Optical Data Links in CMS ECAL

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LHC and Future Experiments

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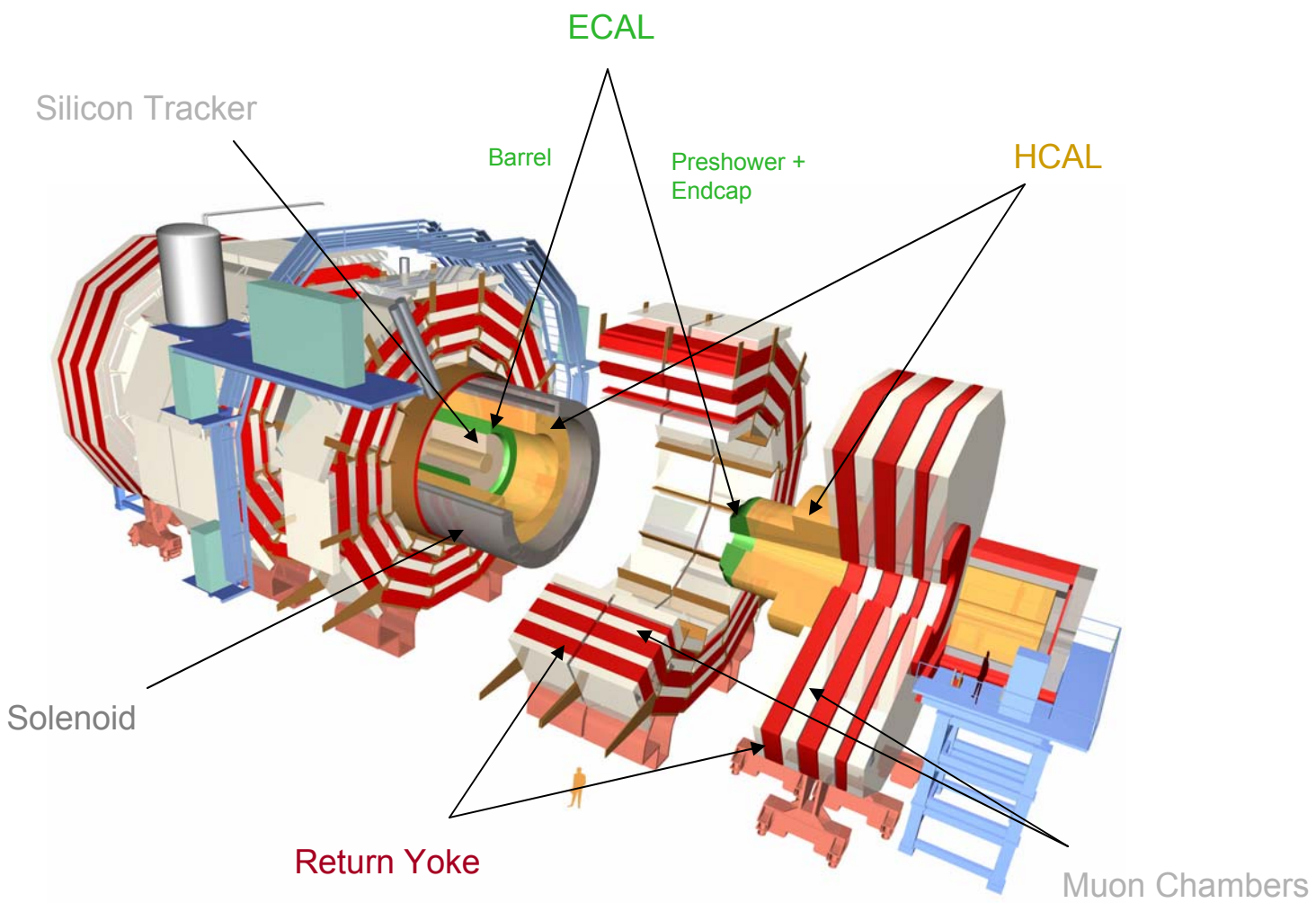
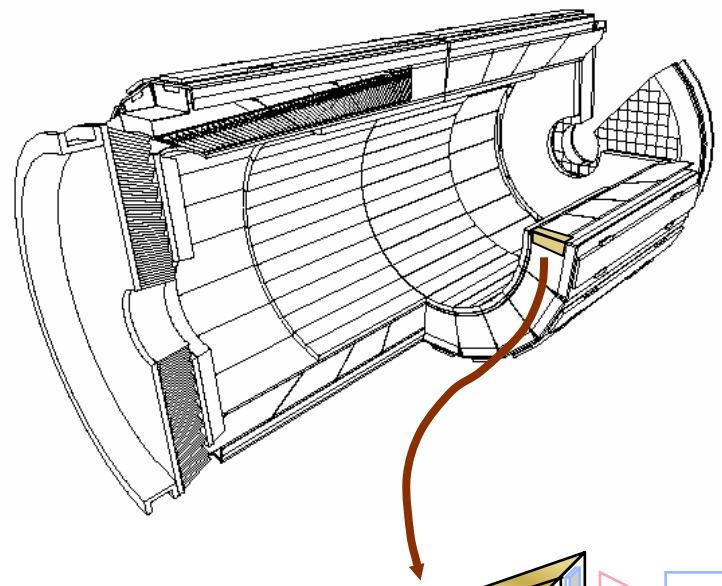
Outline

