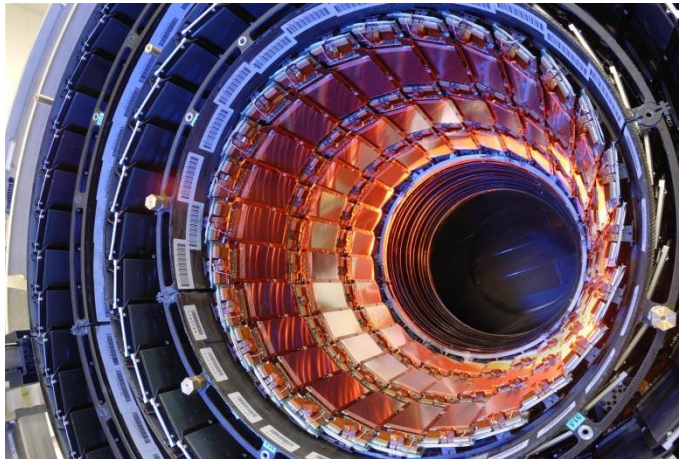


# The Silicon Strip Sensors of the CMS Tracker

Thomas Bergauer (HEPHY Vienna)



## Logistics

Strip Scans on Sensors

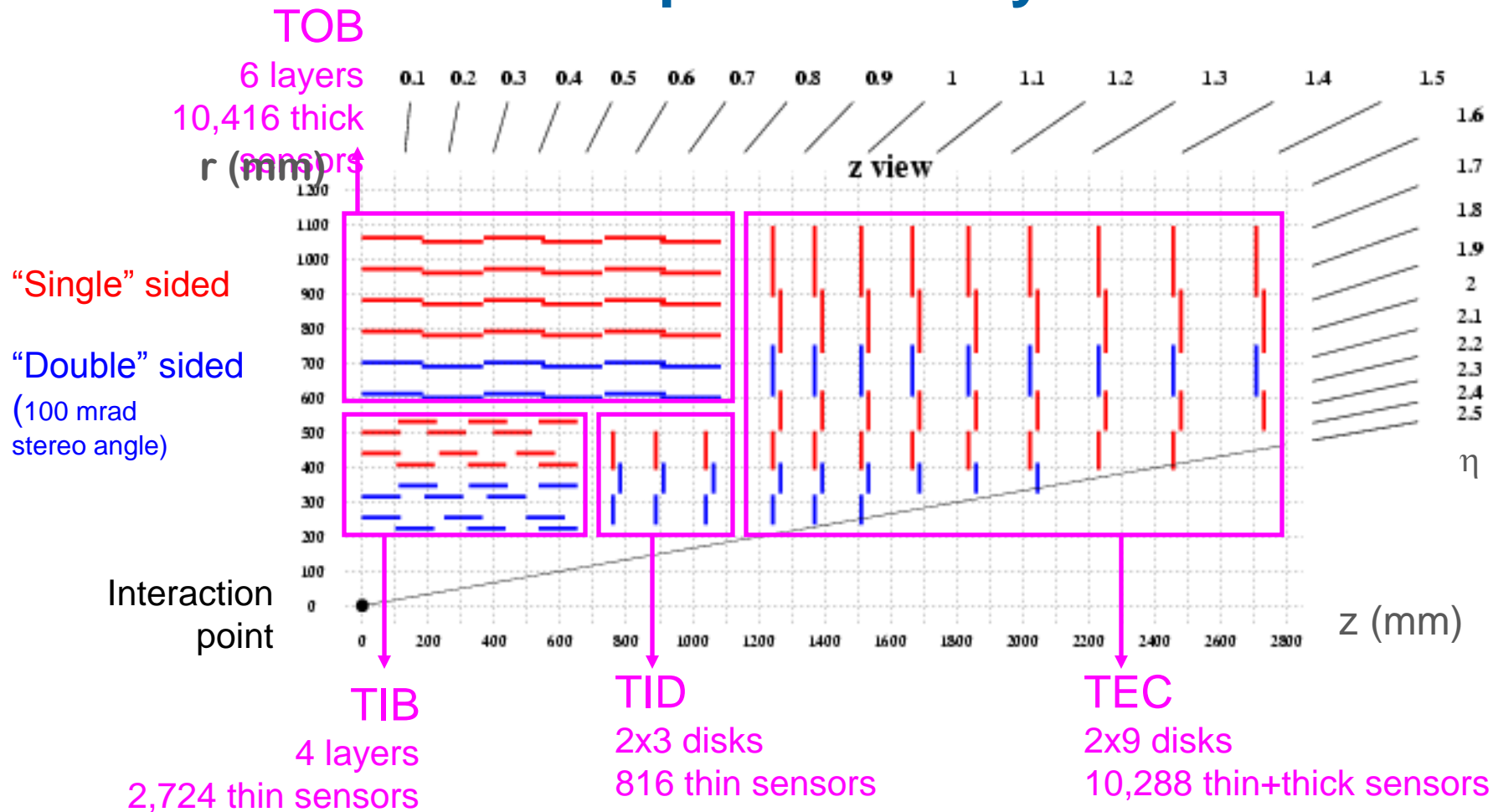
**Process Monitoring**

**Irradiation**

Long-term Stability

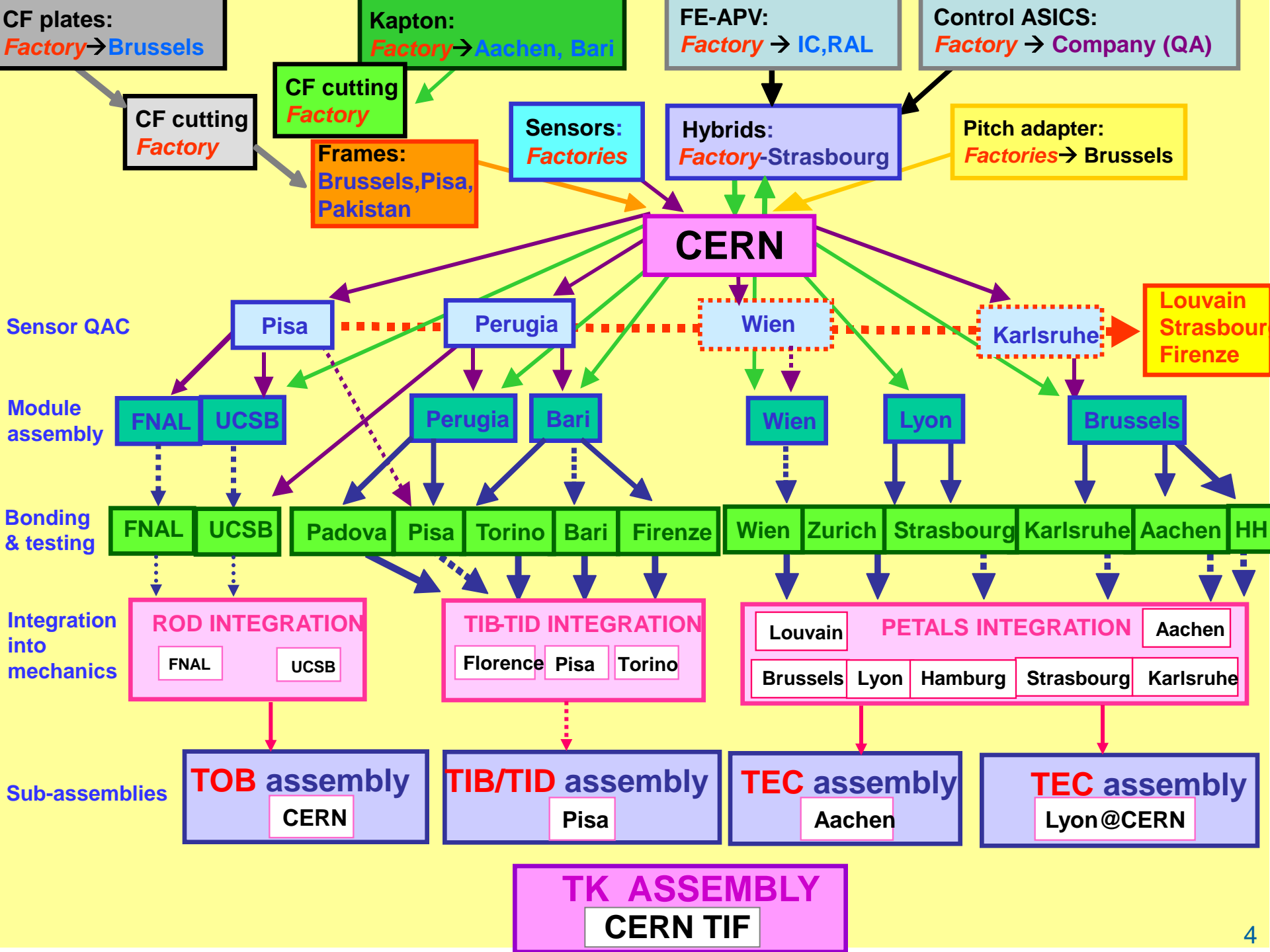
Summary

# CMS Strip Tracker layout



**24,244 pieces (200 m<sup>2</sup>) of sensors necessary; >35,000 delivered**  
**→ Complex Logistic & Quality Assurance**

Barrel: strips parallel to beam  
 End cap: strips in radial direction



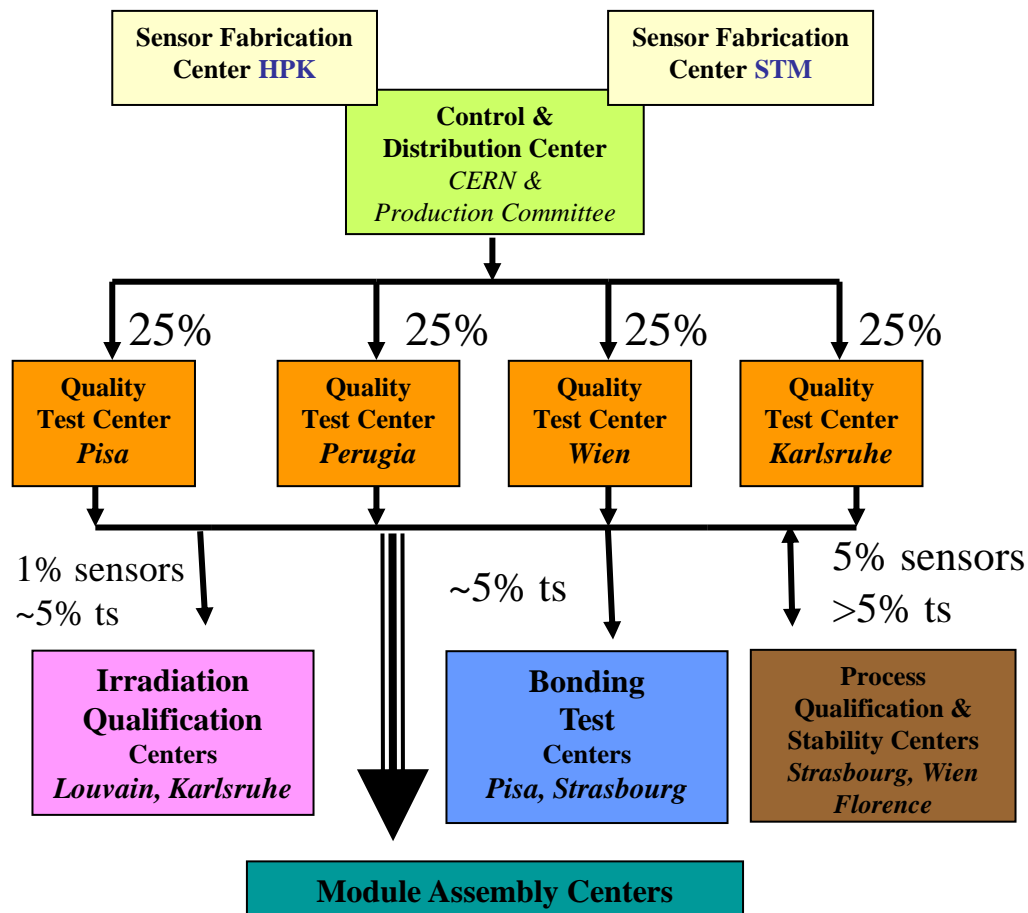
## Silicon Sensors Logistics

### Two producers:

- Hamamatsu Photonics (Japan)
- ST Microelectronics (Italy)

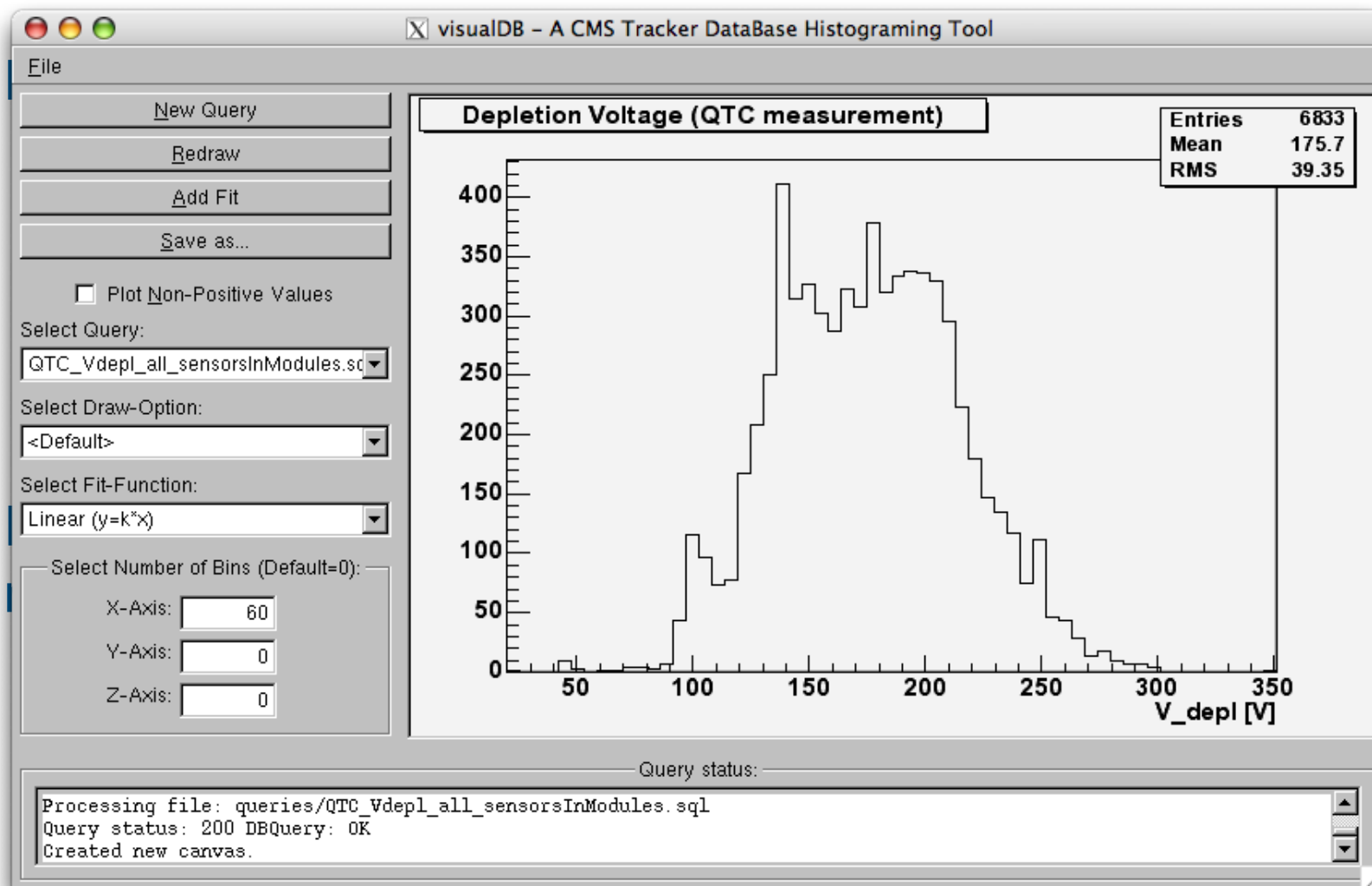
### Four (five) main Test Centers

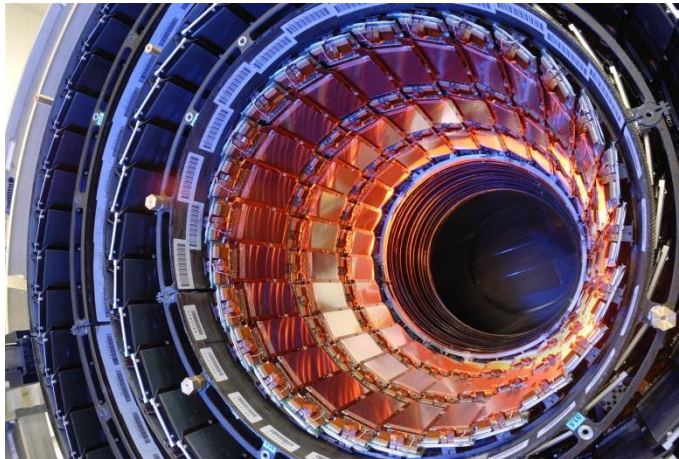
- Later, Rochester (US) joined
  - Pisa, Perugia: Barrel sensors
  - Karlsruhe, Vienna: Endcap sensors
- Supported by smaller tests in different locations for special purposes



