



TWEPP Meeting in Naxos September 2008

Some Lessons from the LHC Projects

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Some Lessons from the LHC Projects

- The LHC Experiments have been Successfully Commissioned
- It is now Useful to Reflect on the Progress we have made over the Construction and Commissioning of these Complex Projects and to Ask how Best to Prepare for the SLHC ?
- This Presentation will Review :
 - Access to Microelectronics Technology
 - Microelectronics and Tracking Detectors
 - Opto-electronics Systems
 - Power Systems, Grounding and Shielding
 - Off Detector Systems



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In the Beginning (1)

- In the Mid 1980s the European Electrical Engineering Communities were beginning to teach the design of Microelectronics for MSc Courses
- This required access to Design Tools, Lithography, Fabrication and Circuit Evaluation ($\sim 5\mu$ Technology)
- Facilities to support the need for an increased number of trained Engineers were established throughout Europe
- ~~One such Facility was an EU project called 'Euro-Chip'~~



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In the Beginning (2)

- **In the Mid 1980s Bernard Hyams and Terry Walker had demonstrated the readout of a Silicon Strip Detector using an NMOS Integrated Circuit. Good Performance, but Large Power Dissipation.**
- **The Solution was to use the emerging CMOS Technologies**
- **So Particle Physics began to use Microelectronics**
- **The Big Question was how could this be Done and What Facilities would be Required ?**



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In the Beginning (3)

- A Review of the Requirements for Electronics Facilities at CERN (Chaired by Chris Fabjan) recognized the growing Importance of Microelectronics to the Future of Particle Physics and Recommended the Establishment of a Properly Resourced Microelectronics Group at CERN
- Properly Resourced included having a Critical Mass of Trained Engineers, the Correct Balance of Design Tools, Technician Support, and Testing Facilities
- **The CERN Group should act as a Centre for Particle**



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In the Beginning (4)

- Which Design Tools should the Particle Physics Community invest in ?
- At RAL we had bought one License for one of a New Generation of Design Tools from 'SDA' (Later 'Cadence')
- It was very good, but was very Expensive even with an Educational Discount (for the MSc Courses).
- RAL and CERN evaluated the software and agreed that we should use it for future Particle Physics Designs
- **How could we obtain Affordable Access to the Design**



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In the Beginning (5)

- The Mandate of 'Euro-Chip' was to Train Electronics Engineers in Microelectronics.
- The EU Commission accepted that most of the Training would take place in University Departments, but also accepted that 'Not for Profit' Research Institutes had an important role in this Training Process
- Hence it became possible for all European Universities and Particle Physics Institutions to gain access to the best available Design Tools through 'Euro-Chip' &

Europractice



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In the Beginning (6)

- Today RAL supports the access to the best Microelectronics Tools to ~ 650 European Universities and ~ 100 Research Institutions within the Europractice Programme.
- In October 1990, at the Aachen Workshop to discuss the design of Future LHC Experiments there were two significant additional meetings:
 - **The First Meeting of the Recently Establish DRDC**
 - **A Meeting to Establish the 'Microelectronics User**



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In the Beginning (7)

- **The Microelectronics User Group became the Forum to discuss the best Design Techniques, the 'State of the Art' in Microelectronics Technologies and Testing Techniques.**
- **The use of Common Design Tools was important in the Transfer of Experiences and in Collaborative designs**
- **Once Design had Started it was Important to Establish an Annual Workshop to Coordinate the Work of the Community and Encourage the Use of Common**

Solutions

Peter Sharp CERN

CMS Tracker 2008 9



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Lesson One from the LHC

- LHC Experiments would not have been possible without Access to Microelectronics Technology.
- Obtaining Affordable Access to the Technology and Tools Requires Continued Coordination and Collaboration
- Future Particle Physics Experiments will Continue to Require Access to these Technologies and this will Require Continued Investment in both Engineers, Tools and Facilities

• **Without these Investments there will be No Future**



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Microelectronics and Silicon Detectors (1)

- At the LEP Experiments, all Silicon Micro-Vertex Detectors used CMOS Technology which provided the required performance with the required Radiation Tolerance
- The Initial Concerns in the Instrumentation of Silicon Detectors for LHC were the hostile Radiation Environment and the Minimization of the Power Dissipation
- Fortunately, access to Radiation Tolerant Technology was becoming available from a number of Specialist



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Microelectronics and Silicon Detectors (2)

- It was clear that the Priority given to the Development of Radiation Tolerant Technologies would decrease with time
- The LHC Electronics Board (LEB) encouraged an Investigation (PJ&AM) into the use of 'Deep Sub-Micron' (0.25μ or 250nm) CMOS Processes for LHC Applications. The LEB Recommended to the LHC that this Project be Approved
- The LHC Experiments gained access to 0.25μ CMOS Technology with sufficient Radiation Tolerance and the Very Good Yield expected of a Modern High Volume



