Application of Metal-Semiconductor (MSM) Photodetectors for Transverse and Longitudinal Intra-Bunch Beam Diagnostics

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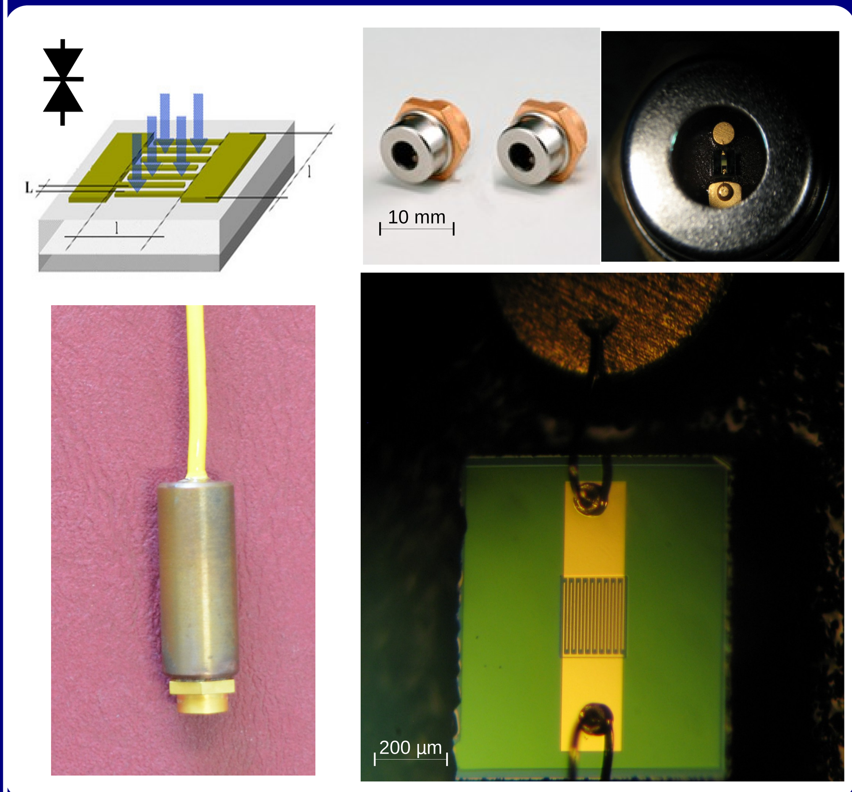
The performance reach of modern accelerators is often governed by the ability to reliably measure and control the beam stability. In high-brightness lepton and high-energy hadron accelerators, the use of optical diagnostic techniques is becoming more widespread as the required bandwidth, resolution and high RF beam power level involved limit the use of traditional electro-magnetic RF pick-up based methods.
This contribution discusses the use of fibre-coupled ultra-fast Metal-Semiconductor-Metal Photodetectors (MSM-PD) as an alternative, dependable means to measure signals derived from electro-optical and synchrotron-light based diagnostics systems. It describes the beam studies performed at CERN's CLIC Test Facility (CTF3) and the Australian Synchrotron to assess the feasibility of this technology as a robust, wide-band and sensitive technique for measuring transverse intra-bunch and bunch-by-bunch beam oscillations, longitudinal beam profiles, un-bunched beam population and beam-halo profiles. The amplification schemes, achieved sensitivities, linearity, and dynamic range of the detector setup are presented.

1 MSM – Photodetector

In order to preserve benefits of working in the optical domain → the optical receiver must match the performances of the optical front-end and fibre transmission. Same MSM-PDs as for the fill-pattern-monitor at the Australian Synchrotron:



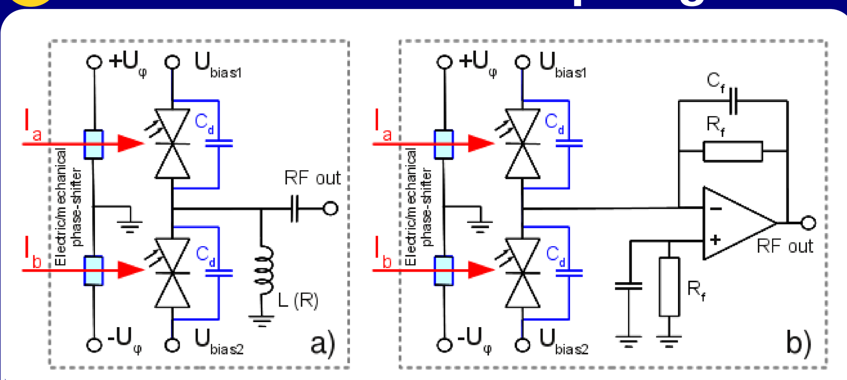
… not quite a P(i)N junction (diode)!

no polarity, ~10 V bias-voltage, variants >350 GHz bw. Exists

MSM from Hamamatsu G4176 (G7096):

Radiant Sensitivity	0.3	A/W
Max. Input Power (t < 1ns)	<50	mW
Spectral Response	[470,870] ([850,1650])	nm
Dark Current	100	pA
Current Noise	1.0	fA/√Hz
Terminal Capacitance C_D	~0.3	pF
10-90% rise-time	~30	ps

2 MSM-PD Receiver Topologies



Studied receiver topologies:

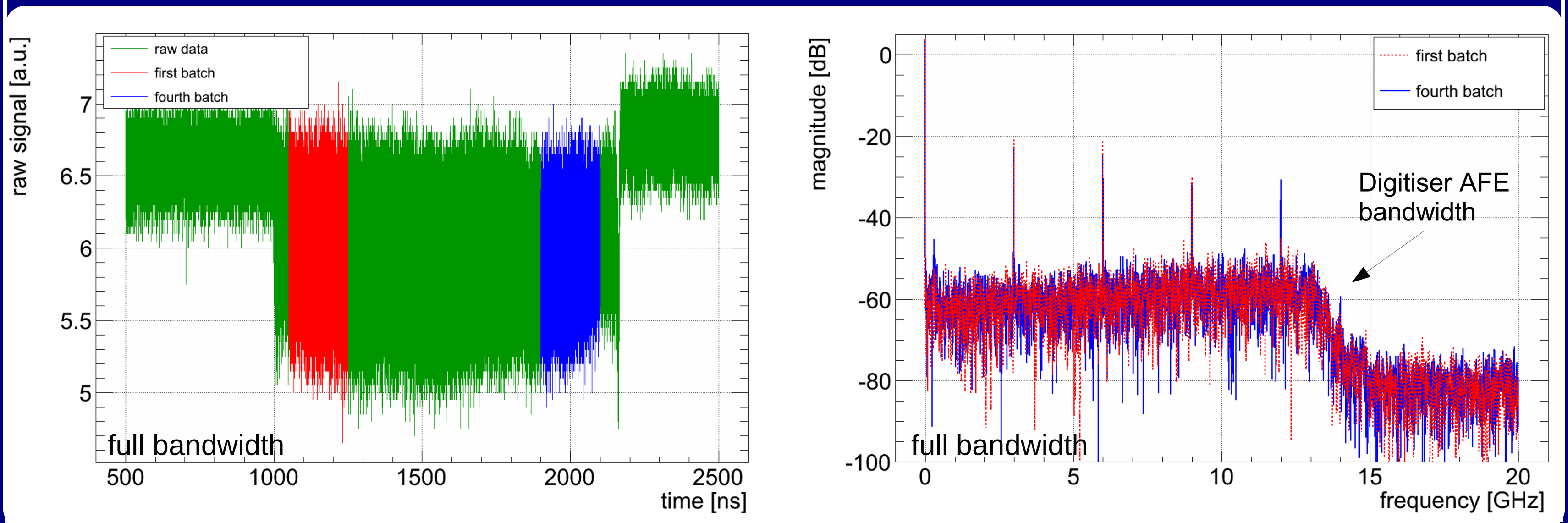
a) MSM-BT – classic balanced Bias-T
- easy wide-band implementation
- presently only option for f_{bw} >12 GHz
- bandwidth limited to $f_{bw\text{-}BT} = RC_D$
- MSM are current-sources → charge-up of AC-decoupling capacitor for high-duty factor
- No-DC response → need base-line recovery (Ghost & Satellite detection BIW'12)