Large-scale production needs tools

# CMS Tracker Construction DB



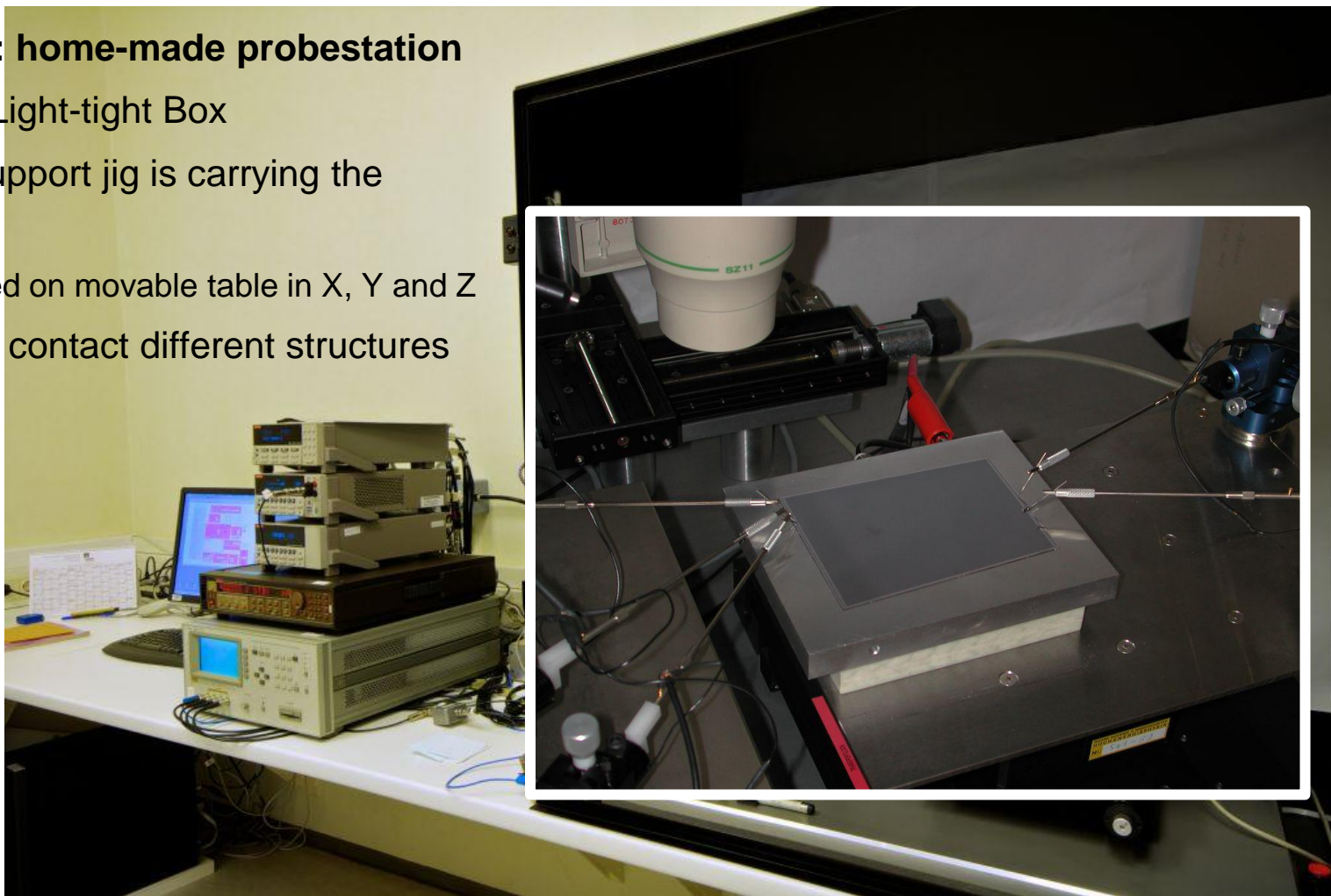


Logistics  
**Strip Scans on Sensors**  
Process Monitoring  
Irradiation  
Long-term Stability  
Summary

## Strip-by-strip Test Setup Vienna

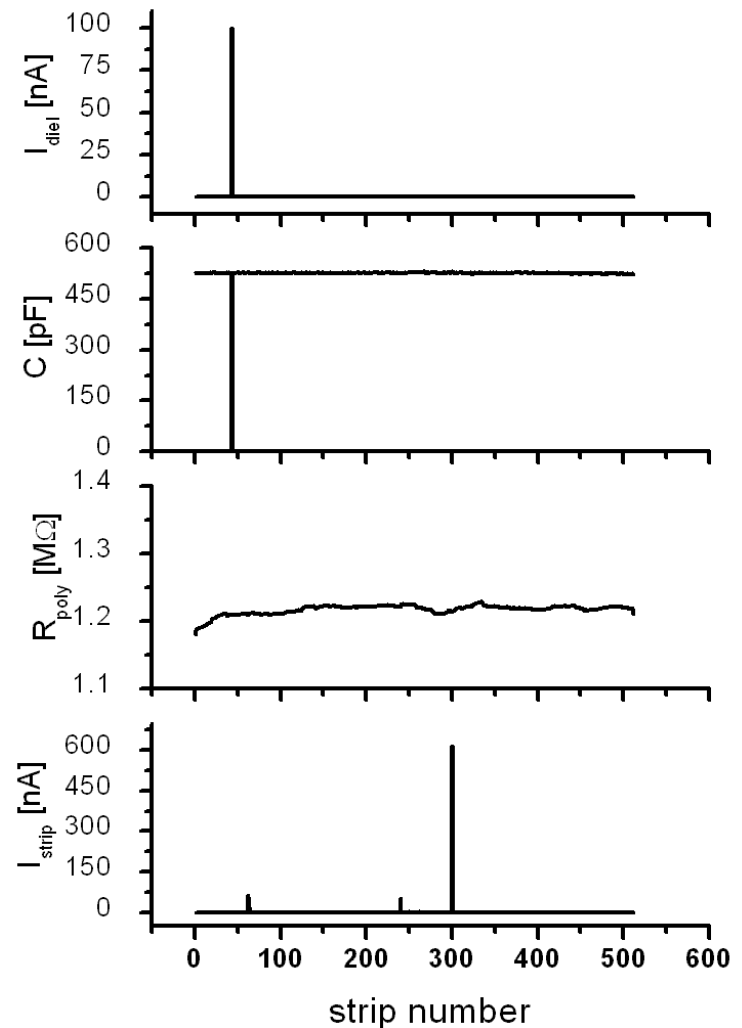
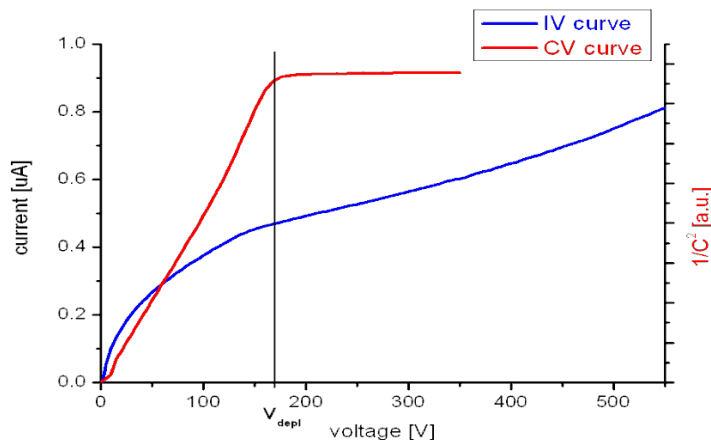
### Vienna Setup: home-made probestation

- Sensor in Light-tight Box
- Vacuum support jig is carrying the sensor
  - Mounted on movable table in X, Y and Z
- Needles to contact different structures on sensor



# What have we tested?

- Global parameters:
  - **IV-Curve:** Dark current, Breakthrough
  - **CV-Curve:** Depletion voltage, Total Capacitance
- Strip Parameters e.g.
  - strip leakage current  $I_{\text{strip}}$
  - poly-silicon resistor  $R_{\text{poly}}$
  - coupling capacitance  $C_{\text{ac}}$
  - dielectric current  $I_{\text{diel}}$

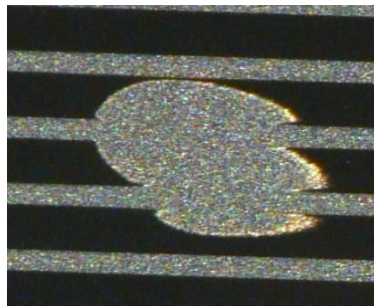


## Common strip failures

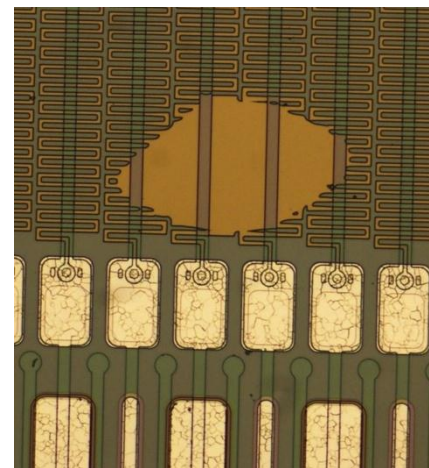
Open Strip:



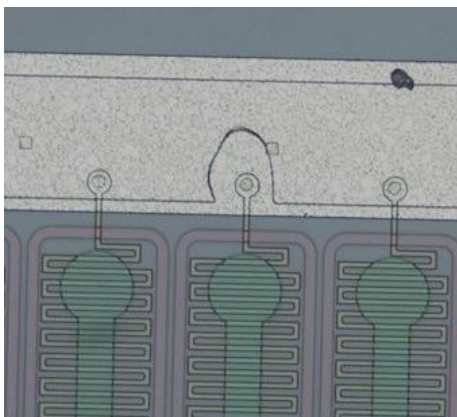
Shorted Strip:



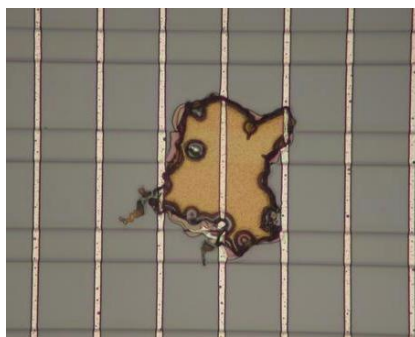
Open bias resistor:



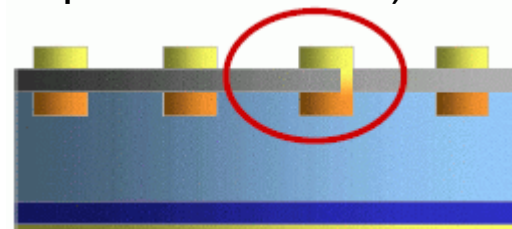
Open implant at via:



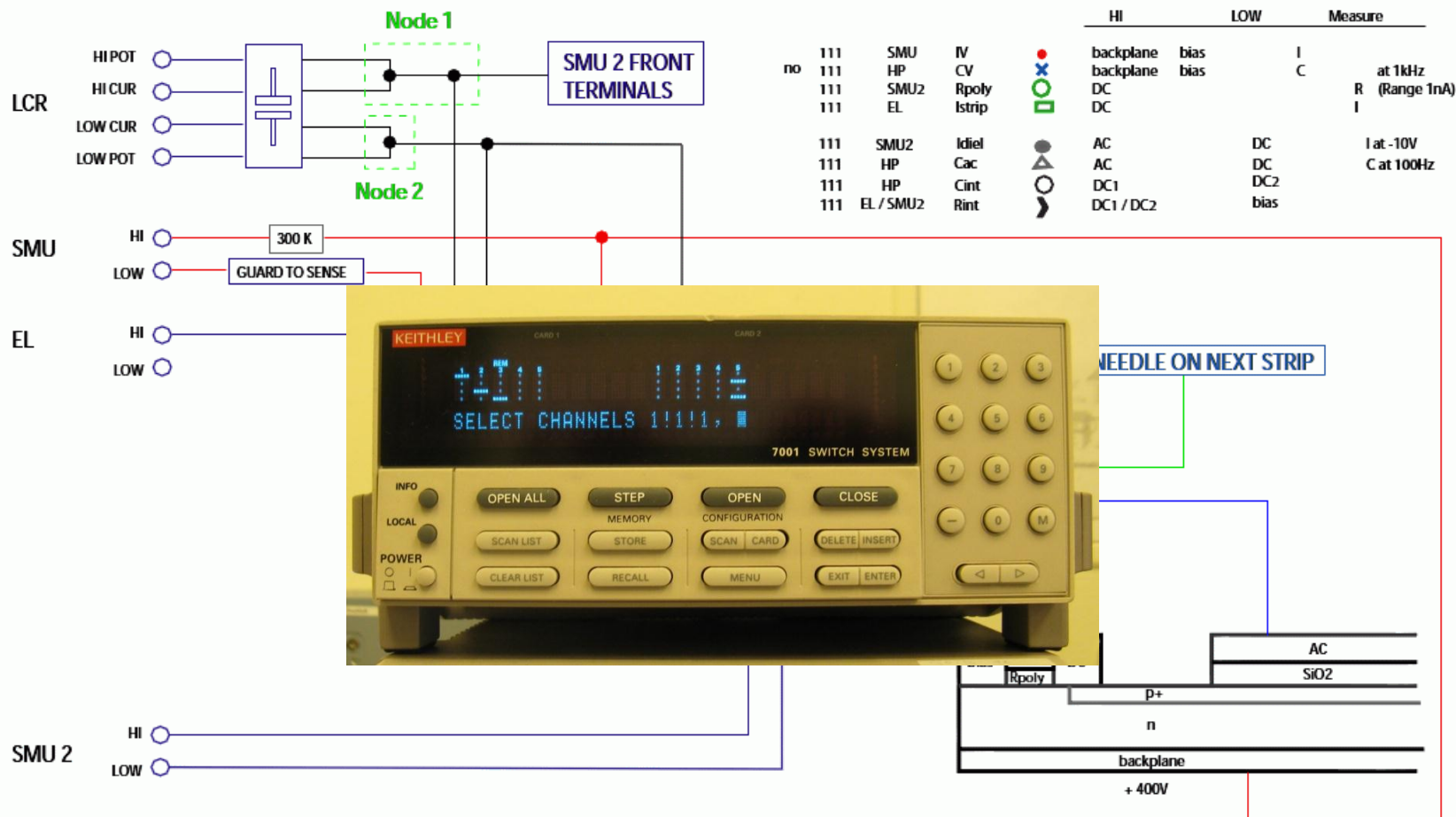
Open implant:



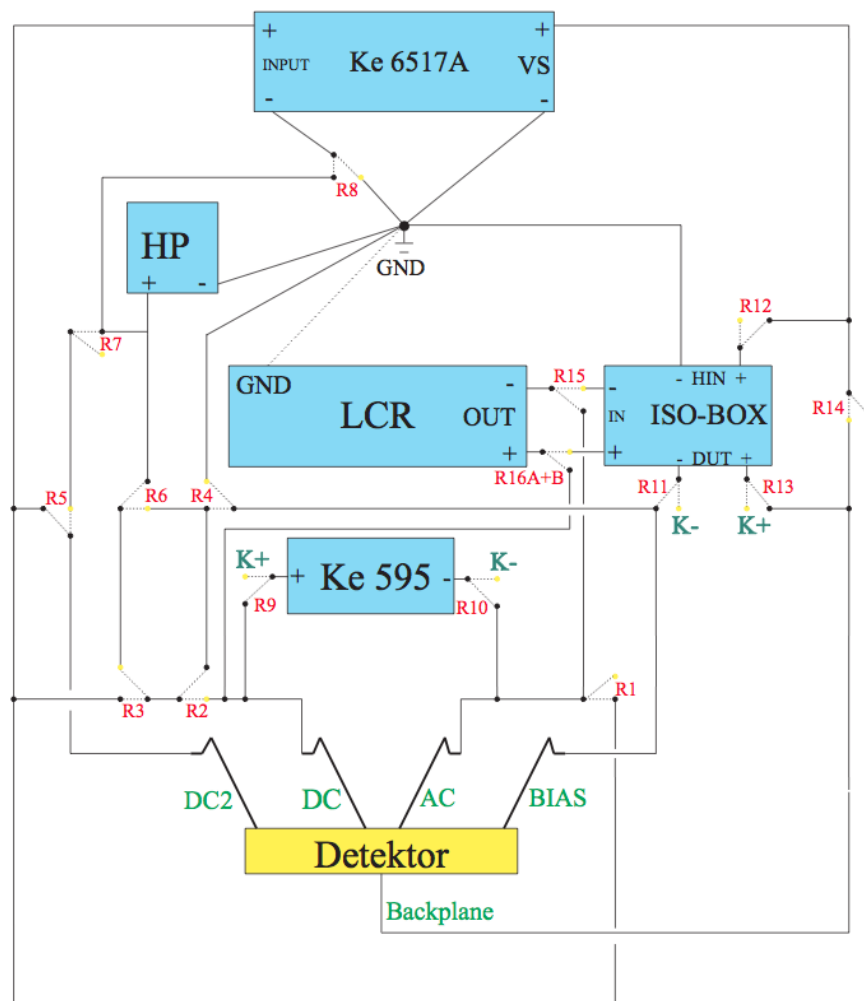
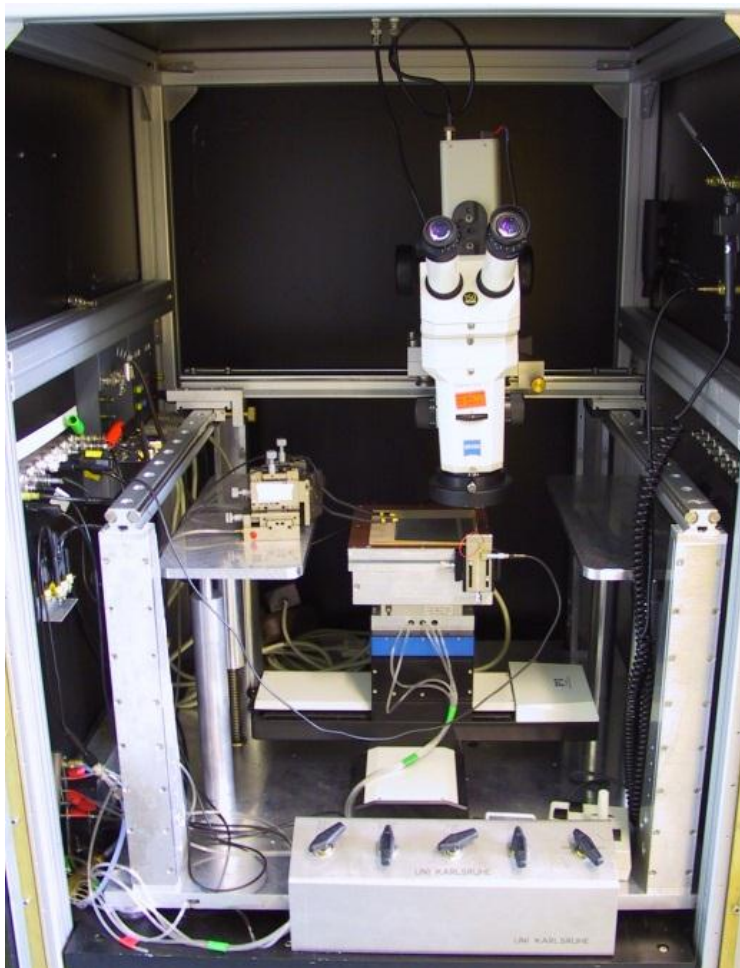
“Pinhole” (short between implant and metal):



