# ATLAS Silicon Tracking at LBNL

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## Overview of the ATLAS experiment

- Significant progress in many areas - general level of activity is very high !

## Survey of the activities of the LBNL group:

- Work on the Semiconductor Tracker (SCT)
- Work on the Pixel Tracker

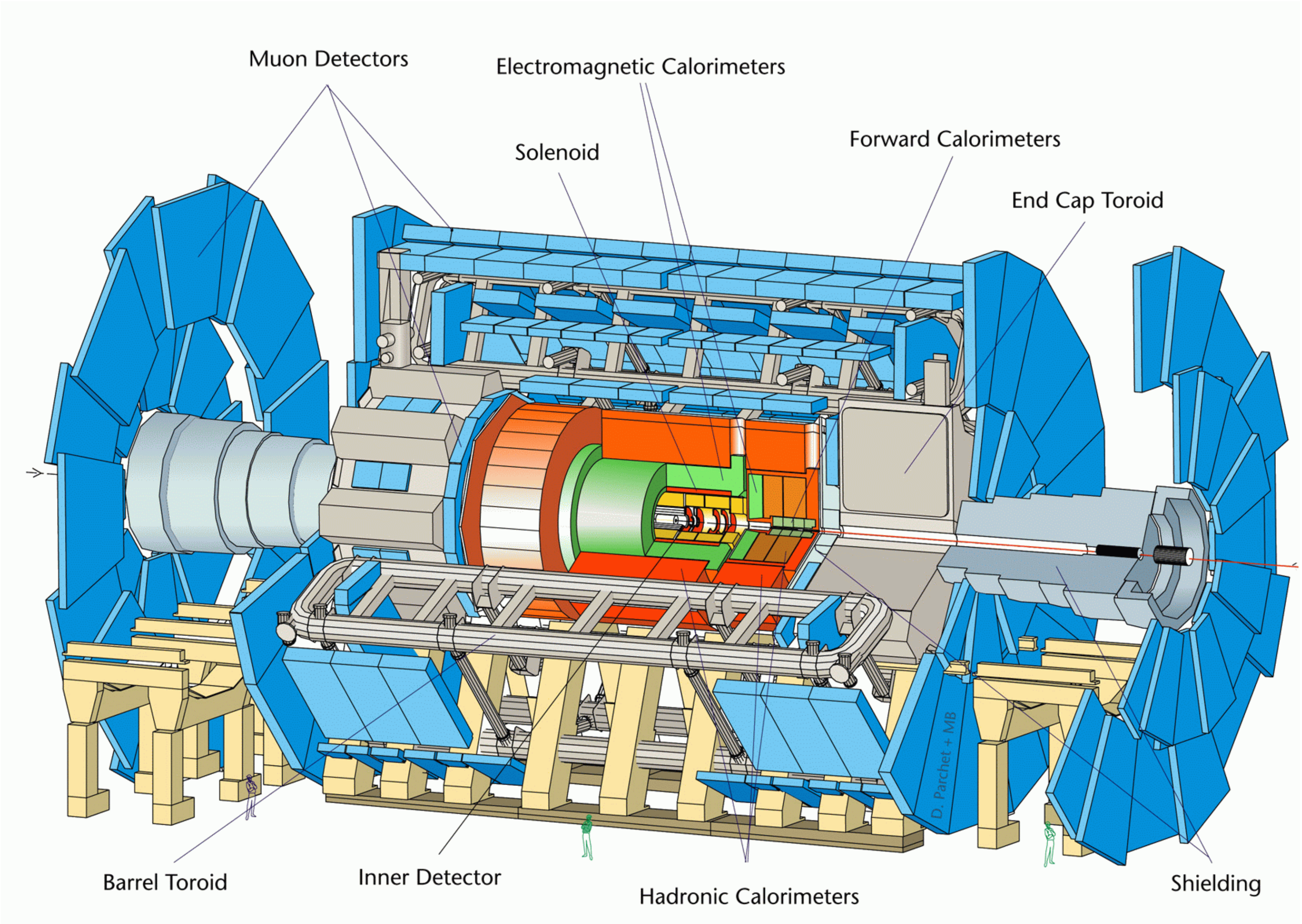
## Upgrade activities:

- First R&D activities for next generation Inner Detector (ID) have started

## Planning for the Future and Issues

# The ATLAS Detector

## Very large, general purpose magnetic detector for the LHC:




- Overall dimensions are roughly 45m long and 25m in diameter (and only 7000 T).

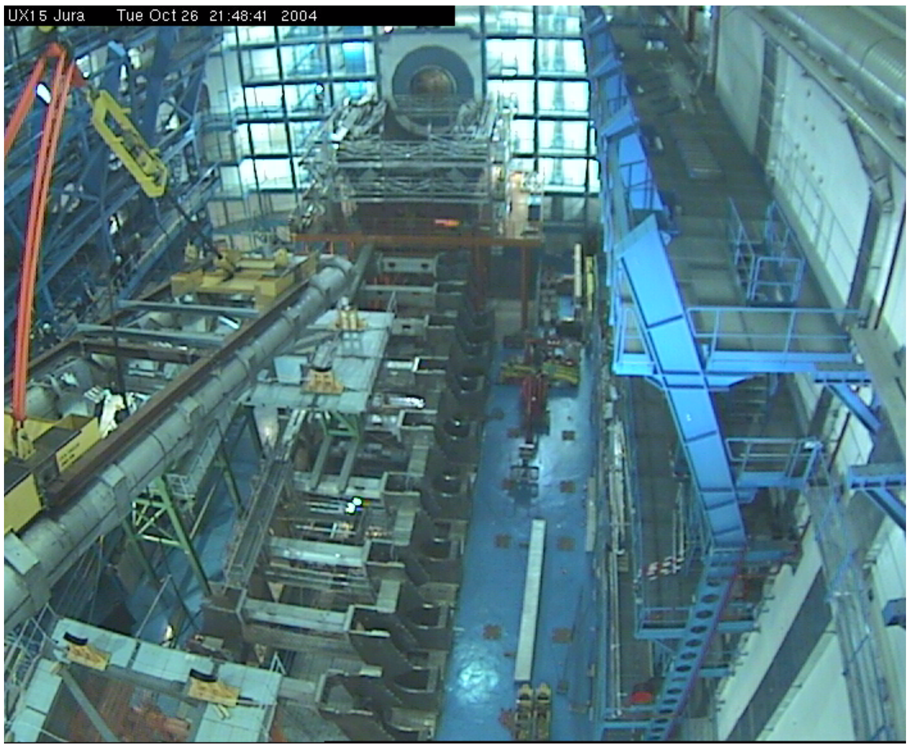
# Highlights of Recent Progress in ATLAS:

## Installation into UX15 Cavern:

Activity has been underway for about one year already. Basic infrastructure complete, including support feet and metal scaffolding structures (11 levels !).

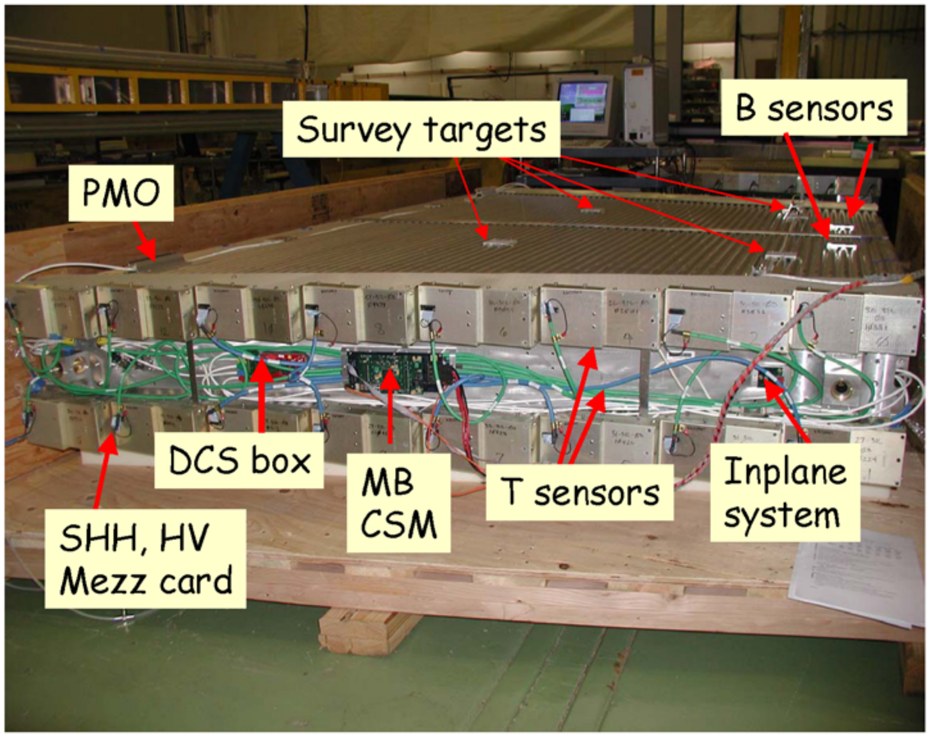
Barrel hadronic calorimetry is already in cavern, and barrel cryostat with electromagnetic calorimeter and solenoid installed inside was lowered on Oct 28 (right).

First barrel toroid coil was lowered on Oct 26 (left). Recall eight superconducting coils, 26m long, used to create 1T toroidal magnet field of muon system (1GJ stored energy):




# The ATLAS Muon System:

- Tracking chambers based on precision drift tubes, in toroidal magnetic fields.
- Have now completed 90% of the tracking chamber construction (total 5000 $m^2$):

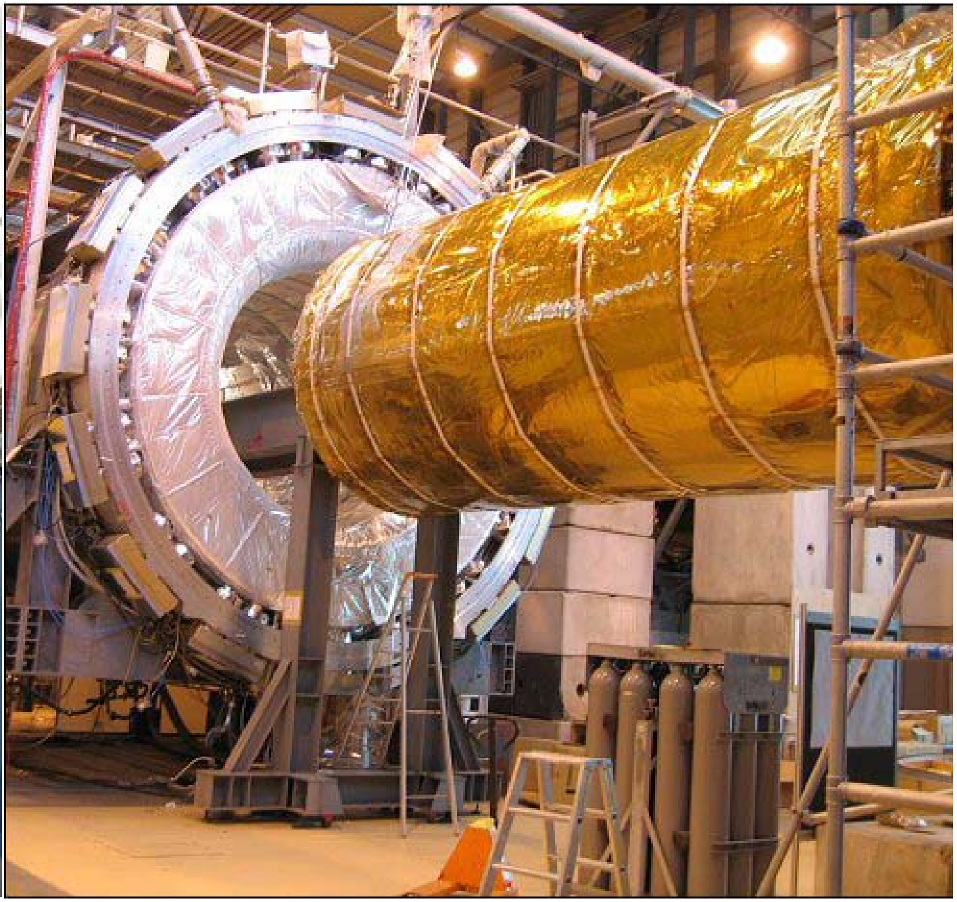




- Total of 1200 chambers produced at 14 sites in 7 countries. Precise to 50µ.

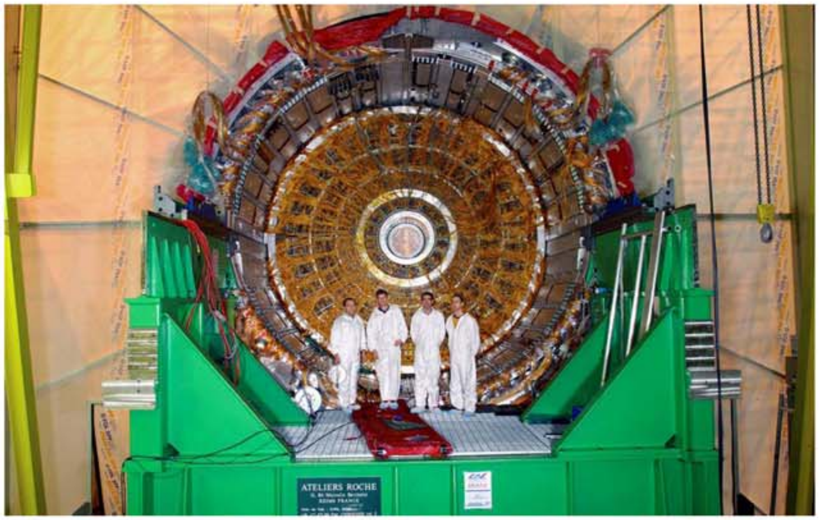
# The ATLAS Calorimeter System:

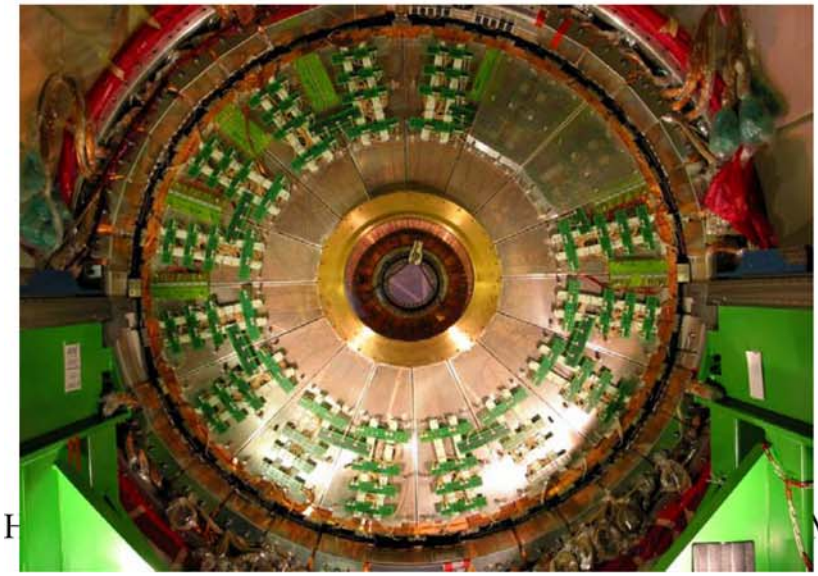
- Complete liquid Argon barrel EM calorimeter already cold-tested in cryostat with solenoid (magnetic field of 2T in volume of 5.3m long by 2.4m in diameter).
- One endcap, including EM and hadronic endcap calorimeters and combined forward calorimeter, now welded into cryostat and undergoing warm-testing.

