Required R&D for FCC(pp) beam instrumentation

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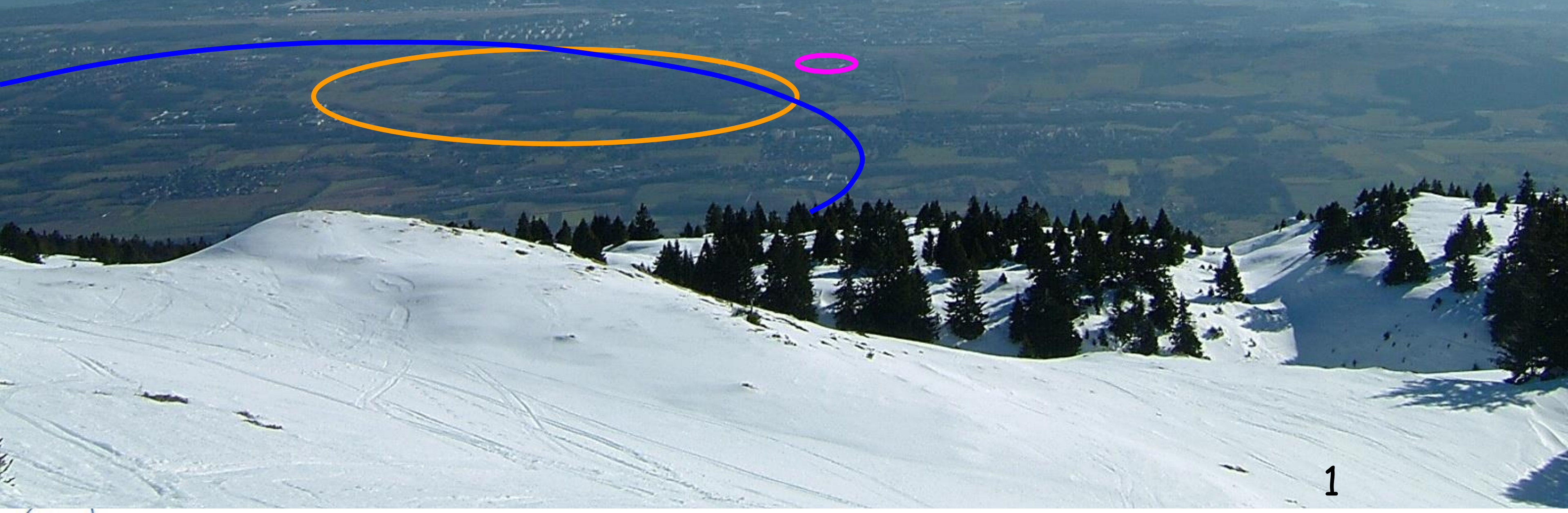
With slides/input from: R.Jones, T.Lefevre, M.Gasior, M.Wendt, B.Dehning, R.Steinhagen, A.Gillespie



Outline

- Why was the LHC instrumentation a success?
- (Any-pp) Collider Instrumentation Overview
- The large scale systems
  - BPMs
  - BLMs and machine protection
- Technologies to further develop for the FCC-pp:
  - beam parameter feedbacks (orbit, q, q’)
    in particular: co-existence of tune measurements/tune feedback and transverse damping
  - non invasive transverse profile monitoring
  - usage of electro-optical devices
  - radiation tolerant fibre optics transmission
- How will the FCC instrumentation be a success?

Why was the LHC instrumentation a success?

1) "Never make an economy on beam instrumentation",
very important quote of L.Evans during all LHC cost reviews…
Final budget about 45 MCHF from original 47 MCHF, less than 1% of total budget; (CERN cost model)

2) Early, well documented specifications; J.P.Koutchouk et al.
Same effort planned for FCC starting this year under guidance of J.J.Gras

3)Common electronics platform for all instruments
developed in collaboration with TRIUMF (=DAB cards)
new version for the years 2015-2025 prototyped (=VFC cards)

4) Highly collaborative effort
with many other institutes and with the high energy physics community

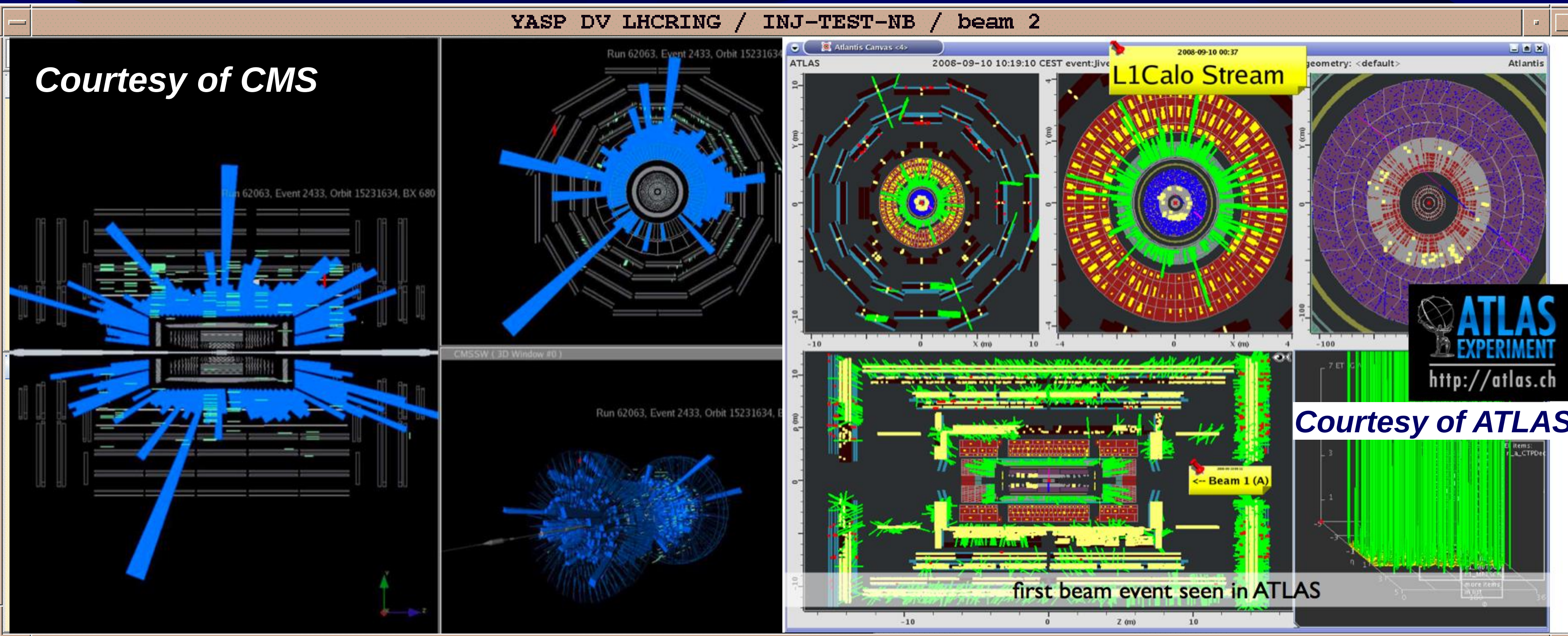
5) Seamless integration into the control system
establish standards…follow them…bash them out in dry-runs

Beam Threading

- Threading the beam round the LHC ring (very first commissioning)
  - → One beam at a time, one hour per beam.
  - → Collimators were used to intercept the beam (1 bunch, 2×10^9 protons)
  - → Beam through 1 sector (1/8 ring)
    - correct trajectory, open collimator and move on.

Beam 2 threading

BPM availability ~ 99%



(Any pp) collider BI overview?

- **Beam Position Monitoring (orbit, bunch by bunch, turn by turn)**
- Tune, Chromaticity…all optics parameters
- Beam and bunch intensities; DC to every RF bucket
- **Beam Loss Monitoring: Machine Protection AND diagnostics**
- Transverse Profiles (all bunches @ all intensities and energies)
- Longitudinal Profiles
- Luminosity Monitoring
- Special diagnostics (usually evolves with machine):
  - interlock signals (abort gap, special BPMs)
  - Schottky Signals
  - Instability Signals (Head-Tail Monitor in LHC)
- Add for e+e-:
  - Polarization
- Will do study 25 ns/5ns implications (if needed)

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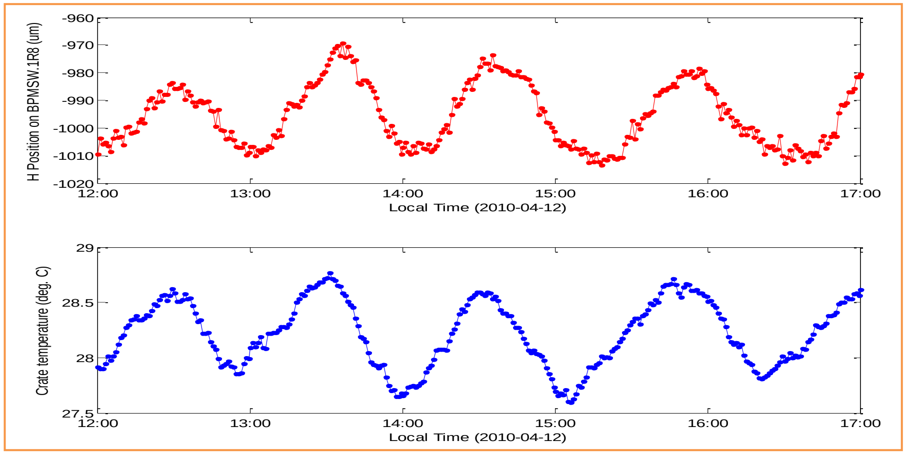
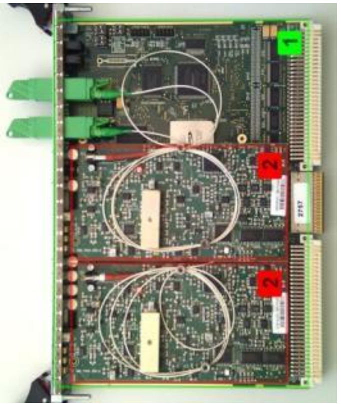
Beam Position Measurement System

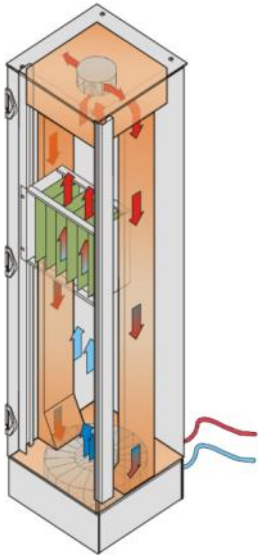
- Large scale system (> 2000 planes of measurement)
- Very good performance in general
- All required functionality: orbit, turn by turn data, bunch by bunch data
- Backbone of orbit feedback system
- Based on the principle idea of time normalization of input signals as "economy measure"; one information carrying link per plane (D.Cocq et al (1998)) basically the position information of each bunch is encoded as pulse width of a single pulse. Width variation 3 ns with about 3 ps resolution (noise) corresponding to 10-3 single shot resolution
- Distributed system -> requires efficient data transmission -> fibre-optics
- Minimisation of cables -> front-end in tunnel -> rad hard design (usually analogue). For future & FCC foresee digitisation in tunnel using radiation hard design.
- Addition of BPMs in collimator jaws to speed up & maintain alignment
- New development of electronics foreseen for HL-LHC= prototype for FCC?

