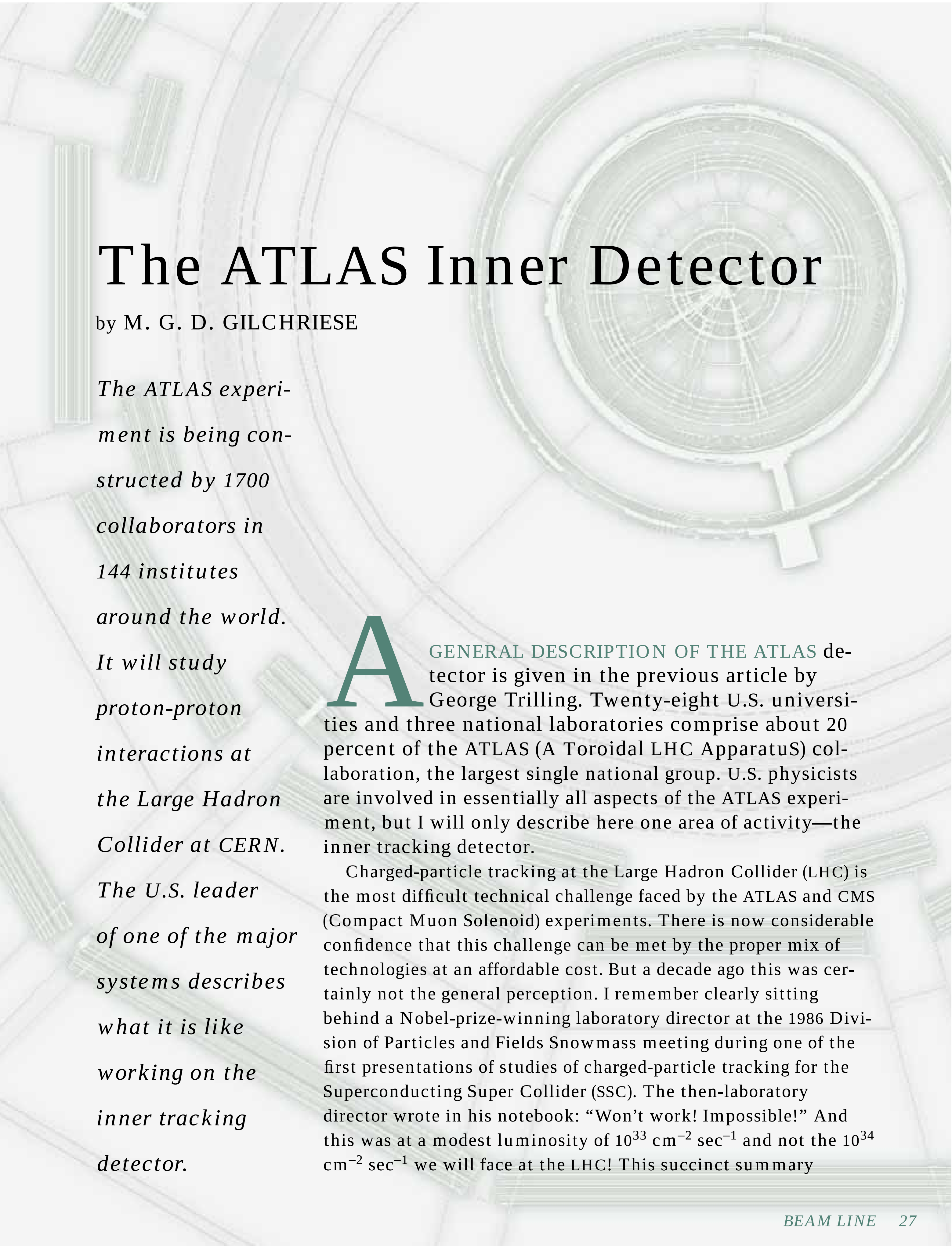


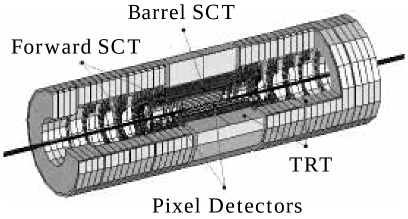
The ATLAS Inner Detector

by M. G. D. GILCHRIESE

The ATLAS experiment is being constructed by 1700 collaborators in 144 institutes around the world. It will study proton-proton interactions at the Large Hadron Collider at CERN. The U.S. leader of one of the major systems describes what it is like working on the inner tracking detector.

