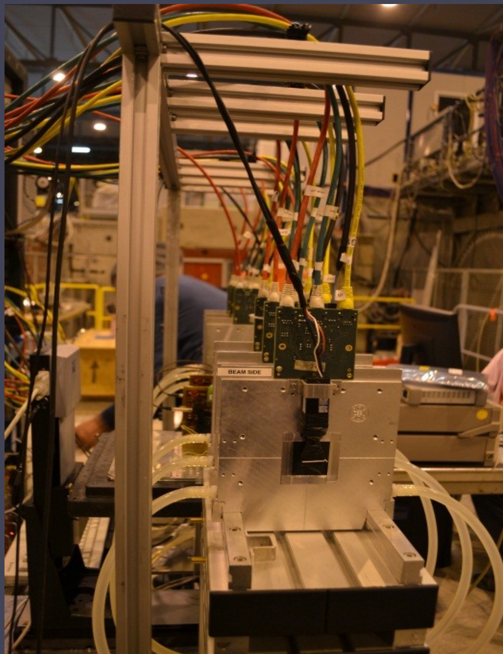
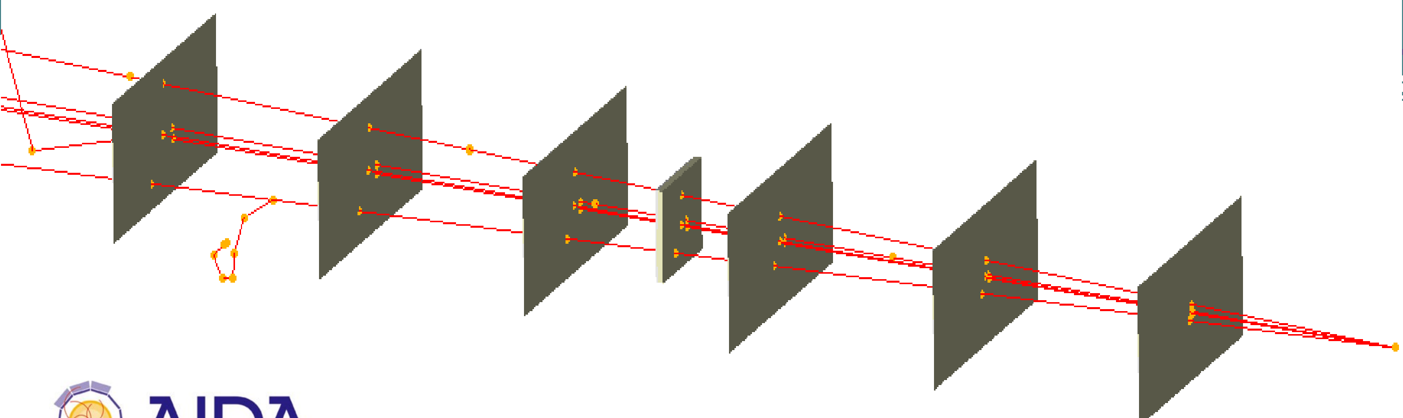
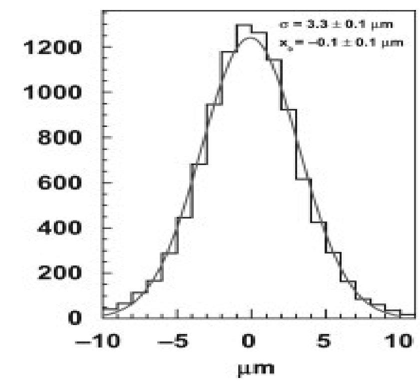
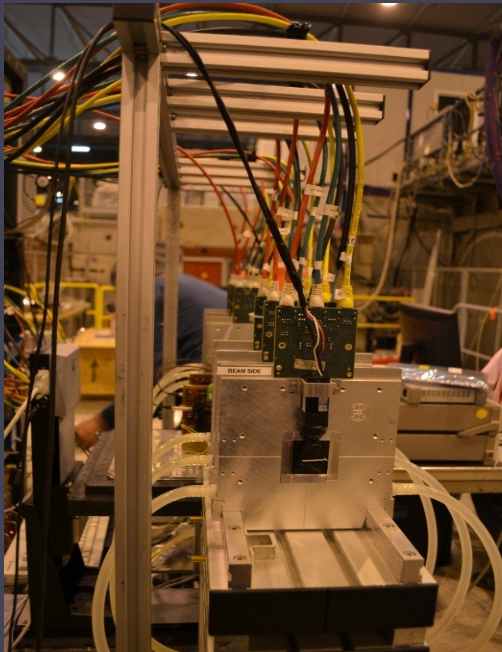