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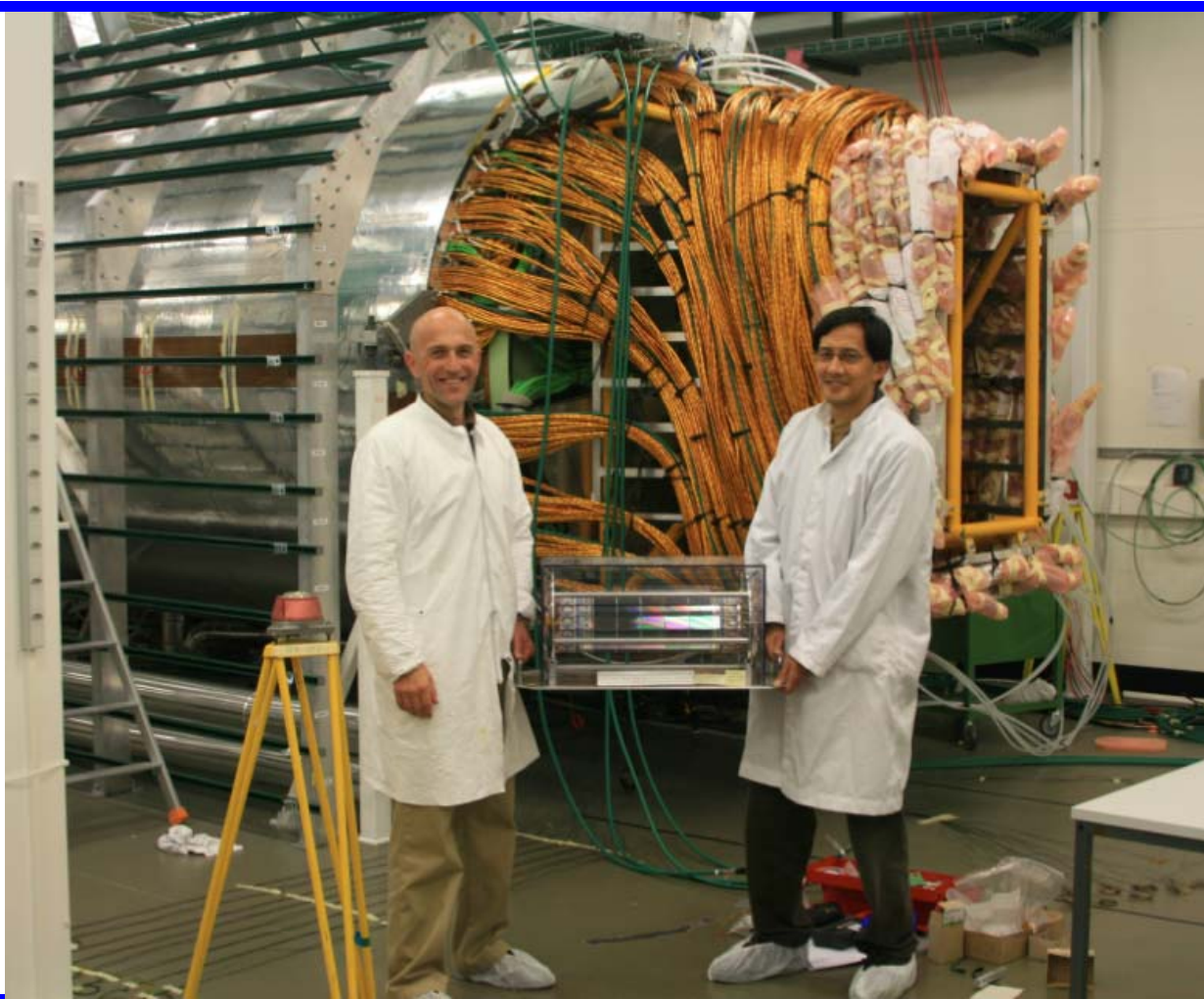
Microelectronics and Silicon Detectors (3)

- The Scale of LHC Silicon Tracking Detectors was larger than the LEP Detectors.
- This Required Much Larger Numbers of Chips (Factor ~100) and the Consequent increase in Quality Assurance (QA)
- Microelectronics had always required a Professional Engineering Approach to Ensure Success, This was now Mandatory, with Careful Reviews at Each Stage.
- With the Best Tools and Discipline the Particle Physics Community proved that it could Reach the Highest



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**Marcello Mannelli
and
Alan Honma
hold the OPAL
Vertex Detector
(1996)
in front of the CMS
Silicon Strip Detector
in the Tracker Integration
Facility (TIF)
in October 2007**





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Scale of the CMS Tracker Project

