

Introduzione ai rivelatori a semiconduttore

D. Creanza

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& INFN - Bari

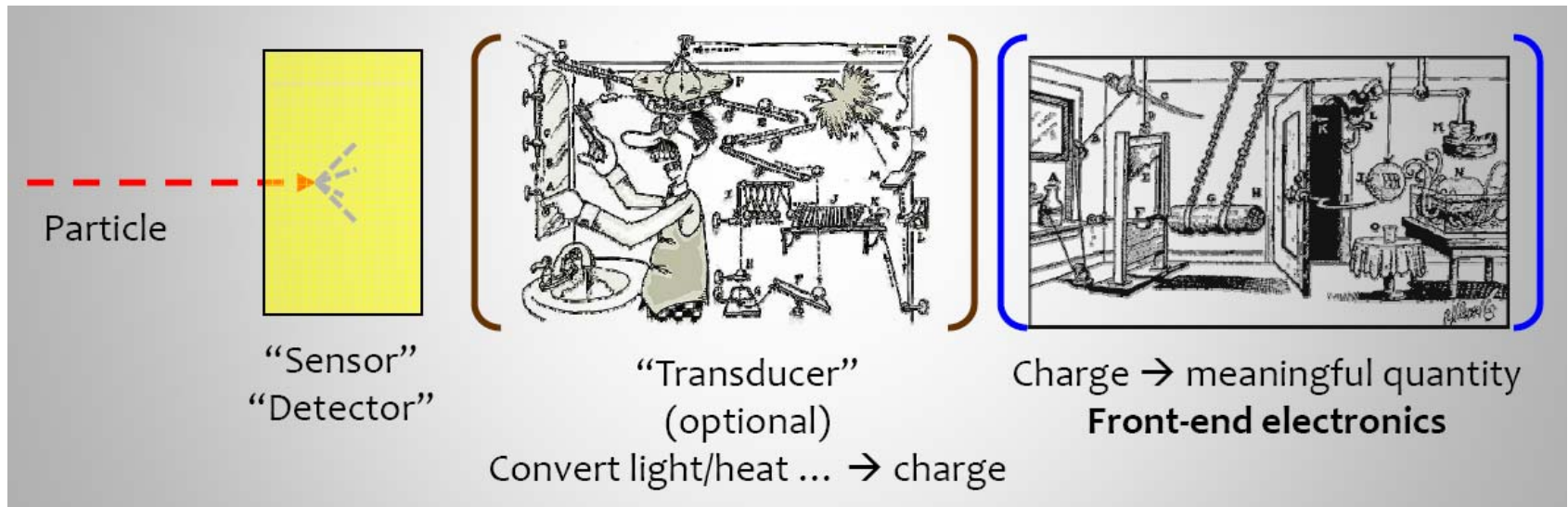
Scuola Nazionale "Rivelatori ed Elettronica per Fisica delle Alte Energie, Astrofisica, Applicazioni Spaziali e Fisica Medica"
INFN Laboratori Nazionali di Legnaro, 20-24 Aprile 2009

Outline

- Aspetti dispositivo:
 - proprietà dei semiconduttori e giunzione $p-n$
 - formazione del segnale
- Applicazioni a sistemi complessi (cenni):
 - l'esempio dell'esperimento CMS ad LHC
- Sviluppi per la fisica delle alte energie ai futuri collider:
 - sensori
 - interconnessioni

Introduction:

Detector/Sensor



Introduction:

What you want – what you get

Generally, we want to measure one or more of the following:

- 1. Energy of particle, or its dE/dx
- 2. Momentum of particle ($\Rightarrow$ position if in a magnetic field)
- 3. Time of particle's passage ($\Rightarrow$ position by TOF, or...)
- 4. Number of particles, or number of particles per unit area

What we end up measuring is:

- 1. Charge [assume $q \propto E$]
- 2. Charge [$q(x,y)$ determines position]
- 3. Charge $\rightarrow V \rightarrow V(t) > V_T$ at time t
- 4. Charge [assume $q(x,y) \propto N(x,y)$]

Particle interaction in sensing/detecting medium creates
charge/light/heat ...

Bibliography & credits

- S. M. Sze: Semiconductor Devices, Physics and Technology, Wiley 1985
- R. S. Muller, T. I. Kamins: Device Electronics for Integrated Circuits, John Wiley & Sons 2003
- H. Spieler: Semiconductor Detector Systems, Oxford University Press, 2005
- Rossi, Fischer, Rohe, Wermes: Pixel Detectors: from Fundamentals to Applications, Springer 2006

La prima lezione si basa sui Tutorial di Helmuth Spiegel disponibili a <http://www-physics.lbl.gov/~spieler/> , con alcune integrazioni.

In particolare : al link

[TRIUMF Summer Institute 2007: Silicon Detectors and Electronics](#)

vedere i capitoli:

[Sensor Physics I](#) (teoria dei semiconduttori),

[Sensor Physics II](#) (formazione del segnale e teorema di Ramo)

Integrazioni a “Sensor Physics – part I”

- Step junction
- External bias
- Capacitance of a *pn* junction

Step junction

$$\frac{d^2\Phi}{dx^2} = -\frac{dE}{dx} = -\frac{q(N_d - N_a)}{\epsilon}$$

$$E(x) = -\frac{qN_d}{\epsilon}(x_n - x)$$

$$0 < x < x_n$$

$$-x_p < x < 0$$

$$E(x) < 0$$

$$E(x) = -\frac{qN_a}{\epsilon}(x + x_p)$$

$E(x)$ continuous at $x=0$
(and max.)

$$\rightarrow N_d x_n = N_a x_p$$

$$\text{if } N_d > N_a \rightarrow x_p > x_n$$

$$N_d - N_a$$

$$N_d$$

n-type

p-type

$$-N_a$$

x

Net dopant concentration

ρ

$$qN_d$$

$$-x_p$$

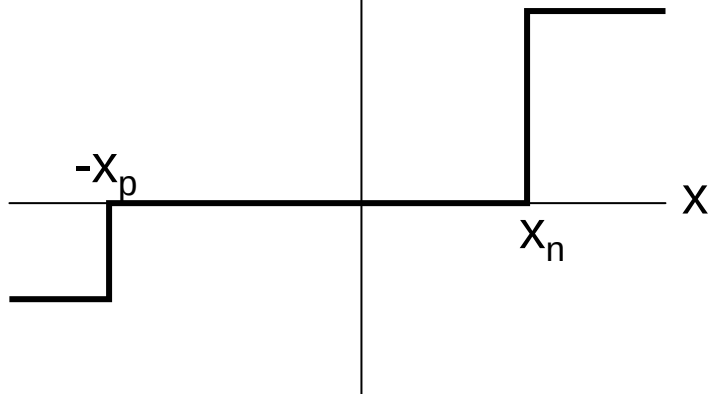
$$x_n$$

x

$$-qN_a$$

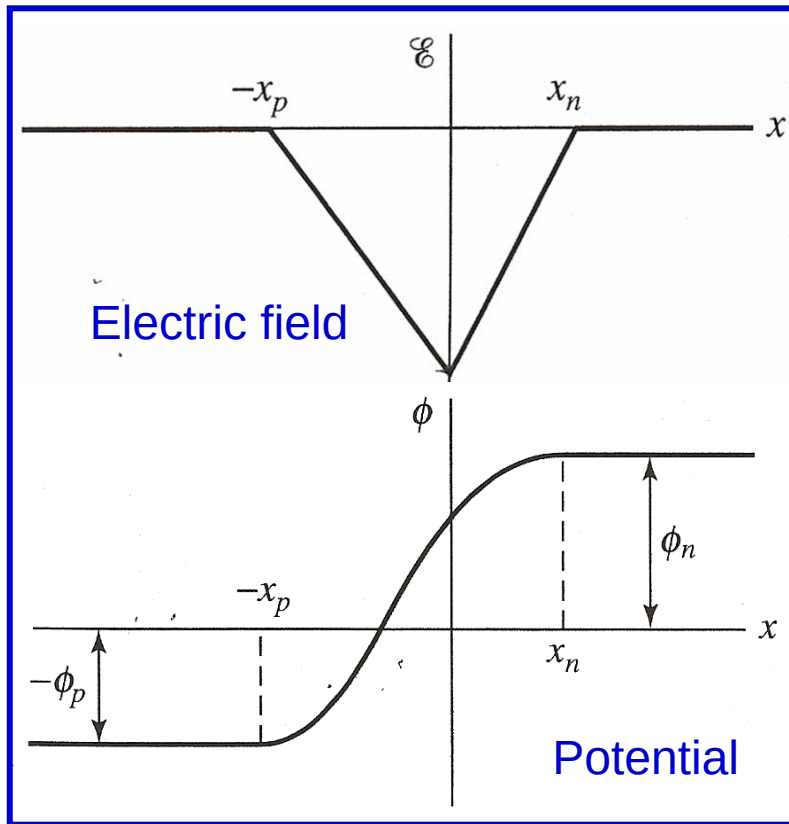
Space charge density

n-p



Carrier density

Built-in potential



At thermal equilibrium, the built-in potential change V_{bi} from the neutral p-type region to the neutral n-type region and the extension $x_n + x_p$ of the space-charge region (depletion region width) are:

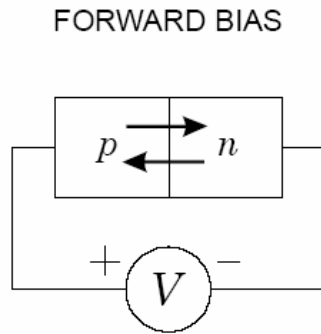
$$V_{bi} = \Phi(x_n) - \Phi(x_p) > 0$$

$$x_n + x_p = \sqrt{\frac{2\epsilon V_{bi}}{q} \left(\frac{1}{N_a} + \frac{1}{N_d} \right)}$$

We see that the depletion region width depends most strongly on the material with the lighter doping, and varies approximately as the inverse square root of the smaller dopant concentration.

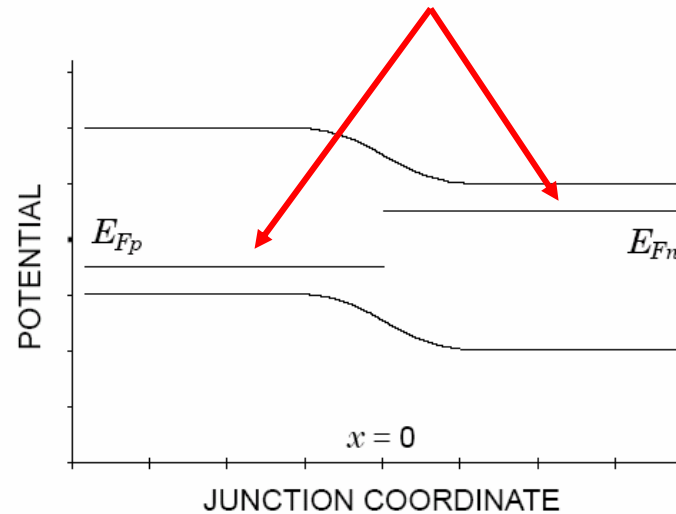
If an external bias is applied to the junction (the voltage drops in the neutral regions are negligible) two different cases must be considered:

- a) positive potential applied to the p region
negative potential applied to the n region



$$\Phi(x_n) - \Phi(x_p) = V_{bi} - V$$

non-equilibrium conditions



The externally applied voltage reduces the potential barrier, allowing increased charge transfer across the junction.

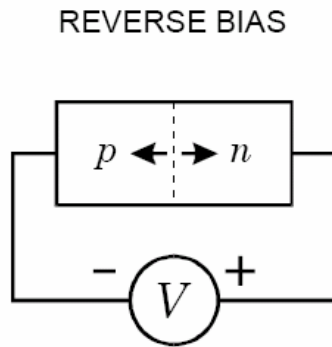
⇒ “forward bias”

Electrons flowing from the n -region across the junction are replenished from the external voltage supply and large current flow is possible.

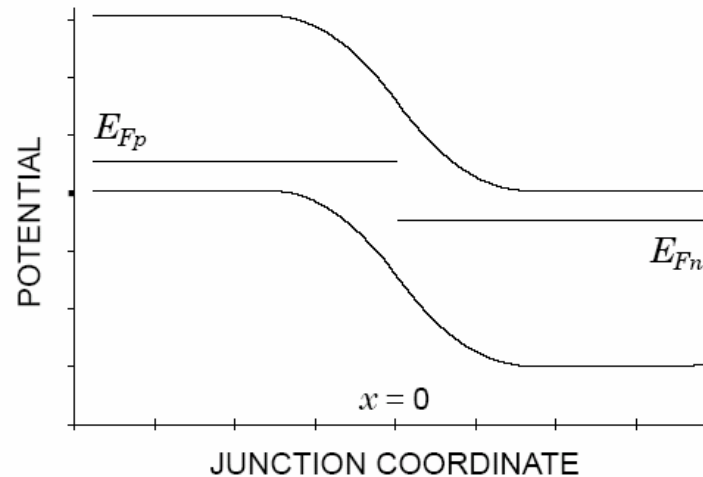
The applied voltage moves majority carriers towards the edges of the depletion region, where they neutralize some of the space charge: the depletion region becomes narrower.

$$x_n + x_p = \sqrt{\frac{2\epsilon}{q} (V_{bi} - V) \left(\frac{1}{N_a} + \frac{1}{N_d} \right)}$$

- b) negative potential applied to the p region
positive potential applied to the n region



$$\Phi(x_n) - \Phi(x_p) = V_{bi} + V$$



This arrangement increases the potential barrier across the junction, impeding the flow of current.

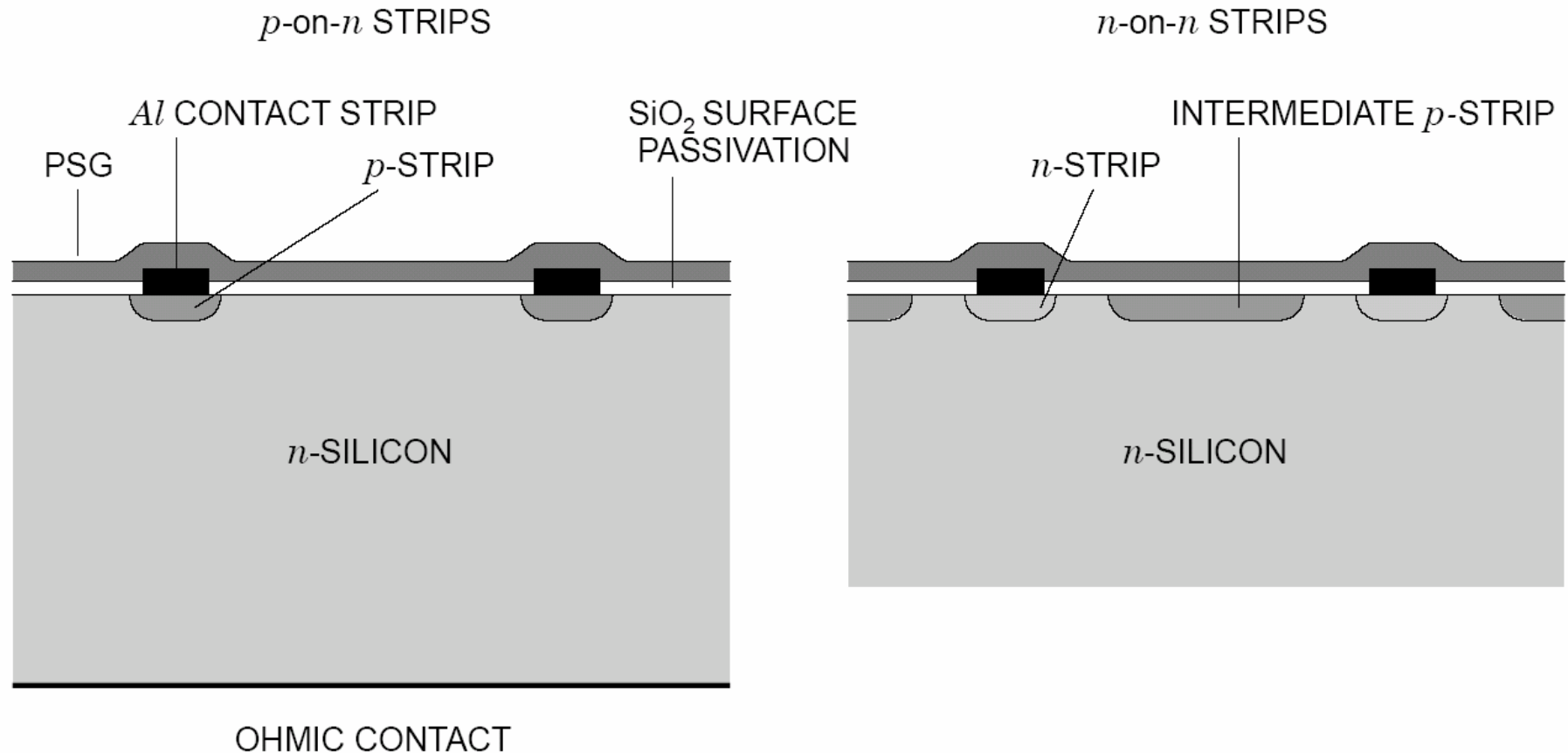
Very little current flows because it is made of minority carriers. $\Rightarrow$ “reverse bias”

Potential across junction is increased $\Rightarrow$ wider depletion region

$$x_n + x_p = \sqrt{\frac{2\epsilon}{q} (V_{bi} + V) \left(\frac{1}{N_a} + \frac{1}{N_d} \right)}$$

Majority carriers are pulled away from the edges of the depletion region, which therefore widens. V_{FD} is the bias voltage value for which $x_d = x_n + x_p$ equals the full detector thickness.

Strip and pixel detectors utilize a similar structure, except that the pn -junction is segmented:



Since the depletion region is a volume with an electric field, it by itself could be used as a radiation detector. In order to increase the active volume, reverse bias should be applied, trying to reach full depletion.

