Available on CMS information server

CMS NOTE-2008/024

The Compact Muon Solenoid Experiment

CMS Note

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

11 May 2008

Bonding of the Inner Tracker Silicon Microstrip Modules

F. Bosi$^{1)}$, S. Brasolin$^{2)}$, M. Brianzi$^{3)}$, P. Cariola$^{4)}$, S. Costa$^{5,a)}$, N. Demaria$^{2)}$, F. Dumitrache$^{2)}$, R. Farano$^{2)}$, L. Fiore$^{4)}$, G. Galet$^{6)}$, N. Giudice$^{5)}$, A. Kaminsky$^{7)}$, P. Mammini$^{1)}$, F. Manolescu$^{3,b)}$, D. Pantano$^{6)}$, A. Profeti$^{1)}$, F. S. Raimondo$^{5)}$, M. A. Saizu$^{8,c)}$, E. Scarlini$^{9)}$, P. Tempesta$^{4)}$, M. Tessaro$^{7)}$

Abstract

Microbonding of the CMS Tracker Inner Barrel (TIB) and Tracker Inner Disks (TID) modules was shared among six different Italian Institutes. The organization devised and the infrastructure deployed to handle this task is illustrated. Microbonding specifications and procedures for the different types of TIB and TID modules are given. The tooling specially designed and developed for these types of modules is described. Experience of production is presented. Attained production rates are given. An analysis of the microbonding quality achieved is presented, based on bond strengths measured in sample bond pull tests as well as on rates of bonding failures. Italian Bonding Centers routinely performed well above minimum specifications and a very low global introduced failure rate, at the strip level, of only ∼0.015 % is observed.

---

1) INFN-Sezione di Pisa, Italy

2) INFN-Sezione di Torino, Italy

3) INFN-Sezione di Firenze, Italy

4) INFN-Sezione di Bari, Italy

5) Università di Catania and INFN-Sezione di Catania, Italy

6) Università di Padova and INFN-Sezione di Padova, Italy

7) INFN-Sezione di Padova, Italy

8) INFN-Sezione di Catania, Italy

9) Università di Firenze and INFN-Sezione di Firenze, Italy

a) Corresponding Author

b) On leave from ISS, Bucharest (Romania)

c) On leave from IFIN-HH, Bucharest (Romania)

1 Introduction

1.1 Tracker Inner Barrel and Inner Disk modules

The CMS [1] silicon strip Tracker [2] has a modular architecture. Its basic unit is the module. A schematic overall view of the Tracker layout is presented in Fig. 1. While size and shape of the Tracker modules are different in different Tracker regions, all modules share a common basic design: a sensitive element, constituted by one or two silicon strip sensors, and its front-end electronics are arranged next to each other in a planar tile.

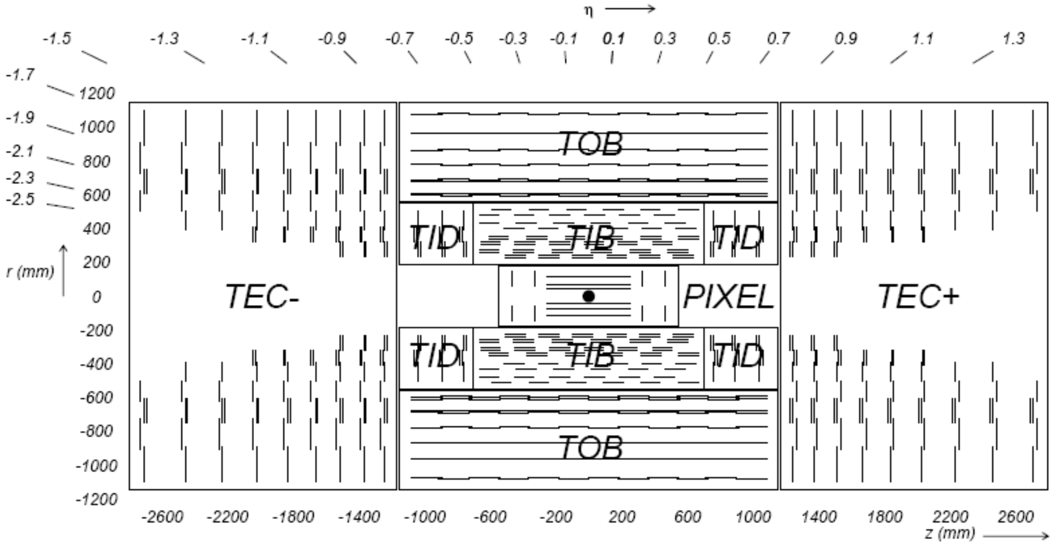


Figure 1: Schematic cross section through the CMS Tracker. Each line represents a detector module. Double lines indicate back-to-back modules which deliver stereo hits.

A detailed description of the Tracker layout can be found in [3]. The Tracker Inner Barrel (TIB) comprises the four inner layers of the barrel part of the Tracker. As the surface of a module is only partially covered by the sensitive silicon, while the rest is occupied by the electronics circuits, to achieve full particle coverage, modules are actually deployed onto both the internal and external sides of each layer's mechanical structure, with a staggered tile arrangement: the areas occupied by electronics on the internal side are covered by silicon on the external side, and *viceversa*. Furthermore, to provide a more precise location in space of the particle hits in the vicinity of the interaction point, the two innermost layers (Layer 1 and 2) are dressed on both their internal and external sides not with simple modules, but with sandwiches of double modules. A sandwich consists of two modules glued to each other back-to-back: one (called a "r-phi" module) whose silicon sensor has the strips aligned with the Z axis (coincident with the beam line) of the experiment, the other (called a "stereo" module) with sensor tilted 100 mrad in either direction ("stereo left" or "stereo right") from the Z axis, thus providing two-dimensional location of the hits on those layers. Layers 3 and 4 are equipped with modules of "r-phi" geometry only. The CMS Tracker Inner Disks (TID) are the innermost part of the Tracker end caps. There is a TID group at either end of the CMS Tracker, along the colliding beams trajectory. Each of the two groups comprises three "disks" placed one after the other at increasing |Z| coordinates. In each disk, modules are arranged into three concentric rings, with increasing radius. Similarly to the barrel layers, disks bear modules on both their front (facing the interaction region) and back sides, with staggered position of sensor and electronics, and the two smaller-radius rings of each TID disk are actually equipped with double-module sandwiches on both front and back sides.

Modules of the TIB [4] have a rectangular shape and mount a single, rectangular silicon sensor, and modules of the TID [4] are wedge-shaped and mount a single, wedge-shaped silicon sensor.

Each TIB or TID module [4] consists of: 1) a carbon frame; 2) one single silicon sensor [5], in turn subdivided into either 768 (for all TIB Layers 1 and 2, TID Ring 1 and TID Ring 2 module types) or 512 (for TIB Layers 3 and 4 and TID Ring 3 module types) $p+$ implant micro-strips on n-type silicon; 3) a hybrid electronics circuit including four or six readout APV25's [6] (each APV25 reads out 128 strips); 4) a pitch adapter between silicon sensor and APV25's; and 5) the HV bias circuit, located alongside the sensor on the carbon frame, isolated from it by a Kapton foil [4]. Each implanted strip of the silicon sensor is covered by an aluminum strip from which it is electrically insulated by means of a silicon oxide and nitride multilayer. This integrated capacitor allows for AC coupling of the signals from the strips to the read-out electronics, which is thus protected from the high leakage currents after irradiation. The side of the sensor on which the micro-strips are fabricated is called the "front' side of the sensor and defines the "front" side of the module. The opposite side, where a uniform $n+$ implantation covered by aluminum forms an ohmic contact which is connected to positive voltage, is called the "back" side.

As can be seen from [3], a total of about 3540 modules are needed to build the TIB/TID. In addition, the module production plan devised by the CMS Tracker Collaboration called for the construction of ~10% of spare modules. The grand total of modules constructed for the TIB/TID is therefore about 3900.

The first step in the construction of a module is the assembly from its component parts. The second step is the realization of electric connections ("bonding") between the silicon sensor and the front-end electronics. The third step is a set of electric tests aimed at verifying the functionality of the just made connections along with the working status of both sensor and electronics in simulated operational conditions. This note concerns the bonding of the modules of Inner Barrel and Inner Disks parts of the CMS silicon strip Tracker.

1.2 Module electric connections

To supply bias and ground reference voltage to the sensor, and to extract from it the output signals in response to particle passage, it is necessary to create electric connections between both: the bias sections of the hybrid circuit and the appropriate rings [5] of the sensor; and each channel of the APV25 readout chips and the corresponding individual strips of the sensor. All these connections are accomplished by welding short pieces of metal wire bridges between the parts to be connected.

Each metallized sensor strip ends with "bond pads" (two at each end) that are two-dimensional areas (rectangular or oval) with linear dimensions of the order of tens of micrometers, to which one end of a wire bridge is welded. Likewise, the APV25's have a rectangular bond pad at each channel input. A direct wire connection between silicon strips and APV25's, however, is not possible. In fact, due to different pitches of the APV25 channel input bond pads (44 μm), and the sensor microstrips (80 μm in 768-strip sensors, 120 μm in 512-strip sensors of the TIB, variable from 119 μm to 143 μm on the sensor edge adjacent to the APV25 chips for the different TID module types), this connection is actually made via a Pitch Adapter (PA) placed between sensor and hybrid circuit. The PA is an electrically passive element, but it is very much relevant to the microbonding operation, which is the subject of this note. It consists of a glass plate on which conductive metal tracks ending with bond pads at each end are deposited in a fan-like pattern, so that the PA track bonding pads on one side directly face the APV25 channel connection pad, whereas on the opposite side they directly face the sensor strip connection pads. Thus the silicon strip detector signals are routed to the readout electronics by placing one relatively short wire bond (typical length of the wire ~4 mm) at each end of each PA track. A direct connection is not possible, as it would imply impossibly long bond wires. Also the ground reference voltage is routed from the hybrid to the sensor bias ring via the PA. Further details about the TIB and TID module designs are available in [4].

The scope of this note includes the wire bonding of: a) the individual sensor micro-strips to their corresponding PA tracks (these bonds are referred to as the module "readout bonds"); b) the sensor bias ring to the ground line of the PA (which in turn is wire-bond-connected to the ground of the Hybrid); c) the sensor bias ring to a filter capacitor of the HV bias circuit; d) the "back" plane of the sensor to the HV line of the HV bias circuit, via a gold-plated pad routed from this circuit to the back of the frame. Among the different CMS Tracker module types, bonds c) are unique to TIB and TID modules only.

Bonding of the APV25 channels to the PA conductive tracks and of the APV25's to other hybrid circuit components is not the subject of this note. The former was performed at CERN prior to shipping both hybrid and PA, already assembled and bonded to each other, to the module assembly Centers. The latter was performed even earlier in the factories which produced the hybrid circuits.

Figure 2 shows a portion of a TIB module centered around the PA, where the regions concerned by the bonds from PA to APV25's and from PA to sensor are marked. The inset at top left shows a few wire bonds from PA to sensor. The inset at top right shows the wire bonds from the HV bias pad to the back plane of the sensor. (The inset at bottom right is referenced in the next paragraph.)

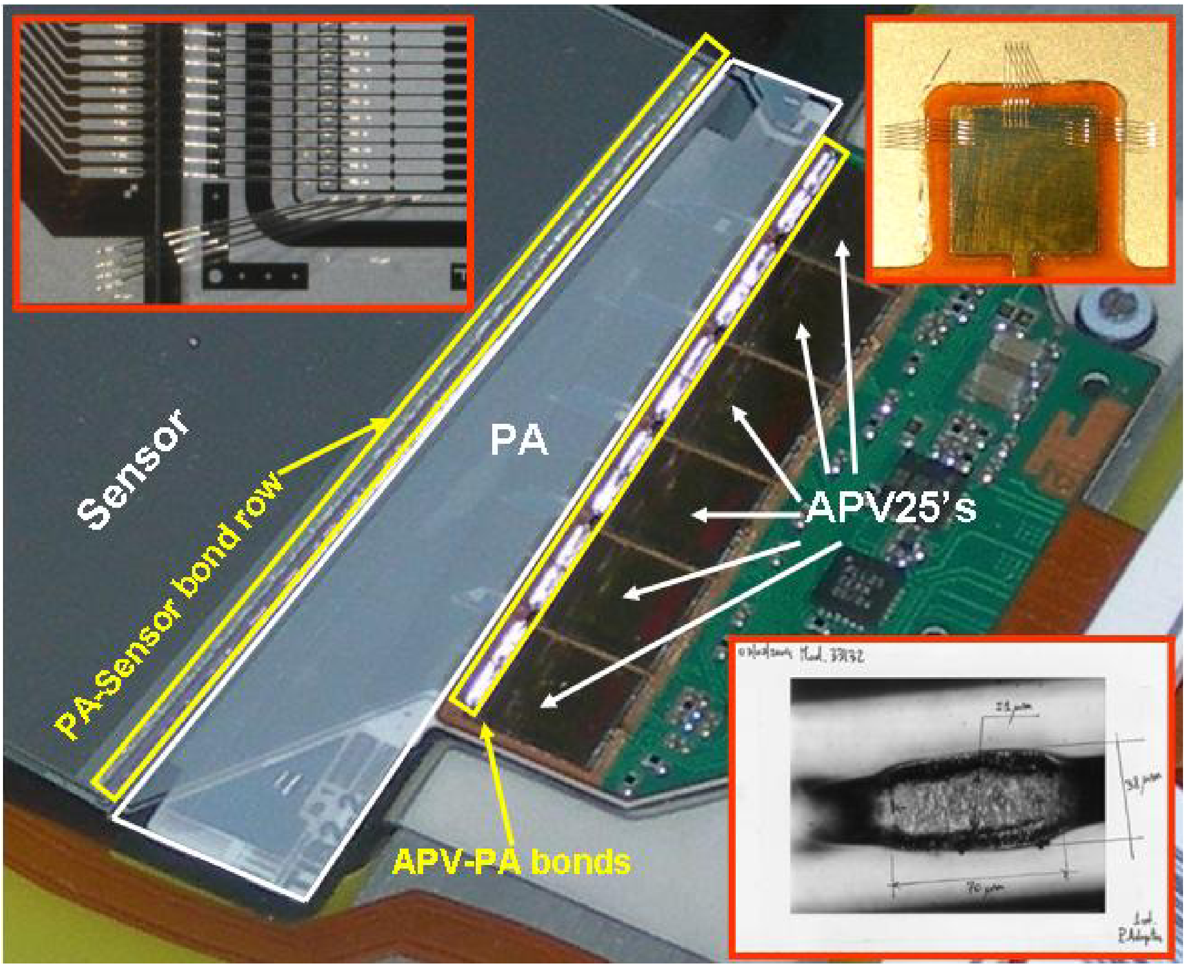


Figure 2: A portion of a TIB Layer 1 and 2 stereo module, centered around the Pitch Adapter (PA). The PA is marked by a boundary white line, the locations of the PA-sensor (the subject of this note) and APV25-PA (not the subject of this note) bonds are marked by boundary yellow lines. - *Top left inset*: zoomed image of a few PA-sensor readout bond wires (upper group) and of the PA-sensor bias bonds (lower group). -*Top right inset*: zoomed image of the HV connection bonds on the back of the sensor. - *Bottom right inset*: Magnified view (50x) of the first bond foot, in this case on the PA, of a PA-sensor readout bond wire.