- ~ 66,000,000 Pixels and 10,000,000 Silicon Strips
- ~ 16,000 Modules
- ~ 100,000 APV Chips, ~ 20,000 ROC Chips (250nm IBM CMOS)
- ~ 40,000 Optical Fibres
- ~ 500 FEDs (Front End Drivers (Off Detector Data Receivers))
- ~ 2500 Power Supplies, ~ 2500 Power Cables
- ~ 450 Cooling Loops (Capable of Cooling Tracker to -30°C)
- ~ 540 Physicists and Engineers (54 Institutes in 10



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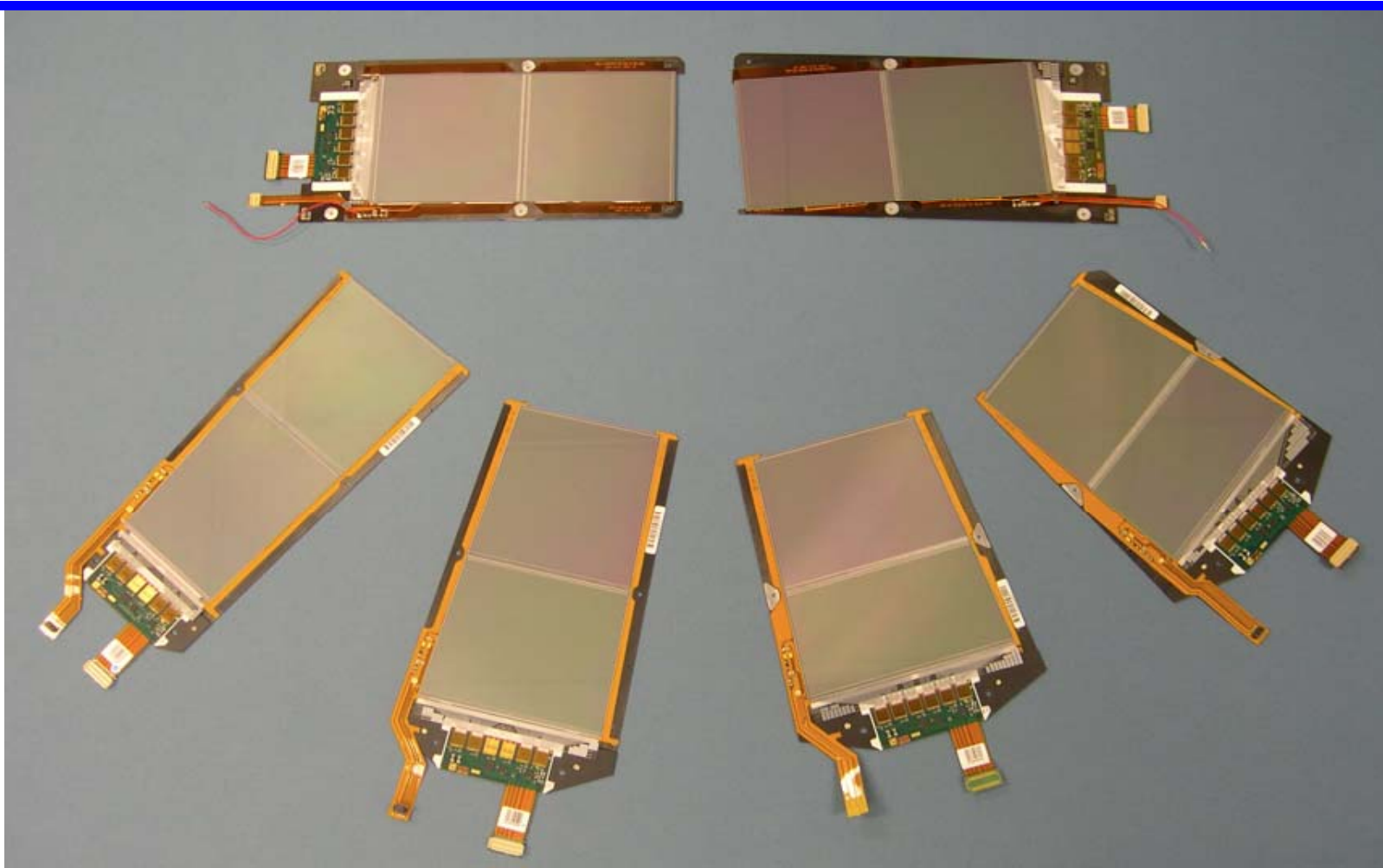
Time Scales Involved in the CMS Tracker Project

- Approval to Completion of Integration – 7 Years
- First Production Modules to Commissioned Tracker – 3 Years
- Strip Tracker Transport and Installation – 2 Days
- Strip Tracker Connection to Services – 3 Months
- Strip Tracker Commissioning to ~ 99% - 3 Months
- Pixel Tracker Transport and Installation – 1 Week
- Pixel Tracker Connection to Services – 1 Week
- ~~Pixel Tracker Commissioning to ~ 99% – 3 Months~~



