Some slides related to:

Options for the design of the new pick-up and schedule

-

Ralph J. Steinhagen,

Beam Instrumentation Group, CERN;

Some of the mentioned Options

A) long strip-line (not ideal for 10 ns bunchlets, >60 cm feasible but requires probably intermediate support)

B) Position sensitive wall-current monitor (Marek's design/tested: 1/10 Mhz <-> >1 GHz should be feasible, 1-10 Ohm loading, differential L~70 nH)

- *M. Gasior, AB-Note-2003-082 BDI*
- *M. Gasior, CERN-AB-2003-053 BDI, CLIC Note 572, CTF3 Note 056*

C) Exponential strip-line (that's what you have)

- *T. Linnecar, “The high frequency longitudinal and transverse pick-ups in the CERN SPS accelerator”, PAC'79, 1979*
- *T. Linnecar, “The high frequency longitudinal and transverse pick-ups used in the SPS”, CERN-SPS-ARF-78-17, 1979*

D) SL-BPM (already tested, good performance, and shares AFE with EO-BPM, probably not sufficient for SPS)

- *Dawson et al., “Storage Ring Tune Measurements using High-Speed Metal-Semiconductor-Metal Photodetectors”, IBIC'12, 2012*
- *R. Steinhagen et al., “Application of Metal-Semiconductor-Metal (MSM) Photodetectors for Transverse and Longitudinal Intra-Bunch Beam Diagnostics, IBIC'13, 2013*

E) EO-BPM (only lab tests for the full assembly until now, hope to have a in-vacuum prototype ready for post-LS1) → *to be published*

Upgrade/Improvement Road-Map

Tackle three domains independently:

A) Pick-up – improve bandwidth, linearity, power-issues, EMC susceptibility:

1. Synchrotron-Light based BPM → dual use CTF3 & LHC
   - Collaboration with ACAS (Uni-Melbourne and ASLS)
2. Direct EO-based BPM → machine/beam type independent
   - Plan to design/integrate prototype monitor to be installed in SPS during LS-1
3. Wider-band, electro-magnetic pick-up → ???

B) Analog front-end:

1. Time-Domain: new wide-band ~DC-6/8 GHz Σ-Δ hybrid
2. Frequency-Domain: new Multiband-Instability-Monitor (MIM)
   - Used also as a pre-/post-trigger for the time-domain acquisition
   - Collaboration with ACAS (Uni-Melbourne and ASLS)

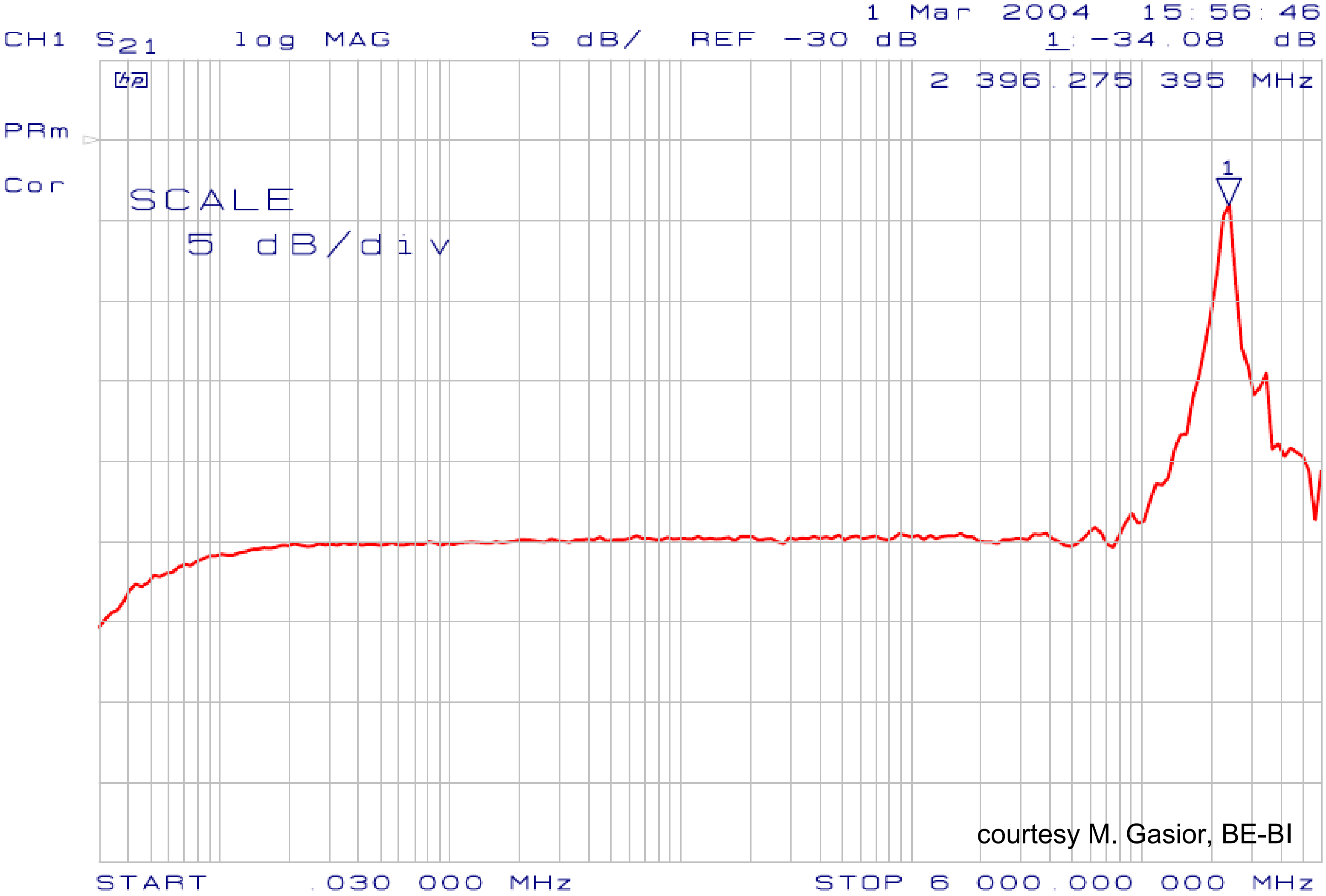
C) Digital-Data-Acquisition – large PM-type history buffer, online pre-processing

1. GUZIK DAQ: 64GB, 20 GS/s, 4.5 – 13 GHz BW, ext. FPGA firmware
2. Bunch-by-bunch DAQ (needed for B.2) ↔ related to b-b-b BBQ activities

-

Position sensitive Wall-Current Monitor

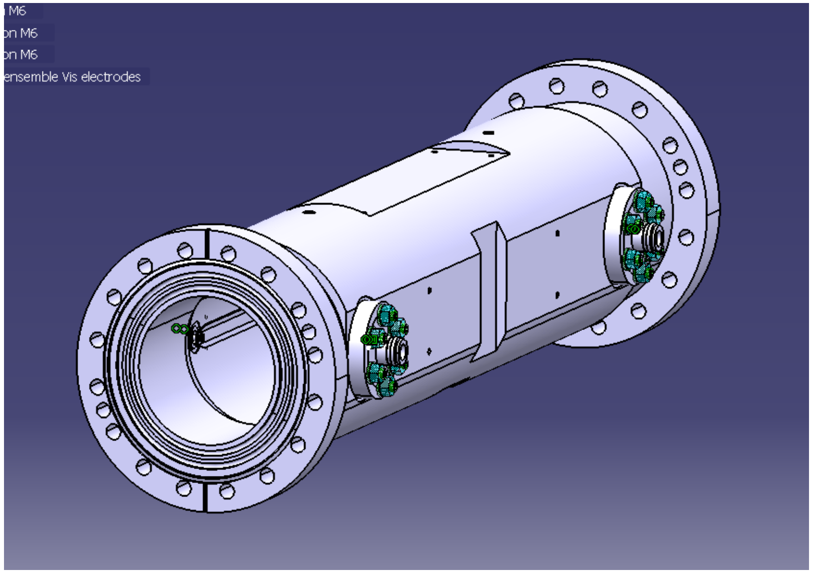
- Based on M.Gasior's design (here resistive load),
  - *AB-Note-2003-082 BDI, CERN-AB-2003-053 BDI, CLIC Note 572, CTF3 Note 056*

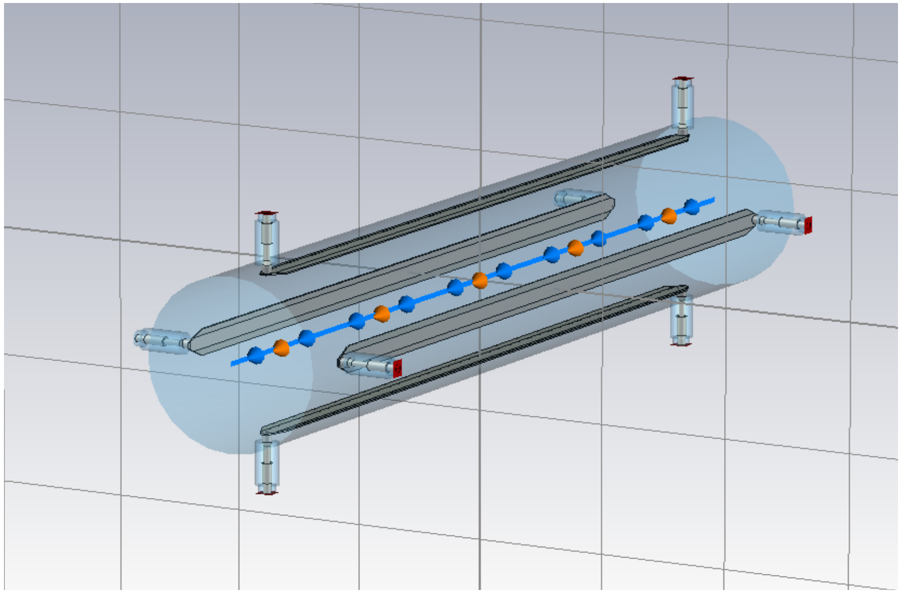


courtesy M. Gasior, BE-BI

Classical Head-Tail Instability Detection I/II

- Fast inter- and intra-bunch beam instability monitor used to detect and study e-could-, impedance- and TMCI-driven head-tail effects
- Diagnostics typically based on strip-line pick-ups, challenges:
  - very wide-band frequency response: 0 ... 2.5 (present)... 8 GHz (target)
  - nom. bunch intensity: $n_b \approx 1.2 \cdot 10^{11}$e+/bunch (20 nC) & $\sigma_t \approx 0.2$ ns
    ↔ $V_{pp} \sim n_b^2 \sim 300$ V and frequency range of 0 - 1.7 - 3 GHz
    → LIU upgrade: $n_b \rightarrow 5 \cdot 10^{11}$e+/bunch
    (x 16 power, not many HF & broad-band components that can handle this)
- Standard HT approach: BPCL.421 – 60 cm long strip-line monitor:

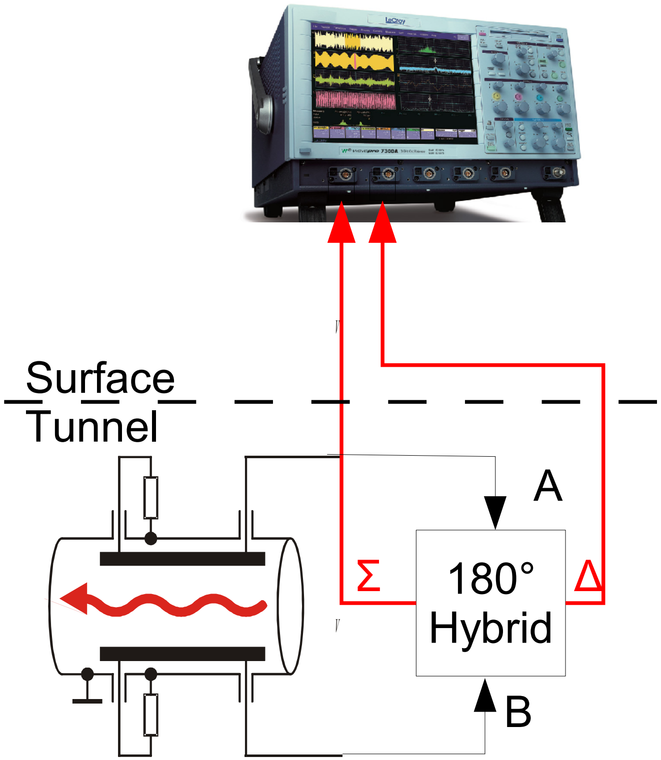




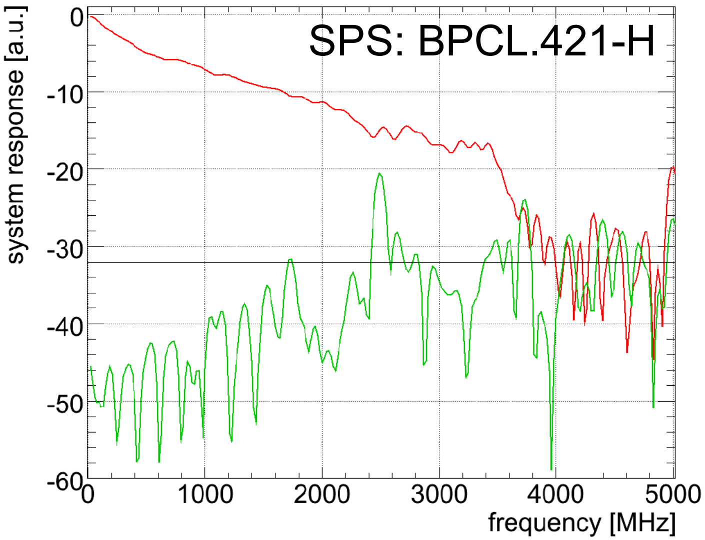
Classical Head-Tail Instability Detection II/II

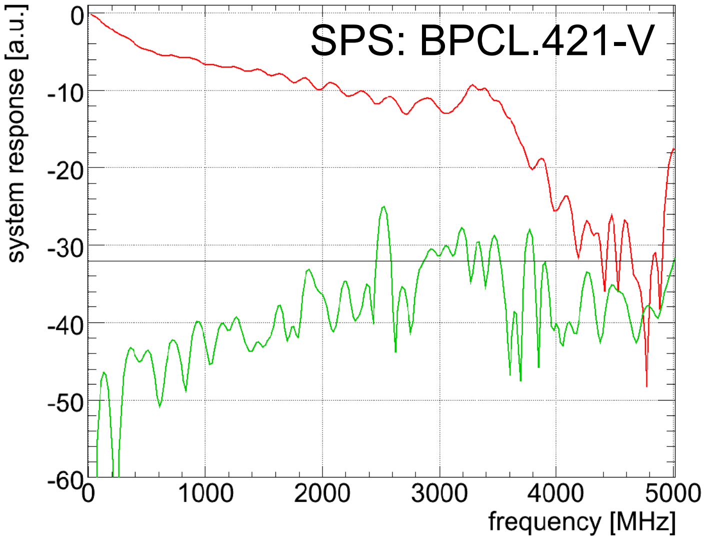
Implemented/tested at CERN-SPS, Tevatron, LHC:

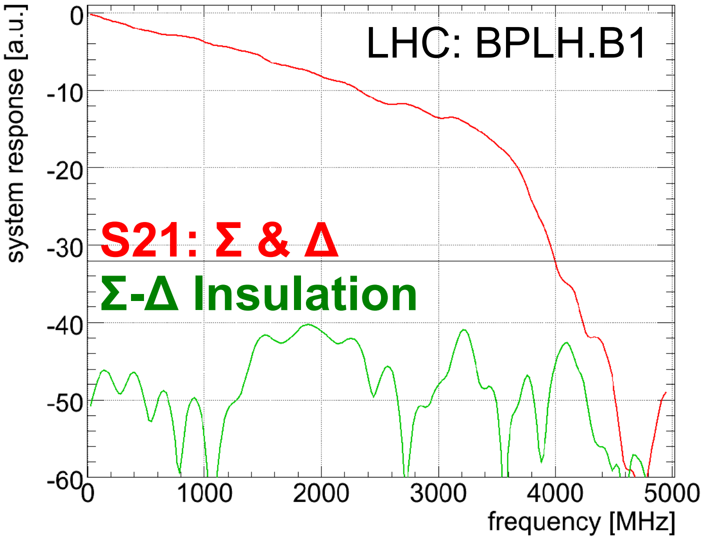
- Long strip-line BPM (60 cm, to avoid signal-reflection mixing)
- Σ-Δ hybrid (removes common mode signal)
- Fast-sampling to resolve bunch structure
  - ~ ns bunch length → GHz scope bandwidth
- Need to compensates for non-beam effects:
  - pickup- & hybrid response,
  - cable dispersion, …
  - cable reflection, imperfect impedance matching
  - electrical offsets

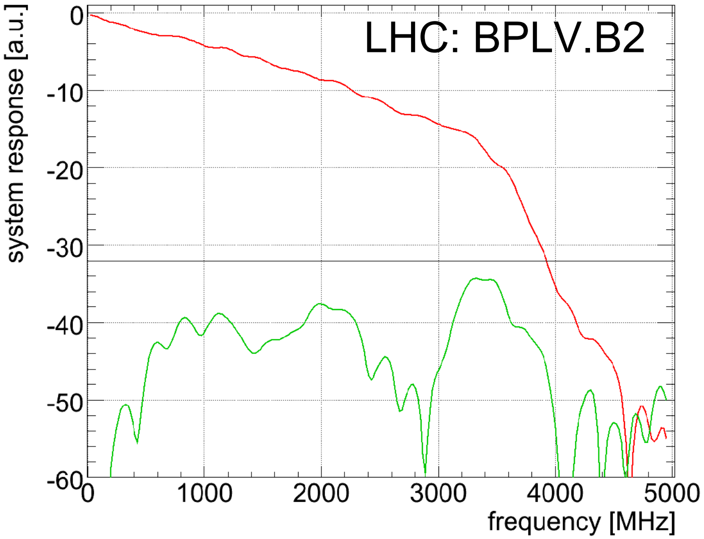


Limits of Classical Head-Tail Monitoring Approach
For Comparison: SPS/LHC HT System Response