A GENERAL DESCRIPTION OF THE ATLAS detector is given in the previous article by George Trilling. Twenty-eight U.S. universities and three national laboratories comprise about 20 percent of the ATLAS (A Toroidal LHC ApparatuS) collaboration, the largest single national group. U.S. physicists are involved in essentially all aspects of the ATLAS experiment, but I will only describe here one area of activity—the inner tracking detector.

Charged-particle tracking at the Large Hadron Collider (LHC) is the most difficult technical challenge faced by the ATLAS and CMS (Compact Muon Solenoid) experiments. There is now considerable confidence that this challenge can be met by the proper mix of technologies at an affordable cost. But a decade ago this was certainly not the general perception. I remember clearly sitting behind a Nobel-prize-winning laboratory director at the 1986 Division of Particles and Fields Snowmass meeting during one of the first presentations of studies of charged-particle tracking for the Superconducting Super Collider (SSC). The then-laboratory director wrote in his notebook: “Won’t work! Impossible!” And this was at a modest luminosity of 10^{33} cm^{-2} sec^{-1} and not the 10^{34} cm^{-2} sec^{-1} we will face at the LHC! This succinct summary



The ATLAS Inner Tracking Detector (approximate length 7 meters).

accurately reflected the uneasiness of many people at that time. So what happened to change this perception and to give us confidence now that even 10^{34} cm^{-2} sec^{-1} may not be the ultimate limit at which charged particle tracking is possible?

The essential change in the last decade has been to realize that it is possible to build tracking detectors with very, very many independent elements (the ATLAS tracking system will have over 10^8 such elements) that can each have a time resolution of a few nanoseconds or better. And that this can be done for an affordable cost (although just barely) and with the ability to survive the hostile radiation environment at the LHC.

Our ability to make these optimistic statements follows from a decade of intense research and development on tracking detectors. A focused program of detector R&D for the SSC began in 1986 and shortly thereafter independently in Europe for the LHC. The results of these R&D programs appear today to be even more successful than the original proponents imagined. The design of the ATLAS inner tracking detector follows directly from these worldwide R&D efforts.

The ATLAS Inner Detector is shown above. It consists of three different tracking technologies. At the outer radii, there are about 400,000 straw tube drift cells that, in addition to their charged-particle tracking function, are used to detect transition radiation X-rays from electrons (therefore named the Transition Radiation Tracker or TRT). At the intermediate radii, there is a large area (60 m^2) silicon strip detector (about 5 million individual channels). For historical reasons this is called the Semiconductor Tracker or SCT. And closest to the interaction point there is about 2 m^2 of silicon pixel detectors with 1.5×10^8 individual elements—pixels.

