LHCb VErtex LOcator (VELO)
Module Production and Performance

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for the LHCb VELO group

RD07 Conference

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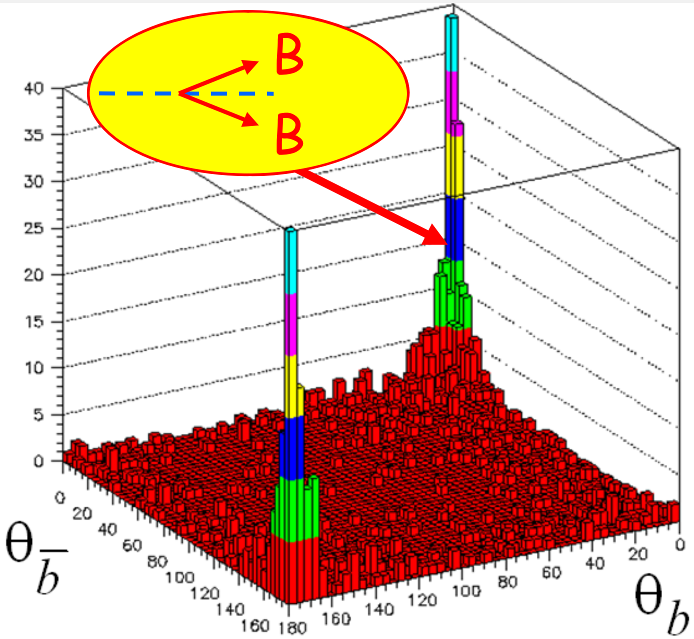
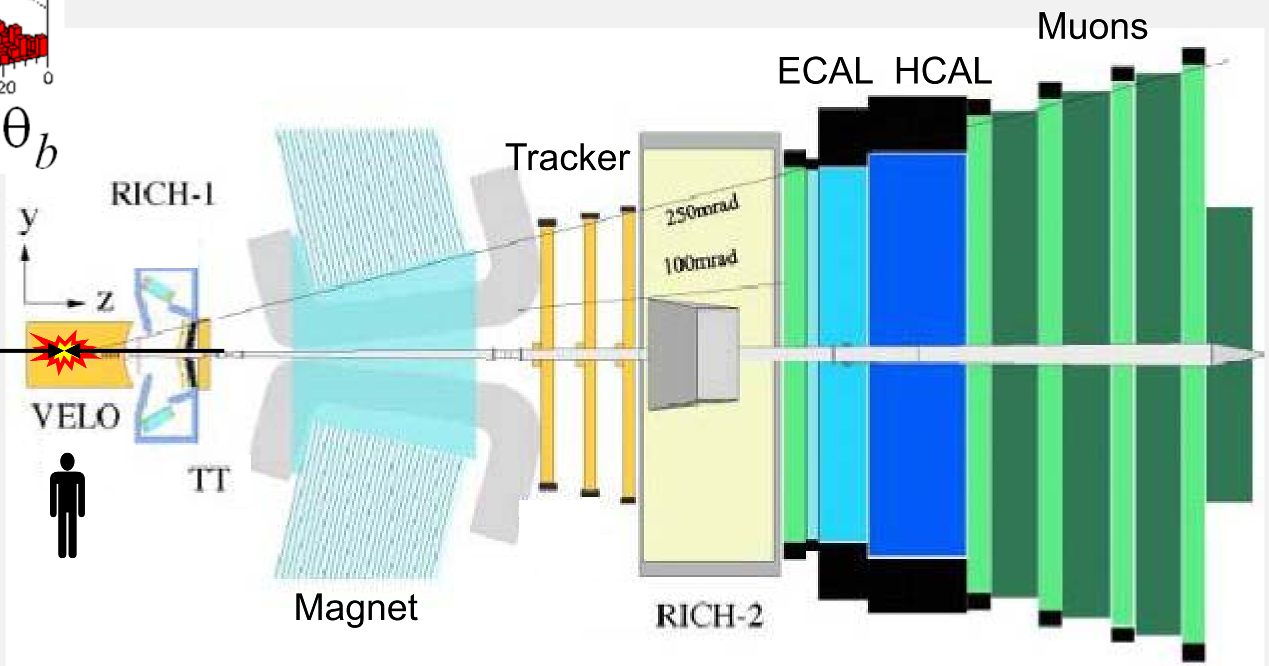
LHCb overview

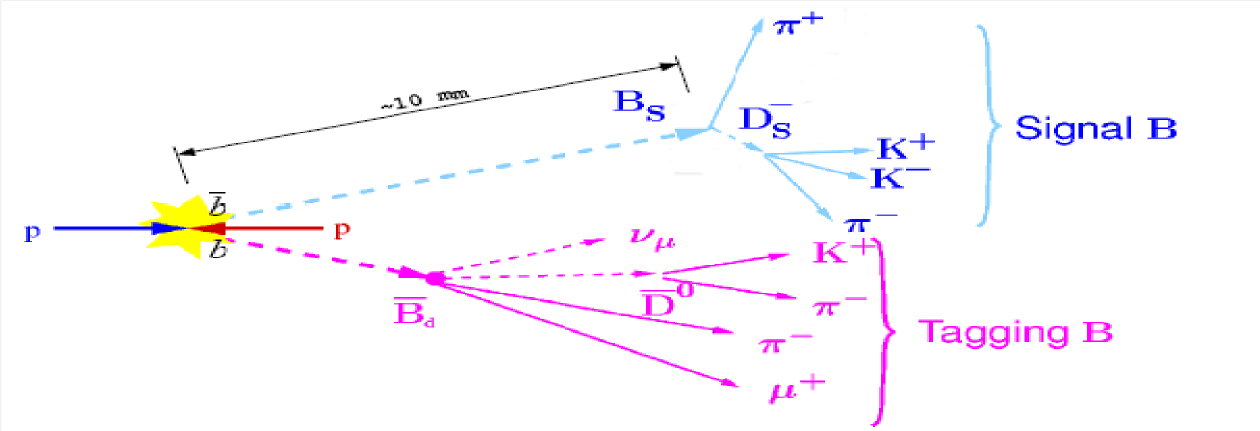


- At LHC, bottom production is peaked at high rapidity with both quarks in the same direction
- LHCb built as forward spectrometer to optimize for the study of bottom quark decays
- The VErtex LOcator (VELO) is the silicon microstrip vertexer at the collision point

This talk focuses on the VELO module production & performance



VELO Design Requirements



Vertexing

- Need to separate (multiple) primary and secondary vertices (<100 μm resolution ∥ beams)
  - Close to LHC beam (8 mm) → **Vacuum**
  - Extreme radiation levels ~10^{14} neq/cm^2/year @inner radius →n-strip silicon sensors
  - Prevent reverse annealing (<-5° C) → CO_2 cooling

Tracking

- Impact parameter ~40 μm (40 fs time resolution)
  - Low mass ~15% X_O

Trigger

- Fast computation of primary vertices and impact parameter
  - R-phi sensor geometry
  - Tight mechanical tolerances

    (Limit: 40 μm ⊥ beams, 200 μm ∥ beams)

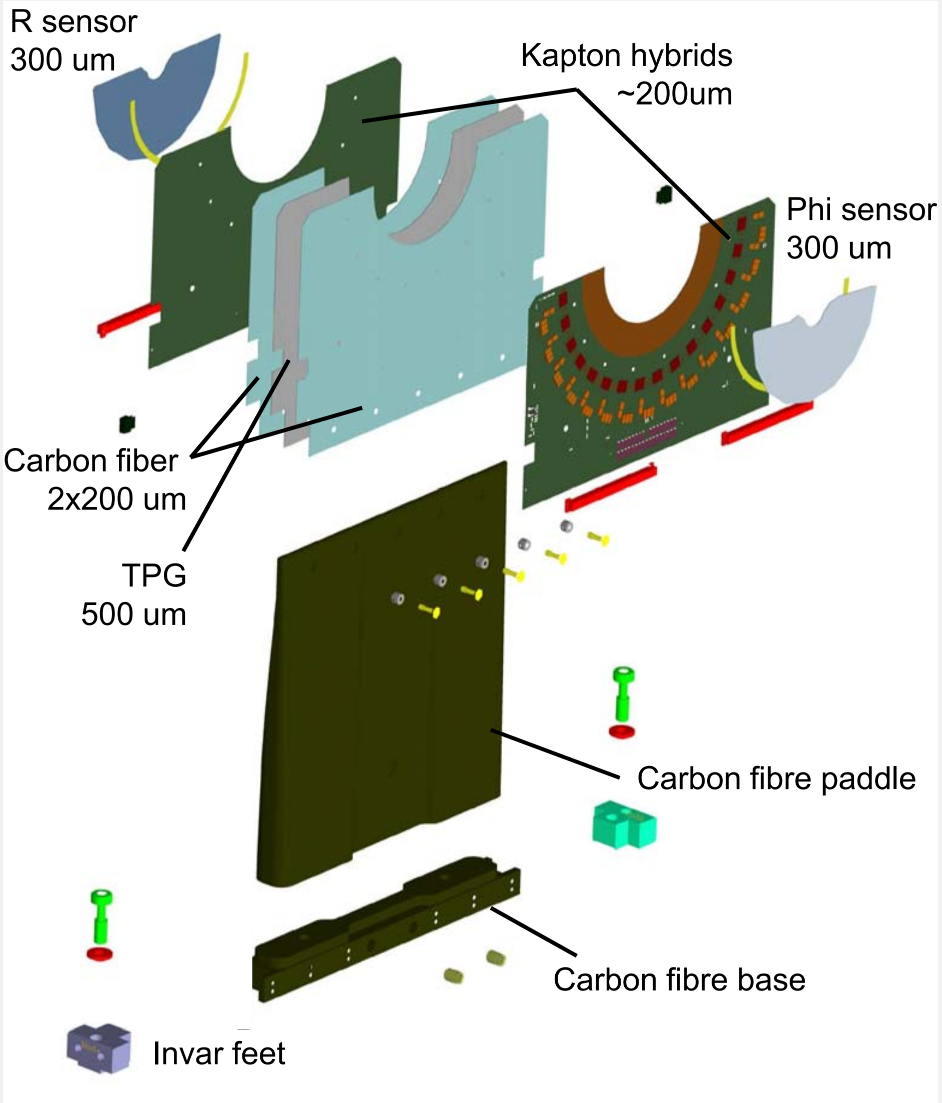
Beams

- Injection Clearance $\mathcal{O}$(30 mm) for each half
  - Moving detectors

Bespoke, severely constrained module design

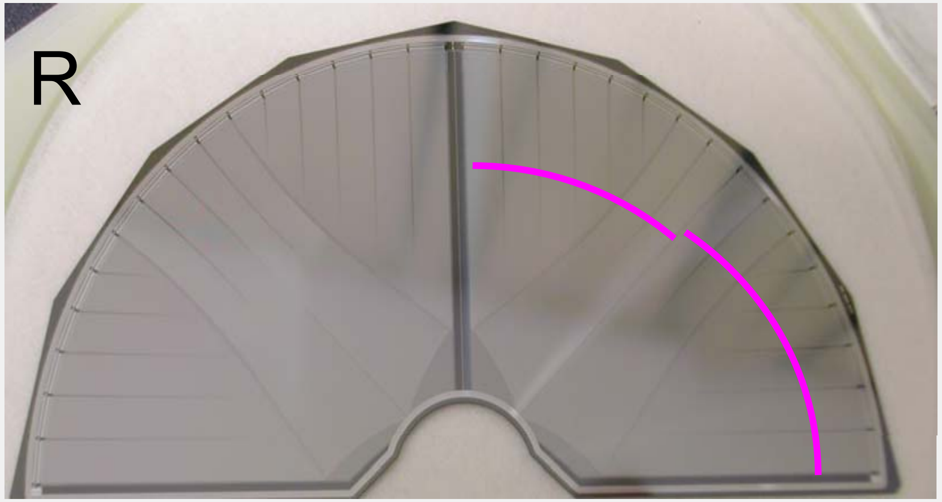
VELO Modules

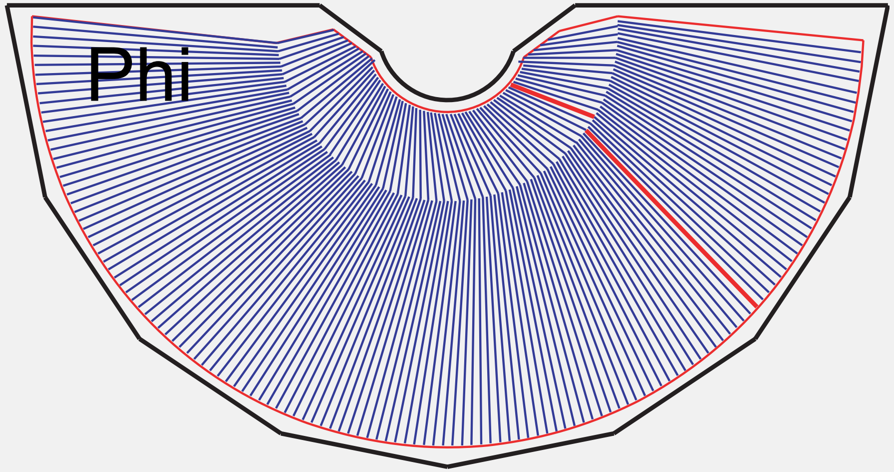
- All 42 installed modules on base
  - Delivery finished Feb. 2007
- Installation at pit late summer 2007
- Data taking starts spring 2008
- Consists of:
  - Carbon fibre clad TPG hybrid core
  - Laminated with flex hybrids
  - 2 sensors (R & phi geometry)
  - Carbon-fibre paddle
  - Precision base
  - Kapton cables
  - Silver-plated ground straps



