-optic crystal polarization responds to passing electric field of the bunch:
  - Can derive transverse positional information of the bunch
  - 1 ns bunch: aim for < 50 ps time resolution
  - Various pick-up configurations considered:



Polarizer-analyser configuration

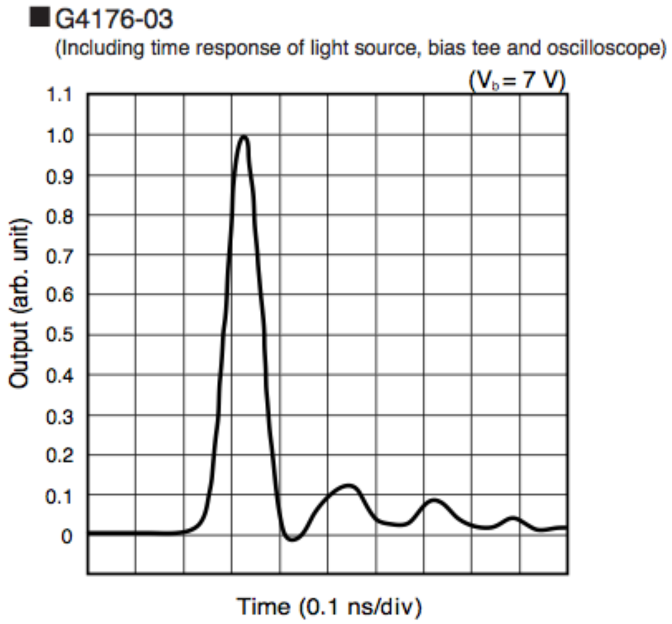
Current baseline design:

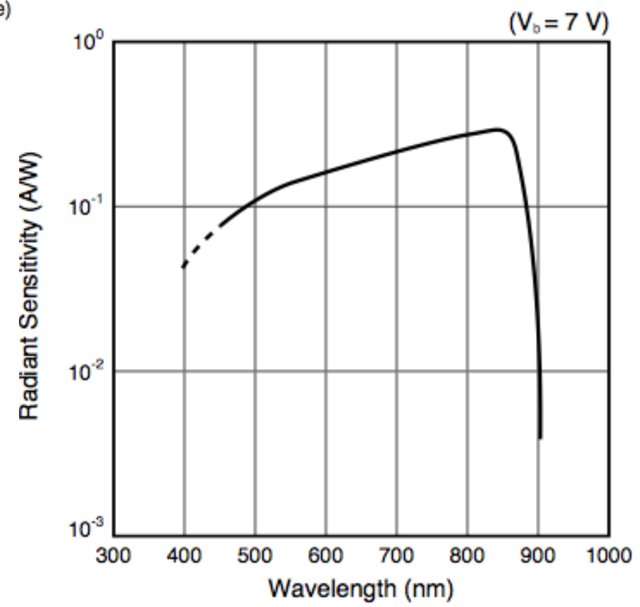


- Effectively a button BPM with pick-ups replaced by eo-crystals.
- Transverse position along the passing bunch is monitored.
- A fibre-coupled design with laser and detectors housed 160 m away from accelerator tunnel.
- Incoming light is collimated by a GRIN lens and polarized before entering the crystal.
- The electric field of passing bunch at the crystal induces a rotation in the polarization, by the linear Pockels electro-optic effect.
- Light emerging from the crystal passes through an analyser and is then fibre-coupled to the distant photodetector.

Detection and digitization

- Detection is envisaged based on Metal-Semiconductor-Metal photodetectors:
  - Rapid rise times, <30 ps; good spectral response (including IR variant); polarity independent bias, low dark current (100 pA at T=25 C).

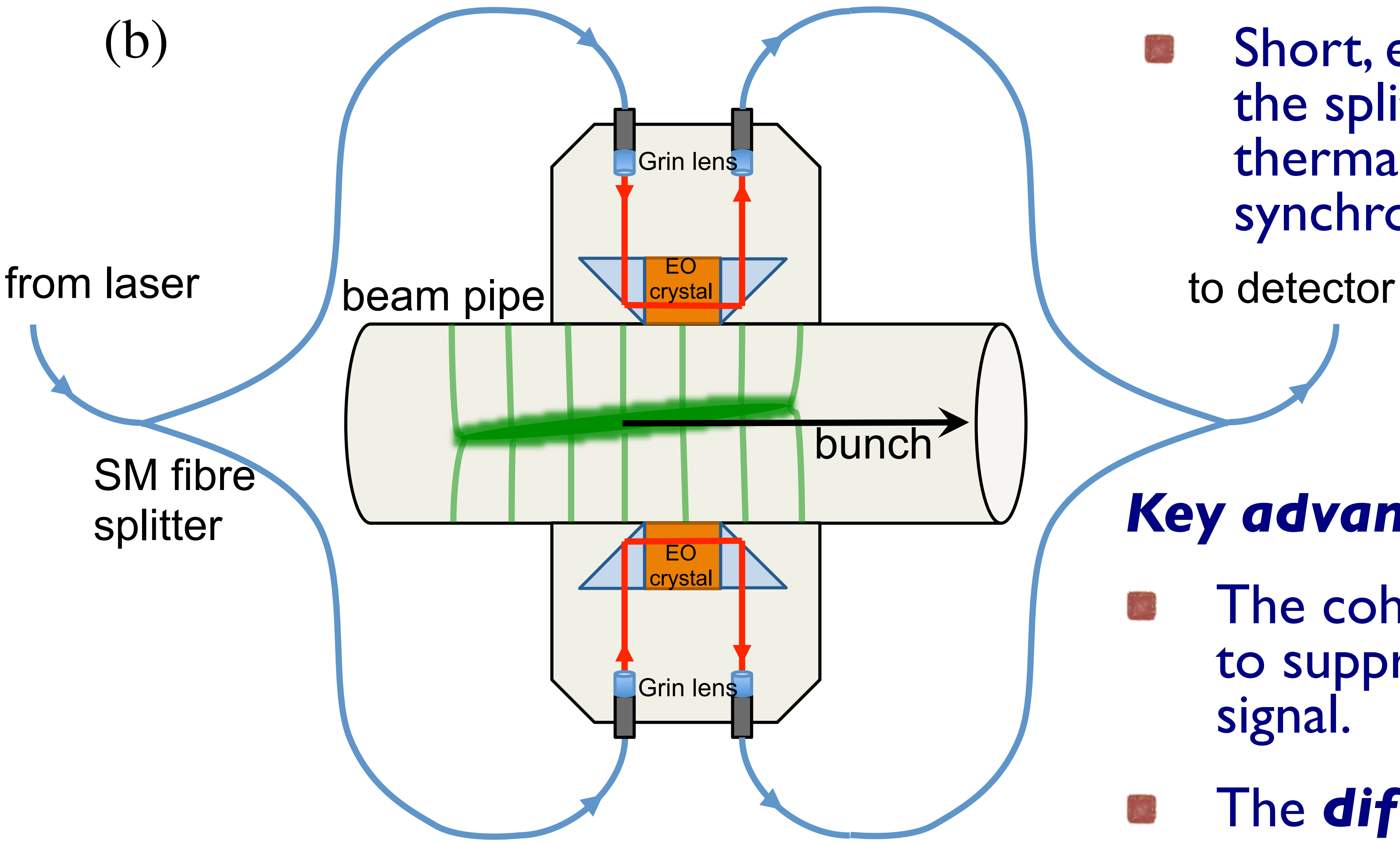




- Acquisition options:
  - Direct acquisition with a fast digitizer is possible, but at these speeds the dynamic range is typically ~6 ENOB, which limits the position resolution for the PA-setup.
  - An alternative is the Multiband-Instability-Monitor that uses frequency domain analogue pre-processing to achieve higher resolutions than direct sampling.
  - The MIM would benefit from the wide frequency coverage of the EO-BPM compared with traditional striplines.

Interferometer configuration

Proposed alternative arrangement:



- A fibre-coupled interferometer which uses phase modulation rather than a polarization analyzer.
- Short, equal fibre lengths between the splitters improve tolerance to thermal instabilities and provide synchronization between pick-ups.

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.

Simulations of EO-BPM response

- A model has been developed by A. Arteche at Royal Holloway, to reproduce the electro-optic signals generated in response to a passing relativistic bunch.

  i. A transverse offset is first applied along the Gaussian charge distributed particle bunch according to the shape of the instability mode.

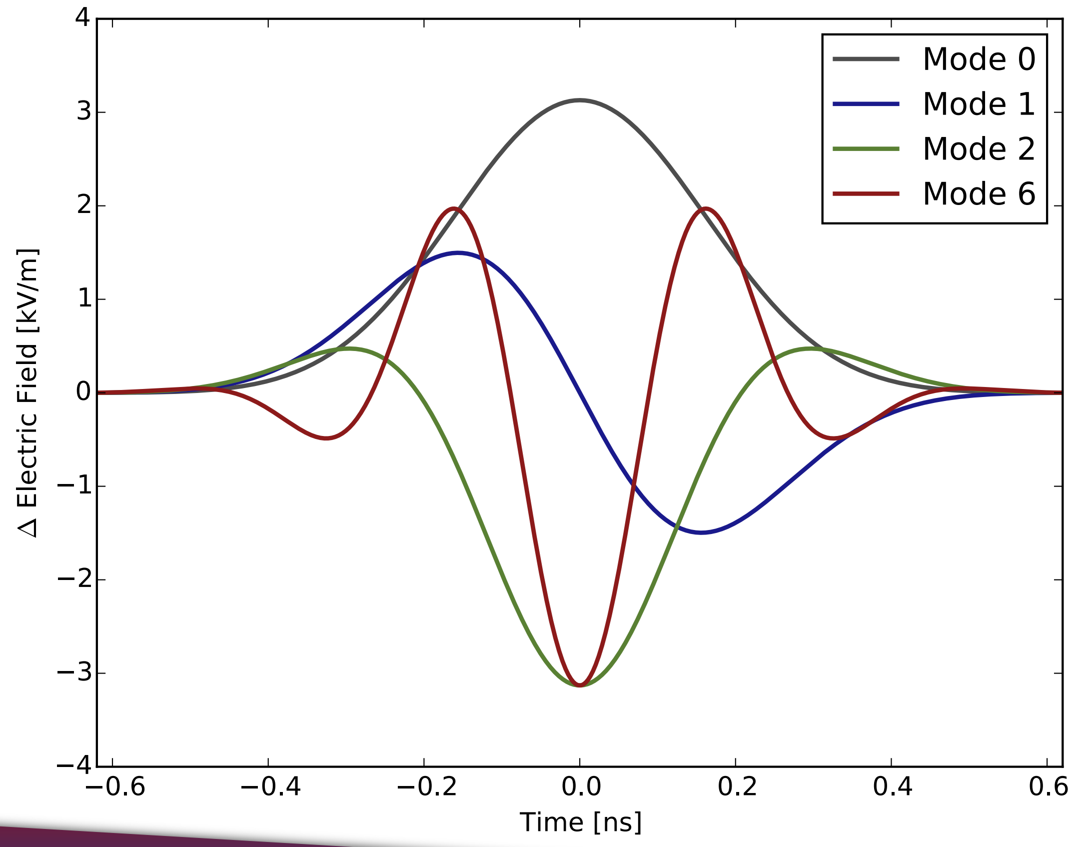
  ii. The time profile of the transverse electric field generated at the radial position of each eo-crystal is calculated for the relativistic perturbed bunch.

  iii. The electro-optic response to the electric field is calculated using the crystal parameters and wavelength, for each optical configuration.

  iv. A simple difference signal is calculated for the polarizer-analyser setup, or the interference signal is calculated.

