Beam Measurements at the CERN SPS using Interferometric Electro-Optic Pickups

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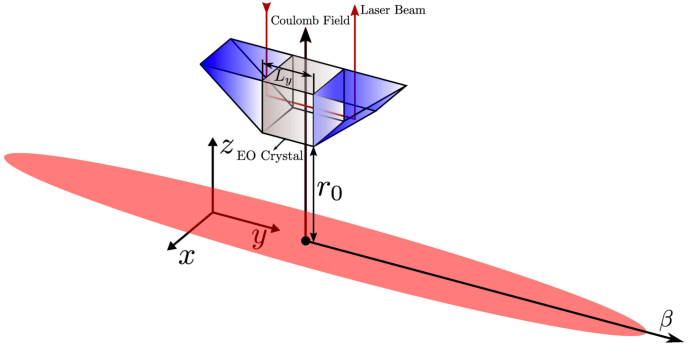
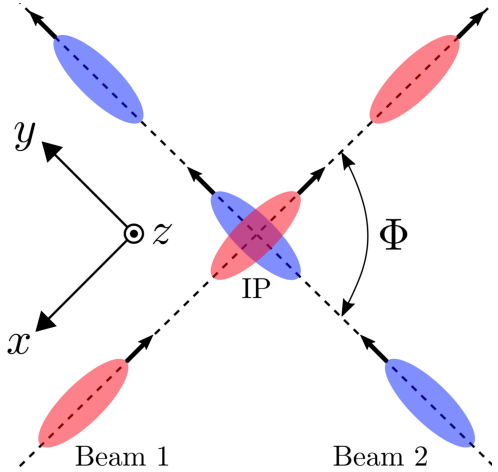
Outline

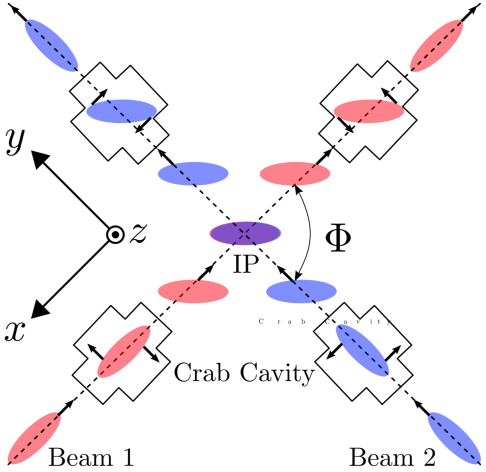
- Motivation.
- Electro-optic BPM concept:
  - Electro-Optic Configurations.
  - EM simulations and sensitivity.
- Summary of results with the SPS prototype.
- Review of projects status.
- Conclusions



Motivation: Crab bunch rotation and pile-up at HL-LHC



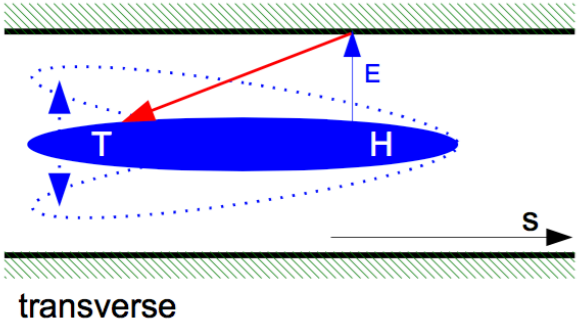
LHC: 23 interactions

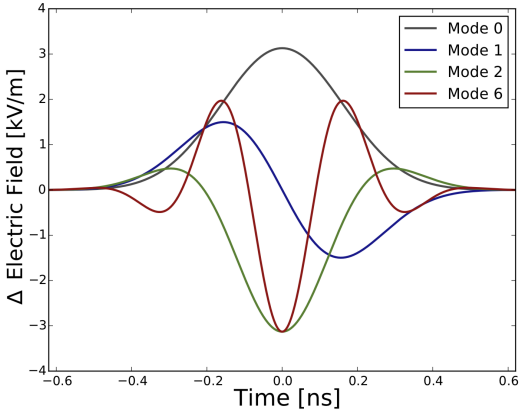


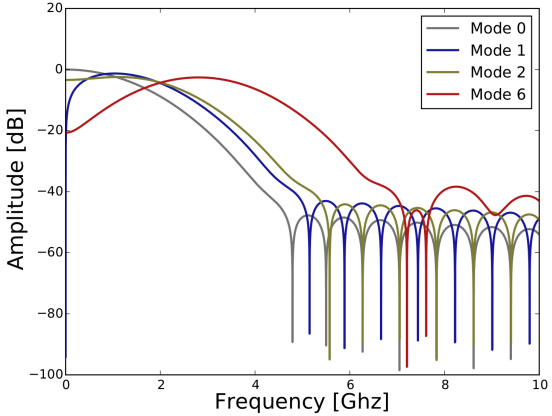
HL-LHC: 140 interactions

To optimize the performance of the crab-cavities for HL-LHC, the EO-BPMs can be the new diagnostic tool to monitor the bunch rotation.

Motivation: intra-bunch diagnostics / crabbed bunches







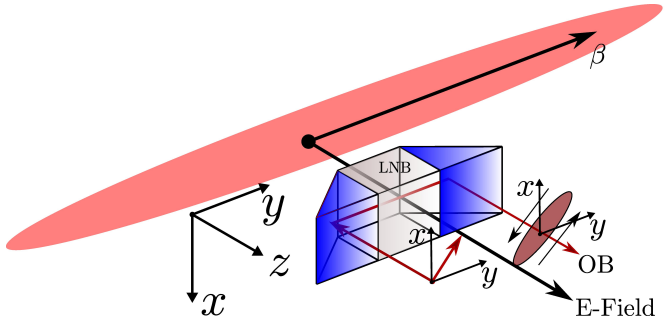
- Standard approach:
  - Stripline BPMs + fast sampling oscilloscopes.
  - Limitation: Bandwidth up to a few GHz, limited by the pick-up, cables, and acquisition system.

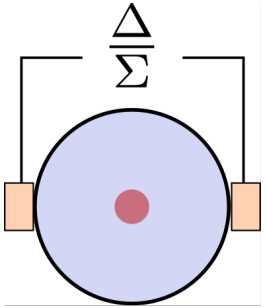
New Technology required to detect higher bandwidth order modes (>6GHz):

Fast electro-optic pick-up

Pickup concept

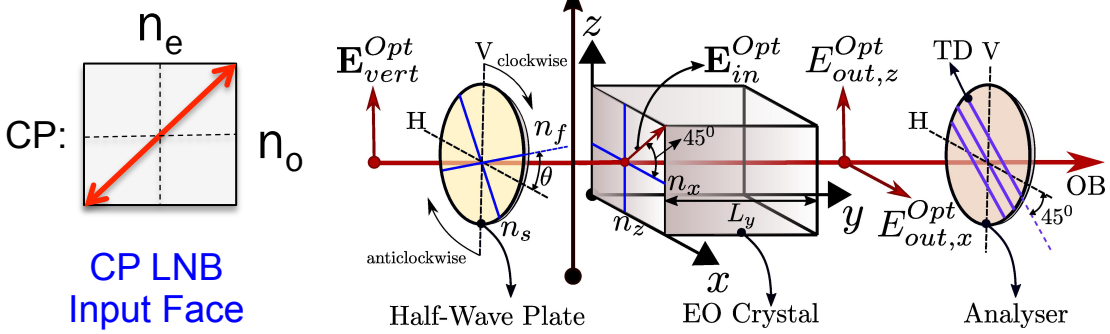
- Replace pick-ups in a button BPM with electro-optic crystals.
- The electric field from a passing bunch induces a phase change of light through the crystal(*).
- Fibre-coupled design with laser and detectors 160 m away from accelerator tunnel.
- GOAL: Transverse position along the 4σ = 1.0ns LHC bunch is monitored with 50ps resolution.