1.3 Wire microbonding technology

Given the small size of the parts involved (bond pad size and inter-bond distances are all order of tens of micrometers) and of the wire employed (diameter 25 μm), the procedure of realizing these electric connections is called "microbonding". Microbonding is a sophisticated technology employing complex and costly machines, however it is not a novel technique especially developed for CMS, as it is instead widely used in microelectronics industry. A thorough review of state-of-the-art microbonding technique can be found in [7].

The basic principle of this technology is that the wire is welded to the metal substrate of a bond pad by means of ultrasonic vibration applied while the wire is pressed against the pad. In ultrasonic wire bonding machines, the wire, coming down from a spool, is fed under a tiny wire-grabbing-and-handling tool, passing through a hole in the tool. The tool has a wedge-shaped, grooved tip under which the end portion of the wire is held by a releasable clamp. As the clamp holds the wire firmly the wedge tool presses the wire against the pad with an adjustable force (order of tens of grams) for a quite short time (tens of milliseconds), while it vibrates with a frequency of 60 to 140 kHz, depending on bonding machine model. This ultrasonic vibration briefly heats up the contact area between wire and pad and also causes the atoms of both materials to intermingle into the other's space by dislocating them and forming new atomic bonds. For this reason the materials constituting the pad metallization and the wire must be chosen so as to be compatible and suitable for microbonding. After welding, the wire appears squeezed onto the pad forming a characteristic bond "foot" (shown in the bottom right inset of Fig. 2).

An electric connection is realized by pointing the tool initially above the first pad to be connected, lowering the tool and closing the wire hold clamp until the weld is done as described, then raising and moving the tool with a controlled movement with clamp released until it rests over the second pad to be connected, lowering it and making the second weld in the same way. During its travel between the two pads the tool guides the wire to form an arch (“loop”) of specified height and shape. Once the second bond is done and the clamp now holds under the wedge tool the wire immediately following the second foot, a brisk pull is applied to the tool so that the wire is torn away from the second foot and is ready for a new connection. The resulting bond is quite robust considering the tiny size of the wire: a typical force of the order of 10 grams is necessary to break a good-quality bond and moreover it is usually the wire that breaks at one of its two weakest points, the “heels” between foot and loop, not the foot that detaches (“lift-off”) from the pad. (Actually the occurrence of lift-offs is considered a problem needing correction before bonding can continue.)

Modern microbonding machines are programmable in at least four ways. First the positions in space of all pads to be connected in pairs, relative to *ad hoc* reference marks fabricated on the work piece, can be stored in memory during an initial survey of the work piece; second, the images of the reference marks themselves can also be stored; third the desired shape and dimensions of the loop can be specified and stored for each individual wirebond (these depend on distance between the two pads, possible height difference, need to avoid touching any parts, etc.); and, fourth, the bonding parameters (force with which the tool presses the wire, time during which the ultrasonic vibration is applied, amplitude of the vibration) can be specified for each individual *bond*, that is they can even be different for the two bonds of a wire connection (this is important as often these parameters have to be different for different substrate materials and different mechanical characteristics, such as rigidity, of the parts to be bonded). Thus after an initial survey of the work piece to locate the reference marks, to capture their images, and to locate all pad pairs, hundreds of bonds can be executed automatically in an unlimited number of work pieces of the same type by executing the same “bonding program”. Each time a new piece of the same type is placed on the machine work table (or “chuck”), the machine first locates the reference marks, then rescales all stored positions of the pad pairs to the current position of the reference marks, then makes all the bonds, each one with the specified loop. The bonding operation must be performed in a relatively clean environment, with stringent temperature and humidity limits, or the wire may have trouble sticking to the pads.

1.4 Inner Tracker module bonding

The TIB and TID detectors, as for all the CMS Tracker modules, were wire bonded using commercial ultrasonic wire microbonders of the same types that are currently used in the microelectronics industry. However, the detailed bonding procedure of the CMS Tracker silicon modules is rather different from standard microbonding of commercial integrated microelectronics circuits. There are indeed a few peculiarities: the very large dimensions of the object to be bonded (approximate area over which bonds are distributed in a TIB module is 70 cm^2); the fragility of the silicon sensor requires special work holders (called “jigs”); and microbonds are placed on both sides of the detector.

This note describes organization, infrastructure, specifications, tooling and procedures involved in the micro-bonding of the TIB and TID modules. The logistic organization and facility infrastructure set up to handle the task are described in Section 2. The bonding operation sequence is described in Section 3. A production report on the bonding, including attained production rates and quality assessment, are given in Section 4. Concluding remarks are given in Section 5.

2 Organization and Infrastructure

The construction of almost 4,000 modules and, specific to the subject of this note, the execution of some 3,000,000 microbonds in a time frame of one to two years is a formidable task for the particle physics research community. This task requires a complex organization and a sharing of the work load amongst several Institutes. It cannot be outsourced to commercial companies because of the aforementioned difficulties, concerning the complexity and fragility of the work piece and the high degree of precision required.

The construction of the TIB and TID has been the sole responsibility of the Italian *Istituto Nazionale di Fisica Nucleare* (INFN). Six INFN Sections were involved in module bonding: Bari, Catania, Firenze, Padova, Pisa and Torino. Such a relatively large number of Centers working in parallel was necessary due to both the workload associated to the bonding process itself and the ensuing cycle of electrical tests (comprising bonding repairs and re-testing of problematic modules).

The assembly of the TIB and TID modules was performed in two INFN Sections (Bari and Perugia), and is described in a dedicated note [8]. With minor exceptions, the Perugia assembly Center supplied modules to the

Padova and Pisa bonding Centers, while the Bari assembly Center supplied its modules to Catania, Firenze and Torino, and kept a fraction in Bari, for bonding and testing. At the end of production, the number of modules bonded at each INFN Section is the following: Pisa: 1064 modules bonded, Padova: 1061, Torino: 521, Firenze: 437, Bari: 414, Catania: 411, for a total of 3907 modules.

Modules arrived from the assembly Centers mounted on NEMA [9] Grade-10 fiberglass carriers for ease and safety of handling. Each module was secured onto the carrier by holding bars and screws and the carrier was sandwiched between an aluminum cradle on the bottom and a Plexiglas lid on the top, for transport and storing (Fig. 3). Sufficient free space between both the aluminum cradle or Plexiglas cover lid and the module carrier, and upward-folded sides of the aluminum cradle, ensured that no part of the module could be damaged during transport and handling. Shipment of the modules from the assembly to the bonding Centers was done using a commercial courier, using sturdy plastic boxes with internal Styrofoam cushioning on all sides (Fig. 4). Each box can hold up to nine modules. These, sitting on their aluminum cradles with cover lid on, were kept from moving during transport by snugly inserting the cradle ends into slots carved in the Styrofoam cushioning of the box interior. For added safety during transport, the plastic box was sealed in a polyethylene bag to keep moisture out and this was in turn enclosed in a much larger cardboard box, with further soft padding on all sides.

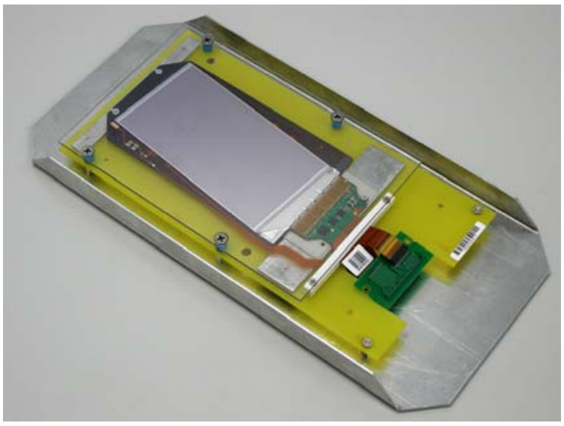


Figure 3: A TIB module mounted on its module carrier (yellow plate), and sandwiched between an aluminum cradle (at bottom, with folded-up sides) and a Plexiglas cover lid. Spacers (blue sheaths of screws) ensure proper clearance between the lid and any module parts. Equally safe clearance is insured by pillars between carrier and aluminum cradle.

Figure 4: Transport box, fitted with only five modules. Full capacity is nine modules. The aluminum cradles of the modules snugly fit into narrow slots cut in the pink Styrofoam padding. In this picture, these slots are more clearly visible in the right-side pink foam pad.

At all involved INFN bonding Centers, bonding of the TIB/TID modules took place in a clean room with controlled temperature and humidity. The facilities deployed in clean rooms for CMS TIB/TID module bonding typically include the following: 1) an area with one or more stereo microscopes for visual inspection of the modules (visual inspection is performed at least twice: upon reception of the modules from the assembly Center and after completion of the bonds; 2) a test station for electric test [10] of the hybrid circuit before module bonding; 3) one or more microbonder machines; 4) one or more precision measuring machines (sensitivity 5 µm or better) to measure geometric characteristics of the bond (e.g. loop height); 5) a pull tester; 6) storage space for the modules; 7) one or more computer workstations for database entries.

A full electric test of the module followed bonding. In some Centers this test occurred in the clean room, while at other Centers the module was forwarded to an adjacent dedicated laboratory. Details about electric tests of the TIB/TID modules can be found in [10].

The relevant facilities deployed at each INFN bonding Center for TIB/TID module bonding are listed in Table 1.

The most important piece of equipment involved in module bonding is the microbonder machine. As reported in Table 1, four of the six TIB/TID bonding Centers (Bari, Catania, Firenze and Torino) are equipped with a F&K Delvotec mod. 6400 microbonder [11] (shown in Fig. 5), whereas two Centers (Padova and Pisa) have a Kulicke & Soffa mod. 8090 microbonder [12] (shown in Fig. 6). The Catania Center used an older Hughes mod. 2470-II microbonder [13] until December 2004, when a F&K Delvotec 6400 was procured.

Table 1: Bonding Center facilities

	Bari	**Catania**	**Firenze**	**Padova**	**Pisa**	**Torino**
Clean Room area (m^2)	70	45	250 (30 dedicated to bonding)	48	300	40
Clean Room class	1000 (20 m^2) 100000(50m^2)	1000	10000	1000	10000-100000	10000-100000
Typical environmental temperature (C)	22	21	21	21-22	21	22
Typical environmental relative humidity (%)	40 - 60	30 - 50	40 - 60	50-60	40-60	45
Microbonder machine(s)	Delvotec 6400	Delvotec 6400 (Hughes 2470-II)	Delvotec 6400	K&S 8090	K&S 8090	Delvotec 6400
Pull tester(s)	manual	manual	automatic	semiautomatic	automatic	manual
Inspection microscope(s)	1) Leica “Wild M3Z“ 2) Leica “MZ12“	1) Olympus “SZ-STB1” 2) Optech “Flexible”	Leica “MZ6”	Vertical tilted	1) Olympus 2) Leika 3) Baush&Lomb 4) Nikon 5) Mitutoyo	Olympus SZ-X12 (qty: 2)
Measuring machine(s)	Mitutoyo “BHN506”	Mitutoyo “Quick Scope”	Dea	Mitutoyo	1) Mitutoyo “BHN506” 2) Mitutoyo “F604” 3) DEA	Delvotec 6400

Figure 5: The F&K Delvotec mod. 6400 micro-bonding machine

Figure 6: The Kulicke&Soffa mod. 8090 micro-bonding machine

Figure 7: The Dage 3000 automatic pull tester

Figure 8: The Dage 4000 automatic pull tester

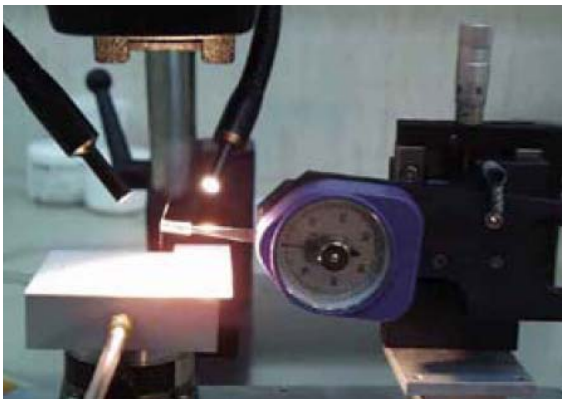


Figure 9: A Correx manual pull tester

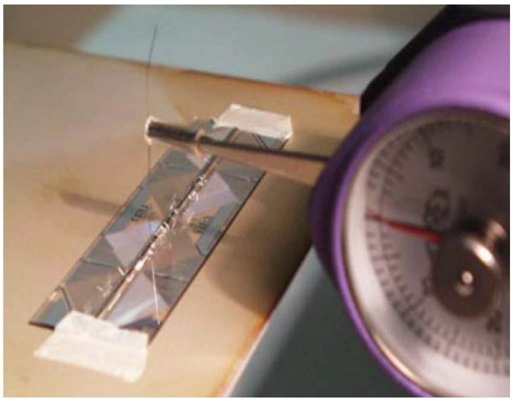


Figure 10: Detailed view of the Correx hook

The other device specifically relevant to bonding is the pull tester. Extra bonds provided specifically for test purposes and a sample of the real bonds (which are redone afterwards) were pull-tested and the force necessary to break the wire bond measured. The value of this force and the way the bond breaks are used to assess the quality and infer the reliability of the bonds made. The six Centers involved with TIB/TID module bonding have different types of pull testers at their disposal. Some of these are automatic, such as the Dage 3000 (shown in Fig. 7) or the Dage 4000 (shown in Fig. 8), some are manual, such as the Correx dynamometer (shown in Fig. 9, with detail of the hook that grabs the bond wire in Fig. 10).

