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

– Status and Update –

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[4]Accelerator Group, The Australian Synchrotron

- Motivation

- Present Limitations and LIU Upgrade Wishes/Plans

- Three complementary upgrade paths being investigated:
  - Wide-band, electro-magnetic pick-up based
    - boost to 6 GHz by classic RF means → BI-TB in January 2012
  - Synchrotron-Light based BPM → dual use CTF3 & LHC
    - Optical regime may solve present power and bandwidth limitations
    - Fiber-based signal transmission
    - Collaboration effort with ACAS (Uni-Melbourne and ASLS)
  - (In-)direct EO-based BPM → machine/beam type independent
    - Proof-of-principle by the end of this year, can re-use acq. system

Head-Tail Instability

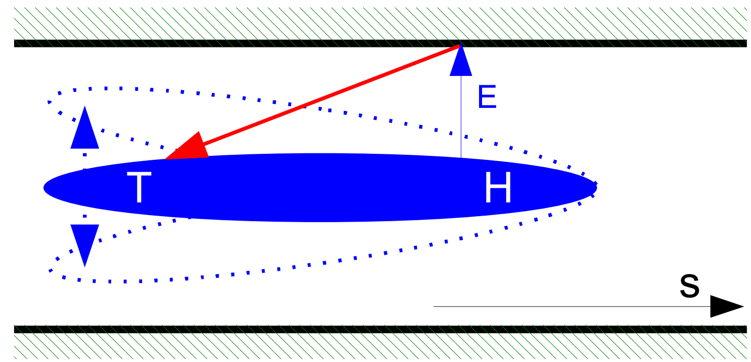
- First discovered at ACO and Adone (1969)[1]
  – mixing of long. and transverse motion
    - Phase advance change:

$$\Delta Q := Q' \cdot \frac{\Delta p}{p}$$

    - Synchrotron oscillation:

$$\frac{\Delta p}{p} = \frac{\Delta \hat{p}}{p} \cdot \sin(\omega_s \cdot n + \phi_i)$$

→ **Head and Tail swap position after half a sync. period!**

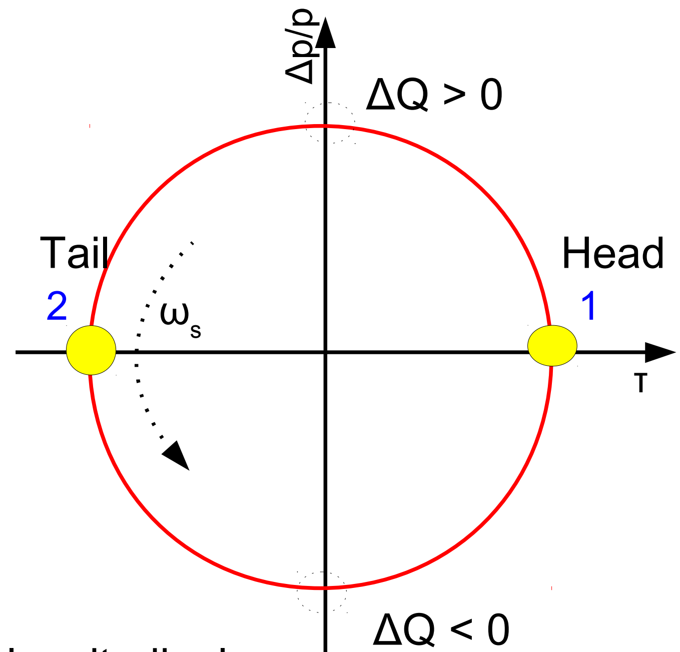


transverse

- Damping time constant (1st order):

$$\frac{1}{\tau_{HT}} \sim N_b \cdot \frac{\hat{\tau} Q'}{Q^2 \cdot \underbrace{(\alpha_c - 1/\gamma_{rel})}_{\eta}}$$

- Head-Tail motion becomes unstable if $\frac{1}{\tau} \overset{!}{<} 0$
  – above transition (η > 0) & Q' < 0
  → usually keep Q' slightly positive!

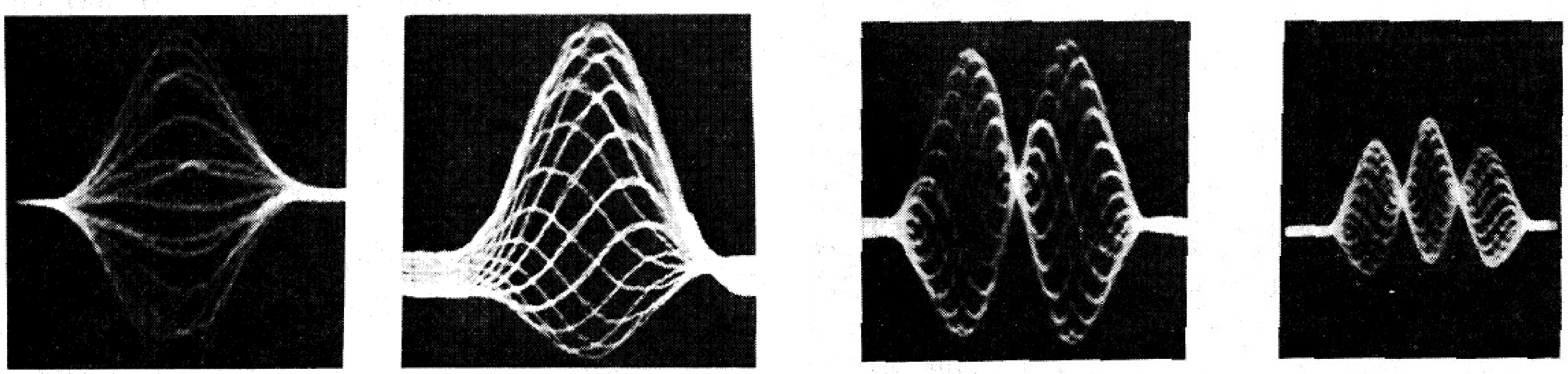


longitudinal

1 M. Sands, *"The Head-Tail Effect: An Instability Mechanism in Storage Rings"*, SLAC-TN-69-008, 1969

- Intra- and inter-bunch beam motion is one of the observables of this instabilities:
  - Lower-order modes: Inter-bunchBPM resolving bunch-by-bunch motion
  - High-order modes: Intra-bunch instabilities → Head-Tail instabiltiies

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

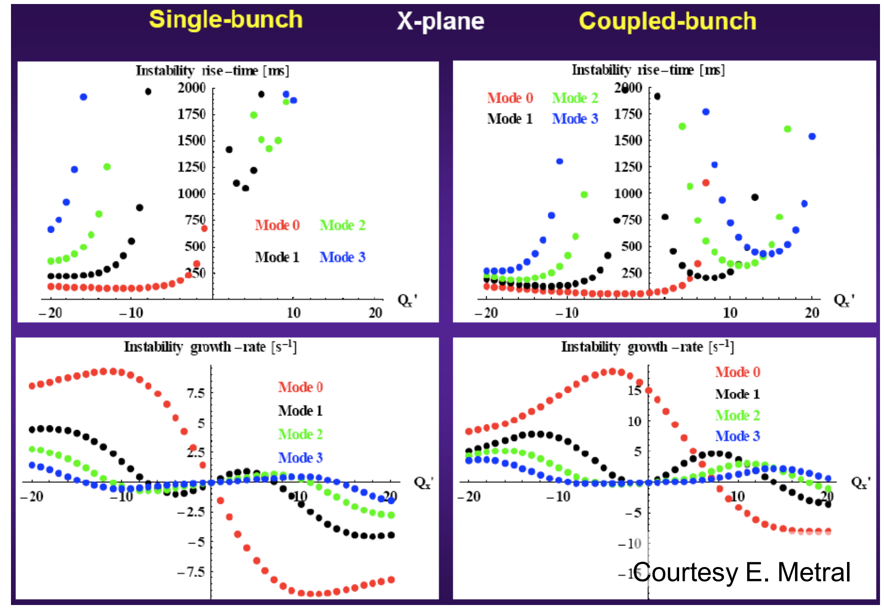


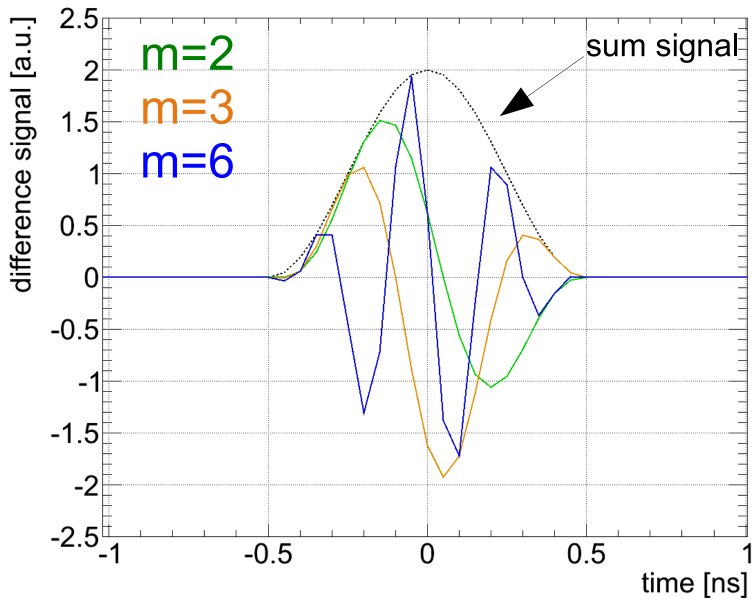
a) mode m = 0, χ = 0   b) m = 0, χ = 2.3 radians   b) m = 1, χ = 6.9 radians   d) m = 2, χ = 6.9 radians

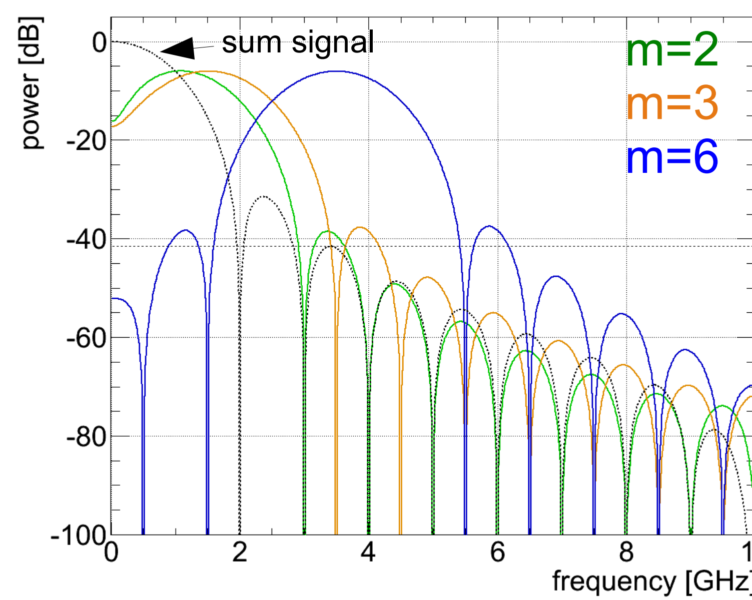
- PS: 120 ns bunch length ↔ less demanding in terms of bandwidth
- SPS/LHC: bunch length down to 1 ns → requires GHz analog bandwidth

Head-Tail Motion Signal-Spectra Simulation

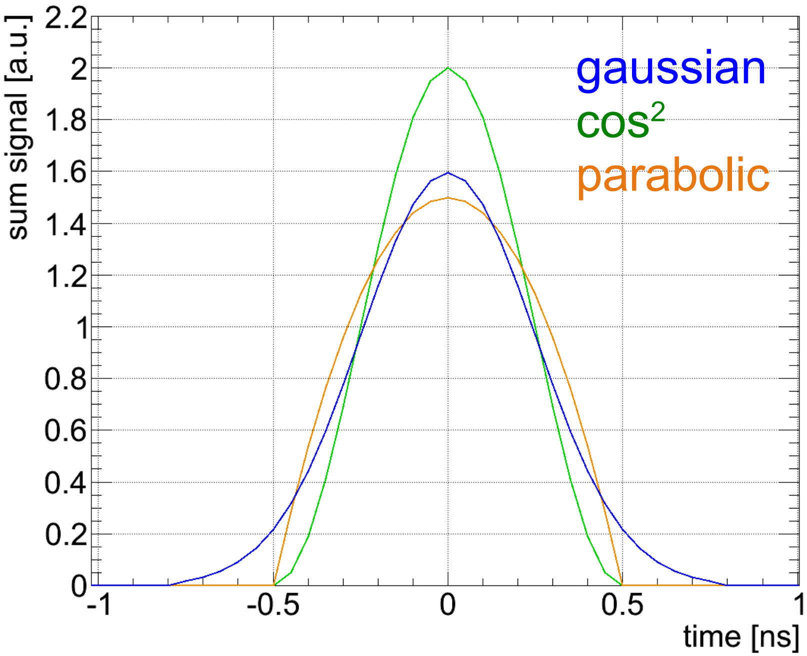
- Higher-order HT instabilities
- Can be detected e.g. via:
  - time-domain: counting number of zero-crossing, rising/falling-edges
  - freq.-domain: standard peak search, provides also indication for
    - mixed modes
    - HT mode strengths

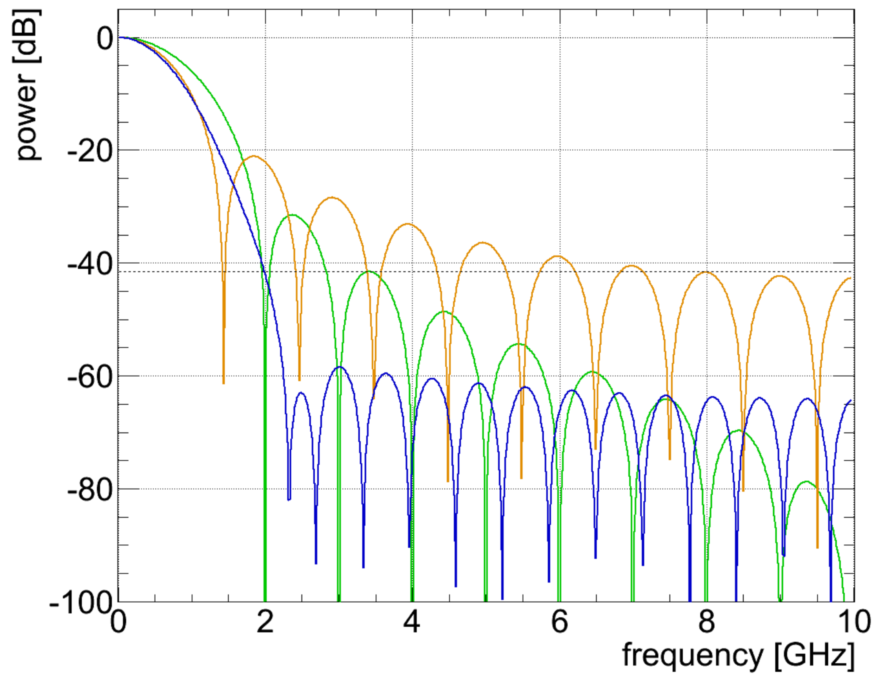




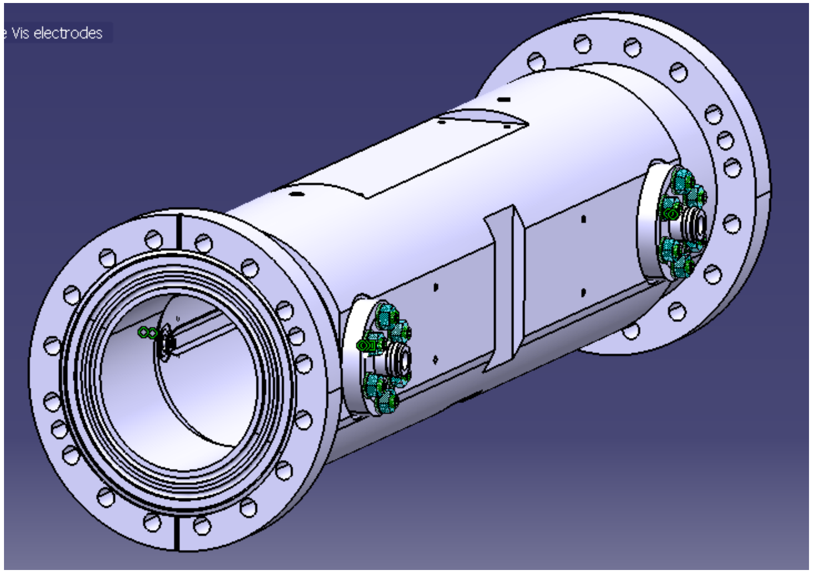


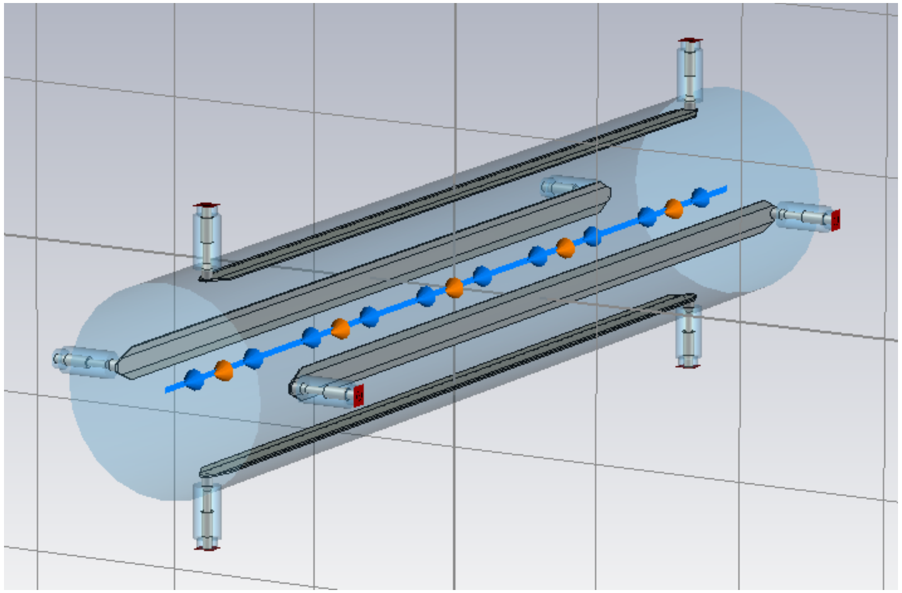
- Additional diagnostics: power spectrum is sensitive to bunch shape, bunch length, bunch intensity, longitudinal phases, …
  - But signal decreases above 1-2 GHz → amplification by 40 dB needed (→ diplexer)





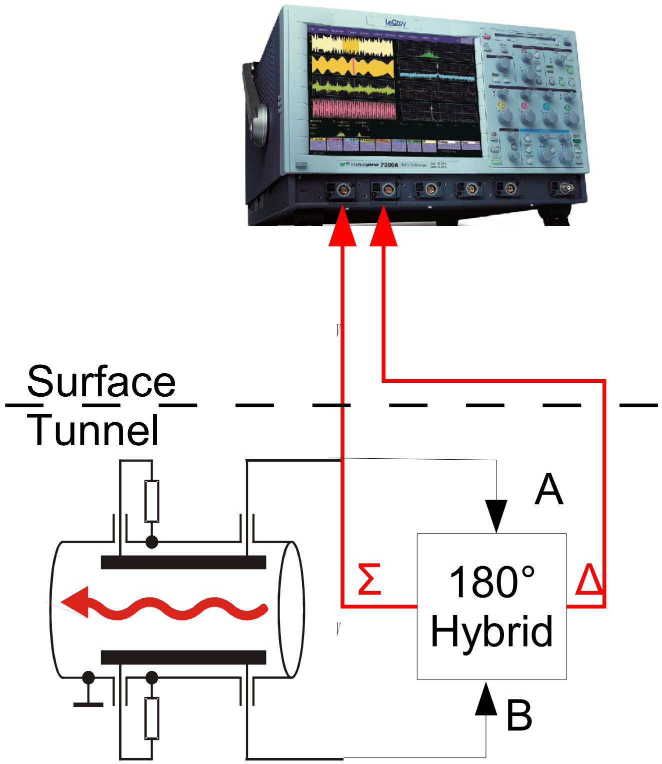
- Fast inter- and intra-bunch beam instability monitor used to detect and study e-could-, impedance- and TMCI-driven head-tail effects
- Diagnostics typically based on strip-line pick-ups, challenges:
  - very wide-band frequency response: 0 ... 2.5 (present)... 8 GHz (target)
  - nom. bunch intensity: $n_b \approx 1.2 \cdot 10^{11}$e+/bunch (20 nC) & $\sigma_t \approx 0.2$ ns
    $\leftrightarrow V_{pp} \sim n_b^2 \sim 300$ V and frequency range of 0 - 1.7 - 3 GHz
    $\rightarrow$ 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:



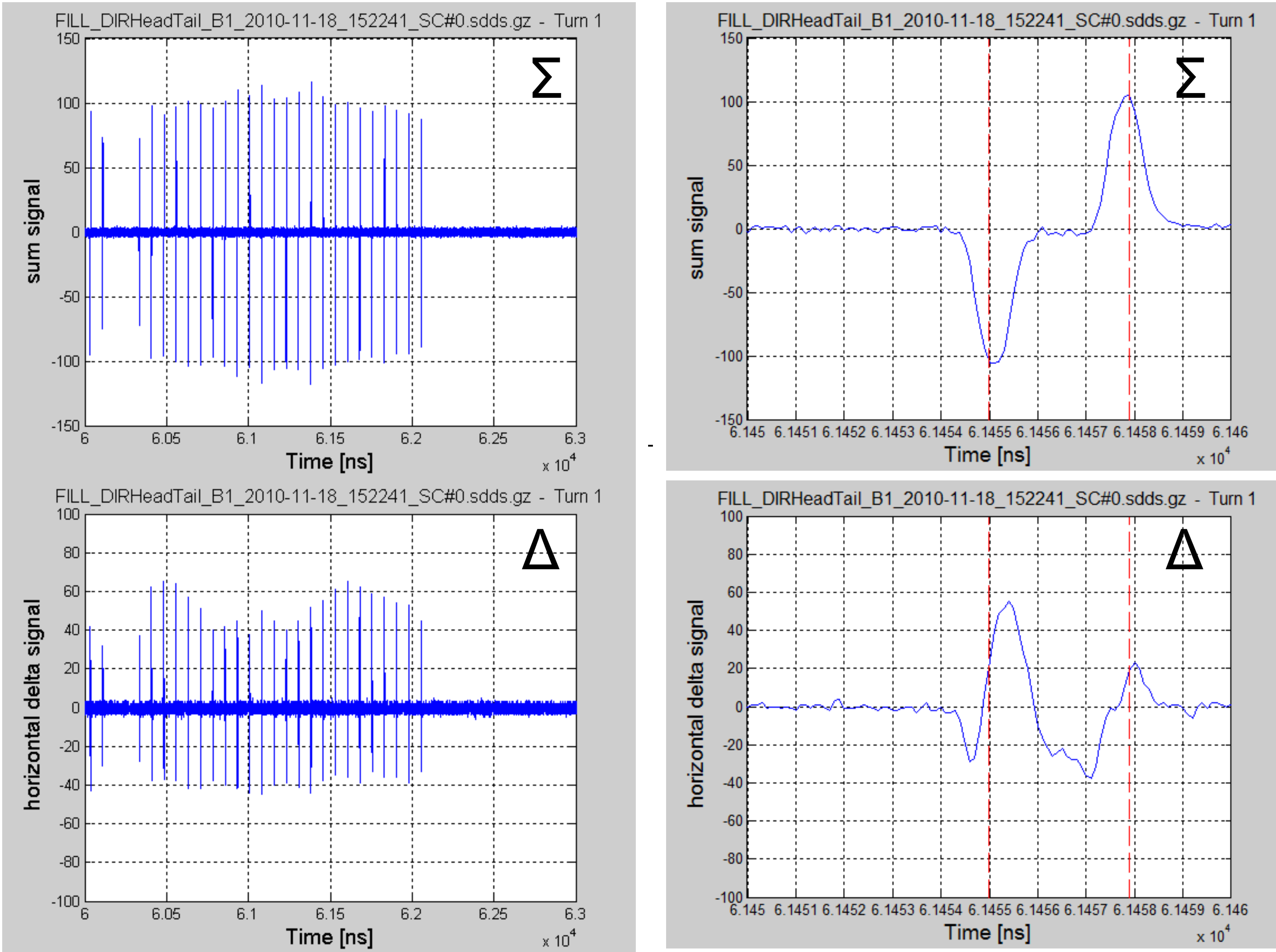


Implemented/tested at CERN-SPS, Tevatron, LHC:

- 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



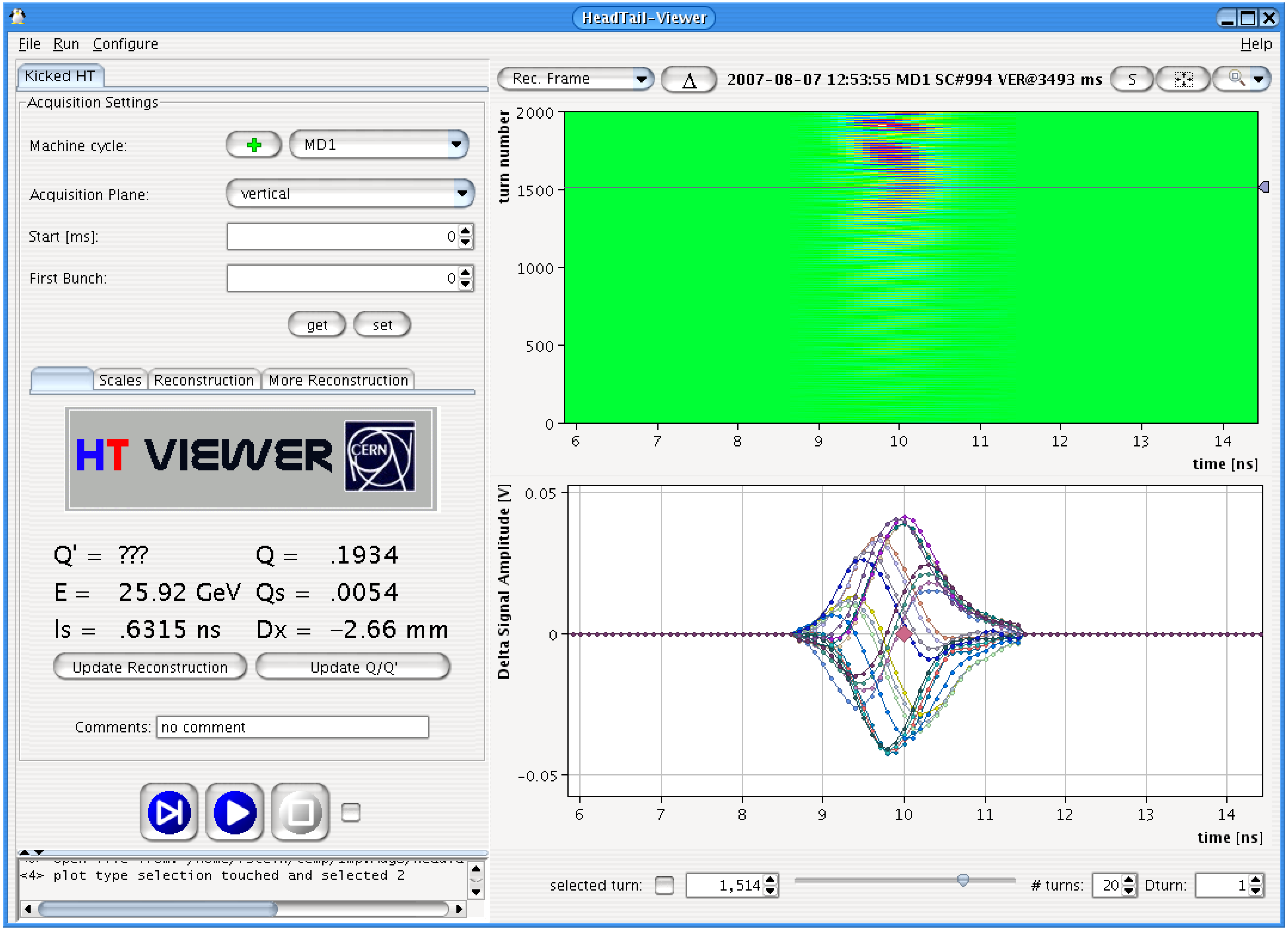
Head-Tail Signal Example SPS



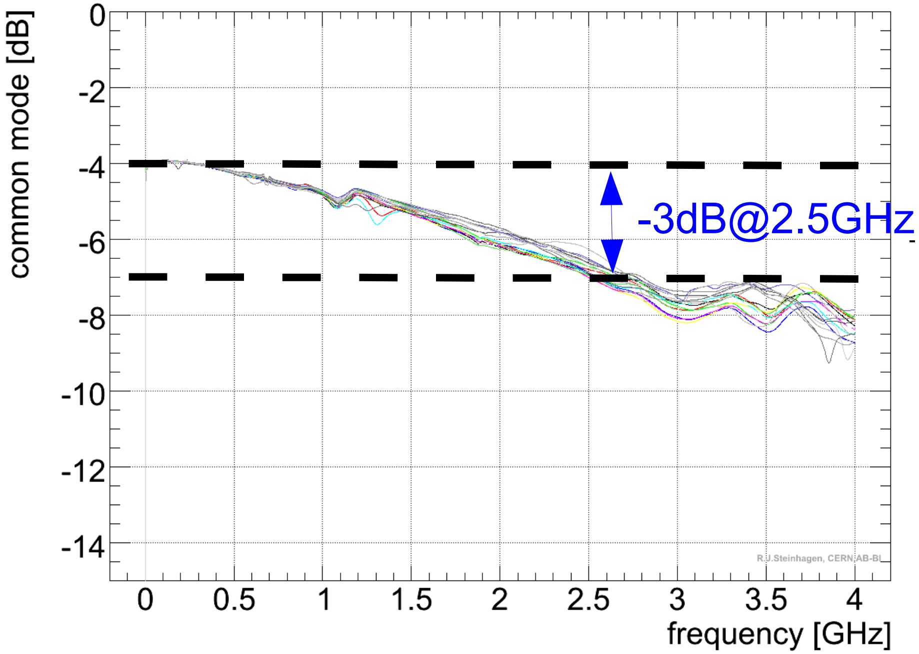
animation courtesy B Salvant (2010)

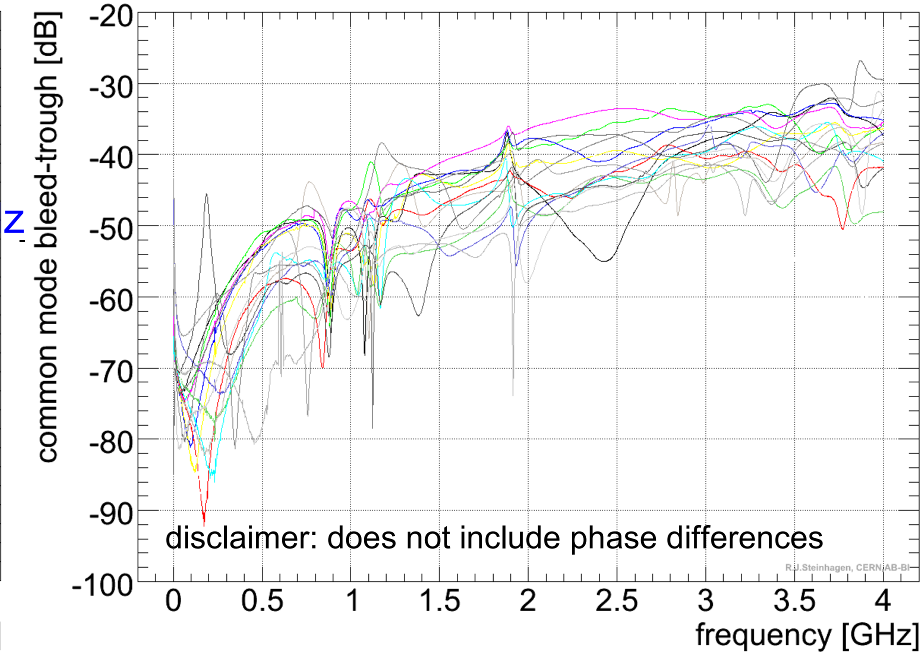
Limits of Classical Head-Tail Monitoring Approach

- What our ABP colleagues like to see (here: HT mode 'm=1'):



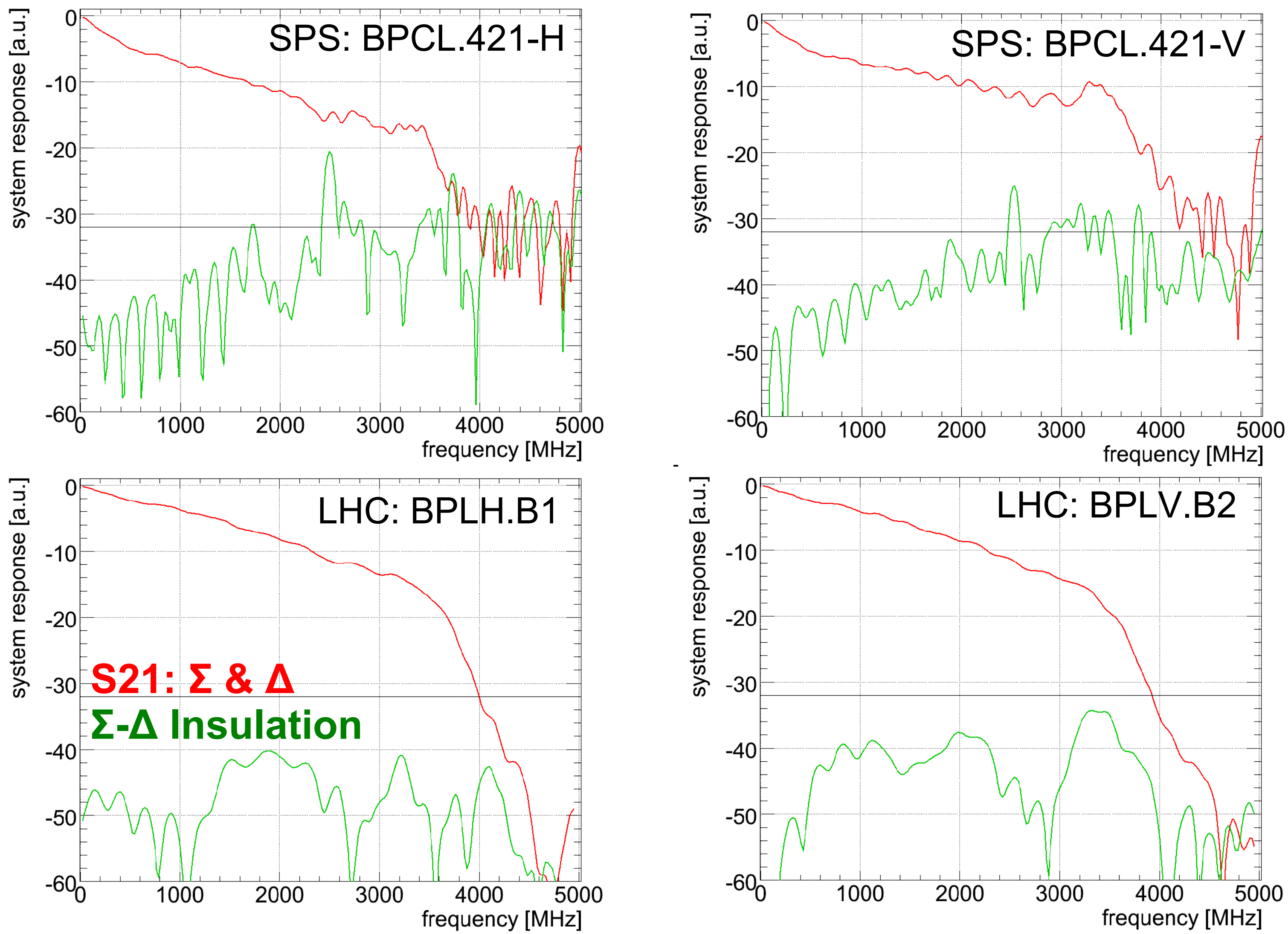
- Batch variations of 22 wide-bandwidth hybrid couplers (H-9, 2-2000 MHz)
  - similar common-mode perf., gentle roll-off for HF (can be compensated)
- All Hybrids/RF components are equal…but some are more equal than others:
  - large variation of insulation between ports:
    (not a strong design constraint for manufactures)





- Best insulation level -40 dB @ high frequencies
  → limits minimum dynamic range of input to ~1% of BPM half-aperture
- electrical offset/non-centered orbit adds to this and is another dominant source of HT resolution reduction

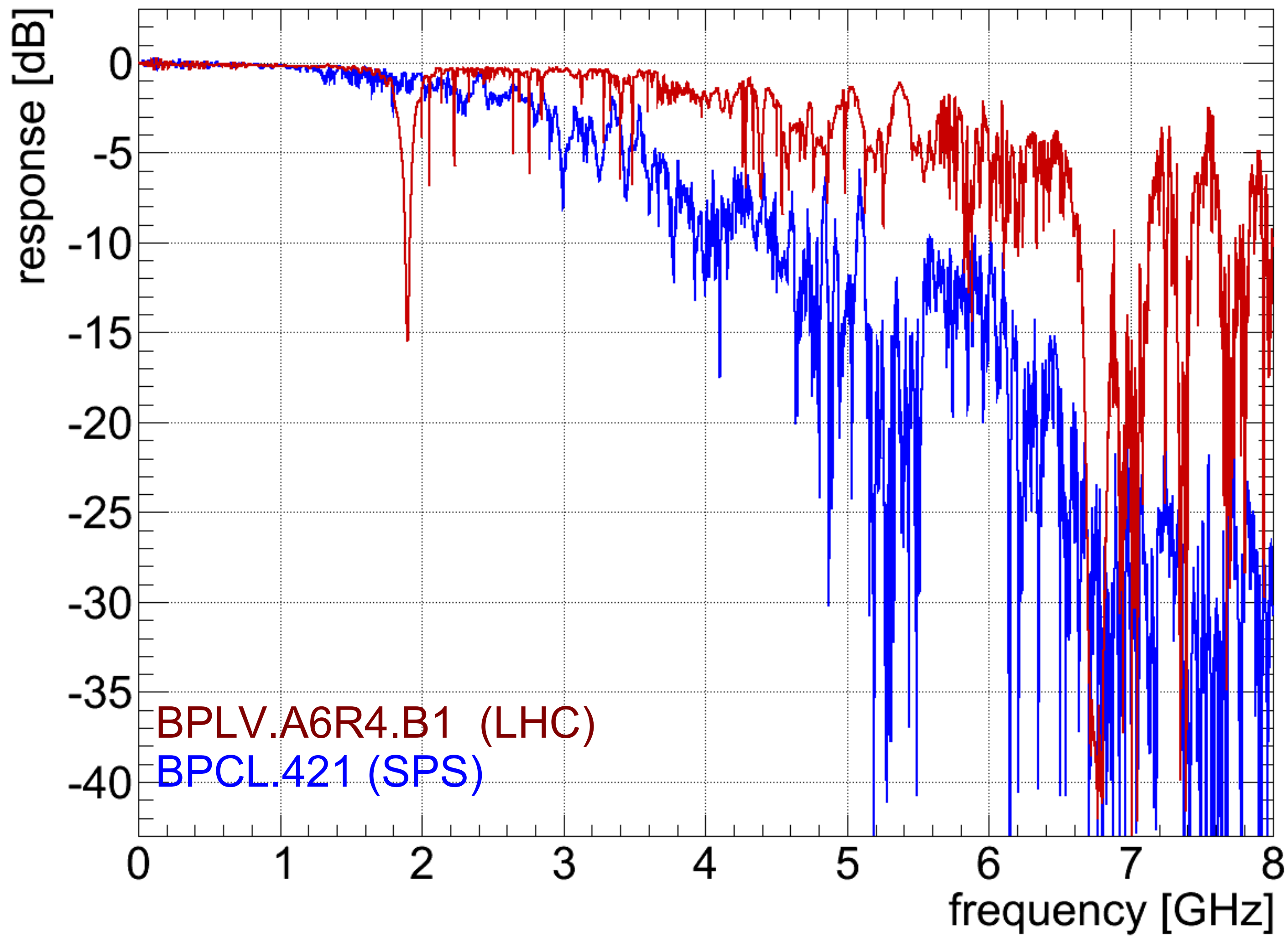
Limits of Classical Head-Tail Monitoring Approach For Comparison: SPS/LHC HT System Response