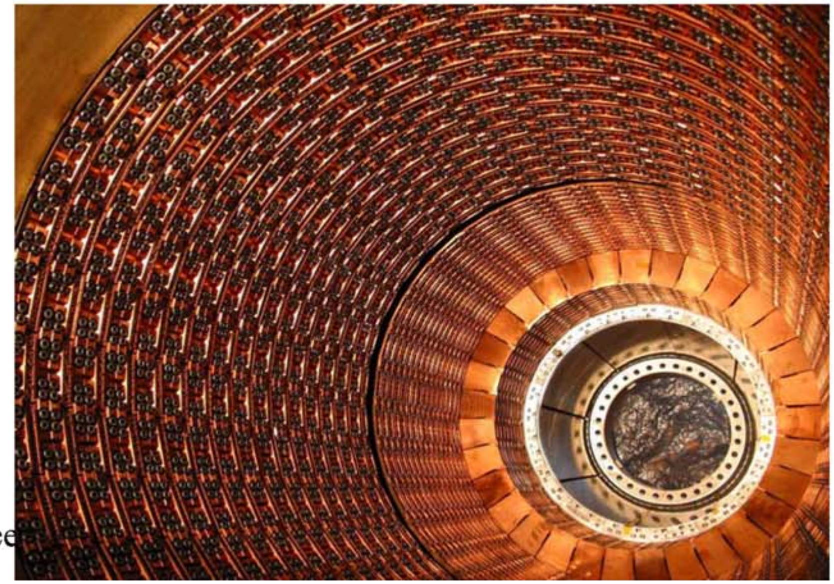


- Left shows barrel EM calorimeter, right shows integration of solenoid magnet.

- Endcap integration several months ago:





- From empty cryostat (upper left) to complete EM and hadronic calorimeters (lower right). Forward calorimeter now also inserted into opening, and cryostat closed. Calorimeters warm-tested, ready for cool-down and cold test.

# The ATLAS Inner Tracking Detector:

## Outermost system uses gas-filled 4mm straws

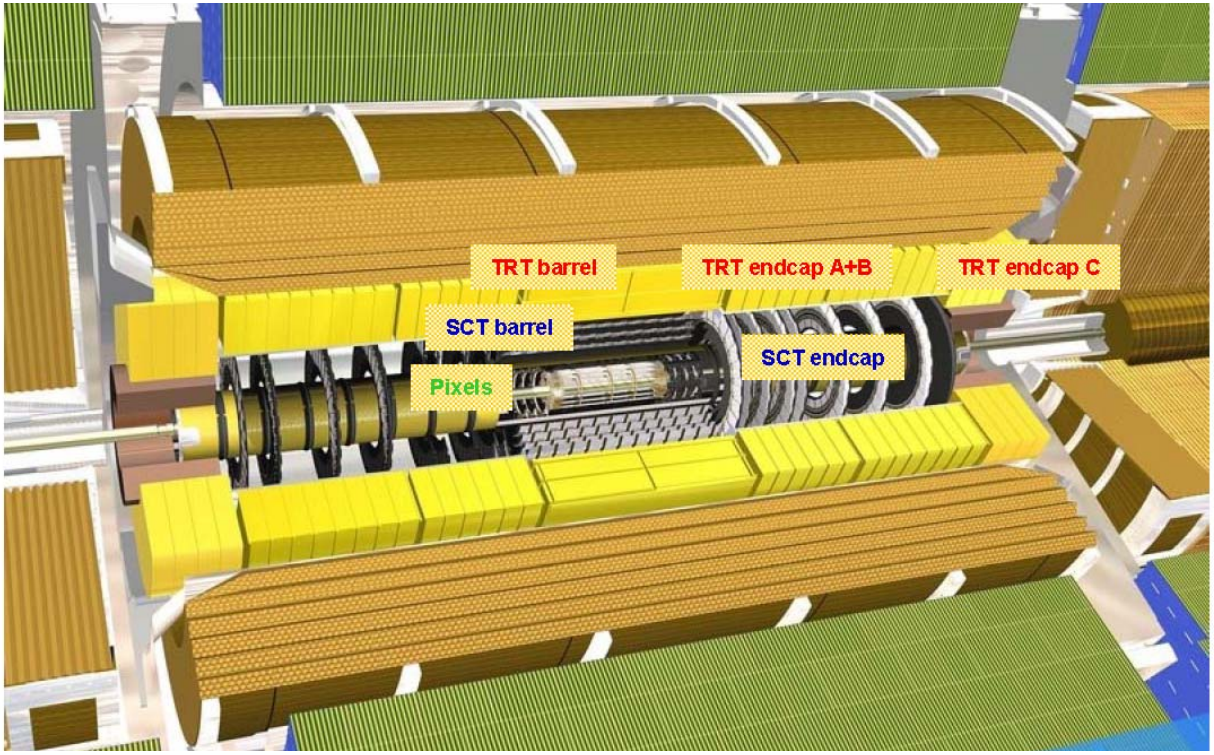
- Contains 420K electronics channels. Transition radiation detector gives particle ID.

## Intermediate system is a large silicon strip tracker

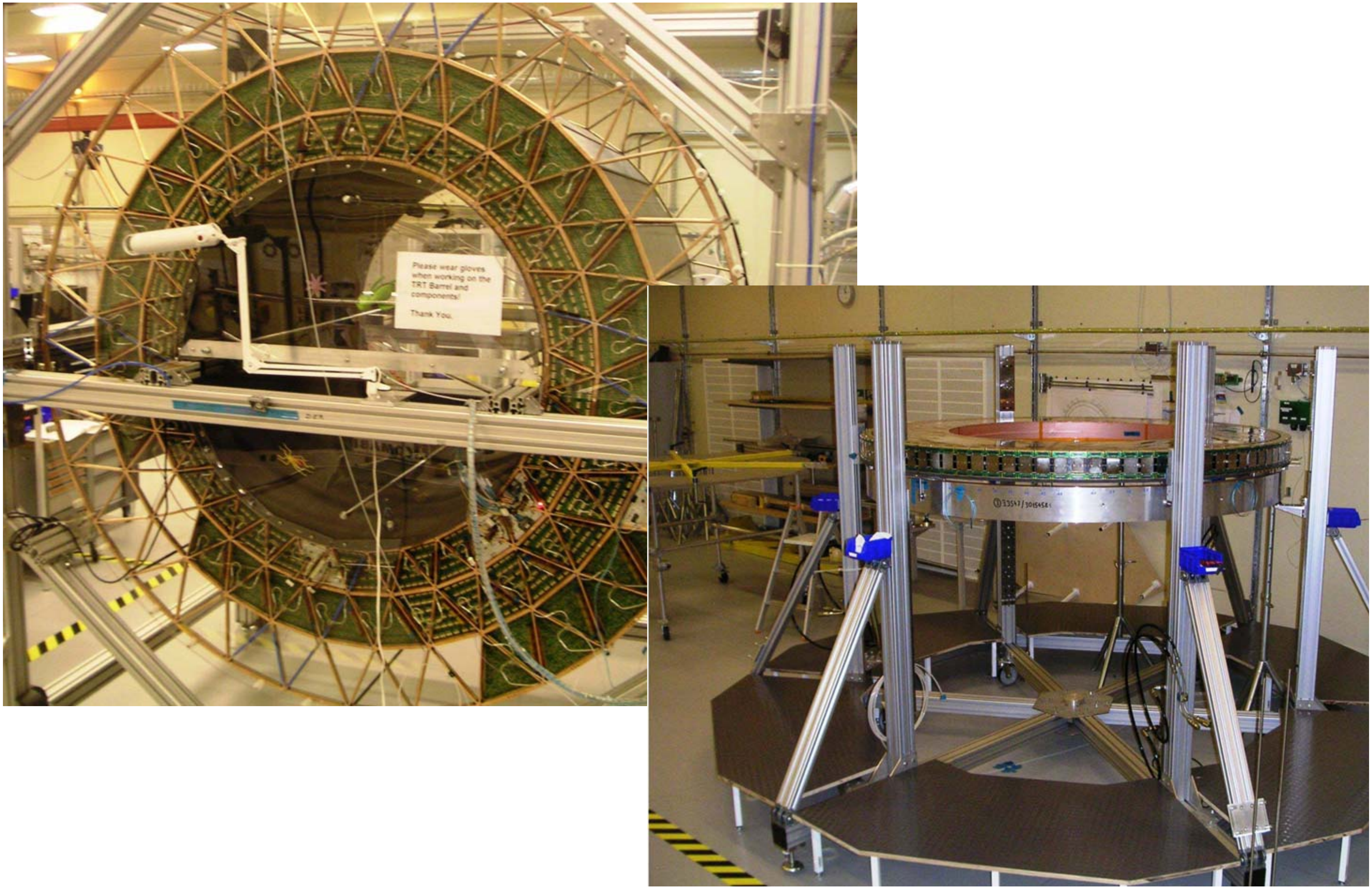
- Four barrel layers and 9 disk layers contain 61 $m^2$ of silicon with 6.2M channels

## Innermost system is a silicon pixel tracker

- Three barrel layers and 3 disk layers contain 1.8 $m^2$ of silicon and 80M channels

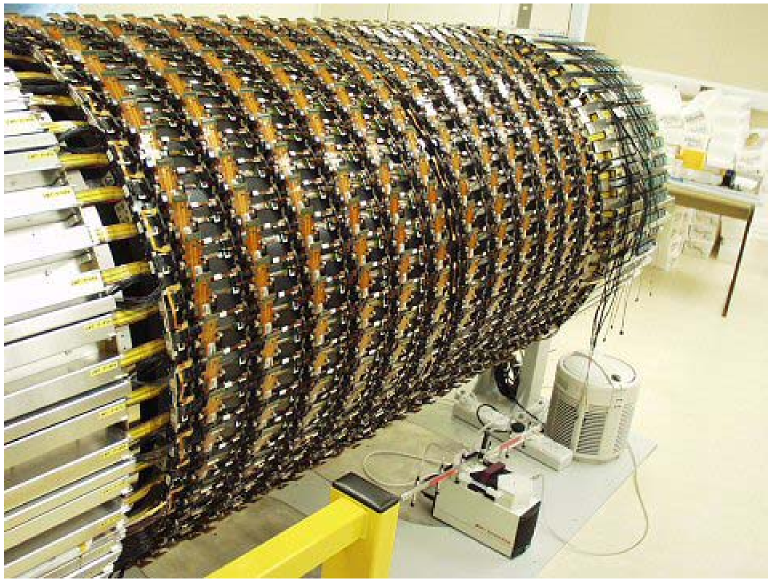


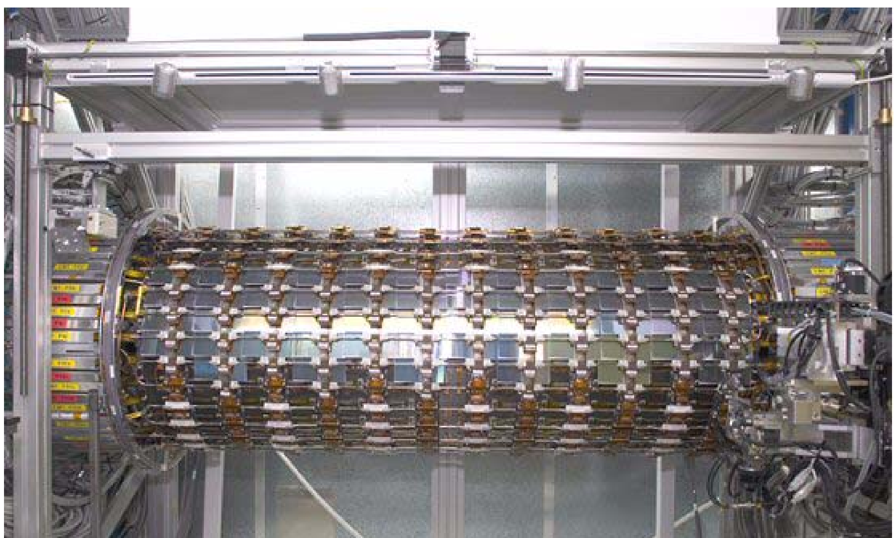
# The TRT Status:



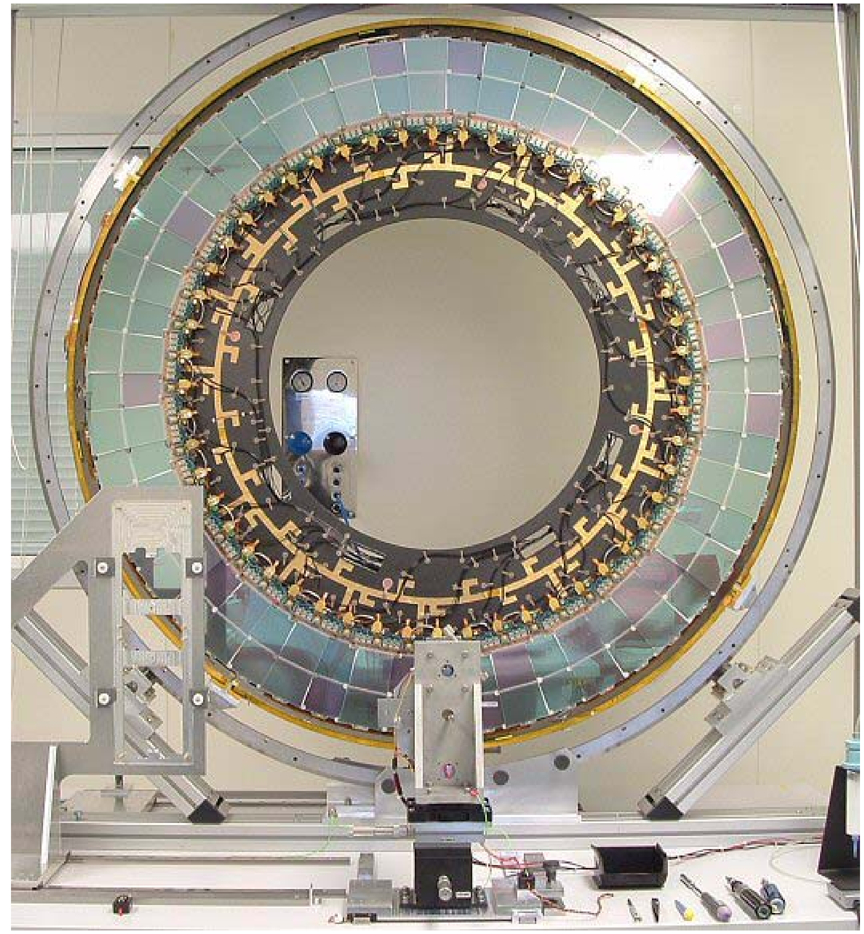

• Barrel (left) and Disks (right) assembly and integration with electronics is ongoing.

