# *Beam Measurements at the CERN SPS using interferometric Electro-Optic Pickups*

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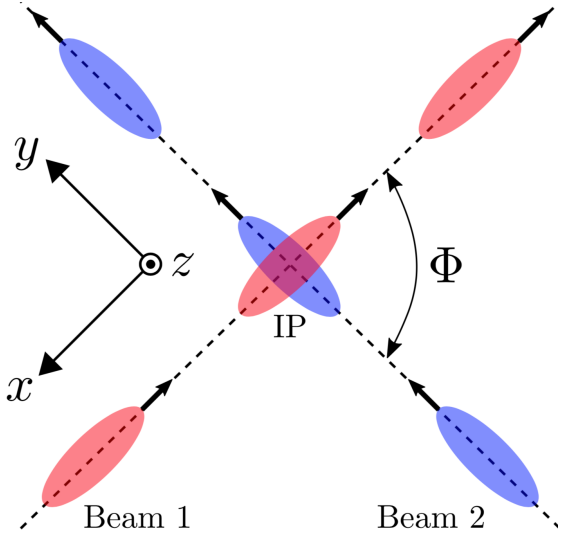
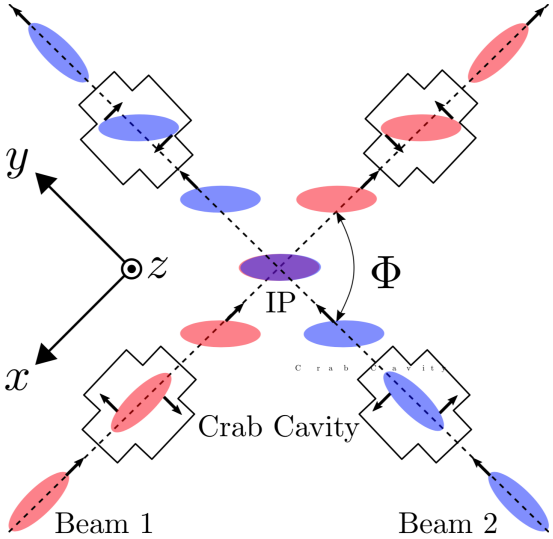
# Outline

- Motivation.
- Electro-optic BPM concept:
  - Electro-Optic Configurations, EM simulations and sensitivity.
- Summary of results with the SPS prototype:
  - SPS 2016-17 prototype run installation and results.
  - SPS 2018 compact interferometric setup run installation and results.
- Review of projects status:
  - Pickup design upgrade towards the HL-LHC prototype: EM simulations.
- Conclusions

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




**LHC: 23** interactions



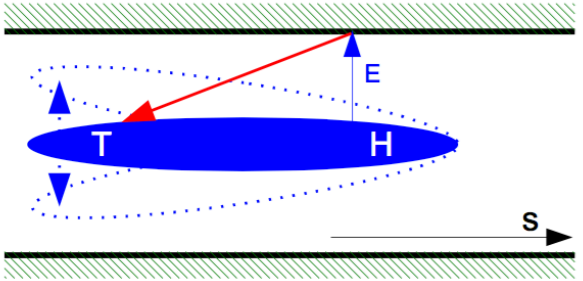

**HL-LHC: 140** interactions

- ***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.***

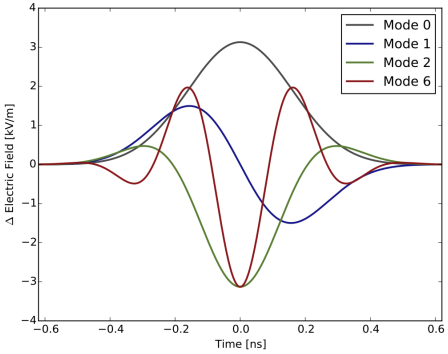
# Motivation: intra-bunch diagnostics / crabbed bunches

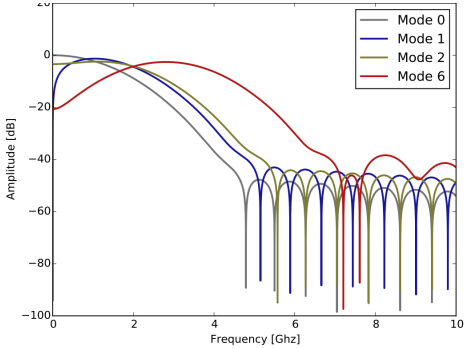
- The EO-BPM project grew out of idea to upgrade the Head Tail monitor; to visualize and study beam instabilities as they occur.
  - Applicable at HL-LHC to monitor effects on crabbed bunches.
- Standard approach:
  - Stripline BPMs + fast sampling oscilloscopes.
- Limitation:
  - Bandwidth up to a few GHz, limited by pick-up, cables, and acquisition system
- A new technology is needed:

***Fast electro-optic pick-up***




transverse



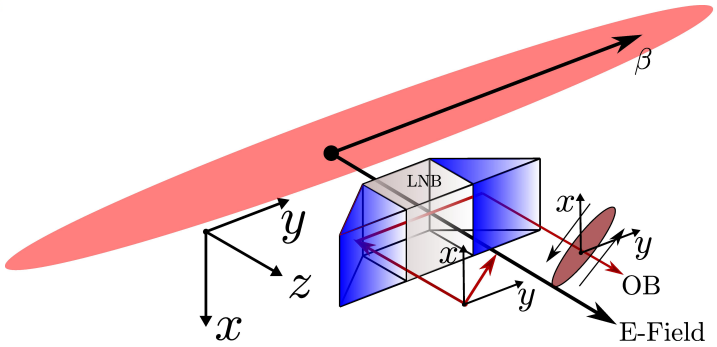




Gaussian Charge Distribution: **4σ = 1.0ns**

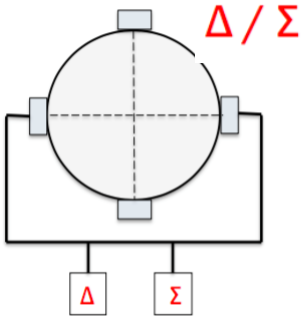
**GOAL:** Mode 6 detection with a time resolution lower than 100ps

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

# Pickup concept

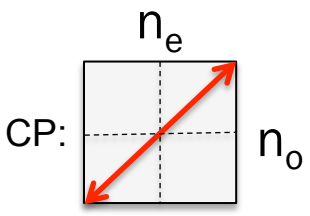



- Replace pick-ups in a button BPM with electro-optic crystals.
- The electric field from a passing bunch induces a polarization and/or phase change of light through the crystal(*).
- Fibre-coupled design with laser and detectors 160 m away from accelerator tunnel.
- Transverse position along the 1 ns LHC bunch is monitored.

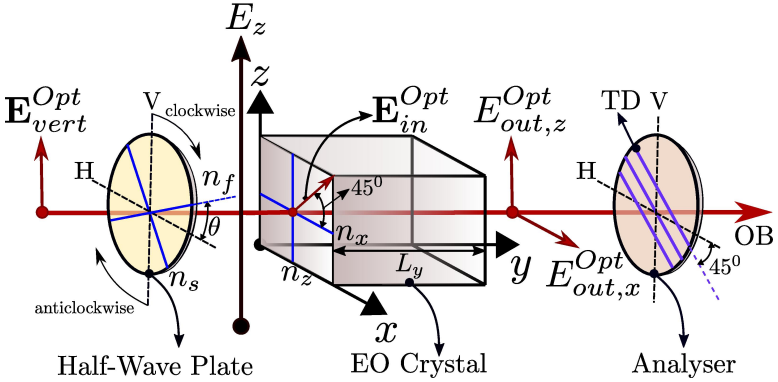


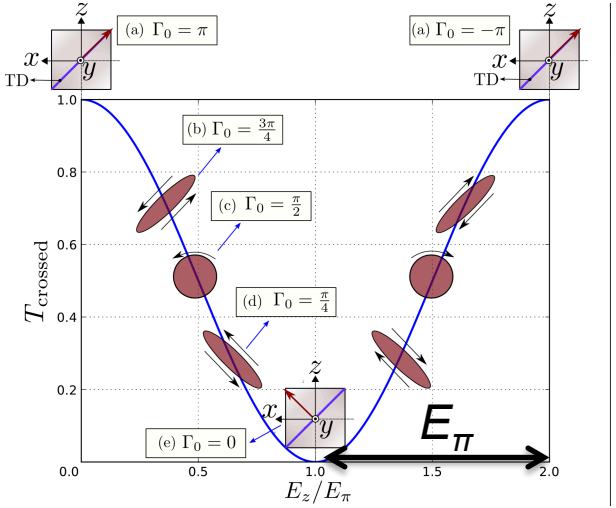

(*) HIGH FREQUENCY ELECTRO-OPTIC BEAM POSITION MONITORS FOR INTRA-BUNCH DIAGNOSTICS AT THE LHC, S.M. Gibson et al., IBIC'15

# Pickup concept: Detection by optical modulation




CP LNB
Input Face



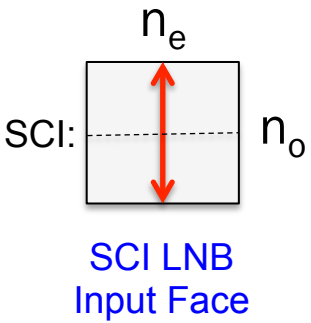



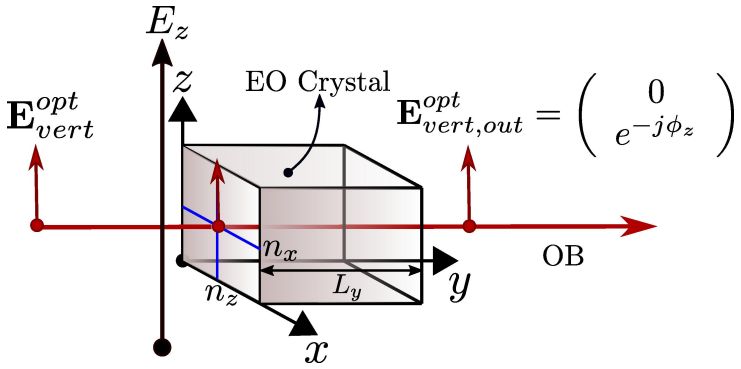

Transfer Function

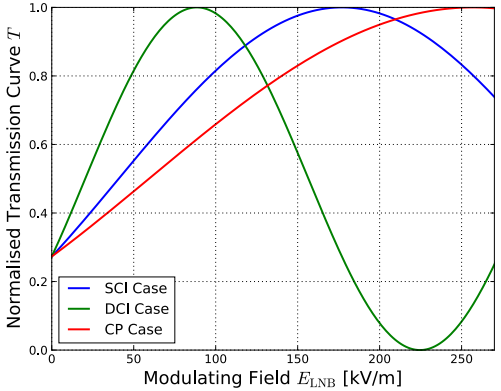
- Crossed Polarisers (CP): Different input and output Polarisation.
- Sensitivity determined by the transfer function *T* and $E_\pi$

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

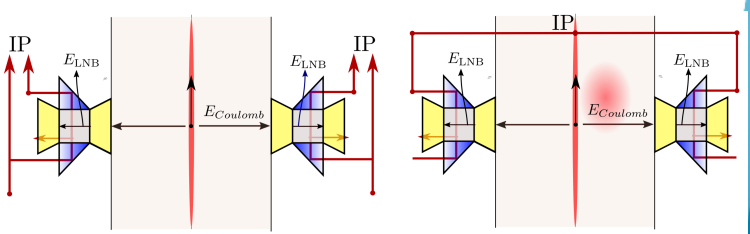
# Pickup concept: Detection by optical modulation



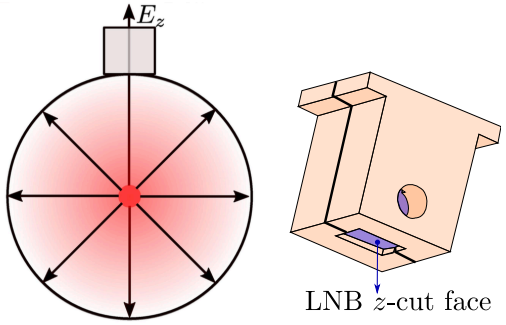



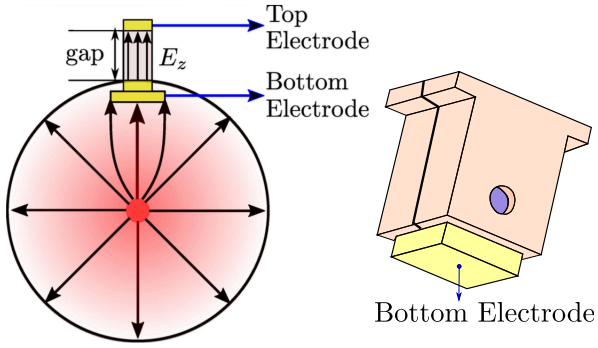

- Single Crystal (SCI) and Double Crystal Interferometer (DCI): Same linear input and output polarisation.
- Sensitivity $E_{LNB}/E_{\pi}$ improved by a factor X1.45 for SCI.
- Sensitivity $E_{LNB}/E_{\pi}$ improved by a factor X1.45 X2 for DCI



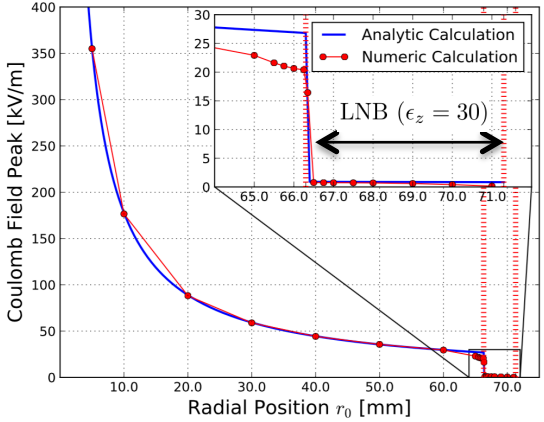
# 2016-17 SPS run: Pickup Design




$\times 8$




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




- Pickup version Zero(*):
  - 5mm cubic crystal.
  - $E_{T\pi}$= @ 780nm.
  - No floating electrode.
  - $E_{LNB}$=0.68 kV/m

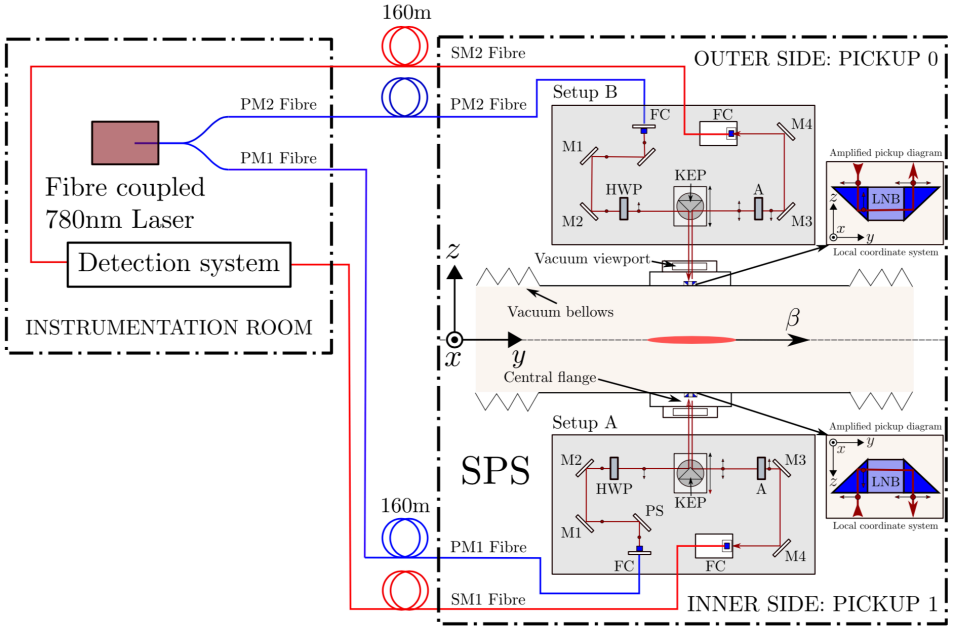
- Pickup version One:
  - 9mm long crystal
  - $E_{T\pi}$= @ 780nm.
  - Crystal between electrodes.
  - $E_{LNB}$=2.8 kV/m

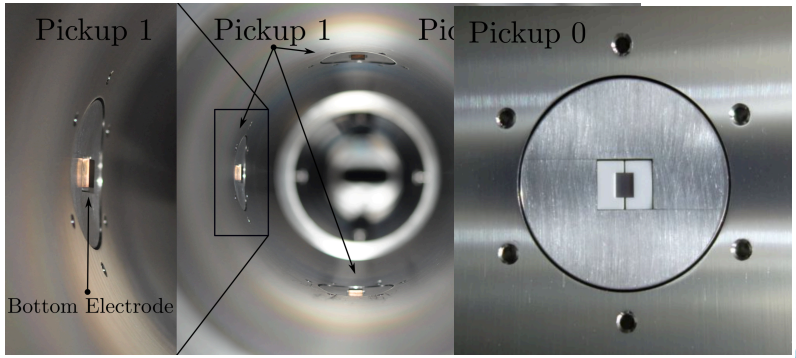
$$\text{Electrode}\left(\frac{w_2}{w_1}\right) \rightarrow \times 4.3$$

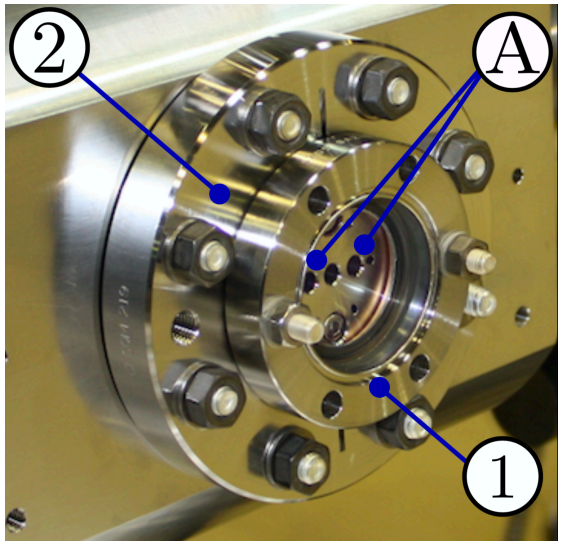
$$\frac{9\,\text{mm}}{5\,\text{mm}} = \times 1.8$$

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

# 2016-2017 SPS run: Installation



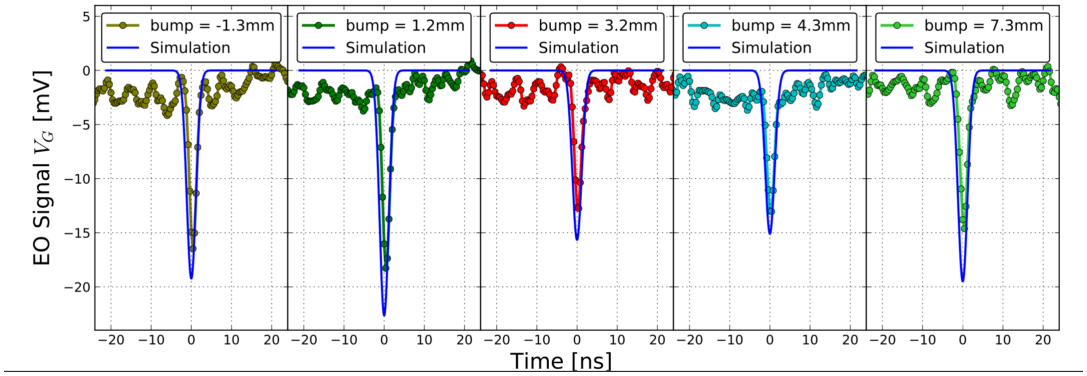



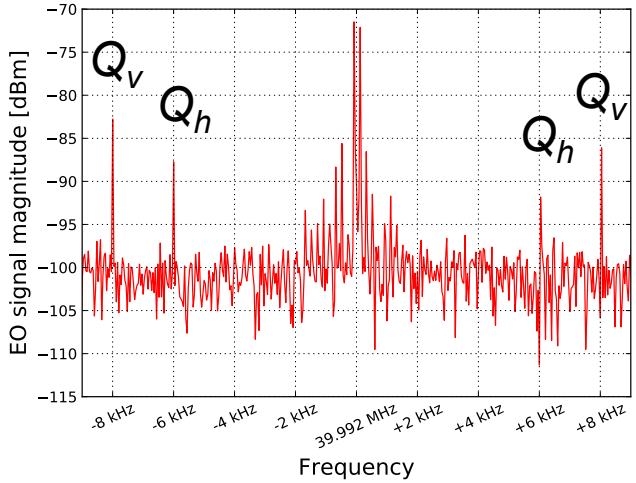

- Installation during the 2015/16 shutdown(*).
- λ=780nm

(*) 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 signals:

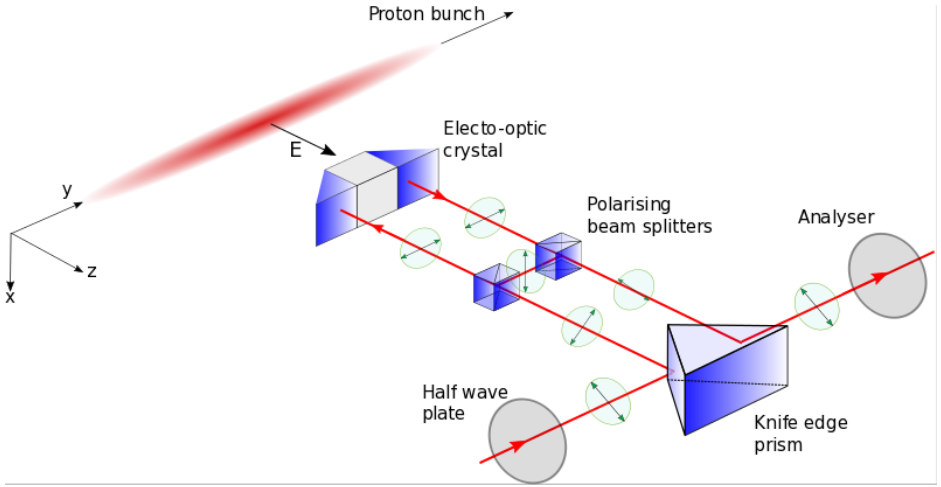


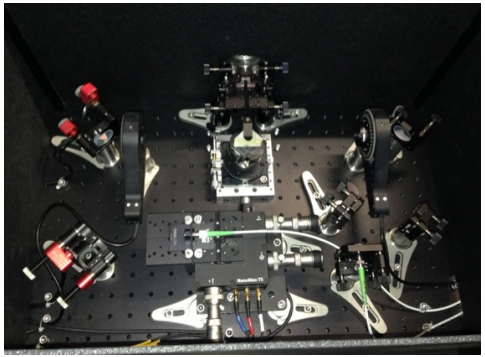



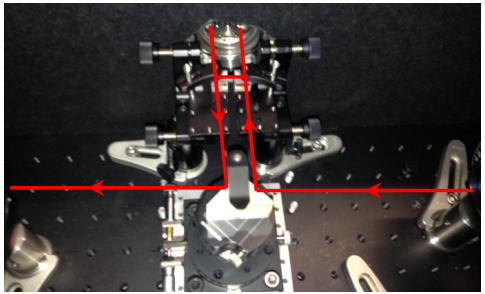

1. **December, 2016:** First proton beam-induced EO detection (PU zero)
2. **June, 2017:** Confirmation of the improvement factor X8 (PU one)
3. **June, 2017**: Confirmation of the transverse offset sensitivity at 66.5 mm (PU one)
4. **July, 2017**: Indirect detection of the SPS betatron tune (PU one)

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

# 2017 SPS run: SCI with PU zero



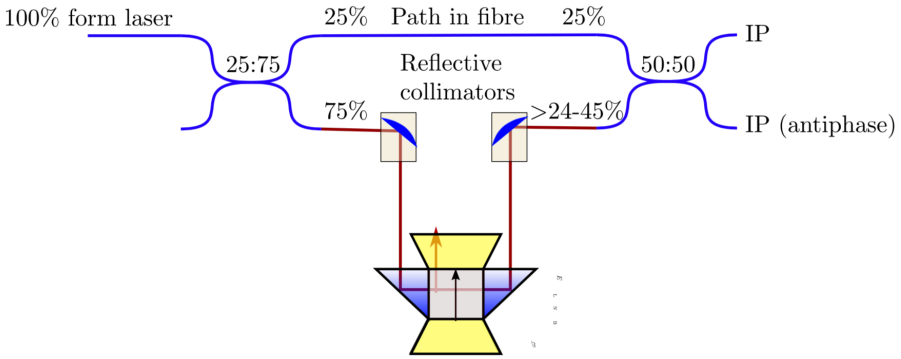



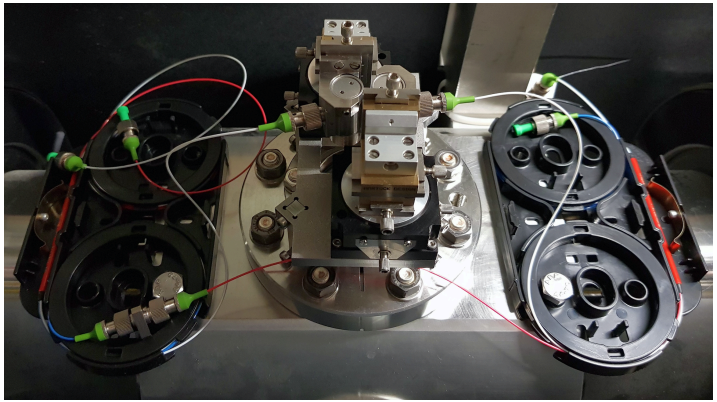


- Gain factor ~1.4.
- Main upgrade: Tunability of the sensitivity by shifting the laser wavelength(*).
- Main Challenge: mechanical stability.

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

# 2018 SPS run: SCI with PU one

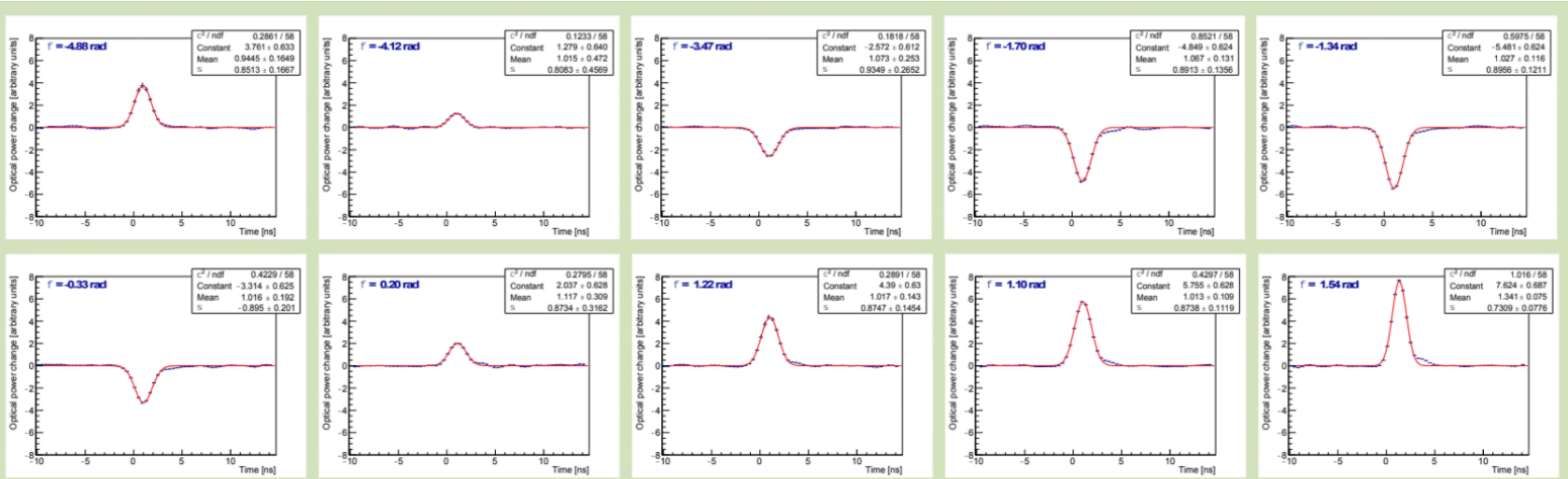


- Installation of the fibre-coupled compact design during the 2017/18 SPS shutdown(*)(**).
- The system uses compact reflective collimators to align the laser beam through the crystal.
- Challenge: Mechanical stability.

(*) 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.*

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

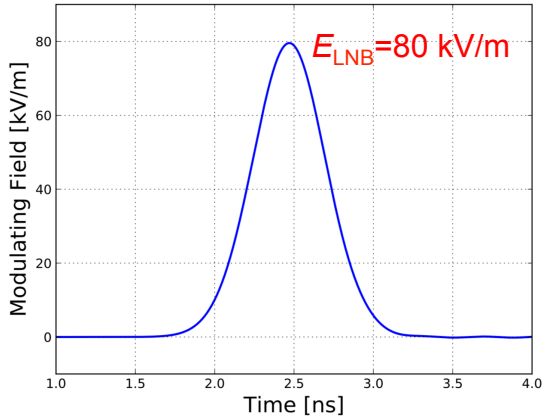
(*) ENHANCED BUNCH MONITORING BY INTERFEROMETRIC ELECTRO-OPTIC METHODS, S.M. Gibson et al., IPAC'18

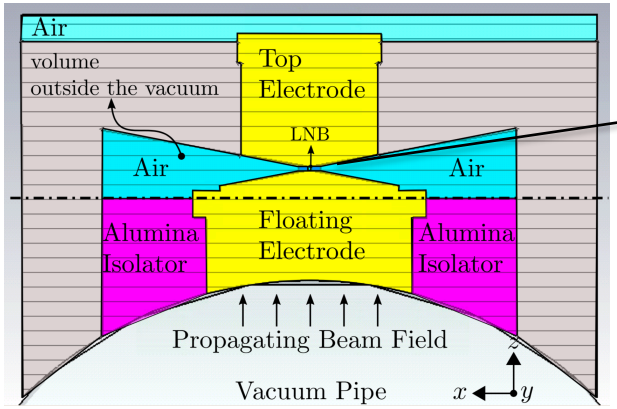
# Future: Hi-Lumi LHC Design

1. High-Luminosity LHC Design studies ongoing based on CST Electro-Magnetic Simulations.
2. Optical waveguide crystal solution with a size reduction: (*Lx*,*Ly*,*Lz*)=(1mm,9mm,0.3mm)
3. Enhancement of the modulating field $E_{LNB}$ from 2.8kV/m up to 80 kV/m (*Ly*=300μm).
4. Important mechanical upgrade: Crystal Outside vacuum.
5. Higher optical power (1mW➔20mW), which in combination with a DCI arrangement (X2) would improve the optical modulation by a factor 1000:

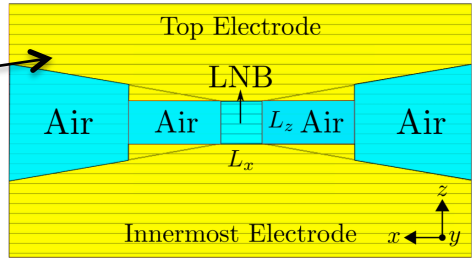
$$\frac{80\,\mathrm{kV/m}}{2.8\,\mathrm{kV/m}} \times \frac{20\,\mathrm{mW}}{1\,\mathrm{mW}} \times 2 > 10^3$$

(*)




Outside Vacuum:




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

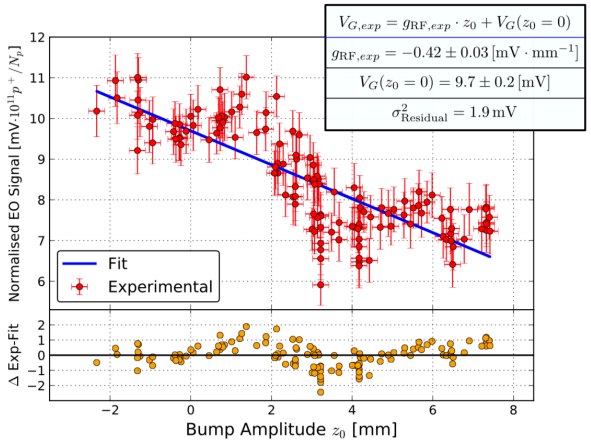
# Conclusions

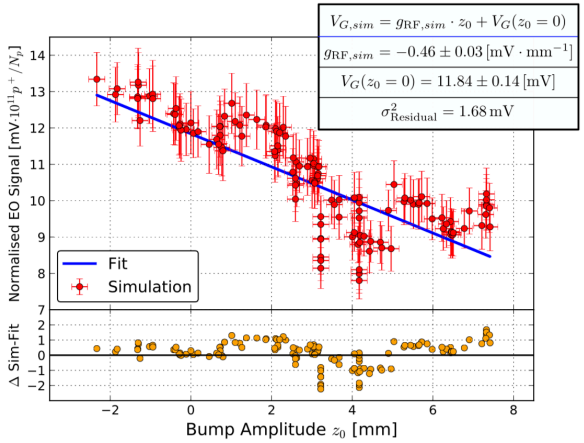
***Electro-Optics Beam Position Monitor developments progressing well:***

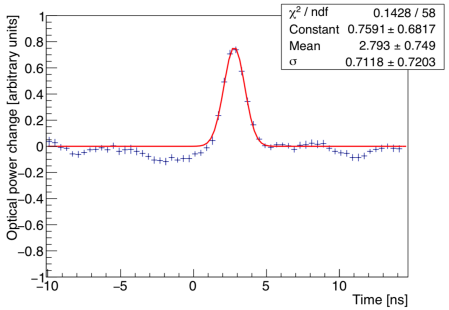
- *The prototype pickup has enabled first transverse position sensitivity by EO means at 66.5 mm away form the proton beam in the SPS.*
- *SPS interferometric prototype has been installed, with first beam signal observed in January 2017.*
- *Measured beam signals match well with electromagnetic simulations, giving confidence in future design work for the LHC prototype.*
- *The HL-LHC design is expected to improve significantly the optical modulation signal by enhancing the modulating field and improving the detection system.*

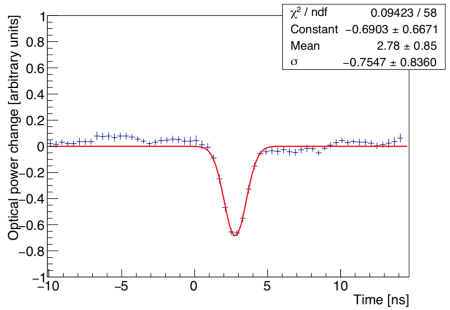
# Thank you for your attention!

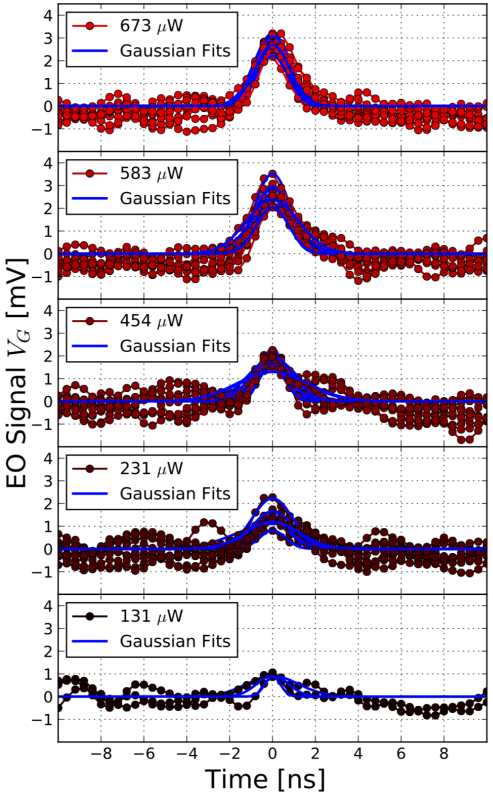
# Backup


$V_{G,exp} = g_{RF,exp} \cdot z_0 + V_G(z_0 = 0)$
$g_{RF,exp} = -0.42 \pm 0.03\,[\mathrm{mV \cdot mm^{-1}}]$
$V_G(z_0 = 0) = 9.7 \pm 0.2\,[\mathrm{mV}]$
$\sigma^2_{\mathrm{Residual}} = 1.9\,\mathrm{mV}$
Normalised EO Signal [mV·10^11 p+ /Np]
Fit
Experimental
Δ Exp-Fit
Bump Amplitude $z_0$ [mm]

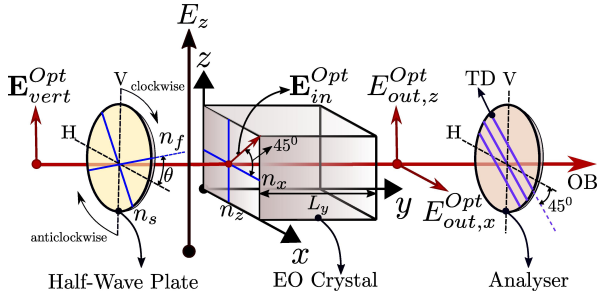

$V_{G,sim} = g_{RF,sim} \cdot z_0 + V_G(z_0 = 0)$
$g_{RF,sim} = -0.46 \pm 0.03\,[\mathrm{mV \cdot mm^{-1}}]$
$V_G(z_0 = 0) = 11.84 \pm 0.14\,[\mathrm{mV}]$
$\sigma^2_{\mathrm{Residual}} = 1.68\,\mathrm{mV}$
Normalised EO Signal [mV·10^11 p+ /Np]
Fit
Simulation
Δ Sim-Fit
Bump Amplitude $z_0$ [mm]


χ² / ndf 0.1428 / 58
Constant 0.7591 ± 0.6817
Mean 2.793 ± 0.749
σ 0.7118 ± 0.7203
Optical power change [arbitrary units]
Time [ns]


χ² / ndf 0.09423 / 58
Constant −0.6903 ± 0.6671
Mean 2.78 ± 0.85
σ −0.7547 ± 0.8360
Optical power change [arbitrary units]
Time [ns]

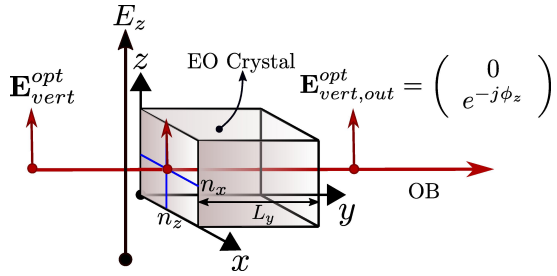

673 μW
Gaussian Fits
583 μW
Gaussian Fits
454 μW
Gaussian Fits
231 μW
Gaussian Fits
131 μW
Gaussian Fits
EO Signal $V_G$ [mV]
Time [ns]

# Backup




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

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

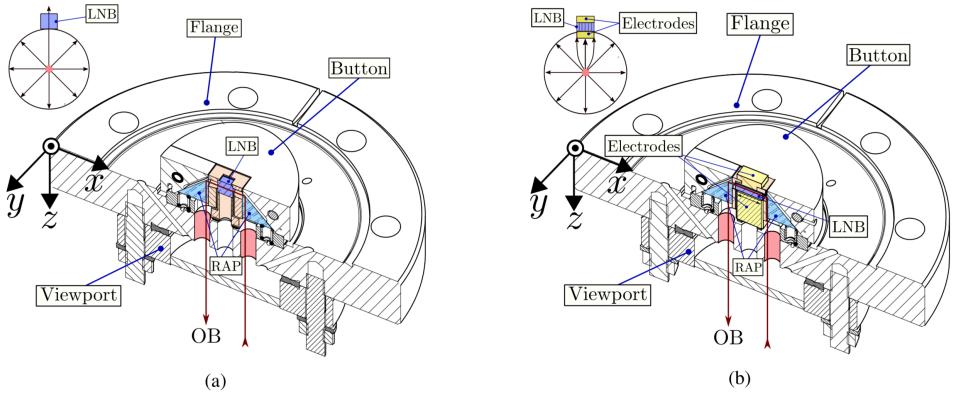



$$\phi(t) = \frac{2\pi}{\lambda} n_e l + \frac{\pi}{\lambda} n_e^3 r_{33} l E_{az}(t)$$

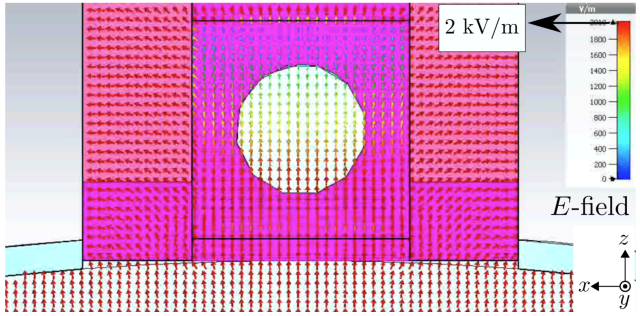
$$\longrightarrow \quad E_{\pi,\text{inter}} = \frac{\lambda}{r_{33} n_e^3 L_y}$$

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

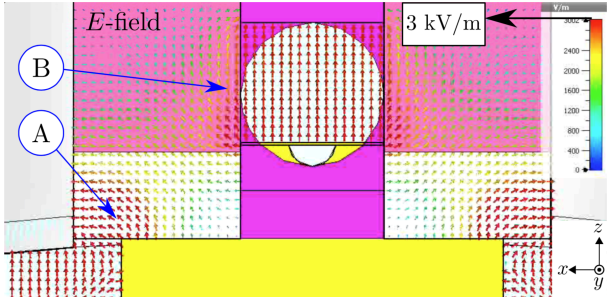
# Backup



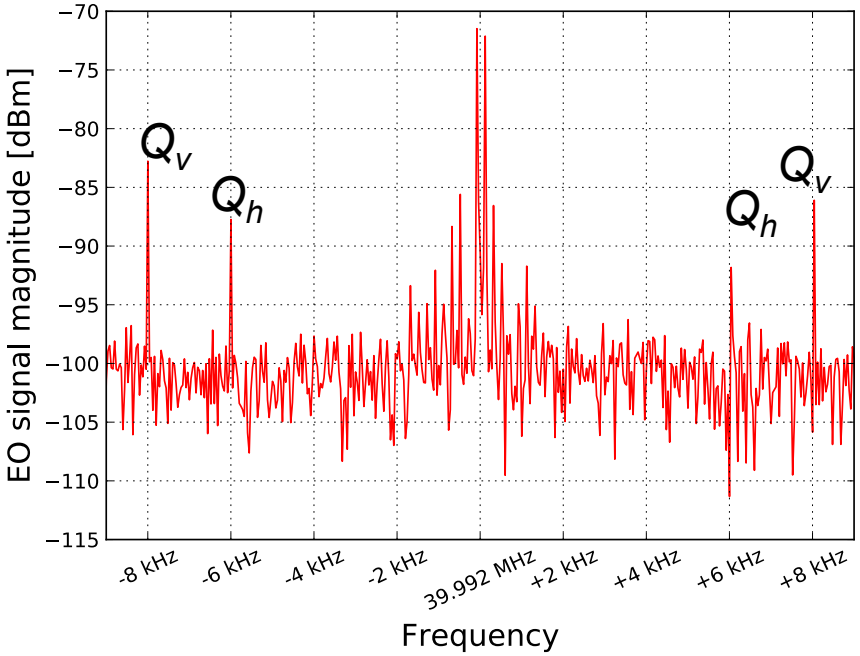

## Pickup Zero




## Pickup One



# Backup




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

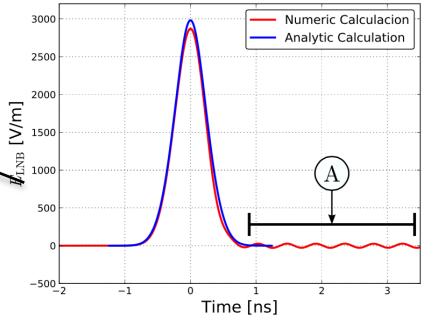
$$Q_h = \frac{6}{43.375} = 0.138$$

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

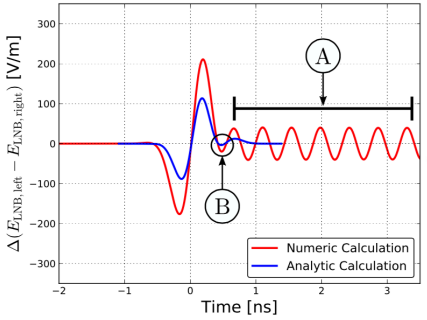
# Backup

## Studies on HT detection

Crabbed-like beam distribution




(a) Single pickup, mode = 1.

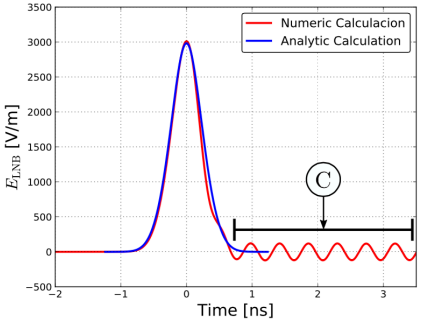



(b) $E_{LNB,right} - E_{LNB,left}$, mode = 1.

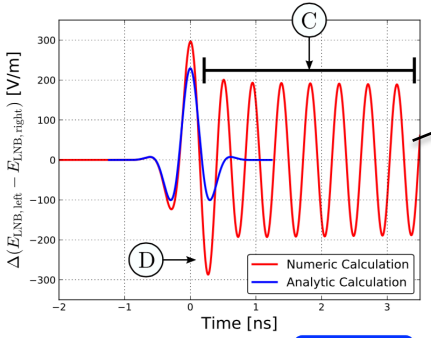
Pickup One

Resonance

For a rod–like shaped electrode!

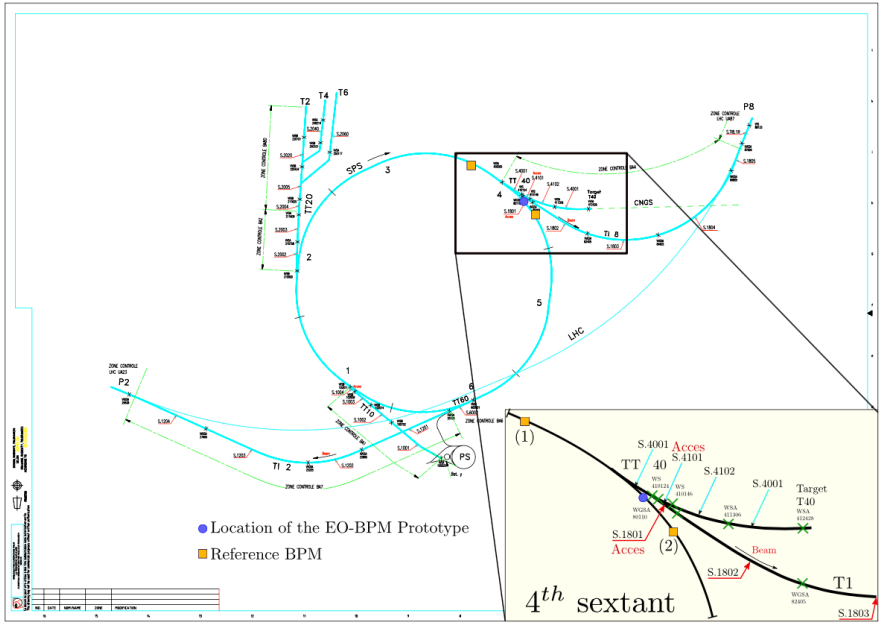


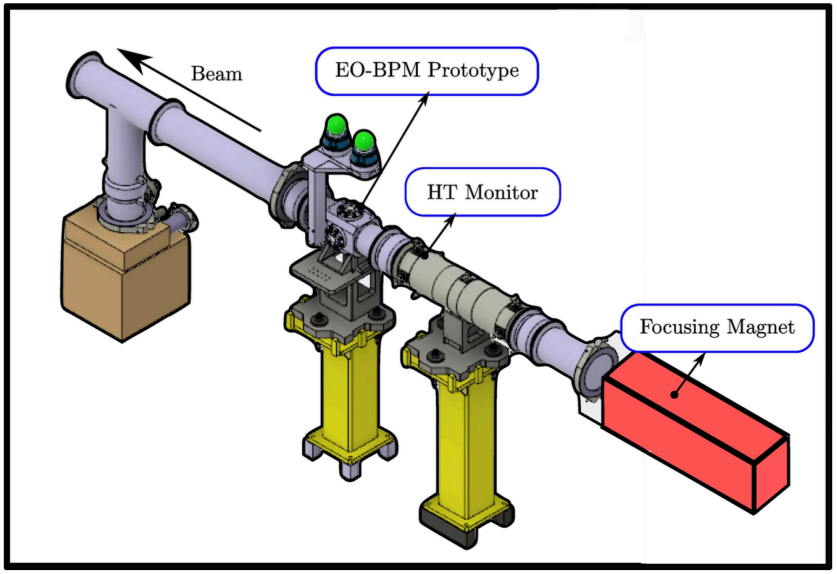

(c) Single pickup, m=6.



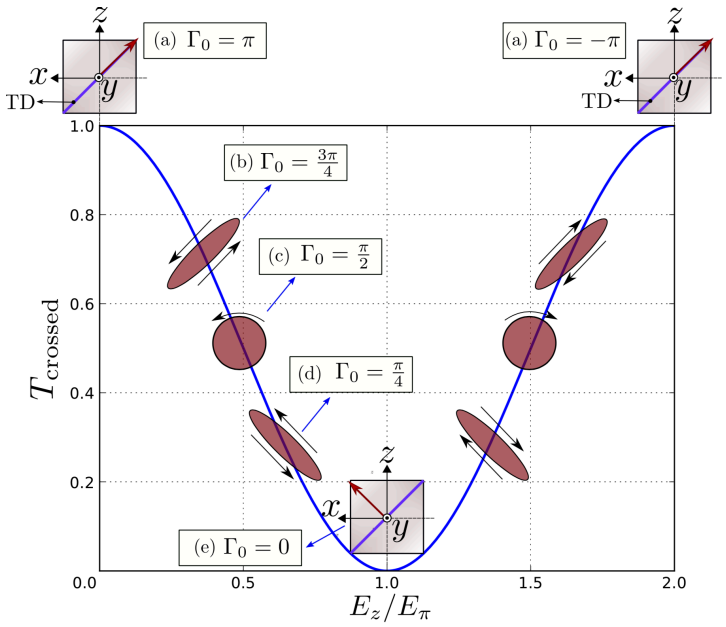

(d) $E_{LNB,right} - E_{LNB,left}$, mode = 6.

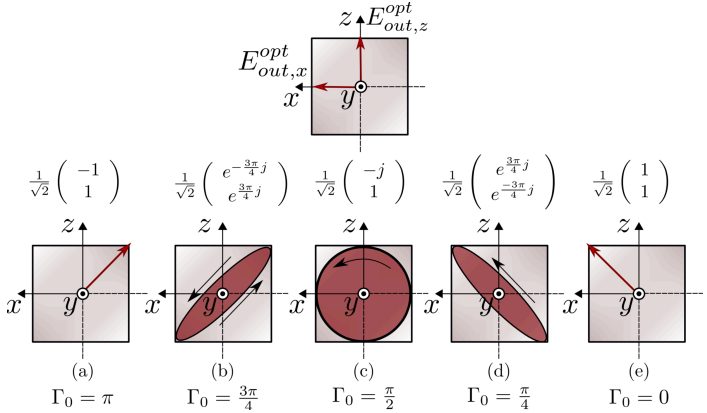
# Backup


T2
T4
T6
P8
SPS
TT20
CNGS
LHC
P2
TT10
TT60
PS
TI 2
TI 8
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

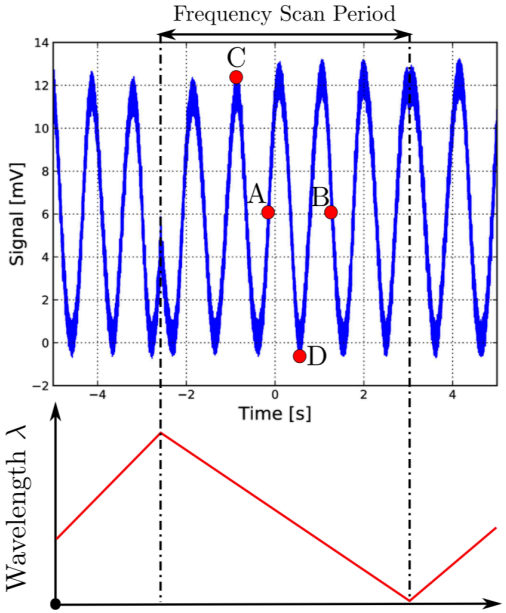

Beam
EO-BPM Prototype
HT Monitor
Focusing Magnet

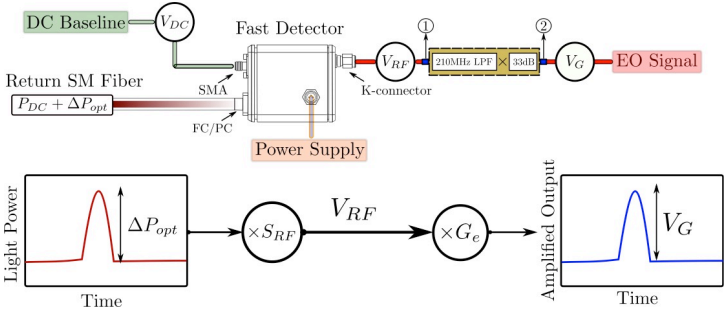
# Backup


(a) $\Gamma_0 = \pi$
(a) $\Gamma_0 = -\pi$
TD
TD
(b) $\Gamma_0 = \frac{3\pi}{4}$
(c) $\Gamma_0 = \frac{\pi}{2}$
(d) $\Gamma_0 = \frac{\pi}{4}$
(e) $\Gamma_0 = 0$
$T_{\text{crossed}}$
$E_z/E_\pi$
0.0
0.2
0.4
0.6
0.8
1.0
0.5
1.0
1.5
2.0


$E^{opt}_{out,z}$
$E^{opt}_{out,x}$
$\frac{1}{\sqrt{2}}\begin{pmatrix}-1\\1\end{pmatrix}$
$\frac{1}{\sqrt{2}}\begin{pmatrix}e^{-\frac{3\pi}{4}j}\\e^{\frac{3\pi}{4}j}\end{pmatrix}$
$\frac{1}{\sqrt{2}}\begin{pmatrix}-j\\1\end{pmatrix}$
$\frac{1}{\sqrt{2}}\begin{pmatrix}e^{\frac{3\pi}{4}j}\\e^{\frac{-3\pi}{4}j}\end{pmatrix}$
$\frac{1}{\sqrt{2}}\begin{pmatrix}1\\1\end{pmatrix}$
(a) $\Gamma_0 = \pi$
(b) $\Gamma_0 = \frac{3\pi}{4}$
(c) $\Gamma_0 = \frac{\pi}{2}$
(d) $\Gamma_0 = \frac{\pi}{4}$
(e) $\Gamma_0 = 0$

# Backup

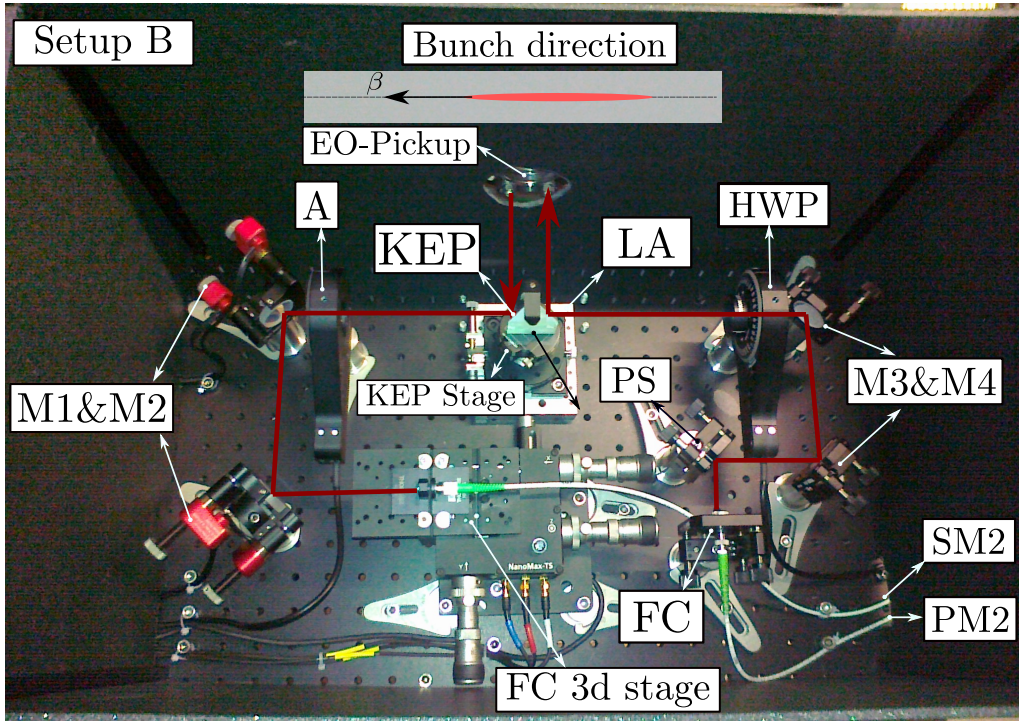


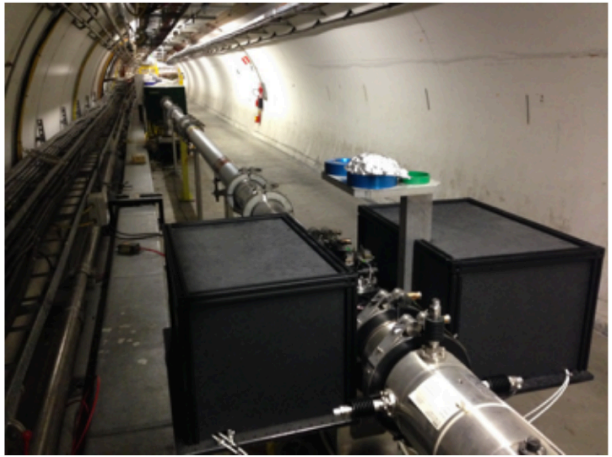



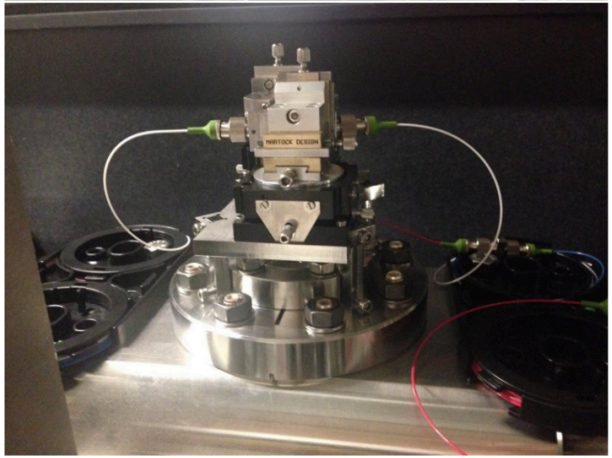

**EO Modulation**
Pickup Design

**Modulation Detection**
Acquisition System

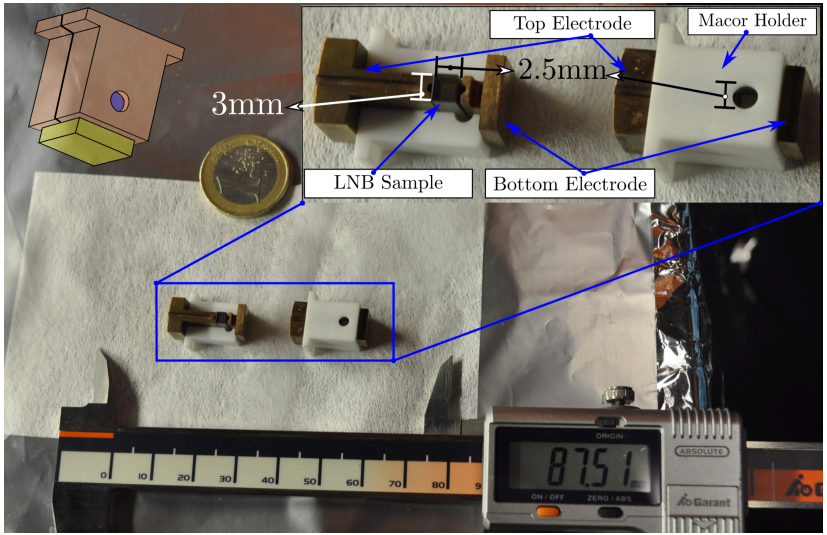
# Backup

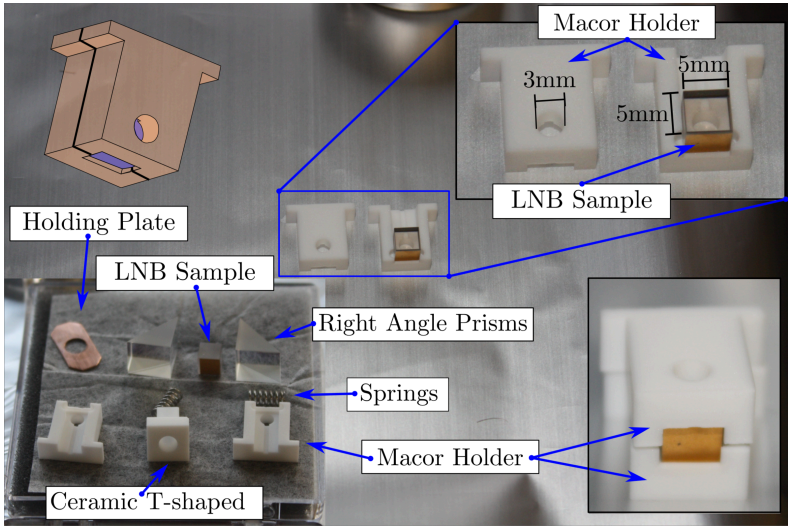

Setup B
Bunch direction
β
EO-Pickup
A
KEP
LA
HWP
M1&M2
KEP Stage
PS
M3&M4
SM2
FC
PM2
FC 3d stage





# 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

# Backup

| | | |
|---|---|---|
| 2016 | D | Pickup zero: First proton-induced EO Signal |
| 2017 | J | Pickup one installation |
| | F | |
| | M | First EO Signal with pickup one |
| | A | Measurement of the factor x8 improvement |
| | M | |
| | J | Transverse offset beam detection at 66.5mm |
| | X | SPS Betatron tune detection |
| | A | |
| | S | Free space interferometric setup installation |
| | O | First free space interferometric detection with pickup zero |
| | N | |
| | D | Interferometric compact design installation |
| 2018 | J | |
| | F | Sensitivity drift problem fixed by laser tunability |
| | M | |
| | A | First enhanced interferometric EO signal with pickup one<br>Obtained from the compact design |
| | M | |
| | J | |
| | X | |
| | A | |
| | S | |
| | O | |
| | N | Further interferometric measurements at continous<br>acquisition and from opposing pickups simultaneously |
| | D | |