# Switching Scheme (Vienna)



## QTC Karlsruhe



## Pisa Setup with Loader

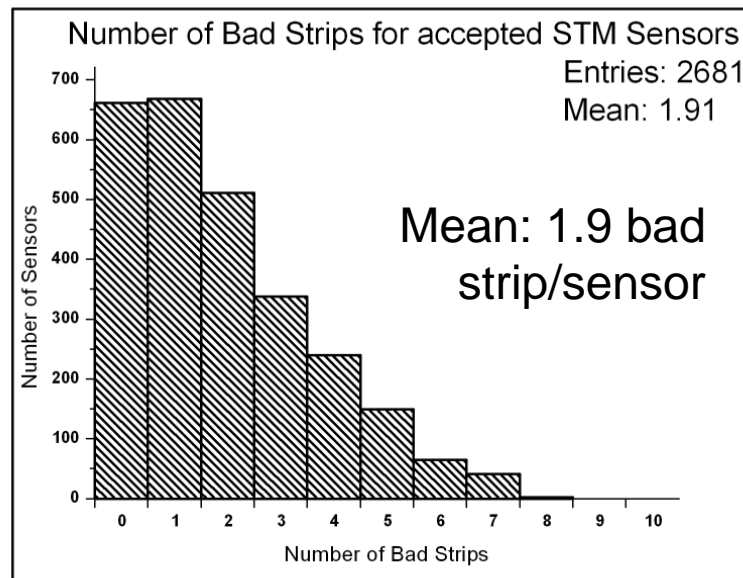
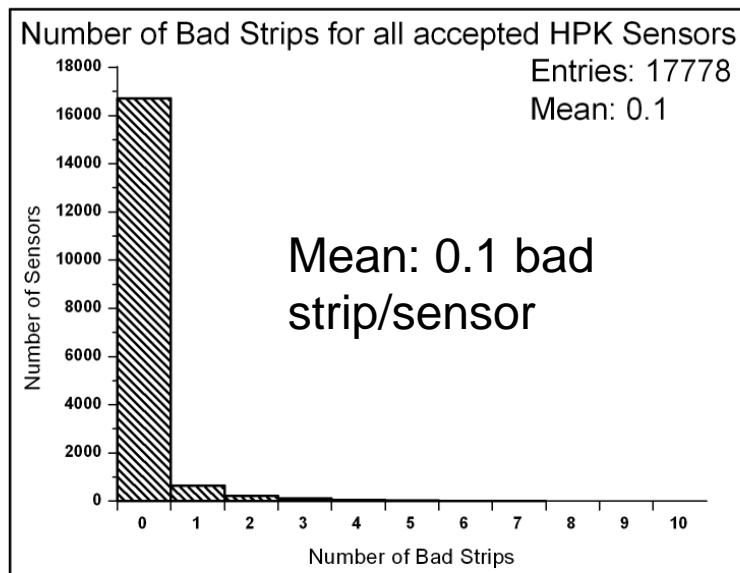


# Quality Tests - Result from Strip Scan

Number of bad strips per sensor (pinhole, bad poly-resistor, Al short, broken Al, open implant, leaky strip,....)

## Number of Bad Strips

Specification: max 1% of 512/768 Channels



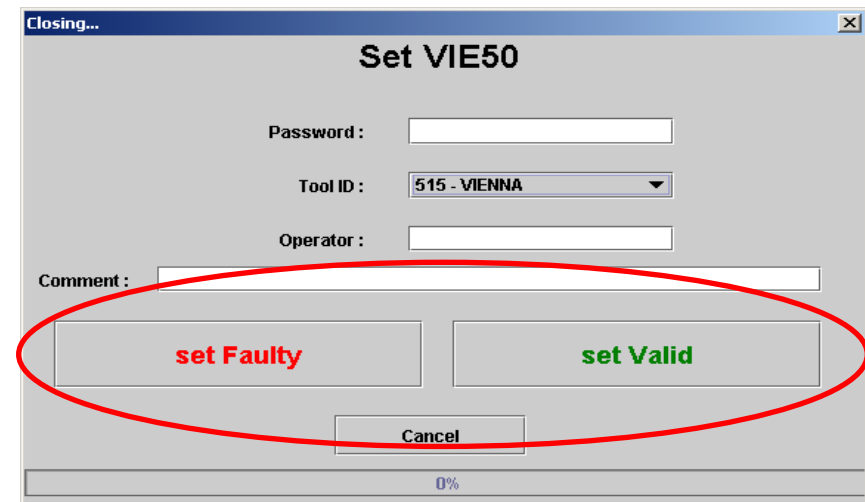
Percentage of bad strips: 0.018%

0.305%

## Sampling & Vendor Data

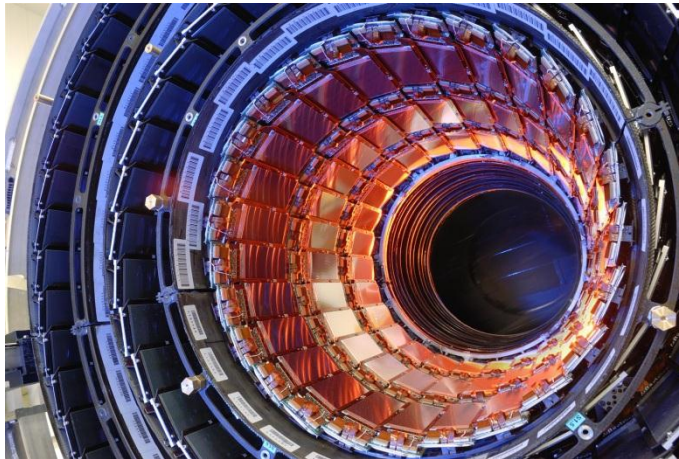
Both vendors, HPK and STM did strip scans already in-house for their QA

- Data has been shipped to CERN on floppy disks together with sensors
  - Stored into TrackerDB via scripts
- After initial verifications we trusted these measurements
  - CMS performed only sample tests on 4% (HPK), but 56% (STM)



TrackerDB “sampling tool”:

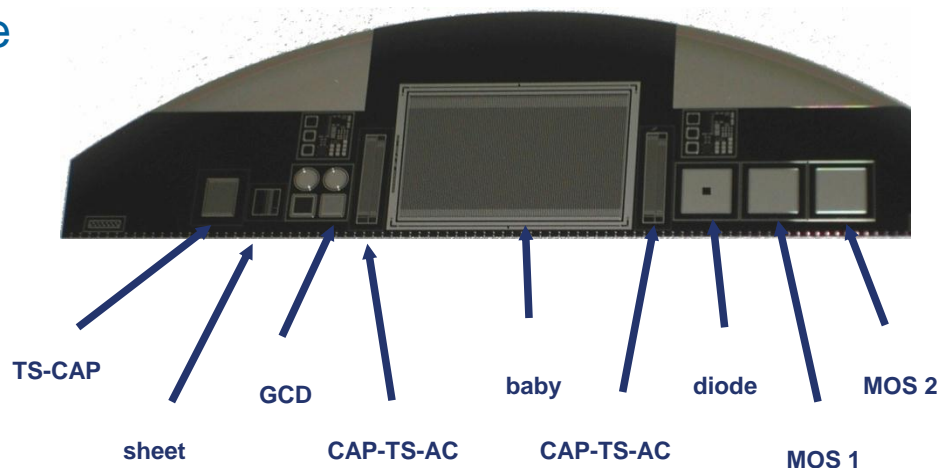
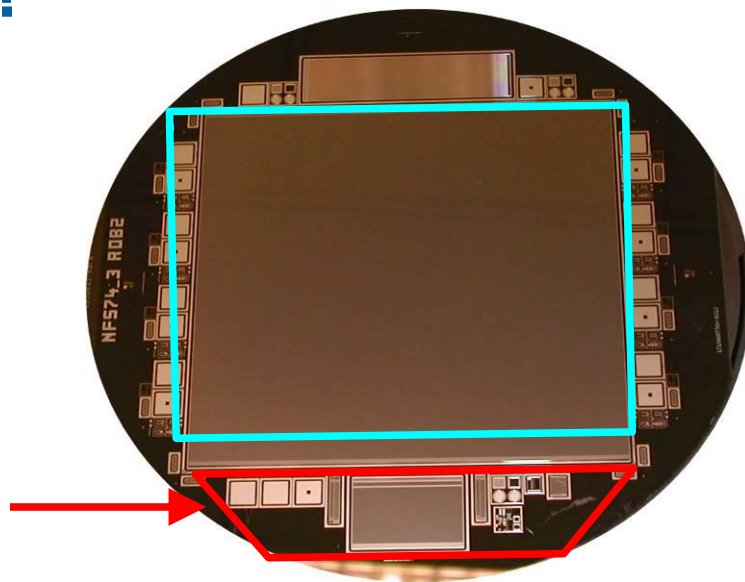
- If some other measurements (PQC, Irrad) reveal some problem, all sensors belonging to one or several batches (i.e. one “set”) can be defined as “faulty”



Logistics  
Strip Scans on Sensors  
**Process Monitoring**  
Irradiation  
Long-term Stability  
Summary

## What is Process Monitoring?

- Each wafer hosts additional test structures around main detector
- “standard” set of test structures is called “half moon” (because of its shape)
- Assuming that sensor and test structures behave identically
- Some parameters are not accessible on main detector (e.g. flat-band voltage of MOS)
- **PQC results often affect complete batch!**

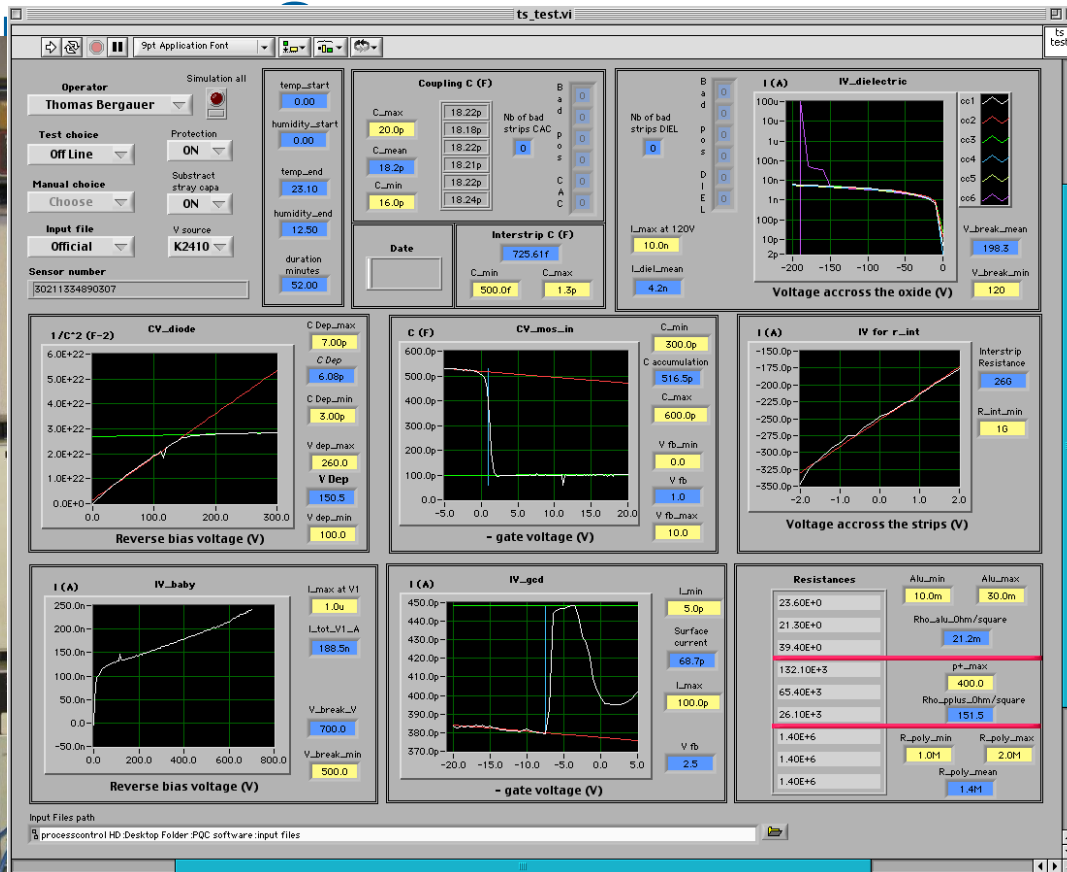


# Test Structures Description

- **TS-CAP:**
  - Coupling capacitance  $C_{AC}$  to determine oxide thickness ( $> 1.2$  pF/cm per  $\mu\text{m}$  of implanted strip width)
  - IV-Curve: breakthrough voltage of oxide  $> 120$  V (destructive!)
- **Sheet:**
  - Aluminium resistivity ( $< 25$  m $\Omega$ /sq.)
  - p<sup>+</sup>-impant resistivity ( $< 200$  k $\Omega$ /sq.)
  - Polysilicon resistor ( $1.5 \pm 0.5$  M $\Omega$ )
- **GCD:**
  - **Gate Controlled Diode**
  - IV-Curve to determine surface current  $5 < I_{\text{surf}} < 100$  pA
  - Characterize Si-SiO<sub>2</sub> interface
- **CAP-TS-AC:**
  - Inter-strip capacitance  $C_{\text{int}}$  (within 10% of parameterization)
- **Baby-Sensor:**
  - IV-Curve for dark current ( $< 100$  nA/cm<sup>2</sup> @ 500 V; 21°C)
  - Breakthrough  $> 500$  V
- **CAP-TS-DC:**
  - Inter-strip Resistance  $R_{\text{int}} > 1$  G $\Omega$
- **Diode:**
  - CV:  $100$  V  $< V_{\text{dep}} < 250$  V depending on resistivity
- **MOS:**
  - CV-Curve to extract flatband voltage to characterize fixed oxide charges ( $< 7$  V)
  - For thick interstrip oxide (MOS1)
  - For thin readout oxide (MOS2)



## Measure



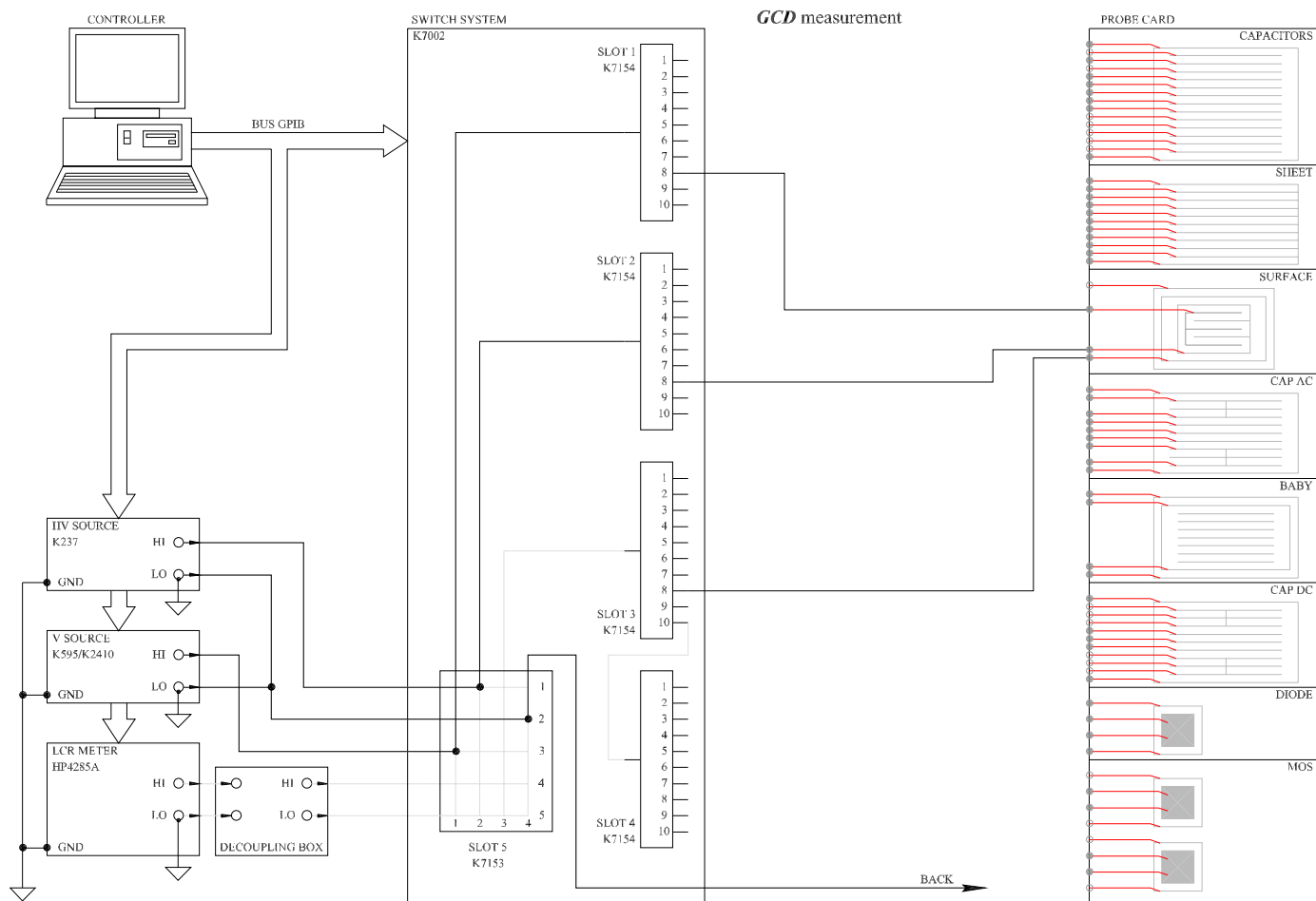
contacts all pads of test structures in parallel