# The Semiconductor Tracker (SCT) Status:





B3 with 54 modules mounted



- Mounting of Barrel and Endcap modules onto mechanical structures is underway.

# LBNL Involvement in ATLAS Inner Detector

## Silicon Strip detector (SCT):

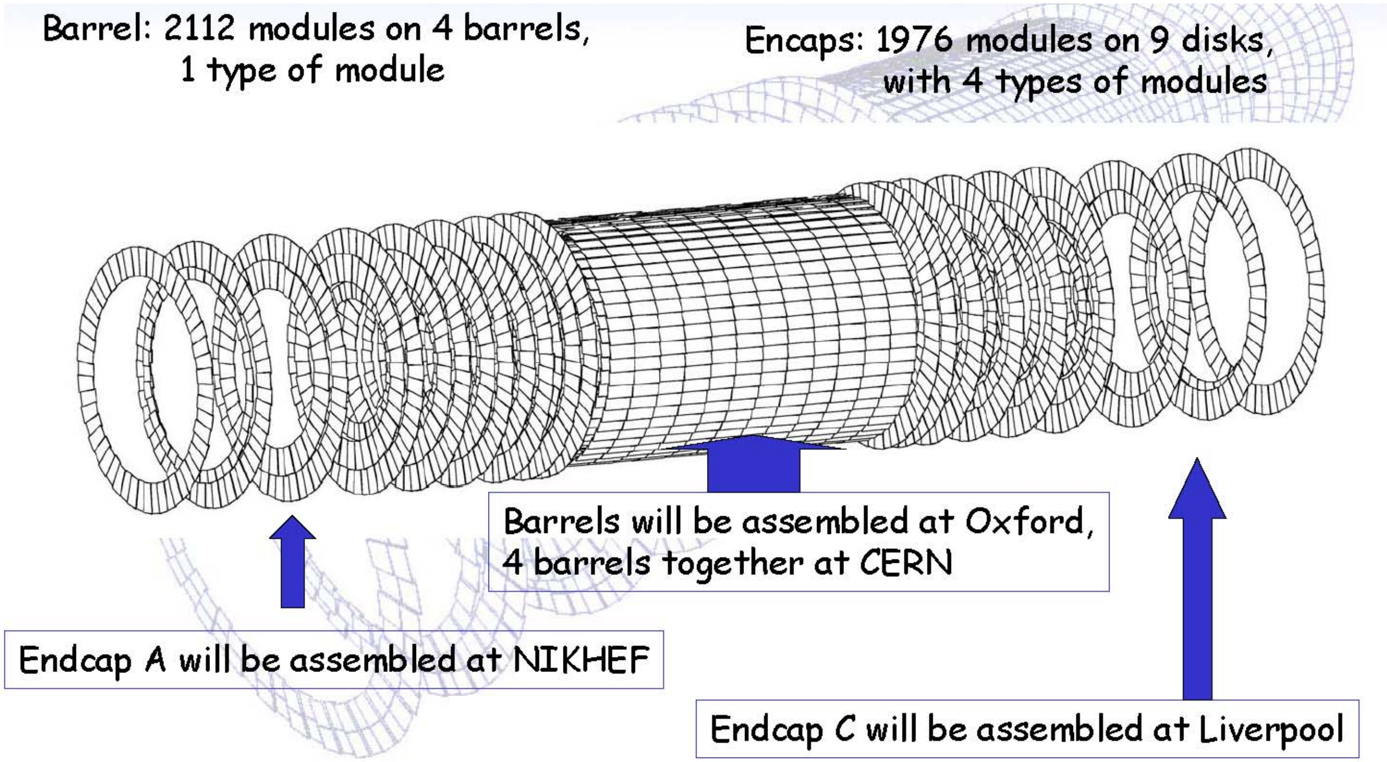
- Development of production IC testing hardware
- Assembly and testing of roughly 500 barrel modules, or 25% of the barrel.

## Pixel detector:

- Development of on-detector electronics (collaboration)
- Development of test system hardware+software for development/production
- Development of off-detector electronics (collaboration).
- Module assembly prototyping (collaboration), and production of 300 pixel modules
- Local mechanics for disk, and integration of disk system
- Global mechanical support, pixel support tube, and integration with beampipe
- Low mass services and integration with mechanics

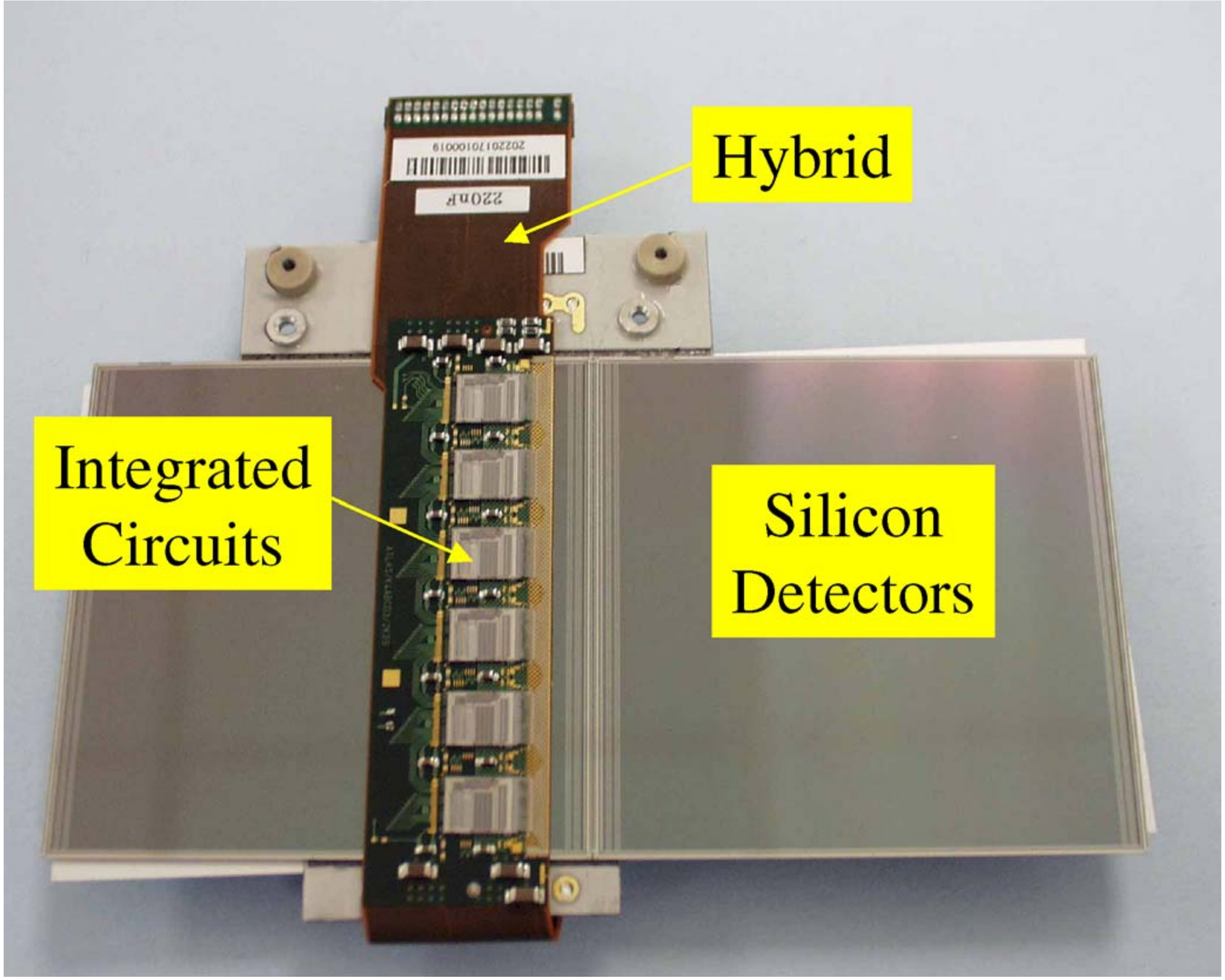
# SCT (Semiconductor Tracker) Activity

- Basic building block (module) is built from four single-sided p+ on n sensors, bonded back to back to create double-sided modules with small angle stereo.
- System consists of about 4000 modules, arranged into 4 barrel layers and 9 disks on each end. LBNL work has concentrated in barrel region.
- Lifetime radiation dose is 10MRad worst case.
- LBNL, collaborating with UC Santa Cruz, has concentrated on electronics and module construction.



# SCT Modules

## Modules are the building block of the SCT system:




**Module consists of:**

Four detectors precisely glued to a heat spreader. Small angle stereo implemented.

Hybrid package attached to the two sides of the module.

Approximate dimension is 6cm x 12cm active area.

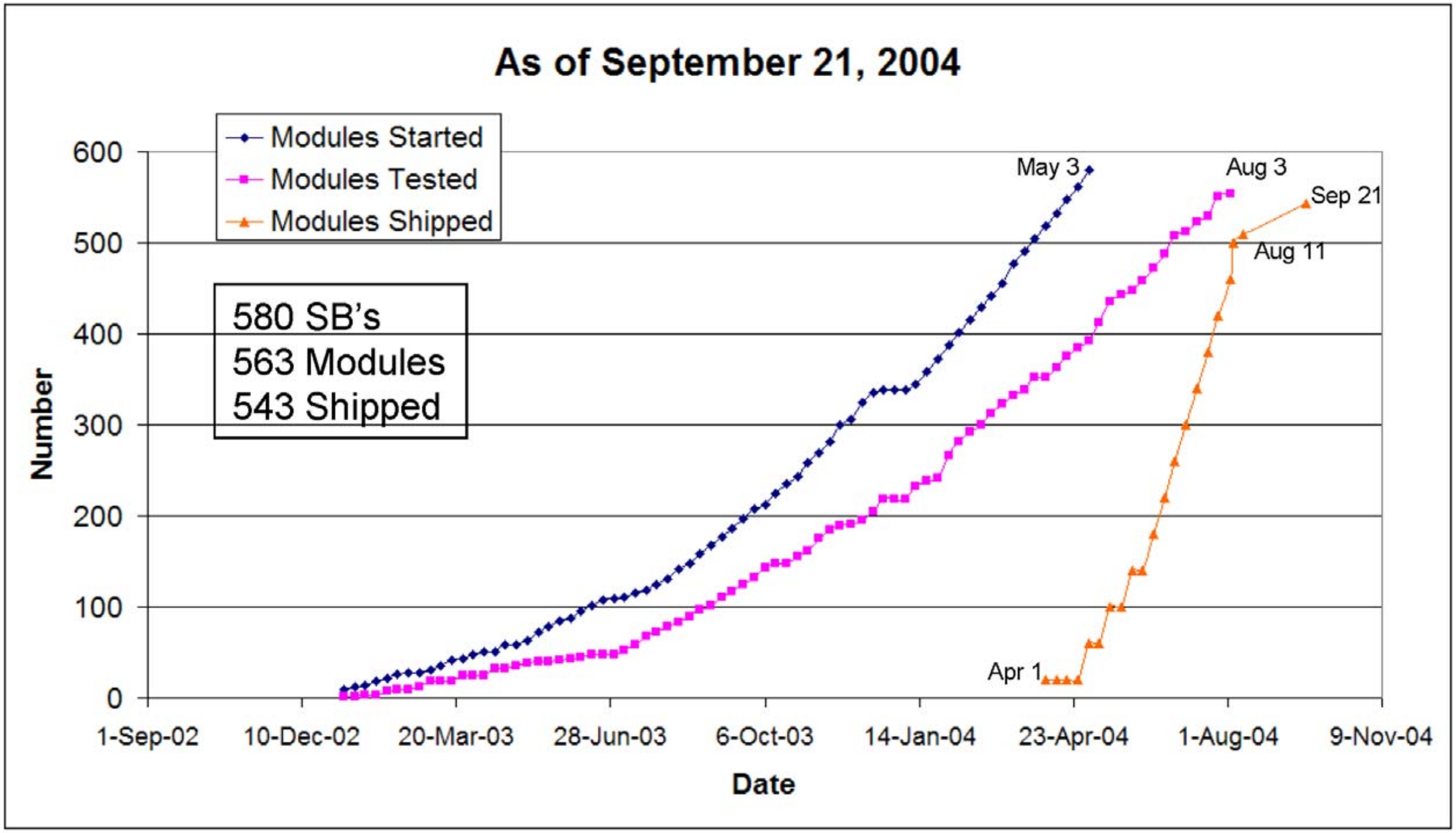
# SCT Module Production

- Assembly of modules took place in large clean room in Bldg 50 (part shown on left).
- Testing of modules took place in temporary clean room in Bldg 50 (right).

