Tracking systems in HEP:
concept and performance of 3 experiments

Davide Bolognini

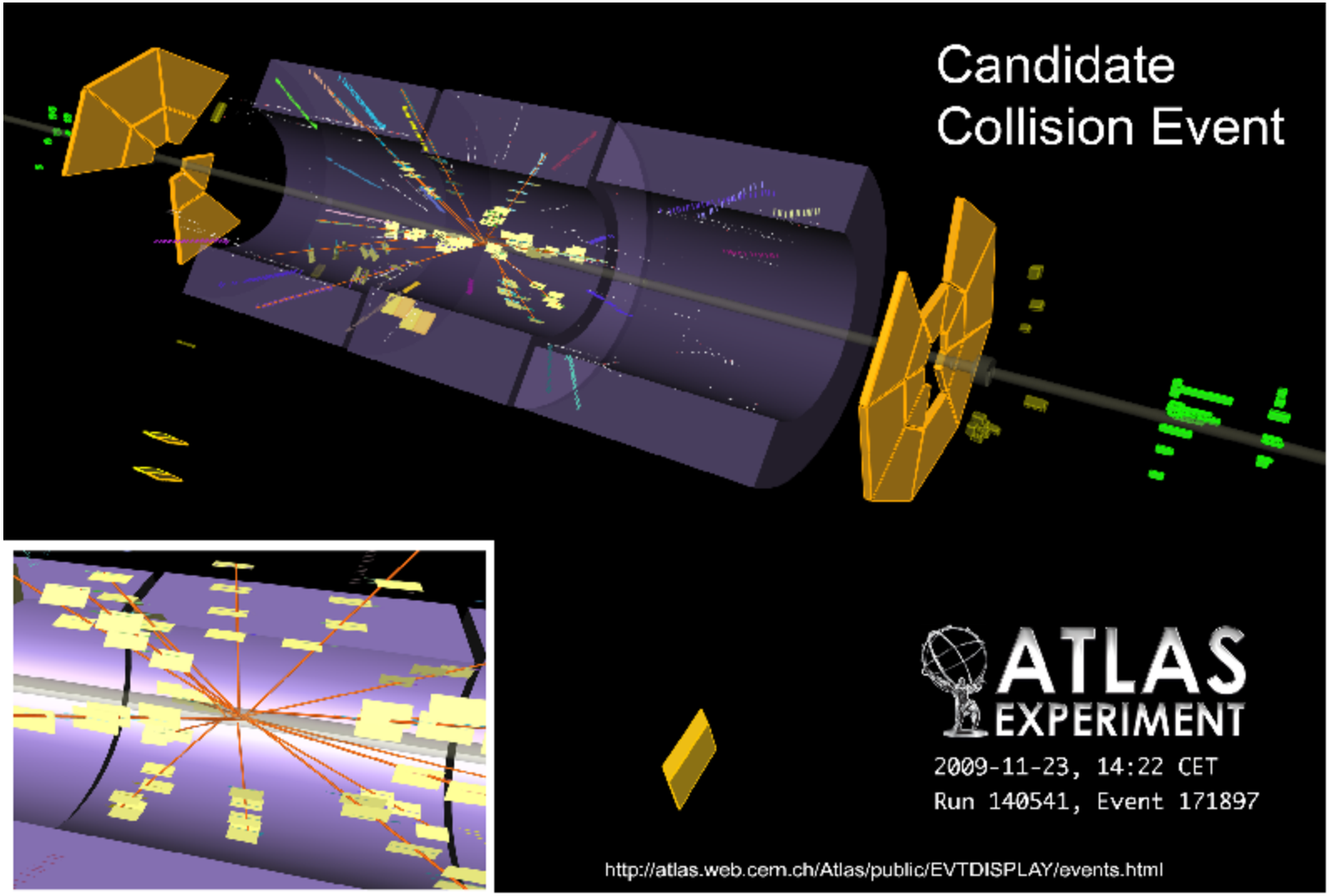
Universita' degli Studi dell'Insubria

Presentazione dottorato – Anno I

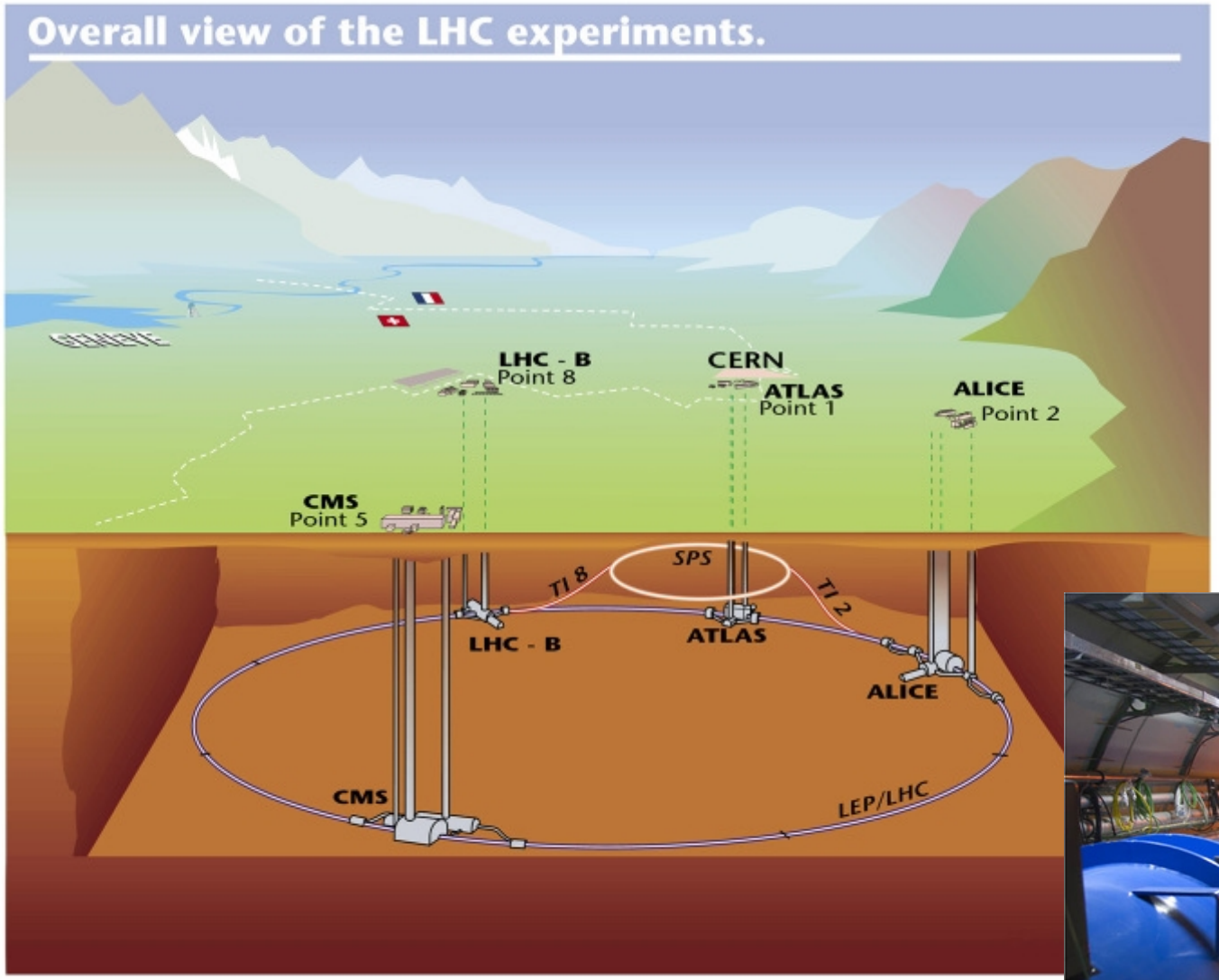
Outline

- **Tracking systems in HEP**
  - CMS @ LHC...but not only: TOTEM
  - ATHENA and the antimatter
- **Tracking systems in 3 experiments:**
  - UA9 & H8RD22
  - MUSASHI / ASACUSA
  - MICE
- **Conclusions**

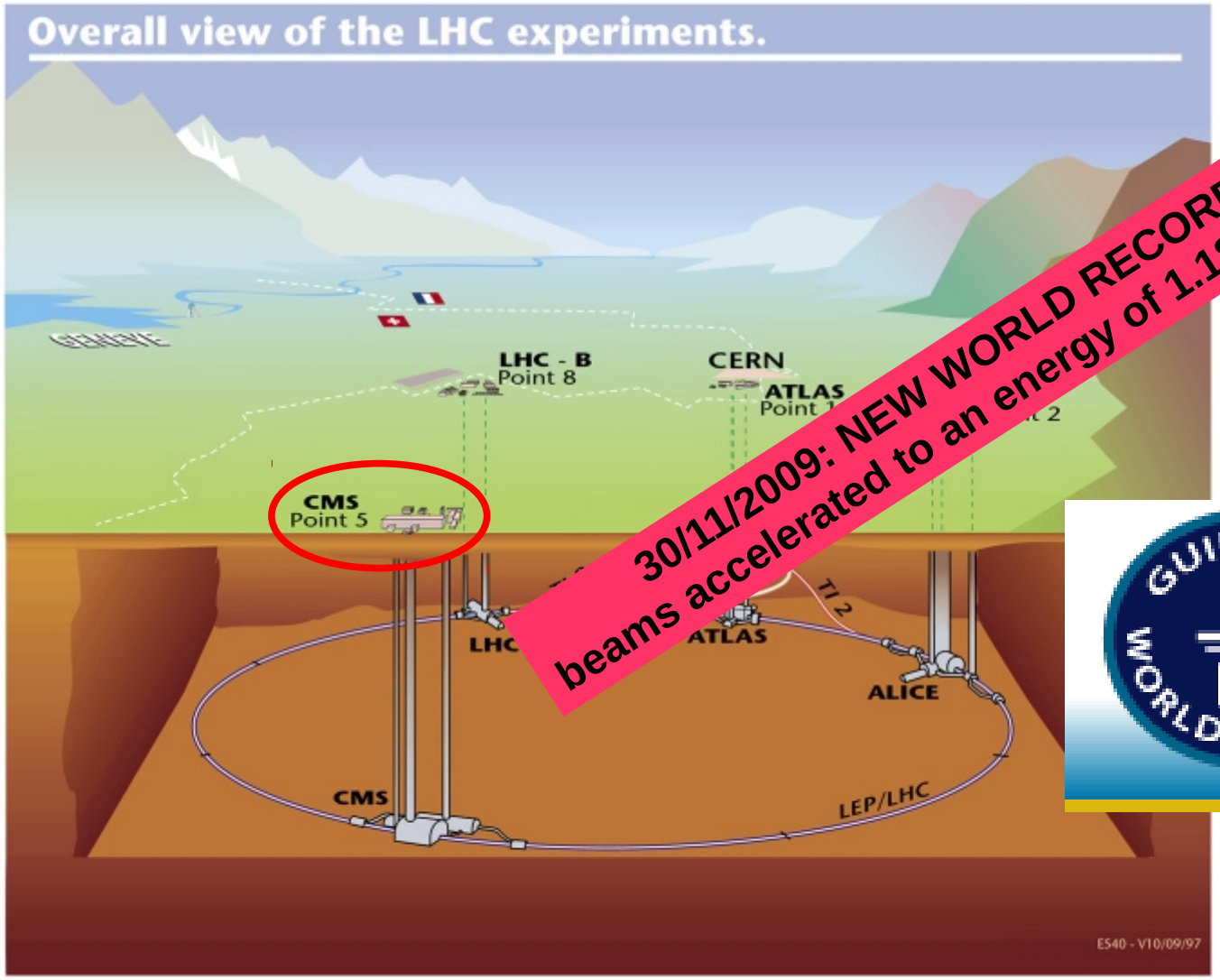
Tracking systems in HEP



LHC



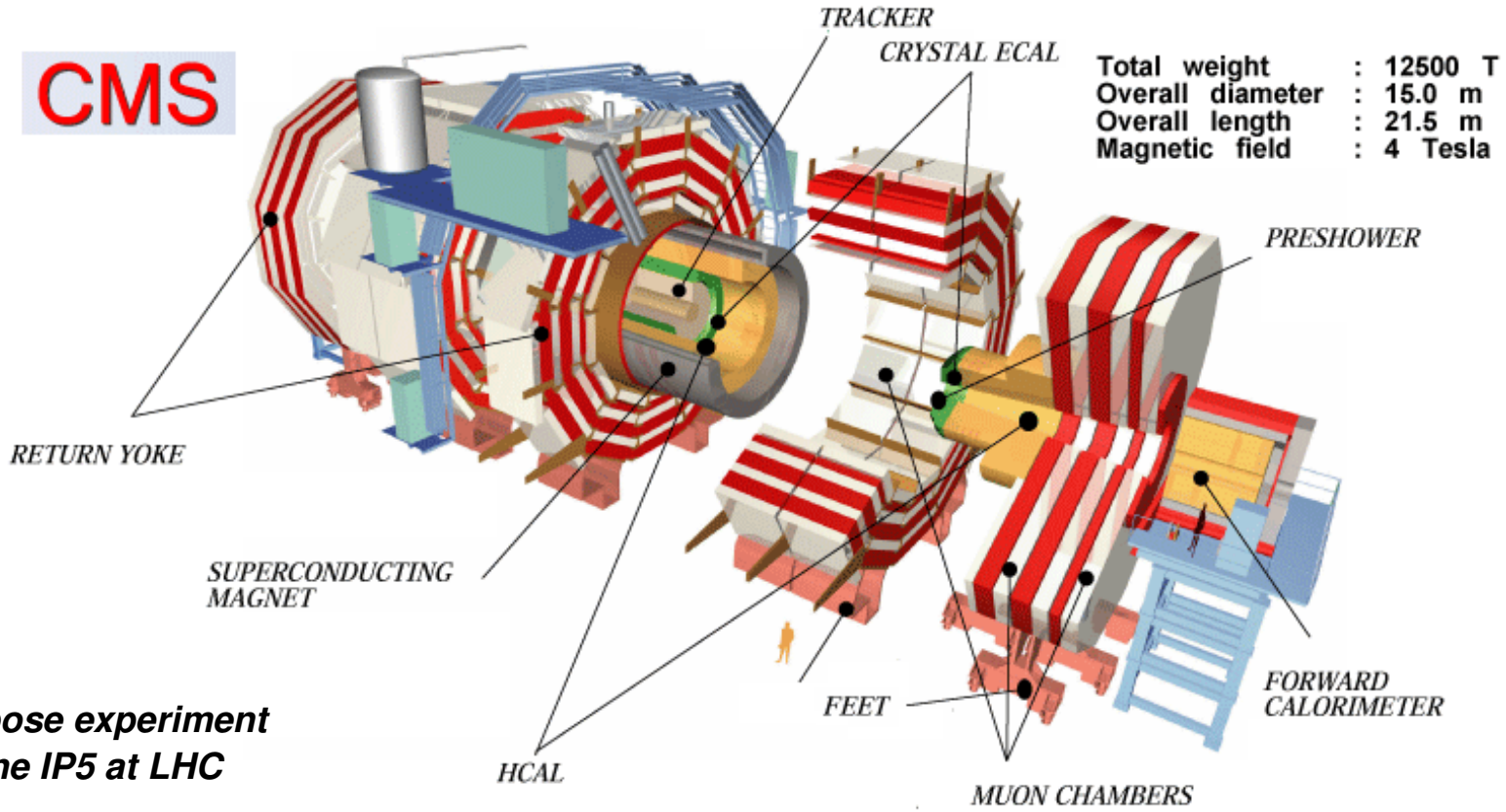
- Proton-proton beam collision
- 14 TeV in the IP
- ~9300 magnets
- 8 RF cavities per beam



30/11/2009: NEW WORLD RECORD: beams accelerated to an energy of 1.18 TeV

- General purpose: CMS, ATLAS
- LHCb for the b-physics
- ALICE for heavy ions physics

CMS @ LHC



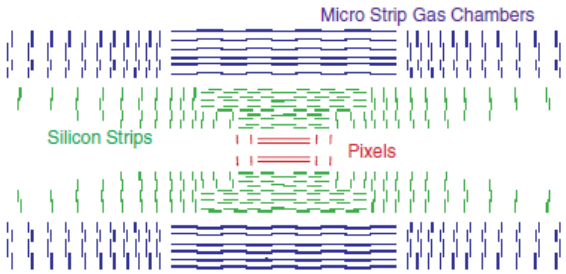
General purpose experiment installed at the IP5 at LHC

GOAL

- **to explore physics at the TeV scale**
- **to discover the Higgs boson**
- **to look for evidence of physics beyond the standard model, such as supersymmetry, or extra dimensions**
- **to study aspects of heavy ion collisions**

The CMS tracking system

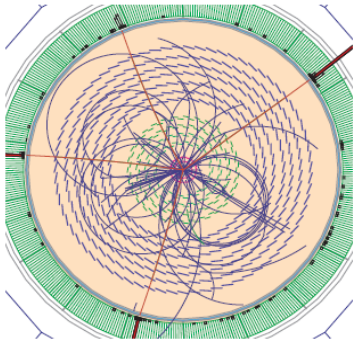
Track identification

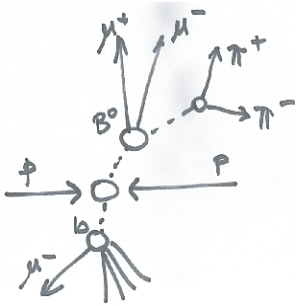


- Pixels, Silicon Microstrip and Micro Strip Gas Chambers (MSGC)
- Stringent resolution, granularity and robustness requirements in the high, medium and low occupancy regions.
- 4T magnetic field

Momentum measurement

- The momentum of electrically charged particles is determined from the bending of the track trajectory in the magnetic field of CMS.
- High efficiency of reconstruction (95%) for charged hadrons with pT above 10 GeV.





Vertex identification

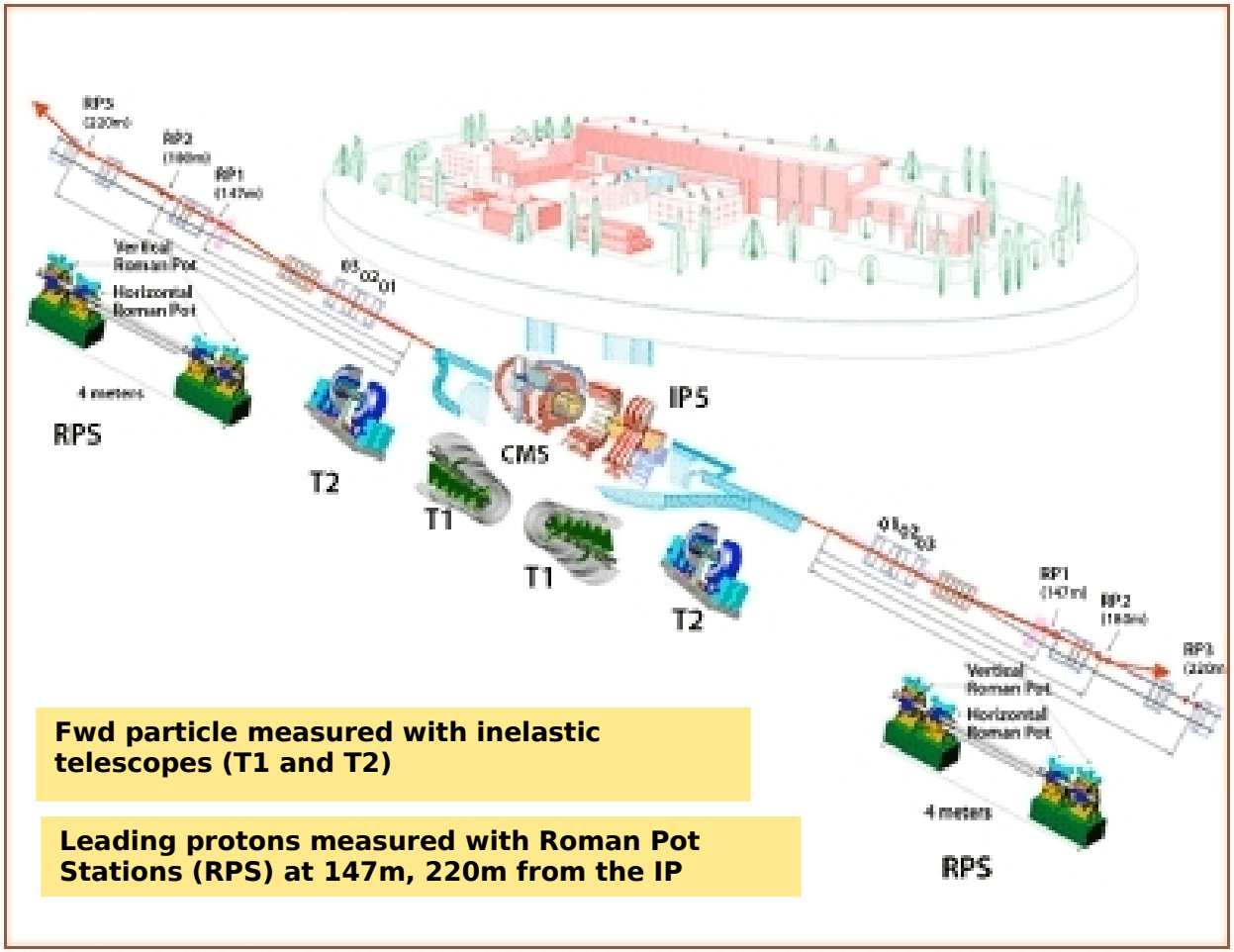
- The position of decay vertices in the tracking volume depends on the lifetime of the decaying particle.
- The reconstruction of such vertices is crucial for "b-tagging", very important tool for many physics studies, from the search of low-mass Higgs bosons to studies of the top quark

TOTEM

Installed in the LHC IP5 (CMS pit) to study small angle events

GOAL

- Total pp cross-section
- Elastic Scattering
- Diffraction
- Forward physics

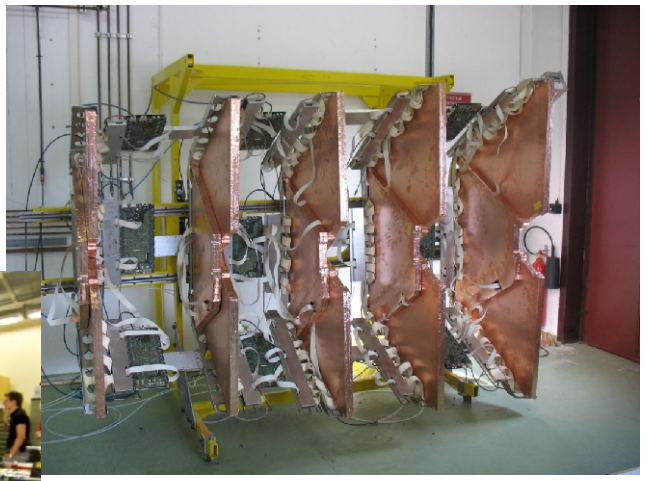


Fwd particle measured with inelastic telescopes (T1 and T2)

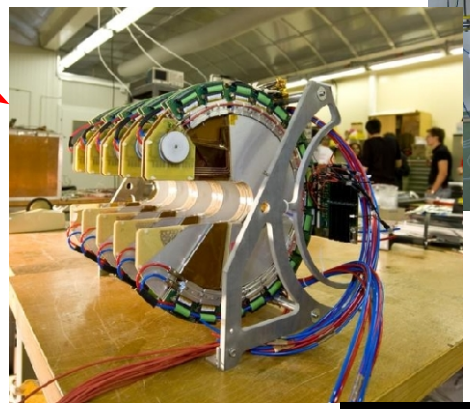
Leading protons measured with Roman Pot Stations (RPS) at 147m, 220m from the IP

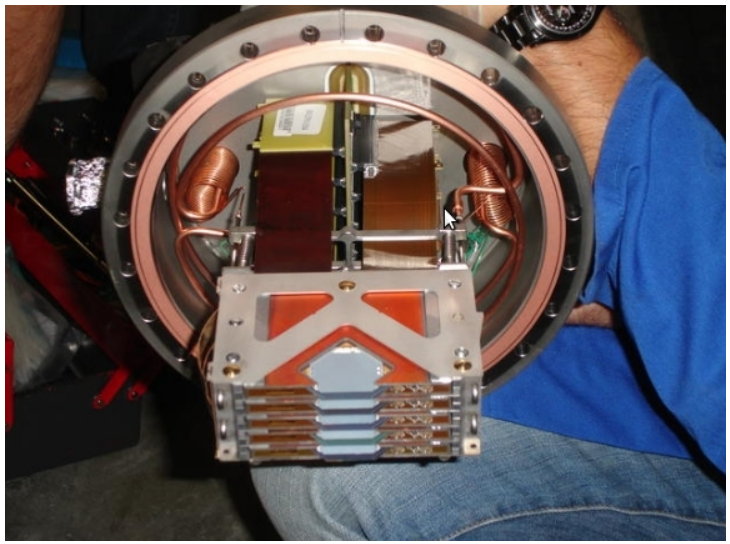
The TOTEM tracking system

T1 & T2: measurement of the inelastic rates identifying beam-beam events with detectors capable to trigger and reconstruct the inter-vertex



Cathode Strip chambers *(CSC)* for T1
Gas ElectronMultiplier chambers *(GEM)* for T2