3 The bonding operation

In this section we describe in detail specifications, parameters, tooling and procedures adopted for bonding the TIB/TID modules.

3.1 Parameters

A variety of specifications, design criteria and parameters apply to module bonding. These include: a) specifications about the bonds themselves, such as geometric shape and mechanical sturdiness; b) design criteria and parameters adopted for module construction and handling which are relevant to quality, reproducibility and efficiency of the bonding operation; c) criteria designed to grade the modules based on the bonding quality actually achieved.

3.1.1 Specifications on module construction parameters related to bonding

Parameters for the module construction (components and assembly) were specified early in the Tracker project. Among those which apply to TIB and TID modules, in Table 2 we list a few which have a direct impact on safe and efficient microbonding.

Table 2: Specifications on Module Components and Assembly relating to Bonding

	Parameter	**Value**	**Reason**
1	height differential between sensor and PA surfaces	< 1mm	to avoid difficult wire shapes and dangerous bonding machine manoeuvres
2	parallelism of PA, sensor and frame surface planes	< 5mrad	to assure uniformity of the height differential across the entire PA-sensor bond row, otherwise it may have to vary wire loop dimensions as bonding proceeds across the bond row
3	quality of PA gluing	no vertical motion of PA during bonding	essential for good adhesion of wire to PA bond pads
4	size of bond pads	> 50μm width and > 200μm length	allows easy placement of bond foot fully on pad for a 25μm diameter wire and leaves room for a second foot in case of bond failure
5	reference marks	circles of diameter > 300μm or equivalent-minimum-surface areas	to allow the bonding machine's pattern recognition systems to unambiguously find the reference mark images

3.1.2 Module carrier design

Module carriers are meant to safely hold the modules for transport and handling. For TIB and TID however, given the relatively smaller dimensions of one-sensor modules, it was possible to devise small enough carriers that are sufficiently rigid and yet light enough to be safely left “hanging from the sensor” during bonding. Thus the module carriers of TIB and TID were specifically engineered taking into account their presence during bonding: carriers allow complete access to the underside of the module for support of the sensor by the bonding jig and their overall size does not exceed the active area of all employed bonding machines.

3.1.3 Bond specifications

The CMS Tracker Bonding Working Group set up a long list of specification parameters concerning the bonds themselves for the Centers to follow, with the aim of assuring state-of-the art bond quality and uniformity of the quality across the entire module production. The full set of specifications can be found in [14]. In Table 3 we have collected the most relevant parameters that apply to TIB and TID modules.

3.1.4 Criteria for final module bonding quality and acceptance

For module grading from the bonding step of the production, two independent criteria groups were employed. Independent here means that a module is Grade A only if both criteria groups designate it as Grade A, but becomes Grade B if at least one of the two criteria groups designates it as Grade B and likewise it becomes Grade C (faulty) if at least one criteria group designates it as Grade C.

1) Electrical quality - The first criteria group is based on the number of electrically bad channels and follows the criteria established by the CMS Tracker Module Test Working Group. Indeed, each channel which exhibits an electrical fault because of a bonding failure (an unbonded strip, a short between adjacent bond wires or between bonding pads caused by bonding errors, a pinhole caused by excessive bond force, etc.) ultimately would reveal itself in the Test screening. Therefore the thresholds for designating a module as Grade A, B, or C fully agrees with those adopted in the Module Test procedures: module is Grade A if it has less than 1% bad channels, or Grade B if it has between 1% and 2% bad channels, or Grade C (*faulty*) if it has more than 2% bad channels.

Table 3: Bonding Specifications that apply to TIB and TID modules

Wire bonds		
1	wire type	Al with 1% Si, 25μm diameter, medium hardness
2	number of bias bonds	In each location, try to place 5 bonds, but place at least 3. For the module back, where space is available, it is suggested to make 15. Specifically: • HV gold-plated pad to back of sensor (on module backplane): 15 bonds • sensor's bias ring to filter capacitor gold pad: 5 bonds • PA bias line to sensor bias ring: 5 bonds
3	loop height and form	• HV gold-plated copper pad to back of sensor (on module backplane): 300μm • sensor's bias ring to filter capacitor gold pad: ≤600μm above sensor in TIB L1 and L2 modules, but must clear sensor edge by at least 300μm • sensor's bias ring to filter capacitor gold pad: ≤800μm above sensor in TIB L3 L4 and TID modules, but must clear sensor edge by at least 300μm • PA bias line to sensor bias ring: 300-350μm above PA • PA-sensor readout bonds: 250-350μm above PA in TIB L1 and L2 modules (e.g. 250-300μm for the inner pad row (even strip numbers) and 350μm for the outer pad row (odd strip numbers)) • PA-sensor readout bonds: 300-350μm above PA in TIB L3 and L4 and TID modules
Pull tests		
4	force needed to break bonds	• mean >5g • standard deviation < 20% of mean
5	wire break modes	In general, wire should break leaving bond foot behind (heel break or mid-span break). However a certain fraction of other break modes (bond foot lift-off, cratering) is commonly considered acceptable in the microbonding process. For CMS Tracker modules, Centers must aim at obtaining • > 80% heel (or mid-span) breaks if mean = 5-9 g • > 50% heel (or mid-span) breaks if mean > 9 g
Bonding failures (*)		
6	failure rate	• sum of all failures should be less than 0.5%

(*) Possible failures are: wire fails strength test, missing wire, broken wire, failed weld, bond pad failure (tear off), uncut wire, damage to substrate, loss of adherence of the metal layers, bad shape of loop, shorted channels due to bonding error.

2) Mechanical quality - The second criteria group considers the mechanical quality of the bonds. In fact, even if in electric tests performed shortly after bonding a channel appears to work perfectly, there might be circumstances which can cast doubts on the long-term reliability of the electrical connection provided by a microbond. The mechanical-quality grading of a module's bonding in turn consists of a group of related criteria logically OR'ed together.

1. Number of bonds in *each* of the three groups of Bias bonds: module is Grade A if group actually includes more than two bonds, or Grade B if group actually includes two bonds, or Grade C if group actually includes fewer than two bonds.
2. Number of "critical" readout bonds: module is Grade A if it has up to 2% critical readout bonds, or Grade B if it has up to between 2% and 20% critical readout bonds, or Grade C if it has more than 20% critical readout bonds. There thresholds where set by the Bonding Working Group based on expert's advice. We define a wire bond as "critical" if its properties fail the specifications defined in Table 3 or its long-term reliability is questionable but cannot be improved for lack of free pad space or because of locally poor metallization quality; the only alternative would be its removal.
3. Operator judgment on all *other* bonds with diagnosis: A, B, C.

The technical implementation of the module grading is via the writing of suitable flags into the Tracker construction Database (*“TrackerDB”*) [15]. This will be described in Section 3.4.11.

3.2 Center Qualification

In an early phase of module production, all Centers were required to undertake a qualification test. Sensor test structures [16] were distributed to the Centers by CERN, with a few standardized bonds already made. Each Center bonded the test structures trying to mimic as close as they could the shape and dimensions of the CERN-made sample bonds, then pull-tested half of the bonds made by the Center. The structures were then shipped to CERN for inspection and testing. Feedback was given to the Centers on the bond quality based on the visual inspection of the bonds, on the pull force values and the statistical consistency of pull force values between tests executed at the Centers and at CERN.

All six Italian Centers were immediately considered qualified for CMS Tracker module bonding.

3.3 Tooling

The tooling needed for the CMS microbonding activity includes the bonding wire, the bond wedge tool and the bonding jigs.

3.3.1 Bonding wire

The bonding wire used by all INFN Centers is a 25μm diameter Aluminum wire with 1% of Silicon, of medium hardness (breaking loads 13 - 17grams, elongation 1 - 4%), made by the Müller-Feindraht Company [17].

3.3.2 Bond wedge tool

Unlike the bond wire, the bond wedge tools used at the different INFN Centers varied both with bonding machine model and personal experience and/or preference of the operators. The wedge tools used are listed in Table 4.

Table 4: Wedge tools used by the INFN bonding Centers

Center	Manufactures	Model
Bari	STP Roth	UT45A-W-2020-1”-CM
Catania (Delvotec 6400)	STP Roth	UT45A-W-2020-1”-CM
Catania (Hughes 2470-II)	Microminiature	4284-1625-W35-AL1ML
Firenze	Microswiss	4WFV4-2020-W7F-M00
Padova	Microswiss	4WFM1-2025-WCS-M00
Pisa	Microswiss	4WFM1-2025-WC6-M00
Torino	SPT Roth	FP45A-W-1520-1”-FM

3.3.3 Bonding jigs

Six different types of special bonding jigs were designed and built by the INFN Centers to hold the modules firmly under the bonding machine bond head and to provide solid support to the regions where bonds were to be placed.

The jigs were designed to be screwed securely onto the chuck or other fixture of the bonding machine, and to hold in turn the module to be bonded firmly by vacuum suction. They consist of an aluminum plate, on which various through holes are drilled to firmly screw them onto the different bonding machine chucks. All jigs also have a raised section in their central area, coated with a Teflon layer. The module is placed on the jig in such a way that the silicon sensor rests on this area. Thus the Teflon areas are shaped differently for the different sensor geometries of different module types (TIB, TID Ring 1, TID Ring 2, TID Ring 3). The entire module is held steady by vacuum suction exerted on the silicon sensor only. To achieve this, vacuum ducts are created in the jig plate leading to a series of small holes punctuating a winding trough milled in the top surface of the Teflon plates in the Teflon raised area. The vacuum ducts originate from an inlet valve connected through a plastic hose to the vacuum system of the bonding machine. Notches and shallows are carved at appropriate spots on the raised Teflon area so as to allow room for protruding fixtures and components of the module.

Figure 11: Bonding jigs for TIB modules with “r-phi” geometry (left: for back repair; right: for regular operation). Overall size of each jig is approximately 25 x 10 cm excluding the handle. White arrows indicate positioning pins, inserted in appropriate holes of the jig, used to lay the modules on the jig in a quick and repeatable way.

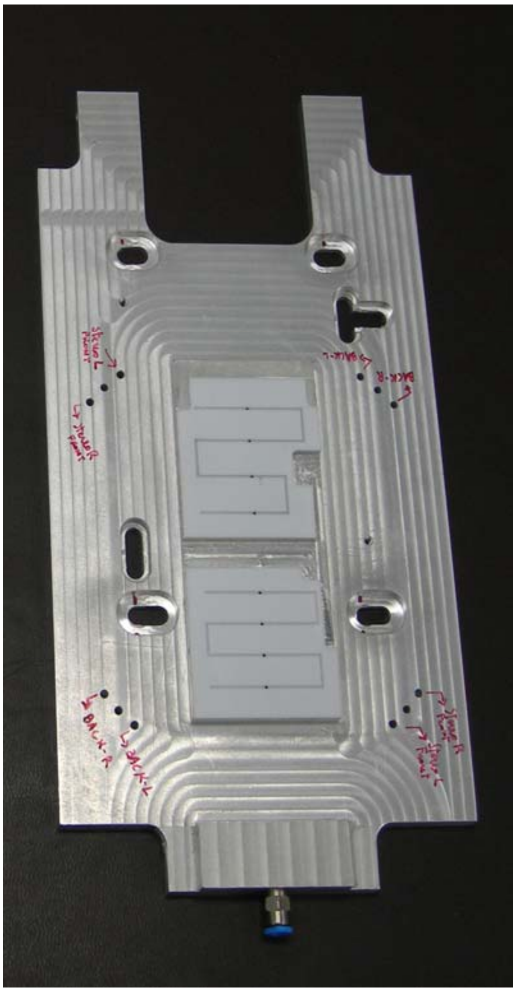


Figure 12: Bonding jig for TIB modules with “stereo” geometry (one single type for both regular operation and back repair - main text, par 3.3.3). Overall size is approximately 25 x 15 cm.