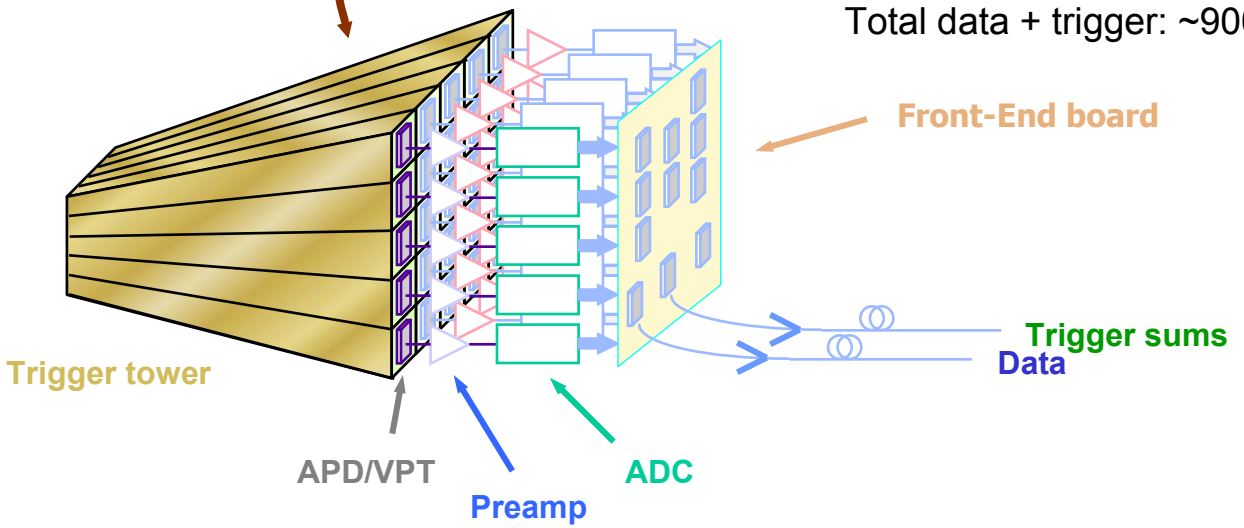
- CMS ECAL architecture and needs
- ECAL Data Link system description
- Data Link components
- Data Link system performance

The CMS Detector



CMS ECAL Front-End architecture





ECAL has ~77,000 lead tungstate crystals arranged in trigger towers of 25.

Front-End electronics of each trigger tower send the data off-detector via the optical links.

This architecture requires links of ≥600 Mb/s with modularities of:

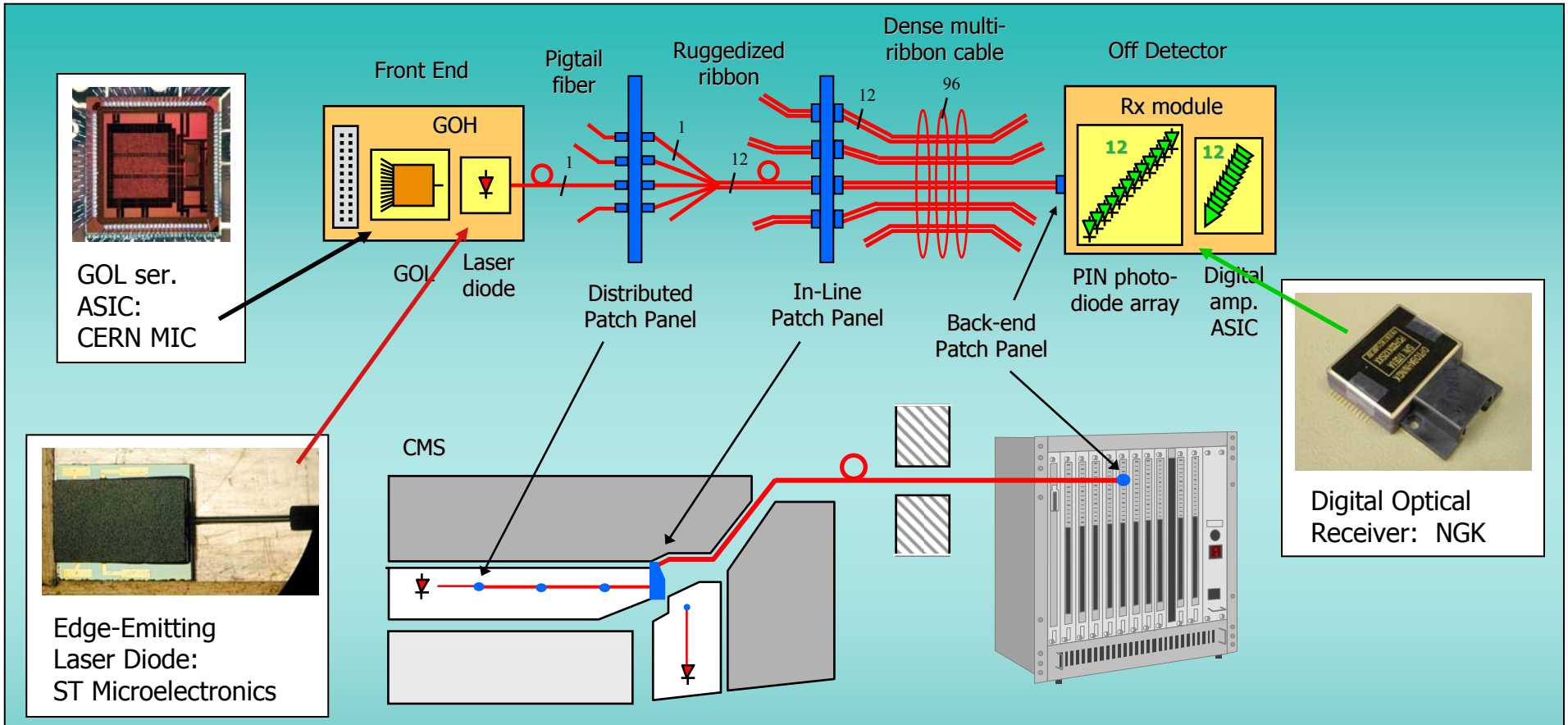
for Data: 1 link / trigger tower

for Trigger: 1 link / trigger tower (barrel)

5 links / trigger tower (endcap)

Total data + trigger: ~9000 links

CMS ECAL Link System Diagram



- **GOL Opto-Hybrid (GOH):** ECAL designs, prototypes, qualifies, defines manufacturing specifications, procures the manufacture, tests samples during production.
- **12-channel NGK Rx:** Off-the-shelf component: ECAL qualifies, procures, tests samples during production.
- **Fiber, connectors and adaptors:** ECAL uses solutions already developed and procured for CMS Tracker.

System Requirements and Specifications

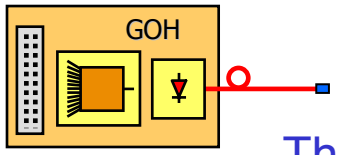
Some general specifications:

- Receives power, clock and control and 16-bit parallel digital signals from FE board at 40 MHz (640 Mb/s data)
- Encode data using either G-Link or 8b/10b protocol
- Provide encoded serial data at Rx output at 800 Mb/s in sufficiently clean form in terms of jitter and quality of eye diagram such that data is not lost at the deserializer

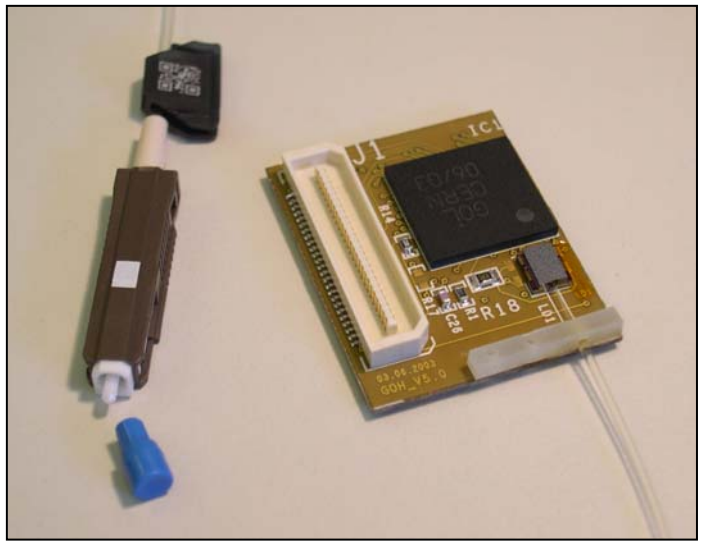
Requirements and specifications in numbers:

Link System Requirement	Minimum Link Specification	Actual Link Specification
Clean Rx eye diagram	HIPPI-6400 mask standard	same
Low jitter (GOH to Rx)	$\lesssim$ 100 ps	< 50 ps
Low Bit Error Rate	$\lesssim 10^{-15}$	$< 10^{-16}$ (est.); $< 10^{-13}$ (meas.)
GOH temperature	-10°C to ~+40°C (FE card)	-20°C to +60°C (FE card)
Rx module temperature	+20°C to +50°C (case)	+18°C to +80°C (case)
Magnetic field	4 T	same
Hadronic fluence	$3\times10^{14}/cm^2$	same
Gamma dose	1.5×10^5 Gy	same
Operating life	10 years, inaccessible	same

Components: Transmitter (GOH) - Overview



The transmitter of the Data Link is the GOH (GOL Opto-Hybrid).



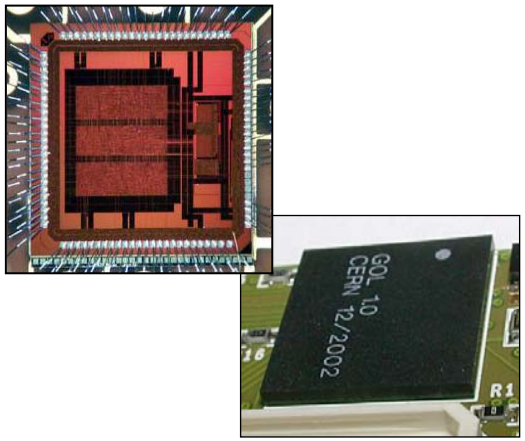
Some specifications of the GOH:

- Receives power, clock and control and 16-bit parallel digital input at 40 MHz from FE board. *(see talk of M. Gastal)*
- Transmits serialized optical output via single-mode pigtail fiber at 1310 nm, 800 Mb/s (640 Mb/s + overhead), using either G-Link or 8b/10b protocol.
- Output signal power ~-6dBm, depending on bias levels chosen. (0 dBm = 1 mW)

Components: Transmitter (GOH) - GOL

The principle components of the GOH are the GOL and the Laser Diode:

Some characteristics and specifications of the GOL ASIC:

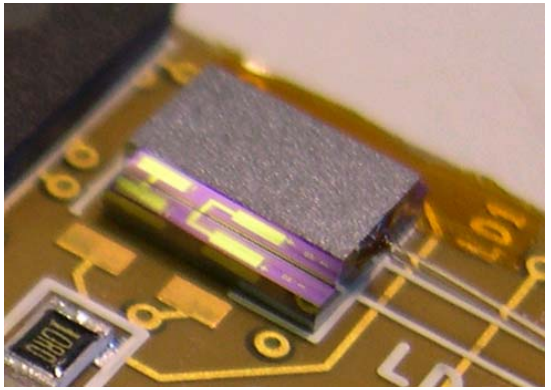


- Designed by CERN Microelectronics group, die produced by IBM, fpBGA packaging by Atlantic.
- Implemented in 0.25 µm CMOS technology employing radiation-tolerant layout practices.
- Designed to prevent or recover from Single Event Upsets with minimal impact on data.
- Capable of two speeds, 0.8 and 1.6 Gb/s. CMS ECAL uses 0.8 Gb/s.
- Capable of transmitting in two protocols (G-Link and 8b/10b). ECAL uses 8b/10b for data and G-Link for trigger primitives (different choices made by designers of the two readout cards).

Components: Transmitter (GOH) - Laser

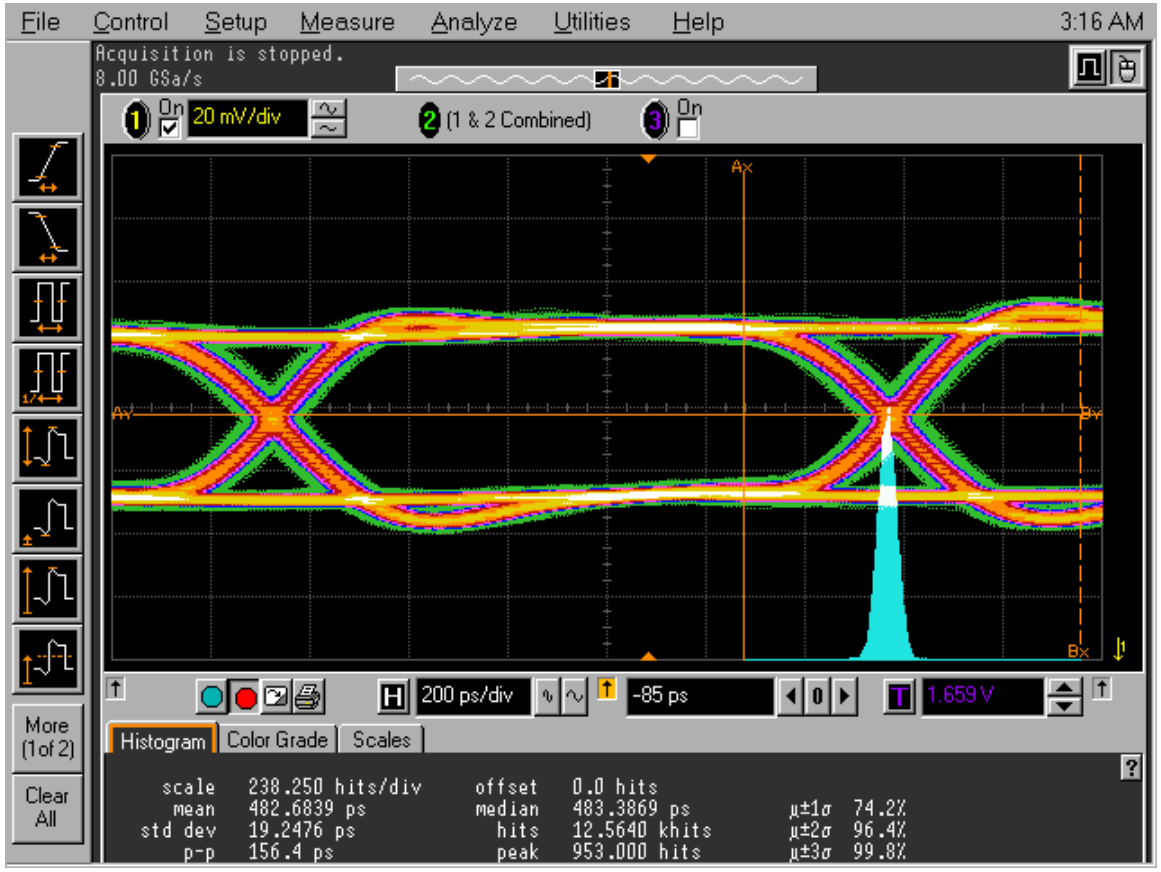
Some characteristics and specifications of the Laser Diode:

- Custom-designed for CMS Tracker (linear response for their analog link) but appropriate for use in ECAL:
  - Rise time consistent with use for 800 Mb/s digital operation
  - Output wavelength 1310 nm (suitable for single-mode fiber)
  - Output power up to 0 dBm.
- Laser die manufactured by Mitsubishi.
- Die wafer lots radiation-qualified (gammas and neutrons) before assembly into laser diodes.
- Laser-pill housing and pigtail-fiber assembled by ST Microelectronics.
- Finished laser diode is glued and wire-bonded on the GOH.