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Some of
the
Modules
used in
the CMS
Silicon
Tracker





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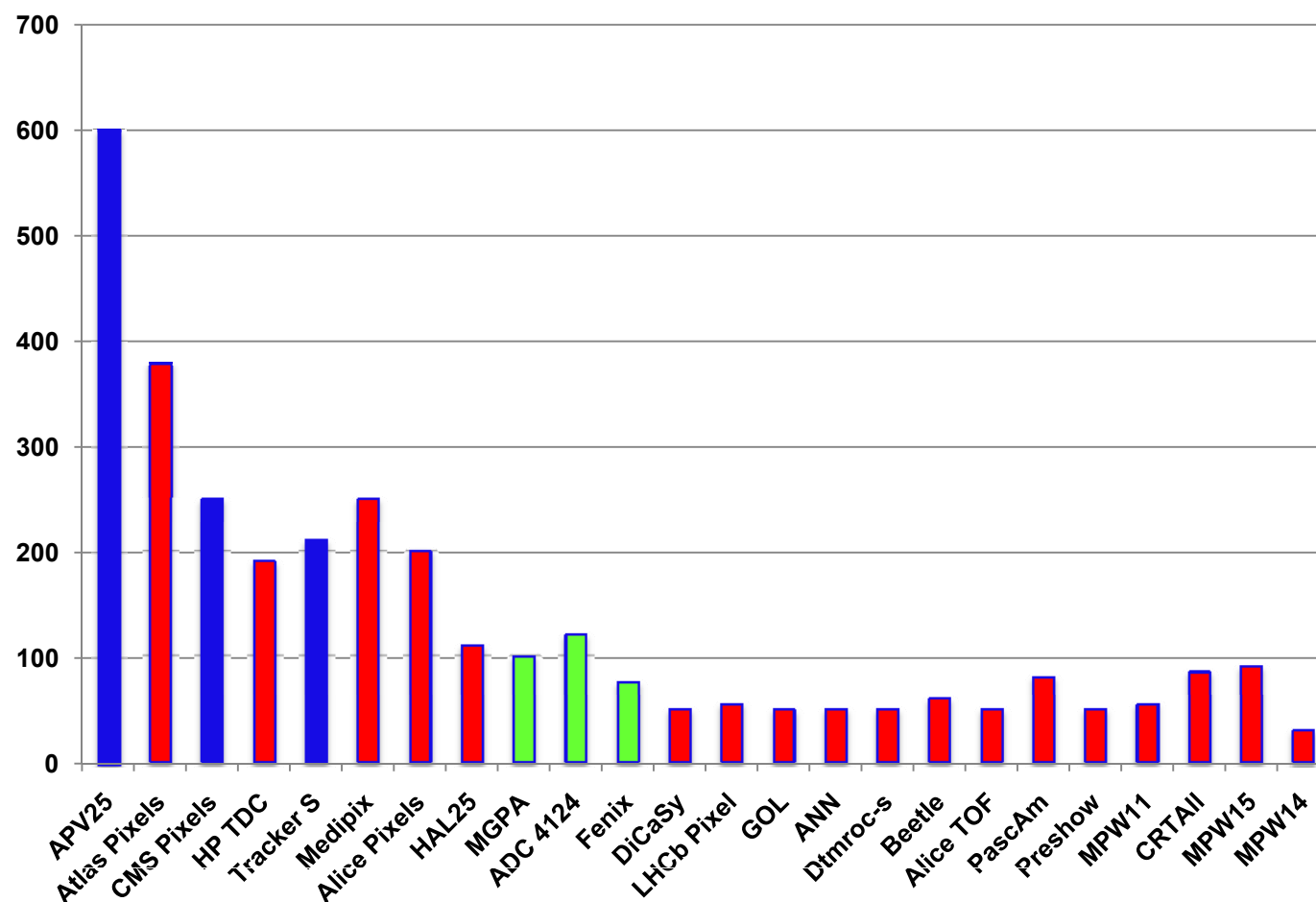
Microelectronics and Silicon Detectors (4)

- It was only Possible to use Reasonably Advanced Microelectronics Technology at the LHC because there was a Very Effective Infrastructure in Existence to provide Access to Design Tools, Design Kits and Libraries, and the CERN Managed MPW scheme that provided Affordable Access to Engineering Prototypes and a Single Interface to Industry
- The Partnership with IBM proved Absolutely Invaluable in Understanding the Solutions to the Complex Problems that always arise in Large and Complex Detector Systems.



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**Number of Wafers
Fabricated for
Projects
From
Sandro Marchioro**





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Why go to more Advanced Microelectronics Technologies ?