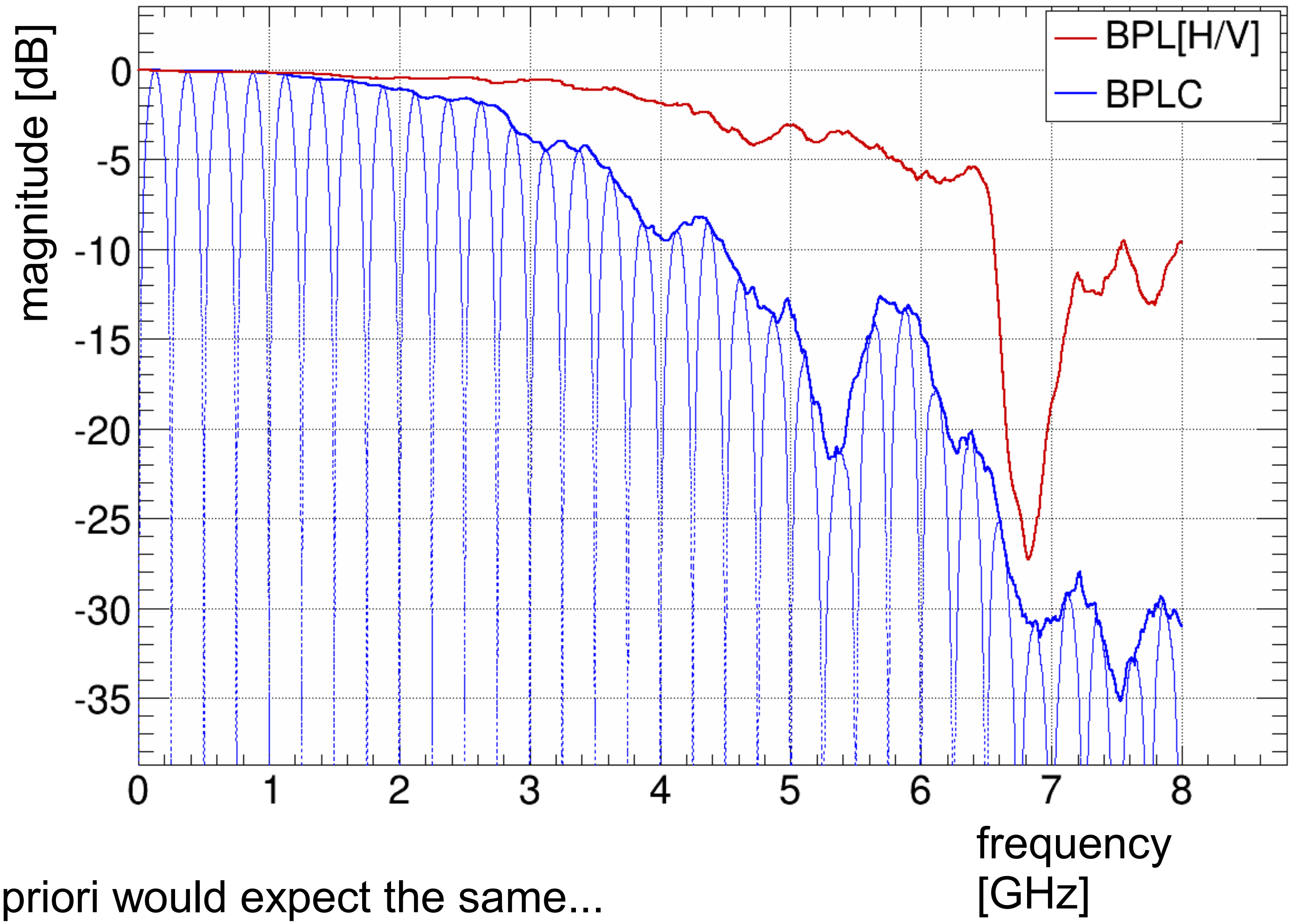




- Roll-off at ~ 3.5 GHz due to limited scope bandwidth
- Better performance for LHC HT → SPS deserves something better

Strip-Line BPM Response

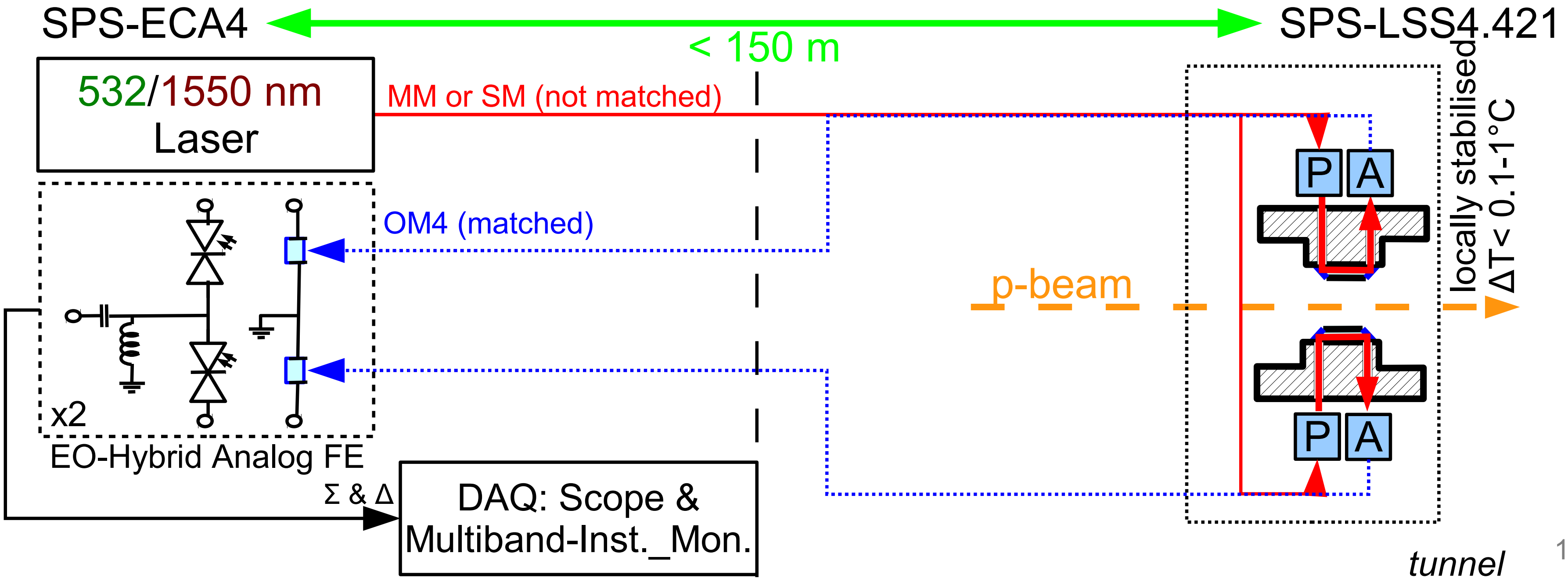
- Similar strip-line design with response up to 3 (5) GHz bandwidth...



- A priori would expect the same...
  … differences likely due to RF feed-through dielectric material/geometry
- N.B. details to published as CERN report...

Analog Frontend and Pickup Improvements I/II
Synchrotron Light- & Electro-Optical Beam Position Pickup

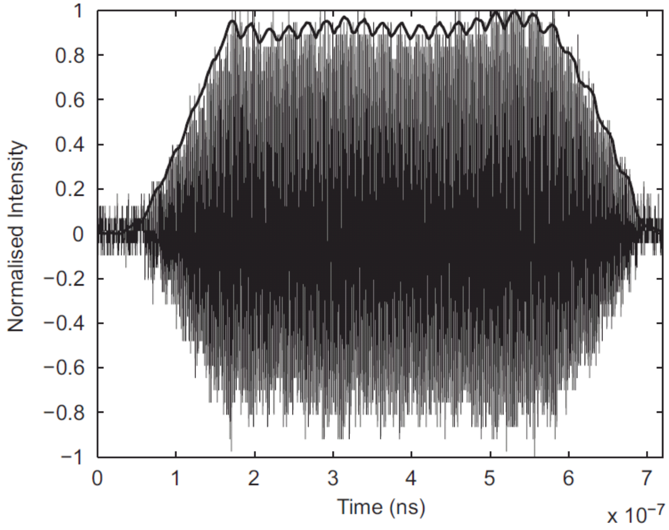
- SynchLightBPM – collaboration with ACAS (Australian Universities & Labs)
  - pro: very wide-band signal (tested up to 12 GHz), large dynamic range, DC response
  - con: not enough free view-ports available → envisage this for LS2?
- Electro-Optical Pick-Up
  - working principle similar to LCD/TFT screen: particle beam modulates crystal birefringence → intensity of two laser beams A & B, position ~ (A-B)/(A+B)
  - pro: very wide-band signal, no beam power issues, true DC response (alt. AGM?)
  - SPS Prototype to be installed during LS-1 → also in LHC (LS-2?)

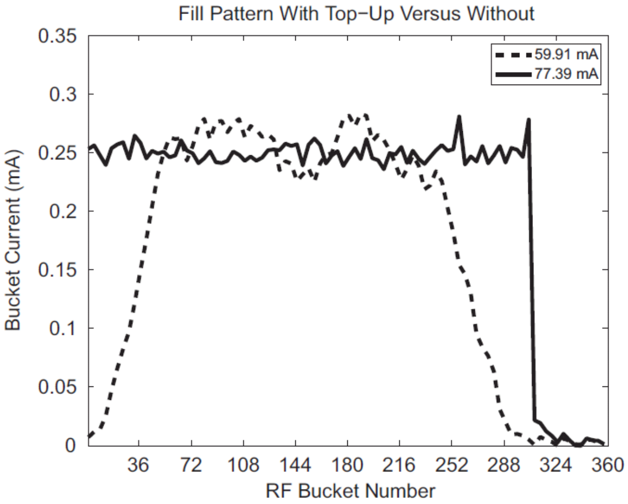


-

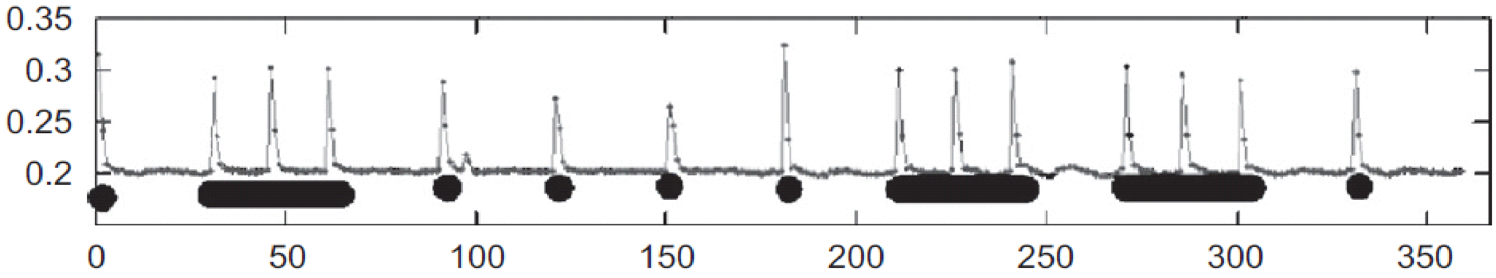
Synchrotron-Light based Fill-Pattern-Monitor