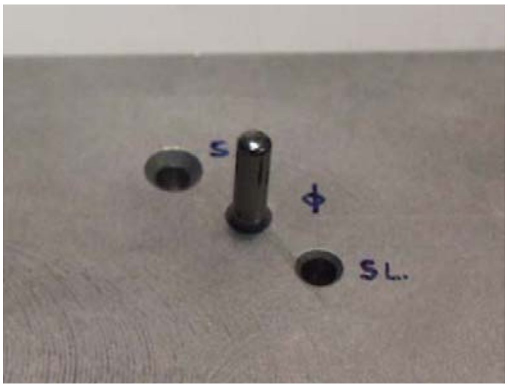


Figure 13: Detail of re-positionable pin and its target holes.

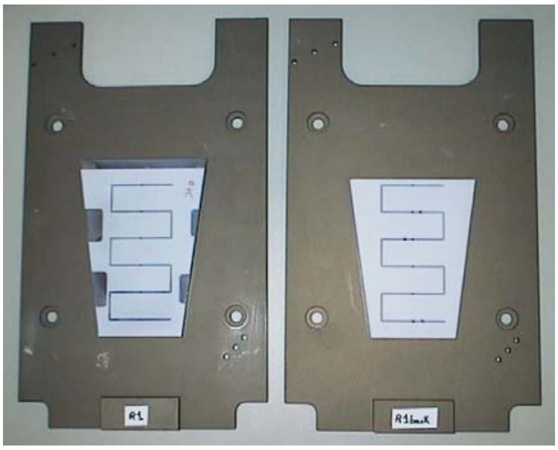


Figure 14: Bonding jigs for TID R1 modules (left: for regular operation; right: for back repair). Size of each jig is approximately 30 x 15 cm. The jigs for TID R2 and R3 modules are very similar to these ones, with just a different size.

A total of 36 jigs were built and distributed among the bonding Centers. Photographs of some of the bonding jigs produced are shown in Fig. 11 to 14. In all pictures the big holes, some of them elongated, are those provided to screw the jigs onto the different machine chucks. The short pipes with blue sheaths, where visible, are the inlet valves for the vacuum where the vacuum system (either the bonding machine vacuum or an independent plant) hose is to be connected.

Except for the TIB stereo modules, jigs for each relevant module geometry were provided in pairs. Of each pair, one jig only was used for the entire "regular" bonding operation; the other one was used only for possible repairs to the bonds on the back once the front was already bonded. All TIB/TID modules are bonded while mounted on the module carrier. Two positioning pins inserted in appropriate holes of the metal plate part of the jig allow to lay the module on the jig in a quick and repeatable way. These pins are easily visible in Fig. 11 indicated by white arrows. For this purpose, the module carrier has corresponding holes, through which the pins must be fitted. After bonding of the HV connection on the back, the module is turned over and placed on the jig with the back of silicon sensor now sitting on the Teflon vacuum-suction part of the jig. A notch carved along an edge of the Teflon plateau of all jigs for "regular" bonding (visible in the right side of the Teflon area of all jigs for "regular" bonding in Fig. 11, 12, 14) now allows the just-made HV bonds to hang in air freely. A second notch near the first one provides room for a protruding part of the Kapton bias circuit.

Note a horizontal, darker, stripe covering the far side of the Teflon area in the jigs for "regular bonding" (If viewing this document in color, this stripe is orange in Fig. 11 and deep blue in Fig. 14). That region of the raised Teflon sensor support is missing in the jigs for "back repair". In jigs for regular bonding that is the region of the raised area supporting the PA-sensor border area where the readout bonds are to be made. If one has to do bonding repair work on a module's back after the readout bonds on the front are already made, or if for some reason one has to bond the HV connection in the back after bonding the front, that PA-sensor border region must have a clear area underneath in order to accommodate the existing bonds. For this reason that portion of the raised Teflon area is removed in all "back repair" type jigs, which are not suitable for "regular" bonding because they would be unable to provide the most-needed support precisely under the PA-sensor border area.

In the case of TIB stereo modules it was considered sufficient to have one single jig for both "regular" and "back repair" bonding, which necessarily has the raised region area under the PA-sensor border region removed, otherwise back repair would be impossible. Thus the PA-sensor border region is not directly supported by the Teflon plateau during regular bonding of the PA-sensor readout bonds, but for the stereo TIB modules this was considered acceptable because an additional layer of ceramic is placed under that region [4], which makes that area of the module rigid enough to allow trouble-free bonding even with no support immediately underneath.

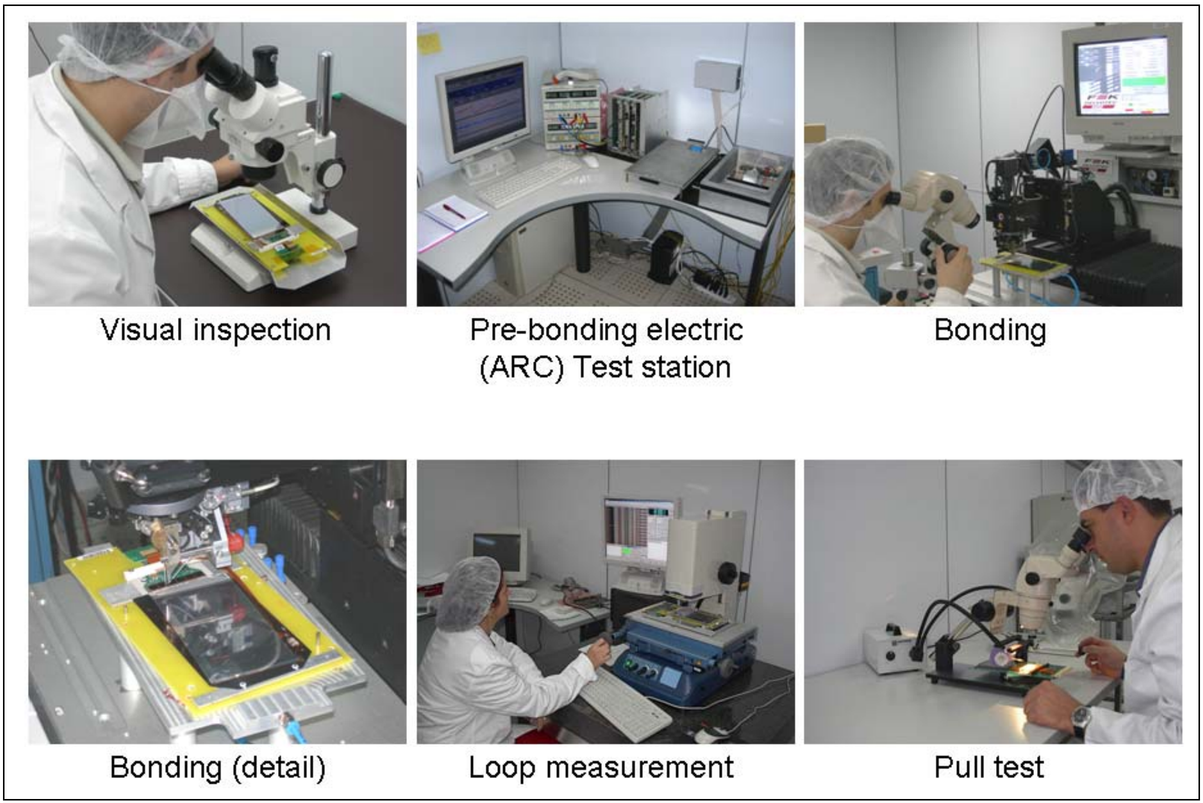
TIB Layer 1 and 2 stereo modules furthermore come in two varieties, "stereo right" and "stereo left", with the sensor tilted 5.73 degrees in either direction. A single jig allows bonding of both. To this purpose the operator just has to move the positioning pin among a set of holes present at all corners of the jig. A detailed view of one such set of three holes, marked "SL" for stereo left, "Φ" and "SR" (the R hidden behind the pin) for stereo right, is afforded by Fig. 13. Such sets of three holes exist on each of the four corners of the jig (areas with pencil scribbles in Fig. 12) and allow to set on the same jig both "stereo right" and "stereo left" modules (or even the "r-phi" ones if so desired) by repositioning the pin on the jig and then inserting the corresponding holes of the yellow carrier over the pin. These corresponding holes are made on the different carriers in positions such that the silicon strips are always parallel to the X (left-right) axis of the bonding machine. Bonds aligned along one of the axes of the machine have in general better accuracy than transversal ones. Once the pins are inserted in the appropriate holes for the variety of stereo module to be bonded, then it is sufficient to place the module on the jig still mounted on its carrier as usual, making sure that the holes existing in the module carrier let the pins through. In fact, the holes in the module carrier for the different varieties of modules are located in positions such that with this technique the long sides of the silicon sensor is aligned with the jig and thus with the bonding machine X axis, no matter what its tilting with respect to the module frame is.

For TID modules, each pair of jigs, concerned with either Ring 1 or Ring 2, allows to bond all geometries ("stereo left", "r-phi" "stereo right"), by repositioning a pin among three possible positions similarly to TIB stereo modules. The corresponding groups of three holes can be seen at opposite jig corners in both jigs in Fig. 14. TID R3 modules come only with "r-phi" geometry.

A significant engineering effort went into careful design of the position of each precision fixture, such as fixing and positioning holes and of the network of ducts that distribute the vacuum suction, and in a suitable choice of the materials employed.

3.4 Bonding Procedure

In this section we describe in detail the step-by-step procedures adopted to bond the TIB/TID modules [18]. A photographic overview of some of the steps, taking place at one INFN Center (Catania), is presented in Fig. 15.



Visual inspection

Pre-bonding electric (ARC) Test station

Bonding

Bonding (detail)

Loop measurement

Pull test

Figure 15: Snapshots of the module bonding process steps as they take place in the Catania clean room

3.4.1 Reception

Boxes of modules were received from the assembly Center and unpacked. Receiving of the package was entered into *TrackerDB*.

3.4.2 Pre-bonding Inspection

Each module was carefully inspected on a stereo microscope with coaxial lighting. For TIB and TID modules, given the compact size of both the modules and the designed carrier and transport cradle this was usually done with module (mounted on its carrier) still on transport cradle. The plexiglas cover was usually left on, unless it hampered clear vision because of dirt, imprints, cracks, etc.

Surfaces to be bonded were checked for foreign substances and cleaned by blowing clean dry air if necessary. Modules were checked for damage (to hybrid bonds, silicon edges and surface, cables…) and for non-standard features (glue failure or improper curing, improper component heights or placement, integrity of the Kapton bias circuit).

The outcome of the visual inspection was entered in *TrackerDB* using a specially designed web-based Bonding-to-*TrackerDB* User Interface [19]. At this time, the Database web Interface automatically queried *TrackerDB* to check if the module assembly personnel, during the module assembly *TrackerDB* logging, had entered a warning (details in [19]) about possible mutual misalignments of PA and sensor such as longer or variable distance between pads to be bonded or variable height difference between PA and sensor that could require special precautions in bonding (such as temporary or local adjustments of loop parameters).

3.4.3 Pre-bonding electric test of the Hybrid

The module was dismounted from its transport cradle, mounted on a test support plate following a procedure documented in [20] and taken to the electric test setup, where a pre-bonding quick readout test of the Hybrid front-end electronics with the ARC [21] System was performed. The electric test procedure will be described in a separate note [10] and can also be found in [22].

3.4.4 Preliminary Bonding operations

At the beginning of each working day the operator performed the following checks in order to ensure that the bonding machine would be correctly set up: amount of wire on spool; tool alignment; good working status of air pressure and vacuum systems; correct wire threading; installation (ensuring proper clearance), inspection and, if necessary, cleaning of the bonding jig. Then the machine was initialized and the program appropriate for the type of module to be bonded and the set of bonds to be made was loaded. Information on bonding machine configuration, program, and wire was recorded in the *TrackerDB*.

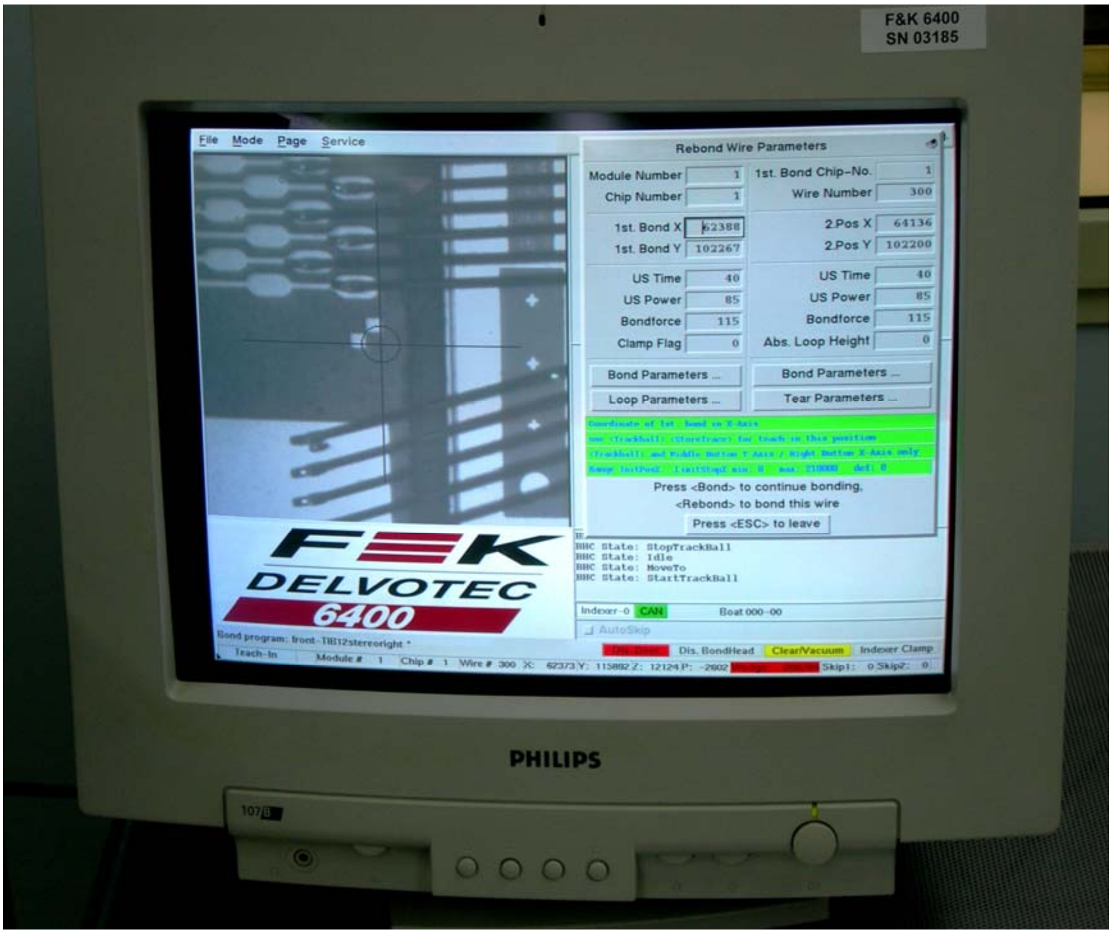
3.4.5 Bonding programs

The bonding programs were created independently in each Center and individually for each type of module.