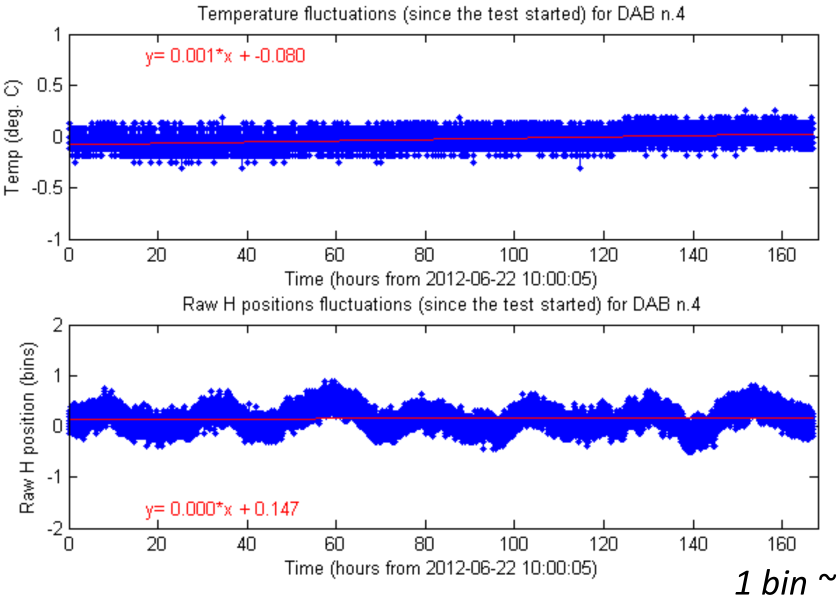
TEMPERATURE STABILITY OF RECEIVING ELECTRONICS

- Improvements for 2015
  - Thermalized racks
  - Maintains temperature within ±0.2°C
  - Prototype successfully tested in 2012



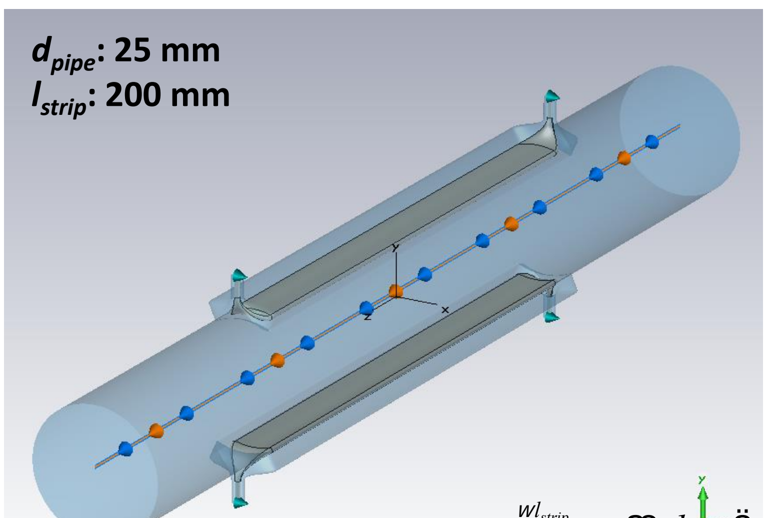






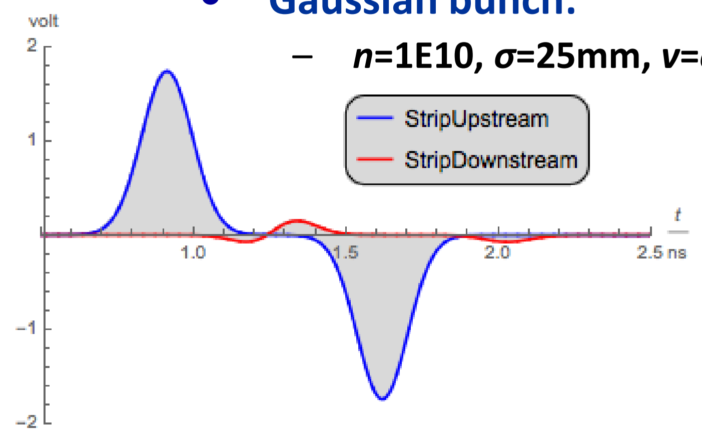
1 bin ~ 30um

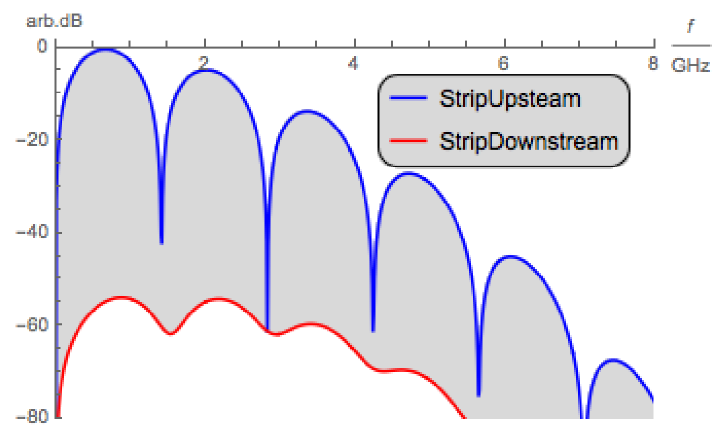
- Beam monitoring, e.g. beam position / orbit measurement of both beams (e^+, e^-) in a single beam pipe
  - Few beam bunches: time discrimination
  - Many beam bunches: difficult!
    - BPM pickups with directivity
    - Advanced BPM signal processing including beam arrival time



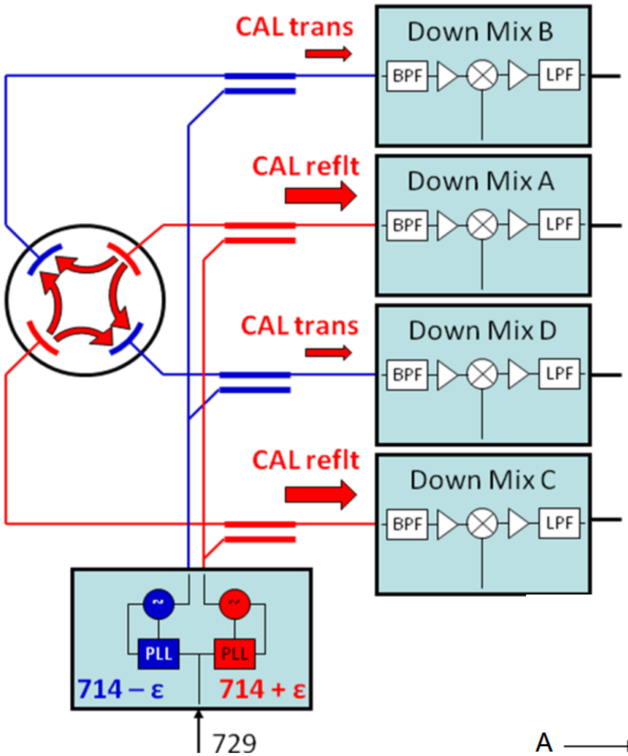
$$Z_{strip}(\omega) = i\phi Z_0 e^{-i\frac{\omega l_{strip}}{c_0}} \sin\left(\frac{\omega l_{strip}}{c_0}\right)$$

- **Gaussian bunch:**
  - ***n*=1E10, *σ*=25mm, $v=c_0$**





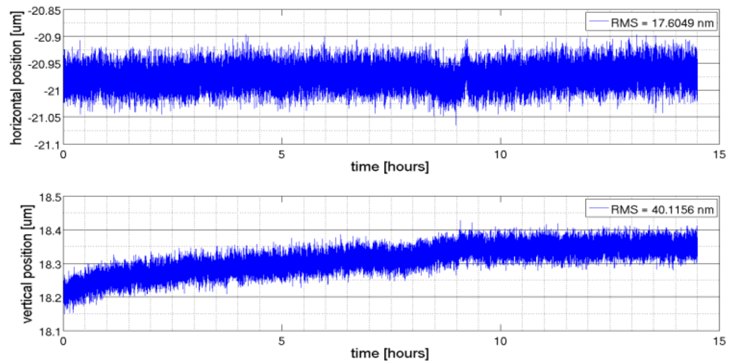
Long-Term Drift Compensation (as used in MANY LIGHTSOURCES)



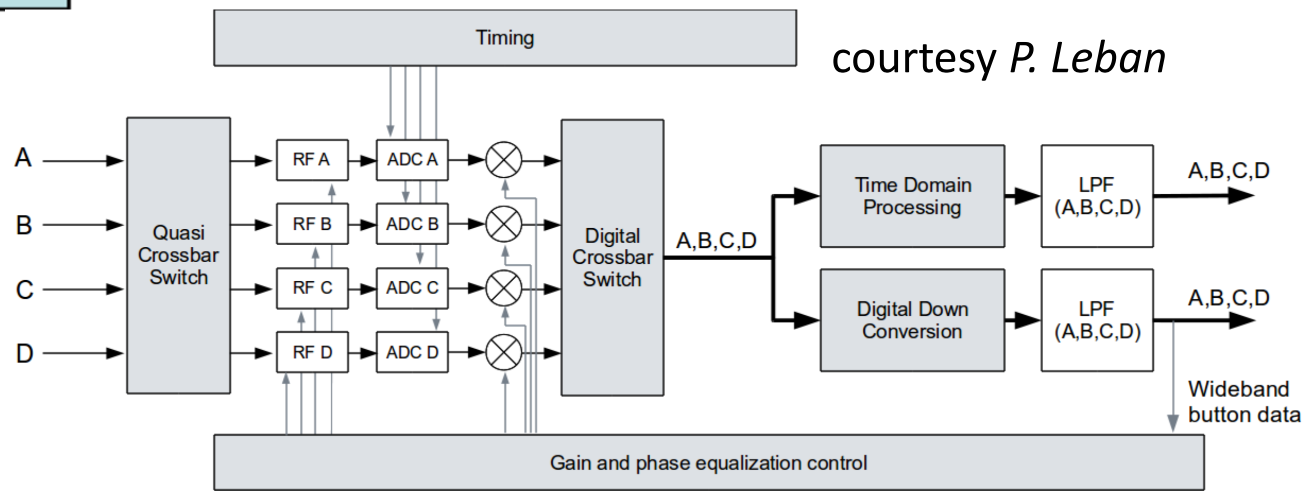
courtesy *N. Eddy*

- **Calibration tone technique (only in narrowband operation)**
  ATF (KEK)