- Module assembly required alignment of sensors to better than 10μ, followed by about 5000 wire-bonds. Each module required about 30 hours to assemble.
- Module testing includes about 10 different digital and analog tests of modules, thermal cycling and long-term operation at 0C, followed by final geometry checks.
- All assembly and testing steps checked/qualified between multiple production sites.

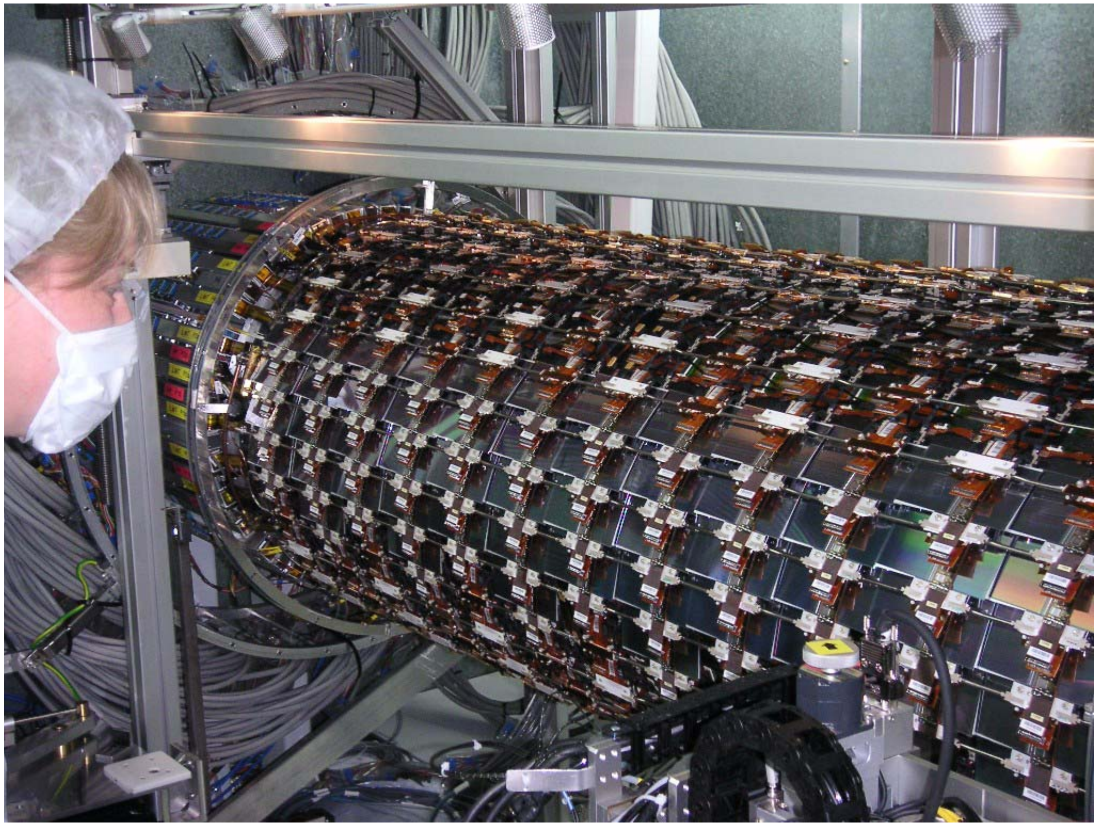
# SCT Module Production Status

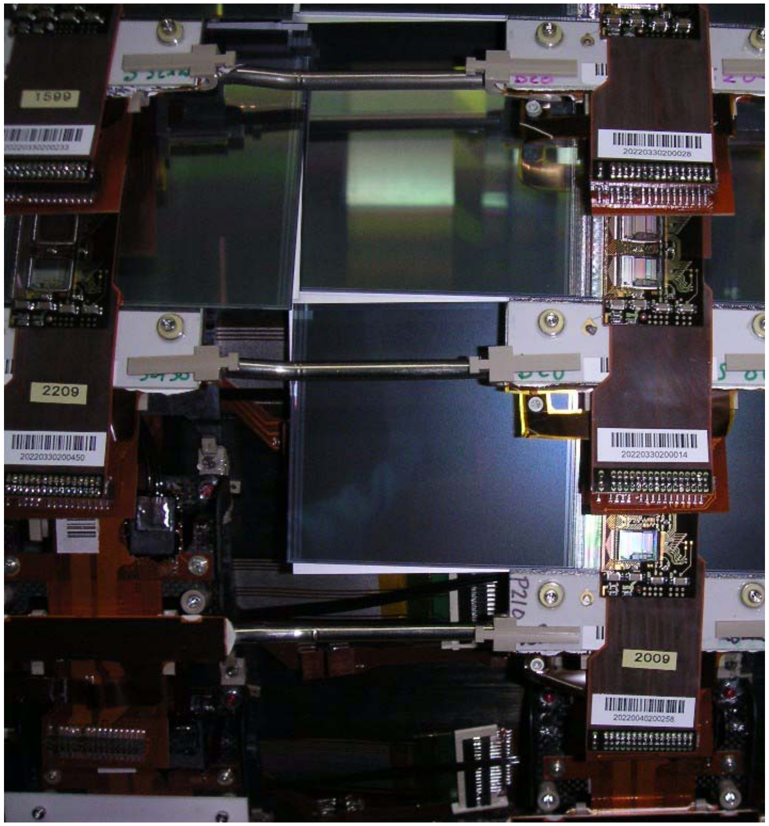
- **Barrel Module production finished !**




- Yield of high quality modules was 83%, similar to the other three assembly sites (UK, Scandinavia, and Japan).
- All US modules have now been shipped to the UK (Oxford) barrel assembly site.

# LBNL Modules at Oxford:

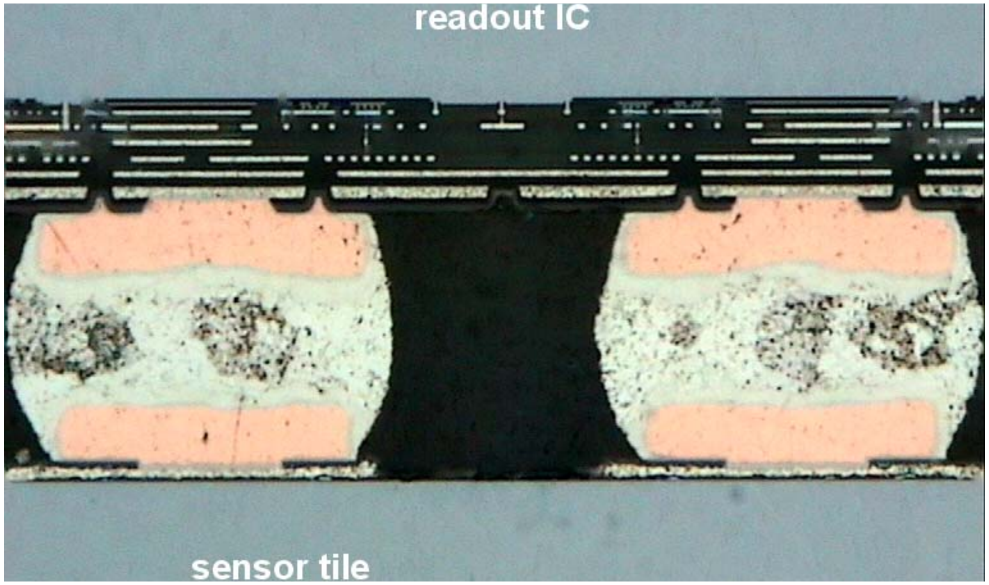





- LBNL Physicist A. Ciocio at Oxford surveying mounted modules on Barrel 3...

# Pixel Tracker Overview

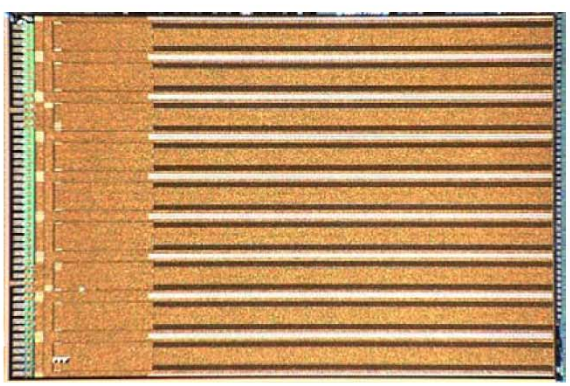
- LHC radiation levels prohibit operation of silicon strip detectors below radii of about 25cm, due to both occupancy and leakage current effects. A much more ambitious approach is needed, with fine segmentation in both directions to give "pixels"
- Lifetime dose expected for electronics in the pixel volume is 30-50MRad, and instantaneous fluences are as high as $3 \times 10^7$ particles/$cm^2$/sec.
- ATLAS pixel tracker is based on pixel size of 50μ x 400μ. This provides lower occupancy, better signal/noise ratio, and greater radiation tolerance. Also, a channel count of 80 million !
- The basic building block is an advanced front-end chip, closely integrated with a silicon sensor. The channel density is 5000 channels/$cm^2$. Non-commercial bump-bonding is used to implement connections between sensor and electronics.



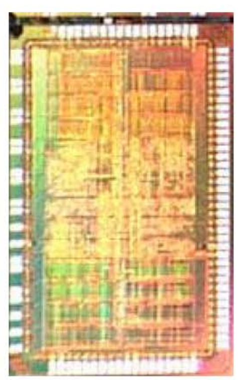

- Section shows 25μ diameter Solder bumps connecting sensor (bottom) and FE chip (top).
- Sensor and electronics are separated by only 10-20μ.
- Can see single-metal sensor design and six-metal CMOS electronics design.

- Readout electronics faced many obstacles to develop needed level of integration, as well as extraordinary radiation hardness and SEU-tolerance. The on-detector chipset required many years of R&D, and was finally implemented in 0.25μ commercial CMOS with modified layout rules to provide radiation hardening.
- Many challenges associated with integrating fast digital electronics into dense matrix with analog front-ends and sensors, while keeping noise to about 200e and avoiding pick-up effects. Significant "tunability" required to cope with transistor parameter changes during irradiation. Result is a 3.5M transistor "system on a chip", one of the most complex ever developed in HEP.
- LBNL led the FE chip development, and the overall integration of 0.25μ chipset for on-detector electronics. Following FE chip (2880 channels, 16 per module), a controller chip builds events, and two chips provide interface to optical links used to send clock/commands to modules, and return data 100 meters to counting room:

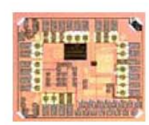
Front End Chip
2880 channels



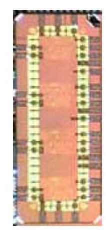
**Module Control Chip**
Manages data & control between module's 16 chips



