TOB Modules with ST Silicon: Experience and Results from Recent Studies

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Slides prepared by A. Affolder, D. Barge, E. Chabalina, P. Gartung and many others in the US groups

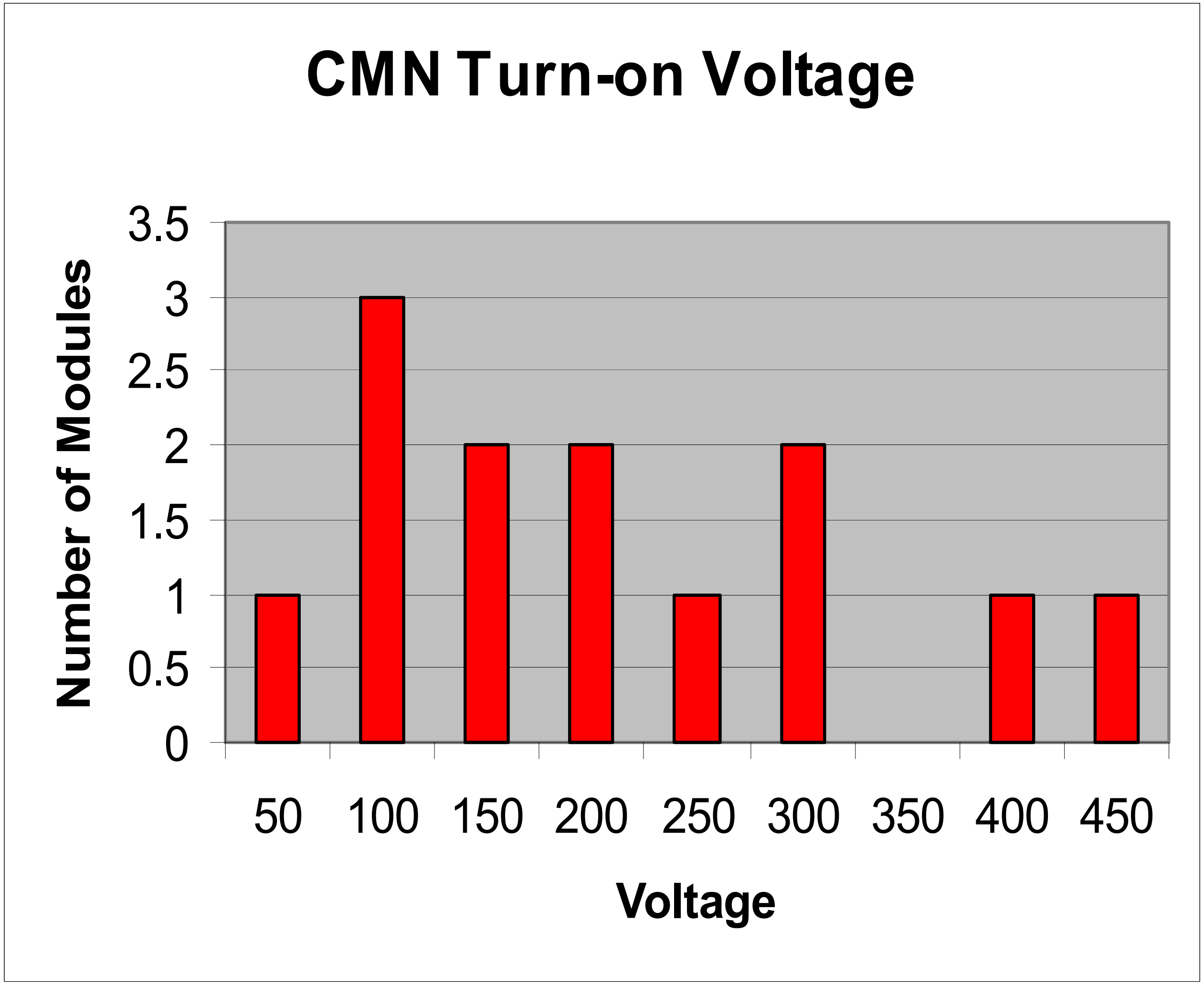
Special thanks to Tony, Derek and Patrick for their dedicated efforts to complete studies of recently received OB2 sensors and studies of CMN spectra on problem modules over the recent US holidays.