- *Libera* crossbar switching technique
  - <100 nm stability over 14 hours



courtesy *P. Leban*



LHC (FCC) BPM Upgrade R&D

- Minimalistic analog front-end
  - Time-domain band-pass filter
  - Single channel processing by analog time multiplexing of two electrode signals (12 ns delay)
    - To minimize aging and "electronic offsets"
- "Brute-force" digitalization of the (almost) raw bunch signals
  - E.g. AD9625 (2.5 GSPS, 12-bit), ADCJ4000 (4 GSPS, 12-bit)
  - We can squeeze out ~60 dB dynamic range at our base-band frequency (400 MHz)
- FPGA-based DDC, filter and decimation
  - Demodulation by convolution with the analog BP filter response
  - CIC-FIR low-pass and decimator, e.g. to 25 ns words.
- Flexible signal processing by FPGA reprogramming or register mods
  - Adapt BPM signal processing to different LHC beam types and formats
- LHC specific BPM R&D with spin-off potential for other accelerators
  - Tailored to the LHC infrastructure and requirements

BEAM LOSS MONITORING

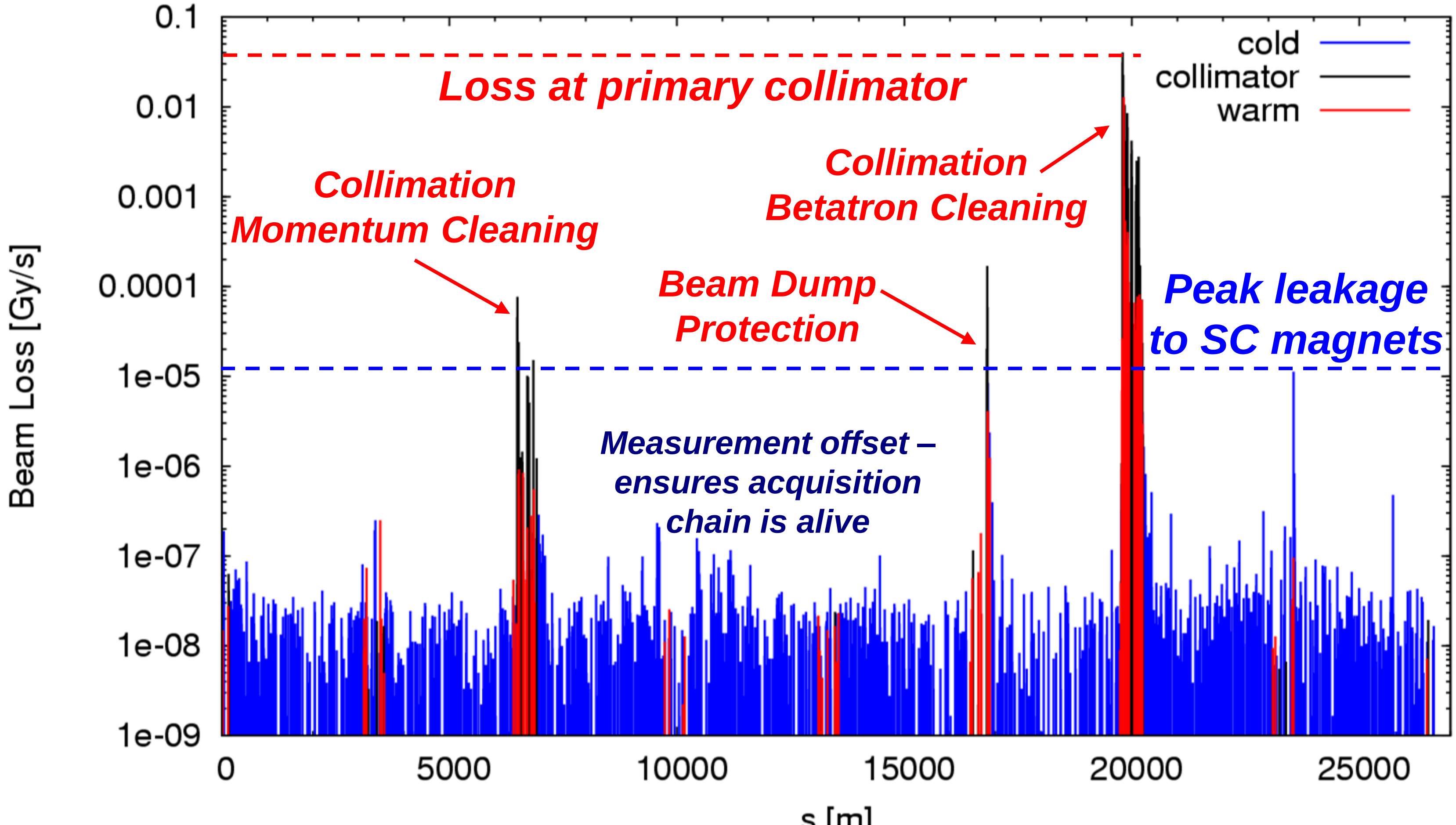
- Backbone of LHC operation and LHC machine protection
- Very solid design based on 1l Ionization gas chambers
- > 4000 channels, high dynamic range
- Similar system should cover FCC needs
- R&D:

  - cost reduction by using Cherenkov radiation in fibers (smaller acceptance, longitudinal resolution by using timing of signals….)

  - faster signals; cryogenics BLMs (= diamond detectors)

Collimation Verification with BLMs

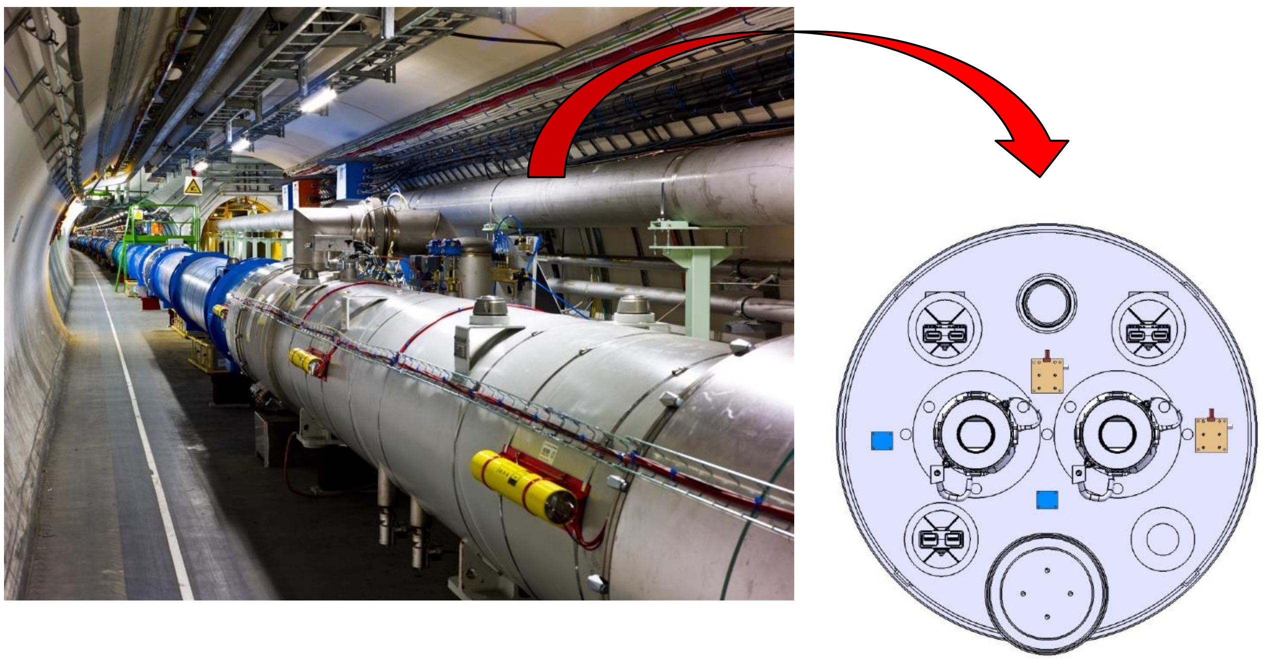
- **BLM system used both for setting-up and qualifying**
- **Beam cleaning efficiencies ≥ 99.98% ~ as designed**

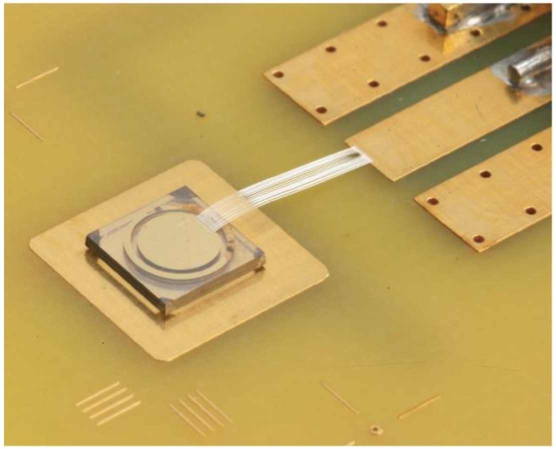


“Cryogenic” BLMs

- **To improve the sensitivity of BLMs: from the outside to the inside of the cryostats – avoid shielding from iron yokes**
  - **BLMs in cryogenic environment (LHe, silicon, diamonds).**
  - **First tests in the LHC in 2015.**
  - **Cryo-BLMs – can be located closer to coils. Better measure of energy deposition**
  - **Can distinguish between losses & collision debris (for triplets).**