– Micropositioner used for Alignment

# Example for switching scheme: GCD

Process Quality Control system (Vienna configuration)

updated: 6.Juli 2004



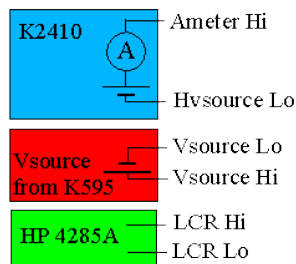
# Setups in Florence, Strasbourg, Vienna

Vienna

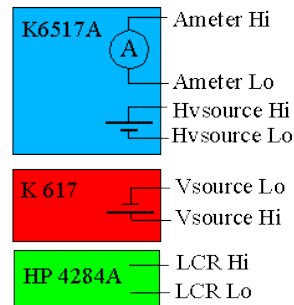


PQC devices for each lab

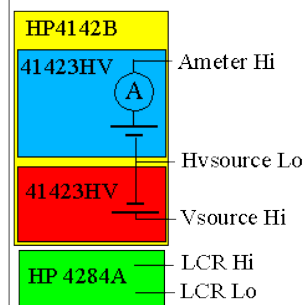
Wien



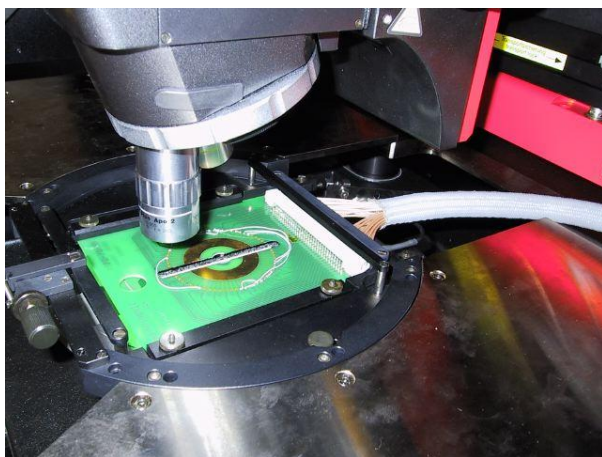
Strasbourg



Firenze



Strasbourg



Firenze

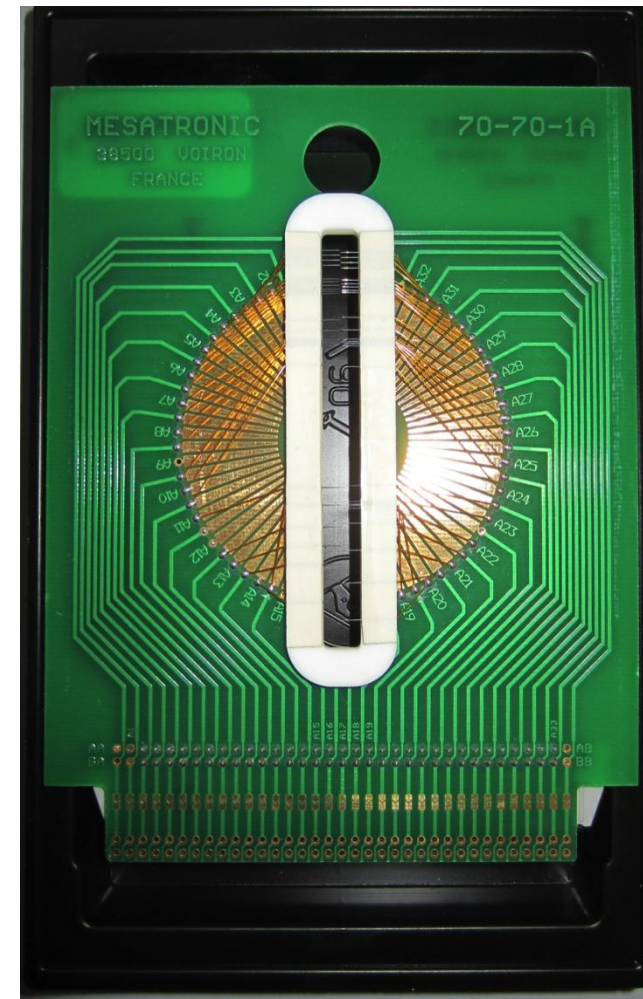
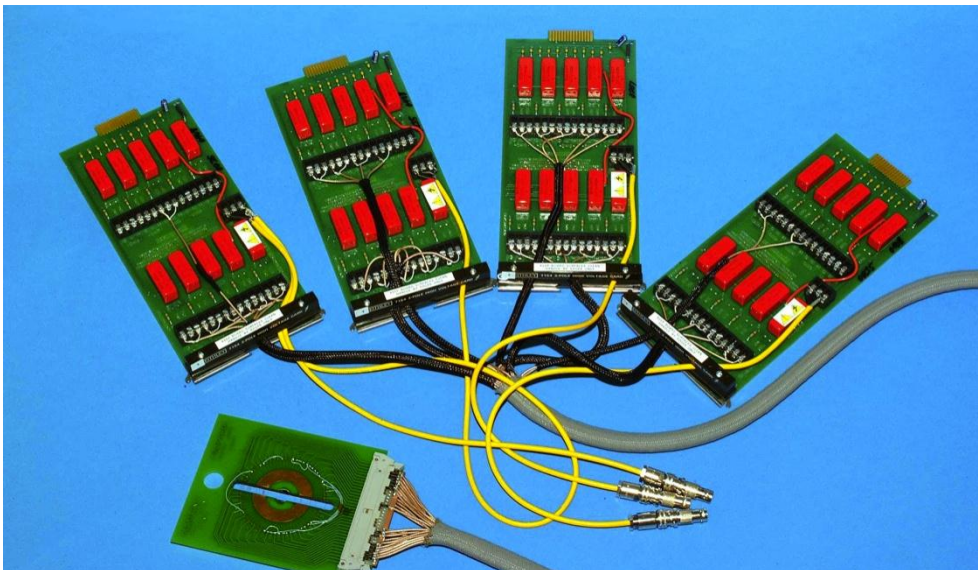


## Probe Card

Printed Circuit board

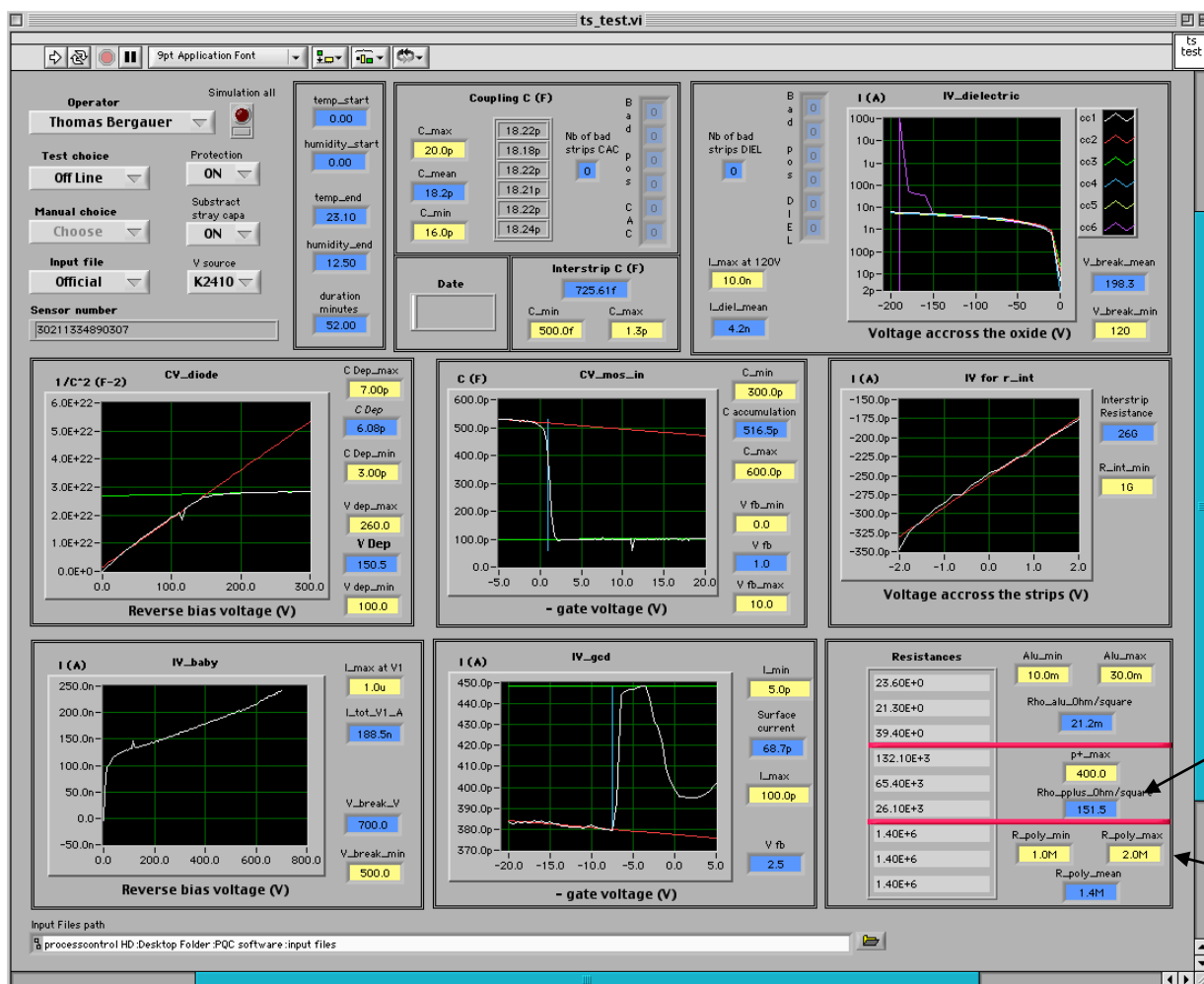
- Size approx. 10x16 cm
- 49 needles to fit pads of all TS at once
- IDC connector (not shielded)

Manufactured by French company



# Measurement Procedure

- TS put on chuck (held by vacuum)
- Alignment and contacting of TS in respect to probe card
- Start Labview program to perform all measurements
- Full characterization: 35 minutes



### Blue Fields:

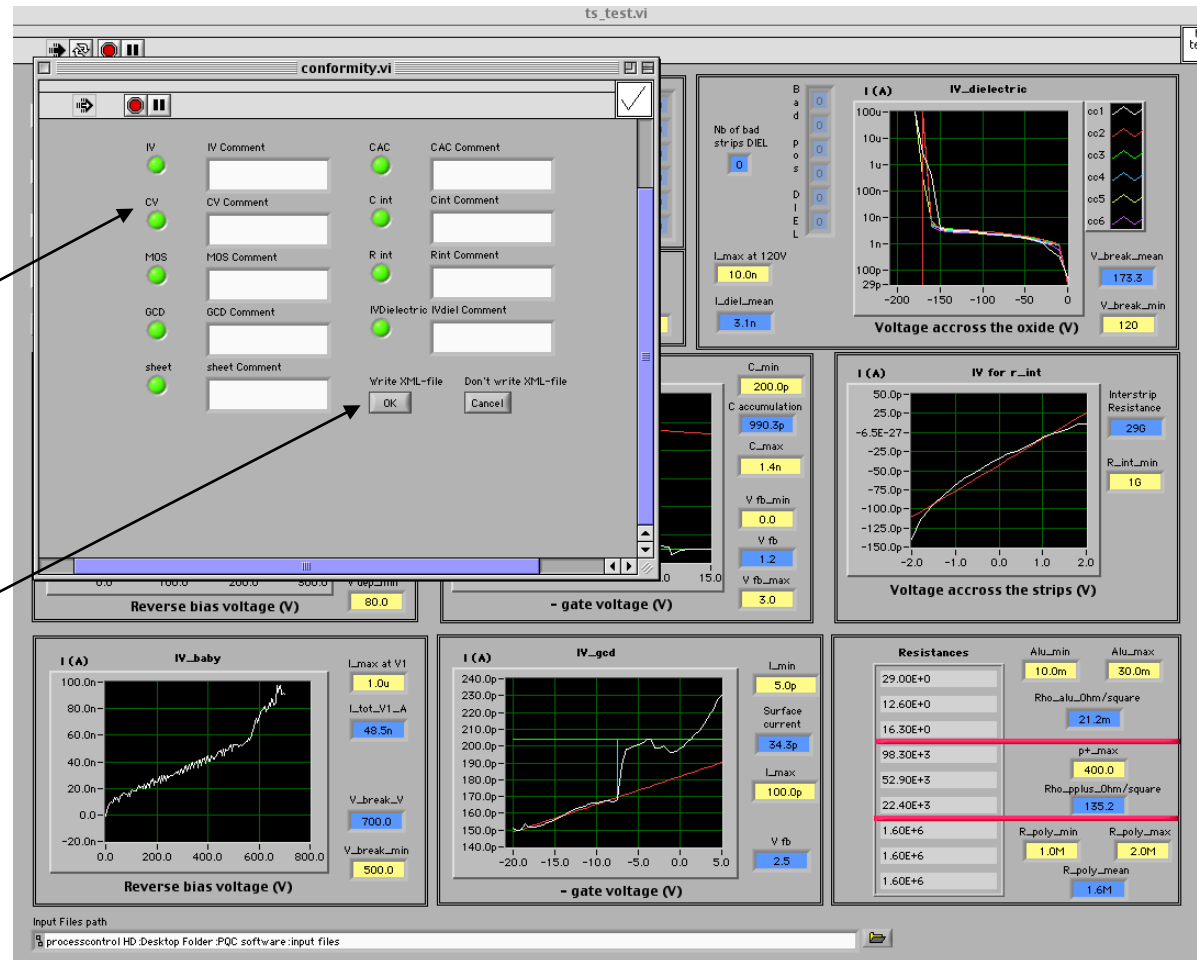
Obtained results extracted from graph by fits

### Yellow Fields:

Limits and cuts for qualification

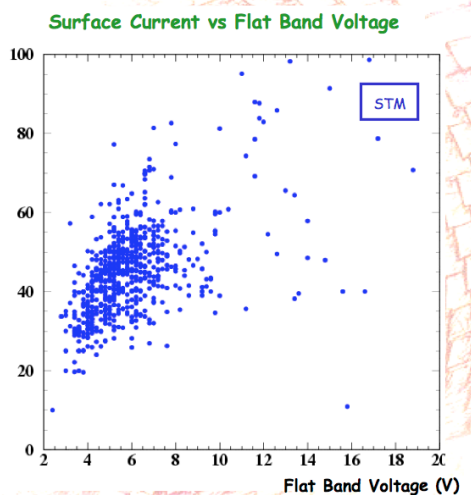
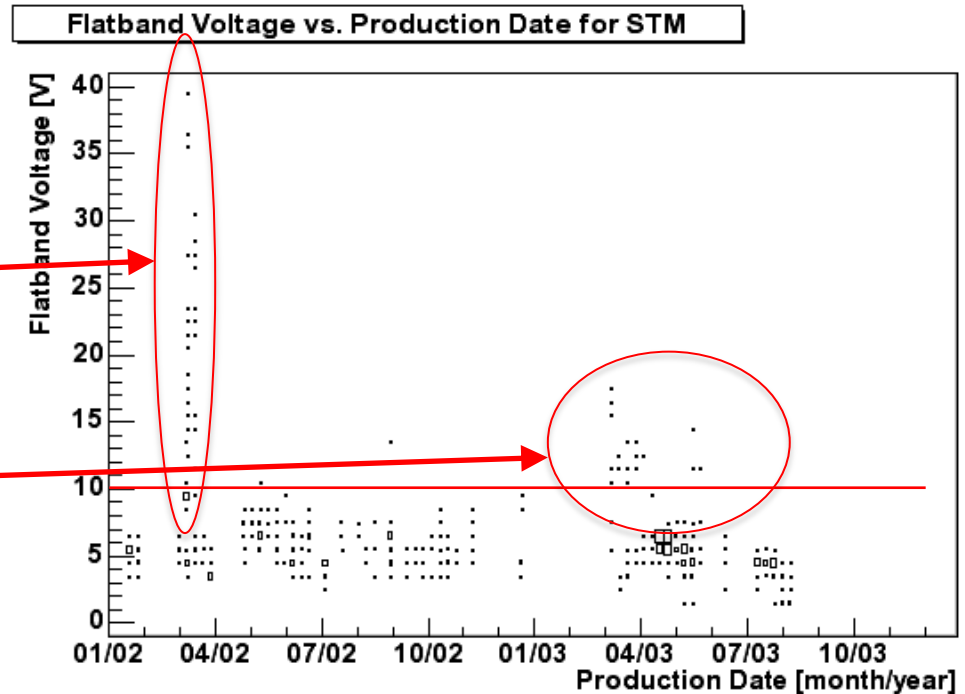
# Passed/Not Passed Lights