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

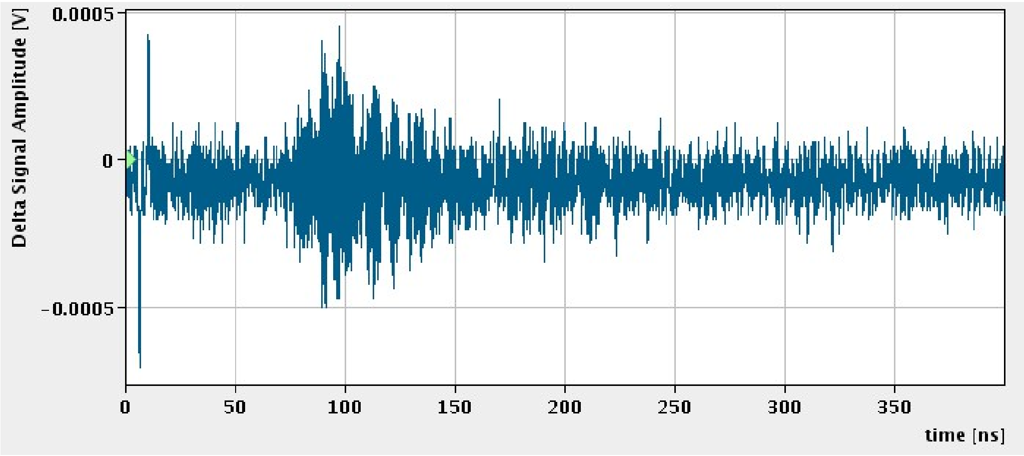
Strip-Line BPM Response

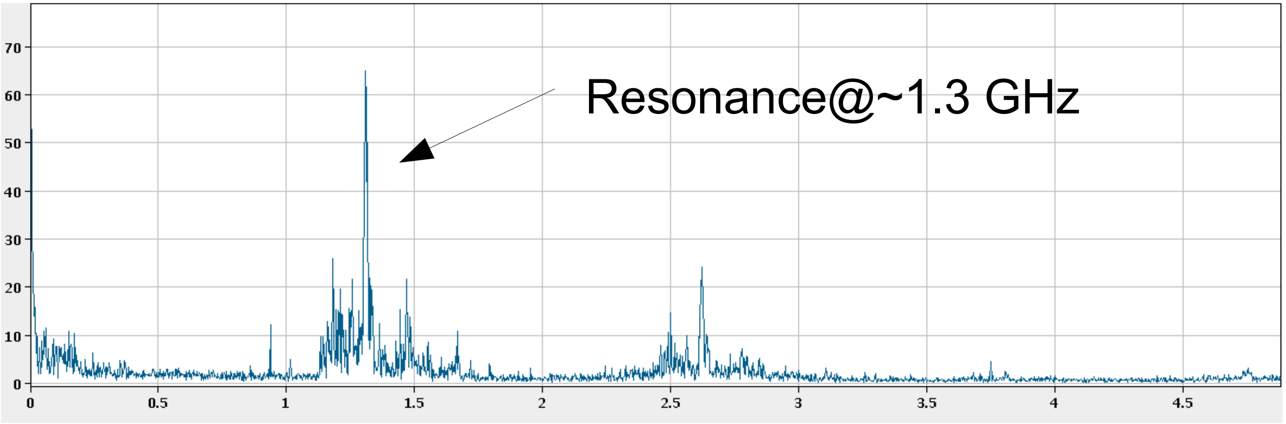
- Similar strip-line design with response up to 3 (5) GHz bandwidth...



- A priori would expect the same...
  … differences likely due to RF feed-through dielectric material/geometry

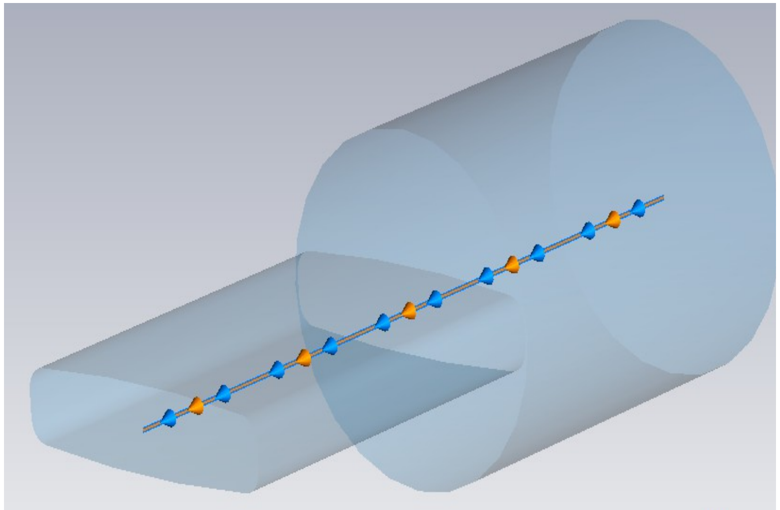
- Ringing in delta signal after main bunch....
  - Eventually traced back to upstream vacuum pipe discontinuity: BPV: elliptical ↔ rectangular ↔ round

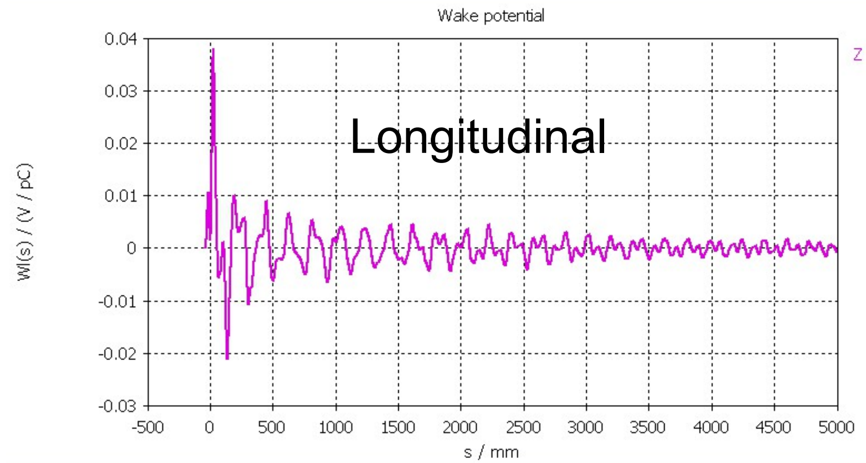


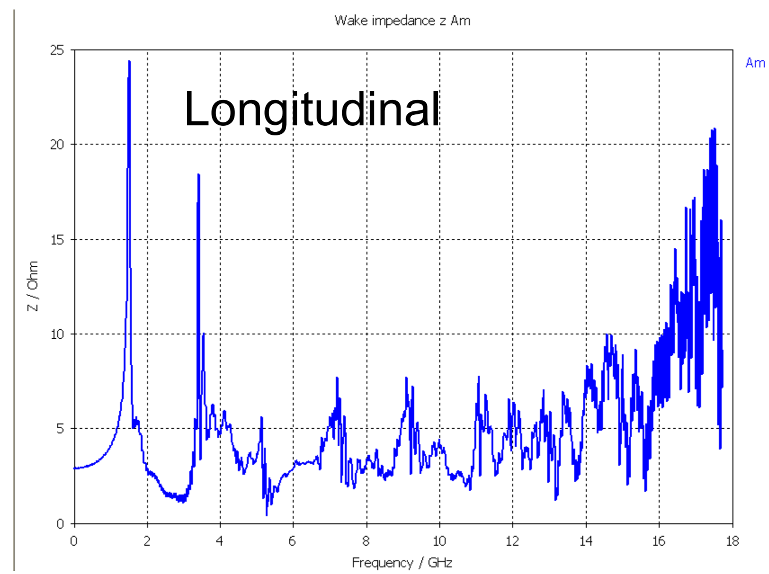


- Hybrid ferrite saturation → addition common-mode signal in delta-signal

SPS: Vacuum Transition Simulation





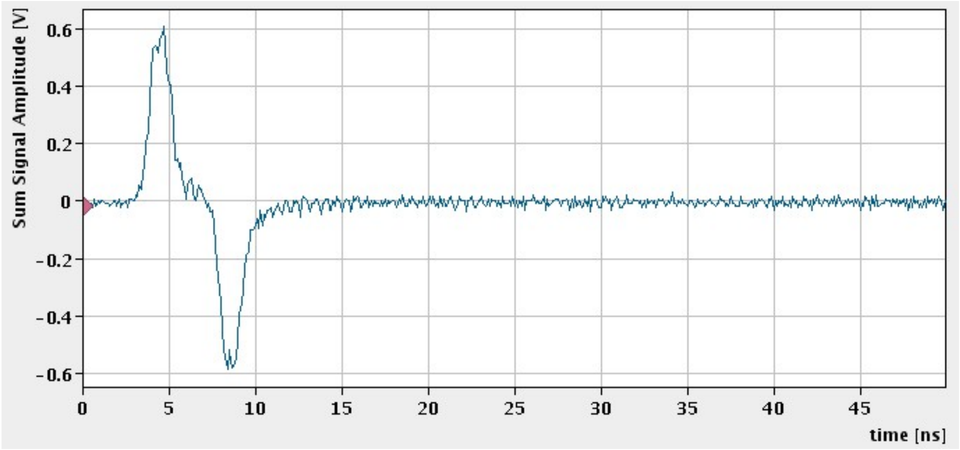


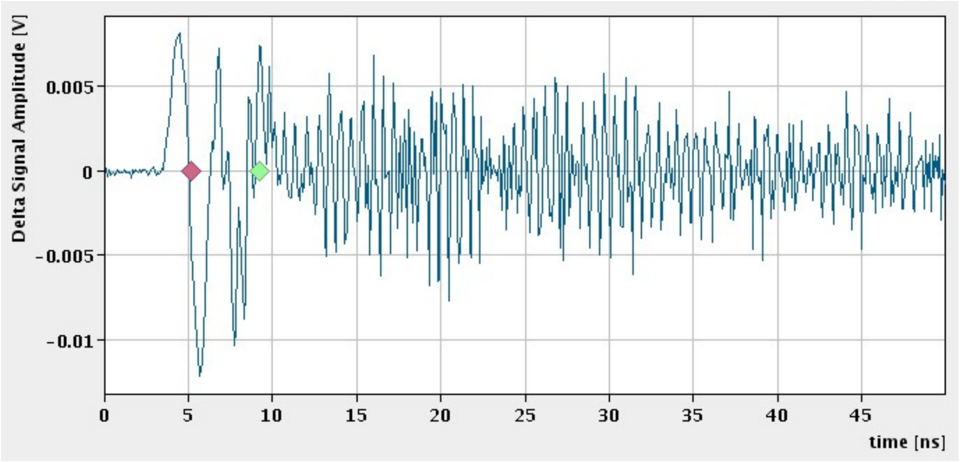
Longitudinal

f	*R*	*Q*	*R/Q*
1.5 GHz	31 MΩ	3200	960 Ω

courtesy B Salvant (2010)

- Additional bunch intensity induced ringing after signal → hybrid saturation





- Can be mitigated by attenuation but may loose dyn. range without switches
  - variable gain attenuation at broad-band GHz frequency is not trivial
- In addition: need to monitor longer (5ns) bunches at injection → increase strip-line length (mechanical tolerances, ….)

Head-Tail Upgrade Specification
As prepared by B. Savant et al.

- Beam observables: transverse position resolved within the bunch
- Objective: qualitative observation of coherent modes of oscillations (intrabunch and interbunch).
- Acquisition:
  - Bunch by bunch,
  - Turn by turn for at least 1000 turns,
  - availability every cycle in both planes
- Dynamic range: 10^{10} protons to $5 \cdot 10^{11}$ protons per bunch
- Accuracy: accurate knowledge of absolute transverse position is not critical
- Resolution: Changes of transverse position by 1% should be detected.
- Repeatability:
  - Within the same turn: same as resolution (1%).
  - From turn to turn: same as resolution (1%).
- Reproducibility from cycle to cycle: not critical.
- Logging: SDDS saving is sufficient for now (no need for logging).
- Required Bandwidth: aim at resolving 'm=6' head-tail modes (σ_t =1 ns → ~6 GHz bw.)
- Miscellaneous: if possible, suppression of reflection signal would be appreciated

Instrumentation Challenges to be addressed

LHC Injectors Upgrade

- Higher ultimate bunch intensities
  - total beam power of 70-80 W seen by strip-line (LHC-type beam)
  - RF components limitations:
    - very high-frequency, but low-power (0-10 dBm up to 20 GHz)
    - very high-power, but low freq. response (typ. few 100 W up to 2 GHz)

- Larger n-GHz level bandwidth (+ lower frequency response in SPS)
  - hybrid response, cables, (acq. system bandwidth), …
  - beam synchronuous timing
  - stability in particular thermal drifts/response in GHz-regime

- "flight-recorder or black-box type functionality"
  - instabilities with uncertain occurrence w.r.t. time and bunch/beam location
  - large amounts of acquired data
    - SPS (LHC): 1000 turns ↔ 220 (850) MB
  - Requires smart/fast processing, triggering scheme (HT instability trigger)
    - answer or indication of the type of instability within reasonable time
    - N.B. data-mining requirements similar to LHC experiements

Aspects covered so far

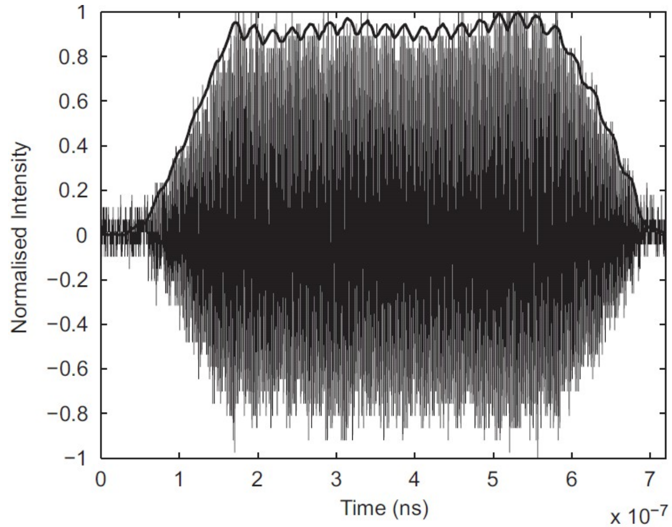
- Higher ultimate bunch intensities (Need to cover large dynamic range ~ (60+40)dB)
  - RF-based switching matrix, handling 60 dB bunch intensity/length var.
  - optical schemes:
    - Synchrotron-Light as viable option for LHC (no EMC, power, impedance issues)
    - Electro-optical Sampling for SPS, LHC, CLIC and other accelerators
- Larger n-GHz level bandwidth (+ lower frequency response in SPS)
  - Calibration presently with PSPL 4015RPH (15 ps, ~4 kCHF)
  - In-tunnel calibration: ADCMP572 & ADCMP580 comparator (15 ps, <20 CHF)
  - Hybrid: found 'one-of' option consisting of res. power-combiner + wide-band RF baluns (200kHz → 6 (8) Ghz, 1 W cw. only)
- “flight-recorder or black-box type functionality”
  - Survey oscilloscope/digitizer market
    - Found two interesting candidates (→ demo presentation next week)
  - CERN Summer/Master student from ACAS collaboration helping with development of the instability trigger & online analysis schemes needed

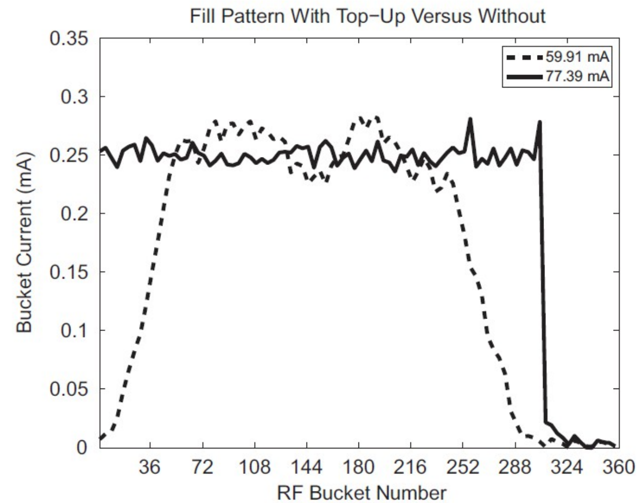
Australian Collaboration for Accelerator Science
http://accelerators.org.au/

- ... a new network with the aim of providing:
  university-based education, maintaining up-to-date au. accelerator science programme, direct funding into high priority research, capitalise on investment in accelerator based user facilities, foster collaborative research (CERN: CLIC-DR, BI), R&D for new facilities and innovative technology

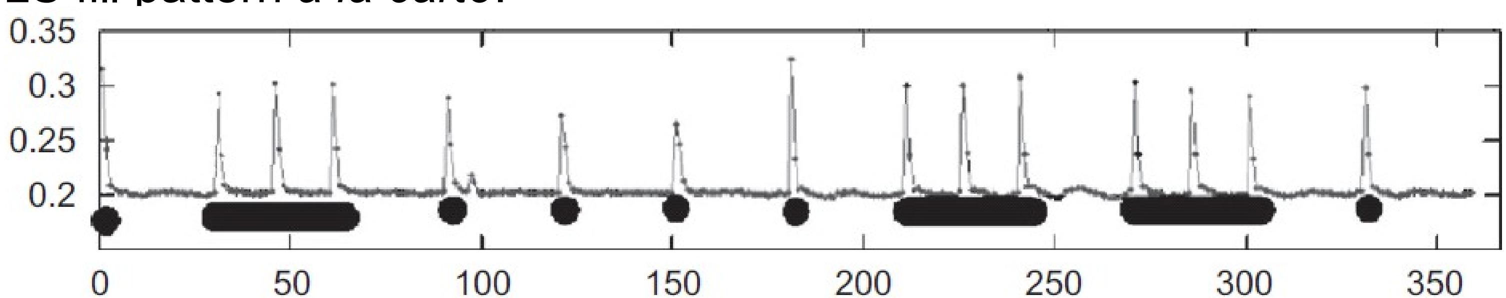
Synchrotron-Light based Fill-Pattern-Monitor

- 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*:

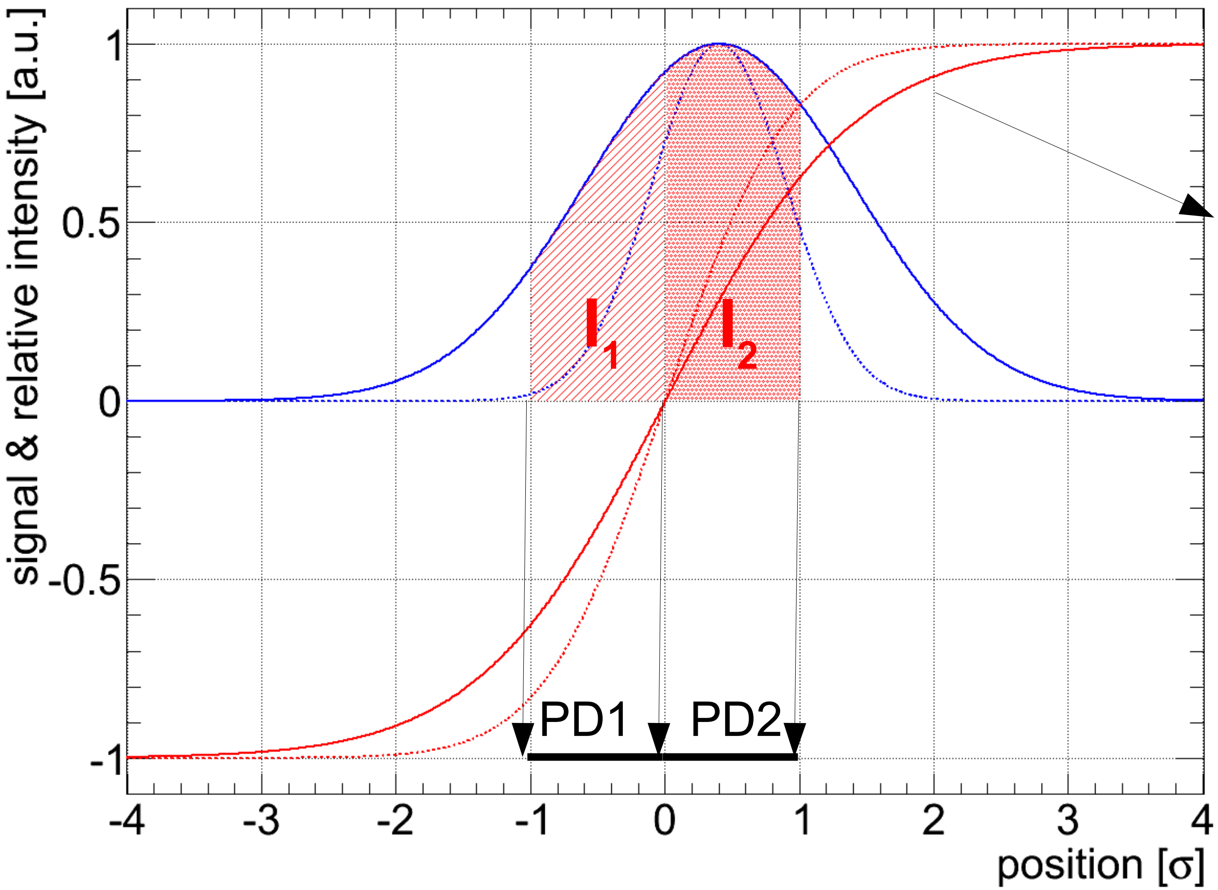


Australian **S**ynchrotron **P**roject

*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...