- Idea: extend FPM functionality to measure dipole momentum of transverse beam distribution, e.g. via 2x2 photo- detector matrix
- Initial idea and infrastructure based on the ASLS's Fill Pattern Monitor (FPM)*





- ASLS fill pattern *a la carte*:

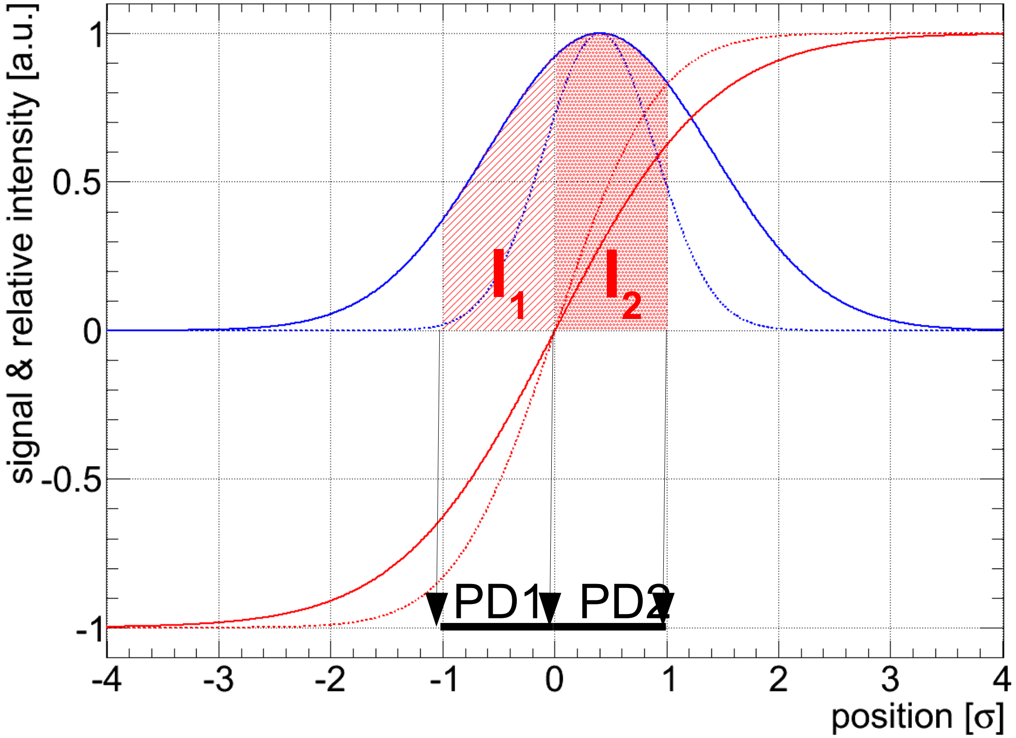


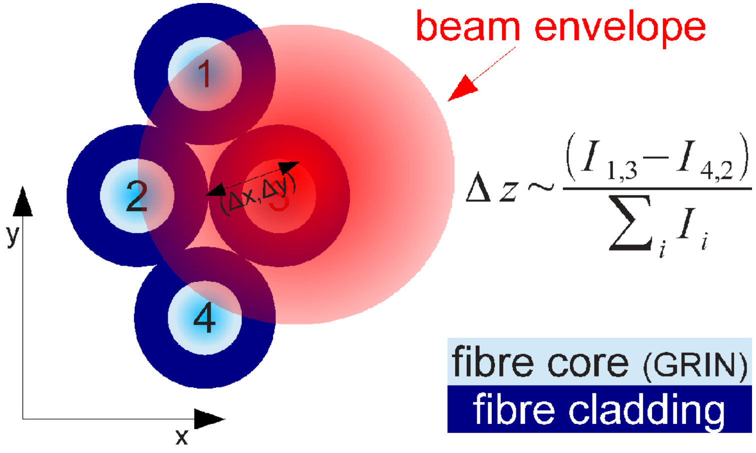
Australian Synchrotron Project

*D. Peak, M. Boland, R. Rassool, et. al., “Measurement of the real time fill-pattern at the Australian Synchrotron”, NIMA, 2008

Synchrotron-Light based BPM

- Idea: measure dipolar momentum of the synchrotron light ...
  - *Dawson et al., "Storage Ring Tune Measurements using High-Speed Metal-Semiconductor-Metal Photodetectors", IBIC'12, 2012*





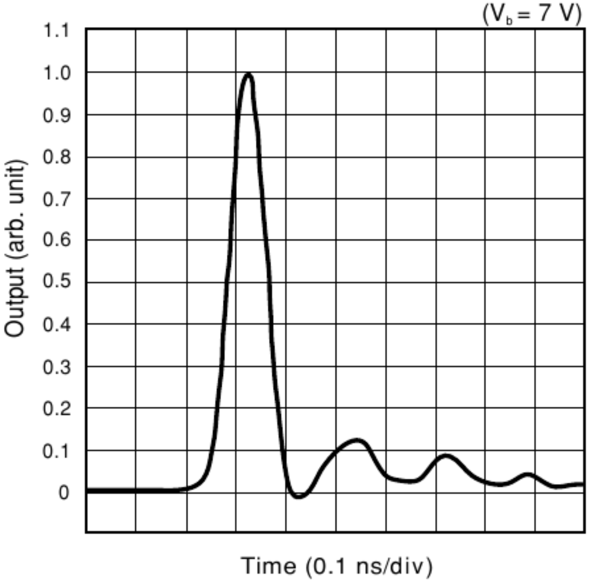
$$\Delta z \sim \frac{(I_{1,3} - I_{4,2})}{\sum_i I_i}$$

- Range limited to ±σ of beam spot size → acceptable as an instability monitor
- Second order: scale is dependence on σ

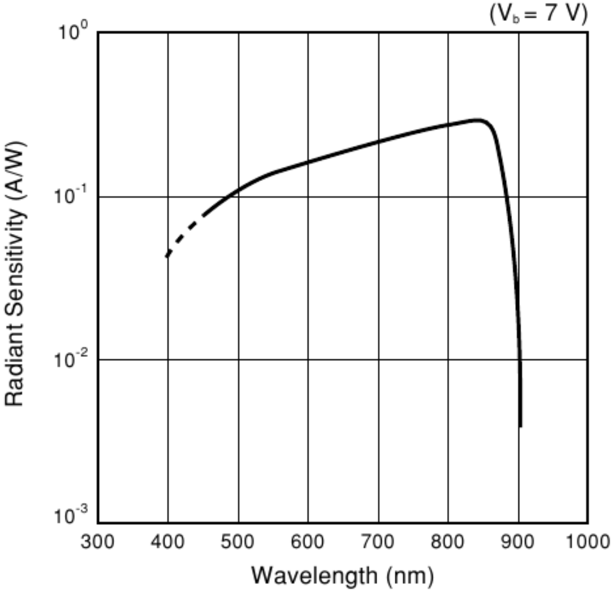
Metal-Semiconductor-Metal (MSM) Photodetector I/II

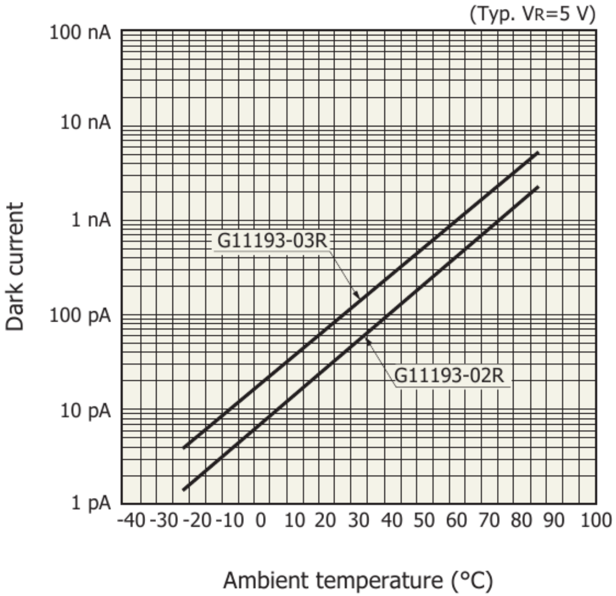
- Hamamatsu's G4176-03 (TO5 package, SMA connector)
  - t_r ≈ 30 ps ↔ nom. 50% atten. @12GHz
  - 0.3 pF for active area of 0.2 x 0.2 mm²
  - typ. light input power ~5-10 mW (50% duty-cycle)
  - dark-current: 100 pA @23°C
  - max. est. S/N: ~150 dB (w/o cooling)

    (very good value for money, prototyping!)
- N.B. alternative variant for infra-red: G7096-03