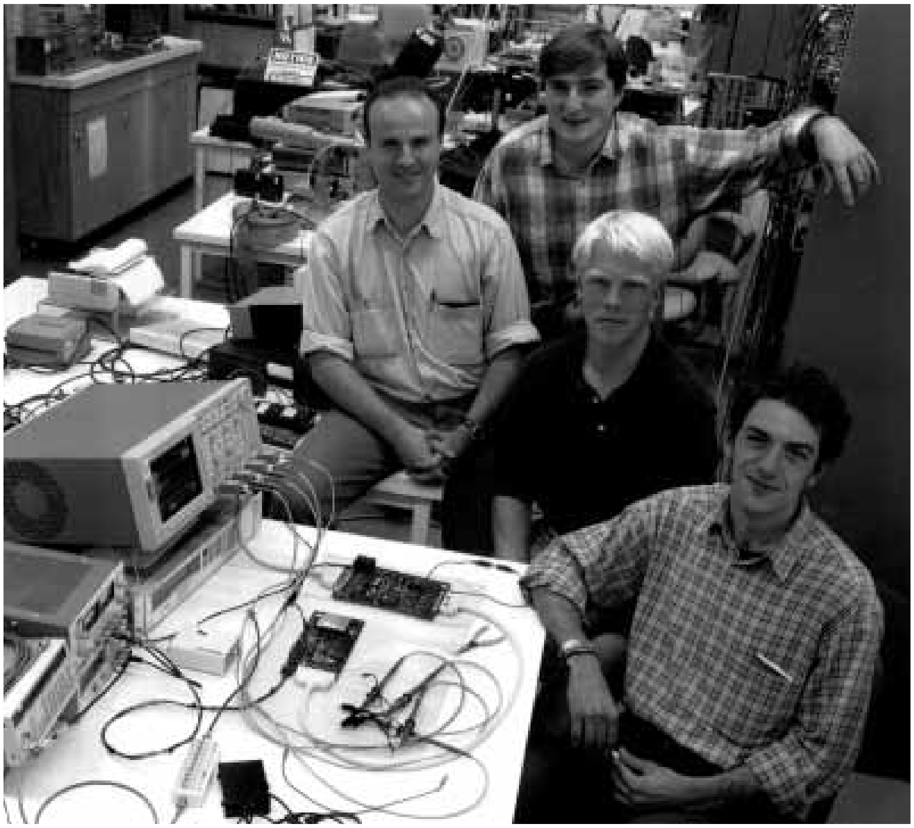
The innermost radius of each of these types of detectors is determined by either their ability to function at the LHC luminosity of 10^{34} (in the case of the TRT) or by their ability to survive about ten years of operation (in the case of the silicon-based detectors). In fact, the innermost pixel system layer, which is critical to the ability to identify particles containing the *b*-quark, will last only about one year at 10^{34}cm^{-2}sec^{-1}. It will be replaced periodically unless a more radiation-tolerant solution is found. The outermost radius of each type of detector is set in part by performance requirements (for example, momentum resolution) but is even more strongly influenced by the need to keep costs within affordable bounds, not just for the inner tracking detectors but for the entire detector.

The components of the inner tracking detector will be built all over the world and shipped to CERN for final assembly and installation. There are about 60 different institutions involved, which is more institutions than even the largest collaboration for an operating experiment in the United States. This "United Nations" approach to detector design and construction does have its strengths and weaknesses. The primary strength is that the available technical expertise is very substantial and it is therefore possible, in principle, to understand every detail in depth. The principal, and inevitable, weakness is that this expertise is dispersed all over the planet and, as a result, it becomes difficult to reach decisions and to achieve the concentration of effort that is necessary in a complicated and long technical project. That all of this (usually) works is a reflection of the intense desire of the physicists in each institution and country to "make it work" and ultimately to build the best experiment.

The U.S. collaborators are working on all three parts of the ATLAS inner tracking detector. Duke University, Indiana University, and the University of Pennsylvania did pioneering work in the development of straw tubes for the SDC detector for the SSC. Duke, Indiana, Hampton University, Norfolk State University, and the University of Pennsylvania are now responsible for the barrel part of the Transition Radiator Tracker and a substantial fraction of the TRT electronics. Modules that make up the barrel TRT will be assembled and tested by Duke, Indiana, Hampton, and Norfolk and then shipped to CERN for final assembly. Some of the parts needed for these modules will be made in the United States and others in Europe, including Russia. The University of Pennsylvania, having specialized in the design of integrated circuits and other electronics for the TRT, will fabricate and test these components and then ship them to module assembly sites in both the U.S. and in Europe. This type of exchange of components from the U.S. to Europe, and vice versa, is typical of almost all parts of the ATLAS detector. It is determined by the availability of local expertise both within the high energy physics community and within industries in a specific country and the desire to minimize costs by realizing economies of scale.