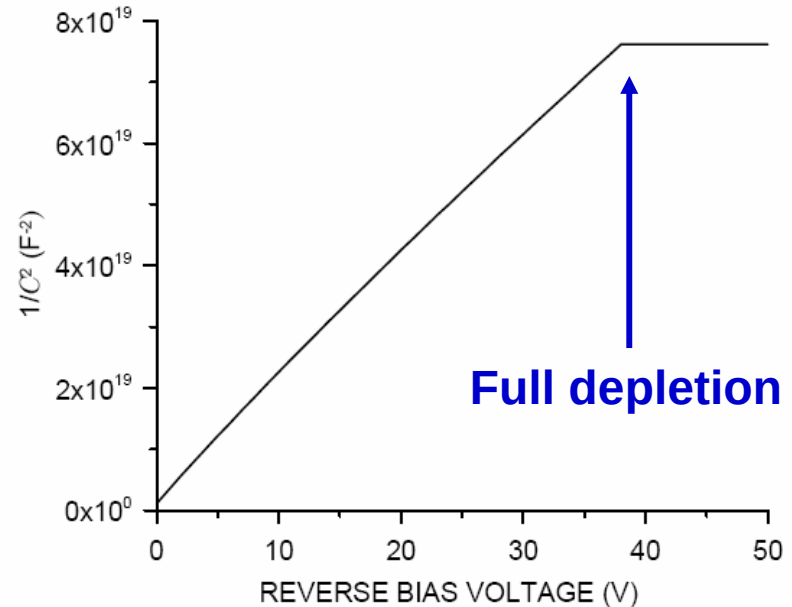
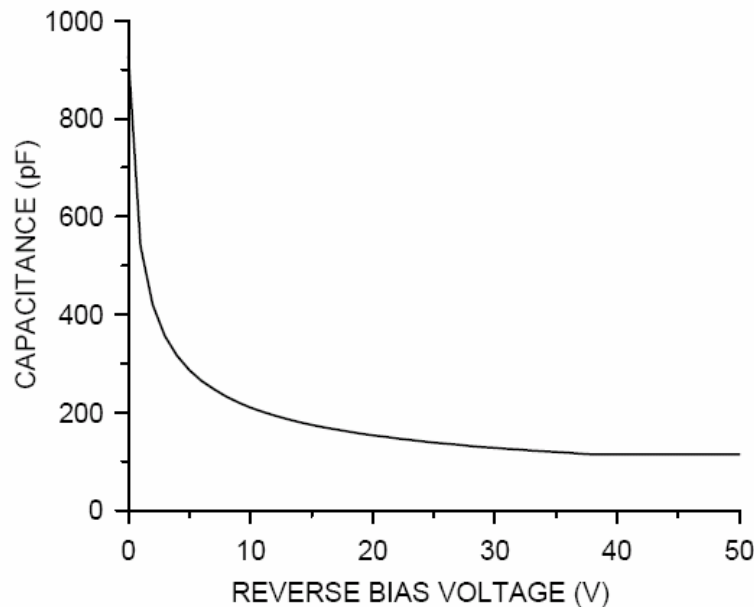
The capacitance vs. voltage characteristic of a diode can be used to determine the doping concentration of the detector material.

$$\frac{C}{A} = \sqrt{\frac{\epsilon q_e N}{2(V_b + V_{bi})}}$$

In a plot of $(A/C)^2$ vs. the detector bias voltage V_b the slope of the voltage dependent portion yields the doping concentration N .

Example: Si pad detector, $A = 1 \text{ cm}^2$, $100 \text{ } \mu\text{m}$ thick

$$\frac{1}{N} = \frac{d(1/C^2)}{dV} \left(\frac{\epsilon q_e}{2} \right) = \frac{1}{5 \cdot 10^{12}}$$



Capacitance of a *pn* junction

The above expression for the capacitance of a *pn* **step** junction can be derived evaluating the modulation of the stored charge in the depletion region as the applied voltage V_a is changed.

If Q_s is the charge per unit area on either side of the junction 

$$Q_s = qN_d x_n = qN_a x_p$$

$$C = \frac{dQ}{dV_a} = qN_d \frac{dx_n}{dV_a} = qN_a \frac{dx_p}{dV_a}$$

Since $x_p = (N_d/N_a)x_n$ and $x_d = x_n + x_p$:

$$\frac{dx_n}{dV_a} = \frac{1}{N_d} \left[\frac{\epsilon_s}{2q \left(\frac{1}{N_a} + \frac{1}{N_d} \right) (\Phi_i + V_a)} \right]^{1/2} \quad \rightarrow \quad C = \left[\frac{q\epsilon_s}{2 \left(\frac{1}{N_a} + \frac{1}{N_d} \right) (\Phi_i + V_a)} \right]^{1/2} = \epsilon_s / x_d$$

This result is valid in general for an **arbitrarily** doped *pn* junction extending from $-x_p$ to x_n . The charge per unit area Q stored between x and the edge of the junction at x_n is:

$$Q = q \int_x^{x_n} N dx$$

Where $N = N_d - N_a$ (net dopant density, also called N_{eff}). $E_x(x_n) = 0$ 

From Gauss' law:

$$-E_x(x) = \frac{1}{\epsilon_s} \int_x^{x_n} qN dx = \frac{Q}{\epsilon_s}$$

As the applied voltage V_a is changed by a small amount dV_a , the width of the *n*-type side of the depletion region changes by:

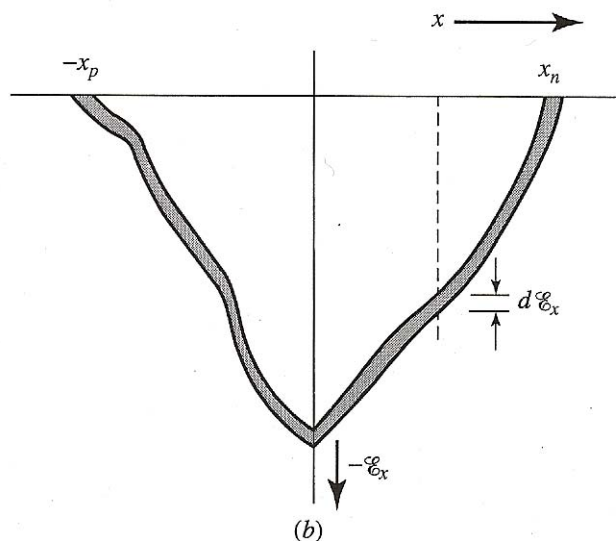
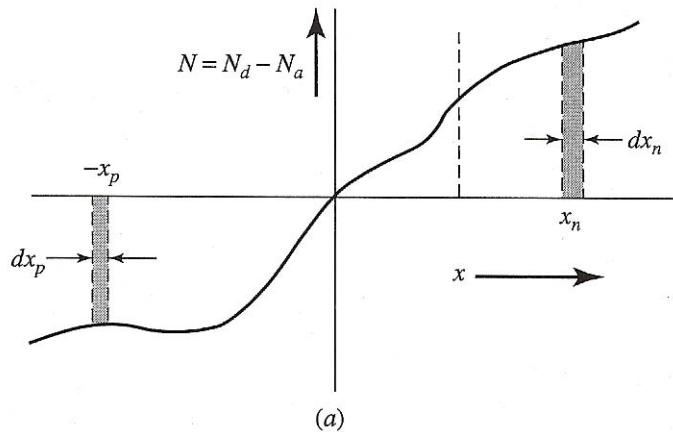
$$dQ = qN(x_n)dx_n$$

Consequently, the field at x changes by:

$$-dE_x = \frac{dQ}{\epsilon_s} = \frac{q}{\epsilon_s} N(x_n)dx_n$$

Since the area under the E_x versus x curve corresponds to the total potential $V_{bi} + V_a \rightarrow dV_a$ corresponds to the change in area under the curve (shaded region):

$$dV_a \approx -x_d dE_x = \frac{x_d}{\epsilon_s} dQ \rightarrow C = \frac{dQ}{dV_a} = \frac{\epsilon_s}{x_d}$$



a) Dopant concentration in an arbitrarily doped junction, showing modulation of the carrier densities at the edges of the space-charge region by an applied voltage.

b) Electric-field distributions for two slightly different applied voltages.

Integrazioni a “Sensor Physics – part II”

Alcune tecniche sperimentali:

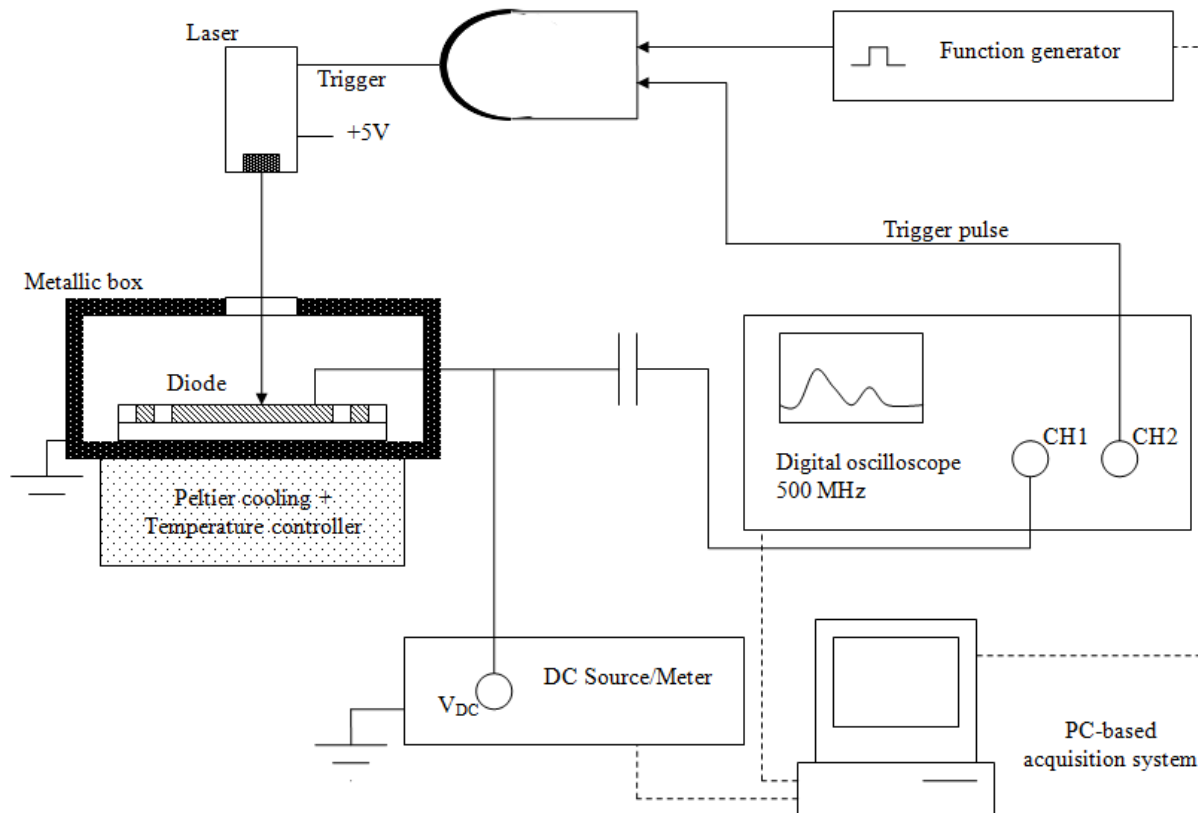
- Transient Current Technique
- Current Transients at Constant Temperature

Alcune tecniche sperimentali

- Transient Current Technique
 - Registra e analizza il segnale (impulso di corrente) indotto durante la raccolta di carica. Con opportuna modellizzazione, consente l'estrazione del profilo del campo elettrico all'interno del sensore.
- Current Transients at Constant Temperature
 - Sfrutta la variazione dello spessore della regione di svuotamento con N_{eff} .

TCT (*Transient Current Technique*)

The TCT technique is used to investigate the electric field profile within the polarized detector bulk. In this way we can study the junctions present within the detector.



Laser-induced carriers drift within the diode, inducing on the electrodes a current signal read by an oscilloscope.

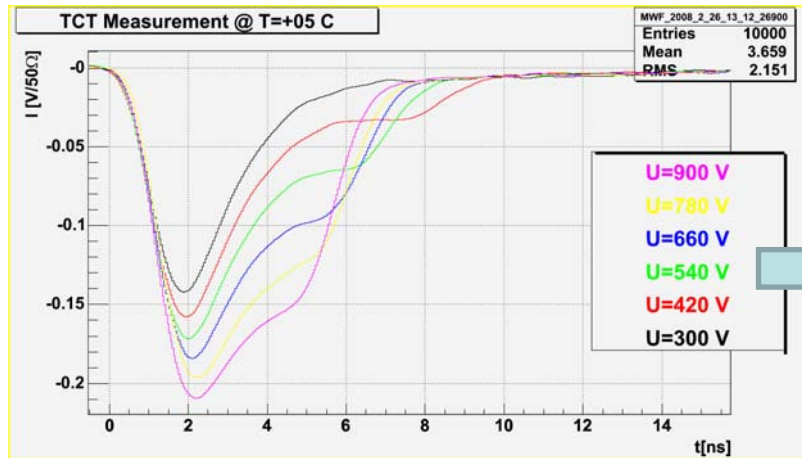
$$j = nev = \mu E$$

$$\Rightarrow j \propto E$$

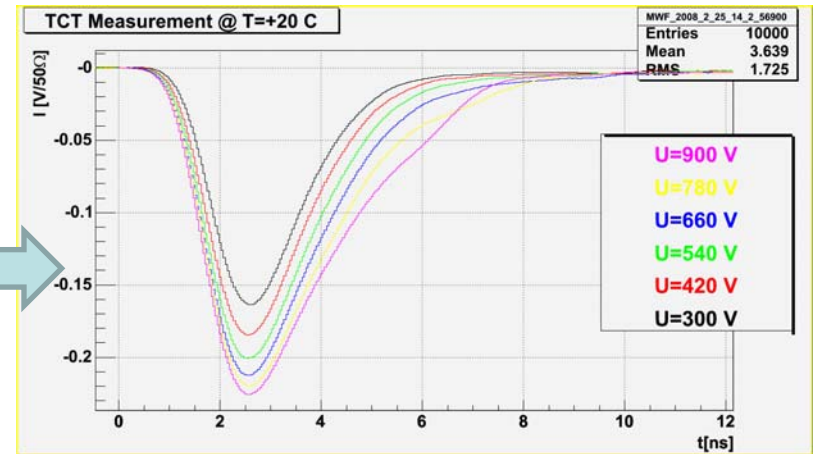
TCT measurements - details

- TCTs performed using a 670 nm laser (generation of carriers within the first μm)
- Trapping times can be determined with Charge Correction Method (i.e. finding the trapping time constant for which the collected charge is independent from $V_{\text{bias}} > V_{\text{FD}}$).
- Plots shown (next slide) are without correction.

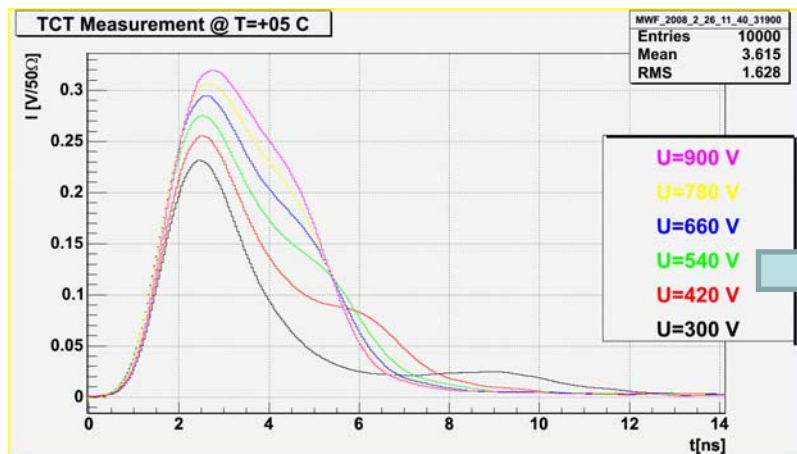
SMART MCz – Annealing study



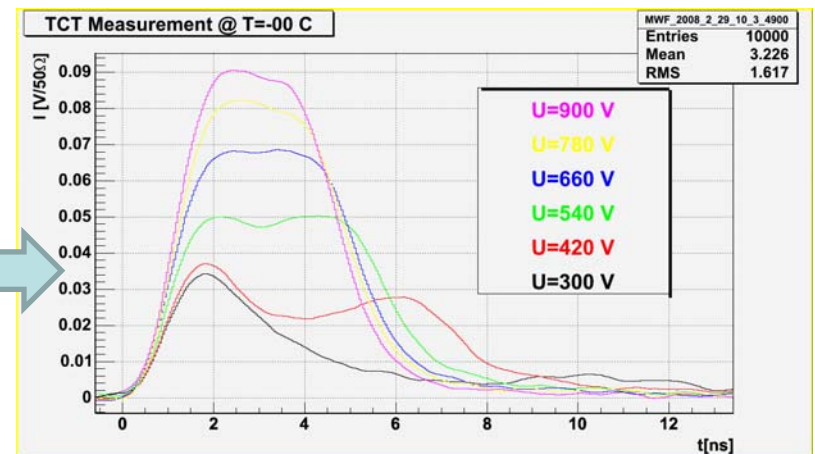
MCz-p@0 min. – 8.8×10^{14} neq/cm²



After 1000 min. @ 80° C



MCz-n@0 min. – 8.8×10^{14} neq/cm²



MCz-n@0 min. – 8.8×10^{14} neq/cm²

Current Transients at Constant Temperature

In sensori irraggiati i difetti introdotti possono contribuire alla carica spaziale, fino a provocarne una inversione di segno (Space charge Sign Inversion).

Dopo un impulso di eccitazione (“filling”) dei difetti, realizzato ad una temperatura T , il sensore viene polarizzato inversamente e si monitora il segnale di emissione.

Se N_t è $\ll N_{eff}$ il volume della regione di svuotamento è praticamente indipendente dal tempo, ed il transiente di corrente conserva la forma esponenziale standard.

Se, invece, N_t è $\sim N_{eff}$ si possono avere forti distorsioni del segnale di corrente $i(T,t)$ che segue l'eccitazione impulsata.