- **Similar ideas at FRIB and IFMIF for high sensitivity halo monitors**





Diamond BLM detector, courtesy of E. Griesmayer

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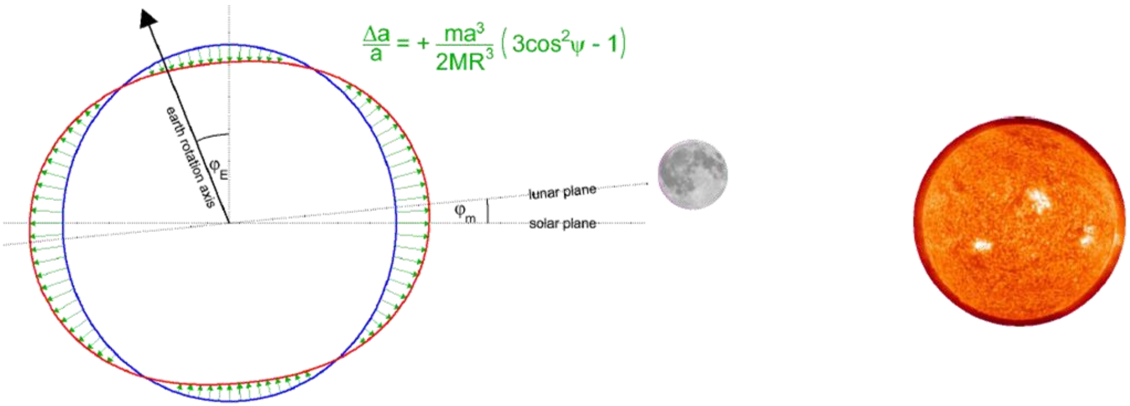
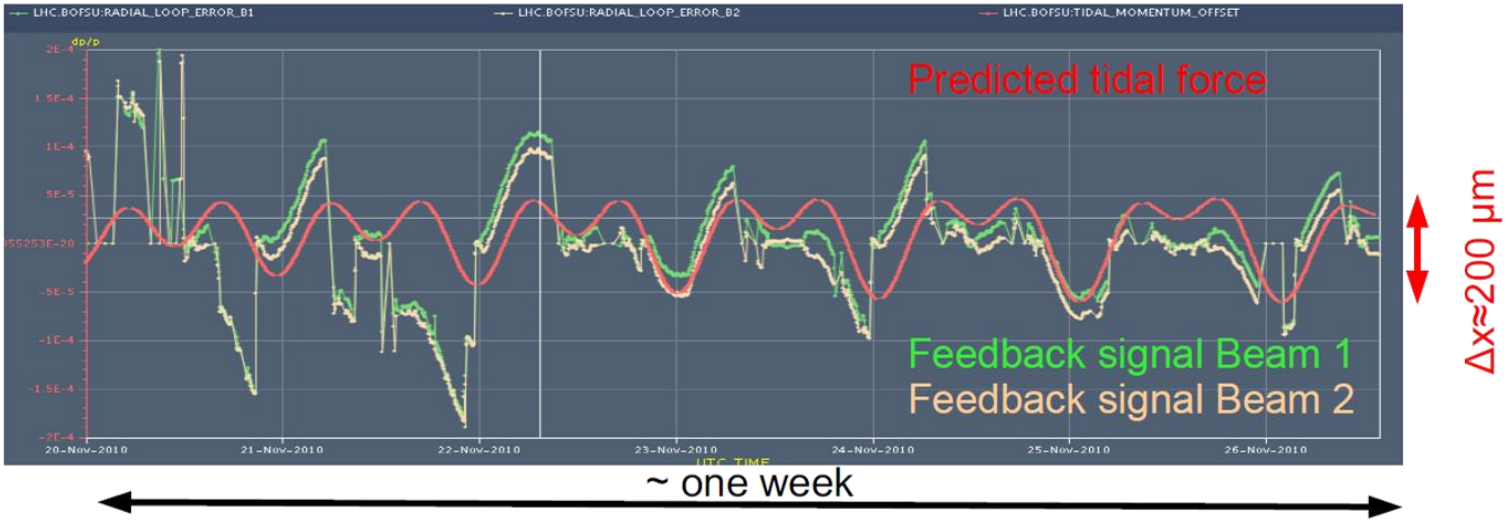
- Three real time beam parameter feedbacks Implemented; orbit-tune-chromaticity
- Different sensors, common controller, separate actuators. Real time decoupling of loops by using different bandwidth.
- Orbit feedback without major problems
- Tune feedback essential; not free of issues, compatibility of tune measurement (BBQ) and resistive damping (ADT)
- Chromaticity feedback not used (=not needed).

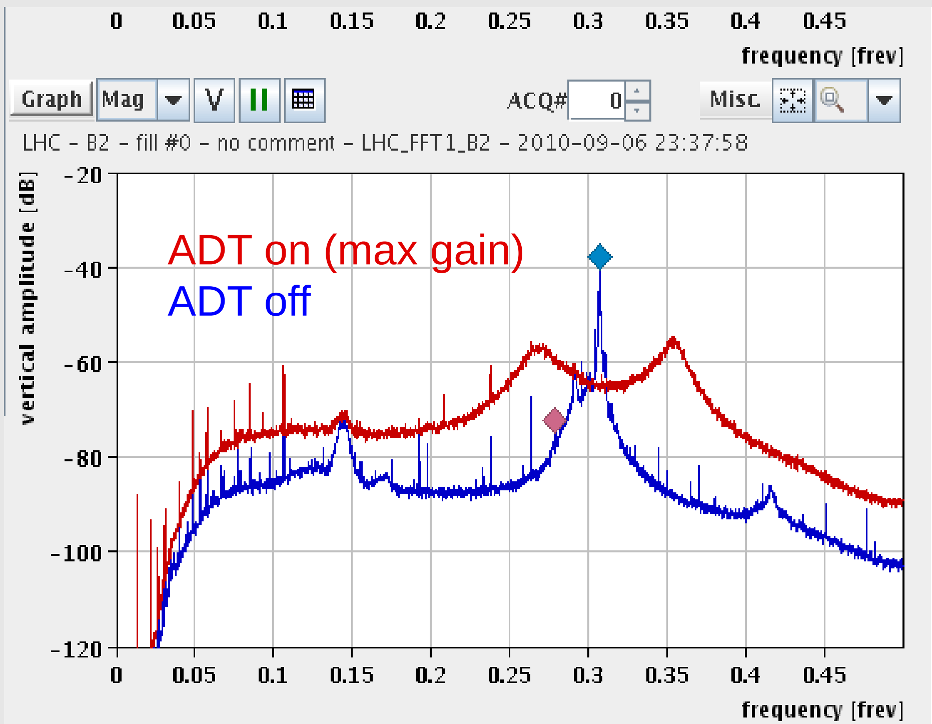
- Earth Tides dominate during Physics

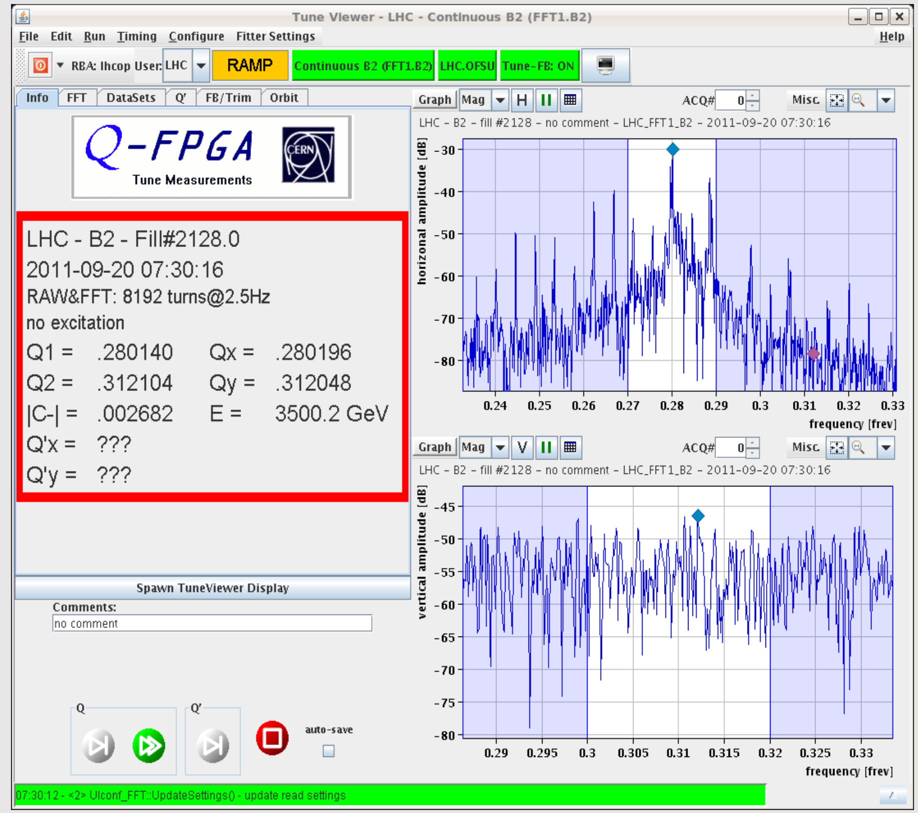




Tune measurement

- 2 different problems:





- S/N ratio = multiple peaks
  - Tune peak damped
  - BBQ vs ADT settings
- Saturation = peak disappearing
  - High bunch intensity
  - Internal limitation of the system