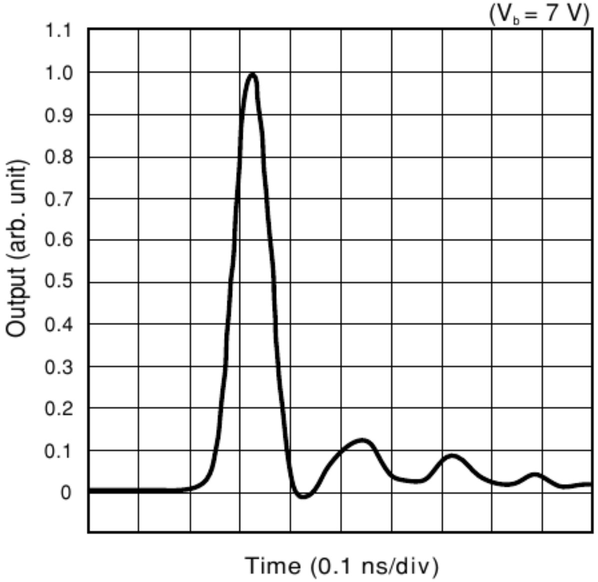
$$X \approx \frac{\Delta}{\Sigma} = \frac{I_2 - I_1}{I_1 + I_2}$$

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

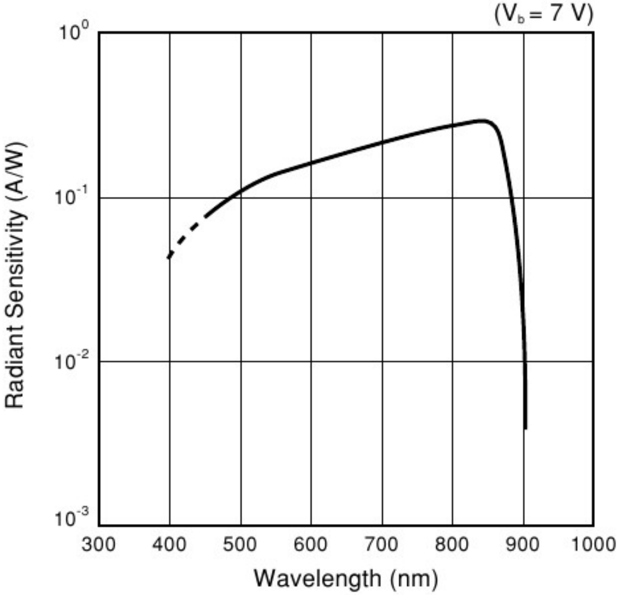
Metal-Semiconductor-Metal (MSM) Photodetector I/II

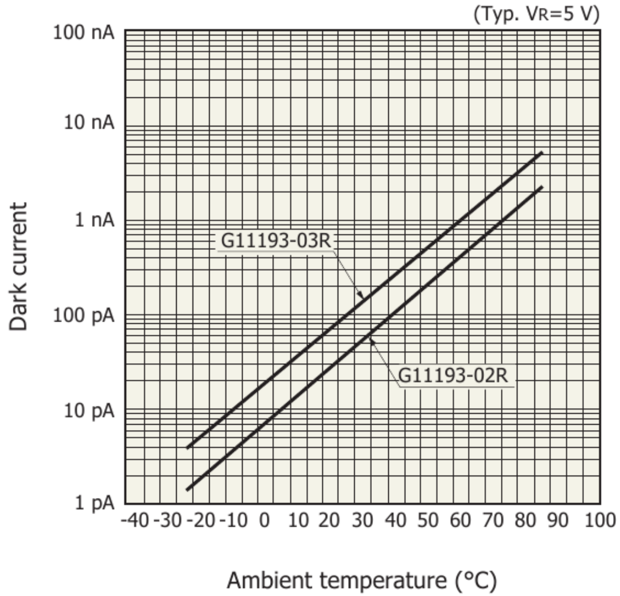
- Hamamatsu's G4176-03 (TO5 package, SMA connector)
  - t_r ≈ 30 ps ↔ nom. 50% atten. @12GHz
  - 0.3 pF for active area of 0.2 x 0.2 mm²
  - typ. light input power ~5-10 mW (50% duty-cycle)
  - dark-current: 100 pA @23°C
  - max. est. S/N: ~150 dB (w/o cooling)

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



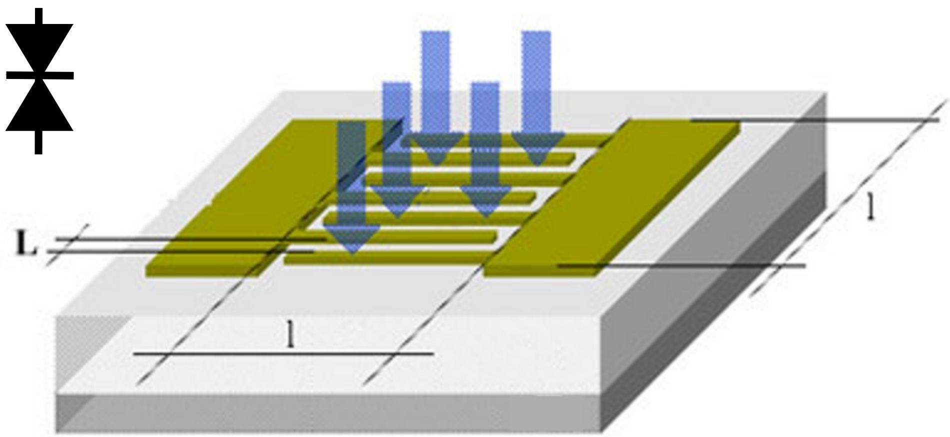
(incl. light soure, bias and scope)

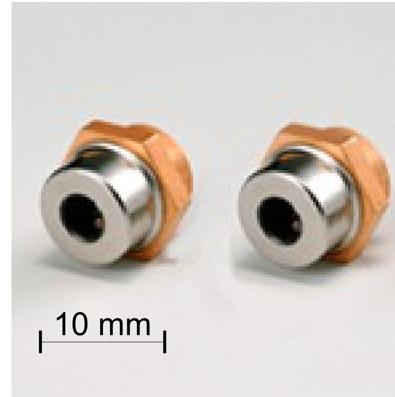


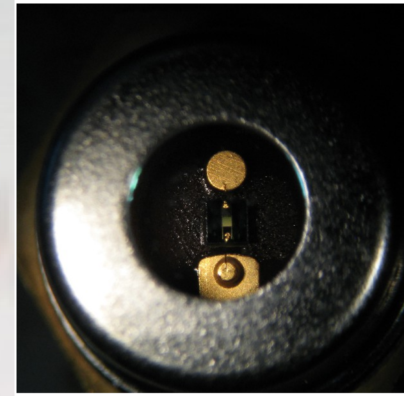


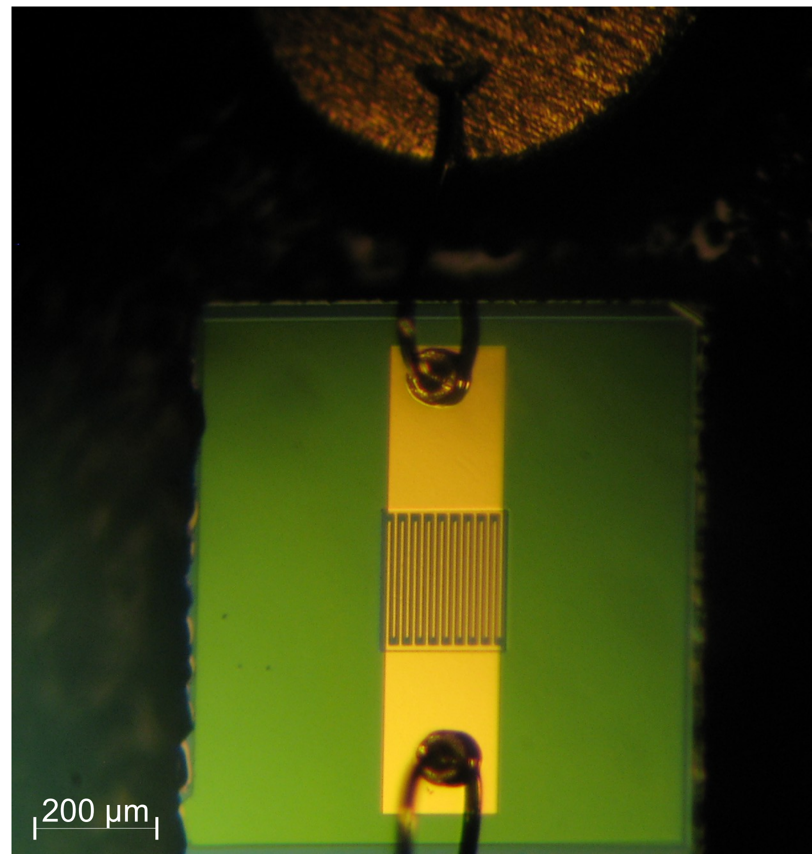
Metal-Semiconductor-Metal (MSM) Photodetector II/II

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









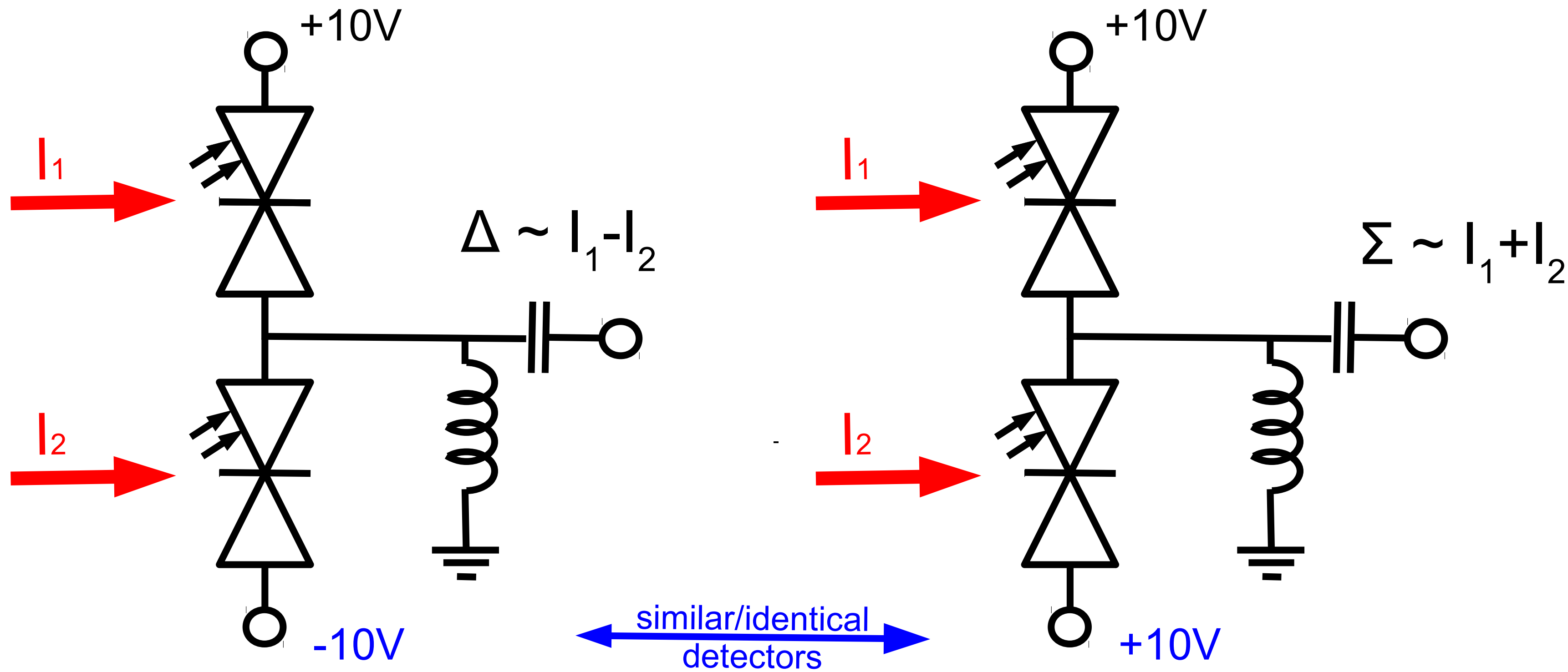
- Speed determined by doping of (In)GaAs SC material and PD geometry (reflection, C, …)
  - Not quite a MS Schottky Diode

- 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:

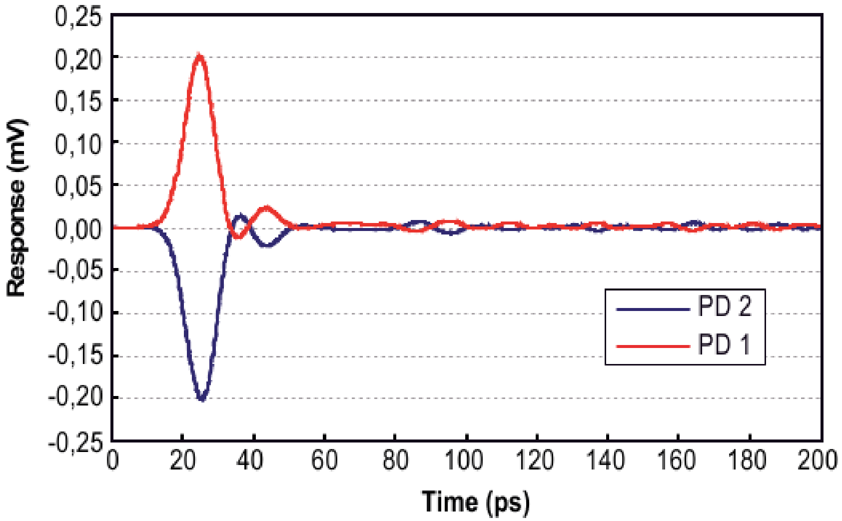
- even lower noise than pure MSM
- Simple phase compensation
- Simple adaptive orbit offset comp.
- 50Ω vs. high-impedance (glued to ADC)
- Can keeps sensitive (== expensive) equipment/control outside the tunnel

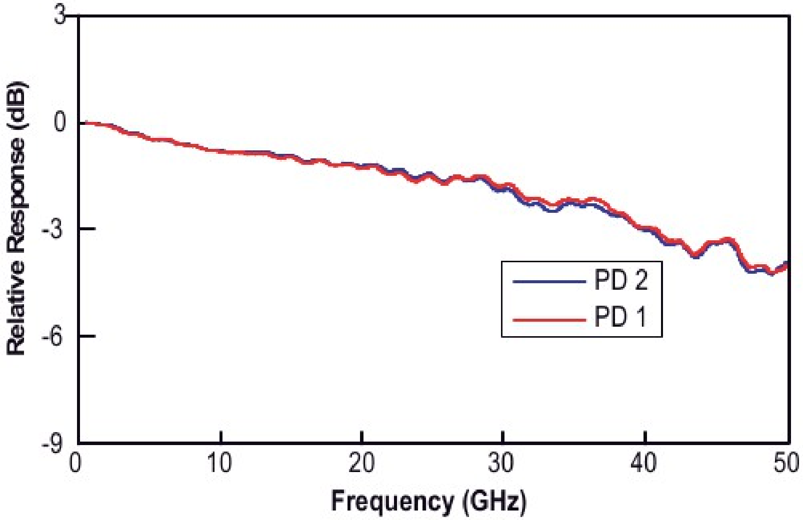
Advantages:

- 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

Strengths of Balanced Photodetectors

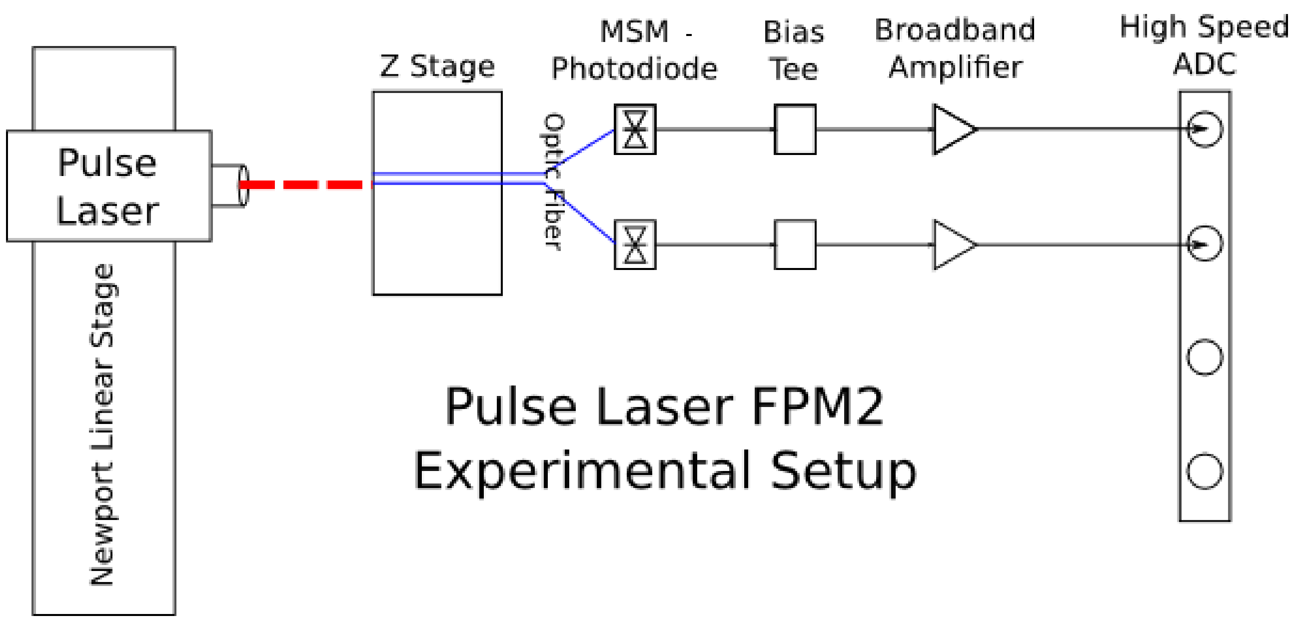
- Specific advantage of MSM photo detect. vs. diodes: no specific bias polarity → can be exploited to dynamically flip signal between delta and sum mode
- Can detect DC changes
- Bias voltage and polarity can be used to:
  - high-frequency difference controlled via regulated DC voltage
    - Noise is an issue → presently batteries (proven* lowest noise impact)
  - simple calibrate for phase difference:
    - Put one PD bias voltage to zero – measure signal with the other and vice versa and adjust for the phase difference (externally e.g. mechanically stressing optical fiber)



