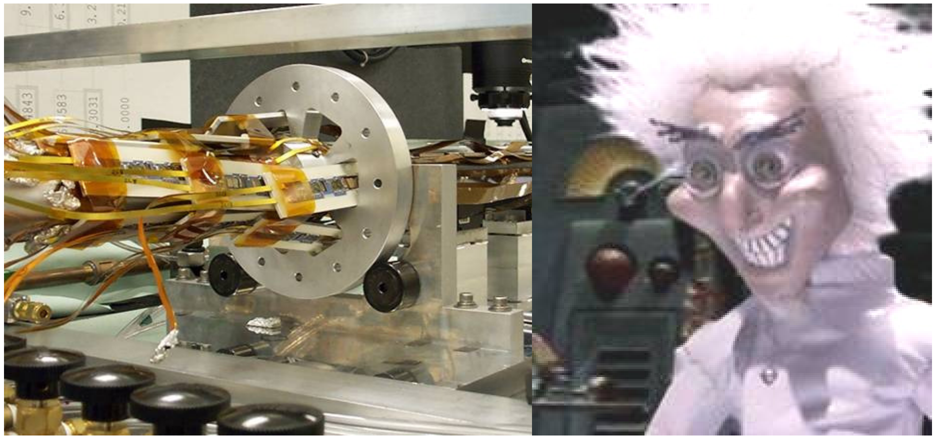
HOW TO BUILD YOUR OWN SILICON DETECTOR

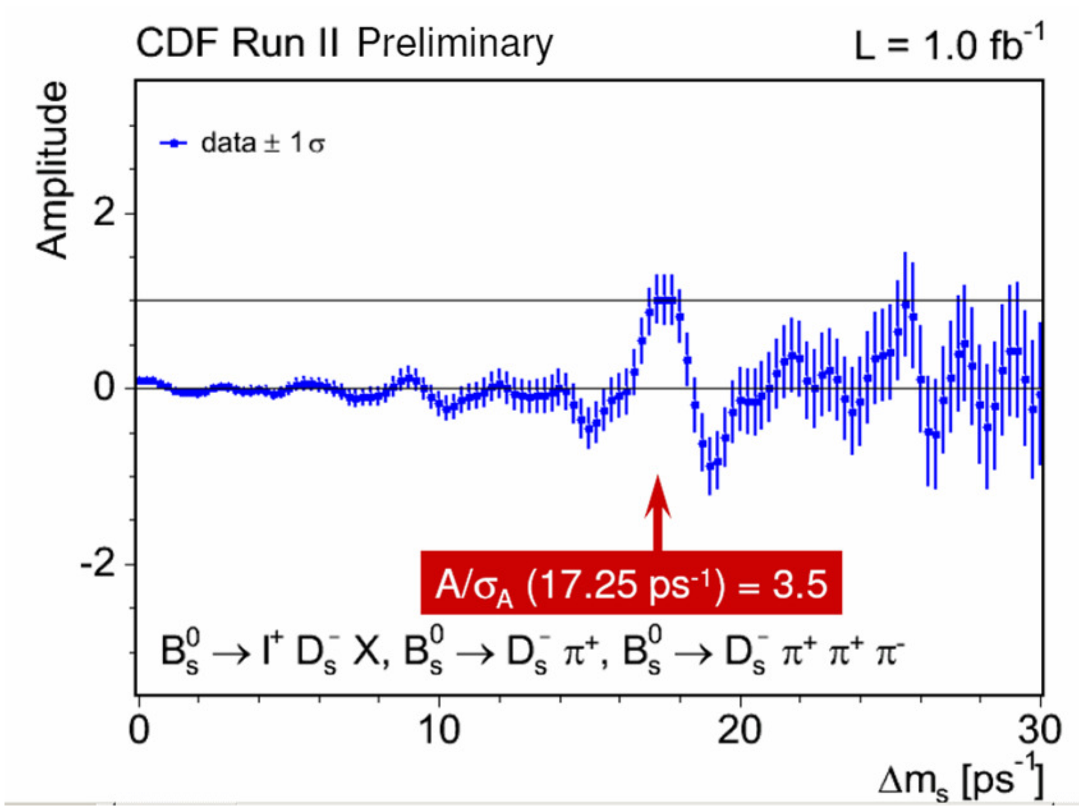


Maurice Garcia-Sciveres
LBNL Physics Division

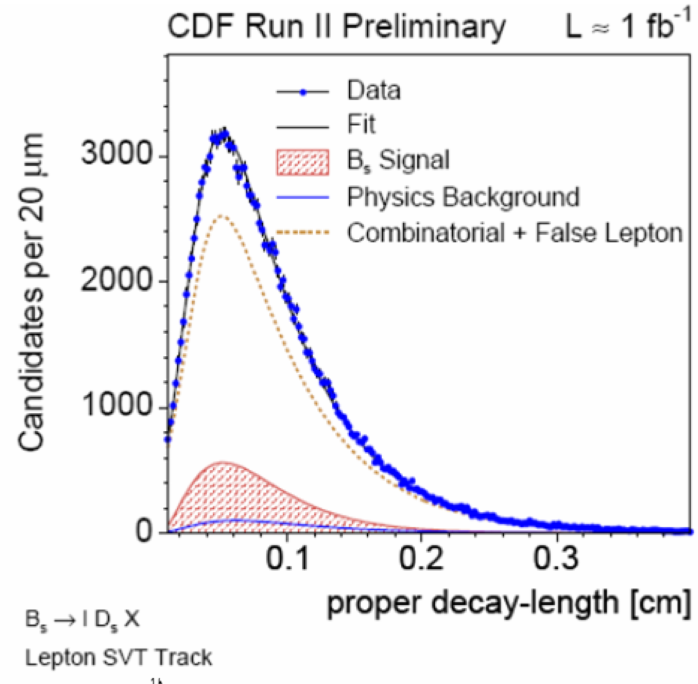
April 19
Interdisciplinary Instrumentation Colloquium

Preface: First direct measurement of B_S Mixing announced last Wednesday!

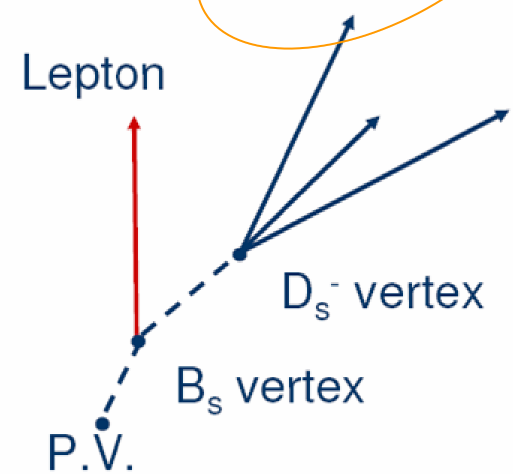
Data from CDF experiment at Fermilab's Tevatron collider

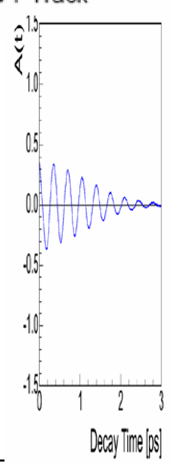


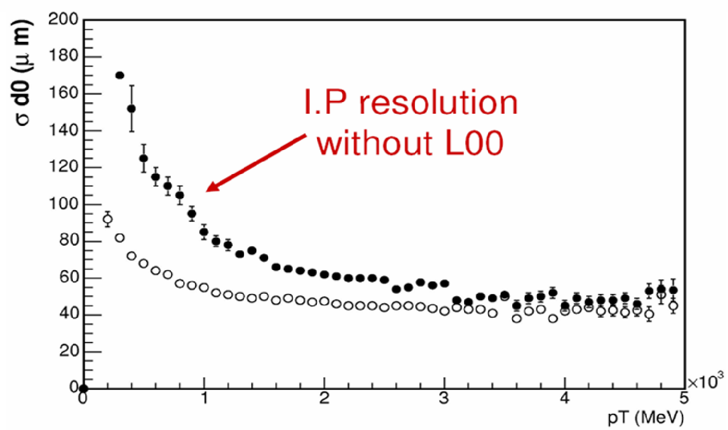
Silicon detector physics at its best



$$ct^* = \frac{L(lD) \cdot m(B)}{p_T(lD)}$$ ~ ½







Introduction

Having to do with silicon detectors, but (naturally) construction methods not in scope on talk

Except this one.
IC's are a big part, but not the whole story…

This talk is chapter 2

(still not the whole story though)

Past Presentations

15-Mar-2006
Compton Telescopes for High Energy Astrophysics (4.3 MB) by Steven Boggs,
01-Mar-2006
Specific Heat Measurements of Films and Crystals Using Si-micromachined Nano-calorimeters Frances Hellman,
15-Feb-2006
Semiconductor Radiation Detector Materials - Fact versus Fiction (7.2 MB) by Eugene Haller,
01-Feb-2006
Cancer "genomics" - Technological opportunities in cancer biology and management (7.0 MB) by Joe W. Gray,
02-Nov-2005
How to Design an Integrated Circuit (5.4 MB) by Peter Denes, Engineering Division,
19-Oct-2005
The Allen Telescope Array: A New Telescope For SETI and Radio Astronomy (13.7 MB) by Dave DeBoer,
05-Oct-2005
3D Silicon Detectors (15.3 MB) by Sherwood Parker,
21-Sep-2005
Molecular Electron Microscopy - Applications and Challenges (slides not available) by Ken Downing,
7-Sep-2005
Is Anybody Out There? Instrumentation for SETI (7.3MB) by Dan Werthimer
24-Aug-2005
Who needs better nuclear detector materials and how do we find them? (5.5 MB) by Stephen E. Derenzo,
20-Jul-2005
One-Dimensional Nanostructures as Subwavelength Optical Elements for Photonics Integration (by Peidong Yang,
29-Jun-2005
The STAR Detector at RHIC (7.4 MB) by Jim Thomas,
15-Jun-2005
From Quarks to Quasars - Advanced Scientific CCDs (23.6 MB) by Stephen Holland,
18-May-2005
The Superconducting QUantum Interference Device: Principles and Applications (16.2 MB) by John Clarke,
4-May-2005
Biological Large Scale Integration (slides not available) by Stephen Quake,
13-Apr-2005
The ATLAS Pixel Detector (3.6 MB) by Kevin Einsweiler,

Which Silicon Detectors?

- There are literally hundreds of silicon particle detectors world-wide (and soon in space) in many types of experiments
- **Narrow down focus of this talk to detectors at colliders (not even fixed target!). Many things generalize.**
- There are still dozens. LBNL had or has major involvement in silicon detectors for
  - **CDF** and D0 at Fermilab
  - Babar at SLAC
  - **ATLAS** at CERN
  - Star at BNL
  - ILC R&D

Most of my direct experience (CDF, ATLAS)

- There are additionally important contributions to other experiments (for example by providing IC technology or even actual ICs)
  - CLEO at Cornell
  - NA60 at CERN (actually fixed target)
  - Phenix at BNL
  - Others I forget or don't know about

Where to begin?