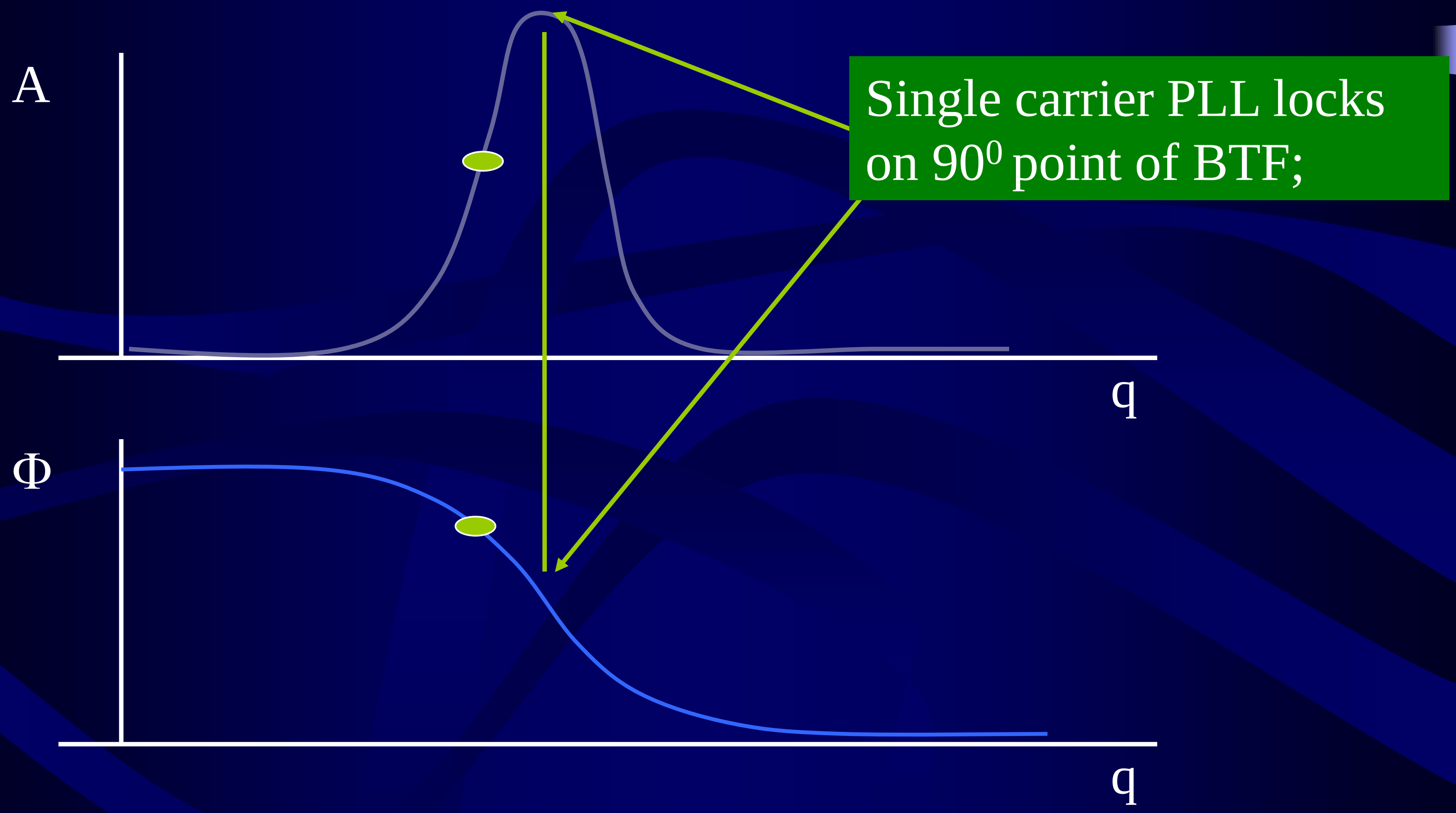
Possible solutions

- Gating of ADT and BBQ for individual bunches (planned after LS1)
- non-linear feedback response curve
- Tune measurement via PLL:

  - multi-carrier PLL (at least 2 carriers outside direct beam response (aka AC-dipole); use symmetry of phase response

  - modulate PLL excitation onto a 20 MHz rectangle (i.e. excite pi-mode oscillations; reduce gain of damper for those)

Illustration of PLL tune tracking



- **Non interceptive profile measurements**

For more information see complete talk of Adam Jeff (Liverpool) at this workshop

Prototyping ongoing in LHC and studies for CLIC

- Beam gas vertex reconstruction
- Imaging of interaction of proton beam with gas sheet target, studies also ongoing to have pencil beam type gas jet, which moves across proton beam (=new “wire” scanner)

shown in detail by Adam Jeff, this workshop

- At CERN presently only some experience for bunch length measurements of electron beams (CLIC studies)

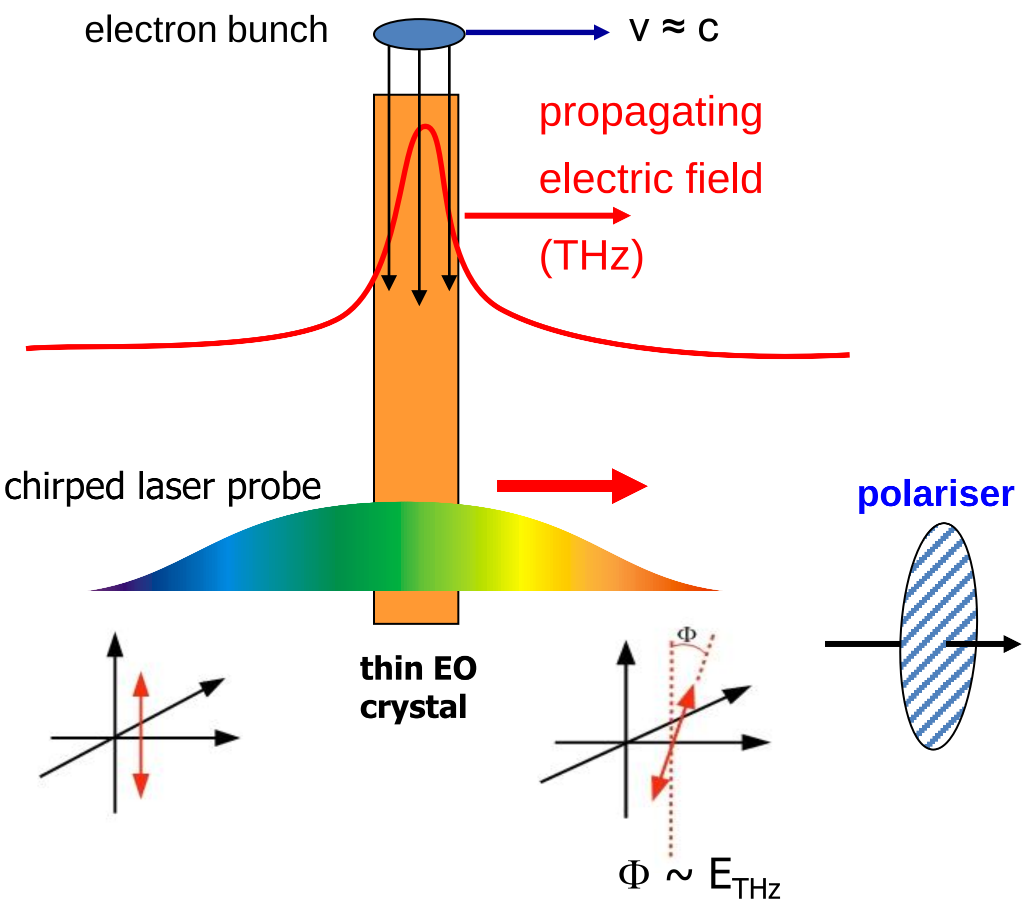
- Possible FCC applications:
  - Longitudinal Profile measurements
  - Electro Optical BPMs
    high bandwidth for:
    - instabilities monitoring
    - crab cavities diagnostics
    - separation of counter-rotating p bunches in same beam pipe

Concept of electro-optic profile diagnostic

(all-optical intra-beamline pickup of relativistic bunch Coulomb field)

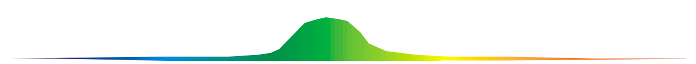
Principle: Convert Coulomb field of e-bunch into an optical intensity variation

Encode Coulomb field on to an optical probe pulse - from Ti:Sa or fibre laser



Decoding: of temporal intensity variations in single laser pulse via single-shot cross correlation in a BBO crystal

yields the temporal intensity variations in a single laser pulse



Detect polarisation rotation proportional to E or E^2, depending on set-up

Range of Electro-Optic Techniques

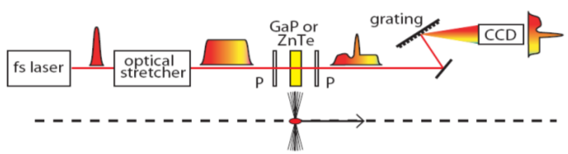
Variations in read-out of optical temporal signal

o

complexity

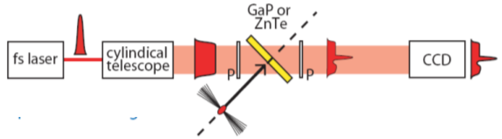
demonstrated
time resolution

Spectral Decoding



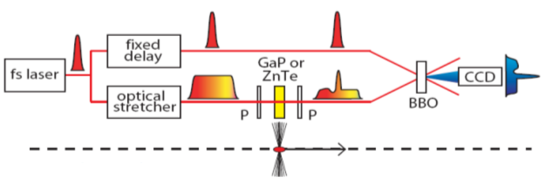
- Chirped optical input
- Spectral readout
- Use time-wavelength relationship

Spatial Encoding



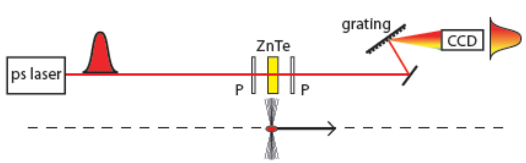
- Ultrashort optical input
- Spatial readout (EO crystal)
- Use time-space relationship

Temporal Decoding



- Long pulse + ultrashort pulse gate
- Spatial readout (cross-correlator crystal)
- Use time-space relationship

Spectral Upconversion/ EO Transposition

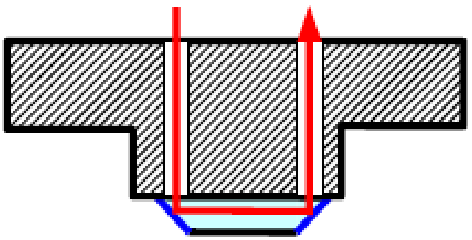


- quasi-monochomatic optical input (long pulse)
- Spectral readout
- Uses FROG-related techniques to recover bunch info

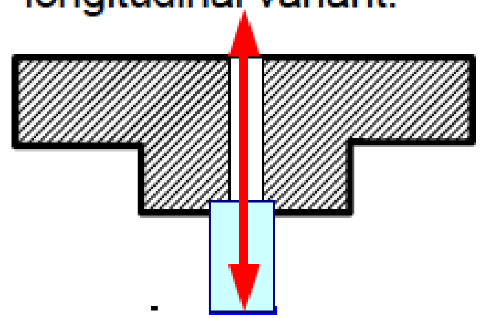
Schematic of EO-BPM

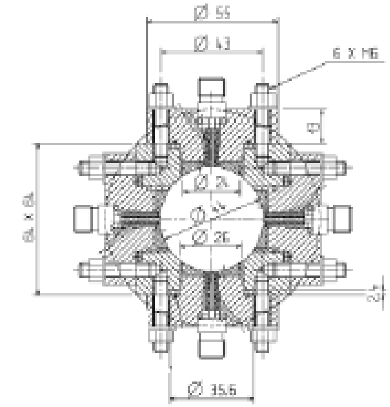
- All-Optical-BPM layout scheme, re-use conceptually LHC BPM design:
  - Keep the same body, keep external button form-factor

transverse variant:

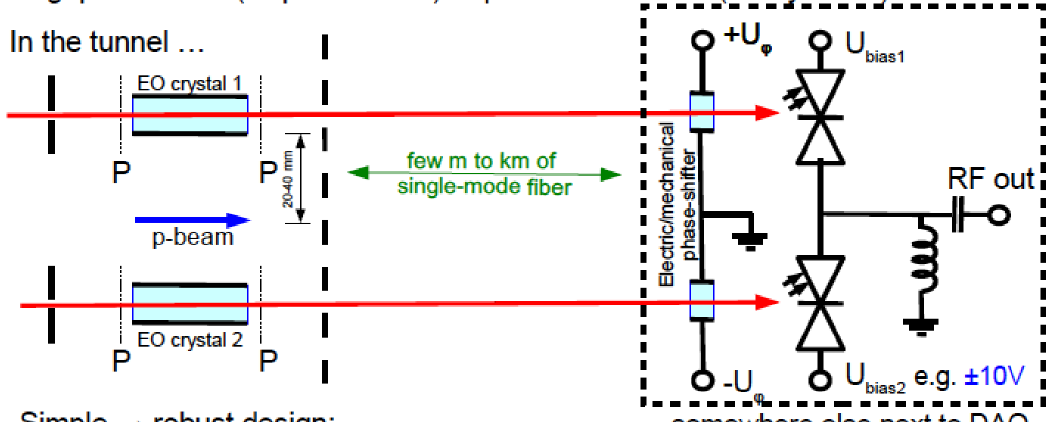


longitudinal variant:



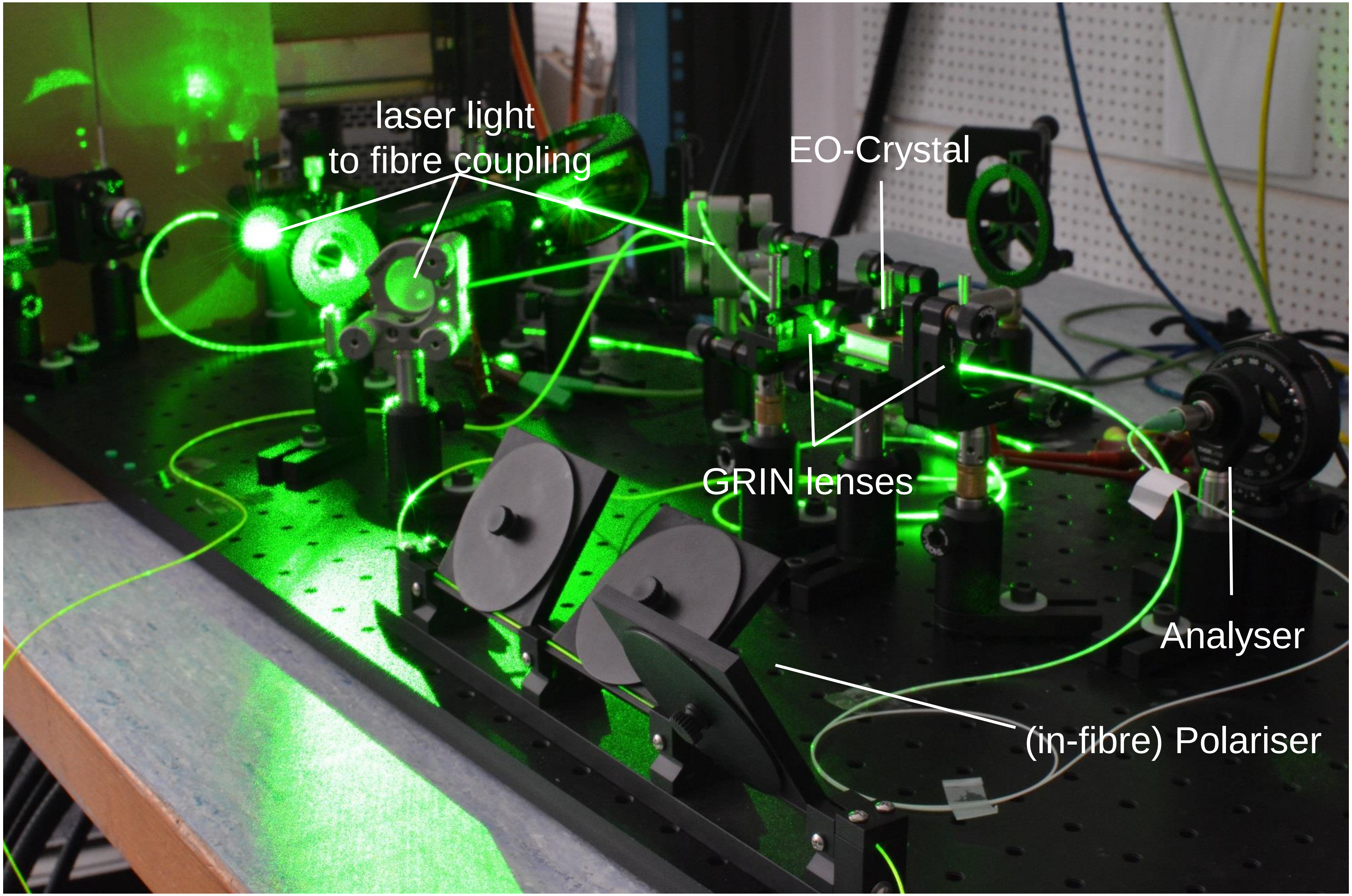


- E.g. polarisation (→ pockels cell) or phase retardation (Fabry-Perot)



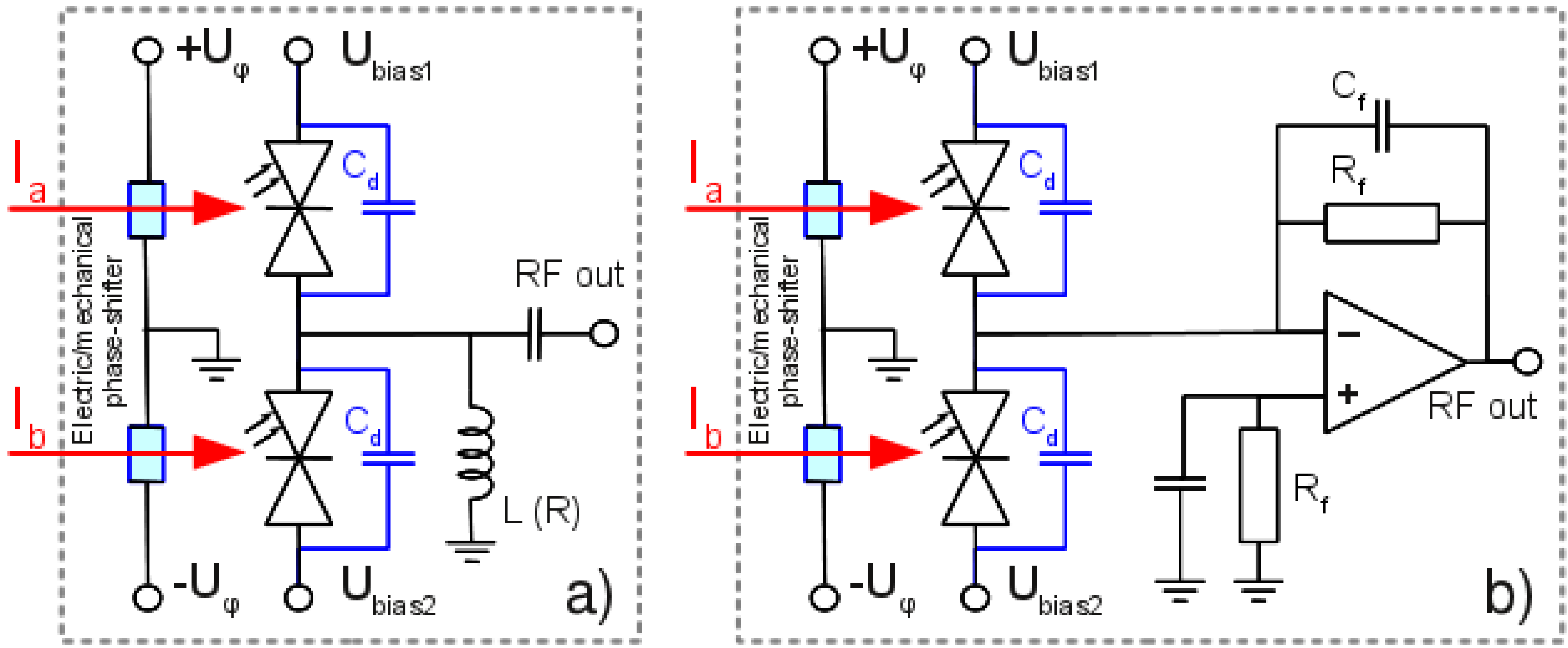
- Simple → robust design:

All optical BPM laser lab set-up



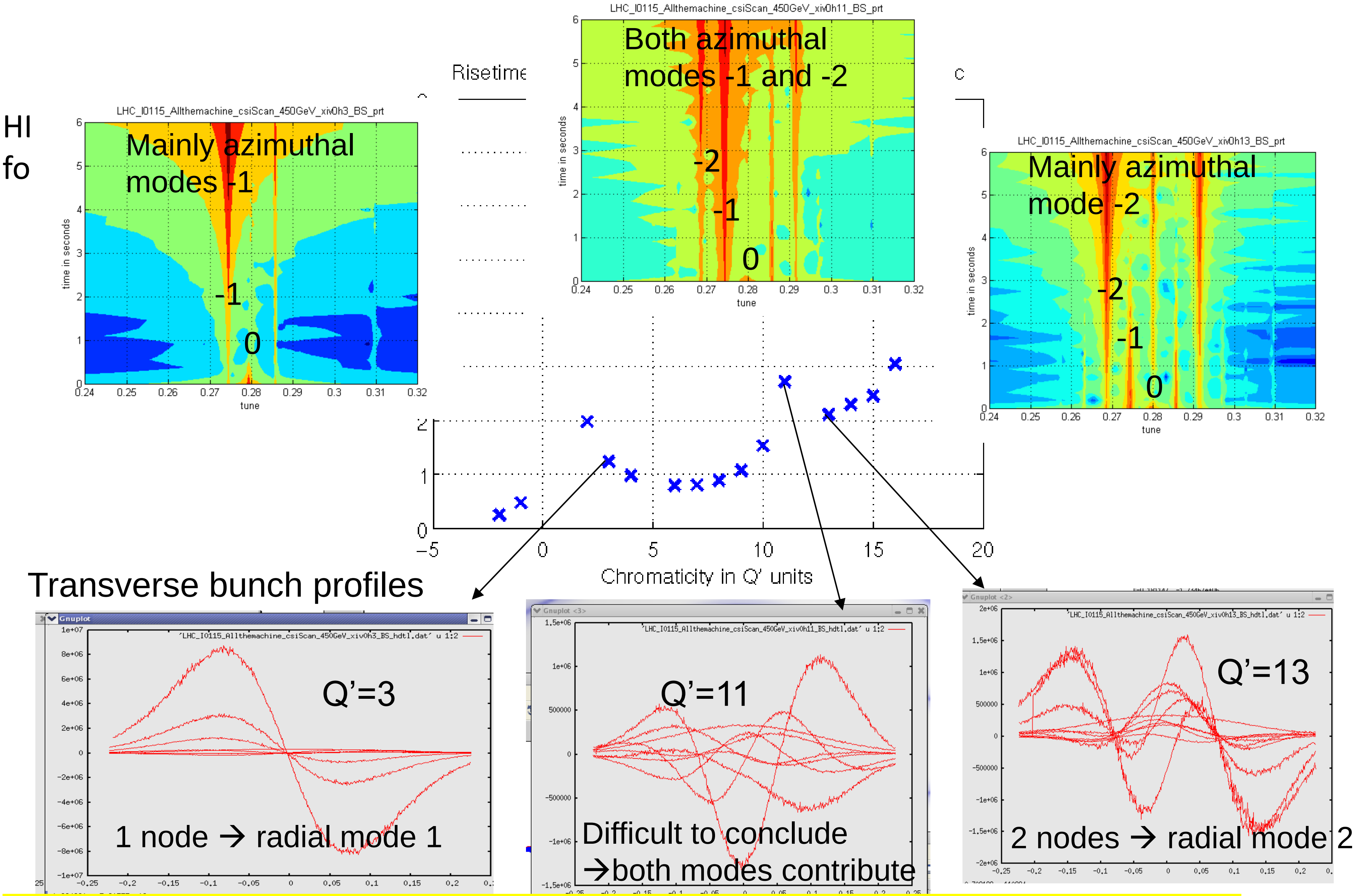
Possible Detection scheme

- Wide-Band Improvement on RF Hybrid Junction: (MSM)



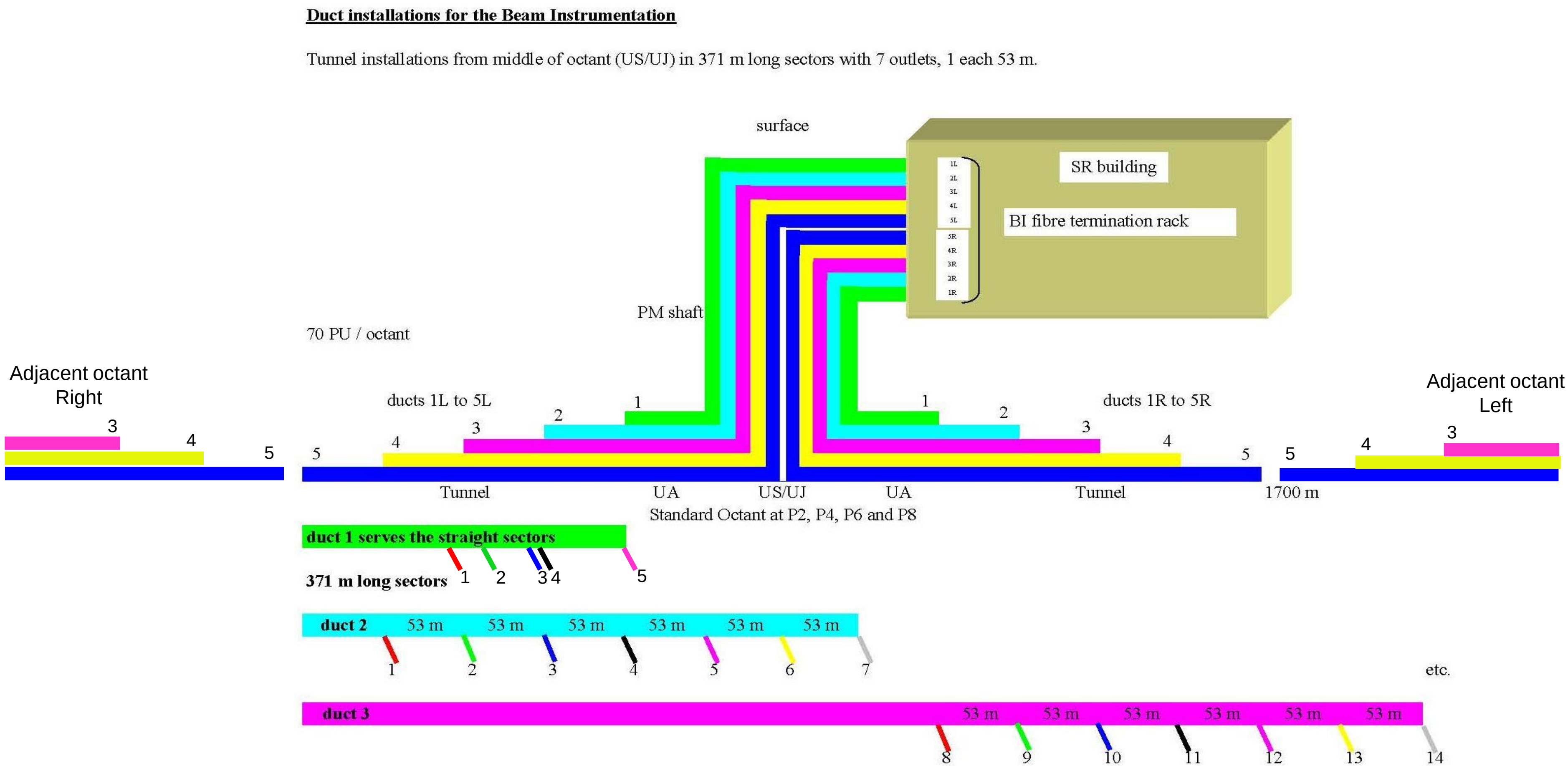
- Sum Σ and Difference Δ signals are computed in electro-optical domain
  - Aim at 12+ GHz Bandwidth

Example of Headtail instabilities with various chromaticities at injection:

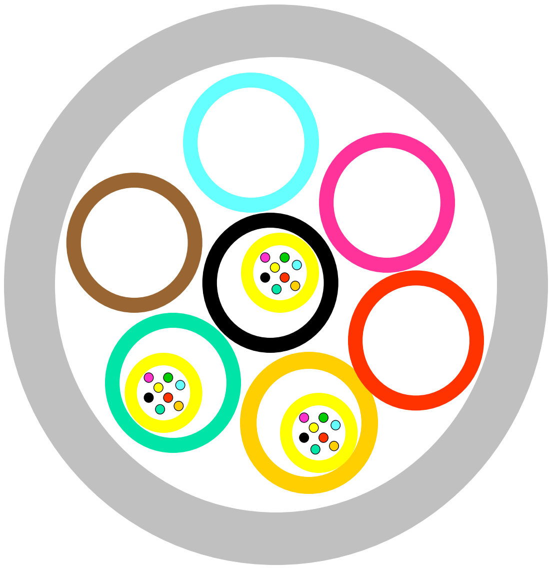


→ It is important to have both intrabunch time domain and bunch by bunch spectra to conclude

Beam instrumentation lay-out



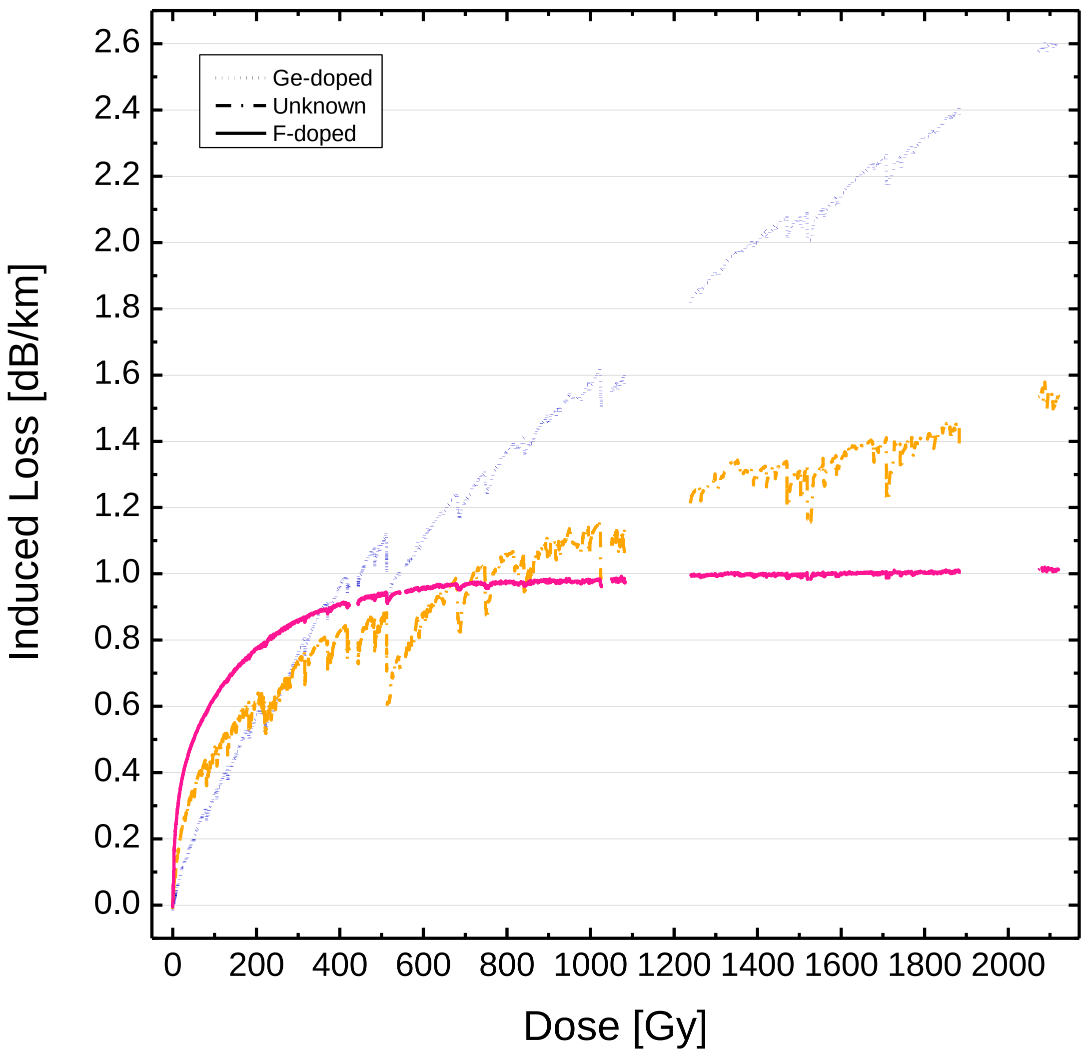
Optical cabling with micro ducts



high precision 25mm
polyamide tube

- Blow 7mm micro ducts
- Blow micro optical cables
- Modular and flexible
- Easy to replace cables

