Fast Inter/Intra-Bunch Activities related to CLIC and LHC

– Update on Electro-Optical BPM Activities –

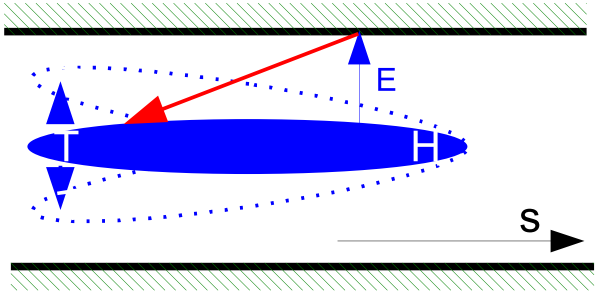
-

Ralph J. Steinhagen

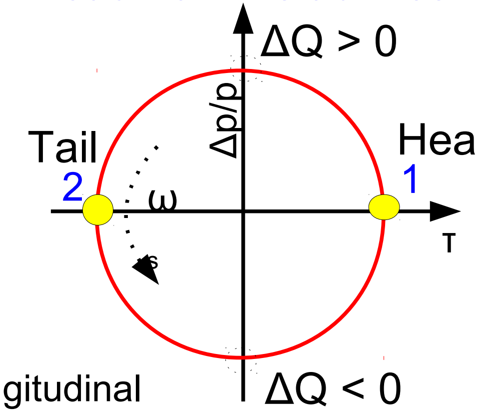
Beam Instrumentation Group, CERN

Motivation I/II – HeadTail Oscillations

- Transverse instabilities come in various flavours, e.g.:
  - Lower-order modes: Inter-bunch resolving bunch-by-bunch motion → BPMs
  - High-order modes: Intra-bunch instabilities → Head-Tail[1] instabilities

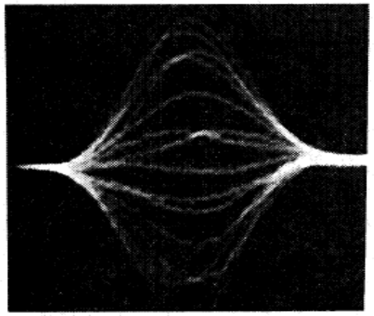


transverse

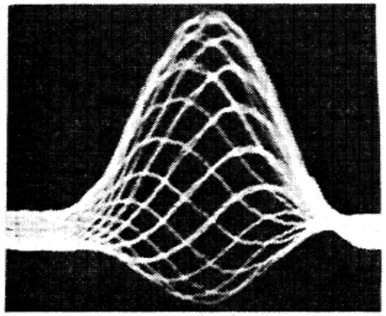


longitudinal

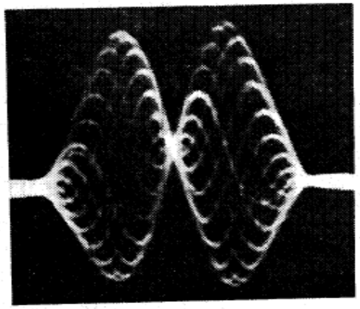
- Studied intensively in the CERN-Booster[2]:



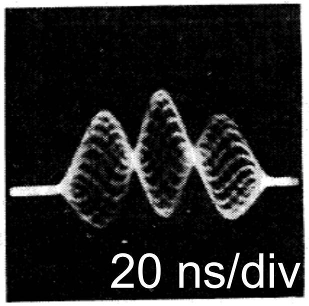
a) mode m = 0, χ = 0



b) m = 0, χ = 2.3 radians



b) m = 1, χ = 6.9 radians



d) m = 2, χ = 6.9 radians

- PS: 120 ns bunch length ↔ less demanding in terms of bandwidth
- SPS/LHC: bunch length down to 1 ns → requires multi-GHz analog bandwidth

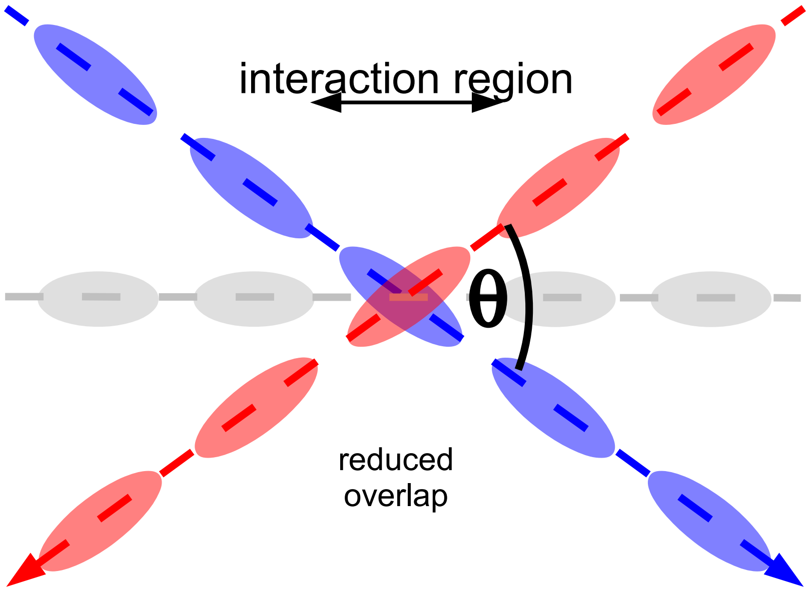
[1] M. Sands, *"The Head-Tail Effect: An Instability Mechanism in Storage Rings"*, SLAC-TN-69-008, 1969
[2] J. Gareyte, "Head-Tail Type Instabilities in the PS and Booster", CERN, 1974

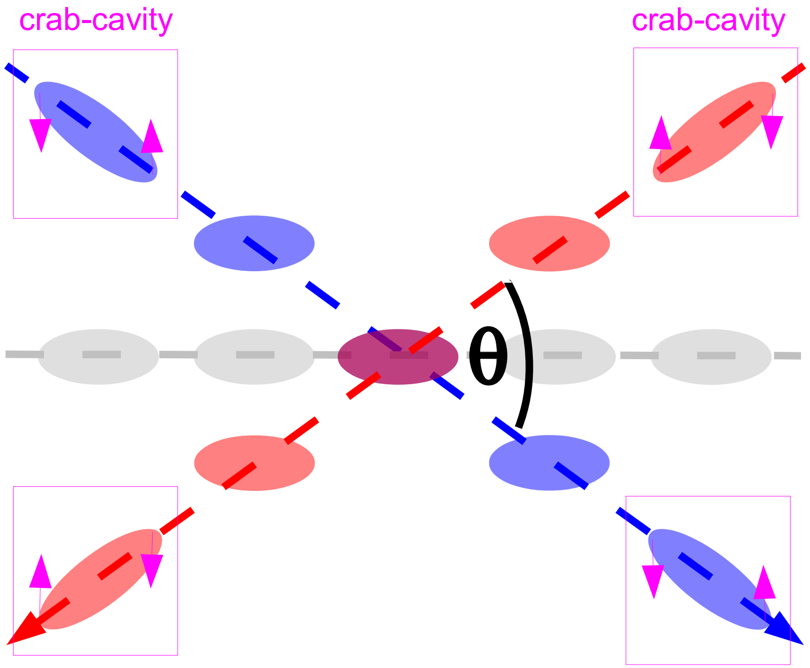
Motivation II/II – Crab-Cavity Diagnostics

- Need crossing angle θ to avoid additional parasitic collisions in the IR → reduces bunch overlap → reduces luminosity:

$$L = L_0 \cdot F_{crossing} \cdot \ldots = L_0 \cdot \frac{1}{\sqrt{1 + \frac{\sigma_s}{\sigma_{x,y}} \tan(\theta/2)}} \cdot \ldots$$

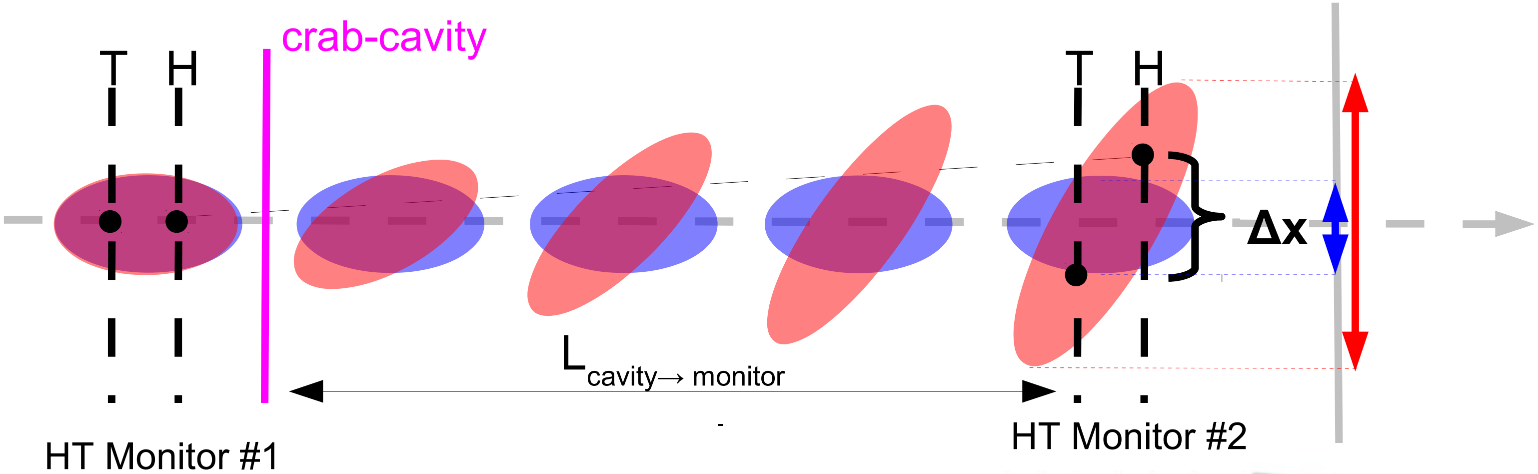
- Without crab-cavity:
- Aim with crab cavity: $F_{crossing} \approx 1$