Quando il contributo di N_t non è trascurabile $N_{eff0} \rightarrow N_{eff}(t, T)$

$$x_d(t, T) = \sqrt{\frac{2\varepsilon V_a}{q |N_{eff}(t, T)|}}$$

Per un dato valore di V_a :

$$x_d(t, T) = d \iff |N_{eff}(t, T)| = \frac{2\varepsilon V_a}{q d^2} = N_{fd}$$

$$\text{Se } |N_{eff}(t, T)| > N_{fd} \implies x_d(t, T) < d$$

$$\text{Se } |N_{eff}(t, T)| < N_{fd} \implies x_d(t, T) = d$$

$$\left. \begin{array}{l} N_{eff}(t, T) > N_{fd} \\ N_{eff}(t, T) < -N_{fd} \end{array} \right\} \implies x_d(t, T) < d$$

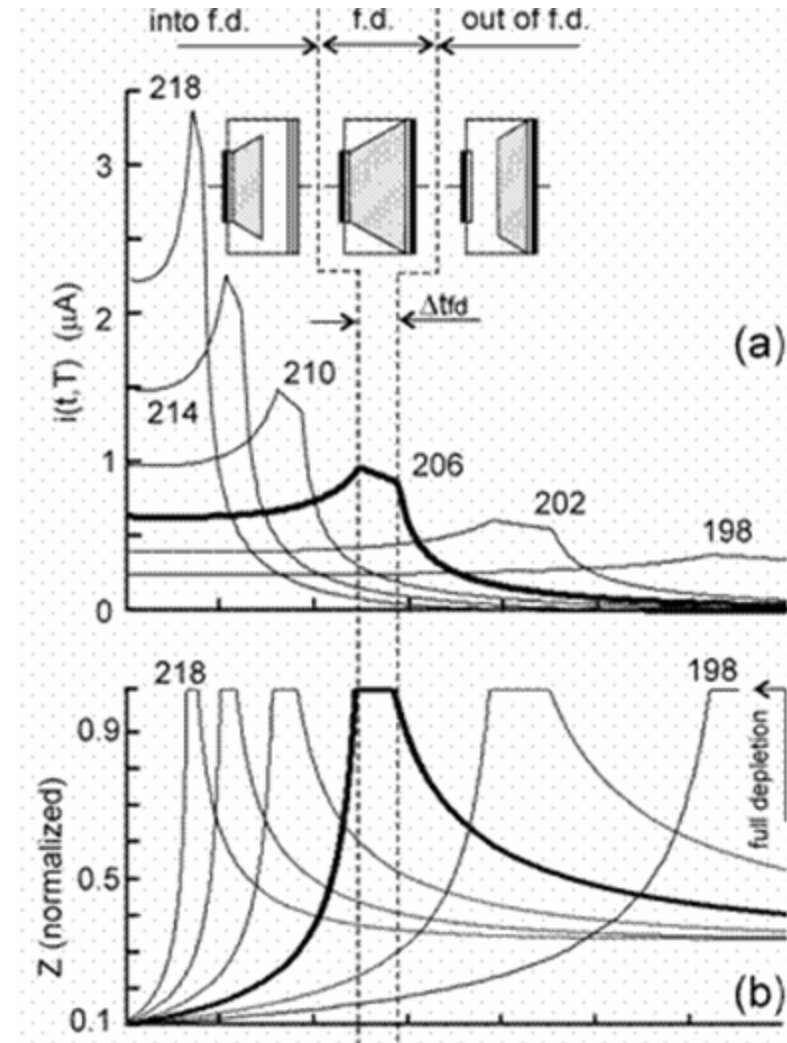
$$-N_{fd} \leq N_{eff}(t, T) \leq N_{fd} \implies x_d(t, T) = d$$

From literature about current transients analysis

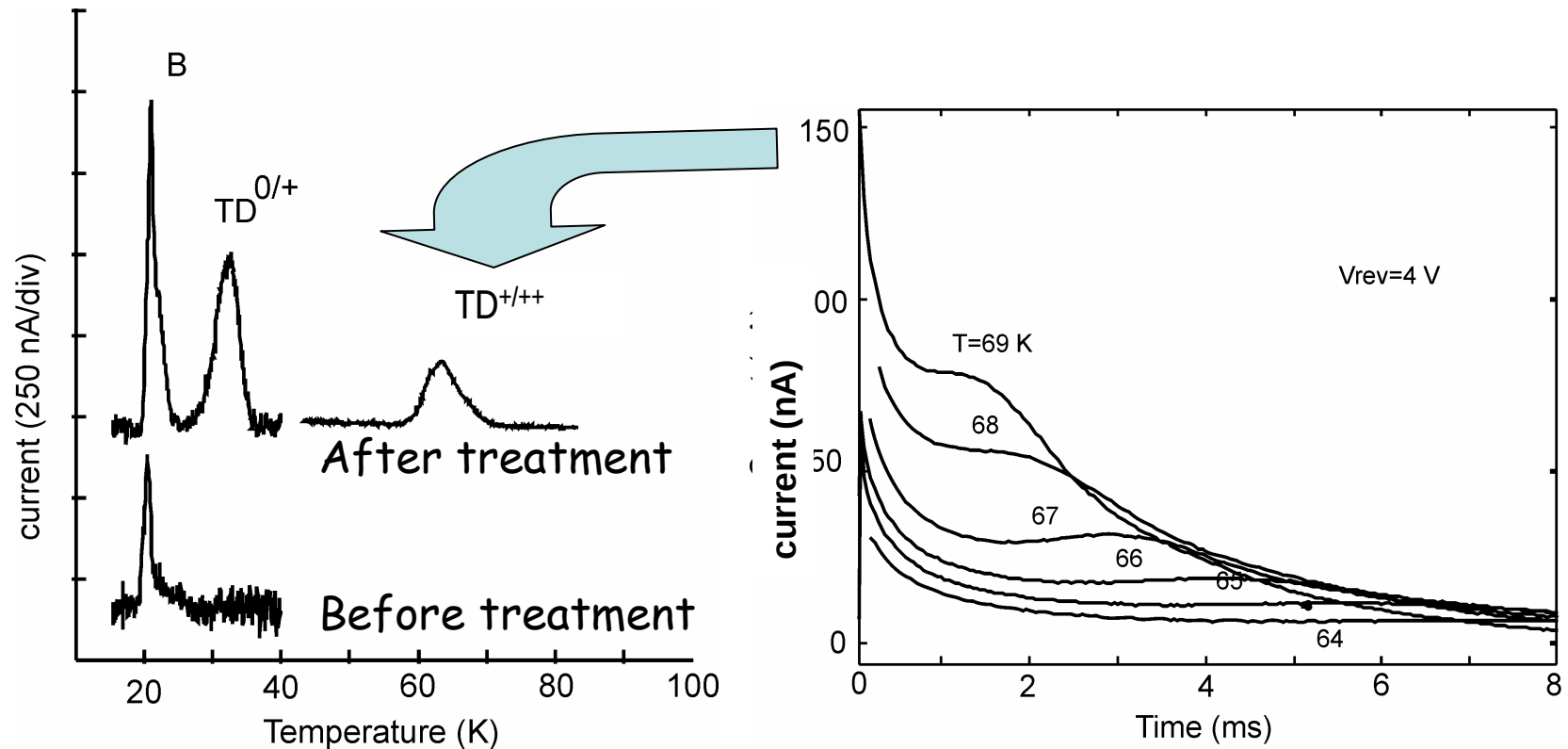
Non monotonic transient of current in I-DLTS are due to changes of N_{eff} and SCSI. When SCSI occurs, if $V_{\text{rev}} < V_{\text{fd}}$, the active volume Z increases, reach the total volume and then decreases, producing a non-monotonic current transient.

By measuring the temperature at which this effect is observed it is possible to reveal which energy level is responsible of SCSI.

D. Menichelli et al. Phys. Rev. B 70, 195209 (2004).



Comparison of i-DLTS spectra before and after thermal treatment at 430° C



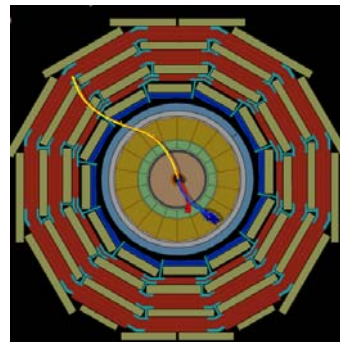
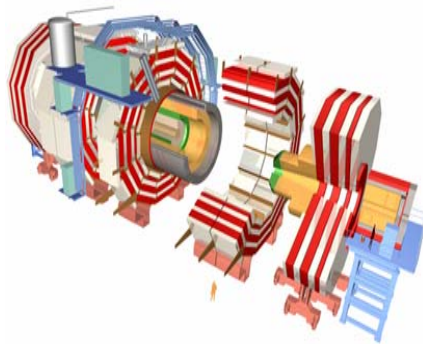
Before treatment, transients are monotonic $\Rightarrow$ the space settled by B is not changing type.

After treatment, the current transient presents a peak at $T = 60\text{K} \Rightarrow \text{TD}^{+ /++}$ is responsible of the change of space charge type.



Dal semplice al (molto!) complesso

Preparazione alla Fisica di LHC: l'esperimento CMS



Bari - 12 Maggio 2008



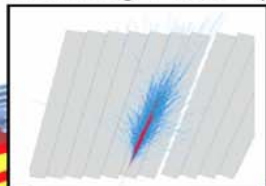
II Compact Muon Solenoid (CMS)

**SUPERCONDUCTING
COIL**

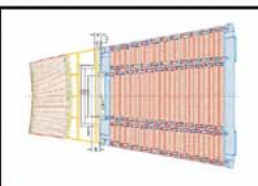
Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla

CALORIMETERS

ECAL Scintillating PbWO_4
Crystals

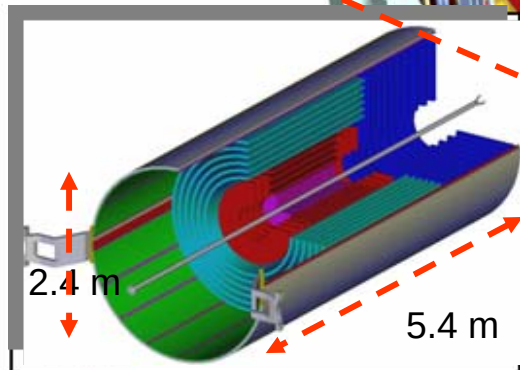


HCAL Plastic scintillator
copper
sandwich



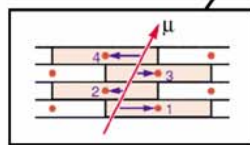
IRON YOKE

TRACKERS

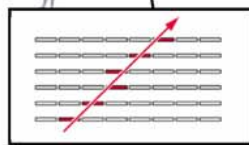


Silicon Microstrips
Pixels

~20 m
MUON BARREL

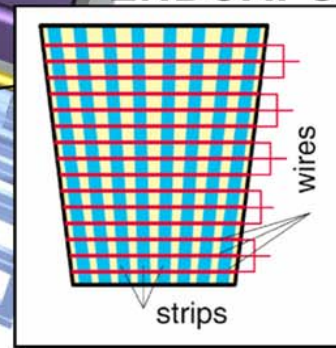


Drift Tube
Chambers (**DT**)



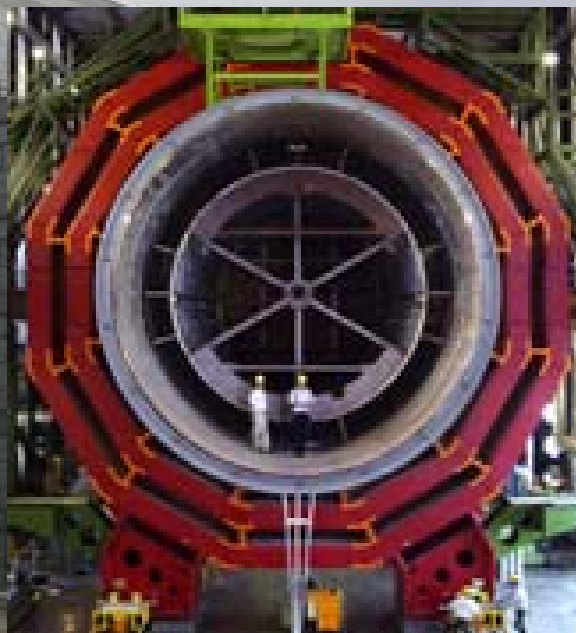
Resistive Plate
Chambers (**RPC**)

**MUON
ENDCAPS**



Cathode Strip Chambers (**CSC**)
Resistive Plate Chambers (**RPC**)

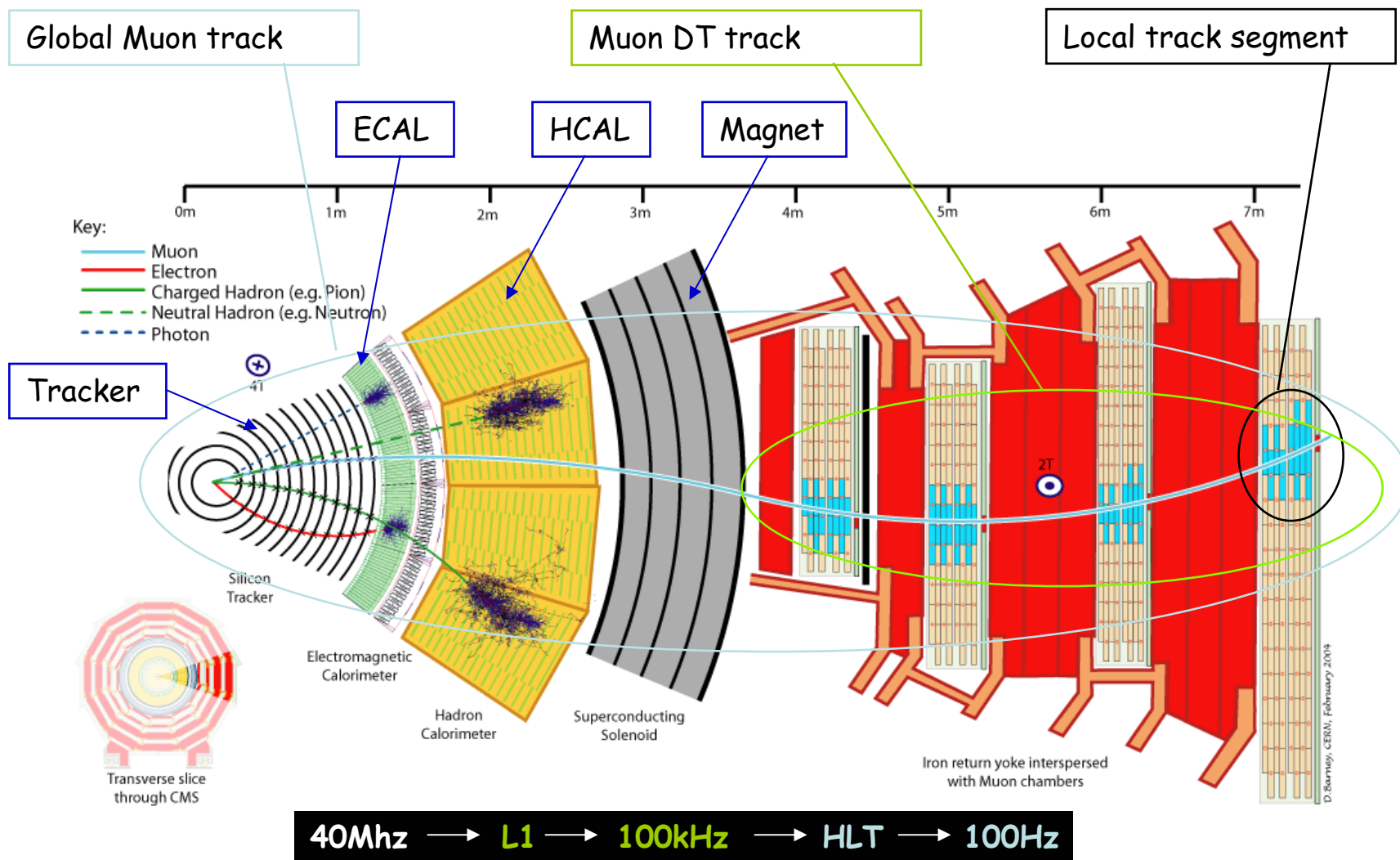
building 40 (CERN)

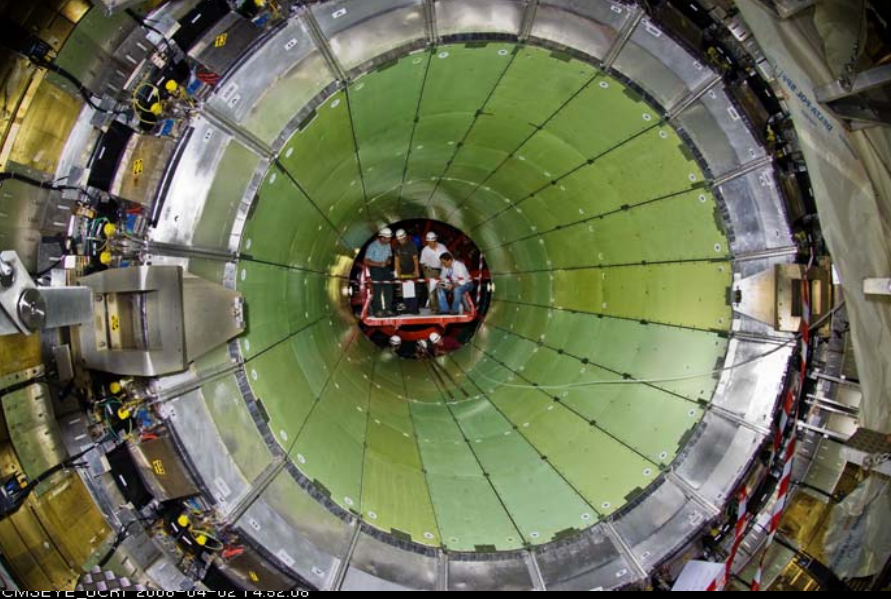


5 piani!