- Consider chips, sensors, performance specs as given
- How do you put them together?
- Isn't this the same problem as building laptops or digital cameras? (Why not just go to manufacturers that do that and have them do it?)
- Yes and no.
  - Not quite the same problem
  - Those manufacturers won't have anything to do with us:
    - Vertical integration within huge company
    - High volume and proprietary solutions
    - Do not do work for others
    - Big defense industry manufacturers are no different
- The industry term for what we want to do is "Packaging"
  - It is a vast field
  - A good reference is IMAPS.org (international microelectronics and packaging society)

Not quite the same as consumer electronics

- Consumer electronics does make all modern experiments possible, but
  - **We have unique constraints that greatly impact assembly**
    - **Our ideal detector is massless**
    - **Detectors go in high radiation environments**
    - **We only ever build one of each, and it has to work the first time**
- From industry we take
  - **interconnection technology,**
  - **manufacturing technology and equipment,**
  - **basic materials such as wire, adhesives, laminates, etc.**
- We then make use of these things in creative ways
- And we insert home-made bits and pieces as needed
- Risk, risk risk!, but often can't be avoided (and sometimes can, but unfortunately isn't)

Technology evolution

- Both industry and detector technology evolve gradually
- Each new detector takes established methods and adds a new twist
- Enough new twists lead to new ways of doing things
- I try to present sharp technology categories for clarity. In reality things are less black and white.
- There are parallel branches which are not necessarily exclusive of one another

Design methods and elements

Increasing channel density

- IC + wire bonding
- Area array bump bonding
- Monolithic
- Further innovation

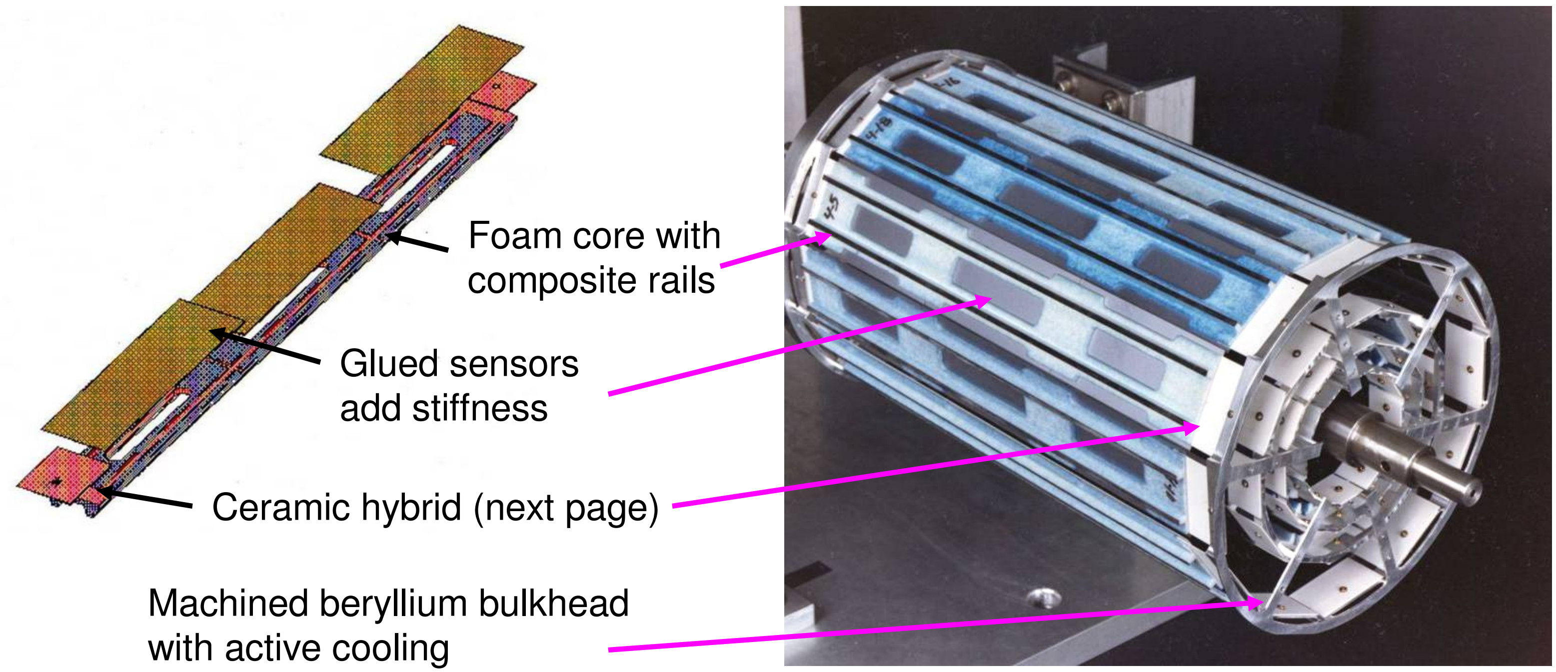
- Ladder
- Module
- Macro-module
- Robotic assembly
- Further innovation

Increasing detector size

- Vertexing
- Tracking

Assembly 101: The barrel of ladders

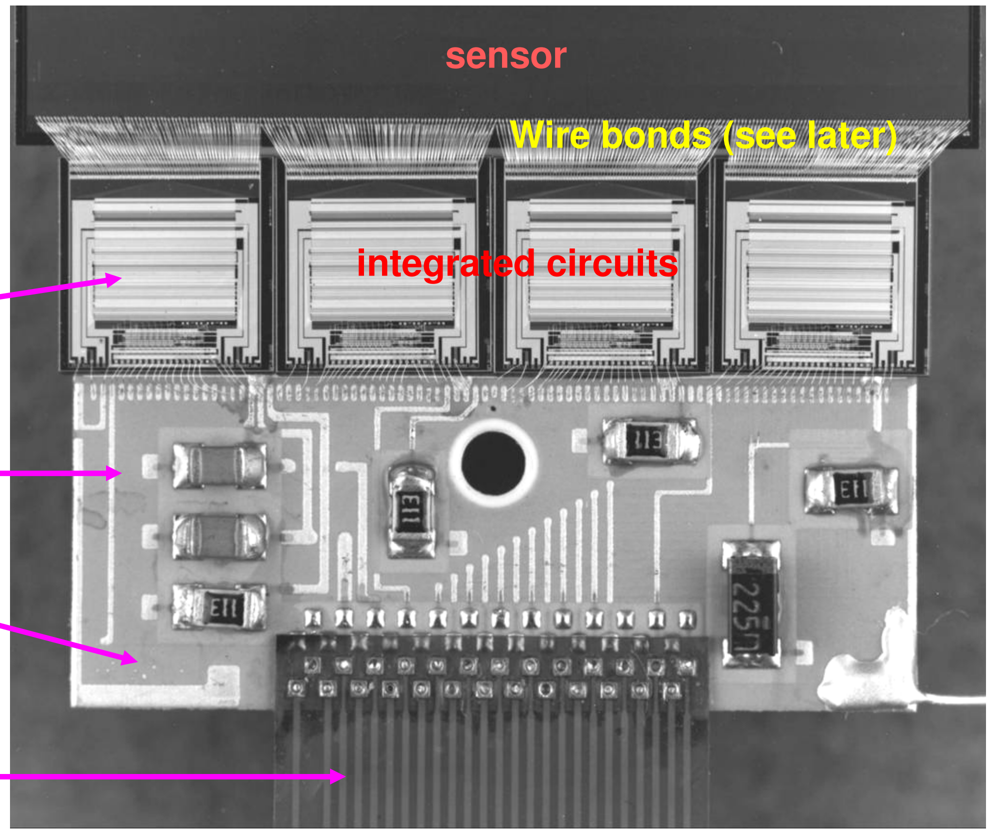
- **Low mass => no thermal mass => cooling must be active**
  - **Need materials with high thermal conductivity and low atomic number**
- **Electrical components (sensors and circuits) can serve mechanical functions to reduce mass**
  - **Rigidity and stability**
  - **Thermal management**
- **The ladder model with a barrel geometry has been very successful**
- **Ideal for geometry with readout at ends only**



Hybrid circuit boards

- The readout electronics at the end of a ladder must be
  - Low mass
  - High thermal conductivity
  - CTE close to silicon
- Integrated circuits need mechanical support and services (external capacitors and interconnects)
- Thick film on ceramic technology
  - we're merely an end user of this industrial technology

Hybrid at end of SVX ladder (1990)



Heat source

Ceramic hybrid

Cooling at this end

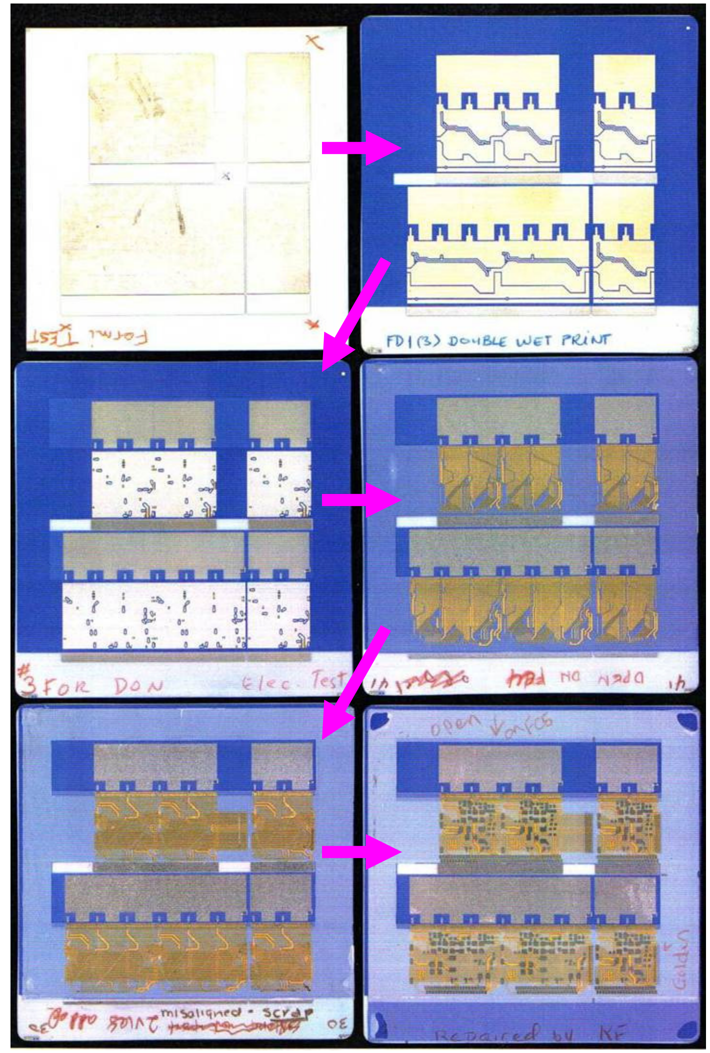
LV power and signal cable to outside world

Ceramic hybrid fabrication

- Conductors and dielectric glazes printed on a ceramic substrate
  - Ceramics have good mechanical properties

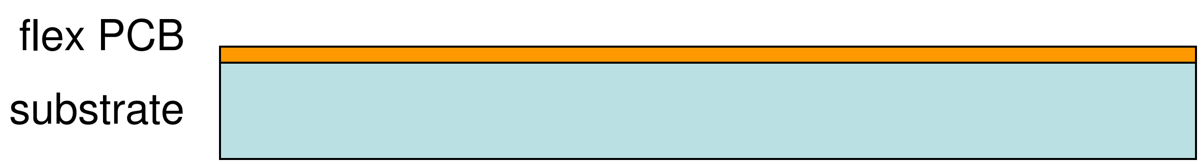
	Rad. Length	T-cond.	CTE/Si
Silicon	9 cm	150 W/m.K	1.0
Alumina	7 cm	25 W/m.K	3.0
AlN	9 cm	160 W/m.K	1.7
Beryllia	14 cm	200 W/m.K	2.7

- Glazes fired at 800-900C.
- This 5 conductor layer circuit has 15 mask steps and 10 firings.
- Unlike IC fabrication, customer can specify steps and materials as well as artwork
  - This can get one into trouble
  - Chemical reactions happen fast at 800C. Minor incompatibilities between materials can have big effects