Optical interface chips

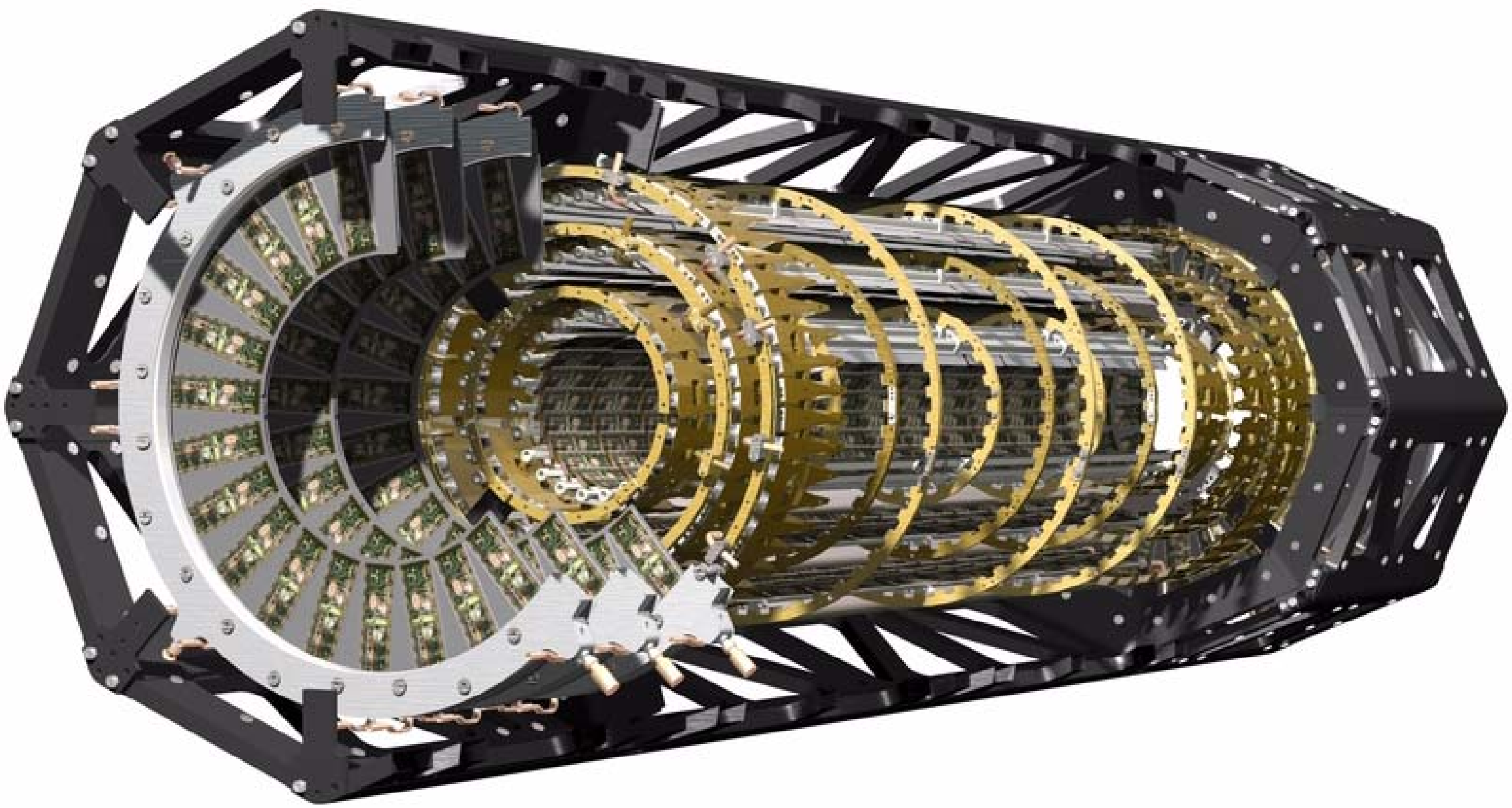


**Doric**
(from PIN diode to decoded LVDS)



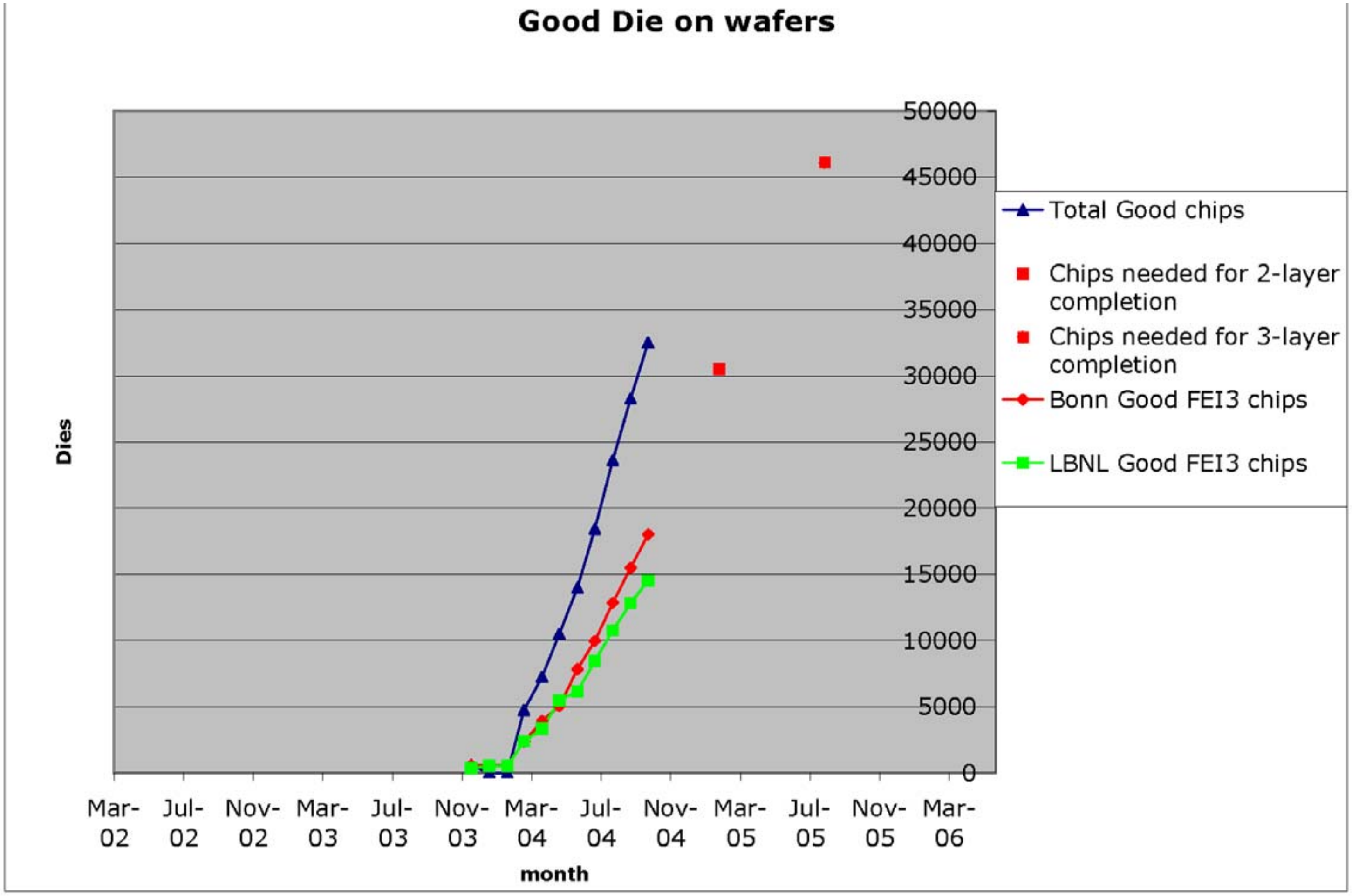
**VDC array**
(from LVDS to laser diodes)

- Physical size of pixel tracker is roughly 1.6m long, with 0.2m radius. It contains 1744 modules, spread over three barrel layers (1456 modules) and three disk layers (288 modules).
- Innermost layer is at 5cm radius, providing best possible impact parameter resolution, within the limits of the beampipe radius.
- Operating temperature is -7C for modules, to preserve sensor performance. Use evaporative fluorocarbon cooling system operating at -25C to remove about 10KW.
- Typical power consumption during operation will be about 3500A at 2V.



# Status of On-detector Electronics

- Production versions of opto-chips and MCC were submitted in Aug 2003. Due to the limited quanitites needed, a single engineering run produced all of these chips.
- FE chip production order was 246 8" wafers. Have now received 80% of production order, and tested 60%. Average yield for recent wafers has been about 85%.




- Testing has given 32,517 good die so far. Predict final total of 56K good die.

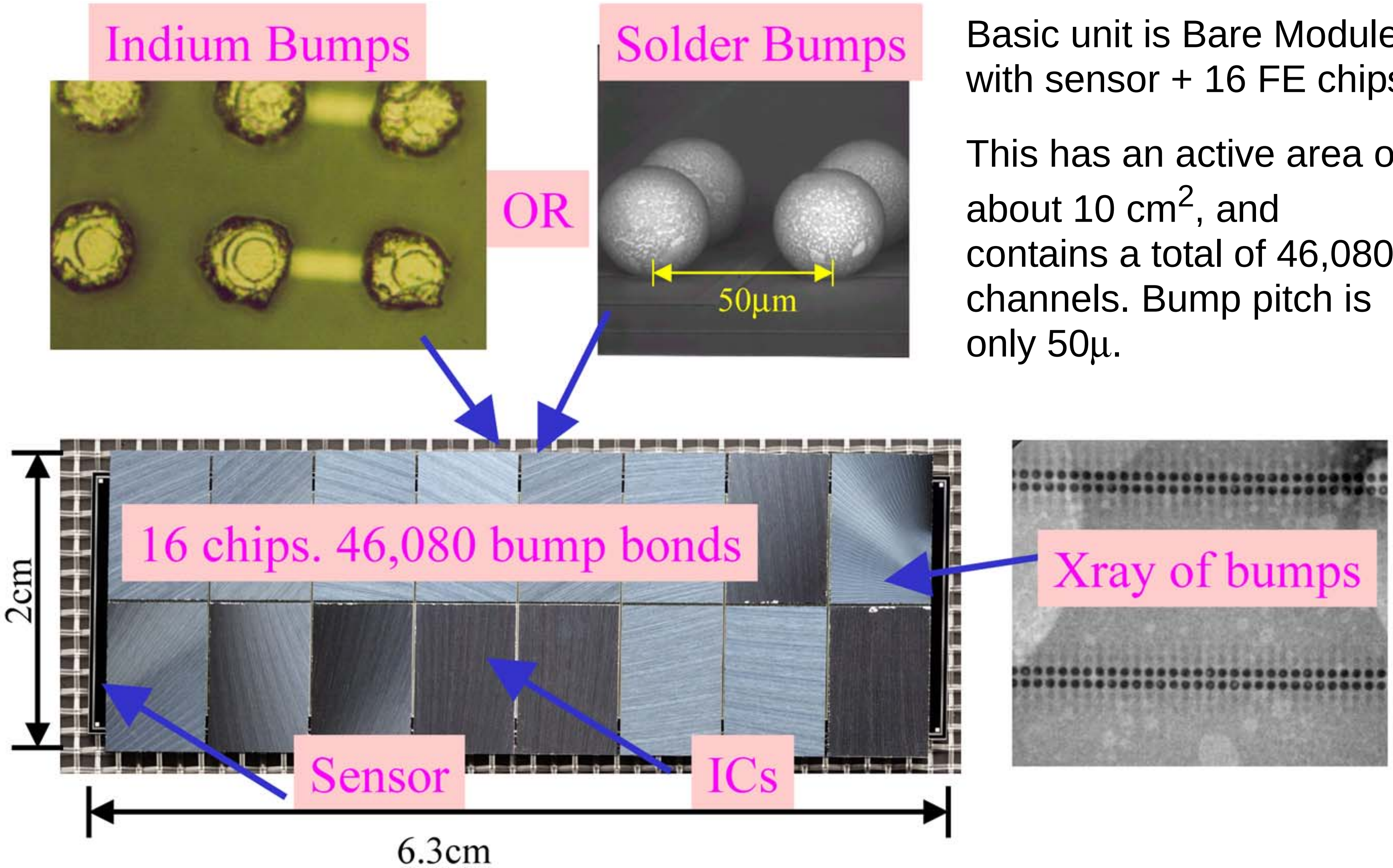
# Pixel Module Production

## Assembly Steps:

- Key steps are bump-bonding and flip-chipping. Two vendors chosen: AMS (Rome) does Indium bumping, and IZM (Berlin) does solder bumping.

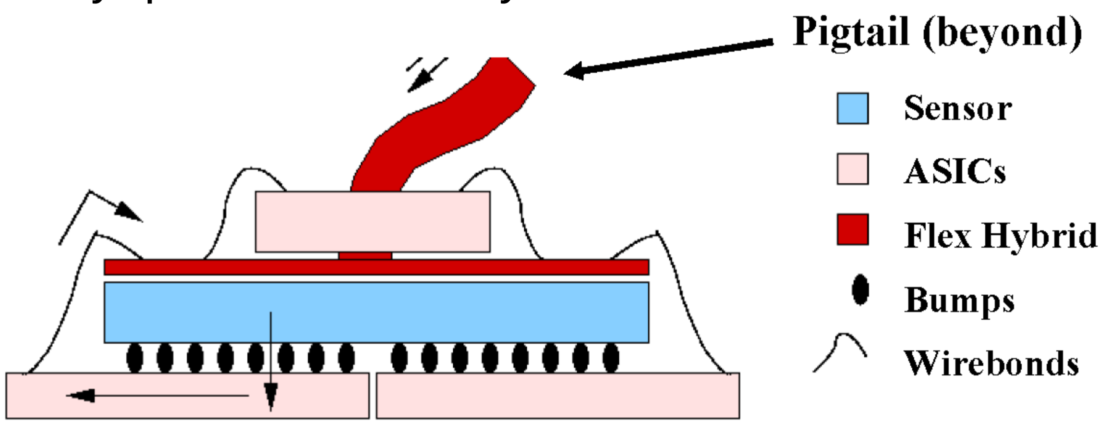
Basic unit is Bare Module, with sensor + 16 FE chips.

This has an active area of about 10 $cm^2$, and contains a total of 46,080 channels. Bump pitch is only 50µ.

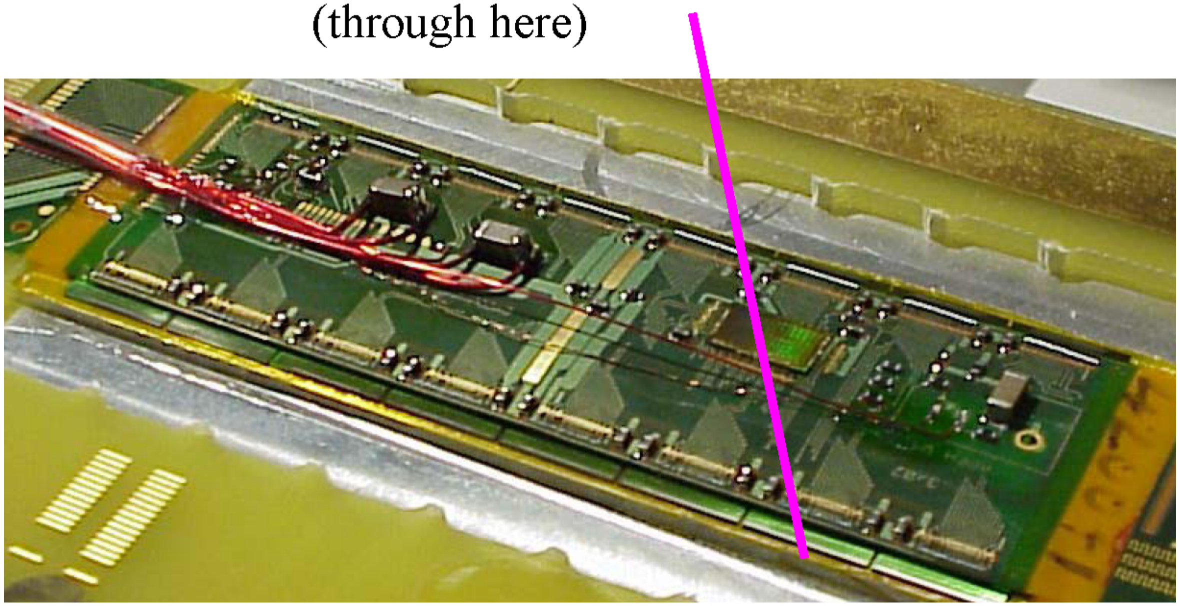


# Module Assembly:

- Bare Module is beginning of assembly process in institutes. LBNL is one of three fully qualified assembly sites, with two more sites in the qualification process.




Schematic Cross Section
(through here)



**Assembly steps include:**

Loading Flex hybrid, and wire-bonding MCC.

Attaching micro-cable (disk) or pigtail (barrel) and testing.