b) MSM-TIA – bal. Transimpedance Amplifier
- larger gain/lower noise-figure
- true DC-response
- Bandwidth given by: $f_{bw-TIA} \approx \sqrt{\frac{GBP}{4R_f C_D}}$
  - OPA847 (GBW=3.9 GHz)
- Linearity limited by OpAmp

c) APD – Time-Correlated Single Photon-Counting using avalanching photodiode
(used at Diamond, SLSA, LHC – C.A. Thomas et al., , NIM A, 566(2) 762766, October, 2006)
- Based on integration – not applicable for fast intra-bunch motion
- 'golden standard' w.r.t. linearity, provided
  - a) well separated bunches ↔ APD dead-time
  - b) Max of one photon/turn → 10^{-6} resolution: 1-2 s integration (SLS), up to ~10 minutes (LHC)

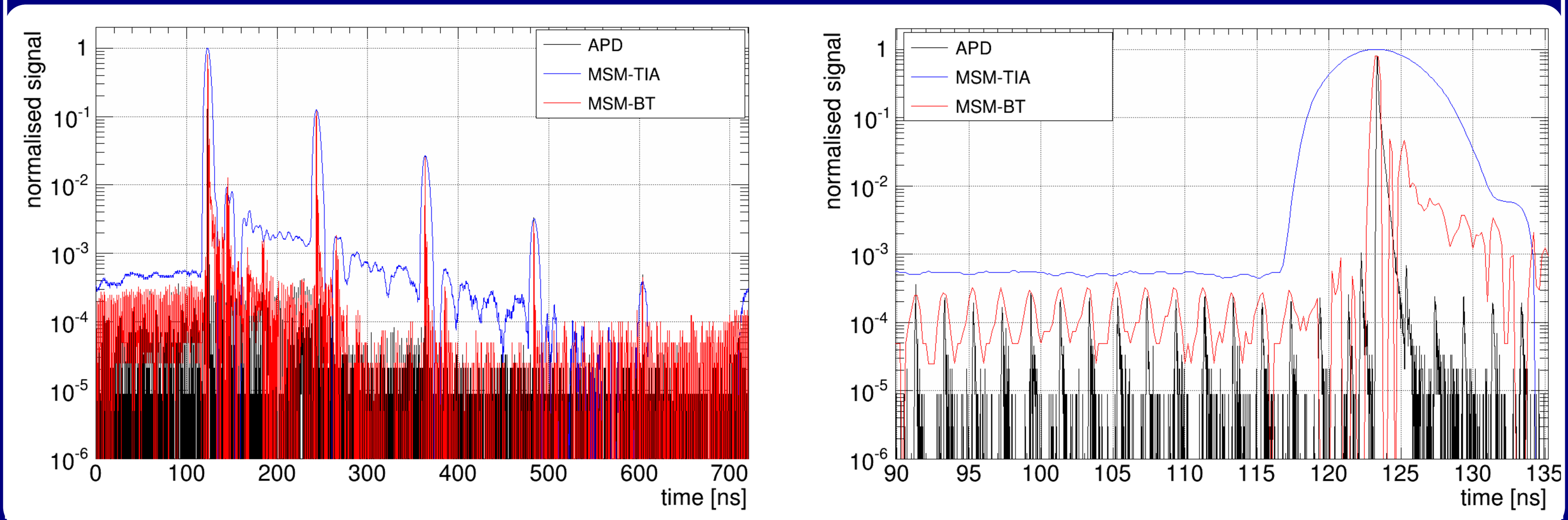
3 MSM-BT Bandwidth Tests at the CTF3 – Combiner Ring (CR)

The high-power CLIC drive-beam is produced by interleaving four 3 GHz bunch trains. The lower RF harmonics diminish in favour of (ideally) only a single line at 12 GHz, seen in the spectra for the fourth batch, and confirms the MSM-PD bandwidth. The prevailing lower harmonics indicate an imperfect batch-by-batch interleaving.