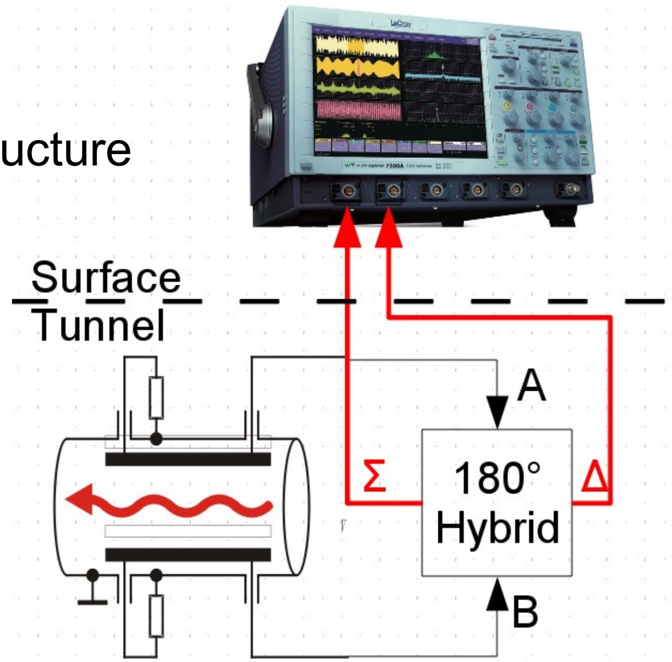


Motivation II/II – Crab-Cavity Diagnostics

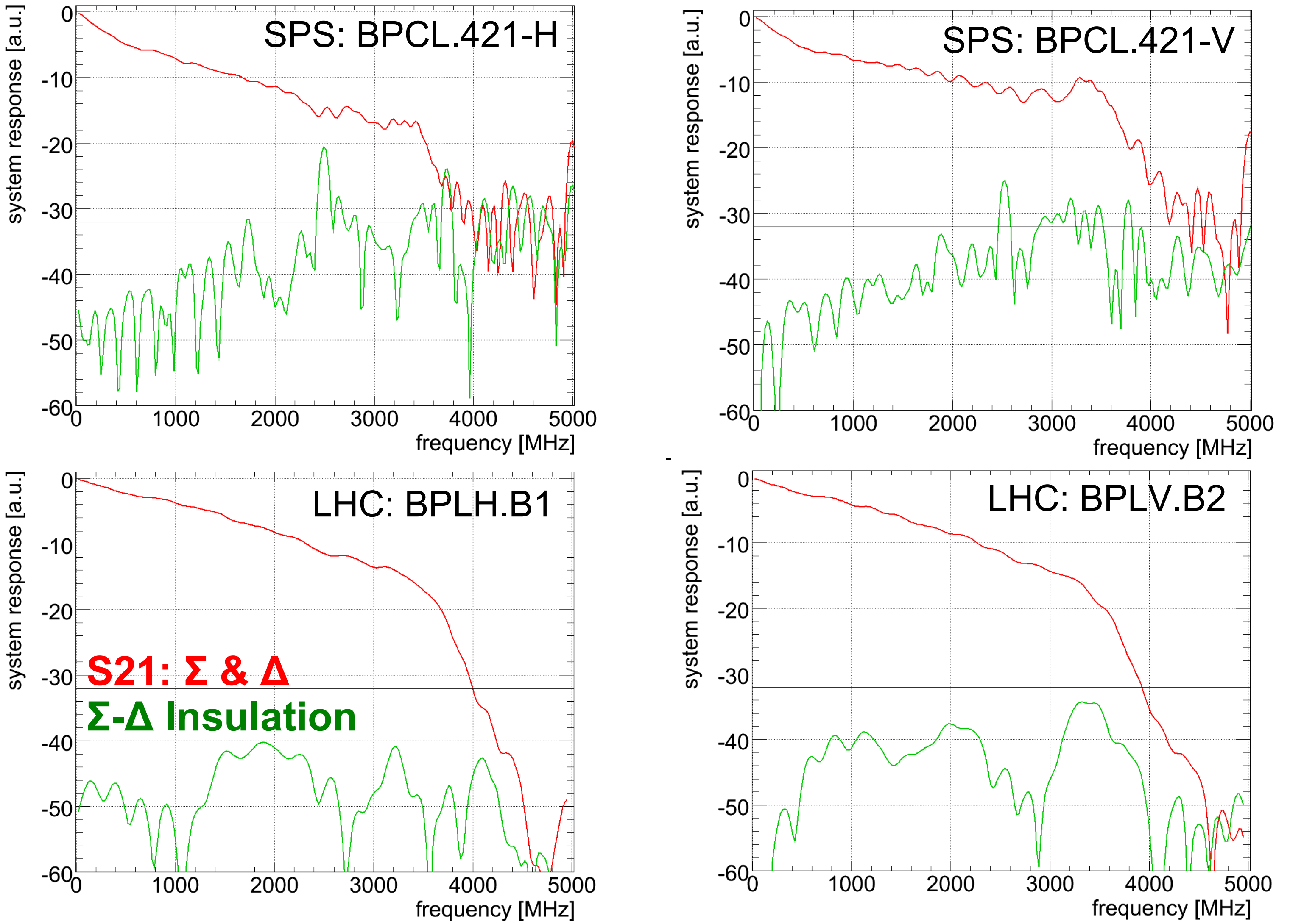
- Direct measurement of crab-cavity kick angle θ and phase error Δφ → orbit difference Δx between head and tail of the bunch



- Present standard implementation: long strip-line, Σ-Δ hybrid & high bandwidth to resolve bunch structure
  Main limitations:
  - Resolution: sampling limited to 8/~6.3 ENOB
    → limits resolution to the 100 um range
    → Beam typ. lost before visible with HT
  - Power issues, linearity over wide bandwidth, …
    limit: ~ 3-5 GHz BW & < 40 dB dynamic range



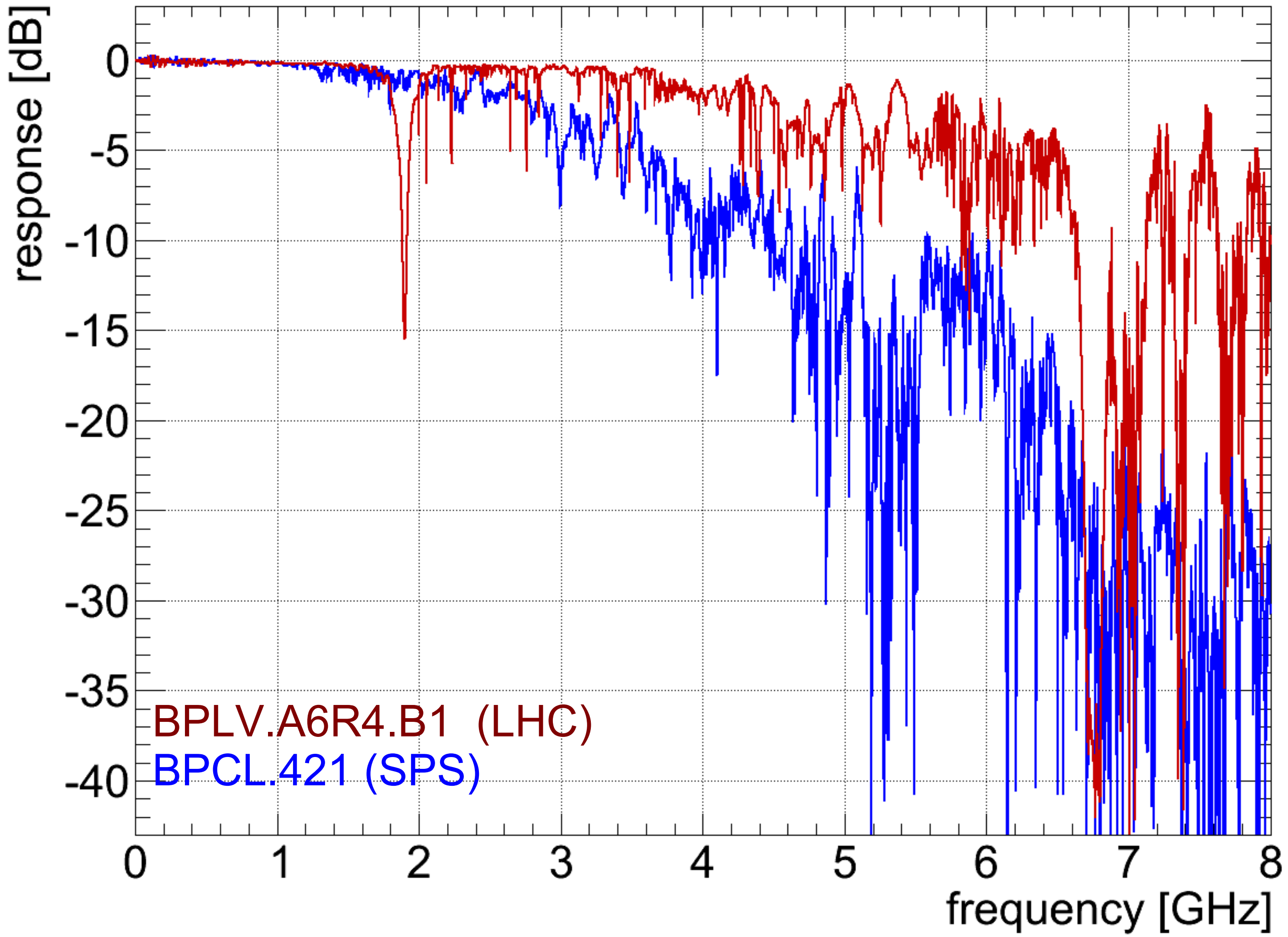
Limits of Classical Head-Tail Monitoring Approach
For Comparison: SPS/LHC HT System Response I/II



- 3.5 GHz due to scope bandwidth, hybrid common-mode bleed-through
- Slightly better performance for LHC HT but not much

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

- 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

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 effort with ACAS (Uni-Melbourne and ASLS)
2. (In-)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 DC-6 GHz Σ-Δ hybrid
   (Marki-Microwave component based but limited power capabilities)
2. Frequency-Domain: new Multi-Band RF Schottky Detector (ACAS)

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

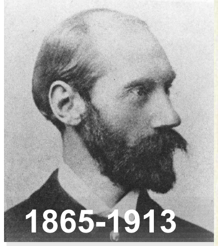
1. GUZIK DAQ: 64GB, 20 GS/s, 4.5 – 13 GHz BW, ext. FPGA firmware
2. Bunch-by-bunch DAQ (needed for B.2) ↔ related to b-b-b BBQ activities

Electro-Optical BPM

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

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

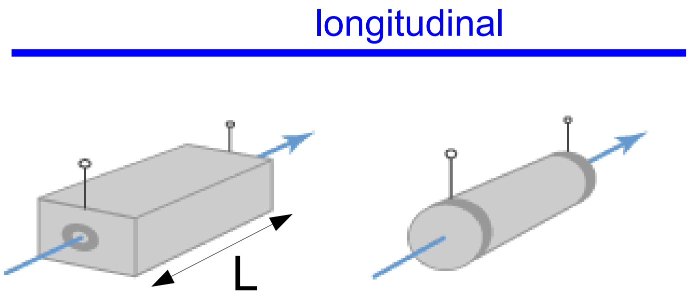
$$n(E) = n_0 \underbrace{+ r_{ij}\cdot E}_{\text{Pockels effect}} \underbrace{+ s_{ij}\cdot E^2}_{\text{Kerr effect}}$$

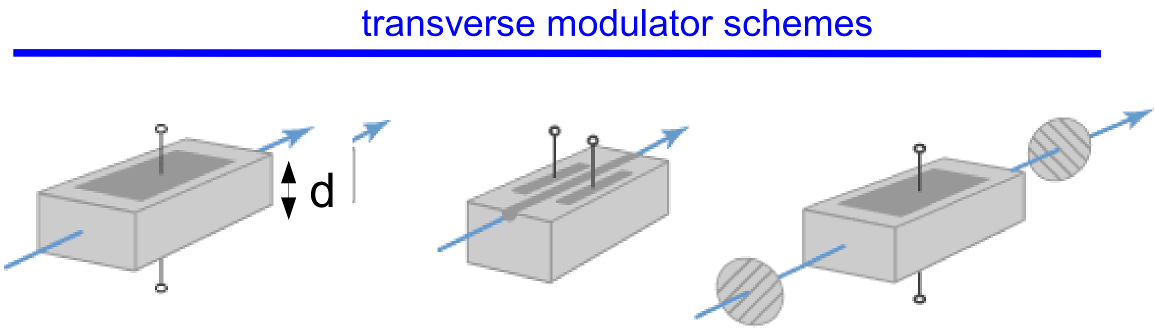

1865-1913


1824-1907

- Optical length differences:
  - Vacuum: c_0 := 299 792 458 m/s; Δt = 1 ns ↔ Δx ≈ 30 cm
  - Glass: $c = c_0/n(E)$; Δt = 1 ns ↔ Δx ≈ 45 cm; ~E

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

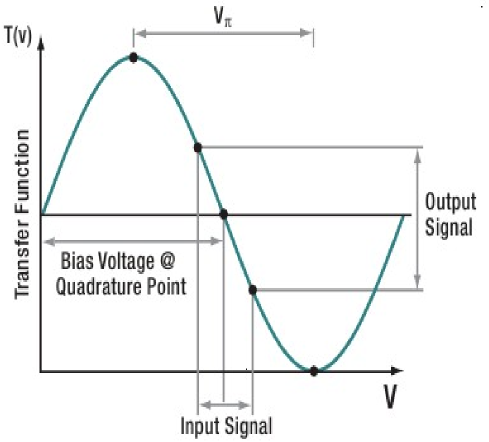

longitudinal


transverse modulator schemes

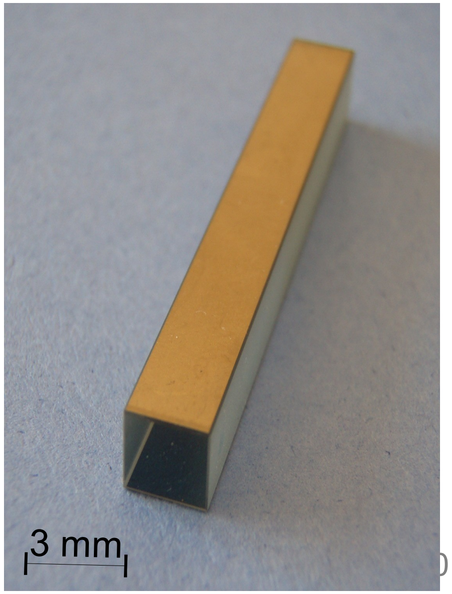
Electro-Optical Modulator: Pockels & Kerr Effect II/II

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

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



  - wavelength *λ*, crystal height *d* and length *L* are basically free parameter
- Large variety of crystals (KTP, GaAs, …), we 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/cm²	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

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

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	$d_{31} = -4.5$, $d_{33} = -0.27$, $d_{22} = 2.1$	$d_{22} = 2.0$, $d_{31} = -1$, $d_{33} = -21$