Flex PCB option

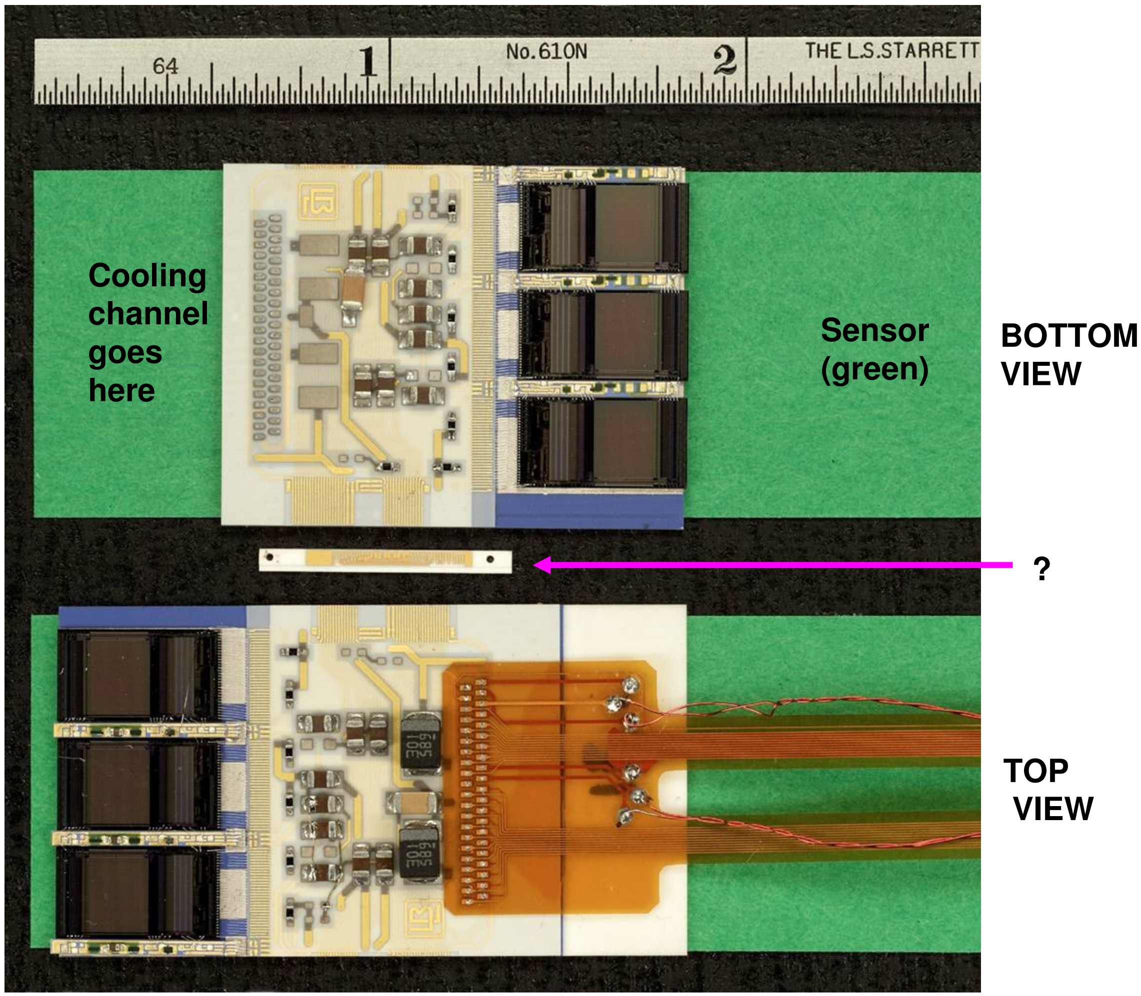
- One can also make a hybrid by gluing a flexible printed circuit board on a mechanically suitable substrate (such as a blank piece of ceramic)
- (Note that rigid printed circuit boards are not mechanically suitable)
- This approach may be favored by certain constraints (have to look case-by-case)
- More on flex later



The ladder pushed further

- Readout ONLY at ends of detector is no longer enough as channel density increases
- Electronics start to intrude into the active area
- Double-sided sensor presents additional complication

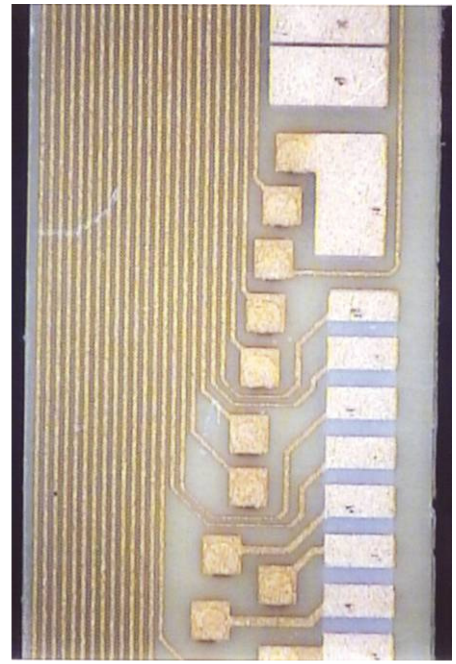
Prototype hybrids for SVX-II detector



Getting around the corner

- One of those home-made elements
- Why not use flex?
  - Depends on available bend radius
  - This part also mirrors all the connections- could not do on flex.
- A mix of thick film filled vias and thin film surface traces
- Manufacturing orchestrated between thick film vendor, thin film vendor, wafer dicing vendor, LBNL shops, and UCB microlab.
- Risk is that in full detector 300 such parts must operate for 10 years. Prototype reliability studies cannot generate the statistics needed to guarantee this.

20μm thin film traces



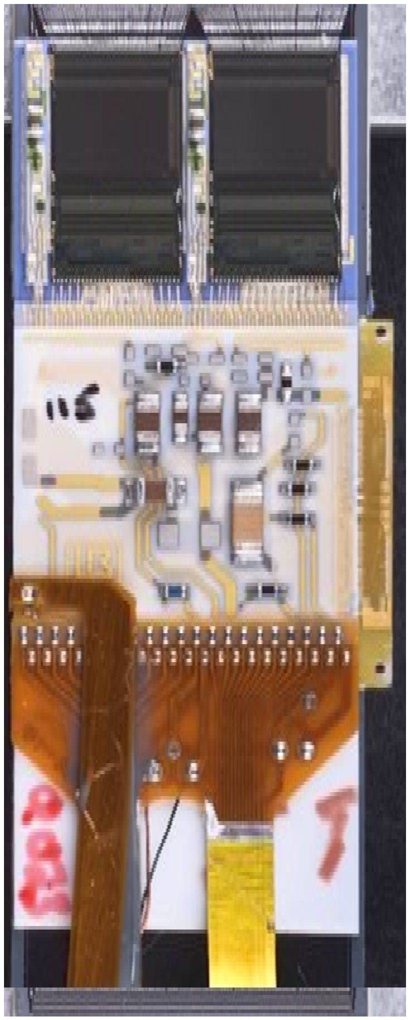
profile

Edge of sensor

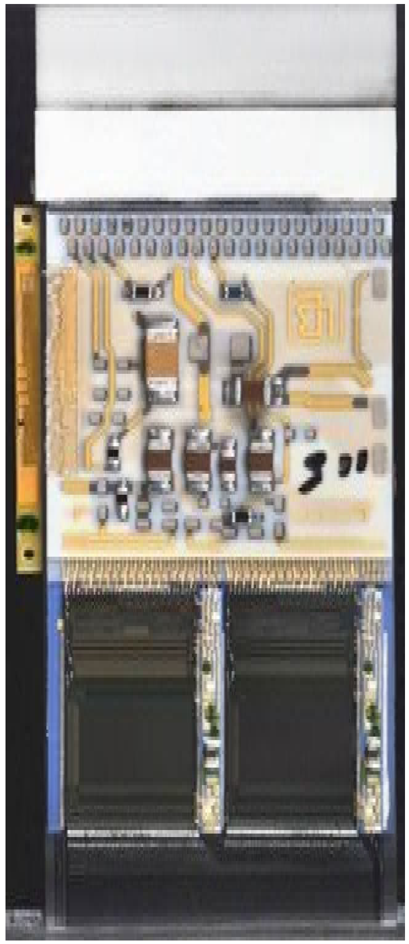
Thick film filled vias through ceramic

Around the corner

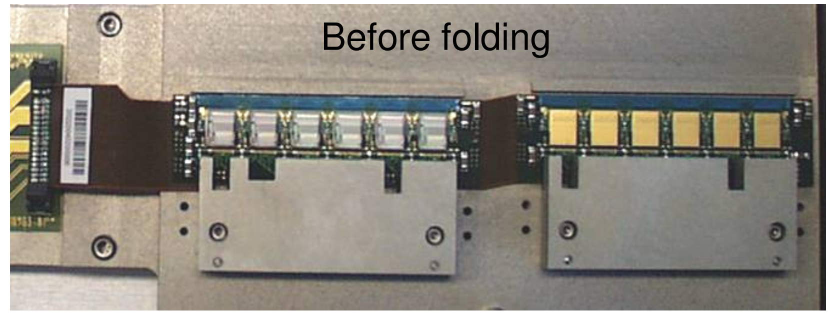
With ceramic jumper

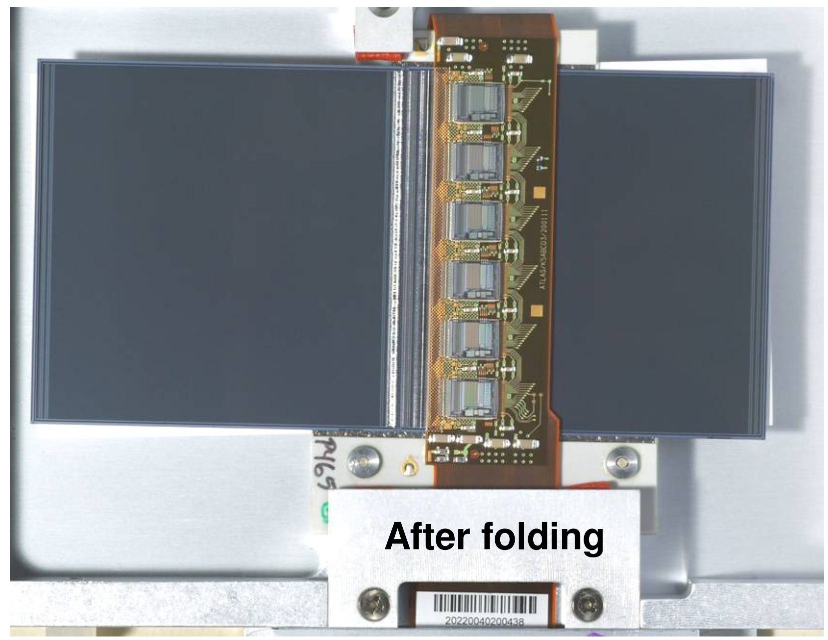


CDF SVX-II L0 ladder



With flex



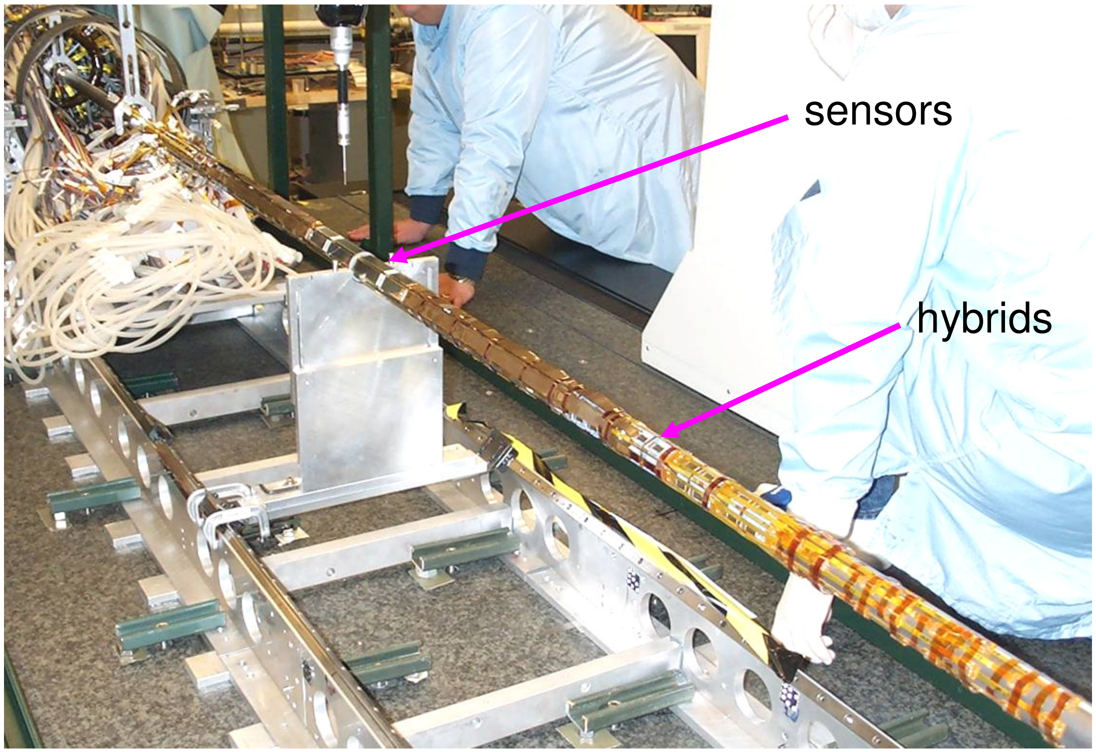


Atlas SCT module

Keeping the electronics away

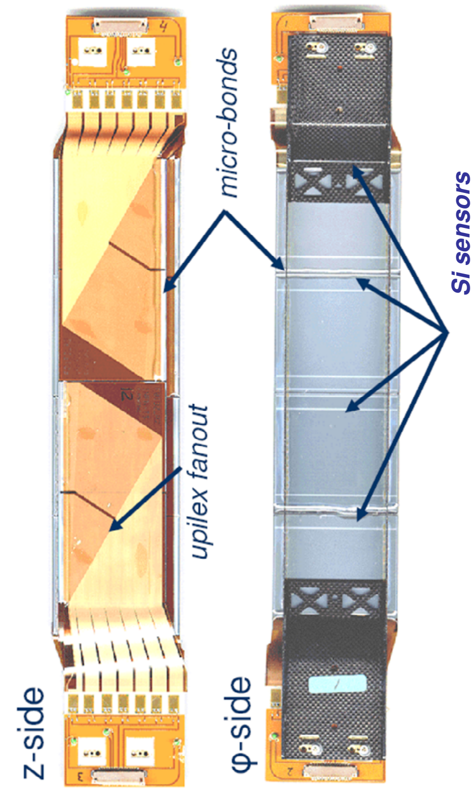
- Have managed to keep electronics out of active area in some cases