Situation as of October 2003

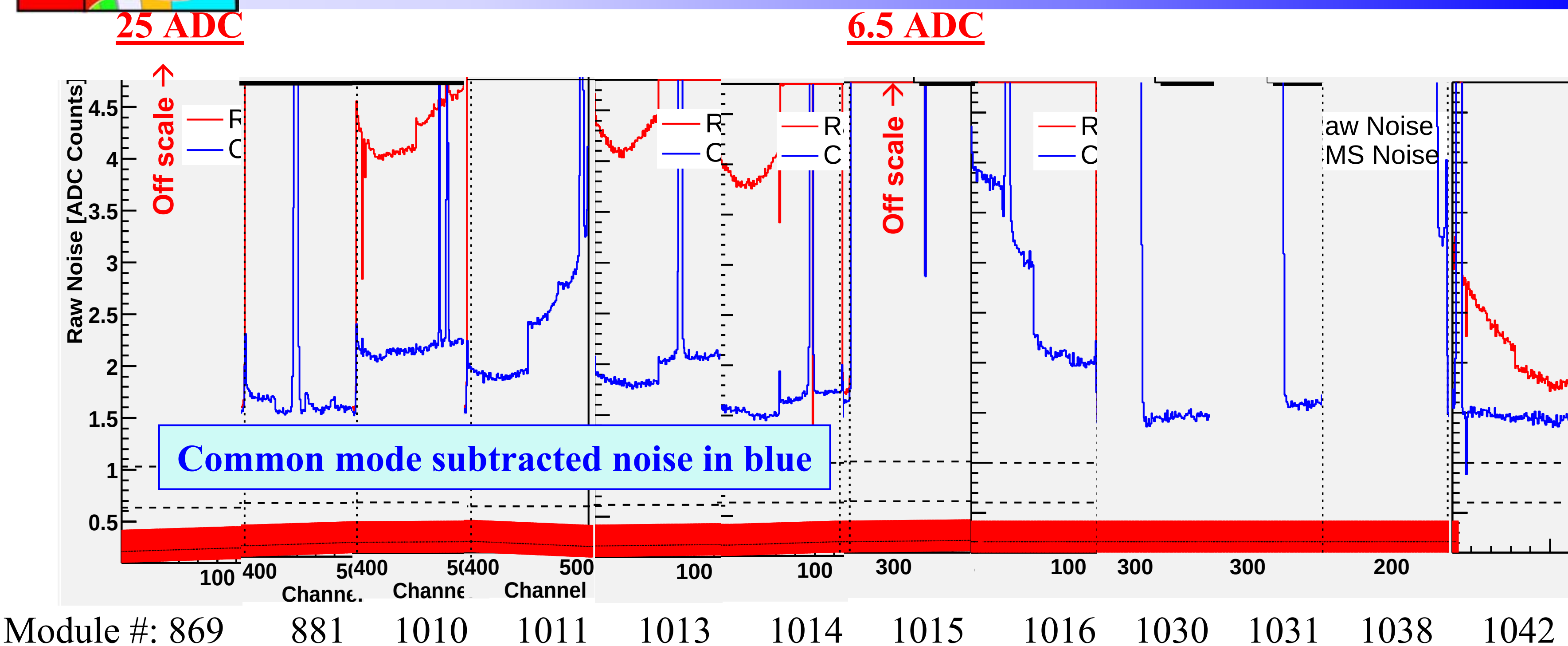
- 14 of 60* modules produced at UCSB exhibit large common mode noise (one chip only)
- Correlated w/increase in bias current w.r.t. QTC probing
  - Initially, increased current was noted after module assembly. There was some concern that it was caused by assembly or bonding.
  - Later, the increased current was seen in measurements made on wafers before assembly, thereby ruling out the hypothesis that it might be due to the assembly process.
- Characterized by high noise on 1-4 channels
  - Current is in fact localized to these channels
  - No obvious associated damage in visual inspection
- At UCSB the problem always appeared by the first module test
  - 1 module at FNAL developed problem during Wien box LT testing after a full ARCS module characterization

*The sampling of sensors was slightly biased toward high-fault rate sensors. Almost all from old OB2 batch. Actual rate is around 10% for early sensors.

CMN Turn-on Voltage



Common Mode Subtracted Noise



Montage of chips with CMN on 12 separate modules

For majority of modules with problems, the CM subtraction is imperfect.
After common mode subtraction, many still have significantly elevated noise.

IV tests in US as of October '03

- Three Sets of Sensors Probed
  - Old OB2 (Week 47 2001 to Week 21 2002)
    - 75 Sensors
  - Old OB1 (Week 43 2001 to Week 2 2002)
    - 31 Sensors
  - Newer OB2 (Week 38-41 2002)
    - 97 Sensors
- Environmental conditions tightly controlled
  - Temperature 23.1-23.8 C
  - RH < 30% at all times

Includes sensors built into modules (as discussed earlier) and some sensors from more recent batches