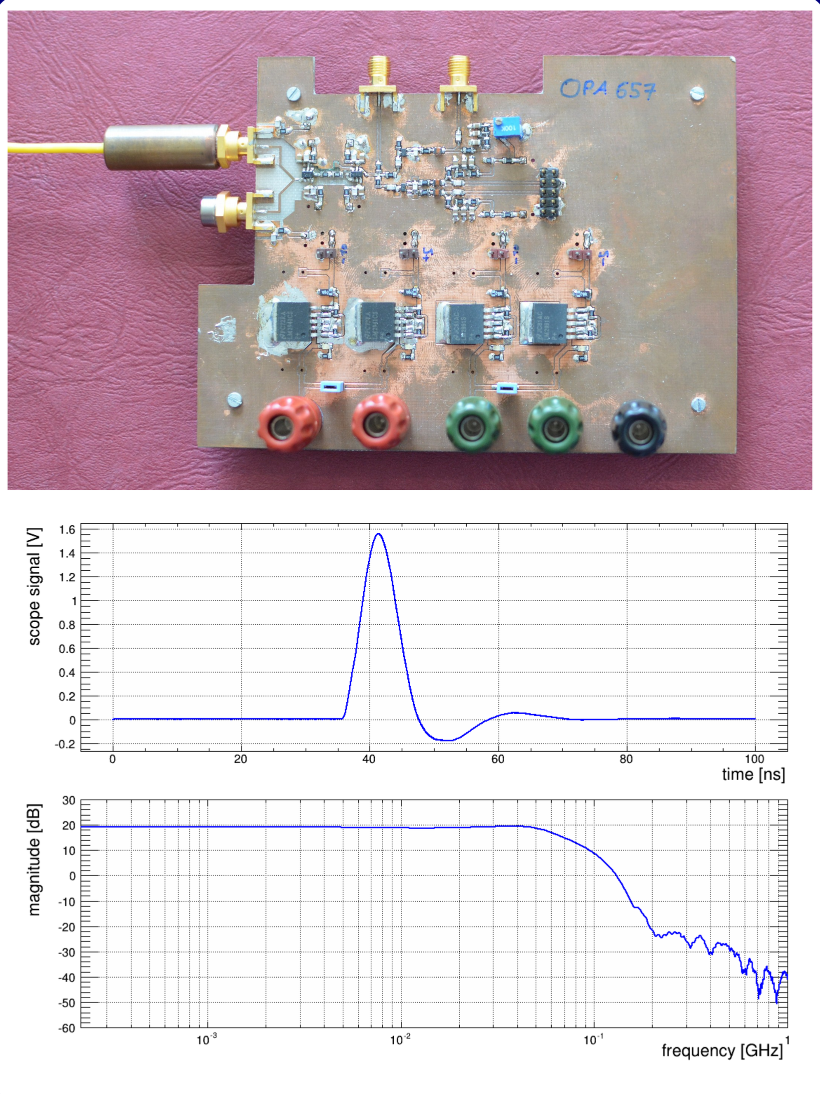


4 Sensitivity and Linearity Tests at the Australian Synchrotron

Achieved ~10^5 vs. theoretic limit of 10^8 dynamic range, limited rather by ENOB of digital acquisition chain than amplifier/Bias-T. Linearity of MSM-BT and MSM-TIA in agreement with APD data down to the 10^{-4}-level. Limit for MSM-BT: compensation of the droop caused by the AC-coupling, notably cable reflections. Limit MSM-TIA: compatible with the spurious-free-dynamic-range of the used OpAmp (TI's OPA847).