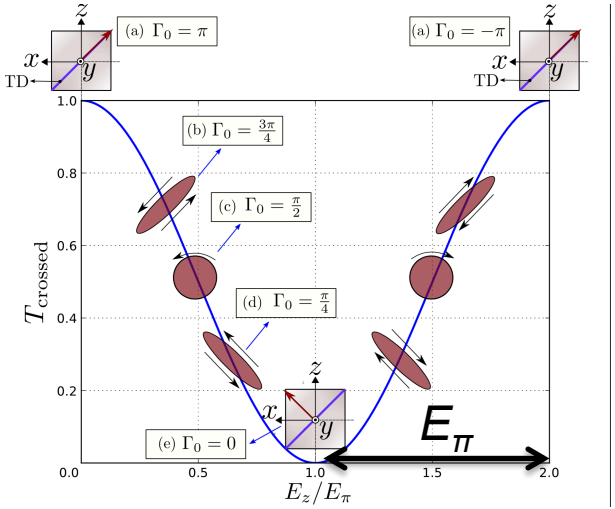




(*) HIGH FREQUENCY ELECTRO-OPTIC BEAM POSITION MONITORS FOR INTRA-BUNCH DIAGNOSTICS AT THE LHC, S.M. Gibson et al., IBIC'15

Pickup concept: Detection by optical modulation



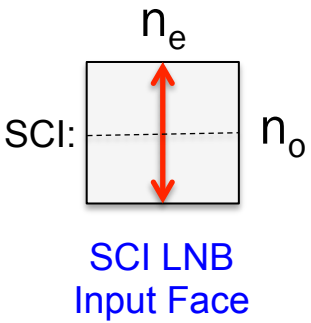


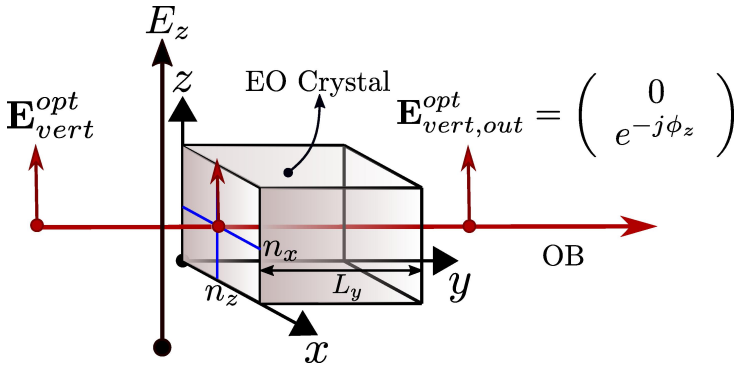
Transfer Function

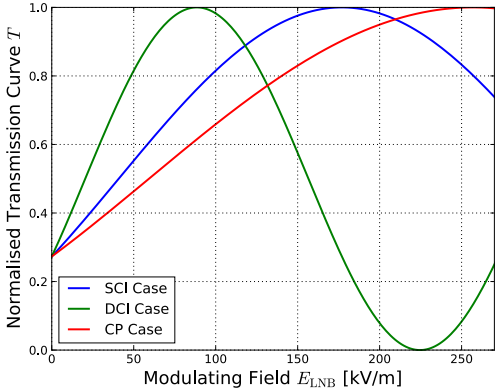
- Crossed Polarisers (CP): Different input and output Polarisation.
- Sensitivity determined by the transfer function *T* and E_π

$$\frac{E_{LNB}}{E\pi} \rightarrow \text{Increase} \quad \rightarrow \text{Decrease}$$

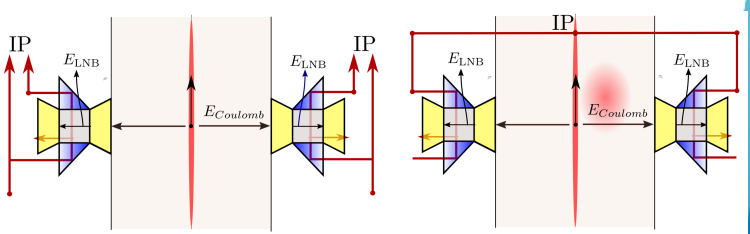
Pickup concept: Detection by optical modulation



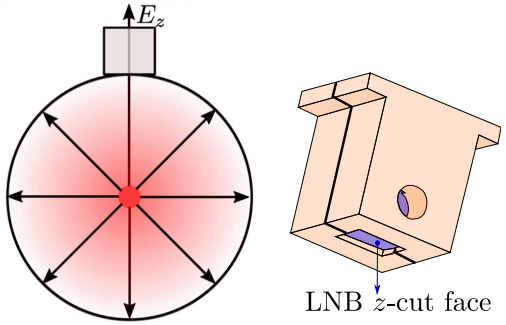




- Single Crystal (SCI) and Double Crystal Interferometer (DCI): Same linear input and output polarisation.
- Sensitivity E_{LNB}/E_{π} improved by a factor X1.45 for SCI.
- Sensitivity E_{LNB}/E_{π} improved by a factor X1.45 X2 for DCI



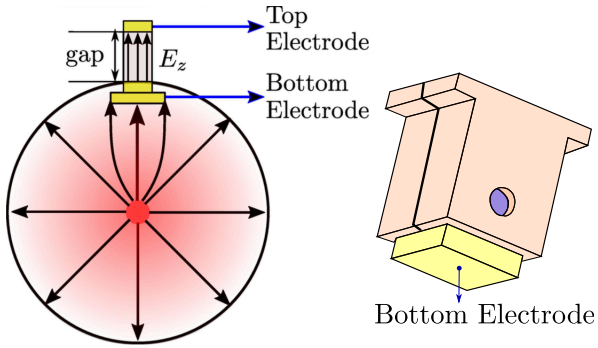
2016-17 SPS Run



No electrode.

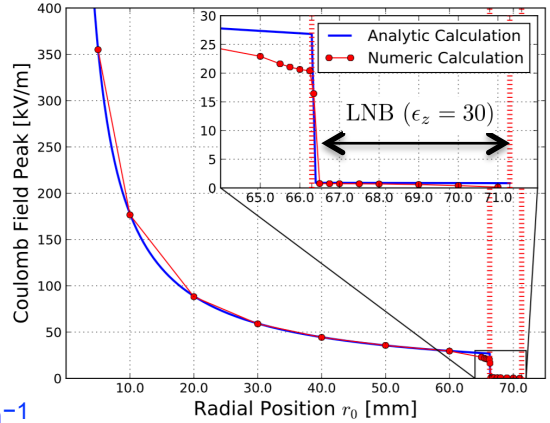
$\times 8$

$r_0 = 66.6\,\mathrm{mm}$



Crystal between electrodes

Model	E_{LNB} [kV/m]	L [mm]	E_{π}[kV/m]	E_{LNB}/E_{π}
ZERO	0.65	5	711 (CP)	0.09%
ONE	2.80	9	395 (CP)	0.70%