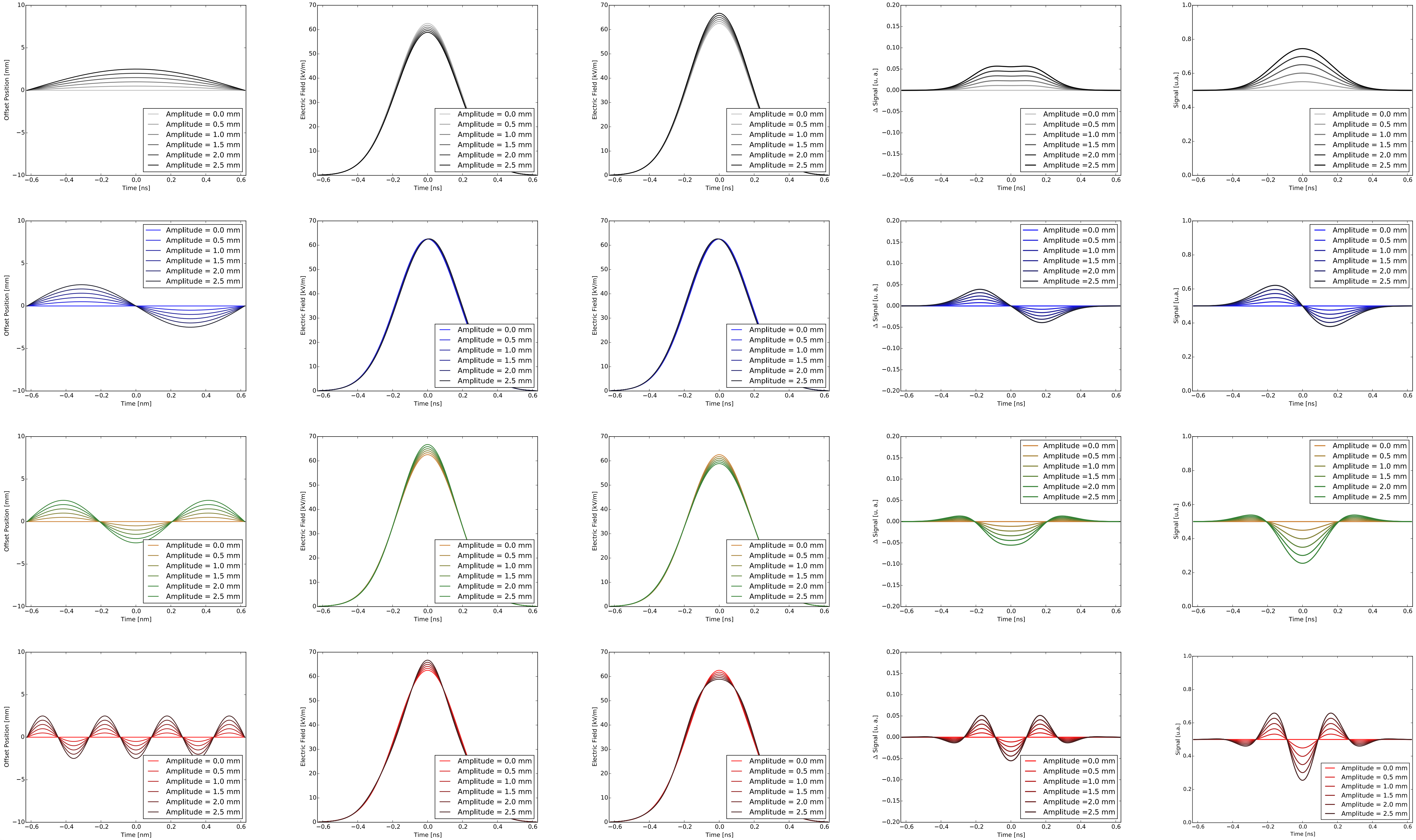
Input parameters

LHC bunch intensity	1.15×10^{11}	protons per bunch
Bunch length 4σ	1.0	ns
SPS beam energy	450	GeV
Instability modes	0, 1, 2 & 6	
Instability amplitude	0 to 2.5	mm
Pick-up radius	40	mm
Laser wavelength	632.8	nm
Crystal type	$LiNiO_3$	[also $LiTaO_3$]
Crystal length	1, 5, 10, **20**	mm



Simulations of EO-BPM response

a) Transverse offset | *b) E-field at left pick-up* | *c) E-field at right pick-up* | *d) P-A: (R-L) difference signal* | *e) Interferometer: direct signal*



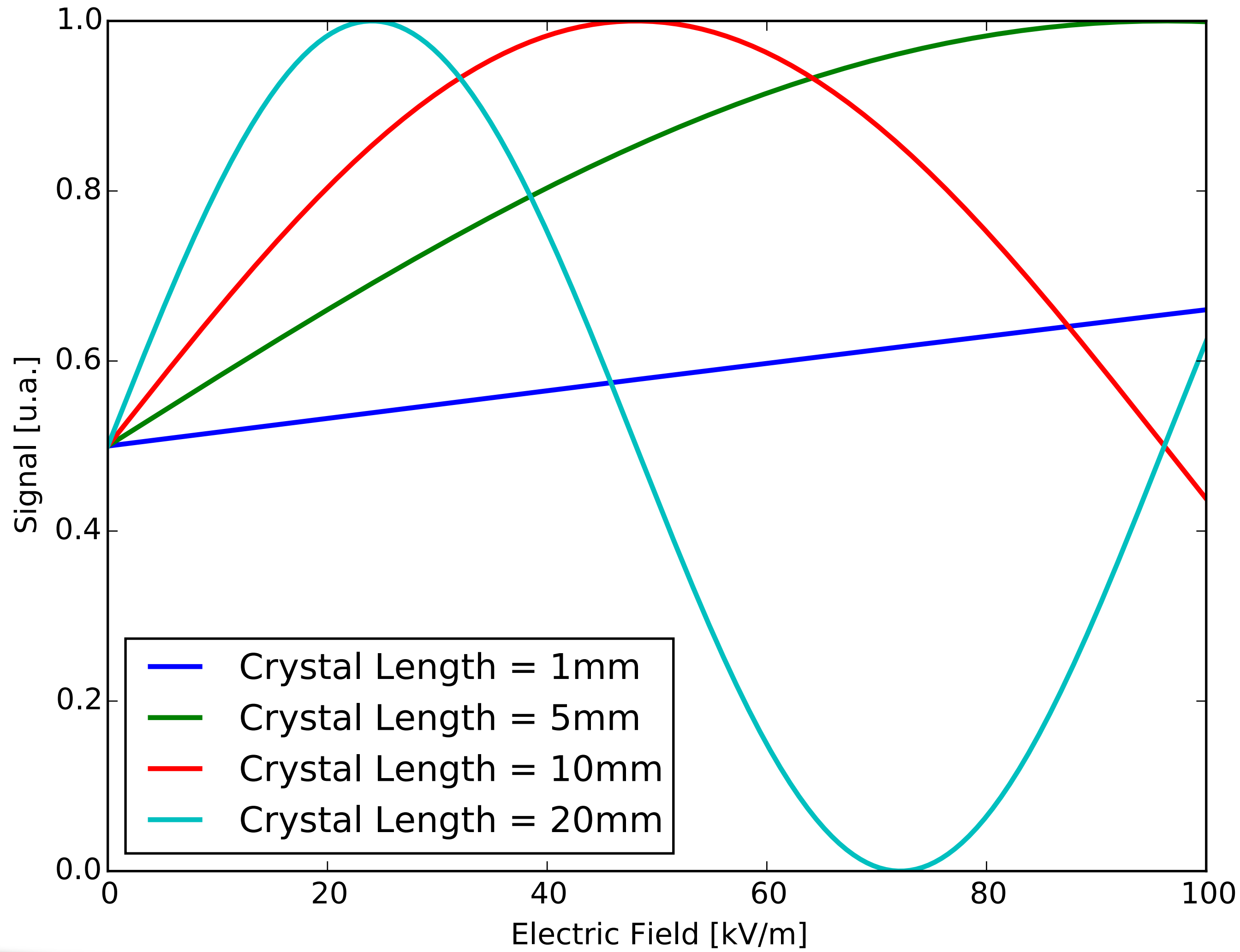
Simulations of EO-BPM response

Observations from simulation studies:

- Both optical configurations are sensitive to the instability modes.
- In the P-A setup, the detector must capture the full Gaussian signal of the passing charged bunch. Σ and Δ derived in processing electronics.
- The interferometer signal is directly sensitive to the difference Δ signal.