12500 t di massa

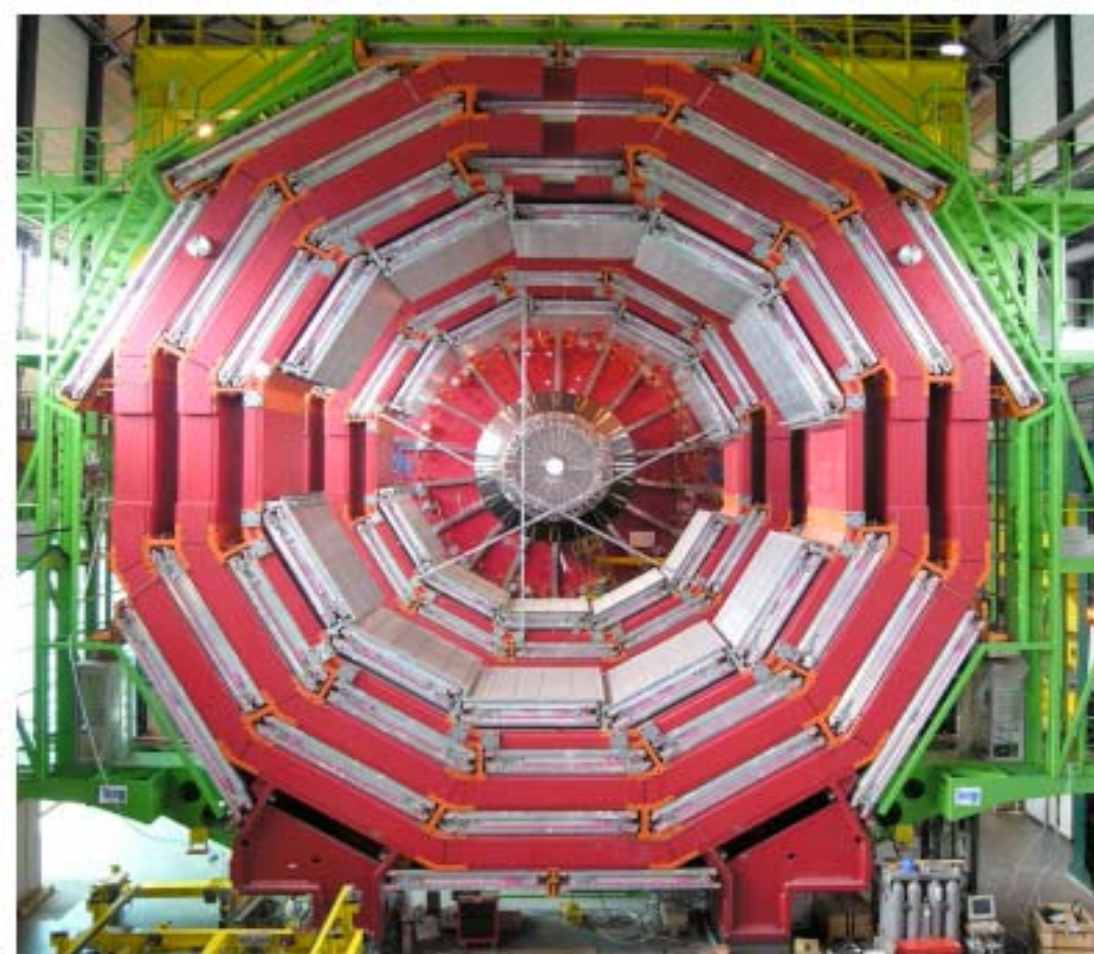
Track Reconstruction

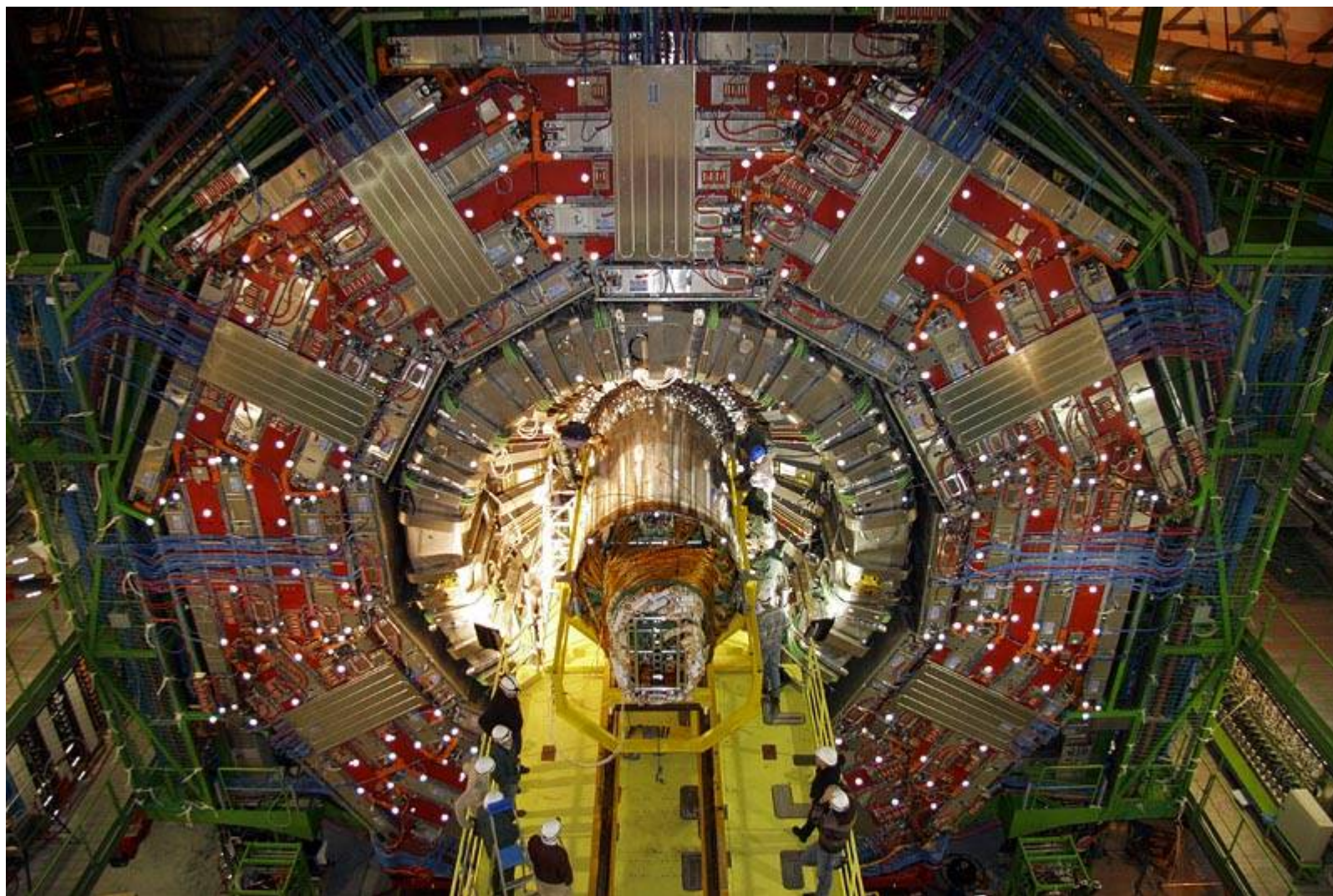




CMS ECAL

Muon Chambers Status



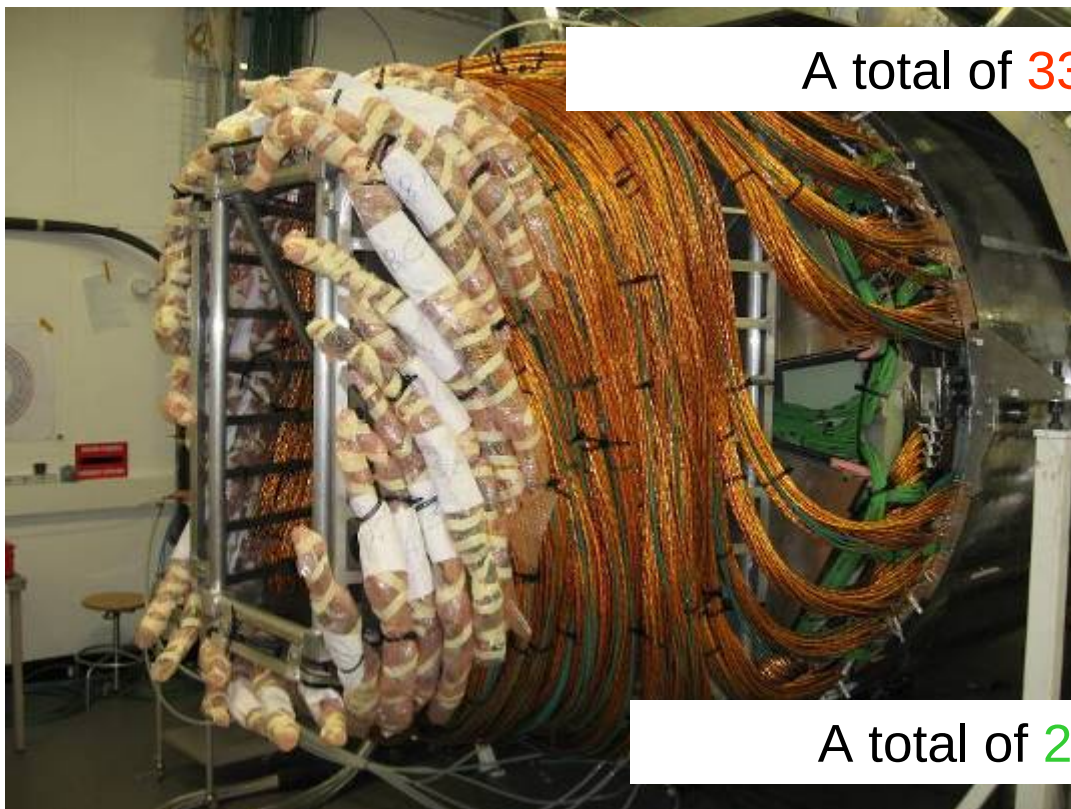


A total of 980 pipe connections to be done.

A total of 3347 fibre connections

A total of 2330 cable connections

And all of these 6657 connections have to be checked out.



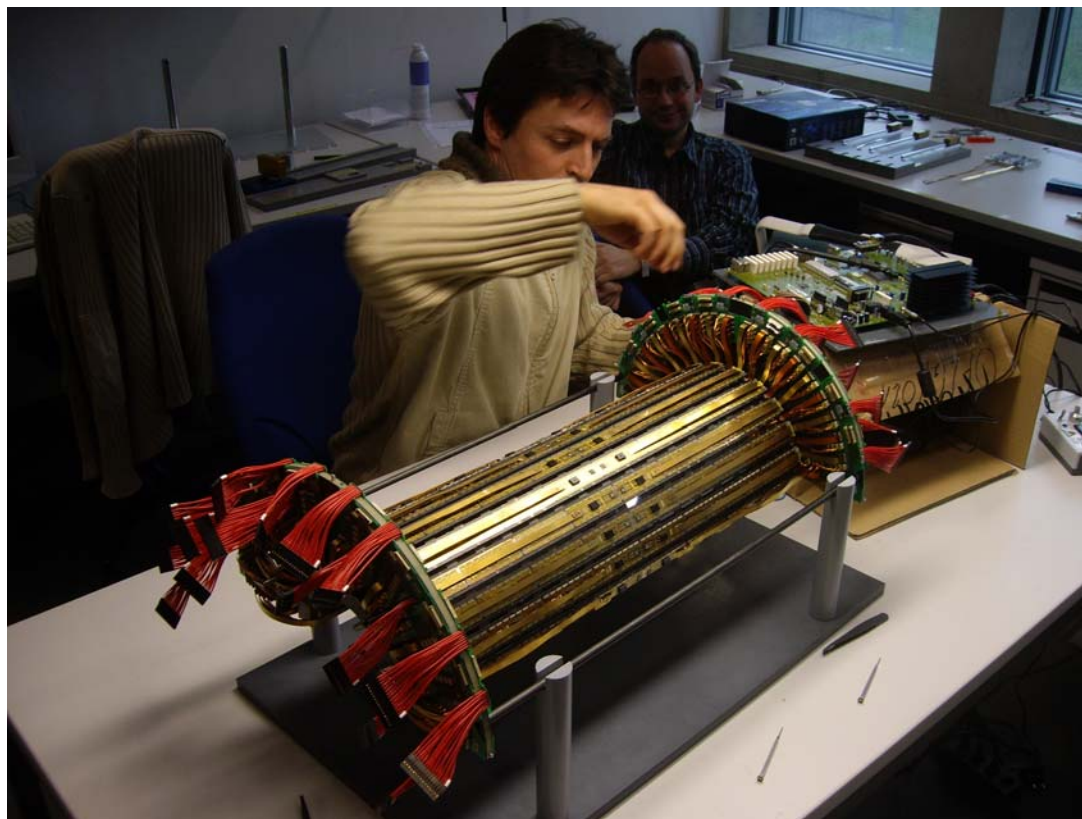
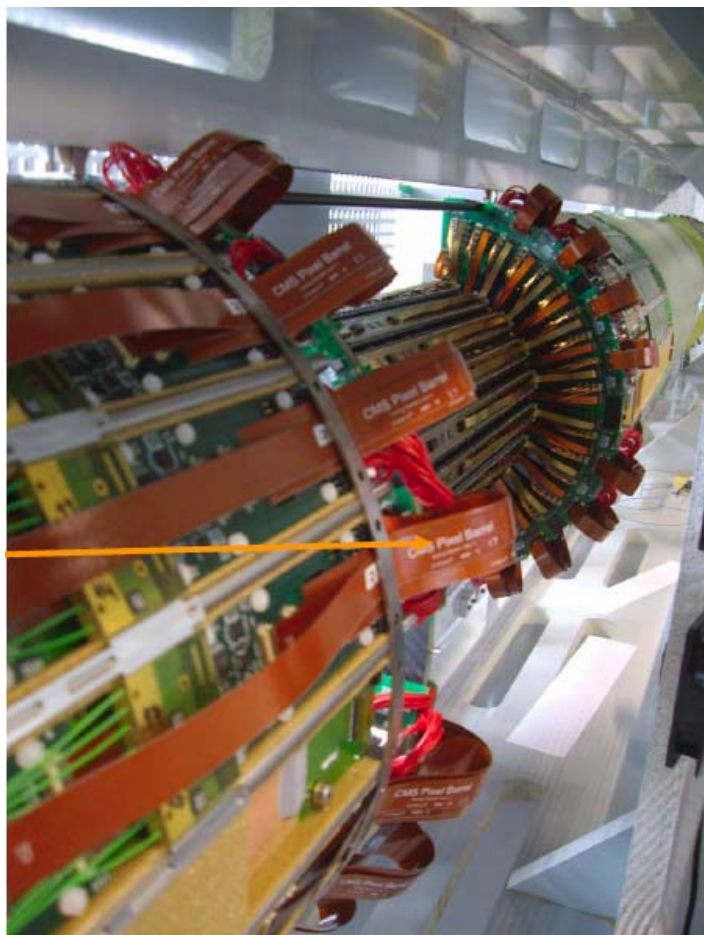
Stato Tracciatore

-Z

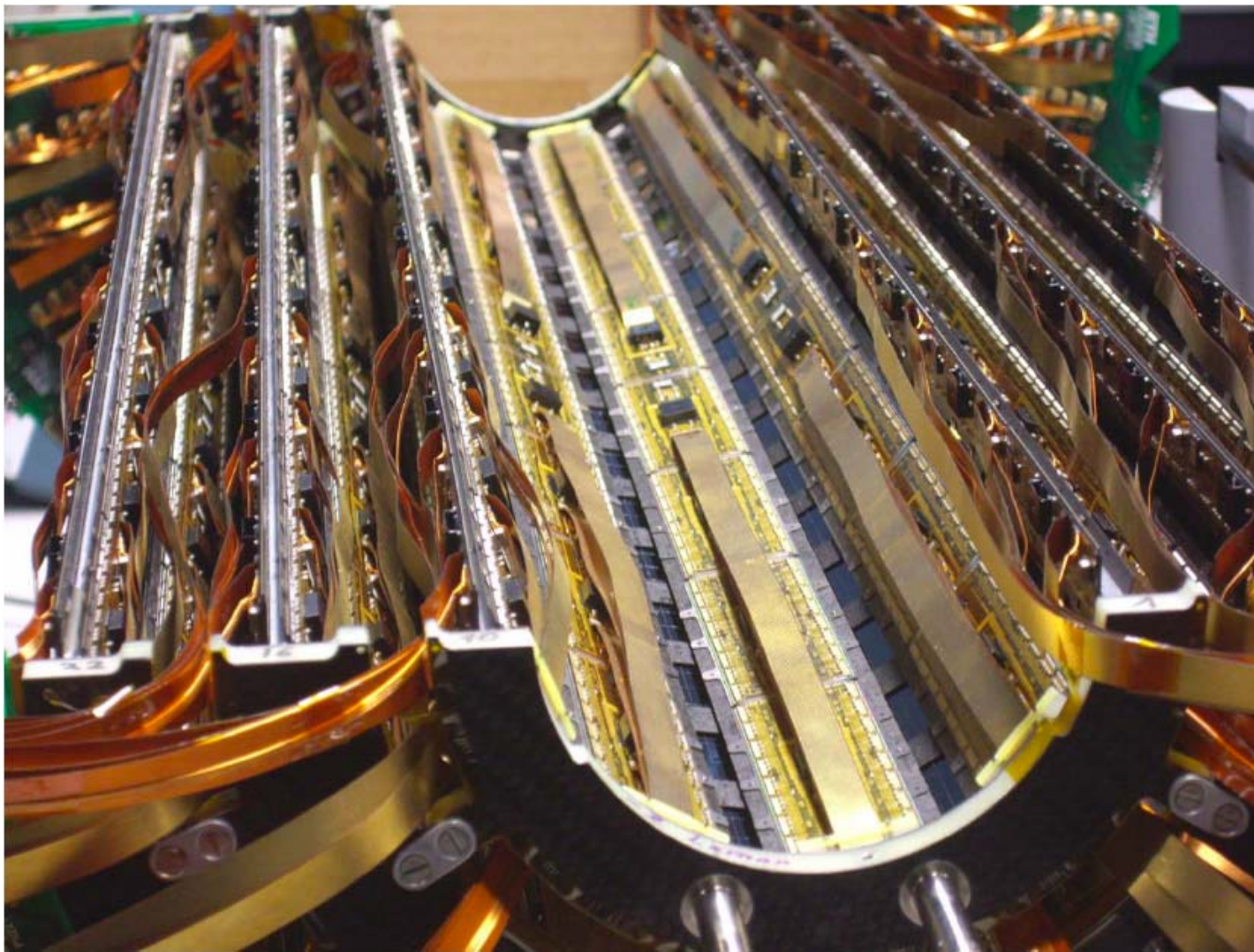


Tutte le connessioni effettuate e controllate!