Components: Transmitter (GOH) - Eye

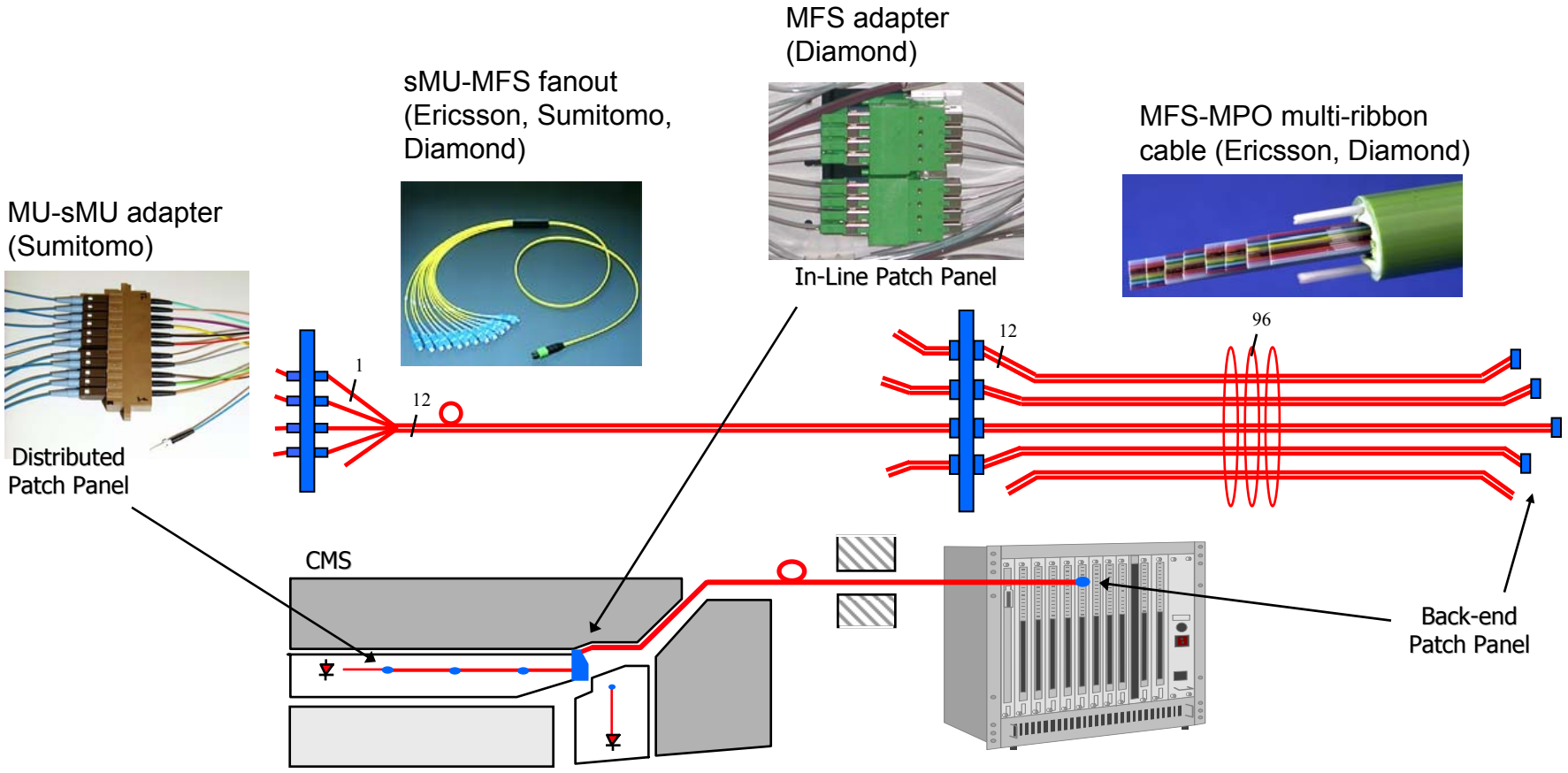
Driven by GOH evaluation board (a modified GOL eval board), the GOH gives a clean eye diagram at 800 Mb/s:



Components: Fiber and Connectors

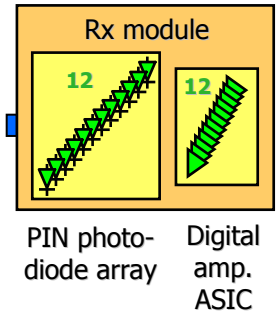
Fiber and connectors are adopted from CMS Tracker system. All specifications consistent with use in ECAL as well (e.g. Single-Mode, temperature limits, rad-hardness, attenuation, safety).

Sub-components of the fiber system:



Components: Receiver

The receiver of the Data Link is the 12-channel digital Rx manufactured by NGK (POR10M12SFP).