IV Test Results

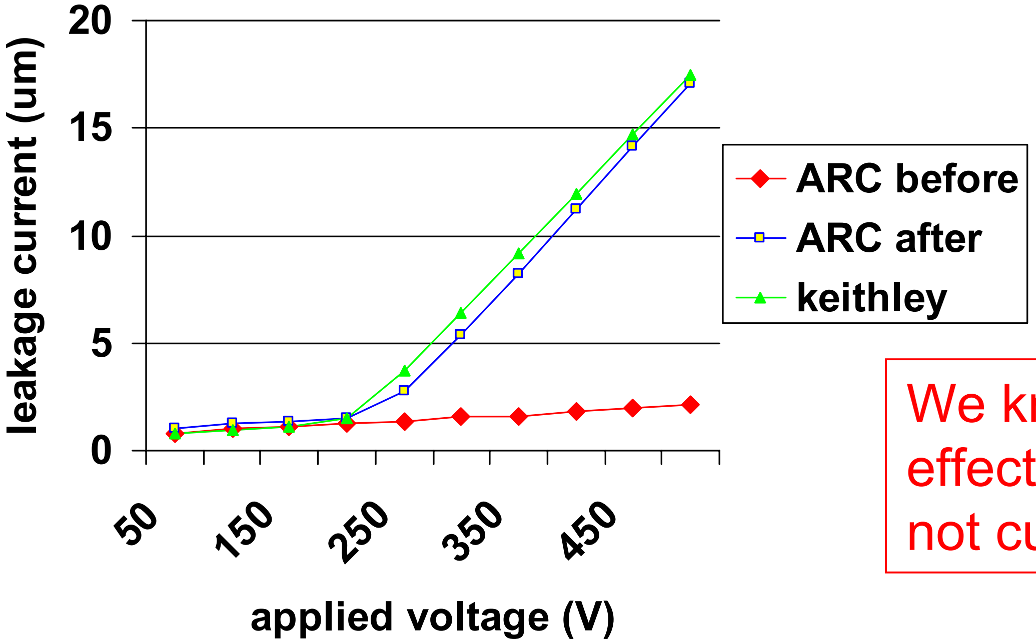
Probed Current @ UCSB (400 V) – QTC Measurement (400 V)

Sensors	> 2 μA	**> 5 μA**	**>10 μA**	**>20 μA**	**>100 μA**	< -2 μA	<-5 μA	<-10 μA
Old OB2	15%	9%	8%	5%	1%	8%	3%	1%
Old OB1	6%	3%	3%	3%	3%	3%	0%	0%
New OB2	3%	3%	0%	0%	0%	2%	2%	0%

- An increase greater than 5 μA can cause common mode noise
  - Rate of CMN problem consistent with percentage of old OB2 sensors with a 5 μA increase
- ***Agreement much better with newer OB2 sensors***
  - ***(Produced Week 38-41 of 2002)***
  - Factor of ~4 decrease in the rate of higher (and lower) current measurement at UCSB relative to old OB2 sensors
- ***We would like to also study the 2003 batches (see below)***

FNAL Module Spontaneously Develops CMN

- ”before” measurement is taken on 09/08 on ARCS before LT
- “after” measurement is taken on 09/23 on ARCS after LT
- green curve is a measurement done using Keithley on 09/24 with 1 minute interval between steps



No visual defects are observed on the sensors around noisy channel #219

We know it is not a humidity effect: 3 weeks in dry air did not cure it

Summary as of October ‘03

- The CMN problem appears to be a sensor problem
  - Not created during module assembly or bonding
  - No visible damage or indication of defects from sensor QTC
- Pre-screening sensors (measuring IV) in US appears to improve situation greatly but:
  - We do not know how the problem will evolve
    - Rate of appearance vs. time, power cycles, etc.
    - Changes with radiation damage
    - How problem parts will act within sub-structures with final electronics and power supplies
  - No current provisions to pre-screen in US production centers
- Pulling wire to APV and bonding ac pad to ground (top bias ring) eliminated problem 100% (2 modules tried) but cannot be done after detector assembly.