A EUDET/AIDA pixel beam telescope
as a tool for testing tracking detectors

Igor Rubinskiy
DESY, Hamburg







A EUDET/AIDA pixel beam telescope
as a tool for testing tracking detectors

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DESY, Hamburg

In this talk:

- FP6 EUDET and FP7 AIDA projects for detector R&D
- Tracking detectors and beam tests
  - why we do beam tests and how we do beam tests (experience within EUDET)
- The best beam test telescope we can think of (within AIDA)

Chapter I

European Union Framework Programms
- otherwise known as EU FP

European institutes and Detector development

European Union funding of research institutes and common projects

EUDET (2006-2010) → AIDA (2011-2014)

EUDET (2006-2010)

31 institute in 12 EU countries
+29 ass. institutes

"Integrated Infrastructure Initiative (I3)"

EU FP6

- **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

AIDA

"Advanced European Infrastructures for Detectors at Accelerators"

EU FP7

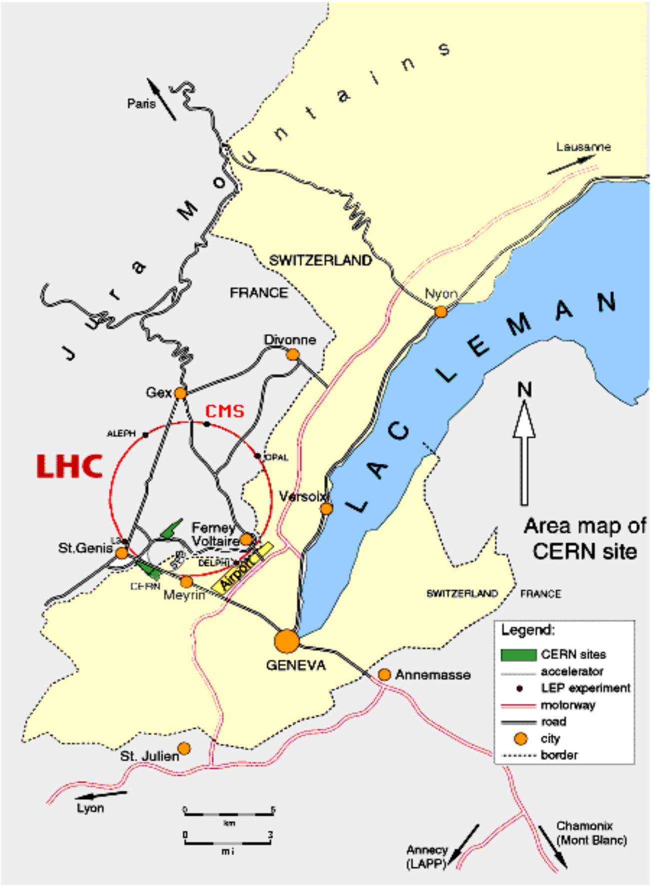
- **upgrade, improve and integrate** key European research infrastructures and **develop** advanced detector technologies infrastructure for future particle accelerators like
  - LHC upgrade, Linear Colliders, Neutrino facilities and Super-B factories in line with European Strategy for HEP
- 26 million EU total (1/3 from EU)

Pixel Beam Telescope only one out of many work packages in both in EUDET and in AIDA