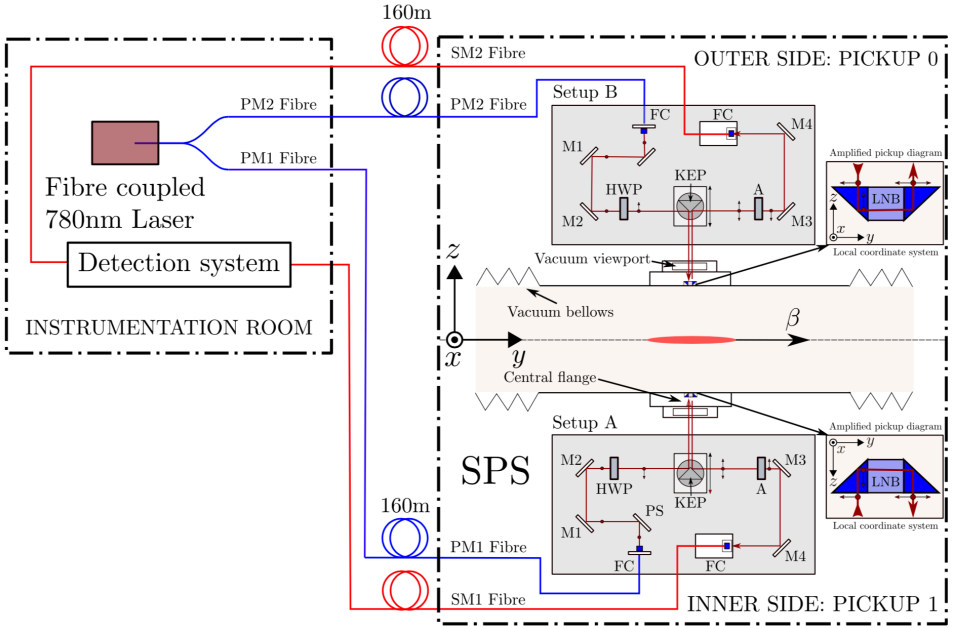
Model	g_{FIELD}[kVm^{-1}mm^{-1}]	g_{OPT}[μWmm^{-1}]
ZERO	0.022	0.05 (CP)
ONE	0.087	0.34 (CP)

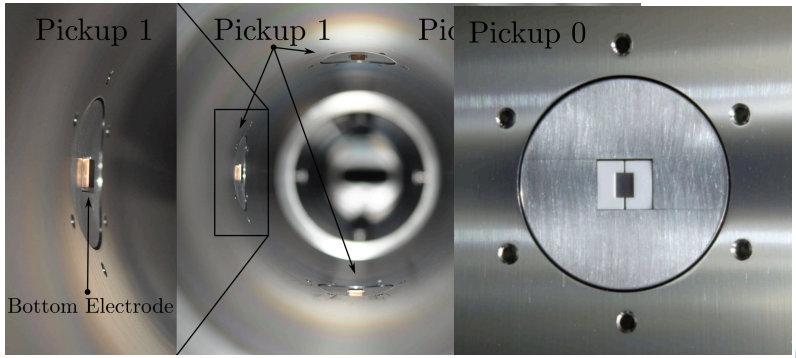
0.13dBmm^{-1} 0.26dBmm^{-1}

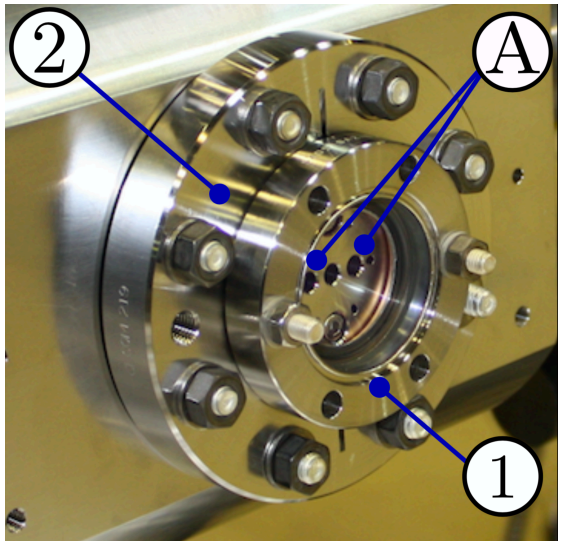
- No single bunch measurement achieved.
- Improvement factor measured.
- Signal gradient measurement: 0.24 dBmm^{-1}
- Experimental signal and simulation in good agreement.

(*) DEVELOPMENT OF A PROTOTYPE ELECTRO-OPTIC BEAM POSITION MONITOR AT THE CERN SPS, A. Arteche et al., IBIC'16

2016-2017 SPS run: Installation





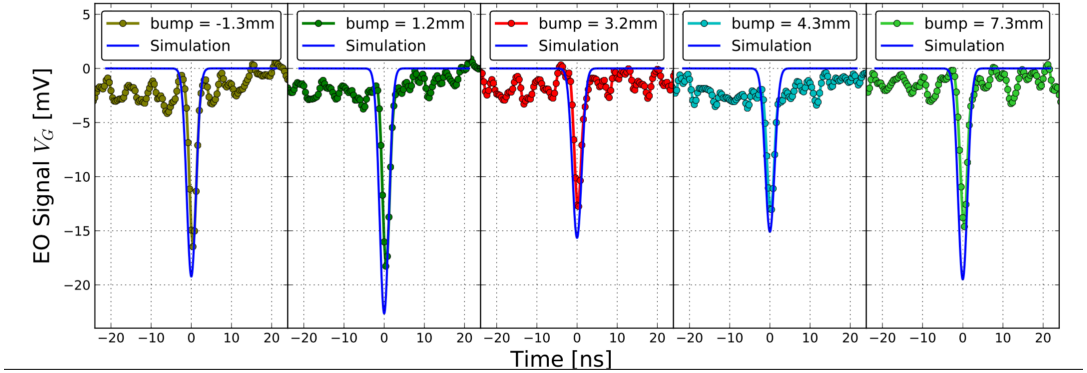


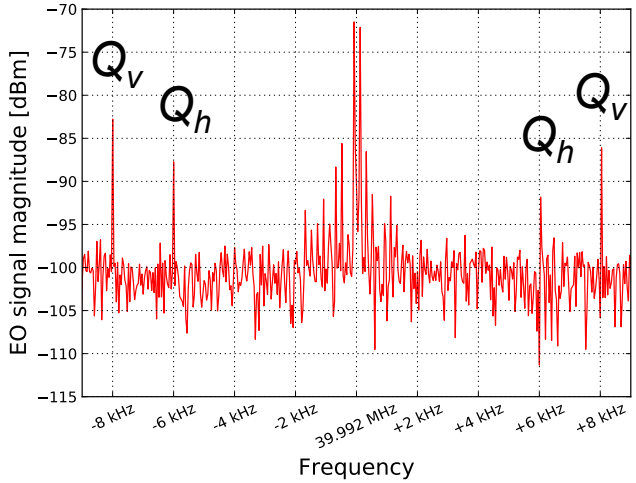
- Installation during the 2015/16 shutdown(*).
- λ=780nm

(*) DEVELOPMENT OF A PROTOTYPE ELECTRO-OPTIC BEAM POSITION MONITOR AT THE CERN SPS, A.Arteche et al., IBIC'16

2016-2017 SPS run: Results

Single EO pickup one signals at Crossed Polarisers:

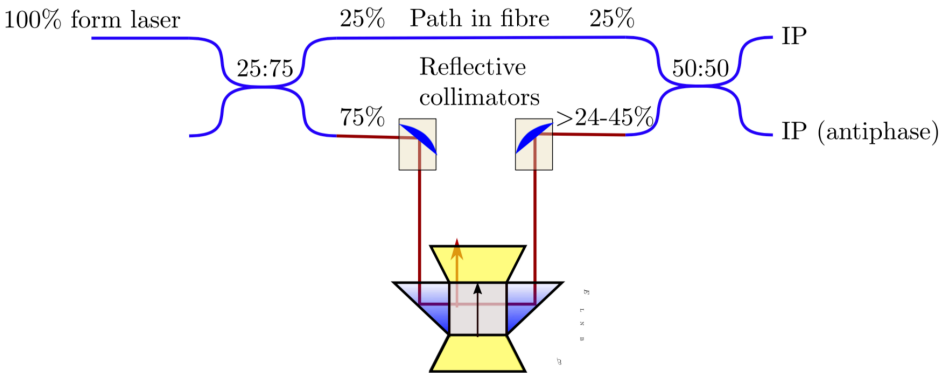


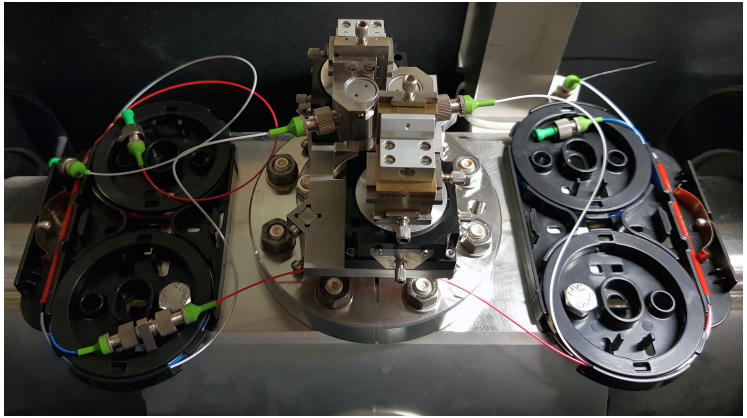


- **December, 2016:** First proton beam-induced EO detection (PU zero)
- **June, 2017:** Confirmation of the improvement factor X8 (PU one)
- **June, 2017**: Confirmation of the transverse offset sensitivity at 66.5 mm (PU one)
- **July, 2017**: Indirect detection of the SPS betatron tune (PU one)