- After all measurements finished
- Window pops up
- One light for each test
  - Green: within limits
  - Red: out of limits
- Allows immediate judgment about quality
- Pressing “OK” button writes XML file containing all data ready to upload to CMS Tracker Construction DB



# Results: High flat-band voltage

- Measured by CV on MOS
- Initial limit of 10V
- No problem with HPK (~1.5V)
- STM: values up to 40V in week 10/02
- Some batches suffer from contamination of production line even later on



- Issues here have been cross-checked with inter-strip capacitances before/after irradiation

# Low $R_{\text{int}}$ problem

Shortly after 2nd incident of high flat-band, STM suffered from very low  $R_{\text{int}}$  values

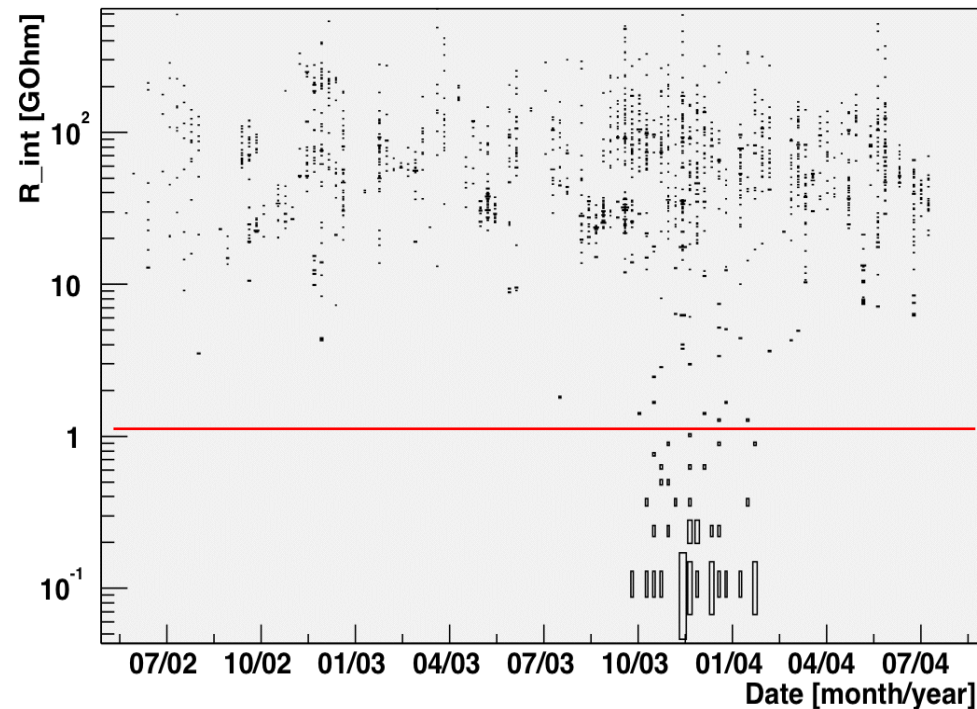
- contamination of production line was addressed by remedy which had bad influence on  $R_{\text{int}}$

~1000 sensors affected

- **all rejected**

Lower limit:  $R_{\text{int}} > 1 \text{ G}\Omega$

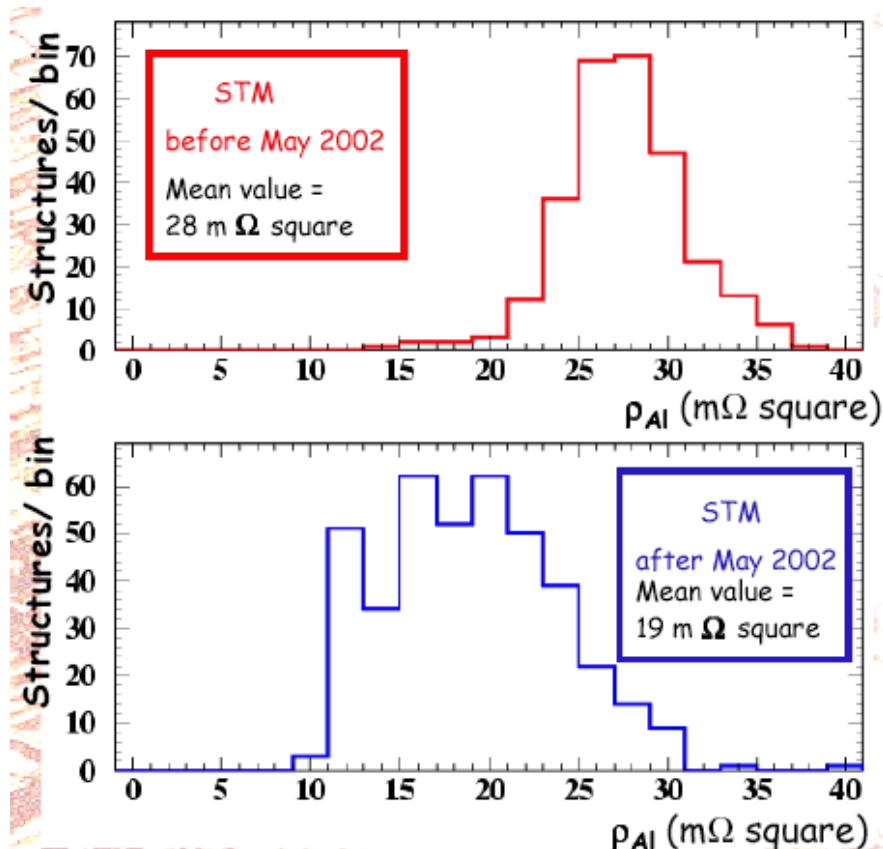
**$R_{\text{int}}$  vs. Date of Measurement for STM**



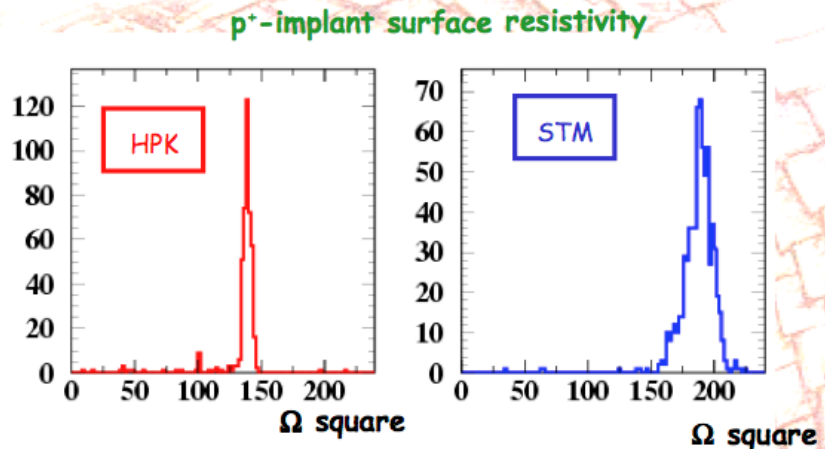
# Results: Sheet Resistivity

- Aluminum resistivity too high for STM up to May 2002
  - Limit:  $<25 \text{ m}\Omega/\text{sq.}$
  - Affects noise of APV
- After discovered, STM was informed by the problem
  - increased Al layer thickness to  $1.2\mu\text{m}$

## Aluminum resistivity



© Anna Macchiolo



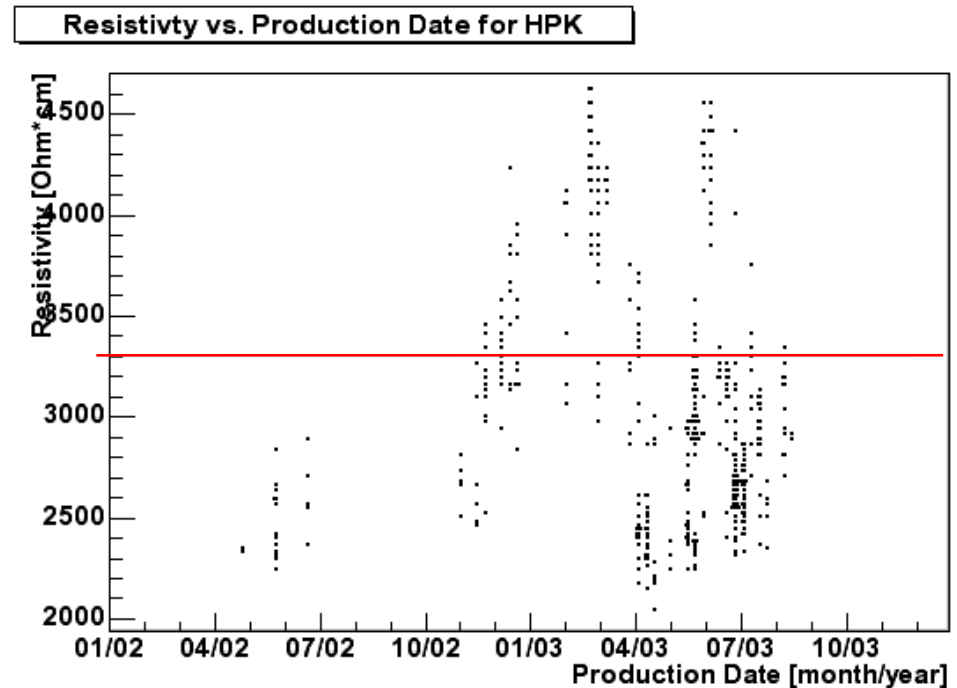
# Results: Bulk Resistivity

## Requirement:

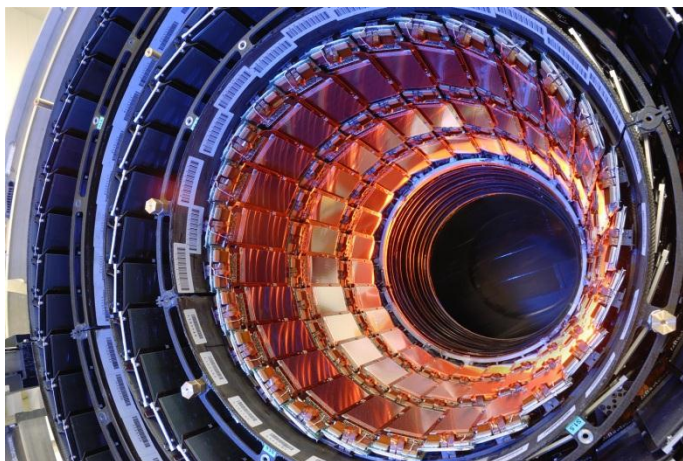
- $V_{\text{depl}} < 400\text{V}$  after 10 years of LHC operation

## Results in resistivities:

- $1.25 < \rho < 3.25 \text{ k}\Omega\text{cm}$  (inner tracker=thin sensors=HPK)
- $3.5 < \rho < 7.5 \text{ k}\Omega\text{cm}$  (outer tracker=thick sensors=STM)



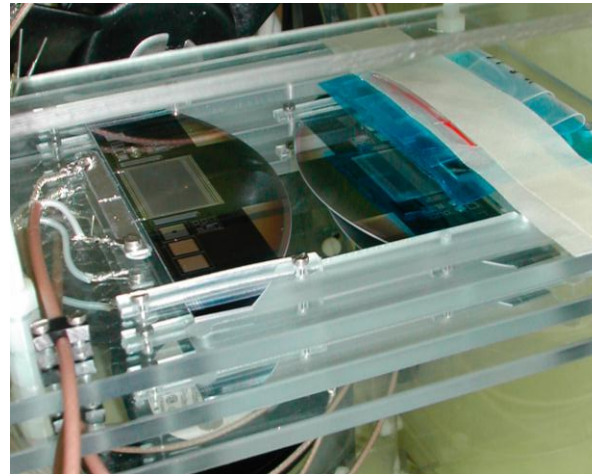
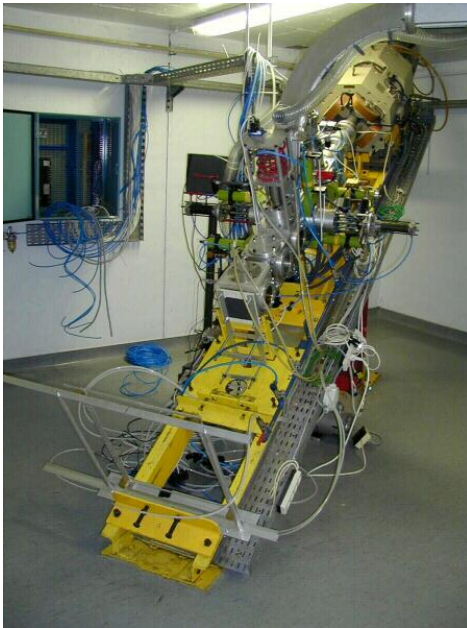
- Agreement: CMS accepted all wafers, but uses the ones with lower resistivity in the inner layers.



Logistics  
Strip Scans on Sensors  
Process Monitoring  
**Irradiation**  
Long-term Stability  
Summary

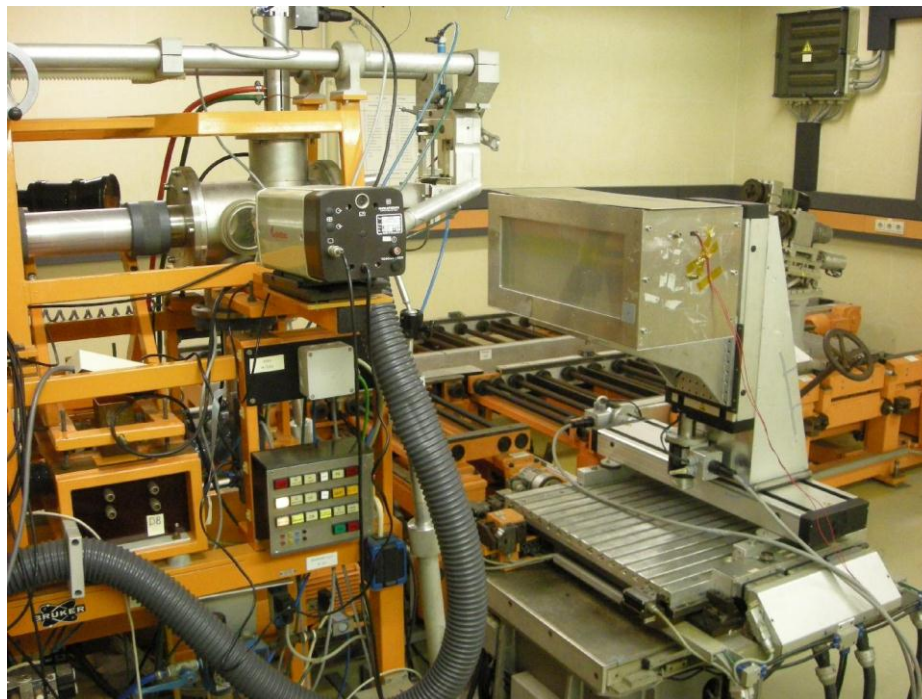
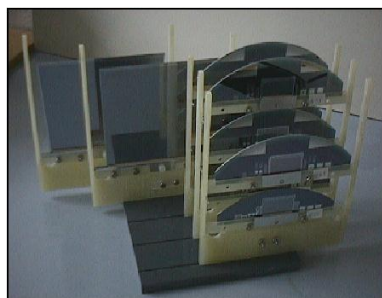
# Neutron Setup at Louvain-la-Neuve

- Fast neutrons (to create bulk damage) by using reaction  ${}^9\text{Be} + d \rightarrow n + X$ .
  - Practically, this is done by steering a 50 MeV deuteron beam on a 1 cm thick beryllium target. (T2 beam line)
  - Deuteron beam is accelerated by the LLN isochronous cyclotron



## Proton Setup at Karlsruhe

- 25 MeV protons at Karlsruhe Cyclotron
- Beam-spot size 4-8 mm, so samples need to be scanned
- Samples sit in cooled box



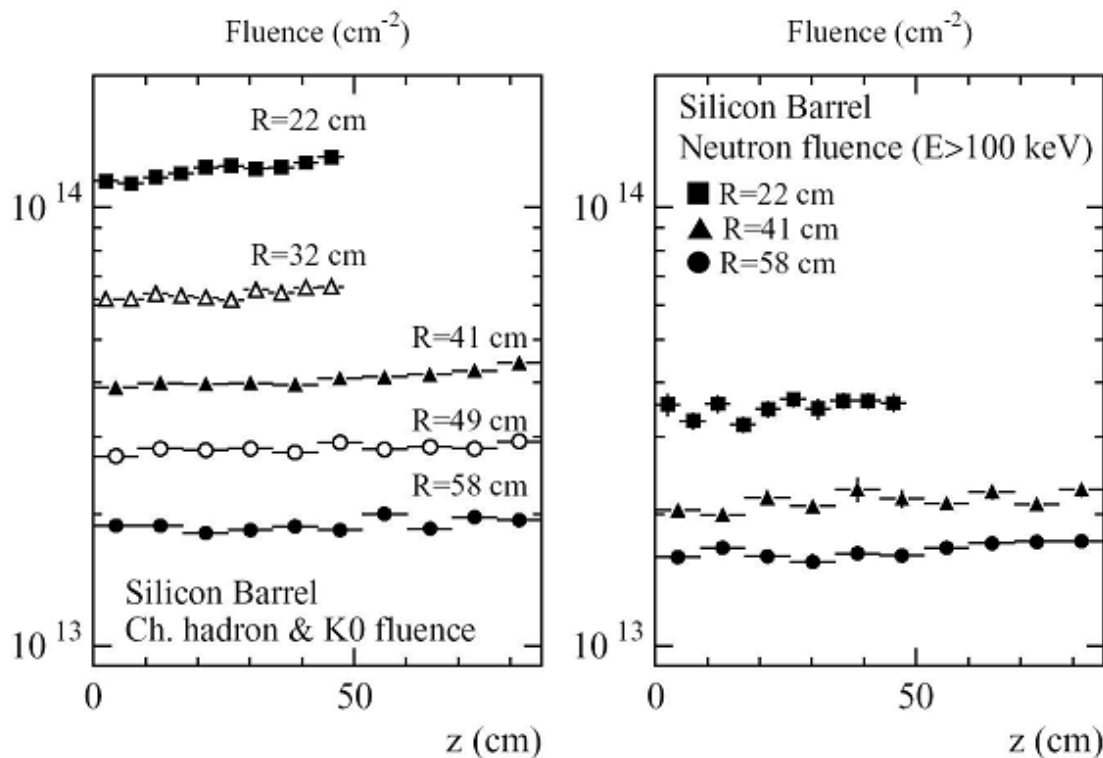
## CMS Radiation Environment

According to TDR:

- Max. particle fluence for thin sensors ( $r < 60\text{cm}$ ):  $1.6 \times 10^{14} n_{\text{eq}}/\text{cm}^2$
- Max. particle fluence for thick sensors ( $r > 60\text{cm}$ ):  $0.35 \times 10^{14} n_{\text{eq}}/\text{cm}^2$
- Safety factor to apply: 50%

**Results in qualification fluences:**

**$2.4/0.5 \times 10^{14} n_{\text{eq}}/\text{cm}^2$  for thin/thick sensors, respectively**

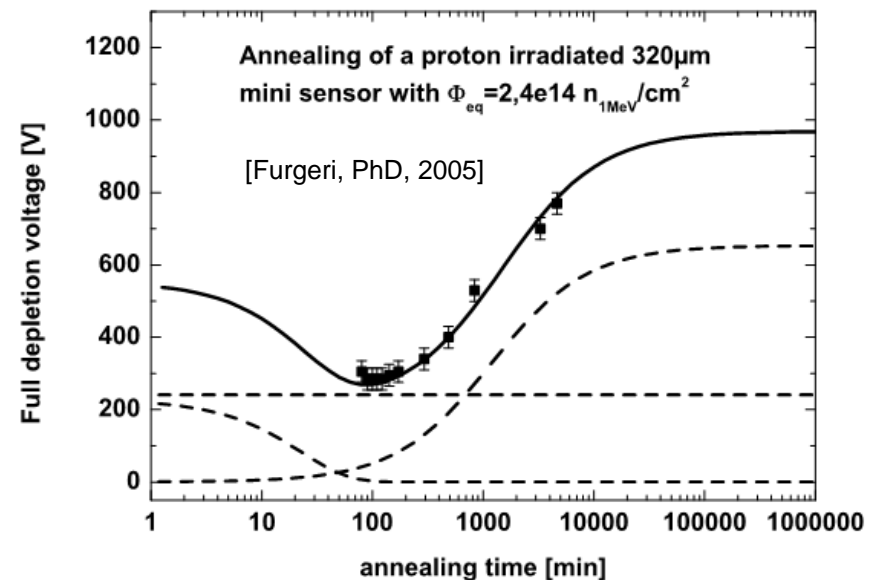


# Annealing

- Measurements should be preformed at defined annealing time to get comparable results
- For a stable full depletion voltage we chose the minimum in  $U_{fd}(t)$ , which turned out to be at 80min at 60°C (or about 10 days at RT)



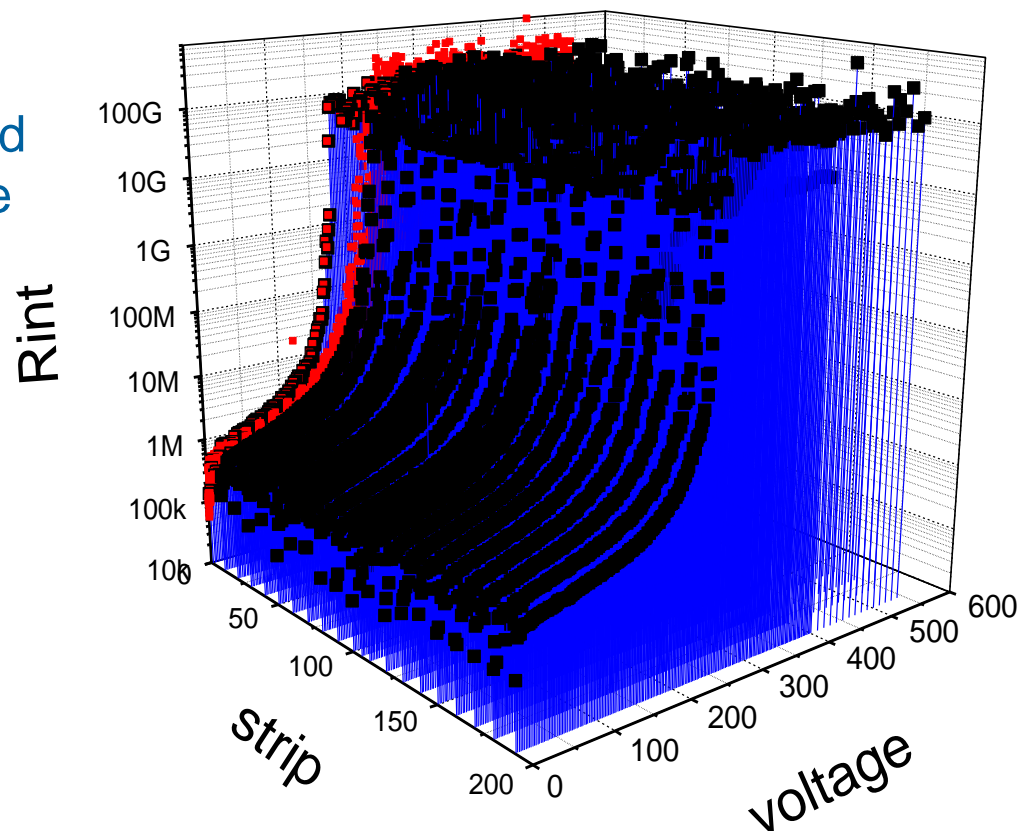
Measurement of  $U_{fd}(t)$  on 320 $\mu$ m mini-sensors  
with HH-model fit



# Measurement/Irradiation Procedure

“Standard” electrical characterization was twice, before and after irradiation ( $T=-10^{\circ}\text{C}$ )

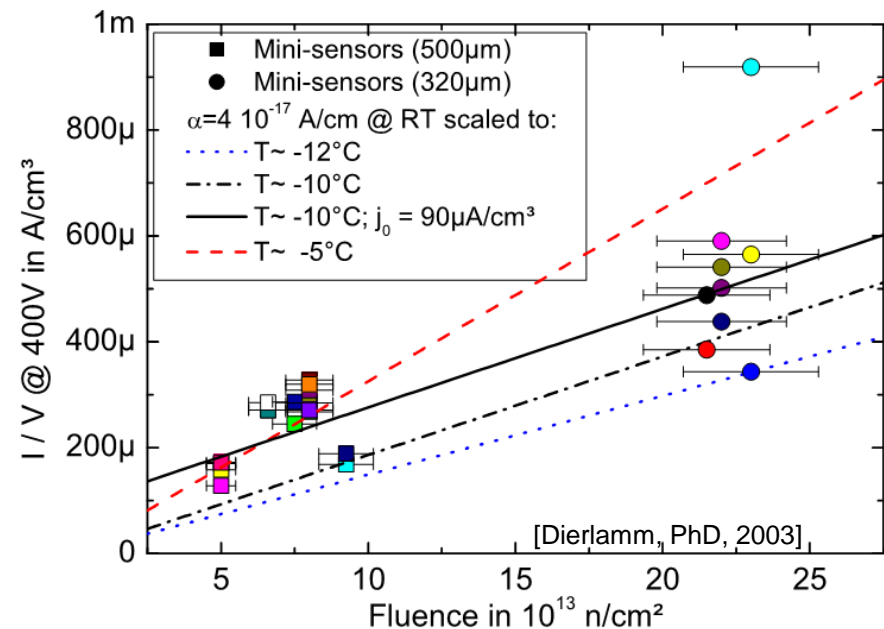
- **Global:** IV, CV
- **Strip:** (all parameters are scanned against the voltage to be sensitive to unexpected behavior)
  - leakage current
  - $R_{\text{poly}}$
  - $I_{\text{diel}}$
  - Coupling Capacitance
  - Inter-strip resistance
  - Inter-strip capacitance



# Total leakage current

Check if leakage currents are within expectations

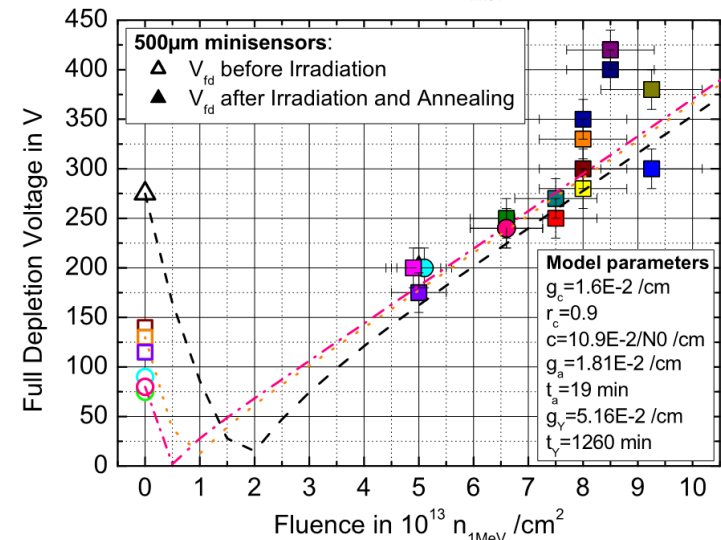
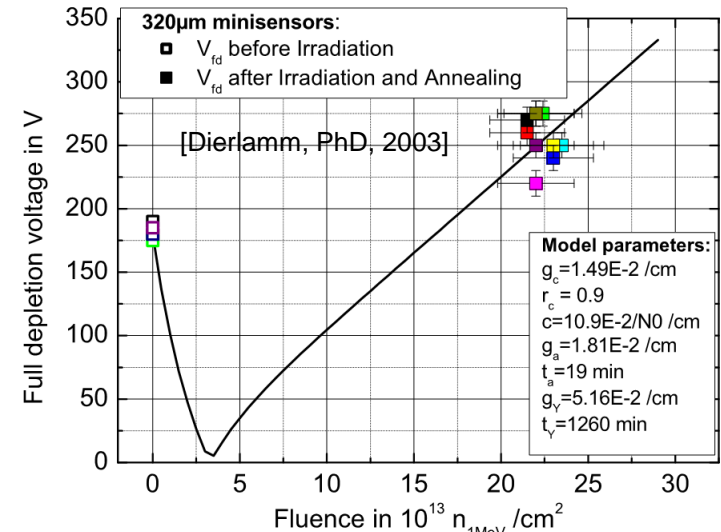
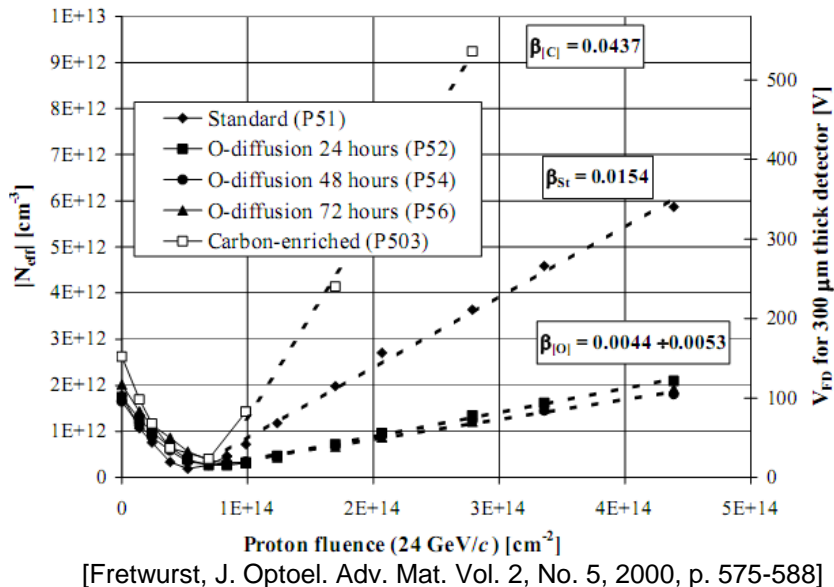
- I/V increase vs. F was shown to be universal for bulk generated current (PhD thesis Moll)
- Can be used to identify additional current sources or problems
- Essential to estimate power budget and cooling power



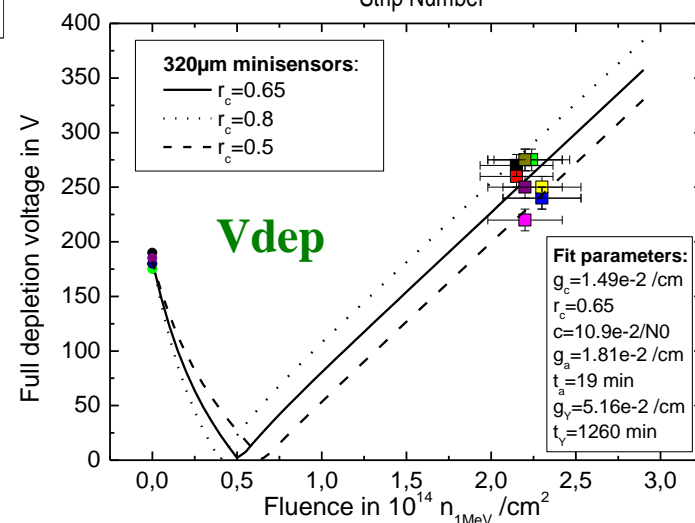
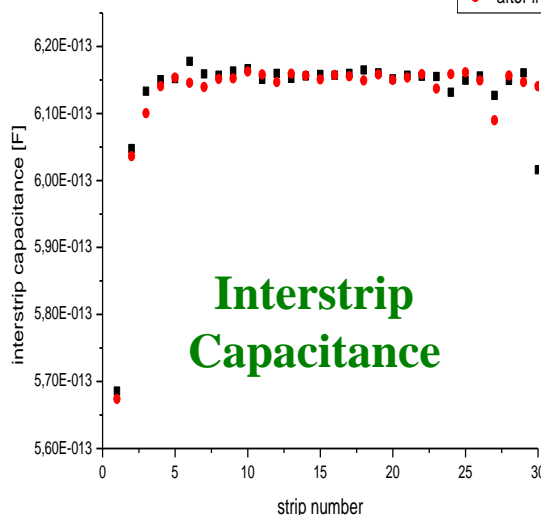
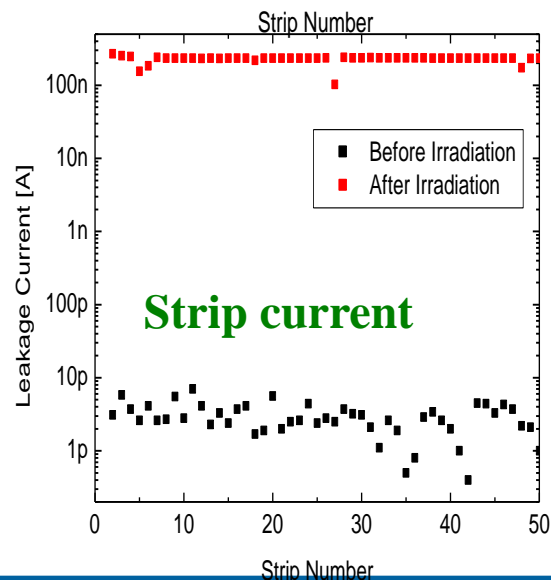
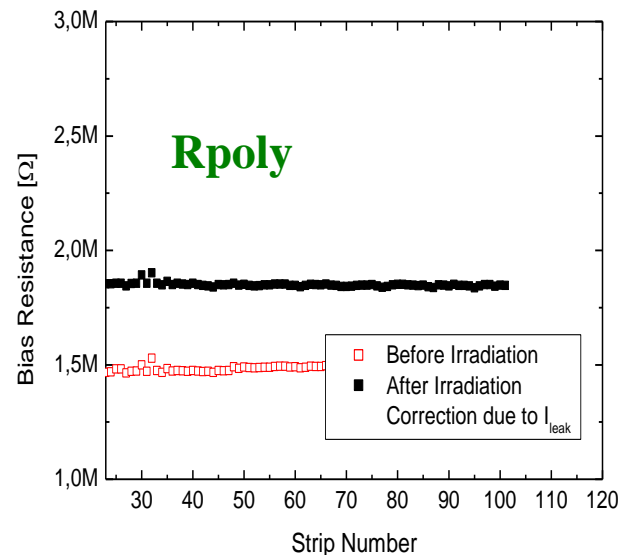
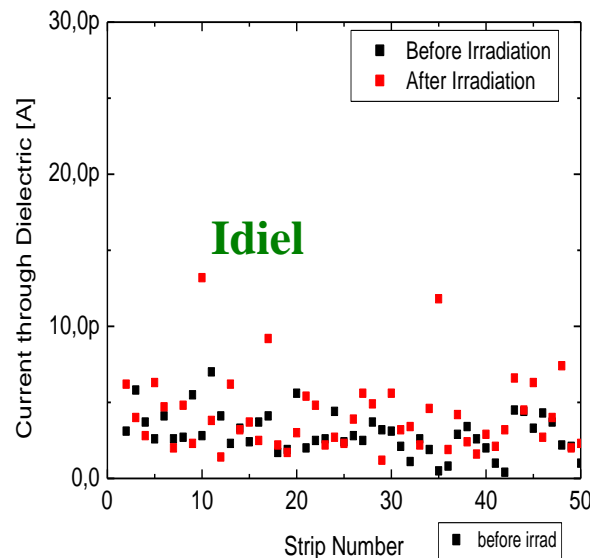
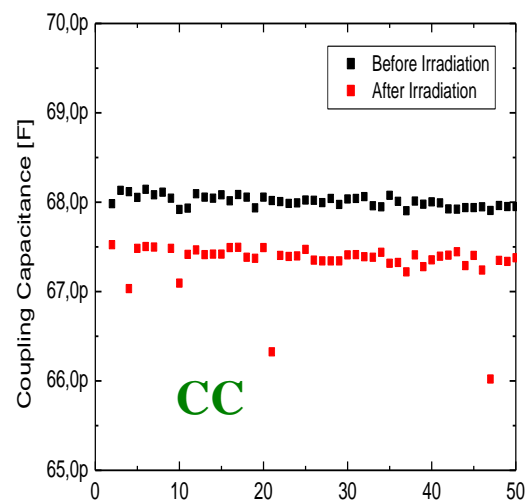
Measurements on CMS mini-strip sensors in operation mode (guard ring floating)