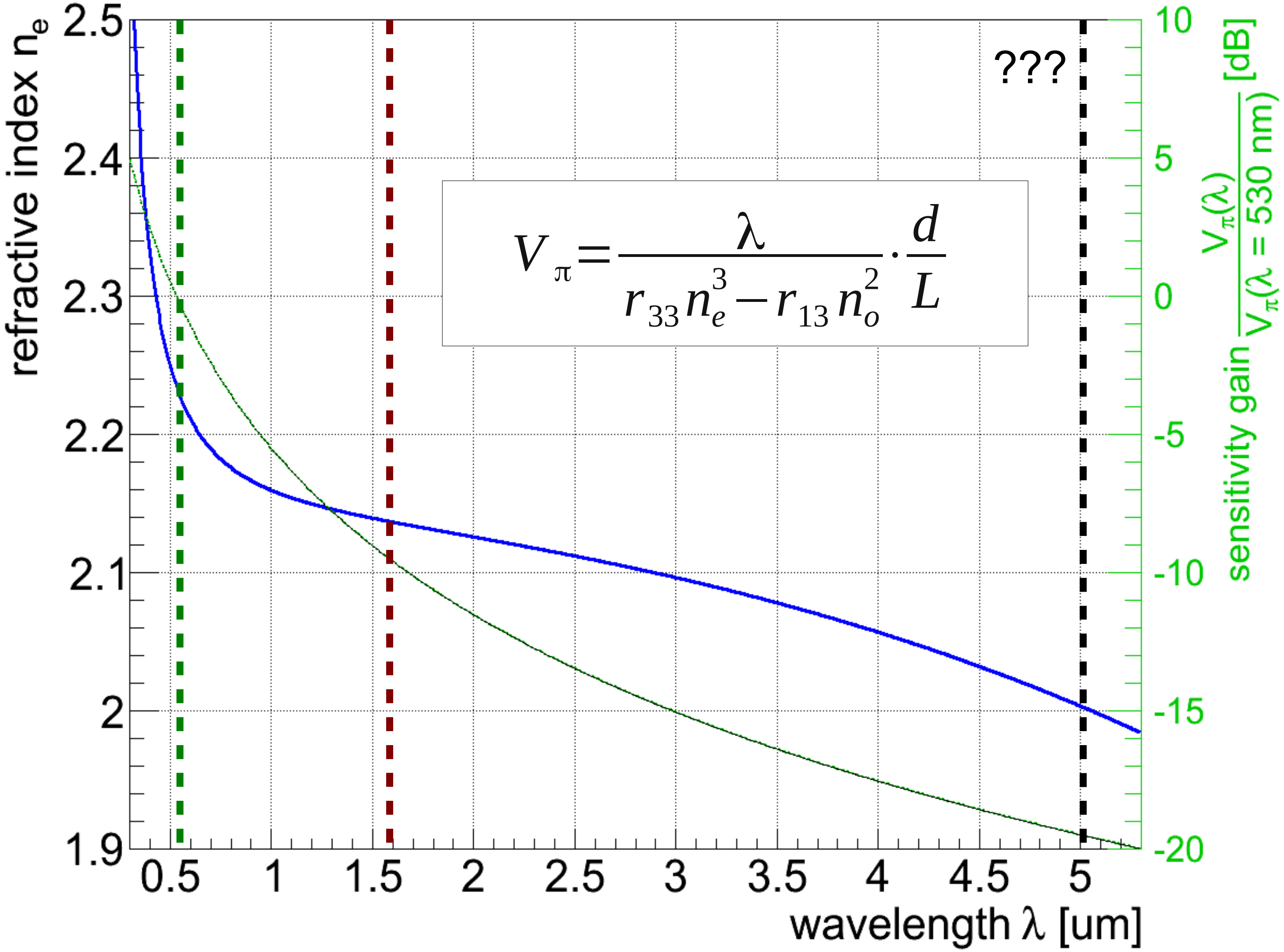
N.B.

*for $LiNbO_3$ and $LiTaO_3$: r12 = −r22 = r61,
r13 = r23, r33, r42 = r51

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

Refractive Index Dependence on Wavelength

- LiNbO$_3$ – gain control possible but limited to factor ~10

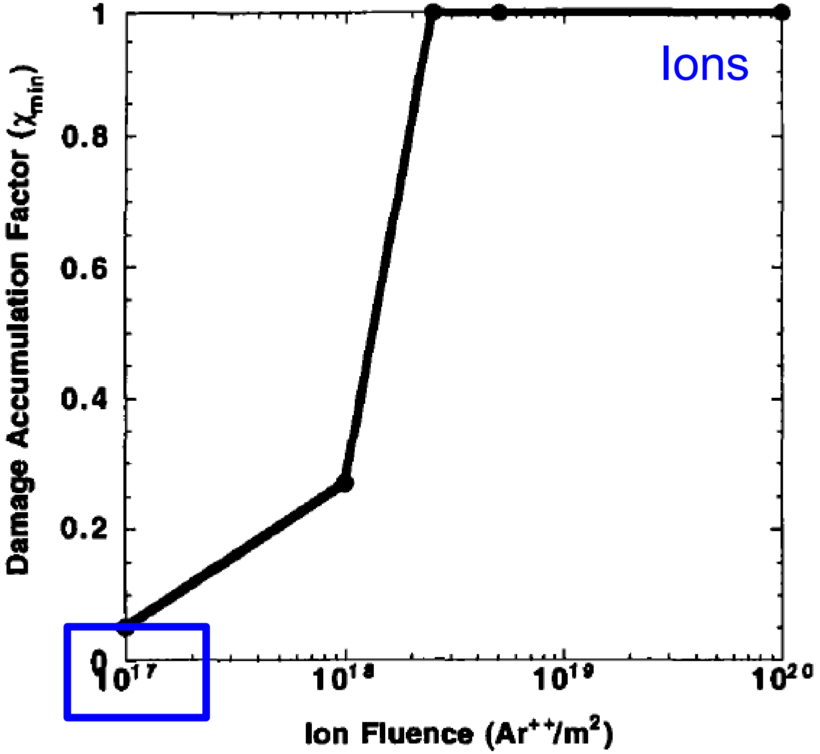


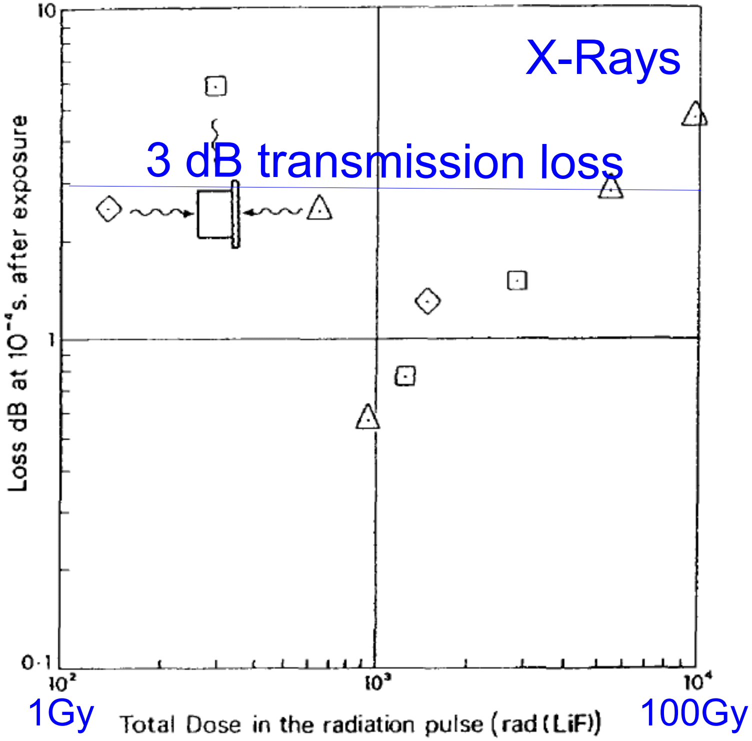
$$V_\pi = \frac{\lambda}{r_{33} n_e^3 - r_{13} n_o^2} \cdot \frac{d}{L}$$

- … 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

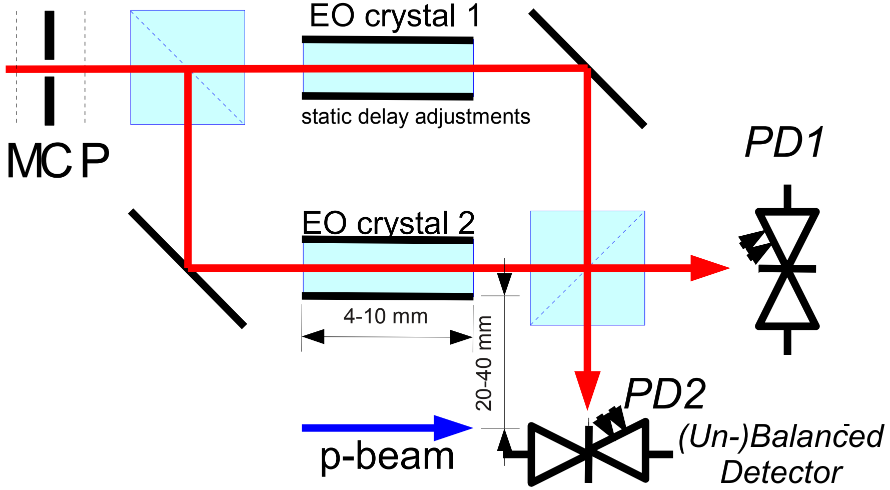
Test & Evaluation Programme

- Two stage demonstration:
  - Re-use existing MSM-PD-based light-to-electrical conversion scheme as being used by Synchrotron-Light BPM (collaboration with ACAS)
  - 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...
  - Bandwidth: commercial LiNbO3 20 GHz EO-Modulator
    - S/N ratio, reflections (limited by coupler)
- 2012-2013: Design of purely-optical BPM pick-up (2013+?)

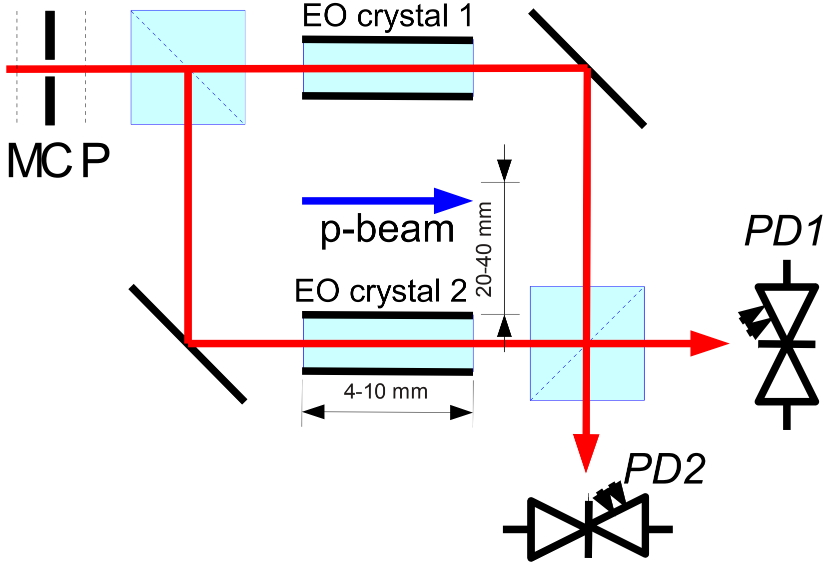
Test & Evaluation Programme
Sensitivity Setup – Phase Modulation-based