CDF Layer 00 (instrumented beam pipe)



BaBar SVT 2-sided ladder

➢Z-side of sensors read out via flex



➢Tricky to get away with this

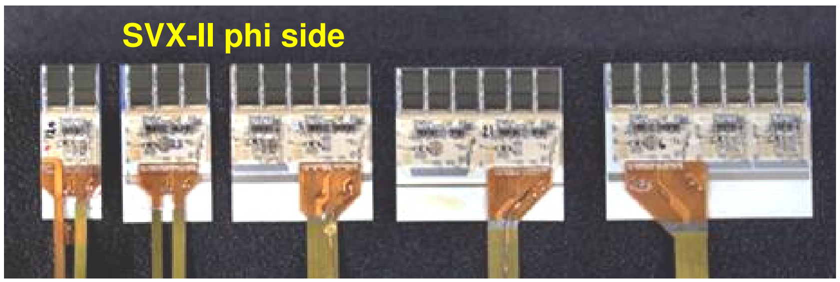
➢Detector has noise issues

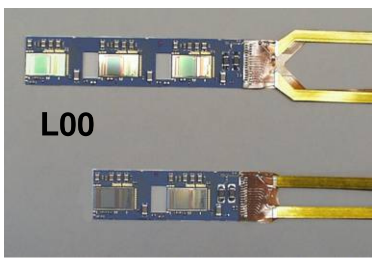
➢It has taken years to produce software and calibrations capable of making the data useful

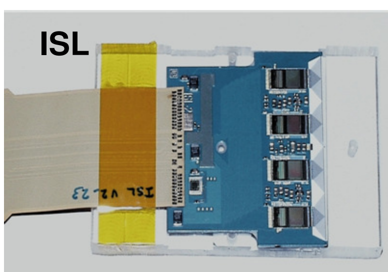
➢Nevertheless, Bs mixing is a very big payoff

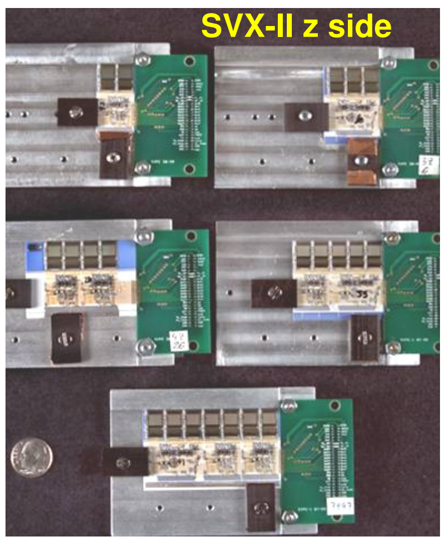
Proliferation of ladder types

13 Ceramic hybrid types (1400 units in total)
for CDF-II silicon

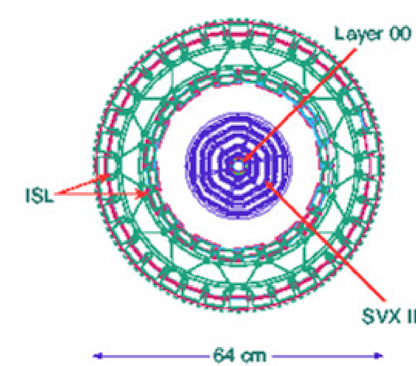




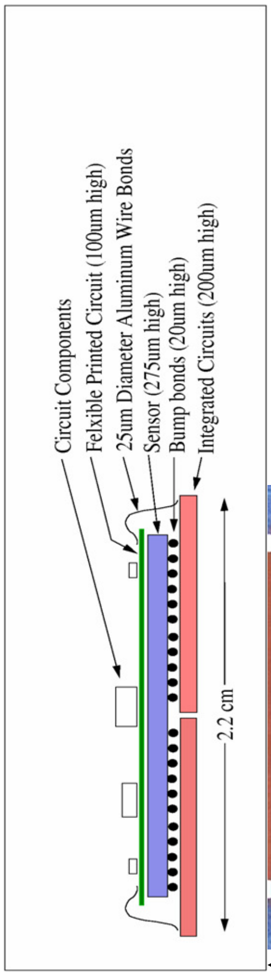




- For any given radial position there is an optimum ladder geometry.
- A detector spanning a large radial range wants to have many types of ladders

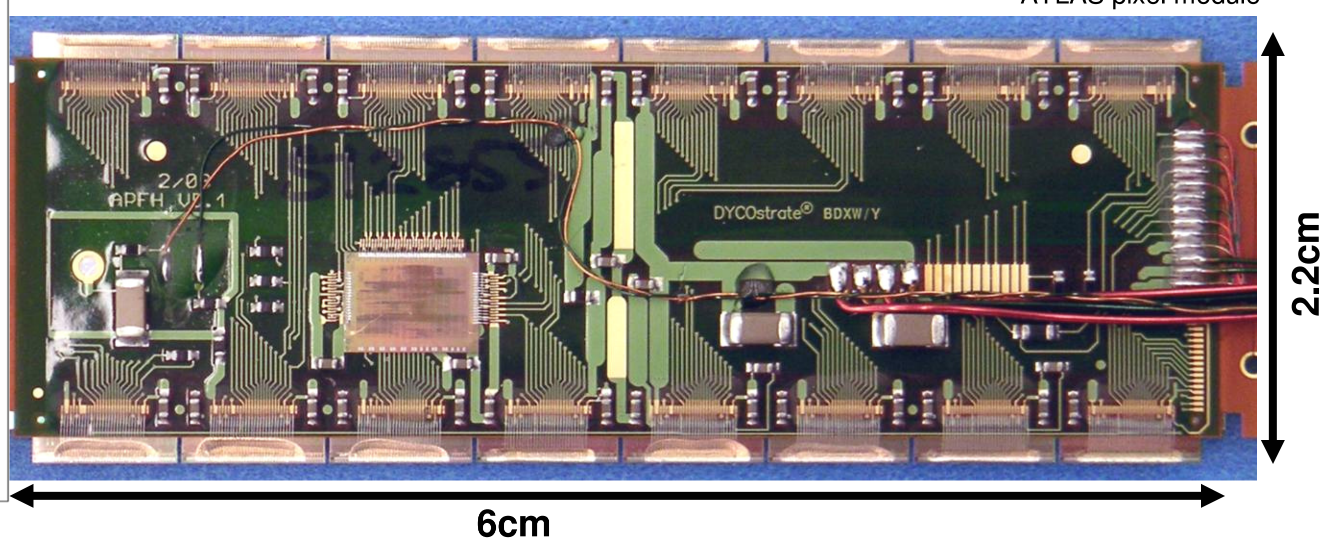


The Module



- As channel density and size increase further the ladder model breaks down.
- The module is conceptually a tile.
  - A passive mechanical skeleton is tiled over with modules.
- In a modular system electronics are distributed throughout
  - Extreme case is hybrid pixels: electronics cover MORE area than sensors.

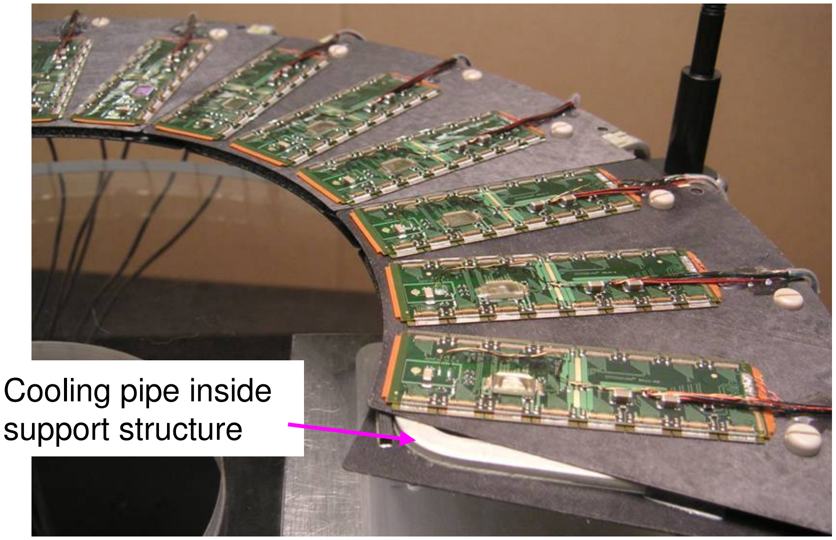
ATLAS pixel module



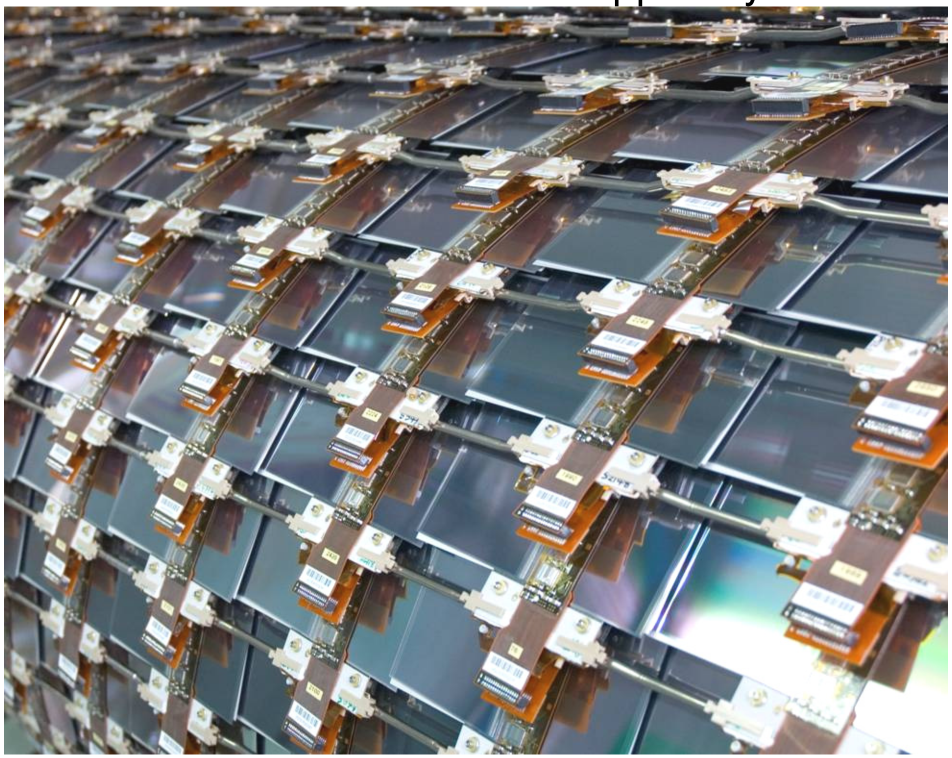
Electrical unit (not mechanical)

- Each module is a unit of electrical functionality
- The mechanical function must be filled by other structures – this is more massive than the ladder approach.