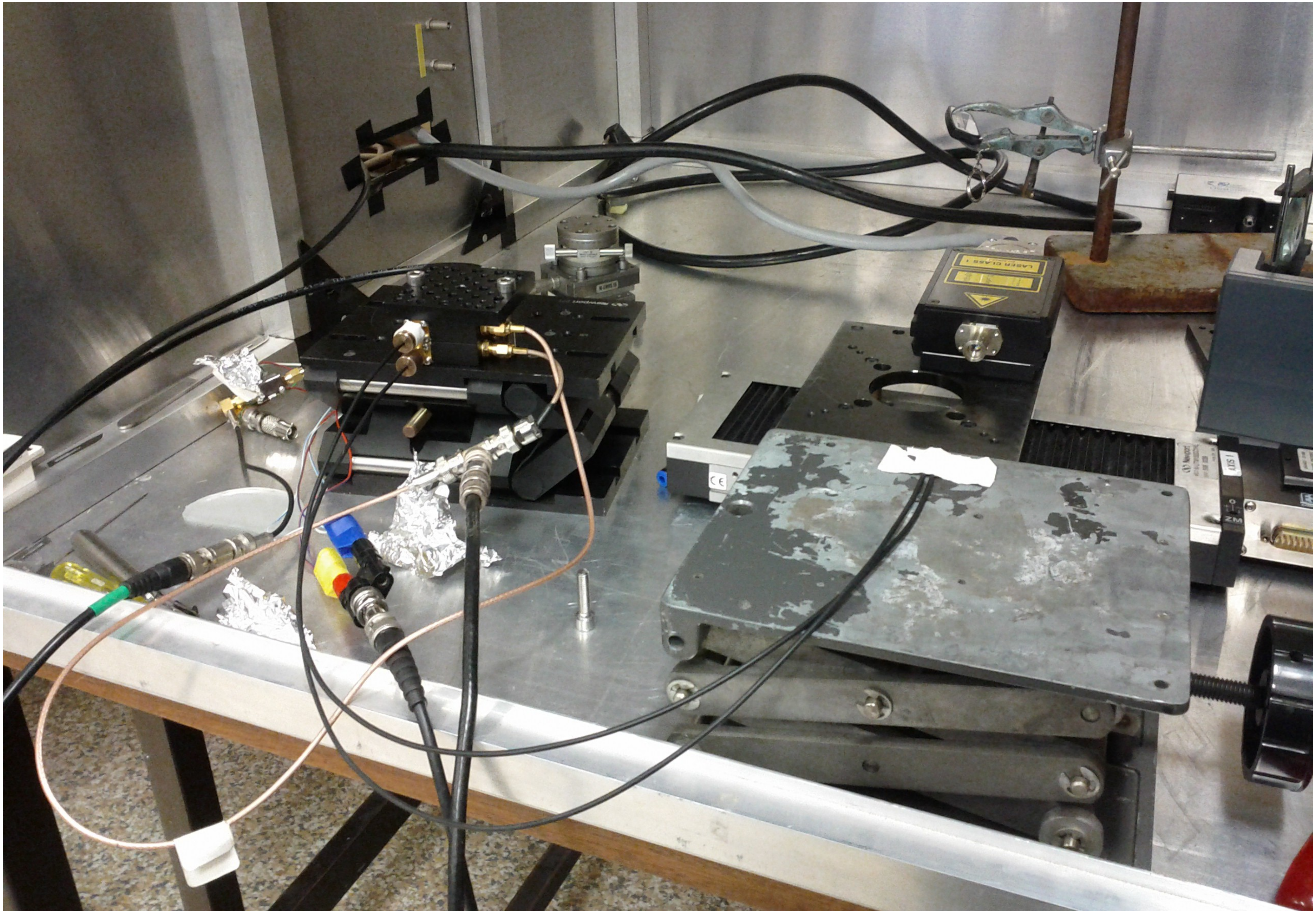


FPM² Laboratory Test Setup I/II

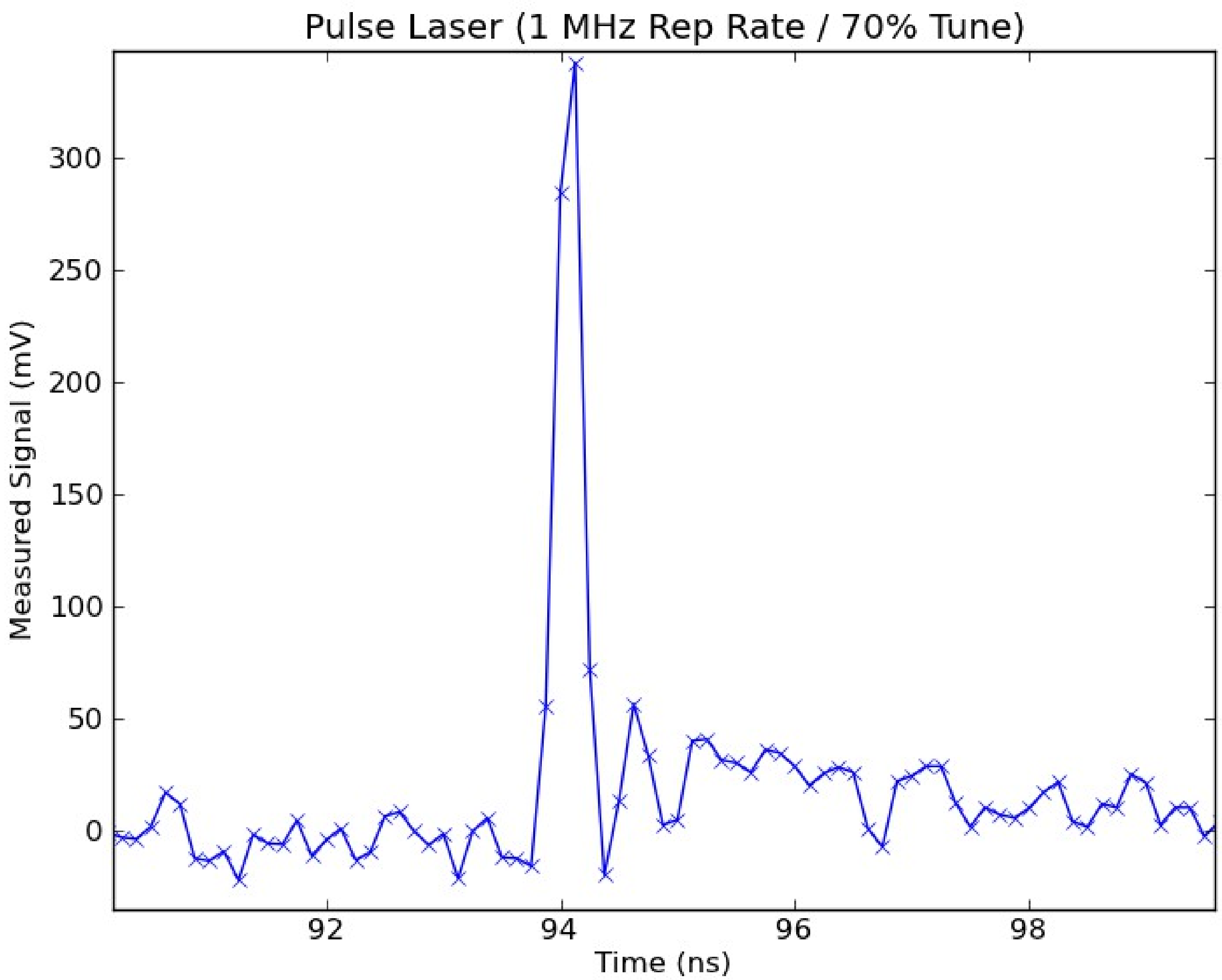
- MSM-Photodetector scheme well established
- Small spot size makes 2x2 matrix difficult to tune/operate remotely
  → decided early to focus on robust delivery system studies
- Proposal of using imaging-fiber optics type synchrotron-light delivery system:
  - Can use spatially distributed, discrete MSM photodetectors
  - Can keep sensitive, less radiation tolerant, expensive equip. in alcoves
  - Some operational experience...



FPM² Laboratory Test Setup II/III

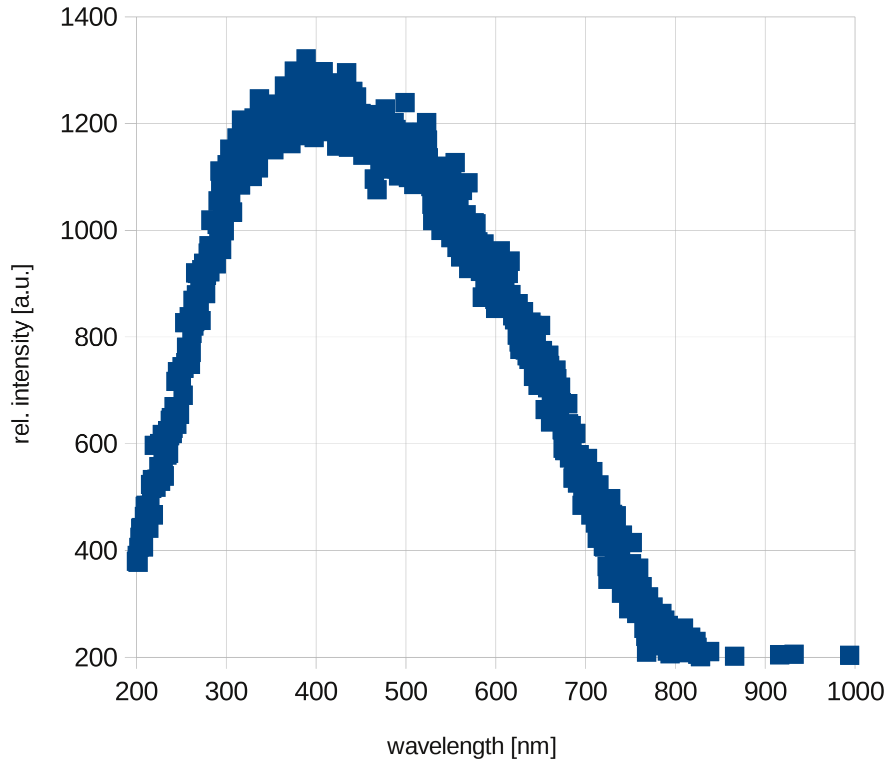


- Lab test setup with pulsed Laser source:



Testbed Comparison

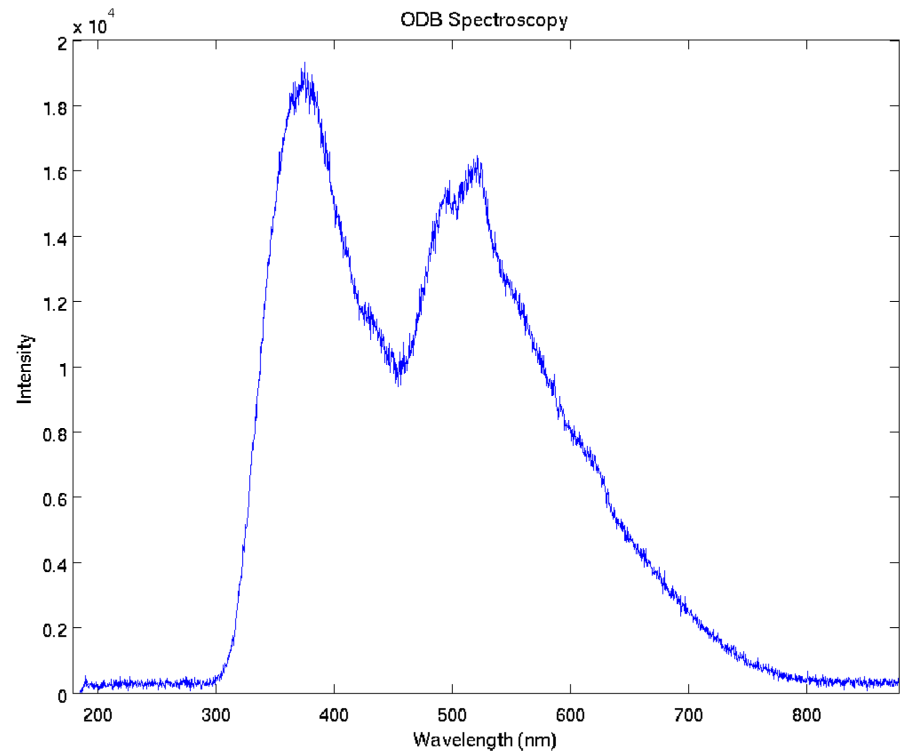
- CTF3 – Combiner Ring
  “La Favella” Streak Camera Lab



- mm-size beam spot size >> PD
  - re-focus with x40 micros. optic
  - 13 GHz amplifier

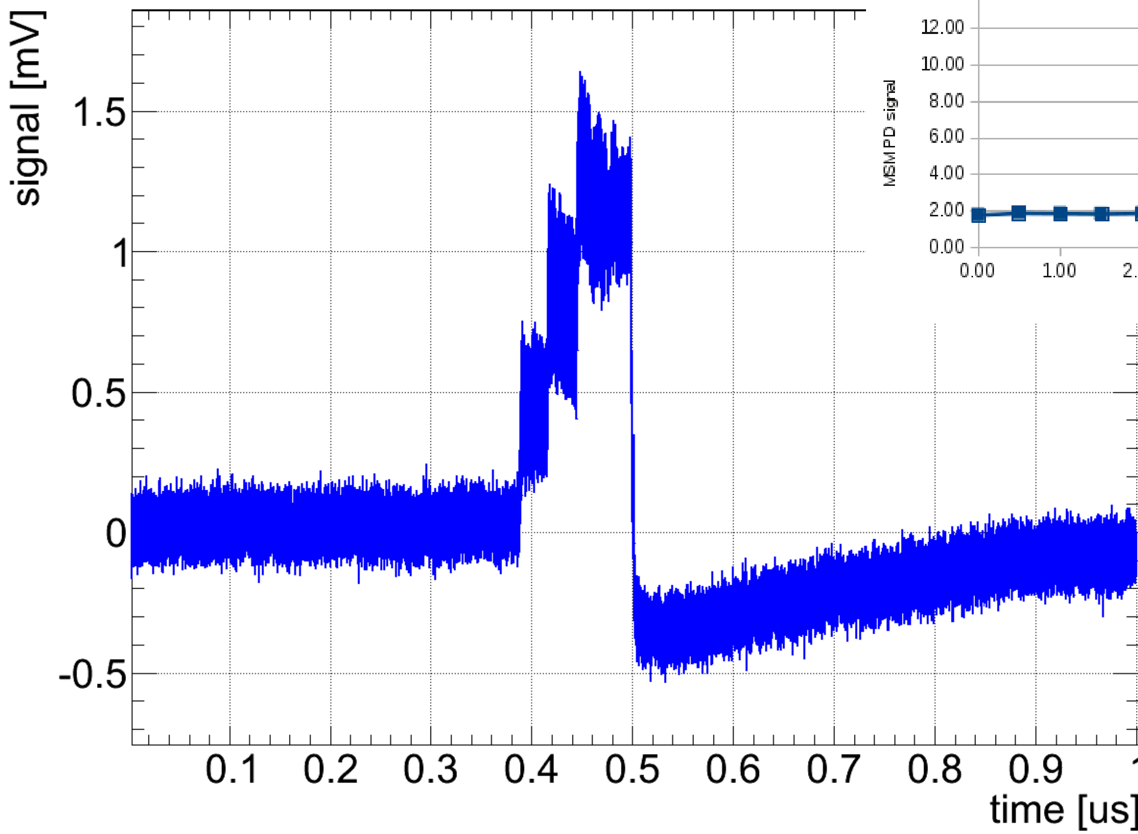
→ mW-level integrated light power

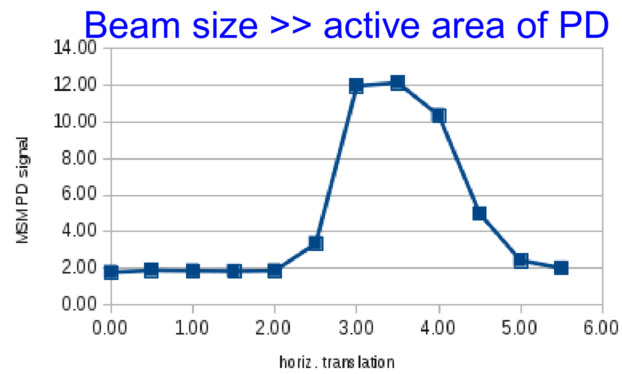
- ASLS – 3GeV Main Ring
  Optical Diagnostic Beam-Line



- compatible power (spectrum)
- stage I: prototyping at ASLS
  (S/N ratio, resolution, systematics, ...)
- stage II: @ CTF3
  (tbd: 12 GHz BW, systematics, ...)

- Typical un-amplified raw MSM signal:





- Photodetector sensitivity → about 5-7 mW light impinging on the the detector
- However: beam spot size >> active detector size (few mm vs. 200 um)
  - needs re-focusing and/or amplification (both available now)
  - delta signal is expected to be on the percent level of this carrier signal → aim at 200 (500) mV (amplified) peak signal

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

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

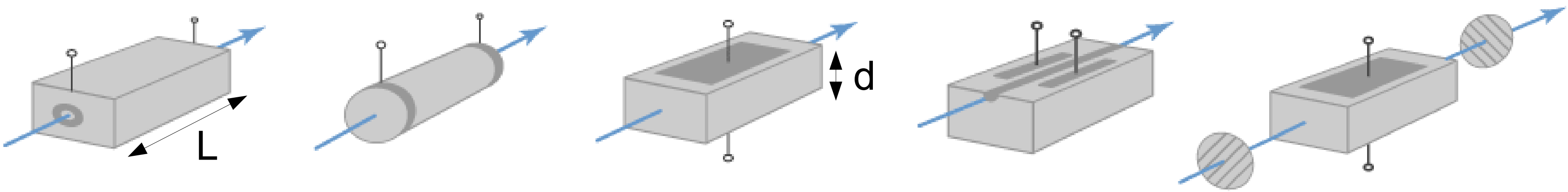
- Refraction in birefringent crystals depends on ex. electrical field:

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

- 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

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

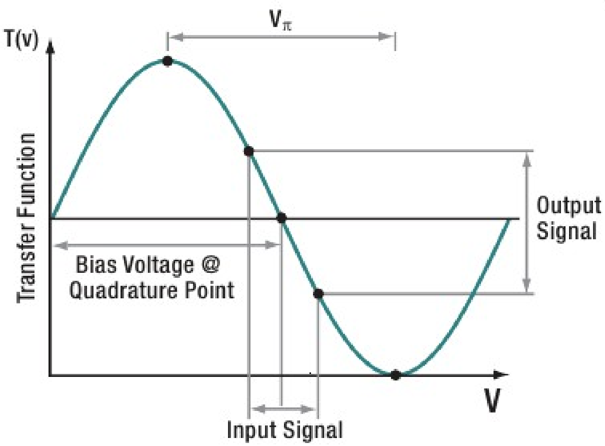
longitudinal | transverse modulator schemes



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

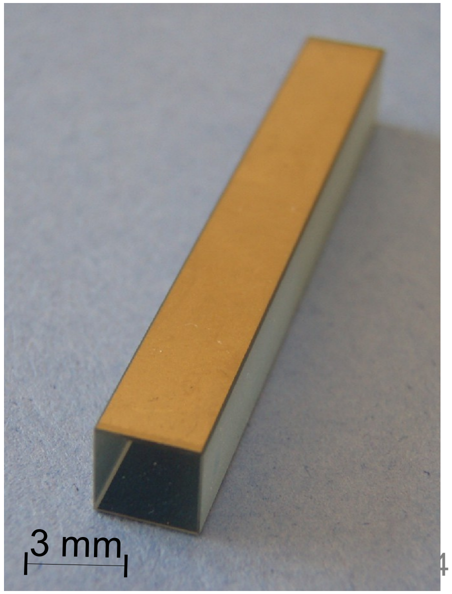
- Typically the *'half-wavelength voltage V_π'* is used to describe electro-optical modulators, i.e. the voltage required to achieve destructive interference:

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



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

- Large variety of crystals (KTP, GaAs, …), 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