- Mach-Zehnder or Michelson Topology

option I: per BPM pick-up electrode



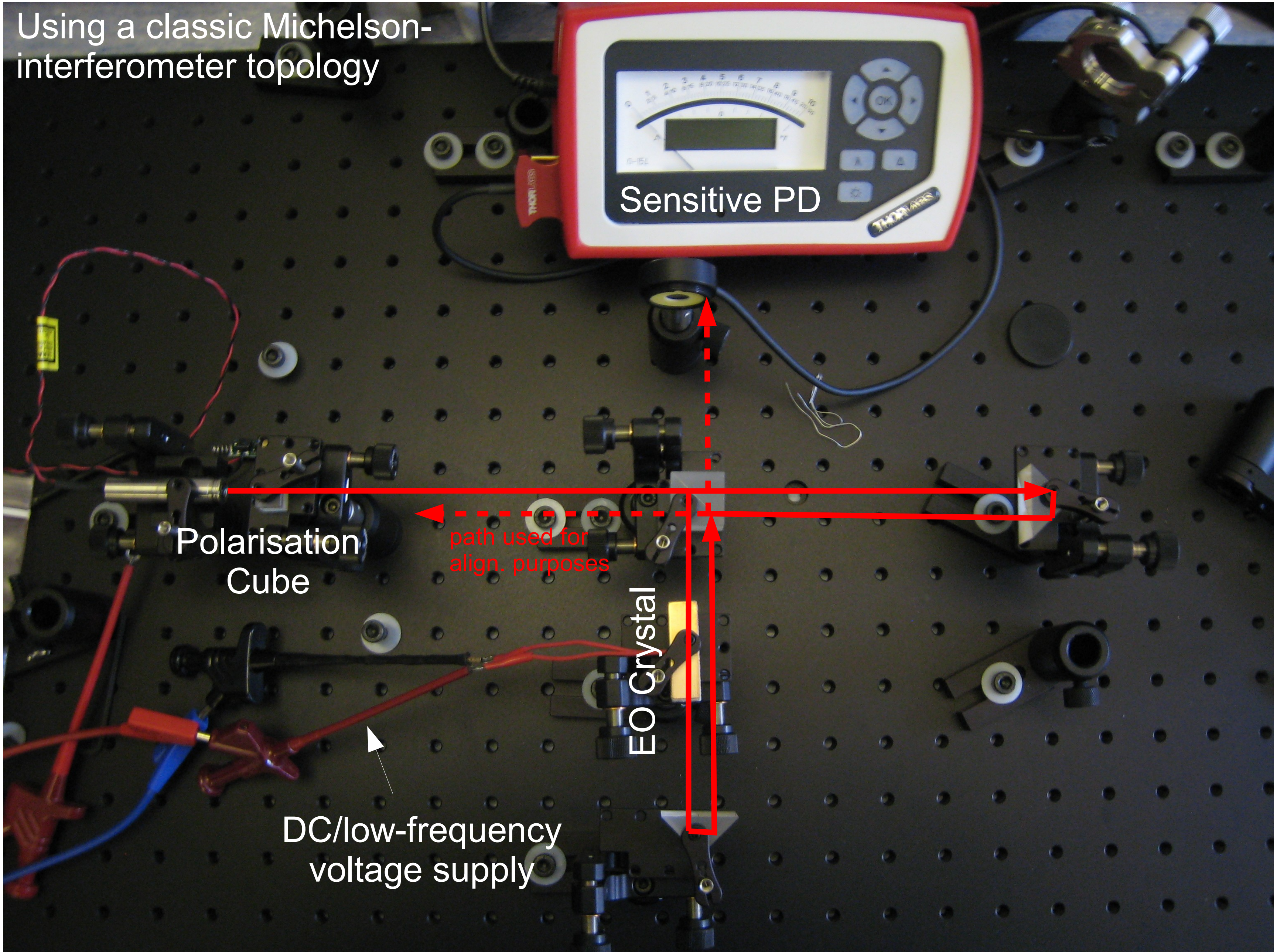
option II: inside BPM



- 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

LiNbO$_3$ Sensitivity Setup – Phase Modulation-based I/II

here: < 1mW, 630 nm Laser



Using a classic Michelson-interferometer topology

Sensitive PD

Polarisation Cube

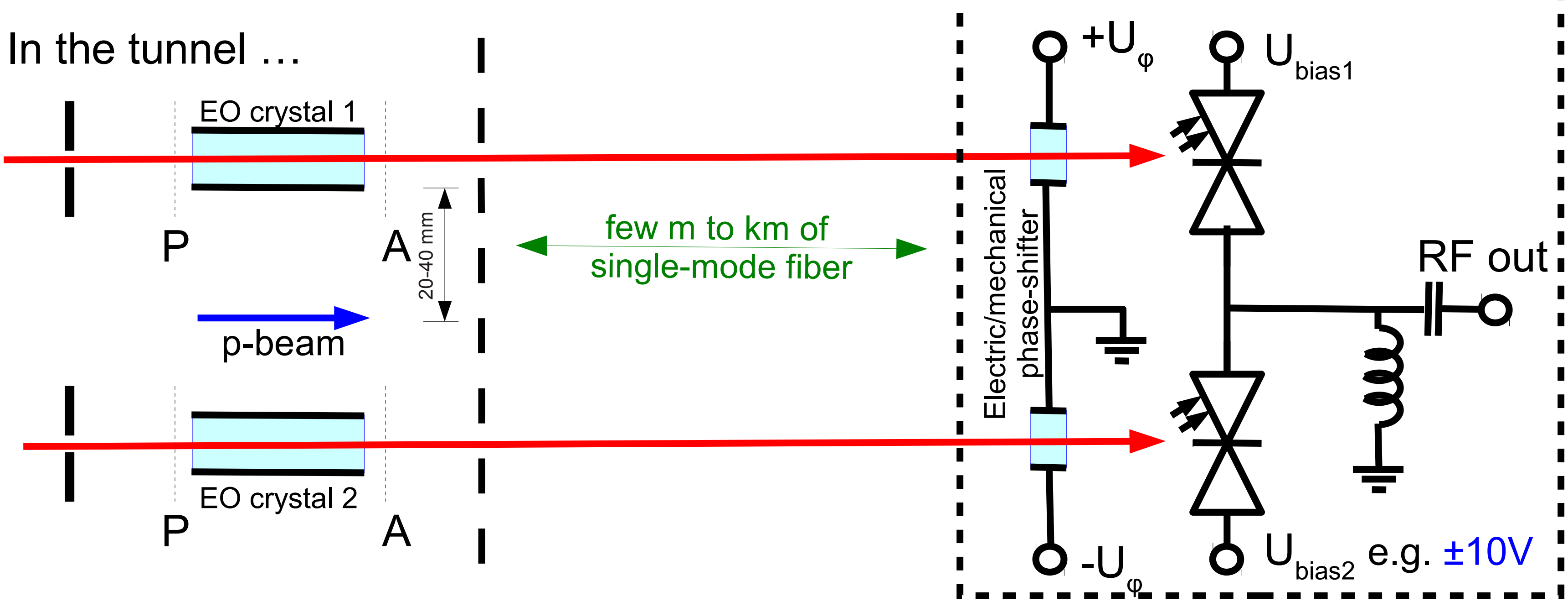
path used for align. purposes

EO Crystal

DC/low-frequency voltage supply

Amplitude Modulation-based Scheme I/II

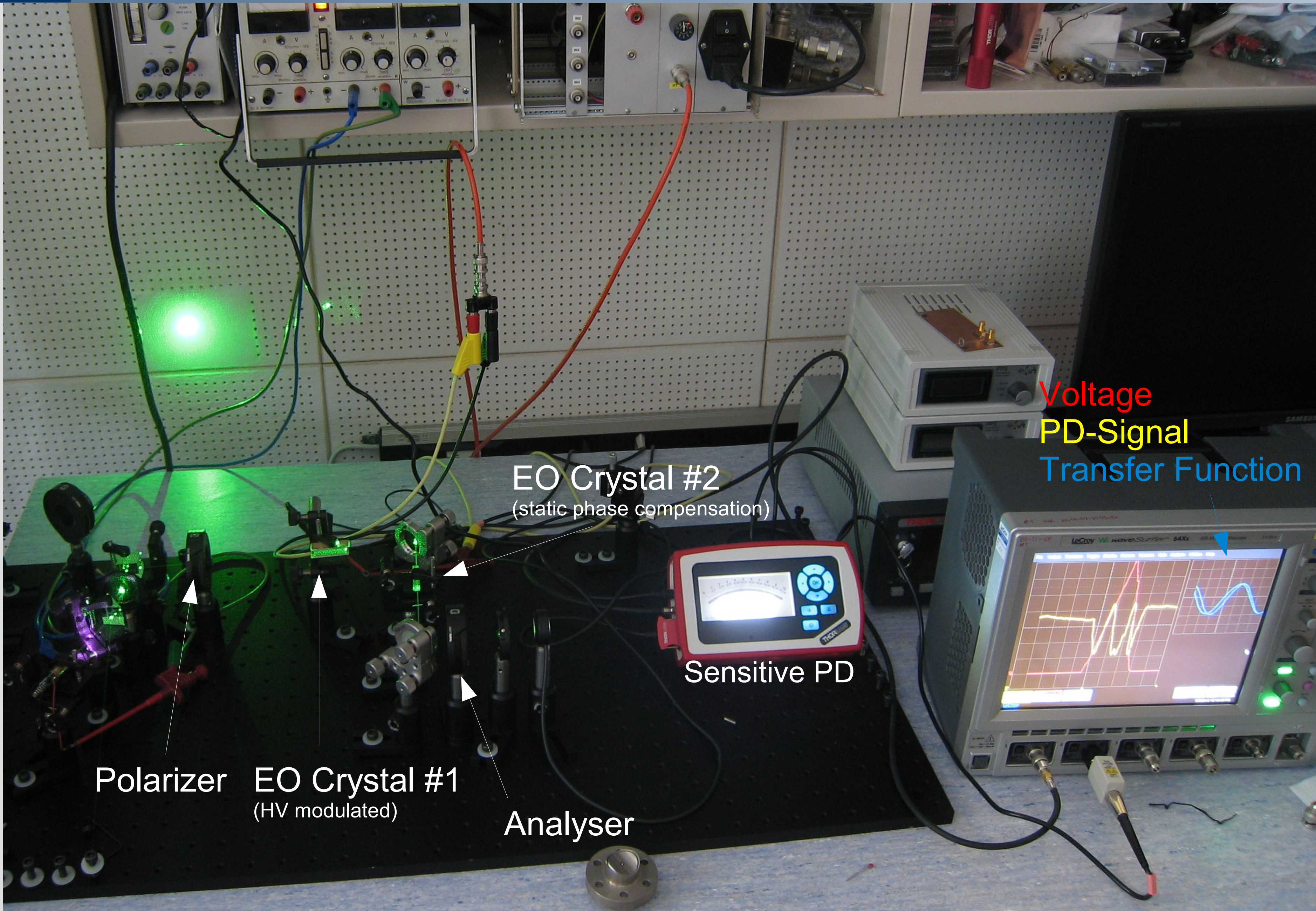
- E.g. polarisation (→ pockels cell) or phase retardation (Fabry-Perot)



… somewhere else next to DAQ

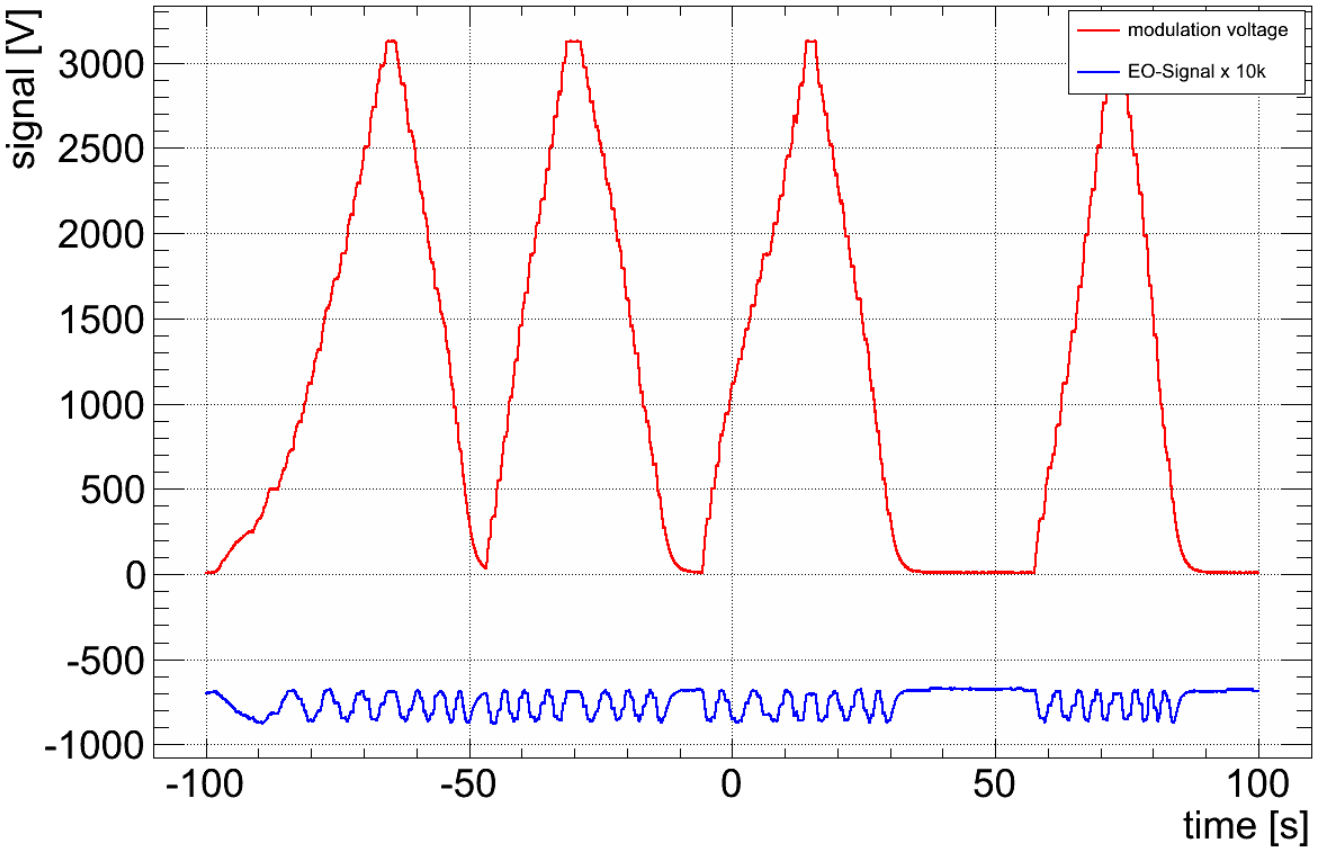
- Simple → robust design:
  - no setup or retuning of electrical/mechanical parts in tunnel
  - complexity kept at DAQ
    - Leverage same MSM-detector design as for synch-light based BPM
    - Phase and amplitude matching possible via U_{φ} and U_{bias}
    - Less radiation issues, could consider cryo-cooling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