Some characteristics and specifications:

- Accepts single-mode fiber ribbon
- Operating wavelength 1310 nm
- Speed: up to 1.25 Gb/s
- Sensitivity: -18 dBm (typically <19 dBm)
- Saturation: -5 dBm
- Jitter: < 42 ps
- Temperature: 0°C to 80°C

Though a part of the data link system, the Rx is integrated into the OD cards (DCC, TCC, Preshower test bench, …). *(See talks of J.C. Da Silva, P. Paganini, P. Vichoudis)*

Performance and System Tests - Overview

Three types of System Tests have been performed:

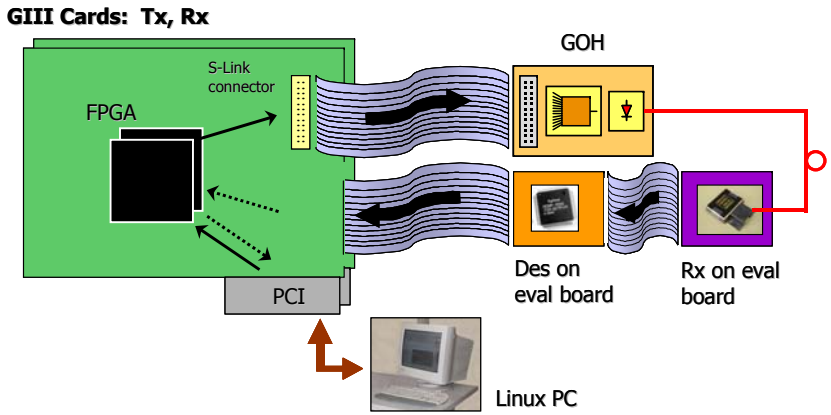
1. Using a Bit Error Rate Test (BERT) system to count BER by comparing input and output data under ideal conditions.

2. Counting Word Error Rate (WER) flagged by the deserializer vs. level of a stress applied to the system.

3. Testing effects of temperature, jitter, irradiation, etc., in these setups.

BERT System Tests

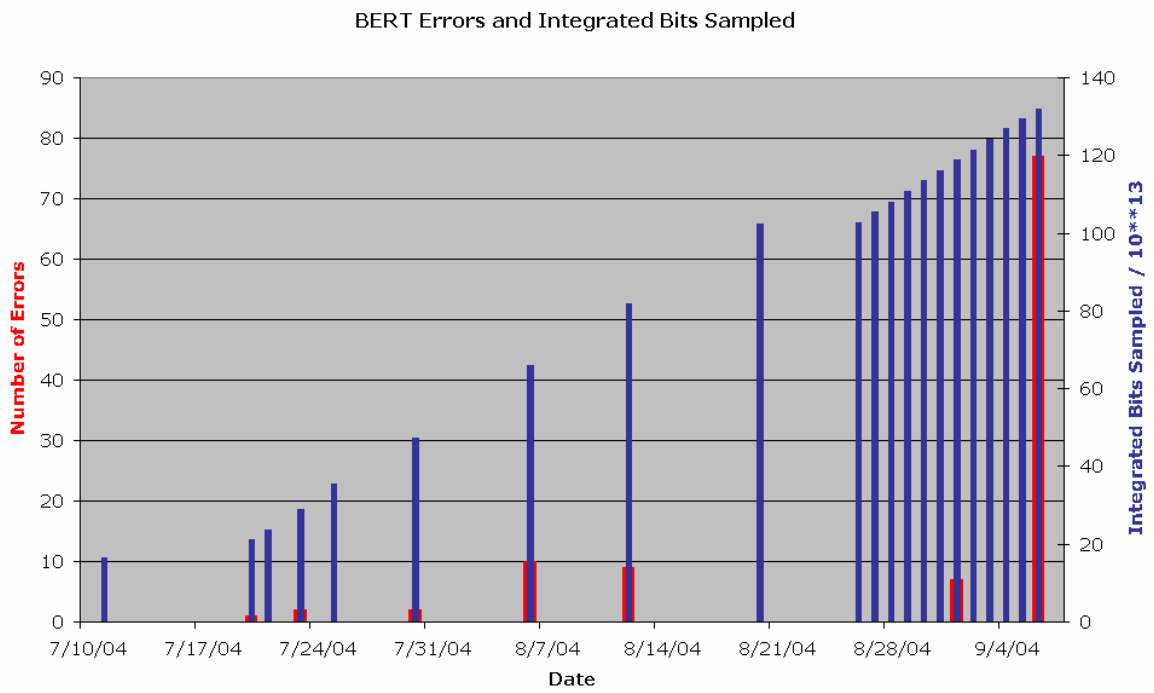
The Bit Error Rate Test system:



- Based on GIII PCI cards developed by CMS DAQ group, all components on evaluation boards, controlled by PC.
- FPGA's on Tx and Rx cards generate data input to the GOH, compare it to deserializer output. Comparison is bit-by-bit, independent of serializer protocol.
- System speed is ~300 Mb/s but perfect stability is difficult to achieve. Use of resources on PC causes synchronization problems and generates "errors".
  What is tested is as much (or more) the reliability of the BERT as it is the reliability of the data link system.

BER Measurements

- Running the BERT over two months allowed to sample 1.3×10^{15} bits (and collect 124 errors). Errors came in bursts, some traceable to resource usage on the PC (network or keyboard activity).