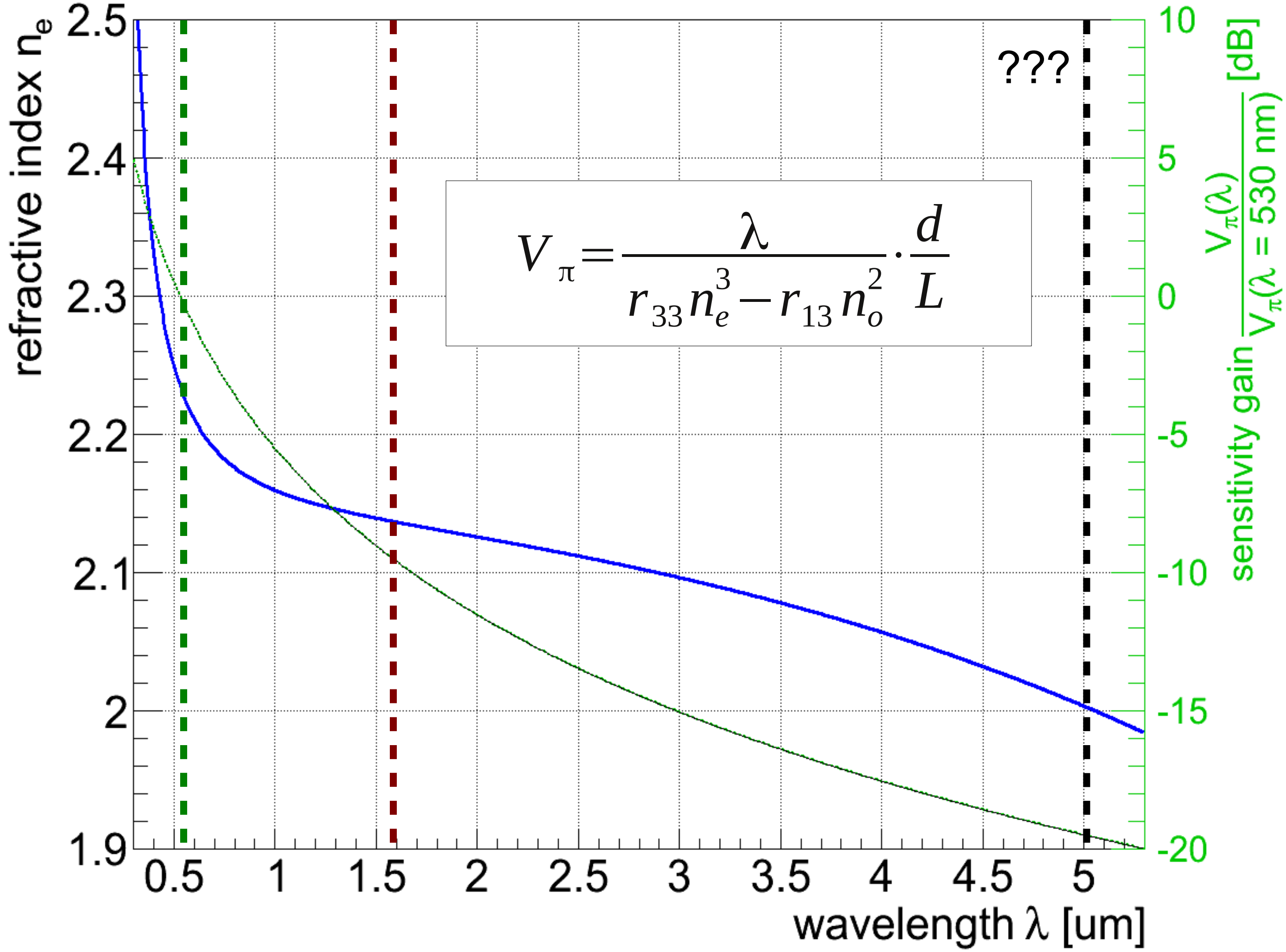
N.B. *for $LiNbO_3$ and $LiTaO_3$: r12 = −r22 = r61, r13 = r23, r33, r42 = r51

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

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

Refractive Index Dependence on Wavelength

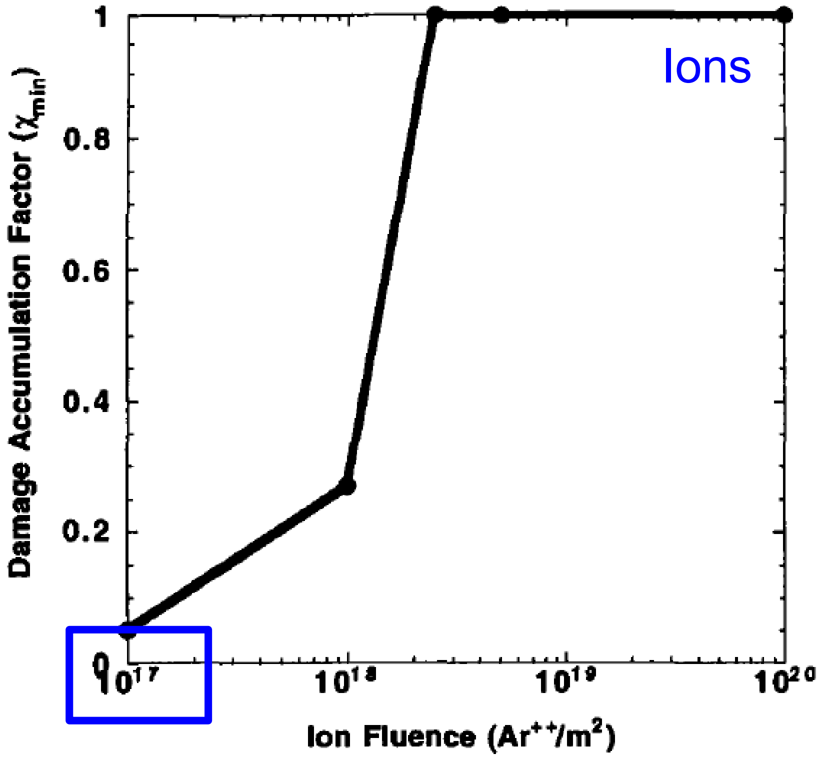
- $LiNbO_3$ – gain control possible but limited to factor ~10

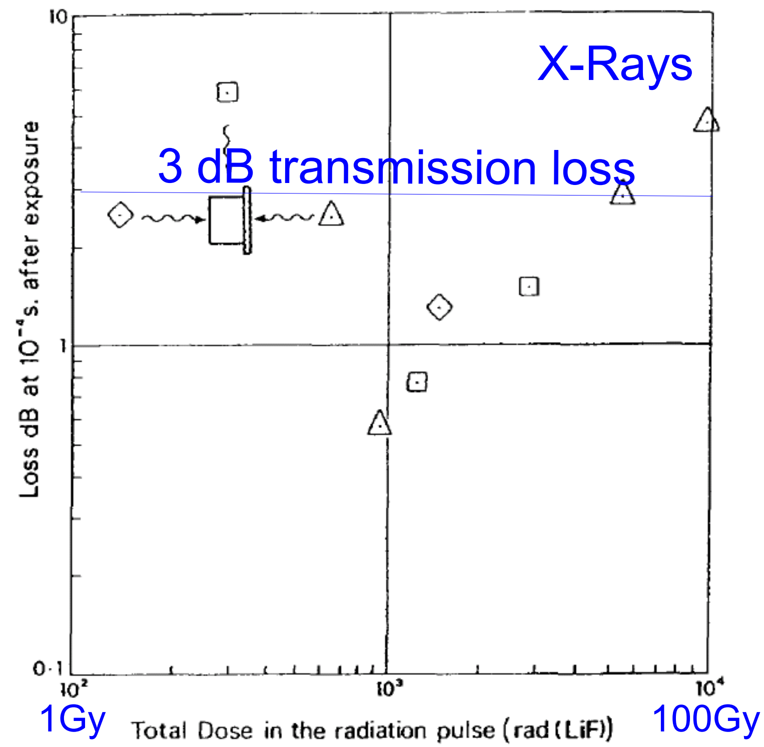


- … thus acquired 530 nm (green) and 1550 um (infra-red) laser for testing this.

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

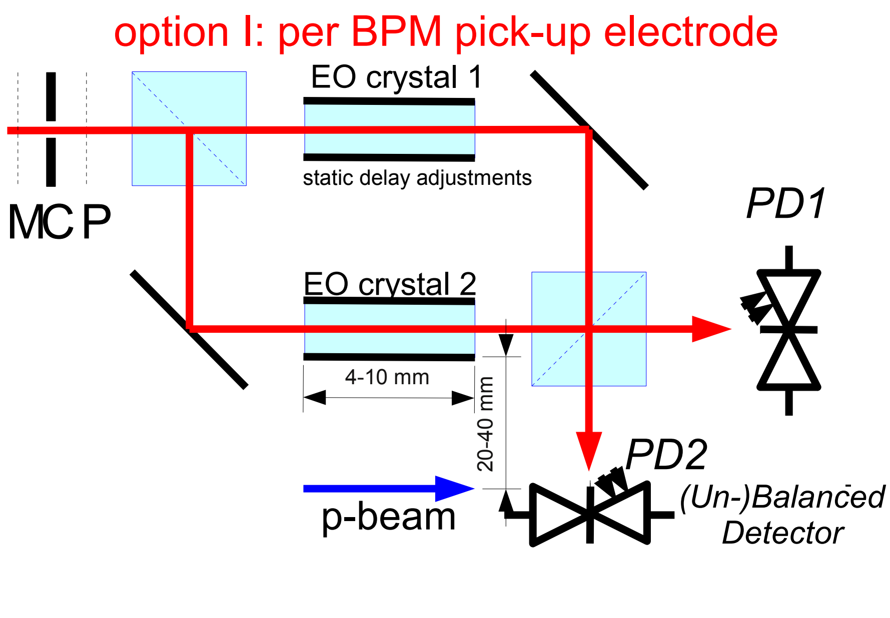
[1]: C. J. Wetteland et al., “Radiation Damage Effects in [..] LiTaO3 Single Crystals”, Mat. Res. Soc. Symp. Proc. Vol. 504 , 1998
[2]: R. H. West, S. Dowling, "Effects in [..LiTaO3..] Exposed to Radiation from a Flash X-Ray Source", Royal Military College of Science, IEEE TRANSACTIONS ON NUCLEAR SCIENCE vold. 41, #3, 1994

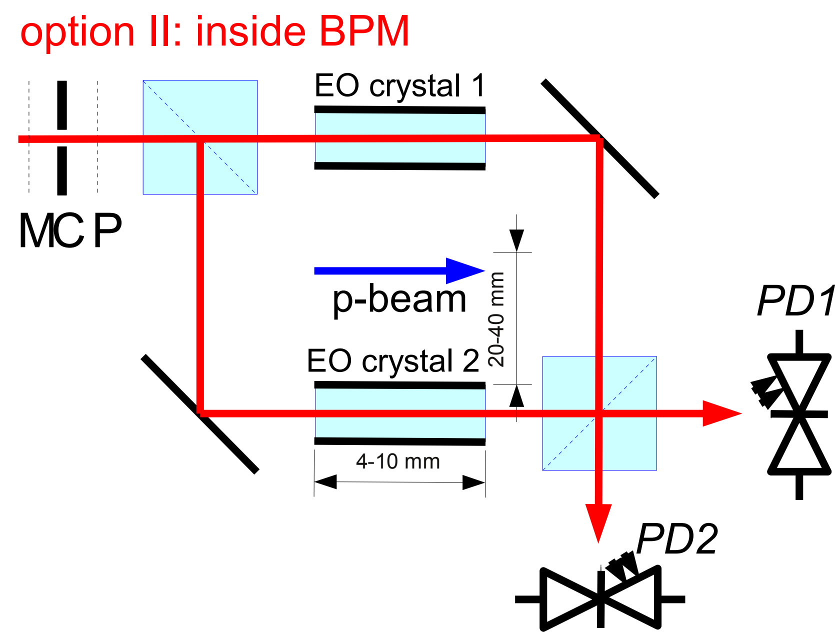
Test & Evaluation Programme

- 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 finished
- After that: design of purely-optical BPM pick-up (2013+?)

Test & Evaluation Programme
Sensitivity Setup – Phase Modulation-based

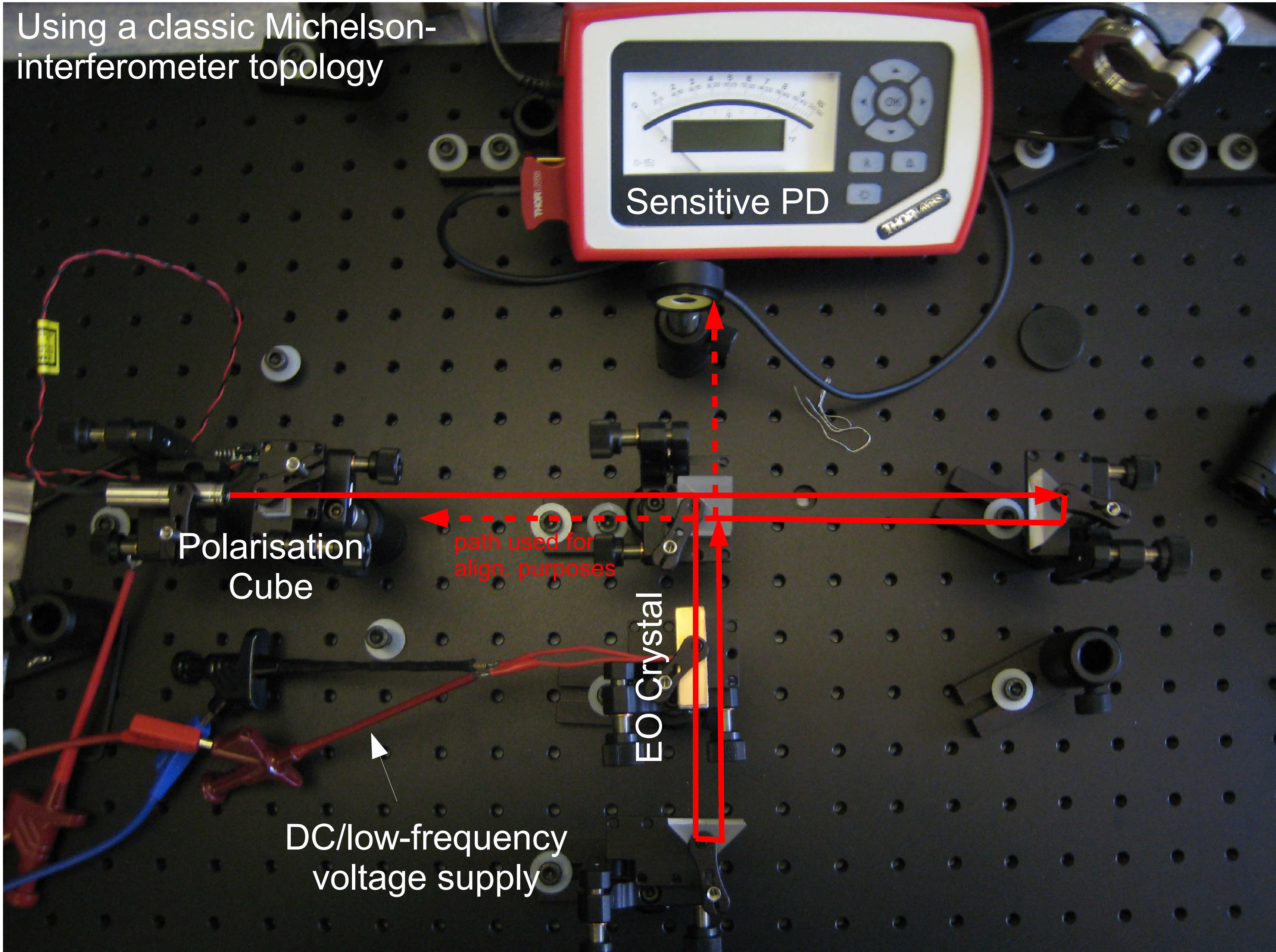
- Mach-Zehnder or Michelson Topology



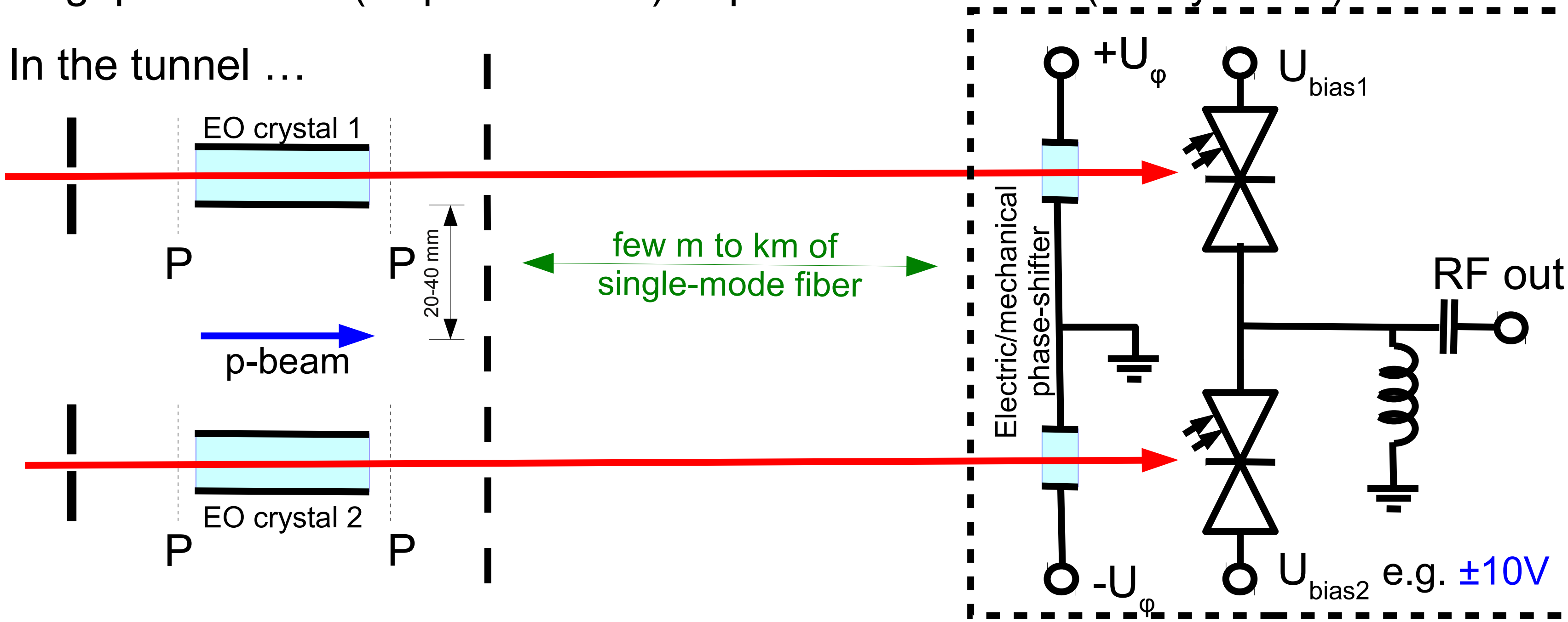


- Utilises wave-front phase interference to suppress common mode signal
- However:
  - Need to maintain polarisation within (larger) structure
  - More delicate/less robust w.r.t. alignment, stability of mirrors and split ratio
    - would need to be done locally close to the pick-up for re-tuning (remote 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



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

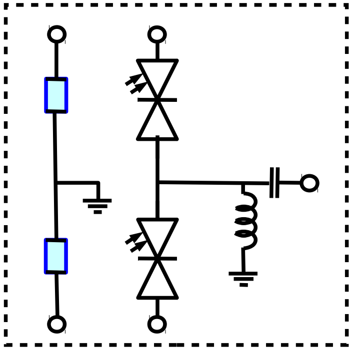


- Simple → robust design:
  - no setup or retuning of electrical/mechanical parts in tunnel
  - complexity kept at DAQ
    - Leverage same MSM-detector design as for synch-light based BPM
    - Phase and amplitude matching possible via U_{φ} and U_{bias}
    - Less radiation issues, could consider cryo-cooling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

Sensitivity & Gain Adjustment

- Main observable:

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



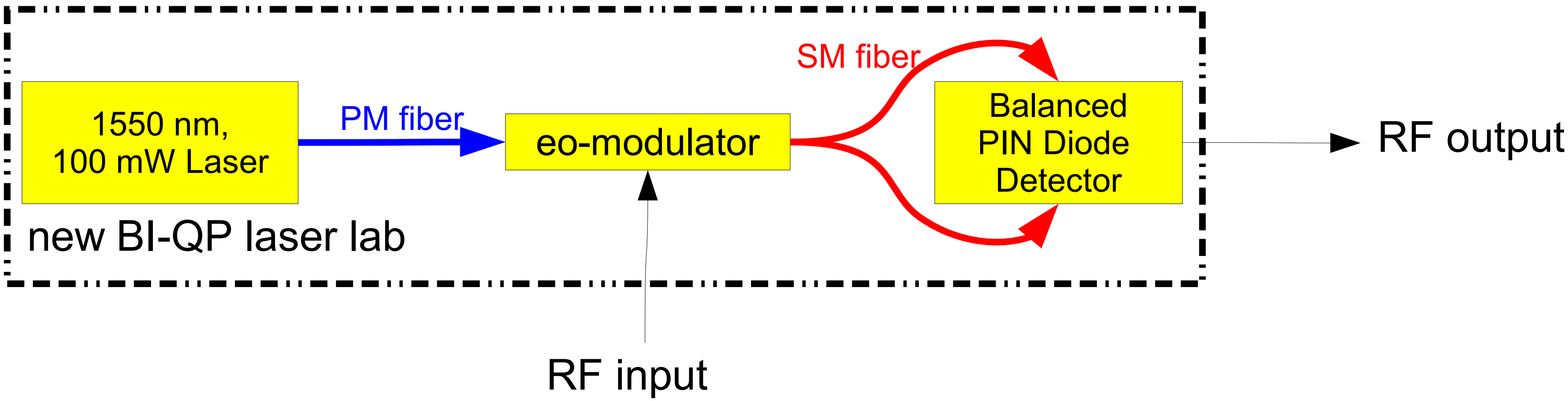
- Some constraints:
  - EO-crystal range (saturation-like): $V_{pickup}\big|_{max} < 0.8 \cdot V_\pi(crystal)$

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

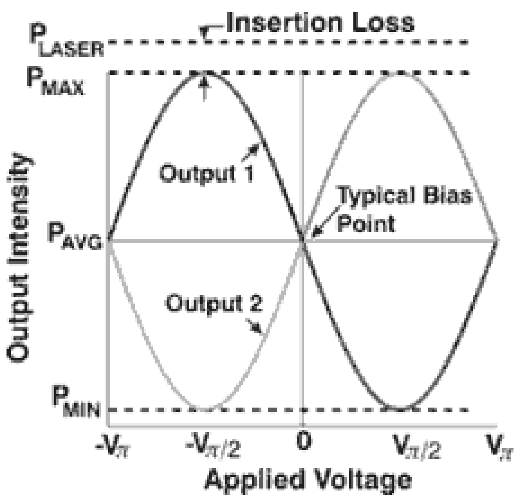
    → *limits maximum laser power for bunch peak signal*
- However, these limits do not apply at the same time
  → can use laser power to adjust dynamic range, e.g.
  - low laser power ↔ high-intensity bunches and vice-versa
  - Bal. detector → little impact of optical amplification on noise performance

LiNbO3 Bandwidth Setup

- Test-setup:



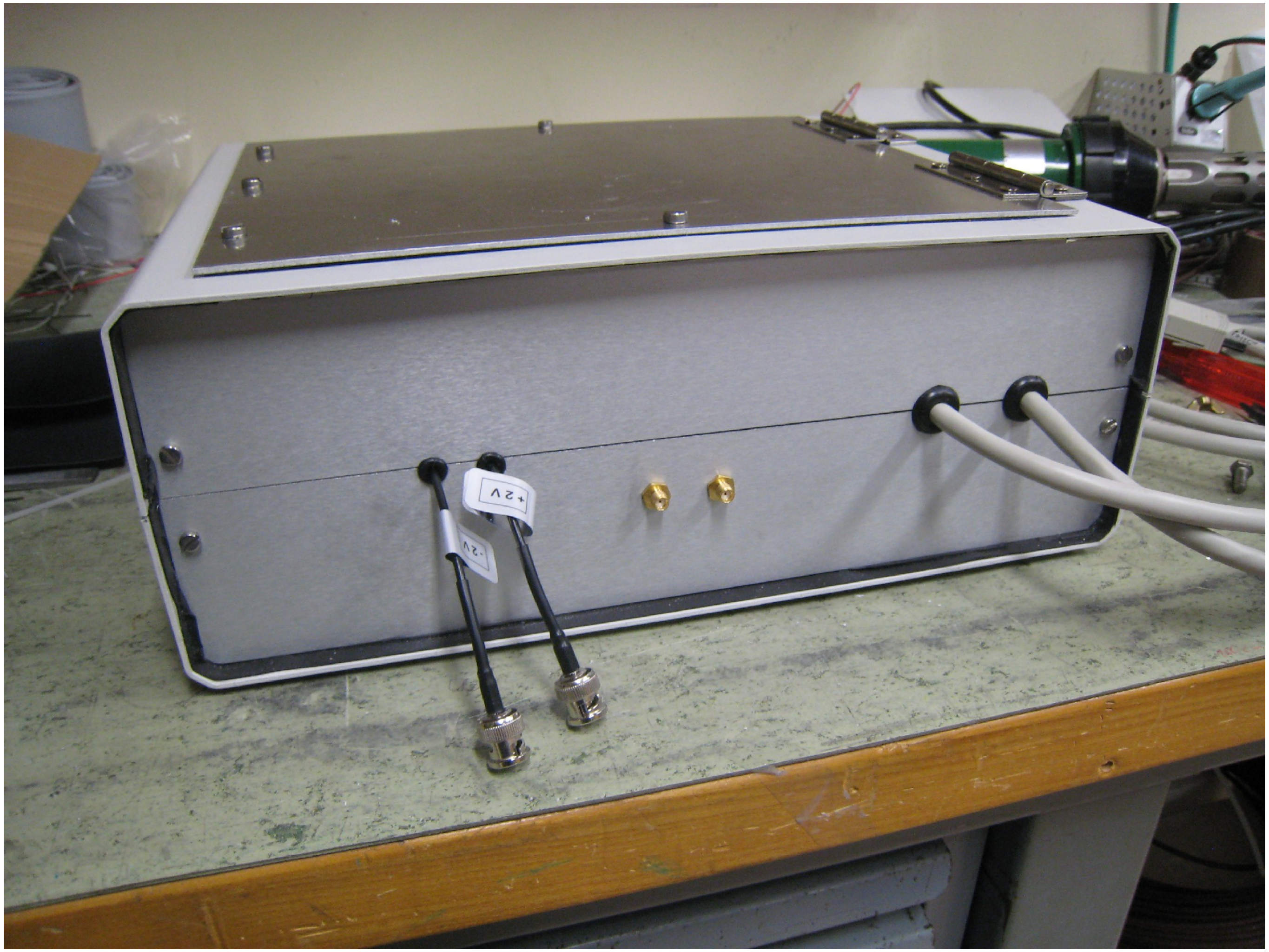
- Aim: confirm bandwidth and achievable S/N ratio
- Basically this is a standard telecommunication setup (modulo fiber length)
  - Reproduce bandwidth
  - Explore limits of link, noise sources etc.



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

Behold: BI-QP's New Laser-Lab

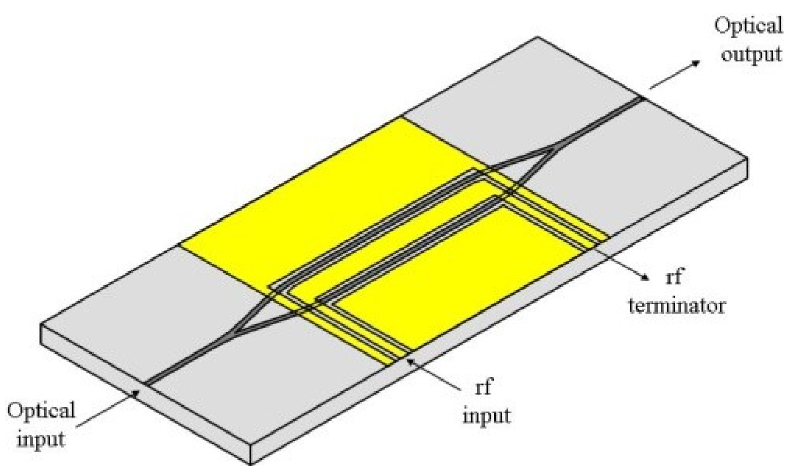
- Requirement from our DSO: light-tight confinement, only tool-based access allowed, laser cut if lid is opened

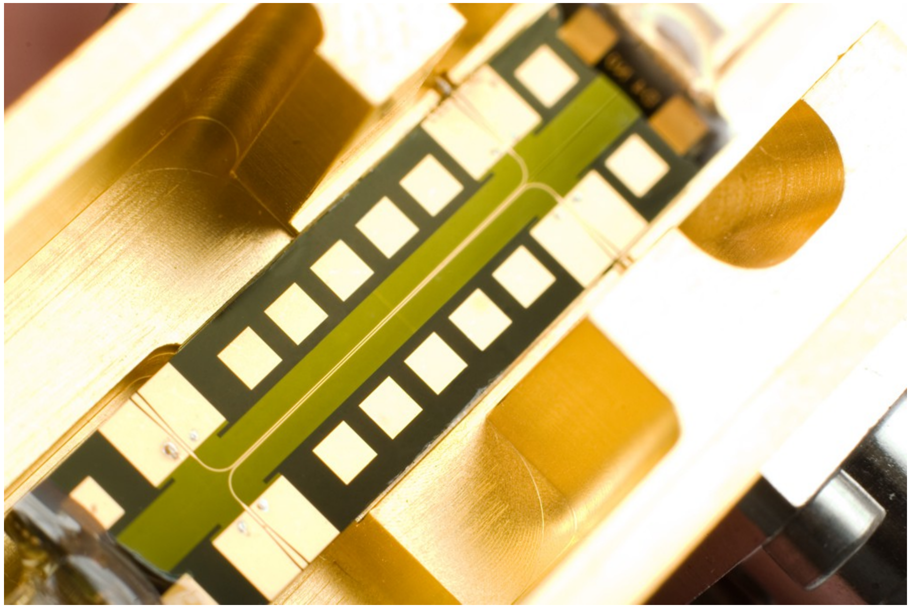


- Courtesy Philippe Lavanchy; awaits DSO approval

Electrical → Optical BPM Signal conversion I/II

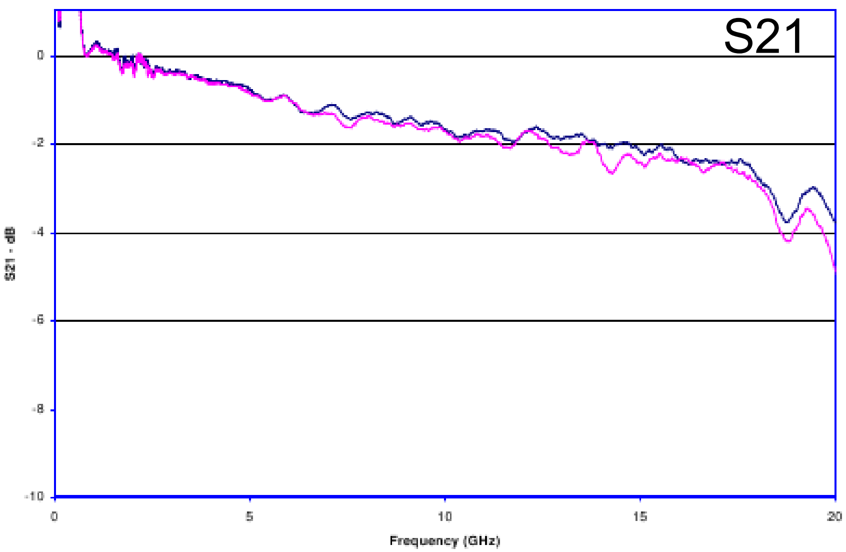
- Creating an optical hybrid translates to the same classical RF hybrid issues
- EO-modulator basically are (un-)matched micro-/strip-line structure
- Critical aspects:
  - Impedance matching
    - Geometry → tricky but similar to our other RF pick-ups
    - Larger dielectric loss-tangent due to $\varepsilon_r(t)$~80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

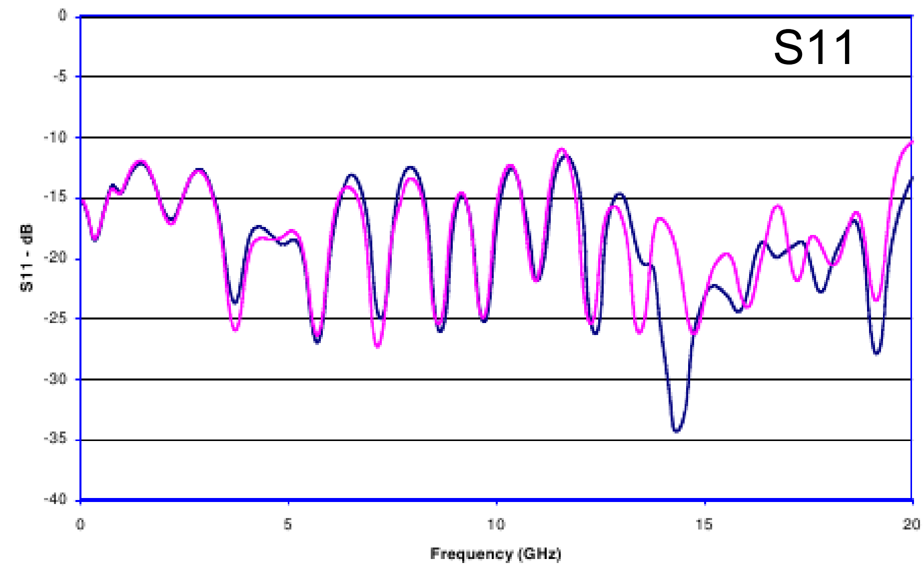




Alternatives...
Electrical → Optical BPM Signal conversion II/II

- 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

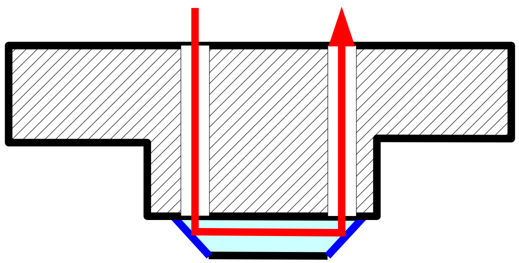
Independent of the electro-optical detection scheme:

- 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

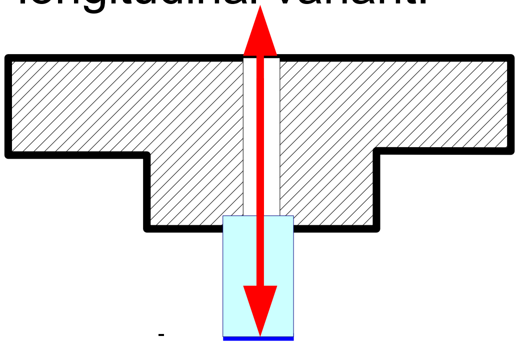
Amplitude Modulation-based Scheme Optical-BPM

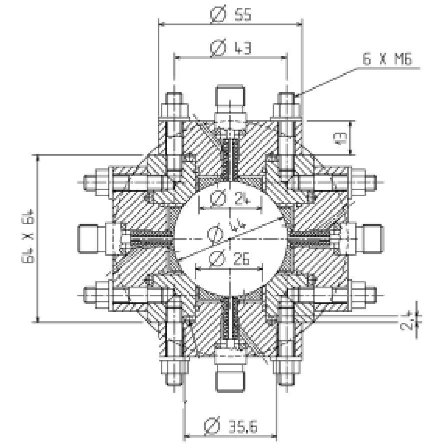
- All-Optical-BPM layout scheme, re-use conceptually LHC BPM design:
  - Keep the same body, keep external button form-factor

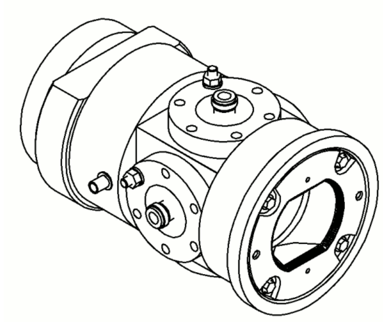
transverse variant:



longitudinal variant:



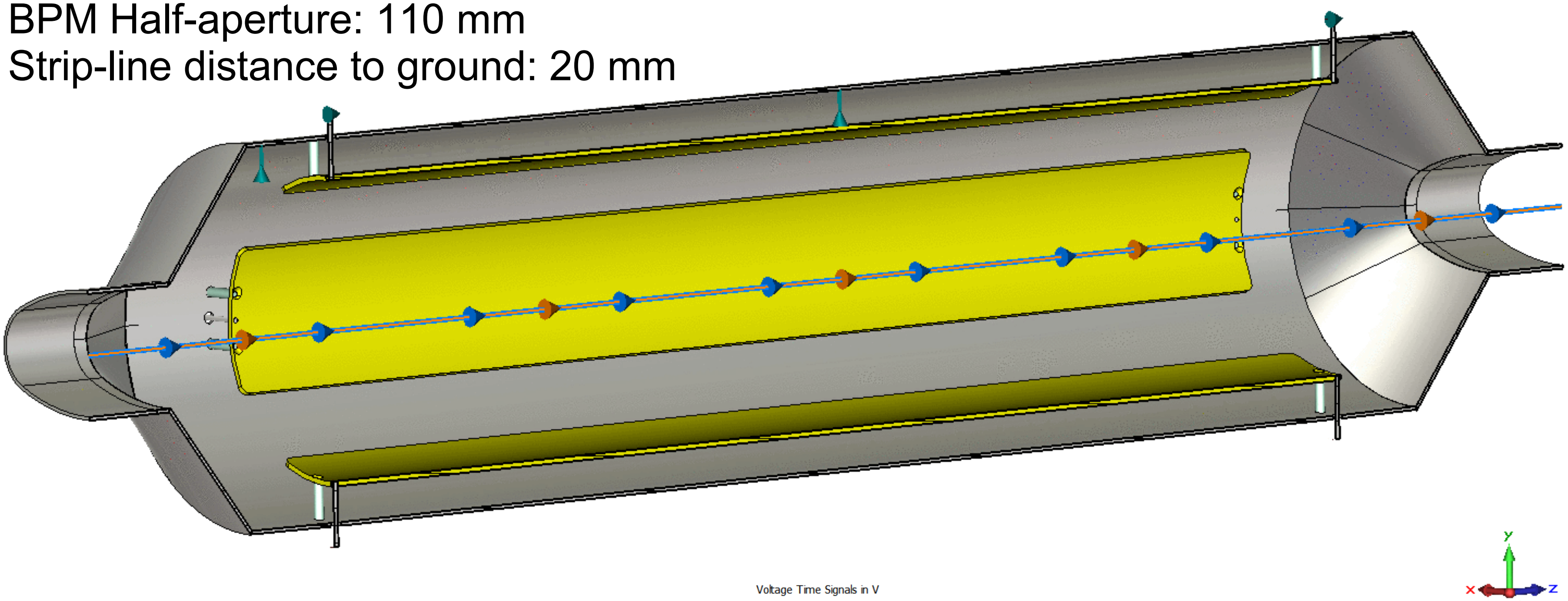


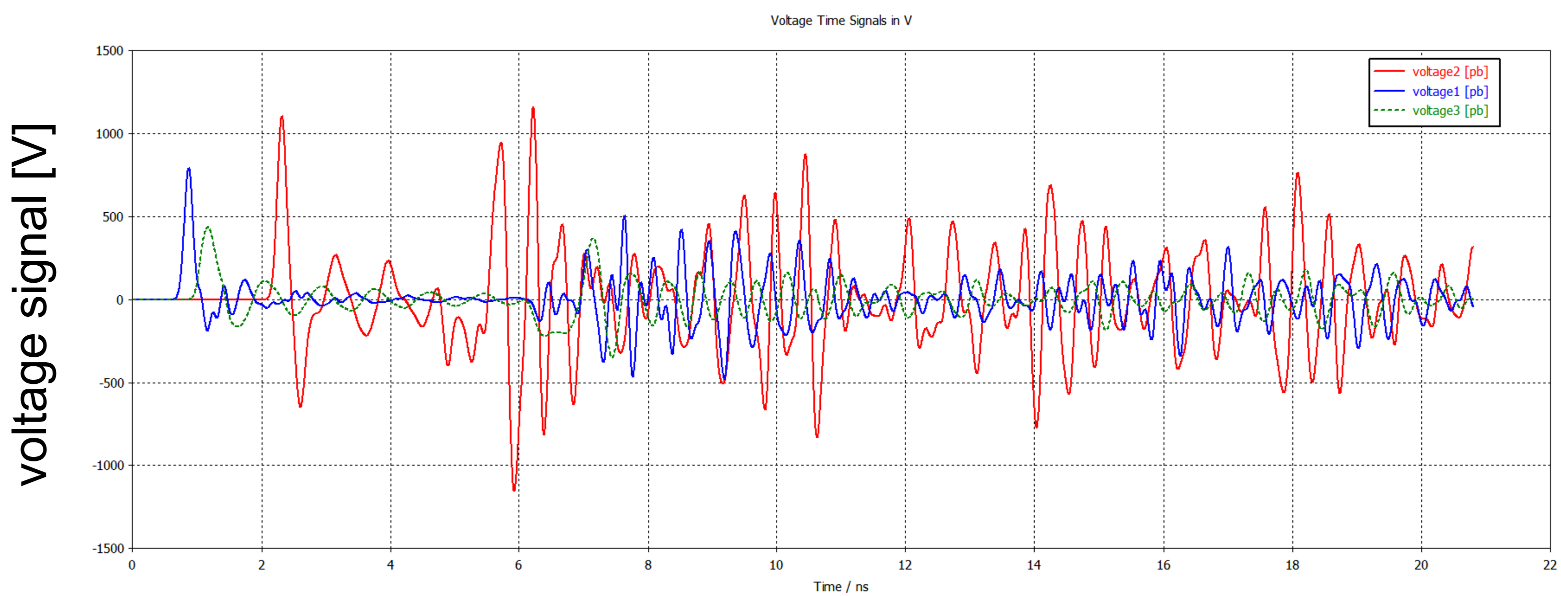


- Impact of EO-crystal (dielectric stup) on machine impedance probably small but should be re-checked by FE-EM simulation
- Mechanical design & construction in 2012/13
  - Need to investigate crystal clamping and fiber-to-feed-through alignment
  - 'flappy-paddle'/'bat-ear' type in-line fiber polariser to be investigated
- Possible prototype installation in LS1?