(*) FIRST BEAM TESTS AT THE CERN SPS OF AN ELECTRO-OPTIC BEAM POSITION MONITOR FOR THE HL-LHC, A. Arteche et al., IBIC'17

2018 SPS run: SCI with PU one

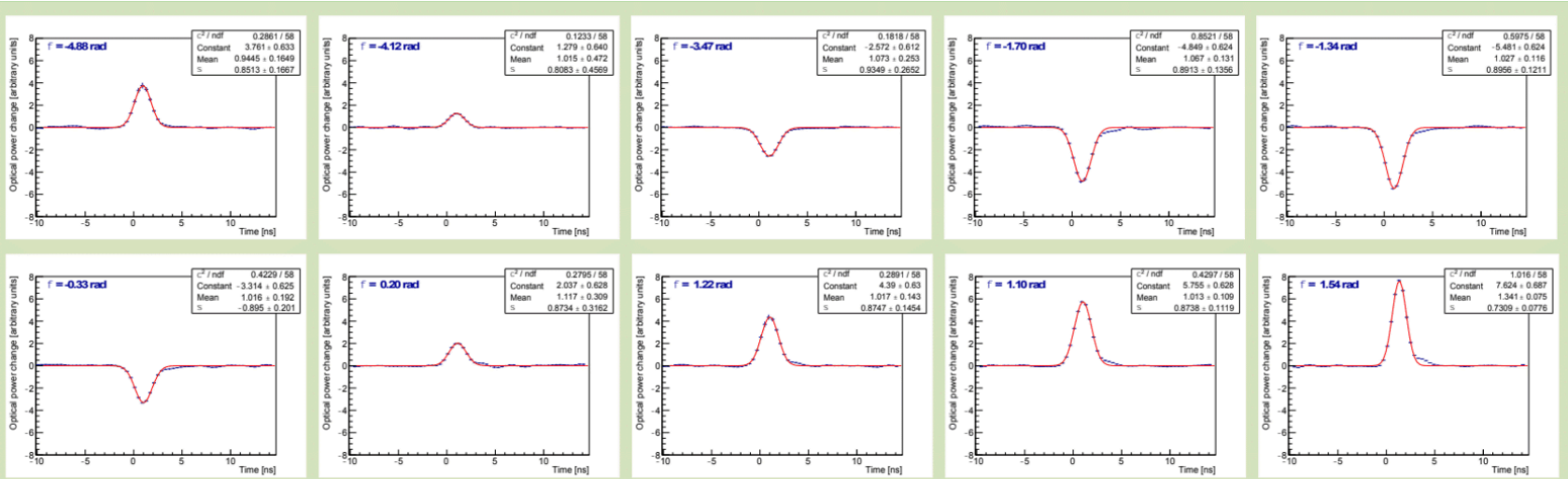




- Gain factor ~1.4.
- Main upgrade: Tunability of the sensitivity by shifting the laser wavelength(*)
- Installation of the fibre-coupled compact design during the 2017/18 SPS shutdown(*)(**).
- Mechanical stability: The system uses compact reflective collimators to align the OB through the crystal.

(*) ENHANCED BUNCH MONITORING BY INTERFEROMETRIC ELECTRO-OPTIC METHODS, S.M. Gibson et al., IPAC'18
(**) BEAM MEASUREMENTS AT THE CERN SPS USING INTERFEROMETRIC ELECTRO-OPTIC PICKUPS, A. Arteche et al., IBIC'19

2017 SPS run: SCI Measurements with PU one



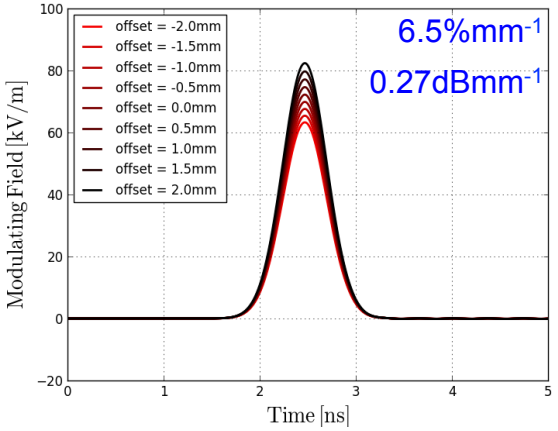
Optical response of the compact interferometer to an average SPS bunch as the laser frequency is scanned.

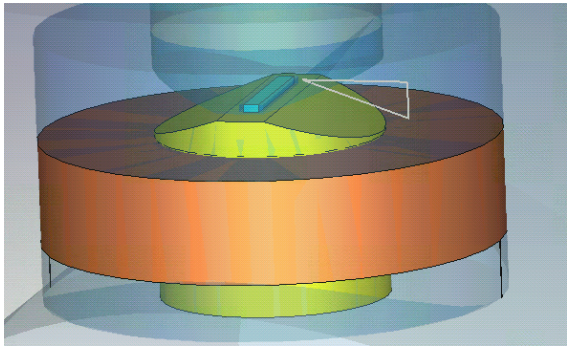
- **September, 2017:** First Free-Space SCI detection with model zero(*).
- **April, 2018:** First interferometric signal with a compact setup and model one(*).

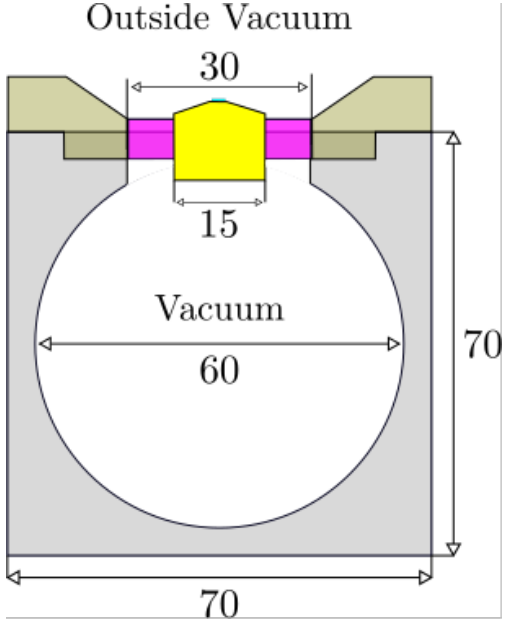
(*) ENHANCED BUNCH MONITORING BY INTERFEROMETRIC ELECTRO-OPTIC METHODS, S.M. Gibson et al., IPAC'18

Future: Hi-Lumi LHC Design

- HL-LHC design studies ongoing based on CST Electro-Magnetic Simulations.
- Enhancement of the modulating field E_{LNB} from 2.8kV/m up to 73 kV/m (Ly=300μm).
- Optical waveguide crystal solution with a size reduction: (Lx,Ly,Lz)=(1mm,9mm,0.3mm)
- Major mechanical upgrade: Crystal Outside vacuum.
- Significant optical power increment (1mW➔20mW).







(*) BEAM MEASUREMENTS AT THE CERN SPS USING INTERFEROMETRIC ELECTRO-OPTIC PICKUPS, A. Arteche et al., IBIC'19

Conclusion: Comparison and Improvement Factor

Model	E_{LNB} [kV/m]	Configuration	L_{LNB} [mm]	E_{π} [kV/m]	E_{LNB}/E_{π}	P_{max}[mW]	g_{FIELD} [kVm^{-1}mm^{-1}]	g_{OPT} [µWmm^{-1}]
ZERO	0.65	CP	5	711	0.09%	1	0.022	0.05 (CP)
ONE	2.80	SCI (x1.45)	9	272 (SCI)	1.02%	1-3	0.087	0.49 (SCI)
NEW PU	73	DCI (X2)	9	136	54.4%	20	4.75	500

Improvement:

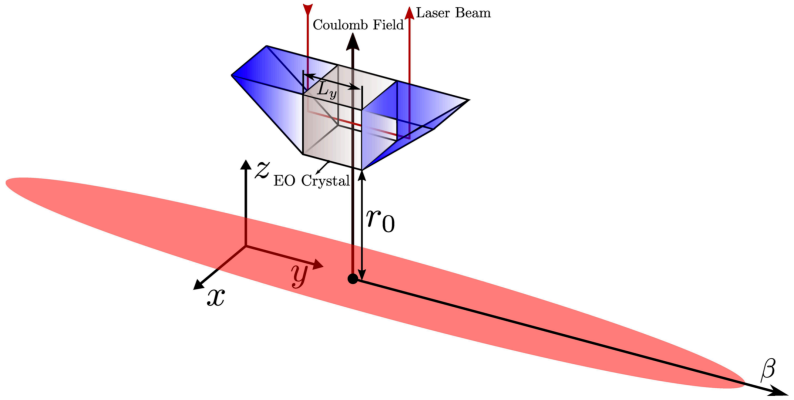
$$\frac{73\,\mathrm{kV/m}}{2.8\,\mathrm{kV/m}} \times \frac{20\,\mathrm{mW}}{1\,\mathrm{mW}} \times 2 > \boxed{10^3}$$

E_{LNB} P_{max} Configuration

- *First transverse position sensitivity by EO means at 66.5 mm away form the proton beam in the SPS.*
- *SPS interferometric prototype has been installed, with first beam signal observed in January 2017.*
- *Measured beam signals match well with electromagnetic simulations, giving confidence in future design work for the LHC prototype.*

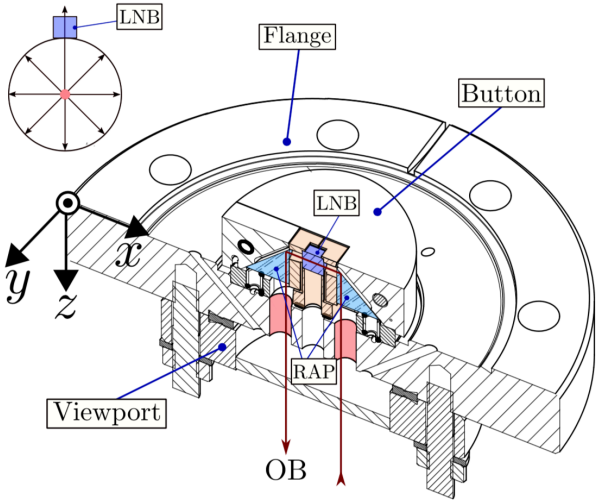
(*) BEAM MEASUREMENTS AT THE CERN SPS USING INTERFEROMETRIC ELECTRO-OPTIC PICKUPS, A. Arteche et al., IBIC'19

Thank you for your attention!



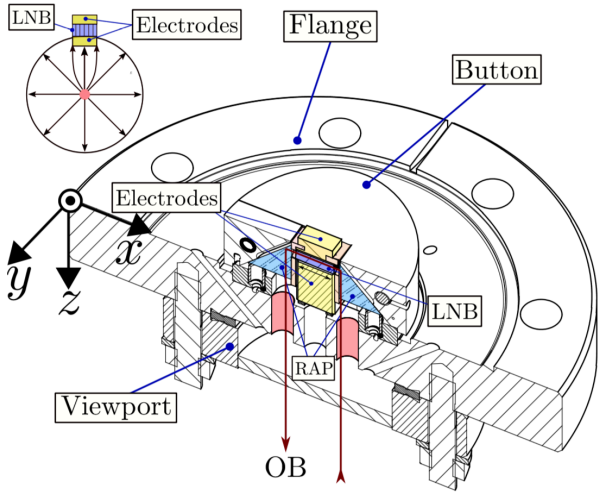
(GO EO!)

Backup



(a)

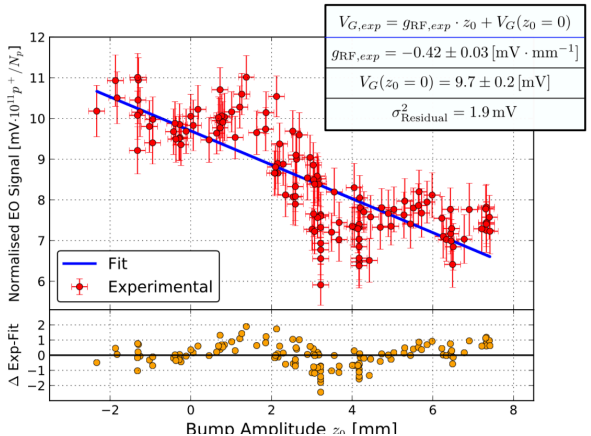
Pickup Zero

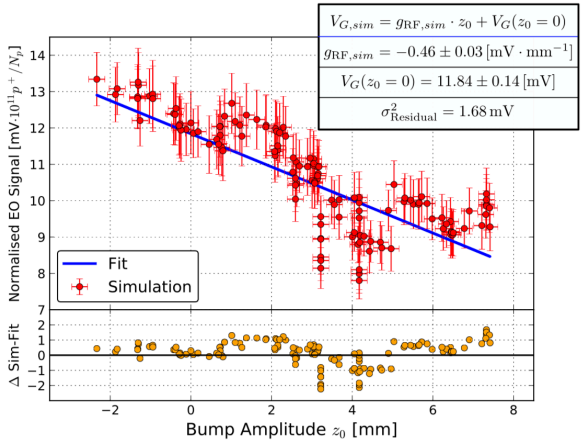


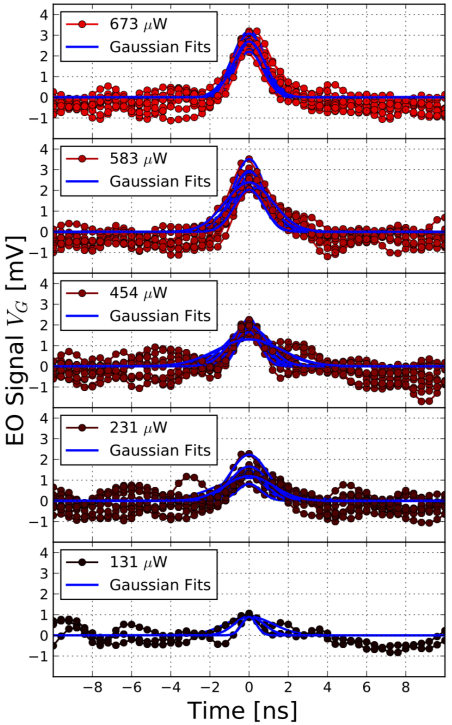
(b)

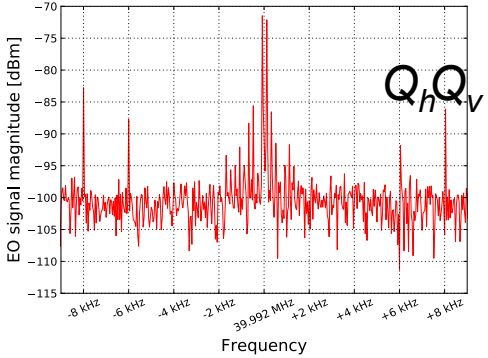
Pickup One

Backup









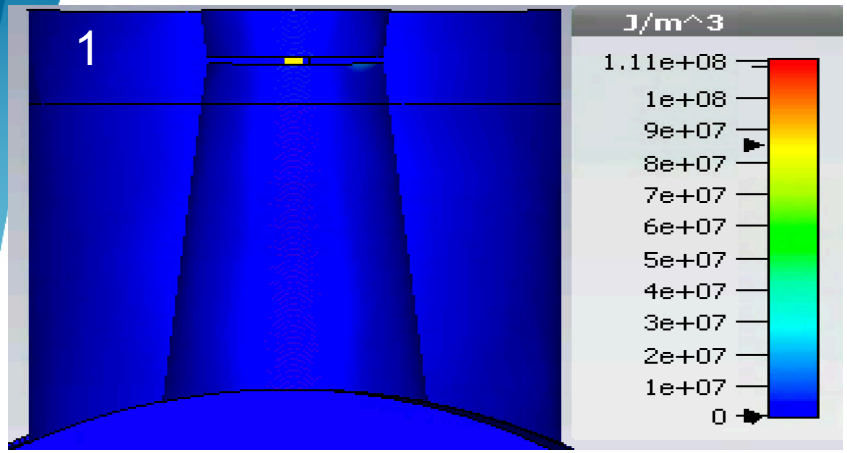
$$f_{Qn} = n \times f_{\mathrm{rev}} \pm Q \times f_{\mathrm{rev}}$$

$$Q_h = \frac{6}{43.375} = 0.138$$

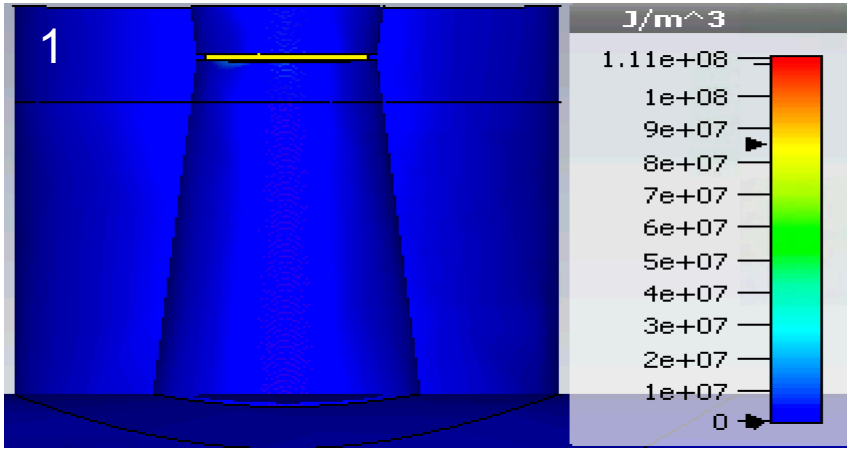
$$Q_v = \frac{8}{43.375} = 0.184$$

24.5mm

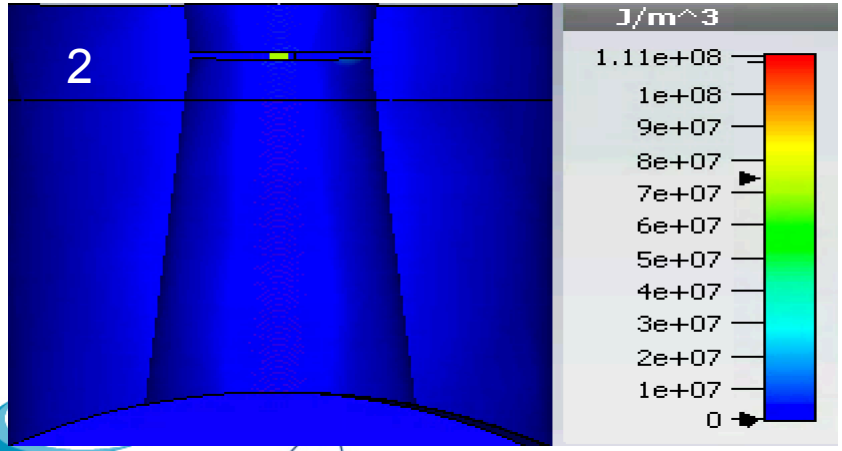
Front View



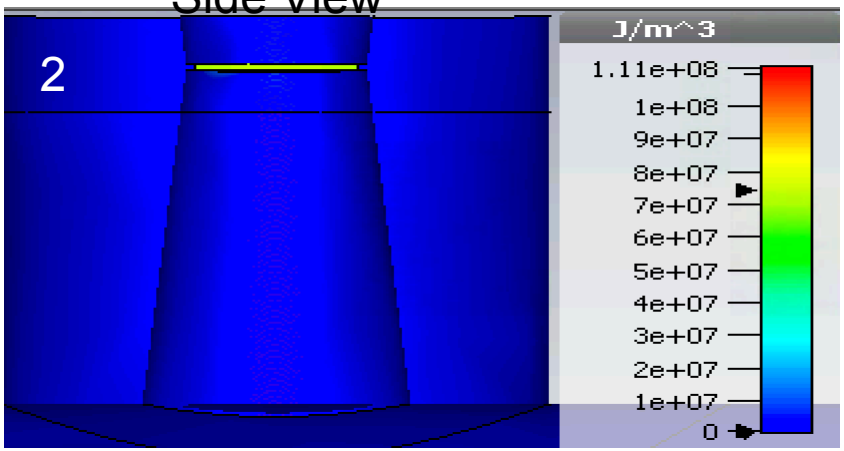
Side View



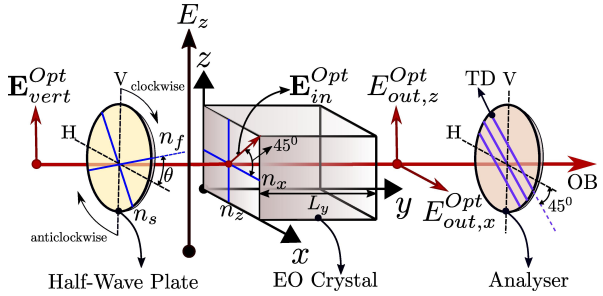
Front View



Side View

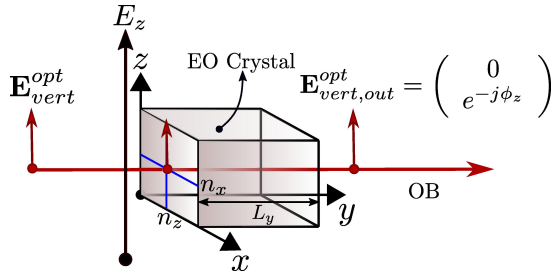


Backup



$$\Gamma(t) = \frac{2\pi}{\lambda}(n_e - n_o)l + \frac{\pi}{\lambda}(n_e^3 r_{33} - n_o^3 r_{13}) l E_{az}(t)$$

$$\longrightarrow \quad E_\pi = \frac{1}{L_y}\frac{\lambda}{n_e^3 r_{33} - n_o^3 r_{13}}$$



$$\phi(t) = \frac{2\pi}{\lambda} n_e l + \frac{\pi}{\lambda} n_e^3 r_{33} l E_{az}(t)$$

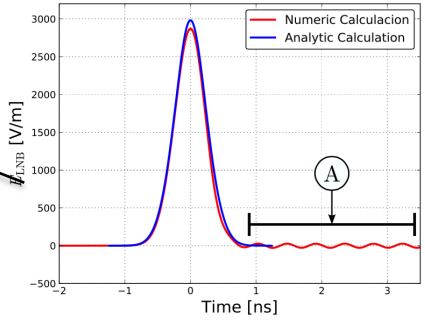
$$\longrightarrow \quad E_{\pi,\text{inter}} = \frac{\lambda}{r_{33} n_e^3 L_y}$$

$$k_{C-I} = \frac{S_{\text{inter}}}{S_{\text{crossed}}} = \frac{E_{\pi,\text{inter}}}{E_\pi} = \frac{r_{33} n_e^3}{r_{33} n_e^3 - r_{13} n_o^3}$$

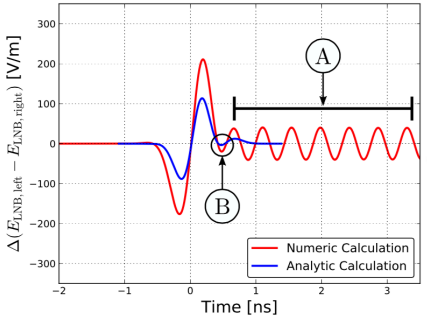
Backup

Studies on HT detection

Crabbed-like beam distribution



(a) Single pickup, mode = 1.

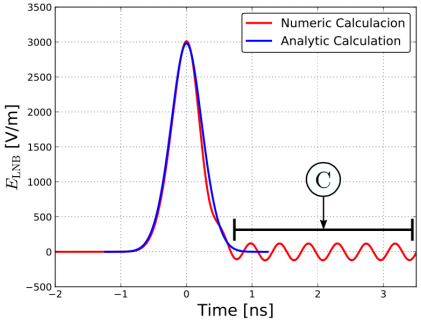


(b) $E_{LNB,right} - E_{LNB,left}$, mode = 1.

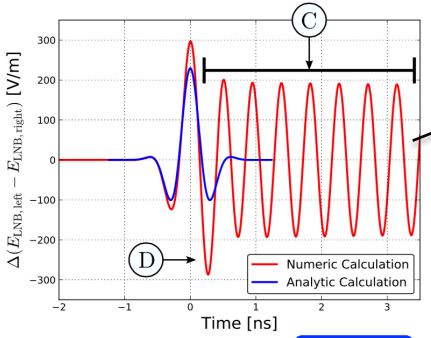
Pickup One

Resonance

For a rod–like shaped electrode!

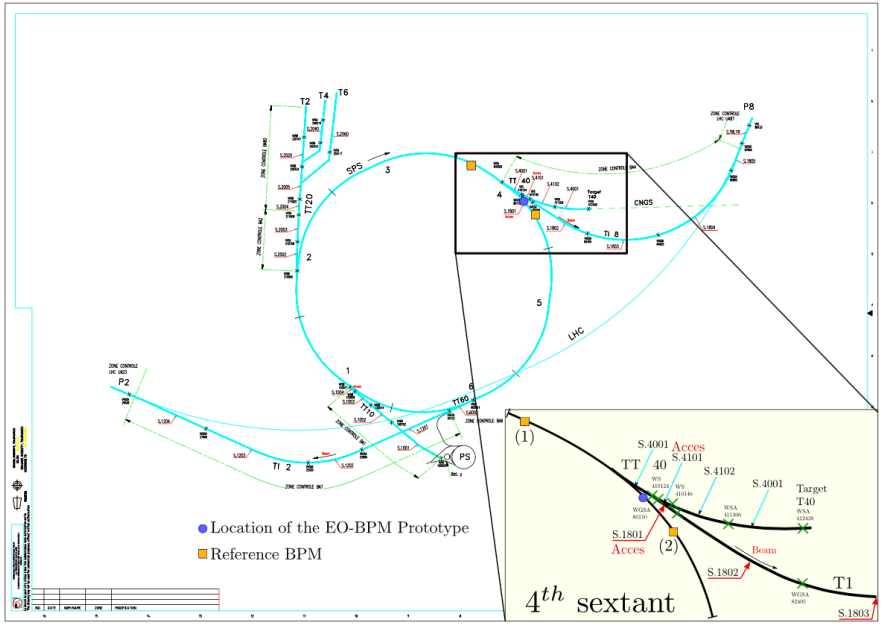


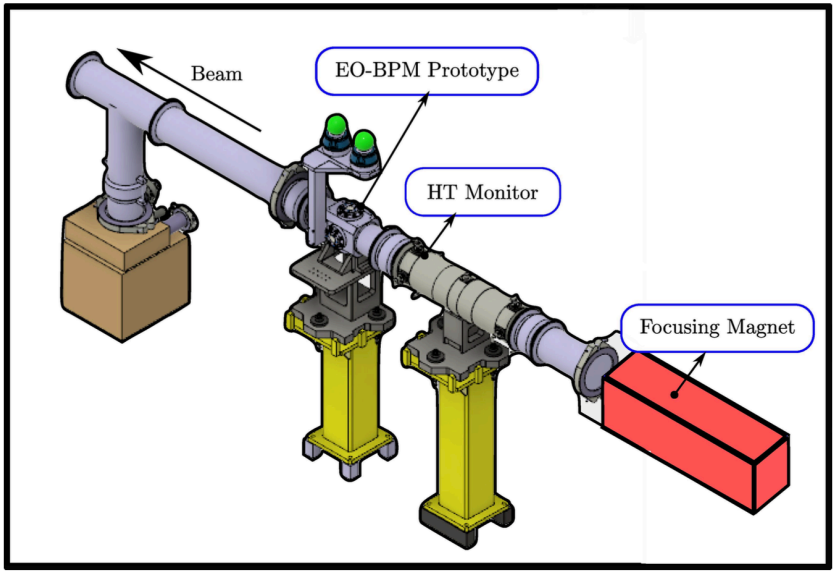
(c) Single pickup, m=6.



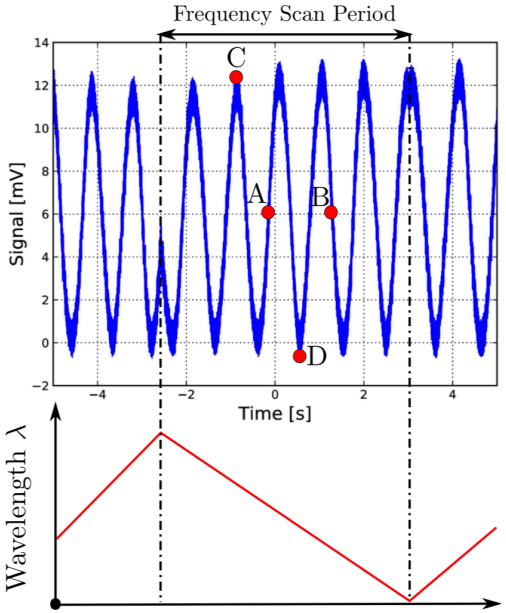
(d) $E_{LNB,right} - E_{LNB,left}$, mode = 6.

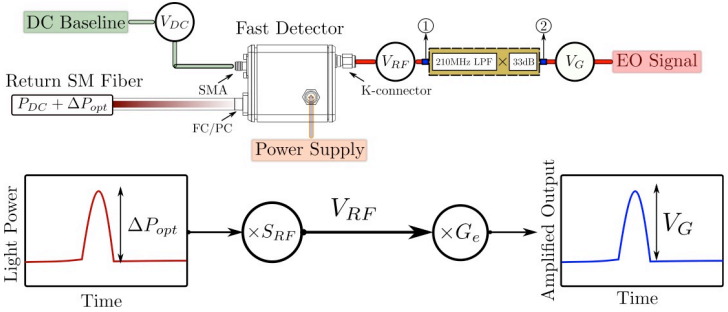
Backup


T2
T4
T6
P8
SPS
TT20
CNGS
TI 8
LHC
P2
TI 2
TT10
TT60
PS
Location of the EO-BPM Prototype
Reference BPM
(1)
S.4001 Acces
S.4101
TT 40
S.4102
S.4001
Target T40
S.1801 Acces
(2)
Beam
S.1802
T1
S.1803
4th sextant


Beam
EO-BPM Prototype
HT Monitor
Focusing Magnet

Backup

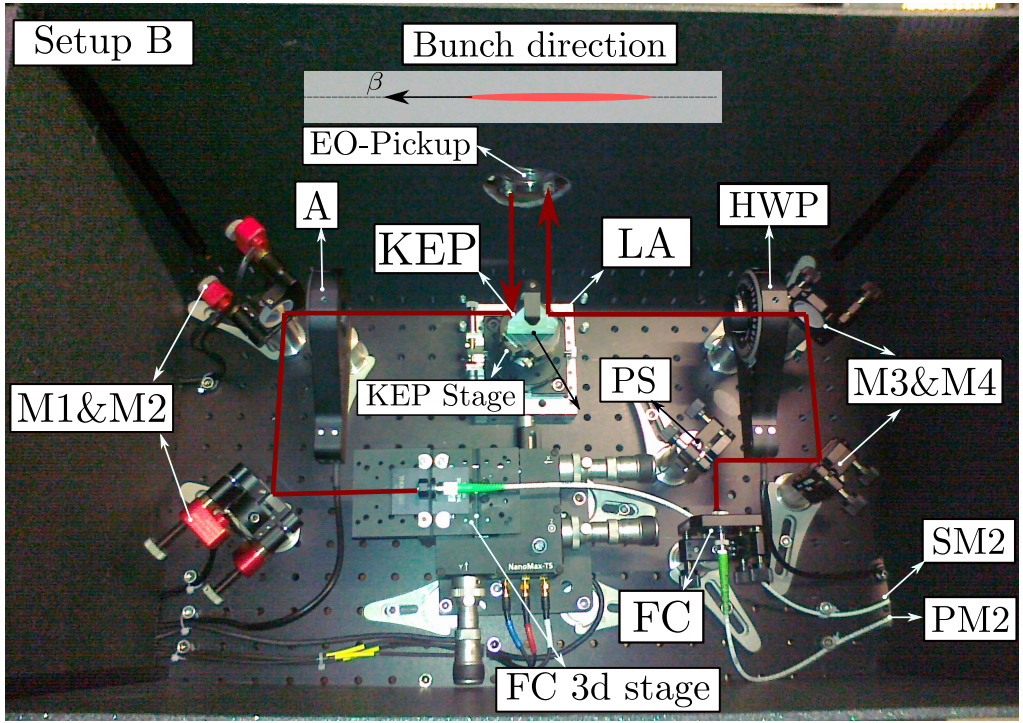


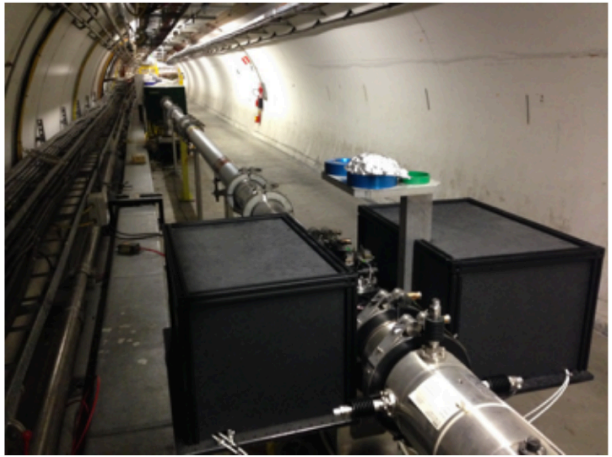


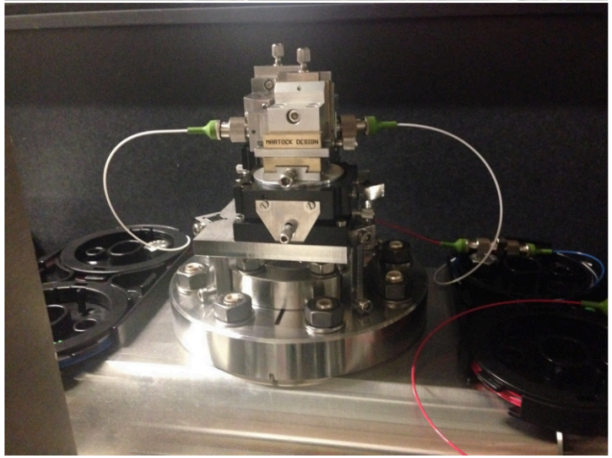
EO Modulation
Pickup Design

Modulation Detection
Acquisition System

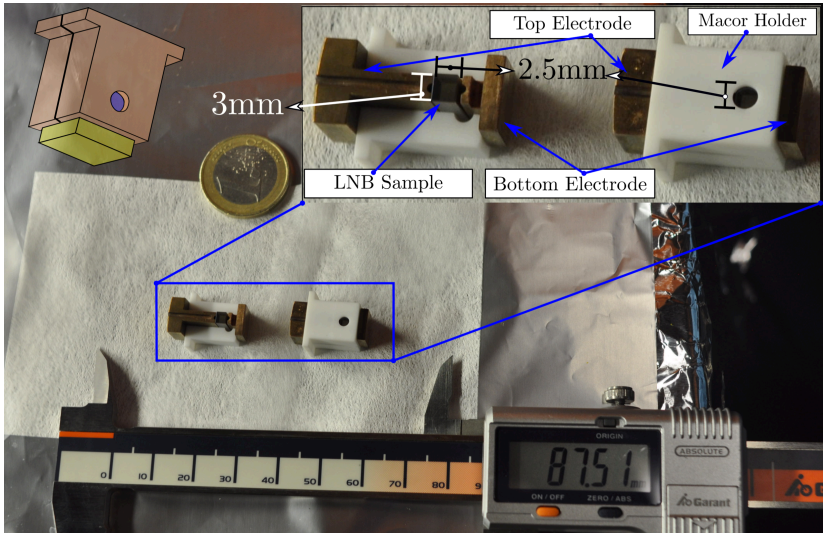
Backup

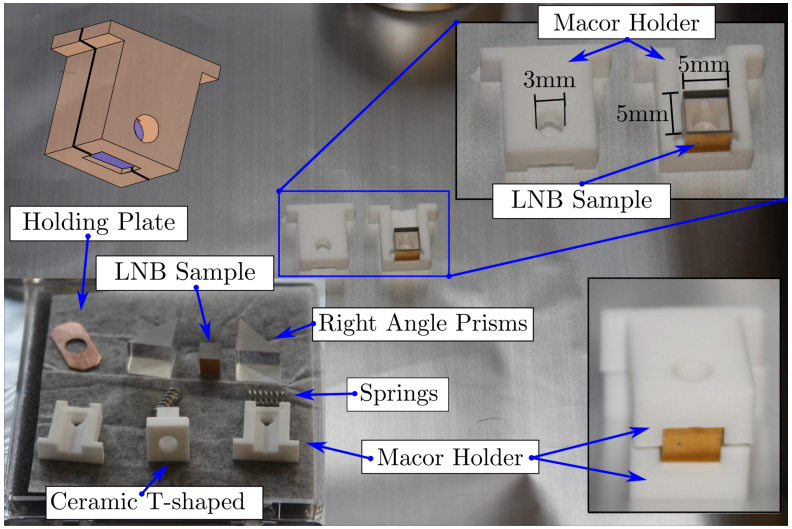

Setup B
Bunch direction
β
EO-Pickup
A
KEP
LA
HWP
M1&M2
KEP Stage
PS
M3&M4
SM2
FC
PM2
FC 3d stage





Backup


Top Electrode
Macor Holder
2.5mm
3mm
LNB Sample
Bottom Electrode


Macor Holder
3mm
5mm
5mm
LNB Sample
Holding Plate
LNB Sample
Right Angle Prisms
Springs
Macor Holder
Ceramic T-shaped