Finishing Construction: Pixels

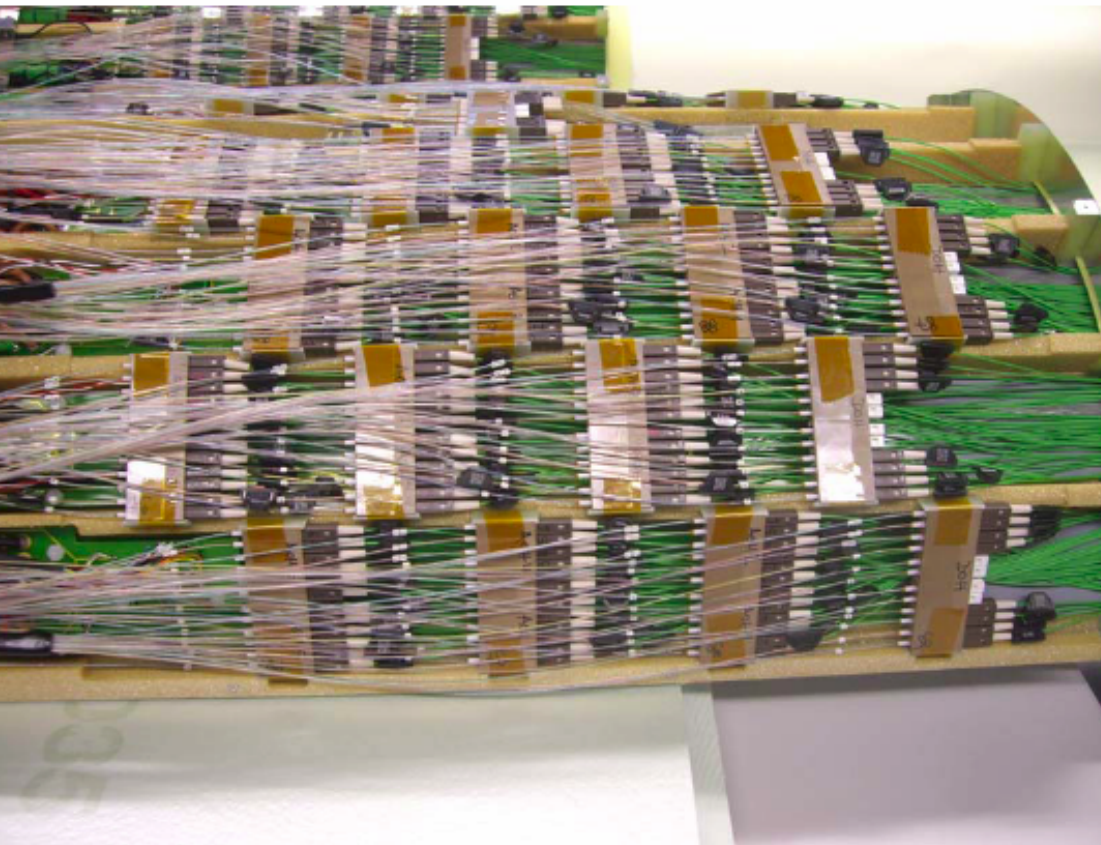


PIXEL Barrel

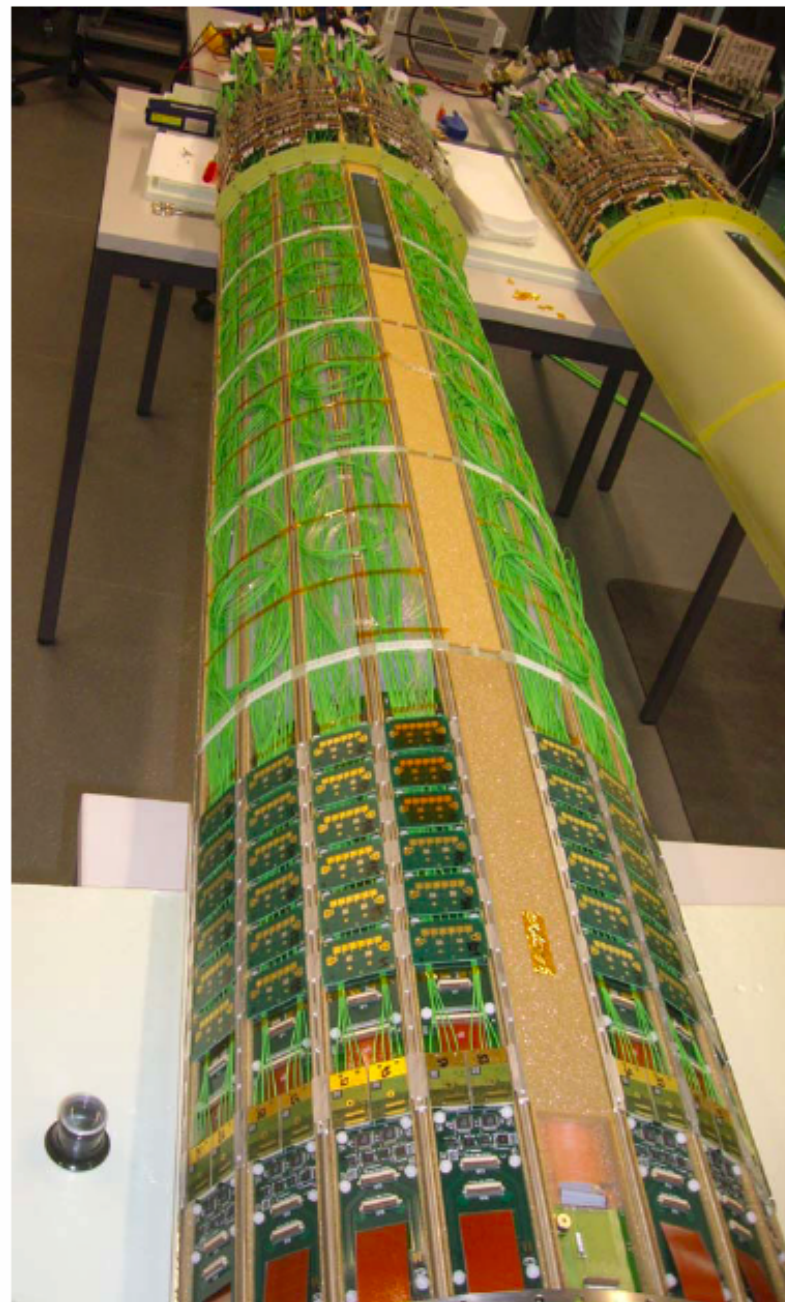


BPIX mechanics all 3 layers +z,-z done

Fibre dressing of the Supply Tube



+x-side

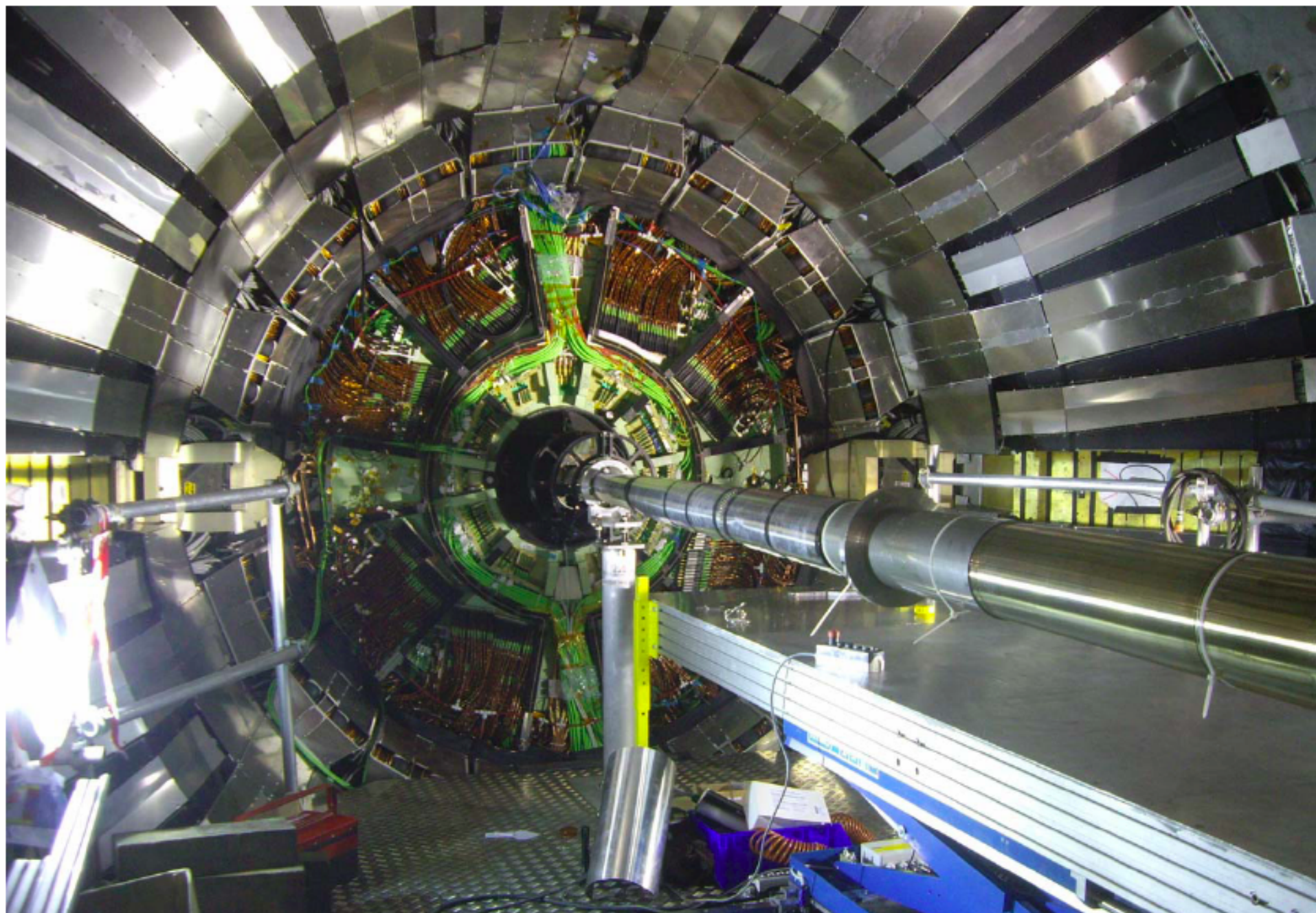


Anyone dreaming of more fibres for SLHC ?

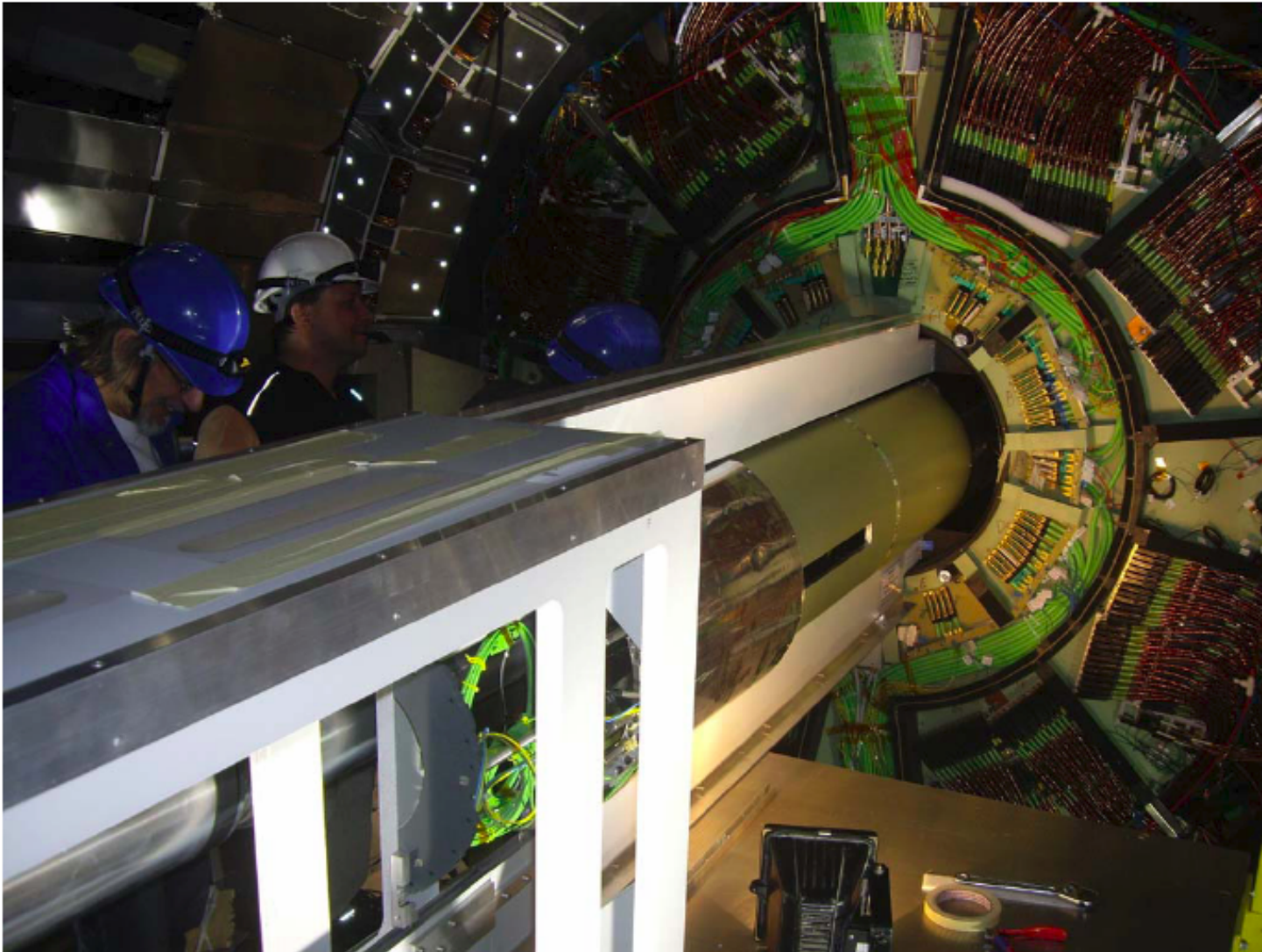
Installazione Beam Pipe



Close up of PP0, beam pipe & installation table



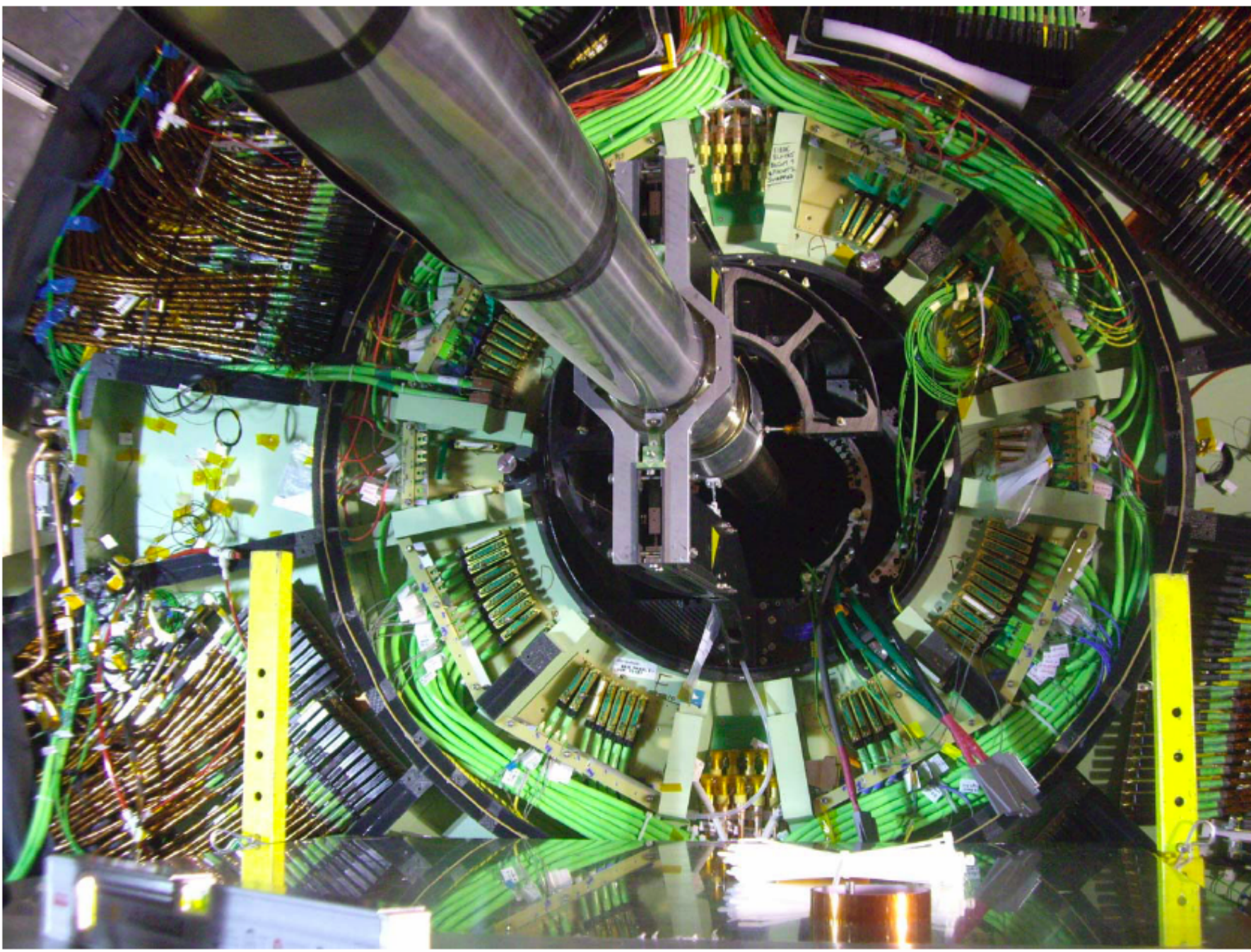
After some leveling troubles now a smooth easy insertion !