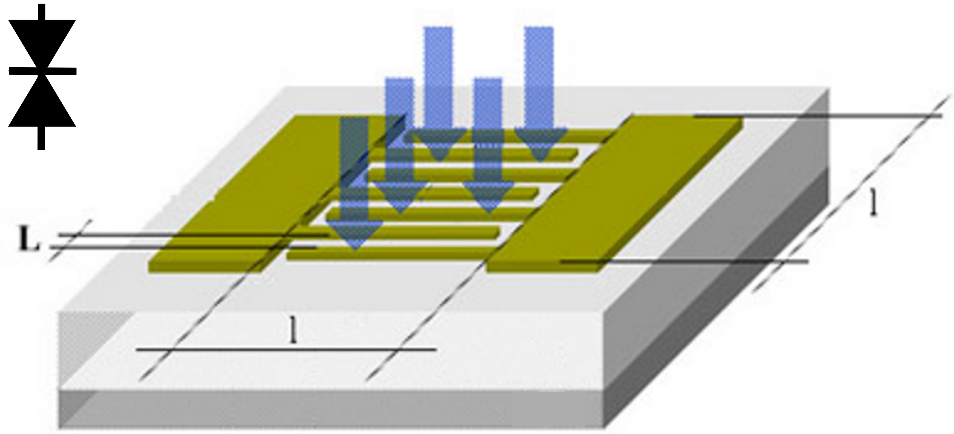
(incl. light soure, bias and scope)





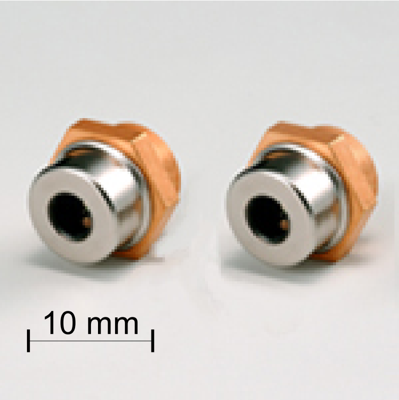
Metal-Semiconductor-Metal (MSM) Photodetector II/II

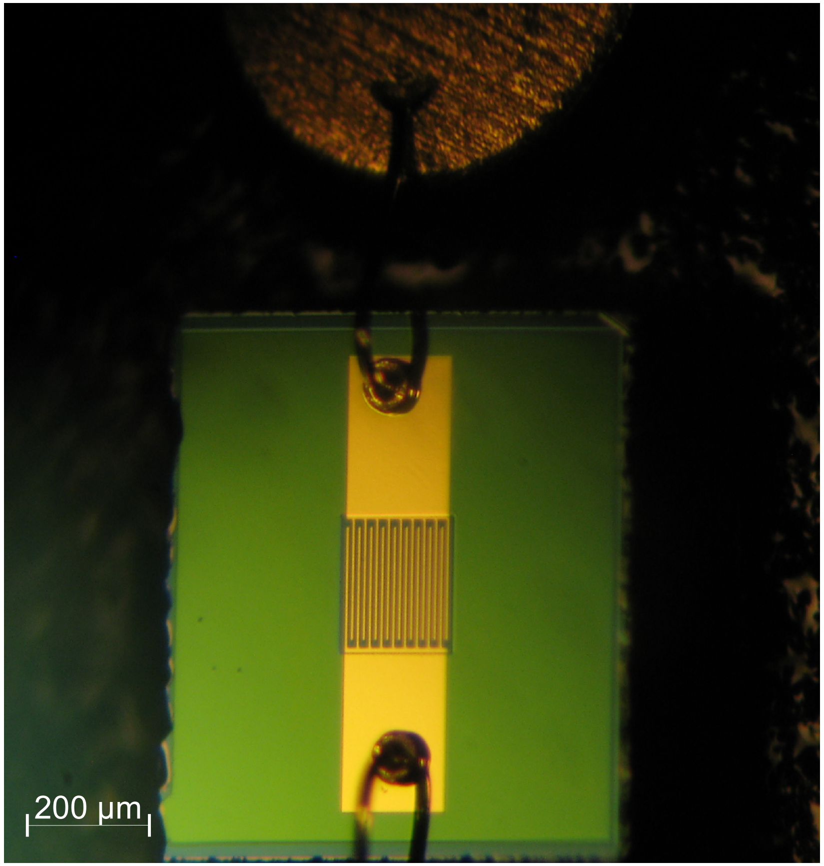
- … not quite a P(i)N junction (diode)!
  no polarity, requires bias-voltage (typ. 10 V)



- Speed determined by doping of (In)GaAs SC material and PD geometry (reflection, C, …)
  - Not quite a MS Schottky Diode
- Variants available exceeding 100 GHz bw. but makes fiber-coupling mandatory

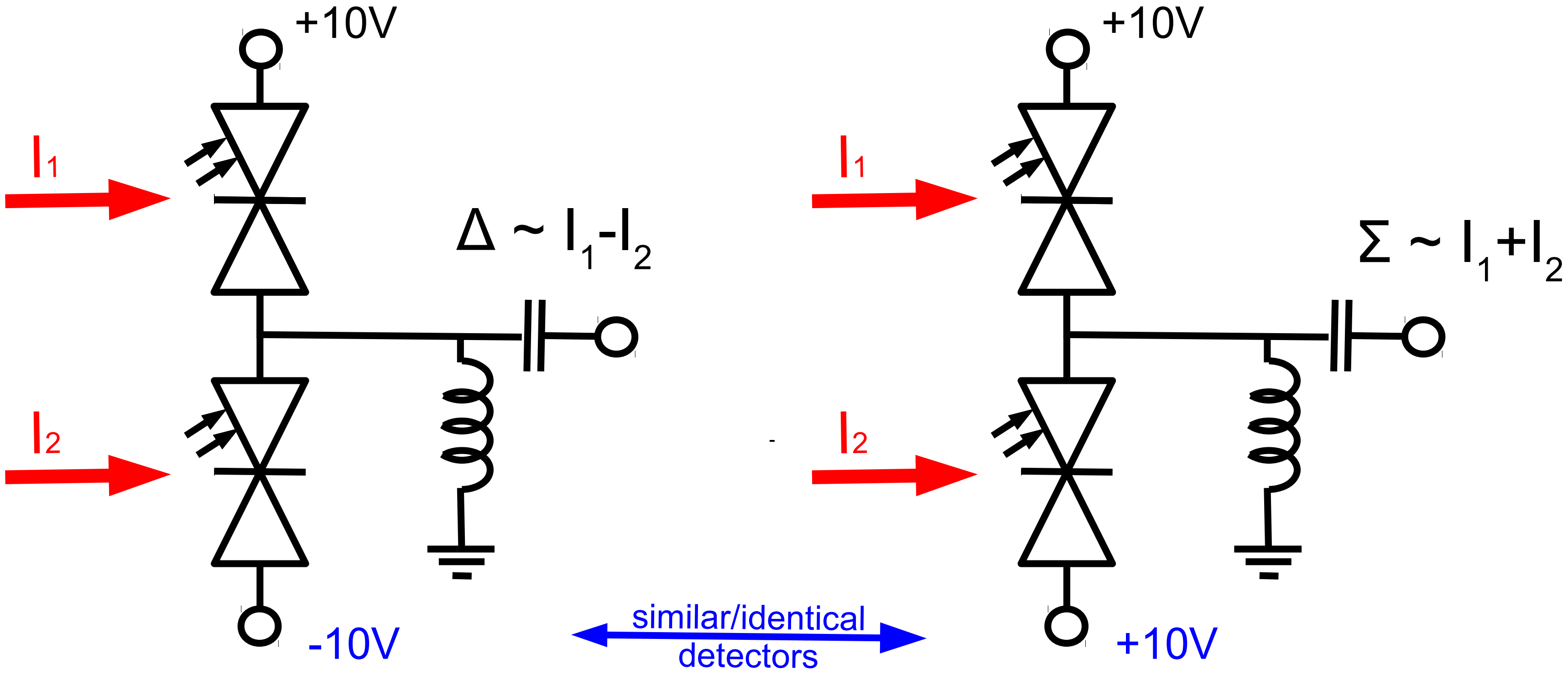
→ KISS: initial prototyping with in-air design





Opto-Electrical Delta-Sum Detection Scheme

- Balanced-Detection
- Common-Mode Detection:



Advantages:

- even lower noise than pure MSM
- Simple phase compensation
- Simple adaptive orbit offset comp.
- 50Ω vs. high-impedance (glued to ADC)
- Can keeps sensitive (== expensive) equipment/control outside the tunnel

Advantages:

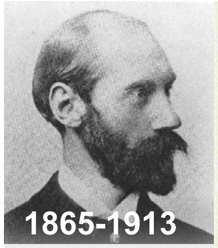
- incoherent sum → indep. on phase of laser wave-front (no expensive PANDA fibres!)
- Can be re-used for other EO-options → see second part of summary
- Future: dependence on beam size → extend scheme to measure σ

Some slides on
EO Optical-BPM and classical RF-based HT Upgrade Activities

Electro-Optical Modulator: Pockels & Kerr Effect I/II

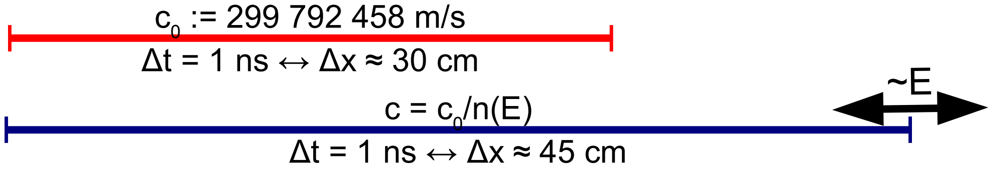
- Refraction in birefringent crystals depends on ex. electrical field:

$$n(E) = n_0 + \underbrace{r_{ij}\cdot E}_{\text{Pockels effect}} + \underbrace{s_{ij}\cdot E^2}_{\text{Kerr effect}}$$