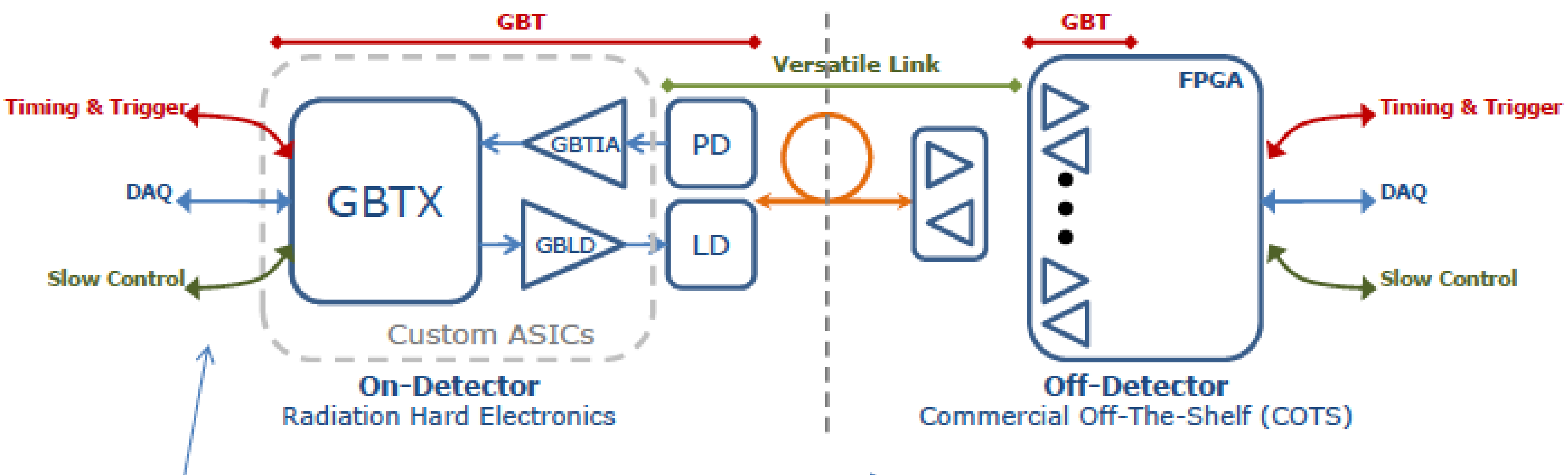
Radiation Resistant Optical Fibers
Irradiation in High Energy Physics Radiation field



HEP Link Architecture

High radiation doses ← → No or small radiation doses

LHC: up to 100 Mrad (10^{14} 1MeV n/cm^2)
HL – LHC: up to 1 Grad (10^{16} 1MeV n/cm^2)



Electrical links to the frontend modules. Lengths: *cm* to few *m*

Short distance optical links: 100 to 300 m

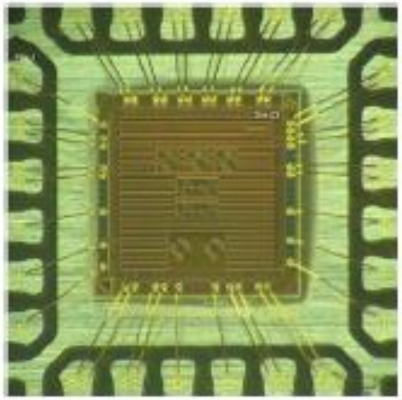
GBTX Chip Set

- The GBT chipset comprises:
  - GBTIA:
    - 4.8 Gb/s Transimpedance Amplifier
    - Amplifies the weak photo-current detected by the PIN diode
  - GBLD:
    - 4.8 Gb/s Laser Driver
    - Modulates laser current to achieve electro-optical conversion
  - GBTX:
    - 4.8 Gb/s Transceiver
    - Manages the communications between the counting room and the frontend modules
  - GBT – SCA
    - Slow Control Adapter
    - Experiment control and environment monitoring

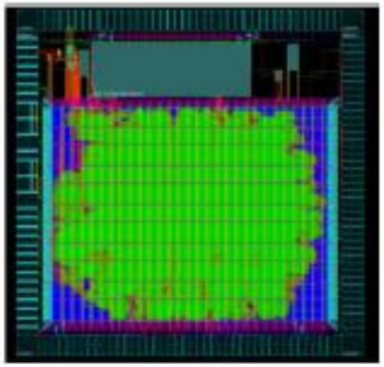
- GBTIA, GBLD and GBTX:
  - Have been successfully prototyped
  - Radiation tolerance proved to > 100 Mrad
- GBT – SCA:
  - currently being prototyped in the GBT chipset engineering run

GBTIA

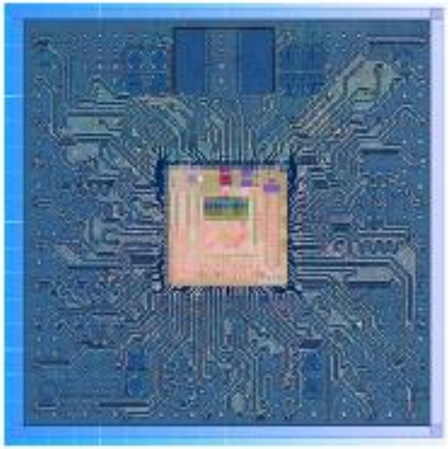
GBLD



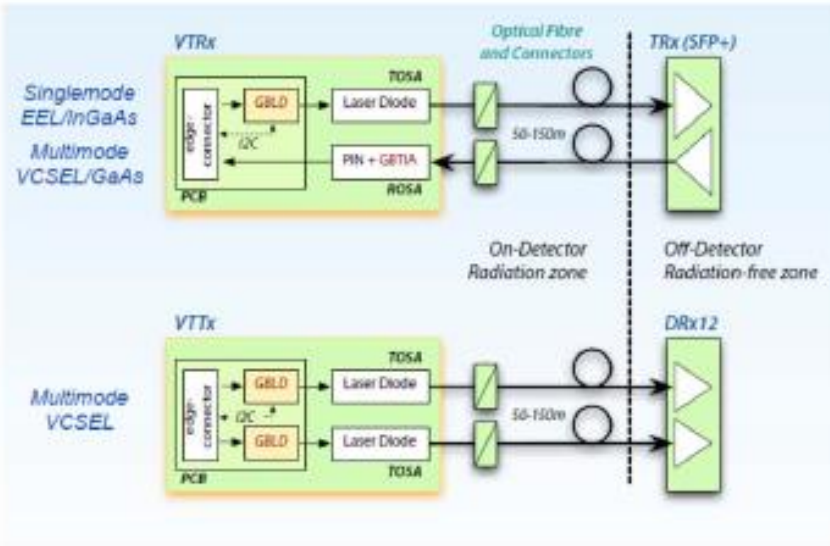
GBT – SCA

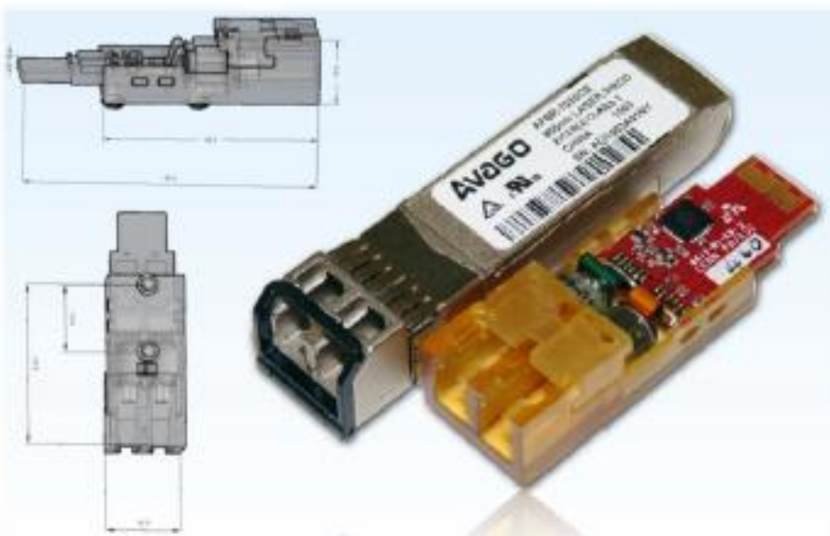


GBTX



Versatile Link





- Small Form Factor (SFP) Transceiver:
  - Data rate: 5 Gb/s
  - Wave length:
    - 850 nm, Multimode
    - 1310 nm, Single mode
  - Function:
    - Point-to-point
    - Point-to-multipoint
- Development of pluggable modules.
  - Two versions:
    - Transceiver (**VTRx**)
    - Double transmitter (**VTTx**)
  - Compatible with the commercial counterparts
  - LC connectors
  - Length reduced to 43.5 mm
  - Contains:
    - The GBTIA & GBLD
    - Radiation qualified PIN diodes and Lasers
  - Radiation tolerant:
    - 50 Mrad
    - 5×10^{14} n/cm^2
  - Prototyping phase concluded:
    - Prototypes available
    - Production planed for 2015
    - Target LS2 upgrades

Why will the FCC instrumentation be a success?

1) "Never make an economy on beam instrumentation",
very important quote still to come from M.Benedikt et al....

2) Direct experience from LHC; relevant for all instruments.

3) Early, well documented specifications
BE-BI will start this year with a small WG under guidance of J.J.Gras

4) New collaborations to enlarge R&D in the following domains:

- Beam parameter feedbacks
- Non invasive profile measurements
- Electro-optical devices for longitudinal diagnostics& instability monitoring
- Radiation tolerant electronics & communication platforms