An EUDET/AIDA pixel beam telescope for detector development

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DESY

On behalf of EUDET and AIDA consortia

11 June 2011
TIPP, Chicago, IL, USA

European institutes and Detector development

European Union funding of research institutes and common projects

EUDET (2006-2010)

31 institutes
in 12 EU countries
+29 ass. institutes

"Integrated Infrastructure Initiative (I3)"

EU funded 6th Framework Programme

- **support** the infrastructure for detector R&D in Europe
  - for next large project (after the LHC) the International Linear Collider (ILC).
- 21.5 million EUR total (1/3 from EU)

AIDA (2011-2014)

80 institutes& labs
in 23 EU countires

"Advanced European Infrastructures for Detectors at Accelerators"

EU funded under the FP7 Research Infrastructures programme

- **upgrade, improve and integrate** key European research infrastructures and **develop** advanced detector technologies infrastructure for future particle accelerators like
  - LHC upgrade, Linear Colliders, Neutrino facilities and Super-B factories

in line with European Strategy for Particle Physics

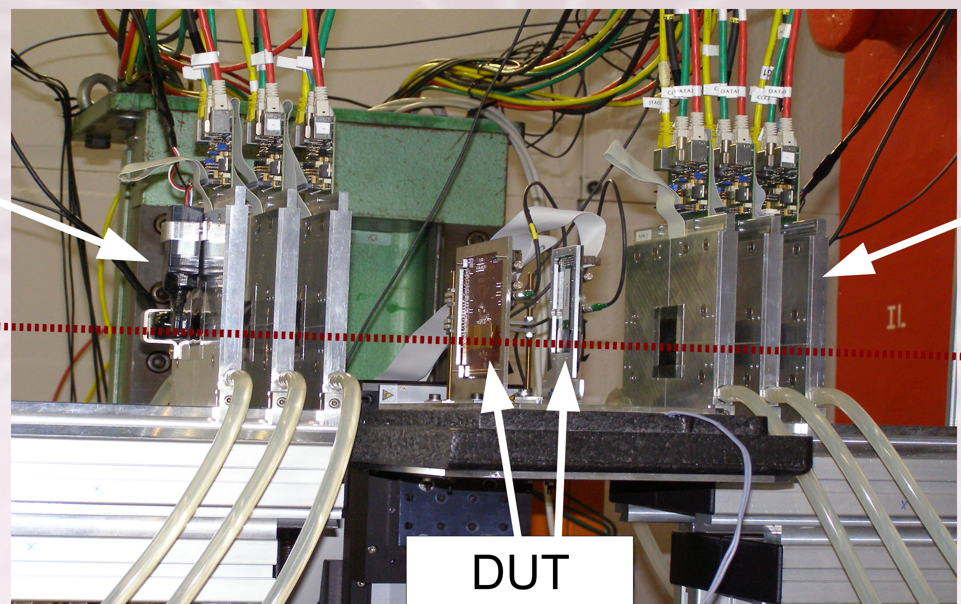
- 26 million EU total (1/3 from EU)

A beam telescope only one out of many work packages in both in EUDET and in AIDA

Why would one need a pixel beam telescope

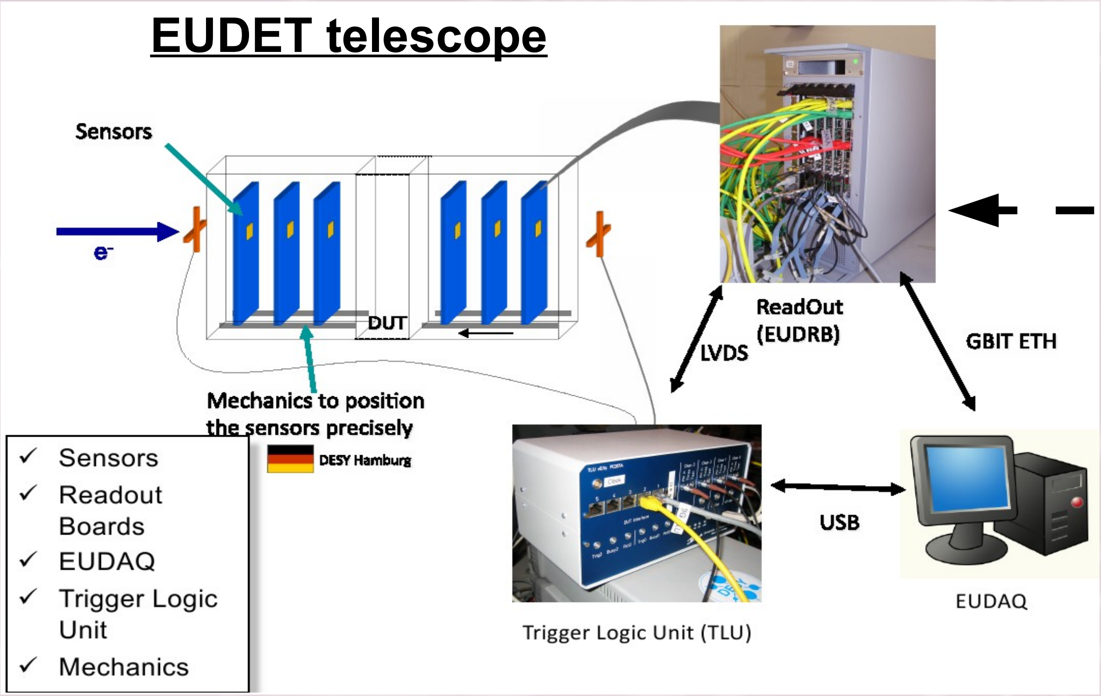
<u>What is a Beam Telescope?</u>
- A tool to define the exact track of a particle in a beam test very precisely
- Used for detailed studies of newly developed detectors
- Pointing resolution should be better than the expected intrinsic resolution of the **Device Under Test (DUT)**

<u>Generally applicable for:</u>
- DUTs: small pixel sensors to larger detectors
- Movement of DUT to scan full surface
- Large range of requirements:
  - cooling (suppress noise),
  - Positioning, rotations, B-field, low material budget (particle track propagation)



An example of a beam telescope setup (DESY e^{+} 4 GeV)

EUDET pixel beam telescope - schematics



New readout for AIDA telescope

New (2011):
National Instruments
PXI PCI-express bus

MAPS sensors (Mimosa 26)
- 4 µm intrinsic resolution (18.4x18.4 µm pitch)
- track pointing resolution ~2 µm

VME based DAQ readout ~700 Hz
- 1 million events in ~25 minutes (~1 GB)

TLU – Trigger Logic Unit (UK, Bristol)
- software controlled PMT coincidence logic

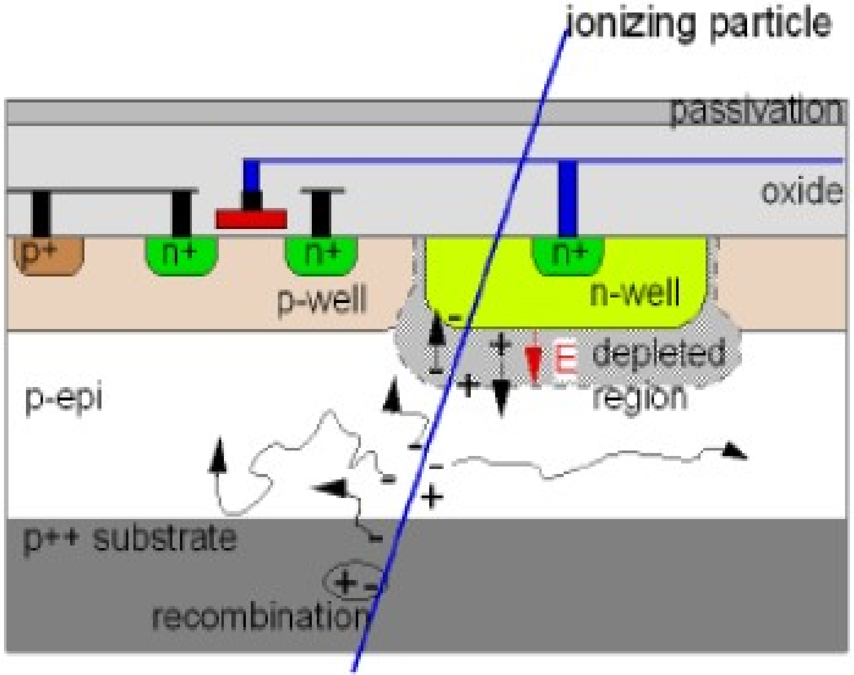
DAQ rate up to ~4(8) kHz

- up to an order of magnitude more data during the same beam time

MAPS – Monolitic Active Pixel Sensor

Sensor technology choice

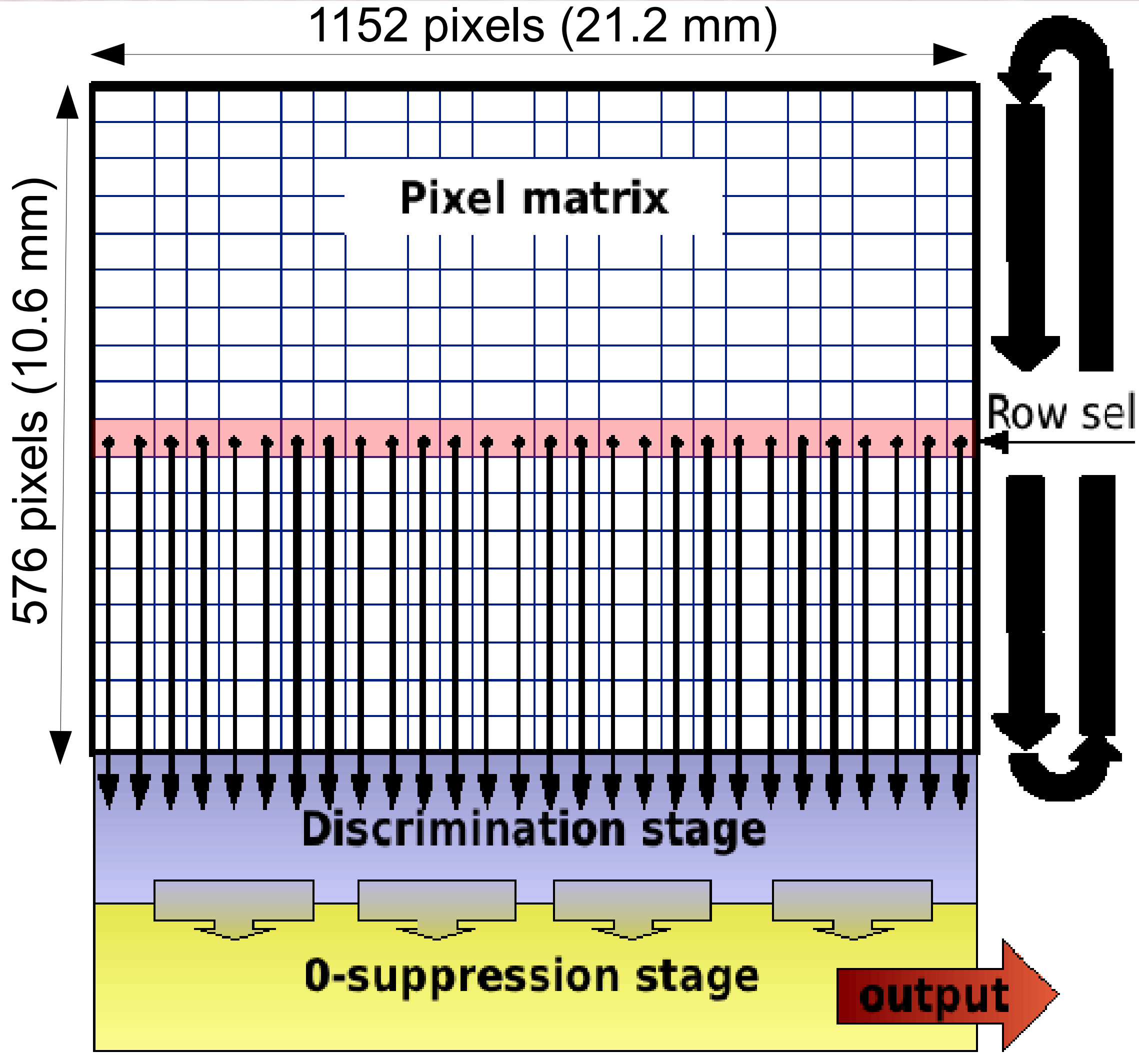
- Prominent features of CMOS pixel sensors:
  - Cost effective
  - high granularity
    - Excellent (~ 1 μm) spatial resolution
  - can be very thin
    - signal generated in 10-20 μm thin epitaxial layer
    - down to 50 μm
- signal processing μ-circuits integrated on sensor substrate
  - impact on downstream electronics (cost)
- Charge collection by diffusion



MAPS in the telescope - Mimosa 26 (by IPHC Strasbourg)

- CMOS 0.35 µm
- Pixel size: 18.4x18.4 μm^2
- Rolling shutter mode
  - at 80 MHz → 112.5 µs per frame
  - no deadtime, continues readout
  - digital (binary) readout
- In pixel amplification
- 1 discriminator per column with
  - Offset compensation
  - Correlated Double Sampling
- Built-in data sparsification

- Current version of Mimosa26:
  - High resistivity epitaxial
  - Backthinned down to 50 µm



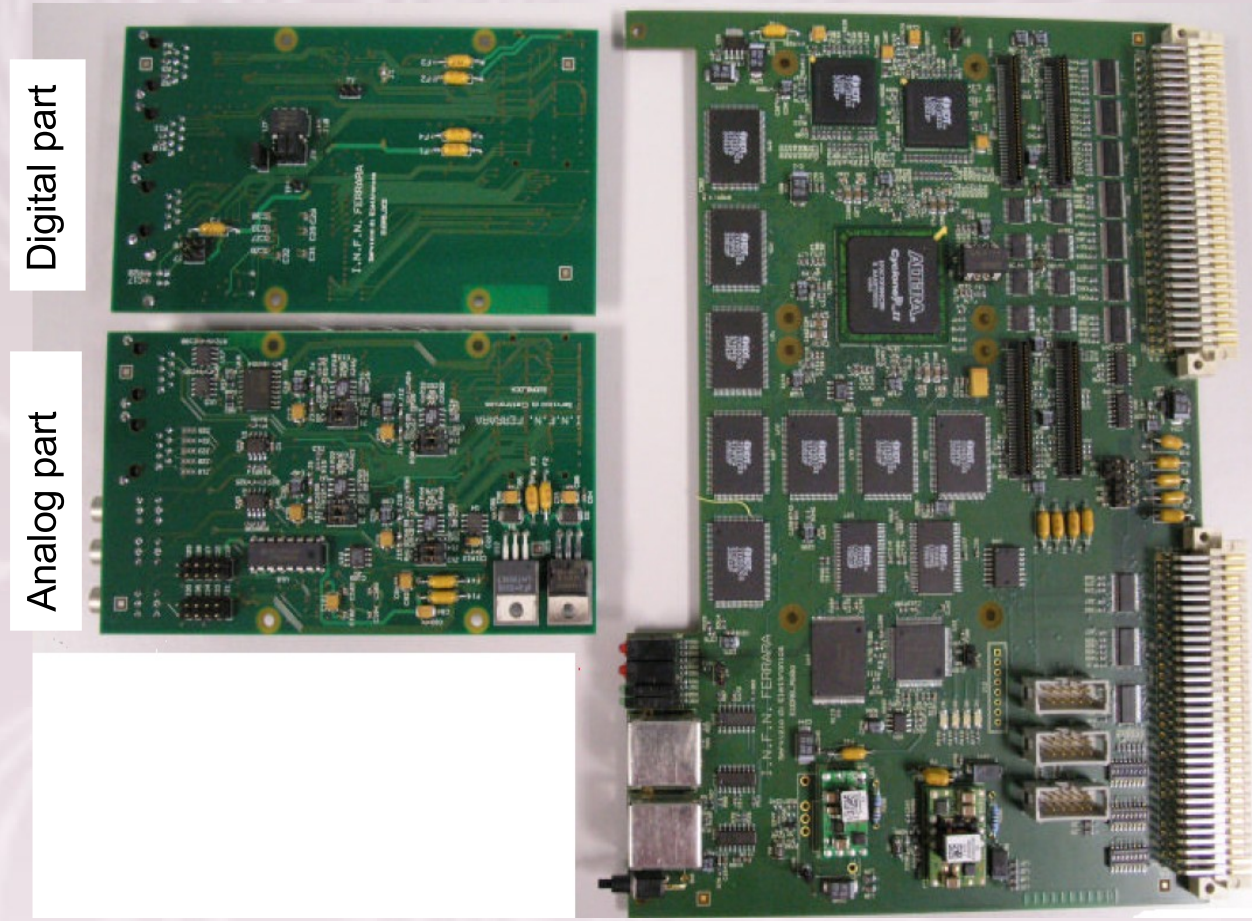
Mimosa sensors readout I – custom made VME boards

EUDRB – EUDET Data Reduction Board
- custom made (INFN Ferrara)
- Mother board built around an ALTERA Cyclone II FPGA hosting the core resources
- provides 80 MHz clock for sensors
- Interfaces (VME64X slave, USB2.0, EUDET Trigger bus)
- one EUDRB per sensor

Can deal with both
- analog sensors (MimoTel and Mimosa18)
- digital sensors (Mimosa26)

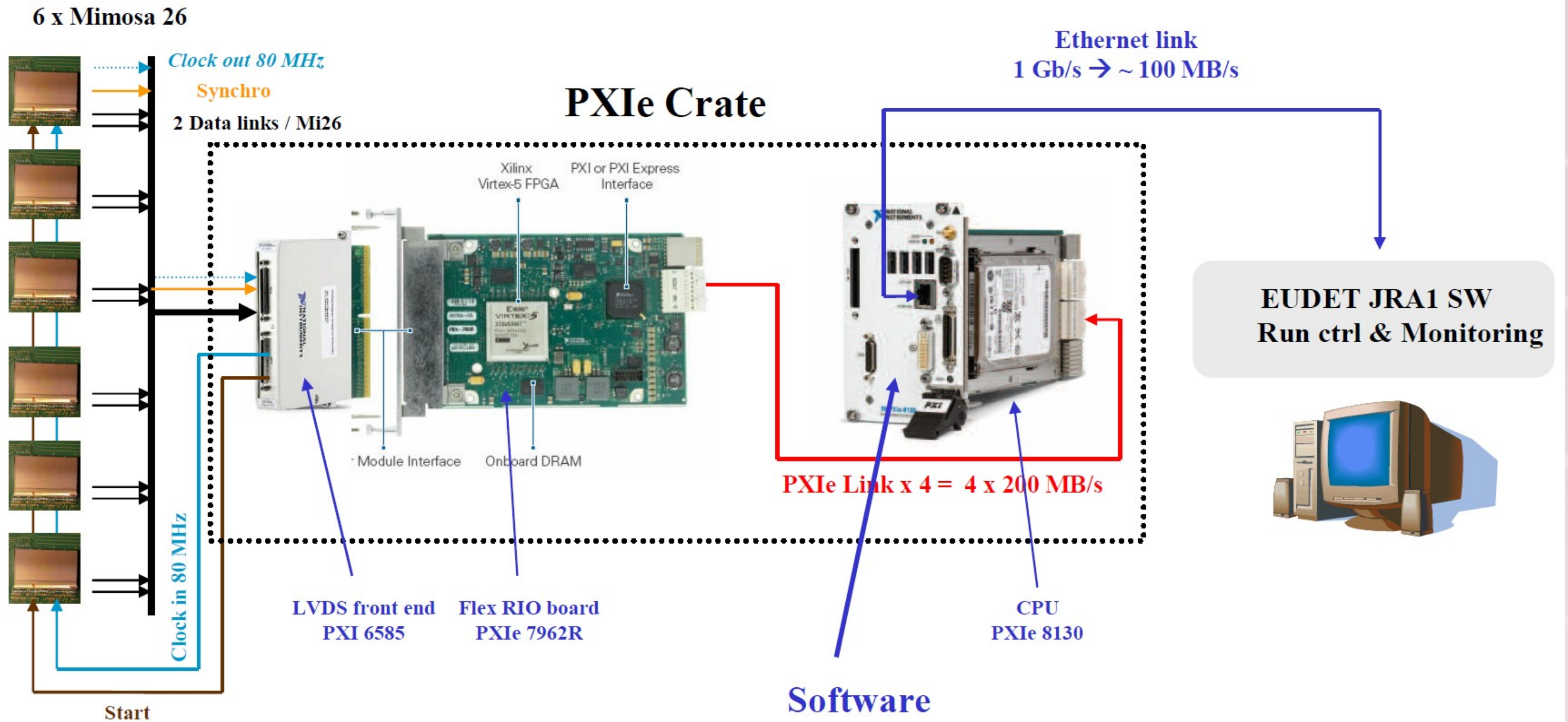
For the final 6 sensor assembly the average readout speed ~700 Hz
- 2 VME crates
- 3 EUDRBs per crate

EUDRB VME - max 80MB/s



see A.Cotta Ramusin, INFN Ferrara, The EUDET Data Reduction Board (EUDRB), EUDET-Memo-2008-38

Mimosa sensors readout II – National Instruments Flex RIO DAQ



NI Flex RIO PXIe – max 800 MB/s no limitations there

Main achievement – eliminates the readout deadtime (reading Mimosa sensors without dropping frames)

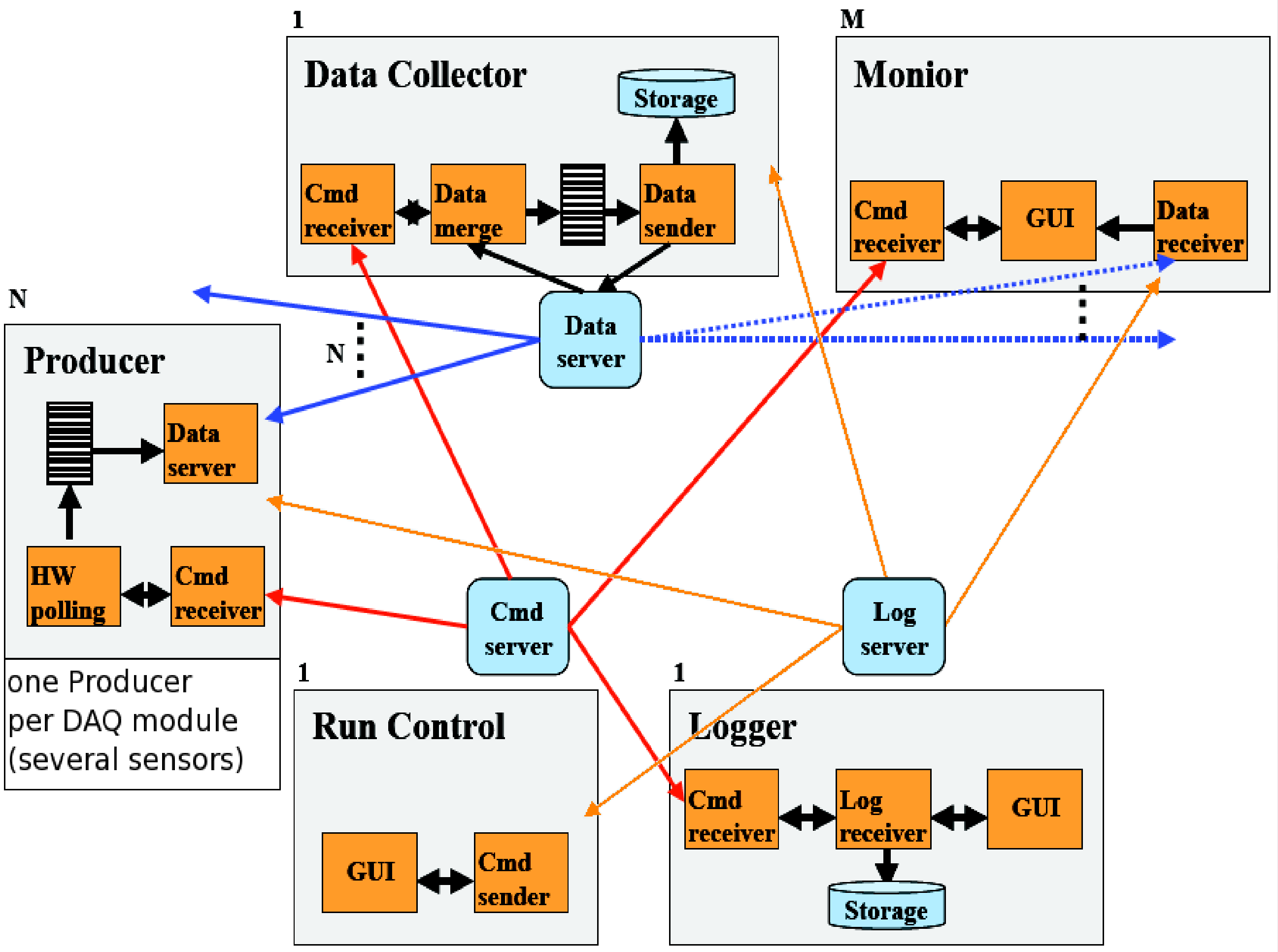
IPHC & NI Flex RIO DAQ for EUDET Mimosa 26 Beam Telescope, EUDET Memo-2010-25

EUDAQ software

- C++
- Multi-thread
- Distributed (TCP/IP)
- Highly modular
- Runs on MacOs, Linux, Windows

Producer

- DAQ system s/w partner, reads the data in and sends it to DataCollector.
- Reference sensor and DUT DAQ systems equal participants.



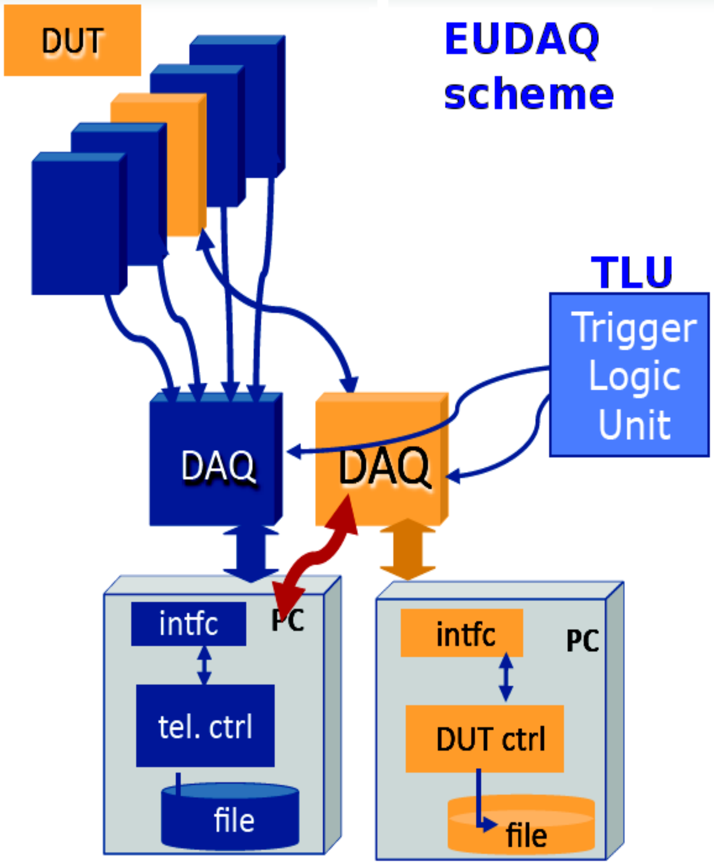
EUDAQ Software user manual, E.Corrin, EUDET-Memo-2010-01

DAQ user integration

General scheme for a DUT integration

A DUT comes with it's own DAQ system

- Important: understands trigger and "handshake" from TLU for synchronisation
- Optionally (recommended): writes into the same data stream with the telescope reference planes DAQ
  - EUDAQ integration
  - Simplifies the subsequent data analysis



EUTelescope - track reconstruction software

Implementation Idea:

- to make a transition in the simplest (for the user) way from single pixel array to a set of 3D space coordinates of measured hits and track fitted hits in the global frame

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Strategy chosen and maintained over the years:

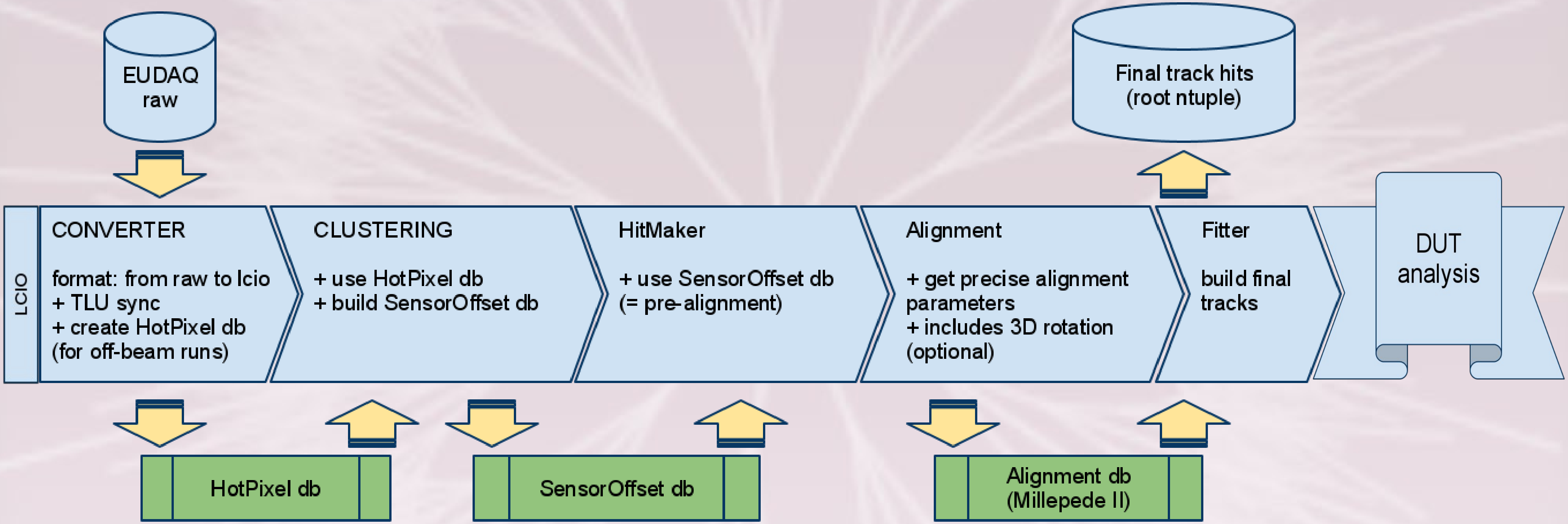
- not reinvent everything
- use existing algorithms as much as possible

Marlin framework chosen:

- Backbone of International Linear Collider software (ILCSoft)
- Open Source, can be used by non-ILC groups
- Highly Modular

EUTelescope: data analysis flow

The data analysis steps



EUTelescope: installation and how-to-run

How-to-install the framework and how-to-run data analysis is well documented
Makes user`s first steps in the ILCSoft easy

Software installation:

- need to install few of the ILCSoft packages
- certified and supported for Linux SL4/SL5
- easy to set up if one follows instructions:
  http://projects.hepforge.org/eudaq/Eutelescope/ilcinstall.html

Data analysis (= Track reconstruction):

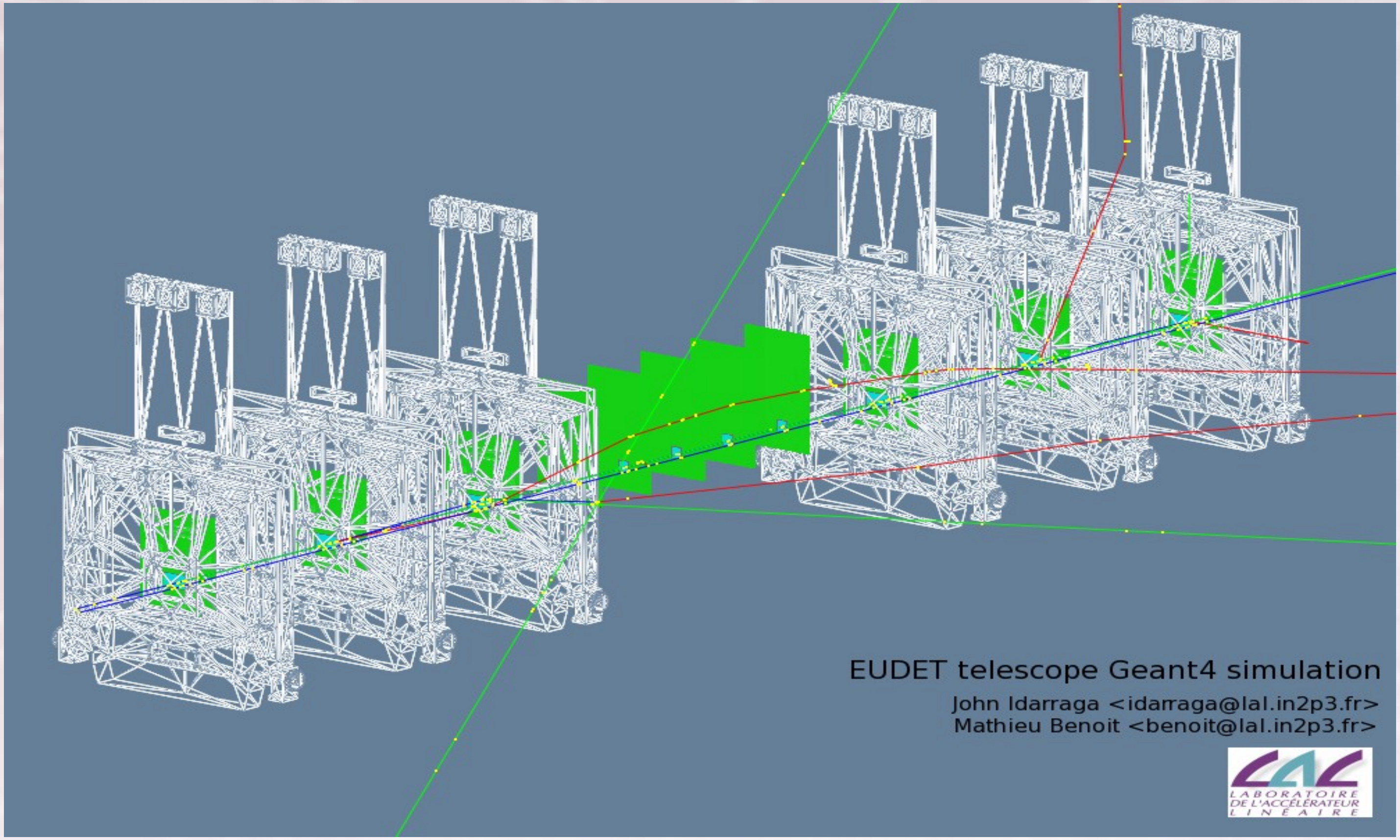
- minimal human intervention needed
- based on a set of scripts
  - to run on a local PC
    http://projects.hepforge.org/eudaq/Eutelescope/pythonScripts.html
  - or on the GRID
    http://projects.hepforge.org/eudaq/Eutelescope/gridtools.html

GEANT4 simulation

Full GEANT4 simulation can be produced

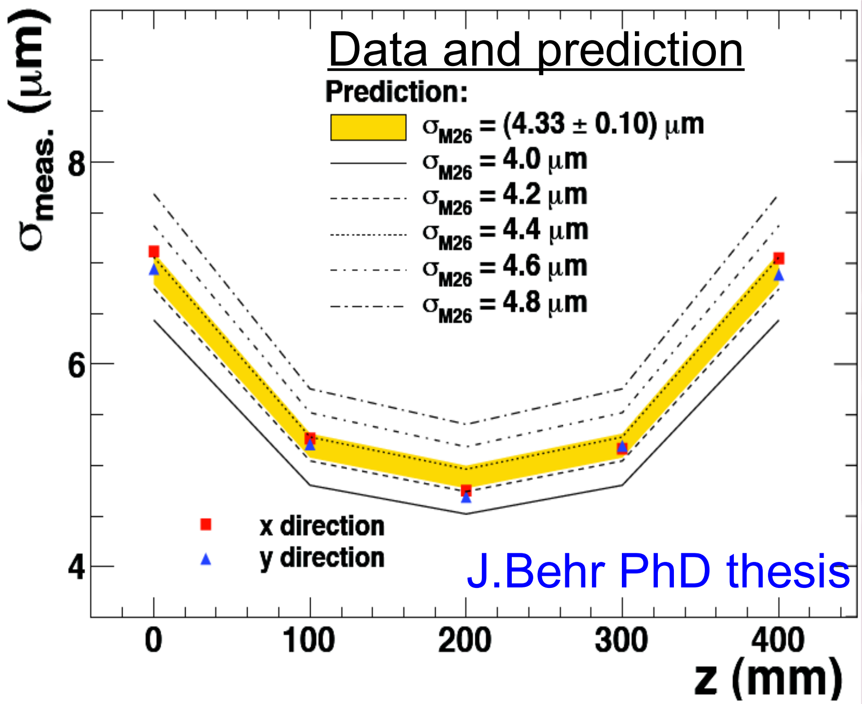
- realistic simulation events for further software developements

On the plot below: positrons 4GeV (Legend: positron, electron, photon)
6 Mimosa26 reference sensors (in Alu boxes)
4 DUTs in the center



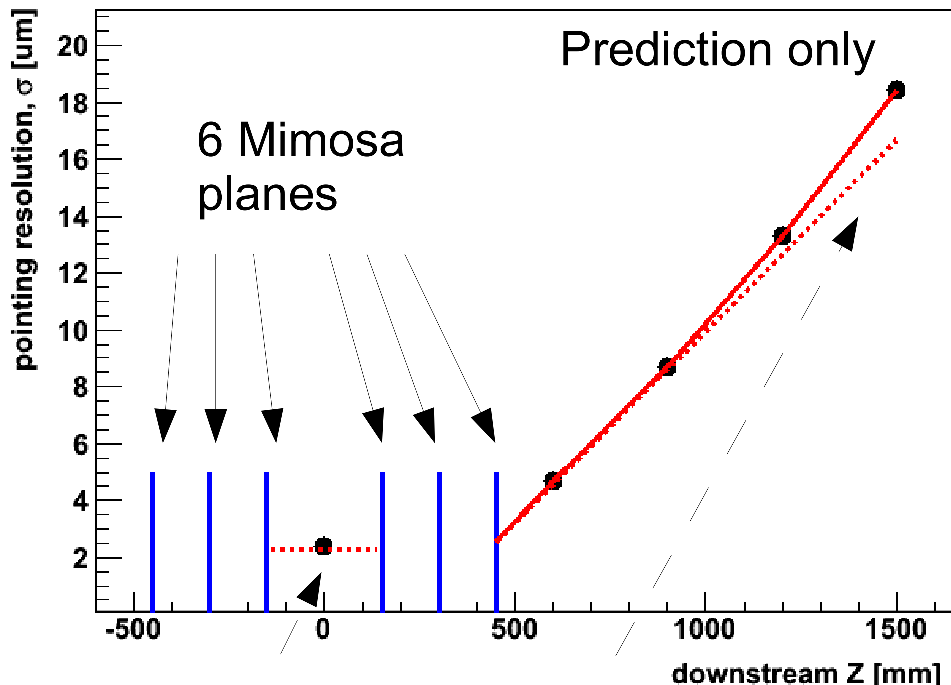
Performance of the telescope (CERN SPS, 120 GeV)

Pointing resolution in between the planes



$$\sigma^2_{meas} = \sigma^2_{m26} + \sigma^2_{pointing\text{-}resolution}$$

Track extrapolation accuracy far behind the telescope planes



A DUT within the telescope arms σ~2 μm

A DUT behind the telescope still can get a very reasonable track pointing resolution σ < 20 μm

Telescope users history

Successfully used since summer 2007

Different reference sensor technology
- analog MAPS telescope data
- digital MAPS telescope data (since Sep 2009)

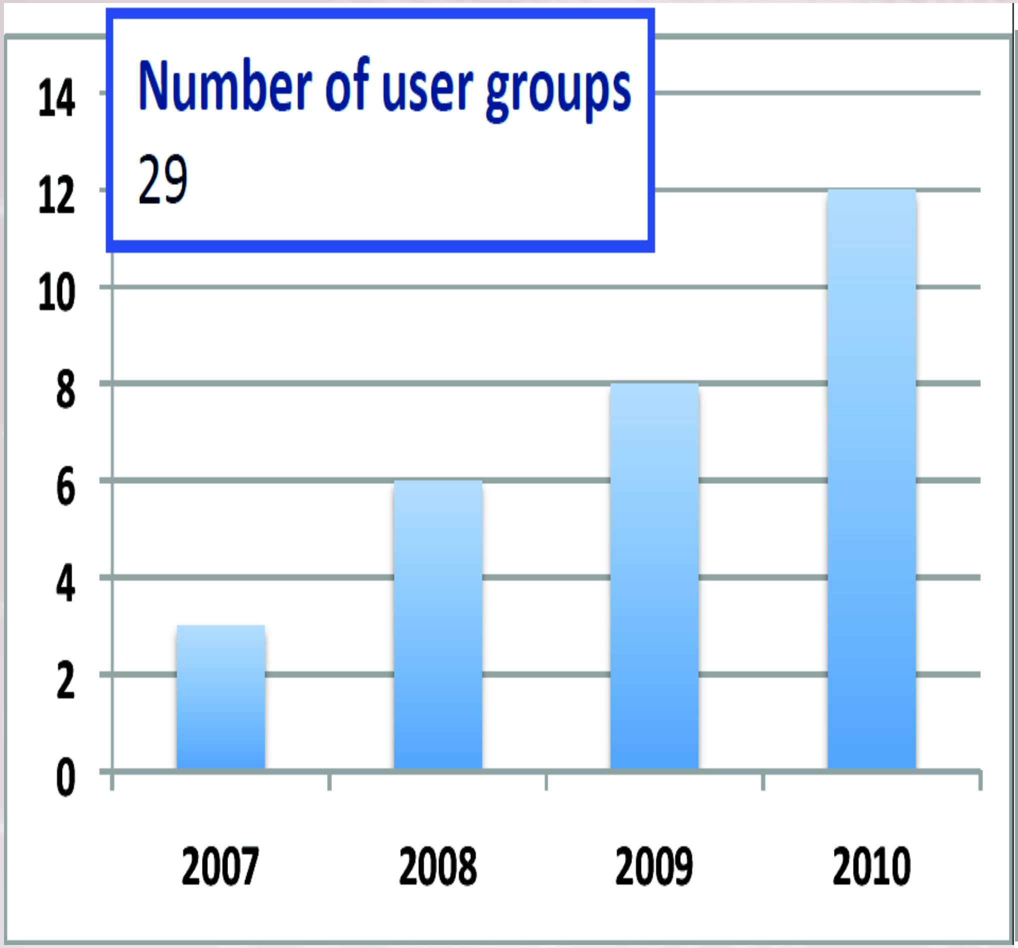
Provide track inter/extra -polation for DUT between/behind telescope arms

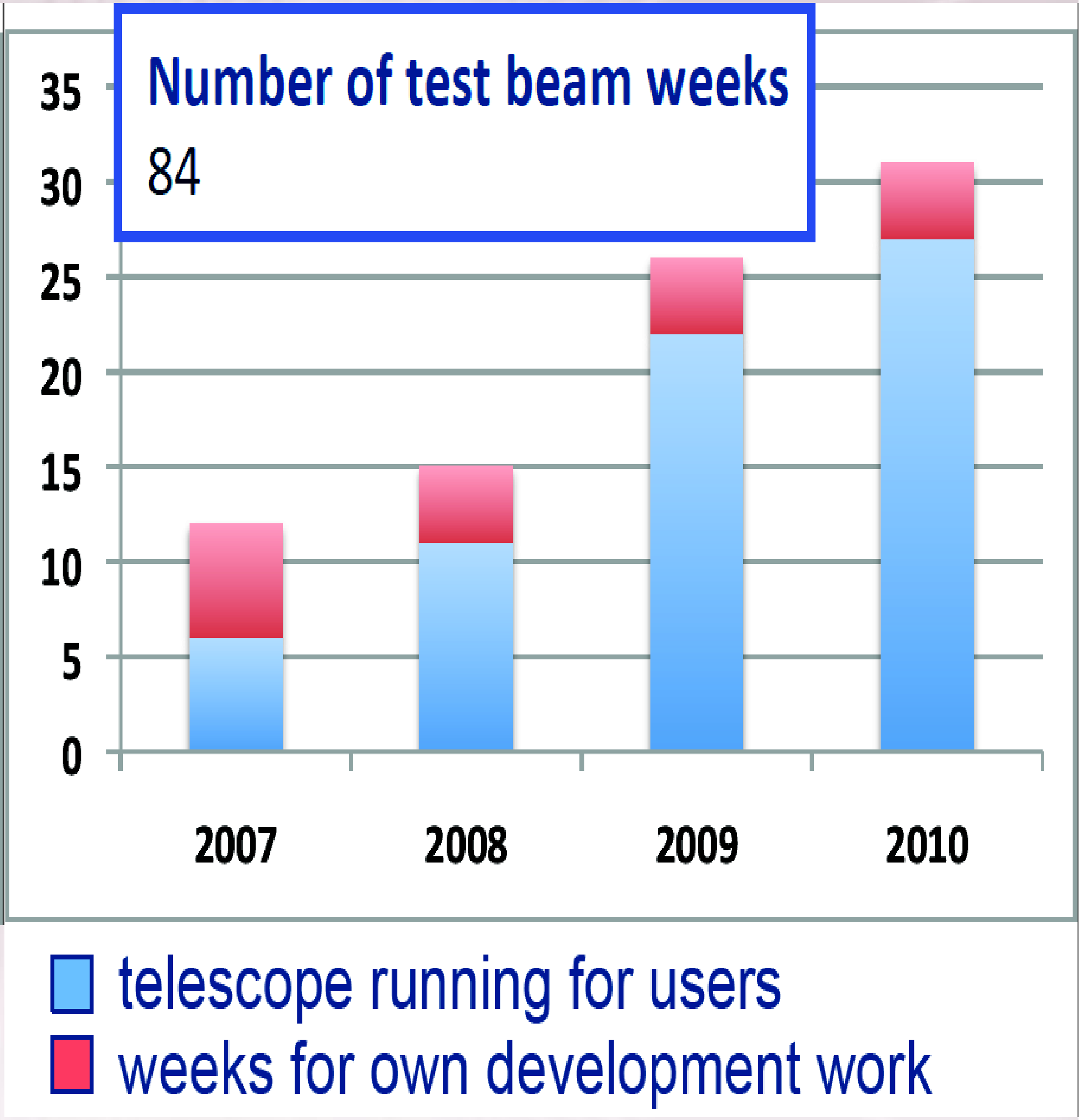
DUT analysis
- included in the framework
  - DEPFET, HighVoltage-MAPS,
  - Hybrid pixel (ATLAS pixels: Planar Pixel, 3D, Diamond),
  - Different versions of MAPS sensors
- also interfaced to external analysis software
  - Atlas groups (ALFA, TRT, Lucid), NA62
  - Atlas pixel groups specific software (TBMon)

More exotic applications:
- “Low Mass” measuring material X_0
- no DUT (for track fitting algorithms)
- very thick DUT (tungsten shower studies)

The beamline with the Telescope is always in high demand and attracts users!

Telescope users history





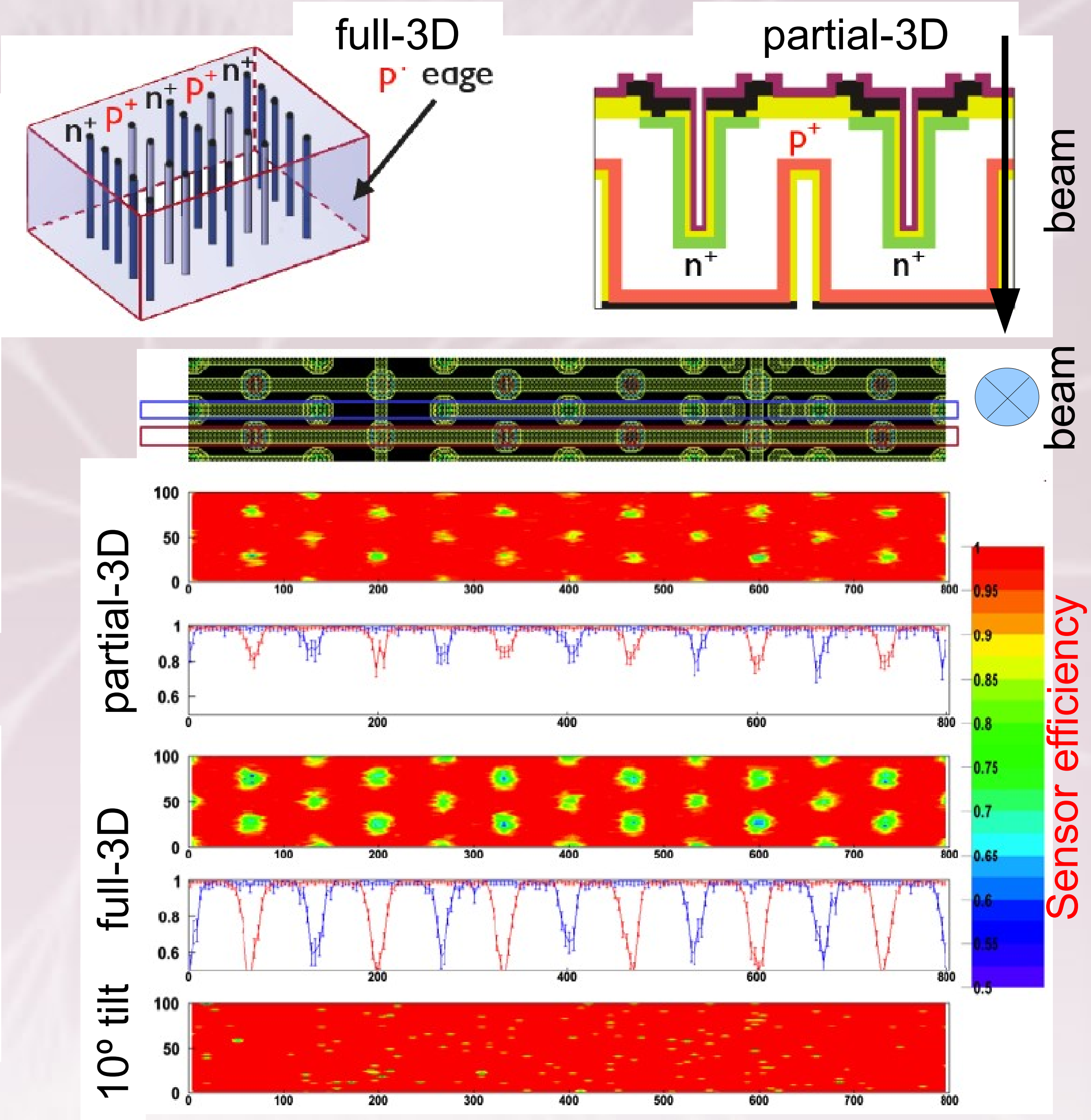
2011- very busy year as well
10 weeks for ATLAS IBL + more

An example of final plots of the testbeam data analysis with 3D sensors as a DUT (http://arxiv.org/abs/1101.4203), CERN SPS 120 GeV, autumn 2010

New 3D sensor technology

Full-3D sensors:
- active edge and electrodes penetrating through the entire wafer thickness

Partial-3D sensors:
- bias and read-out electrodes do not penetrate through the entire wafer thickness, slightly overlap



- Excellent telescope track pointing resolution (~2 μm)
- allows for really fine **2D efficiency** studies
  - clearly seen **higher efficiency** of **partial-3D** sensors
  - higher efficiency of 10° tilted sensors

Telescopes for everyone

- Final EUDET telescope ready in September 2009
- At the moment 2 copies of the EUDET telescope are in preparation:
  - with the latest improvement (r/o based on NI PXI express)
  - For Bonn university, will stay in Bonn @ELSA
  - For ATLAS group, will stay in CERN @SPS
- More improvements to the EUDET telescope will turn it into AIDA telescope
  - Improved TLU for particle time stamping
  - add MediPix and ATLAS Pixel sensors

Sensors for AIDA telescope

The task - development of a "versatile modular precision pixel telescope" operated by a common infrastructure and "user configurable reference planes"

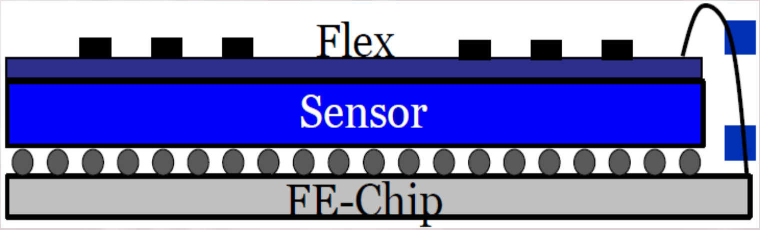
To be based on either combination of the following sensor technologies:

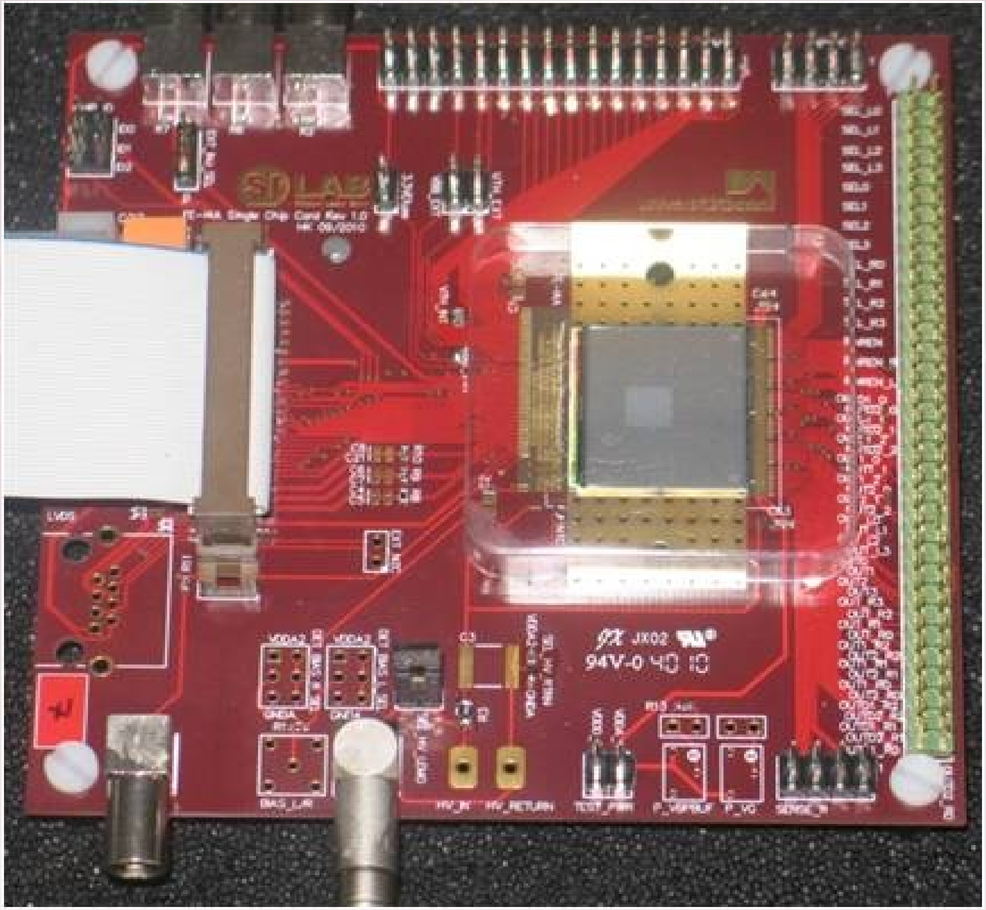
1. ATLAS hybrid pixel
2. Mimosa family
3. Timepix family

for more see http://www.iphc.cnrs.fr/-CMOS-ILC-.html

Sensors for AIDA telescope

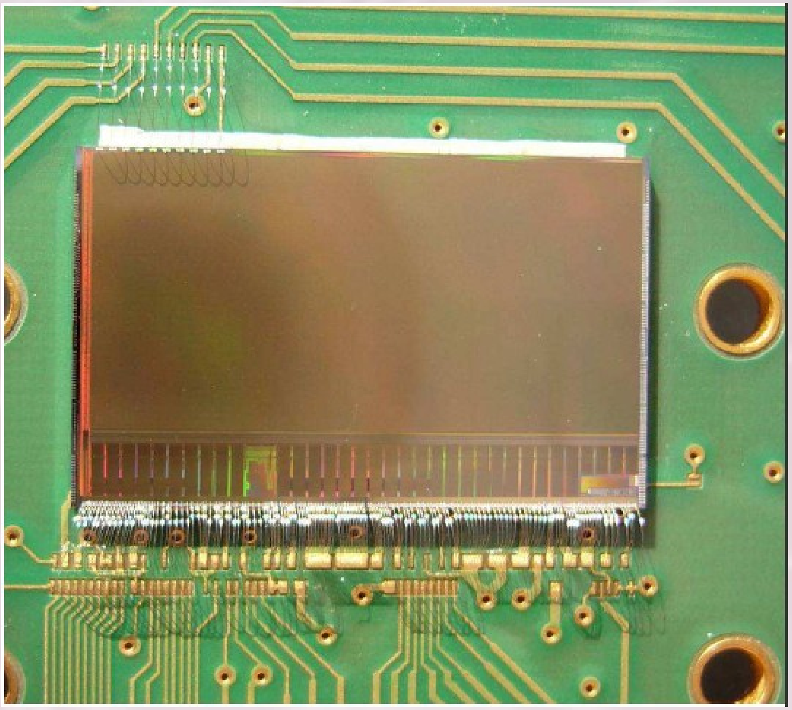
1. ATLAS hybrid pixel (FE-I4)
- high rate and high occupancy
- reading out 16 sensor frames in a sequence upon trigger arrival
- 25 ns per frame
- 50x250 μm^2 pixel dimension
- 80x336 pixel matrix
- large area: 1.68 x 2.0 cm^2
- High radtiation tolrance ($5 \times 10^{15}\ n_{eq}/cm^2$)
- integration into EUDAQ and EUTelescope software framework is complete and performed well during the ATLAS IBL testbeam campaign
- in the CERN SPS H8 at the moment (Morpurgo magnet 1.9 T)





Sensors for AIDA telescope

2. Mimosa family
(IRFU-Saclay / IPHC-Strasbourg collaboration)
– based on current Mimosa26 (covers 1x2 cm^2),
keep σ_{sp}~3.5 μm^2
– but much larger detection area:
- ULTIMATE – 2x2 cm^2,
  - being fabricated for 2012 beam tests
- MIMAIDA - 5x5 cm^2,
  - to be fabricated in 2013/14

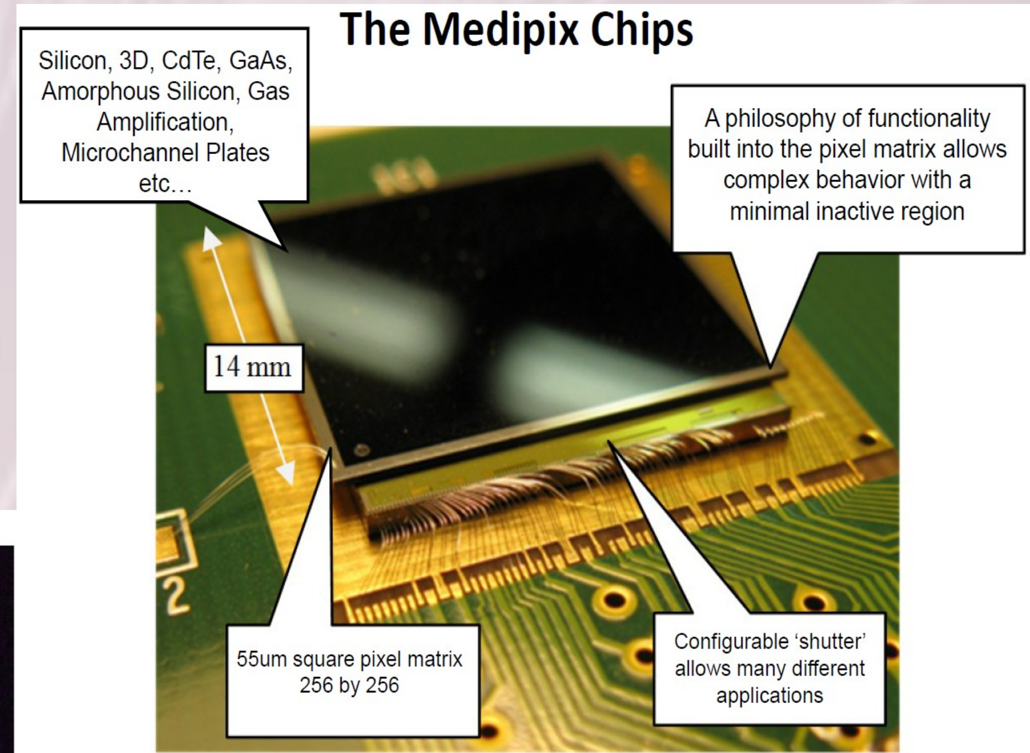


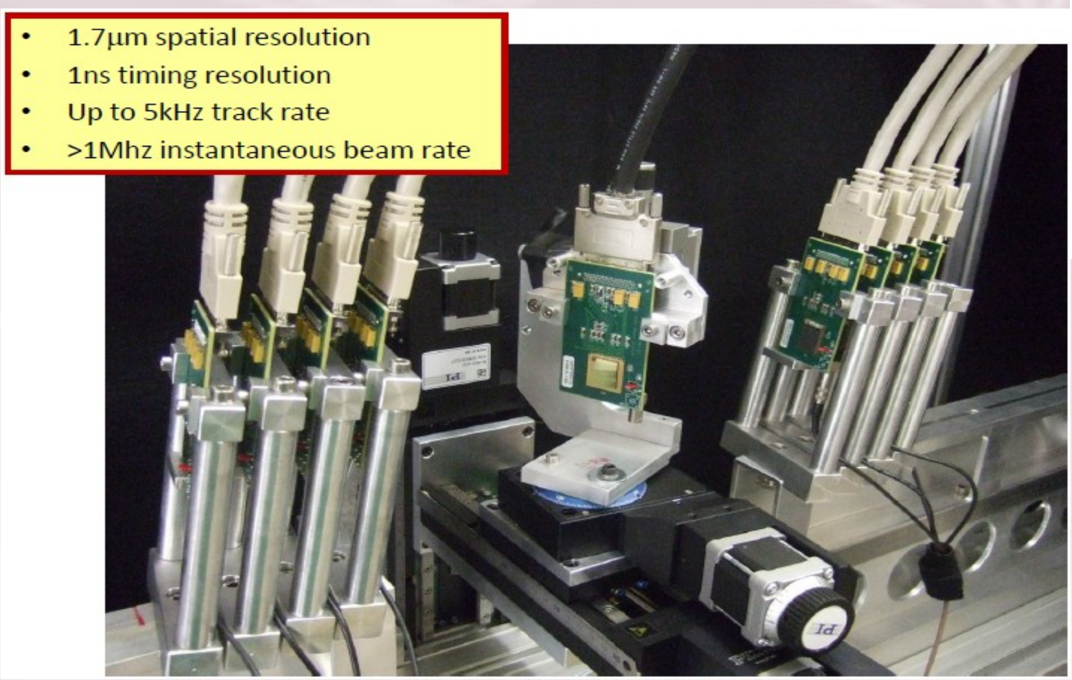
Mimosa 26

for more see http://www.iphc.cnrs.fr/-CMOS-ILC-.html

Sensors for AIDA telescope

3. Timepix
- CMOS, 130 nm IBM
- 55x55 μm^2 high resolution,
- 256x256 pixel matrix (14.1x14.1 mm^2)
- relatively slow (~20 ms per frame)
- Time over Threshold mode for tracking
- Time of Arrival mode for time stamping





to-do:
- TLU integration
- mechanics integration
- readout integration

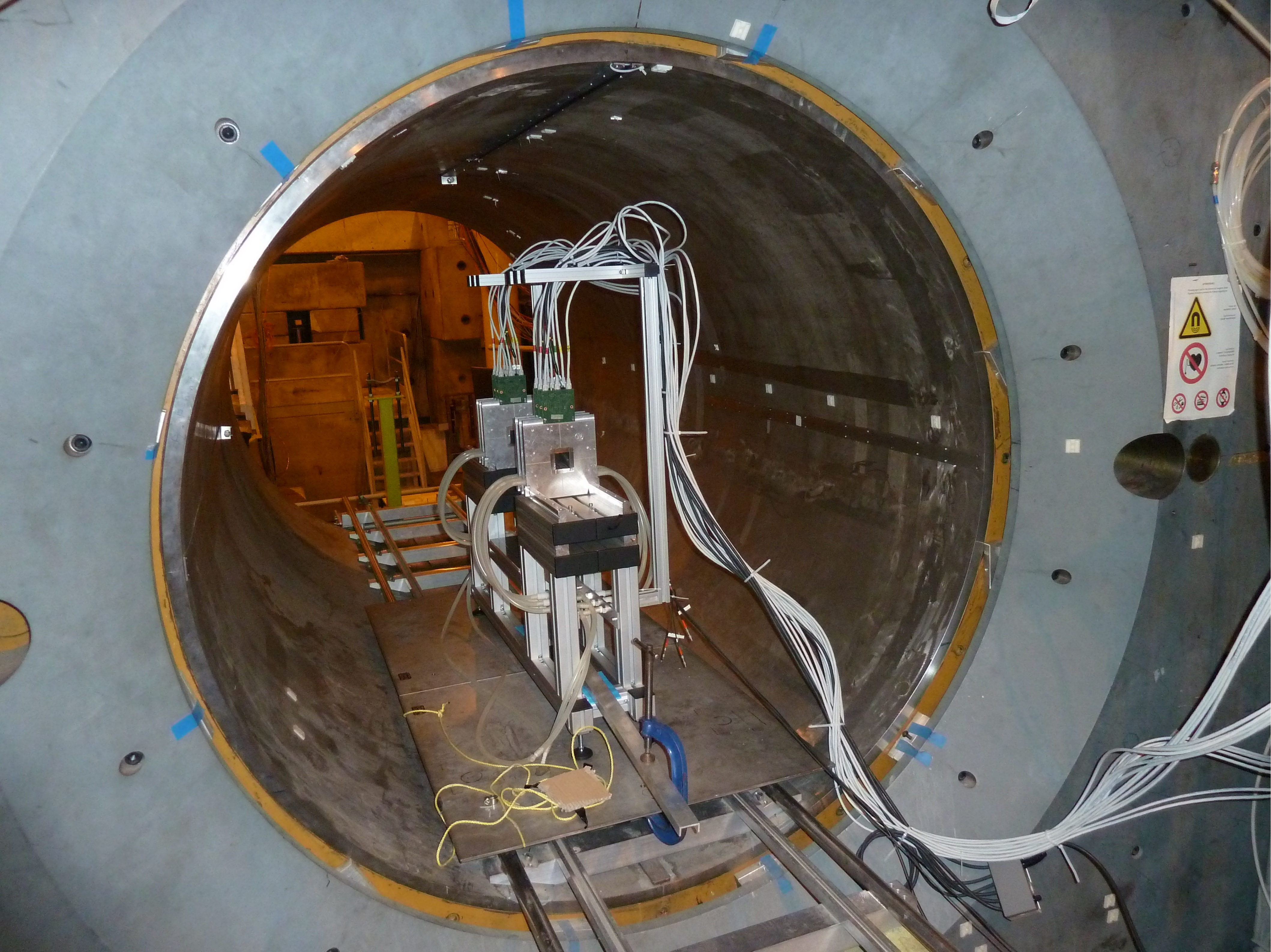
Summary

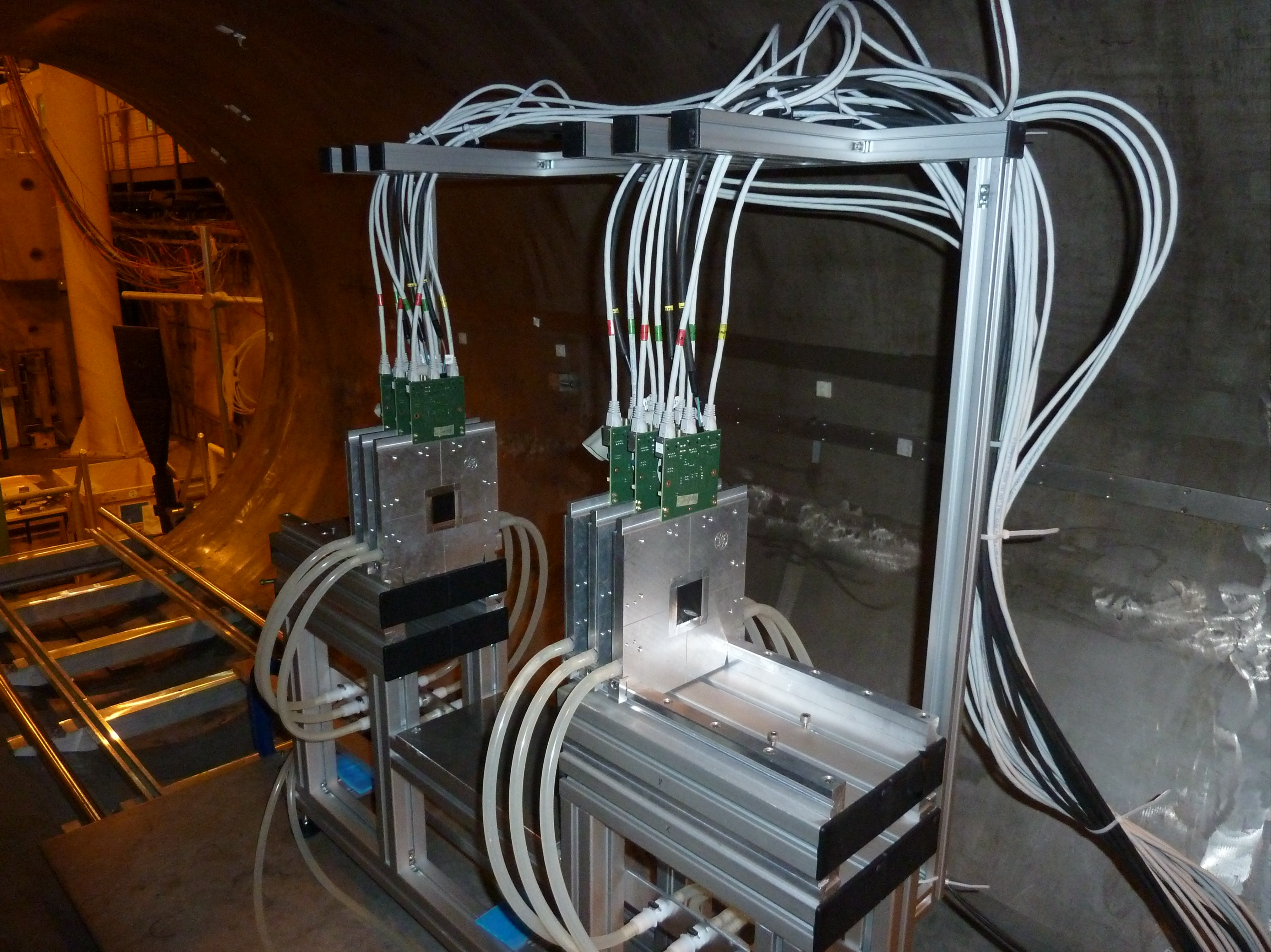
A high resolution pixel beam telescope was developed as part of the EUDET project

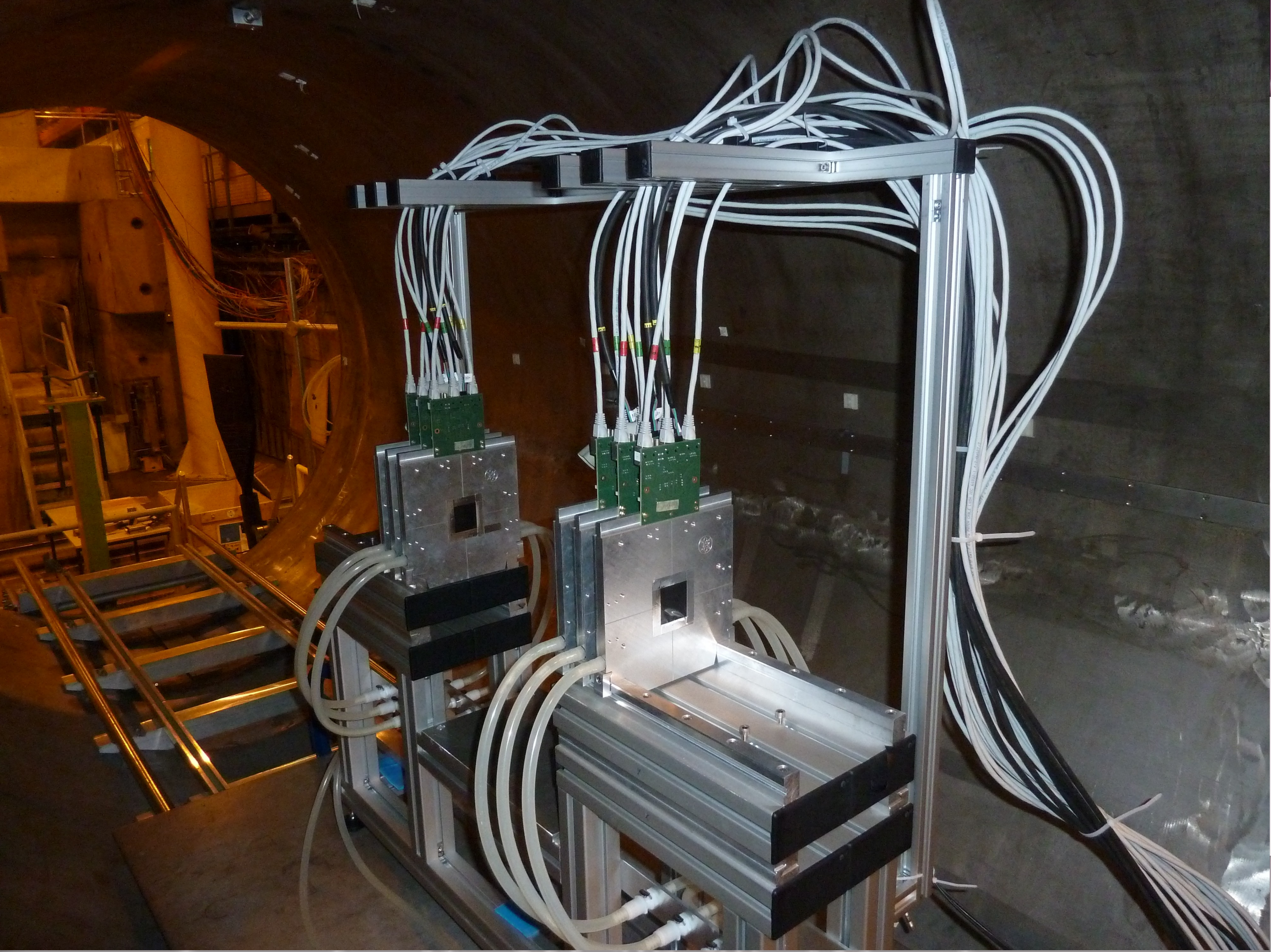
- common effort of several institutes
- big success
- high demand led to the production of the copies
  (Bonn University, ATLAS collaboration)

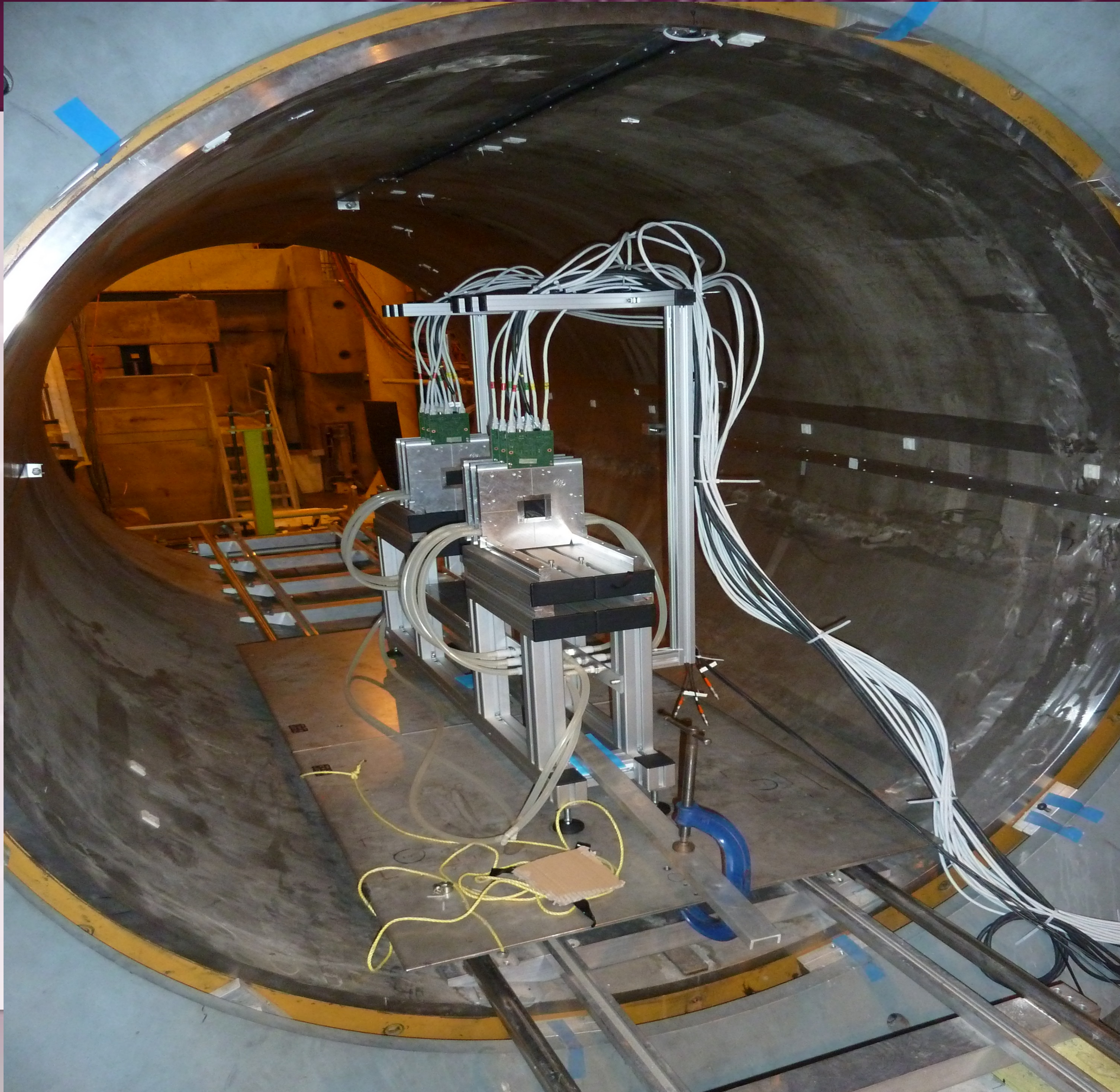
Further development of the pixel beam telescope within AIDA project discussed

- Larger test area coverage and higher particle rate being main focus









Backup slides

Plans

- There is always room for improvement
  - Keep EUDAQ modular concept
  - Faster readout: for Mimosa sensors – National Instruments
  - Smarter triggering with TLU: multiple triggers per frame
  - More flexibility: include other sensor technology
    - TimePix
    - ATLAS Pixel – PPS and/or 3D

EUTelescope: features

Can deal with

Sensors of many readout types

- analog, digital, binary
- (none) zero suppressed, with/-out Correlated Double Sampling

In terms of:

- block clustering (nxm pixel in cluster)
- sparse clustering (nearest neighbour search)
- η-corrected cluster center or by center-of-gravity

DUT arbitrary rotated

- tilted sensors analysis, challenge for parallel beam tracks (alignment, tracking)

In terms of:

- Alignment with Millepede II
- Tracking with: Analytic Track Fit or
  Deterministic Annealing Filter (DAF fitter)

Plans for AIDA

Continue to

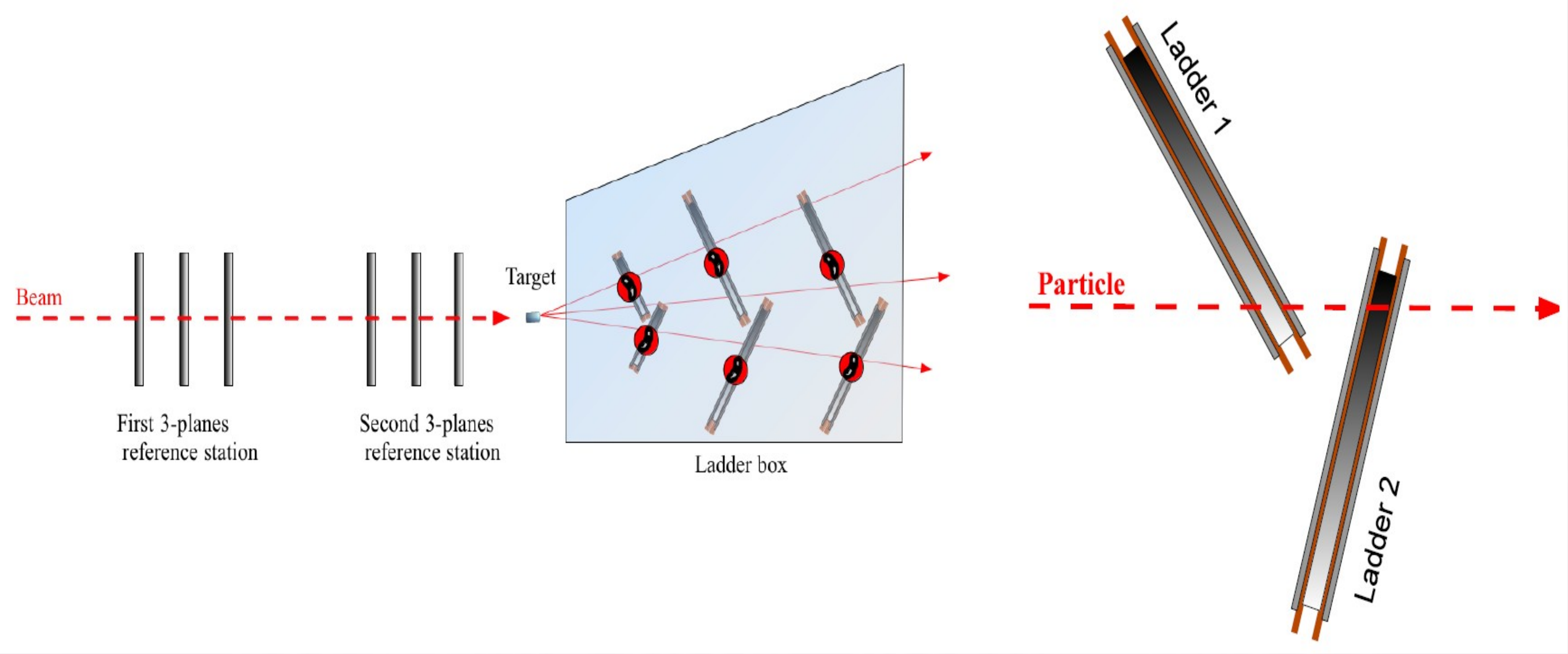
- maintain software
  - central repository at DESY
    http://svnsrv.desy.de/public/eutelescope/Eutelescope/trunk/
- support users
- store data on GRID
  - backup on tapes in 2 places: DESY-Hamburg, DESY-Zeuten)

Development plans

- full GEANT4 simulation
- alignment and tracking in Magnetic field
  (beam tests already in June 2011, ATLAS IBL)
- new geometry based on TGeo
- extend to use of hodoscope for particle time tagging
  and new TLU logic

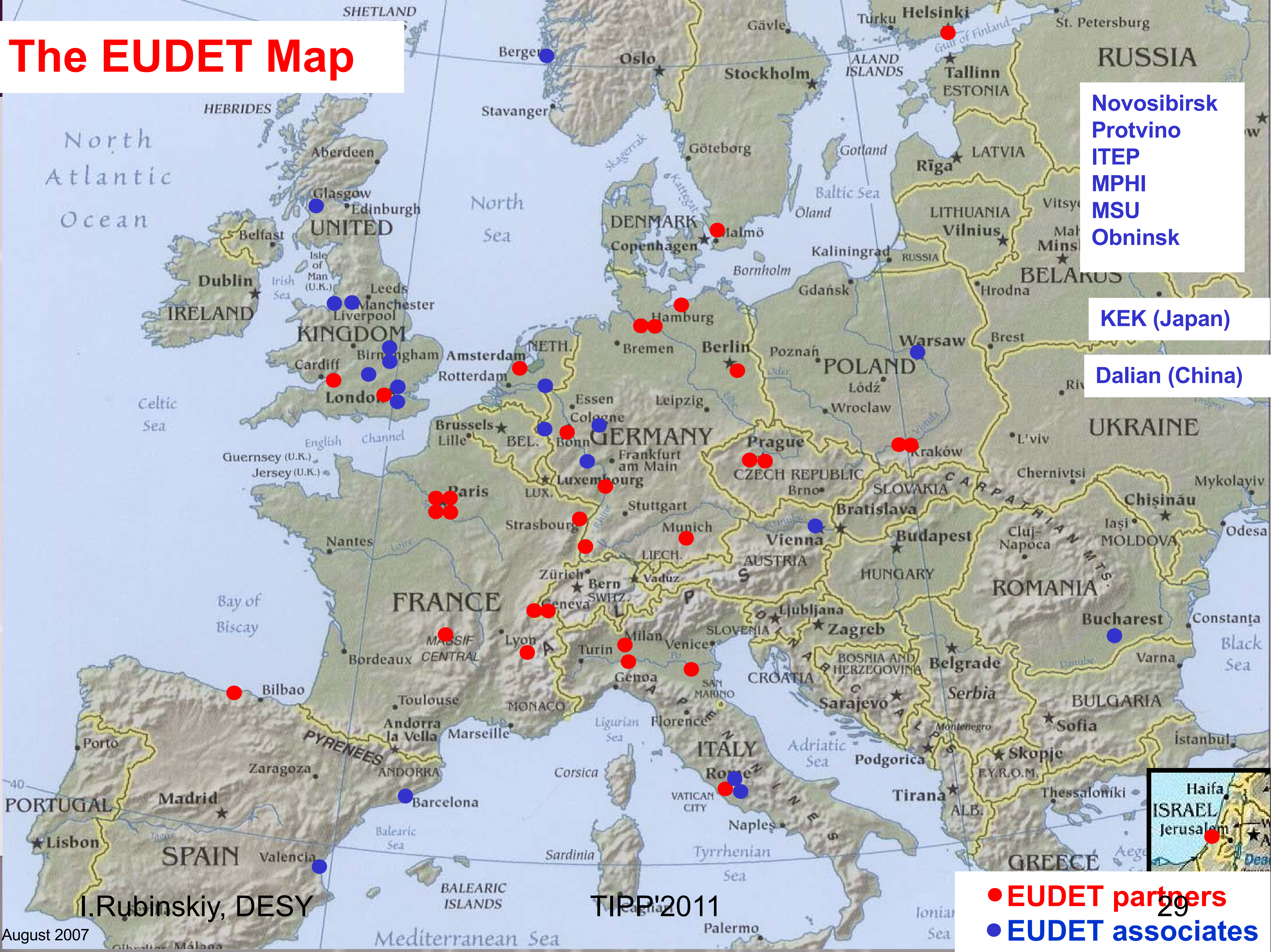
Sensors for AIDA telescope

SALAT – Single Arm Large Area beam Telescope
AID – Alignment Investigation Devices (mini telescope and/or ladder box)



for more see http://www.iphc.cnrs.fr/-CMOS-ILC-.html

The EUDET Map



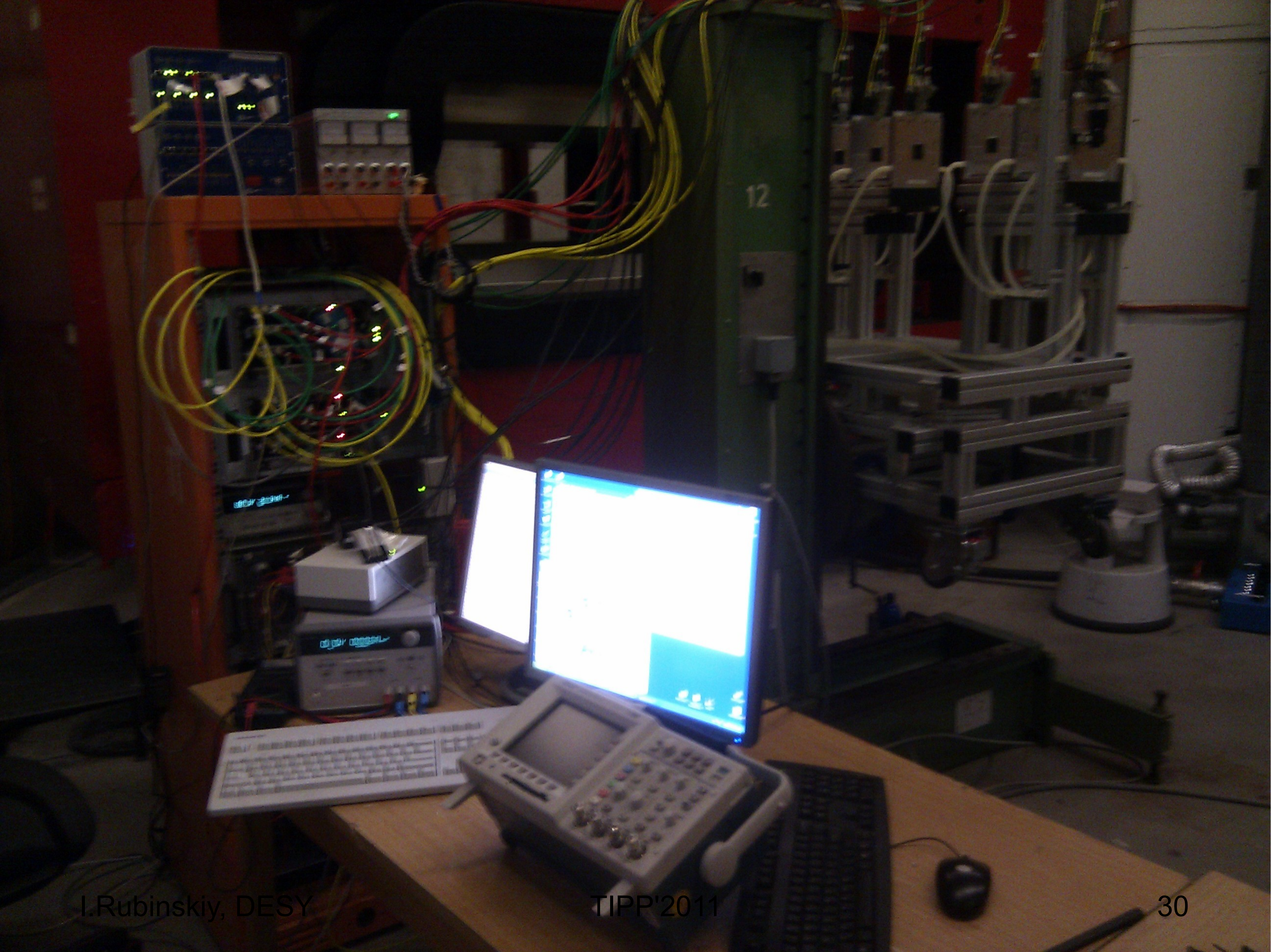
Novosibirsk
Protvino
ITEP
MPHI
MSU
Obninsk

KEK (Japan)

Dalian (China)

● EUDET partners
● EUDET associates

August 2007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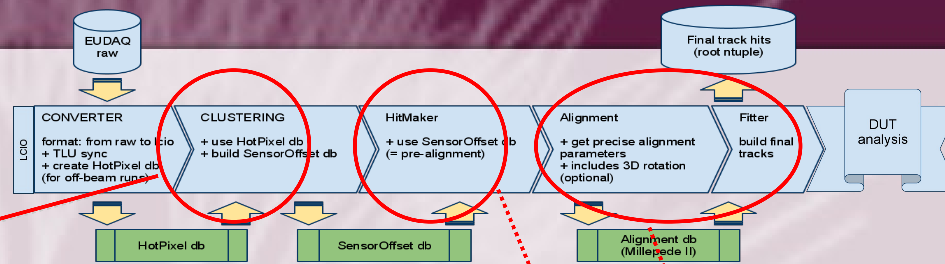


the software **can deal with**

Clustering

Sensors of many readout types
- analog, digital, binary
- (none) zero suppressed, with/-out Correlated Double Sampling

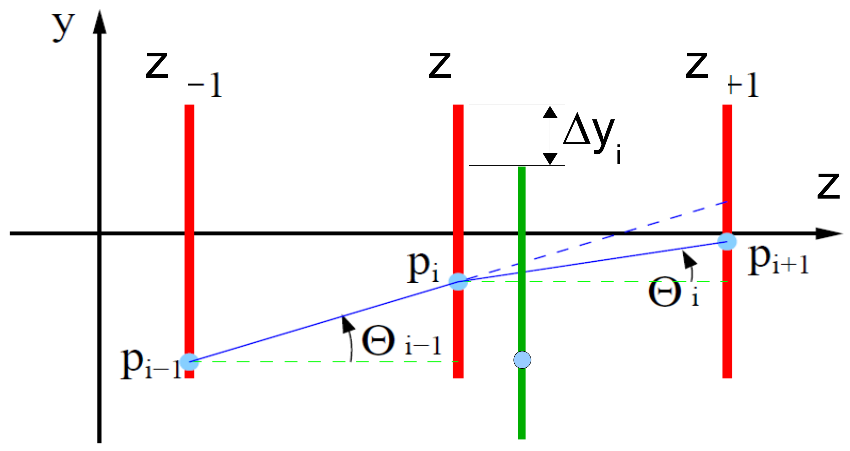
In terms of:
- block clustering (nxm pixel in cluster)
- sparse clustering (nearest neighbour search)
- η-corrected cluster center or by center-of-gravity

Hitmaker

Alignment + Fitter

DUT arbitrary rotated
- tilted sensors analysis (users demand since 2010)
- trickier for parallel beam tracks (alignment, tracking)

solved in terms of:
- Alignment with Millepede II
- Tracking with: Analytic Track Fit or
  Deterministic Annealing Filter (DAF fitter) [new]



<u>We know that</u>

all sensors are not perfectly aligned
(X,Y shifts up to ~1mm, tilts ~1 mrad)
track pointing resolution **can not** be better than our knowledge of the hit coordinates (x,y,z)
<u>must</u> know perfectly well where the hits are

<u>Solution</u>

build a track model based on separation of parameters into
local - track model parameters (unique for each track)
global - sensor shift and tilt correction ("alignment constants")

<u>Example (1 dimensional)</u>

track: $f_{ik} = a_k + b_k z_i$

sensor: $y_{ik} = y_{0k} + \Delta y_i$

define:

$\Delta_i = f_{ik} - y_{ik}$ ("residual")

σ_i – sensor resolution in "y"

where k-track index
i-sensor index

K - number of tracks can be very large
I - sensor parameters is a constant,
<u>but that is all we need to know!</u>

<u>Global objective function to minimize</u>

$$F(\boldsymbol{p},\boldsymbol{q}) = \frac{1}{2}\sum_{\text{data sets}}\left[\sum_{\text{events}}\left(\sum_{\text{tracks}}\left(\sum_{\text{hits}}\Delta_i^2/\sigma_i^2\right)\right)\right]$$

Millepede II
– FORTRAN library
– can handle very large data sets
– standard for large experiments (H1, ZEUS, HERAb, CMS, LHCb,..)
– very fast
– but preparing the input requires work

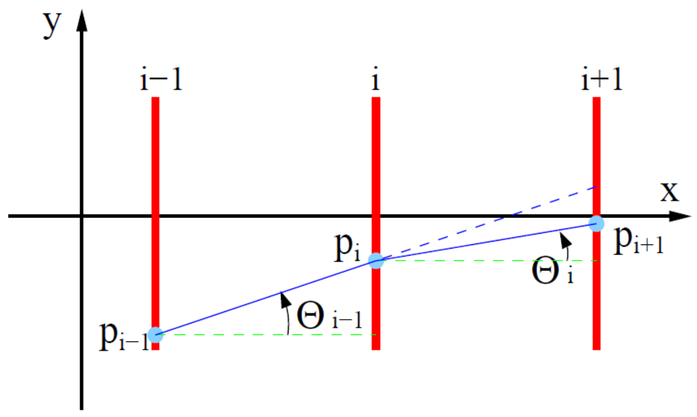
Tracking on aligned data is based on minimizing the χ^2 which takes into account multiple scattering

position measurement — multiple scattering

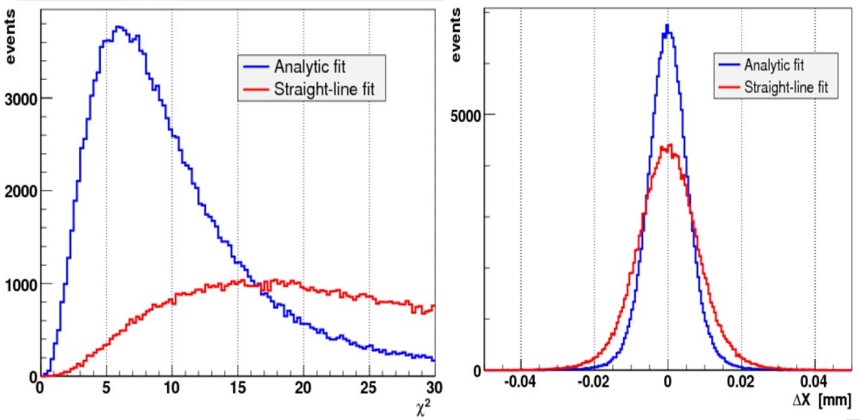
$$\Delta\chi_i^2 = \left(\frac{y_i - p_i}{\sigma_i}\right)^2 + \left(\frac{\Theta_i - \Theta_{i-1}}{\Delta\Theta_i}\right)^2$$

where: $$\Theta_i = \frac{p_{i+1} - p_i}{x_{i+1} - x_i}$$

$\Delta\theta_i$ - known from the sensor thickness and radiation length X_0



<u>Assumptions</u>:
- all planes are parallel to each other
- the incoming beam is perpendicular to the telescope planes
- has a small angular spread
- particle scattering angles are small
- sensor thicknesses are small compared to the distances between the planes
- particle energy losses in telescope layers can be neglected



Both the track χ^2 and the track pointing resolution improve in analytic fit

Further copies can be made

- Copies of the telescope can be made
- Includes
  - 6 new high resistivity Mimosa sensors
    - developed/supplied by IPHC Strasbourg
  - new National Instruments DAQ for Mimosa sensors
    - with LabView license and support
  - all software: EUDAQ/EUTelescope – free of charge (GPL-style license “scientificware”)
    - Initial support from University of Geneva (EUDAQ) and DESY (EUTelescope + ILCSoft)
  - Mechanics (by DESY)
- Does not include
  - a 1 μm precision positioning XY table