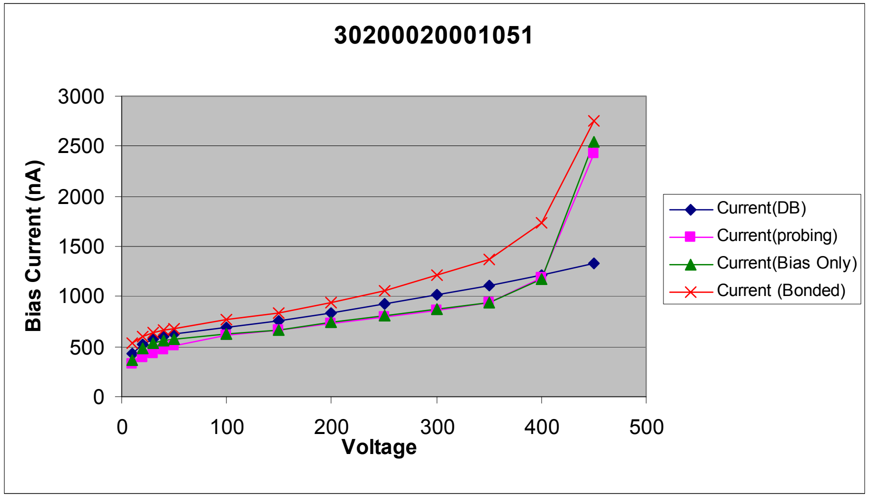
UCSB: All Modules to Date

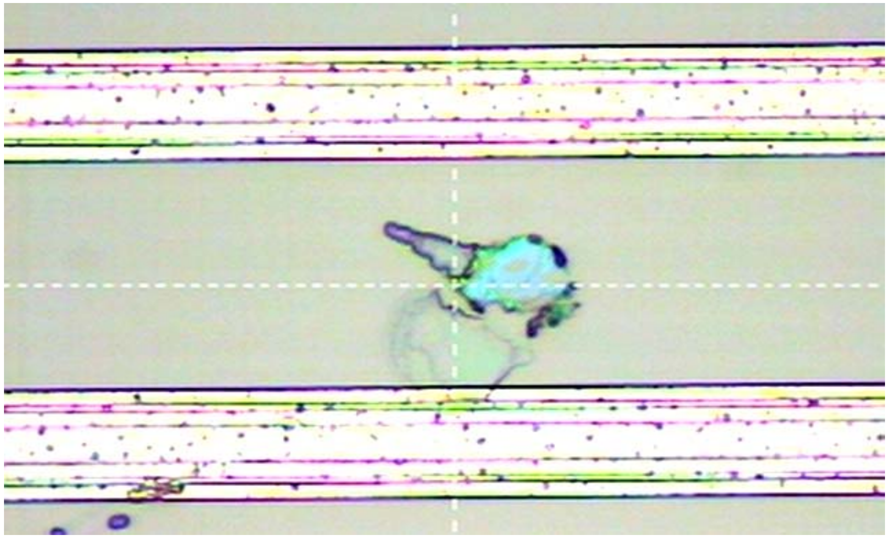
- All UCSB Modules to date, including those built recently
  - 4 of 5 modules with a ***high*** current sensor had CMN problems
  - 37 of 39 modules with ***low*** current sensors had no problems
- New TOB SS6 module with CMN.
  - Worrisome because IV in db indicates below the 1.5 μA cut.
  - Remarkably draws only 1.8 μA at turn-on of problem (400 V)
    - Previously we thought that the problem was limited to cases where the current drawn was over ~ 5 μA.

New CMN Problem Module (1051)

- Last SS6 module built using one sensor with 1.2 μA extra current (1700 nA vs 50 nA) in UCSB re-probing at 450 V.
  - Well within old selection criteria
  - No significant increase of current during module assembly
  - Uses somewhat older sensors
    - 30210320274206
    - 30210320274214
- CMN seen in chip 46 with extremely high noise in channels 423-424
  - Sensor flaw seen between two channels – not known if relevant.
  - Begins at 400 V where measured current diverges from database