Atlas pixel modules on a disk support

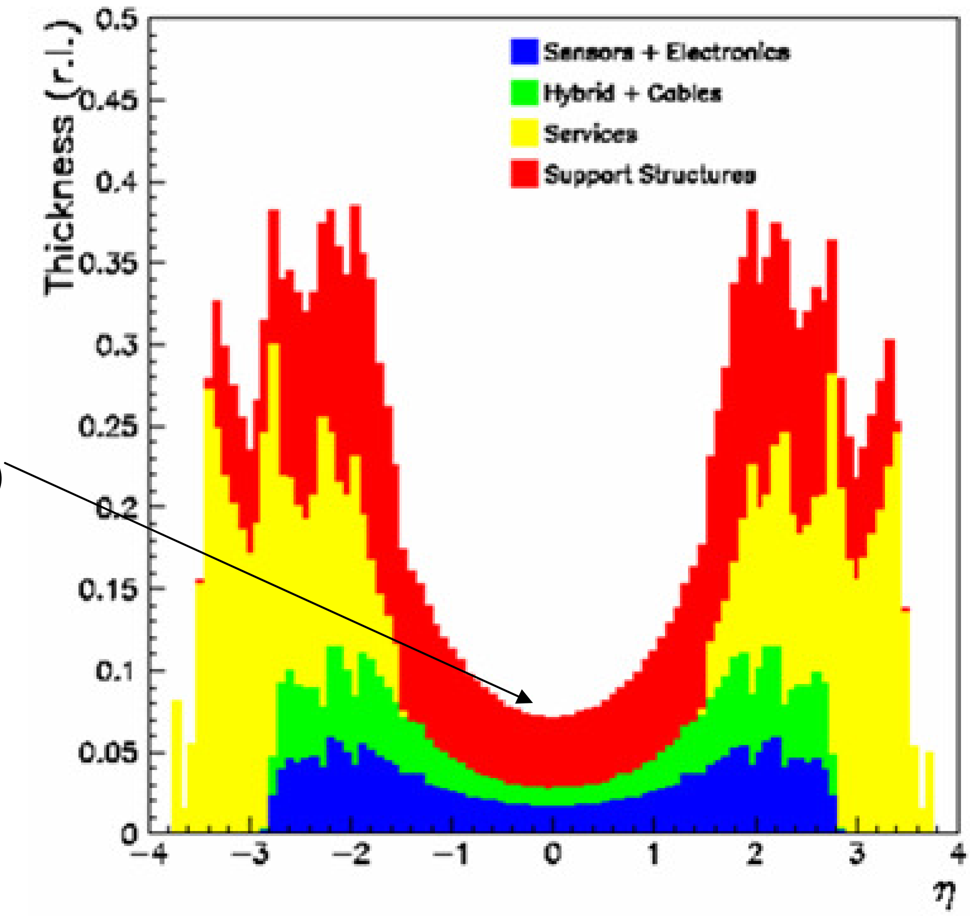


Atlas SCT modules on a support cylinder



Material Penalty

Ionizing energy loss for particles passing through ATLAS pixel detector
(in Radiation Lengths)



65% due to support structures and cables (worse at shallow angles)

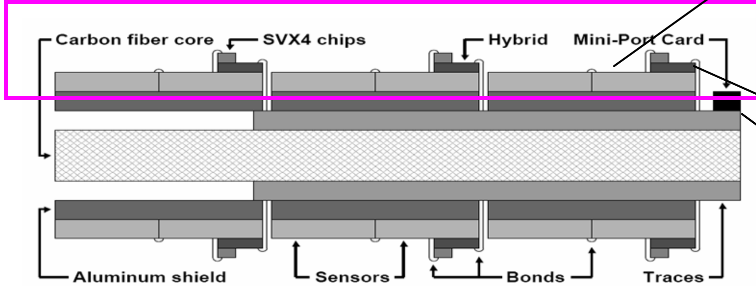
Only **15%** due to silicon sensors
=> Only 15% of energy lost by particles is used for detection.

Macro-modules to the rescue

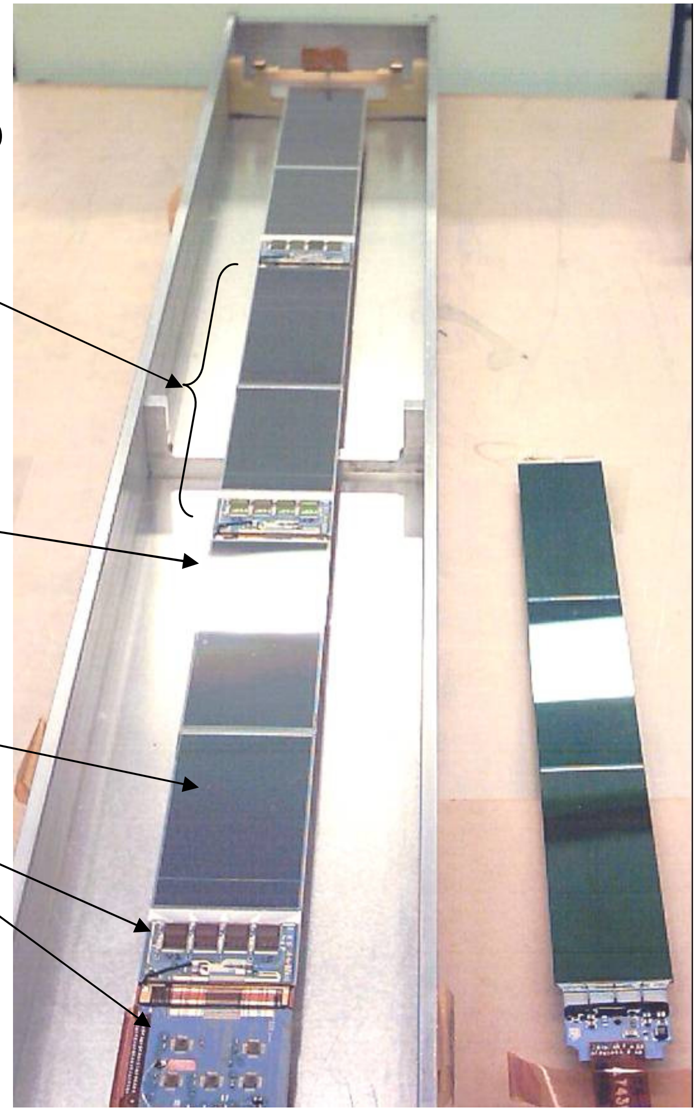
- Integrate electrical services with mechanical support structures to reduce material
- Units of macro-module are simpler than previous module, not fully functional on their own (missing connectivity)

Stave macro-module prototype
Used like a giant ladder, but has higher channel density

Seen from top in photo



Simplified stave side view (not to scale)



Ladder from original SVX

Connecting them up

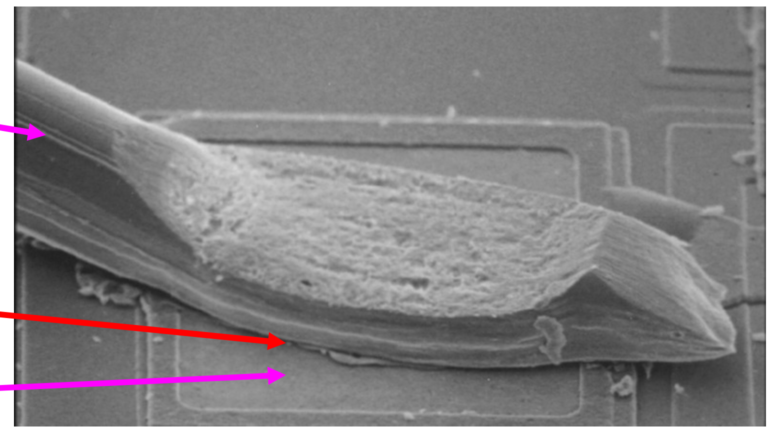
Wire boning

- Wire bonding is the link between integrated circuits and the “real world”.
- It is a vast subject that could take up many 1hr talks.
- We are purely an end user of this industrial technology

25µm round wire of just the right Al alloy

Not a traditional weld. Not a solder joint. A special kind of metal-metal bond formed over only a part of the contact area

IC “bond pad” of just the right Al alloy (a different one than the wire)

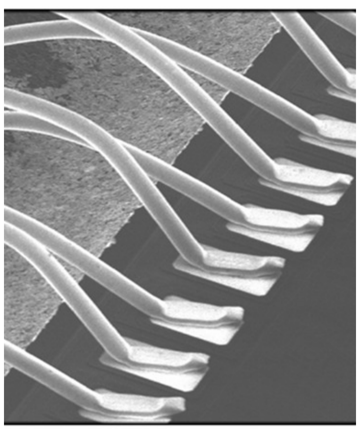


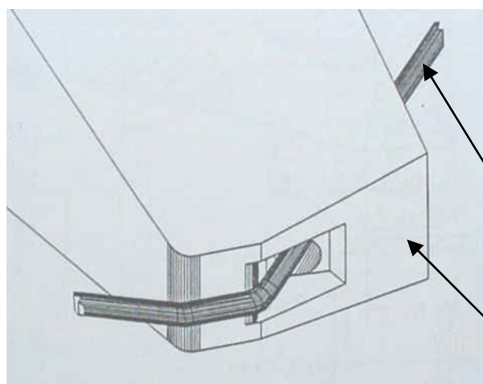
An aluminum wedge wire bond

- It is a fine-tuned process that is highly reliable ONLY if done just right.
  - Small process variations can have big negative effects
  - Often a source of problems for detector builders of all expertise levels

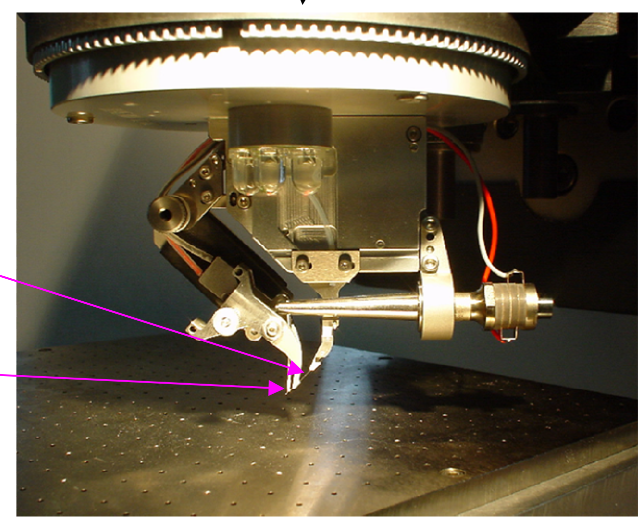
Wire bonding (cont.)

- **We use off-the-shelf industrial equipment for wire bonding silicon detectors.**
- **Many contract vendors have the same equipment and it is possible to outsource, but in general not done**
  - **Detector assemblies are delicate**
  - **In-house capability is convenient**





Bottom view of wire in wedge



Bonding head

- **Wire bonding is a serial operation**
- **This bonder can run at 5 bonds/second**

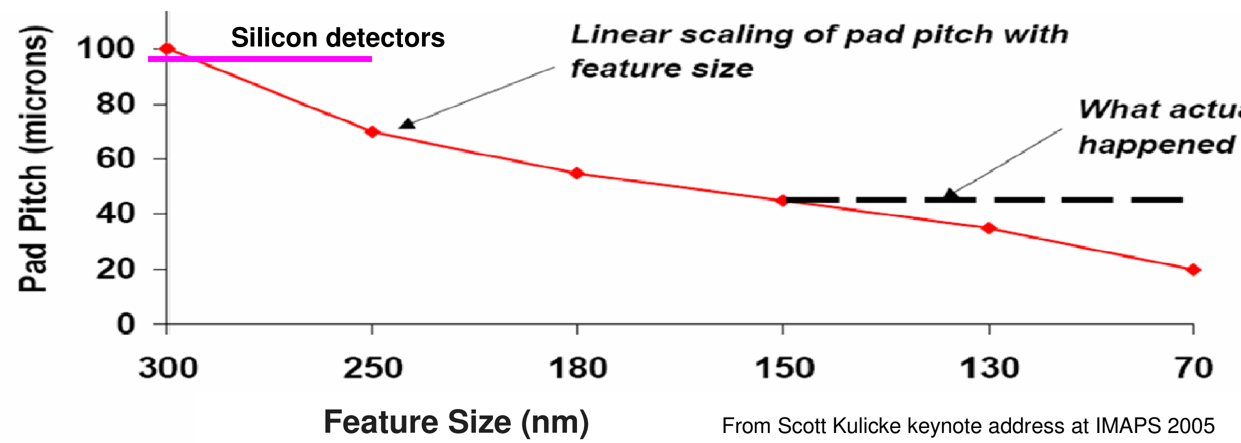
Wire bonding trends

- Industrial output of order 10^{12} bonds / year
- Majority are gold ball bonds => $1 m^3$ of gold every ~2 years
- We use Al bonds because gold ball bonding requires heat
  - But gold preferred in industry because x2-4 faster than Al