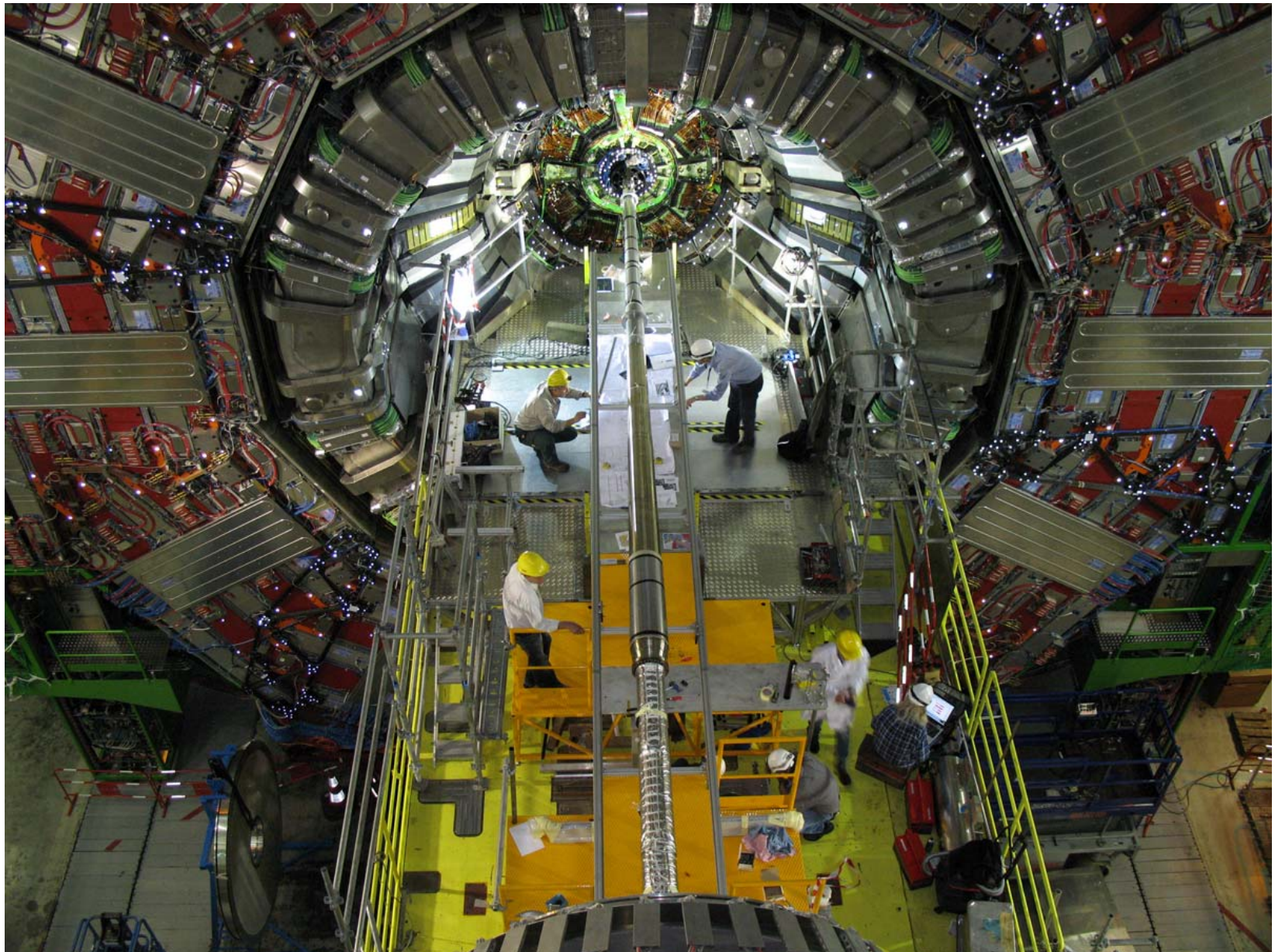
- after ~4 hours we are in fine
- beam pipe group is happy
- we are happy
- No real modifications needed

Conclusion: Insertion of BPIX system went according to plan and very smooth !

View of -z-Side with endcap beampipe & FPIX & BPIX installed



Attuale Situazione a Point 5

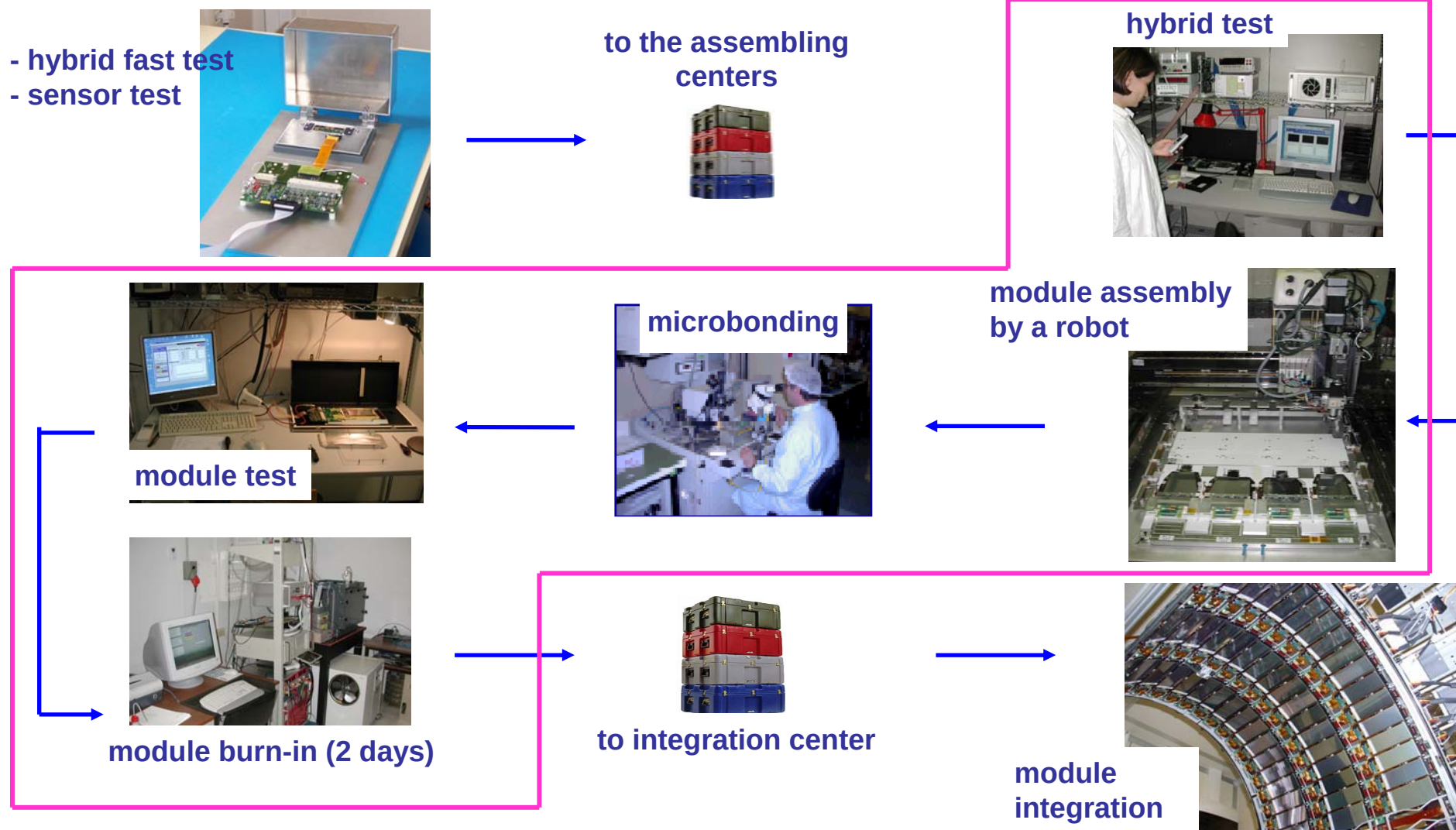




Aspetti organizzativi

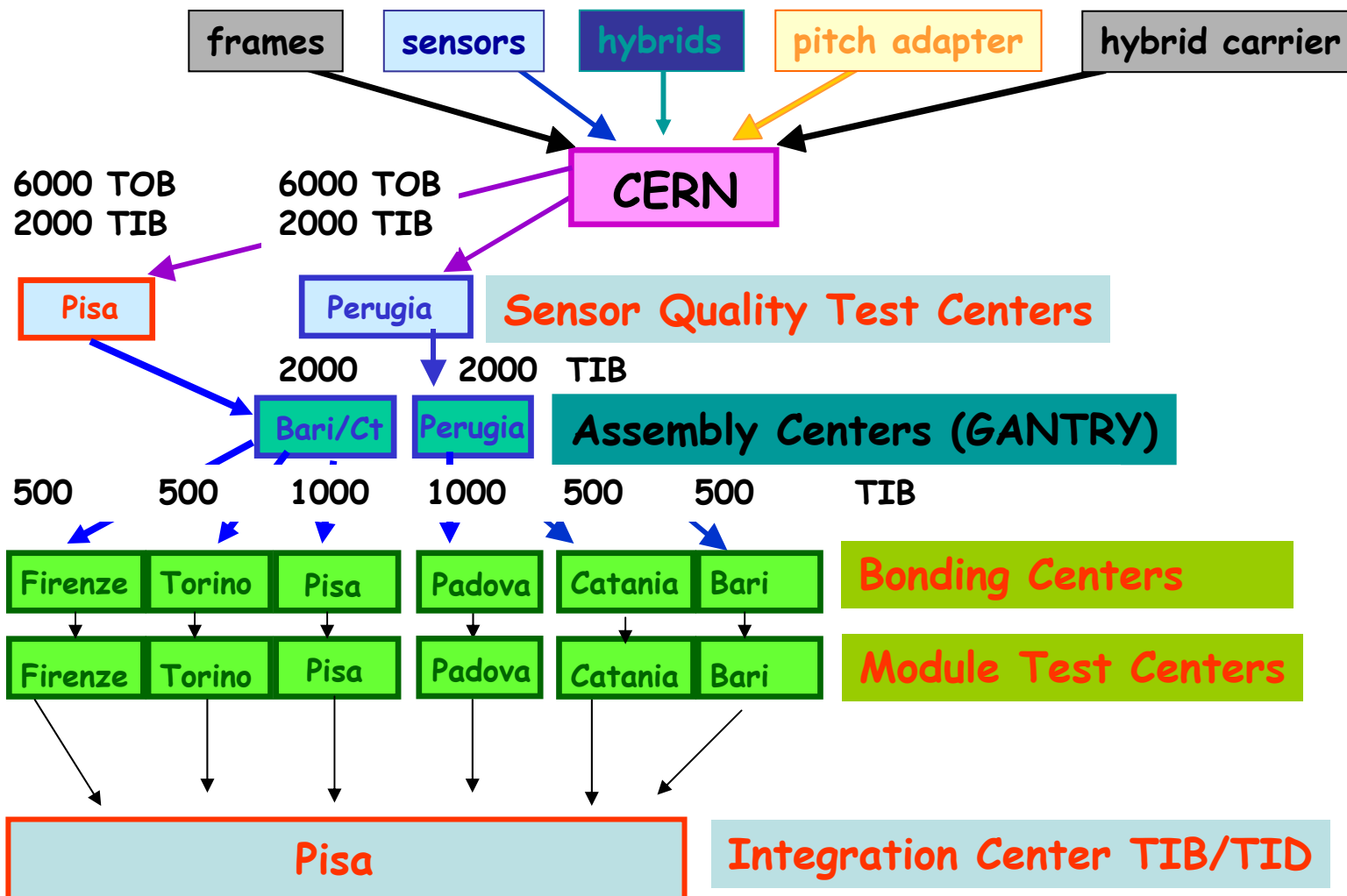
- Per dare un'idea della complessità dell'organizzazione richiesta nella costruzione di grandi apparati, prendiamo come esempio il tracciatore di CMS (rivelatore a pixel escluso):
- seguono 3 slide che illustrano le tipiche attività svolte da un centro di produzione locale, il flusso di produzione in Italia e in tutto CMS

Module Production in Bari



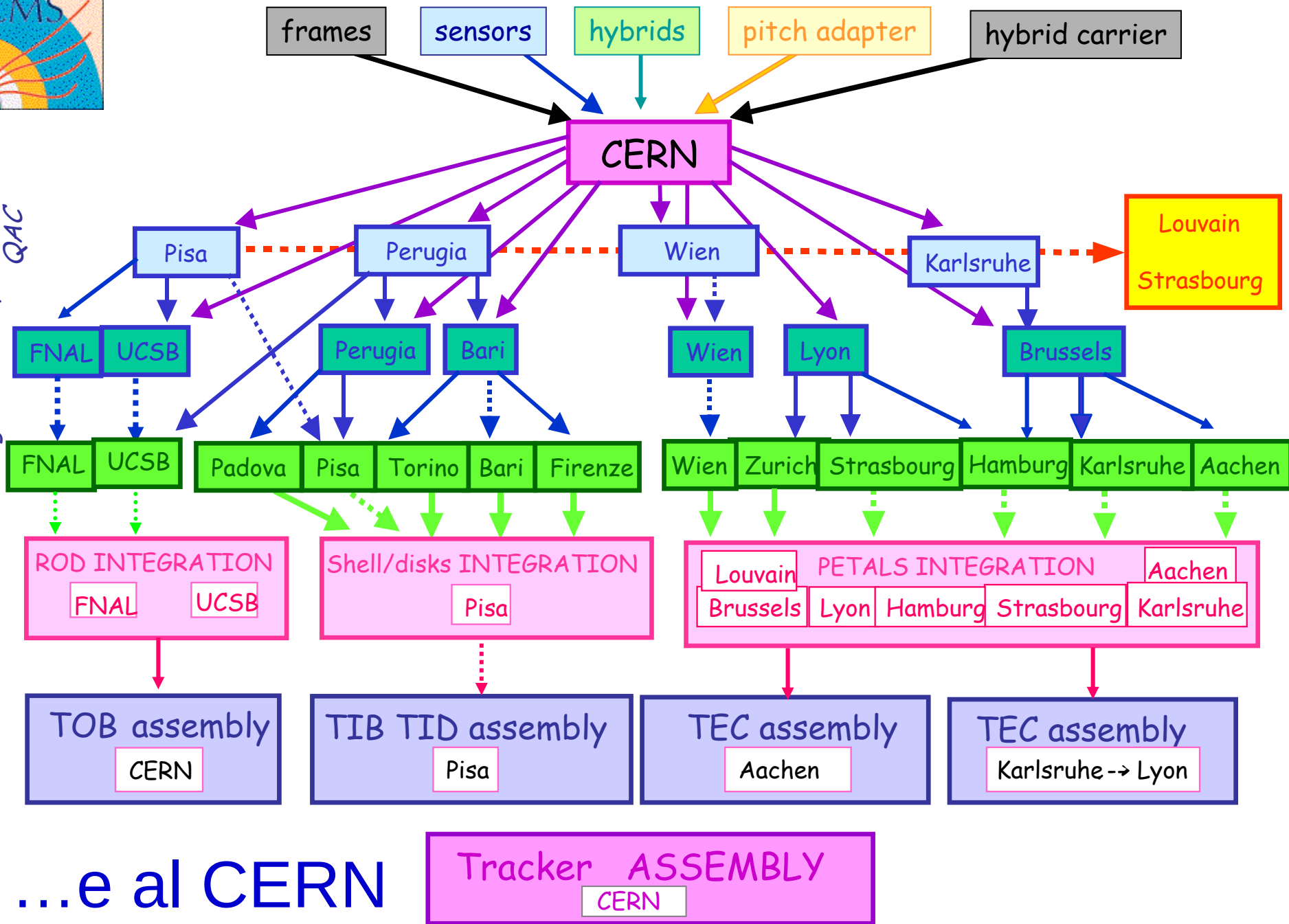


Production flux in Italia





Sensor
Assembly
QAC



...e al CERN

The background of the slide is a grayscale abstract pattern. It features numerous overlapping circles of varying sizes, some of which are solid dark gray, while others are lighter and semi-transparent. Superimposed on this circular pattern are several thin, horizontal, slightly wavy lines that create a sense of depth and movement.

Sviluppi per la fisica delle alte
energie ai futuri collider

Rivelatori al silicio a pixel

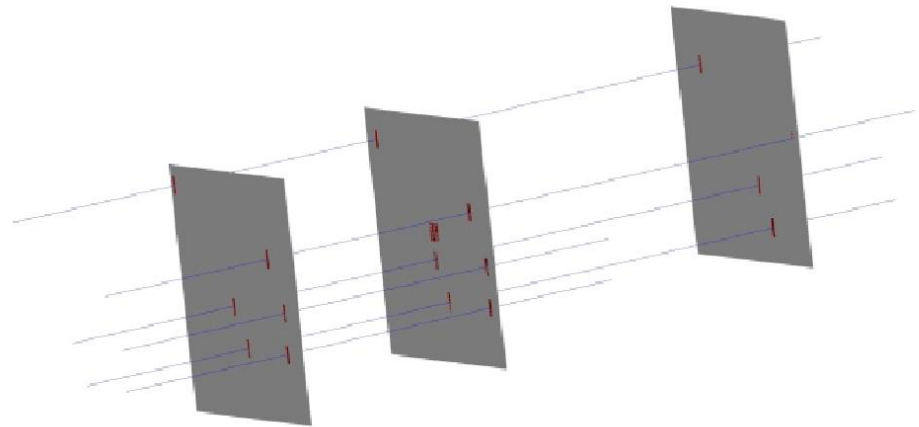
Struttura a pixel prodotta su un lato del silicio segmentando gli elettrodi come una matrice

Vantaggi:

- Basso rumore
- Vero 2d detector
- Veloce

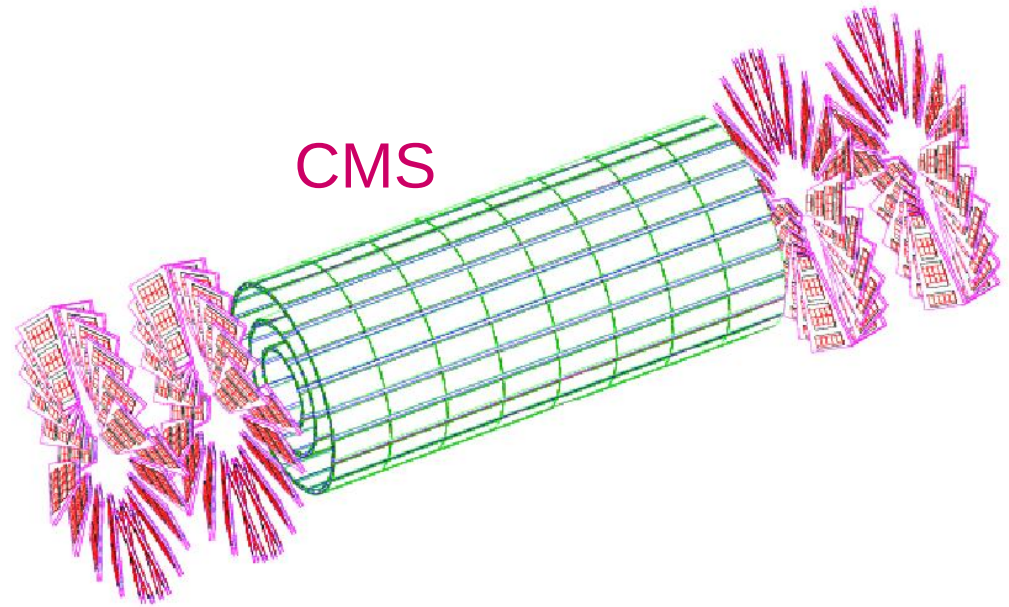
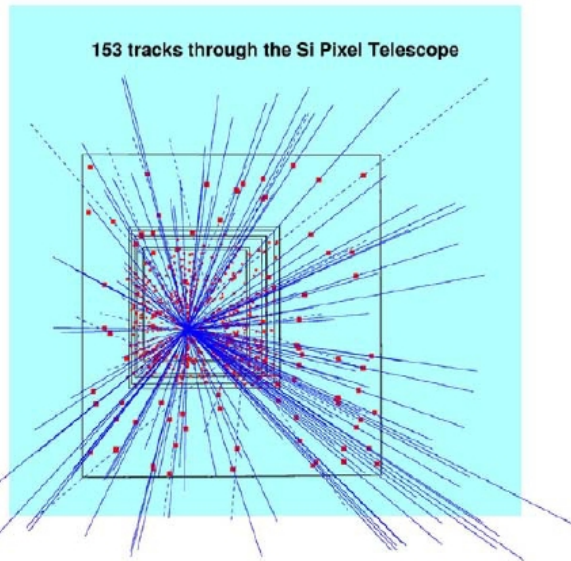
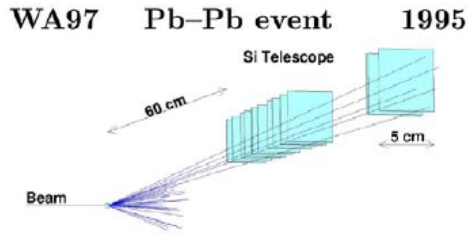
Svantaggi:

- Delicati
- Microtecnologia avanzata
- Elevati costi di produzione



Coordinate x-y fornite dalla matrice
Z ottenuta considerando più piani

EVOLUZIONE DEI DETECTOR A PIXEL



1776 moduli

Pixel $150 \times 150 \mu\text{m}^2$

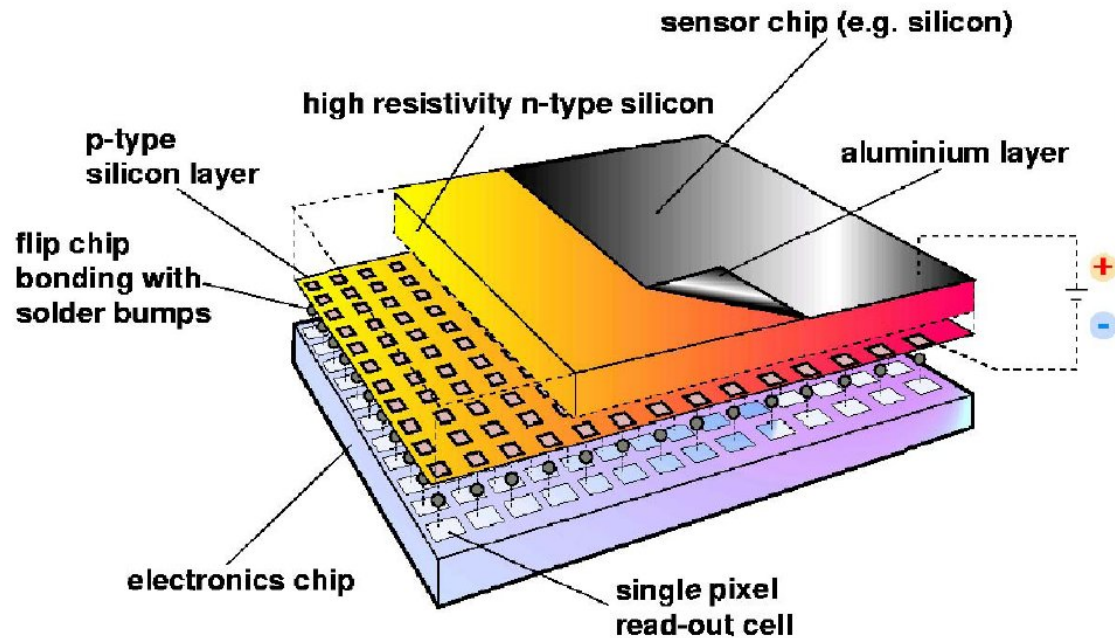
7.5×10^7 canali

Sette piani ($5 \times 5 \text{ cm}^2$)

72000 celle a pixel ($75 \times 500 \mu\text{m}^2$)

0.5×10^6 canali

Tecnologia ibrida a pixel



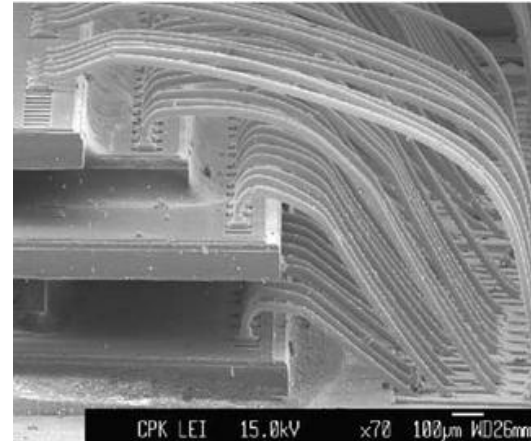
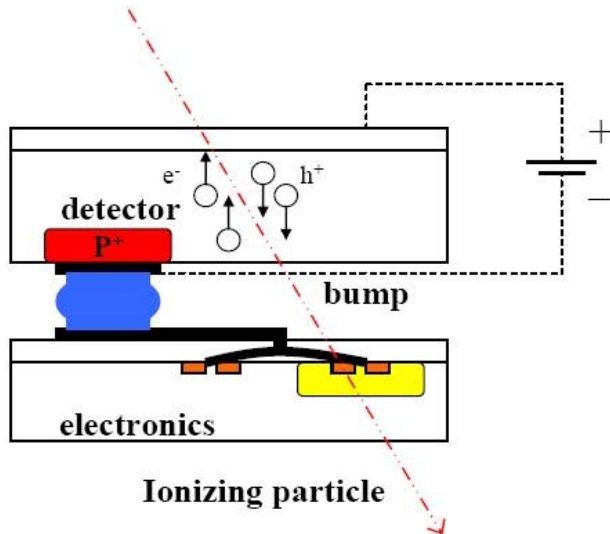
Base di silicio segmentata come matrice ad alta granularità

Ogni cella a pixel connessa all'elettronica di lettura

Elettronica di read-out della stessa geometria della cella a pixel

Connessione effettuata con bump bonding

Tecnologia ibrida a pixel



Vantaggi:

- Assemblaggio in step
- Standard industriale
- Utilizzo di materiali diversi oltre il silicio

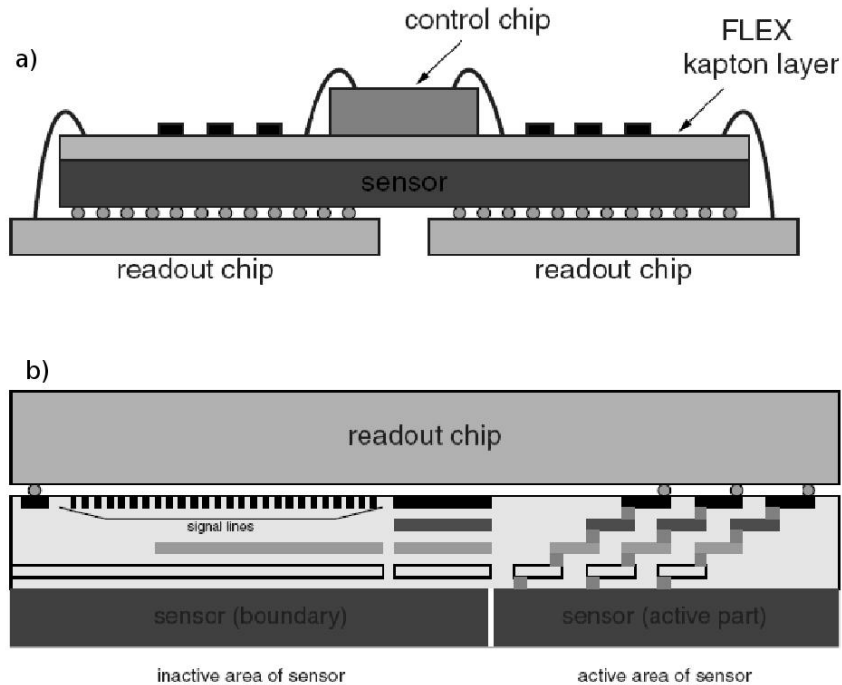
- Alta granularità

➤ Svantaggi

- Processi di saldatura e flip chip
- Corrispondenza uno-a-uno sensori e chip di lettura
- Densità di potenza (fattore critico in SLHC)

} **COSTI!**

Integrazione MCM-D⁽¹⁾



Integrazione sensori – chip di lettura in apparati quasi monolitici

Canali di alimentazione integrati nella zona inattiva

Layer metallici collegati per mezzo di vias

Applicazione di tecniche di bonding e flip-chip

Vantaggi: ⁽²⁾

- Moduli compatti
- Miglioramento S/N

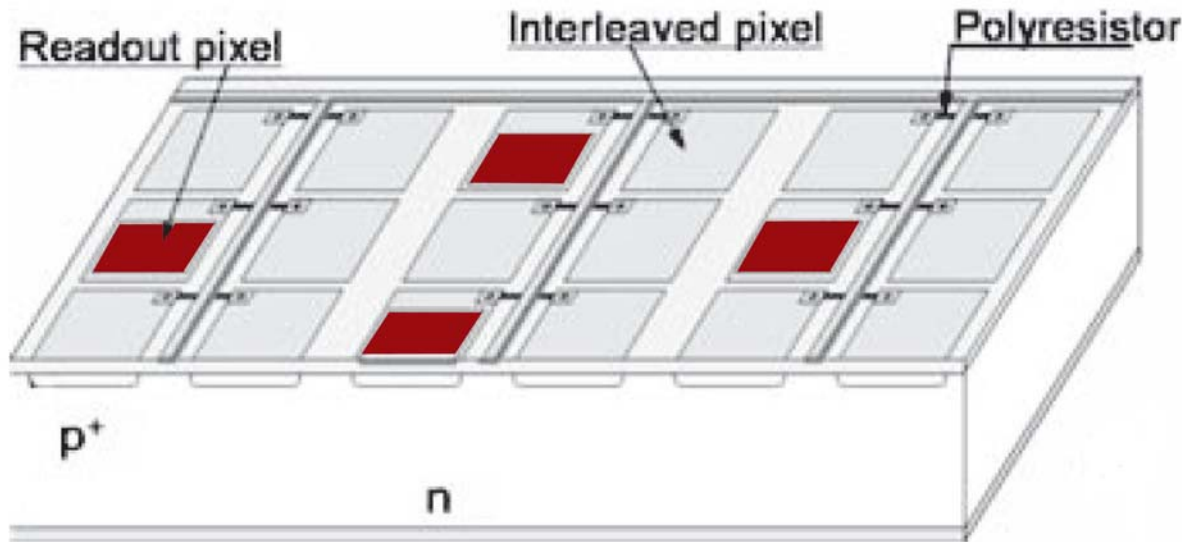
Svantaggi

- Elevati costi di produzione

(1) J. Wolf: High density pixel detector module using flip chip and thin film technology. SPIE Conference Vol. 4217

(2) P. Gerlach: Nuclear Instrument Methods A 473

Interleaved Hybrid Pixel⁽¹⁾



Accoppiamento
capacitivo dei pixel

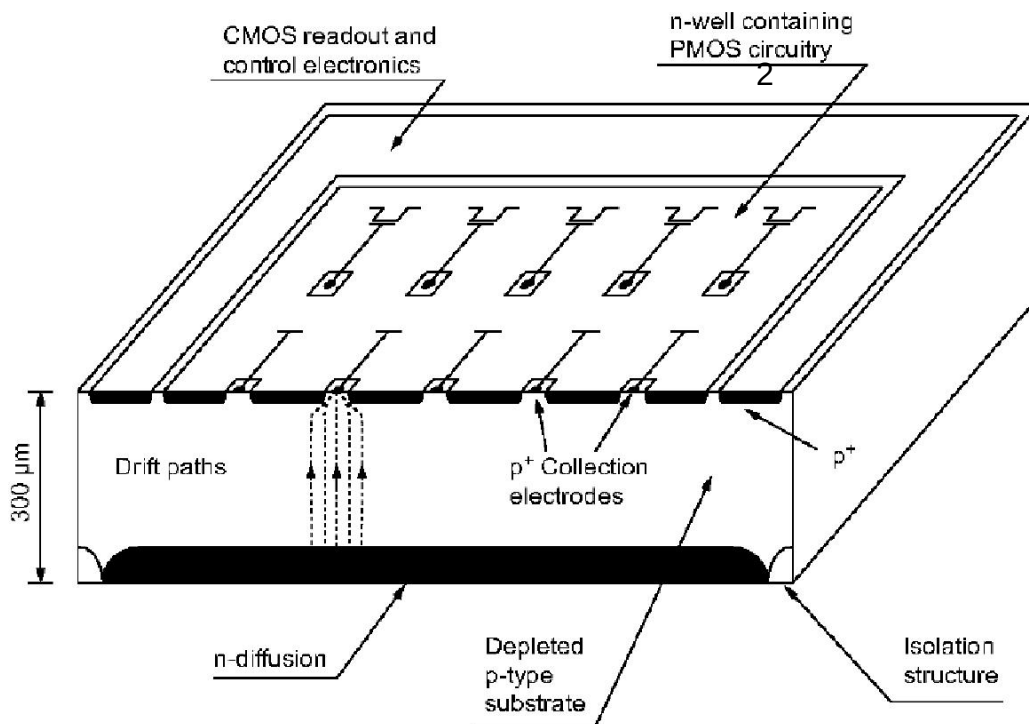
- Tutti i pixel sono polarizzati
- Lettura dei pixel parziale
- Passi dell'elettronica di lettura e bump-bonding maggiori del passo dei pixel
- Charge sharing e capacità interpixel migliora la risoluzione spaziale

Vantaggi

- Minori costrizioni sui processi di saldatura
- Riduzione del consumo totale di potenza

(1) W.Kucewicz: Acta Physics Pol. B 30

Pixel monolitici⁽¹⁾



Realizzata una matrice 10x30
(125x34μm²) ⁽²⁾

- Caratterizzata in un fascio di muoni
- Telescopio costituito da 4 array
- S/N=55
- $\sigma=2,2\mu\text{m}$

Sensore realizzato su un substrato *p* ad alta purezza e resistività

Giunzione realizzata da uno strato di diffusione *n*

Matrice di contatti ohmici costituisce gli elettrodi di raccolta

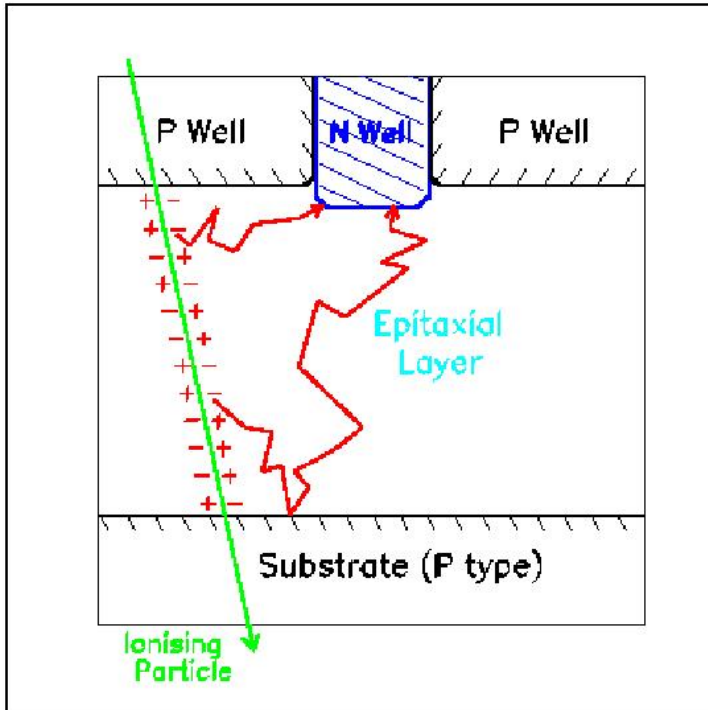
Lettura di ogni cella a pixel con PMOS

⁽¹⁾ G.Claus: NIM A 473

⁽²⁾ C.J. Kennedy: NIM A 342

Pixel monolitici CMOS: MAPS⁽¹⁾

(Monolithic Active Pixel Sensor)



CMOS utilizza silicio a bassa resistività

Strato epitassiale di silicio di $15\mu\text{m}$

Carica mantenuta nello strato epitassiale

Carica raccolta nella *n-well*

Segnale di carica molto piccolo ($<1000e^-$)

Rumore dell'elettronica molto basso

Tempo di raccolta ($\sim 100\text{ns}$)

(1) W. Dulinski: CMOS monolithic active pixel sensor for high resolution particle tracking. Proc. Frontier Detectors for frontier Physics 2003.