- The Drive for smaller feature size Microelectronics comes from the Commercial Requirements to obtain Greater Functionality at less Power for Large Volume Applications
- These are also the requirements of SLHC Applications
- Use ADCs to Compare Power Dissipation per Conversion
- Atlas Calorimeter 200K Channels, 16 bits at 40MHz

In 250 nm Technology 262 KW 1pJ/Conv



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Microelectronics and Silicon Detectors (5)

- Fifteen Years Ago, Technologies were $> 1\mu$ and Wafers $\leq 6''$
- In Future Technologies will be $\ll 1\mu$ and Wafers $> 8''$
- Hence the NRE costs will be much higher !!
- How do we maintain the same cost / chip as we have now ?
- Limited Number of Design Iterations and $> 100,000$ Chips
- ~~This will inevitably involve a small number of tightly~~
coupled Design Centres with University Groups



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Lesson Two from the LHC

- The Engineering of Large and Complex Systems Requires a Very Disciplined and Professional Approach.
- Adoption of Formal QA Methods has enabled the Particle Physics Community to Achieve the Highest Standards in both System Performance and Number of Iterations.
- When Considering the Challenges of the SLHC, We should Consider whether we need to Further Improve our Techniques and Organization



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Opto-Electronics Systems (1)

- **There are a number of reasons for using Opto-electronics systems to Transport Data from the Detectors to the 'Off-Detector' Electronic Systems**
 - **Electrical Isolation of the Detector from Counting Room**
 - **Potential for High Speed Data Transmission**
 - **Potential for both Digital and Analogue Data Transmission**
- **In the Beginning there was very little Experience in the Particle Physics Community and although there were Commercial Links there was still much R&D Activity**



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Opto-Electronics Systems (2)

- There was a DRDC R&D Project to evaluate the Options available and to provide a Focus for the Community
- It was Clear from the Outset that Power would be an Issue
- It was Clear from the Outset that Cost would be an Issue
- The CMS Tracker chose to use Analogue Links to provide more Diagnostic Information in Commissioning the System



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Opto-Electronics Systems (3)

- Initially it was thought that the Cost would be Different
- The Final Costs were :

| | | | |
|--------|--------------|-----------------|---------|
| CMS | 42,800 Links | Production Cost | 294 CHF |
| / Link | | | |
| Atlas | 12,264 Links | Production Cost | 284 CHF |
| / Link | | | |
- Considering that almost every aspect of these Systems were Different this is an interesting Conclusion
- ~~To Engineer Large Complex Systems it is Crucial to~~
Establish a Excellent QA at every Stage of the Project



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Opto-Electronics Systems (4)

- It is Crucial to Test at every Stage of Procurement, Assembly and System Commissioning
- It is Crucial to do Complete System Tests before the starting Production Procurement. Details Compromise Quality
- CMS Tracker 0.04% Dead Links, 0.38% Problematic Links
- Atlas Tracker 0.8% Dead Links, 0.6% Problematic Links

- The CMS Analogue Links required more QA from the



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Opto-Electronics Systems (5)

Lessons from the CMS Tracker Experience

- **Avoid fibre pig-tails.**
- **Do not allow excessive fibre-slack without corresponding management scheme.**
- **Use Ruggedized ribbon/fibre only.**
- **Avoid simplified and/or compact connectors which are difficult to dismount and clean.**
- **Develop and distribute fibre-test tools which allow on-line testing, providing immediate channel quality feedback during construction.**



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Opto-Electronics Systems (6)

Lessons from the Atlas Tracker Experience

- Better ESD precaution
- More longer term testing of the VCSELs at an earlier stage in the assembly to weed out any damaged devices.
- Avoid all use of fragile single fibres on the detector.
- Always used balanced codes.
- Ensure that QA is performed for identical conditions to the final system.



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Lesson Three from the LHC

- **All of the Experience in Constructing and Commissioning and the Quality Assurance of the Opto-Electronics Systems for LHC must be Preserved**
- **Most of the 'Know-how' is stored in the Groups that have Successfully Engineered these Systems**
- **It is Crucial to Maintain a Critical Mass of Engineers with the Facilities and Equipment to ensure that the Present Systems Maintain their Performance and that the Engineering of Future Systems is Built on the Experience from the LHC Projects**



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Power Systems, Grounding and Shielding (1)

- Initially there was Concern that it would not be possible to Install the Power Systems in the LHC Caverns because of both the Radiation and the Magnetic Field Environments
- These are not Problems that Commercial Systems commonly encounter and Hence there were No Commercial Solutions
- The Alternative was to Place the Power Systems Outside the Caverns with the Additional Cost of Cables and the Increase in the Power Dissipation



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Power Systems, Grounding and Shielding (2)