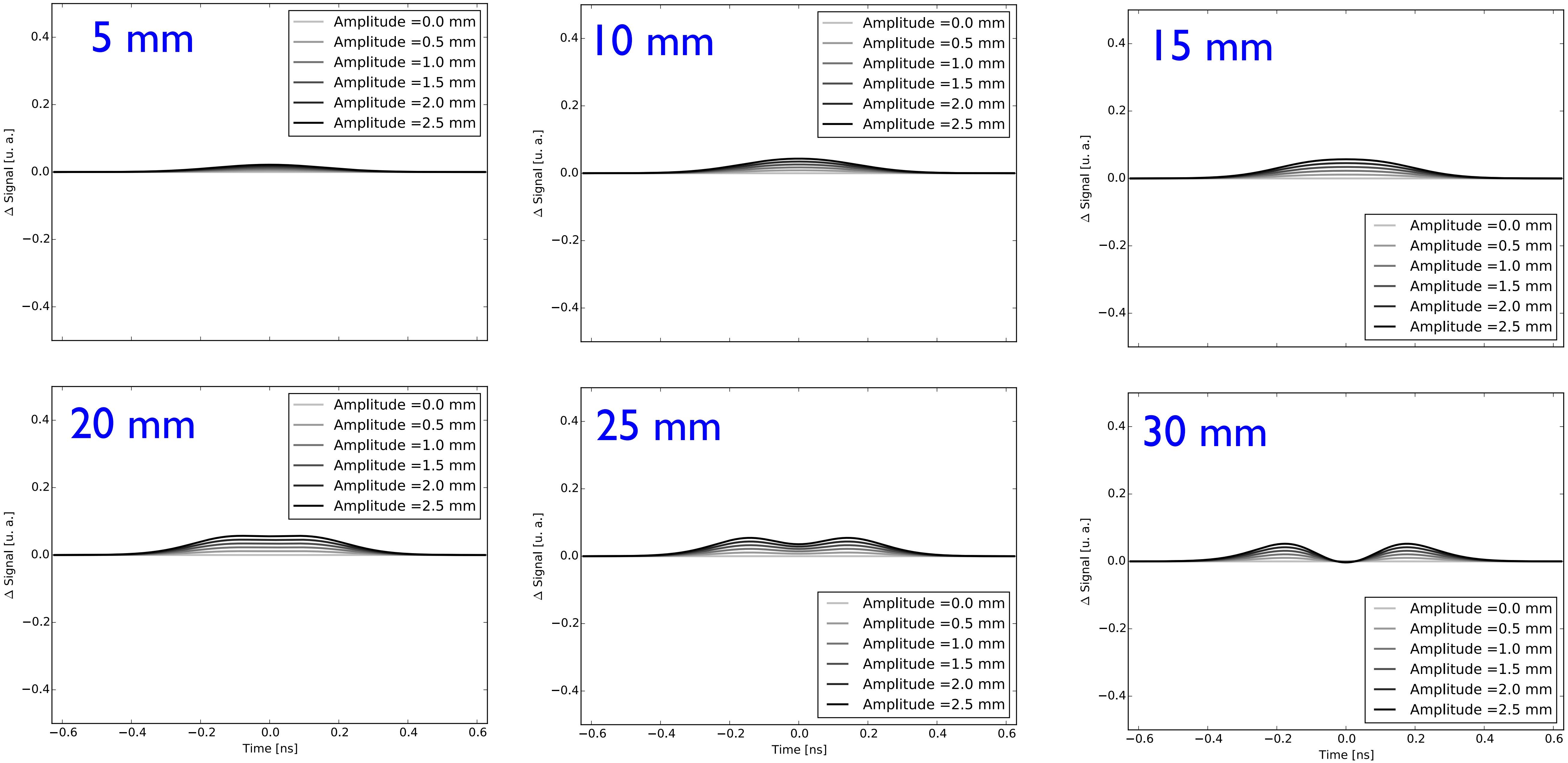
Effect of crystal length:

- Lengthening the crystal increases the sensitivity to the electric field.
- Must select an appropriate linear range of the sinusoidal transfer function:



Simulations of EO-BPM response

Crystal length study shows effect of the sinusoidal transfer function between the applied voltage and intensity. For crystal lengths of 20mm and above, the response of the P-A setup becomes very non-linear.

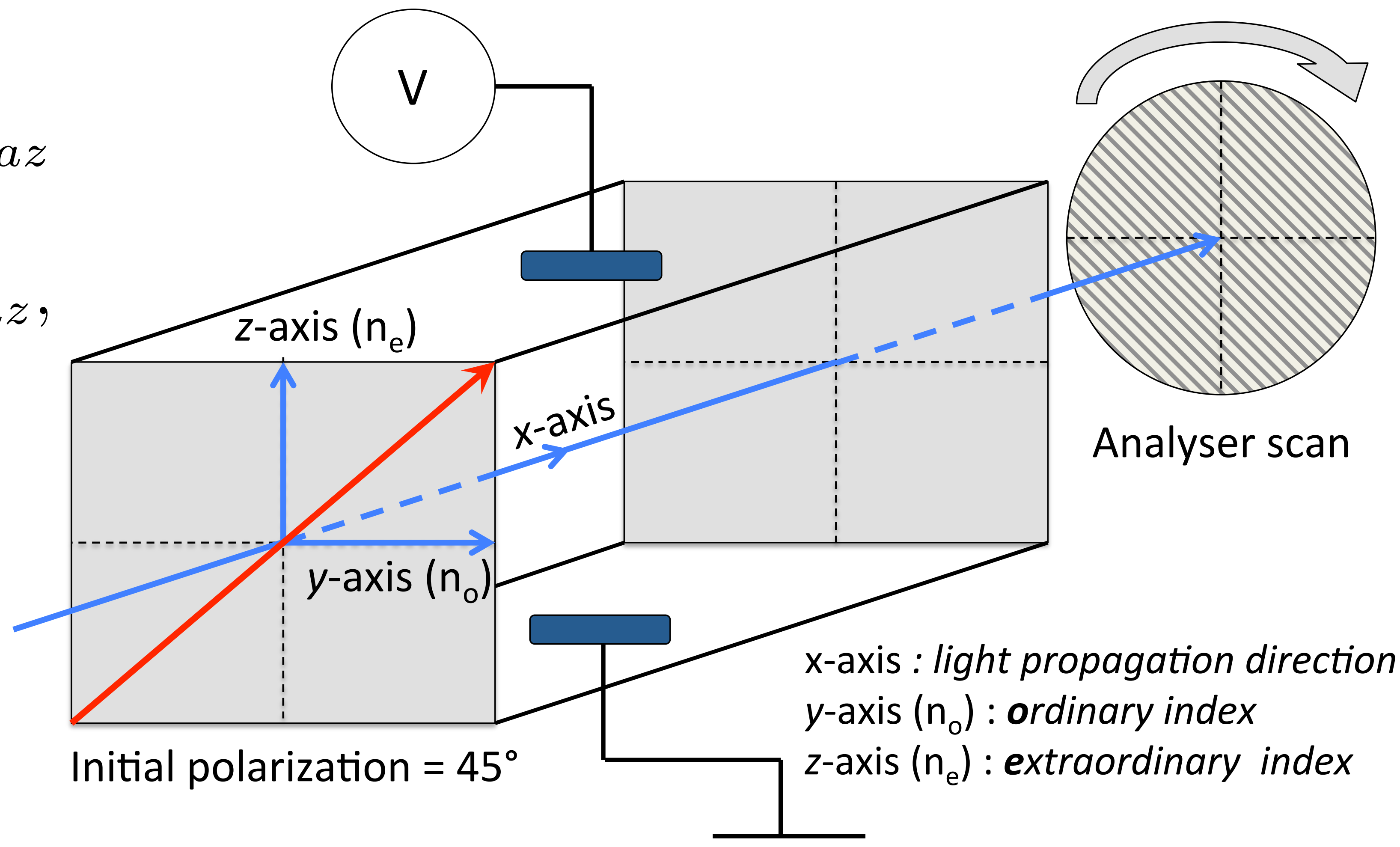


Crystal Choice and Characterisation

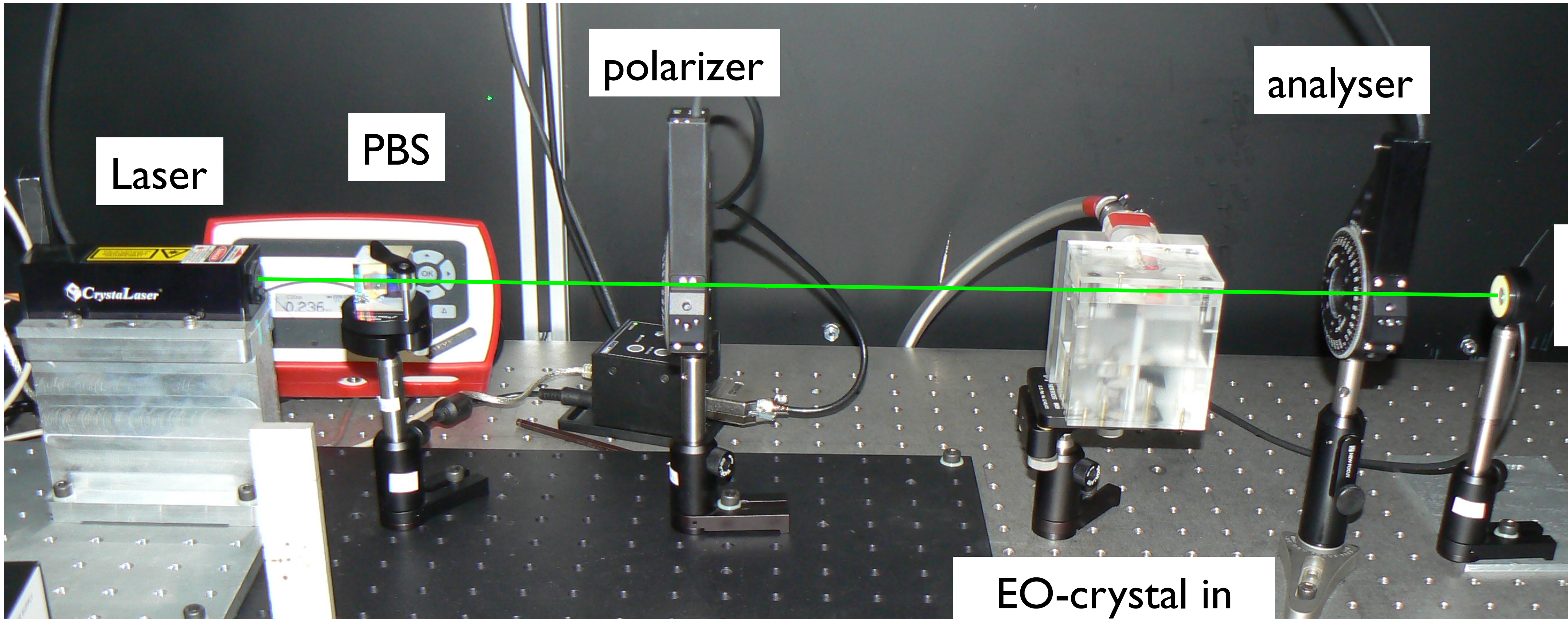
- Crystals of $LiNiO_3$ and $LiTaO_3$ have been characterised with a HV modulator and optical test stand at Royal Holloway.
  - HV is applied across a Z-cut crystal with light propagating in the X direction.
  - Polarizer at 45 degrees and analyser at 135 degrees.
  - The voltage induces a rotation in the polarization axis of light emerging from the crystal.