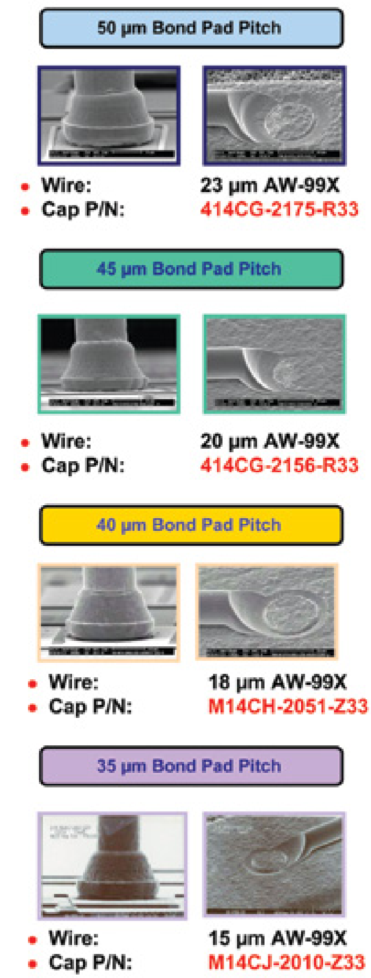
2003 Industry projection

Year of Production	2003	2004	2005	2006	2007	2008	2009	2010	2012	2013	2015	2016	2018
Technology Node		hp90			hp65			hp45		Hp32		hp22	
Chip Interconnection Pitch (µm)													
Wire bond-ball	40	35	30	25	25	20	20	20	20	20	20	20	20
Wire bond-wedge	30	25	20	20	20	20	20	20	20	20	20	20	20
TAB	35	35	30	30	25	25	25	20	20	20	15	15	15
Flip chip area array	150	150	130	130	120	110	100		90		80		70
Peripheral flip chip	60	60	40	40	30	30	20	20	20	20	15	15	15

Source: K. Lang, G. Harman, IZM and NIST internal report



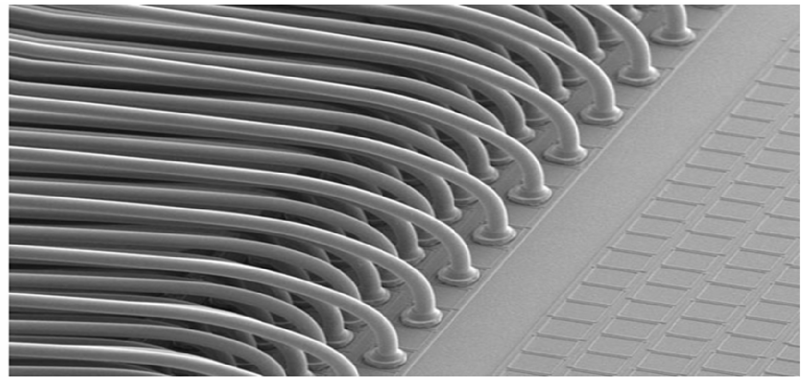
From Scott Kulicke keynote address at IMAPS 2005



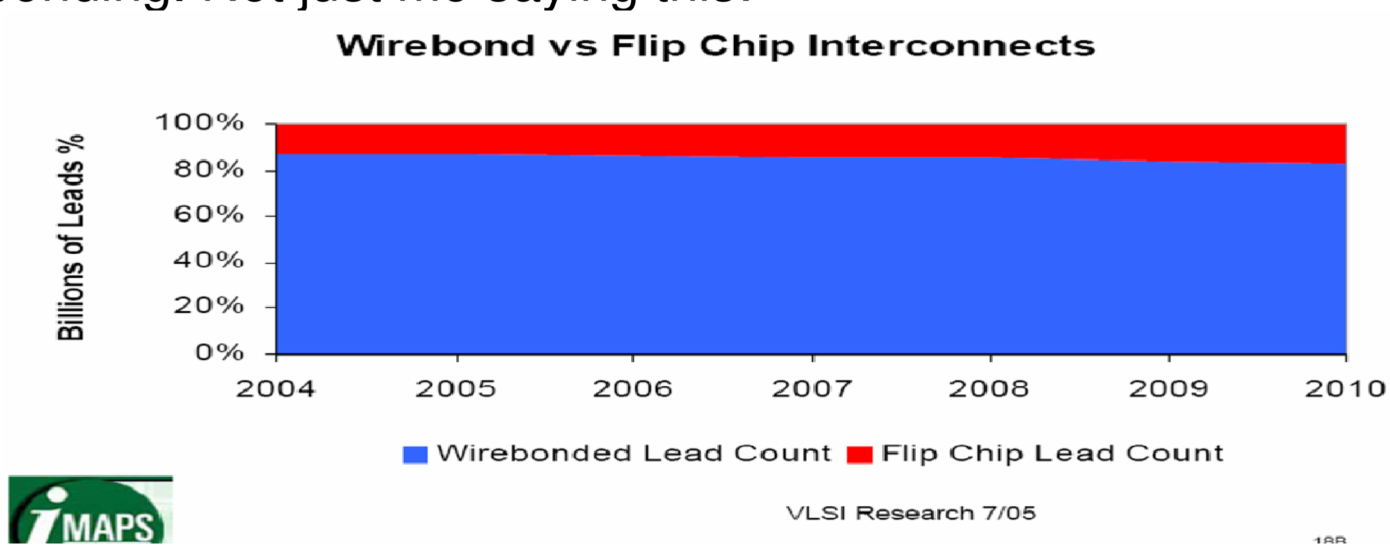
Bump bonding

Why the wire bond pitch stopped decreasing: →

Why not use the entire chip area for interconnection then?
=area bump bonding



- Bump bonding makes it possible for us to build hybrid pixel detectors.
- But it is a much more “high maintenance” technology than wire bonding. Not just me saying this:



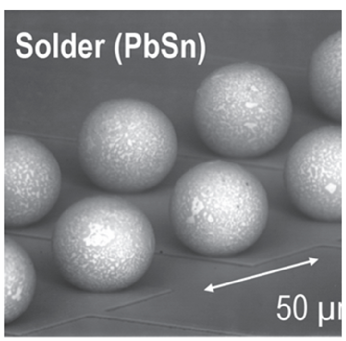
Bump bonding (cont.)

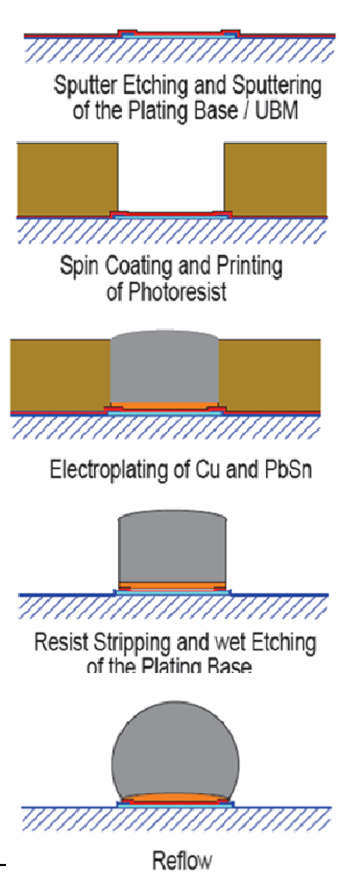
- Unlike wire bonding, we do NOT do our bump bonding in house (yet).
  - Long process and expensive equipment.

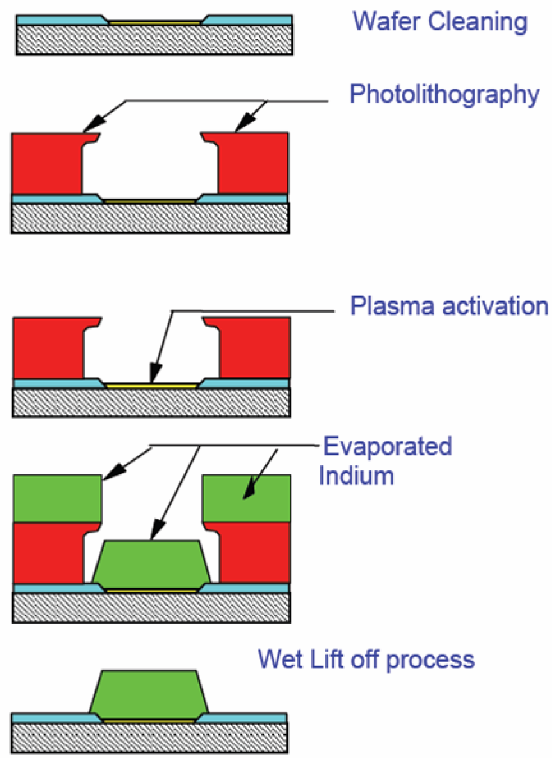
SOLDER BUMPING **INDIUM BUMPING**

(bump deposition is only half of the story)