- **There had also been a contraction in the Number of Companies providing Electronics for Particle Physics Applications**
- **Development Projects were started with Two Companies (CAEN and Wiener) to Provide both Radiation and Magnetic Field Tolerant Power Systems**
- **Both Projects were Successful and Provided the Range of Systems to meet the Requirements of the LHC Projects**
- **However Most Power was Transmitted at Low Voltage**



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Power Systems, Grounding and Shielding (3)

- Initially Compact Radiation Tolerant Voltage Regulators were Not Available. Hence the CMS Tracker did not have 'On-Detector' Voltage Regulation.
- A Very Successful Partnership with CAEN developed a Power System (including a Low Inductance Cable) that delivered both Low Voltage Power and the Bias for the Silicon Sensors without Introducing Transients at the Silicon Modules that could have damaged the Chips
- An Extension of this System Development became a



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Power Systems, Grounding and Shielding (4)

- It is Crucial to design a Complete System, which involves Power Supplies, Cables, Control and Safety Systems, and Grounding and Shielding Systems
- In General this did Not Take Place at LHC
- Initially a lot of Effort was absorbed in Engineering the Front-End Chips and Electronics Coordinators worked hard to bring Power, Grounding and Shielding Issues into Focus
- On Occasion Schedule Pressure prevented the
attention to the detail that would have improved noise



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Power Systems, Grounding and Shielding (5)

- Fortunately, Good Engineering at the Integration Stage Reduced the Grounding & Shielding Issues to a Manageable Level and so far there have been no Show Stoppers
- In General the Particle Physics Community is not well Equipped to Diagnose and Solve Grounding and Shielding Problems.
- Since the Power Systems are in the Experimental Caverns, System Reliability is an Important Issue. It has been important to 'Burn In' the Power Systems



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Lesson Four from the LHC

- It is Important to Design Complete Power Systems From the Start, which involves Power Supplies, Cables, Control and Safety Systems, and Grounding and Shielding Systems
- Solving Problems is always Easier, and Usually Cheaper at an Earlier Stage of the Project.
- It is Crucial to Maintain a Critical Mass of Engineers with the Facilities and Equipment to ensure that the Present Systems Maintain their Performance and that the Engineering of Future Systems is Built on the

Experience from the LHC Projects



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Off-Detector Electronics Systems (1)

- **The Engineering of the ‘Off-Detector’ Electronics Systems has been dominated by the Development of FPGA Technology**
- **Early Developments of some Systems fixed the Technology before FPGA Technology was Available, Other Systems Adapted to the New Technologies**
- **Large Systems with many FPGAs Need Very Careful Engineering to Delivery High Yield, Highly Reliable Systems**



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Off-Detector Electronics Systems (2)

- **The Issues with FPGAs is that Many People can write the Firmware required to programme an FPGA, but Not Many People can Engineer a Reliable System that is Easy to Commission and Maintain.**
- **Other Issues are Obsolescence of both Hardware and Software and the Version Control of the Firmware**
- **Again QA and Attention to Detail in the layout of Large Multi-Layer Circuit Boards are Essential**



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Off-Detector Electronics Systems (3)