Pixel monolitici CMOS (MAPS)

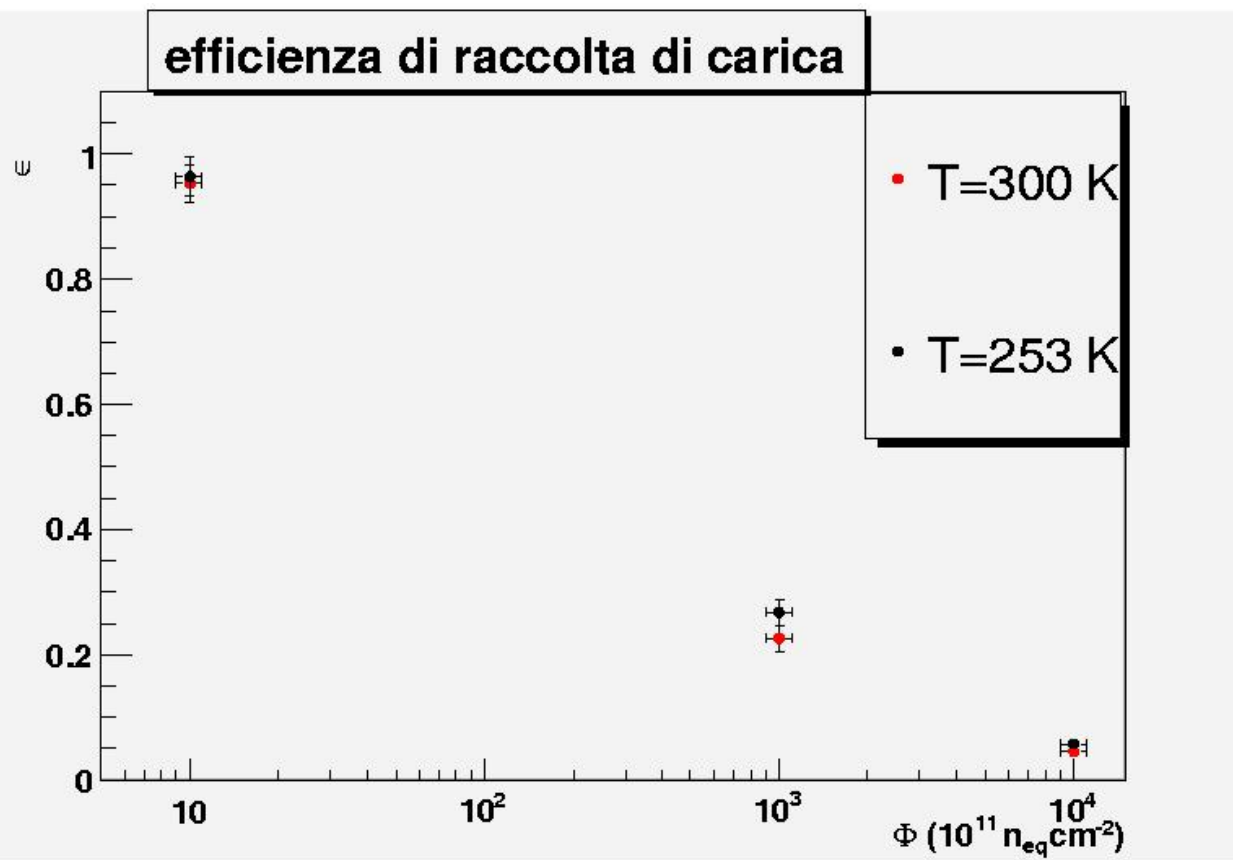
Limitazioni:

- Utilizzo di dispositivi NMOS nell'area attiva
- Resistenza al danno di radiazione (vedi slide successiva)

Vantaggi :

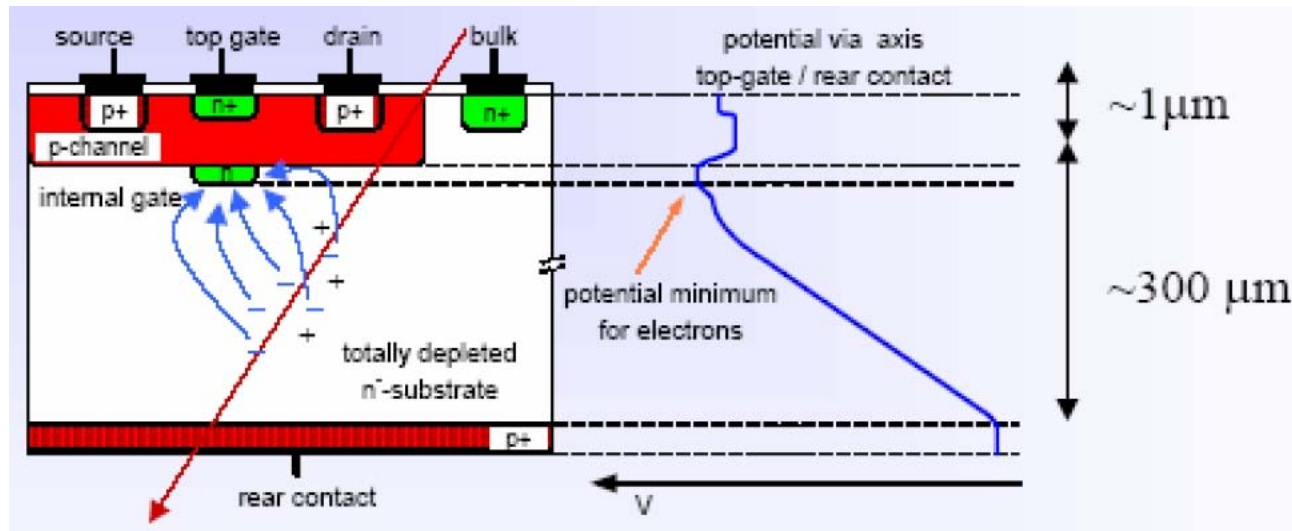
- Bassi costi di produzione

Pixel monolitici CMOS (MAPS)



Degradazione del segnale
del 77% dopo fluenze di
 $10^{14} \text{ p } 24\text{GeV/c}$ (1)

DEPFET Pixel⁽¹⁾



Substrato ad alta resistività totalmente svuotato lateralmente

Primo stadio di amplificazione a transistor ad effetto di campo

Elettroni raccolti da un gate interno

➤ Corrente del transistor modulata dalla carica raccolta

➤ Carica rimossa da un contatto dedicato (clear)

Bassa capacità (~fF) e amplificazione in situ => basso rumore ($ENC=4,8 \pm 0,1e^-$)

Possibilità di realizzare rivelatori molto sottili (~50 μm)

(1) E. Gatti: NIM A 225

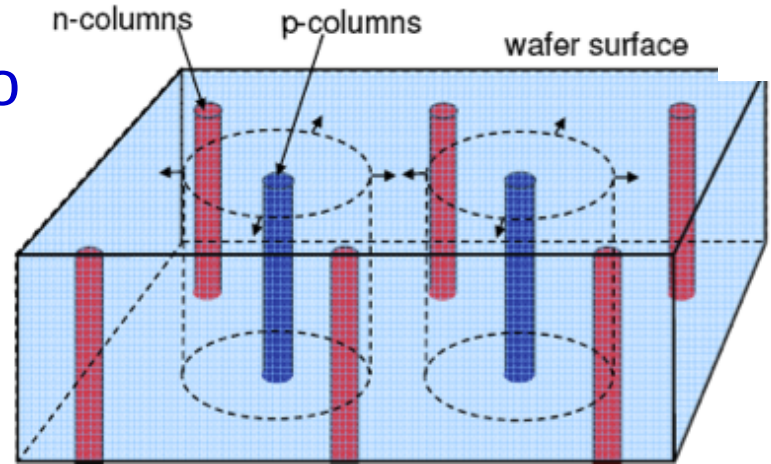
Basso consumo di potenza => rivelatori privi di sistema di raffreddamento

Sensori 3D

Proposti da S.I. Parker, C.J. Kenney and J. Segal NIM A 395 (1997) 328

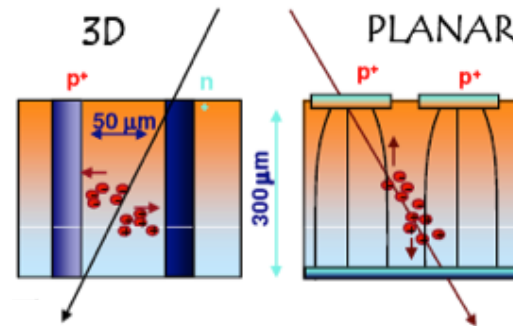
elettrodi che penetrano nel substrato
(colonne) → **3D**

diametro colonne : 10 μm
pitch: 50 - 100 μm



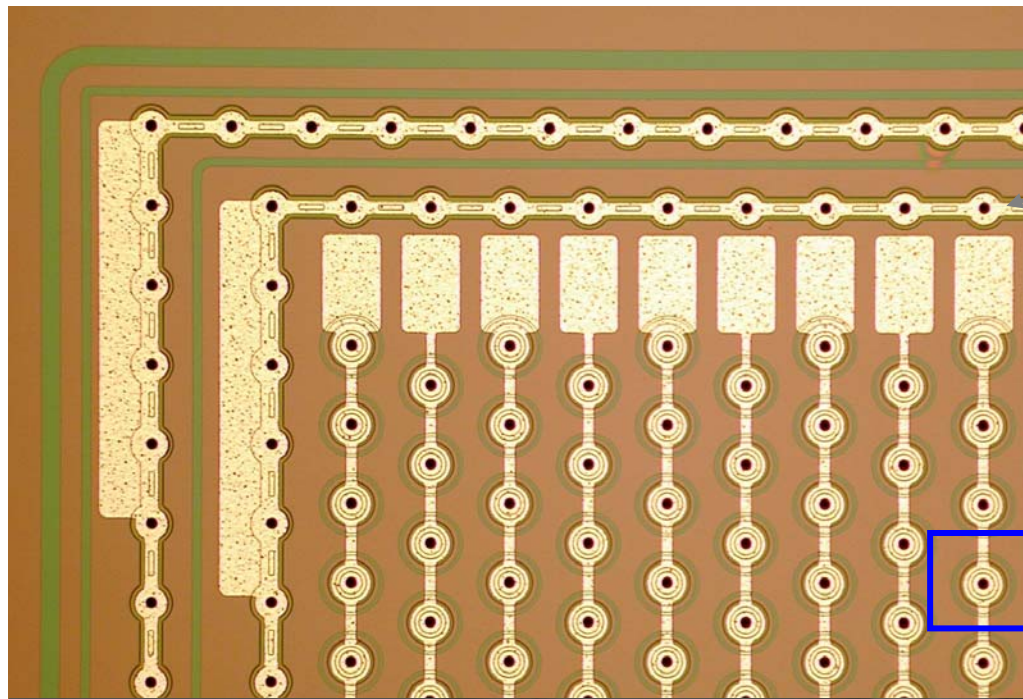
vantaggi della tecnologia 3D:

- minore tensione di svuotamento
- maggiore risoluzione spaziale
- spessore tutto attivo
- minore distanza di drift
 - segnale più rapido
 - maggiore resistenza alla radiazione



SingleTypeColumn-3D detectors: Strip detectors layout

C. Piemonte et al, Nucl. Instr. Meth. A 541 (2005)



guard ring

bias line

metal

p-stop

hole

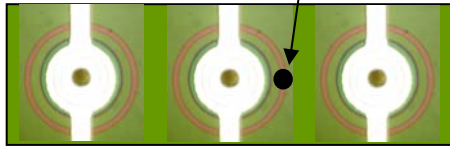
n⁺

Contact opening

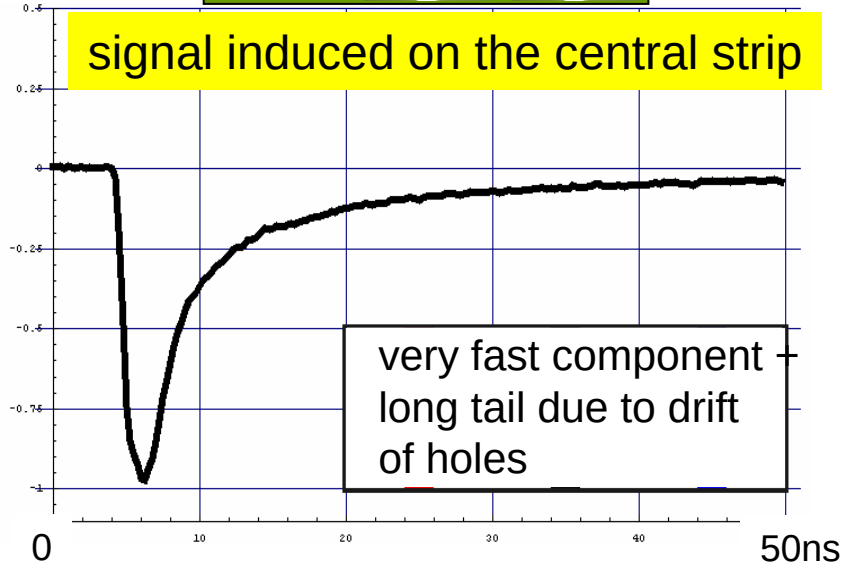
Measured current signal in 3D-stc (2)

Many data available! Two examples shown below.

beam position



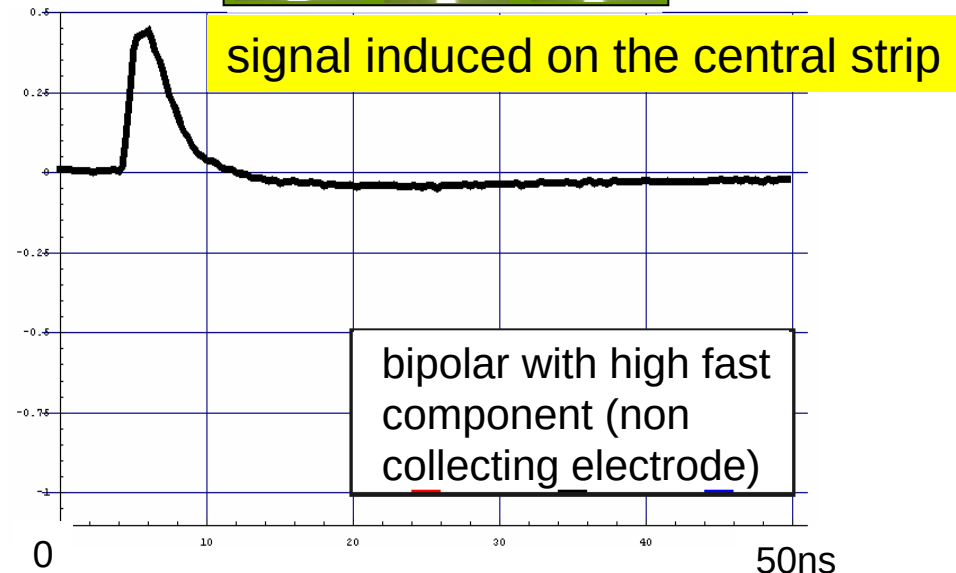
signal induced on the central strip



beam position



signal induced on the central strip



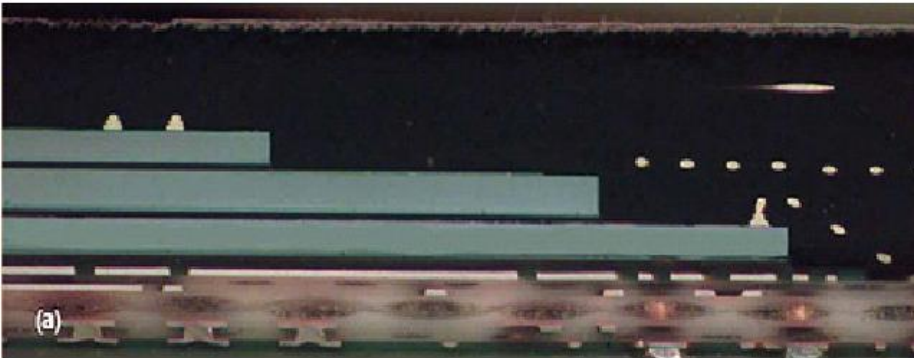
Measurements well reproduce the simulations previously reported!

More work has to be done, above all on irradiated detectors.

Interconnessione 3D⁽¹⁾

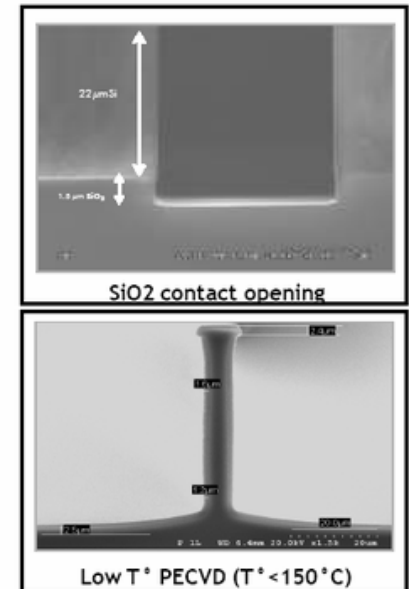
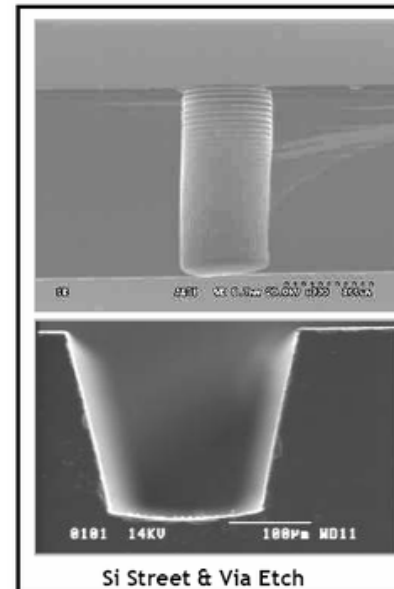
Sviluppi tecnologici indirizzati:

- Miglioramento performance e funzionalità
- Riduzione dimensioni, potenza assorbita e costi



Collegamento assicurato da TSV
(interconnessioni verticali)

3D-stacking (apparati assemblati in
senso verticale)



(1) R. Lipton: NIM A 579 (2007)

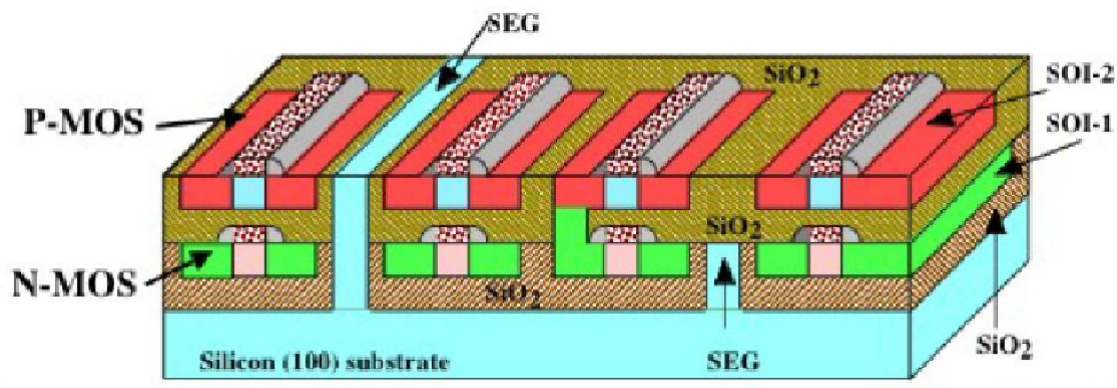
Interconnessione 3D

Vantaggi:

- Riduzione delle misure del package
- Aumento della velocità di comunicazione fra i vari componenti

Performance migliori:

- Pixel più piccoli
- S/N più elevato



Integrazione tecnologiche diverse:

Elettronica CMOS su dispositivi DEPFET

Elettronica CMOS su dispositivi MAPS

Interconnessione 3D

Problematiche legate alle tecnologie costruttive da adottare

- Creazione vias: laser Vs. DRIE
- Riempimento vias: materiali da utilizzare (Cu, Poly Si) e tecniche (elettroimpiantazioni, CVD)
- Saldature: Cu-Cu, fusione diretta
- Stacking: wafer-wafer, chip-to-wafer, chip-to-chip.

EMC-3D (Alcatel, Fraunhofer IZM, TAMU...)

CONCLUSIONI

- Canale di ricerca attivo e in costante sviluppo
- Soluzioni descritte (DEPFET, 3D...) sono ancora in fase di R&D
- SLHC: si utilizzeranno probabilmente ancora pixel abbastanza convenzionali, tranne che nello strato più interno
- Attenzione alle tipologie di interconnessioni da utilizzare: sono in corso sviluppi interessanti.