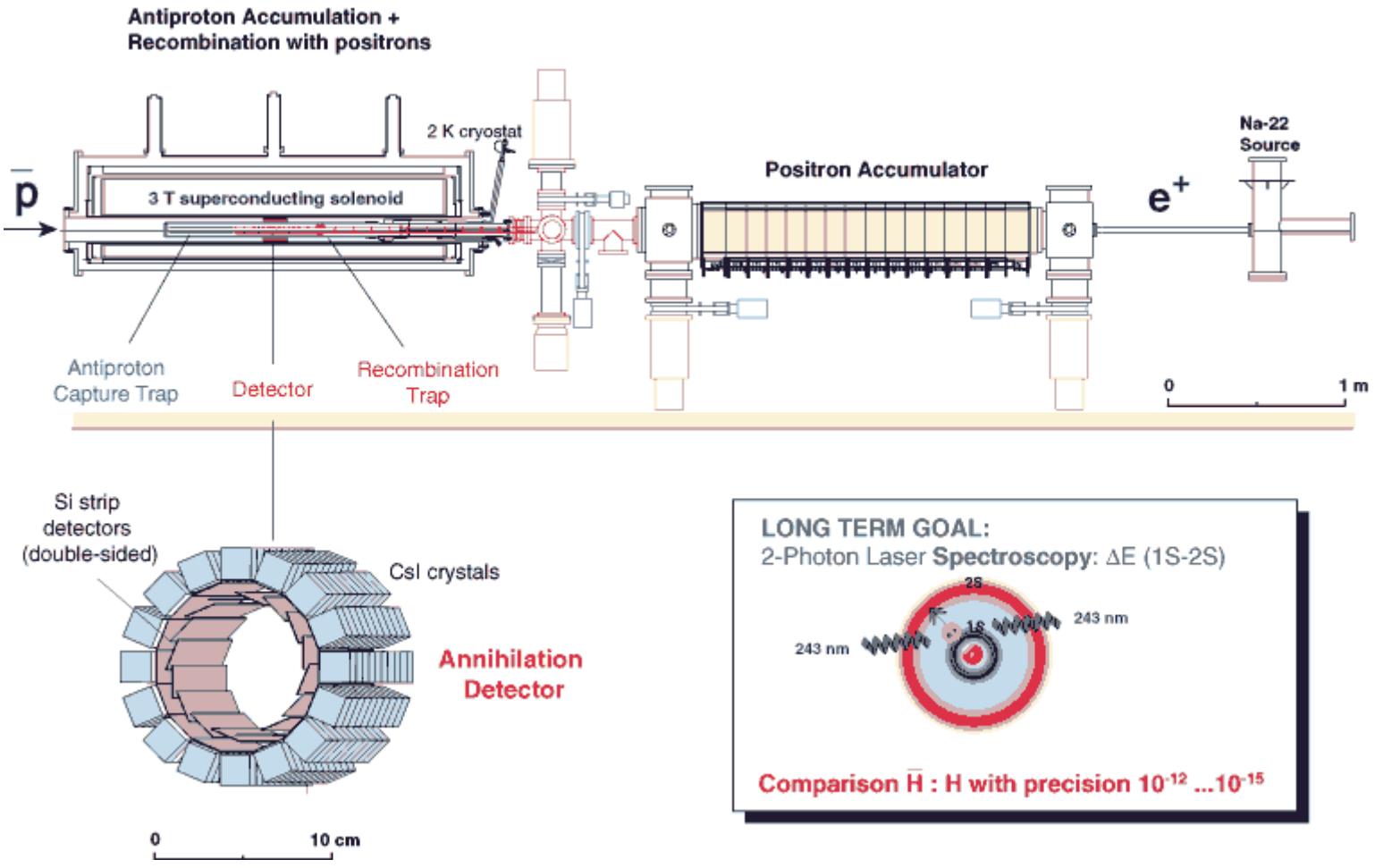


ROMAN POT: maximize acceptance at low angle

Edgeless Si-detectors
Minimized space between detector edge and window
Minimized window thickness

ATHENA @ AD

ATHENA / AD-1 : Antihydrogen Production and Spectroscopy



LONG TERM GOAL:
2-Photon Laser **Spectroscopy**: ΔE (1S-2S)

Comparison $\bar{H}$: H with precision 10^{-12} ...10^{-15}

- $2 \cdot 10^4$ antiprotons captured and cooled in antiproton capture trap
- These antiprotons transferred and captured in recombination trap
- Multiple AD shots stacked without significant losses
- 150 million positrons accumulated per 5 minute cycle
- 25 million positrons stored in recombination trap for several hours
- Antihydrogen detector fully commissioned
- Antiproton vertex resolution s ~ 3-4 mm (“antiproton tomography”)

ATHENA working principle

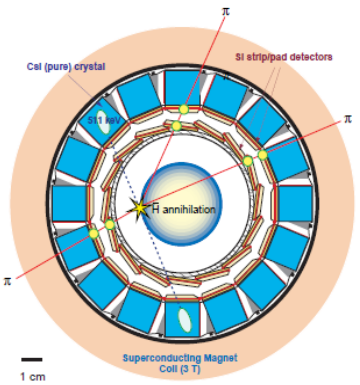
The ATHENA tracking system

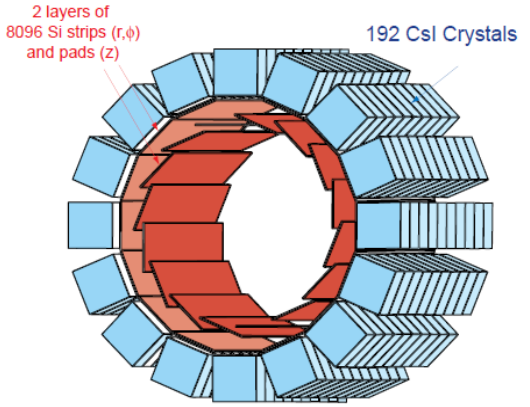
GOAL

- Vertex from tracking of charged particles
- Identification of 511 keV gammas
- Time- and space coincidence of tracks + gammas
- High rate capability (trigger: 1 MHz, readout: 100 Hz)

DESIGN

- Compact (radial dimension ~ 3 cm)
- Large solid angle (> 70 %)
- High granularity (8 K strips, 192 crystals)
- Operation at T ~ 140 K, B = 3 Tesla



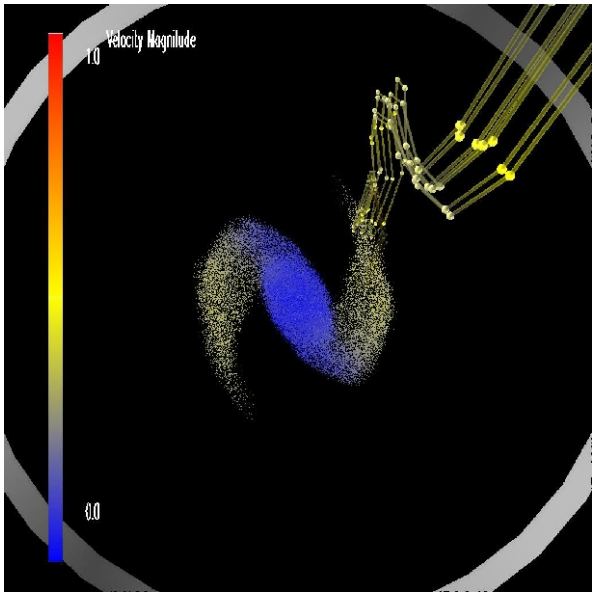


The “recipe” for a tracking system

To track particles (charged or neutral), you need:

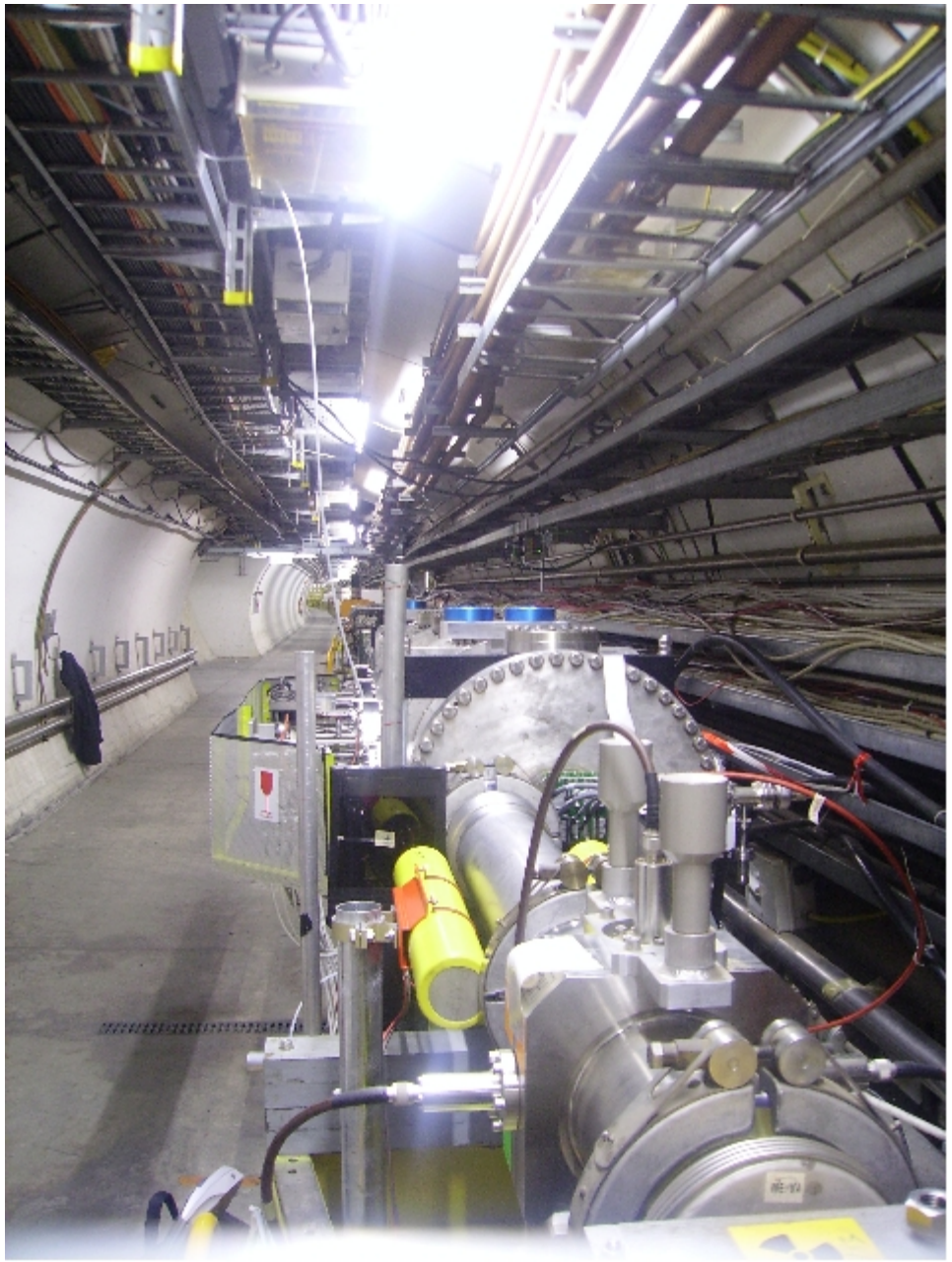
- **High spatial resolution...** **but NOT always...**
- **Silicon detectors...** **but NOT always...**
- **A lot of material or channels** **but NOT always...**
- **Very fast DAQ...** **but NOT always...**
- **A lot of money...** **but NOT always...**

IT DEPENDS



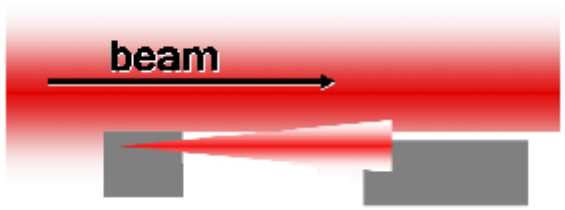
3 tracking systems for 3 experiments

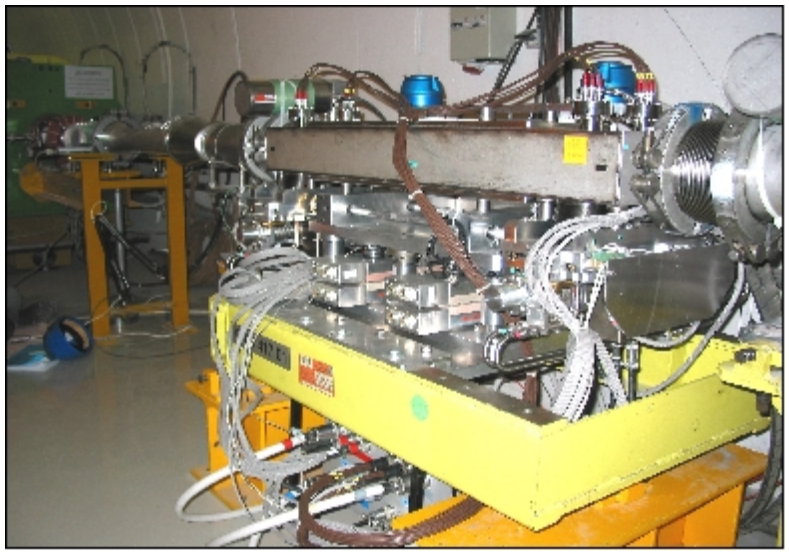
UA9 & H8RD22

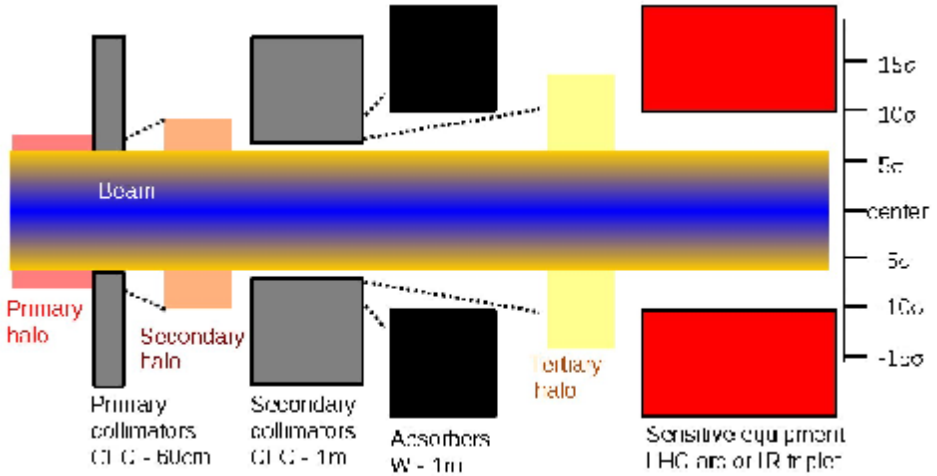


Hadron accelerator collimation system

Present system: a multistage collimation system like the LHC one







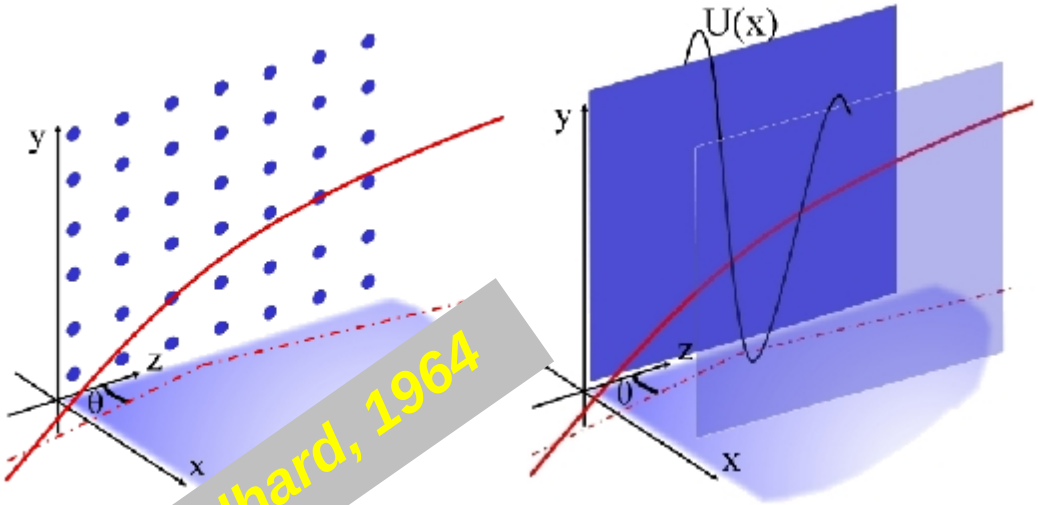
The halo beam is spread on the whole solid angle by CFC collimators:

- ⇨ **Superconducting magnets could quench**
- ⇨ **High impedance level**

40% of the nominal luminosity

A new idea: bent crystals

"In a crystal, a charged particle feels an average potential due to the atomic planes"

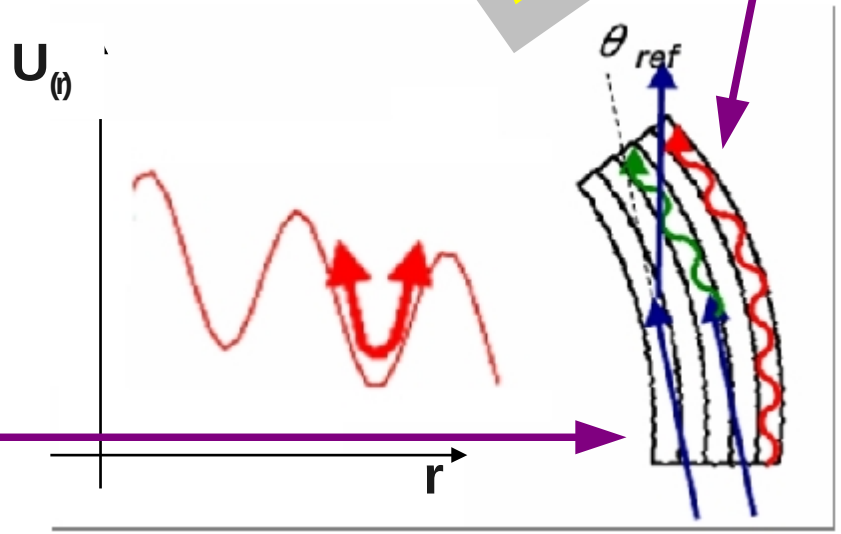


Lindhard, 1964

Channeling

"In a bent crystal, a charged particle follows the bent planes and can be deviated from the original trajectory"

Tsyganov, 1976



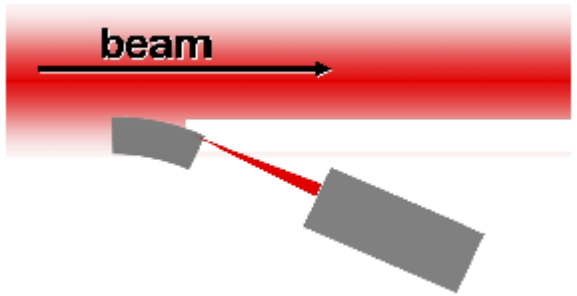
Volume reflection

"In a bent crystal, if a charged particle encounters the atomic plane tangency point it can be reflected by the crystal volume"

Taratin/Vorobiev, 1989

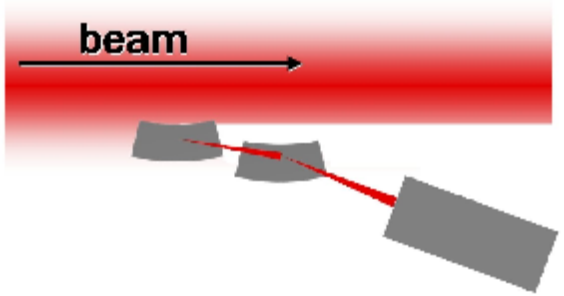
A bent crystal: a clever collimator?

Channeling



- **Angular acceptance** limited by the Lindhard critical angle (~10µrad @400 GeV/c)
- Efficiency of the order of 50% @400 GeV/c
- **Large deflection angle** (~130µrad @400 GeV/c)

Multi volume reflection



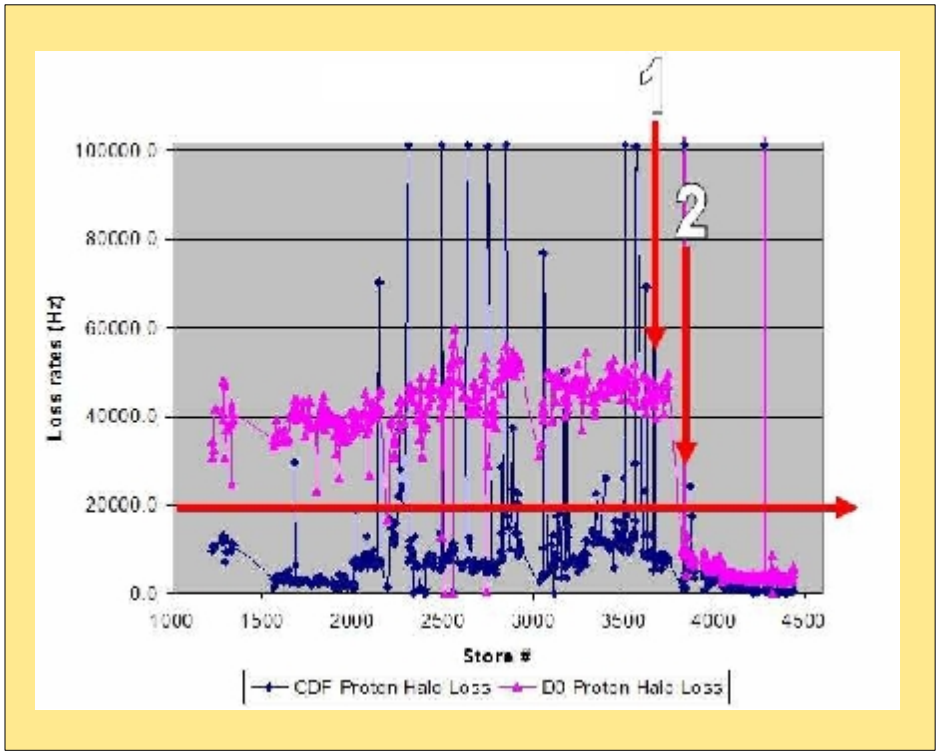
- **Larger angular acceptance** (channeling deflection angle)
- Efficiency of the order of **100%** @400 GeV/c
- Small deflection angle (~14µrad @400 GeV/c)
- It is possible to align **more than one crystal** to increase the deflection angle, keeping the efficiency high

The FNAL test (2005)

- **O-shaped crystal** (PNPI) of RHIC
- detectors = **PIN diodes**, ionization beam

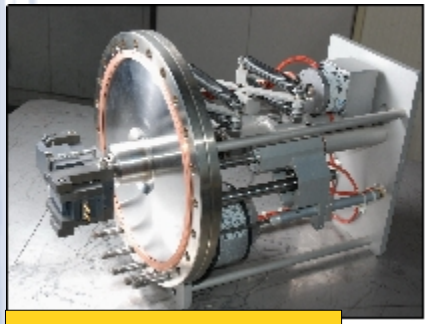
- **Effective reduction of the background**
  horizontal line = proton halo loss limit
  vertical ones = machine developments to
- **reduce background:**
  1 = installation of a double scraper
  2 = improvement of the vacuum system
  + alignment + installation of the crystal