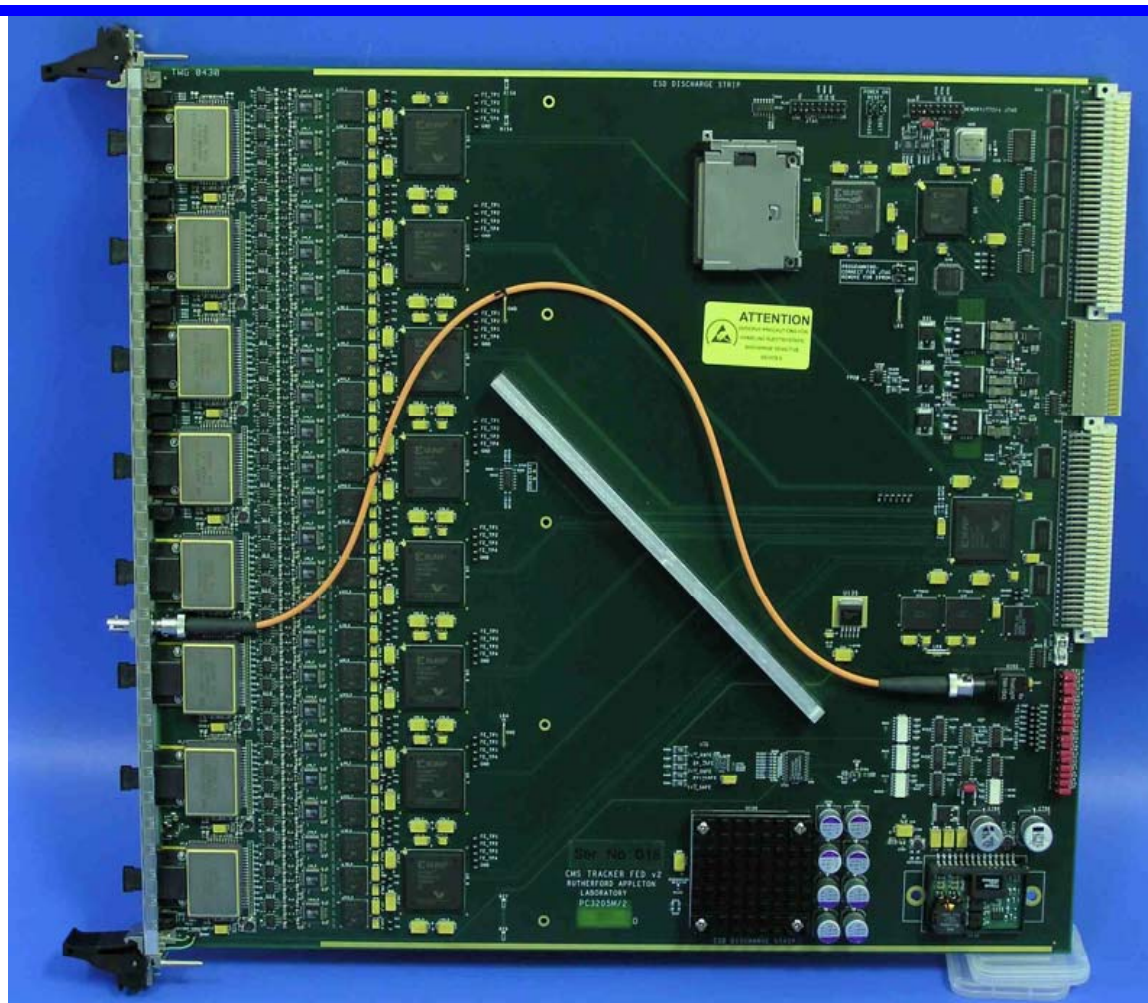
- A Example of Good Practice is the Front-End Driver System for the CMS Tracker.
- It involves 500 9U Boards (See next Slide)
- The Fabrication Company was Chosen with Care
- 99% of the Boards worked on Receipt from the Fabrication Company, who were also responsible for Board Fabrication & Board Testing, with Test Equipment supplied by the User
- The System was Easy to Commission and has proved to be Very Reliable



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**The CMS Tracker FED
(Front End Driver)**

A 9U Board





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Off-Detector Electronics Systems (4)

- The Issues are by now Very Familiar:
 - Careful Systems Design
 - Careful Tuning and Reviews of the Specifications
 - Professional Design Teams for Hardware, Firmware and Software, Commissioning and Maintenance Systems
 - Careful Preparation of Commissioning and Performance Evaluation
 - A QA System that promotes Continuous Improvements



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Lesson Five from the LHC

- Large Complex Systems Can only be Efficiently Commissioned and Maintained if Best Engineering Practice has been followed throughout the Design of the System
- Too Often Gifted Individuals become Single Point Failures
- LHC Systems have to be Maintained for ~ 10 years well beyond the Commitment of Individuals
- Hence it is the Institutions that must Underwrite the Commitment to Maintain the Systems for the Life of



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Summary (1)

- **The Problems faced in the Engineering of the Electronics Systems have been Significantly Larger and More Complex than any Previous Particle Physics Projects**
- **Success has only been Possible by Merging Many Gifted Individuals with an Engineering Structure that has Provided the Environment in which the most Creative Ideas could be Transformed into Reliable and Maintainable Systems**



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• Summary (2)

- It is Important that we recognize what has worked well and what is required to Maintain the Improvement**
- Coordination, Collaboration and the Search for Common Solutions to avoid Duplication have been Very Important**
- We should Continuously Review our Organization and Adapt to Changes in both Requirements and Technologies**
- We must Maintain a Critical Mass of Engineers with the Facilities and Equipment to Build on the Experience of**



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• Summary (3)

- In General our Approach to System Design could be Improved. It is Very Difficult to Control the System Design without having Control of the Budget. Hence the Method of Funding LHC Projects has made this more Difficult
- Formal QA Systems need to be Adapted to the Particle Physics Environment. In Many Projects, more in-depth Reviews would have found Problems much Earlier and Hence saved both Time and Money



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Conclusions

- **The LHC Electronics Systems have been Very Successful and the Community should Reflect with Pride at this Massive Achievement**
- **Many of the Organizations Establish at the Beginning of the Projects Worked Well. New Working Groups Work Well**
- **We need to Build on these Experiences and Ensure that we have a Strong Community to take on the Challenges of SLHC**