$$n'_y = n_o - \frac{1}{2} n_o^3 r_{13} E_{az}$$

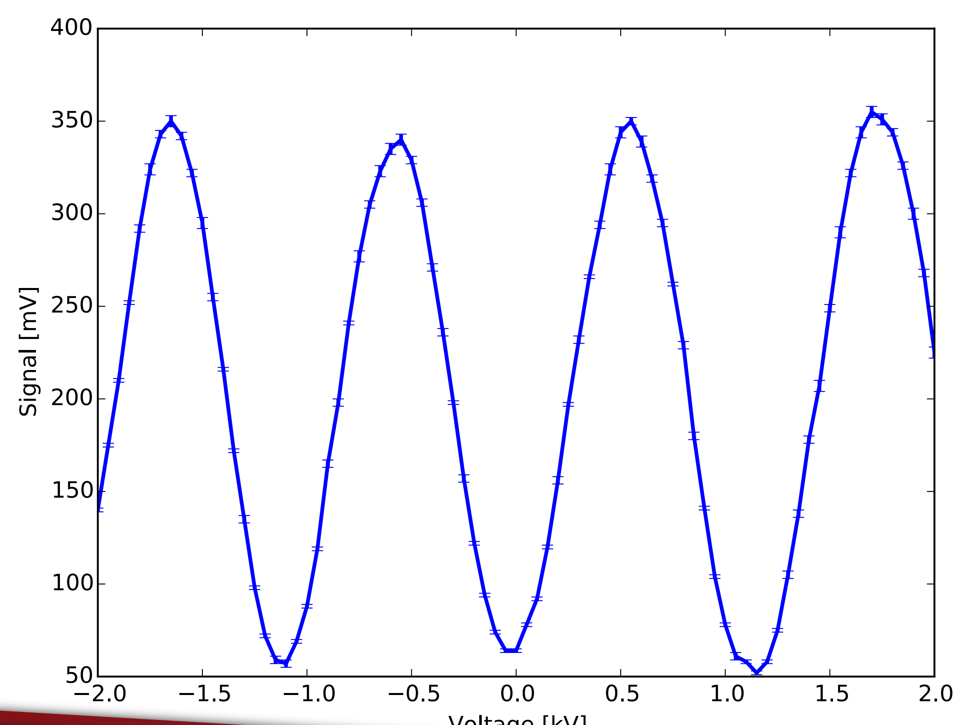
$$n'_z = n_e - \frac{1}{2} n_e^3 r_{33} E_{az},$$

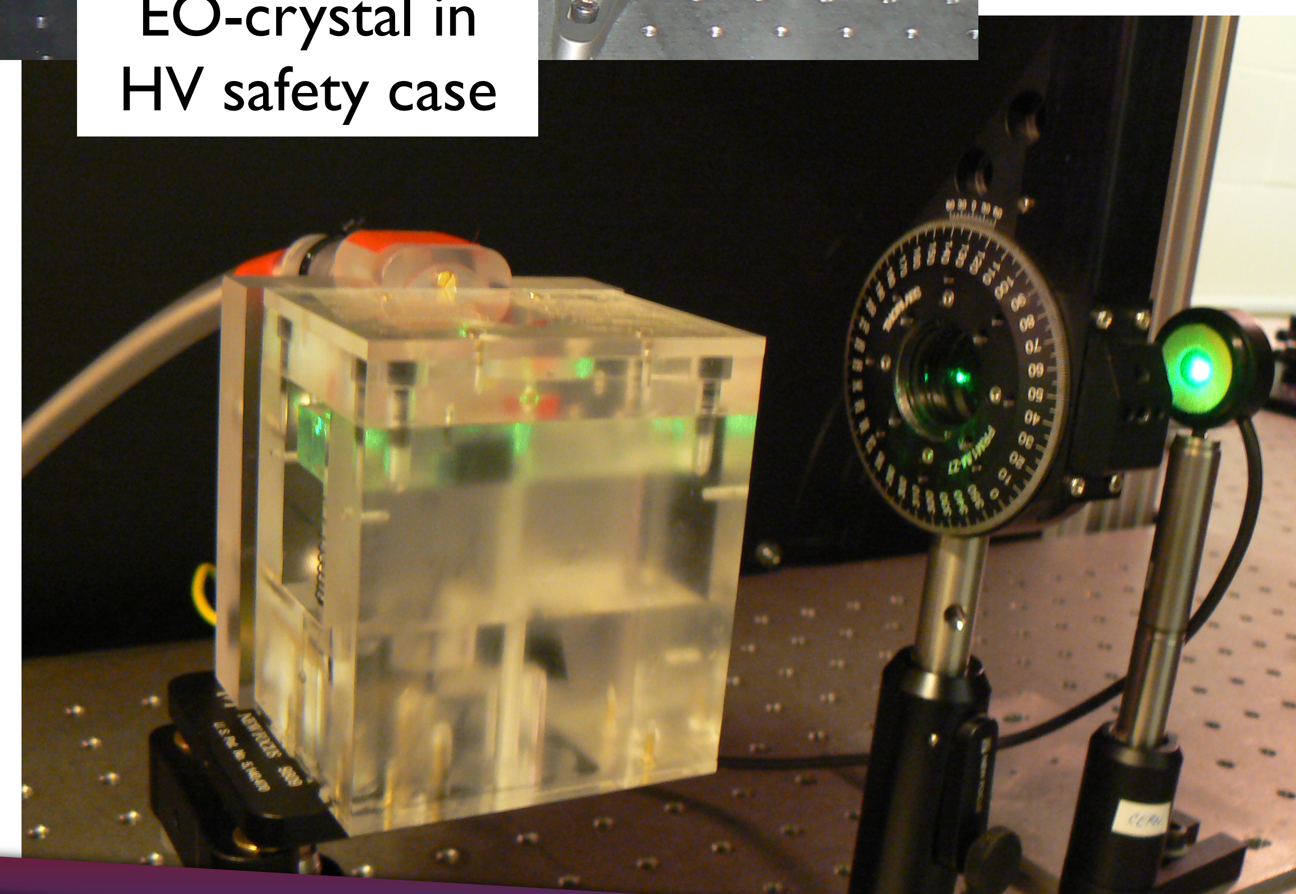


Optical test stand at RHUL

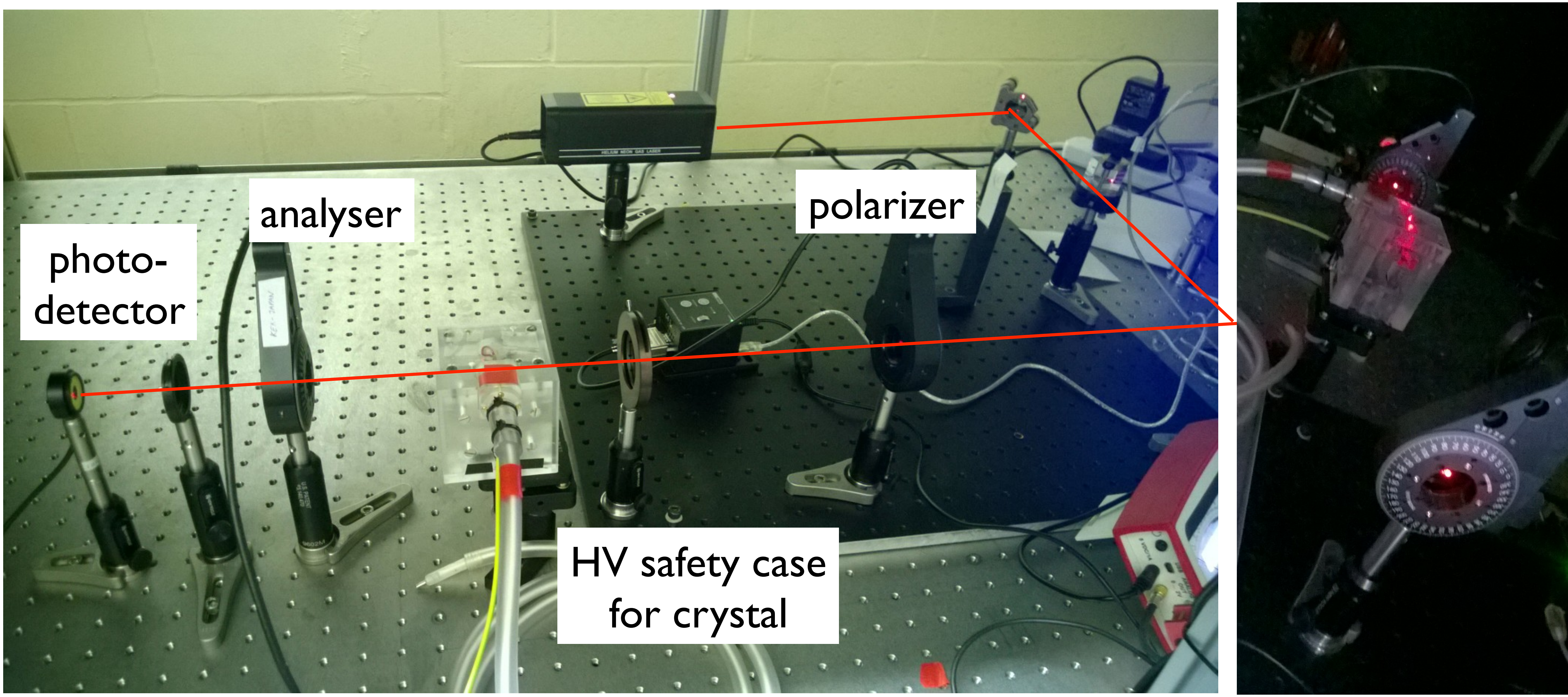


Tests at $\lambda = 532$nm, for z=20mm $LiNiO_3$ to validate setup with J. Doherty's earlier CERN student study.