- Optimistic interpretation (consider each burst of errors as having at most one real data link error as its source): 12 errors out of 1.3×10^{15} bits => BER < 10^{-14}

- Pessimistic interpretation (consider all errors as data link errors): 124 errors out of 1.3×10^{15} bits => BER < 10^{-13}

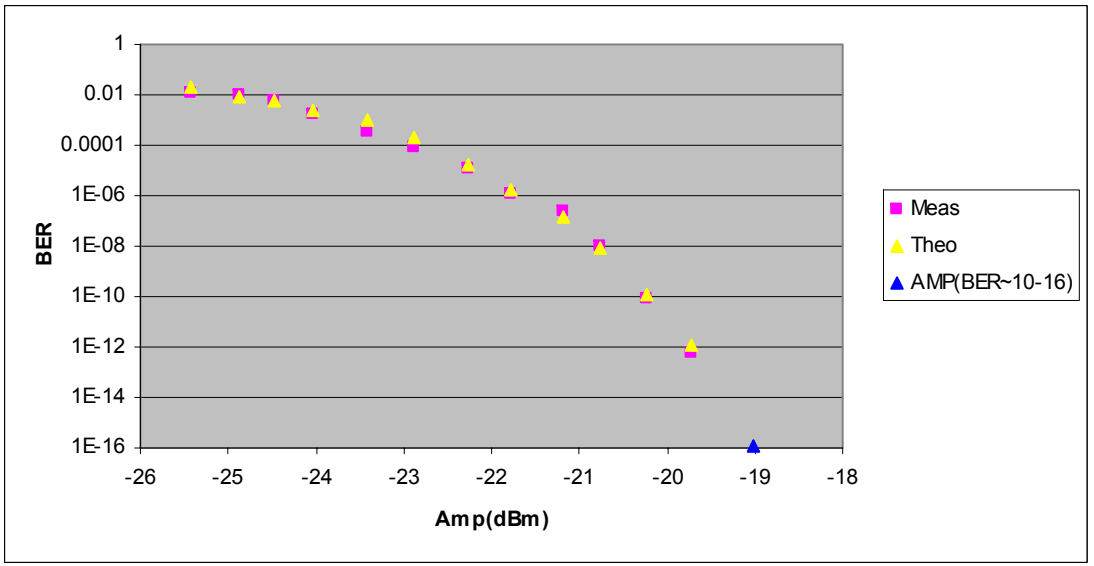
- More work to be done on the BERT system.

Bit Error Rate Estimation

- The BERT System at present can only give an upper limit on the error rate. It is useful to have another measure. A simple, standard calculation allows one to estimate the BER from the signal-to-noise or Q of the eye diagram:

$$BER_{TH} = \frac{1}{2}[erfc(\frac{Q}{2\sqrt{2}})]$$

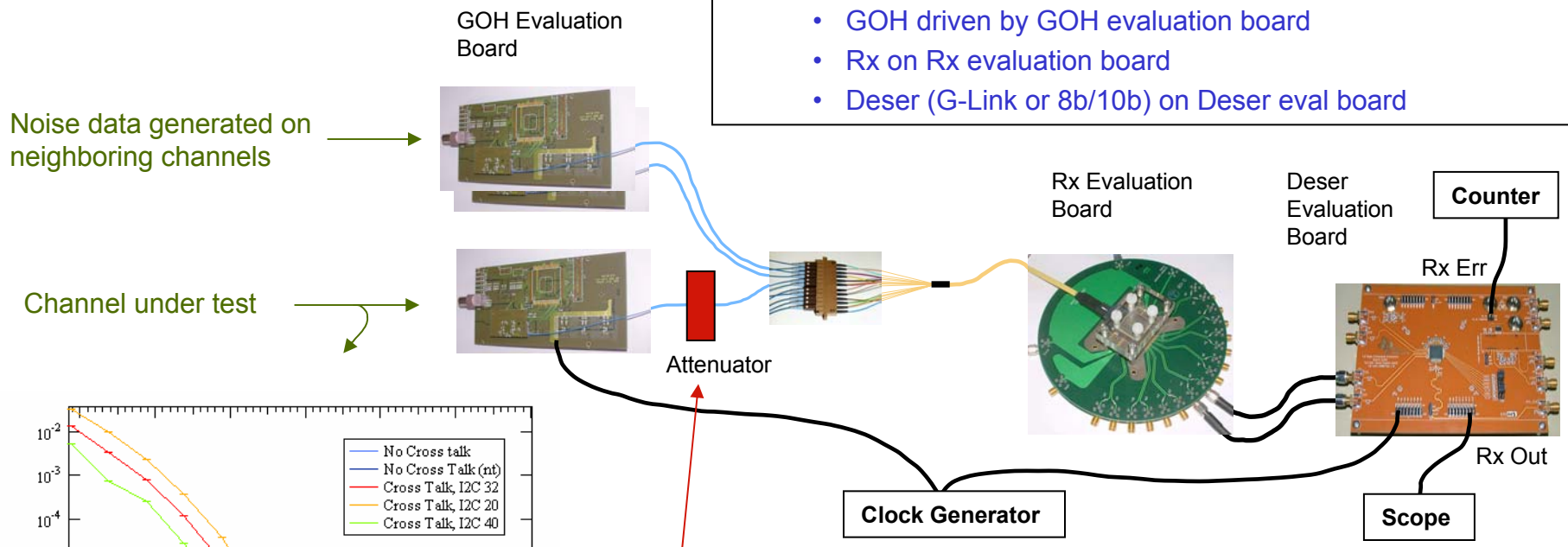
- An estimated BER may thus be plotted for GOH eye diagrams at various optical power levels:

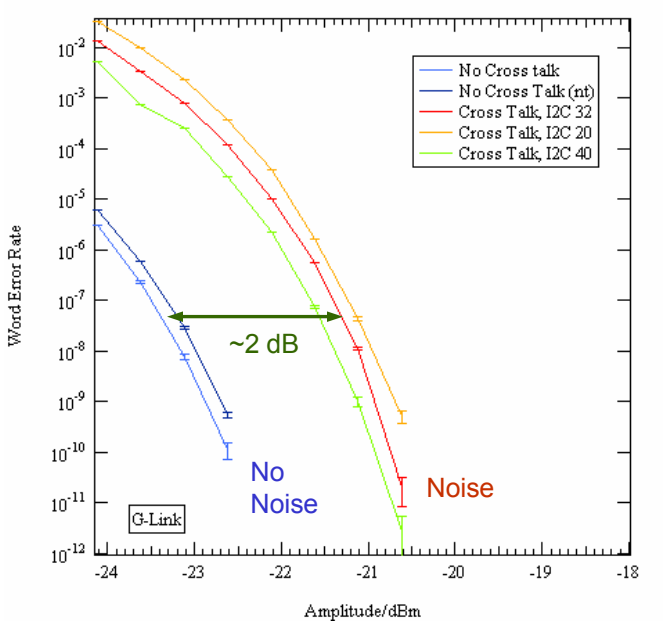


- From this, BER < 10^{-16} is expected at –19 dBm (Rx sensitivity threshold).

Word Error Rate System Tests

- Word Error Rate tests involve:
  - GOH driven by GOH evaluation board
  - Rx on Rx evaluation board
  - Deser (G-Link or 8b/10b) on Deser eval board



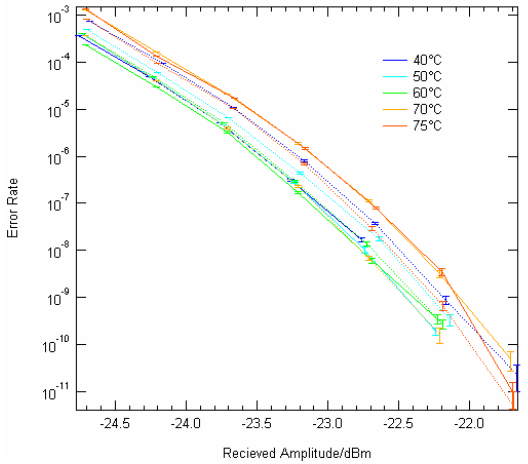


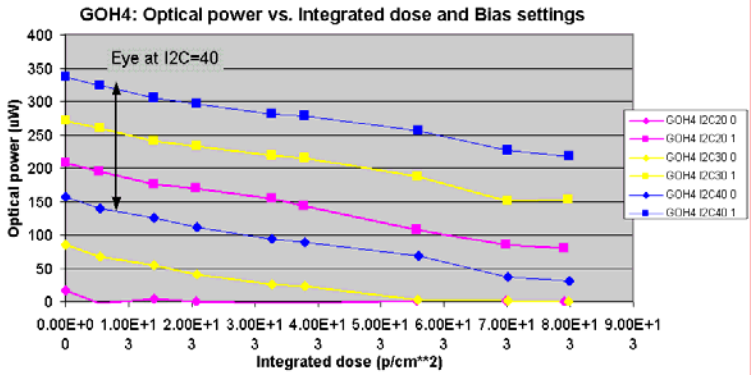
- Deserializer WER is counted as a function of additional inserted optical attenuation. In this particular setup, what is studied is effect of crosstalk in the Rx.
- Conclusions:
  - Rx is well within sensitivity specification (-18 dBm)
  - Crosstalk costs about 2 dB of the optical power budget

Other System Tests

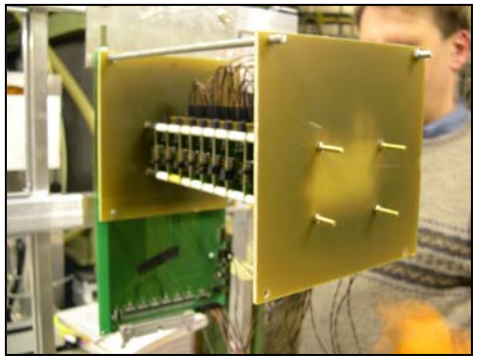
Other System Tests performed include:

- Effect of GOH temperature (to 60°C) and Rx temperature (to 80°C): No significant effect on WER vs. optical power plot.
- Jitter measurement at various stages of the link: GOH < 20 ps; GOH to Rx < 50 ps (well within specifications).
- Integration with Front End Electronics during 2003 and 2004 ECAL testbeam programs: no loss or corruption of data observed.
- GOH irradiation:
  - 10 GOH in operation irradiated with proton doses up to $8 * 10^{13}$ p/cm^2.
  - BER of one GOH monitored: Zero to 5 (SEU) errors observed depending on how results are interpreted.





- Eye diagrams of other nine GOH monitored: evolution of laser diode power output vs. input current was as expected.
- No GOH died.



Optical Power Budget

Launched from GOH	**-6 dBm**
Laser diode efficiency	1 dB
Fiber and connector interfaces	3 dB
Rx crosstalk	2 dB
Effective signal power at Rx	**-12 dBm**
Rx sensitivity limit	**-18 dBm***

*Rx sensitivity spec is “-19 dBm typical, -18 dBm minimum”.
We have so far observed better than –20 dBm.

=> At least 6 dB of margin in the power budget

Conclusions

- The Optical Data Link which has been developed for the CMS ECAL meets the various requirements:
  - Serialization, encoding and transport of data
  - Data rate of 800 Mb/s
  - Tolerant to environment (temperature, irradiation, etc.)
  - Low error rate and low jitter
  - Ample optical power budget margin