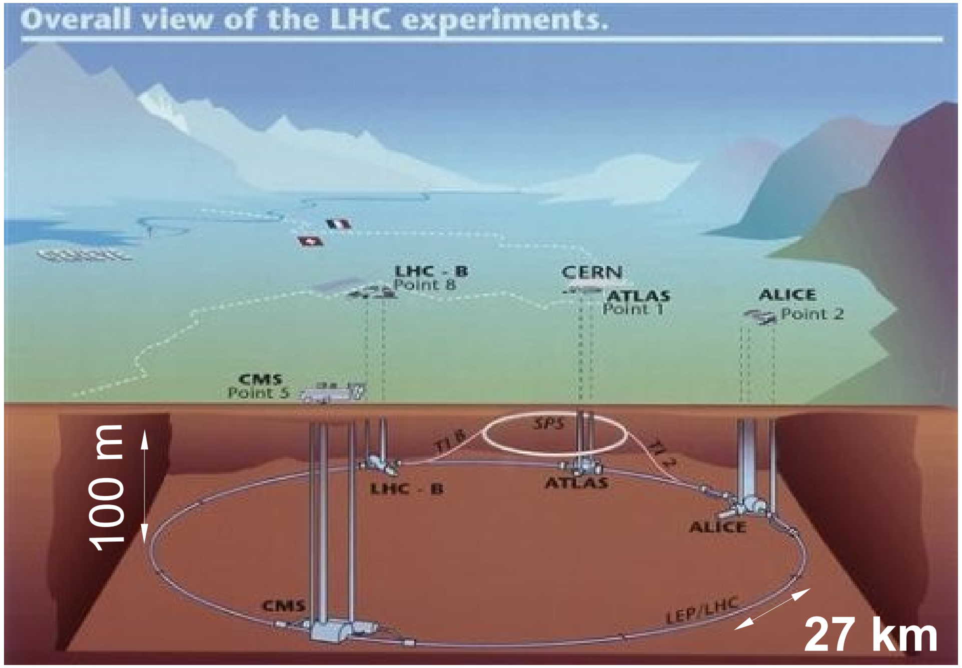
Chapter II

High Energy Physics and Tracking Detectors

HEP detectors now



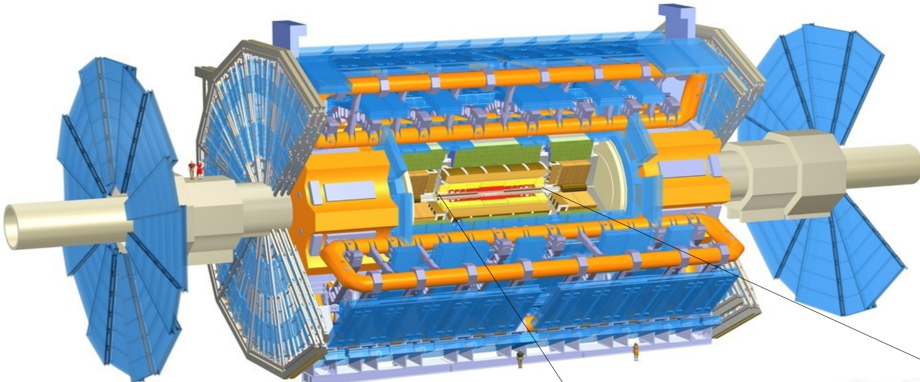
LHC = Large Hadron Collider
largest ever machine to accelerate protons
... but there are more to come



Four large scale detectors – ATLAS, ALICE, CMS, LHC-B

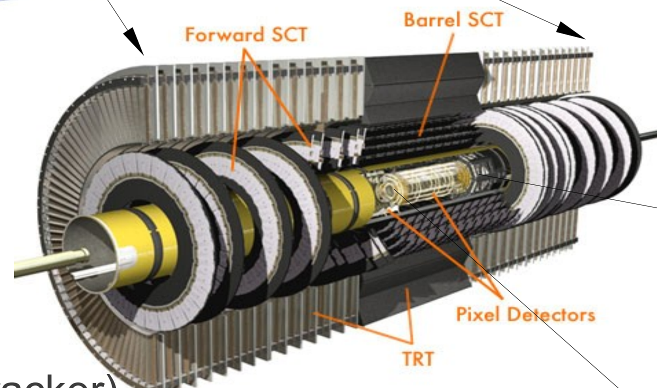
An example of a HEP Detector and the place of a Tracking Detector in it

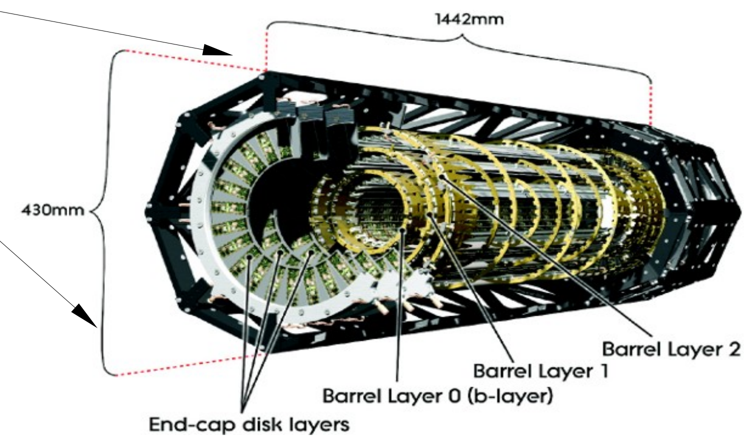
"onion style"