A bonding program stores four types of information: a) digitized images of reference marks present on the module components to be bonded; b) geometrical location of the bonds (i.e. position of source and destination pad of each wire bond); c) loop parameters (shape and dimensions) of each wire bond; d) bond parameters (*force*, with which the tool presses the wire on the pad; *time*, during which the tool holds the wire pressed against the pad; *amplitude* of the ultrasonic vibration that welds the wire to the substrate of the pad). Thus, individual programs are needed for each module type because elements a), b) and c) depend on the module geometry.

Different programs are necessary, even for the same module geometry, on different bonding machines. So, albeit conforming to a general common layout, each Center had to develop its own unique set of bond programs needed to bond all types of modules.

Fig. 16 shows a few realized bonds, along with one of the panels which control the bonding parameters during development of a bonding program, as they appear on a bonding machine monitor.



Module Number 1
Chip Number 1
1st. Bond Chip-No. 1
Wire Number 300
1st. Bond X 62388
1st. Bond Y 102267
2.Pos X 64136
2.Pos Y 102200
US Time 40
US Power 85
Bondforce 115
Clamp Flag 0
US Time 40
US Power 85
Bondforce 115
Abs. Loop Height 0

Press <Bond> to continue bonding.
<Rebond> to bond this wire
Press <ESC> to leave

```
BHC State: StopTrackBall
BHC State: Idle
BHC State: MoveTo
BHC State: StartTrackBall
```

Bond program: front-TIB12stereoright *

Teach-In Module # 1 Chip # 1 Wire # 300 X: 62373 Y: 113882 Z: 12124 P: -2602 Skip1: 0 Skip2: 0

Figure 16: Bond loops, and bonding parameter control panels, on a bonding machine monitor

3.4.6 Bonding

After dismounting from the test plate, the module (on the carrier) was placed by hand on the bonding jig, face down, to bond-connect the HV on the back of the sensor. The positioning pins inserted on the jigs, which match the position of corresponding holes drilled on the module carriers, aid in this operation. Care was taken that Hybrid cable connectors and interface card (Fig. 17) would float free from the jig in order to achieve accurate positioning of the sensor on it and avoid any damage to the cables. At this point, vacuum was supplied to the jig and it was checked that all parts to be bonded were held securely.

Then the program to make the bonds between bias pad and the back of the sensor was run. Fig. 18 shows a typical example of these bonds.

The module was then turned over and placed on the jig face up. After re-applying vacuum and checking that all parts to be bonded were again held securely, the program to make the bonds on the module front side was run.

Using this program, first a few bonds were made on PA test areas (Fig. 19). This was meant to check the machine, as well as the bondability of the PA. If bonding problems occurred during this test bonding, pull test would be done immediately, as well as a check of the machine for problems. Regular bonding did not resume until a set of these test bonds could be made without problems.

Figure 17: Interface card of hybrid connector

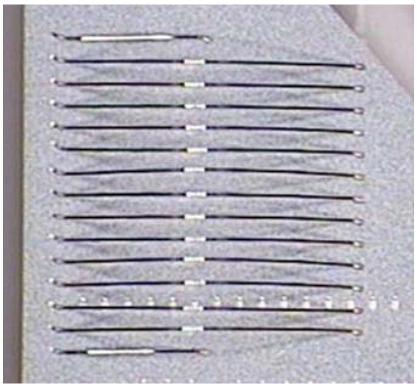


Figure 19: Test bonds on PA test area

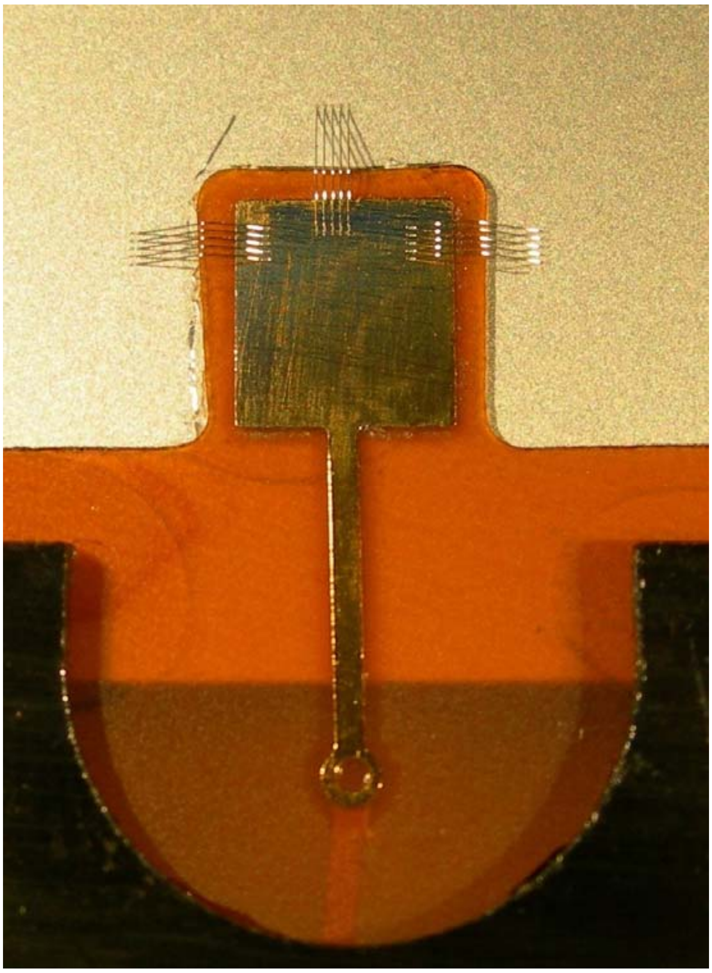


Figure 18: HV bonds on back of sensor

Next, PA to sensor bias bonds were made (three to five bonds). Fig. 20a (lowermost group of wires) and 19b show the typical geometry of these bonds. Fig. 20c affords a clear side view of their loop shapes.

Next, the bonds (again three to five) between the bias ring of the detector and the filter capacitor gold pad on the Kapton were made. Fig. 21a and 21b show the typical geometry of these bonds. Fig. 21c affords a clear side view of their loop shapes. Loop height had to be more than 300 μm above the cutting edge of the sensor to avoid the risk that the wire touch the cutting edge, however the overall loop height was required to be ≤ 800 μm above sensor in TIB, Layer 3 and 4, and TID modules, and ≤ 600 μm above sensor in TIB, Layer 1 and 2, modules.

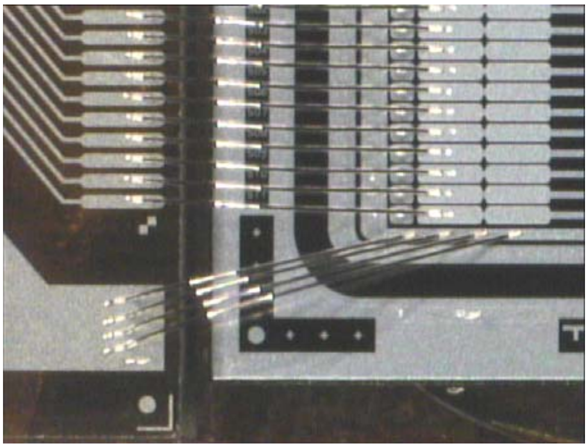


Figure 20a (TIB Layer 3 and 4 module)

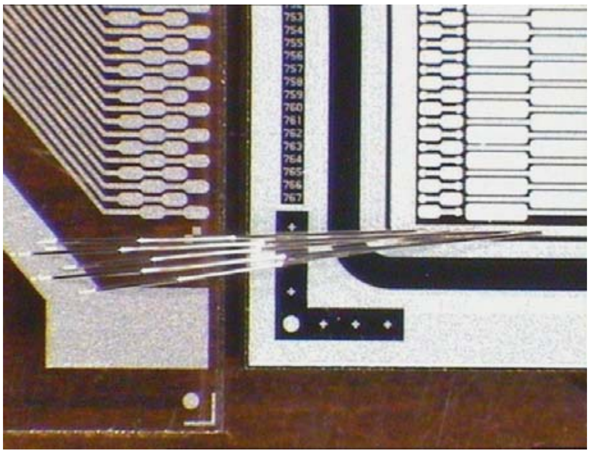


Figure 20b (TIB Layer 1 and 2 module)

Figure 20c (View from the side)

Figure 20: Bias bonds between Pitch Adapter (on the left in all three pictures) and sensor bias ring

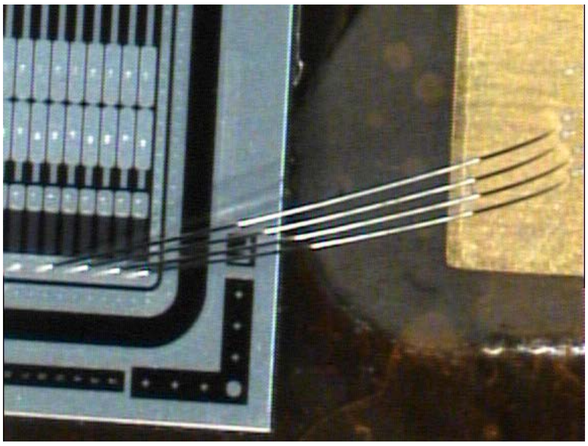


Figure 21a (TIB Layer 3 and 4 module)

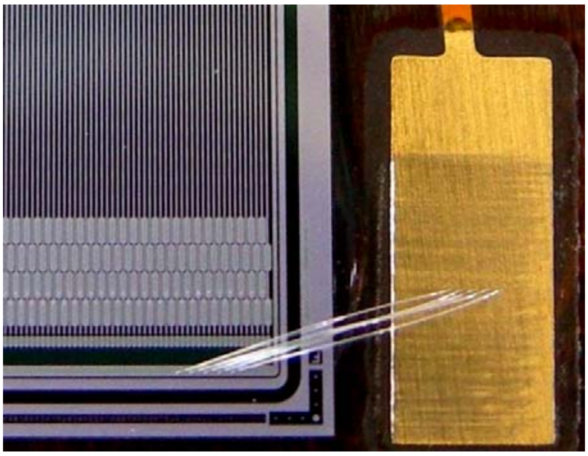


Figure 21b (TIB Layer 1 and 2 module)

Figure 21c (View from the side)

Figure 21: Bias bonds between sensor bias ring (on the left in all three pictures) and filter capacitor pad

Last, the PA to sensor read-out bonds were made. For TIB, Layer 3 and 4, and TID modules, with a pad spacing of at least 119 μm, a single row of parallel bonds was made with a loop height of 300-350 μm above the PA surface. Fig. 22a shows a typical geometry of these bonds, in this case for a TIB, Layer 3 and 4, module. Fig. 22b affords a clear side view of their loop shapes.

For TIB modules, Layer 1 and 2, which have 768-strips and a pad pitch of only 80 μm, the readout bonds were made in two phases: first the even strip-number pads only were bonded, making an inner row of bonds spaced by 160 μm, with typical loop height of 250-300 μm; any repairs on these bonds were made if needed. Then the odd strip-number pads were bonded, making an outer row of bonds, also spaced by 160 μm, with a higher loop (~350 μm). Fig. 23a shows the typical geometry of these bonds. Fig. 23b affords a clear side view of their loop shapes.

For clarity, this picture was taken after only one single bond of each array had been made. Also the read-out bonds had to clear the PA edge by at least 100 μm.