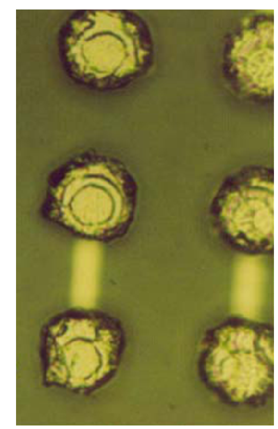
Bumps on chip
UBM on sensor





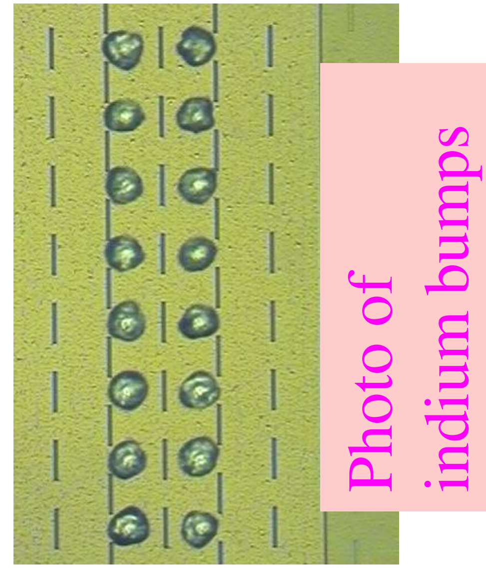


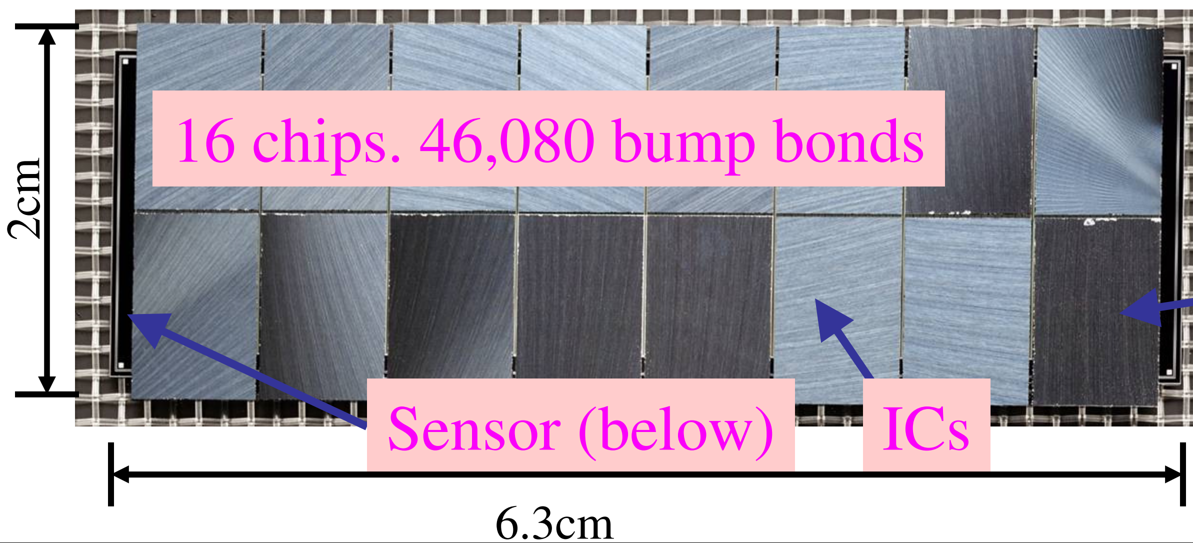
Bumps on both chip and sensor

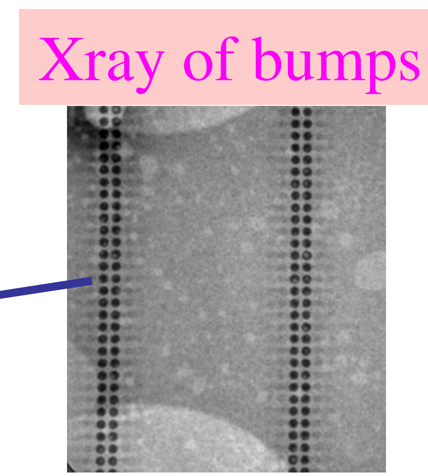


Bump bonded pixel "bare" modules

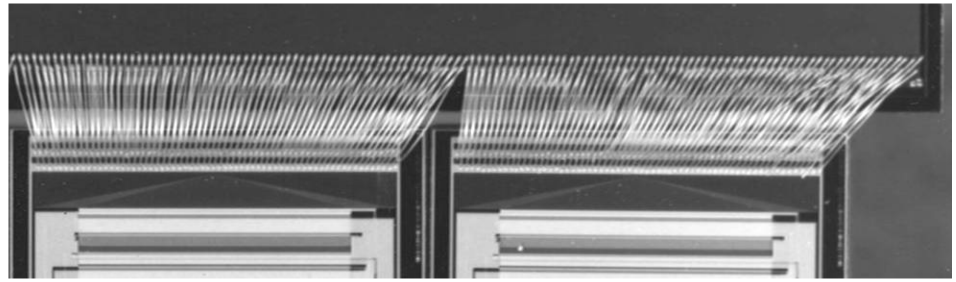
- After bump deposition comes "flip chip" to complete the bump bonding process *
- **High accuracy flip chip equipment**
- Recall area bump pitch in industry roadmap is 70µm even by 2018
- ATLAS modules use 50µm pitch! => non-standard process (expensive and low volume)







Future possibilities

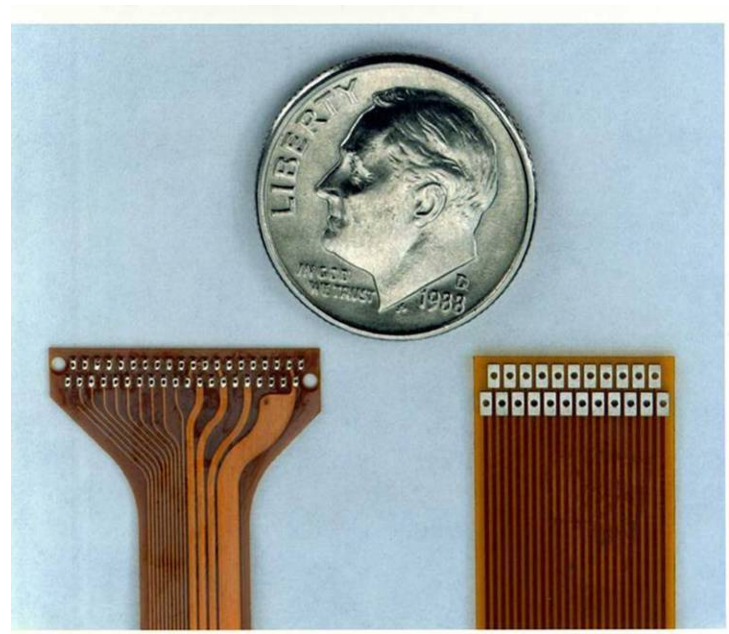


- Plain finer pitch
  - The silicon detectors built in 1990 were ahead of industry using 96μm single row pitch and dual row wire bonding
  - Exactly the same parameters are being used in today's detectors, significantly behind what industry is doing
  - There are gains to be made by reducing bond pitch

- Novel wire bonding methods could be exploited
  - Laser bonding works with a wire range of substrates and wire metals
- Novel wafer level processing techniques
  - Sensor active edges could open the possibility of small basic units with no need for overlap- good for robotic assembly
  - Reticle stitching offers the option of very large ICs
- Many potential alternatives to flip-chip could even involve nanotechnology

Cables and interconnects

- Copper on polyimide printed circuits are widely used for cabling hybrids.
  - Standard manufacturing process
  - 200μm signal pitch standard
  - Low mass
  - Radiation hard
- High reliability ONLY when properly designed.
- If cables will bend repeatedly often need several design cycles to fix weak spots
- Flex occasionally used for hybrids as well as cables. Even more iterations typical in this case.

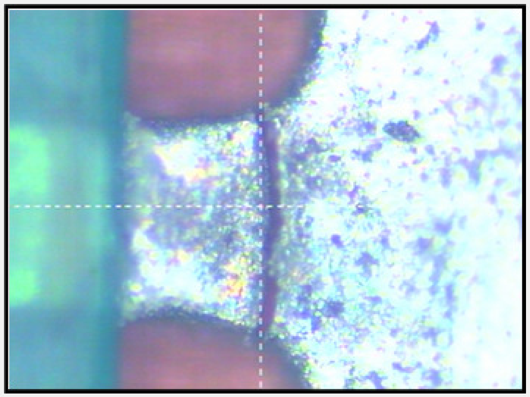


CDF SVX-II hybrid cable

CDF SVX hybrid cable

A constant of nature

Flex Cable Fragility

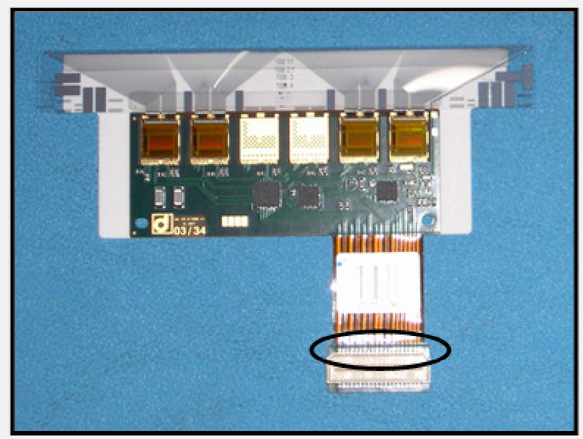


- Signal traces break if you bend the cable by 90°
- Problem quickly solved by adding a stiffener and changing the cable layout
  - Success of the collaboration's QA structure

4000 hybrids in pipeline:

1000 throwaways

3000 retrofitted

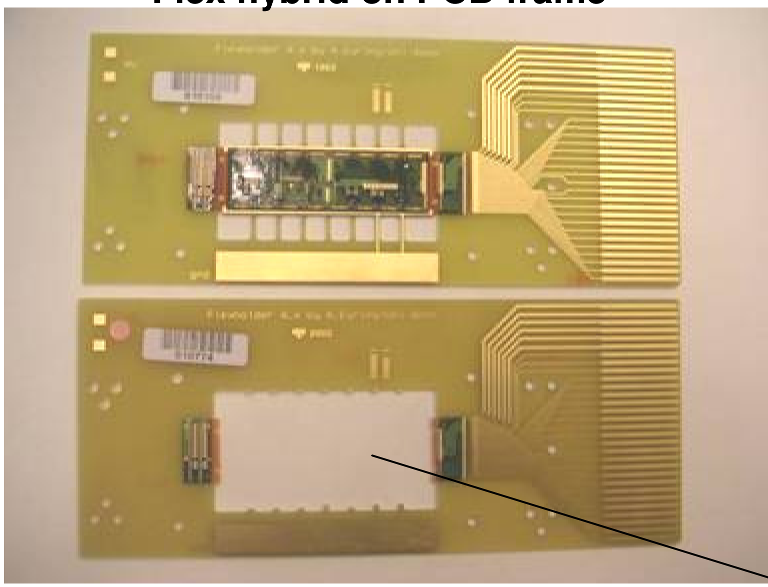


HEP Seminar, Liverpool, February 9, 2006 CMS Silicon Tracker at UCSB -Anthony Affolder Slide 28

A necessary evil

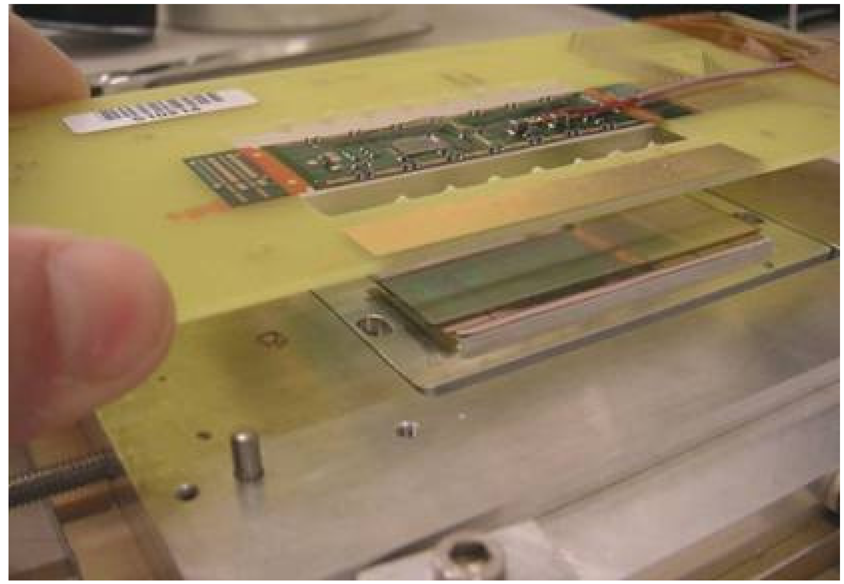
- Sometimes flex PCB can't be avoided
- ATLAS pixel detector geometry leaves no space for anything thicker
  (if we had found a rigid circuit board technology thin enough we would have gladly used it instead)

Flex hybrid on PCB frame



- Rigid PCB frame used to manage flex handling
- This "flex" circuit is never bent.
- PCB frame provides mechanical support and temporary packaging for stand-alone operation

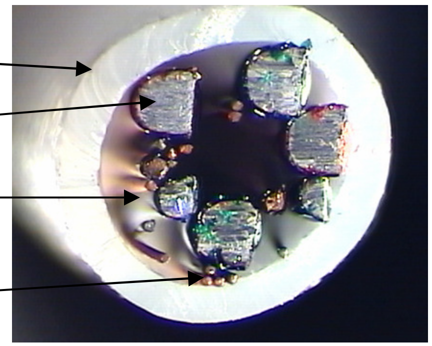
Combination of "FlexMCC" + Bare module

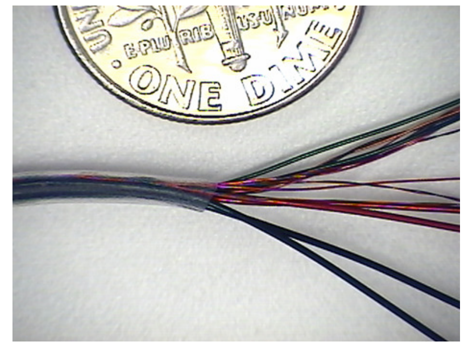


- The flex hybrid is glued to the bare module without leaving the frame
- Flex module is detached only at time of loading on detector support structure.

Non-standard cables (another home-made thing)

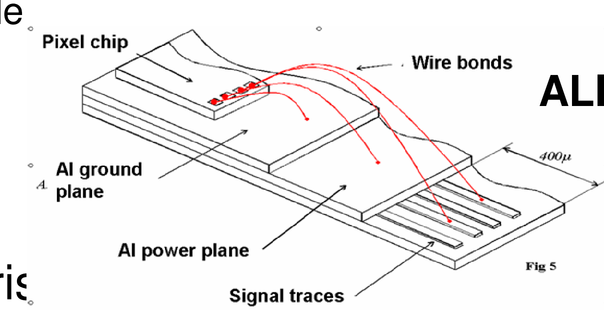
- Case 1: discrete round wires:
  - High current (2A low voltage and return), high voltage (1KV), and 80MHz LVDS signals in the same cable.
  - Oh, and it has to be able to bend in 3 dimensions.





ATLAS pixel module cable

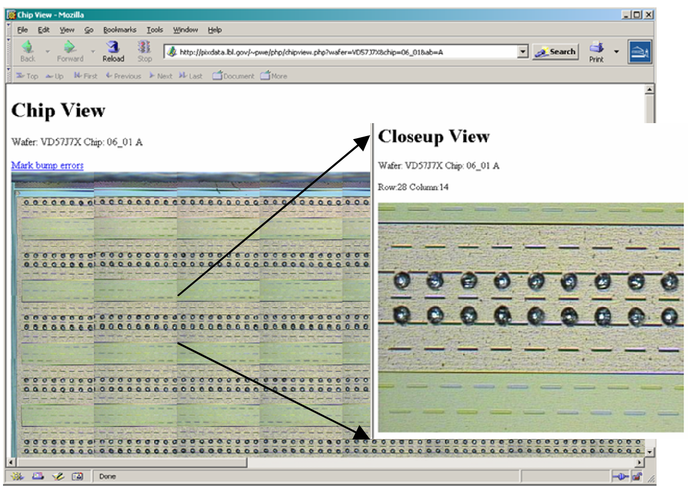
- Case 2: Flex cables with Al instead of Cu
  - Done to reduce mass
  - **NOT** done for industrial applications.
  - Commonly done for shielding planes (low ris
  - Occasionally attempted for critical elements such as power distribution
    - Note that resistivity of Al is higher than Cu => reduction is modest
    - Performance Impact of such modest reduction had better be significant before resorting to this!



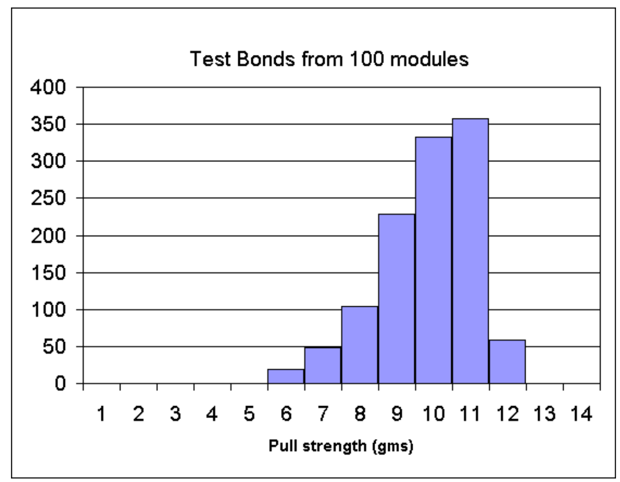
ALICE

Quality control

- Recall one difference with industry is that we build only one detector and it has to work the first time.
- Different quality control problem
- Must track and store information <u>individually</u> for each component
- Only this permits investigating any single failure of any type as soon as observed
- Statistics of prototyping and construction are very much lower than detector operation- a very prominent effect in operation may only show up once in production!

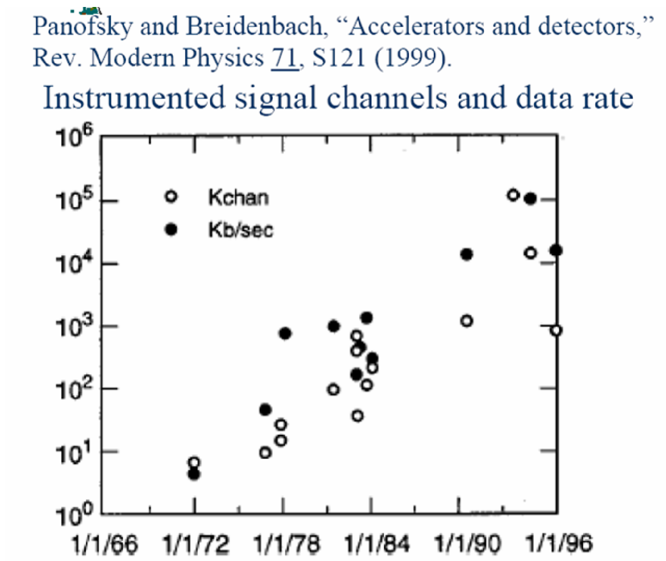


➢A picture of every ATLAS pixel bump is viewable online
➢This has helped understand failures during flip chipv

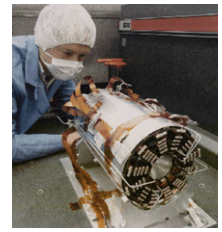


➢Each ATLAS pixel module has 16 wire bonds whose sole purpose is to be pulled
➢This has helped understand and correct subtly problems

The silicon detector arms race

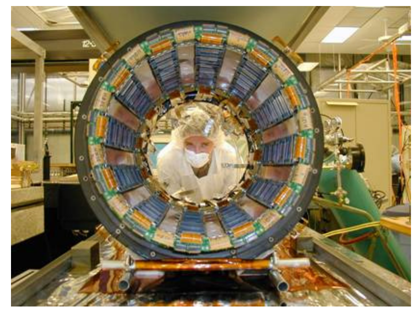


1990



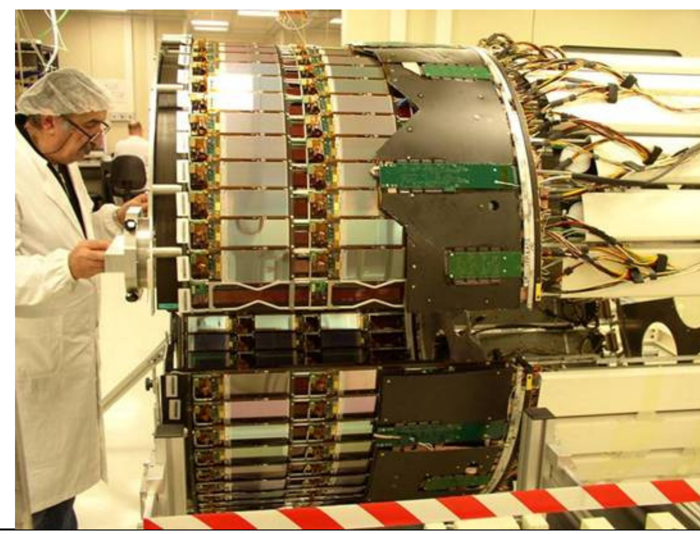
CDF

2000



CDF

2007

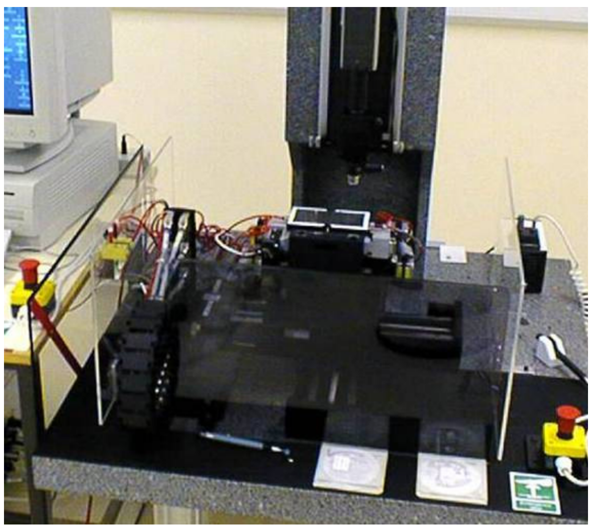


CMS

- Not just bigger, but at the same time faster.
- Bigger => automated assembly
- Faster => power, cooling and interconnect advances

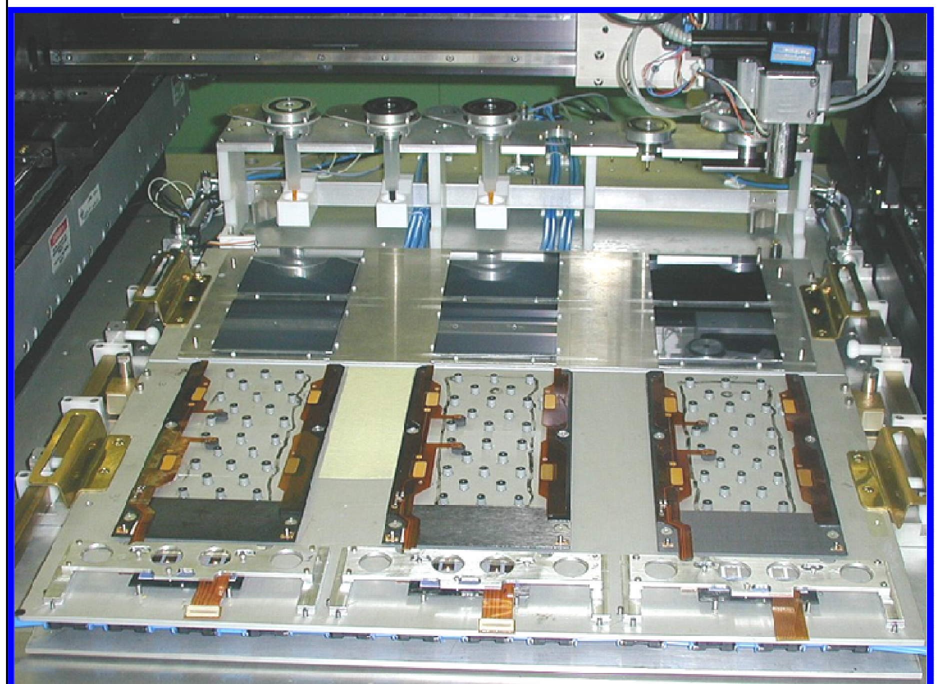
Robotic Assembly

ATLAS tracker: sensor tile alignment on robot, followed by manual full module assembly.
Custom made robot



3,100 modules in detector.

CMS tracker: Full module assembly on robot (except wire bonding).
Modified industrial pick-and-place robot



15,000 modules in detector.

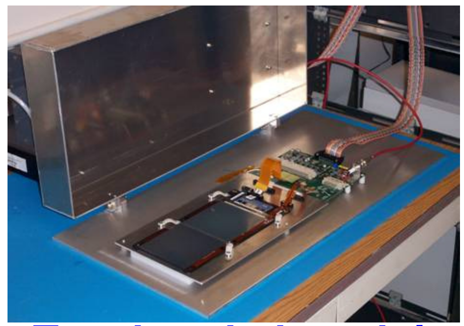
CMS "Rod" Assembly Line (courtesy Anthony Affolder)

Wire bond hybrid

Thermal test hybrids

Assemble modules

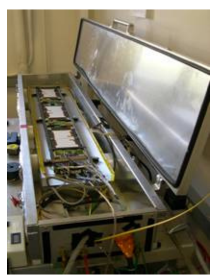
Wire bond module



Test bonded module

Thermal test module

Assemble rods



Single rod test

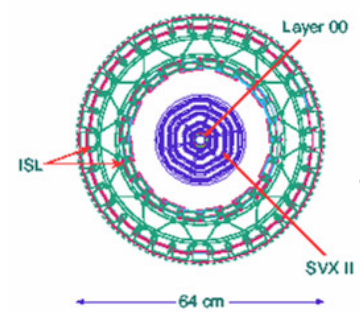
Rod burn-in

Ship to CERN

THE END

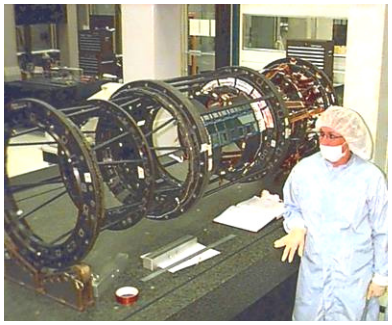
(Left over for Chapter 3)

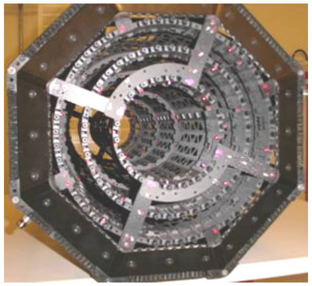
- How to decide on a detector layout.
  - Barrels, disks, number measurements / track
  - Speed, occupancy, granularity
  - Point resolution, 2-hit separation, stereo angle
  - Iteration with construction constraints
- Mechanical structures
  - The carbon composite era
  - Cooling
- Other problems
  - Reduction of service plant
  - Optical readout
  - Etc., etc.



CDF-II layout

CMS barrel shell



CDF-II ISL frame


ATLAS pixel barrel