Gluing Flex to Bare Module

Wire-bonding between FE chips and Flex

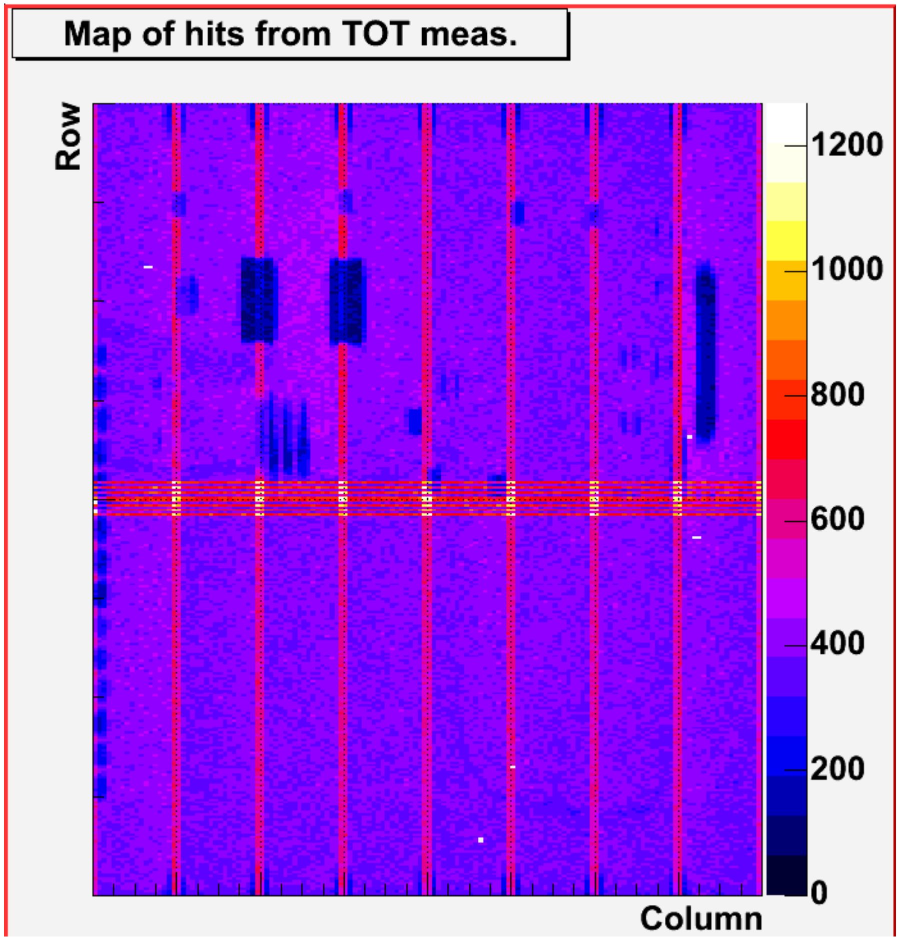
Disk module shown here, attached to assembly jig.

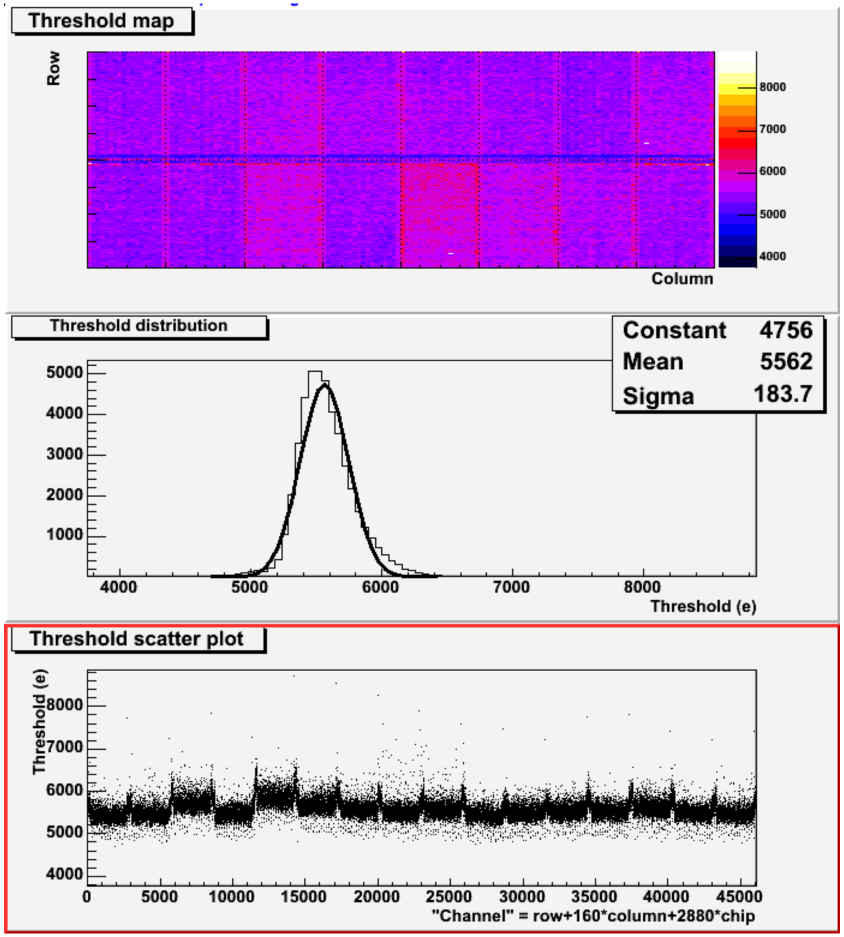
Flex is cut at edge of sensor prior to assembly to final mechanical structure.

- Assembly going well, limited by bare module delivery, 100 modules built at LBNL.

# Module Testing:

- Once modules are assembled, very extensive test program is performed. Including initial room-T testing, followed by burn-in and thermal cycling for 48 hours with constant monitoring, followed by second room-T test looking for any changes during burn-in. Final module tests done at -10C operating temperature, and exercise all aspects of module performance, including X-ray source tests.



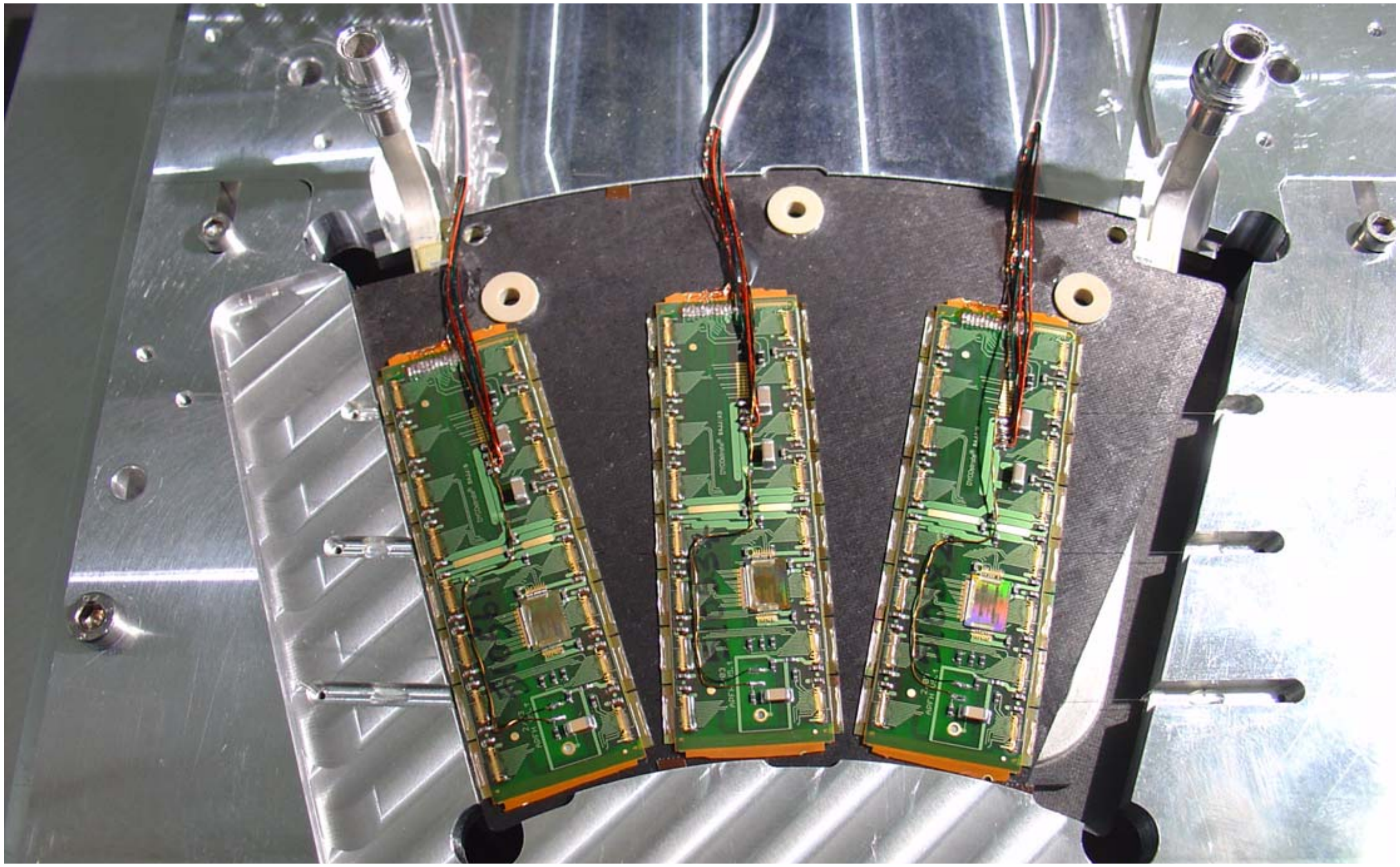




- Left plot is pixel occupancy for Am241 scan, right plot is in-time threshold scan.

# Pixel Detector Assembly

## Assembly of Local Supports:

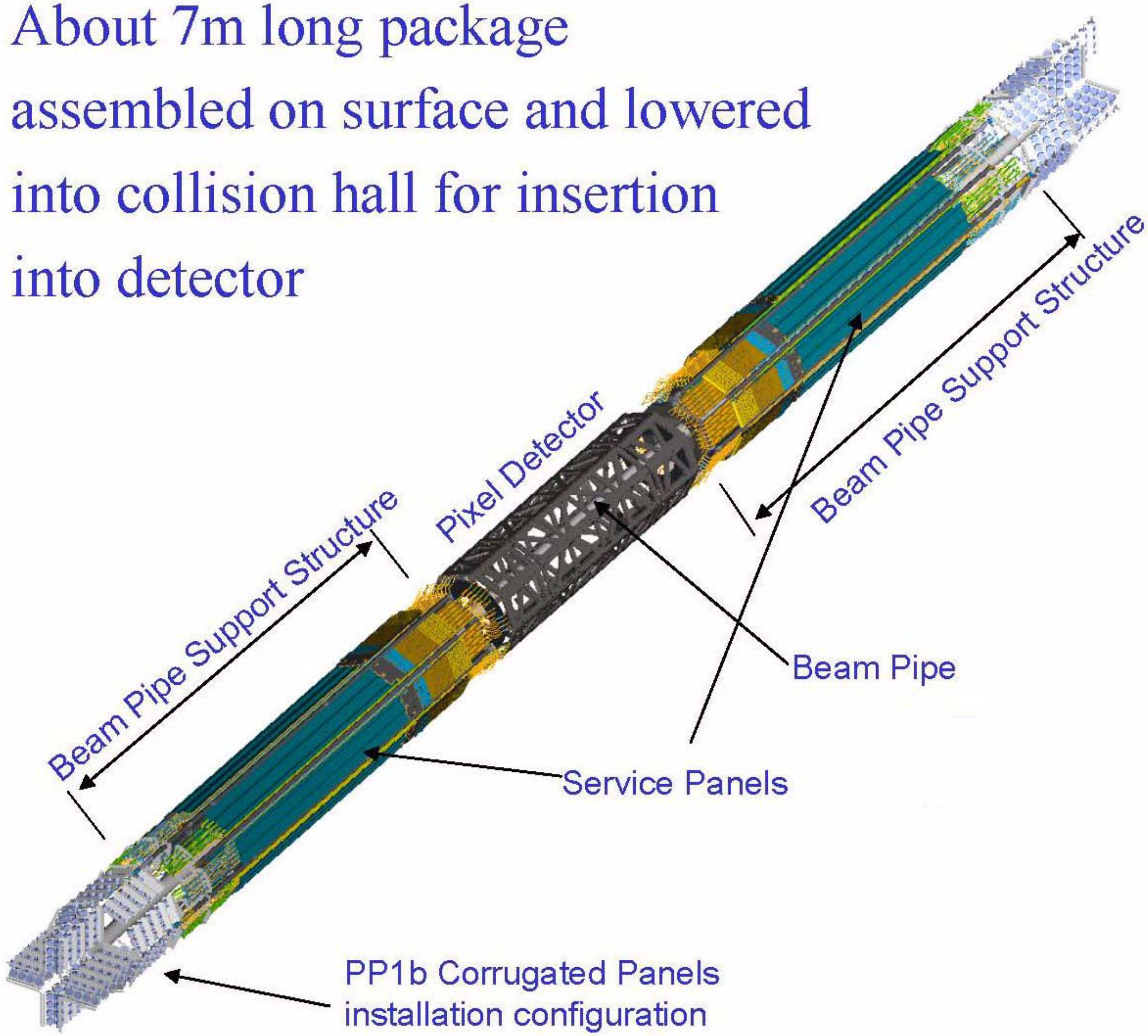
- Disk region is an LBL responsibility, and consists of sectors, each with 6 modules (3 on each side). Eight sectors form a disk, and there are three disks on each end.
- Sectors consist of carbon-carbon face plates and Al cooling pipes. Have produced about 20 production disk sectors so far.
- Production sector loading began in September, and three sectors are loaded so far.



# Pixel Mechanics Production

## Pixel Package is deliverable to ATLAS:

About 7m long package assembled on surface and lowered into collision hall for insertion into detector




**Package includes:**

Pixel detector in Global Support Frame

Service panels, containing connections for electrical, optical, and cooling services.

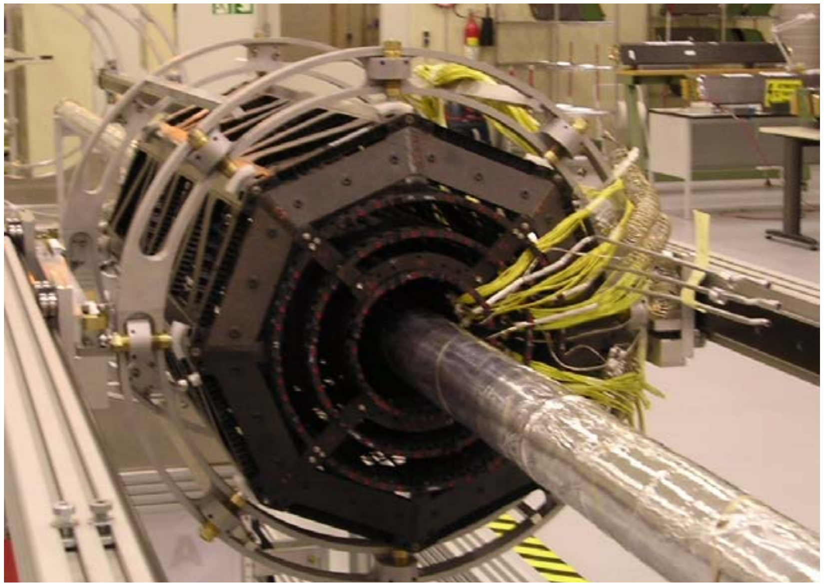
Beampipe (VI) and Beampipe Support System (BPSS).