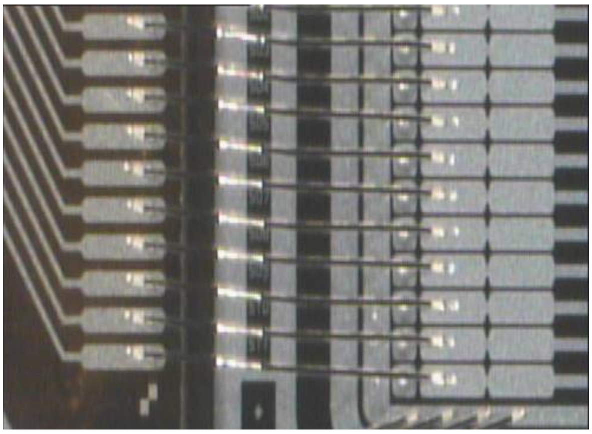


Figure 22a (View from top)

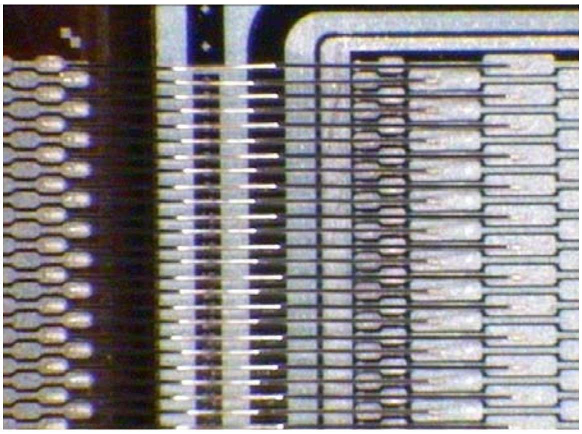


Figure 23a (View from top)

Figure 22b (View from the side, entire row)

Figure 23b (View from the side, only two wires)

Figure 22: PA (left) - sensor readout bonds in a TIB Layer 3 and 4 module

Figure 23: PA (left) - sensor readout bonds in a TIB Layer 1 and 2 module

The typical distance between PA and sensor bonding pads is about 2 mm; the resulting length of the wires, given their arching shape, is approximately 4 mm for all PA-sensor bonds. The wire bonds from the sensor bias ring to the filter capacitor pad are longer, approximately 8 mm.

Bonds to be skipped due to known broken capacitors ("pinholes") or shorts on the sensor were suggested by the Database web Interface, where a prescription about strips to leave unbonded based on sensor defects found in *TrackerDB* was implemented. This prescription, in brief, is: leave unbonded all pinholes and, in a group of adjacent shorted strips, all but one. These strip numbers were noted prior to bonding, then, depending on operator preferences, either the machine was instructed to skip those bonds, or they were removed afterwards

3.4.7 Pull tests

The quality and the reliability of a wire bond is quantified by a pull test, which consists of pulling upward on the wire, measuring the force necessary for the wire to break or the bond weld to fail and observing the break or failure mode. The wire may break in its theoretically weakest point (*heel break*) or somewhere in the middle leaving wire legs at both feet (*mid-span break*). Sometimes the bond foot lifts off from the bond pad leaving only a faint mark (*lift-off*). Other wire break modes involve damage to the bond pad, the most common being *cratering*, in which part of the bond pad metal layer remains attached to the bond foot and lifts off with it, leaving a shallow hole (a "crater") in the bond pad. A detailed description of the pull test practice and the treatment of the pull test data can be found in [23].

Pull tests were performed systematically on the first 20 modules bonded at each INFN site, thus serving as an additional step of qualification. Thereafter they were performed on a sampling basis (1 module/week), in order to monitor continuously the bonding quality. Pull tests were also done if a suspicion arose about the quality of the bonds, e.g., in the post-bonding inspection (described later), or if bond problems or failures were encountered.

The scheduled pull tests were executed according to a specific protocol, devised so as to have minimal impact on the regular bonds and yet allow to measure the strength of the regular bonds and not just that of test bonds made on different areas of the module. This protocol called for pull testing every 50th wire of the readout bond wire array, but it was implemented differently for the TIB Layer 1 and 2 modules as opposite to all remaining TIB and TID module types.

For all module types except TIB Layer 1 and 2, a special program led the machine to skip the bonds immediately before and after those to be pulled, making all the remaining bonds. The module was taken off the bonding machine and the designated wires were pulled. Afterwards, another special program led the machine to make now all the missing bonds (the ones initially skipped plus the one pulled), redoing the bond on the second sensor pad for the pulled wires. This procedure samples the bond pads along the entire area of the sensor and PA, and it is close enough to normal, as far as the machine head travel steps are concerned. An acceptable alternative to the procedure outlined above, sometimes used in some Centers, was to program the machine to make an additional bond every 50th wire, using the extra space available on the PA pad and the 2nd available Sensor pad, and use these bonds for the pull test. These bonds would typically have to have a (slightly) higher loop than the standard ones, but after the test, there would be no need to return the module to the bonding machine.

For TIB Layer 1 and 2 modules, the even-numbered pads were bonded first, following the solid lines as shown in Fig. 24. Any necessary repairs on these bonds were made, but taking the module off the machine only if the nature of the repair required it. Then the odd-numbered pads were bonded following the dashed lines. An additional bond was then made every 50th wire, following the dotted lines, using the outer pads of each PA-track/Sensor-strip , with a loop higher than both the "solid" and "dashed" ones. Finally the pull test was performed on the "dotted" bonds.

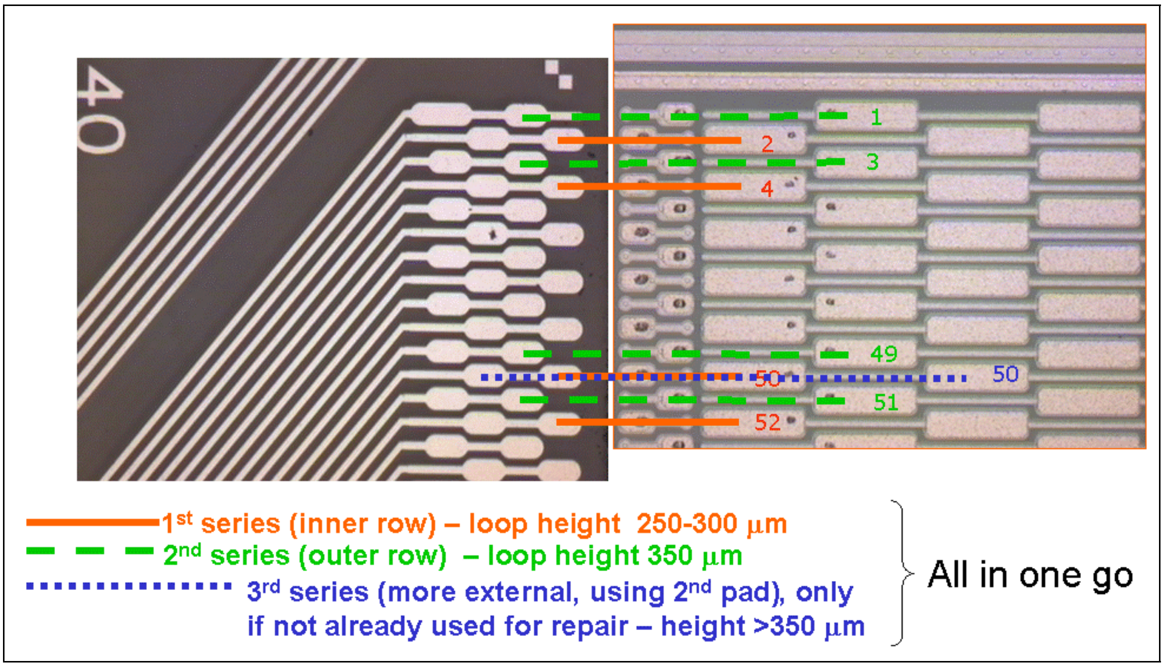


Figure 24: Wire paths for regular and to-be-pull-tested bonds in TIB Layer 1 and 2 modules

Bonds should have had at least 5 grams *mean* pull strength and should break at the heel. Failure of this test required that the machine stop module bonding until the problem was corrected or at least understood.

The pull test data were also entered in the *TrackerDB*, using a dedicated function of the Database web Interface. In this function, for each module being pull-tested, the operator manually entered the observed break force for each pulled wire bond. Separate fields were provided for the test bonds placed in the PA test area and for the readout bond sample. The operator also was required to enter the number of bonds breaking in each of the possible modes listed above, again separately for test bonds on PA test areas and for sample of readout bonds. Then for each of the two groups of bonds separately, the software determined the lowest and highest value, computed the mean and the standard deviation and wrote these four values to the *TrackerDB*.

3.4.8 Post-bonding inspection

After the completion of the standard bonding cycle, the completed bonds were first inspected with the bond machine microscope. Any missed bonds were added if possible. Any bad or incomplete bond wires were removed and replaced if it was possible to do that safely *in situ*. Then the module was removed from the bonding machine and brought to the inspection area. All bonds were visually inspected under a stereo microscope looking for broken, damaged or missing bonds. Bond placement accuracy and correct loop height and shape was also checked, as well as checking that bonds did not short to each other or to the edge of the sensors.

Any problematic bonds were repaired, or, if repair was not possible, simply removed, leaving an open channel in the detector.

3.4.9 Final operations

Bonding log data and post-bonding inspection information were entered in *TrackerDB*.

The module was then passed on to the Module Test crew for electric qualification tests [10, 22]. A repair cycle would start at this point if faults were found by the electric test. Problematic channels would be first cross-checked with known sensor defects and already known (and unrepairable) bonding faults. New faults would be individually investigated and treated as appropriate. In case of new bonding repairs, the module would be electrically tested again, in an iterative way, until further repairs would no longer be possible.

3.4.10 Bonding failures and repairs

A number of different failures might occur during routine bonding. The action taken depended on the observed type of failure.

Bonding failures (no-stick, lift-off, bad loop shape, foot misplacement) might be due to machine failures or to operator mistakes. In many cases the failure would affect only one of the two bonds of a wire bond. In case of no-stick or lift-off, rebonding was attempted after cleaning the pads and/or changing parameters. Bad loop shape, resulting in a risk of short to adjacent bonds, would be corrected by slightly moving the bond if possible, otherwise by removing the wire and attempting to rebond it. When a misplaced bond foot caused a short, the short was cleared by scraping off the unwanted metal with a sharp tip if this could be done safely (feasible on the PA but dangerous on the sensor.) The involved bonds were removed and redone. If the short could not be cleared and it was located on the sensor, all involved bonds except *one* were removed. If the short could not be cleared and it was located on the PA, following that prescription would not have been sufficient, as the hybrid channels would still be shorted together on the PA. So, the corresponding APV25-PA bond(s) were removed instead. In all the cases above, when a channel was rebonded, rebonding occurred in an unused part of the pads as far as possible; it was done on top of an existing tool mark or on top of an existing foot only when there was no other available space.

During the bonding operation itself or later on, damage to bonds by mishandling might occur. Often, a bond was deformed so that it was shorting or extremely close (<10 μm) to another bond, or it was touching the edge of PA or other conductive structure at a different potential, or it would be out of the defined safe "envelope" for the module, i.e. might touch some other module or structure of the Tracker. In these cases, if it was technically possible and practical, the affected bond was touched to move it just enough to avoid the shorting or to get it back into the "envelope", not necessarily back to its normal position. If damage was more serious, the wire was removed and re-bonding attempted.

Sometimes electrical defects were detected at the module electric test after bonding [10]. Note that this might actually be due to a bonding failure, or to a pre-existing sensor defect which had not been recorded in *TrackerDB*, or to a defect developed in the module with time. In case of pinhole or dead channel, the bond was removed. In case of a short the repair action was dependent on the nature of the short. In case of a misplaced bond foot shorting two or more sensor strips or PA pads, the action was the same as for a bonding failure. If some readout bonds were touching each other, the appropriate bonds were moved apart if possible, just enough to avoid shorting, otherwise the ones that could not be so corrected were removed and rebond attempted. If the short was found on the sensor itself, such as a scratch that had dragged metal across strips or bonding pads of the sensor, all involved readout bonds were removed except one, if possible the lowest-number one. In case of a noisy strip, depending on the severity of the problem as evaluated during the module test, the strip would be unbonded or left bonded.

3.4.11 Bonding final quality grading and acceptance

Assessment of the module for electrical and mechanical quality of its bonding was performed in each Center, grading the module with the criteria described in Section 3.1.4. To that end, the final list of unbonded strips, the number of bias bonds in each group, the number of poor-bond-quality channels and special comments if appropriate, were fed to a function of the web Interface. The technical implementation of this grading is via coded numerical flags, which the function computed and wrote into *TrackerDB*.

The success or failure of a construction operation is recorded in *TrackerDB* in the form of "quality flags" for the table(s) holding data from that operation. In the case of the bonding operation, the relevant quality flags were computed automatically by the Database web Interface [19]. All computed quality flags comply with a standard convention in *TrackerDB*: each table has a variable named "<tablename>_val", which is an array of one or more "flags", e.g. integer numbers separated by semicolons. There is one single flag if only one condition determines the success or failure of the operation with which the table deals; there are multiple flags if multiple independent conditions may contribute. Each flag has the following conventional meaning:

- a flag "0" means all variables of the concerned table were within "optimal" limits with regard to that condition, so that we can say the whole operation went "well";
- a positive flag means some variables were outside "optimal" limits but still within "acceptable" limits; it is a sort of warning that something did not go perfectly but as far as that operation is concerned the module can still be used;
- a negative flag means some variables were outside even acceptable limits. As far as that operation is concerned the module is *faulty* and should not be used.

Based on the information that the bonding operators entered during the bonding operations as described in the appropriate subsections of Section 3.4 and on the input data supplied for the final module grading, the web Interface [19] computed and wrote to *TrackerDB* the flags collected in Table 5.