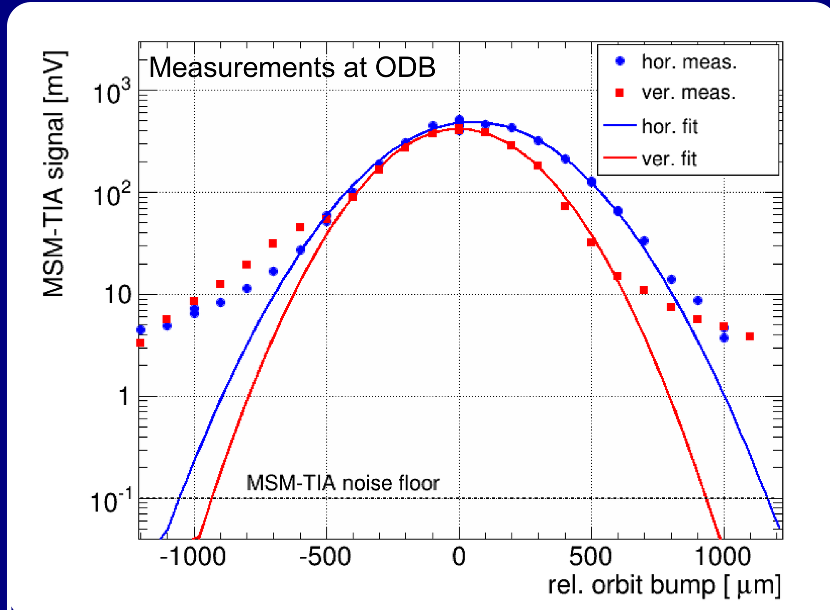
2 MSM-TIA Prototype



Reduced bandwidth to 80 MHz in favour of higher transconductance R_f=25 kΩ for sensitivity tests (P_{in} < 100 µW, from initially R_f=500 Ω@≈700 MHz).

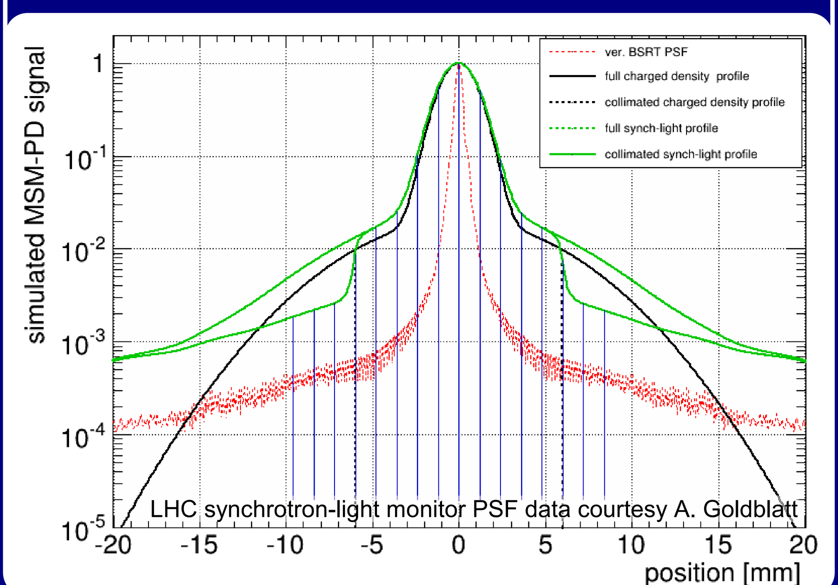
Achieved 5.2 pA/√Hz vs. 4.8 pA/√Hz (theoretic design) TIA noise floor.
Next steps: cascaded two-stage TIA design with $R_f=(500\Omega)^2@f_{bw}$>500 MHz.
(N.B. ASLS RF: 500 MHz, LHC-RF: 400 MHz)