1865-1913


1824-1907

- Optical length differences:
  - Vacuum:
  - Glass:


c_0 := 299 792 458 m/s

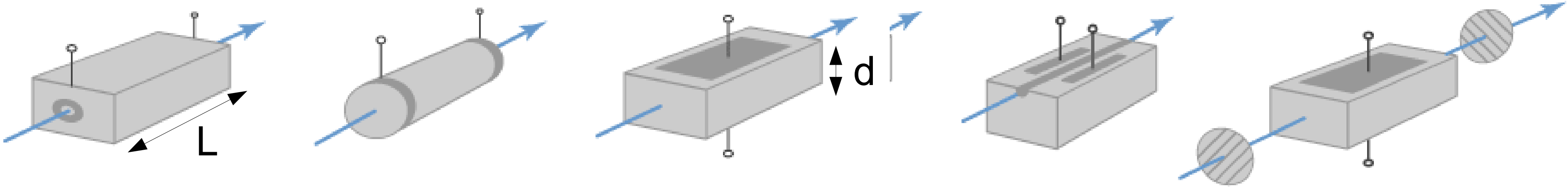
Δt = 1 ns ↔ Δx ≈ 30 cm

c = c_0/n(E)

Δt = 1 ns ↔ Δx ≈ 45 cm

$$\left.\begin{array}{l} E_x = E_0 \cos\left(\omega t - \dfrac{2\pi}{\lambda} n_x z\right) \\ E_y = E_0 \cos\left(\omega t - \dfrac{2\pi}{\lambda} n_y z\right) \end{array}\right\} \rightarrow \Delta\varphi = \frac{2\pi}{\lambda}(n_x - n_y)L = \frac{2\pi}{\lambda}(n_{x_0} - n_{y_0})L + \left\{\begin{array}{l} \overbrace{\dfrac{\pi}{\lambda}\left(r_x n_{x_0}^3 - r_y n_{x_0}^3\right)V}^{\text{longitudinal modulator}} \\ \underbrace{\dfrac{\pi}{\lambda}\left(r_x n_{x_0}^3 - r_y n_{x_0}^3\right)\dfrac{V}{d}L}_{\text{transverse modulator}} \end{array}\right.$$

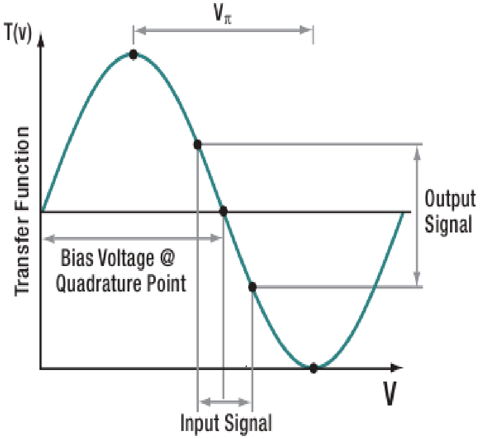
longitudinal transverse modulator schemes



Electro-Optical Modulator: Pockels & Kerr Effect II/II

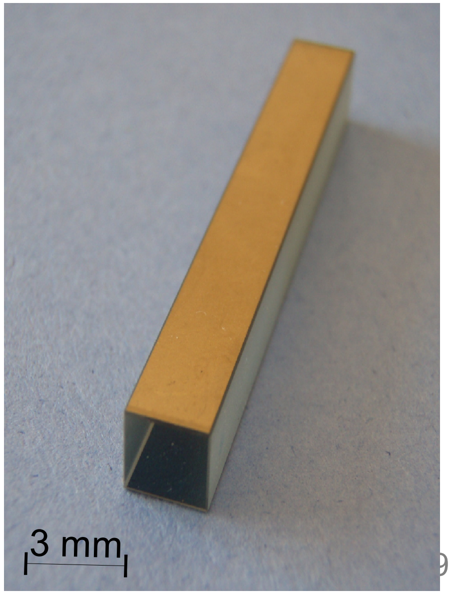
- Typically the *'half-wavelength voltage V_π'* is used to describe electro-optical modulators, i.e. the voltage required to achieve destructive interference:

$$\Delta\varphi := \pi \rightarrow V_\pi = \frac{\lambda}{r_{33} n_e^3 - r_{13} n_o^3} \cdot \frac{d}{L}$$



  - wavelength *λ*, crystal height *d* and length *L* are basically free parameter

- Large variety of crystals (KTP, GaAs, …), I chose:
  - Lithium Niobiate ($LiNbO_3$) – 5x5x15 mm^3
    - common and the 'standard' in telecommunication
    - typ. (only) low V_π~6-10 V available
  - Lithium Tantalate ($LiTaO_3$) – 3x3x15 mm^3
    - more robust but similar to LiNbO3 or Al_2O_3



Detector Materials:
Lithium Niobate ($LiNbO_3$) & Lithium Tantalate ($LiTaO_3$)

	Lithium Niobate	Lithium Tantalate
	$LiNbO_3$	$LiTaO_3$
Density:	4.65 g/cm^3	7.46 g/cm^3
Melting point:	1257 °C	1650 °C
Thermal expan. [$10^{-6}K^{-1}$]	15, 5	16, 4
Thermal cond. [W/mK^{-1}]	5.6	4.6
Damage threshold	250 MW/cm^2	500 MW/cm^2
ε_r @ 100kHz	$\varepsilon_\perp$ 85, $\varepsilon_\parallel$ 29	$\varepsilon_\perp$ 54, $\varepsilon_\parallel$ 43
transmission range [nm]	350-5500	400 - 5500
refractive index (@589 nm, 25°C & @633 nm, 25°C)	n_o 2.30, n_e 2.21	n_o 2.19, n_e 2.18
EO-coefficient* [pm/V]	r_{13} = 9.6, r_{33} = 30.9, r_{22} = 6.8, r_{51} = 32.6	r_{13} = 8.4, r_{33} = 30.5, r_{22}=20
Non-linear EO coeff. [p/m/V] @ 1064 nm	d_{31} = -4.5, d_{33} = -0.27, d_{22} = 2.1	d_{22} = 2.0, d_{31} = - 1, d_{33} = -21

N.B.

*for $LiNbO_3$ and $LiTaO_3$: r12 = −r22 = r61,

r13 = r23, r33, r42 = r51

$$\Delta\left(\frac{1}{n^2}\right)=\sum_{j=1}^{3} r_{ij}E_j$$

$$n=\sqrt{\epsilon\mu}$$

Detector Materials: Zinc-Telluride (ZnTe) & Gallium-Phosphide (GaP)

	Zinc-Telluride	Gallium-Phosphide
	ZnTe	GaP (110)
Density:	6.34 g/cm^3	4.14 g/cm^3
Melting point:	1238 °C	1477 °C
Thermal expan. [10^{-6}K^{-1}]		
Thermal cond. [W/mK^{-1}]		
Damage threshold		
ε_r @ 100kHz	$\varepsilon_\perp$ XX, $\varepsilon_\parallel$ XX	
transmission range [nm]	650-22k	400 - 5500
refractive index (@10.6 um, 25°C & @633 nm, 25°C)	n_o 2.30	n_o X.XX
EO-coefficient* [pm/V]	$r_{41} = 4.25$	$r_{41} = 1.0$
Non-linear EO coeff. [p/m/V] @ 1064 nm	$d_{31} = -4.5$, $d_{33} = -0.27$, $d_{22} = 2.1$	$d_{22} = 2.0$, $d_{31} = -1$, $d_{33} = -21$

N.B.