# Full Depletion Voltage

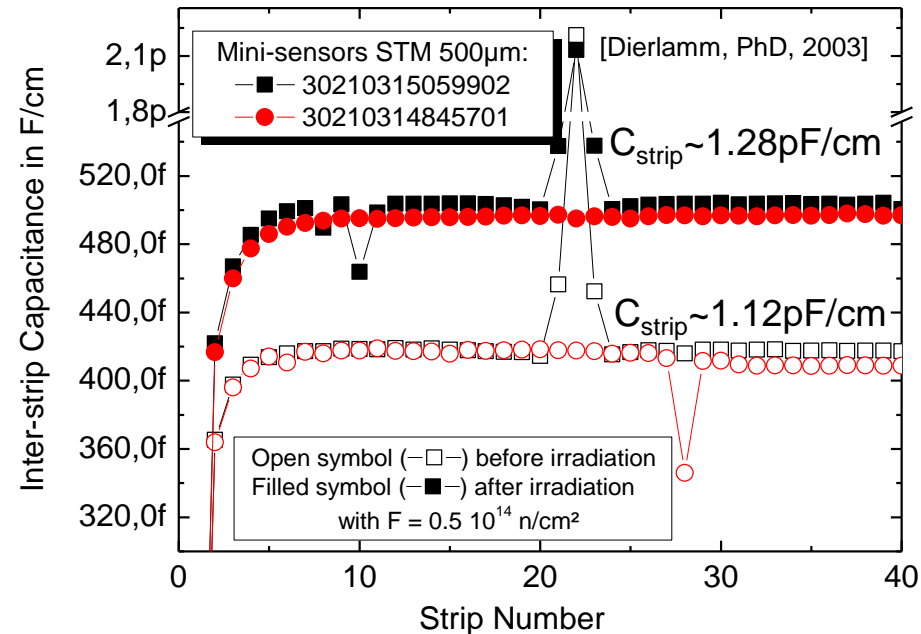
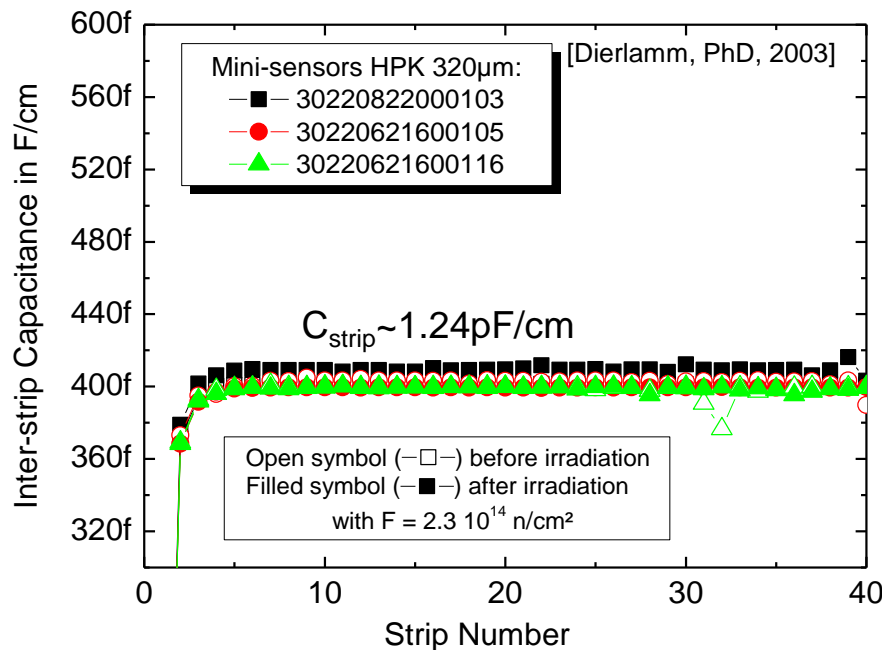
- $U_{fd}(F)$  depends on material and particle type
  - might reveal material contaminations
- Favorable to have several fluence steps
- Parameterization can be used to model certain operation scenarios



# Strip Scan Example



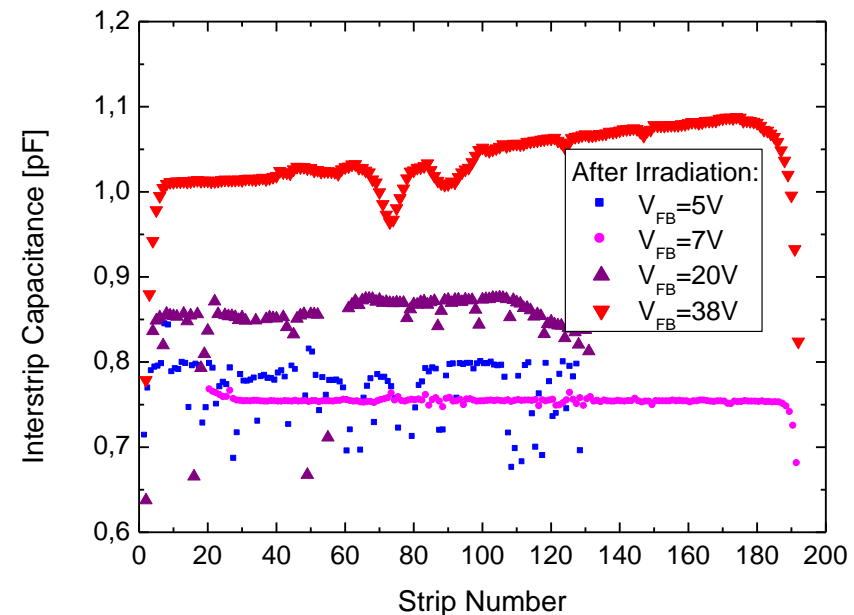
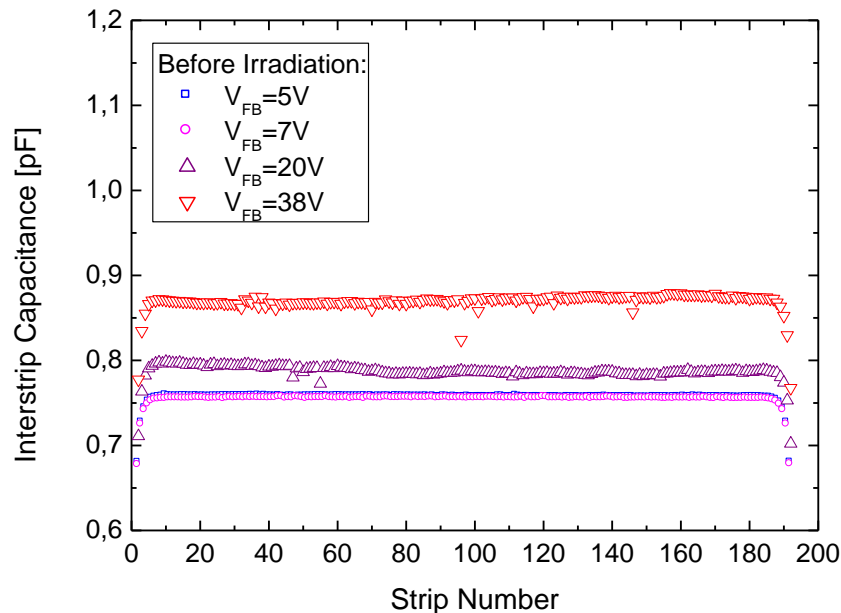
# Inter-strip Capacitance



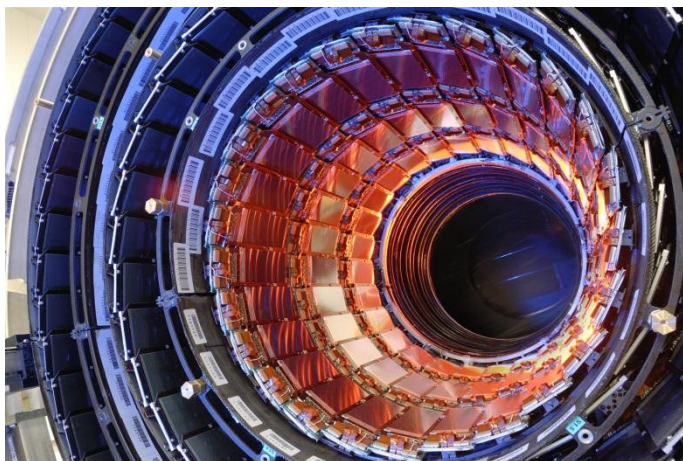
- Thin HPK sensors showed marginal increase after high irradiation
- Thick STM sensors showed significant increase ( $\sim 15\%$ ) already after low dose
  - this indicated some weakness in the ST production

# Inter-strip Capacitance variations for different flat-band voltages

Increase in  $C_{\text{int}}$  scales with  $V_{\text{FB}}$  before and after irradiation !

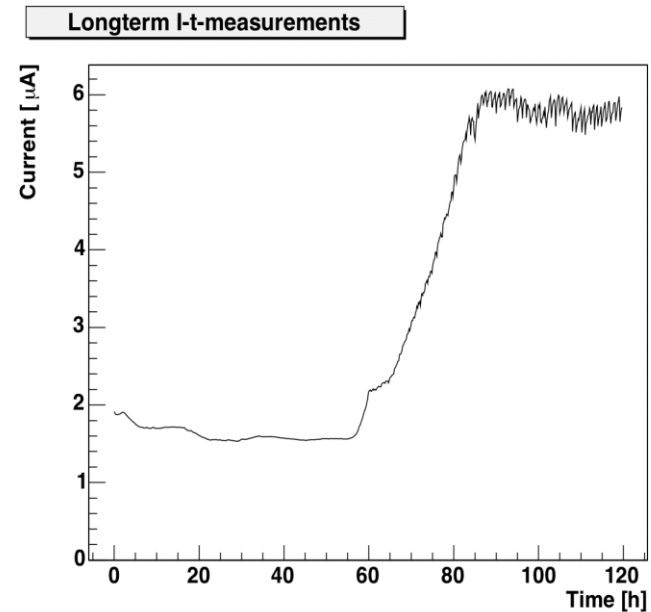
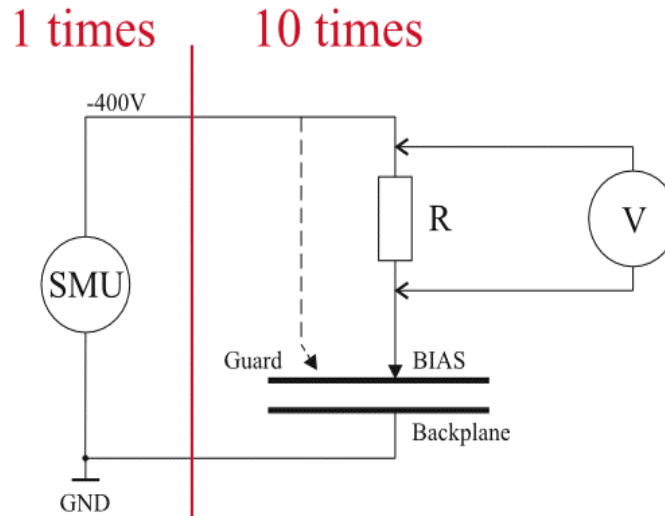


→ new limit for  $V_{\text{flat}}$  acceptance at PQC:  $<7\text{V}$



Logistics  
Strip Scans on Sensors  
**Process Monitoring**  
Irradiation  
**Long-term Stability**  
Summary

# Long-term stability

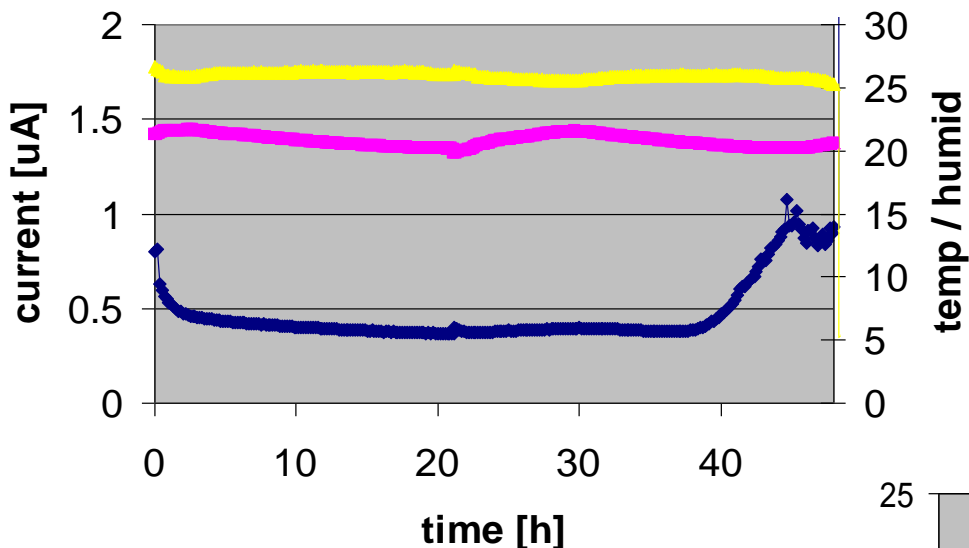


Monitoring of leakage current over certain timescale, usually 1 week

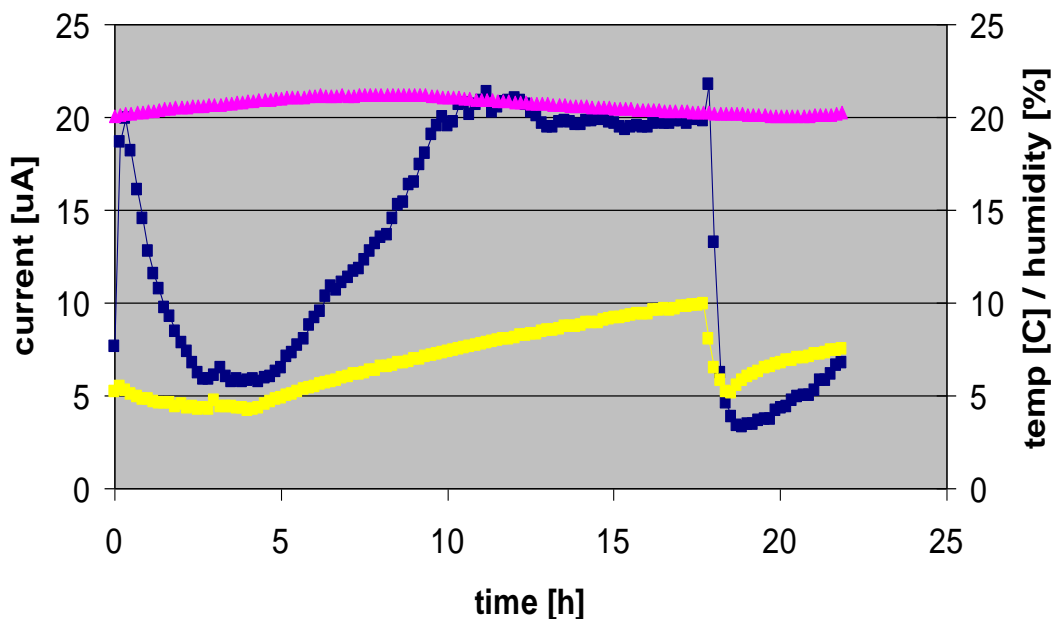
- Regularly at room temperature
  - Humidity control by nitrogen blow
- Special investigations also at -20 degC in Vienna Box

# Influence of humidity

Sensor 3021 13 331 24002



- current increase after 40 hours
- Re-measurement shows clear correlation with humidity (5-10% range)

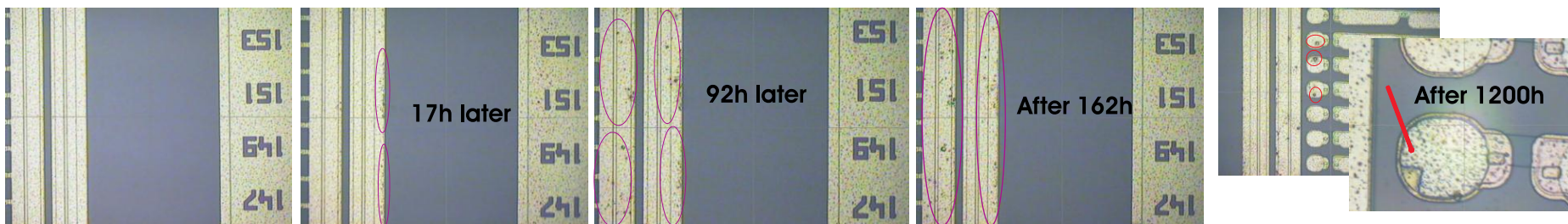
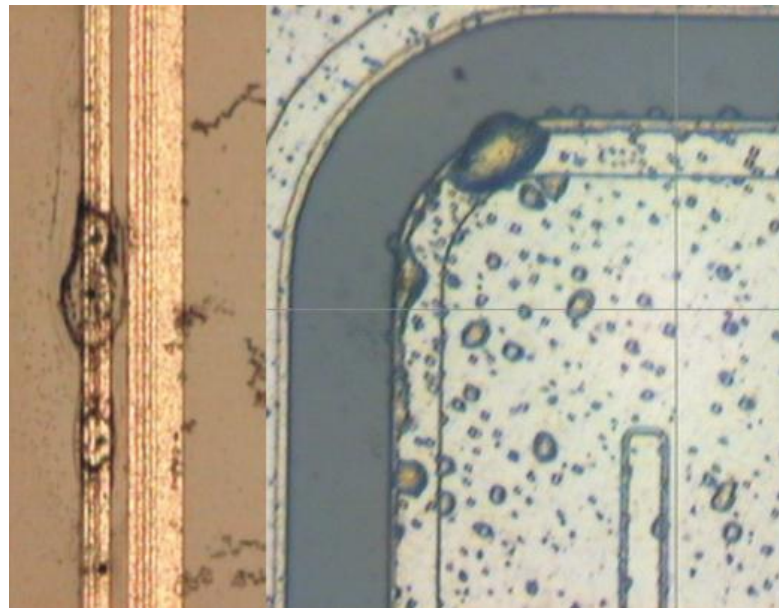