Pixel Package is then lowered into UX15 inside of DST (Dummy Support Tube), and slides into PST (Pixel Support Tube) pre-installed into SCT.

- Global Support, Service Panels, BPSS, and PST are all LBL deliverables.

# Mechanics Status:

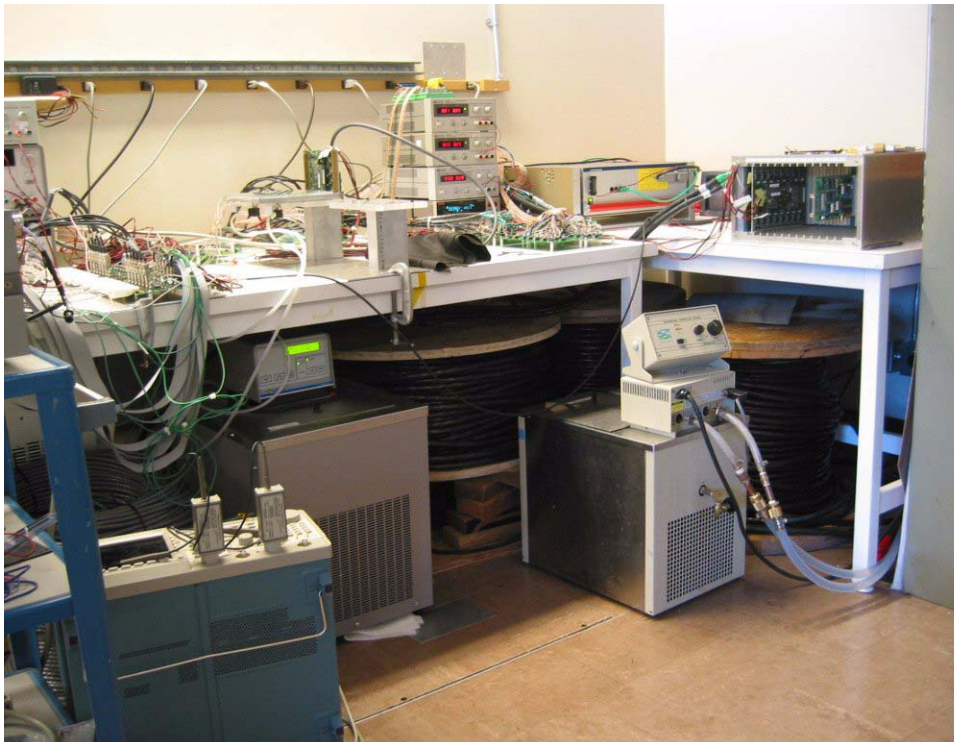
- All major mechanical structures now delivered or in final stages of fabrication. Photos are (clockwise): Pixel Support Tube prototype, Global Support Frame, Trial fit of Global Support and Barrel Half-shells at CERN, and Disk Support Rings:

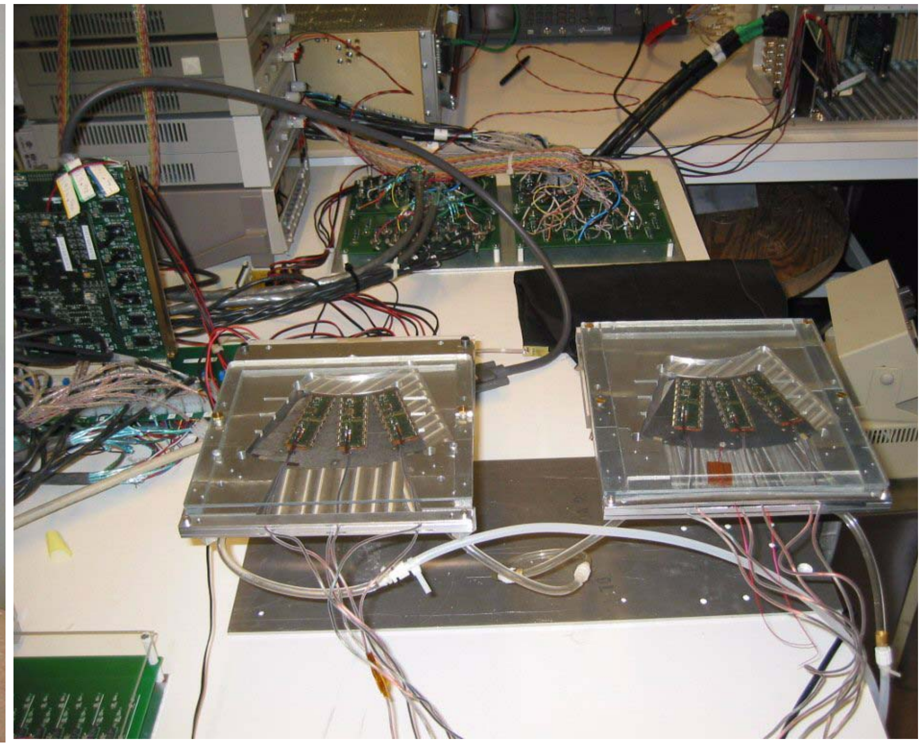


# Pixel Detector Test Results

## System Tests at LBNL (roughly 1% of complete detector):

- Have carried out systematic studies of complete system of LV/HV power supplies with services of nominal 100m length, connected to pre-production pixel modules attached to mechanical structures:

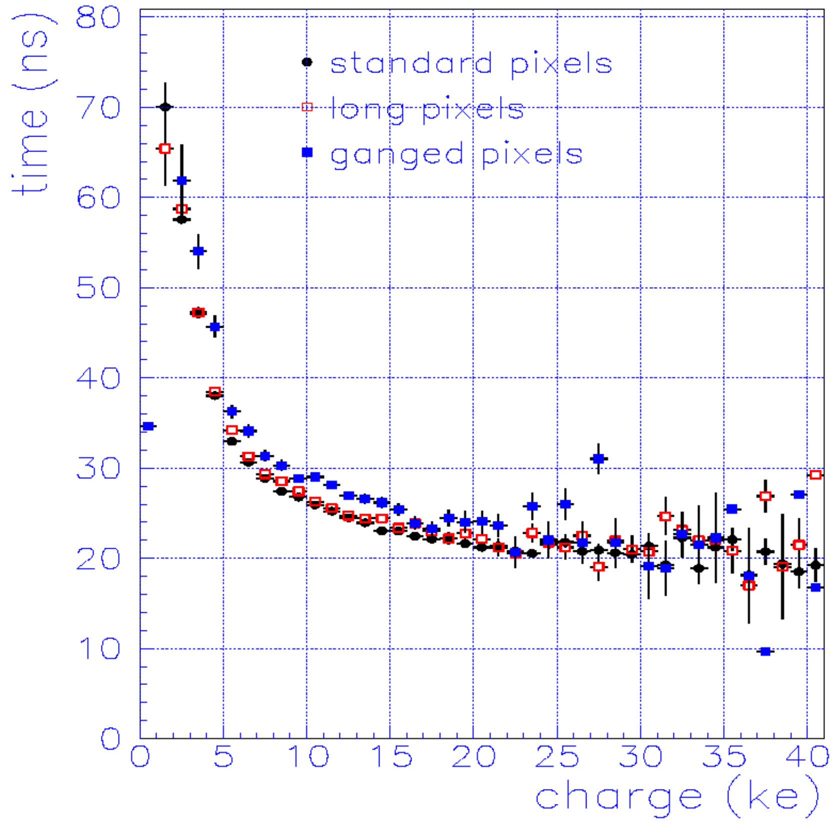


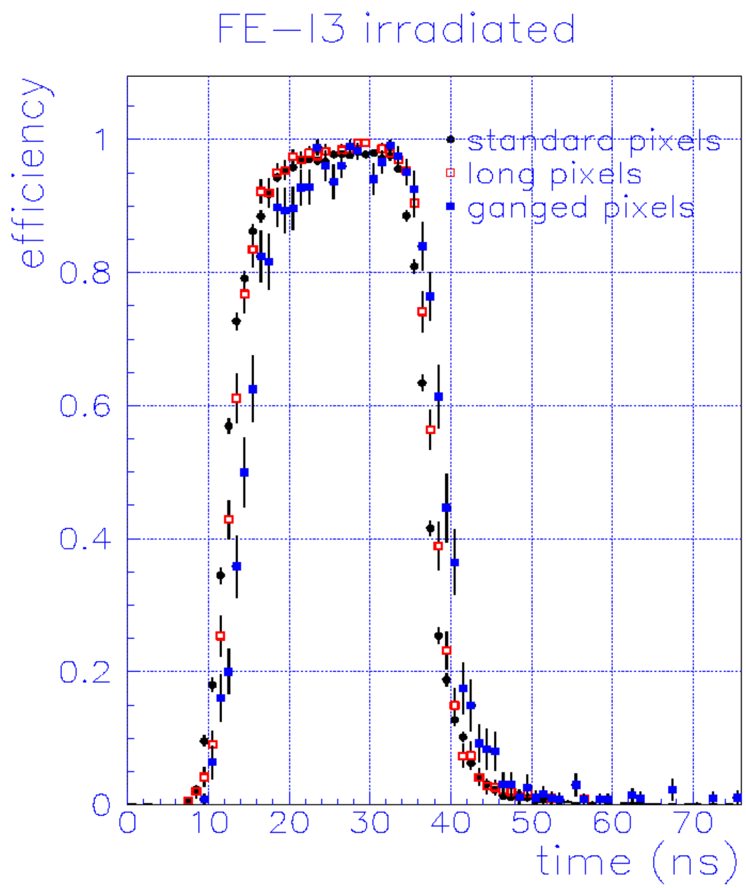


- Operation is quite robust, and even attempts to inject noise into the mechanical support structure show no significant effects.
- Studies continuing, including long-term operation with thermal cycling.
- Studies using actual off-detector readout system are also underway.

# Irradiations and Stand-alone Testbeam (at CERN):

- Detailed studies of production modules, both un-irradiated and irradiated, in H8 testbeam. In-time ε=99.9% (pre-rad), ε = 98% averaged over 7 (post-rad) modules.

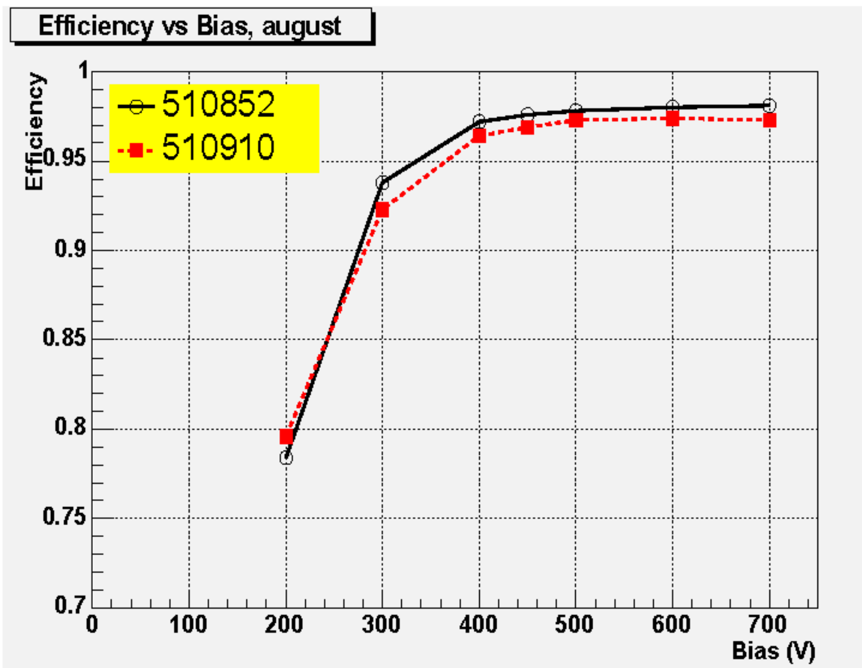


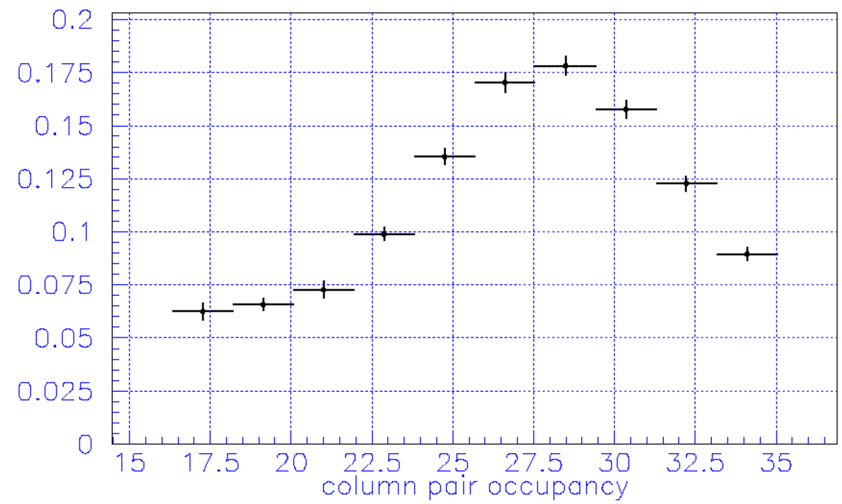



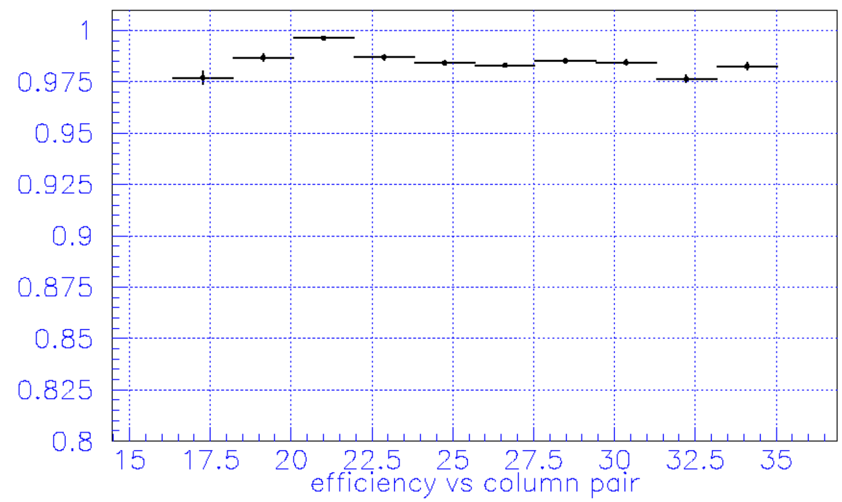

- Plot on left is timing performance versus charge for hit, showing excellent performance down to about 5Ke charge, as indicated by in-time threshold plots.
- Plot on right is in-time efficiency for different pixel types, showing uniform results, and efficiency plateau of about 10ns width.