*for $LiNbO_3$ and $LiTaO_3$: r12 = −r22 = r61,

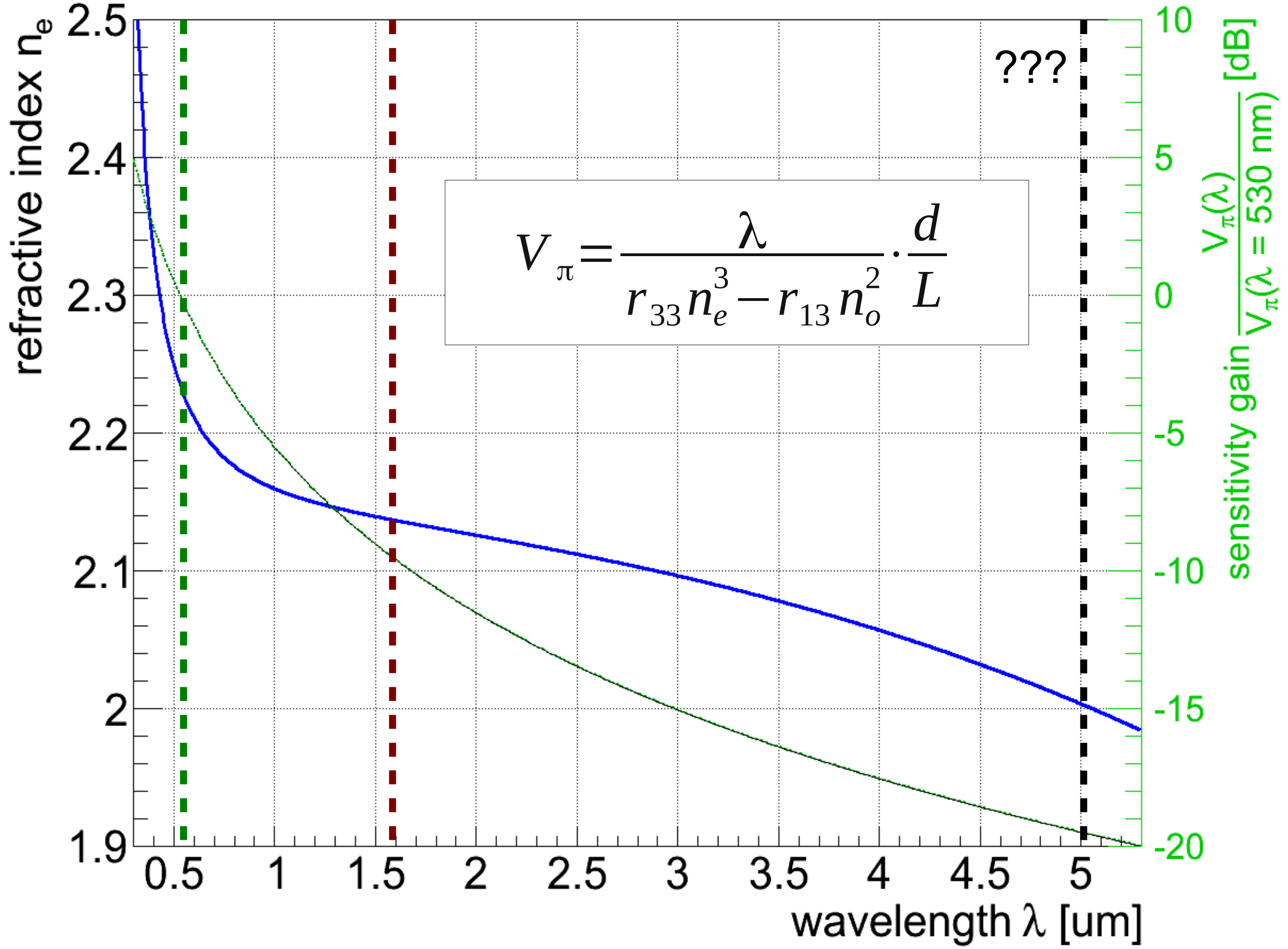
r13 = r23, r33, r42 = r51

$$\Delta\left(\frac{1}{n^2}\right) = \sum_{j=1}^{3} r_{ij} E_j$$

$$n = \sqrt{\epsilon\mu}$$

Refractive Index Dependence on Wavelength

- $LiNbO_3$ – gain control possible but limited to factor ~10

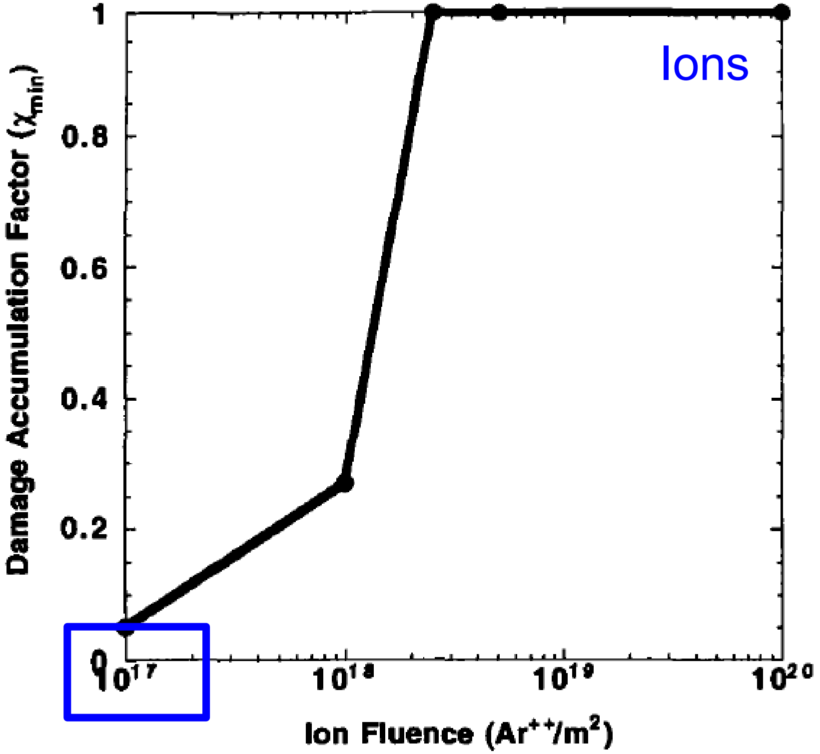


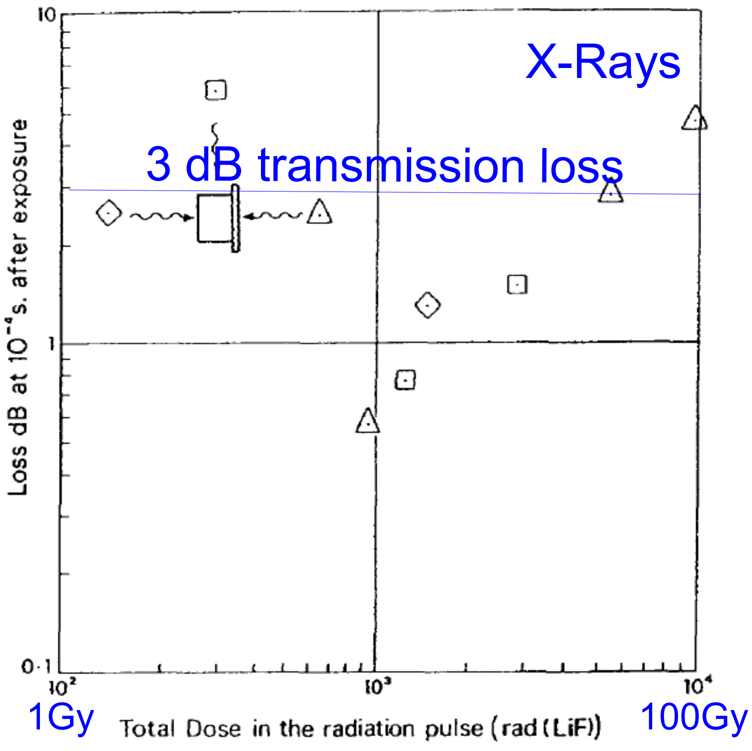
$$V_\pi = \frac{\lambda}{r_{33} n_e^3 - r_{13} n_o^2} \cdot \frac{d}{L}$$

- … thus acquired 530 nm (green) and 1550 um (infra-red) laser for testing this.

Robustness w.r.t. Radiation Damage

- $LiNbO_3$ and $LiTaO_3$ are related to Al_2O_3, known to be fairly radiation hard
- Nevertheless, should get more precise numbers to assess long-term damage
  - Radiation damage level on $LiTaO_3$ according to [1,2]:





- Conversion factor tbc. but '10^{17} Ar^{++}' is probably much more than 100 kGy

---

[1]: C. J. Wetteland et al., “Radiation Damage Effects in [..] LiTaO3 Single Crystals”, Mat. Res. Soc. Symp. Proc. Vol. 504 , 1998

[2]: R. H. West, S. Dowling, "Effects in [..LiTaO3..] Exposed to Radiation from a Flash X-Ray Source", Royal Military College of Science, IEEE TRANSACTIONS ON NUCLEAR SCIENCE vold. 41, #3, 1994

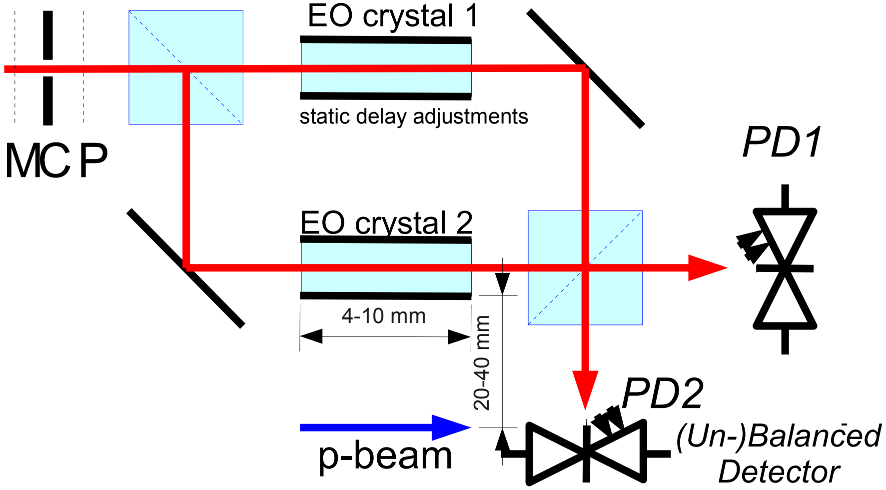
Test & Evaluation Programme

- Two stage demonstration:
  - Re-use existing MSM-PD-based light-electrical conversion scheme
    - two options: optical (I) or electrical (II, favoured) hybrid
  - Sensitivity: 1% beam movement ↔ 3V signal, resolve a fraction of this
    - Michelson interferometer with EO-crystal as trans. Modulator
    - EO-crystal as amplitude modulator per pick-up
      → insensitive/lose laser phase information → turns out to be more robust...
    - Setup ready, need to redo scans (with low-intensity meter, DSO constraints)
  - Bandwidth: commercial LiNbO3 20 GHz EO-Modulator
    - to be tested: S/N ratio, reflections (limited by coupler)
    - Mini-Laserlab nearly finished → test before Christmas!
- After that: design of purely-optical BPM pick-up (2013+?)