Optical test stand at RHUL

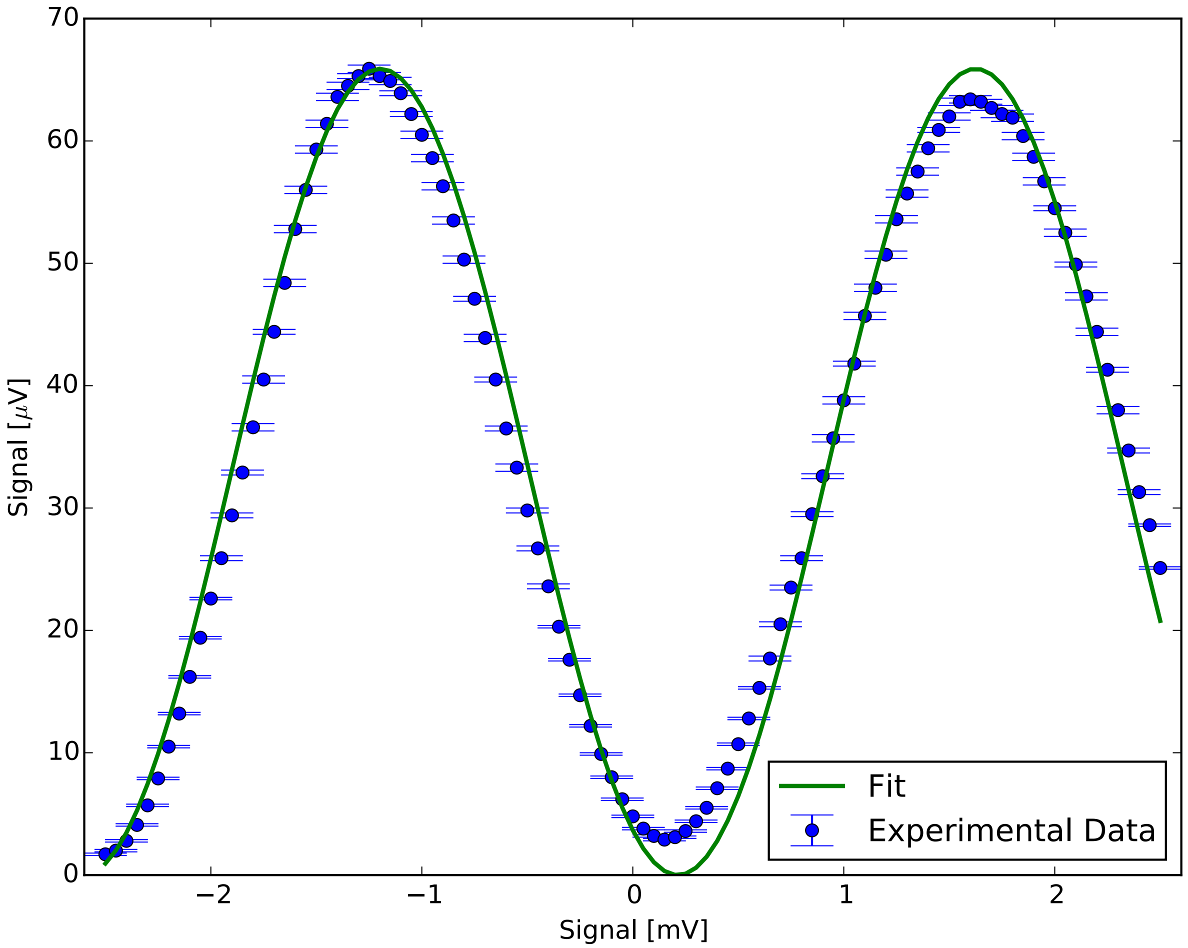


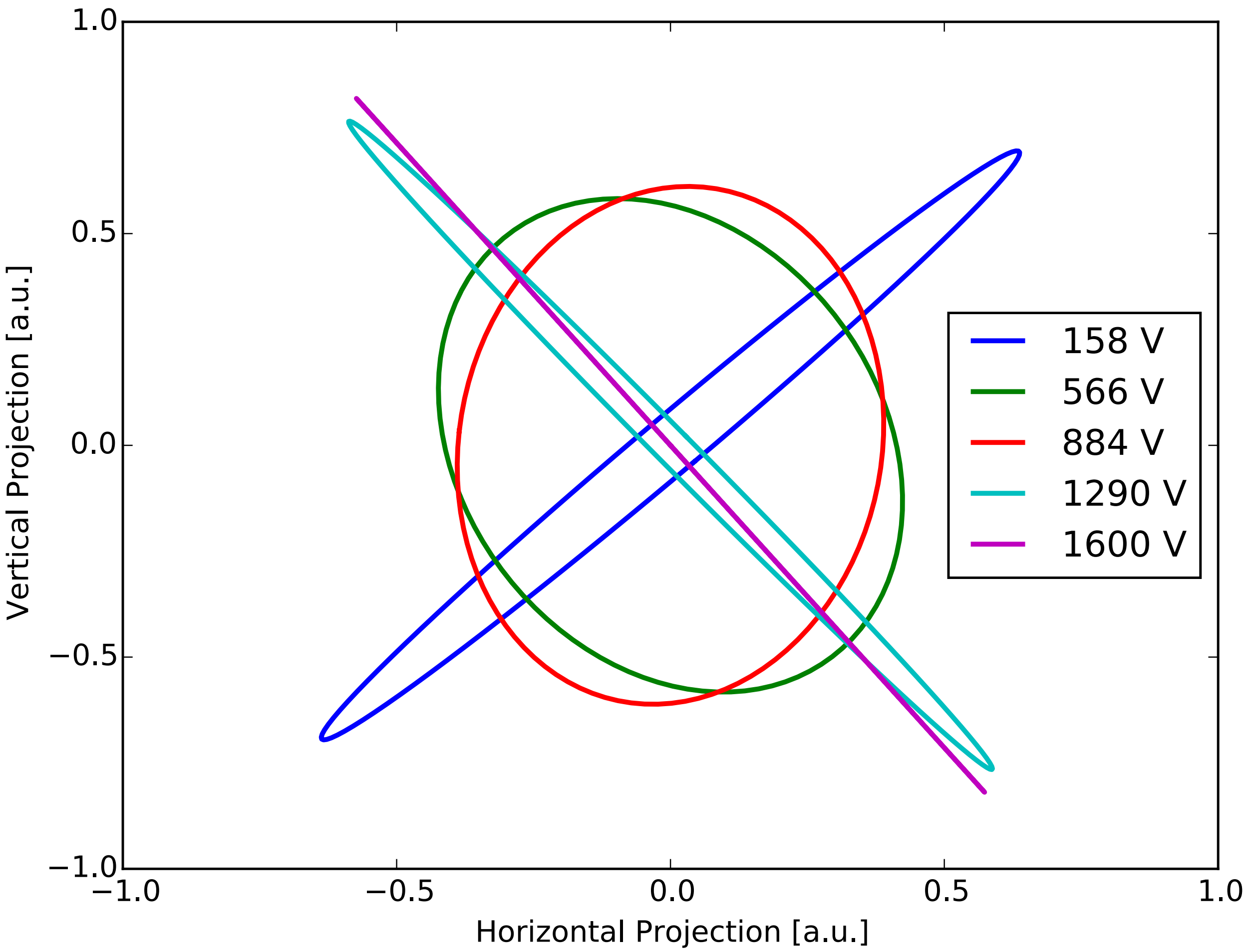
- Photorefractive effect dominates at 532 nm, even with MgO doped $LiNiO_3$.
- Instead use HeNe laser at 632.8nm. We want λ short due to dispersion.
- Fully automated setup: *Polarizer and analyser orientations controlled by rotation stages, enabling the polarization state at any voltage to be assessed.*

Crystal Choice and Characterisation

- HV scan for a z=5 mm, x=10 mm, MgO:LiNiO3 crystal. The polarization state at key voltages is analysed.
- The measured half wave voltage shows good agreement with the predicted value:
  - Prediction: $V_\pi = 1398.2\,\mathrm{V}$
  - Measurement: $V_\pi = 1410 \pm 19\,\mathrm{V}$

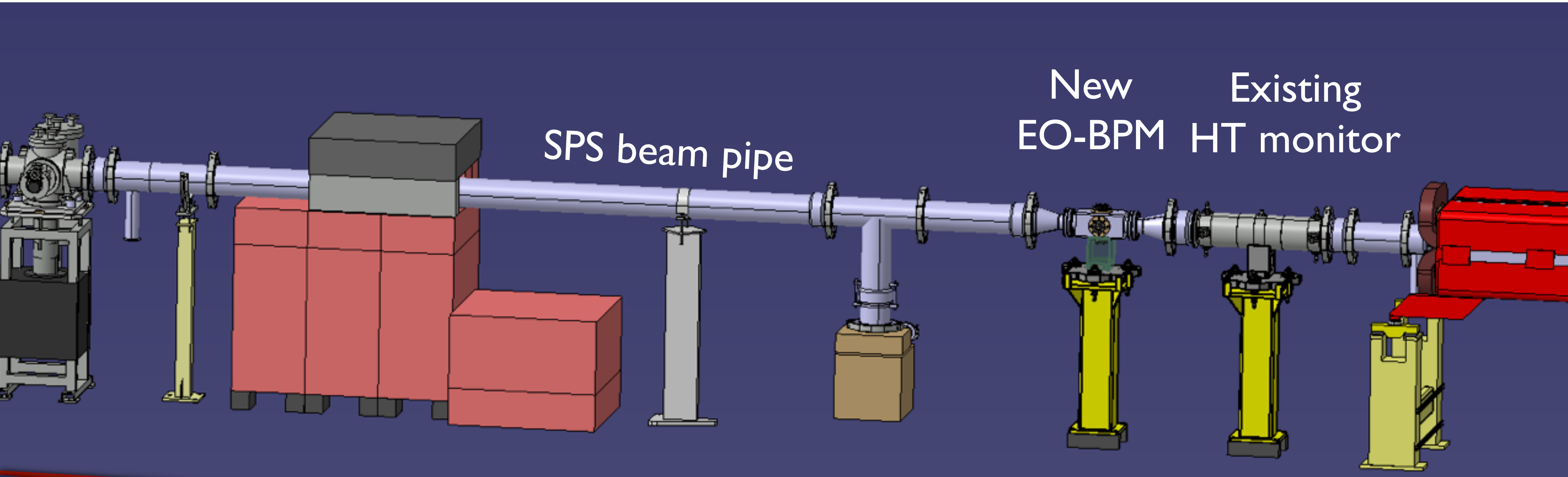
$$\boxed{V_\pi = \frac{\lambda}{r_{33} n_e^3 - r_{13} n_0^3} \frac{d}{L}}$$