$LiTaO_3$ Sensitivity Setup – Amplitude Modulation II/II
here: < 20 mW, 532 nm Laser (cheap-o 7$, not stabilised)



$LiTaO_3$ Sensitivity Setup – Result I/II
V_π Measurements

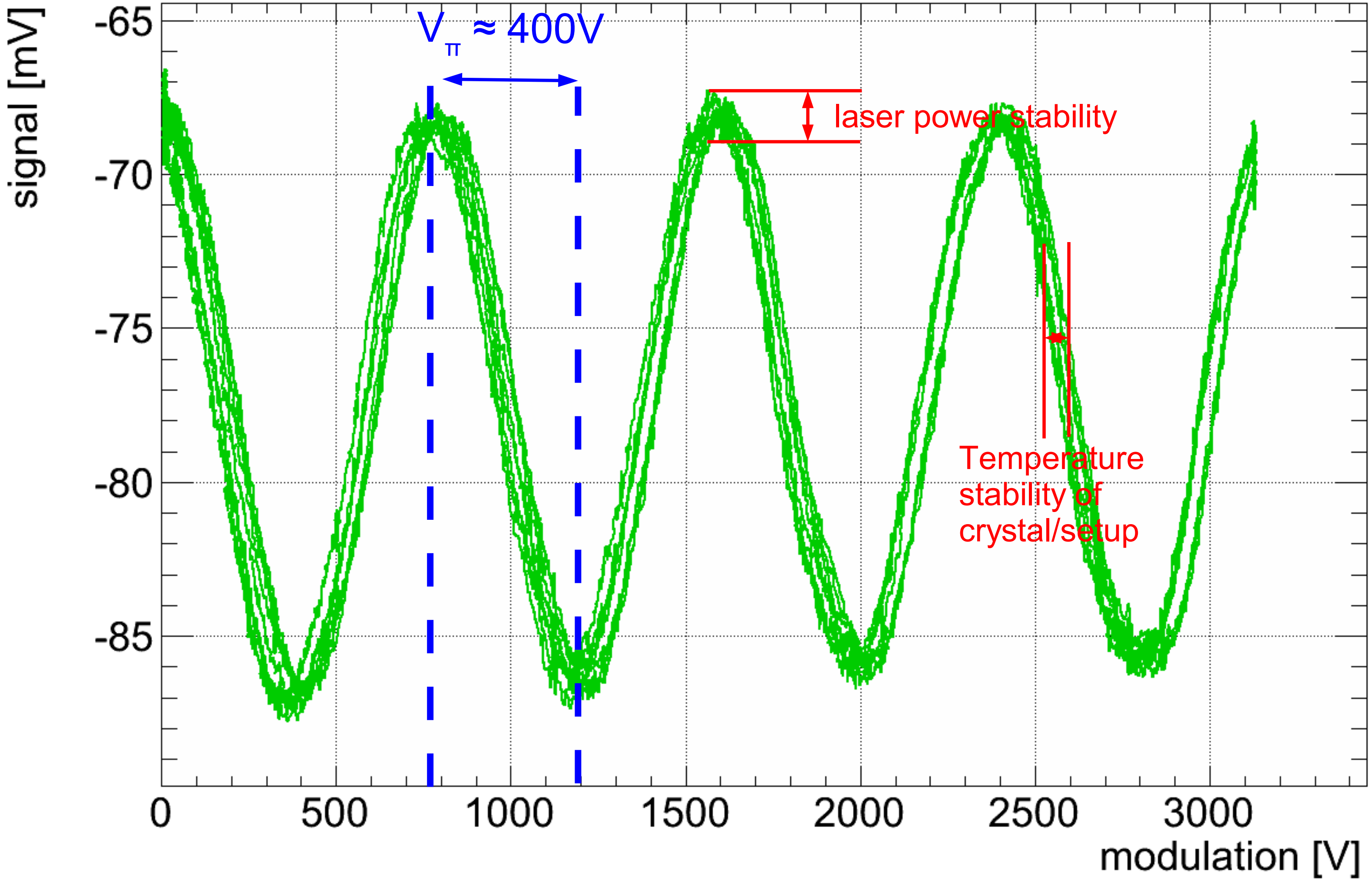
- In agreement with crystal parameter and geometry



- Drifts in time traced back to temperature changes and laser power stability
  - Mitigated since position measurement is differential, furthermore these effects can be reduced through stabilisation of the of the laser power and setup temperature (relative differences between crystals)

$LiTaO_3$ Sensitivity Setup – Result II/II
Temperature Dependence

- Not unexpected:
  thermal crystal dilation/contraction → changes optical path-length



Outcome of Lab-Tests

- Valuable lessons learned:

  A) amplitude-mod. much more robust than interferometric approach

  - less (no) laser wavelength/phase-coherence issues
    → less constraints on required laser bandwidth Δλ
    → works even with incoherent light (however: laser easier for fibres-coupling)

  B) 'all-fibre-based' setup easier to handle and more stable than tested 'in-air' setup using mirrors, prisms, film polarisers, etc.
  → integrate as much (all!?!) into fibres and BPM body.

  C) MSM-PD quite robust, low-noise, wide-band and eventually easier to be efficiently coupled to fibres than anticipated (thanks to Sophie)
  → light detection/conversion to electrical signal is not an issue

  D) Laser worked (and was safe to use) but should spend more than 7$
  → better laser power stability

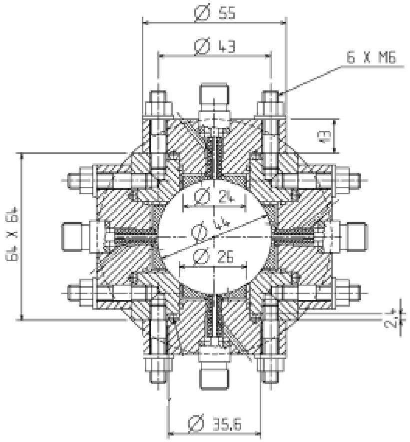
  E) Main environmental effects:

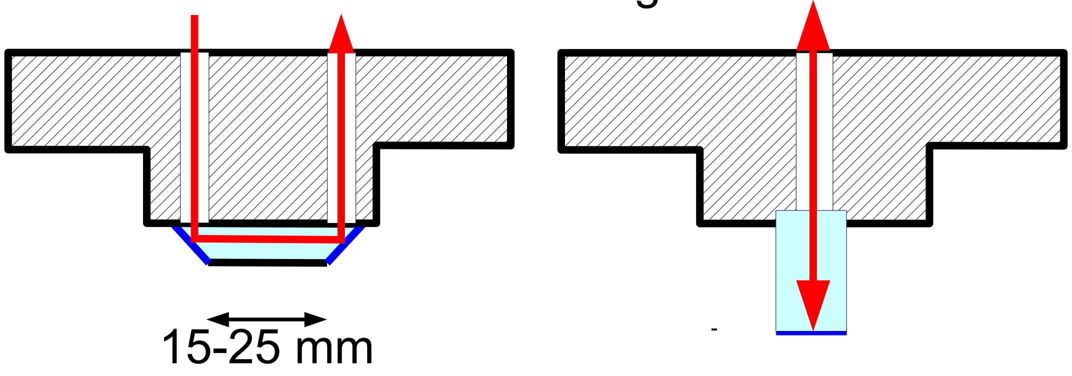
  - Stray ambient light (~5 uW) interference with signal (~ mW)
    → eliminated through using fibres
  - Temperature induced optical, particularly crystal path length changes
    → path between polariser→crystal→analyser needs to be stabilised

- Not been tested (yet): impact of radiation (should be minimal) & vacuum

Amplitude Modulation-based Scheme
Proposed Optical-BPM Design for SPS Prototype

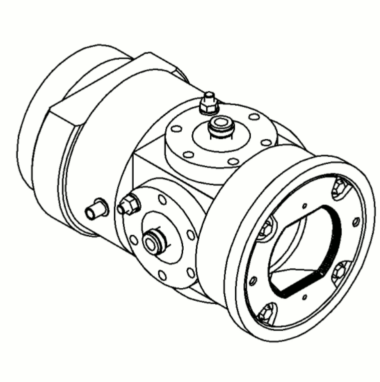
- All-Optical-BPM layout scheme, re-use conceptually LHC BPM design:
  - Keep the same body, keep external button form-factor




transverse variant:

longitudinal variant:

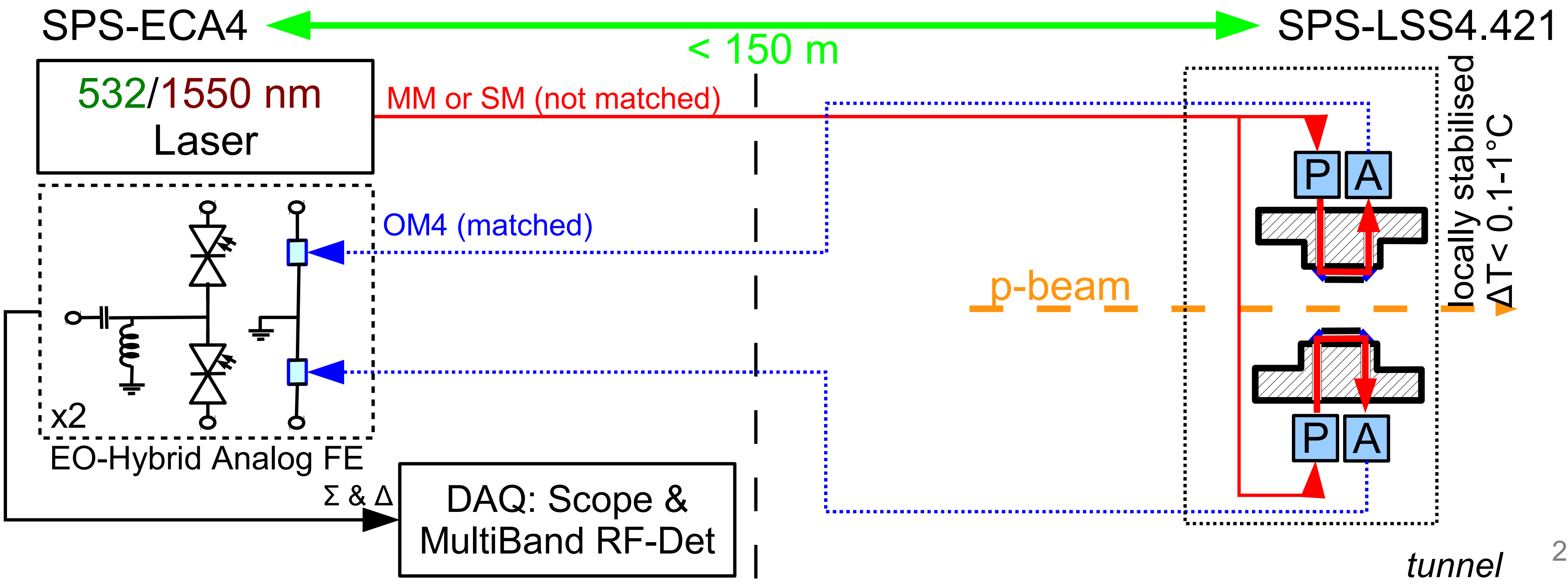
15-25 mm



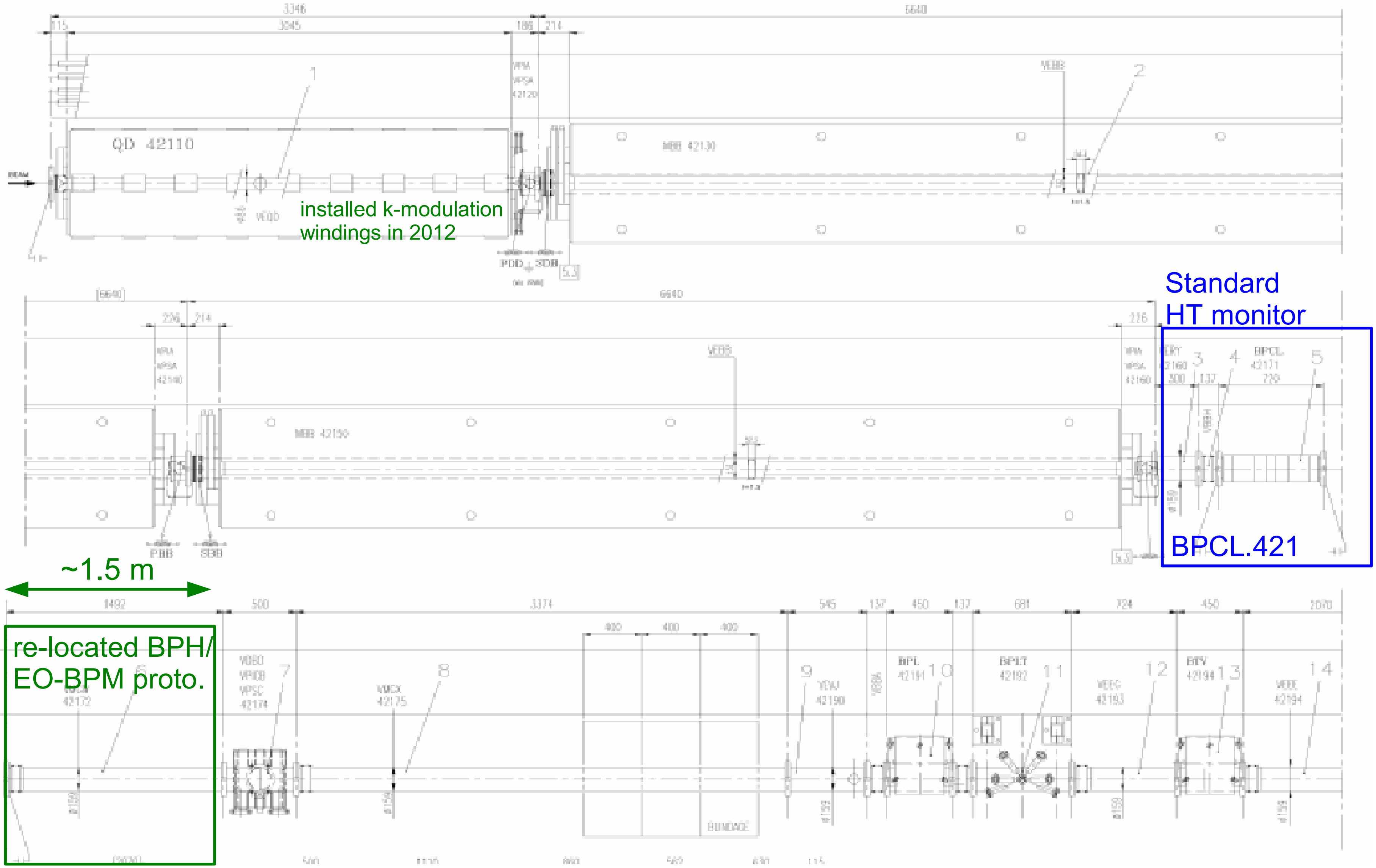
- Impact of EO-crystal (dielectric setup) on machine impedance small but should be re-checked by FE-EM simulation
- Mechanical design & construction in 2012/13
  - Need to investigate crystal clamping and fiber-to-feed-through alignment
- Possible prototype installation in LS1?

Fibre Choices & System Layout

- CERN Standard Fibres:
  - DRAKA, C03e single-mode SM fibre
  - DRAKA, MaxCap-BB-OM2 gradient index multi-mode fiber, 50 um core
    - attenuation < 2.6 dB/km (@850 nm), modal bandwidth > 0.5 GHz*km
- Application would benefit from higher-quality fibre:
  - DRAKA, MaxCap-BB-OM4 gradient index multi-mode fiber, 50 um core
    - attenuation < 3.0 dB/km (@850 nm), modal bandwidth > 4.7 Ghz*km
- Layout (N.B. fibre lengths are fairly short):



LSS4 – Layout



installed k-modulation windings in 2012

Standard HT monitor

BPCL.421

~1.5 m

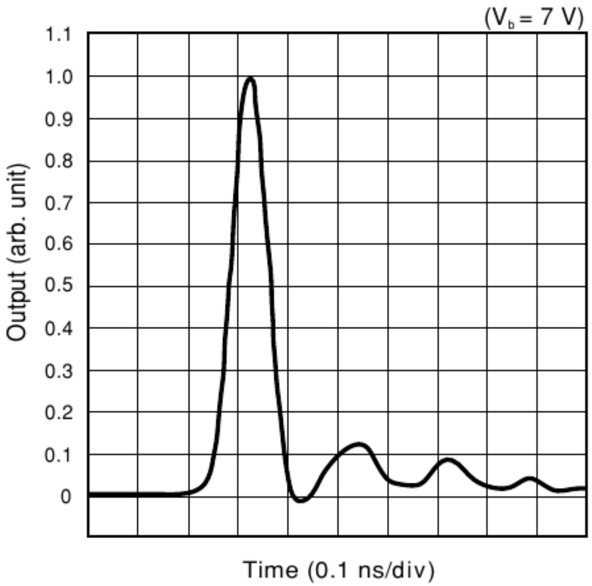
re-located BPH/ EO-BPM proto.

reserved space ECR **1099630**

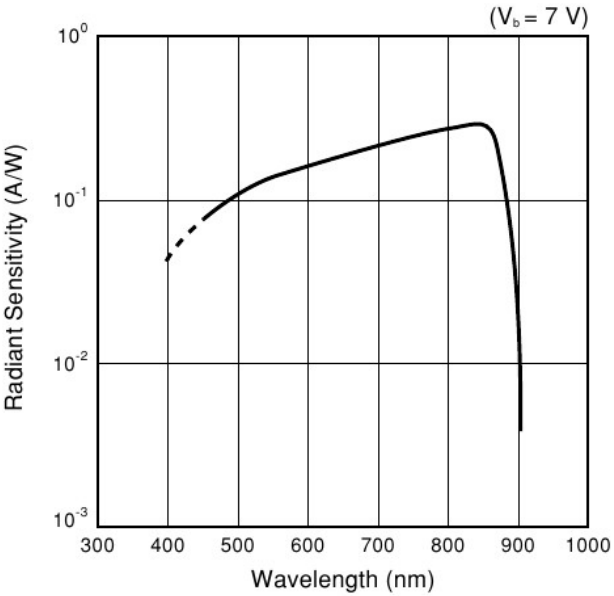
Need to Digitise Signal: Optical-to-Electrical Conversion Metal-Semiconductor-Metal (MSM) Photodetector I/II

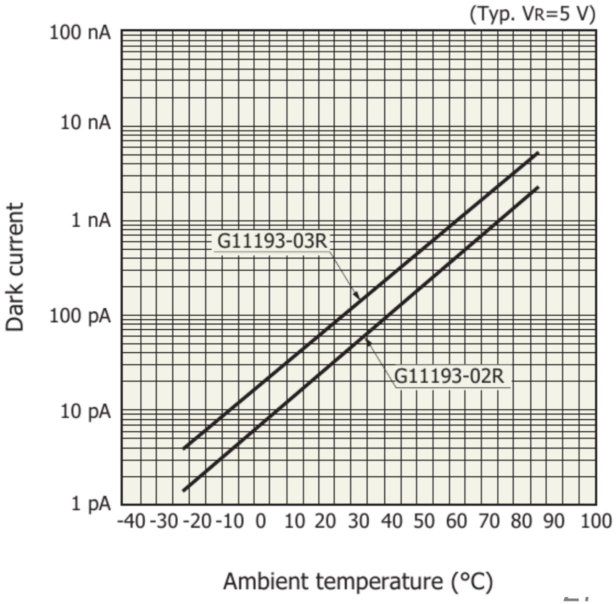
- Hamamatsu's G4176-03 (TO5 package, SMA connector)
  - t_r ≈ 30 ps ↔ nom. 50% atten. @12GHz
  - 0.3 pF for active area of 0.2 x 0.2 mm²
  - typ. light input power ~5-10 mW (50% duty-cycle)
  - dark-current: 100 pA @23°C
  - max. est. S/N: ~150 dB (w/o cooling)

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



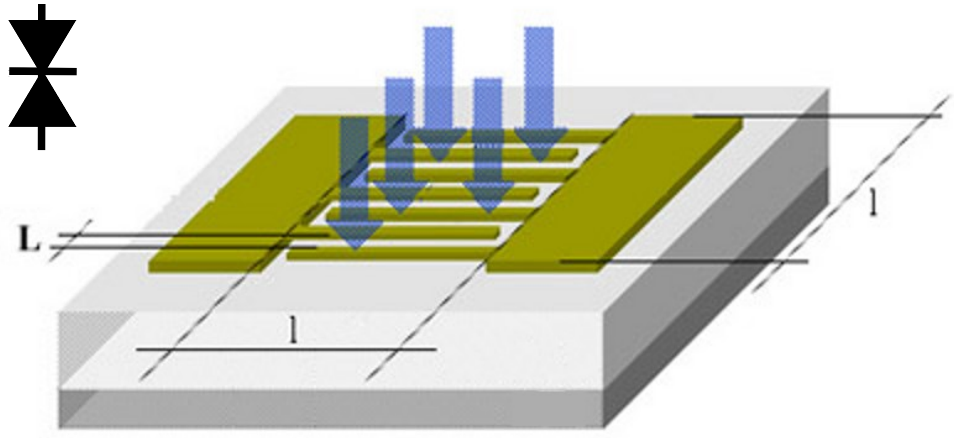
(incl. light source, bias and scope)





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

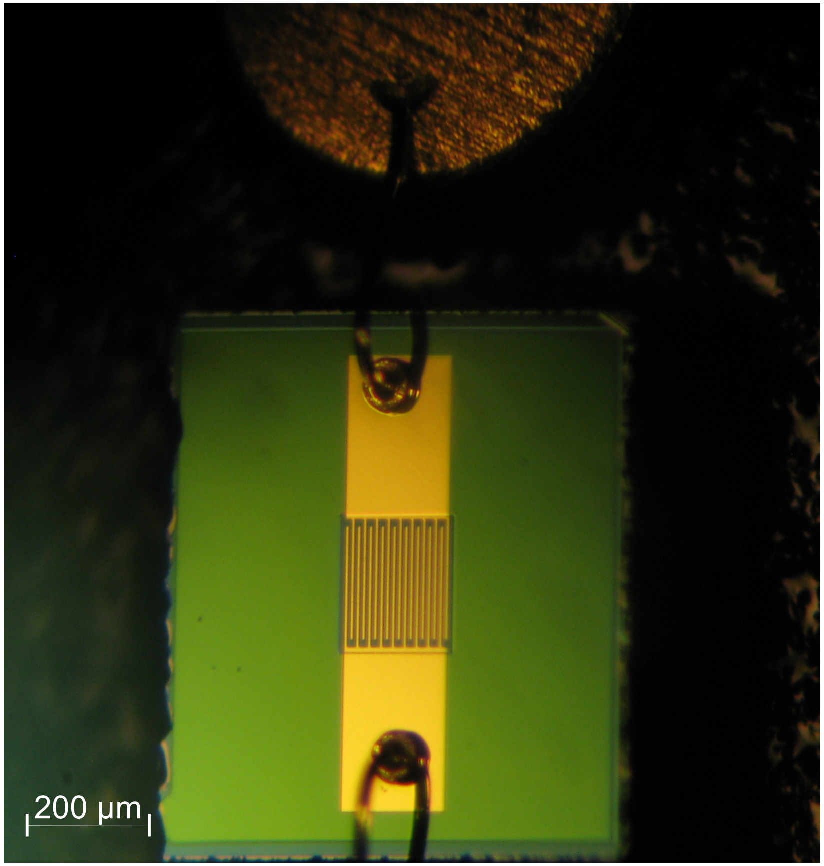
- … not quite a P(i)N junction (diode)!
  no polarity, requires bias-voltage (typ. 10 V)



- Speed determined by doping of (In)GaAs SC material and PD geometry (reflection, C, …)
  - Not quite a MS Schottky Diode