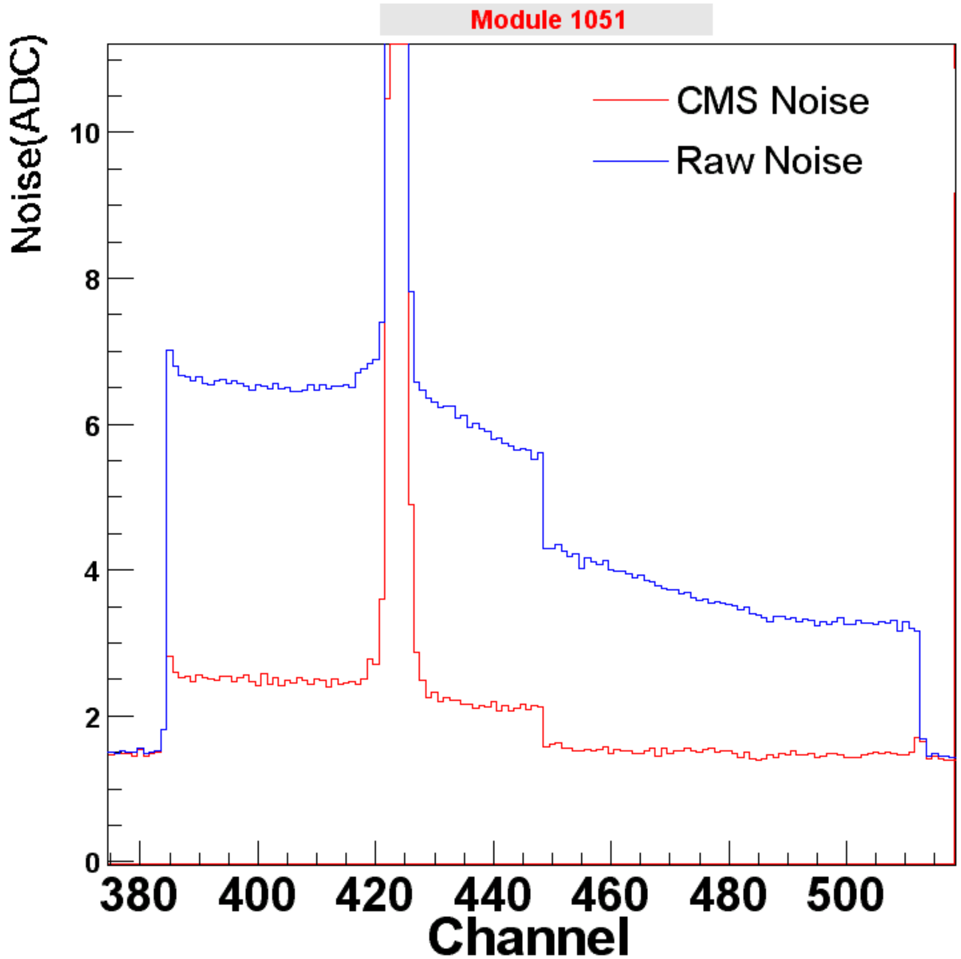
    ~0.5 μA difference





CM Noise on Module 1051

- Module tested at slightly elevated voltage
  - Bias current 3.7 μA, < 2 μA more than expected from database
- First half of chip has CM subtracted noise a factor of ~1.75 higher than typical.
  - A very little amount of micro-discharge can cause the CM subtraction algorithm not to work properly
    - CM subtraction algorithm used is same as LT, and test beam software



Recent Results

- New sensors received from ’03 batches very recently
    - 37 OB2 produced in weeks 18-23 of 2003
  - Plan was to build into modules and perform very extensive LT tests with multiple thermal cycles.
  - So far
    - 20 probed at UCSB and built into 10 modules
    - 17 shipped to Rochester to determine if there are strain effects – increased noise when mechanically stressed.
      - These will be sent to FNAL to be built into modules.
- Further studies of CMN on problematic modules
  - Studied 5 modules with a single high current strip
  - Quantified CMN effect by looking at spectrum of noise on other strips in the same APV chip
    - Fit to a double Gaussian.
    - Fit parameters studied as a function of bias current (voltage)

IV Tests including '03 Sensors

Probed Current @ UCSB (400 V) – QTC Measurement (400 V)

Sensors	> 2 μA	> 5 μA	>10 μA	>20 μA	>100 μA	< -2 μA	<-5 μA	<-10 μA
OB2 ('00-01)	15%	9%	8%	5%	1%	8%	3%	1%
OB1 ('00-01)	6%	3%	3%	3%	3%	3%	0%	0%
OB2 ('02)	3%	3%	0%	0%	0%	2%	2%	0%
OB2 ('03)	0%	0%	0%	0%	0%	0%	0%	0%

- An increase greater than 5 μA can cause CMN
- *Much better results with newer OB2 sensors (2002)*
  - Factor of ~4 decrease in the rate of higher (and lower) current measurement at UCSB relative to old OB2 sensors
- *None of the 20 newest (2003) OB2 sensors studied at UCSB show any increase in bias current*

Module Quality & Fault Sources

	Sensor % (In DB)	Sensor % (Not In DB)	Bonding %	Other %	Total Fault %
Before IV Screening	0.31	0.36	0.05	0.13	0.85
Pilot	0.40	0.11	0.02	0.03	0.55
New Sensors	0.13	0.02	0.02	0.00	0.17

- Sensor quality greatly improved
  - *Sensor pre-screening clearly reduces rate of unexpected problems from sensors*
  - *New sensors had much lower rate of (un)known problems*
    - *Only 2 additional pinholes found. Correlated with scratch in sensor.*
      - *Small statistics*
- ***Results in much higher quality modules***
  - *Much faster testing due to reduced rework/failure analysis*