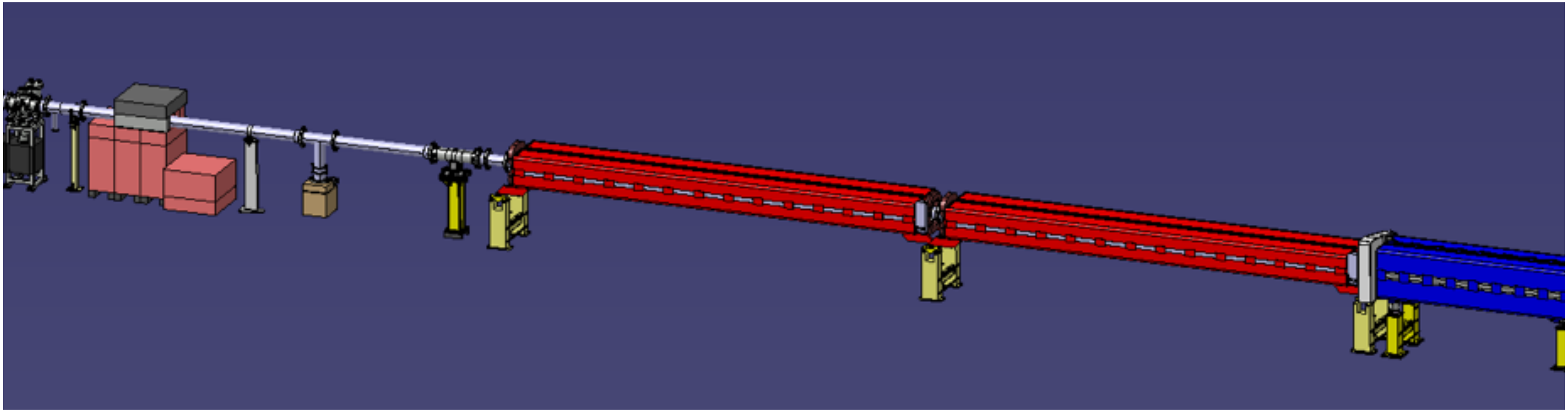
A prototype EO-BPM for CERN SPS

- A beam test of a prototype EO-BPM is planned at the CERN SPS in 2016
- A space has been reserved at SPS p4, adjacent to the existing stripline BPM head-tail monitor that will be useful for cross-checks.
- The beam test aims:
  - to validate the operational performance of the eo-pick with LHC bunch parameters
  - to monitor SPS bunch instabilities in a region with high beta function.



A prototype EO-BPM for CERN SPS

- Existing layout and reserved space:



A prototype EO-BPM for CERN SPS

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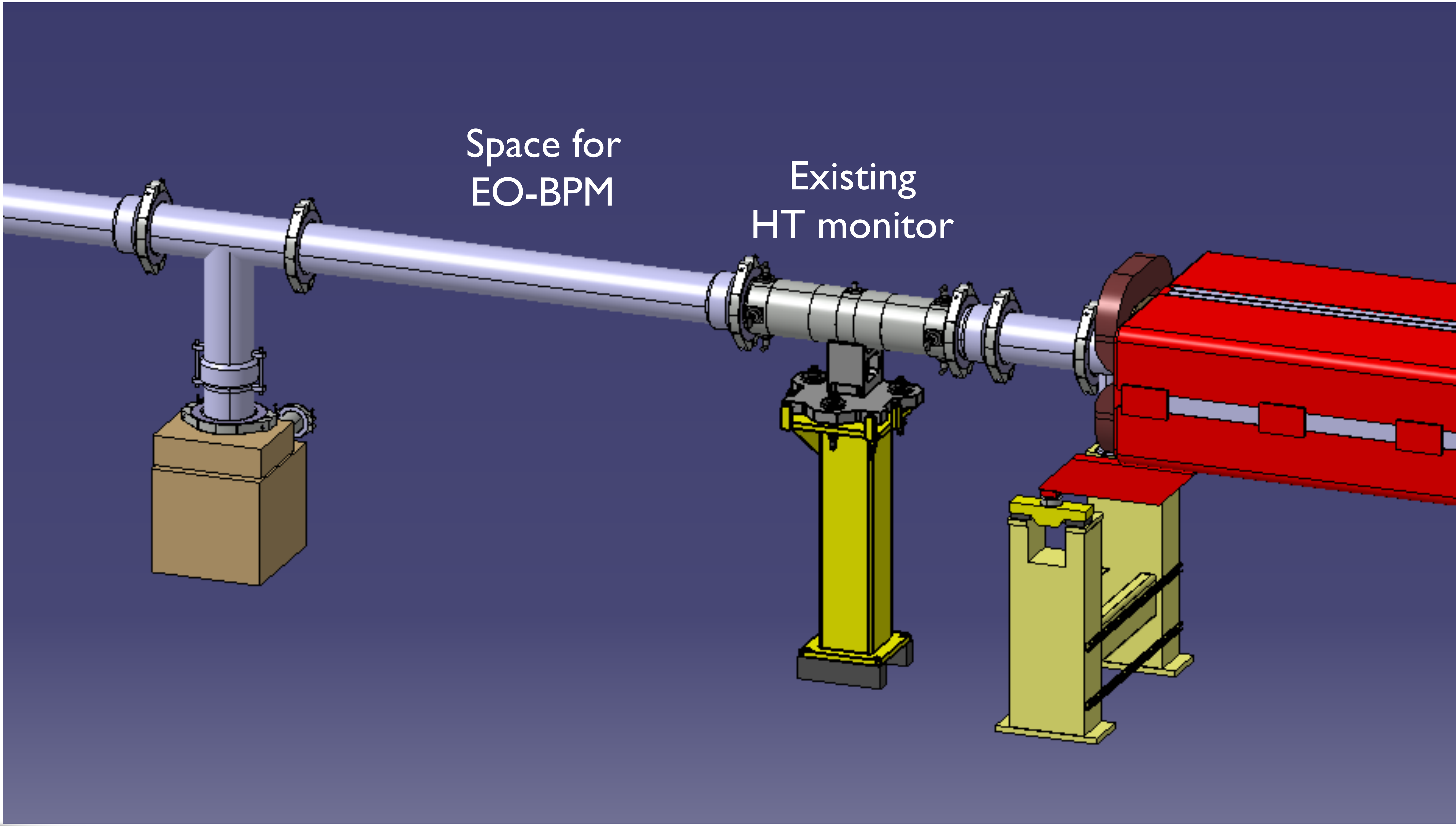
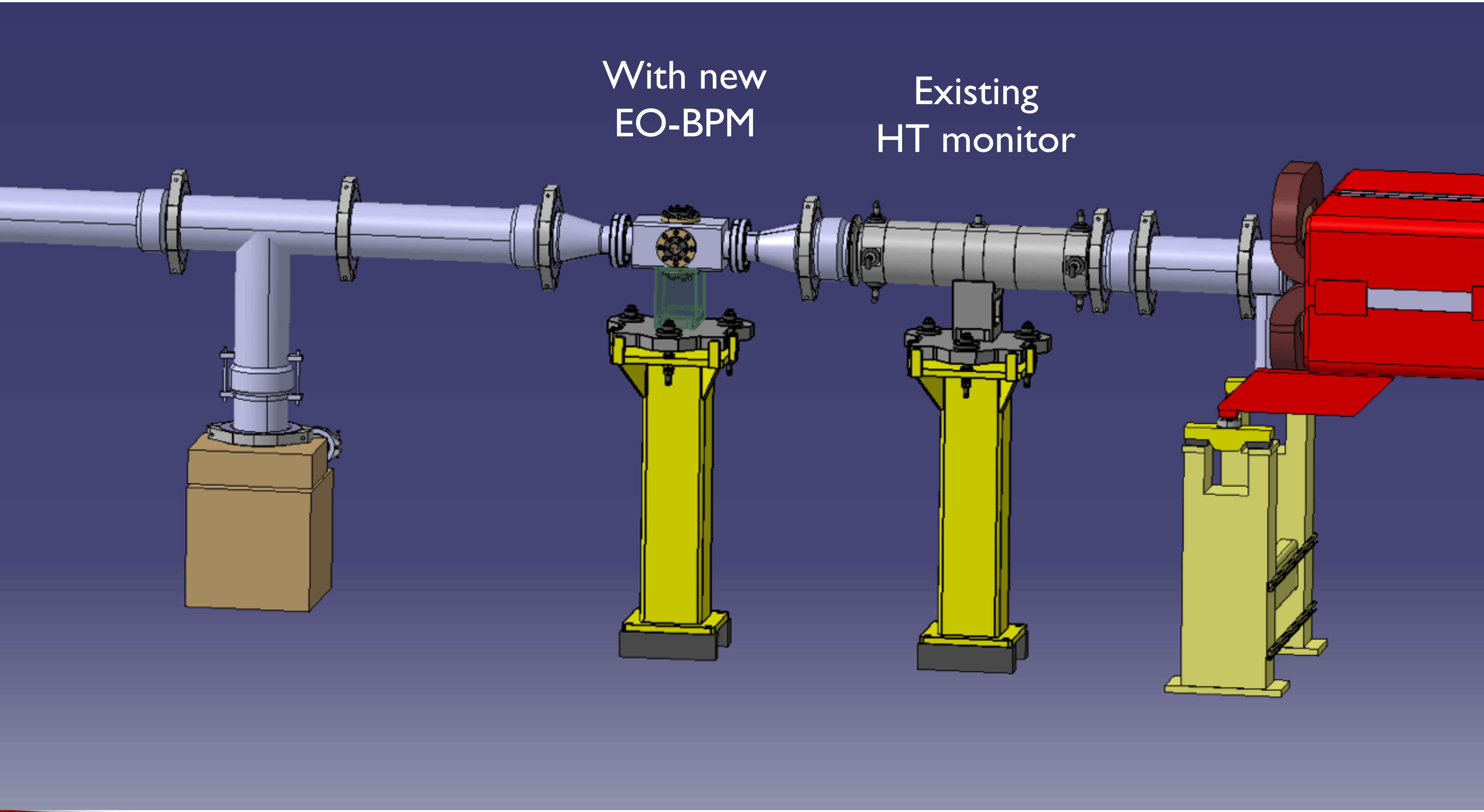