No results in 2006/2007
due to mechanics problems

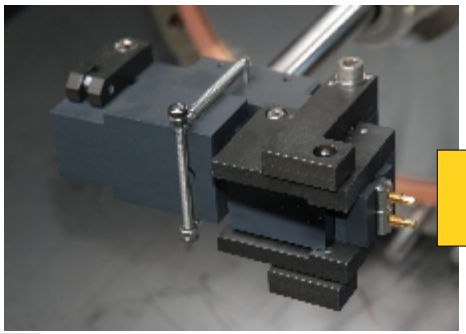


Crystal behavior evaluation
REQUIRED

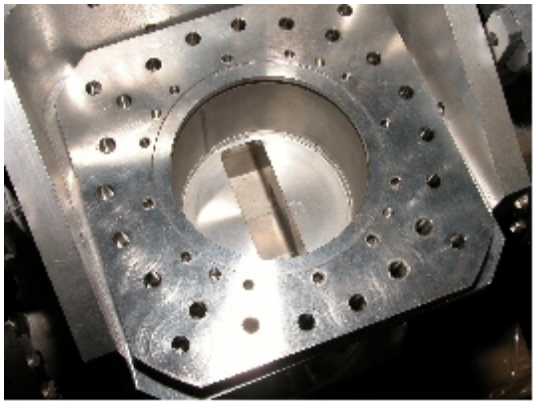
The UA9 experiment

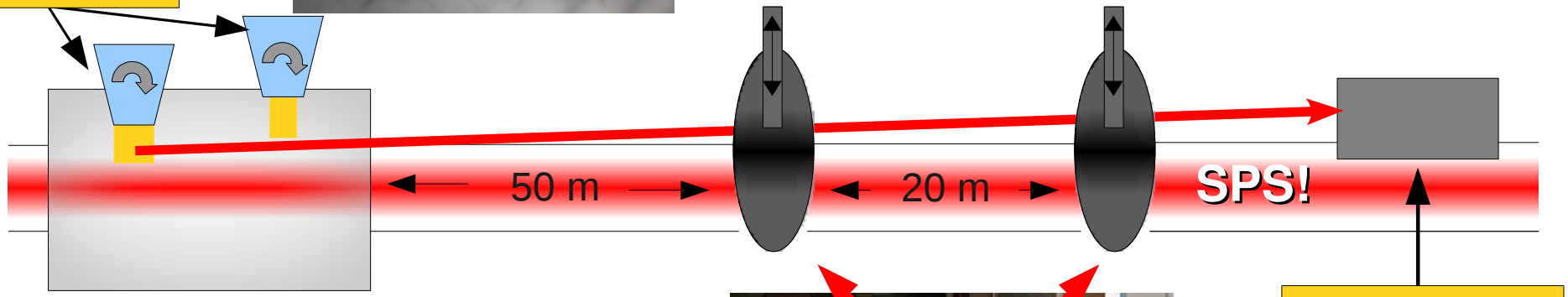


Goniometers

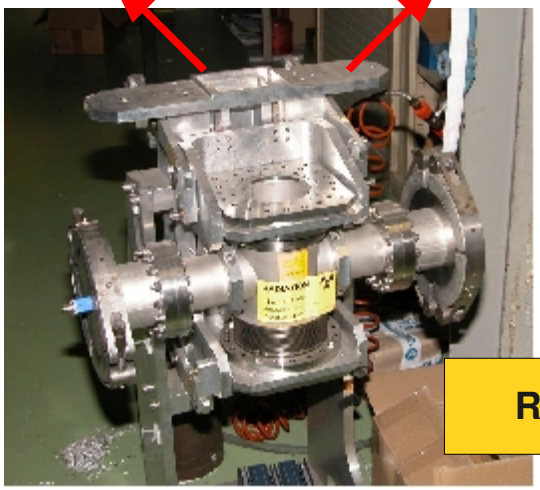


Crystals





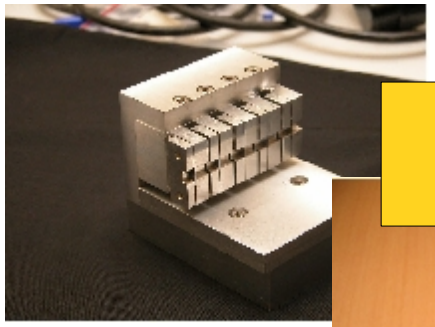
Tank

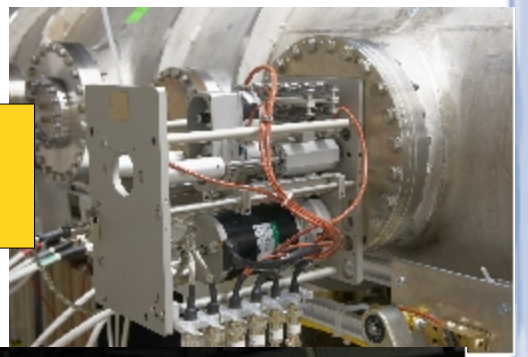


Roman pot

TAL

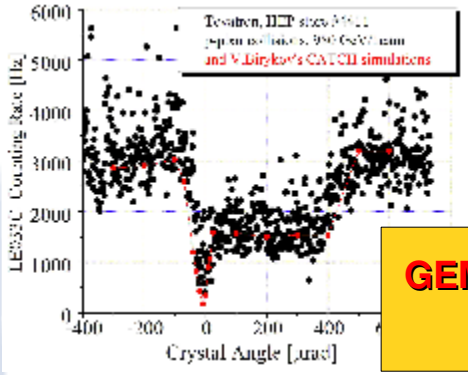
UA9 idea





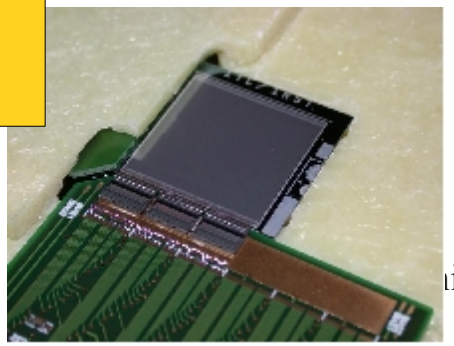
Single and multi quasi-mosaic and strip **crystals**
@ 6σ from the beam core

Ad-hoc beam halo:
Protons @ 120 GeV/c



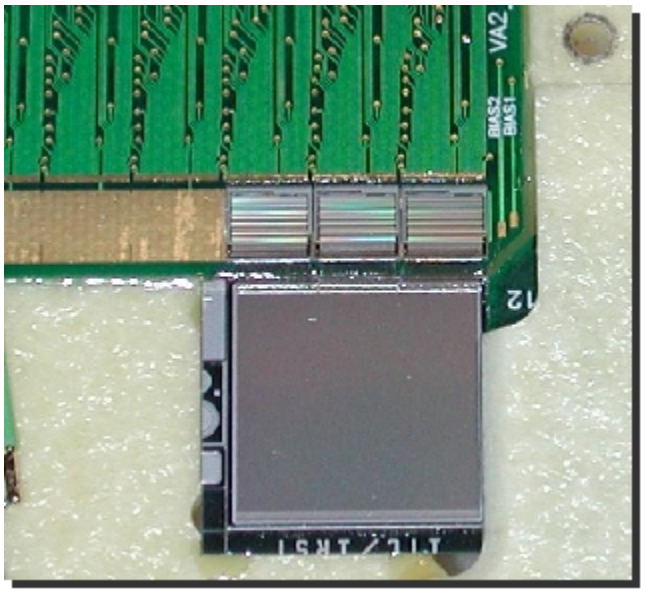
GEMs and **scintillators** to measure the nuclear interactions of the beam with the crystal in order to align it

To measure....



The tracking system...

Golden rules

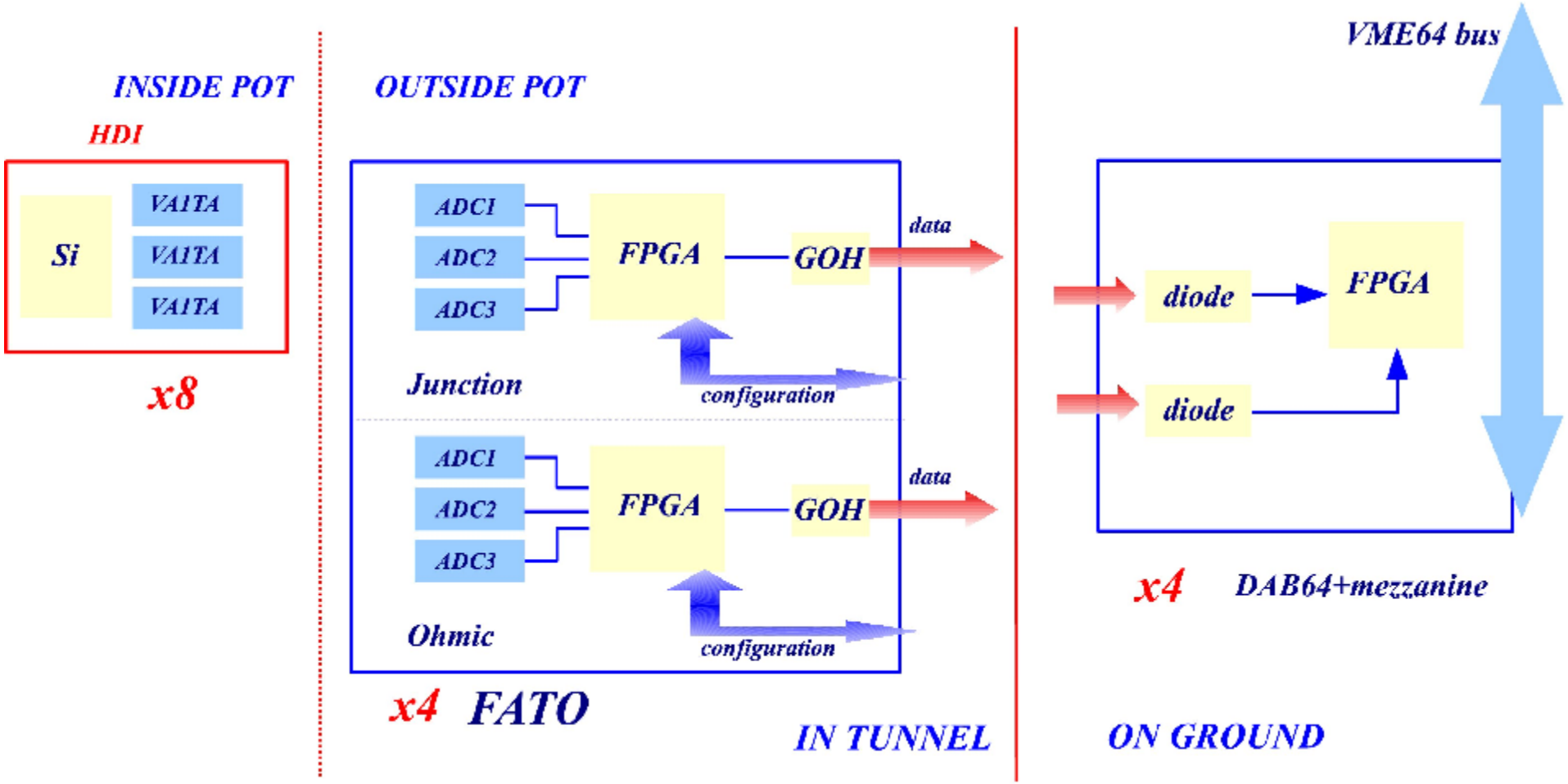


REQUIREMENTS

- Limited **multiple scattering**
- High **spatial resolution**
- **Self triggering**
- **Active region** on the beam
- Every parameter **under control**
- **No PC and power supplies** near the electronics (radiation!!)

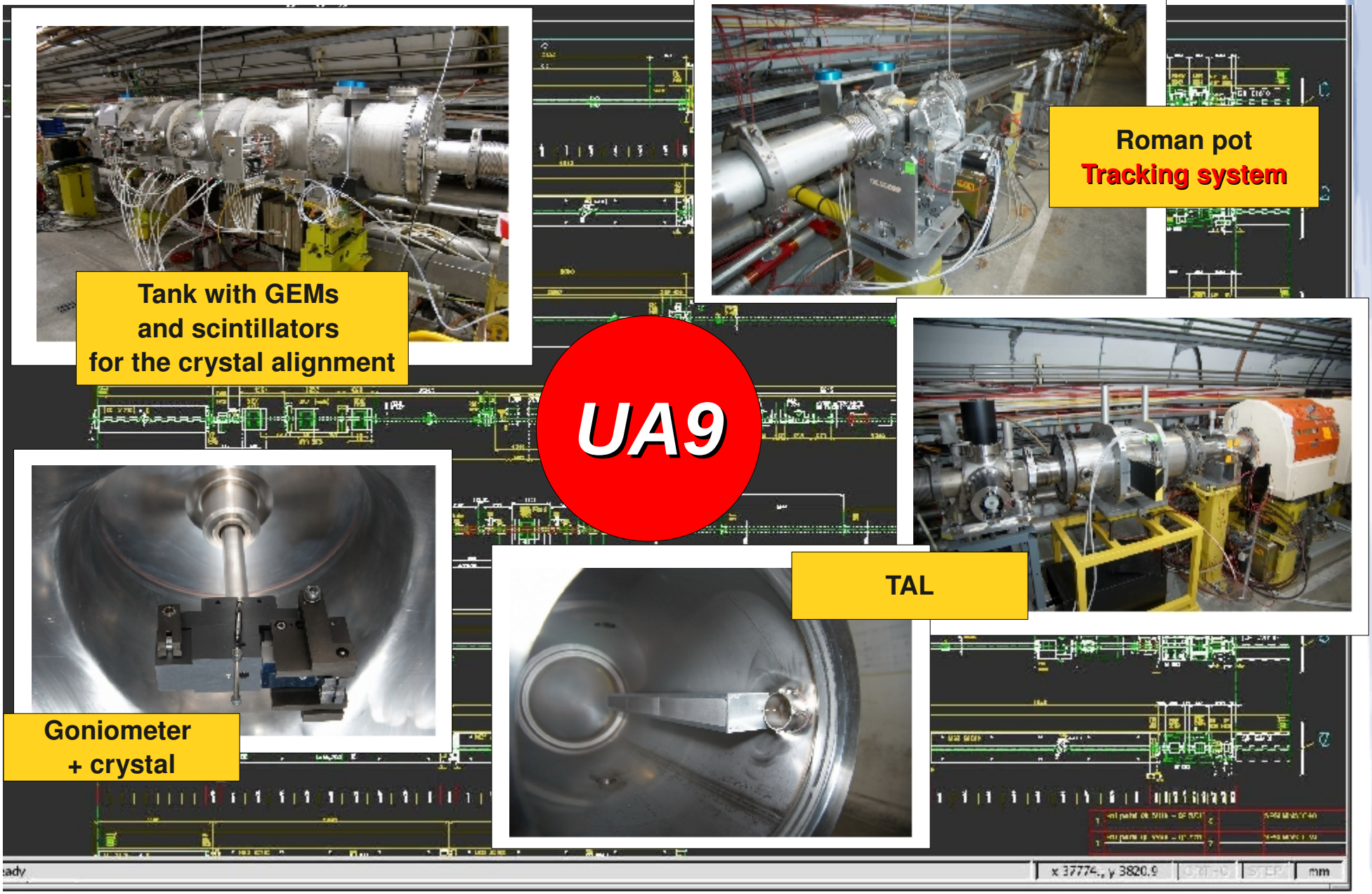
- Double side microstrip silicon detectors: **300μm thick**;
- Readout pitch: **50μm** and floating strip system;
- Cut at **500μm** from the border;
- **VA1TA** self-triggering ASIC;
- Digital info sent by **optical links**
- Remote **configuration and monitoring** with long cables (150 m)

The complete electronics chain

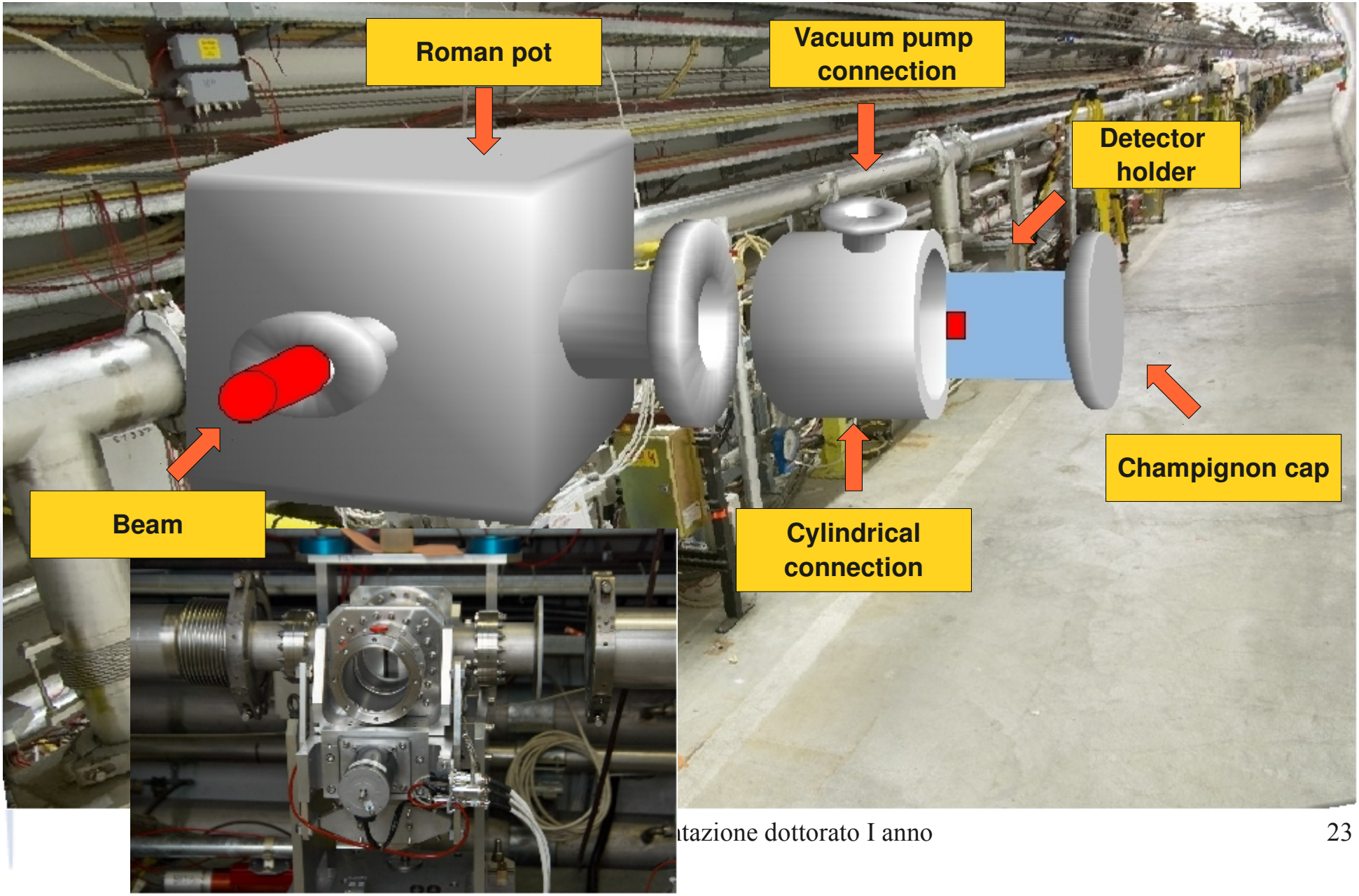


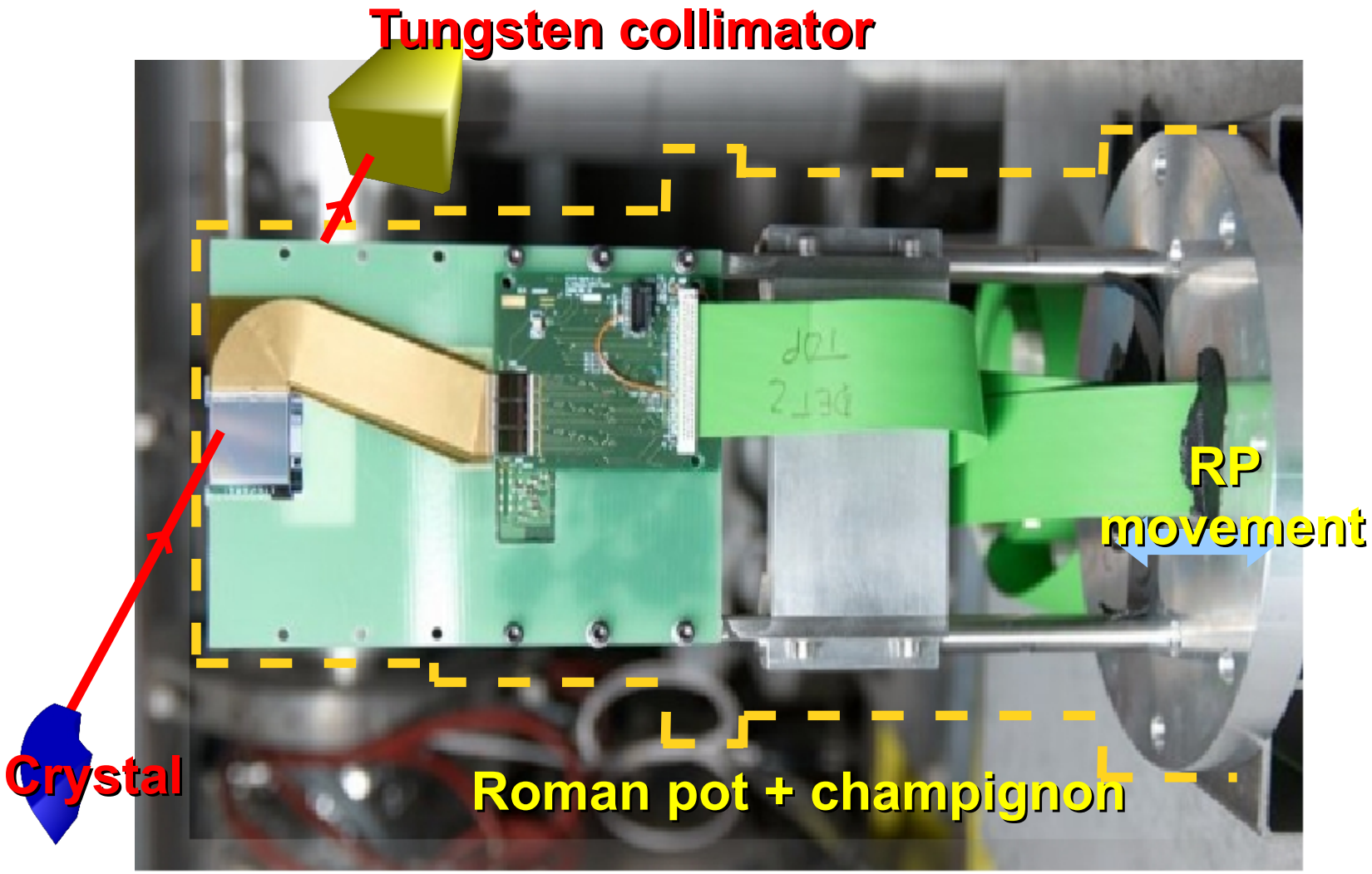
Let's start with a prototype...

The installation and commissioning phase in the SPS

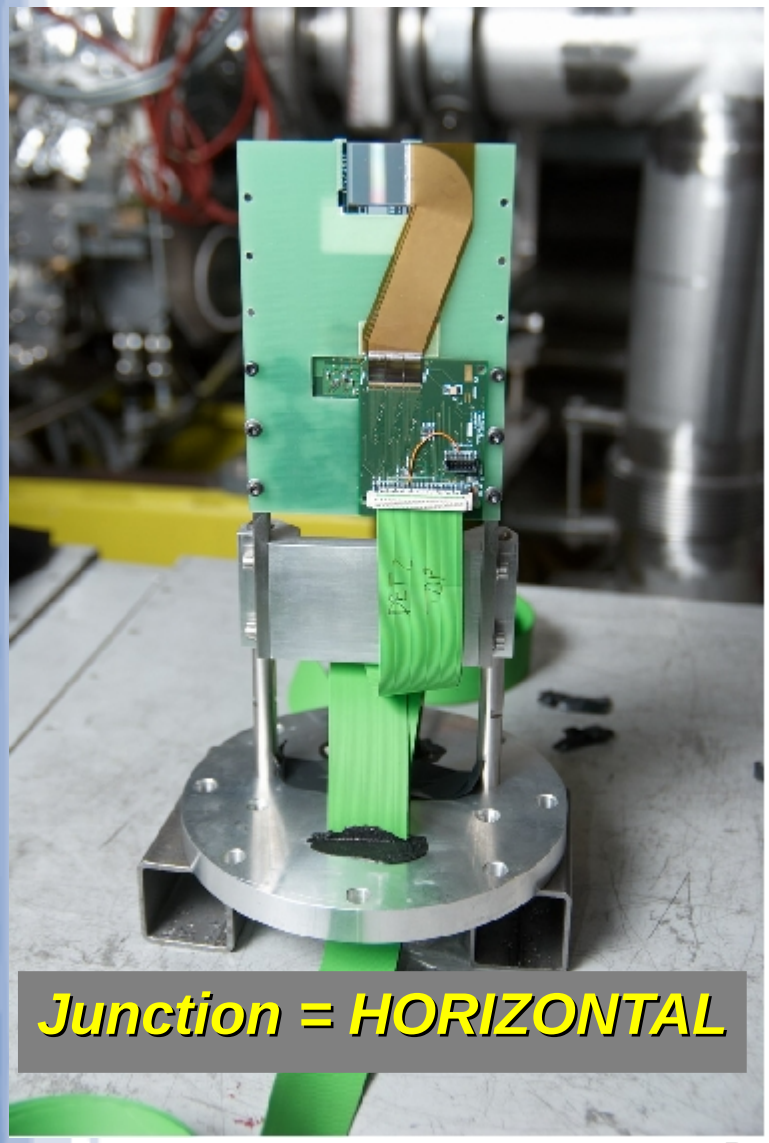


The detector on the beam: mechanics principle

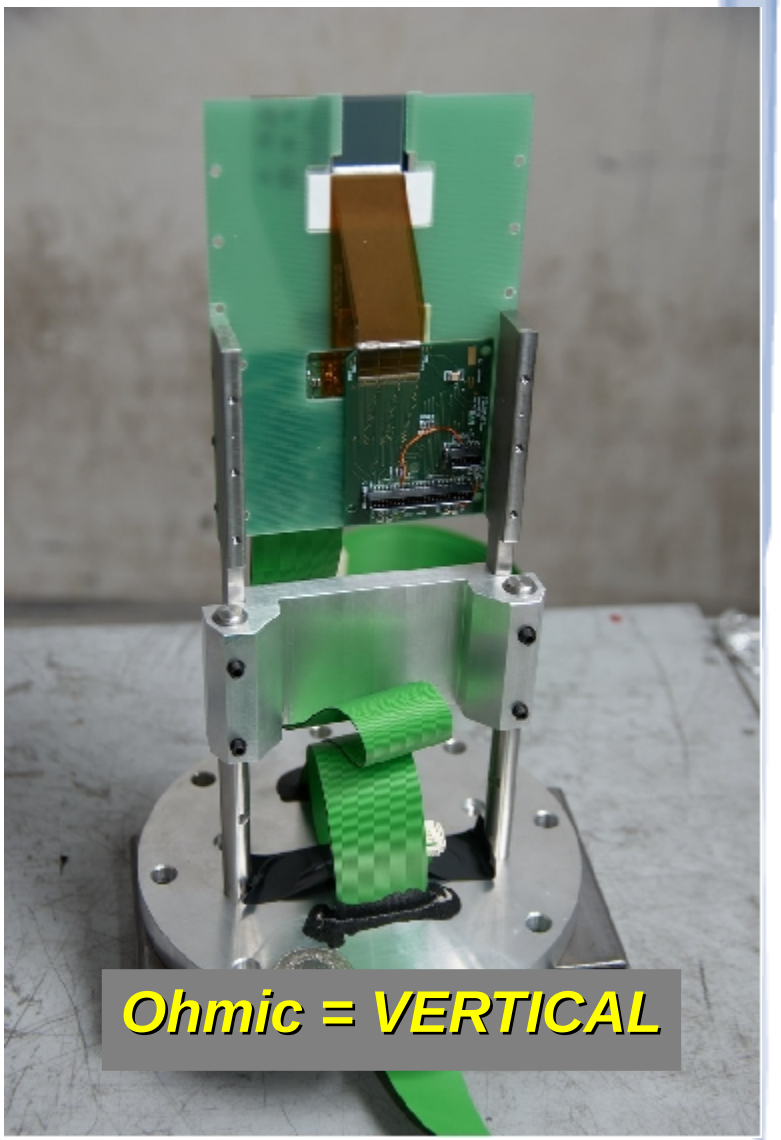



Tungsten collimator
RP
movement
Crystal
Roman pot + champignon

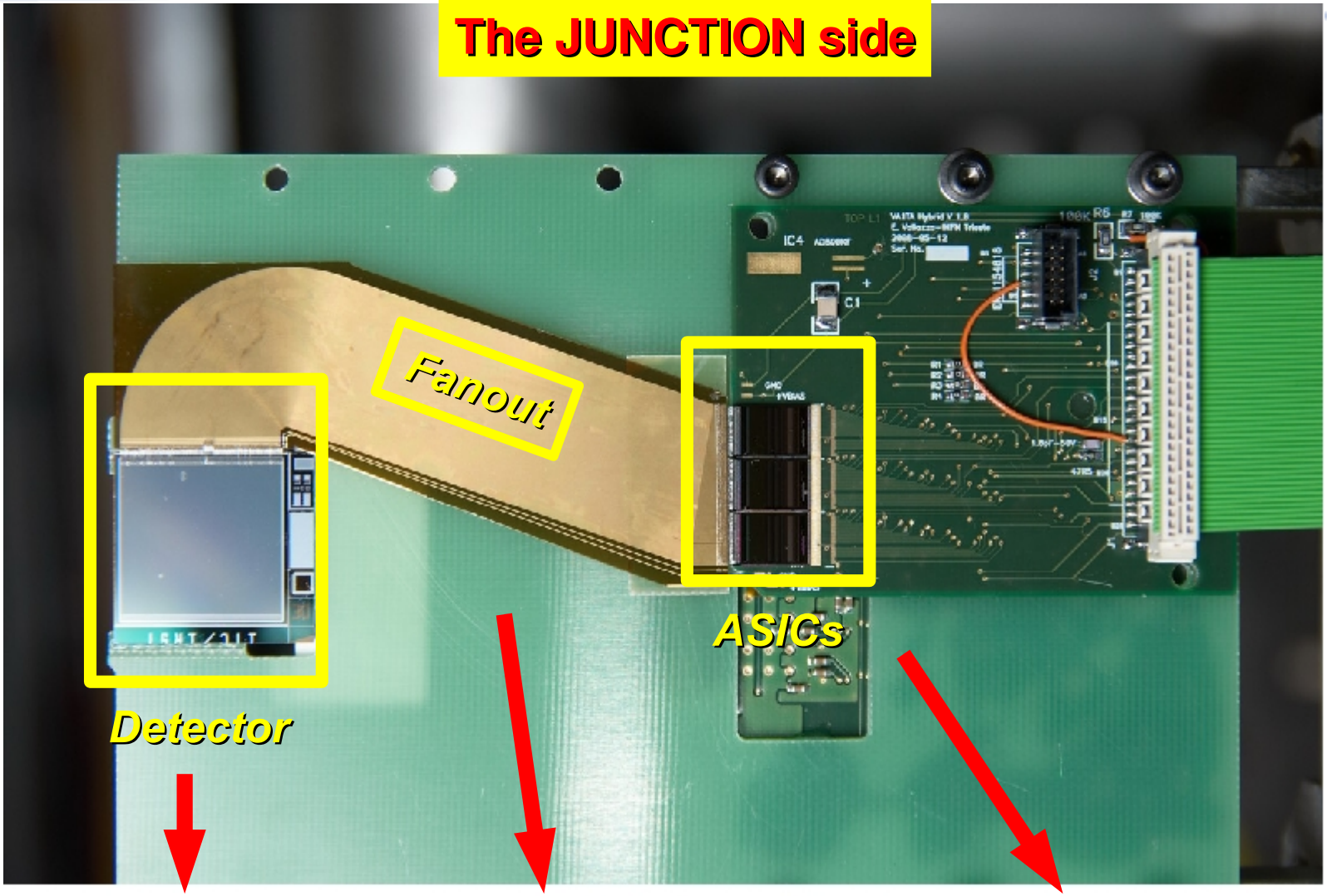
The PROTOTYPE on its holder



- 1.92x1.92cm^2 FBK double side detector
- 6 VA1TA ASICs
- 1 FR4 board for the support
- Upilex fanouts for the connection between the detector and the ASICs
- Temperature, pressure and radiation probes



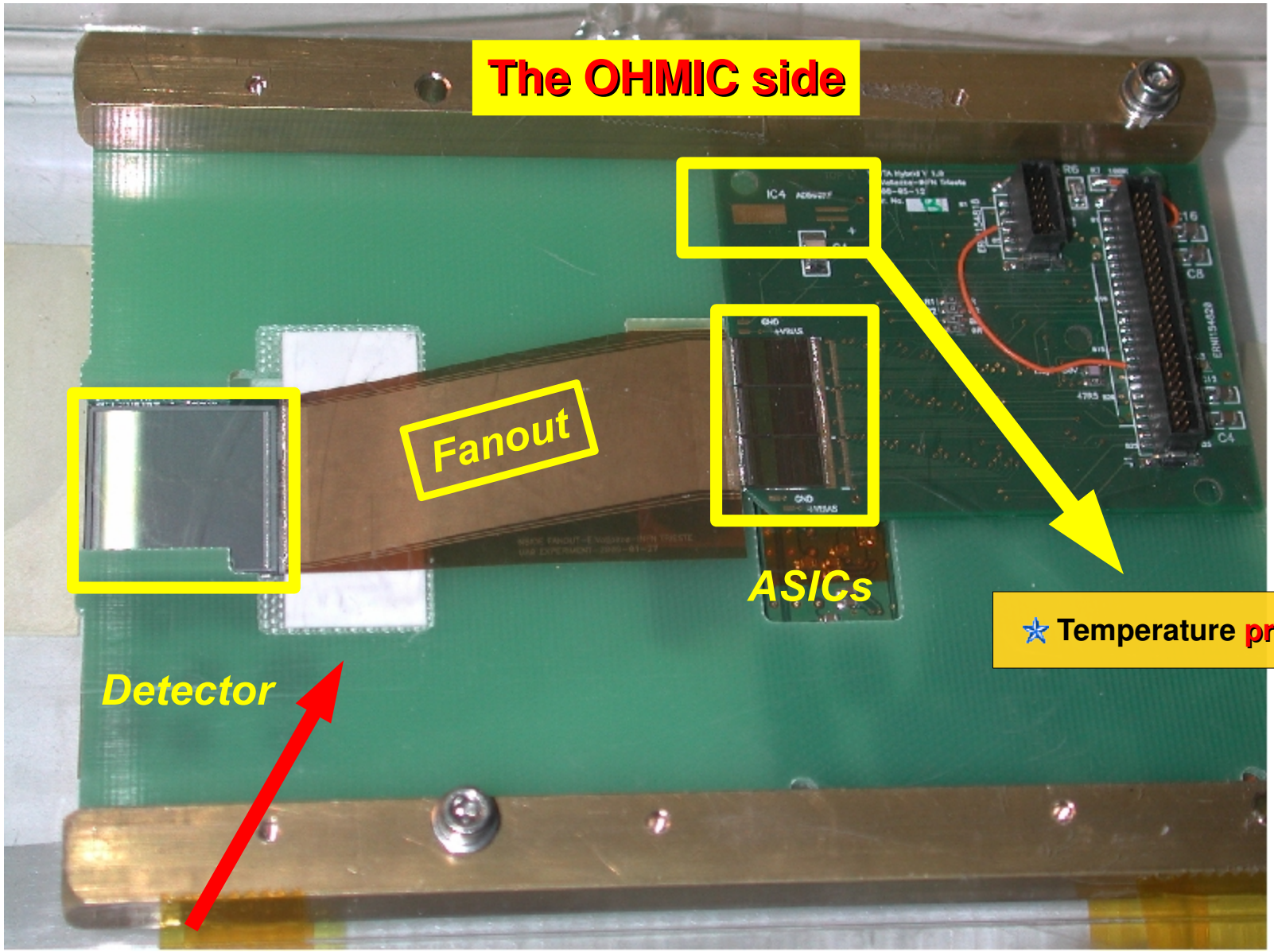
The JUNCTION side



- 1.92x1.92 cm²
- Physical pitch: 25µm; Readout pitch: 50µm = floating strip system
- Produced by FBK

- Upilex fanout
- Gold tracks, 50µm pitch
- Produced by CERN

- VA1TA ASIC with preamplifier, shaper and sample&hold
- Self-triggering (200 ns)
- Produced by Gamma Medica-Ideas



☆ Ceramic support for the upilex bonding

The electronics

Tunnel

ZONE

- Radiative

WHAT

- Detector
- Frontend electronics
- FPGA programmable from the surface

External pit

ZONE

- Not radiative but not accessible

WHAT

- Repeater
- Power supply

Surface

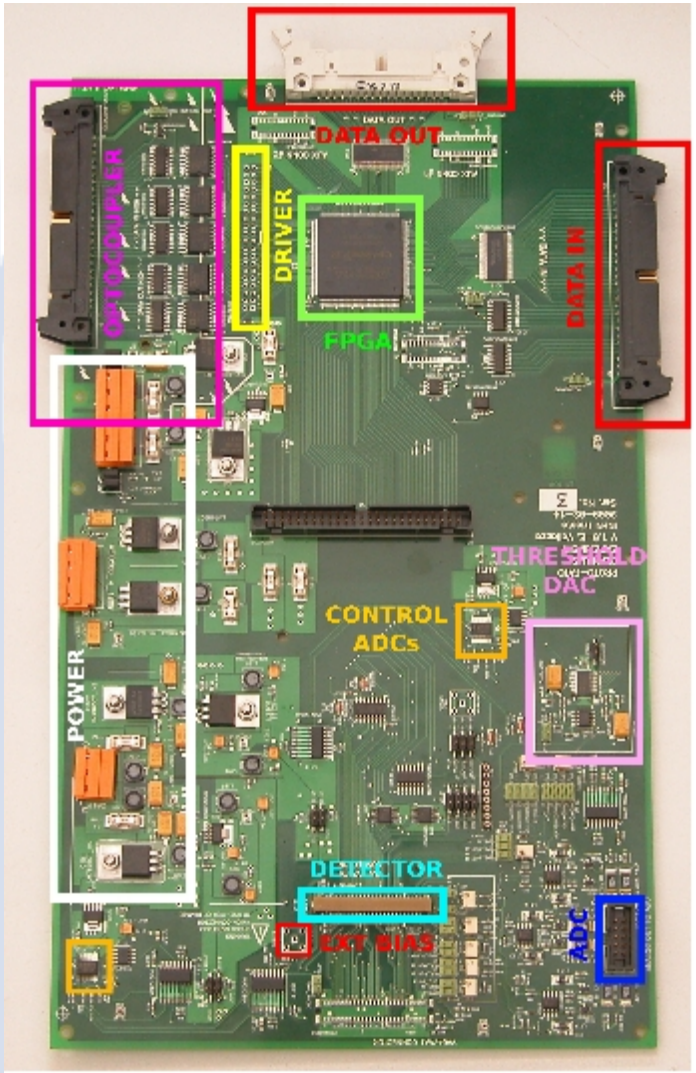
ZONE

- No radiation: accessible

WHAT

- PC
- VME crate with clever board

The prototype electronics

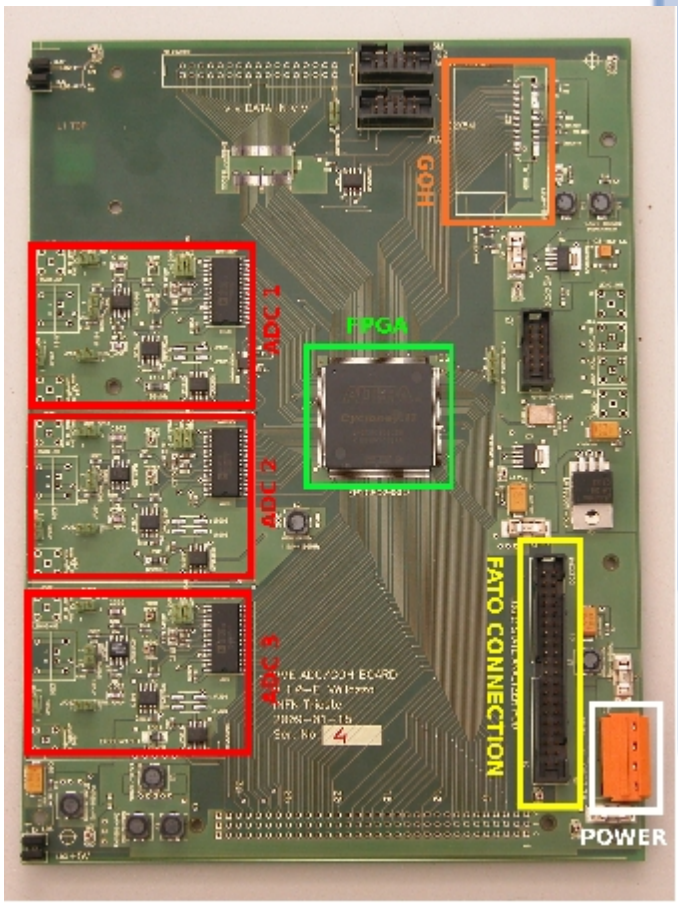


PROTOFATO

- Configuration
- Interface
- Monitoring
- Readout
- 1 Master (J) and 1 Slave (OHM)

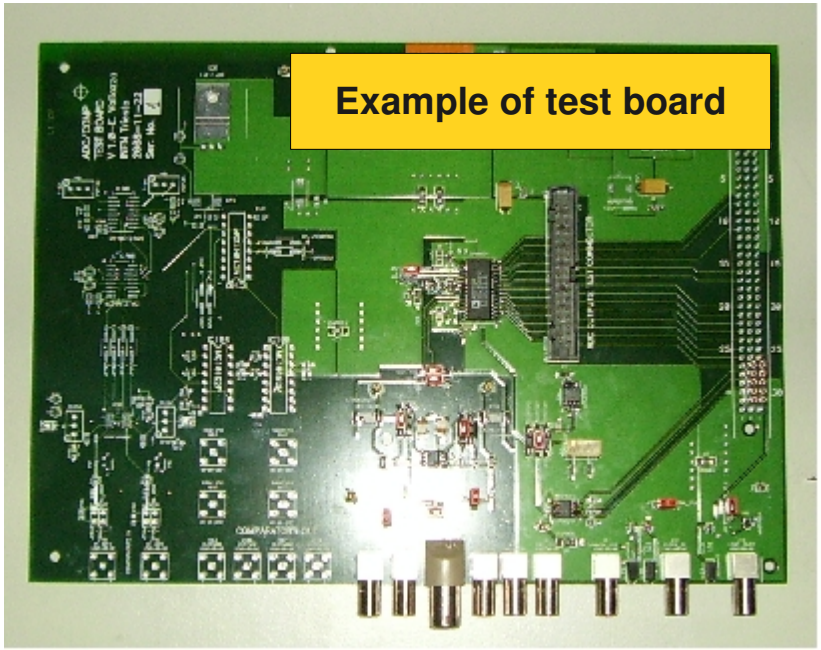
DRIVER

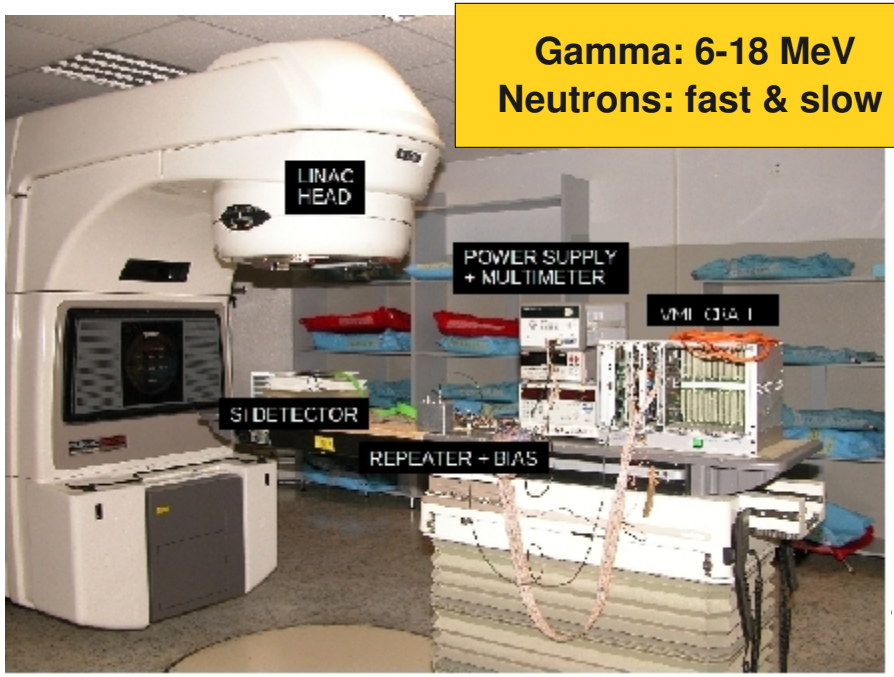
- ADC (1 per ASIC)
- Fiber link (GOH)
- 1 per protofato



Irradiation tests

- Test performed with a clinical **LINAC** @ S. Anna Hospital in Como
- Each critical component has been tested for **radiation damage** independently with specific boards and specific setup
- Radiation tolerance tests with gamma (up to **1 kGy**, 300 Gy/year are expected); SEU with neutrons



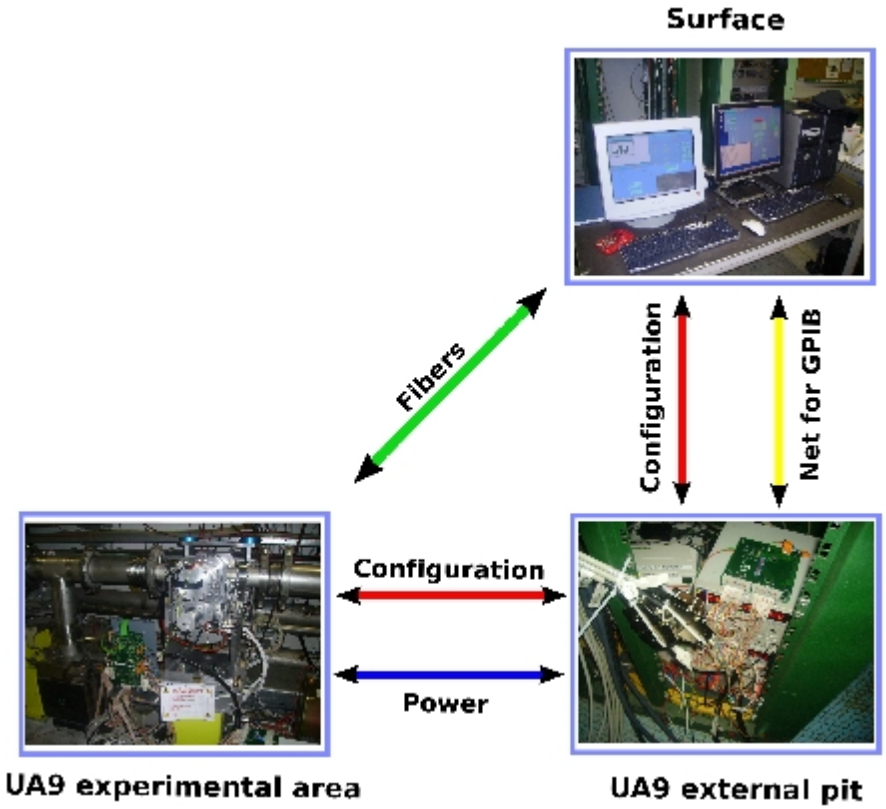


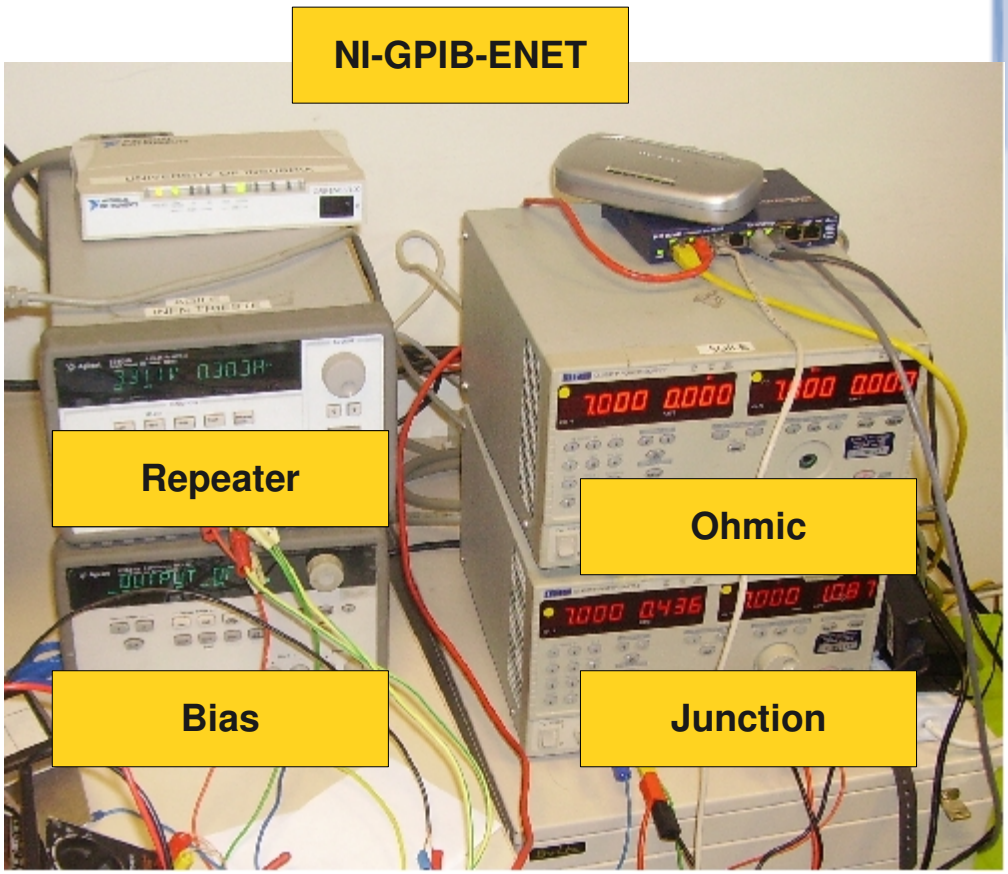
Gamma: 6-18 MeV
Neutrons: fast & slow

- ASIC, ADC, DRIVER, RECEIVER and REGULATORS with photon and neutrons: ***OK***
- DAC: ***KO (after a 1 year UA9 equivalent run)*** ➡ a new more tolerant DAC has been chosen

The Slow Control system

- A slow controls system is implemented to **control and protect** the system during the operation.
- This system is able to control and log the power supplies, the ASICs currents and the temperature in the pot
- In case of problems, the system **shutdowns automatically**.
- The slow controls program is written in C and Tcl/Tk for the user interface

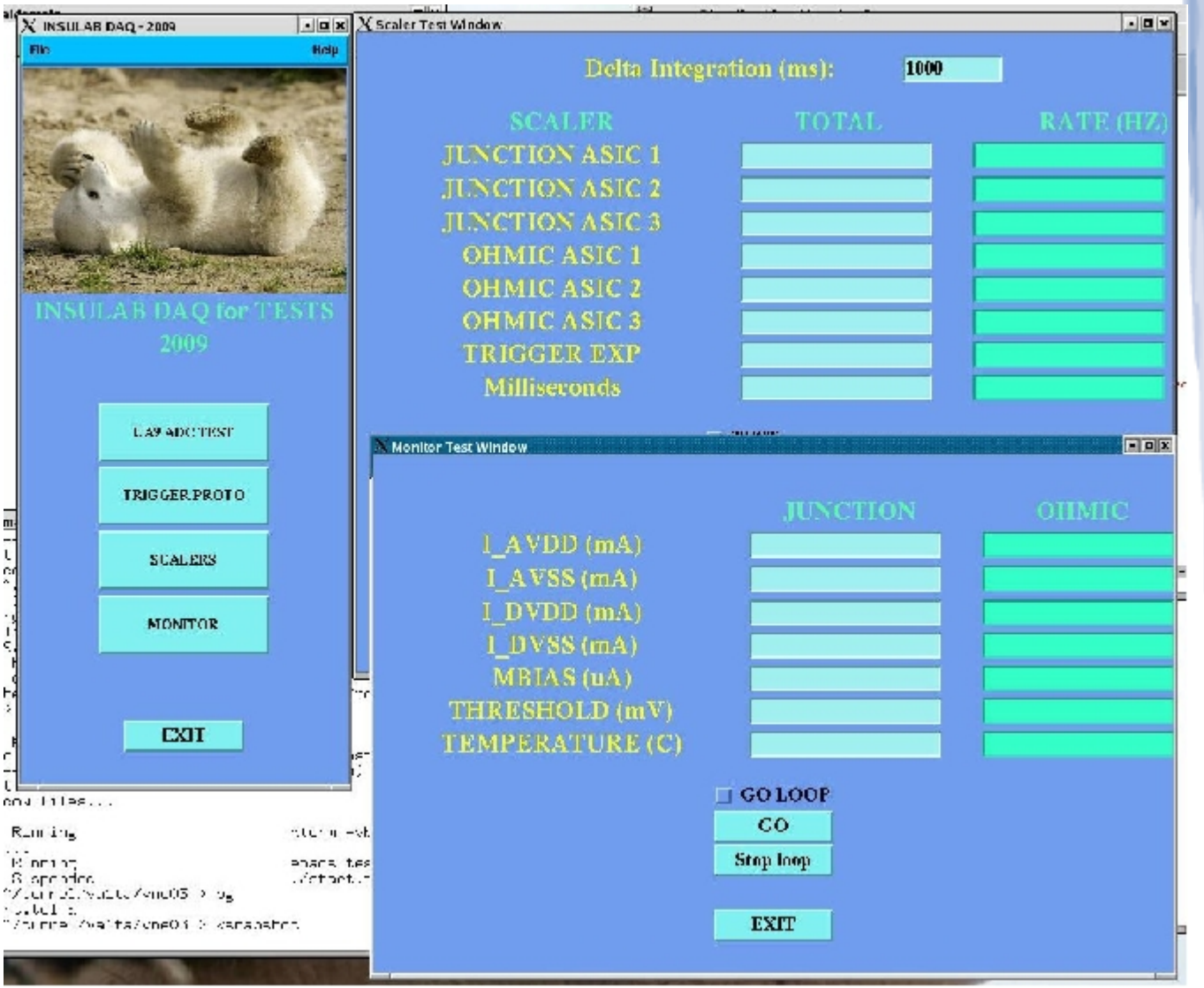




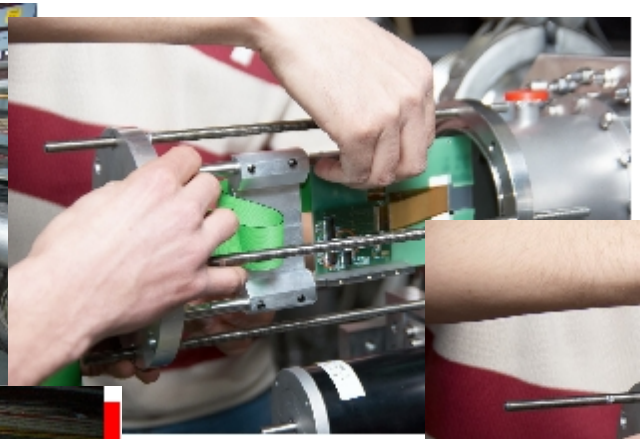
- Power supply for the intermediate station repeaters, ohmic and junction sides, silicon bias
- **Remotely controlled** by a GPIB - Ethernet

DAQ

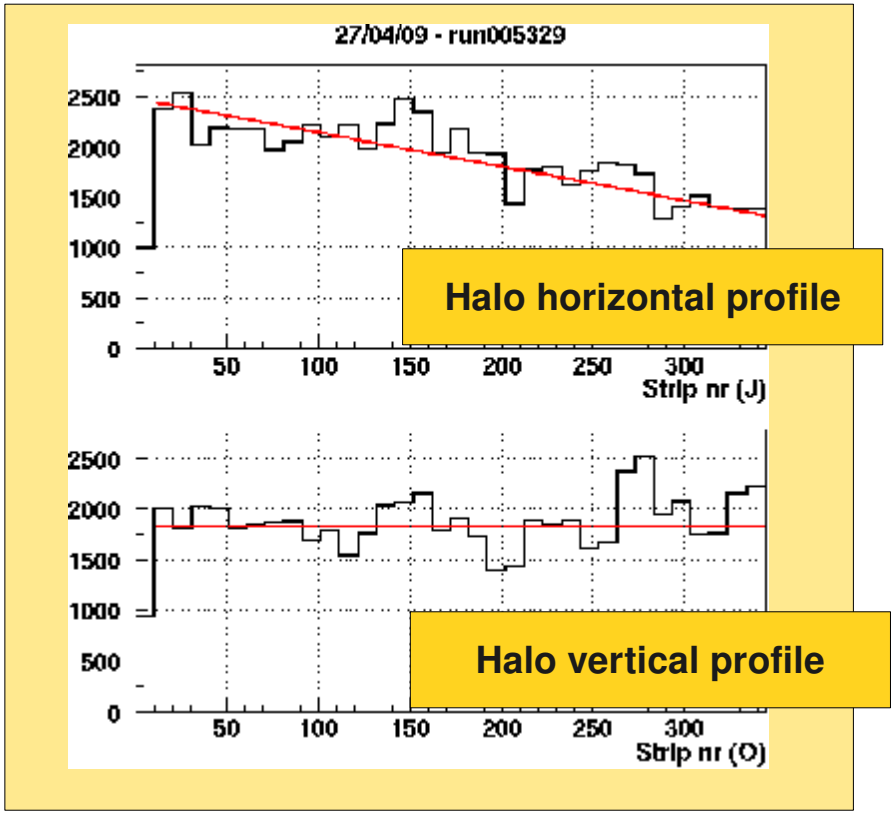
- **Remotely controlled**
- **Trigger mask and threshold selection allowed**
- **Monitor of ASIC currents, trigger threshold, bias, temperature, trigger scalers**
- **Written in C and Tcl/Tk**



A critical step...

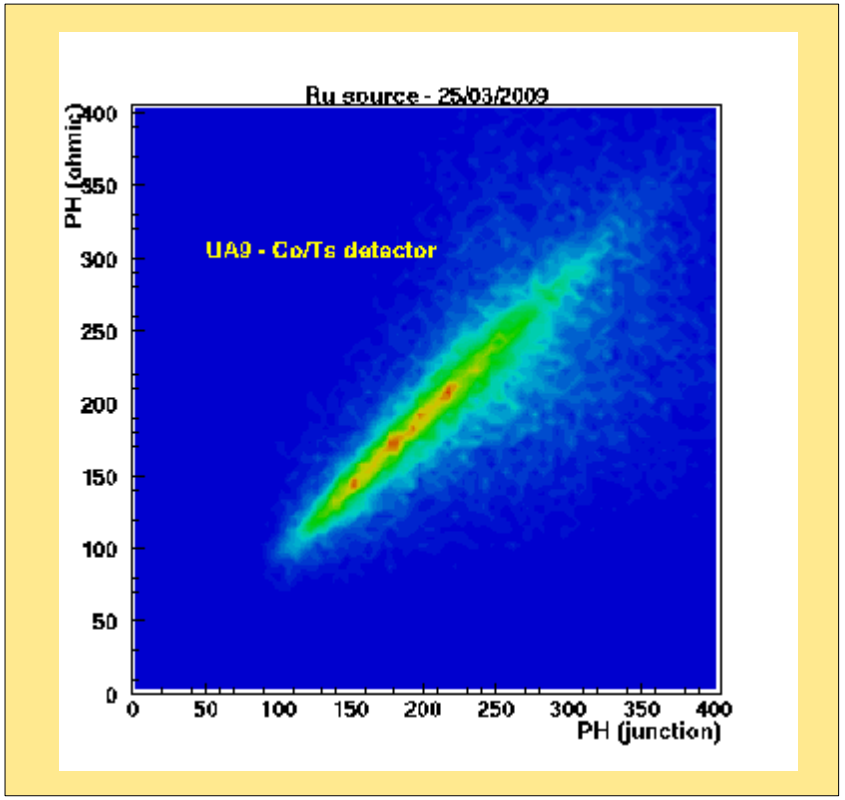


Results (1): GOOD NEWS during the SPS commissioning



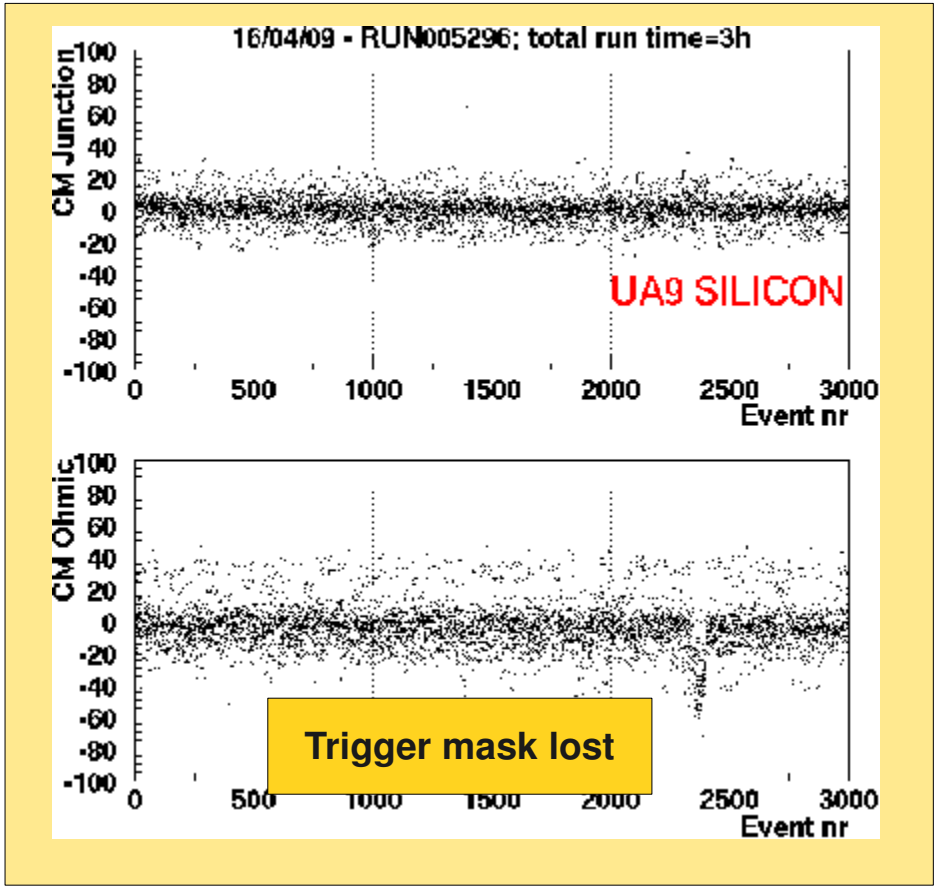
Beam profile

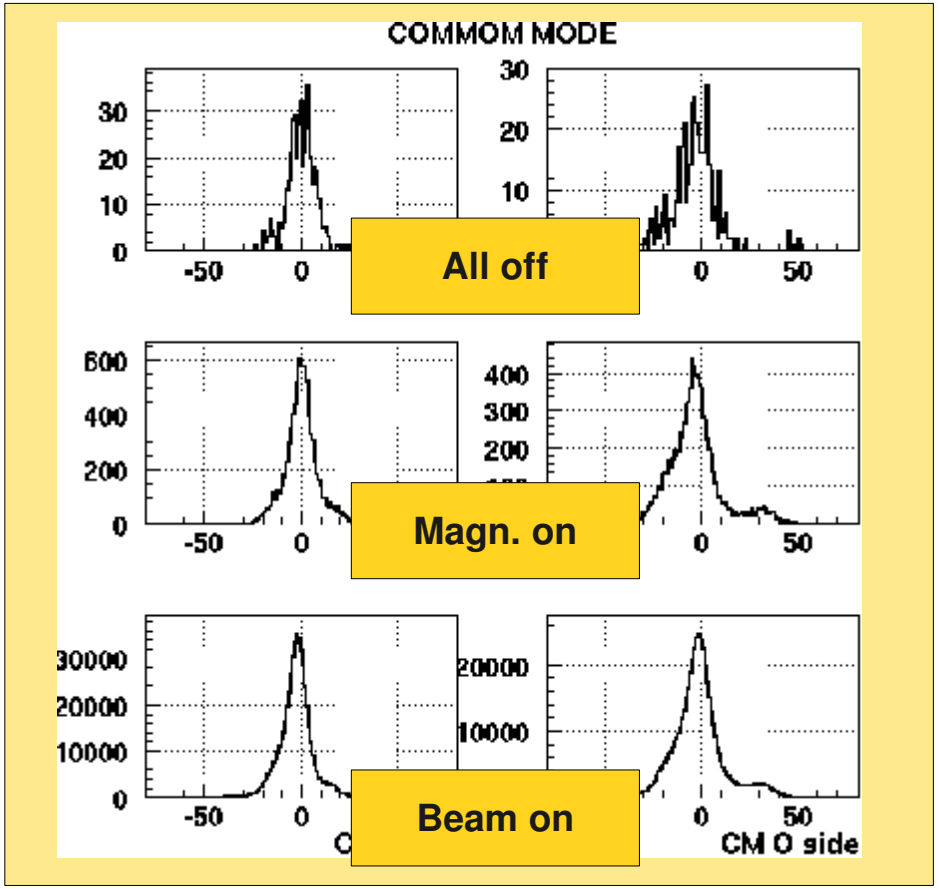
PH correlation J-Ω



April / May 2009

Results (2): system stability



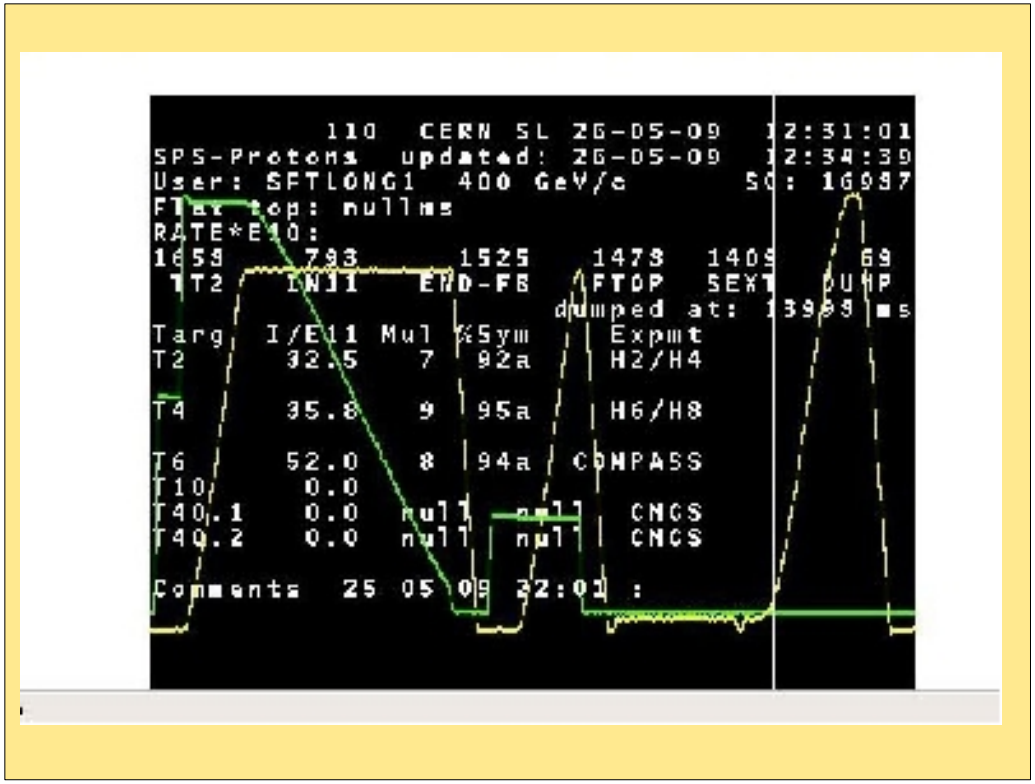


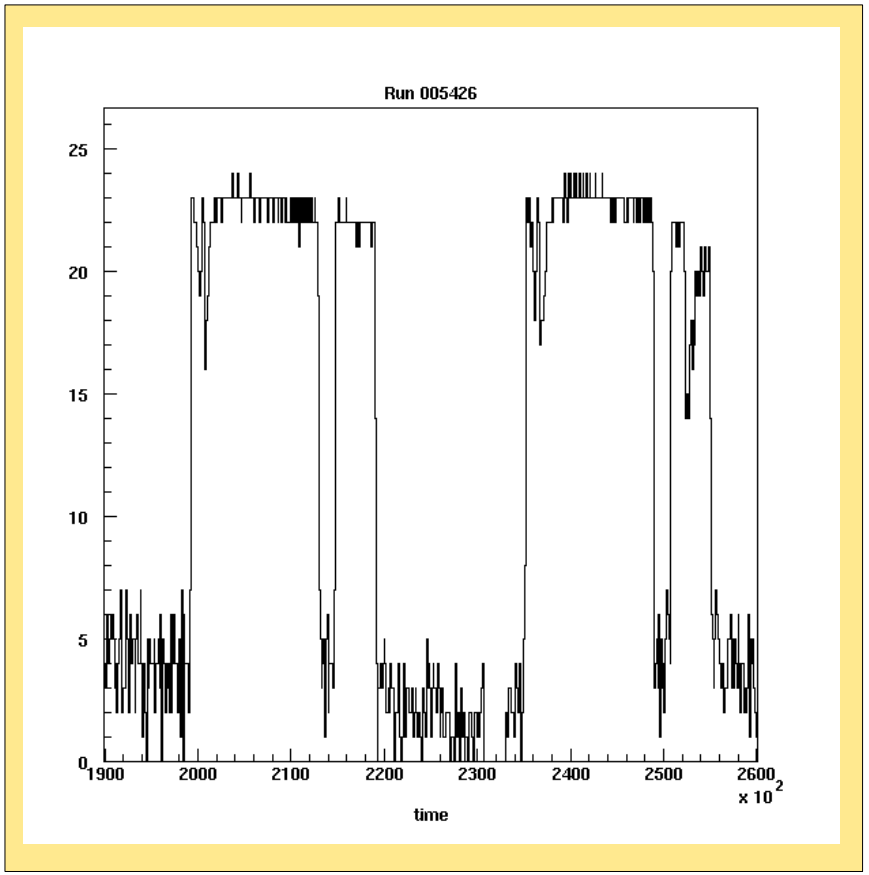
Common mode vs time

Common mode vs environment

Results (3): performance with beam

SPS signal

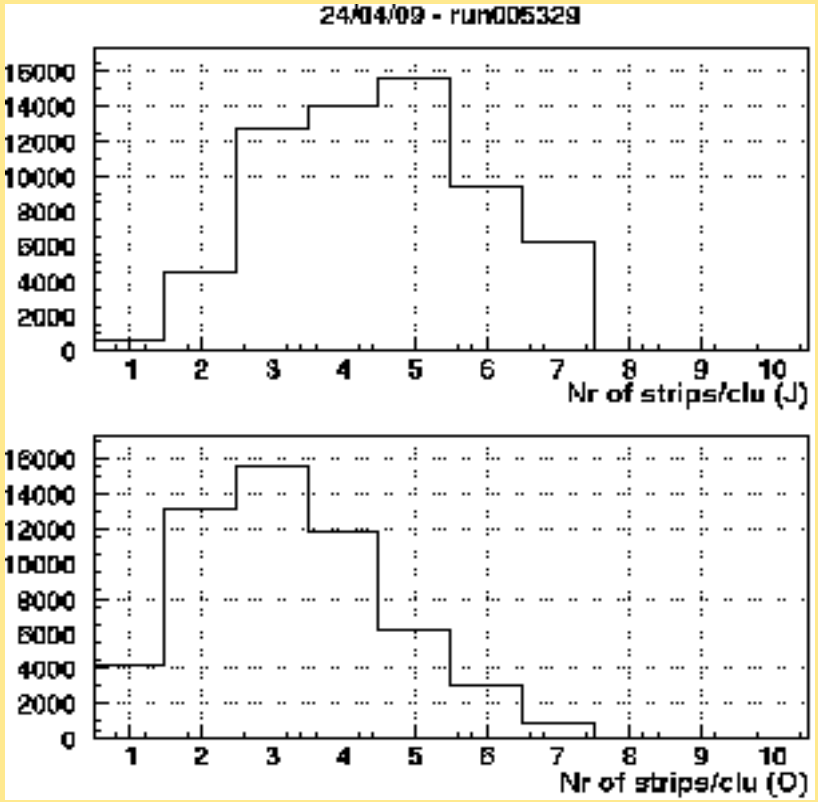




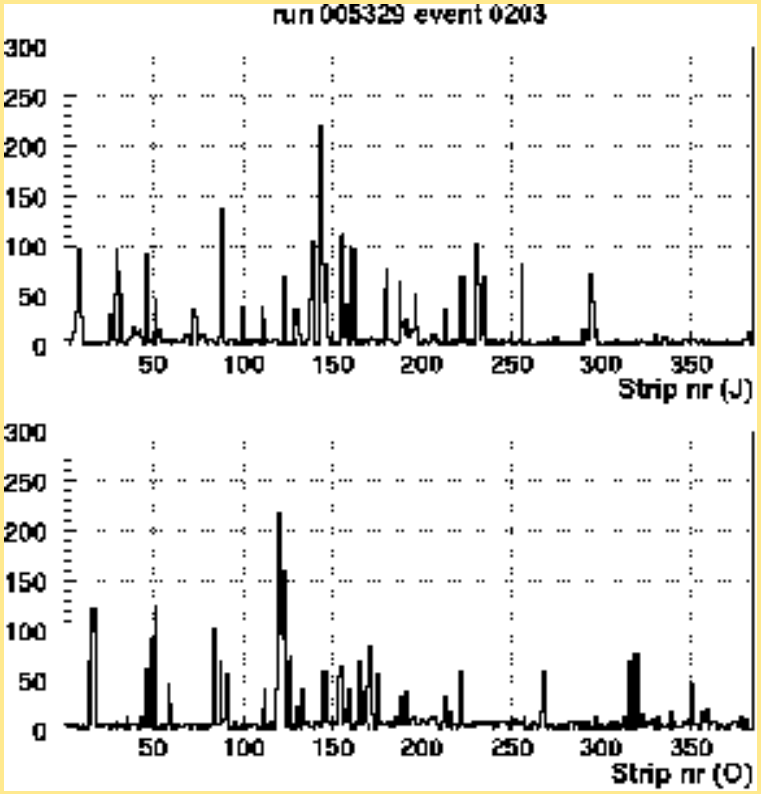
Triggers vs time

Results (4): BAD NEWS with the beam

strips per cluster

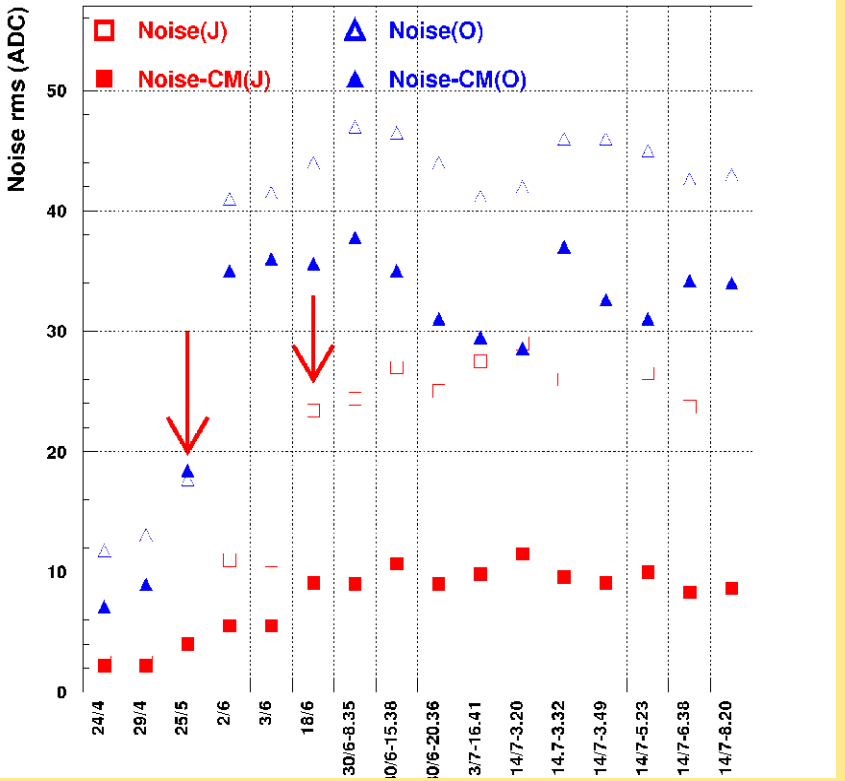


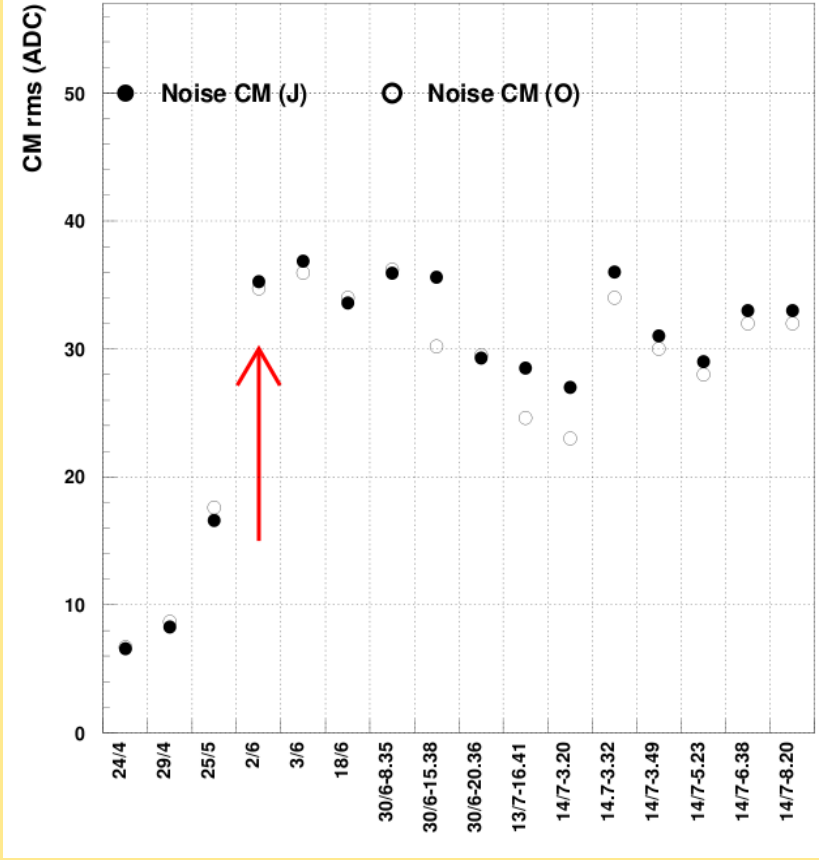
Event display



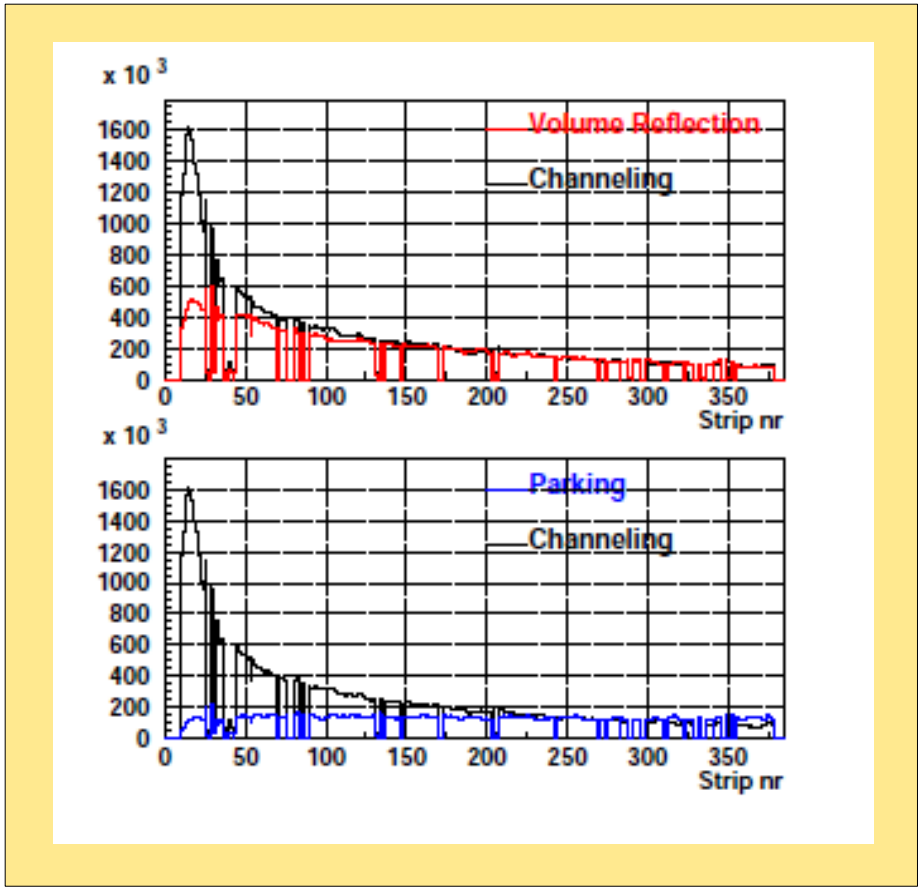
Results (5): BAD NEWS with the beam

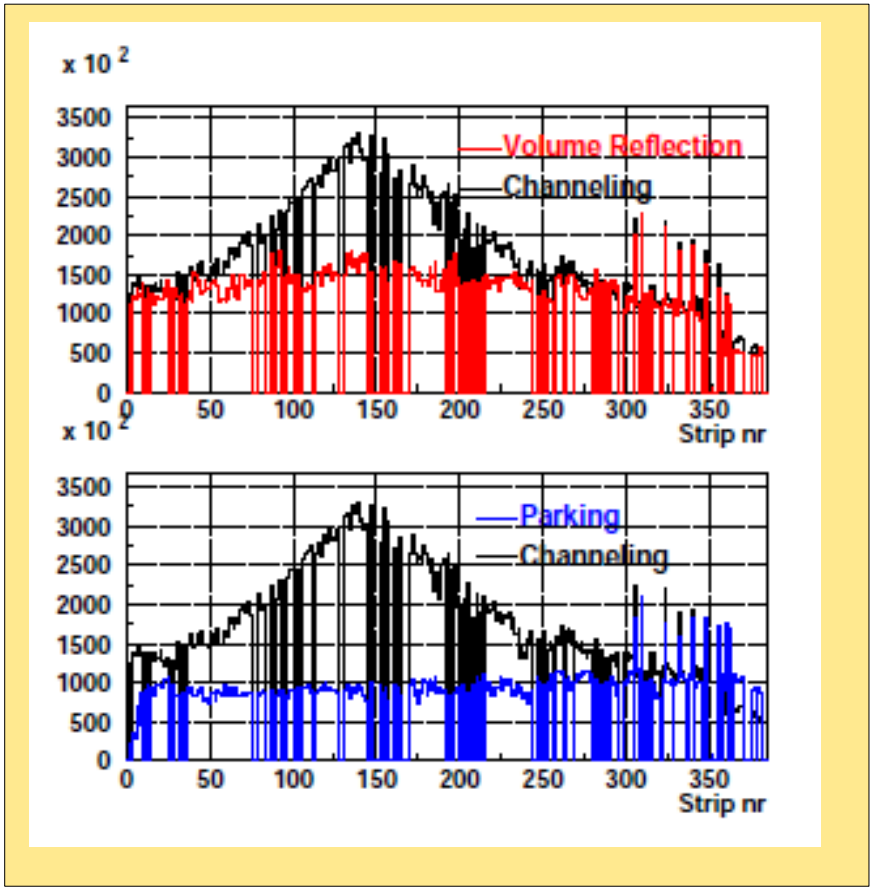
Common mode and intrinsic noise increased





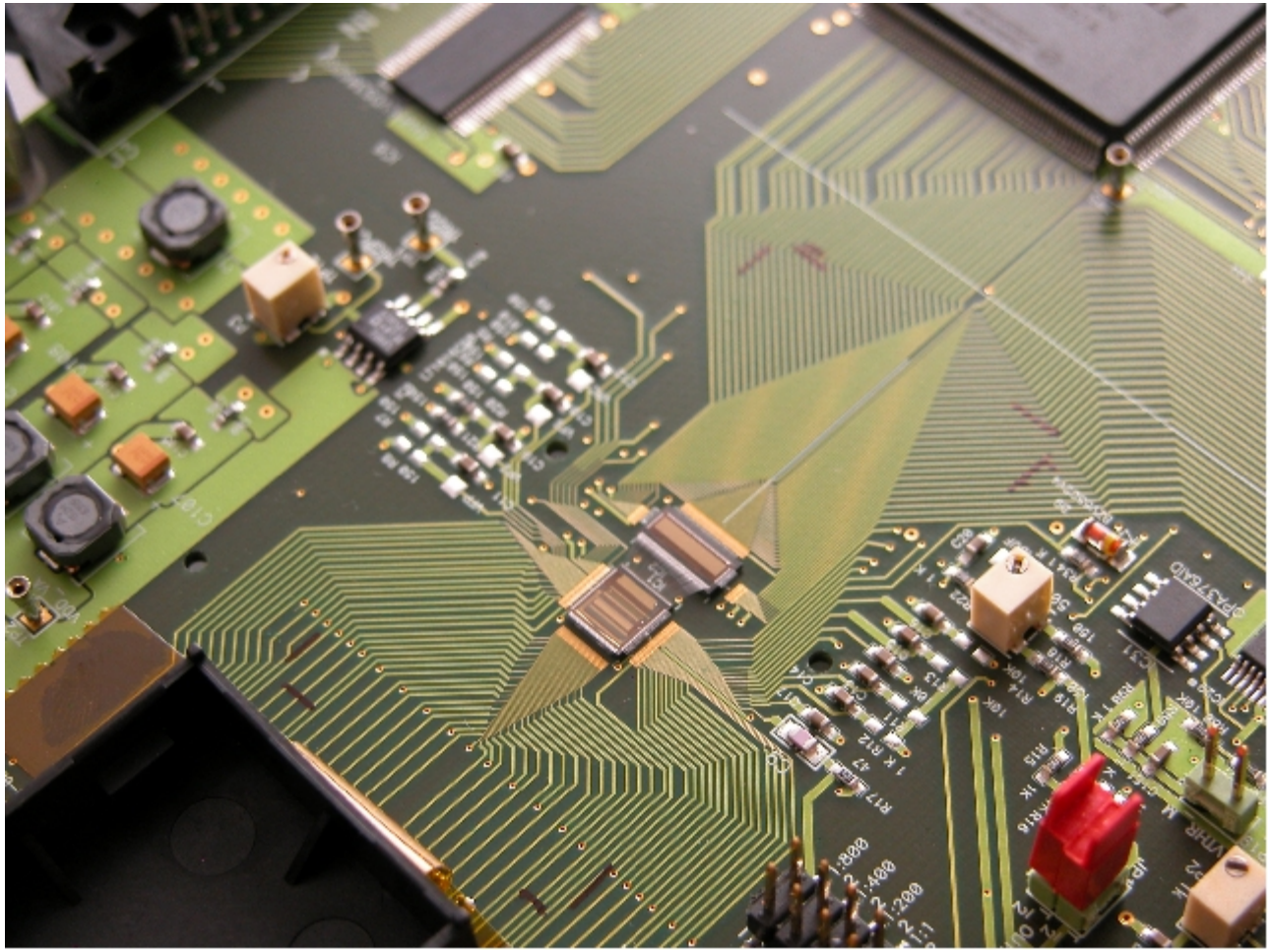
Results (6): … but channeling!





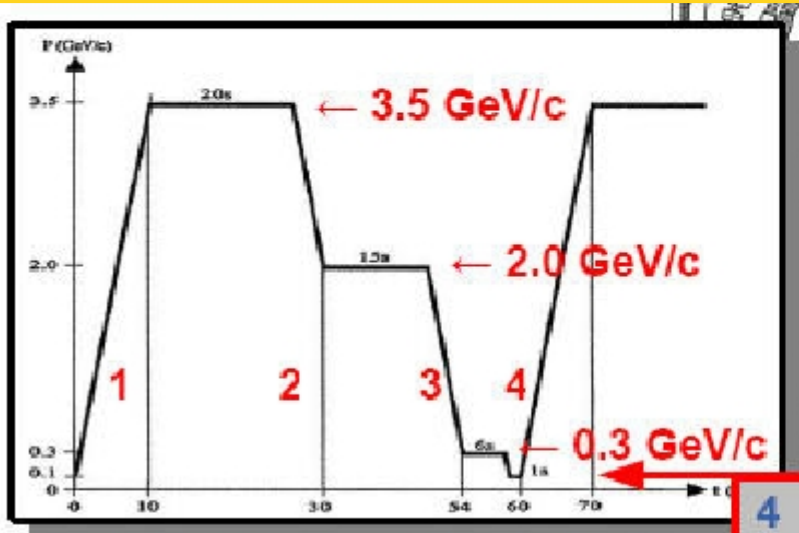
Channeling!!

MUSASHI

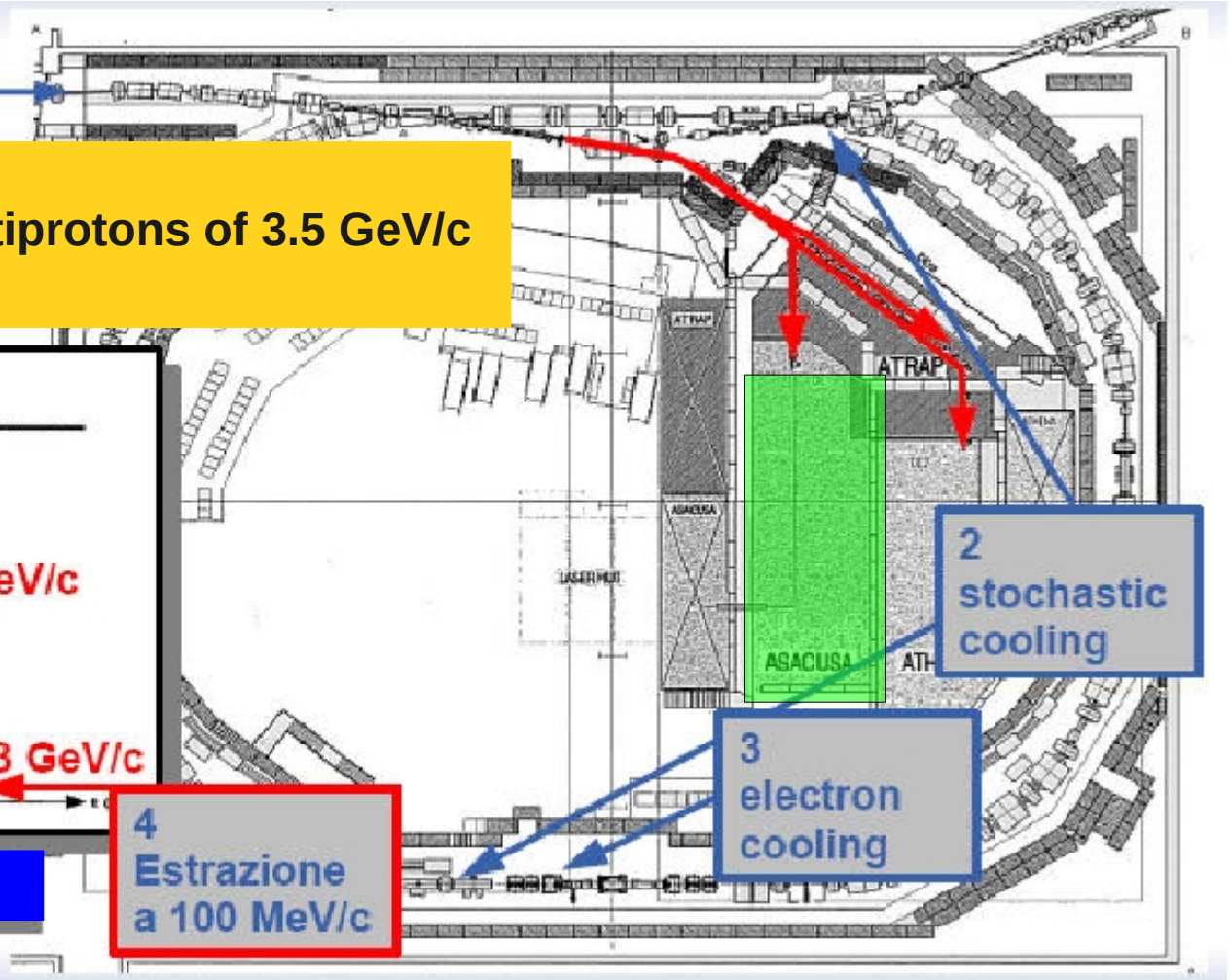


Antihydrogen @ AD (CERN): antiprotons @ ASACUSA

PS extraction:
Protons of 26 GeV/c => antiprotons of 3.5 GeV/c



Deceleration cycle



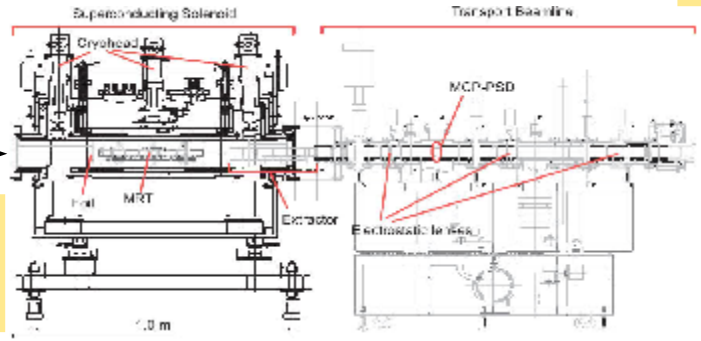
ASACUSA: Atomic Spectroscopy And Collisions Using Slow Antiprotons

Cusp trap: the MUSASHI experiment

RFQD: 100 keV

Liquid He SC solenoid: 250 eV

$\bar{p}$

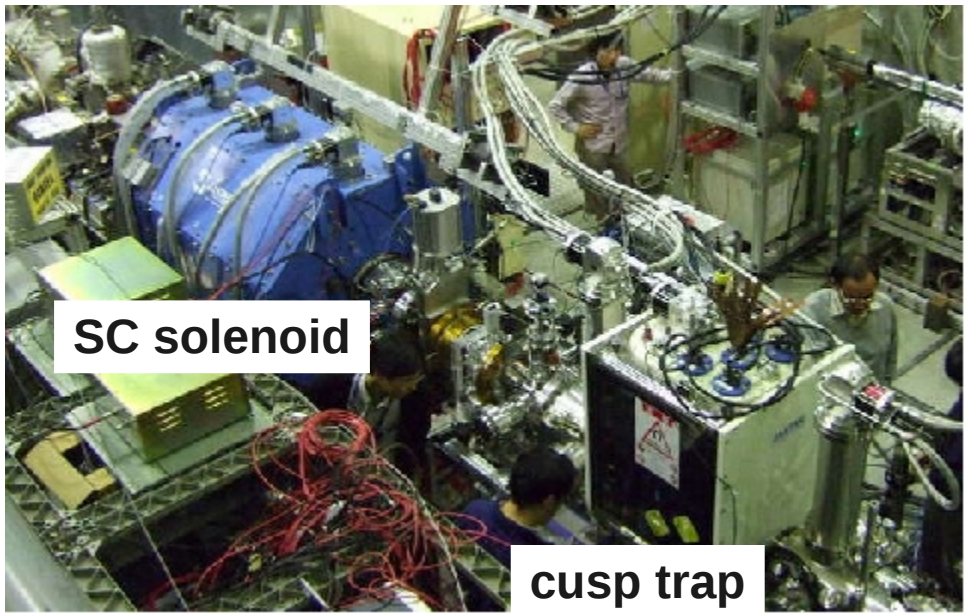


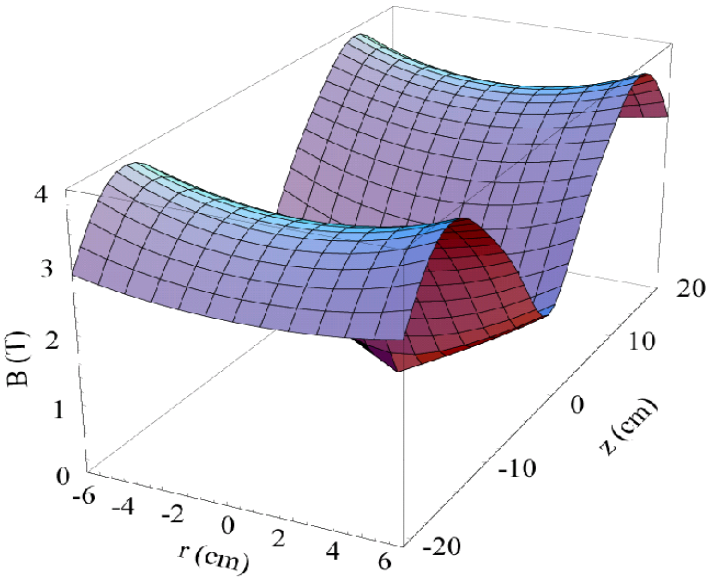
pbar @ 5 MeV (CERN AD)

e^+ source

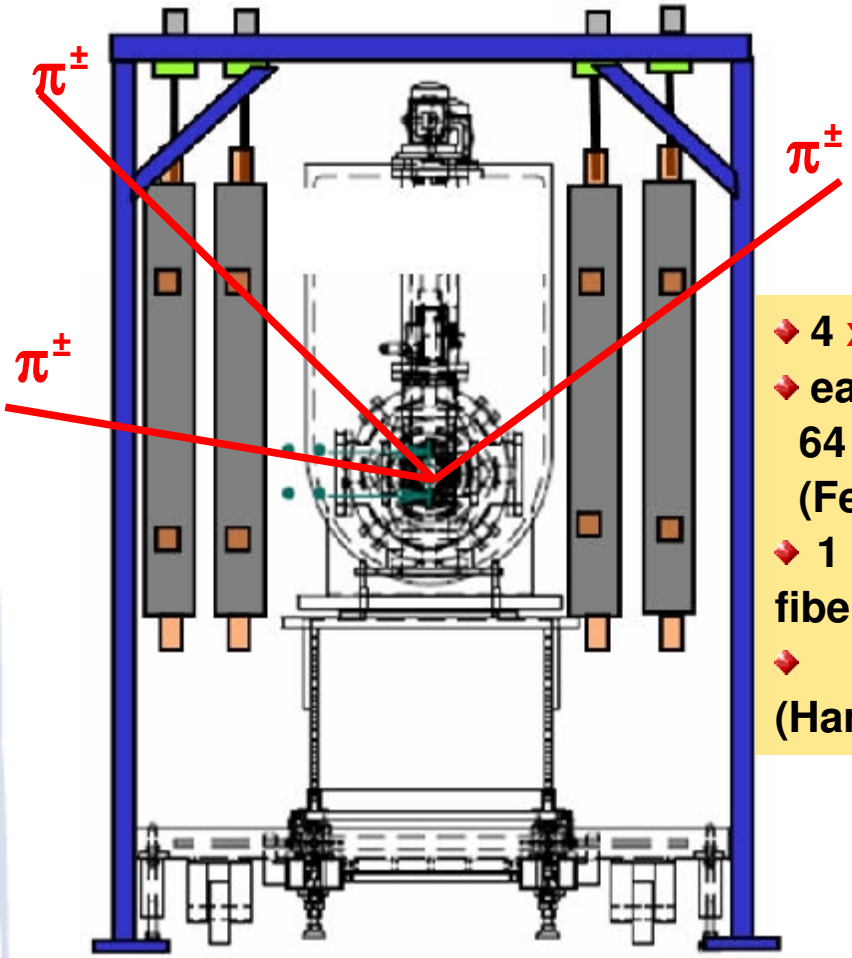
Cusp trap:

- up to 3 x 10^6 pbar entrapped
- antihydrogen

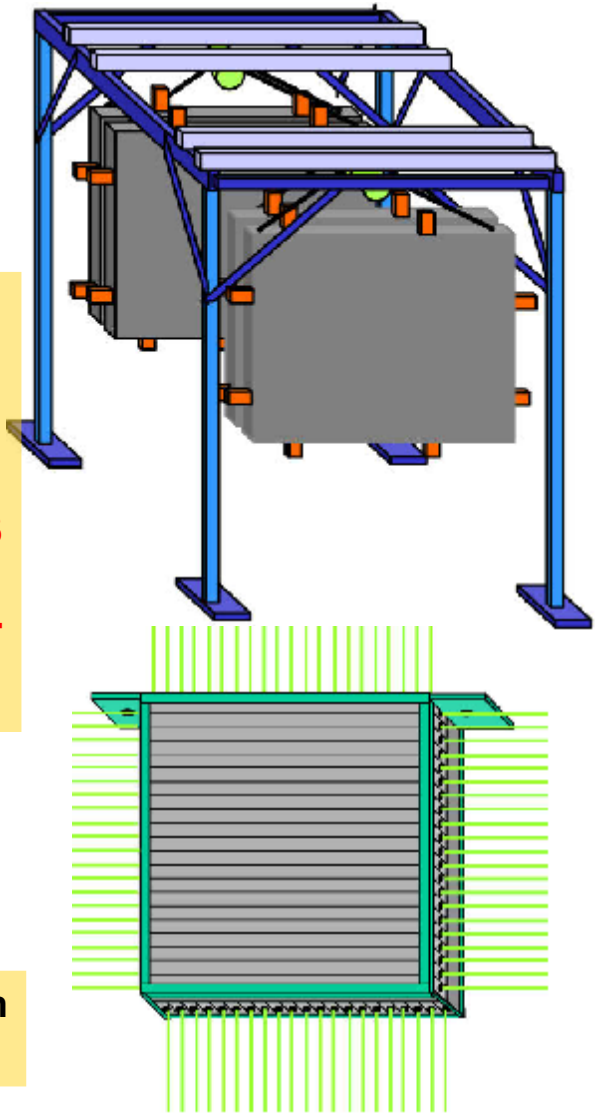




A tracking system to monitor the antiprotons



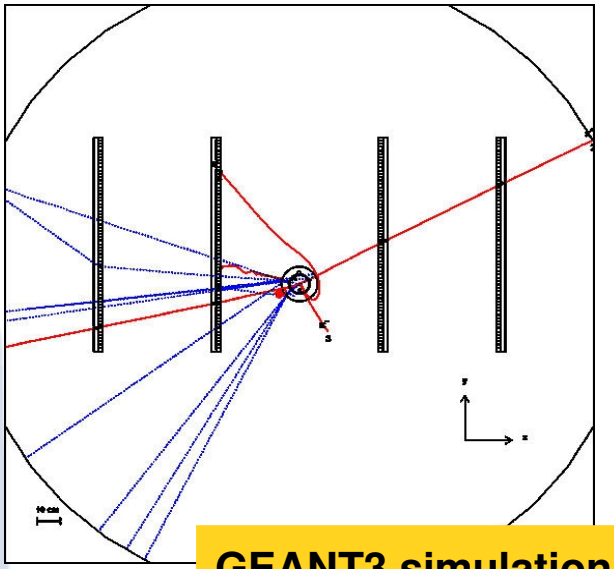
- 4 x-y modules
- each module:
  64 15x19x960 mm^3 bars (Fermilab)
- 1 1mm of diameter WLS fiber per bar
- 64 channel MAPMT (Hamamatsu, H7546B)

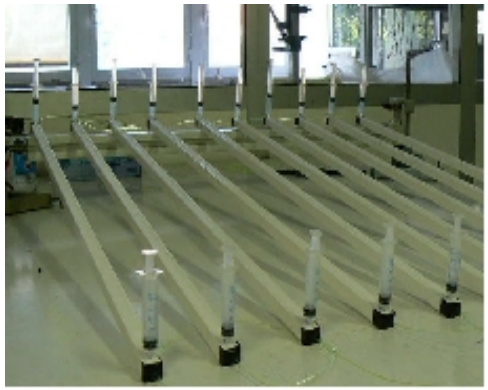


Tracking of the charged pions to evaluate the antiprotons annihilation inside the trap to evaluate the confinement

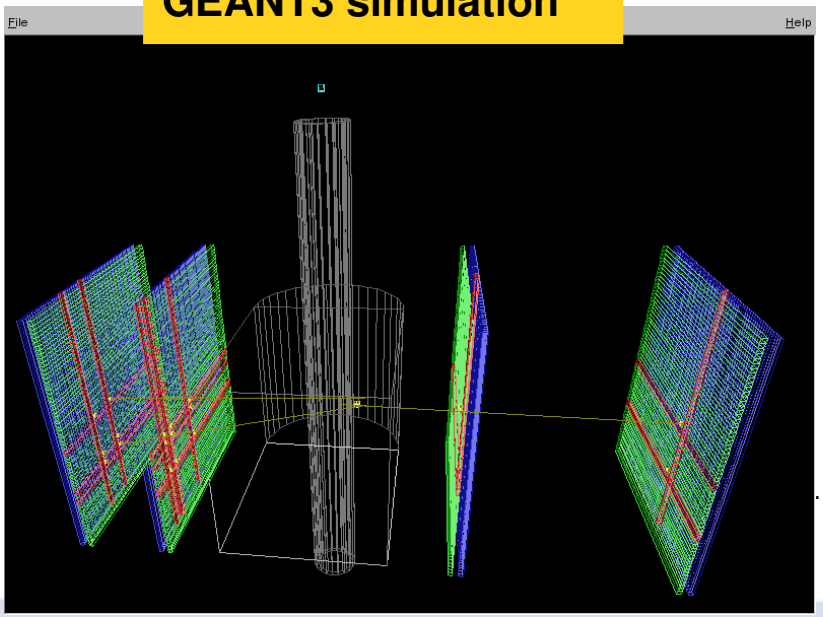
Assembling and commissioning

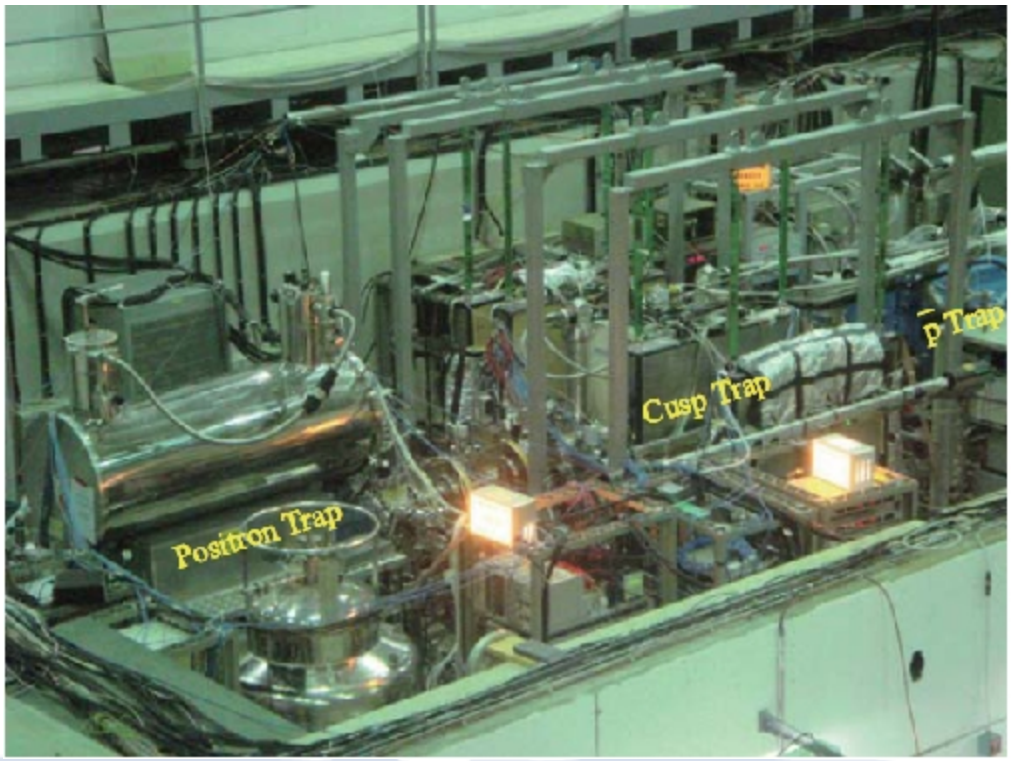
WLS glued in the bars





GEANT3 simulation





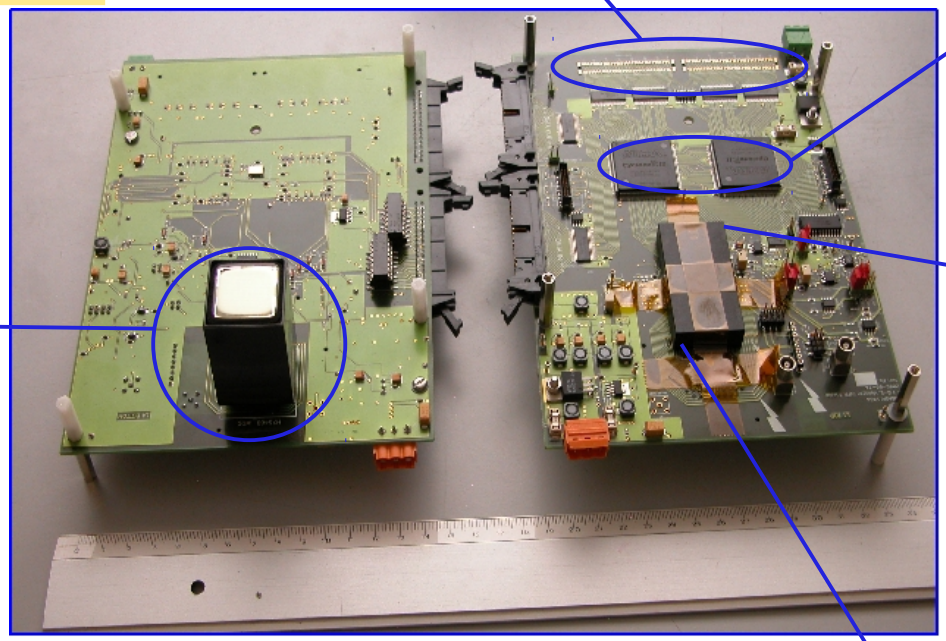
The electronics

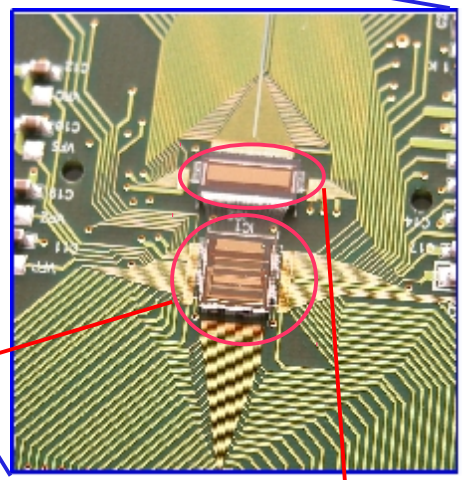
MUSASHI exploits just the analog readout

Memory board connectors

FPGAs Altera Cyclone II

Socket for a 64 MAPMT





VA64TAP3

- 64 channel low noise/low power ASIC (Gamma Medica-Ideas)
- pre-amplification, shaping and discrimination;
- multiplexed analog output
- 64 digital parallel outputs

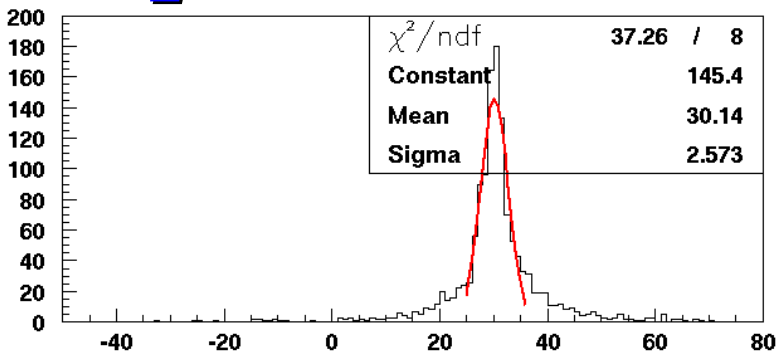
LS64_2

To feed digital VA64TAP outputs to FPGA

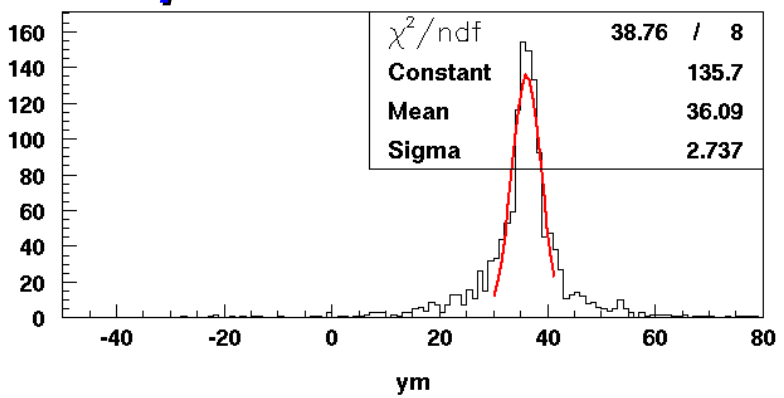
Results

Spatial resolution

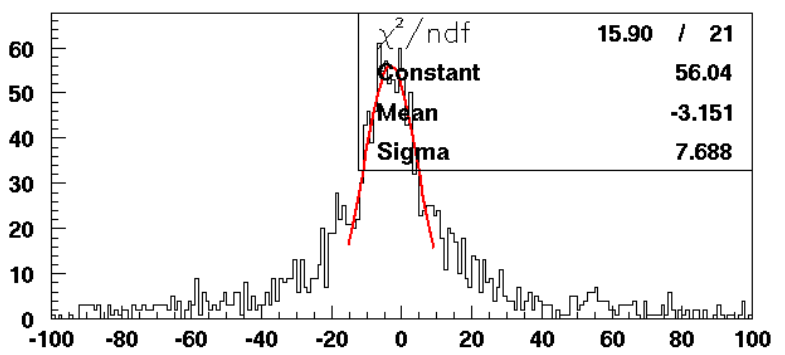
Z



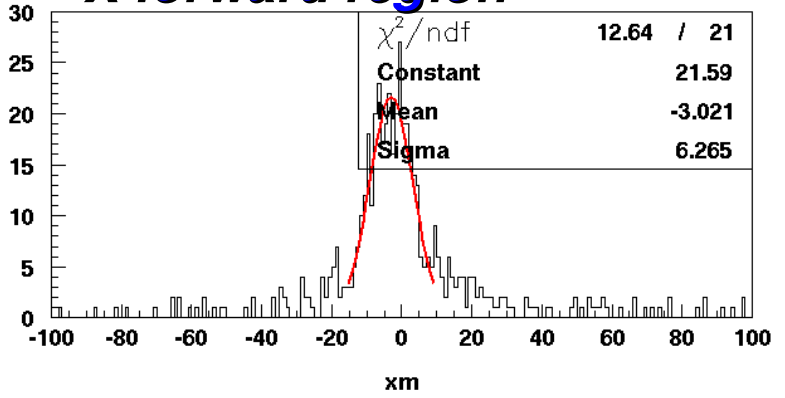
Y



X all

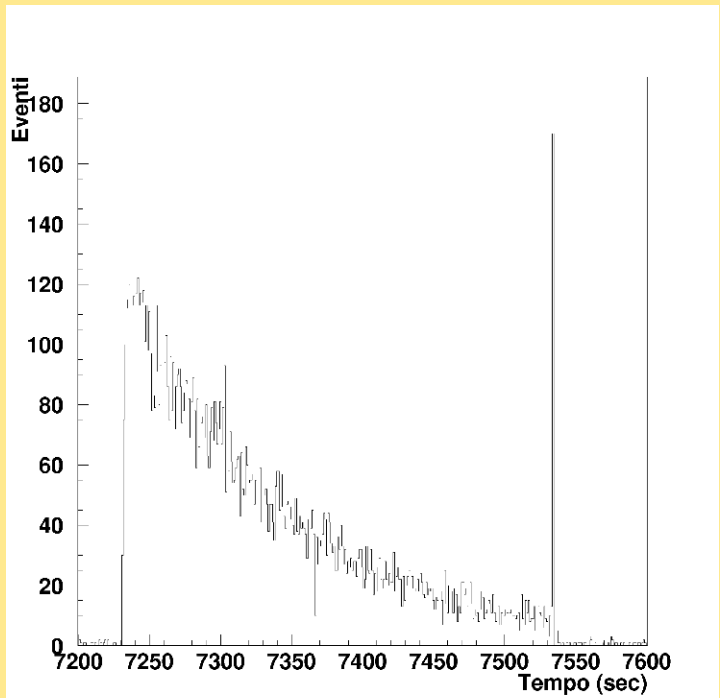


X forward region

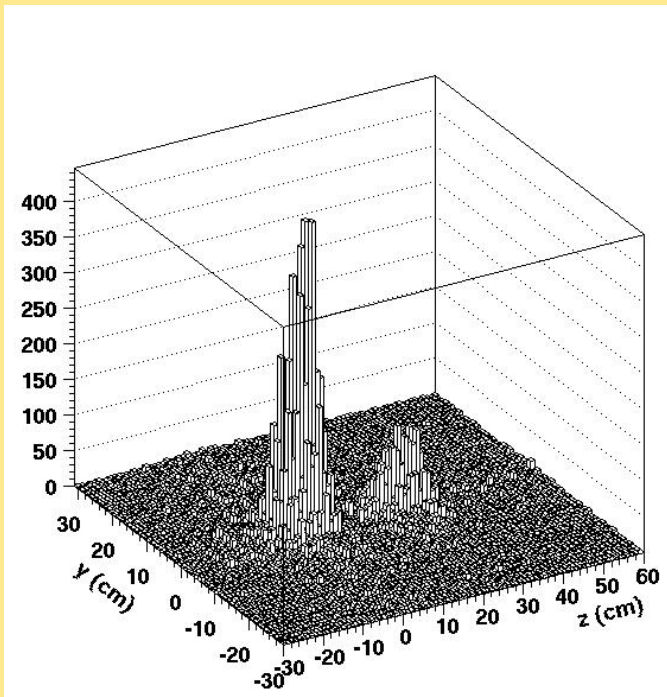


Results (2)

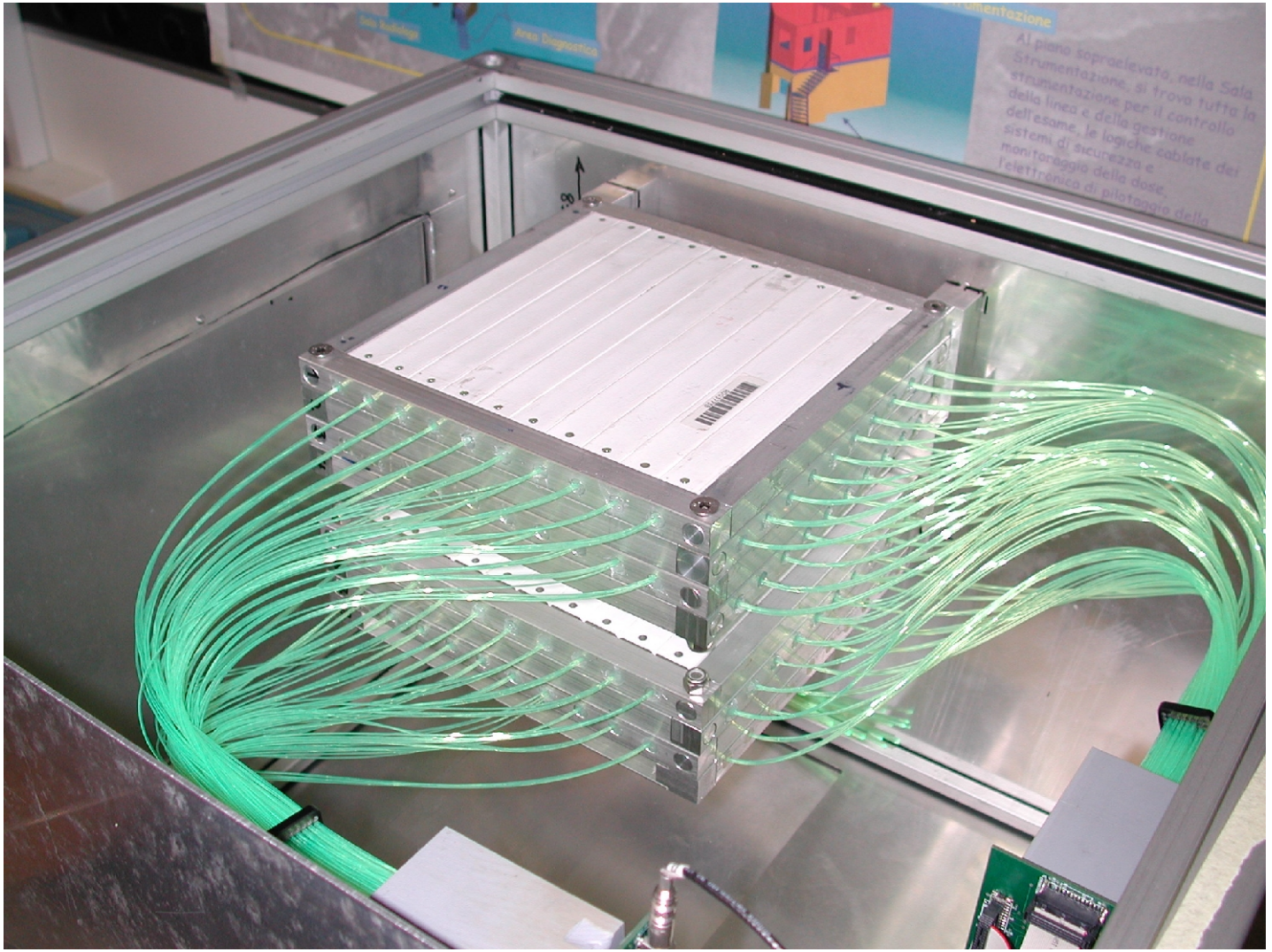
Extraction time structure



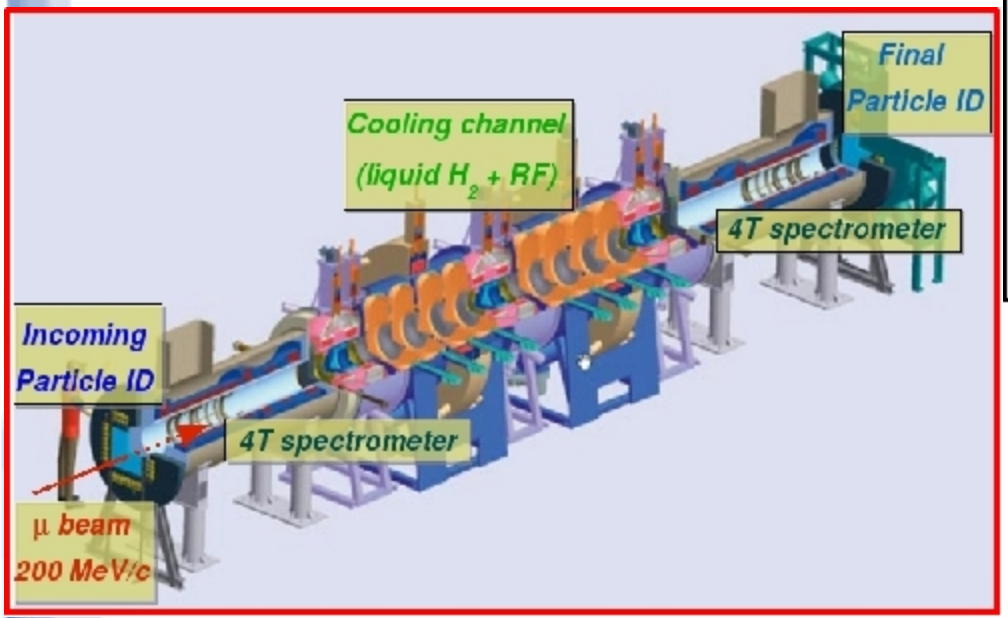
Annihilation in the CUSP trap

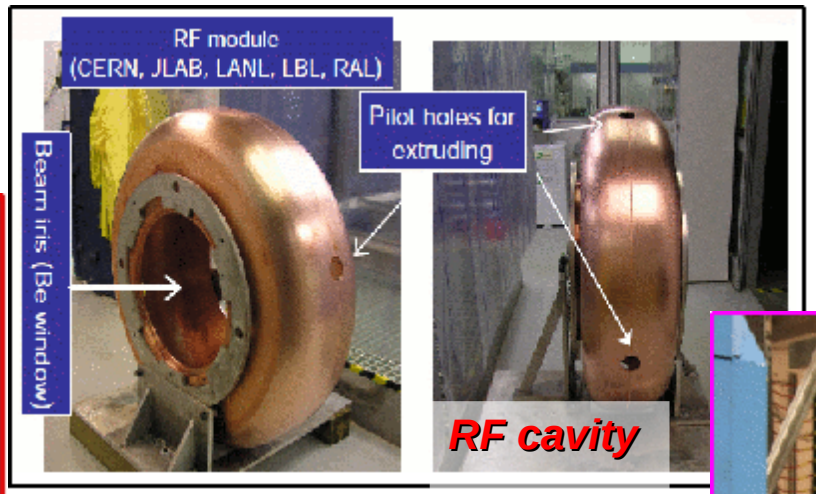


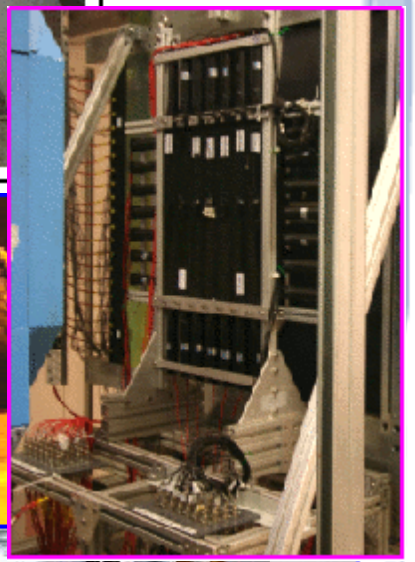
MICE



The MICE experiment



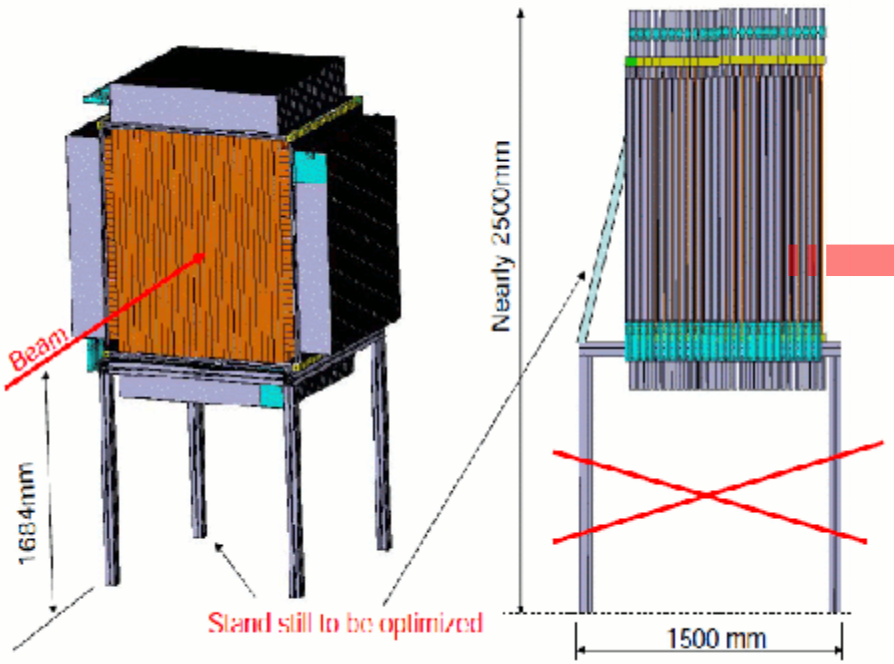




- Cooling channel: **RF (4 201.25 MHz cavity) +absorber (liquid H_2)**
- **4 T Solenoid + spectrometer (scintillator)**
- Particle ID **(upstream): TOF + Cherenkov**
- **Particle ID (downstream): TOF + Cherenkov +** Calorimeter
- **Muon beam: 140 – 240 MeV/c (from 800 MeV protons of** ISIS @ RAL**)**

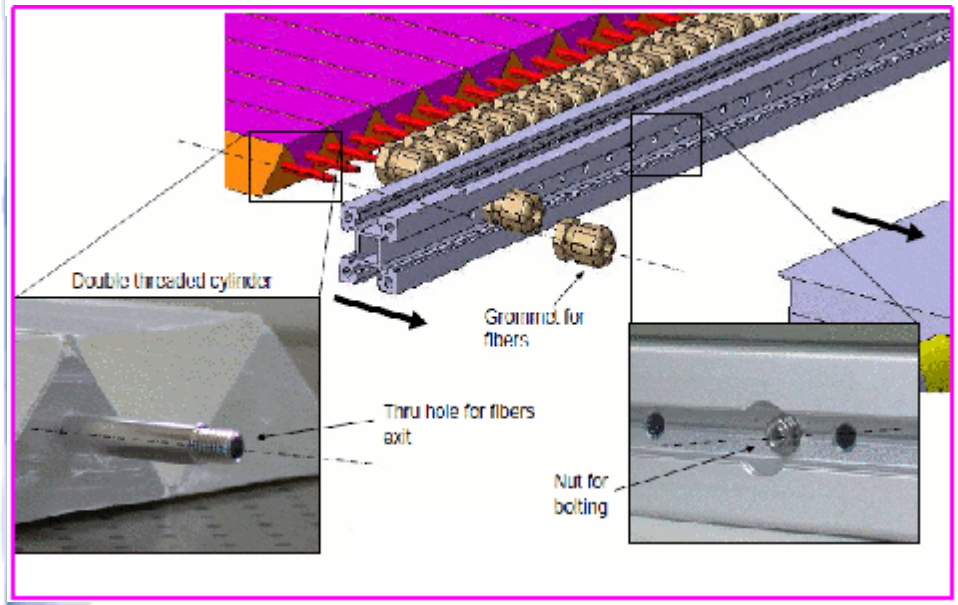
D. Bologni

EMR: Electron Muon Ranger



Calorimeter + tracker

- 50 planes of plastic scintillator arranged in a x-y geometry
- 59 bars, 1.1 m long with a triangular shape
- 1 WLS fiber of 1.2 mm of diameter, glued inside each bar
- On one side a single PM (XP2972, Philips) for the calibration and charge measurement
- On the other, 64 MAPMT (H7546B, Hamamatsu)



The EMR electronics

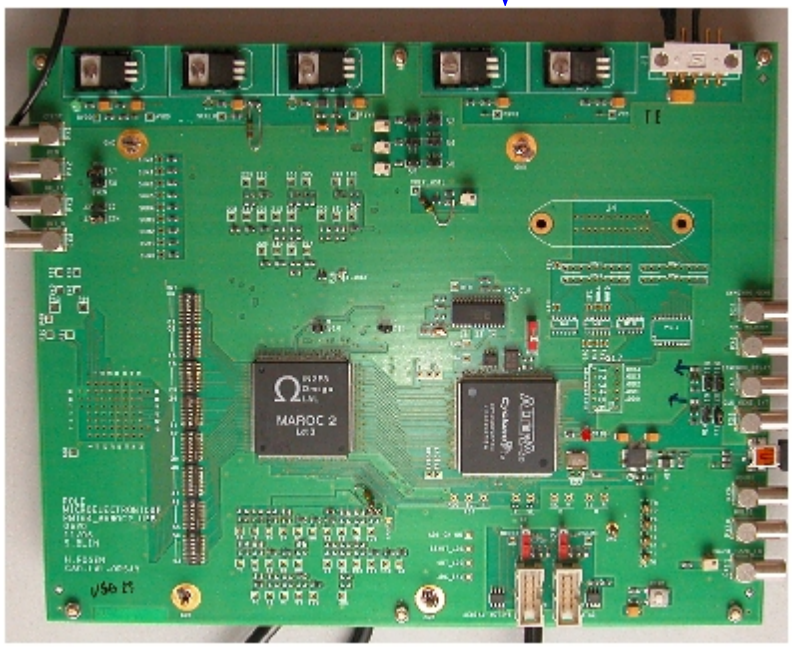
Standard digitizer for the single PM:

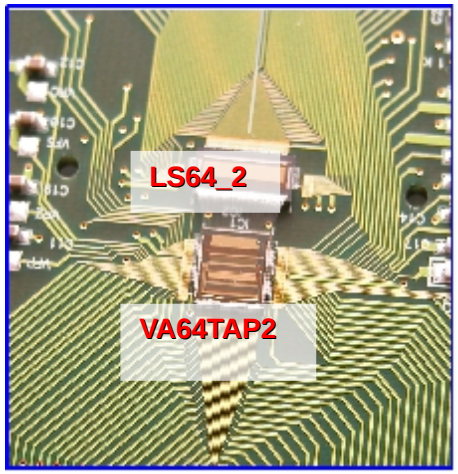
Based on ASICs for the MAPMT:

VA64TAP3 (Gamma Medica-Ideas): 64 channel 0.35 µm N-well CMOS low noise ASIC;
LS64_2 (Gamma Medica-Ideas)

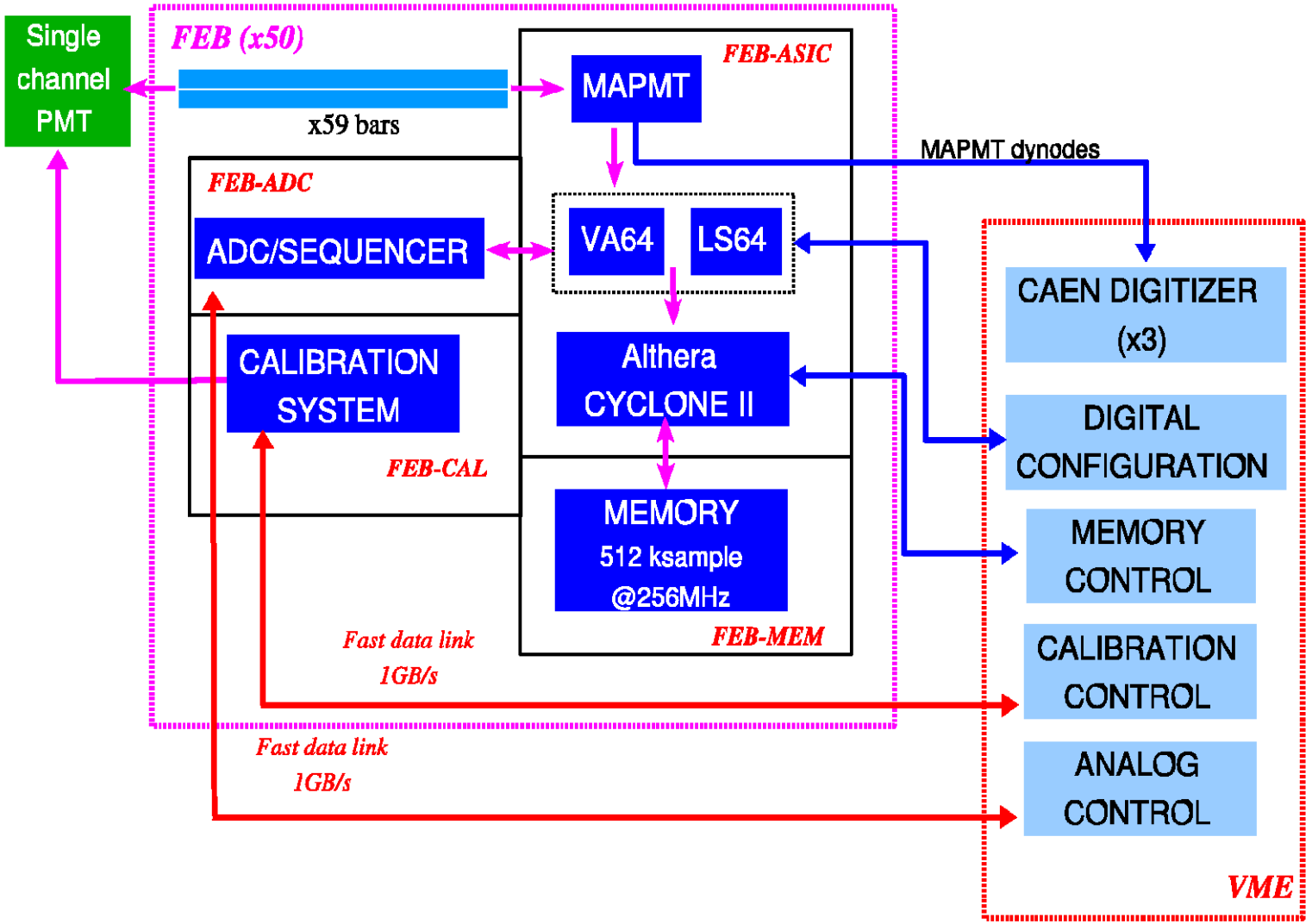
or

Maroc-II (Omega-LAL)





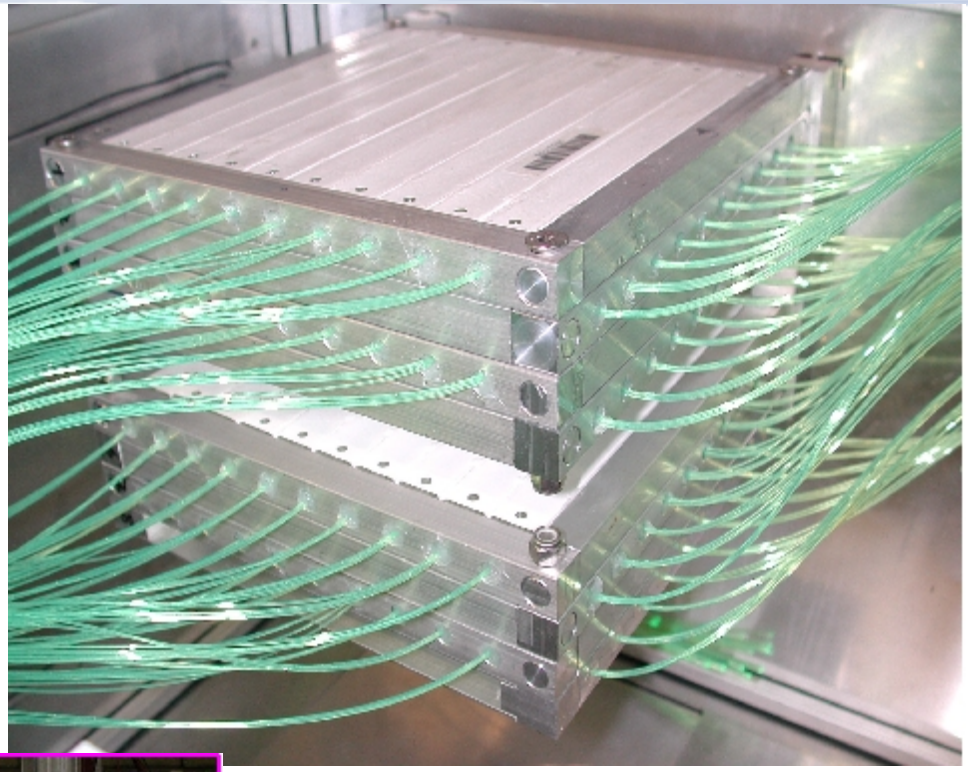
The EMR electronics

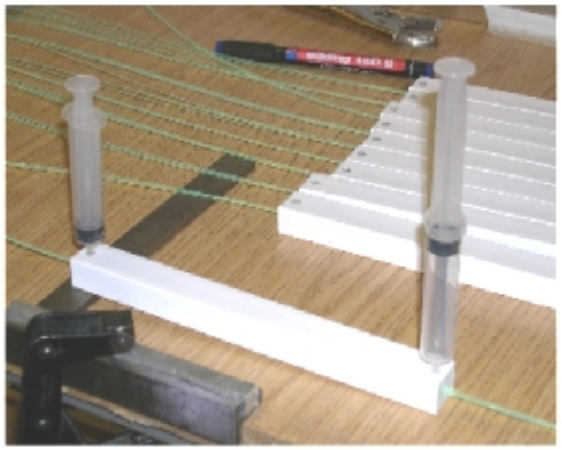


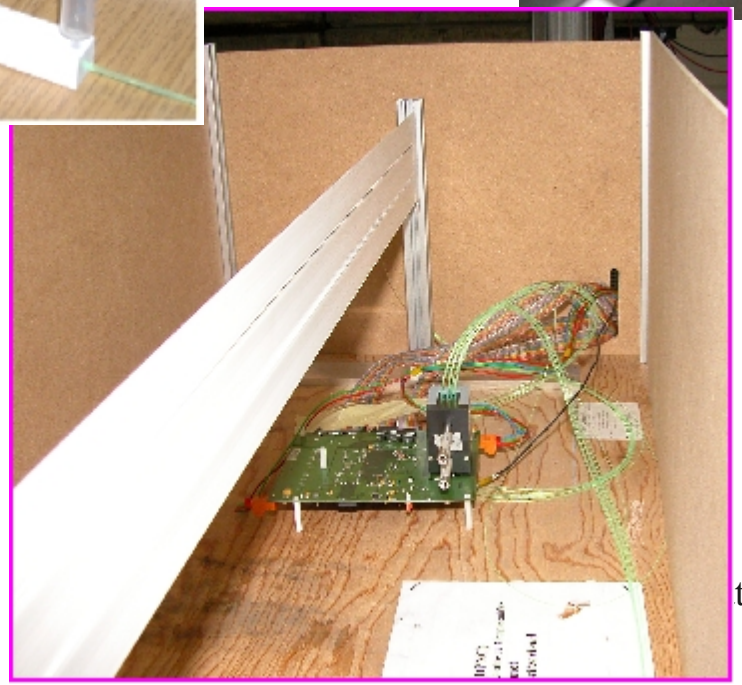
The EMR prototypes

1)

- 8 modules organized in 2 blocks (2x-2y)
- 10 squared bars per plane (cross section 15x19 mm^2, 19 cm long)
- 4 WLS fiber (0.8 mm of diameter) glued into the bar: light collection!





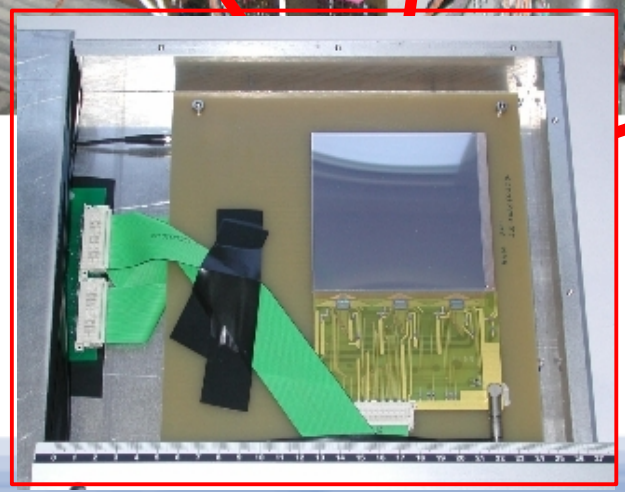


2)

- 5 1.1 m long bars with a triangular shape
- Scintillator light is readout from both the sides with a MAPMT

Beam test setup @ CERN PS T10 line

EMR prototype



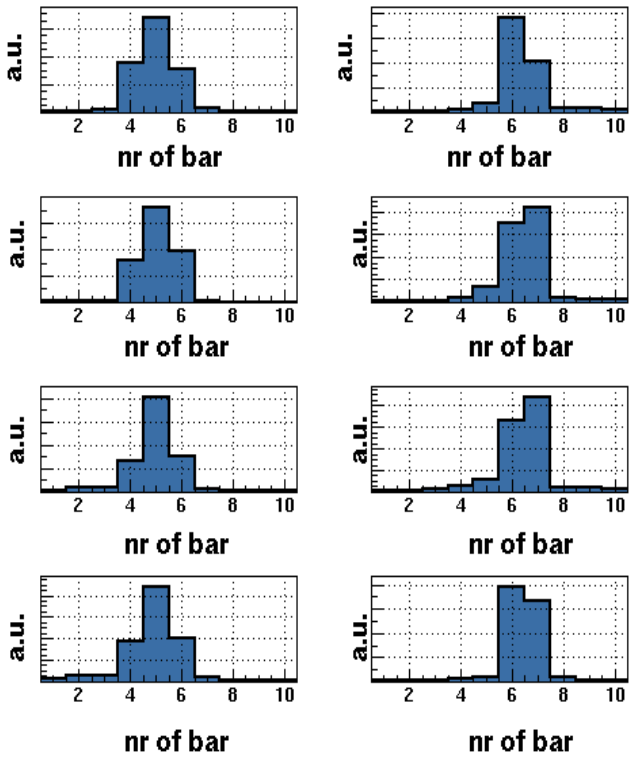
TRIGGER

2 3x10 cm^2 plastic scintillator

Silicon beam chambers

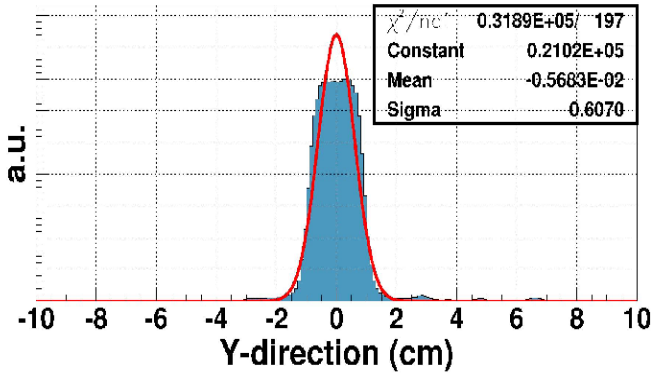
- Single side microstrip silicon detector of 9.5 x 9.5 cm^2; 410 µm thick
- strip pitch 121µm: readout pitch 242µm with strip floating system: ~30 µm of spatial resolution
- 3 TAA1 ASICs (Gamma Medica -Ideas) for an analog readout

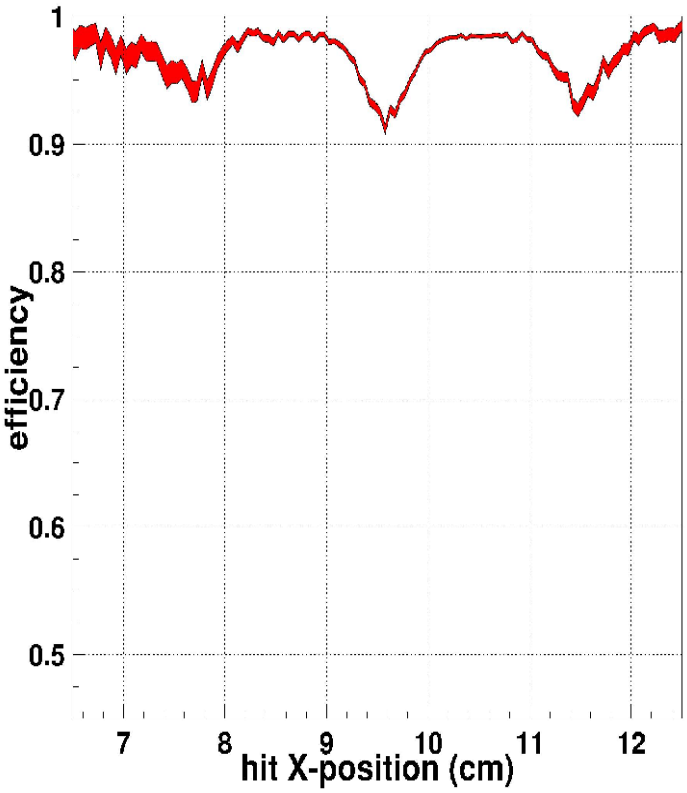
First EMR prototype results

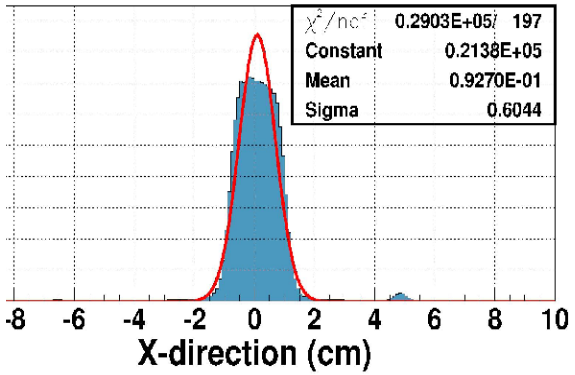


Beam profile X & Y

Efficiency:
98.3 % in Y
97.4 % in X;

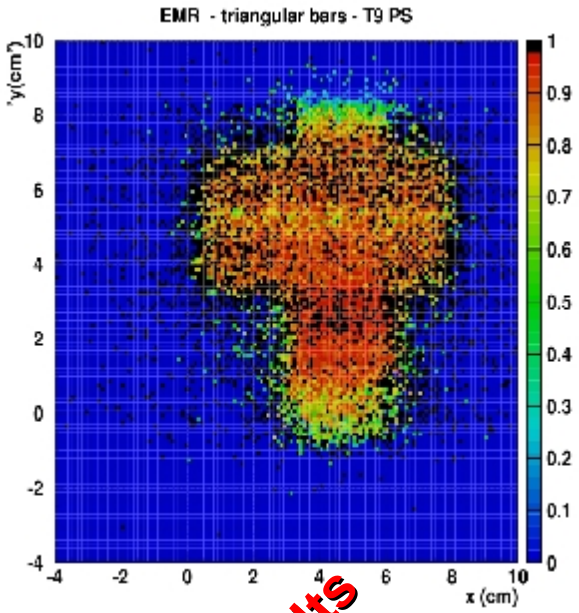




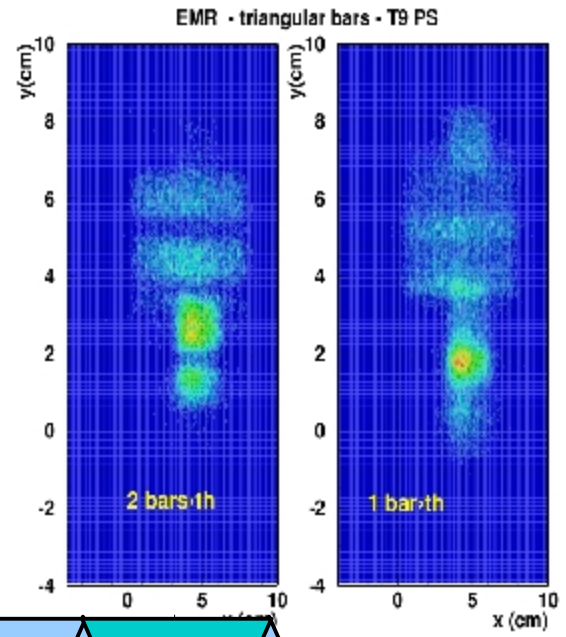


Residuals:~6 mm

Second EMR prototype

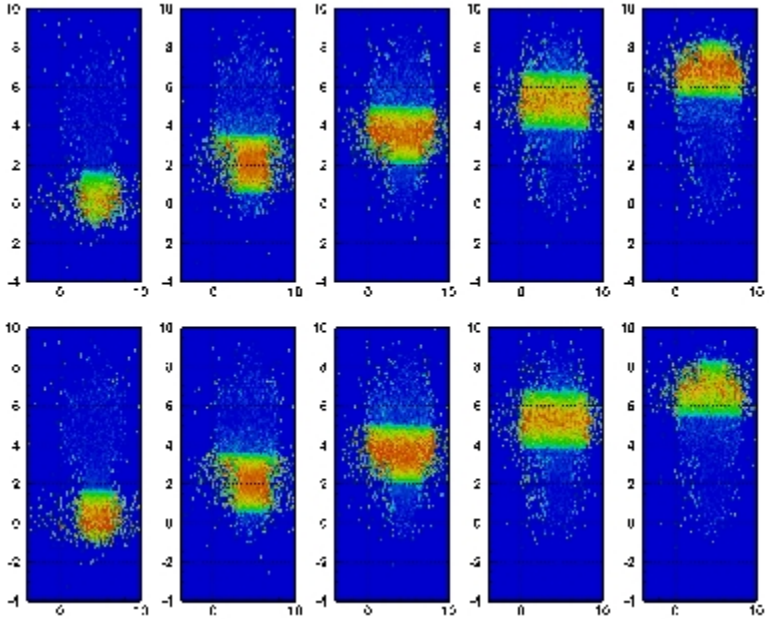


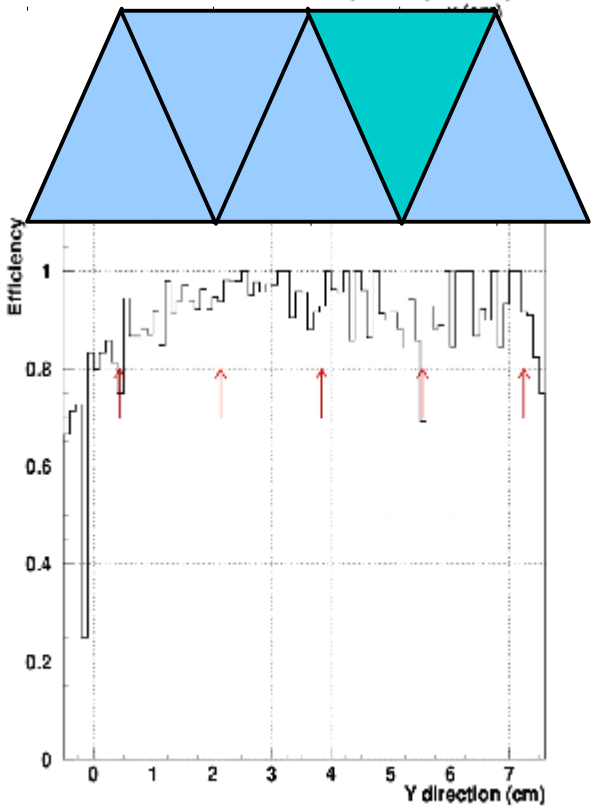
Efficiency



Beam profile

Preliminary results





tt

CONCLUSIONS

Conclusions

- From smaller to bigger experiments, a tracking system plays a key role in HEP

- There're no global features common to different tracking systems (apart from the track identification!!) and each single characteristic is determined by the observable

- The 3 experiments (UA9, MUSASHI & MICE) have been developed to satisfy certain constraints and the preliminary tests and measurements have shown good results

- An upgrade is foreseen for the MUSASHI electronics, passing from the analog to the digital readout (V. Mascagna, 10/12/2009)
- MICE will be installed in summer 2010
- At present, the UA9 experiment activity is suspended...but a lot of work is foreseen in the bent crystal field!!

Tracking system in HEP:
concept and performance of 3 experiments

Thanks