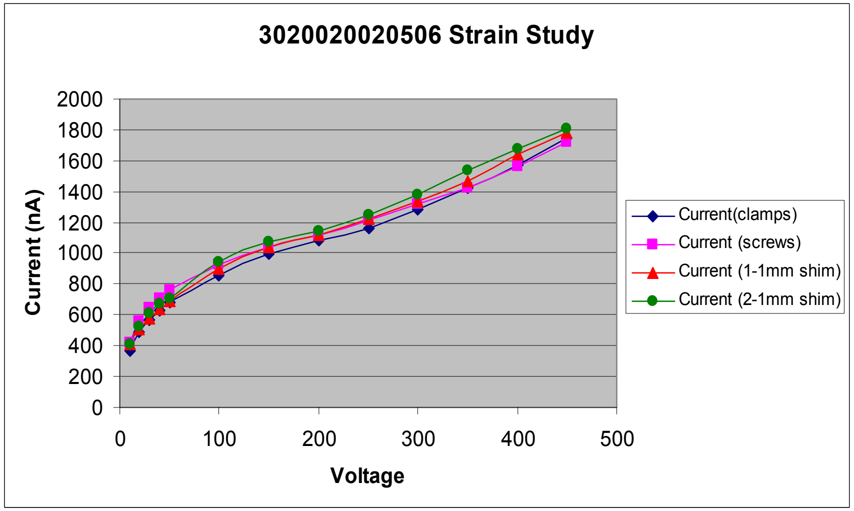
Studies with “Final” Sensors

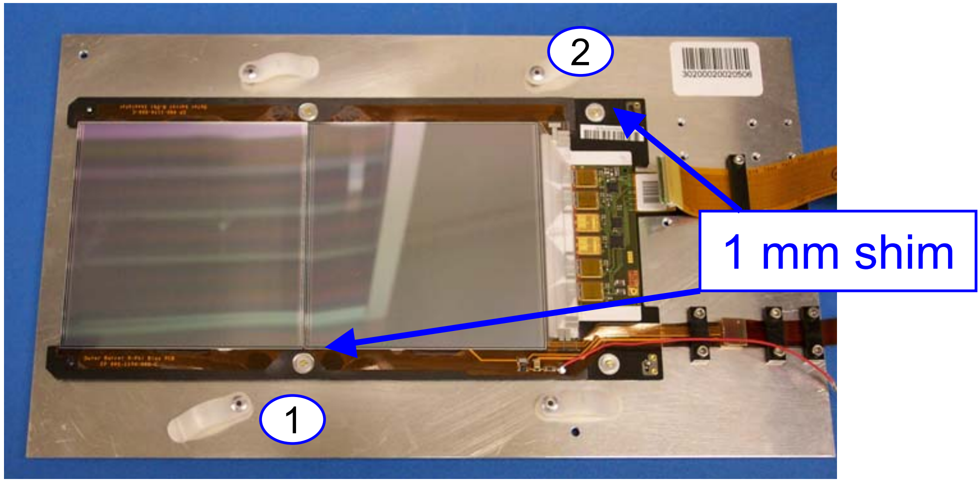
- 10 modules with 20 “final” production sensors
  - Appear to be higher quality
    - Bias currents between 1 and 2 μA
    - Only 2 pinholes were *not* indicated in sensor database
      - No high noise channels
- Effects of thermal cycling and mechanical strain:
  - Modules fixed to cold box plates at thermal contacts by screws
    - This may be somewhat more severe than the rod configuration
      - Modules thermal cycled for more than one week
  - 1 mm shims added under 1or 2 contact points to stress silicon

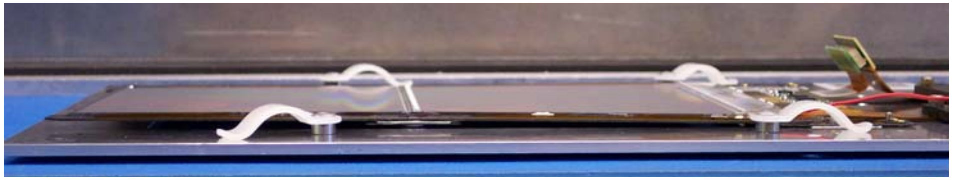
    ~3 times the offset in rod attachment points
      - Significantly more extreme mechanical distortion than expected in the final rod configuration

Mounting on cold plate

- Modules attached to cold plate with 4 screws through thermal contacts
- To test the effects of twisting modules, 1 mm shims added under thermal contacts
  - Bias current measured with 1 or 2 shims for all 10 modules
    - No observed change in current





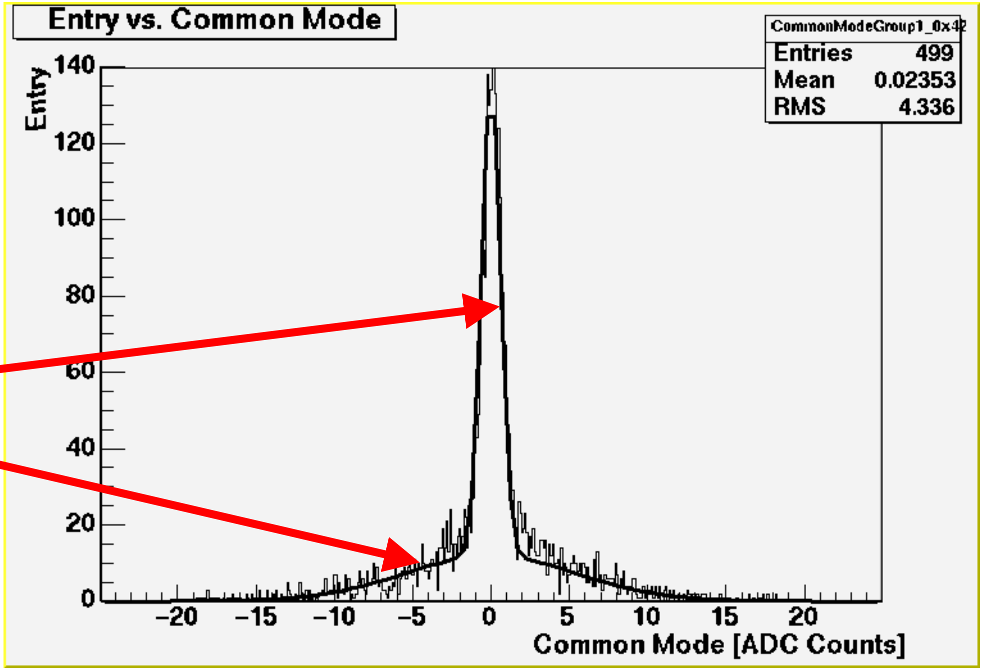


Modules Thermal Cycles

- Modules thermal cycled on modified cold plates with/without shims
  - 168 module-hours with a total of 36 thermal cycles without shims
  - 708 module-hours with a total of 126 thermal cycles with 2 shims
- No change seen in bias currents or noise!