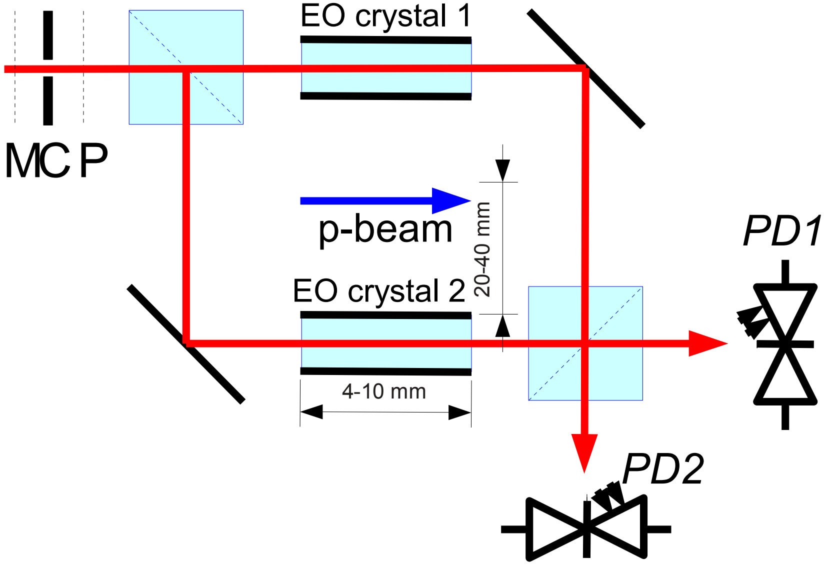
Test & Evaluation Programme
Sensitivity Setup – Phase Modulation-based

- Mach-Zehnder or Michelson Topology

option I: per BPM pick-up electrode

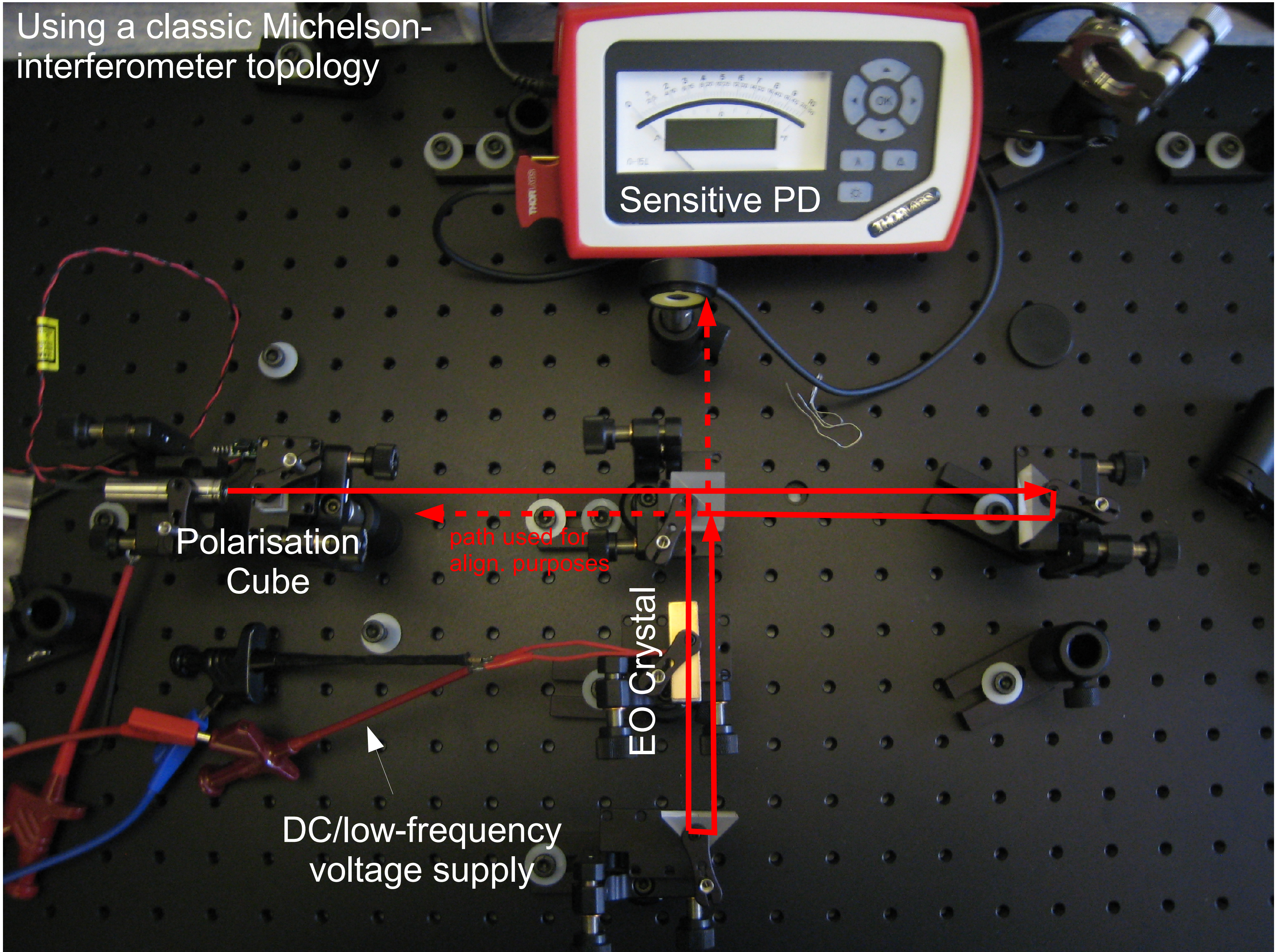


option II: inside BPM



- Utilises wave-front phase interference to suppress common mode signal
- However:
  - Need to maintain polarisation within (larger) structure
  - More delicate/less robust w.r.t. alignment, stability of mirrors and split ratio
    - would need to be done locally close to the pick-up for re-tuning (remote motorisation, local instrumentation, ...yikes)
- Structure size limited by coherence length ↔ laser line-width
  - manageable on lab-scale but challenging w.r.t. in-tunnel operation

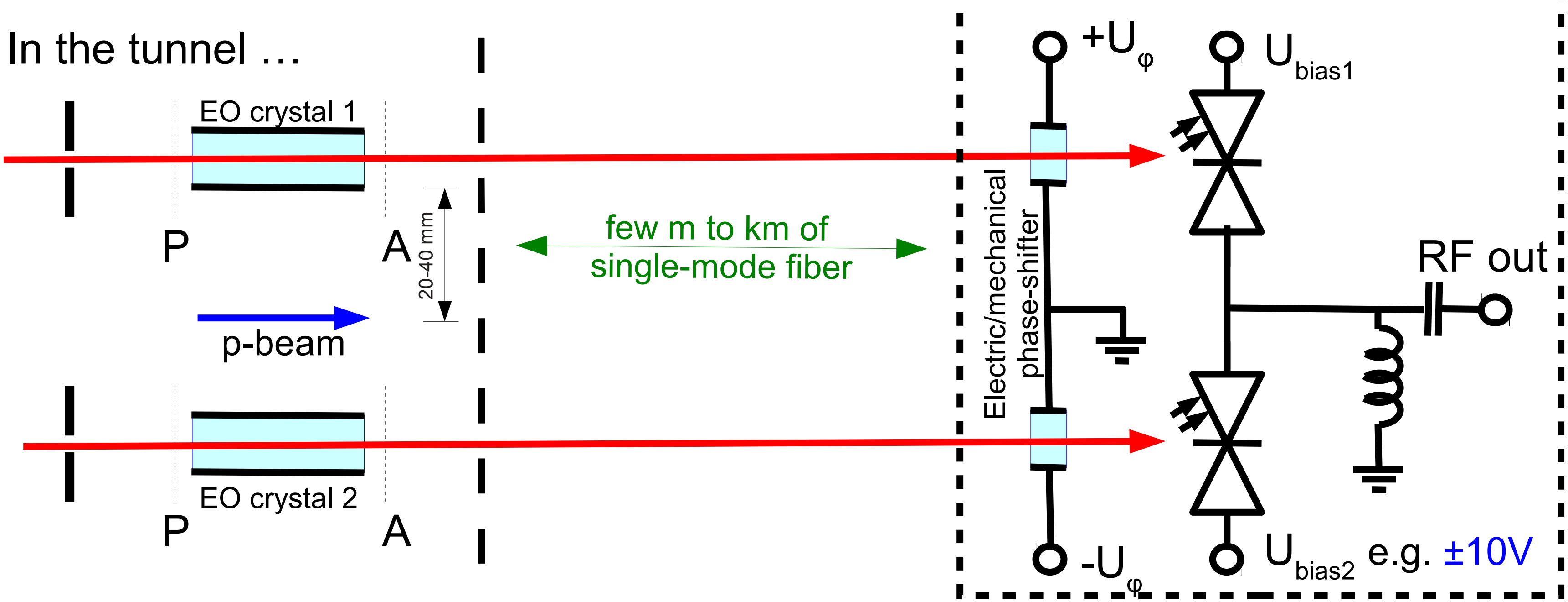
LiNbO3 Sensitivity Setup – Phase Modulation-based I/II here: < 1mW, 630 nm Laser



Using a classic Michelson-interferometer topology

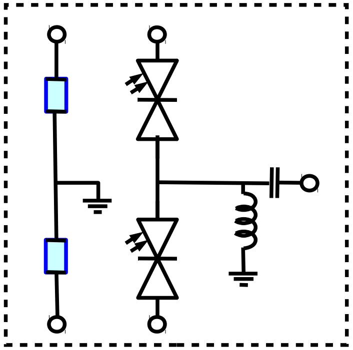
Amplitude Modulation-based Scheme

- E.g. polarisation (→ pockels cell) or phase retardation (Fabry-Perot)



- Simple → robust design:
  - no setup or retuning of electrical/mechanical parts in tunnel
  - complexity kept at DAQ
    - Leverage same MSM-detector design as for synch-light based BPM
    - Phase and amplitude matching possible via U_{φ} and U_{bias}
    - Less radiation issues, could consider cryo-cooling MSM detectors
- Could daisy-chain/mix multiple pick-ups on the same two optical fibres

Sensitivity & Gain Adjustment



- Main observable:

$$\Delta I \simeq I_0 \cdot \frac{\Delta x}{R}$$

- Some constraints:
  - EO-crystal range (saturation-like): $V_{pickup}\big|_{max} < \; 0.8 \cdot V_{\pi}(crystal)$

    → *adjust crystal length/width to maximum bunch intensity/length*
  - MSM-PD saturation (~10 mW ↔ 150 mV on 50Ω): $\Delta I\big|_{max} < I_{max}(MSM)$

    → *limits maximum laser power for bunch peak signal*
- However, these limits do not apply at the same time
  → can use laser power to adjust dynamic range, e.g.
  - low laser power ↔ high-intensity bunches and vice-versa
  - Bal. detector → little impact of optical amplification on noise performance