Another, even more diverse, example of this type of interchange of components and expertise is in the fabrication of the silicon strip modules for the Semiconductor Tracker. A module consists of silicon detectors, the integrated-circuit-readout electronics that are mounted on these detectors, and the electromechanical parts that support and cool the module and connect it to external electronics. About 4100 such modules are needed, which represent more than an order of magnitude increase in scale over existing silicon detectors. In addition, the many institutions involved are located from Australia to Russia, making it possible to accumulate the financial resources required but in so doing creating a substantial organizational challenge.

There will be seven regional centers for assembly of modules, with components coming from even more places. The United States is one regional center, with mod-


Roy Kaltschmidt, LBNL

From left to right, John Richardson, (LBNL); Julio Bahilo-Lozano (Spain); Leif Ericson (Sweden), and Roberto Marchesini (Italy) are working at Lawrence Berkeley National Laboratory on pixel and semiconductor tracker detector prototypes.

ules and related electronics being designed, assembled, and tested by Lawrence Berkeley National Laboratory (LBNL), the Universities of California at Irvine and Santa Cruz, and the University of Wisconsin. The U.S.-built modules will be assembled and tested at LBNL and UC Santa Cruz, then shipped to England for placement on a supporting structure. UC Irvine and Wisconsin have the primary responsibility for the design and fabrication of electronics that reside outside the detector, in fact outside the ATLAS underground hall, and which are connected by fiber optics to the SCT modules.

The pixel system is located closest to the interaction point. There are two reasons why silicon pixel detectors are needed at the LHC. First, the intense radiation environment of the LHC, especially at small radii, damages silicon detectors. At some point, the damage reduces the signal induced by the passage of a charged particle so much that the fast electronics used, for example by the SCT, cannot sense the charge with good efficiency above the intrinsic noise that is inherent to the system. The trick in the case of a pixel detector is to reduce the noise by reducing the input capacitance seen by the electronics, which means reducing the size of the individual silicon sensing areas from 12 cm×80 microns in the case of the SCT modules to 300 microns × 50 microns in the case of the pixel detector. As a consequence, the pixel electronics must be mounted directly on top of the silicon sensing elements, and thus the ATLAS pixel detector contains about 2 m^2 of integrated circuits, a large fraction of the integrated circuits needed for the whole experiment. The LHC interaction rate and radiation environment are such that CCD pixel detectors, such as those so successfully used in the SLAC Large Detector at the Stanford Linear Collider, cannot be considered. The second need for pixel detectors is driven by the high density of tracks in hadronic jets at the LHC and the desire to find particle tracks within these jets for tagging particles containing the *b*-quark as well as for other reasons. The enormous granularity of the pixel detector, located near the interaction point where the track density is highest, greatly improves the track finding capability.

The essential change in the last decade has been to realize that it is possible to build tracking detectors with very many independent elements that can each have a time resolution of a few nanoseconds or better. And that this can be done for an affordable cost and with the ability to survive the hostile radiation environment at the LHC.

The U.S. institutions working on the ATLAS pixel detector are LBNL, UC Irvine, UC Santa Cruz, University of New Mexico, University of Oklahoma, SUNY Albany, and the University of Wisconsin. Irvine and Wisconsin are responsible for the off-detector electronics, which are similar to those used for the SCT. The other groups are working on all aspects of the pixel detector—integrated circuit electronics, silicon detectors, module construction and mechanics—and will be responsible for delivering the forward/backward disk elements of the pixel system for the experiment.

The construction phase of the subelements of the ATLAS Inner Detector has started. The TRT has entered this phase, to be followed by the SCT next year and then the pixel detector a year later. It has taken more than a decade of R&D involving almost all of the major countries in the high energy physics world to get to this stage. Although the final proof awaits the turn-on of the LHC, it appears now that this long effort has been spectacularly successful. In this sense, the ATLAS inner tracking detector is an example of the best of international collaboration in high energy physics.