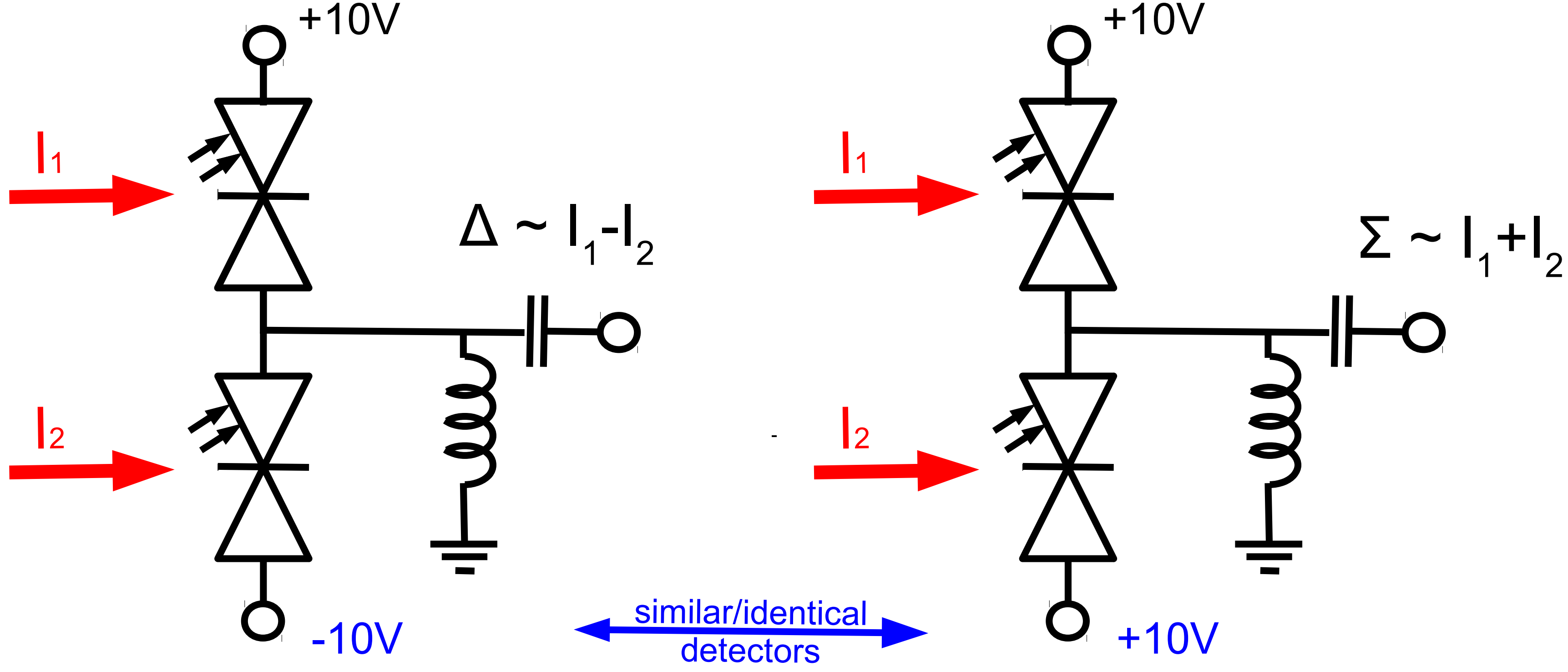
- Variants available exceeding 100 GHz bw. but makes fiber-coupling mandatory

→ KISS: initial prototyping with in-air design



Opto-Electrical Delta-Sum Hybrid Scheme

- Balanced-Detection
- Common-Mode Detection:



Advantages:

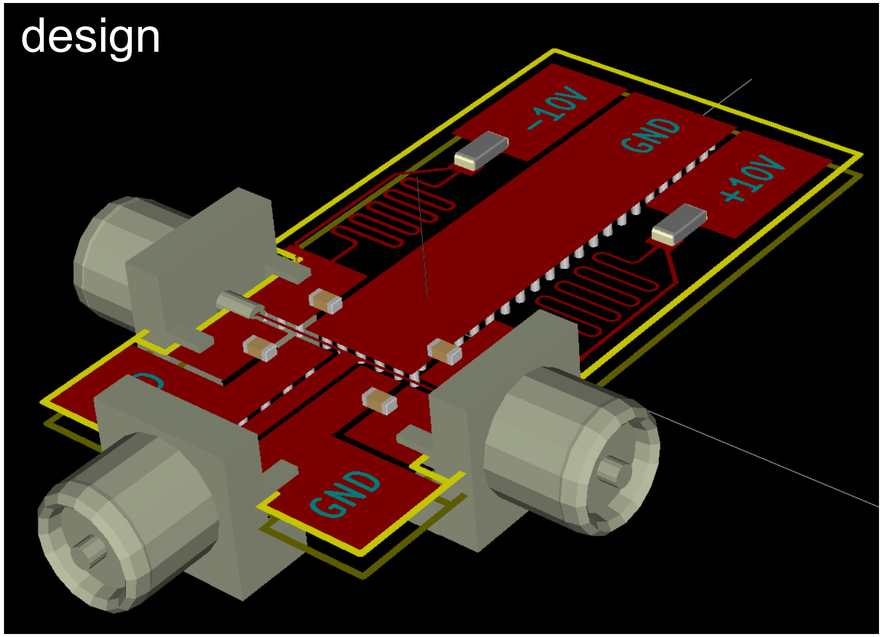
- even lower noise than pure MSM
- Simple phase compensation
- Simple adaptive orbit offset comp.
- 50Ω vs. high-impedance (glued to ADC)
- Can keeps sensitive (== expensive) equipment/control outside the tunnel

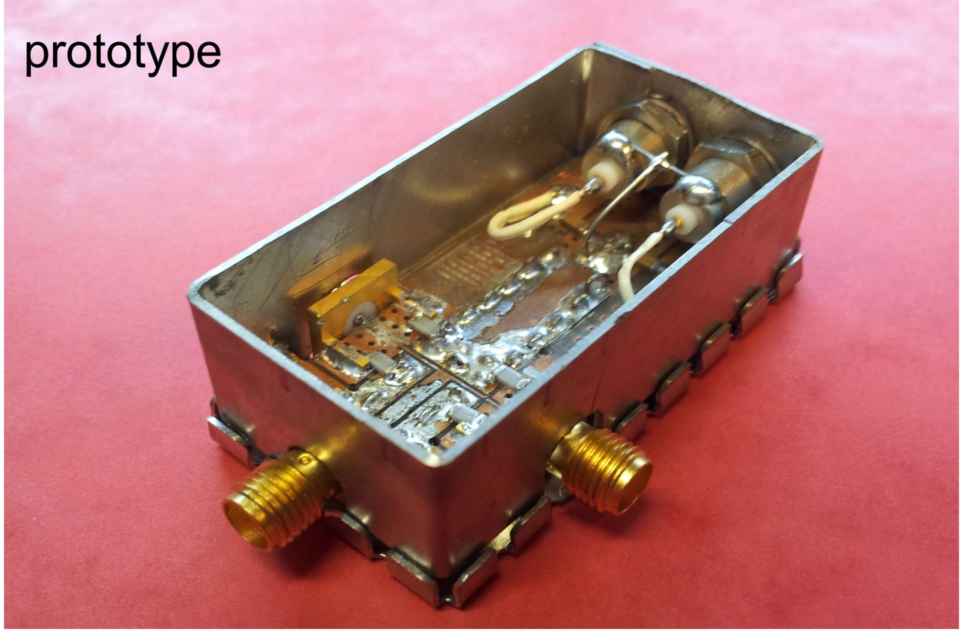
Advantages:

- 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

Opto-Electrical Delta-Sum Hybrid Scheme

- First RF prototype tested at the ASLS (Synchrotron-Light BPM)
  - good S/N and noise rejection but produced on poor off-the-shelf FR4 (ε(f)=4.2±0.4, tan(δ)=0.01) → limits bandwidth to < 2 GHz

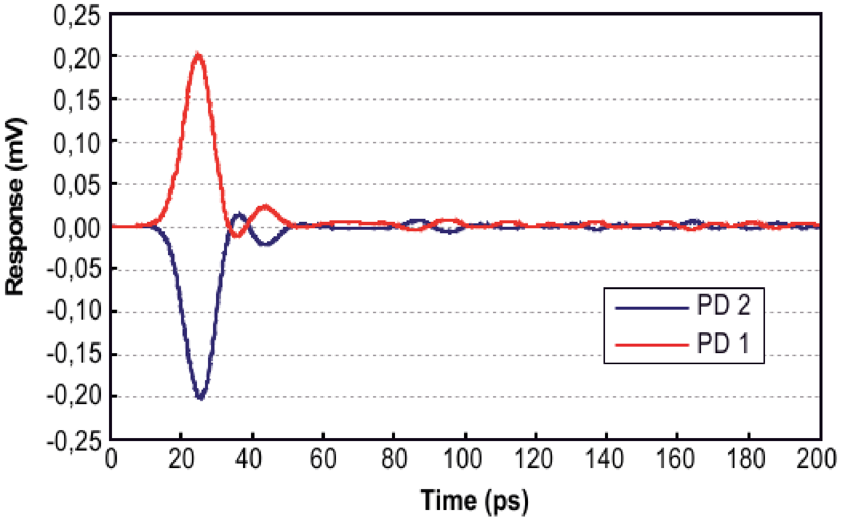


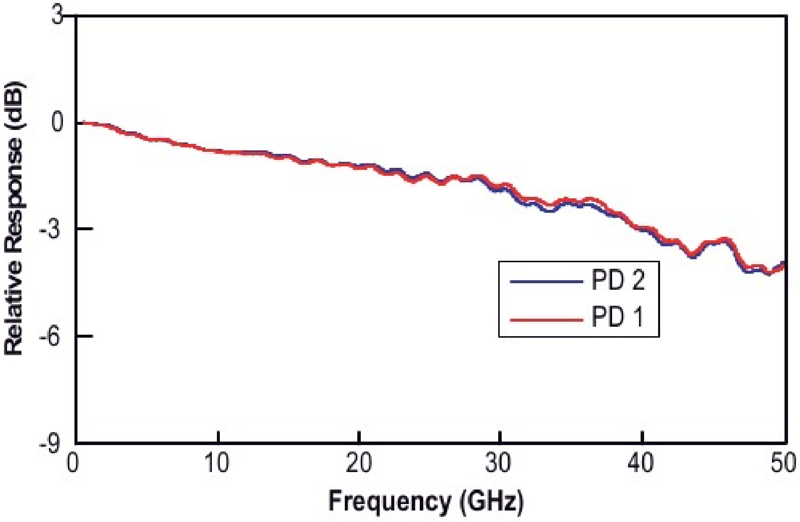


- Next batch will be re-done with proper RF substrate, ordered for testing:
  - Rogers RT/Duroid 5880: ε=2.20±0.02, tan(δ)=0.0009, const ε!
  - Rogers RO3003: ε=3.00±0.04, tan(δ)=0.0013, const ε!

Strengths of Balanced Photodetectors

- Specific advantage of MSM photodetector vs. diodes: no specific bias polarity → can be exploited to dynamically flip signal between delta and sum mode
- Can detect DC changes
- Bias voltage and polarity can be used to:
  - high-frequency difference controlled via regulated DC voltage
  - simple calibration for phase difference:
    - One PD bias voltage is set to zero – measure signal with the other and vice versa and adjust for the phase difference (externally e.g. mechanically stressing optical fiber)





Summary

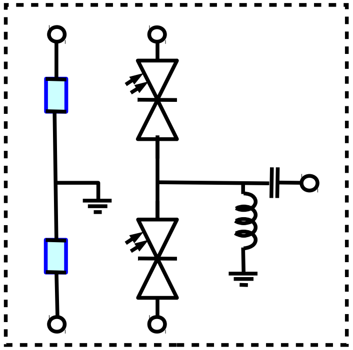
-

Additional slides

Sensitivity & Gain Adjustment

- Main observable:

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



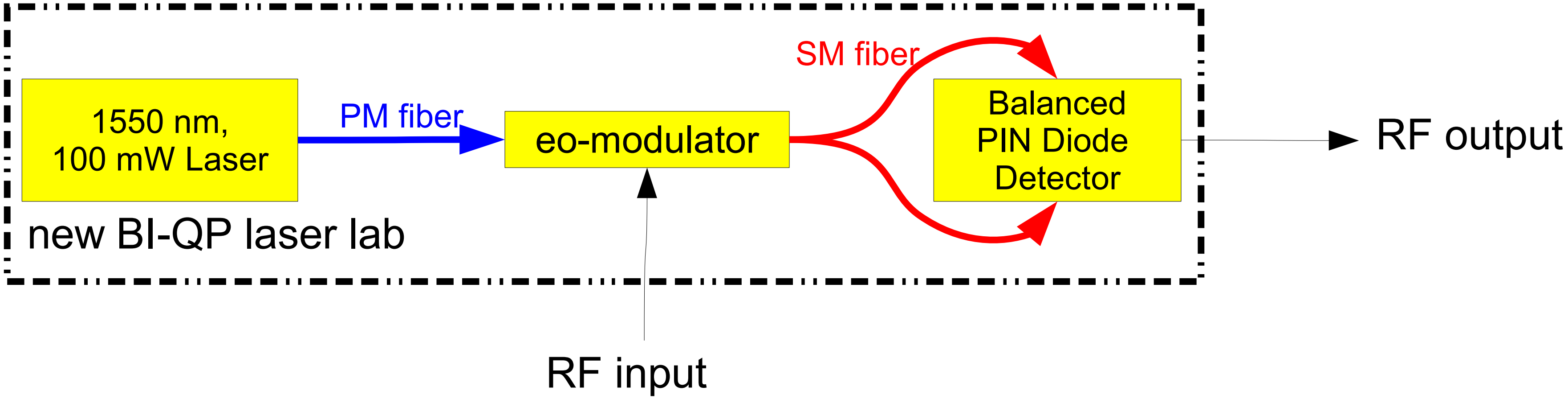
- Some constraints:
  - EO-crystal range (saturation-like): $V_{pickup}\big|_{max} < 0.8 \cdot V_{\pi}(crystal)$

    → *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

LiNbO3 Bandwidth Setup

- Test-setup:



1550 nm,
100 mW Laser

PM fiber

eo-modulator

SM fiber

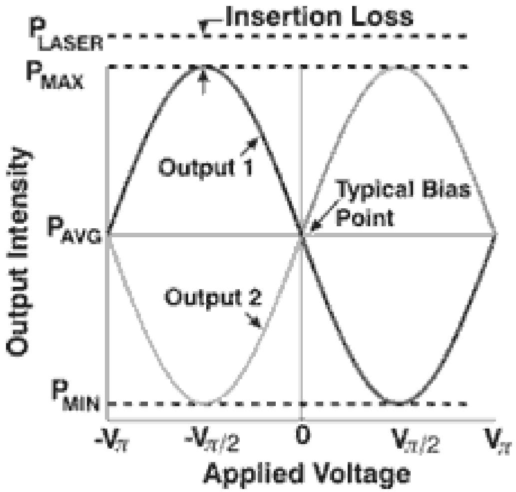
Balanced
PIN Diode
Detector

RF output

new BI-QP laser lab

RF input

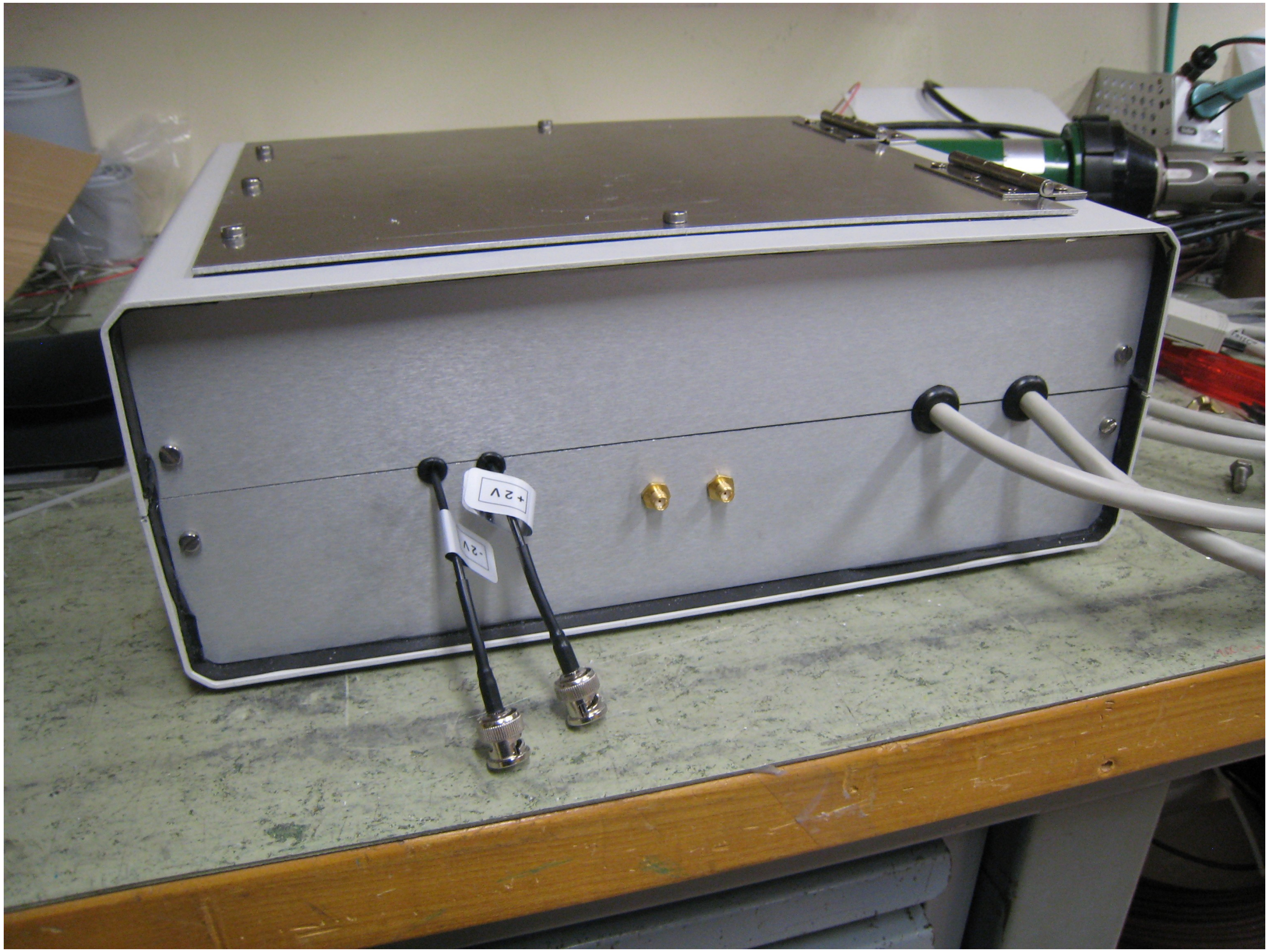
- Aim: confirm bandwidth and achievable S/N ratio
- Basically this is a standard telecommunication setup (modulo fiber length)
  - Reproduce bandwidth
  - Explore limits of link, noise sources etc.



- DSO: > 1 mW → operation in dedicated lab and armoured fiber mandatory
  - Don't have one on the Prevessin site ...

LiNbO3 Bandwidth Setup
Behold: BI-QP's New Laser-Lab

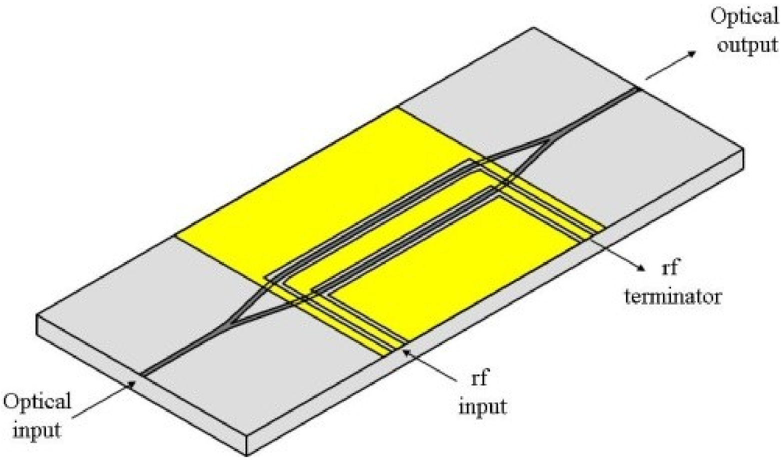
- Requirement from our DSO: light-tight confinement, only tool-based access allowed, laser cut if lid is opened

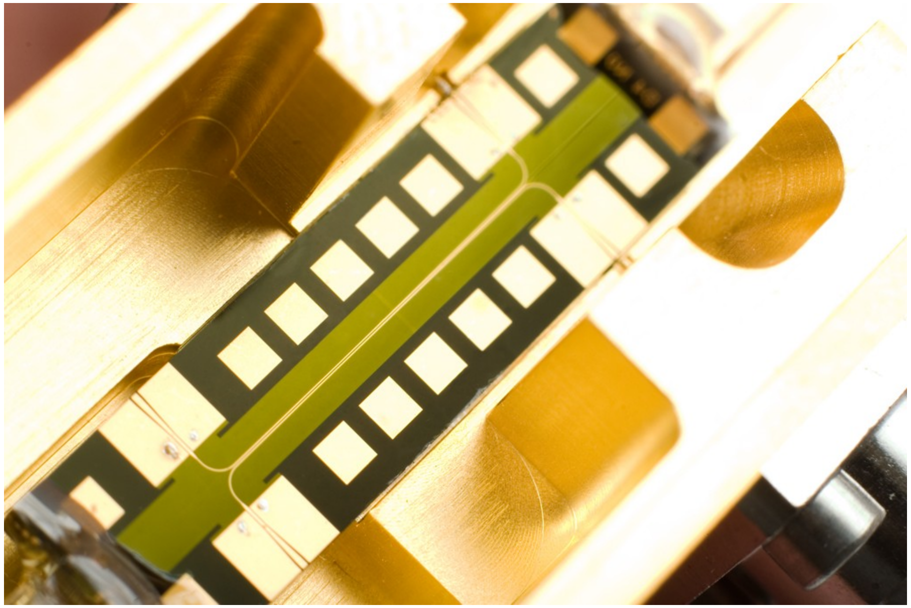


- Courtesy Philippe Lavanchy; awaits DSO approval

Alternatives...
Electrical → Optical BPM Signal conversion I/II

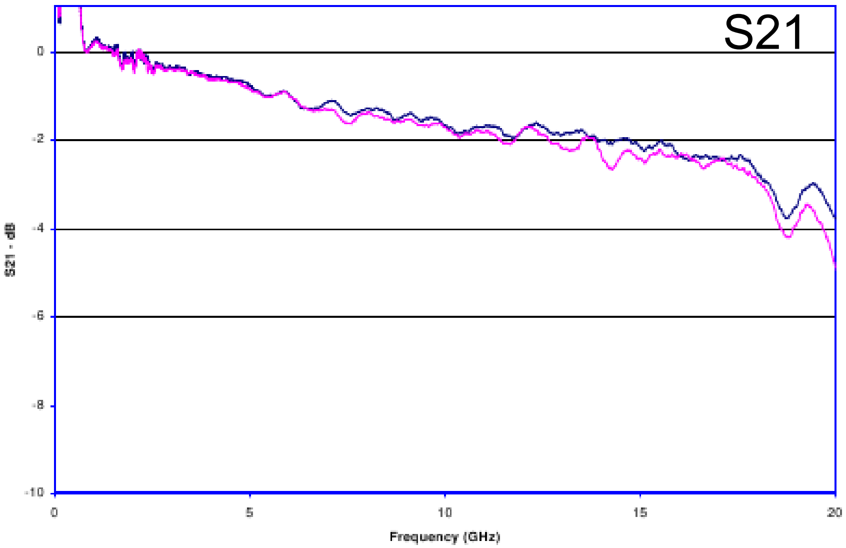
- Creating an optical hybrid translates to the same classical RF hybrid issues
- EO-modulator basically are (un-)matched micro-/strip-line structure
- Critical aspects:
  - Impedance matching
    - Geometry → tricky but similar to our other RF pick-ups
    - Larger dielectric loss-tangent due to $\varepsilon_r(t)$~80 (BPMs strip-lines are in vacuum)
  - Insulation
    - hasn't been demonstrated (yet) that we can achieve -40dB or better

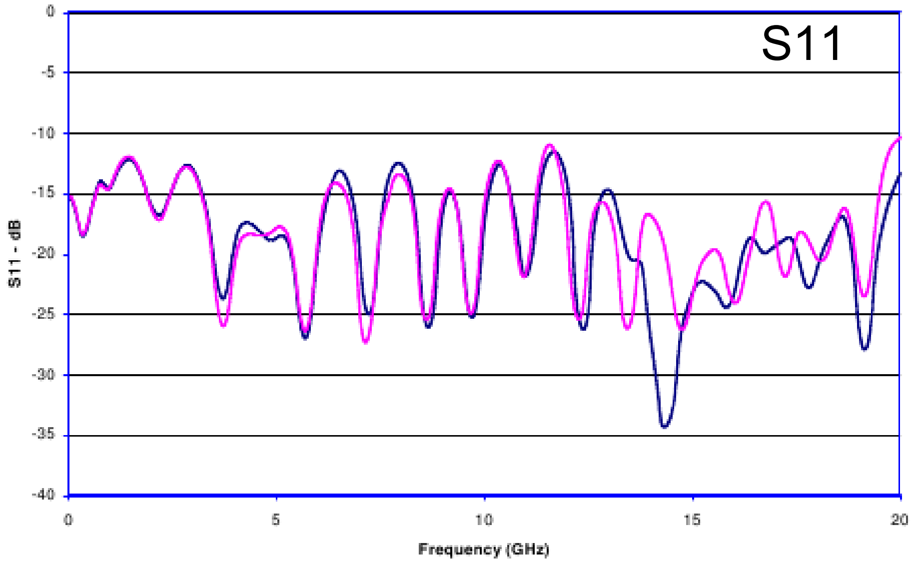




Alternatives...
Electrical → Optical BPM Signal conversion II/II

- Directly connect em-BPM → eo-modulator → fiber → MSM detector
- Compared to BPMs, Eo-mod. typ. have badly matched strip-lines





  - Not a design criteria for telecommunication (digital signals)
  - Reflections may possibly perturb measurements of consecutive bunches
- If not done properly – probe laser noise (typically 1%) may propagate and superimpose onto the beam signal
→ balanced detector scheme may mitigate this to some extend.

Some Caveats using EO-Crystals

Independent of the electro-optical detection scheme:

- Sensitivity and signal levels are given by crystal geometry which can be adjusted to the expected maximum/minimum bunch intensity, however:
  - A priori static sensitivity, i.e. easy no optical gain switching
    - with added complexity: add more than one crystal per pick-up
    - Sensitivity depends on laser wavelength λ
→ could be exploited but only up to 100% variations in n_b
(Synch-Light BPM is better in this aspect)
    - gain adjustment would need to be addressed on the analog front-end
- Radiation damage effects of fibers vs. cables need to be further assessed