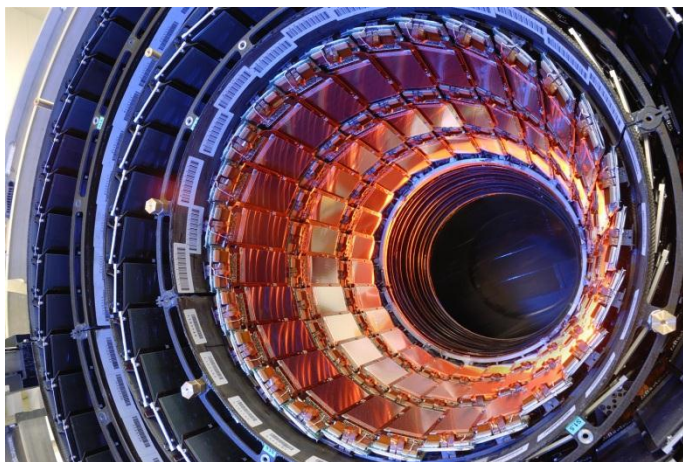
## Corrosion

Chemical reaction:  $\text{Al} \rightarrow \text{Al}_2\text{O}_3$

- fueled by water (air moisture)
- heated by electricity (HV needed)
- Catalyzed by impurities like potassium
  - Leftover from  $\text{SiO}_2$  etching
- $\text{Al}_2\text{O}_3$  non-conductive, the corrosion may affect our high voltage stability

Ultimate trigger to drop almost all STM sensors from CMS Tracker

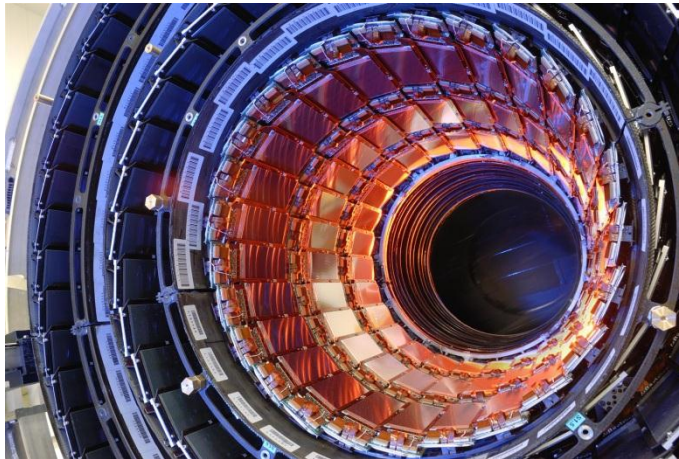




Logistics  
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**Summary**

# Summary

- Size of CMS Tracker needs automatization in Sensor QA
  - Approx. 35,000 sensors delivered in total
- Rely on measurements done at vendors for strip-by-strip characterization
  - after verification that these measurements are reliable
  - Save everything in centralized database
- Quality stability over 2 years of production has to be maintained
  - Quick measurements on test structures revealed some problems during production (only 35" each)
- Systematic p- and n- irradiation complementary to process monitoring (e.g. to find limit on flatband voltage)
  - Link between process control, general qualification and irradiation qualification.
  - Whenever one spotted a problem, the others can look deeper into it.



The End.

Backup slides follow

# Numbers

Total sensors delivered:

- HPK: 26,878
- STM: 8,781

Initially planned:

- HPK: ~8k
- STM: ~25k

Stripskans performed at  
CMS QTC:

- HPK: 1,140
- STM: 4,948

Process measurements on  
test structures performed:

- HPK: 2,491
- STM: 2,020

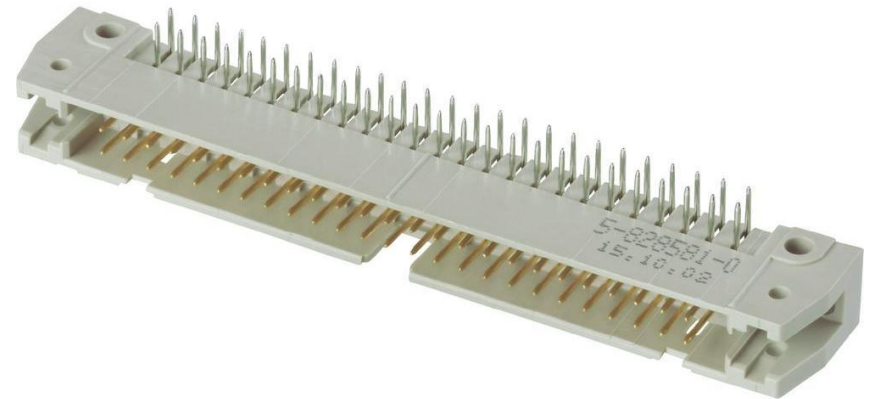
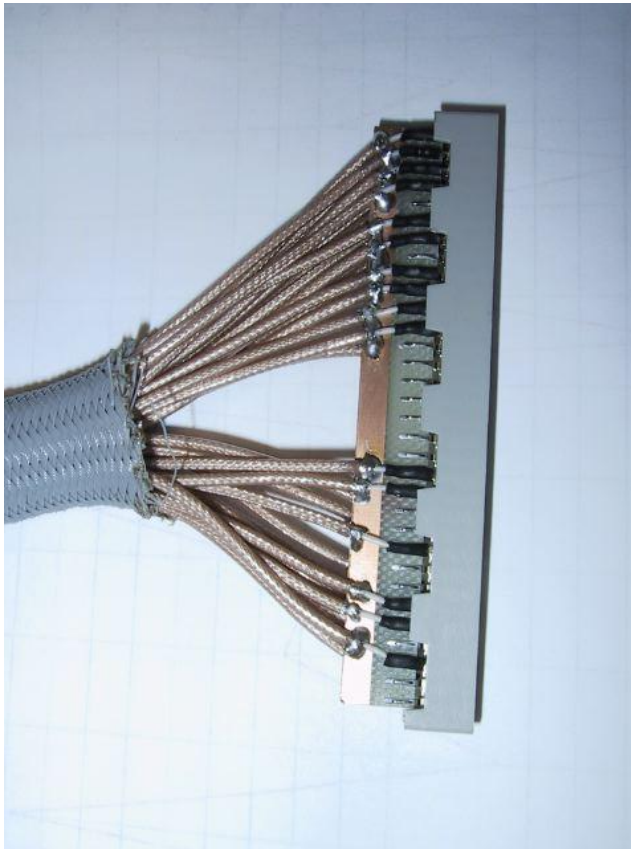
Irradiations:

- ~100

Bonding pull-tests on  
sensors:

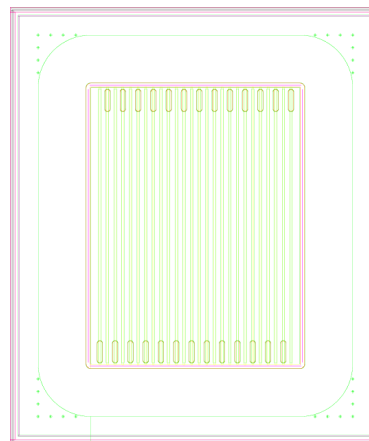
- HPK: 553
- STM: 512

# Probe Card Connectors



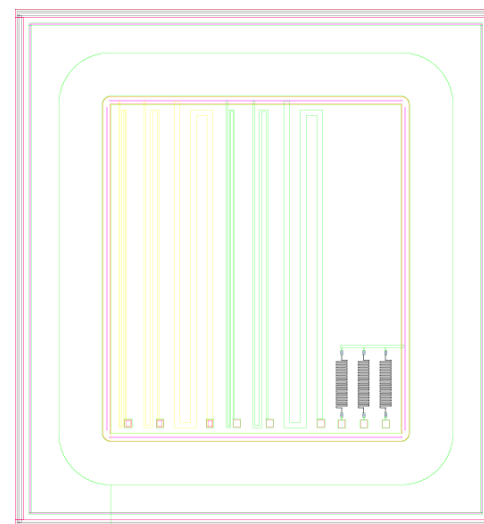
## TS CAP

- Array of 26 AC-coupled strips
- Test of Coupling Capacitance
  - Oxide Thickness can be calculated
- Test of dielectric breakdown
  - Destructive !

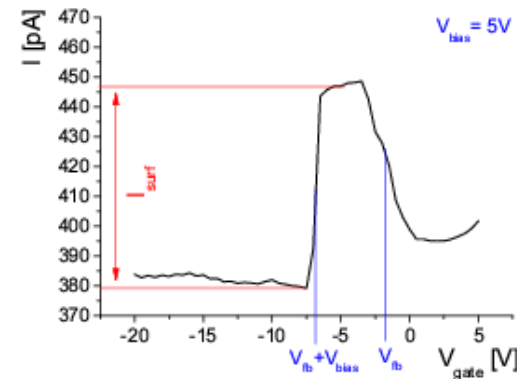
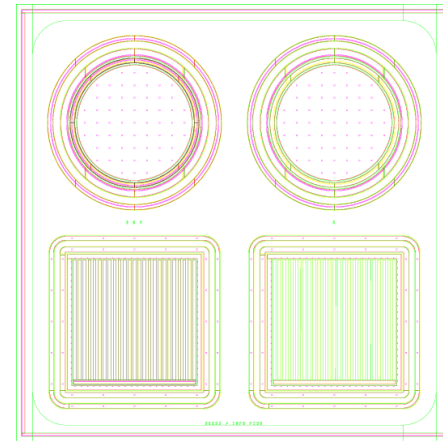


## Sheet

- Combination of
  - Three polysilicon resistors
  - Three Aluminium Strips (10, 20, 50  $\mu\text{m}$  thickness)
  - Three p+ Strips (10, 20, 50  $\mu\text{m}$  thickness)
- Used to determine resistivity of implant, Aluminium and polysilicon
- These Parameters have influence on noise behavior of readout chip

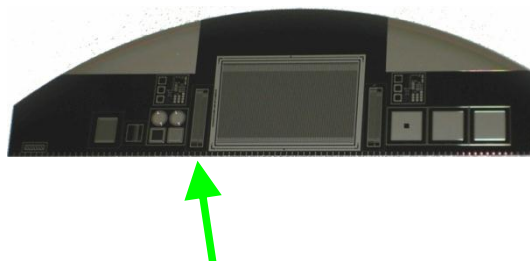
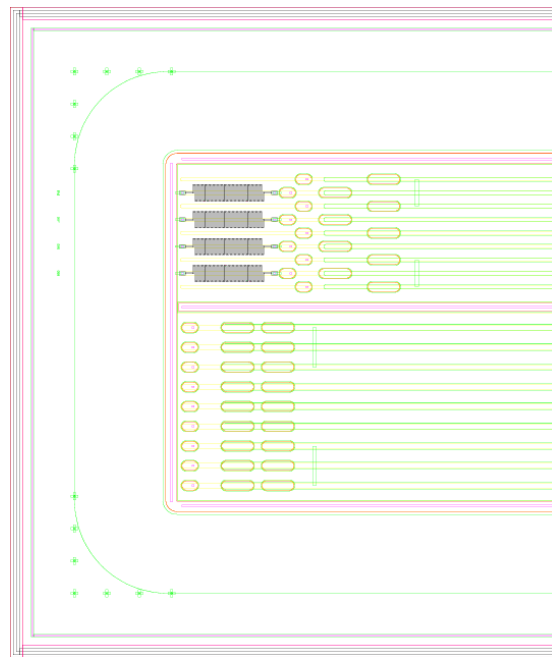


- Gate controlled diodes
  - Two circles ones (not used)
  - Two squares ones with comb-shaped p<sup>+</sup>-Diodes and comb-shaped MOS structures alternately arranged
- Used to extract surface current
  - by applying a constant reverse bias voltage through the diode
  - while varying the gate voltage of the MOS structure.
  - Sharp decrease of dark current in the inversion region gives the surface current
- Important Parameter to monitor oxide and Si-SiO<sub>2</sub> interface quality
- Limit determined experimental by irradiation



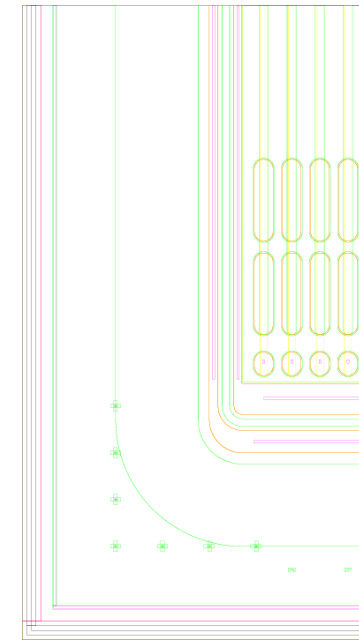
## CAP-TS-AC

- Measurement of inter-strip capacitance
  - Between single central strip and two neighboring ones
  - Outer strips on top and bottom are shorted and connected to ground (directly on the structure)
  - While biasing of structure is mandatory
- Parameter related to noise and SNR of readout chip



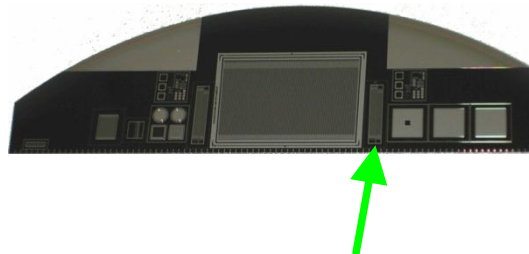
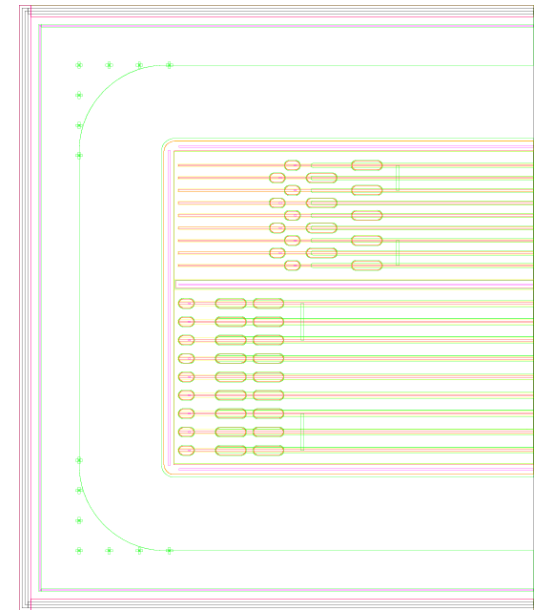
# Baby Sensor

- Structure with 192 AC-coupled strips
- Identical to main detector
- Used to measure IV-curve up to 700 V
  - Breakthrough voltage is determined

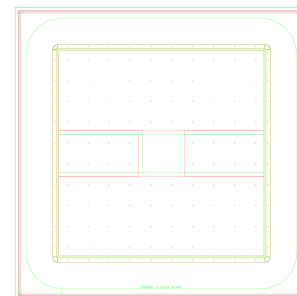


# CAP-TS-DC

- Used to determine inter-strip resistance
- Similar structure like CAP-TS-AC (used for C\_int) but with exceptions
  - no polysilicon resistor (strips do not have a connection to bias ring)
  - p<sup>+</sup> strips are directly connected to Aluminium strips
- High value of inter-strip resistance necessary to have a good electrical separation of strips



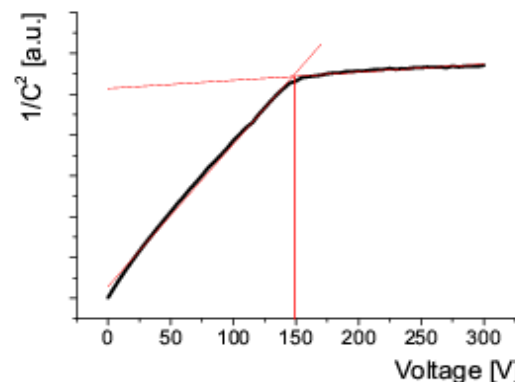
- Simple square diode
- Voltage scan is used to measure Capacitance and to extract
  - total bulk thickness



$$C_{depl} = e_0 e_r \frac{A}{d}$$

- Bulk resistivity

$$r = \frac{d_{\text{nominal}}^2}{2e_0 e_r m_e V_{depl}}$$



# MOS

- **Metal Oxide Semiconductor**
- Oxide composition represents configuration of
  - Thick dielectric in inter-strip region
  - Thin dielectric underneath strips (right)
- Extraction of **flatband voltage**  $V_{fb}$ 
  - Seen by sharp decrease of Capacitance (between accumulation and inversion)
  - to determine fixed positive charges in Oxide
- Limit defined experimental after test beam