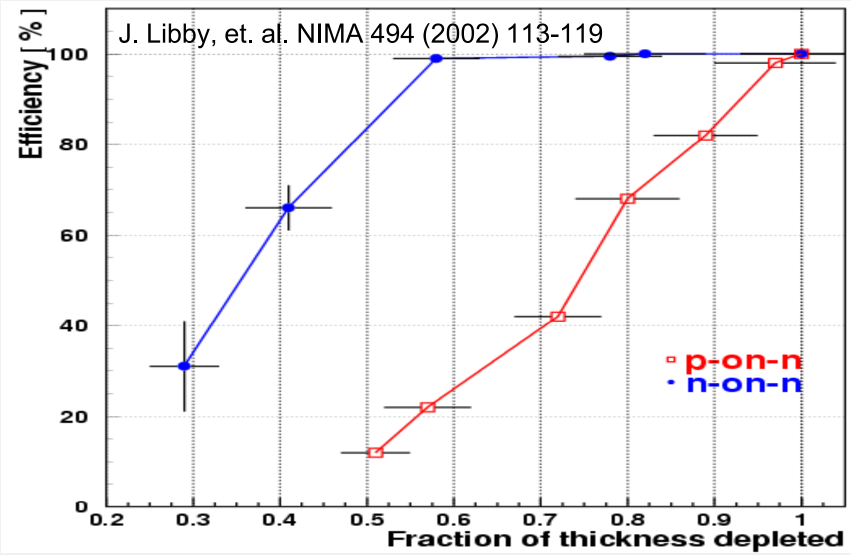
Sensors

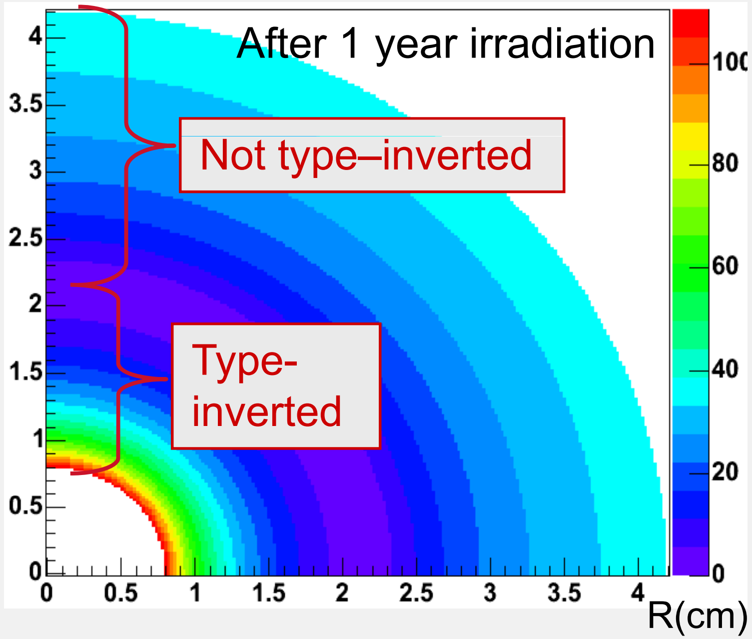
- n strip sensor technology (Micron)
  - n bulk-46 modules (43 installed)
  - p bulk-2 modules (1 installed)
- Double metal for signal routing
- Closest active strip 8.2 mm from beam
- R sensors
  - 4 quadrants
  - Pitch from 40 μm to 101 μm
- Phi sensor
  - Divided into inner/outer sensor
  - Pitch from 35 μm to 96 μm
  - Stereo angle
    - -20° inner, 10° outer
- **<u>0.3%</u>** faulty strips in production sensors

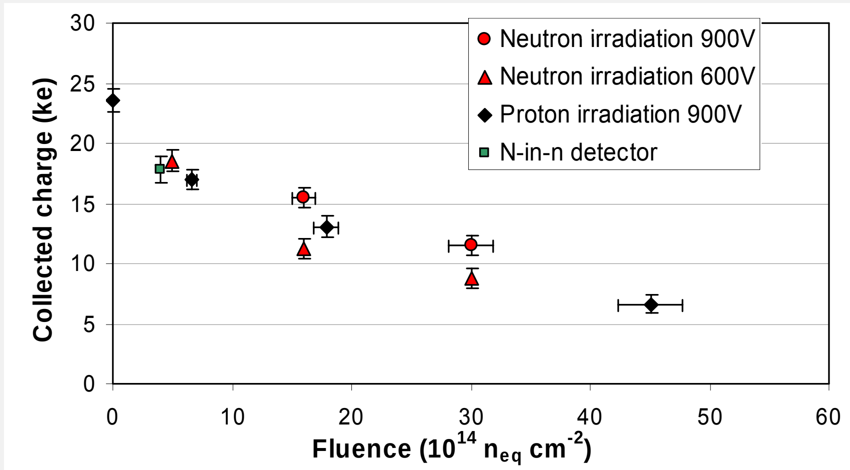




Radiation Hardness



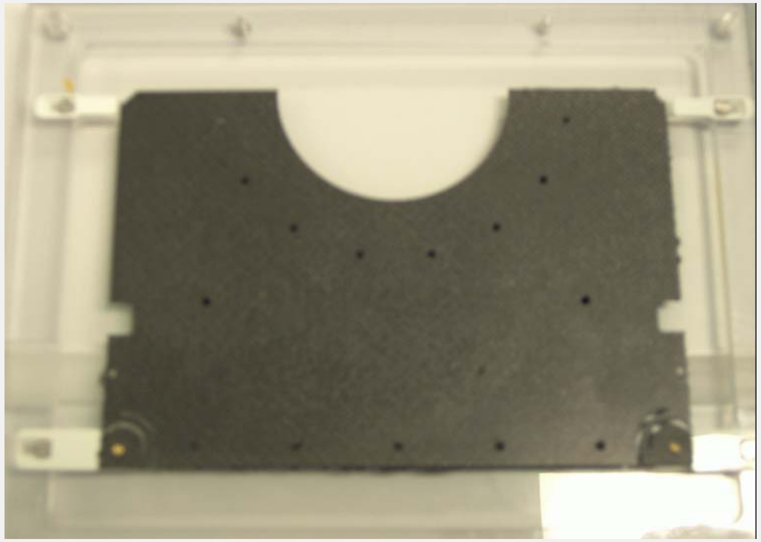


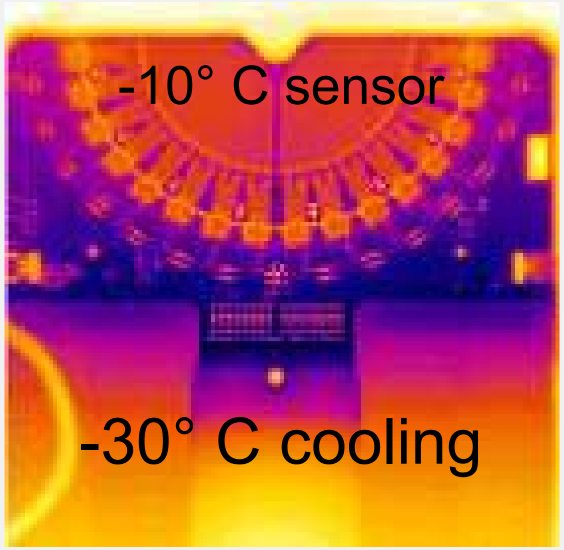


- n strip sensors inherently radiation hard
  - Collecting electrons increases trapping times/mean free path
  - With p-spray, isolated even when partially depleted
- After 3-4 years (6-8 fb^{-1}), the inner region of the sensor cannot be fully depleted
  - Dose estimates
    - $1.3 * 10^{14}$ neq/cm^2/year at R = 8 mm
    - $5 * 10^{12}$ neq/cm^2/year at R = 42 mm
- Running partially depleted, the estimated lifetime is ~16 fb^{-1}

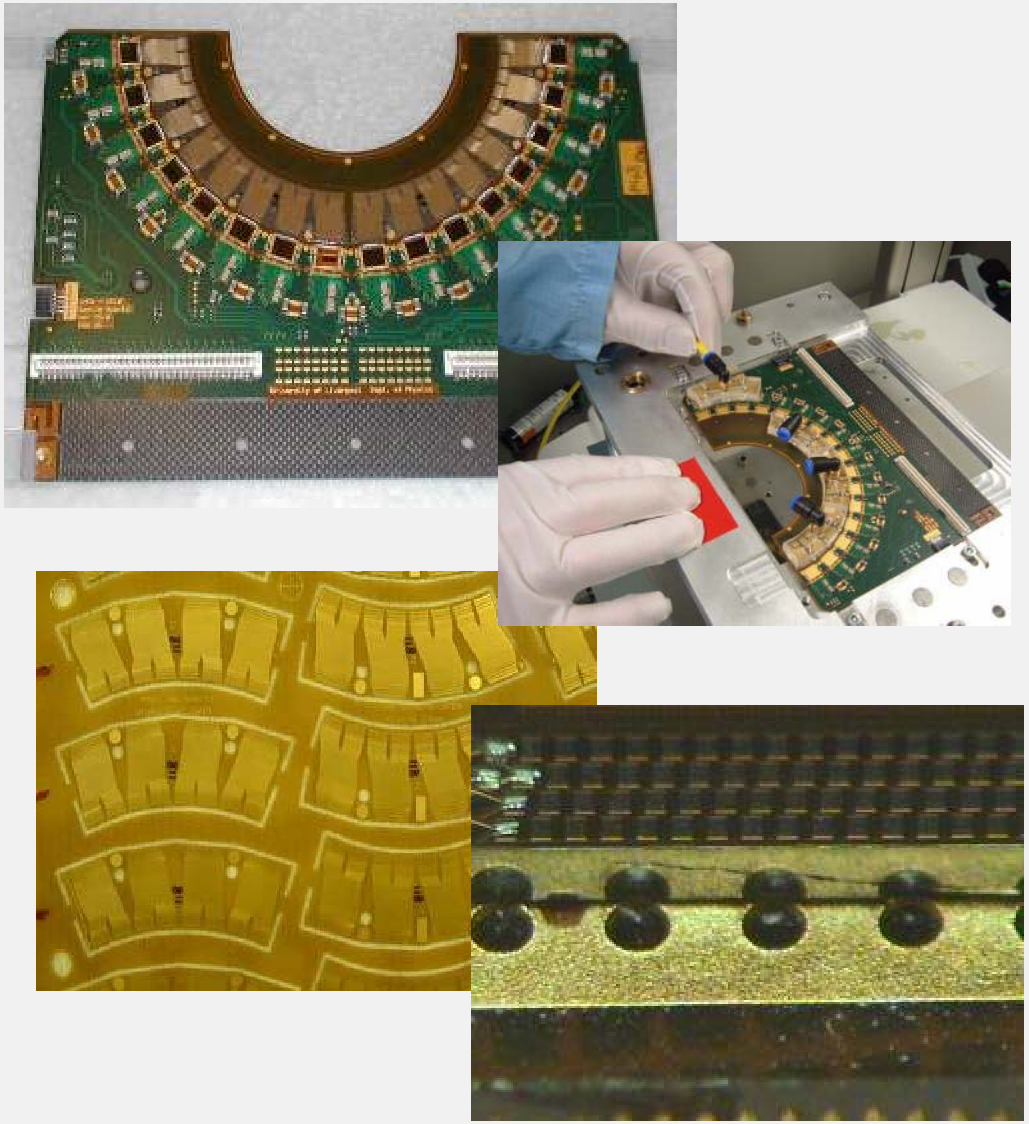
Hybrid Substrates

- TPG (Thermal Pyrolitic Graphite) core
  - 4x more thermally conductive than copper
  - Removes 24 W of heat with a designed ΔT of 20° C between coolant and sensors
    - ~8° C coolant-hybrid,
    - ~8° C within hybrid
    - ~4° C hybrid-to-sensor
- Clad in woven Carbon fibre for rigidity





Hybrids

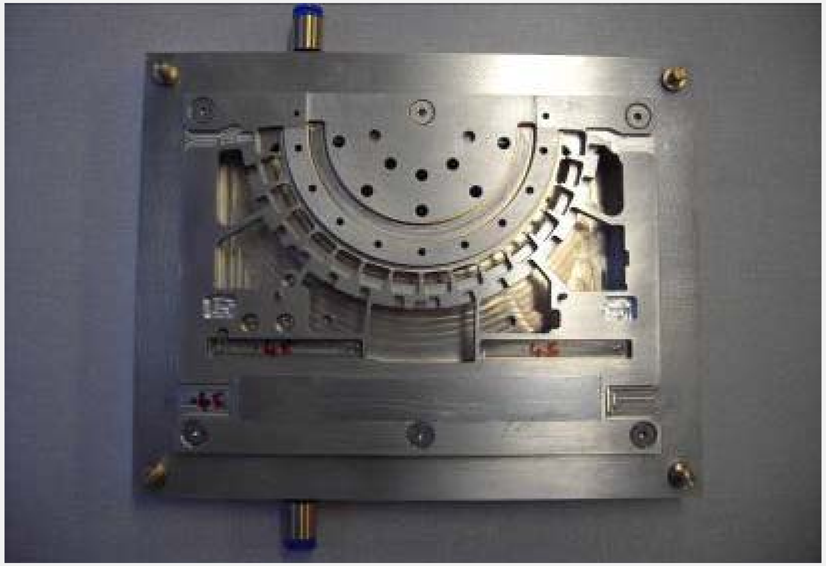


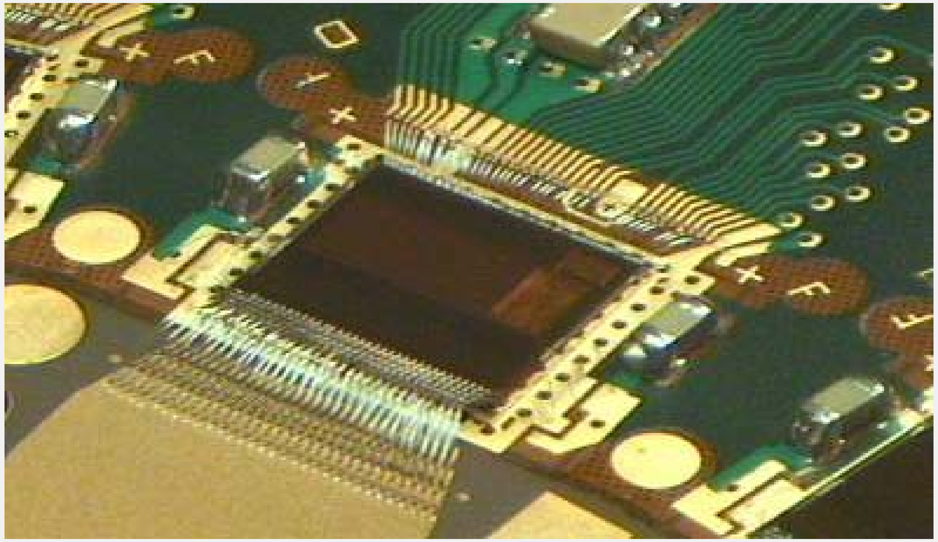
- 4 layer flex Kapton hybrid (Stevenage)
  - Laminated under vacuum to prevent trapped air
  - Double-sided to balance stresses due to “bi-metallic” effects
  - Flatness extremely difficult to achieve over 12.1 x 17.5 cm
    - 20% rejection of bare hybrids
- Beetle readout ASICs and Kapton pitch adapters (CERN) attached by hand
  - Pitch adaptors extremely fine pitch
    - Inner bond pad 40 μm
  - Not flat → difficult to glue
    - 5% loss due to ASIC and pitch adapter gluing
  - 2 Beetle wafers worth of chips had edge cracks due to dicing
    - Had to replace 4 modules worth of chips

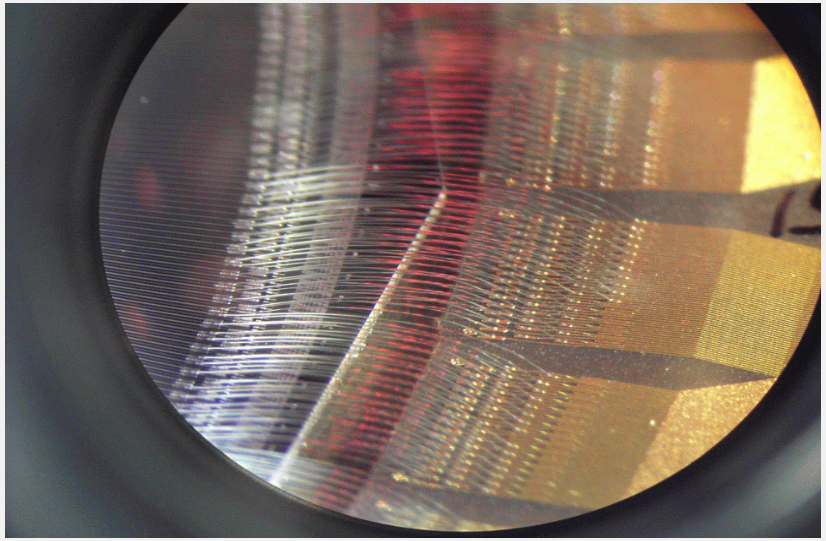
Wirebonding

Extremely difficult wire bonding

- Double-sided hybrid with cylindrical geometry
  - Complex bonding jig
- 4 row wire bonding
  - Kapton can shrink/stretch during manufacturing
    - Each FE and sensor bond had to be re-positioned by hand
  - Wire bonds per module
    - 2320 Back-end
    - 4096 Front-end and sensor



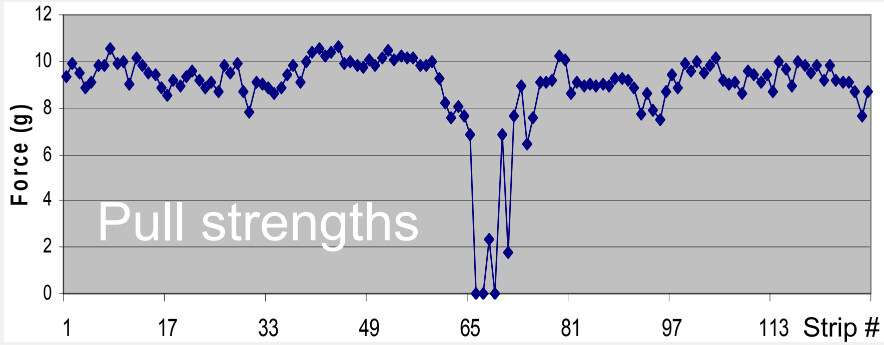


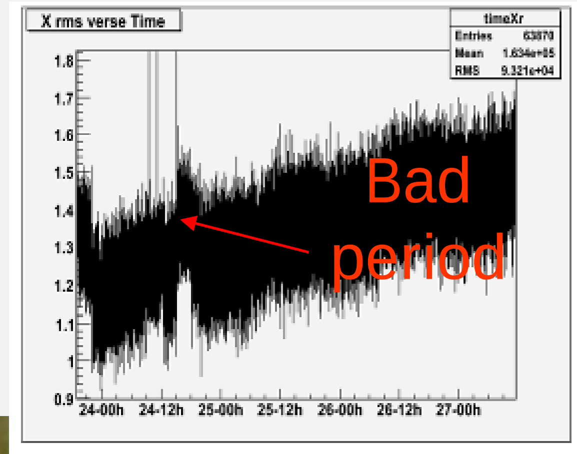


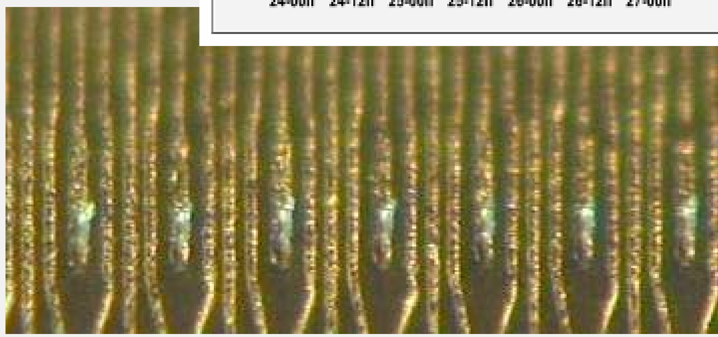
Wirebonding Results

- Problems encountered
  - Hybrid movement during bonding- took 1 year to remove
  - Vibration due to nearby construction (pile-driving)
    - H & K 710 wire bonder severely sensitive to motion

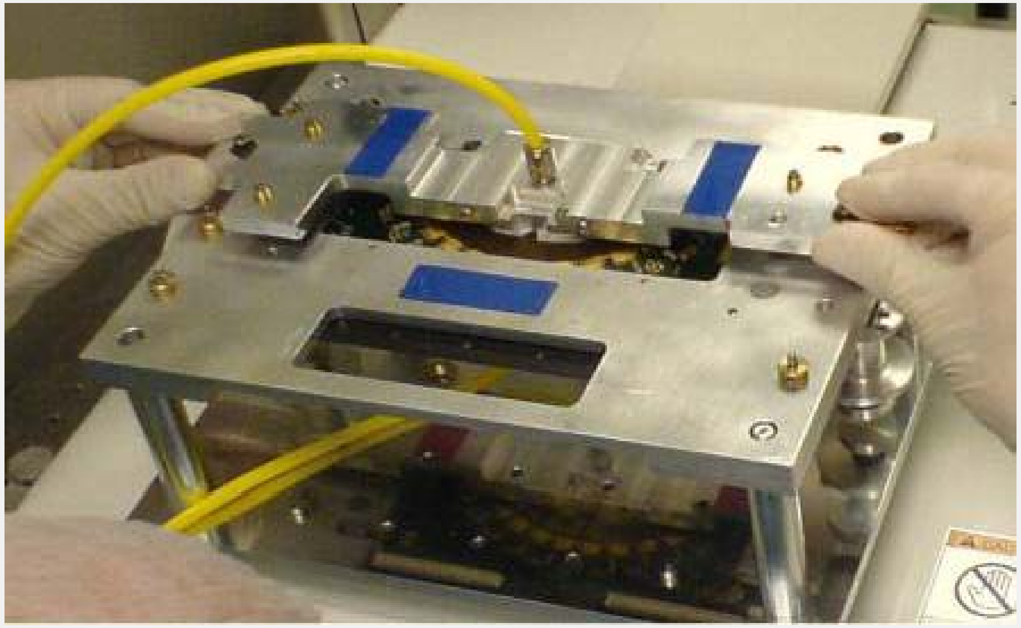
      Weak wire bonds
    - Purchased seismometer (Apple Power Book) to monitor motion
  - Smallest bonding pads on Kapton pitch adaptor over-etched to 20-25 μm
- Average time for bonding of 3 man-days per module
  - But no module failures due to bonding and only *0.3%* extra faulty channels introduced

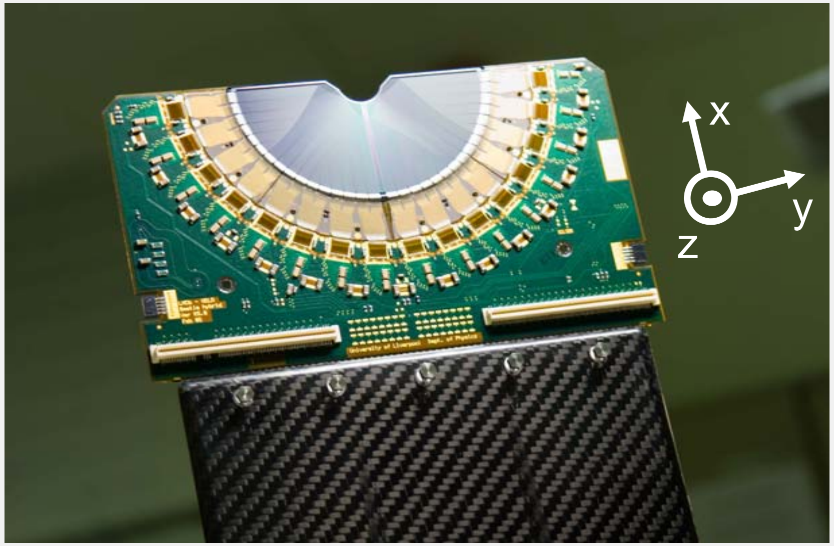






Sensor gluing

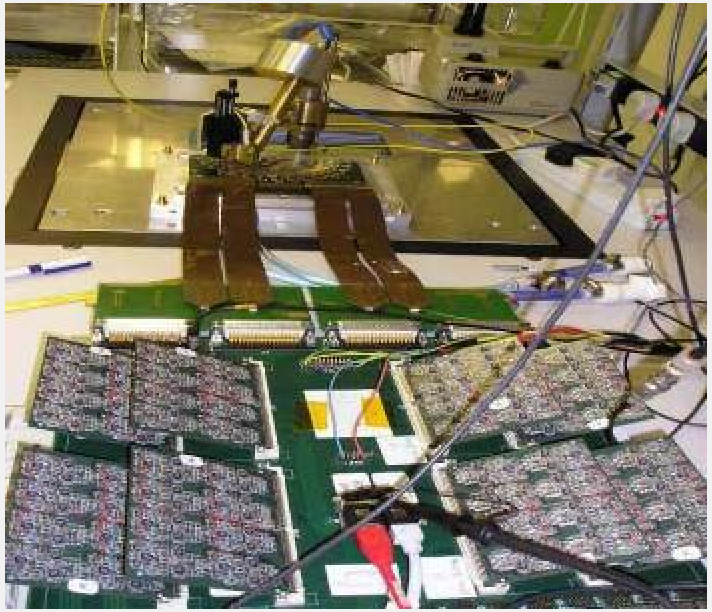


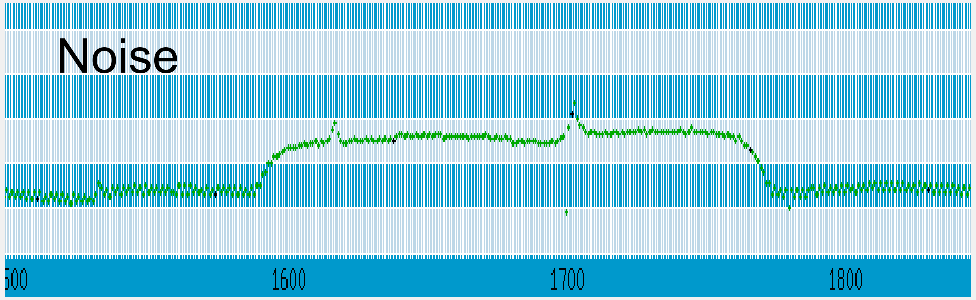


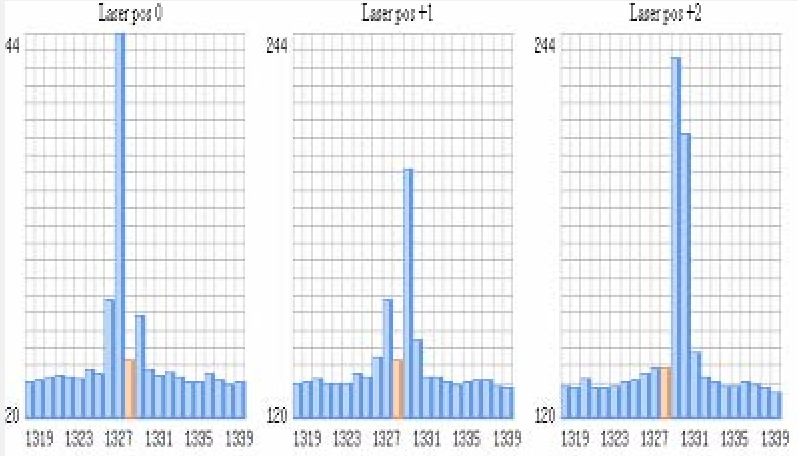
- Sensor attached using custom flip-jig
  - Align sensors to better than 50 μm in translation, 1 mrad in rotation
    - Δx=0.2±6 μm
    - Δy=2±11 μm
    - Δθ=-0.041±0.034 mrad
  - Tricky to glue such large surfaces
    - Flatness, material & glue thickness
    - 6% lost to gluing errors

Electrical Testing

- After each bonding step, the hybrids are electrically tested
  - Pedestal, noise, and laser (with sensors)
- Opens and shorts easily found
  - But pinholes impossible to see
    - Full laser signal with only 20% increase in noise when inducing a bias current of 5 mA with light
    - Beetle chip could probably be used with DC coupled sensors
- Found 3 sensors (6% of modules) with problems with p-spray isolation
  - Was not possible to test for during probing with current sensor design



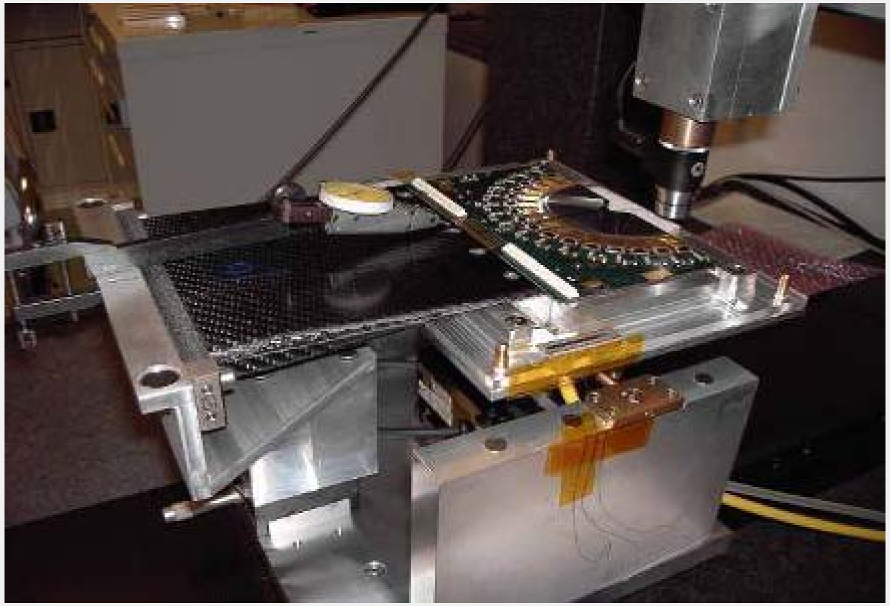




Pedestals

- Hybrids mounted to VELO base on carbon-fibre pedestals
  - ~ 0 CTE
  - Manufactured in-house to avoid air volumes

- Hybrid glued to pedestal with Smartscope system
  - For trigger, R sensor aligned to 40 μm translation, 1 mrad rotation relative to pedestal base pin



Mechanical Precision

- Each module measured on assembly, on cable attachment, and after vacuum testing on CMM
  - **R-sensor (in trigger):**
    - Δx=-0.4±9 μm, Δy=3±13 μm
      $\Delta\theta$=-0.072±0.131 mrad
  - Phi-sensor:
    - Δx=-2±8 μm, Δy=5±18 μm
      $\Delta\theta$=-0.067±0.141 mrad
  - ***But translation along beam difficult (44% outside of ±200 μm specification)***

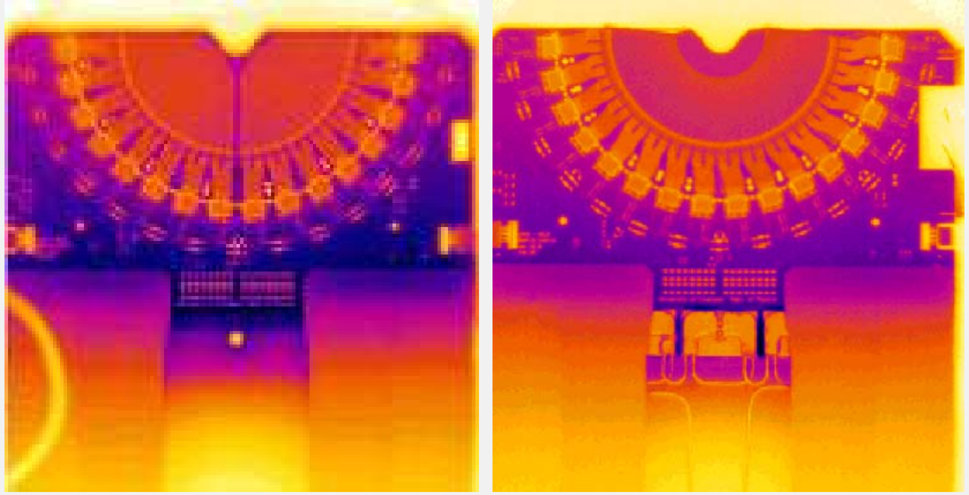
Added constraint system to hold hybrids at proper location along beam

Thermal Test

- All modules tested in vacuum tank with near final CO_2 cooling system and DAQ
  - ~$1x10^{-3}$ mbar with coolant at -30° C

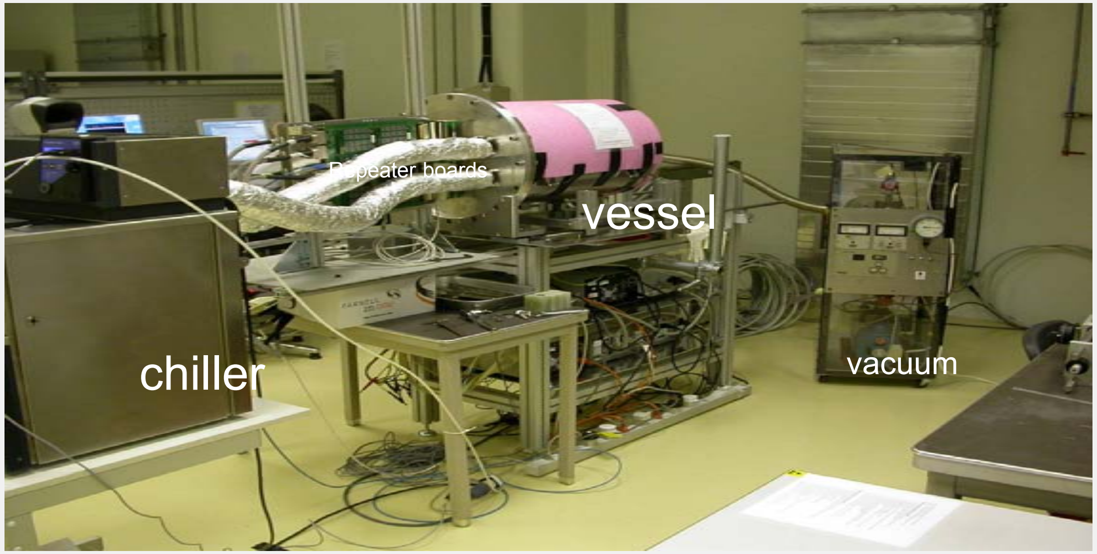
- Electrical tests confirmed previous faulty channel lists

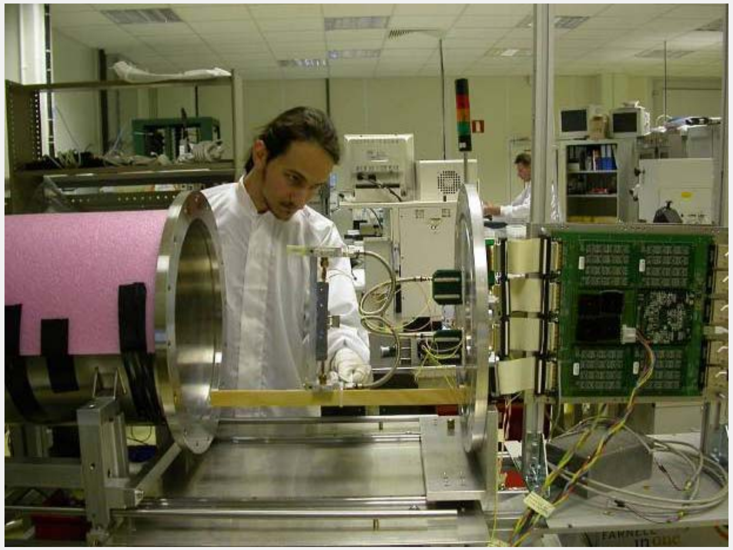
- Thermal performance as expected
  - ΔT=-22.8° C between coolant and sensor
    - Should be 2-3° C less with cold neighbours
  - 2 modules had anomalous cooling performance and were rejected (4%)



Reception/Burn-in@CERN

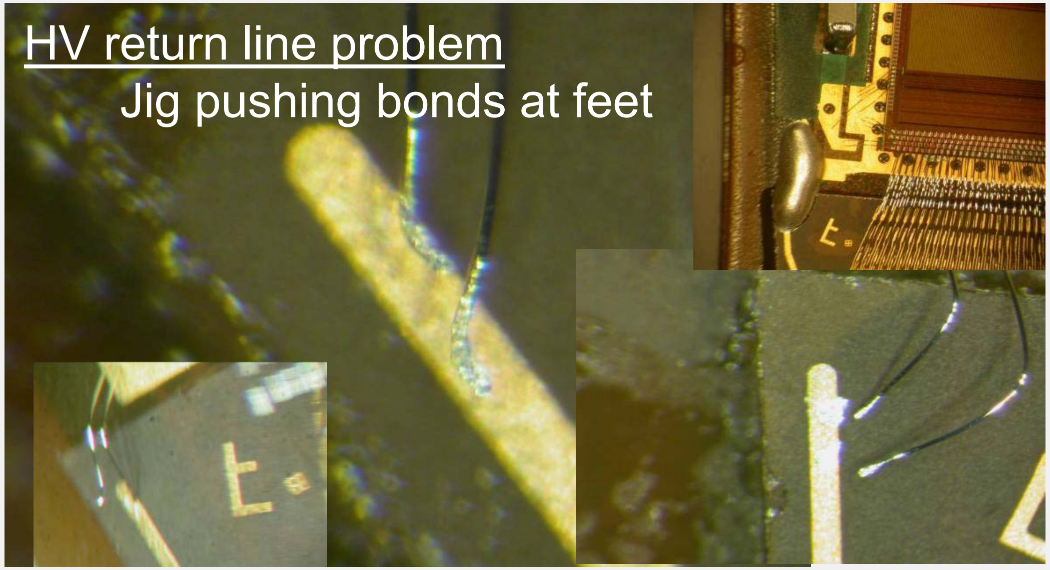
- Every module visually re-inspected on arrival at CERN
  - 3 hrs per module
- Module Burn-in
  - Electrical tests in vacuum (10^{-6} mbar)
    - Noise, pedestals, bias currents
  - Thermal stressing
    - 4 cycles between -30° C and 30° C
  - Electronics burn-in
    - >16 hrs at 30° C

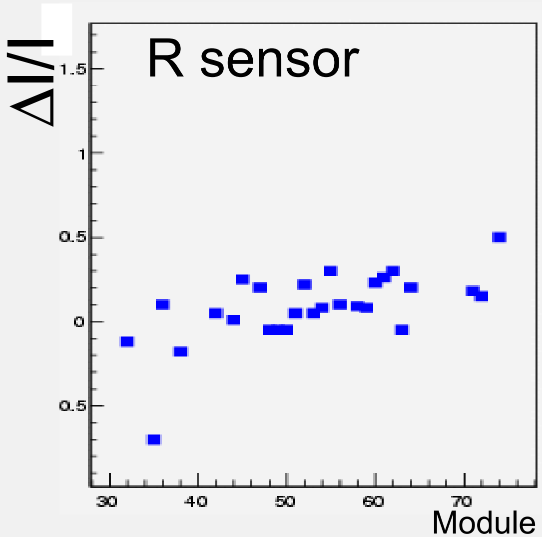


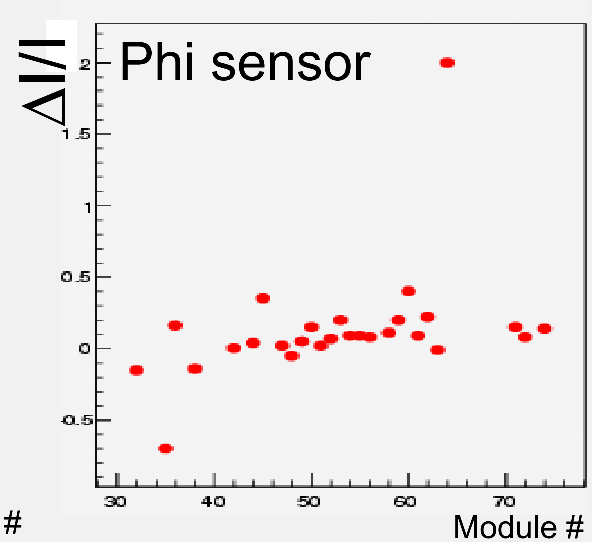


Reception/Burn-in Results

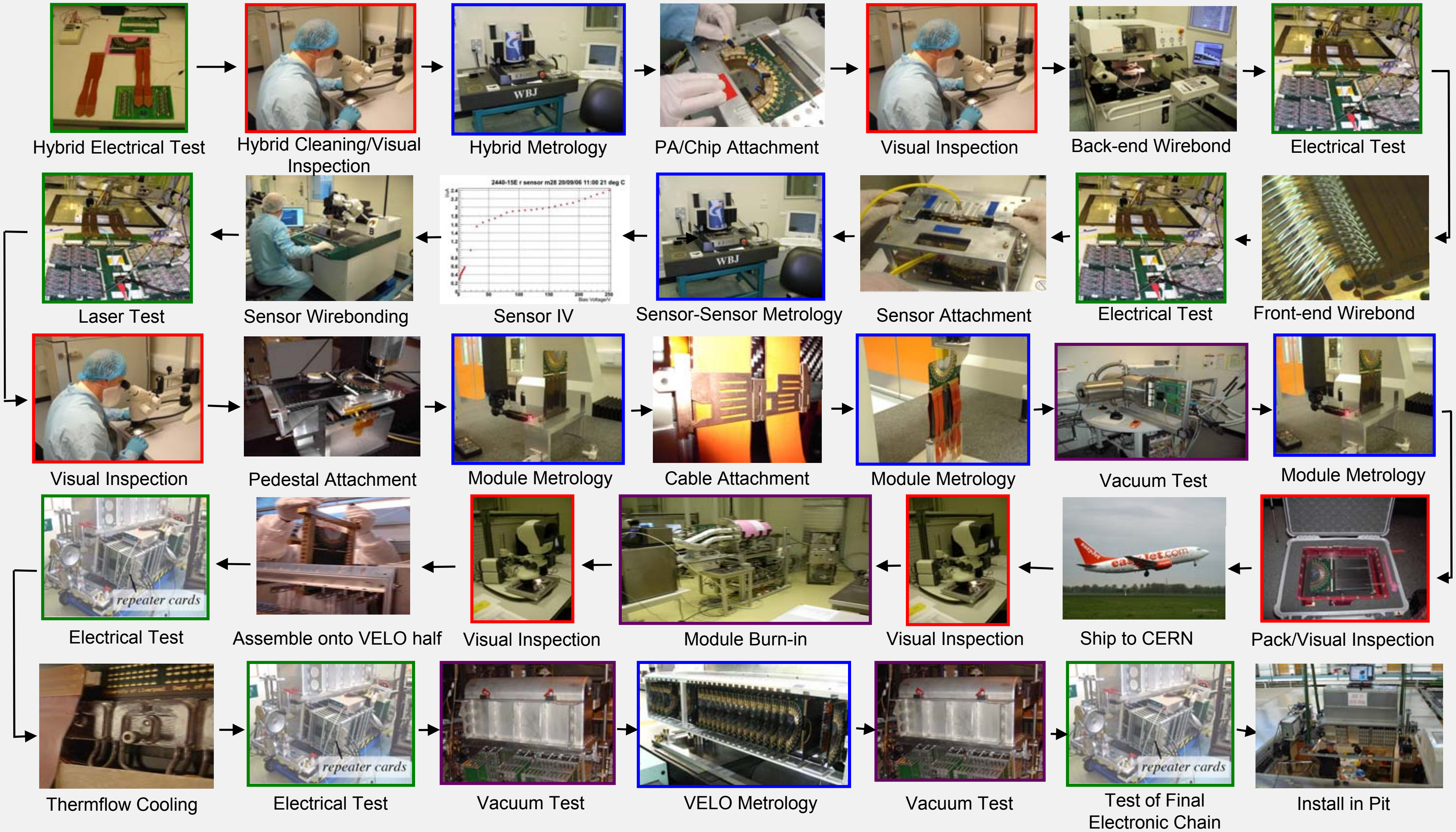
- Found damage to bias return wire bonds
  - Required emergency epoxy fix on first few modules
- Great stability of module performance
  - No additional opens/shorts
  - No ASICs failures
  - Only 1 sensor showed significant bias current increase during burn-in
    - Stable for over 3 days





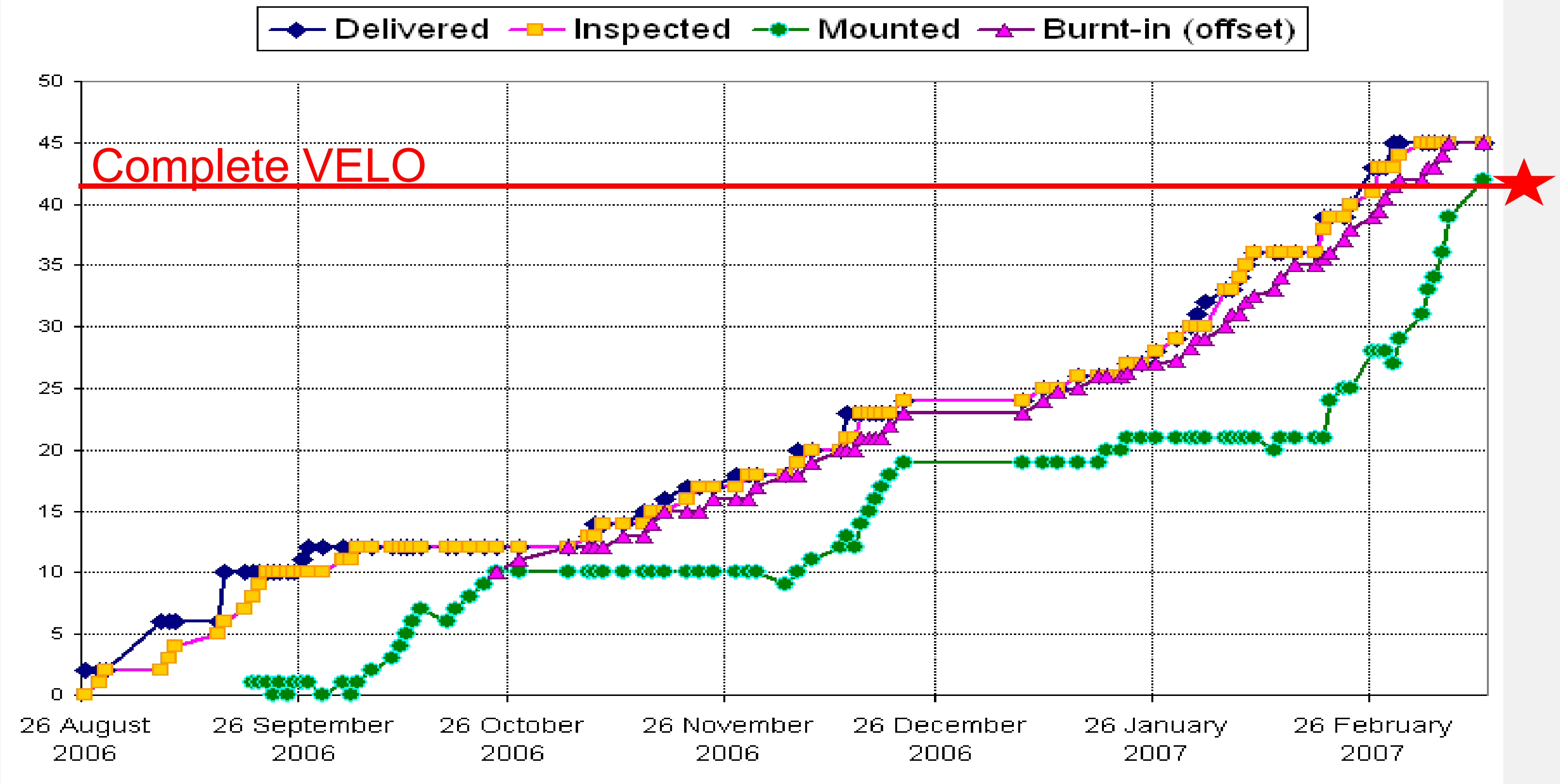


Quality Assurance



6 Visual Inspections, 6 Metrologies, 7 Electrical Tests, 4 Vacuum Tests

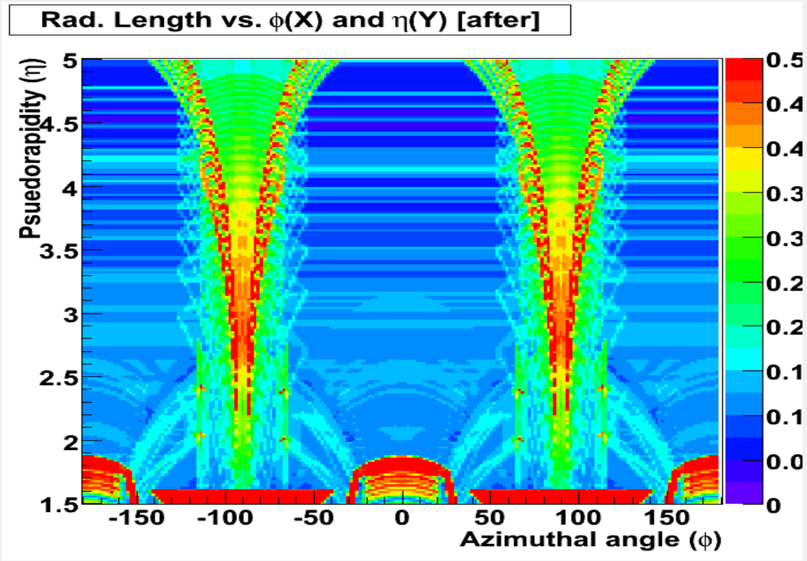
Final Production Numbers

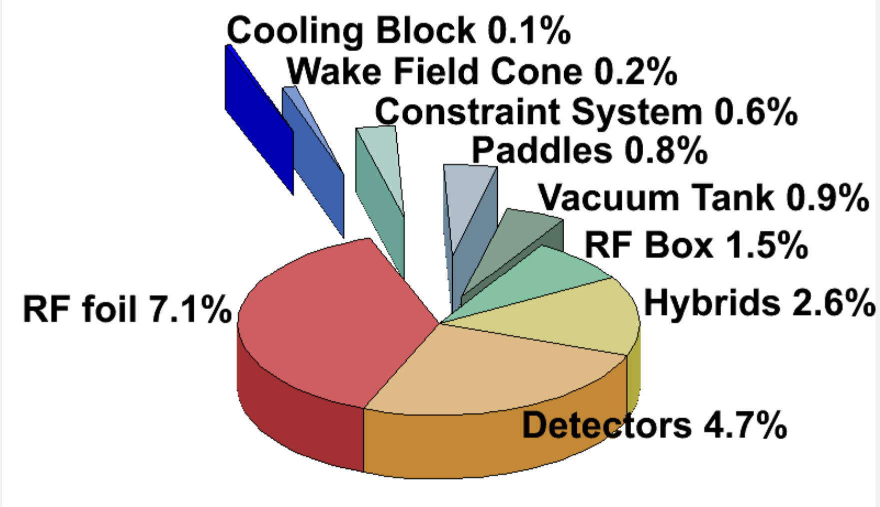


- 42 installed modules produced over 10 months
  - 63% yield of hybrids
  - 87% yield of sensors
- 0.6% bad channels per module
- ~100 man-hours per module

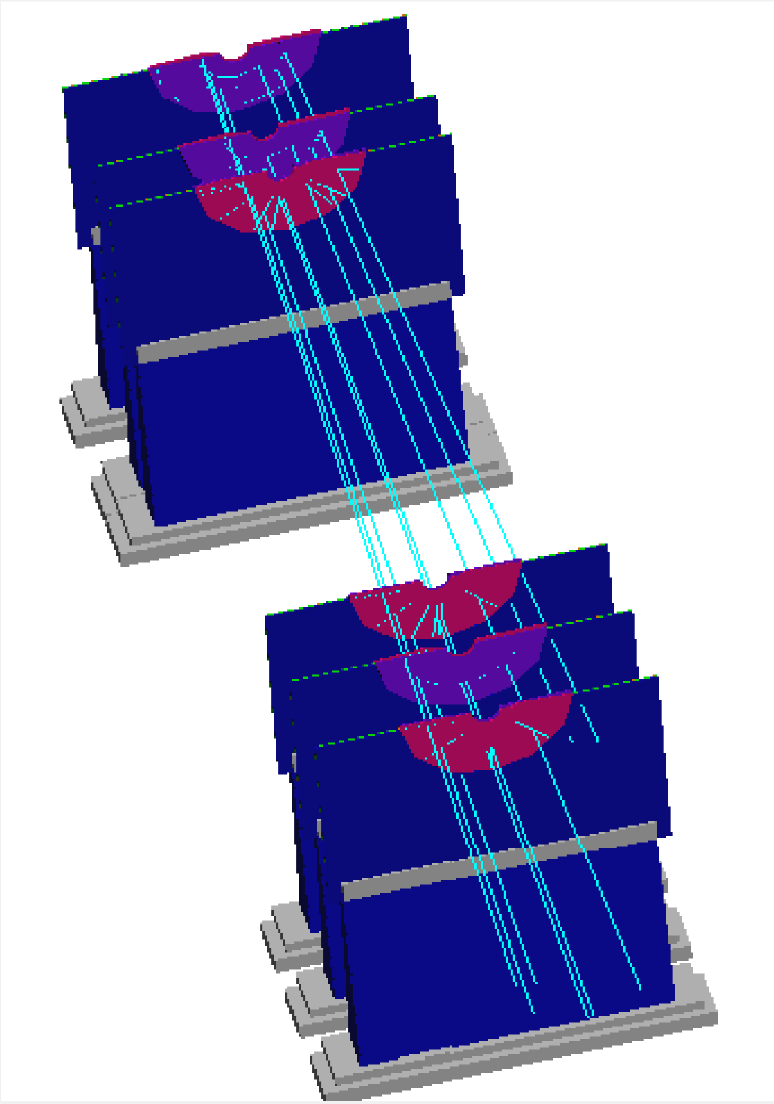
Radiation Thickness

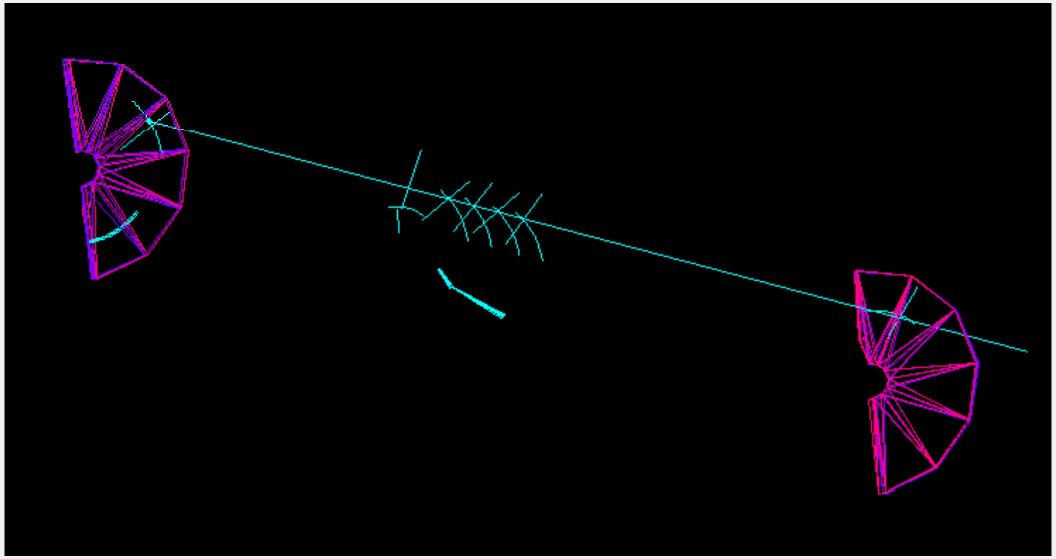
- Total radiation thickness of system 18.5% X_0
  - Largest single source of material is the RF Foil (7.1% X_0)
    - Effort to reduce/remove foil in upgrades
  - Modules 8.1% X_0
    - Sensor 4.7% X_0
    - Hybrid 2.6% X_0
    - Paddles 0.8% X_0





CERN Test Beam





A production VELO half with 10 module installed was brought to the CERN muon test beam Nov. 2006

Targets were added in order to test tracking and vertexing algorithm

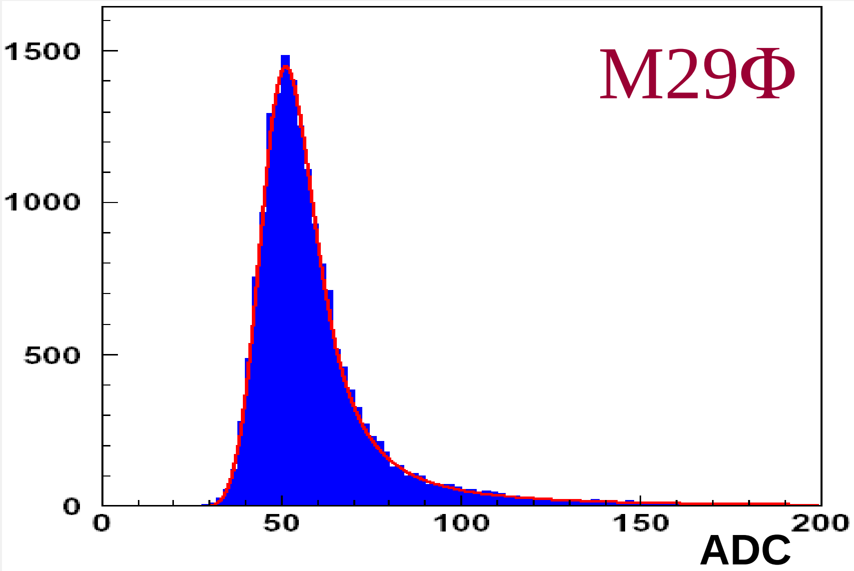
Enough cooling and DAQ present to operate 6 full modules at a time

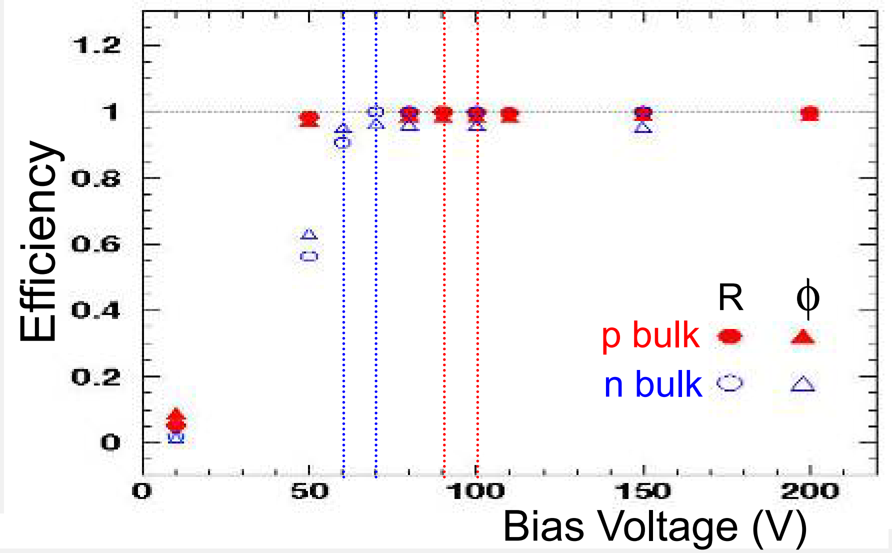
Module Performance

(Very) preliminary results of test beam

- Robust signal-to-noise
  - Average signal (ADC): 52 R, 52 phi
  - Noise varies within sensor due to changing capacitance
    - 1.9-2.6 ADC R
    - 1.7-2.2 ADC phi
  - Signal-to-noise ~20-27 R, ~24-31 phi

- p bulk detector module shows expected performance under-depleted
  - n bulk sensors after inversion will behave similarly



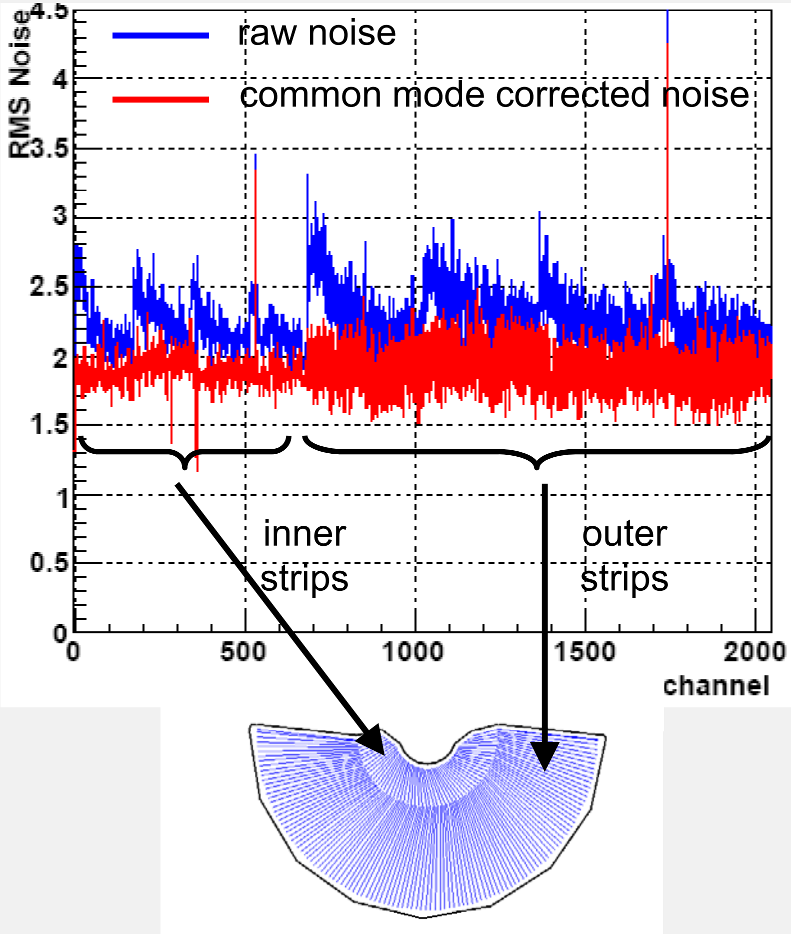


Conclusions

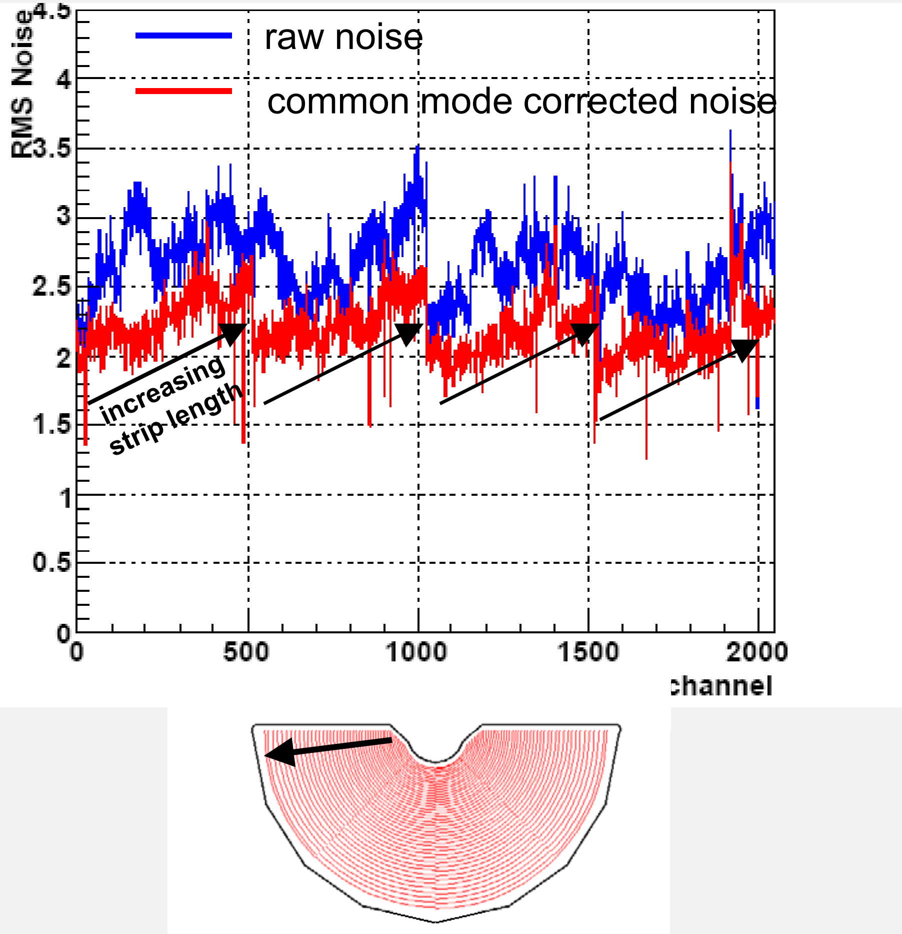
- VELO module production completed in February 2007
  - Some of the most complicated silicon strip detectors ever built
  - Mechanical and electrical performance as expected
- Commissioning starting now in the pit with data-taking in 2008
- In near future, we hope to build a complete spare VELO made with p bulk sensors
  - Quick replacement in case of beam accident
  - Hopefully guarantees full functionality until end of LHC run

Noise Performance

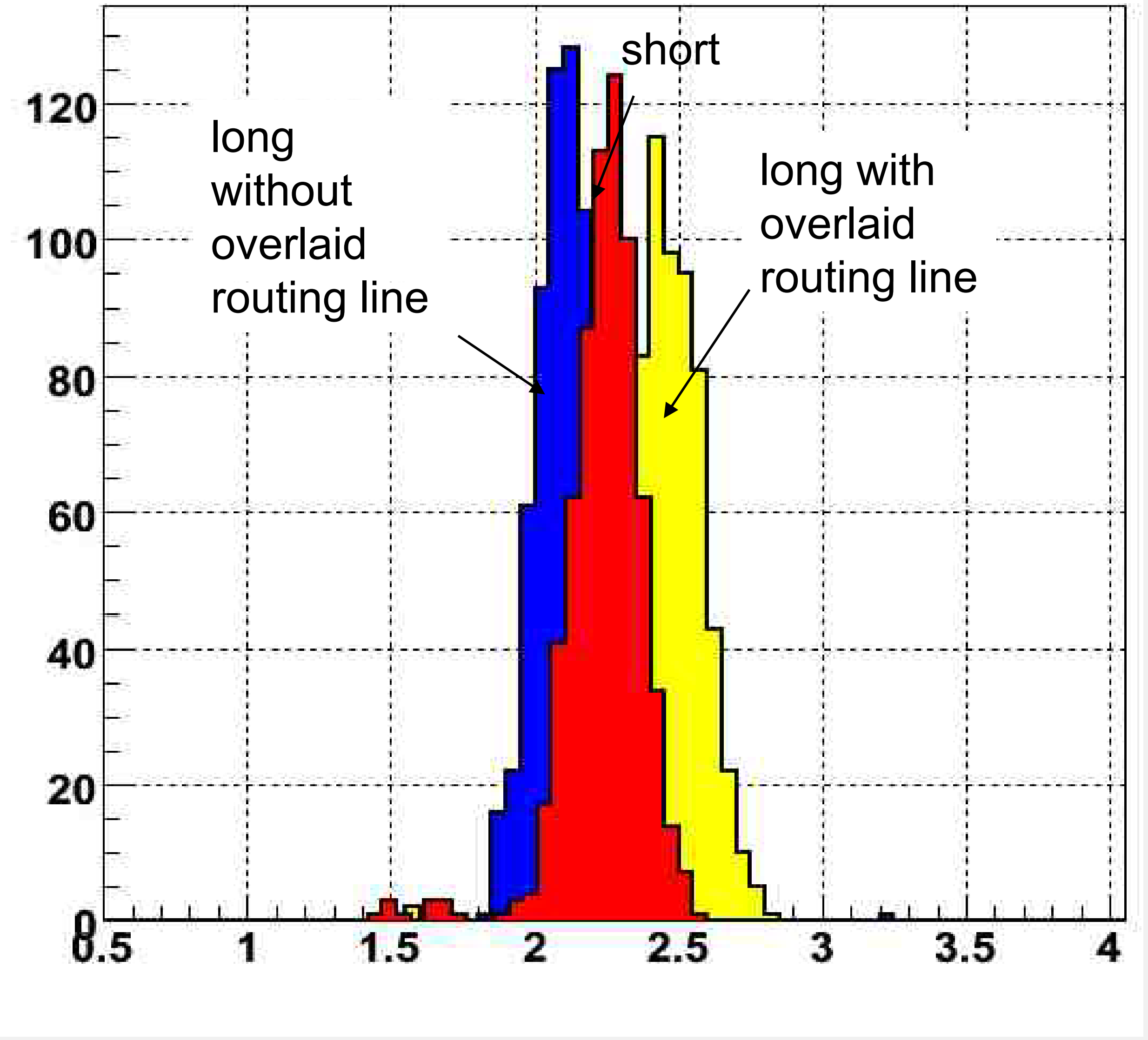
PHI SENSOR



R SENSOR

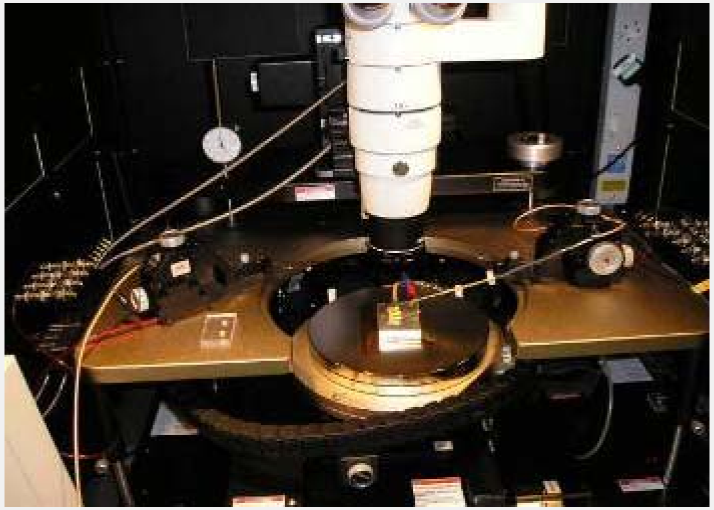


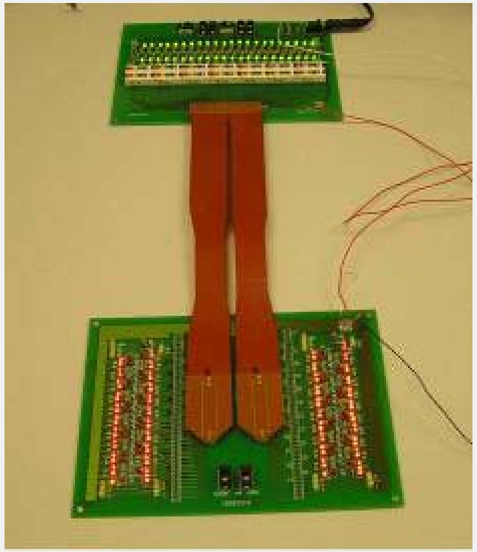
Noise Performance

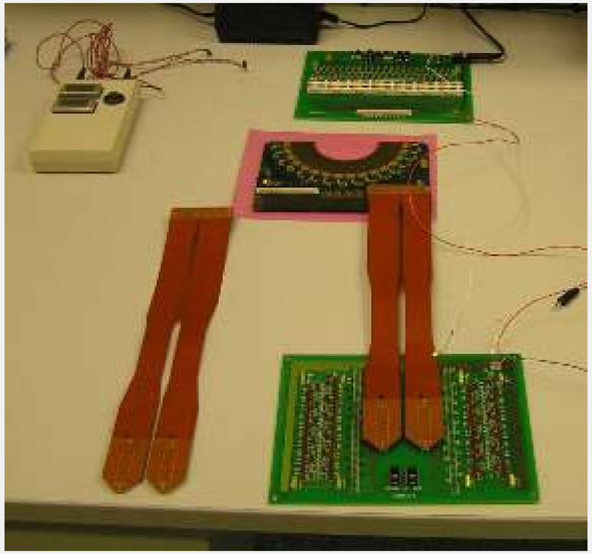


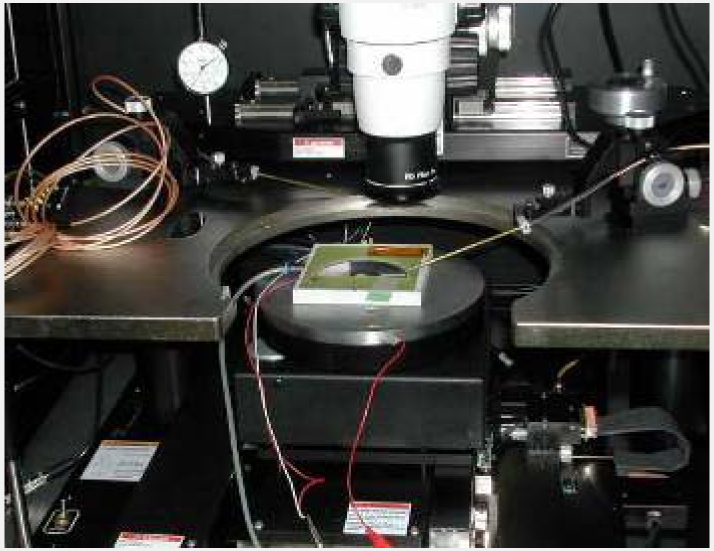
Component Testing

- All components are tested on arrival from vendors
  - Sensors
    - Probe station measurements of IV, CV, strip capacitance
    - Smartscope measurement of size
  - Pitch Adaptors
    - Probe station measurement of strip capacitance
  - Cables
    - Resistances, opens, shorts
  - Hybrids (bare & with surface mounts)
    - Connectivity, shorts, temperature sensors



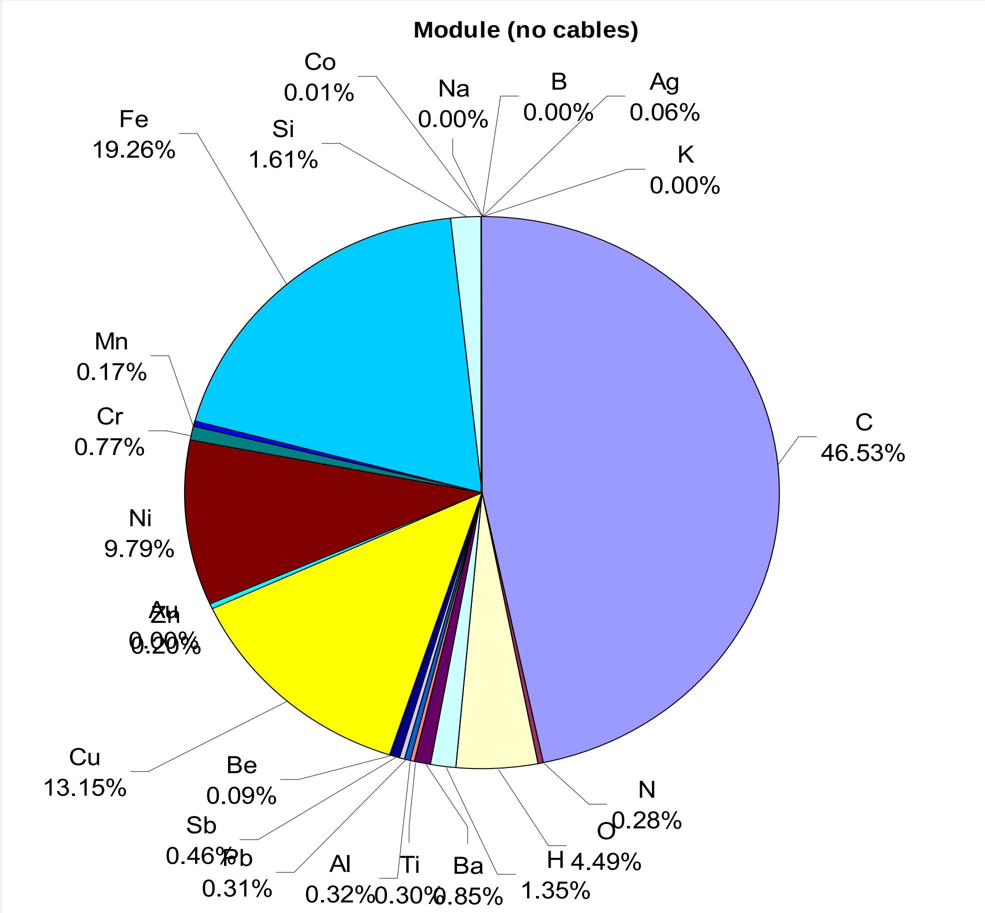




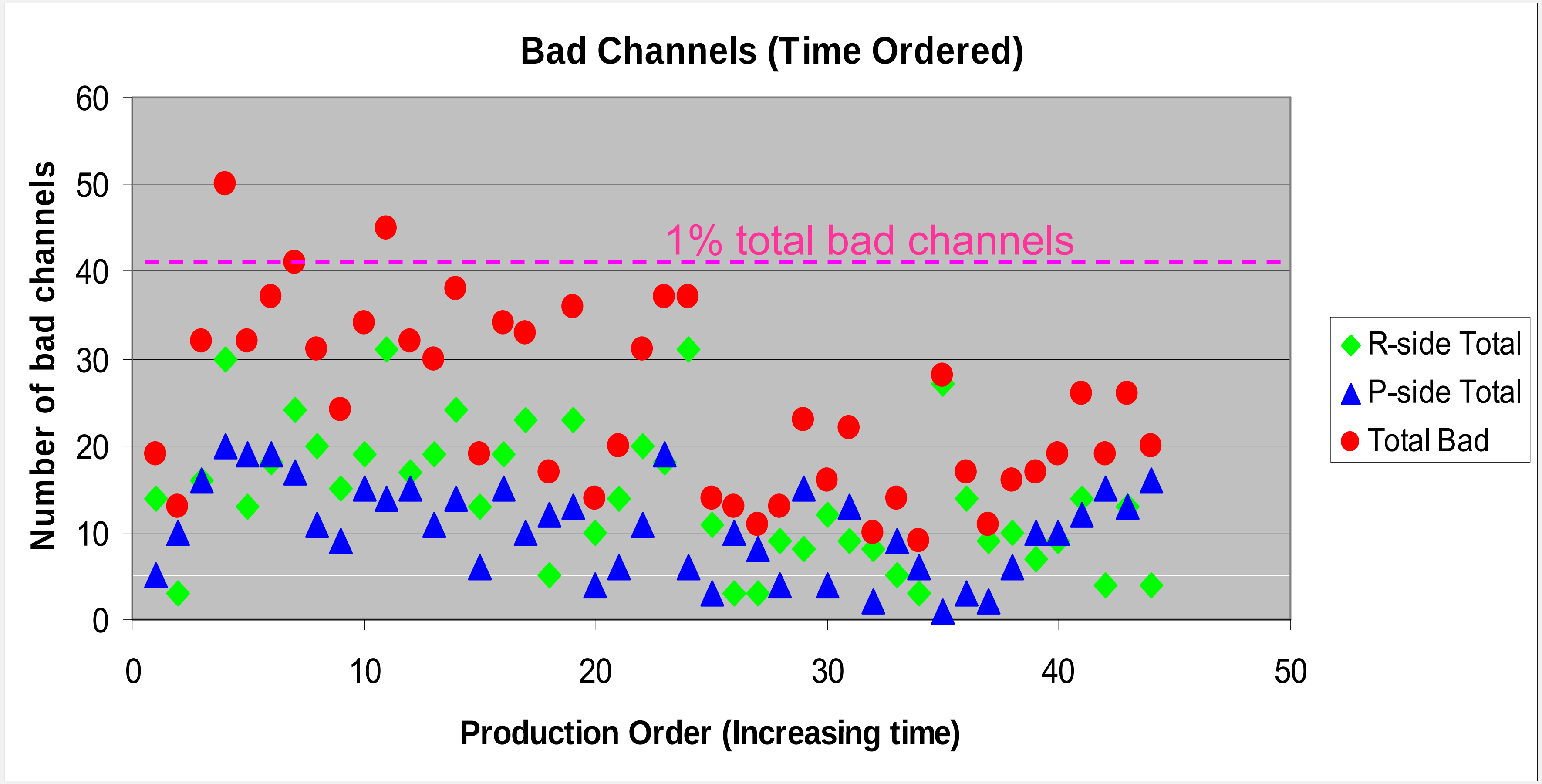


Module Materials

- Detailed assay of all materials in module made
  - Module mass: 321.3 g
  - With cables: 406.9 g
  - ➢ Heavy elements are a concern for activation
  - ➢ Activation under study
    - May impact repair strategy



Bad Channels

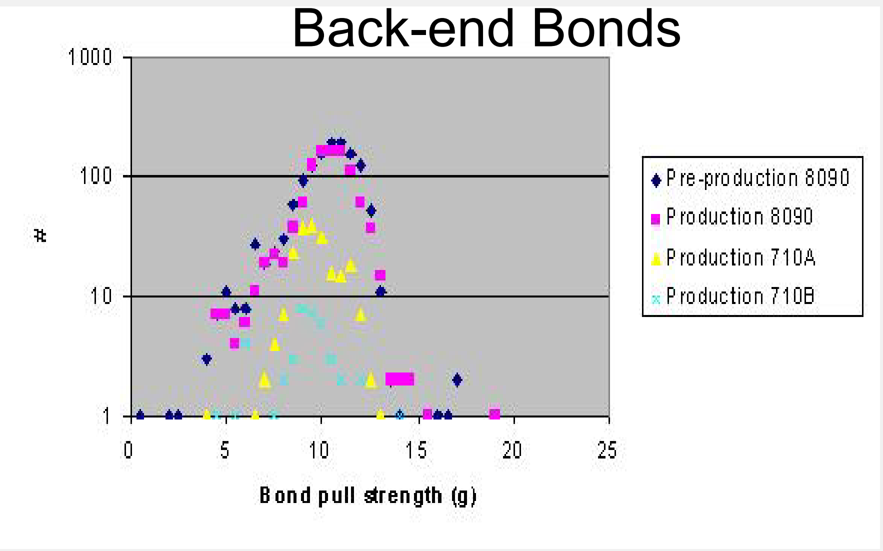


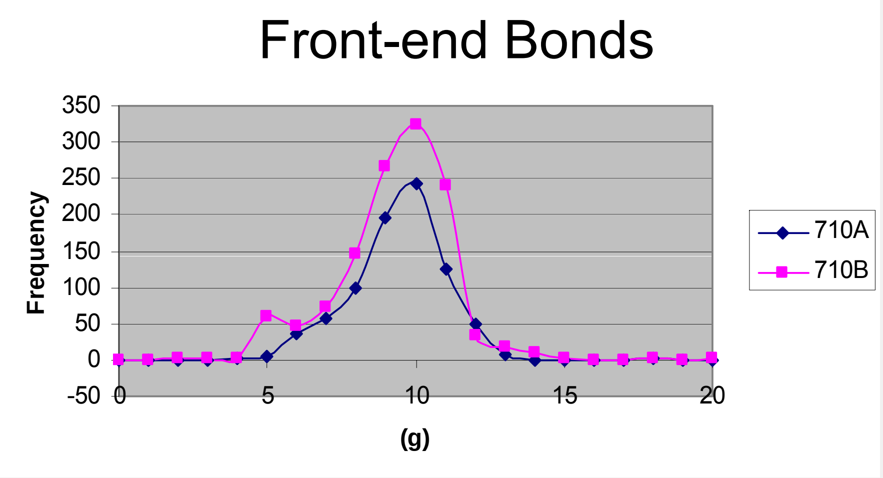
- 23.5 faulty channels (0.57%) on average
  - Improving throughout the production

LHCb VELO Collaboration

Wire Bonding Quality

- Production wire bonding performed by K&S 8090 and 2 H&K 710
  - Low re-bond rates
    - Back-end: 0.6%
    - Front-end: 0.6%
    - Sensor-end: 0.7%
  - Extremely low failure rates
    - Front-end: 0.01%
    - Sensor-end: 0.002%
  - Good pull strengths
    - 8090: 10.0±1.5 g
    - 710A: 9.4±1.5 g
    - 710B: 8.9±1.9 g





Front-end chip

LHCb: 160x25ns deep, read out in 900 ns => SCTA not OK

Design a new chip => the Beetle:

- 0.25 um CMOS ASIC
- Used in LHCb by VELO, Pile-Up system, Silicon tracker