Linking it to existing Experience/Technology I/II – PS tune strip-line prototype (courtesy Andriy)

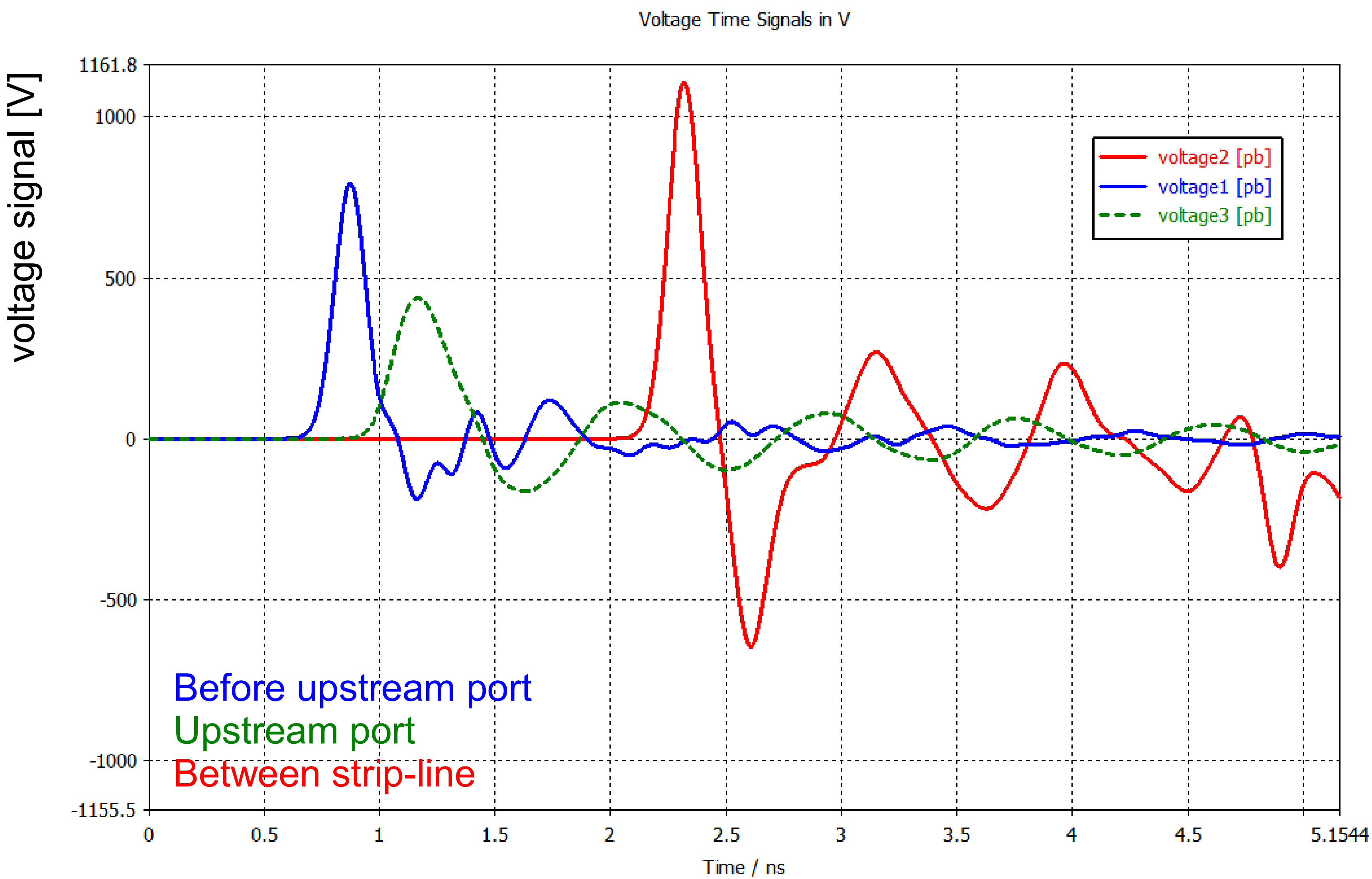
BPM Half-aperture: 110 mm
Strip-line distance to ground: 20 mm





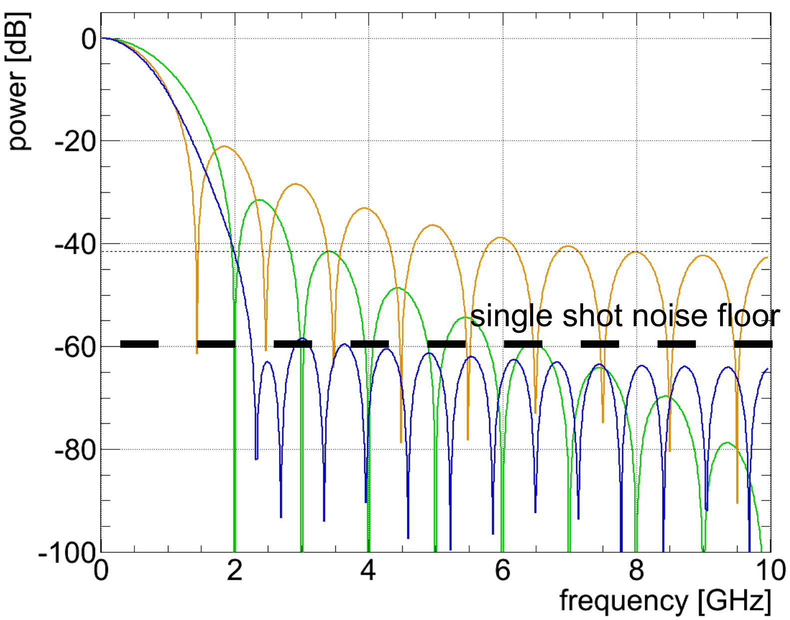
Linking it to existing Experience/Technology I/II – PS tune strip-line prototype (courtesy Andriy)

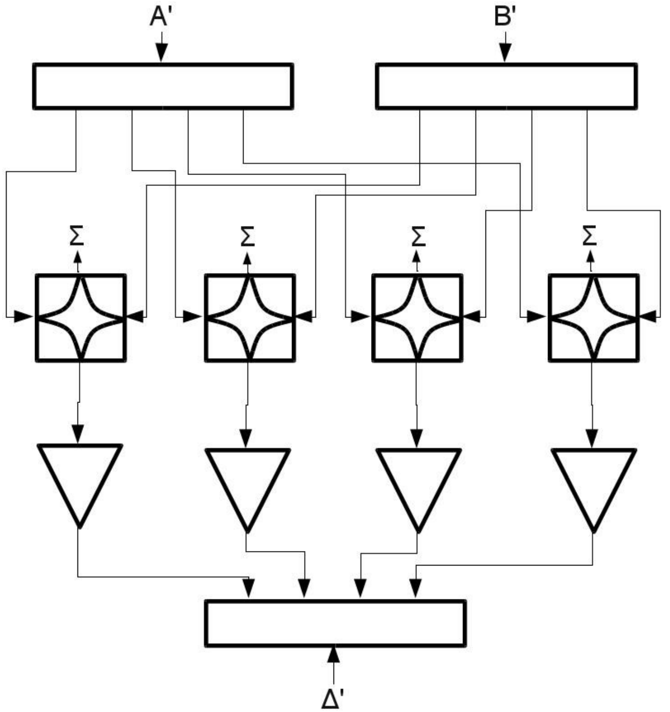
- Zoom of previous plot, N.B. V_π adjustable between few Volts to kVolts



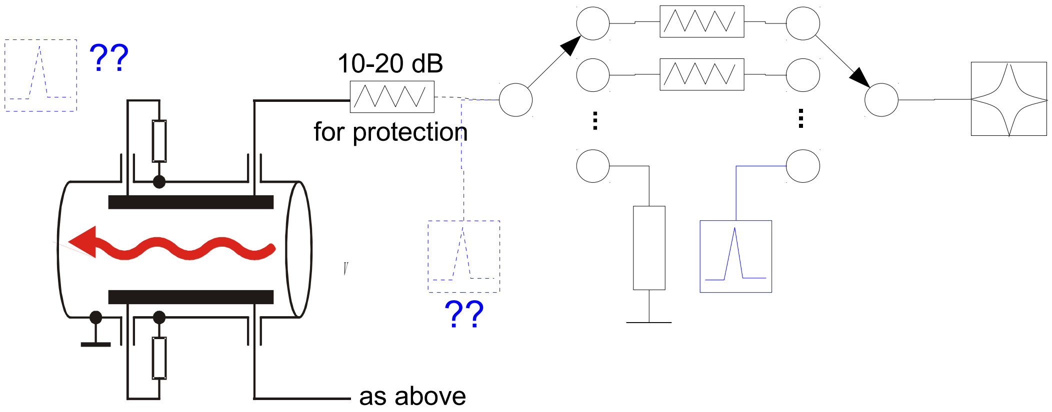
Meanwhile I/V: Classic RF Improvements
Divide and Conquer Strategy for System Bandwidths

- Split signal into manageable bandwidths and treat them separately and re-combine them in the end
  - Attenuate/amplify bands with expected strong/weak power contributions
  - Post-processing (de-convolution) probably mandatory
    (difficult to passively match each part)
- For the time being: aim at two hybrids
  - H-9 or H-183 working from 0.002 (0.003) → 2 (3) GHz, no amplification
  - New broad-band hybrid → 8 GHz, ~2GHz HP and 40 dB amplification





- Dynamic range of oscilloscope <40 dB vs. bunch peak n_b/σ_t variation > 60 dB
  - adaptive signal attenuation mandatory
    - Requires tlc at n-GHz range and given power levels
    - matching, particularly insulation and gain calibration



- Some high-frequency SP67 and DPDT switches being evaluated
- Have <20 ps pulse generators (PSPL[1]) but looking into robust solutions that can be placed permanently in tunnel (radiation issues):
  - Initially avalanche generator (<1 ns), NLTL
  - 50 ps generator based on fast comparator ADCMP572BCPZ, ADCMP580BCPZ[3]

1: James R. Andrew, "Picosecond Pulse Generation Techniques and Pulser Capabilities ", Application Note AN-19, PSPL, 2008
2: Linear Technologies (p.93 & 94): http://www.linear.com/pc/downloadDocument.do?navId=H0,C1,C1154,C1009,C1028,P1219,D4138
3. Analog Devices: specs at www.analog.com

Meanwhile III/V: Digital Acquisition System

- First steps, tackle existing DAQ limitations, initial system was designed to:
  - track 1 bunch over 1000 turns
    → now need to track batches of bunches over 1000 turns
    - Requires more memory → more post-processing to reduce data rates
  - measure 'm=1' HT modes (~1 GHz) → need to go higher for 'm>1' modes

- 'Usual suspects' for suppliers for systems with f_{bw}>2 GHz bandwidth, all providing systems with >6 GHz bandwidth but with difference w.r.t. RAM:
  - Agilent (DAQs and Scopes): up to 1 GB/channel
  - LeCroy (Scopes only): up to 256 MB/channel
  - Tektronix (Scopes only): up to 128 MB/channel
  - Guzik (DAQ): up to 32 GB/channel
- Huge buffers simplify triggering and data selection but also make smart memory management, online and automatic post-processing mandatory, i.e. *"1 GB of data requires >10 seconds for read-out with standard Gigabit Ethernet link – no post processing yet" we ideally desire an answer/pre-analysis every ~30 seconds"*
  - technically feasible but should be kept in mind during design stage

- Gigabyte Sampling Buffers: The aim is not to systematically process, analyse and store the whole buffer but to allow data-mining in case of instabilities:
  - Use-case example 1: Unstable bunches or batches are not known in advance. However, the guilty ones and timing can be identified with e.g. FastBCT and other instruments after the instability occurred
    → can be used to narrow the range of the data to be retrieved
  - Use-case example 2: instrument could be used by several users with different diagnostics indicators at the same, e.g. 'user 1' monitors few bunches over maximum number of turns while 'user 2' acquires the first 500 full turns looking for bunch-by-bunch oscillations but at a reduced sampling frequency.
  - Use-case example 3: do not just fit the minimum required but keep specification open to allow future upgrades and R&D, i.e. present HT monitor was designed to measure Q' but not as instability monitor, larger buffer and bandwidth allowed the exploitation for other beam studies outside the scope during the design.
    (N.B. small difference in price for going from 2.5 → 6 GHz, ~ 25% of total costs)

Meanwhile V/V: Digital Acquisition System

- Exploitation using scopes from Agilent, LeCroy and Agilent are time-proven but ultimately limited in available sampling memory, post-processing and integration (M$ Windows oscilloscopes, Gigabit Ethernet data transfer, …)

- Interesting new candidate:
  Guzik's GSA & ADC 6000 Series
  - 4 (2, 1) channels
    @ 4 (6.5/8, 13) GHz
  - 16 (32) GB/ch sampling buffer ↔ monitoring of 1.6 s of beam data!
  - Various on-line processing that could be exploited to pre-select data:
    - FFT & DFT (per bunch, mag. Average, sub-frequency ranges), rise-time, bunch-width (FWHM), bunch statistics (average, r.m.s., min., max. signal), number of rising/falling edge → possible HT mode detection already in HW?
    - Functionality to be explored → requested demo system for evaluation
      (closed FPGA firmware for the time being but user-specifc space under investigation)

- Some ongoing negotiations with the manufacturer:
  - Price is important but similar to others if normalised to sampling buffer
  - PCIe bridge integration aspects: what would need to be done by us?

Summary and Outlook

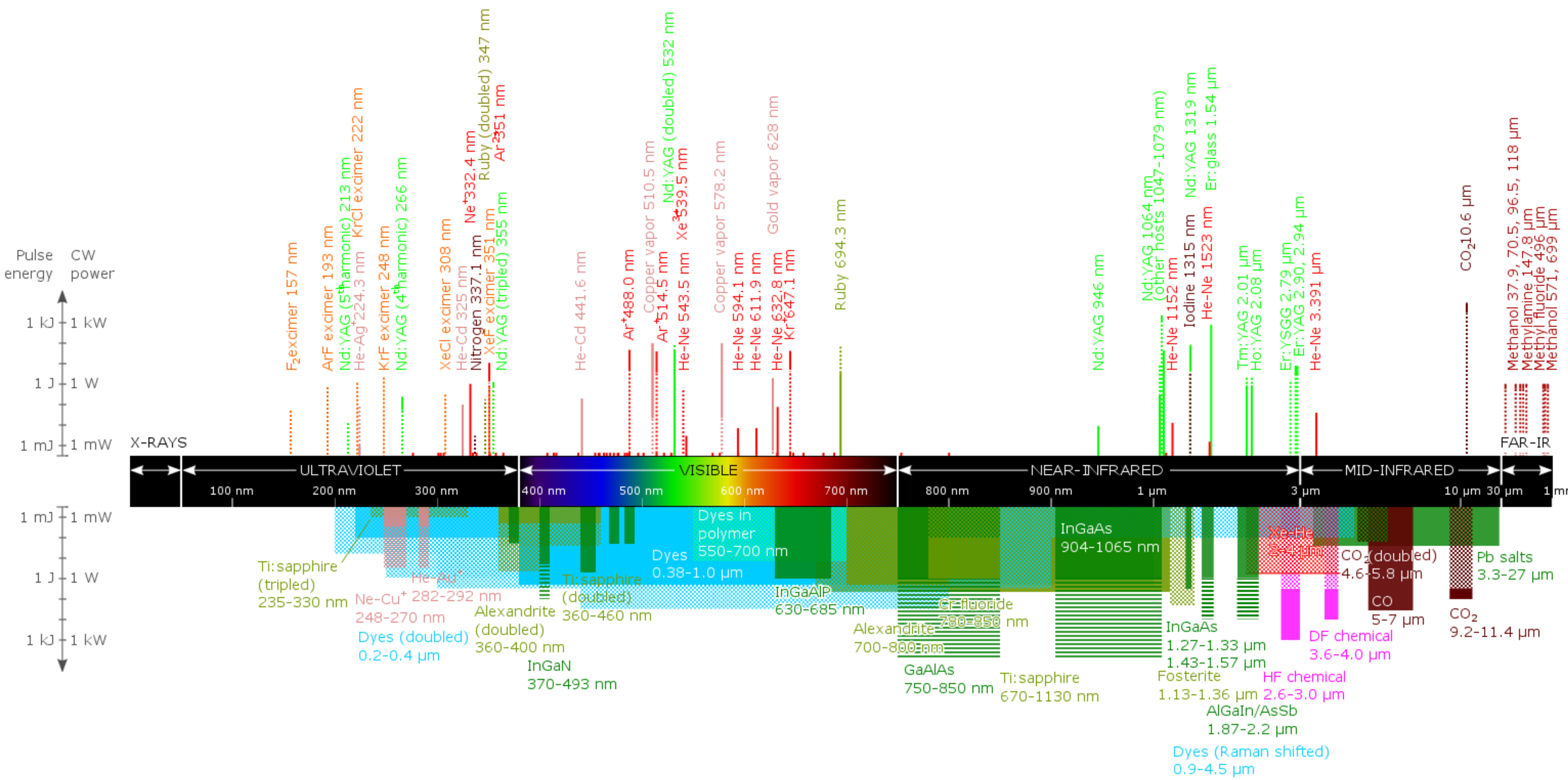
- Present limitation hierarchy:
  DAQ → hybrid → transmission (cable/optic) → new/better pick-up (response)
- Several options addressing immediate and future performance aspects
  - Synchrotron-Light – higher-bandwidth, better adapted to ultimate bunch charge
  - Electro-Optical Pick-up – higher-bandwidth, easier signal transmission
  - Improve existing system by classical RF means (pushing the limit)

- Upgrade plans/wishes/target:
  - 2012/13: upgrade of the DAQ system for HT (LIU budget confirmed)
    - aim: higher bandwidth, more memory, more in-built post-processing
    - Can be re-used whatever the other upgrade decisions
  - Mid-end 2012:
    - install and test hybrid RF-hybrid scheme
    - Synch-Light BPM Prototype at ASLS → translate this to CTF3
    - EO BPM design?
  - LS1?!? – New Pick-up Prototype Installation:
    - Synch-Light based HT monitor (CTF3/LHC more suitable)
    - EO BPM prototype installation in SPS

Reserve slides

Commercial Laser

LHC Injectors Upgrade



Head-Tail based Q' Diagnostic I/II

- Instability can be exploited to give in estimate on Q' in the first place:
  - track two slices, 'head' and 'tail' in the bunch distribution: $\Delta z_{HT}(n) \propto \sin(\psi_{HT}(n))$

    (tune: Q, long slice position: τ, synchrotron frequency: ω_s, turn: n)

    - Phase difference of betatron oscillations:

$$\psi_{HT}(n) = 2\pi Q\cdot n + \Delta\phi_\beta \quad \textit{with} \quad \Delta\phi_\beta \approx Q' \cdot \underbrace{\frac{\omega_0 \hat{\tau}}{\eta}\cdot \sin(\omega_s \cdot n)}_{\Delta p/p\, modulation}$$

one synchrotron period