- Left plot shows in-time efficiency versus sensor bias voltage for irradiated module, showing plateau above 400V (nominal operating voltage is 600V post-rad):

Full efficiency at 400-500 V




- Lower right plot shows in-time efficiency for irradiated module at full B-layer intensity ($3\times10^7$ particles/cm$^2$/sec, occupancy of 0.15 in a column-pair of FE chip).

# Inner Detector Upgrade Activities at LBNL

- Expect to replace innermost pixel layer (B-layer) on a timescale of 2011-2012. This layer defines impact parameter resolution for B-tagging, and is critical to ATLAS performance. Will concentrate on improvements in micro-electronics and sensors.
- Longer term CERN planning has targeted next upgrade as a factor 10 luminosity increase to $10^{35}$, known as SLHC, perhaps in about 2015. US ATLAS organized a first workshop in Jan 2004 to begin discussion of concepts for upgrades. Some first US ATLAS R&D activity along these lines is beginning in FY05 at LBNL.

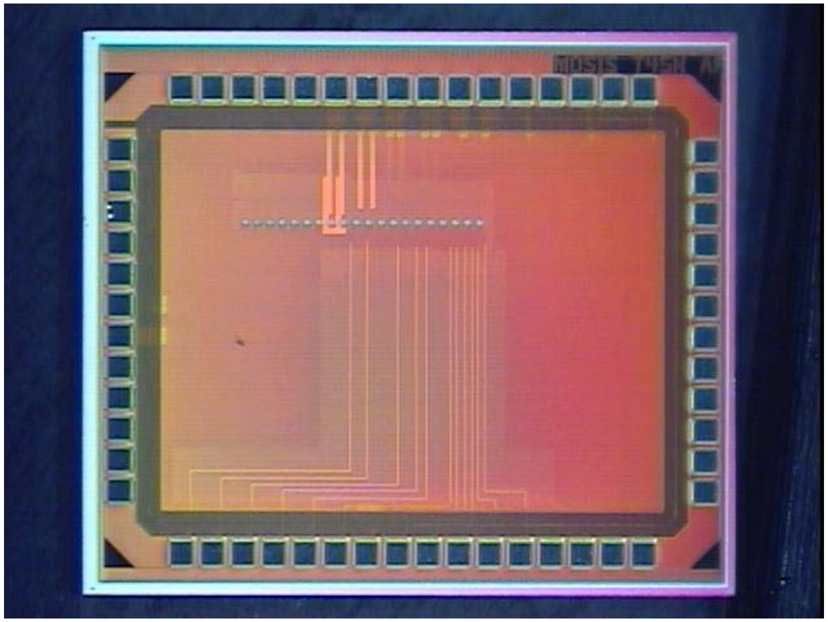
## Outer Silicon Upgrades:

- Effort beginning on integration of services into mechanical structure to reduce material. Based on developments coming from CDF Run2b silicon effort.
- This could lead to significant reductions in material in next-generation tracking systems for particle physics (not only for SLHC, but potentially for ILC as well).

CDF Ladder:
length = 60cm

# Pixel Upgrades:

- Performance of hybrid pixel system driven largely by front-end electronics. High dose environment implies that optimal design would attempt to use most advanced commercial CMOS processes available (but process must offer reasonable analog as well as digital performance). Long learning curve for cutting-edge processes.
- Designed a first test chip in IBM 130nm CMOS technology (most advanced mixed-mode CMOS process available to us today), and submitted in May via MOSIS:

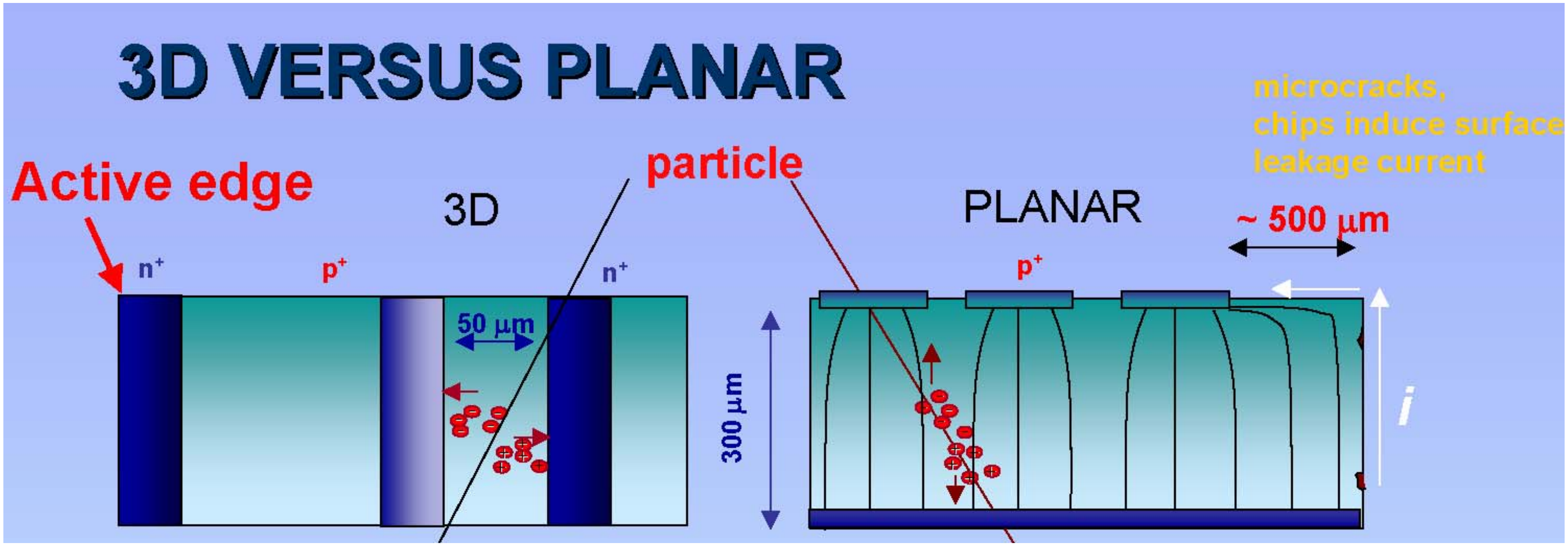


Test chip addresses two sets of issues:

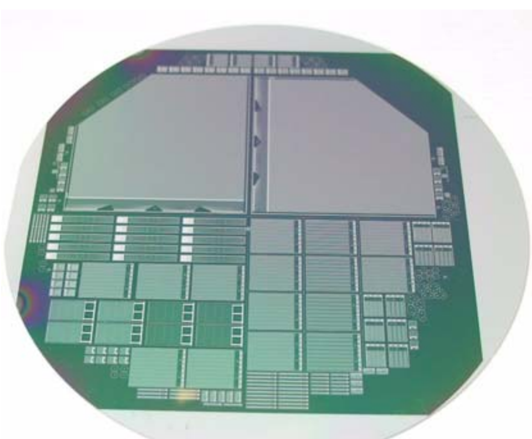
- First, will examine performance of different SEU-tolerant storage schemes.
- Second, will study agreement between simulation and measurements for pixel front-end design (preamp/discriminator) based on present FE-I3 design, to learn more about pixel analog design issues.

- Next steps are to characterize this first test chip, and work towards more complete designs over the next two years. Limited support available from US ATLAS Research Program, LBNL Engineering Division, and LBNL Physics Division.

- Proceeding in collaboration with 3D sensor effort, and will evaluate performance of this novel sensor concept using current production pixel electronics.




- 3D design approach is radical departure from traditional planar silicon sensors, and has potential to provide greater radiation hardness due to short collection length.



First prototype run by C. Kenney and S. Parker at Stanford Microsystems Lab has produced prototype 3D sensors matching the existing pixel FE-I3 geometry.

Will bump-bond these to existing FE chips and study performance, both before and after irradiation.

# Comments on Upgrade Work at LBNL:

- Pixel activity is a partnership, capitalizing on extraordinary LBNL teams in mechanics and electronics, and very close integration between engineers and scientists during all stages of the project.
- LBNL also has strong partnerships with university groups (both US and European in ATLAS), enabling them to play a larger role in challenging instrumentation projects, and in turn we reap the benefits of working with many first-rate groups.
- LBNL has been the intellectual leader of the ATLAS pixel effort in large part because of this unique environment. Capabilities developed in this project have been of great benefit to the rest of the lab as well, particularly in the area of micro-electronics.
- The trail-blazing work in using 0.25μ CMOS technologies for pixels has led to new applications for beyond state-of-the-art instrumentation for synchrotron radiation facilities, electron microscopy, and X-ray astronomy.
- Next steps in micro-electronics, into 130nm and beyond, should provide comparable advantages for novel instrumentation systems. It makes sense for LBNL to nurture such efforts, as the knowledge and skills acquired produce many synergistic developments in instrumentation for a wide range of science fields.

# Silicon Tracking: Next Year and Beyond

## SCT:

- SCT production now completed, and entire effort ramping down to close to zero. LBNL will have a limited involvement in integration and commissioning at CERN.

## Pixel Tracker:

- Pixel production solidly underway. Expect to be shipping first major components to CERN in first half of 2005. Will have a significant role in pixel integration and commissioning, which will require continuous presence of a number of engineering and physics personnel in Geneva beginning next year (about 7 people).
- Integration activities of electronics and mechanics will take place at CERN during 2005 and 2006. Installation of pixel package should be in Fall 2006, followed by extensive commissioning work within the overall ATLAS context.

## Software (physicist software related to pixels):

- LBL will also play a modest role in ID/pixel reconstruction software, due to our specialized knowledge of the design and construction of the pixel detector. The scope of this activity is not yet defined.

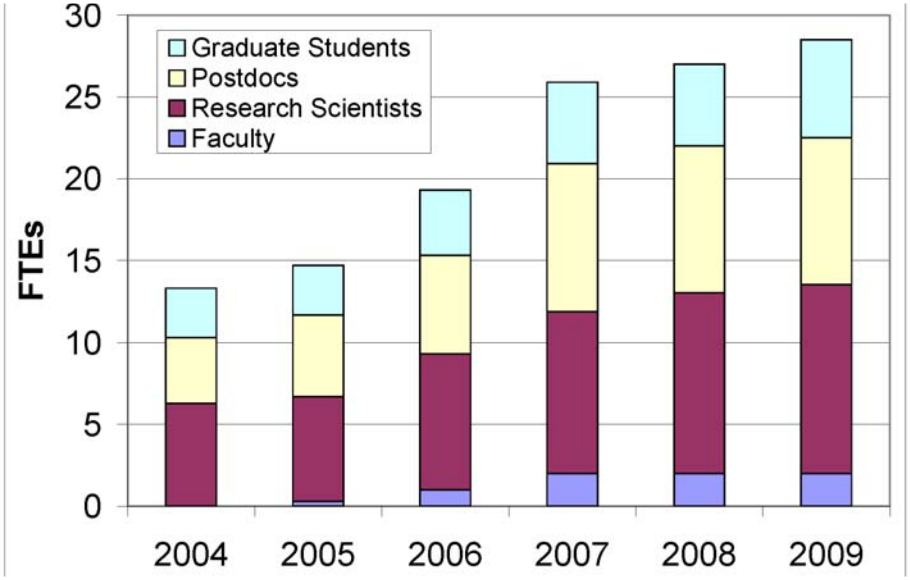
## Upgrade work:

- Upgrade R&D work needs to continue at reasonable level to retain our leadership roles in critical technologies. Expect modest funding from US ATLAS.

# Planning

## Towards Physics:

- Significant increase in simulation and analysis areas needed to prepare for initial ATLAS physics, and benefit from decades invested in reaching the TeV scale.
- Presently have one postdoc and one senior physicist working in Physics area. Remaining manpower is already over-committed with existing responsibilities.
- During last year, LBNL ATLAS group hired four postdocs, the most recent will arrive in Feb 2005. We are searching for another postdoc and a Divisional Fellow now. Will continue recruiting aggressively to ramp up for LHC turn-on.
- Physics Division has an overall manpower plan for ATLAS, which includes continued ramp-up of postdoc level within the local group to about 8-10 by 2008, as well as a second Div Fellow search in 2008.




Asymptotic planned staffing levels look adequate for our program, but no guarantee we will get there...

The ramp-up has been delayed by funding issues, and manpower will be very tight for the next two years.

# Summary

- LBNL ATLAS activities in silicon tracking are very substantial, and are progressing well. SCT Module production has now finished, and everything has been delivered.
- Pixel project is in full production now, in all areas. No major technical obstacles seen, but a vast amount of work remains to be done. LBNL have been leaders in this effort for many years, including Electronics coordination (K. Einsweiler) and Module coordination (M. Garcia-Sciveres). Beginning in Mar 05, K Einsweiler is overall Project Leader. Expect to continue with a large role in future upgrades.
- In 2005, will begin delivering major pixel components to CERN, and will establish a significant presence at CERN for integration and commissioning work.
- LBNL has a critical role in the core software for ATLAS, led by D. Quarrie as overall Software Project Leader, and including a team of four other software professionals.
- Also have roles in software for simulation of pixel detector and physics event generation. Expect to develop modest roles in pixel reconstruction software.
- Have a small but very high quality effort in the physics area (I. Hinchliffe and D. Costanzo). This needs to grow dramatically over the next two years, as we begin real physics preparations.
- **Major Challenge:** During 2005 and 2006, we will be very short of key manpower to carry out integration and commissioning obligations, launch healthy R&D efforts towards future upgrades, while becoming fully engaged in physics and computing activities before LHC turn-on arrives.