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Electronics at SLHC



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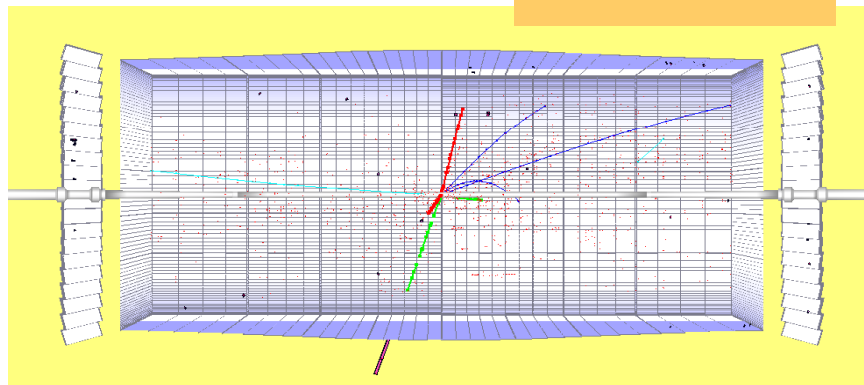
An Optimistic Plan for LHC Luminosity



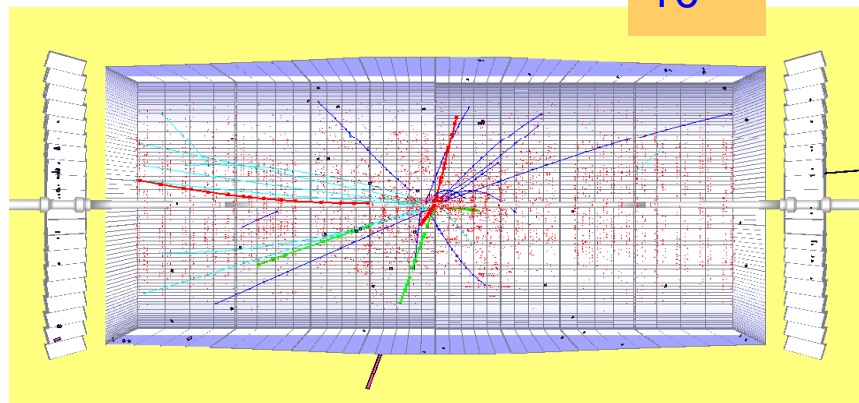


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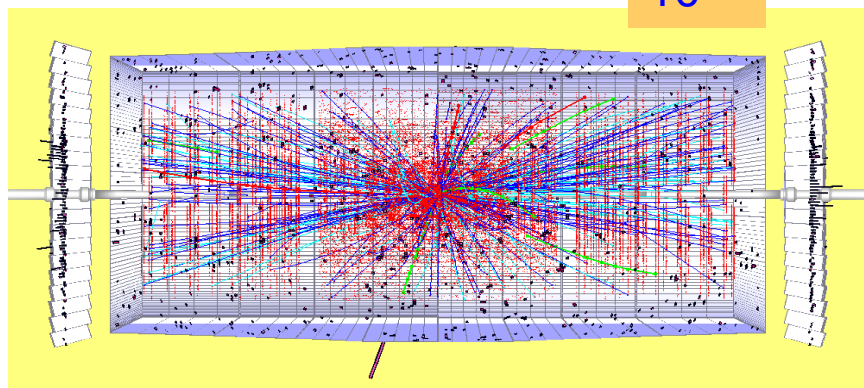
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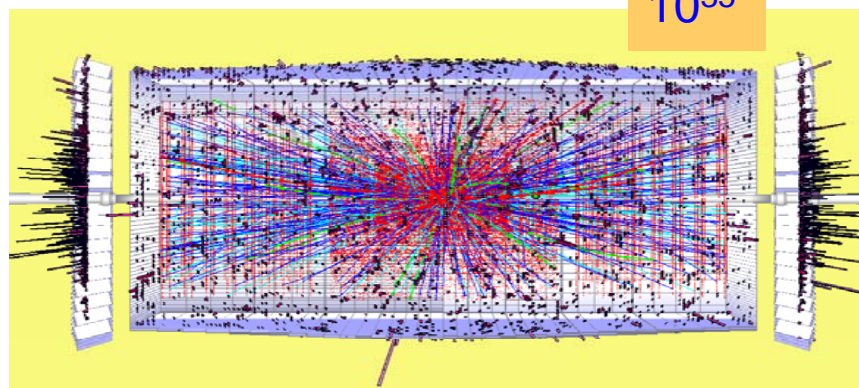
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Some of the Issues for Electronics at SLHC

- Which Microelectronics Technology Should we Use ?
- Do we have the right Organization in Place to Obtain Cost Effective Access to Advanced Technologies ?
- Which Interconnection Technologies Should we Use ?
- Will we have Access to Cost Effective Optical Links ?
- Can we Transmit Power to the Detector at High Voltage and obtain Efficient Conversion to Low Voltage at the Detector ?
- How will Future Off-Detector Systems Evolve ?
- How do we Establish Effective Partnerships with



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Thank You