Table 5: *TrackerDB* flags for module grading based on bonding quality

Table name	**Flag name**	**Flag values and their meaning**
PREBOND	PREBOND_val	0 : Module can be bonded -1 : Module is damaged, cannot be used 1 : Sensor is mounted with wrong orientation
BONDSTATUS	BONDSTATUS_val	2-component flag array :U:M: (U for unbonded strips, M for Mechanical Grading) • U = 0 : < 1% unbonded strips • U = 1 : 1-2 % unbonded strips • U = -1 : > 2% unbonded strips • M = 0 : < 2% critical readout bonds AND at least 2 bias bonds everywhere AND no special reason to consider module not trustworthy for mechanical soundness of bonds • M = 2 : None of the conditions for M=-2 below and at least 1 of these 3 conditions: 2-20 % critical readout bonds; only 2 bias bonds in (at least) 1 place and nowhere less than 2; a special reason to consider module not perfect for mechanical soundness of bonds, but still usable • M = -2 : at least 1 of these 3 conditions: > 20 % critical readout bonds; < 2 bias bonds in (at least) 1 place; a special reason (described in a text comment) to consider module not trustworthy for mechanical soundness of bonds to the point that it should not be used
POSTBOND	POSTBOND_val	0 : Module can be tested 1 : Module needs some repair -1 : Module is damaged, cannot be used

4 Bonding production report

We now evaluate bonding production rates, present a thorough review of the most important bond quality control tool, i.e. the pull tests, show an analysis of module grading from the bonding operation, and assess the rate of channel defects introduced in modules by the bonding operation. It will be shown that the number of new channel defects caused by bonding is extremely low.

4.1 Bonding Times

Based on the actual experience accumulated bonding ~3900 modules. a mean total bonding time of about 55 - 70 minutes for a single module was evaluated. Routine maintenance typically required a maximum time of one hour (e.g. in case of tool replacement) whereas common failures such as wire loss needed a typical time of 15 minutes to solve the problem.
As in the different Centers, and also at different times, the number of people working in parallel on the different tasks involved in bonding varied, it is not possible to give a single solid figure as the average time for bonding of one module. Nevertheless, the times mentioned above are a good starting point to infer reasonable production rates that could be expected at the Centers.

4.2 Production rates

The raw average bonding rate of the INFN Consortium, computed as the total number of modules bonded divided by the number of weeks spanning the production period, is 34 modules/week. However this number is in no way representative of the Consortium bonding capacity, nor of that of any individual bonding Center, because the incoming flow of modules to be bonded, due to major problems in the production of module parts, was discontinuous, completely halted for several months when those technical problems occurred, and in the end it spanned a much longer time period than originally planned.

A figure more representative of the real bonding rate achieved by the INFN Consortium can be obtained by dividing the number of modules bonded by the number of days in which there was any bonding activity at all. This evaluation is based on the bonding date of each module recorded in *TrackerDB*. This daily average production rate was ~10 modules/day. A normalization to a week of five working days brings up the average weekly production rate, limited to the periods of availability of modules, to ~50 modules bonded/week.

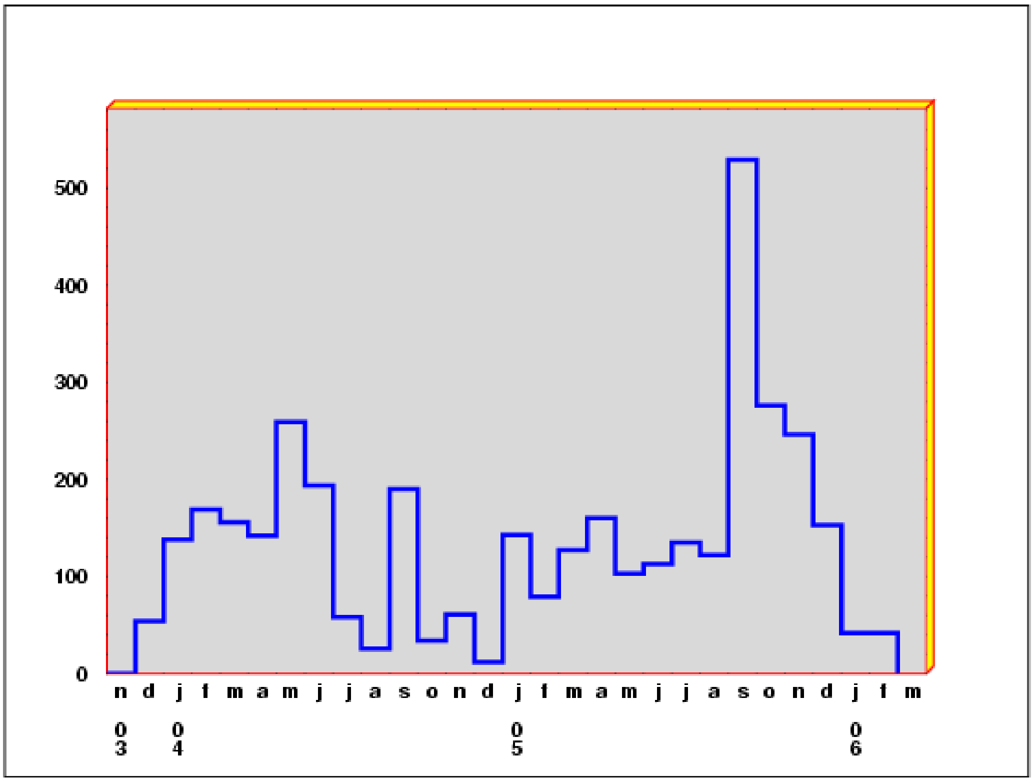


Figure 25: Number of TIB/TID modules bonded vs. calendar month

The actual timeline of the production, limited as mentioned above by slow and discontinuous incoming module flow rather than by reached capacity limits, is documented in Fig. 25, where we show the number of TIB and TID modules bonded by the six INFN Centers globally, versus calendar month. Two dips in throughput, in July-August 2004 and October-December 2004 are clearly visible as the Centers gradually ran out of modules to bond when production of sensors or hybrids was halted to solve technical problems. When production of parts became more steady in year 2005 and the stock of modules to be bonded built up, it can be seen in the same figure that at one point there was no difficulty bonding more than 500 modules in a single month.

The daily production rates are documented in the histogram of Fig. 26 where we show the number of working days in which a given total number of modules was bonded.

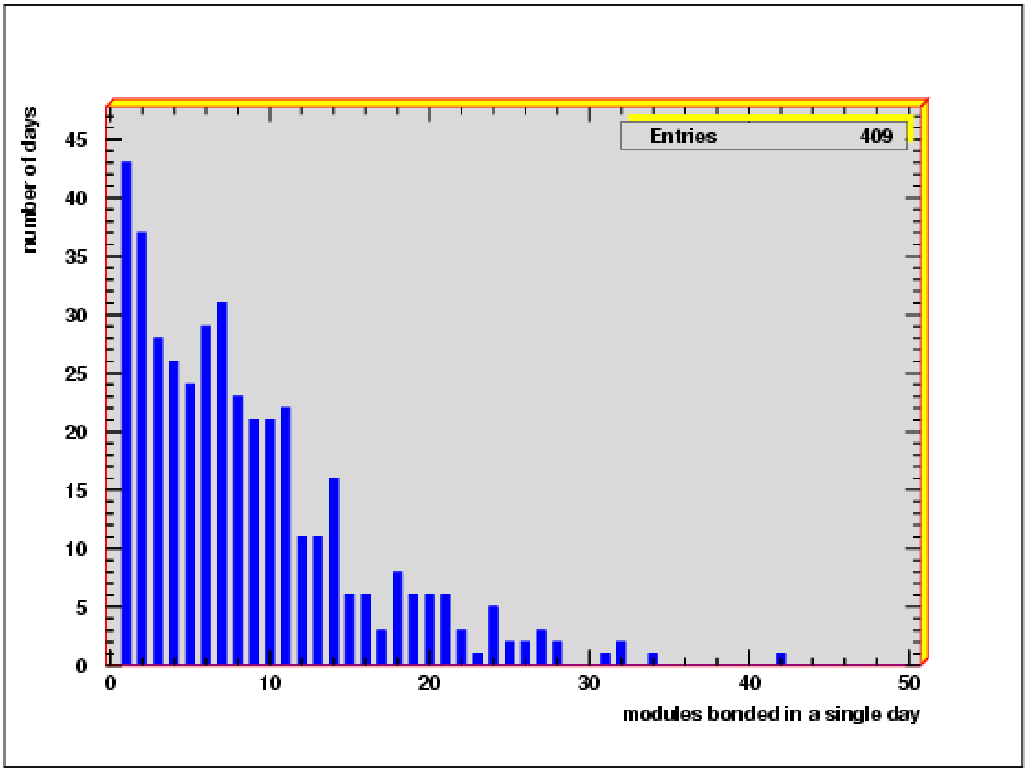


Figure 26: Daily bonding rates

4.3 Pull strengths

To monitor and assess the sturdiness and reliability of the bonds, the bonding protocol required a pull test of a sample of the real PA-sensor readout bonds. Furthermore most Centers also regularly pull tested the test bonds made in specific PA test areas, although this was required only when bonding problems were suspected. In addition, the bias bonds were also pull-tested from time to time: should they be of doubtful quality, the operator had the possibility to insert a special text comment in *TrackerDB* which would be used by the Database web Interface to assign the negative flag "-2" when evaluating the module grading.

Pull tests results on the sample of PA-sensor readout bonds are reported in *TrackerDB* for 17.4% of the bonded modules, while pull test results on PA test area bonds are reported for 23.5% of the modules. We now show the results of these pull tests, separately for the sample of PA-sensor readout bonds and for the PA test area bonds.

Fig. 27 shows a box scatter plot of the mean pull forces vs. Center. The spec limit of 5 grams minimum *mean strength* is marked by the black line. The same data are shown as a histogram of the mean pull forces, for all six Centers together, in Fig. 29. Here the spec limit is marked by a black arrow. In both Fig. 27 and 29 it can be immediately seen that all Centers performed always above the required limit.

It can also be noted that the forces observed at Catania in a few cases attain quite high values, between ~14 grams and ~16.5 grams. These were obtained with the older Hughes 2470-II bonding machine. This performance is attributed to the 60 kHz frequency of that machine, while at least 100 kHz is now the standard in the Delvotec 6400, K&S 8090, and others. However, the Catania group changed to a Delvotec 6400 because the older Hughes was unstable. Indeed also the lowest values of Catania, between the 5 grams limit and ~6,5 grams, were obtained with the Hughes in times of less-than-perfect performance.

As can be observed in Fig. 27, the typical ranges of the mean pull forces, although always above the required limit, varied significantly among Centers. A variety of factors contribute to the forces to be different among Centers and to vary from one module to another: general conditions of the bonding machine, such as age and tune-up status, conditions of the wire, wear of the bond wedge tool, metallization quality and cleanliness of the surfaces to be bonded, and even pull tester model and pull test practice. Notwithstanding these unavoidable variations, all tests satisfied the specs and the bulk of them were between 8 and 12 grams approximately, which in the CMS Tracker community is considered an excellent result.

It was also aimed at a certain uniformity of the pull force values among the pulled wirebonds of each given module. The specs asked for the standard deviation (computed using the *n* pull force values resulting from pulling *n* bondwires in the *same* module) to be < 20% of the mean.

Indeed, the Centers equipped with automatic pull testers (Firenze and Pisa) always had more uniform values across each module, resulting into a smaller standard deviation. The technical difference between automatic and manual pull testers is that an automatic one always grabs the wire in a reproducible position and with a reproducible angle, while by placing the hook by hand under the wire some variations in position and angle are possible even with the greatest care. These result into larger variations among force values.

Fig. 28 shows a box scatter plot of the standard-deviation-to-mean ratios of the pull forces obtained in each module, vs. Center. The target limit of 0.2 is marked by the black line. The same data are shown as a histogram of the ratios, for all six Centers together, in Fig. 30. Here the target limit is marked by a black arrow. In both Fig. 28 and 30 it can be immediately seen that all Centers performed better than the target limit in the great majority of the cases, although all except Pisa occasionally exceeded that target limit.

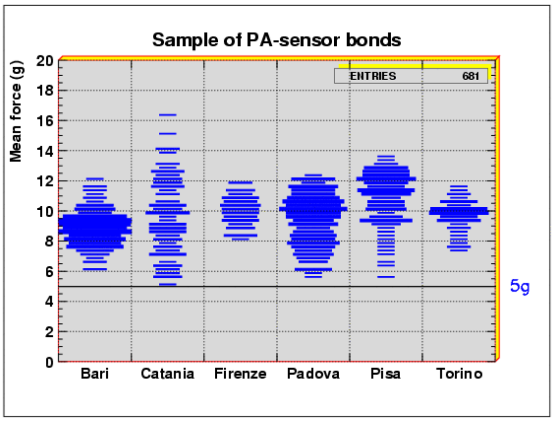


Figure 27: Scatter plot of mean pull forces vs. bonding Center

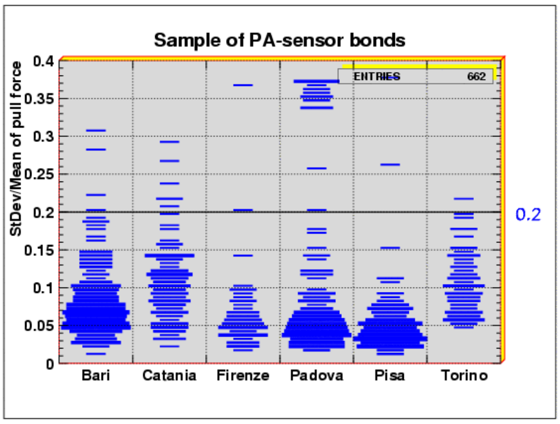


Figure 28: Scatter plot of the ratio standard-deviation-to-mean of pull forces vs. bonding Center

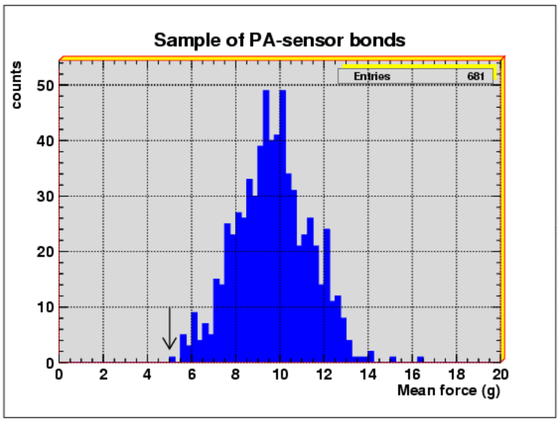


Figure 29: Histogram of all mean pull forces

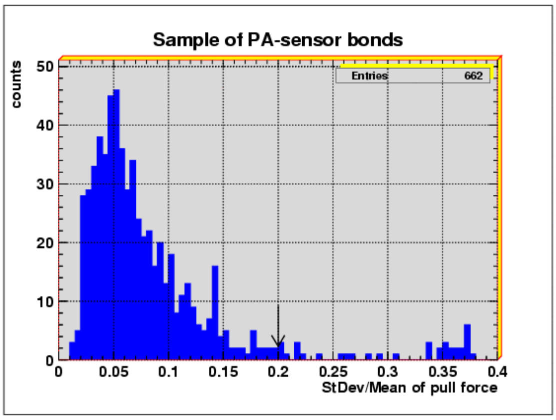


Figure 30: Histogram of all standard-deviation-to-mean ratios of pull forces

The same analysis just reported for the sample of PA-sensor readout bonds is then repeated for the test bonds placed in the PA test area, Fig. 31 to 34. The same comments as above apply, with an additional, quite important, one. As it can be seen in Fig. 31 and 33, the mean pull force here occasionally falls under the limit of 5 grams. This happens in Catania and these cases correspond indeed to situations in which the older Hughes bonding machine performance was degrading to the point that required major maintenance, which happened a few times and ultimately led to the decision to replace that machine.