5 MSM-Beam Halo Measurements

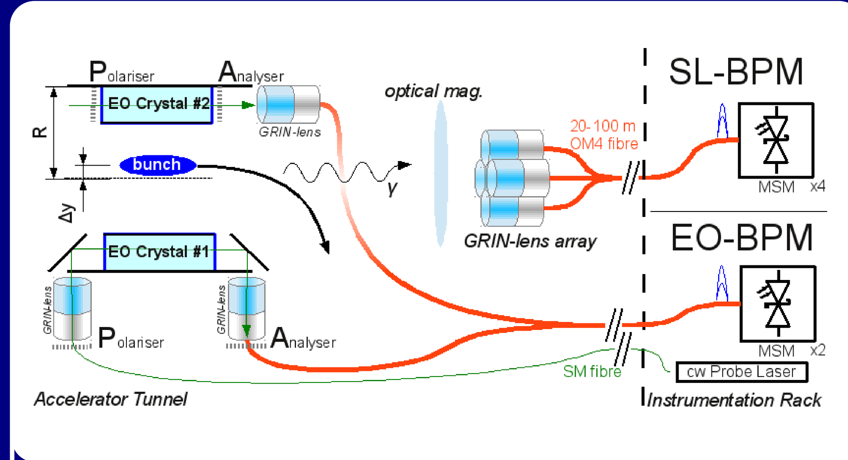


Measured large spot size dominated by chromatic aberrations as the full visible spectrum was taken into account to maximise the incident light power. Dominating limiting factor is the accuracy of the point-spread-function (PSF) relating the actual charged particle distribution to the measured SL-beam distribution.

Prediction for LHC SL-PSF:



6 MSM Applications being studied:



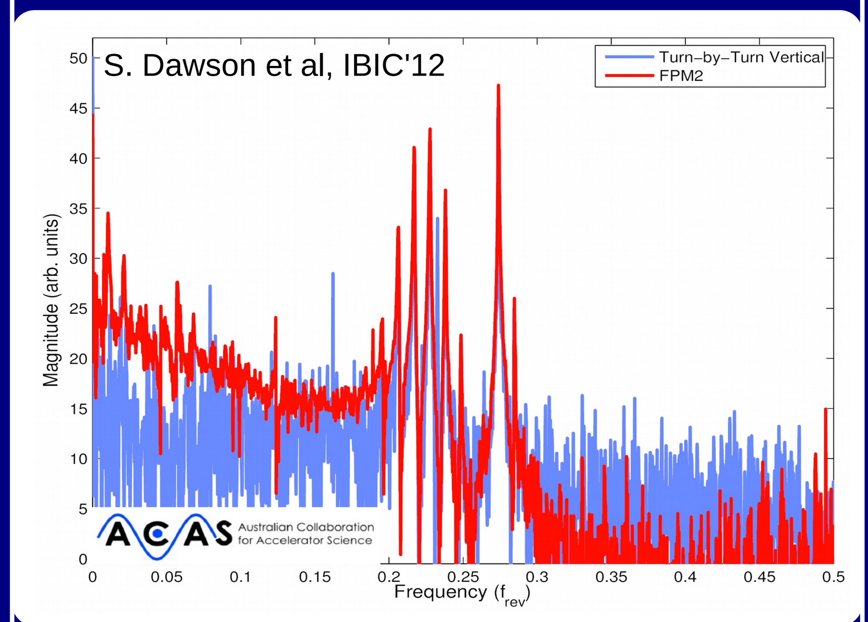
Fibre-coupled MSM-PDs being studied as an back-end option for:
A)Electro-Optical-BPM (EO-BPM), &
B)Synchrotron-Light-BPM (SL-BPM)
aiming at transverse and longitudinal intra-bunch beam diagnostics to study ultra-fast intra-bunch head-tail instabilities up to about ~13 GHz → talk: TUBL3

Advantages:
- Non-invasive, more robust w.r.t. EMC
- Handling of high beam-power
- For accelerator typical distance of 100 m: OM4 (GRIN) fibre bandwidth ~ 47 GHz vs. 7/8" coaxial cable ~ 600 MHz
- Position resolution sensitivity:

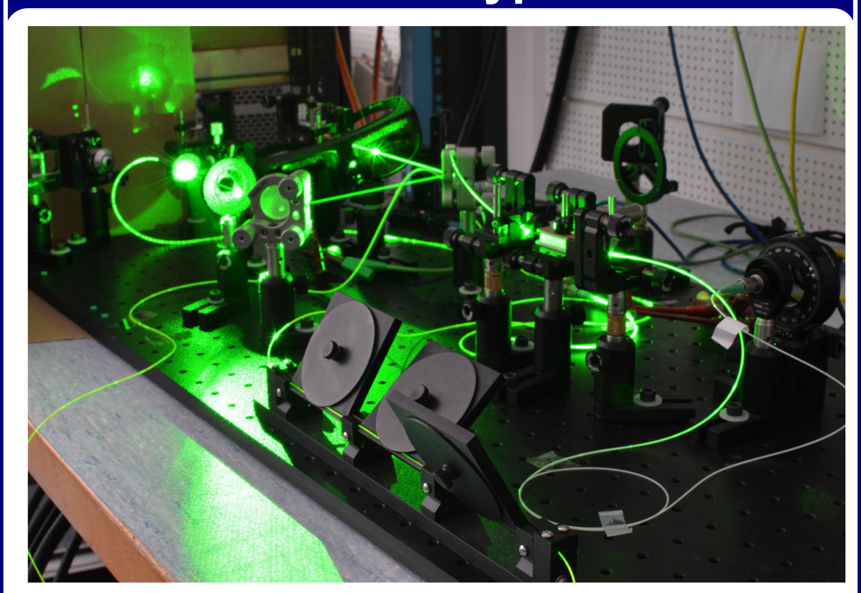
$$SL-BPM \sim \frac{rel.\ position}{beam-width}$$

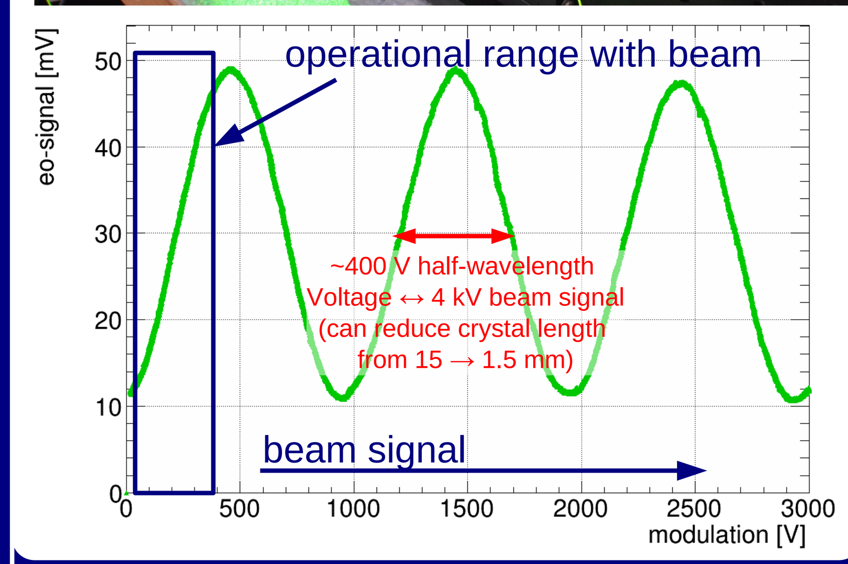
$$EO-BPM \sim \frac{rel.\ position}{half-aperture}$$

SL-BPM Measurement Example:



EO-BPM Lab Prototype Tests:





Studies ongoing in view of mechanical and prototype integration at the SPS...

Conclusion

MSM-PD provide an alternative, dependable means to convert signals deriving from electro-optical and synchrotron-light based diagnostics systems. The optical receiver must match the performances of the optical front-end and fibre transmission, in order to preserve the benefits of working in the optical domain. Beam measurements performed at CTF3 and the Australian Synchrotron confirm bandwidth, dynamic range and linearity for the tested receiver topologies.
In combination with the tested fibre-coupling, this opens the possibility to further exploit the MSM-PD as a robust, wide-band and sensitive device for measuring transverse intra-bunch and bunch-by-bunch beam oscillations, longitudinal beam profiles, un-bunched beam population and beam-halo profiles.