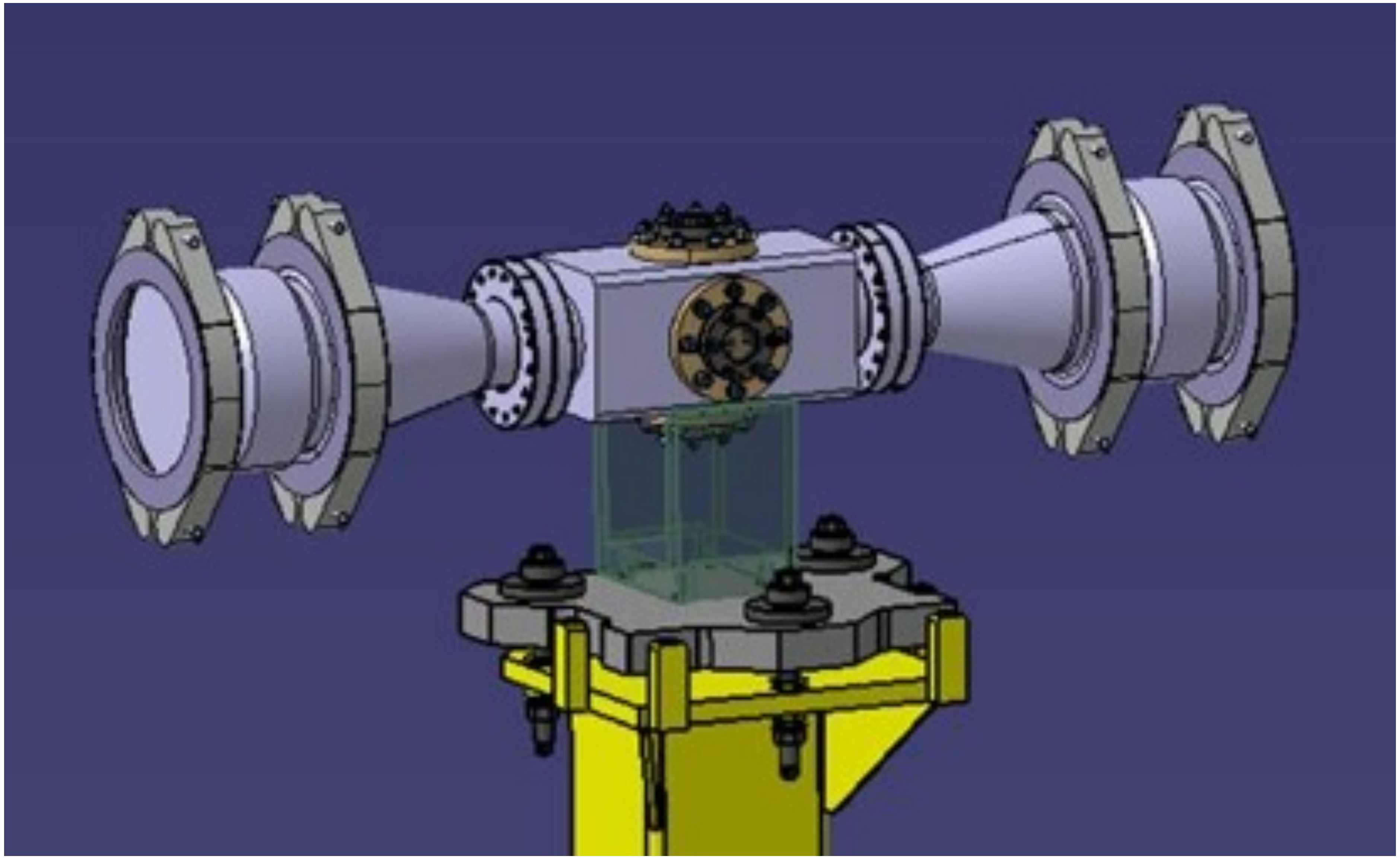
A prototype EO-BPM for CERN SPS

- Layout with new EO-BPM inserted:



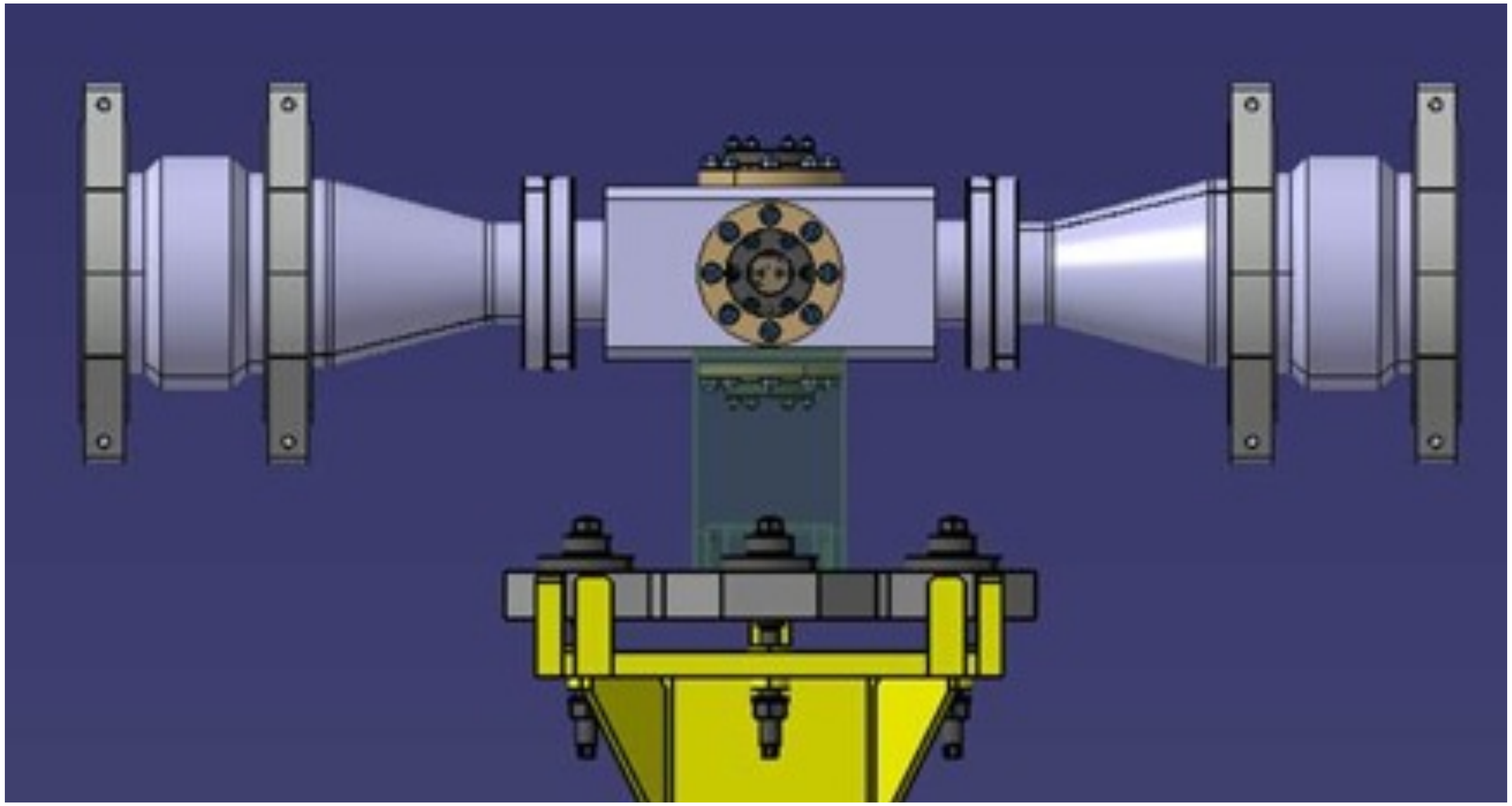
A prototype EO-BPM for CERN SPS

- Zoom on electro-optic BPM, current design has taper to match SPS aperture.