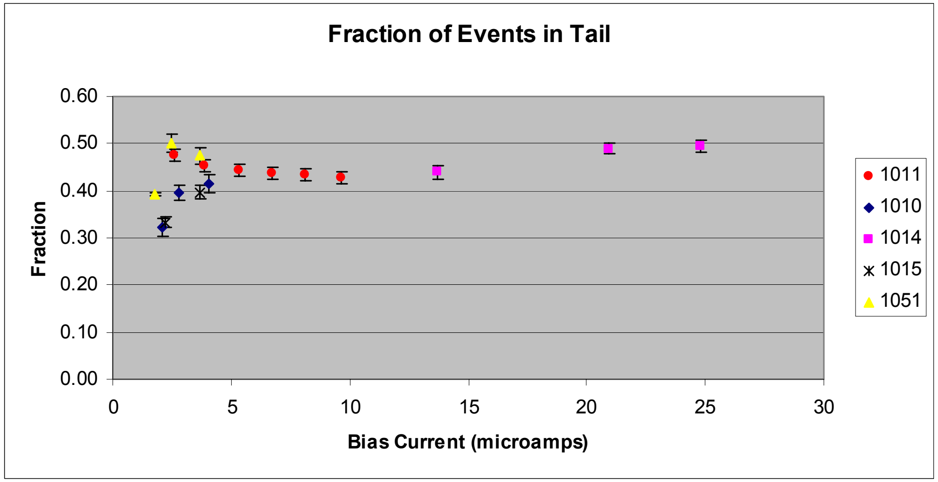
Study of CMN Spectra

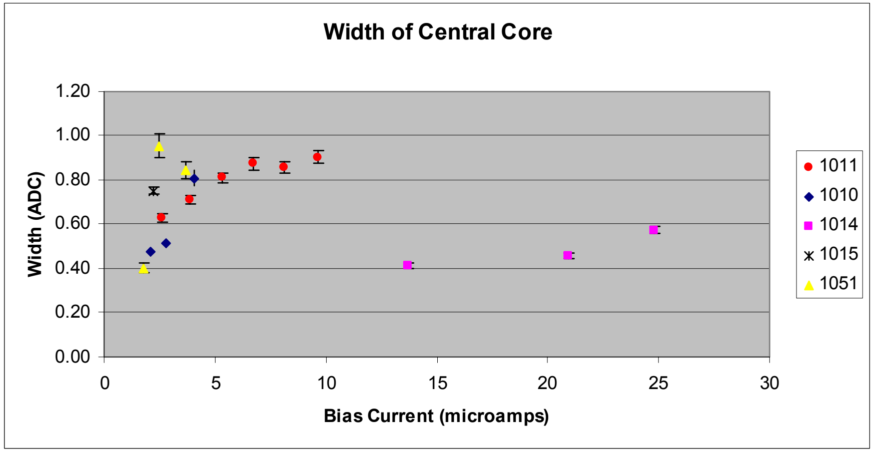
- The common mode point is calculated event-by-event for groupings of 32 channels
  - The spectra of the common mode is fit for the groupings within a chip with CMN problems - excluding the grouping with the high noise channel
- Spectra is fit with two Gaussians
  - Central core ⊕ tail
  - Fit parameters are:
    - Fraction of events in tail
    - Width of central core
    - Width of tail
- Study variation of parameters with bias current by increasing bias voltage in steps of 50 V