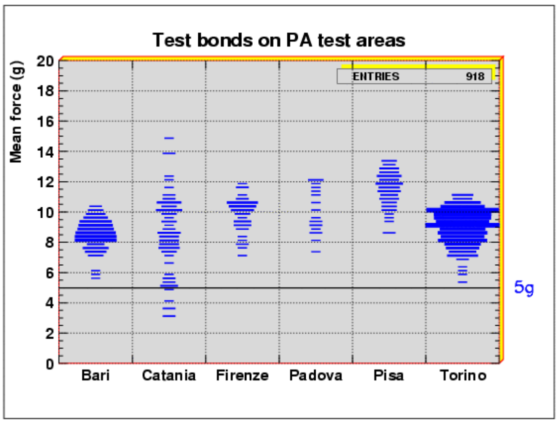


Figure 31: Scatter plot of mean pull forces vs. bonding Center

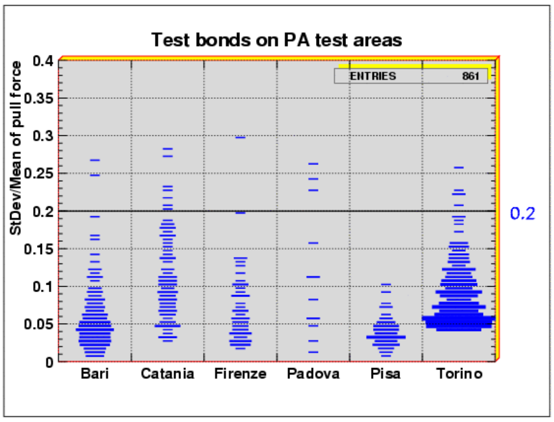


Figure 32: Scatter plot of the ratio standard-deviation-to-mean of pull forces vs. bonding Center

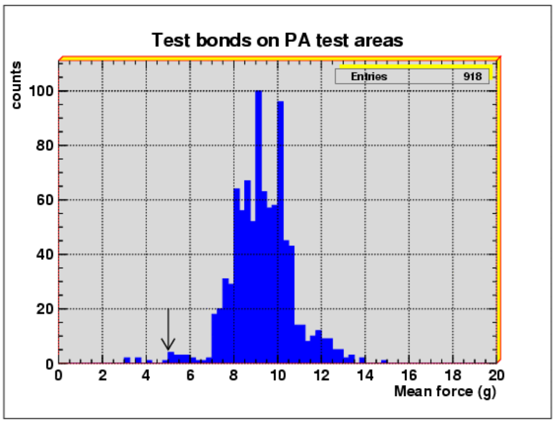


Figure 33: Histogram of all mean pull force

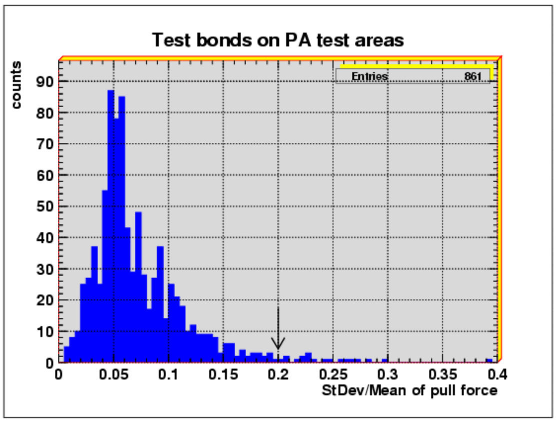


Figure 34: Histogram of all standard-deviation-to-mean ratios of pull force

4.4 Module grading from bonding

Grading of all TIB and TID produced modules after the bonding operation, according to the two independent criteria illustrated in Section 3.1.4, is performed using the *TrackerDB* flag BONDSTATUS_val described in Table 5. Grading based on the final number of unbonded channels results in a 99.82 % of Grade-A modules, 0.15 % of Grade-B modules and 0.03 % Faulty modules. Grading based on the mechanical quality of the bonds results in a 99.08 % of Grade A-modules, 0.84 % of Grade-B modules and 0.08 % Faulty modules.

4.5 Bonding failure analysis

In addition to module grading, we now quantify the rate of occurrence of bonding failures at the single wirebond level, that is a the strip level, not the module level.

For each bonded module, we look into *TrackerDB* for the list of unbonded strips. In this phase we do not care what the final grade assigned to the module was (whether A, or B, or C), but we simply see how many strips remained unbonded at the end of the bonding operation and which ones they are individually.

We then check *TrackerDB* to see if the sensor mounted into that module was tested.

If the sensor was not tested, this module is removed from the analysis as it is impossible to determine in an automated way if, for example, an electric defect such as a pinhole found at post-bonding electric tests, which led to the decision of removing a bond, pre-existed in the sensor or was created by bonding.

If the sensor was tested, the module is considered “comparable”, in the sense that the actual list of unbonded strips and the list of strips that were supposed to be left unbonded for known sensor defects can be compared. We generate the list of strips that were supposed to be left unbonded according to the same prescription adopted during the production (and implemented in the bonding Database interface that suggested to the operators which strips had to be left unbonded). This prescription is: leave unbonded all pinholes and, in a group of adjacent shorted strips, leave them all unbonded but one. We then compare one by one the strips actually unbonded with this list of not-to-be-bonded strips: if any strip, which was *not* supposed to be left unbonded, is actually unbonded we count it as an "*unplanned unbonded strip*" which may well be due to a bonding failure.

Looping over all modules, we count in this way the *unplanned unbonded strips*, separately for each Center, while simultaneously keeping count of the total number of strips involved, which is incremented by 512 or 768 for each module depending on the module type. Center by Center we then calculate the percentage of these unplanned missing bonds over the total number of strips comprised in the modules bonded by that Center. Finally the same percentage is calculated for the entire INFN Consortium.

In Table 6 we report the final results of this analysis. For each Center we list the number of modules bonded, the number of modules for which the comparison was possible (i.e. the number of modules for which sensor test data exist in *TrackerDB*), the total number of strips comprised in these comparable modules, and the total number of *unplanned* unbonded strips The fraction of these to the total number of strips involved is then computed. As it can be seen from Table 6 the rate of *unplanned* unbonded strips is in no Center greater than 0.1% and it is globally 0.025% for the whole INFN Consortium. For comparison, also the number of strips that were supposed to be left unbonded because of known sensor defects is listed in the last column. We also remark that the total number of 628 *unplanned* unbonded strips corresponds to only one missing bond every six modules bonded (approximately).

Table 6: Bonding failure rates

Center	Modules bonded	Modules comparable	Strips involved	Unplanned unbonded strips	Strips to be left unbonded
Bari	414	413	274432	11 (0.004 %)	24
Catania	411	411	270848	229 (0.085 %)	29
Firenze	437	436	291584	61 (0.021 %)	13
Padova	1061	1049	693760	242 (0.035 %)	41
Pisa	1064	954	638464	38 (0.006 %)	32
Torino	520	510	336896	47 (0.014 %)	18
INFN Consortium	**3907**	**3783**	**2505984**	**628 (0.025 %)**	**157**

To first order one might attribute all *unplanned* unbonded strips to bonding failures, but in reality their number must be regarded as an upper limit for the number of bonding failures. The reason is that, as it can be seen by reading the comments recorded in the *TrackerDB* for the modules with *unplanned* unbonded strips, in many cases the damage which led to the resolution of removing the wire bond of a bad channel was due to mishandling after bonding rather than to an original true bonding failure. Unfortunately those comments were meant to trace back, later, problems found in the data coming from a given module, rather than for elaborating bonding data statistically, so they are not standardized and cannot be analyzed in an automated way. Thus the true figure for the bonding failure rate in the end cannot be quoted, but it must obviously be smaller than 0.025%. Our educated guess is that it is not far from one half of this upper limit, that is we estimate the true global bonding failure rate of the TIB/TID module bonding at ~0.015% of the strips to be bonded.

5 Conclusion

The INFN Consortium has bonded ~3900 modules of the CMS Tracker TIB and TID subdetectors, using the facilities deployed at six of its Sections. A total of ~3,000,000 wire bonds were made, of which ~2,750,000 and ~250,000 were readout bonds and bias bonds, respectively. The production lasted for about two years. The conventional industrial ultrasonic wedge-tool microbonding was used, but the supporting jigs and the bonding programs were specifically developed to tailor them to the unique geometric and material characteristics of the TIB and TID modules. Furthermore, these programs had to be individually developed at each bonding Center. The quality of the bonding process was constantly monitored via visual inspection of *each* wire bond made and via pull tests of special sample groups of bonds. Notwithstanding a discontinuous flow of incoming modules and thus a discontinuous work rate, the quality of the process was excellent, as the pull strength minimum requirement of 5 grams was always fulfilled and, overall, only an estimated ~0.015% of the readout wire bonds to be made are missing.

References

[1] CMS Collaboration, "*The Compact Muon Solenoid: Technical Proposal*", CERN/LHCC 94-38, Dec.1994.

[2] CMS Collaboration, "*The Tracker Project: Technical Design Report*", CERN/LHCC 98-6, April 1998; CMS Collaboration, "*Addendum to the CMS Tracker TDR*", CERN/LHCC 2000-016, February 2000.

[3] D. Abbaneo, *"Layout and performance of the CMS silicon strip tracker"*, Nucl. Instr. and Meth. A 518 (2004) 331, *Erratum* - ibid. A 525 (2004) 626.

[4] A.Basti et al., *"Design of the Inner Tracker Modules"*, CMS Note in preparation.

[5] L. Borrello et al., *"Sensor Design for the CMS Silicon Strip Tracker"*, CMS Note 2003/020.

[6] M.J. French et al., *"Design and results from the APV25, a deep sub-micron CMOS front-end chip for the CMS tracker"*, Nucl. Instr. and Meth. A 466 (2001) 359.

[7] George C. Harman, *"Wire Bonding in Microelectronics: Materials, Processes, Reliability, and Yield"*, MCGraw-Hill, 1996.

[8] P. Cariola et al., *"Assembly of the Inner Tracker Silicon Microstrip Modules"*, CMS Note 2008/004.

[9] The *National Electrical Manufacturers Association* (www.nema.org) sets standards about electric materials used in electric and electronics applications.

[10] S. Albergo et al., *"Test of the Inner Tracker Silicon Microstrip Modules"*, CMS Note in preparation.

[11] Visit www.fkdelvotec.com for information on the F&K Delvotec 6400 microbonder.

[12] Visit www.kns.com for information on the K&S 8090 microbonder.

[13] Visit www.palomartechnologies.com for information on the Hughes 2470 microbonders.

[14] The full set of specifications set up by the CMS Tracker Bonding Working Groups is documented at cms.ct.infn.it/bonding/bondspec.htm.

[15] The *CMS Tracker Database* is described at http://cmsdoc.cern.ch/~cmstrkdb

[16] J.-L. Agram et al., "*The Silicon Sensors for the Compact Muon Solenoid Tracker - Design and Qualification Procedure*", CMS Note 2003/015.

[17] Müller Feindraht AG, Zürcherstrasse 73, 8800 Thalwil (Switzerland).

[18] The official procedures adopted by the CMS Tracker Bonding Working Groups are maintained at cms.ct.infn.it/bonding/bondproc.htm.

[19] The Bonding-to-*TrackerDB* User Interface was installed locally at each Bonding Center. One site where its description can be found is for example cms.ct.infn.it/bondingdb/Catania/man.html.

[20] sirad.pd.infn.it/CMS/modtest/LedSupport.

[21] M.Axer et al., *"Testing of FE Hybrids on Si detector modules for the CMS Tracker"*, Nucl. Instr. and Meth. A 485 (2002) 73.

[22] hep.fi.infn.it/CMS/moduletest/proc_prod/Procedure.html.

[23] cms.ct.infn.it/bonding/pullcorr.htm.