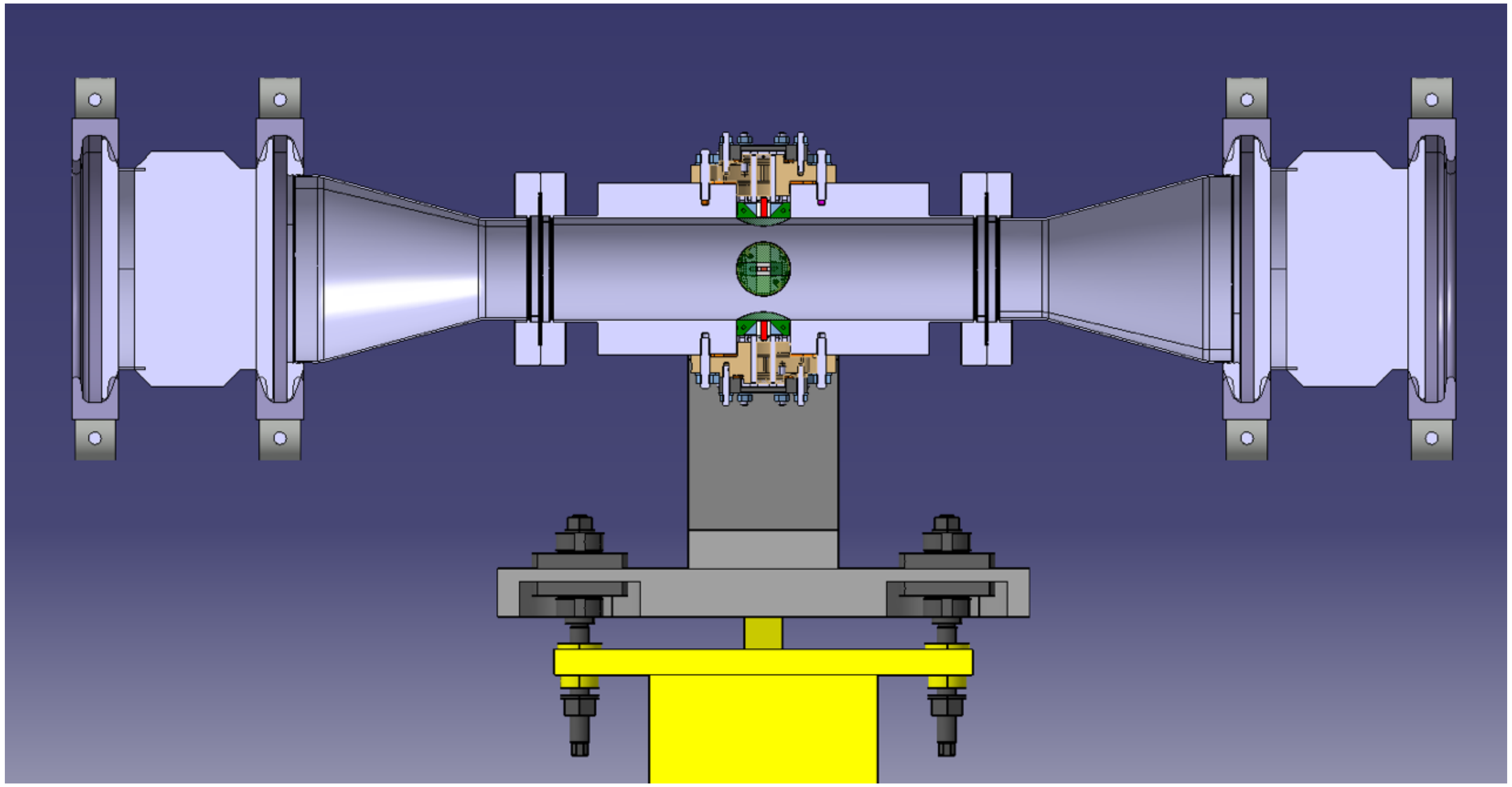
A prototype EO-BPM for CERN SPS

- Side view



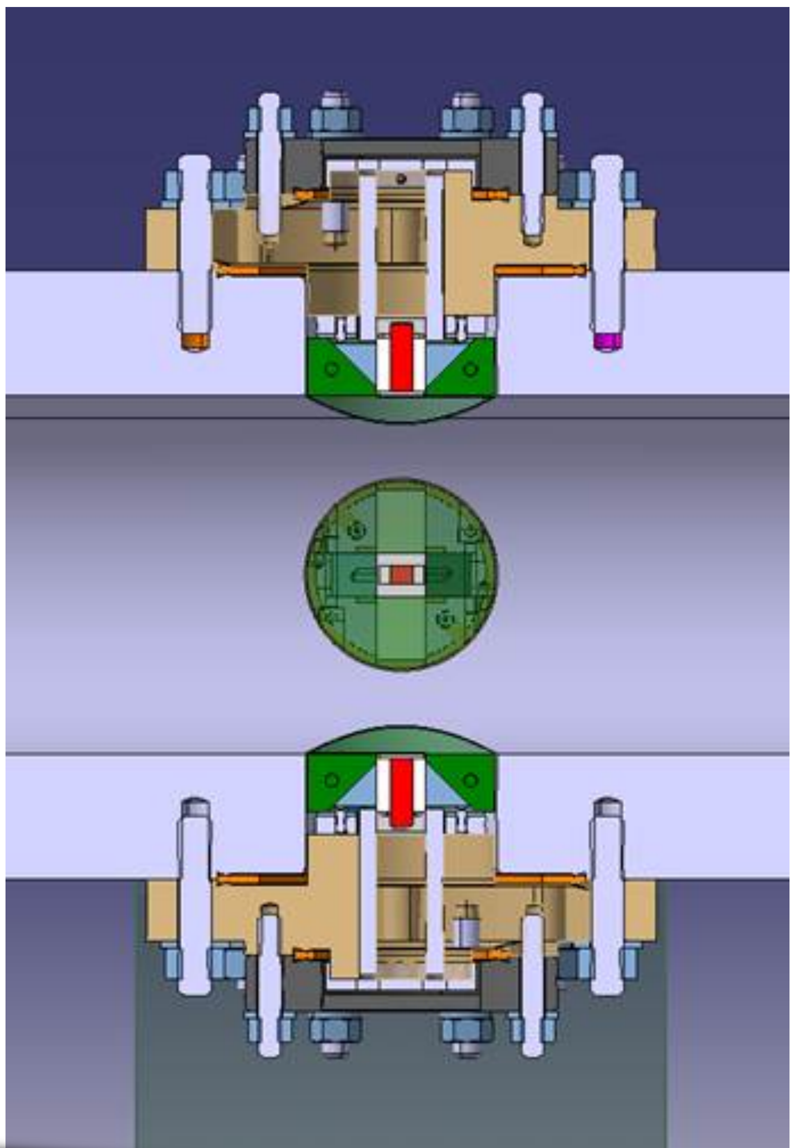
A prototype EO-BPM for CERN SPS

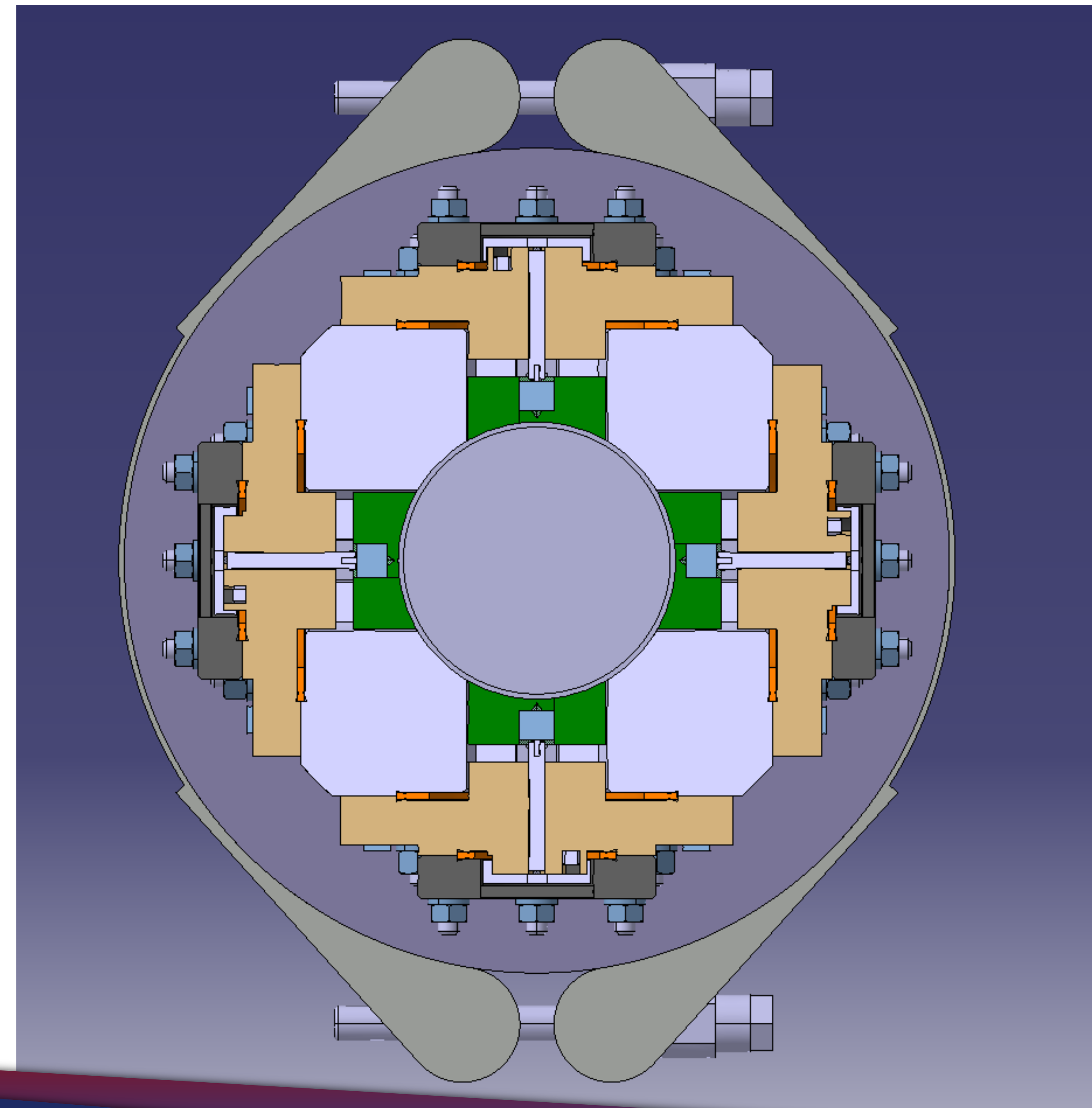
- Side view ***cross-section***



A prototype EO-BPM for CERN SPS

- Cross-sectional view design with eo-crystal highlighted in red, between two reflecting prisms. Illuminated via anti-reflection viewports for maximum flexibility and/or fibre-vacuum feedthroughs.
- Plan to test ***Polarizer-Analyser*** and ***Interferometric*** configurations in orthogonal planes.





Summary and future

- An electro-optic BPM is being developed, aimed at high-frequency bunch ***instability monitoring*** at the CERN SPS and ***intra-bunch diagnostics*** at the HL-LHC.
- The electro-optical response has been simulated and indicates ***good sensitivity*** to high order bunch instability modes for electro-optic crystal lengths of 10-20 mm.
- The e-o crystal response has been validated in laser laboratory bench tests, using the ***polarizer-analyser*** configuration.
- An ***interferometric*** setup has been proposed with the potential for enhanced sensitivity.
- The opto-mechanical layout of an EO-BPM has been designed, in preparation for installation of a prototype in the CERN SPS in early 2016.

Summary and future

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Thank you for your attention

- *Questions?*

Back up

Crystal Choice

- The electro-optic crystals are investigated are $LiNiO_3$ and $LiTaO_3$
  - Both are uniaxial crystals, with excellent electro-optic coefficients;
  - $LiTaO_3$ is slightly more robust (higher density, melting point, damage threshold)
  - Sensitivity improves at short wavelengths due to dispersion: