Quality Assurance and Reliability of Silicon Trackers

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Outline

- Quality Assurance and Reliability (Testing) – what/why?
- Real-life examples of QA problems in silicon trackers
- Reliability and lack thereof – consequences
- The CERN Quality Assurance and Reliability Testing (QART) Lab: tools for testing
- Conclusions

Introduction

My background:

Experimental physicist, very hardware oriented, worked on spark chambers (what?), proportional (“Charpak”) chambers, scintillators, Cerenkov detectors, calorimeters (scintillator and liquid argon), trigger electronics, drift chambers, silicon strip detectors, and front-end (FE) electronics for nearly all the above detectors.

What makes me qualified to talk about quality assurance (QA) and reliability testing?

My recent work has been with very scale large production of detectors and FE electronics: the FE hybrids for the CMS silicon strip tracker, the module production and FE electronics for the CMS preshower (silicon pad) detector.

I am now in charge of the CERN wire bonding lab and of the quality assurance and reliability testing (QART) lab.

What is Quality Assurance?

I'll try to avoid the boredom of an instructional lesson on QA and reliability:

A minimum the formal stuff and concentrate on applications to HEP and real-world examples.

So, lets get the formal definition of QA out of the way:

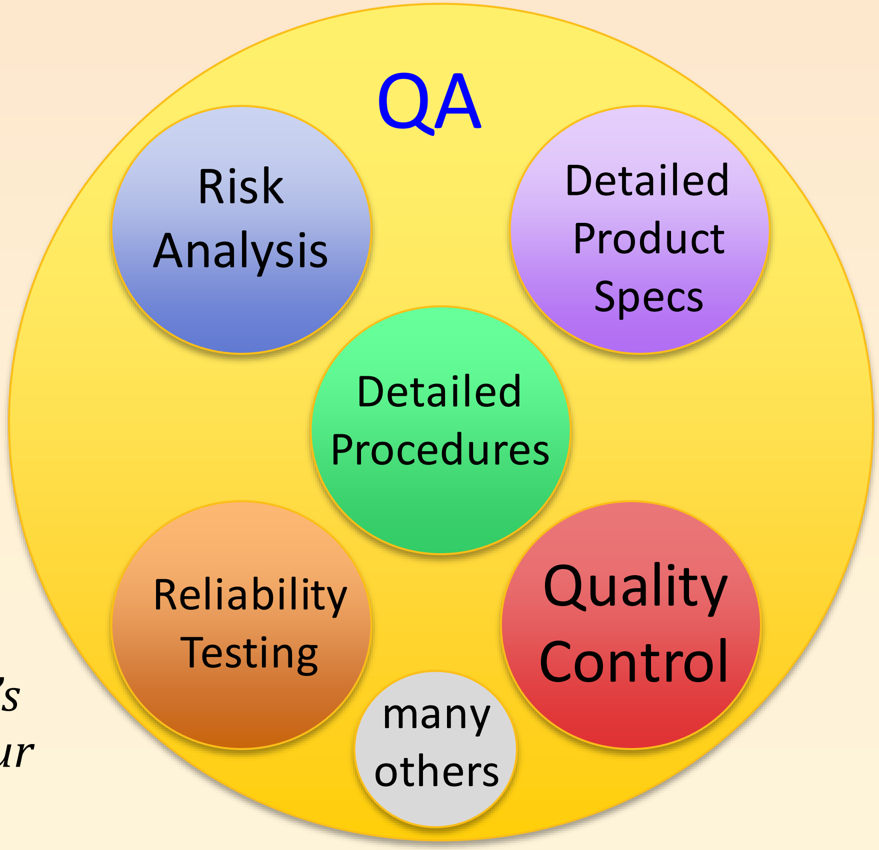
"a program for the systematic monitoring and evaluation of the various aspects of a project, service, or facility to ensure that standards of quality are being met." *(Miriam-Webster dictionary)*

I'll redefine that as: "make a good plan covering design, fabrication, assembly, commissioning and operation of the silicon tracker."

What is Quality Assurance?

But a "good plan" means looking at each phase of the project and assessing risks and weak areas, then implementing quality checks at appropriate points. This is a pro-active approach. Note that quality control (QC), on the other hand, is a re-active mechanism. So, QA≠QC, but QC should be an integral part of a QA plan.

The QA plan includes other steps taking place prior to, during, as well as after the production and construction phase.



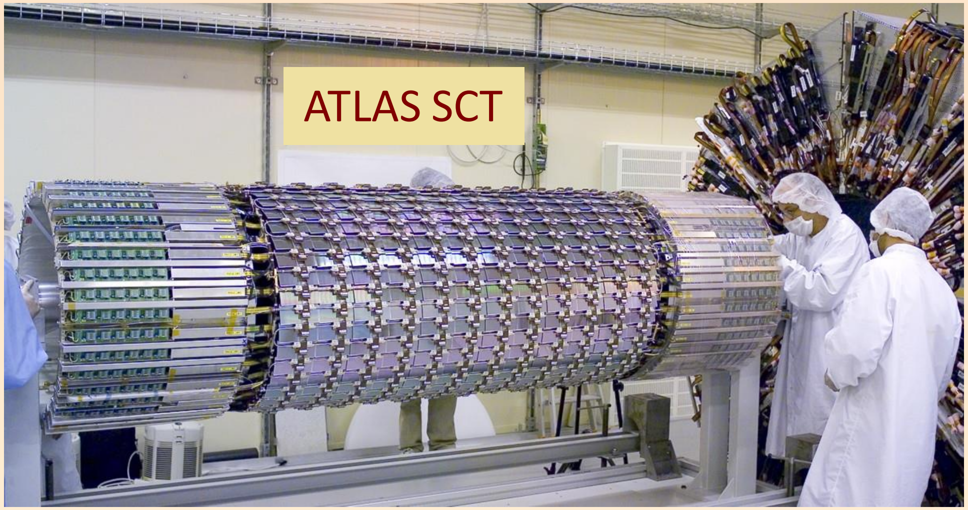
Note also: QA ≠ ISO9000/9001

The ISO certification applies to the company's quality capabilities but not necessarily to your product made by that company.

Why is Quality Assurance important?

OK, now let’s take an example… our project will be:

The upgrade of an LHC experiment’s silicon tracker.



The words “quality assurance” are often considered to be equivalent to “common sense” to many physicists, including myself some years ago. I am now convinced that for large scale production of detectors having limited or no access, QA and reliability testing are essential and should be better understood by those building detectors and electronics. WHY?

Why is Quality Assurance important?

Some key requirements for building an LHC detector upgrade:

- A large number of identical or very similar units to be produced
- Time scale is very tight (the spokesperson or project manager will always see to this)
- The budget is X% below what you think you need to do this project
- The environmental conditions for the detector and front-end (FE) electronics are very "challenging" (high radiation, large temperature excursions, variable humidity, possibility for vibration and shocks).
- The detector and FE electronics will be effectively inaccessible once installed and must work flawlessly for at least 10 years.

What do these requirements imply for the project management?

Why are QA and Reliability Testing important?

Implications for building an LHC silicon detector upgrade:

- Large number of units $\Rightarrow$ mostly in industry (not in-house)

  If you want a good product, better understand industrial QA

- Tight time scale $\Rightarrow$ must get it right on 1st or 2nd try

  QA is essential for avoiding mistakes and bad procedures

- Tight budget (but large total cost) $\Rightarrow$ probably need to use lowest bidder

  Lowest bidder can often mean "cutting corners", must impose QA and verify compliance

- Difficult and complex environmental conditions $\Rightarrow$ need extensive testing

- Inaccessibility and long life $\Rightarrow$ need highest levels of reliability

  These last two imply high reliability but one also needs <u>verification</u> of reliability = Reliability Testing

What is Reliability and Reliability Testing?

Reliability (*wikipedia definition*): "the ability of a system to perform and maintain its functions in routine circumstances, as well as hostile or unexpected circumstances."

In industry, especially electronics, it has an implied meaning of longevity as well.

- Works correctly
- Under routine and difficult environments
- Over a long lifetime

The verification of reliability leads to the need for Reliability Testing

Reliability testing is not necessarily something done as a last step (like is often the case for QC). It should be implemented at the R&D stage to evaluate if the "product" has the required level of reliability before going to the production stage. It is part of a good QA plan.

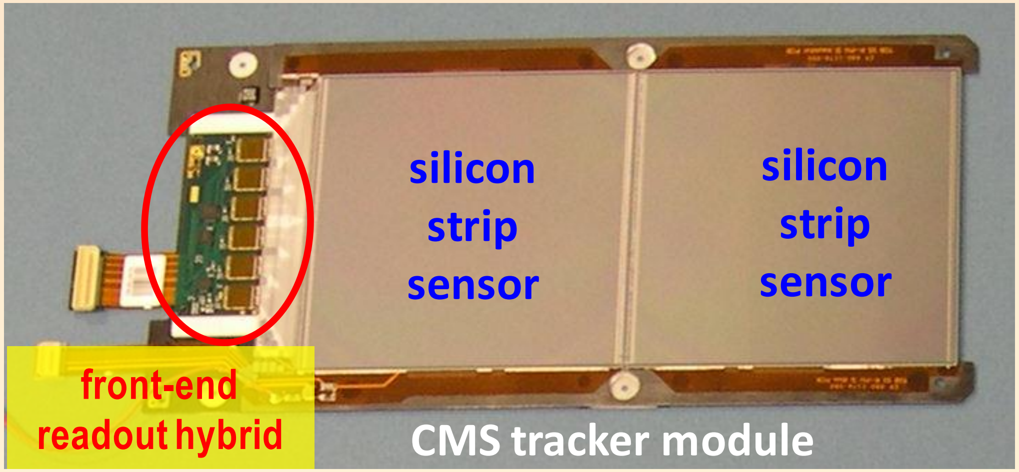
We will come back to reliability testing later…

Examples of large production QA problems

Let's look at QA problems occurring at the design, R&D, and prototyping stage.

Example 1: CMS silicon strip tracker front-end (FE) read-out hybrid design

The project: CMS silicon strip tracker. Need to produce the front-end (FE) read-out hybrid.



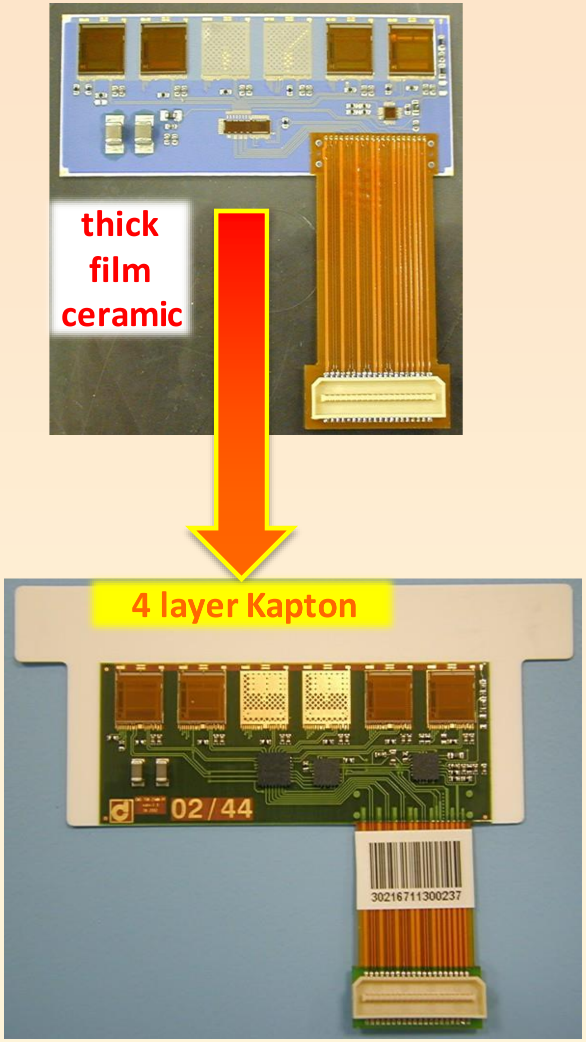
Low mass, compact hybrid circuit to be mounted with 4 or 6 read-out chips. Final circuit should be consistent with robotic assembly techniques.

Examples of large production QA problems

Example 1: CMS silicon strip tracker FE hybrid design

Number needed: 15,148 (17,000 including spares)!

Time scale: "1 year for development, 2 years for production"



Qualification of design is not so easy

- First design was a thick film ceramic hybrid technology (the "tried and true" technology of the 90's)
- Although functioning prototypes produced, after 2 years of R&D, no company could produce the numbers required at an affordable price. (cost = 3 x budget)
- Technology change to FR4+flex (Kapton). Short-lived because incompatible with low CTE module structure, with mechanical constraints of robotic assembly and other technical production problems.
- Technology change to full-flex Kapton. Big effort to find qualified PCB manufacturers but success at last.

Examples of large production QA problems

Example 1: CMS silicon strip tracker FE hybrid design

Some QA lessons learned in the CMS hybrid design:

Qualification of design is part of a QA plan. This should be well defined and structured so that not only the technical, but the financial and time constraints as well, are taken into account.

1. Need a complete set of technical requirements, not just electronic but mechanical and thermal.
2. R&D phase should include an evaluation of the expected production cost. Different technological choices should be investigated in parallel if possible.
3. One should be aware of the scale. A company that can produce 20 good pieces in a month during R&D may not be able to produce the 2000 good pieces per month you will need in production.

Examples of large production QA problems

Example 2: CMS silicon strip tracker FE hybrid production

When we started production, we quickly found that what we got was not what we expected…

Lessons from early production, especially for products coming from industry:

1. A QA plan requires detailed and thorough specifications for all components. In addition, when working with industry, a complete Technical Specifications Document is essential. TSD ≠ "product description + drawings + schematics". Should also include: Dimensional and tolerance specs, component placement accuracy, assembly (soldering, wire bonding) specs, requirements for testing, environment, longevity, …
2. Even a complete TSD is not sufficient, the QA plan of the company should be requested and examined and modified if necessary. Intermediate testing steps, analyses of samples and cross-sections (of PCBs), and further QC documentation may be advisable.
3. A company advertising itself as ISO 9000 or 9001 does not mean they will follow a well defined and strict QA plan. This means only that they should be capable of defining and following such a plan. It is up to the customer to require this and check that they comply. Even that is sometimes not enough.

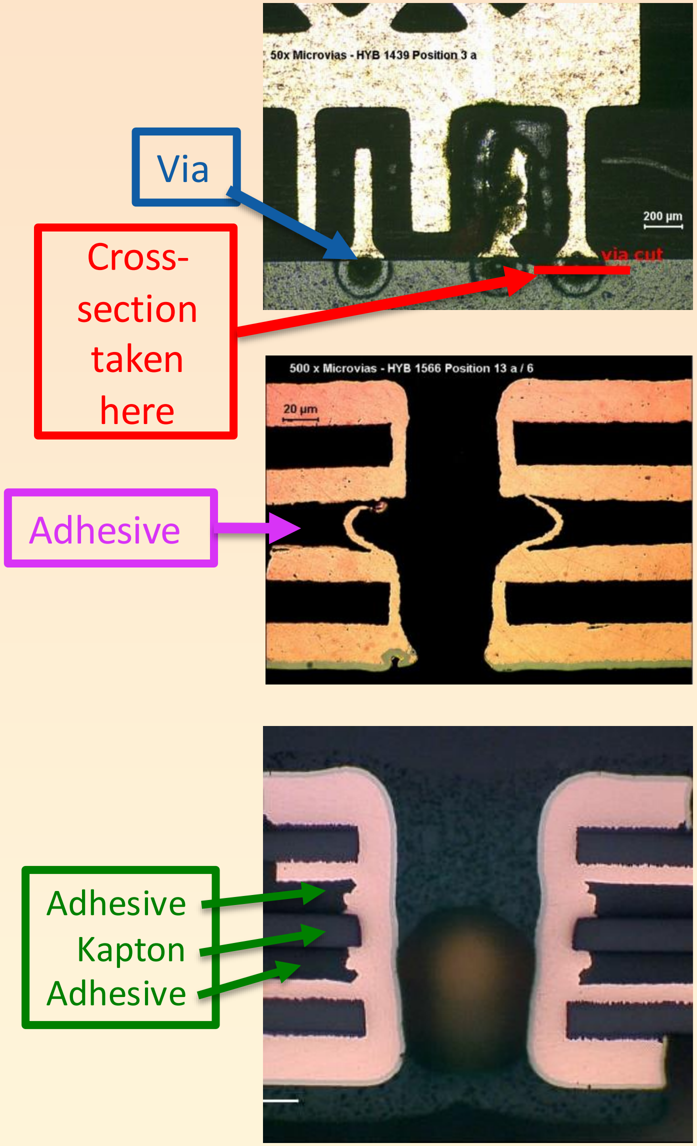
Examples of large production QA problems

Example 3: Front-end hybrid fabrication failure

The most significant problem encountered in the hybrid production was detected only after >10% had been delivered. Fortunately, 100% electrical testing was applied to all hybrids because an electrical failure was found on a significant fraction of the hybrids in a batch. After much investigative work, the problem was traced to poorly plated through holes ("vias") on the PCB. This was found to exist from the beginning.

A double layer of adhesive was used to hold together the upper and lower circuit layers. This thick layer appeared to be eaten away ("because laser drilled") and underplated.

Solution: replace the double-layer adhesive with adhesive-Kapton-adhesive. Also, increase the copper plating in the via. Via walls now look good.



Examples of large production QA problems

This problem took 8 months to solve. About 4000 hybrids were rejected although only 2-5% of the hybrids failed the electrical test. However, more failed in thermal cycling.

QA Lesson: was it possible to avoid this problem in advance?

Yes, in principle. Could have required test structures with vias and had cross-sections done regularly (this was implemented after these problems occurred).

But: Have to be an expert in PCB manufacturing problems to know there might be a weakness. Company said they made “similar” PCBs before and had no problems. Now we know better than to believe a company about the ease of making vias (or other critical structures).

Part our QA recommendations for large scale production of PCBs with high via counts: via test structures and cross-sections.

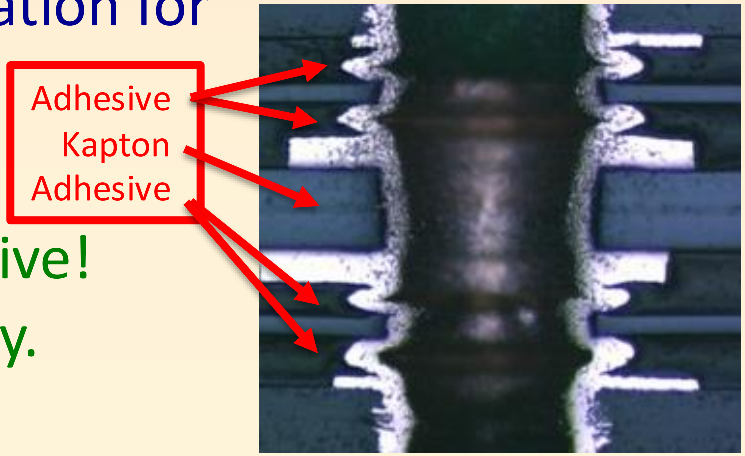
Examples of large production QA problems

Example 3': "You never learn" – another front-end hybrid via failure

In my next project (CMS preshower silicon pad detector), the front end hybrids (rigid/flex) also showed occasional open circuits. 3 PCB manufacturers assured us this was not a difficult build-up. Vias were large and mechanically drilled. Again, no via cross-sections were required from the manufacturer.

Same "eaten away" and under-plating problem despite a thin adhesive layer and a mechanically drilled (NOT laser) via hole!

Again, months spent to understand and solve the problem. This time the real explanation for the "eating away" was found.



The plasma etching step used to prep the via hole ate away the acrylic adhesive!

⇒ Replaced acrylic adhesive with epoxy.

Lesson: Do a complete failure analysis

Examples of large production QA problems

Example: Other QA problems

Numerous other problems throughout the R&D and production in both projects.

1. Damage to ceramic rigidifier for flex PCB during production.
2. Cracking of PCB traces owing to Cu-Ni-Au in flexible region.
3. Placement of read-out chips of insufficient accuracy.
4. Poor wire bond connections to read-out chip (almost 1000 hybrids rejected).
5. Cratering of silicon of read-out chip under bonding foot (bonding machine parameter problem).
6. Poor solder quality of BGA solder balls (about 100 hybrids rejected).
7. Contamination of bonding pads with chlorine residues (will destroy aluminium wire in presence of humidity).

Some of these problems were detected during the prototype qualification.

Some in the QC checks on production batches.

Some in module and system testing.

Some found only after doing reliability testing.

Many of these were found in time because of proper QA procedures.

Good solutions often require another QA element: ***failure analysis.***

Examples of large production QA lessons

Summary

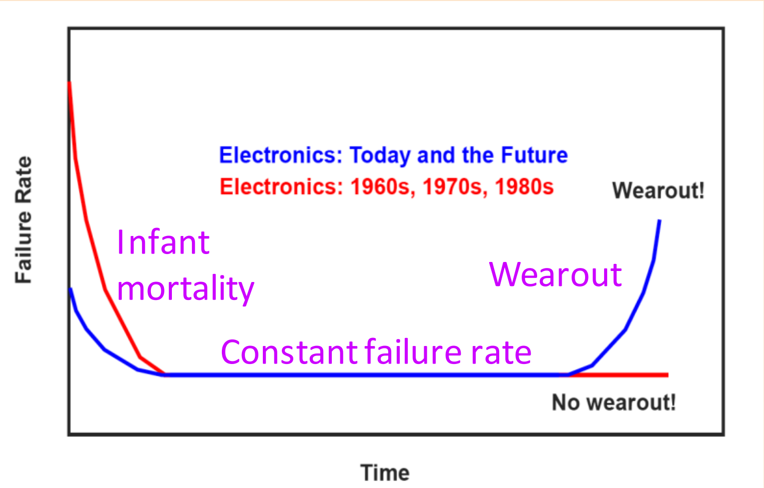
1. Part of qualifying a technology choice is that it will be within the budget. When possible, qualifying different choices in parallel benefits budget and schedule.
2. When accepting an industrial product, all that you can demand is that it meets the specifications. So, a detailed and complete specification document (TSD) is essential: it must reflect the real life requirements.
3. When requesting a non-standard product or non-standard processing of a product, find technical experts to help identify in advance possible weaknesses or problems that might arise. Many companies will not be able to solve unusual problems without outside aid. CERN has many excellent technical experts: PCB workshop, SMD workshop, in PH/ESE (electronics group), in PH/DT (detector support group), in the EN-MME labs, in the experiments.
4. In very large scale production of complex objects, it is unlikely to find all major problems at the prototype stage. Plan for a high level of testing at many stages of the production and in the % of pieces undergoing test. Use failure analysis.
5. If there is a requirement for high reliability (to be discussed next), reliability testing is needed both at the prototype stage and during production.

The role of reliability testing

Reliability testing is meant to ensure that your product will function properly in its (often challenging) environment for the duration you require (no wearout). The failure rate of individual pieces should meet your specs.

Reliability testing can be used to identify non-conformity. It can also be used as a screening method (to remove infant mortality).

The "bathtub" curve



When is reliability testing required or advised?

For "in-house" products: it is advised, unless the design and construction is well understood to be inherently reliable and proof of this already exists.

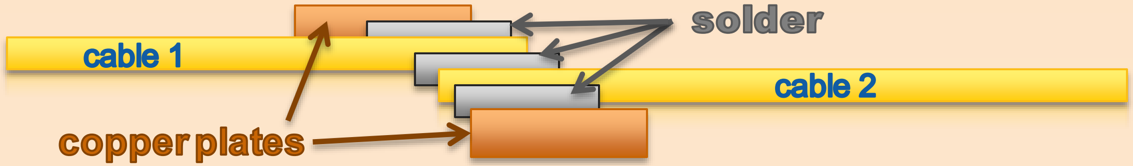
For industrial products: if the product need only meet consumer goods (portable phones, PCs, digital cameras,…) lifetimes, i.e. 3 years or less, and basic industrial standards were applied, then reliability testing is probably not required.

For all products that must work for >3 years, in harsh environmental conditions, or with no access for repair or replacement (or all of these): reliability testing should be required.

An example: What is the level of reliability?

Real life example, can we estimate the reliability?

The project:



- Solder the ends of cables together by overlapping the ends and putting solder in between and around. Add two copper covers plates over the joint and a machine will heat the joint to melt the solder.

If this is to power up a Christmas tree light string, not much reliability testing is required. Still, you don't want to have a fire so you would probably do a good visual inspection and measure the resistance of the joints.

Now let me add a few extra requirements:

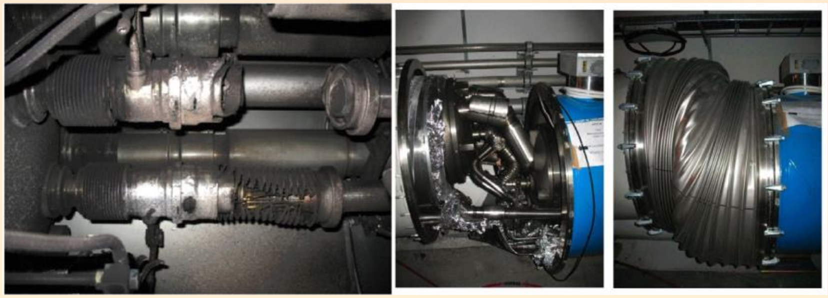
- A total of >10,000 of the solder joints are required.
- Each cable is superconducting and will carry 13,000 amps.
- If one joint fails, you will probably destroy a lot of expensive equipment and the whole apparatus will be down for repair for at least 12 months (and about 7000 physicists will be very upset).

YES, I am talking about the splices on the power lines for the LHC magnets.

An example: What is the level of reliability?

Some background for those not familiar with the LHC splice "accident":

In September 2008, a week after a first short demonstration that the LHC was able to circulate proton beams, an electrical failure in the solder joint ("splice") between two superconducting cables caused the joint to explode. This caused the liquid helium to vaporize and the overpressure caused massive damage to the magnets and beam line around the failed splice. More than 50 magnets were destroyed or seriously damaged. It required 14 months to repair or replace the damaged accelerator parts and to re-commission the LHC. The repair cost was many 10's of millions of Swiss Francs



1. These cables are meant to carry up to 13K Amps. The failure occurred at about 9K Amps.
2. Because of the uncertainty in the reliability of the un-replaced splices in the LHC, it was decided that the maximum current at which it was safe to run was 6-7K Amps. This has limited the maximum LHC beam energy to 4 TeV compared to the nominal value of 7 TeV.
3. The current long shutdown is primarily to fully repair these faulty splices.

An example: What is the level of reliability?

Here is the quality assurance and reliability testing plan that was used to construct the splices in the LHC:

1. Visual inspection of solder joint by the soldering machine operator (check that solder exits from copper shell). Visual inspection by another inspector.
2. Sample testing (at about a 1% rate) of joints made with short test cables so that the joint could be cut open and inspected (no bad splices found).
3. Low sample testing (1-2 per mil?) of real splices with an x-ray machine
4. Low sample testing (1-2 per mil?) of test splices operating in real conditions

A risk analysis based on this plan gave the probability of a splice failure in the 10000 splices was 1 in ~10 years of operation = desired reliability. Was it right?

Note that after the disastrous splice failure during the LHC commissioning phase, many splices were then measured for resistance and a number were found with values indicating a poor solder joint. These were opened and most showed either poor soldering or little (even no) solder in the joint. The "double" visual inspection clearly did a poor job verifying the presence of solder. An evaluation of the reliability of a visual inspection should have shown an error rate of >2%.

An example: What is the level of reliability?

Reliability analysis: A failure rate of less than 1 in 10000 joints in 10 years would require an extremely high reliability, at the level required for spacecraft.

The visual inspection (#1) should have given a failure rate of about 0.4%. The sample testing (#2,3,4) can only claim that the bad solder joint rate is less than about 2% at best. Only one reliability test (#4) was performed. It could not be used to demonstrate a reliability of less than 1 failure in 10000 joints in 10 years.

It is not clear how to demonstrate this level of reliability with no obvious means of accelerated testing possible. Still, it is possible to improve the reliability:

- Redundancy (i.e. two joints instead of one)
- A visual inspection should have had tangible proof of visible solder (a photo).
- Larger samples of real and simulated joints should have been tested.

Experts on this subject informed me of two further important points:

- Adding a clamp system on the copper plates could avoid catastrophic failure.
- Resistance measurements could have found some of the poor solder joints.

Improved starting reliability was certainly possible as was a better reliability estimate. But to demonstrate the desired reliability was probably beyond the available time and resources. A very difficult reliability assessment problem!

What is reliability testing?

Examples of typical types of reliability test for silicon detectors and electronics:

- High or low temperature
- High or low humidity
- Thermal cycling or thermal shock
- Vibration and shock
- Radiation (EM or hadrons)
- Over-voltage

There are a large variety of accelerated testing methods since reliability is usually a requirement over a long time period, too long for actual testing:

HALT = highly accelerated life testing (find weakness in product)

HAST = highly accelerated stress testing (measure time rate of failure)

HASS = highly accelerated stress screening (remove infant mortality)

The user must decide which tests types are relevant and what is the goal of the test. There are many texts devoted to this subject as the actual test formulation is quite technical and requires an understanding of the <u>failure mechanisms</u>.

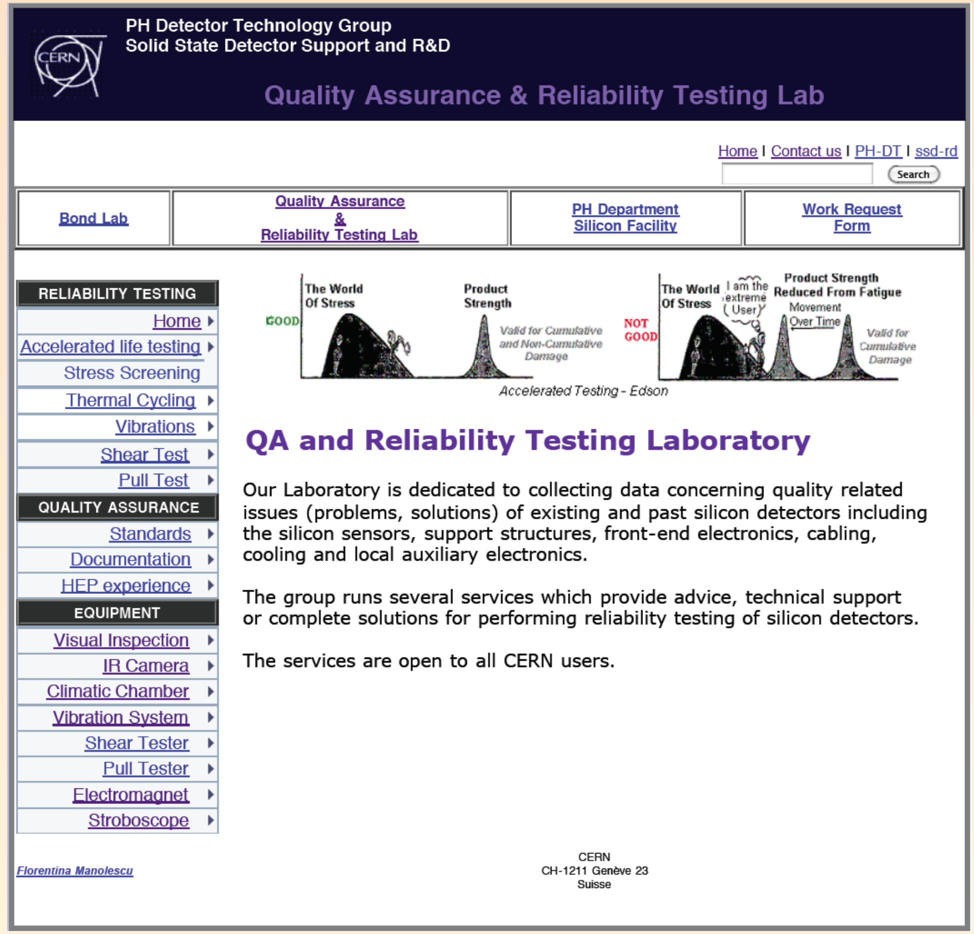
Where to do reliability testing?

The Quality Assurance and Reliability Testing (QART) Lab

CERN DSF
QART and
Bonding Lab

At CERN there are many labs and workshops that have some reliability test equipment but it is not very easy to find out what exists and where. In PH, the Quality Assurance and Reliability Testing (QART) lab is a dedicated lab with a variety of reliability test equipment.

Although priority is given to work from the LHC experiment silicon detectors (and upgrades), the lab is open to all CERN related activities.



Web address:
http://bondlab-qa.web.cern.ch/bondlab-qa/QA.html

QART Lab Site

Location of QART lab is inside B186-R (ground floor) in the Departmental Silicon Facility

Part of the lab is in a clean room, shared with the CERN Wire Bonding lab

We are here

B186

Restaurant 2

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QART Lab

Personnel:

- Florentina Manolescu, technician (80%)
- Ian McGill, technician (20%)
- Alan Honma, physicist (10%)

Equipment (major items):

- 2 Climatic chambers (fast temperature cycling with humidity control)
- Vibration tester
- Infra-red thermal imaging video camera
- Die shear tester / bond wire pull tester
- Small bore 2T electromagnet and 0.7T permanent magnet
- High frequency stroboscope
- Many inspection stereo-microscopes with video cameras

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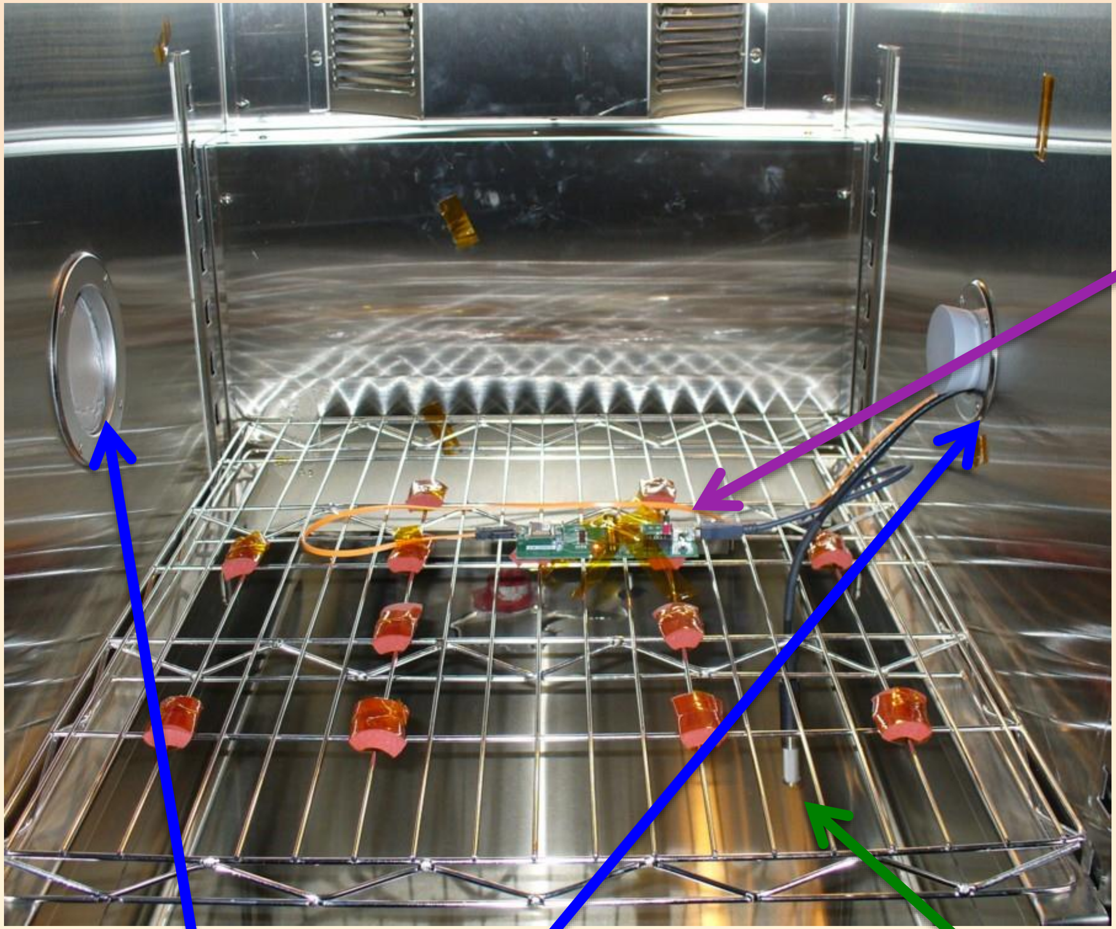
Equipment: Climatic Chambers

Tests:
- Thermal cycling
- Accelerated lifetime
- Humidity tolerance
- Cold tolerance
- Stress screening
- Environment simulation

Climatic Chamber #1
Temp range: -70°C to +180°C
Hum range: 10% to 95%RH
Heating speed: 15°C/min
Cooling speed: 11°C/min
340 Liters

Climatic Chamber #2
Temp range: -70°C to +180°C
Hum range: 10% to 95%RH
Heating speed: 17°C/min
Cooling speed: 11°C/min
140 Liters

Equipment: Climatic Chambers



<u>Tests made or in progress:</u>

- ATLAS IBL flex connector tests (thermal cycling)
- ATLAS optohybrids (high humidity, high temp)
- CMS humidity sensor R&D (low temp, variable hum.)
- Bump bonding R&D (thermal cycling)
- Qualification of PCBs (accelerated life, high temp)
- Medipix (low temp)
- Totem Roman Pot Hybrids (thermal cycling screening)

Two ports for cables

Precision temperature and humidity probe

Equipment: Vibration Tester

Mono-axial shaker with control system and analysis tools for Random, Sine, Shock, and Recorded vibration inputs.
Can perform:

- Destructive testing
- Stress screening
- Modal analysis
- Playback of transport and handling vibrations and shocks
- 30cm x 30cm head expander allows testing of large objects (CMS silicon tracker module)

Vibration system specifications:

Frequency range: DC – 6300 Hz
Max acceleration (sine peak): 100G
Max displacement: 25mm
Armature diameter: 110mm

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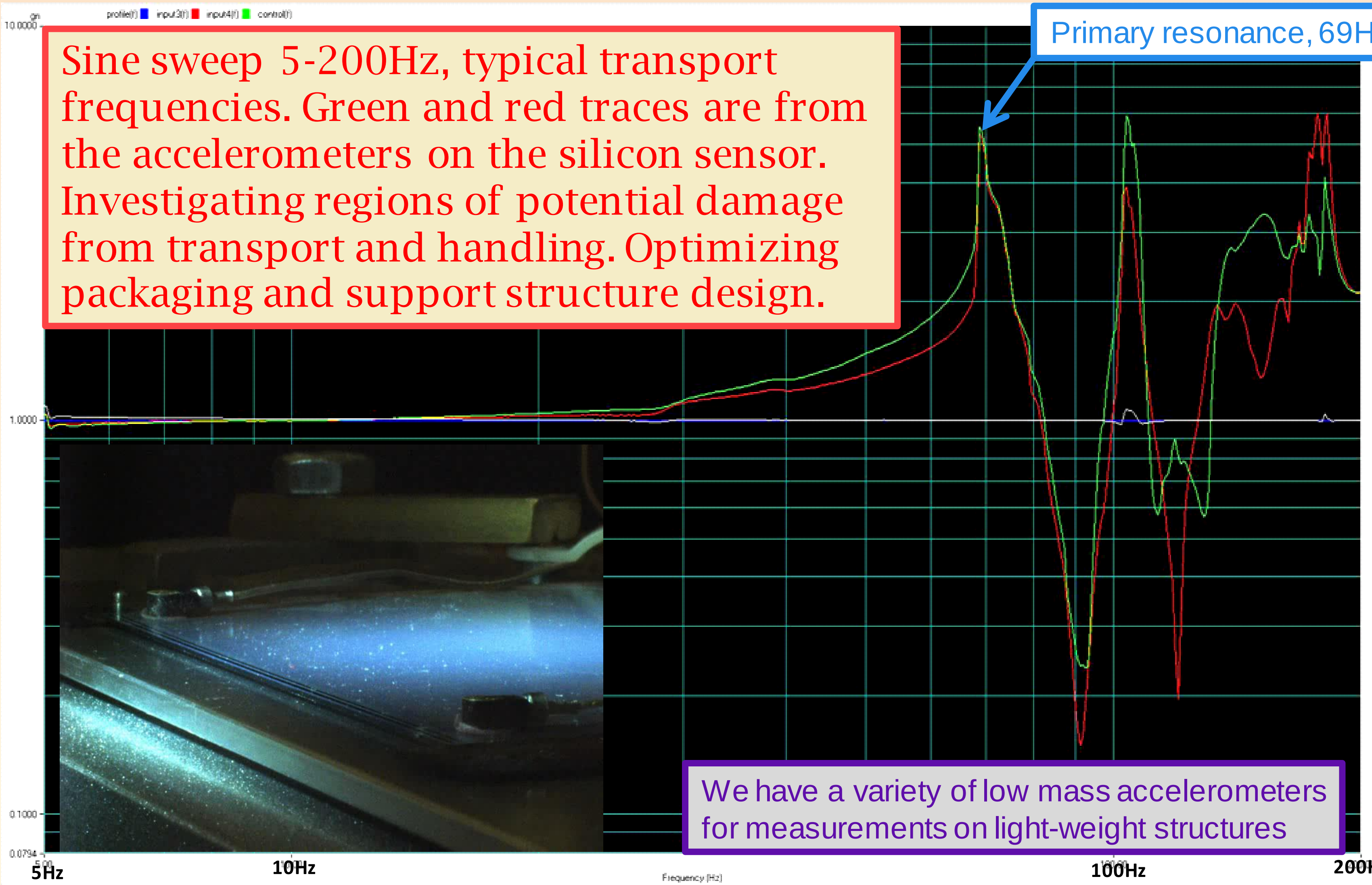
Vibration Test: Silicon strip detector module

Sine sweep 5-200Hz, typical transport frequencies. Green and red traces are from the accelerometers on the silicon sensor. Investigating regions of potential damage from transport and handling. Optimizing packaging and support structure design.

Primary resonance, 69Hz



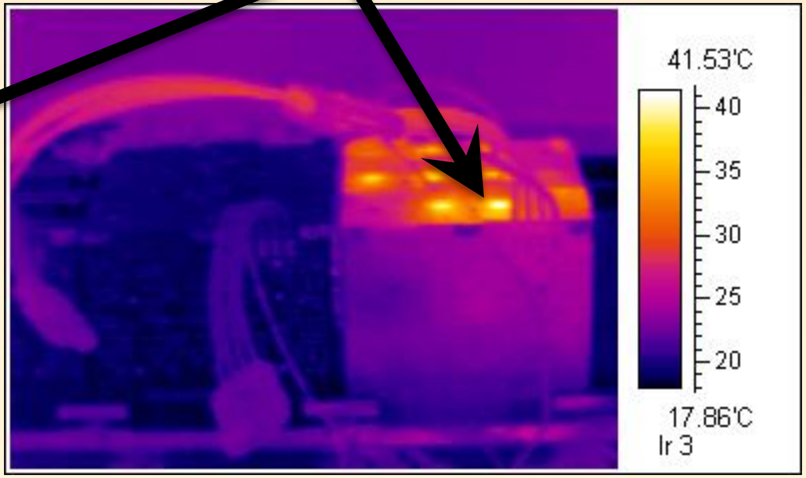
We have a variety of low mass accelerometers for measurements on light-weight structures

Equipment: IR Video Camera

High sensitivity (0.1°K) thermal imaging IR video camera. 160 x 120 pixels. Measurement range: -20°C to +250°C. Expected uses:

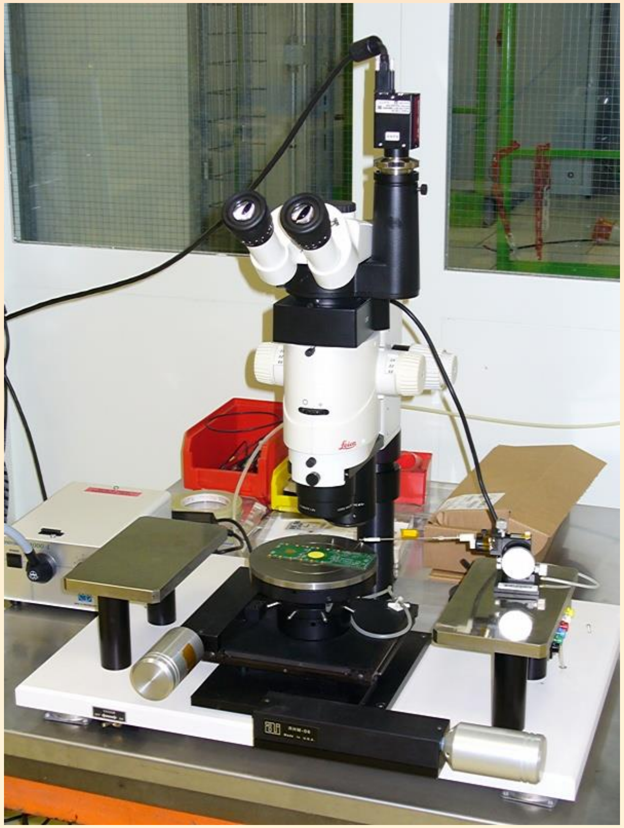
- Identifying hot spots on silicon sensors
- Heat flow study on front-end PCBs and detector modules

Example: Hottest spots on CMS electromagnetic calorimeter front end electronics easily found.



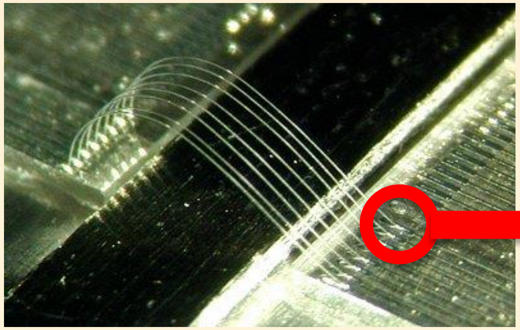
Equipment: High Magnification Stereo-microscope

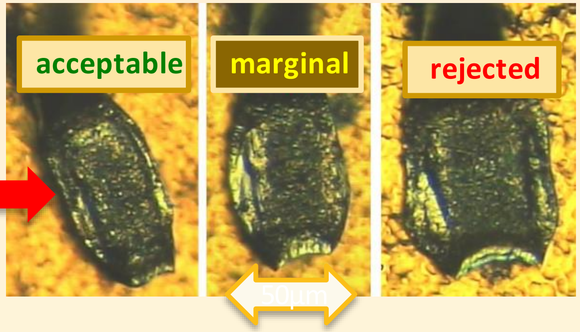
Leica MZ16



- High magnification needed for silicon sensors (pixel or strips) and for (bare) read-out chips.
- Stereo needed for 3-D structure identification.
- Video camera useful if object's visual aspect has time dependence.
- Possibility to probe the observed object.

Example of usage for failure analysis:
Poor wire bonding quality can often be easily spotted from surface details and form of welded bond "foot". In this case right most bond foot is heavily over-deformed (squashed).

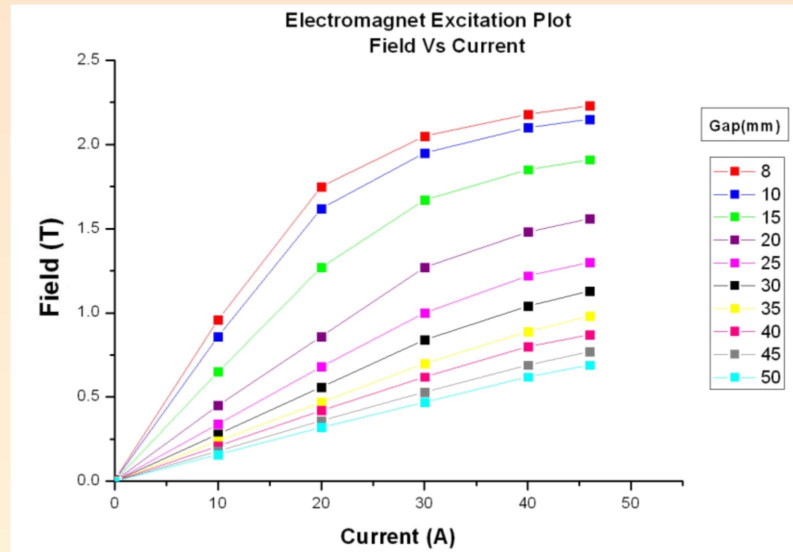


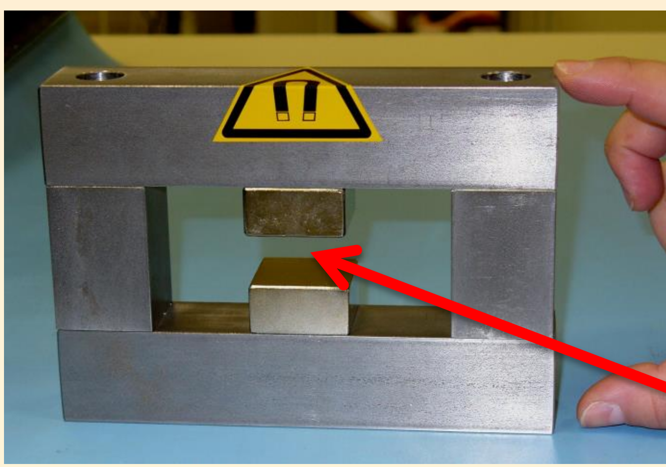


Equipment: High Field Magnets

Small aperture laboratory electromagnet:

- Pole diameter: 38 mm
- Variable pole gap: 0-86 mm
- Magnetic field: 0-2T





Small aperture permanent magnet:

- Pole size: 30 mm x 30 mm
- Pole gap: 15 mm
- Magnetic field: 0.7T

0.7 T dipole field using neodymium magnets

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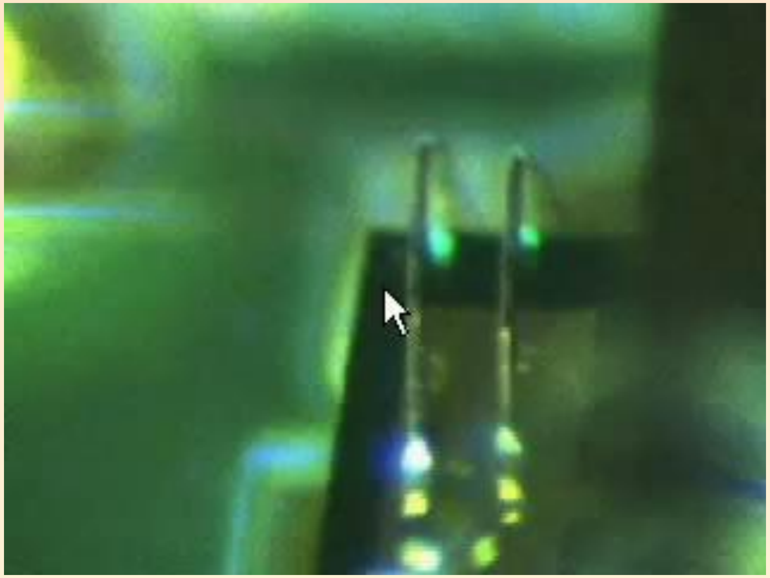
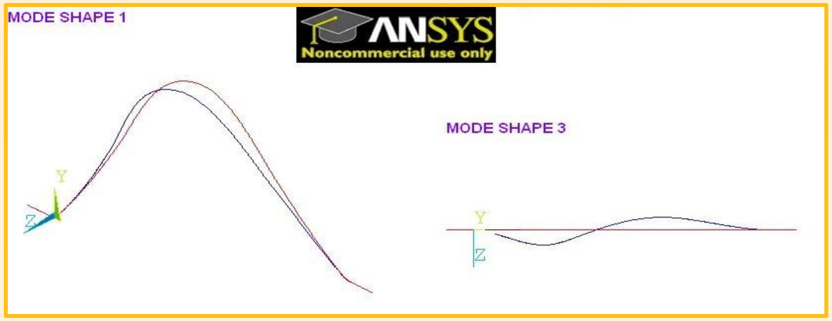
Why High Field Magnets?

Resonant oscillation on bond wires of CMS optical hybrids found at 22KHz



Motivation: CDF silicon strip detector had broken bond wires from vibration owing to AC current at resonant frequency of wires (10-30KHz) in high B field (1.4T).

Example: Oscillations driven in bond wire of real CMS optical hybrid. Primary frequency is 22KHz (simulation said 21KHz). Required current to drive this oscillation in a 3.8T field is only about 5mA.



No known systematic study of effect of wire loop shape, length and bonding quality on breakage risk. We would like to quantify the risk as a function of the bond parameters so as to indicate the risk zones for bond wires in a general way.

Some recommendations concerning high reliability

If the project requires a high level of reliability:

- Design for reliability. It saves time, money and effort to avoid finding reliability problems at the later stages in a project. This applies to all components, assemblies and procedures.
- Carefully evaluate the operational and environmental conditions in the final functioning system. New technologies (deep-submicron, through silicon vias, fine pitch bump bonding), new materials and build-ups all should be qualified for harsh environments such as in SLHC tracking detectors and tested for long-term reliability.
- Do not assume that reliability will be provided by the industrial supplier. It is your responsibility to require the necessary levels of reliability and to either demand proof or test it yourself.
- Unless good accelerated life tests were performed, it is still too early to determine if detectors in the LHC are reliable for a 10+ year lifetime. Results may change with the radiation and thermal cycling to come.

Conclusions

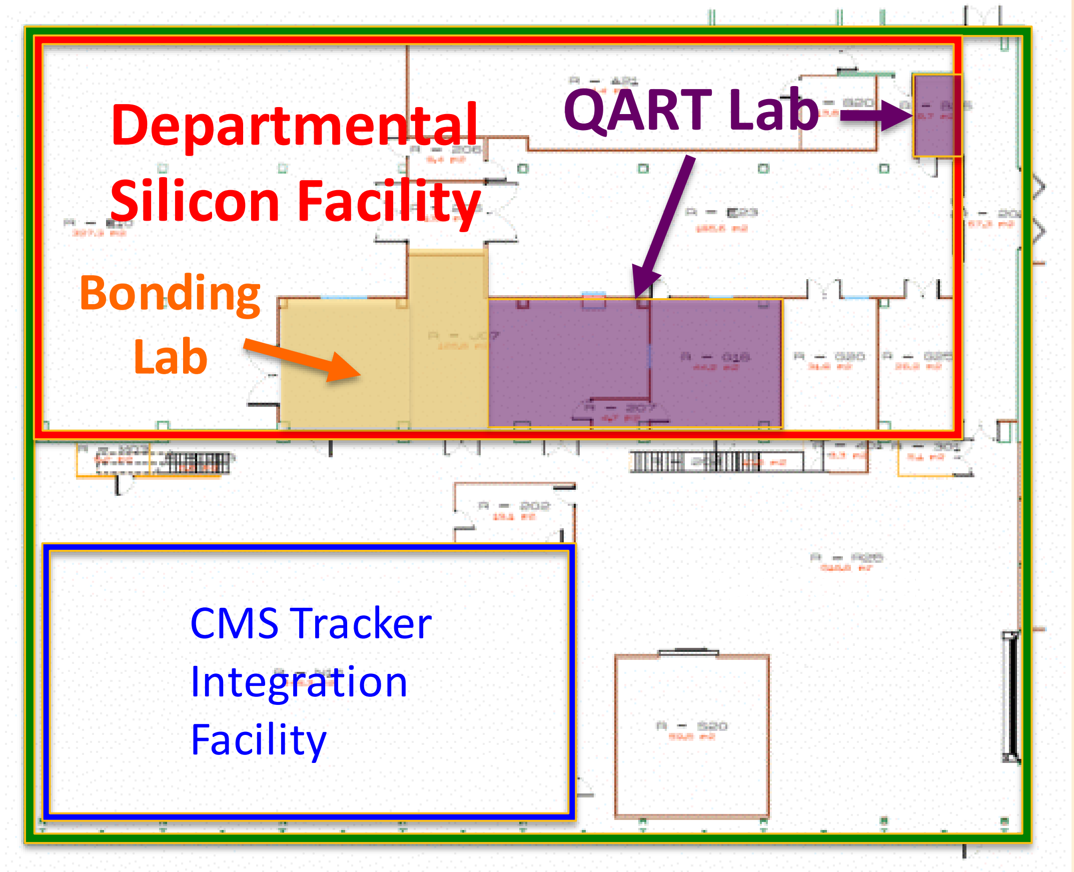
- QA is a detailed plan for assuring the quality for any project.
- QA involves all project phases from design to operation.
- Poor QA can cost financially, in lost time, or in manpower.
- In many HEP silicon detectors, high reliability is mandatory.
- Reliability testing is a part of a good QA plan.
- Many resources for QA and reliability testing exist at CERN.

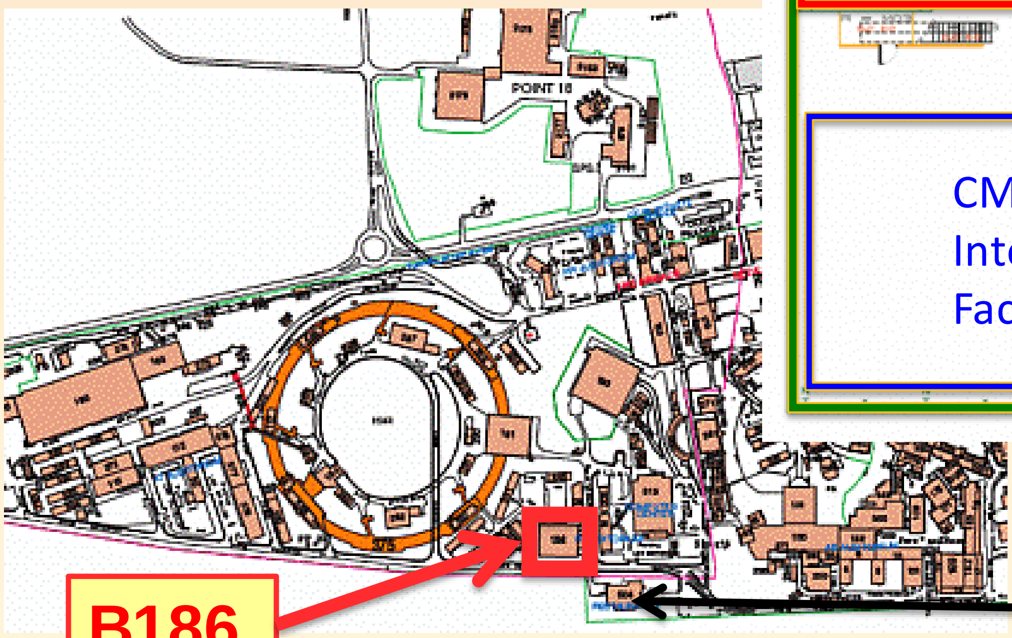
Spares

QART Lab Site

Location of QART lab is inside B186-R (ground floor) in the Departmental Silicon Facility

Part of the lab is in a clean room, shared with the CERN Wire Bonding lab





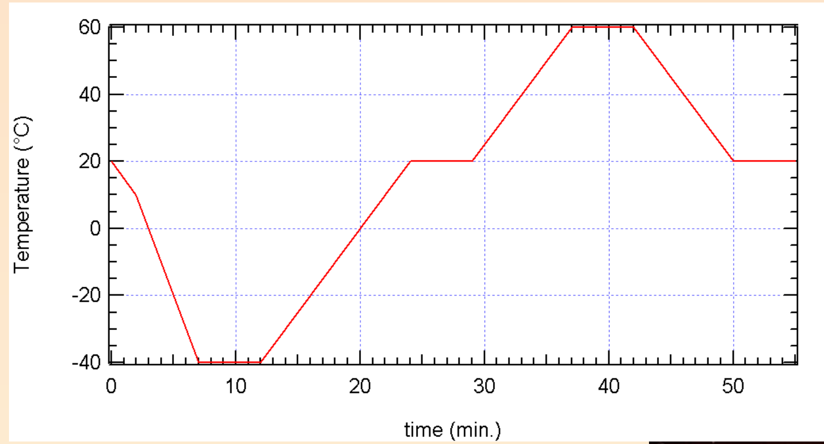
CERN DSF
QART and
Bonding Lab

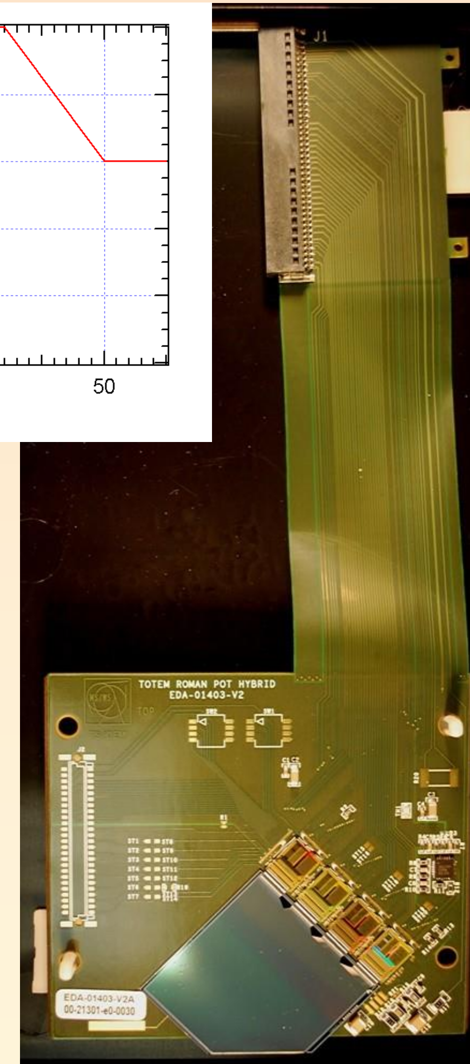
Equipment: Climatic Chambers

<u>Example of thermal cycles:</u>

Totem Roman Pot Hybrids thermal cycling test for lamination quality

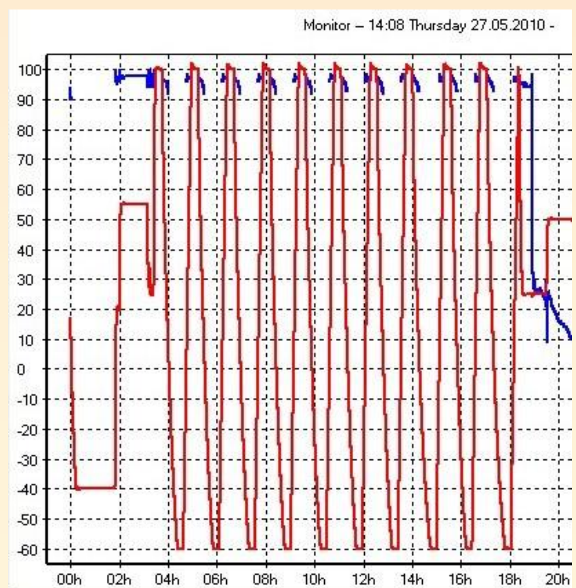
-40˚C to +60˚C, 100 cycles



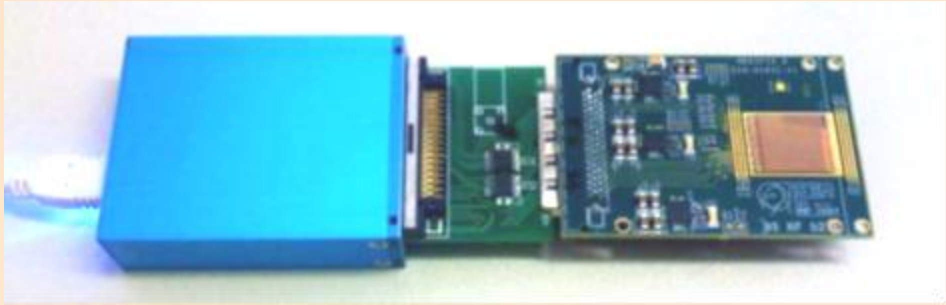


Another more extreme (chamber test) cycle:

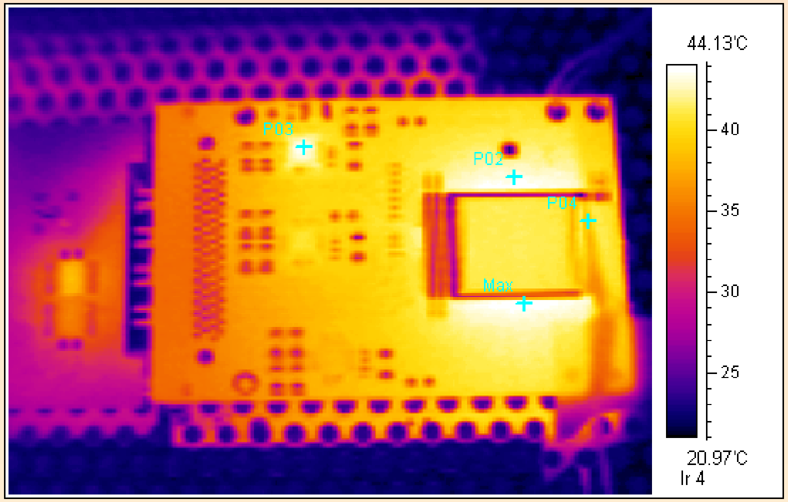
-60˚C to +100˚C, 10 cycles



Example of IR Video Camera usage



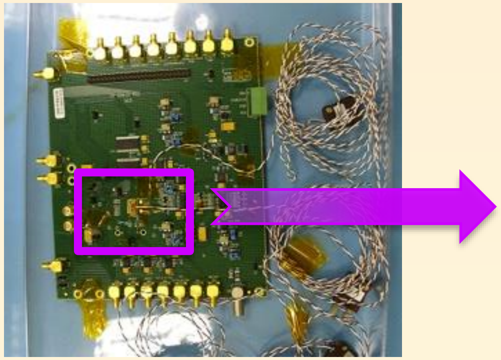
Photos courtesy Rafael Ballabriga Sune



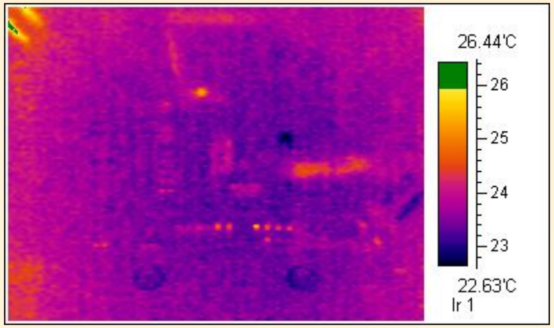
Medipix with USB read-out:

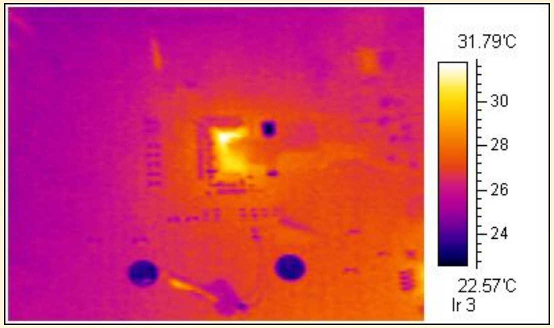
- Thermally cycled in our climatic chamber
- Thermal map of powered device using IR camera

NA62 bare die test: Thermal map of powered device with time sequence



Photos courtesy Massimiliano Fiorini





Vibration Test: Other applications

Test of transport packaging for radio-protection group (shielded radioactive source to go inside) done by EN/MME mechanical testing group. They required a shaker with a large support plate and a high payload capability, ours is probably the most powerful at CERN.

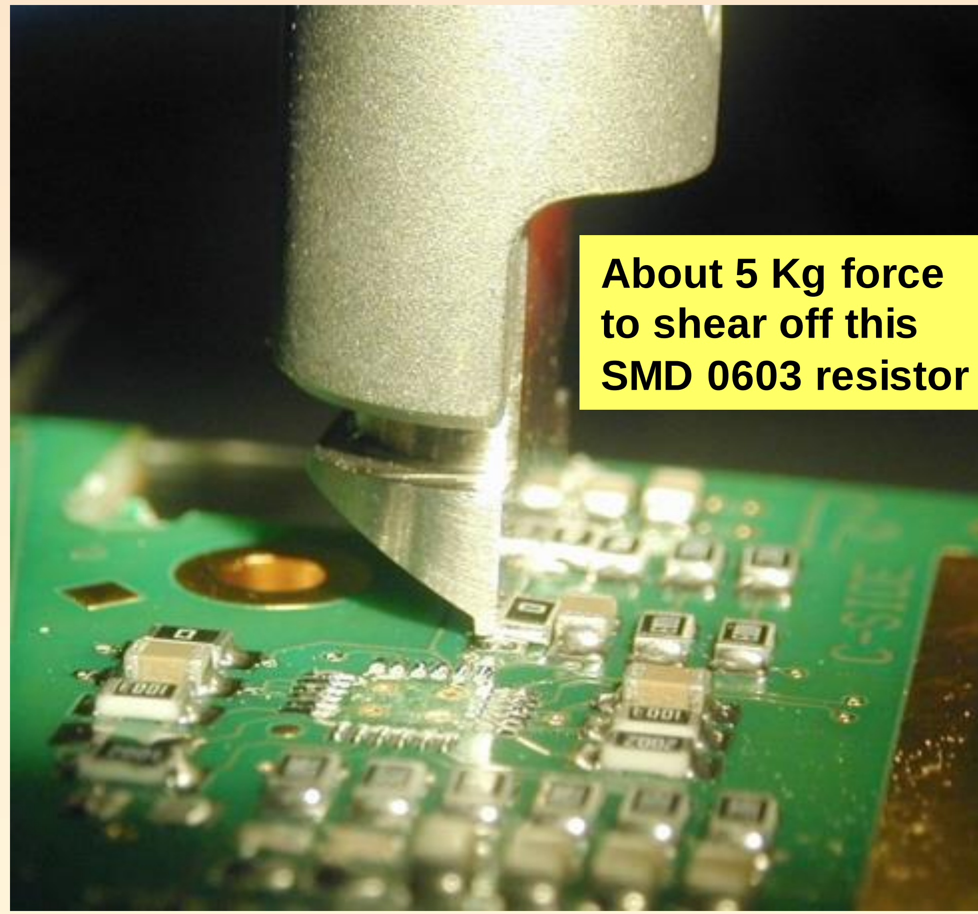
The EN/MME mechanical testing group also used our system to do ground motion transmission measurements needed for the CLIC accelerator study. The CLIC machine will be sensitive to very small ground motions.

CERN DSF
QART and
Bonding Lab

Equipment: Pull and Shear Tester

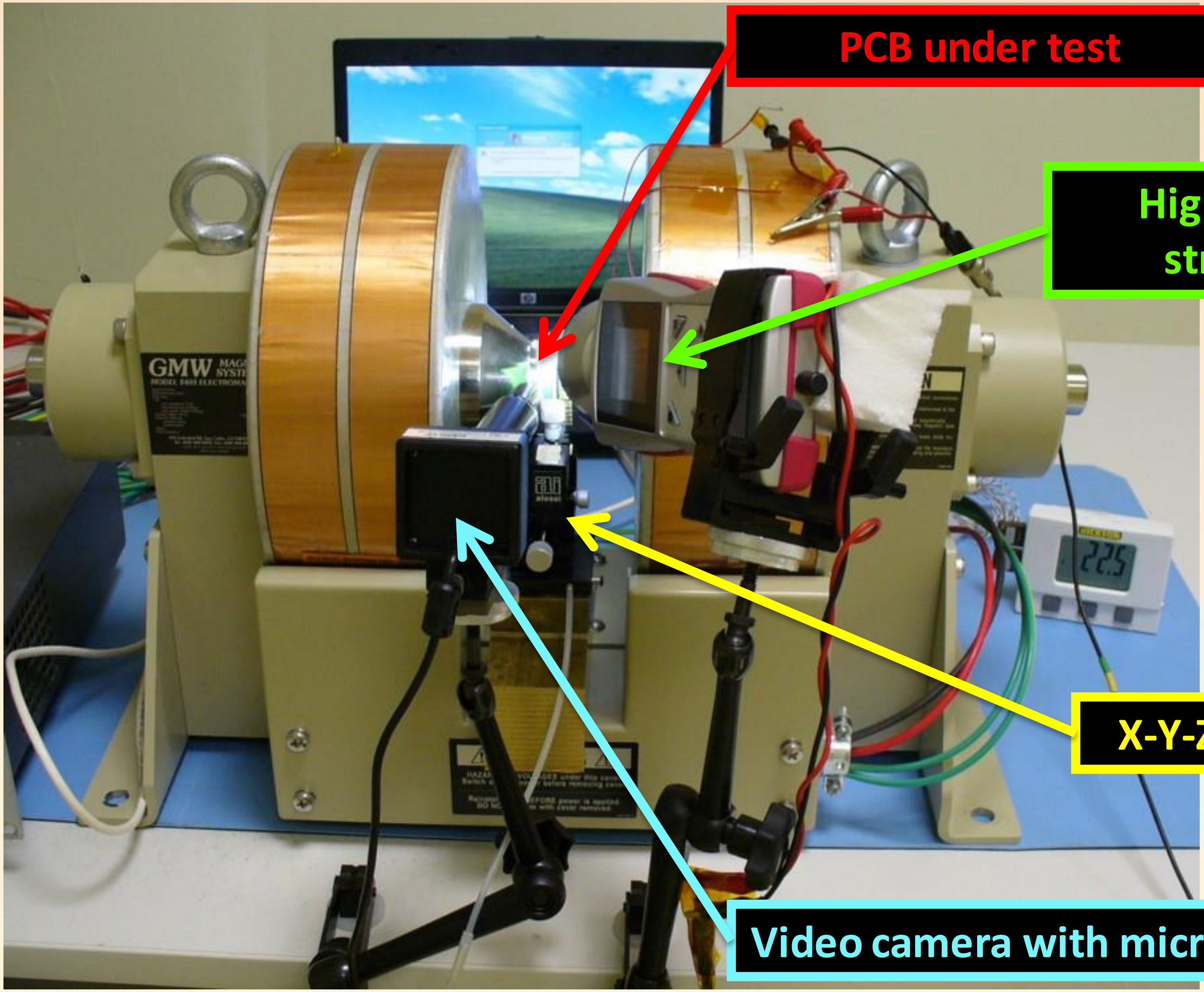
Pull testing is the only sure method to evaluate wire bonding quality. The DAGE 4000 pull tester requires manual positioning but the pull is automated. The machine can be quickly converted to do shear testing.

Shear testing is for checking die attach adhesion, bond wire adhesion and soldering quality for small components.



CERN DSF QART and Bonding Lab

Equipment: High Field Magnets



QA resources

The Quality Assurance part of the QART lab is:

- Knowledge and experience concerning QA for silicon detectors (but for some electronics and other detector systems as well). We try to provide advice and assistance concerning any QA issues.
- A reference library of books, articles and documentation on QA and reliability testing, including some relevant industrial standards.
- We are trying to collect as much information as possible concerning QA and RT issues based on the experience of the LHC experiments and all other projects with similar needs. We welcome any contributions to this knowledge base.

Please feel free to contact us for questions, discussions, planning and requests for QA, reliability testing, equipment usage, wire bonding and chip gluing.