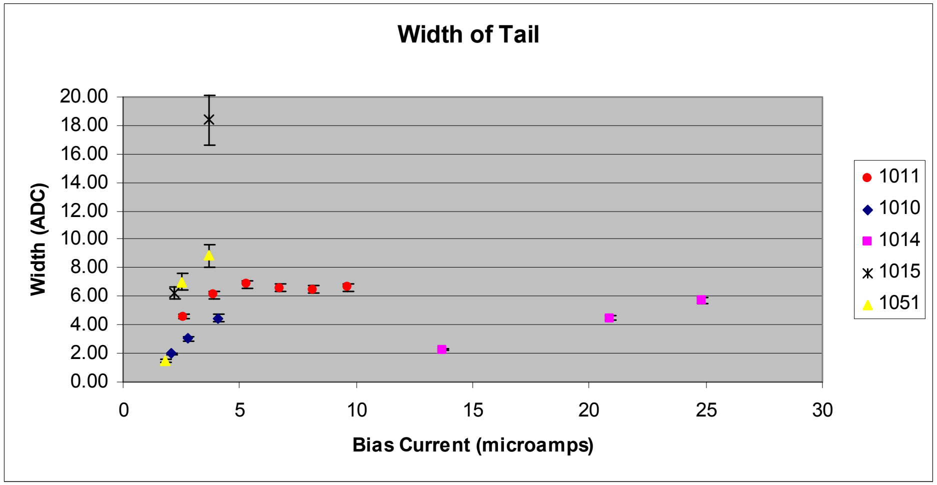


Fit Result of Common Mode Point

- Fraction of events in tail is relatively flat with bias current (~strip current)
- Width of central core increases with bias current (~strip current)
- Width of tail also increases with bias current (~strip current) and may flatten out at some current







This is only the start of this study. We have a number of ideas for how to proceed.

Summary

- CMN noise seen in modules built with ST sensors
  - Correlated with increase of bias current relative to QTC
    - Source unknown, but it is not module assembly process
  - Newer sensors have less difference relative to QTC
    - Not known if this will change as these sensors age
- Worrisome characteristics of the CMN
  - Not always removed by the CM subtraction
  - Varies event to event
  - Turn-on bias voltage can be almost any value
  - Has occurred when the bias current of sensor is low
  - Has developed spontaneously in a module that tested fine
- 10 modules with '03 sensors tested to "extremes"
  - Appear to be fine

Working Hypothesis: Micro-discharge

- On the basis of the data available to us we believe that the CMN effect is induced by micro-discharge.
  - We see is a channel or cluster of channels producing the full dynamic range of ADC values. The other channels in the APV shift up to a MIP in the opposite direction, causing large CMN.

- The effect increases with applied voltage, eventually reaching the point where there is enough current to effect the whole APV similar to a HIP or pinhole but now more likely due to high frequency micro-discharge instead of a DC current.
- CMN starts right where the bias current exceeds the curve obtained at the QTC probing centers.

Supporting Information

- A simple increase in the leakage current would not cause a CM fluctuation of the entire chip
- Current rises linearly with voltage once the CM noise begins.
- Karlsruhe re-probing of 3 affected modules indicates the increased current is isolated to channel(s) with the vastly increased noise.
- On several modules we removed the wire bond to the APV of the noisy strip. Neighboring channels see an increased noise. CMN is not significantly reduced until ~5 channels are pulled around the problem channel (i.e. until the capacitive coupling of the discharge bonded strips is less than that to the back plane).
- Finally, we have bonded the aluminum strip of the affected channel to the bias ring after removing the bond to the APV. In this modification we use the coupling capacitor as a high frequency path to ground.
  - The neighboring channels no longer show an increase in noise, but the strips at the sensor's edge show a slight increase.
  - The edge strips probably show a noise increase because the discharge is dumped onto the bias ring to which the edge channels have the strongest coupling.

Why be concerned?

- In all cases where we've tried it this fix has worked.
- Also, Frank Hartmann's group has irradiated a module with this problem, and after type inversion, the problem disappears.
- Why are we still concerned?
  - We don't know the cause of the micro-discharge or rate at which bad strips might develop later.
    - We cannot fix it if it occurs after installation
    - We don't know if the fix works long-term
    - We could find that bad strips occurs at a large accumulated rate over 10 years, and have to deal with time-dependent efficiencies, and other problems

- After inversion?
  - We don't know if a problem on the n+ implant side will start to rear up on many modules

- General and Generic Issues
  - Given the sensitivity that the CMS readout has shown to micro-discharge and other large current effects, a clear premium must be placed on the stability of sensors.
  - ST sensors show broad variability of characteristics, yields, and processing.
    - Sensors without such variability must be given significant weight to avoid unknown risks over 10 years of operation.

In Conclusion

- Large variety of ST problems and variability of quality
  - Makes it difficult to be confident in long-term operation
  - CMN could eventually disable some fraction of modules
  - Even if CMN does not disable modules, it seems relatively likely that the variability of the effect could create an operational problem.
    - The CM subtraction algorithm proposed for the FED does not always work. Many times the regular noise is still seen in some cases.
    - In addition, the CM subtraction is unstable; it differs for the different modes of the chip and more importantly it differs in time.
      - The effective noise would thus vary during operation.This means:
        - Burdensome performance monitoring and operational adjustments ?
        - Multiple CM subtraction schemes with time dependence ?
        - Calibration database maintenance nightmare ?
  - Quantifying inefficiencies could be difficult.
  - Matching simulation to detector performance could be difficult.
- The new sensors appear to be ok
  - Encouraging but not conclusive
    - Are these sensors representative of all subsequent ST production?
    - Will they evolve to be bad over longer time periods ?