A sketch of a typical
High-Energy Physics (HEP) detector

- outer parts – gas based subdetectors (low segmented)
- Inner detector – high segmentation Silicon based (pixels & strips)





SCT (Semi-Conductor Tracker)
- Si, strips (80 μm x 12 cm, 285 μm thick) 6M Ch. 61 m^2

Pixel Detector → Si, pixel (50x400 μm^2, 250 μm thick)
- 93M Ch. ~90% of the whole Experiment

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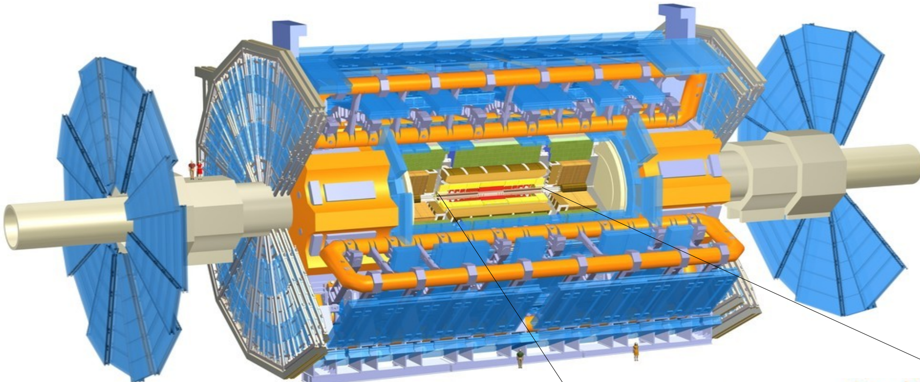

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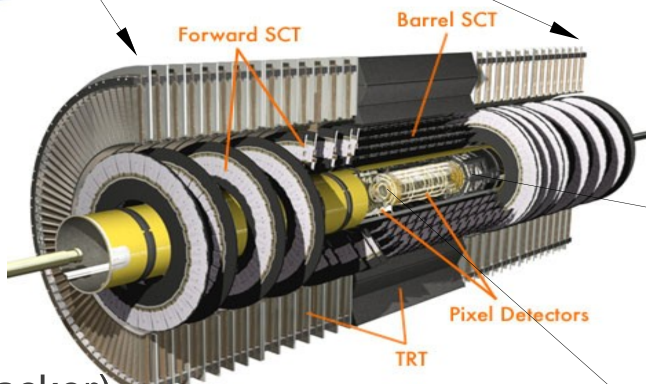

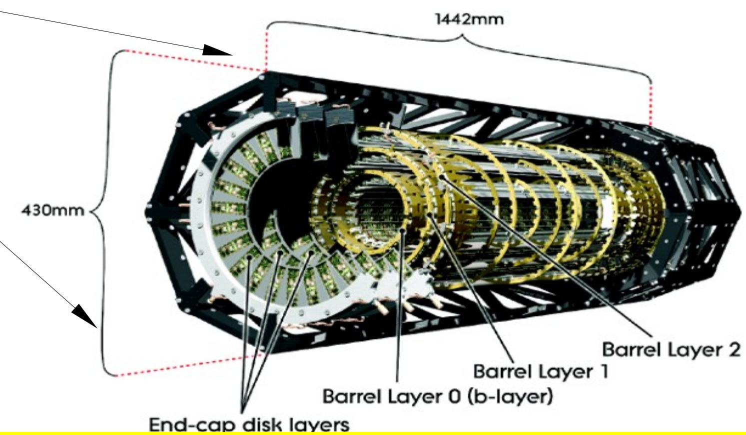

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<u>Talks on LHC Trackers at the Instrumentation Seminar:</u>

ATLAS: Ingrid Gregor 11.05.12
CMS: Daniel Pitzl 16.09.11, Duccio Abbaneo 8.06.12
LHC-B: Paula Collins 25.03.11
ALICE: Petra Riedler 12.10.12

New HEP trackers planned

- ATLAS IBL (+1 barrel layer, now)
- Belle II, pixel + strip (by 2014)
- CMS pixel (4 barrel layers by 2016/17)
- ALICE tracker (2018/19)
- LHCb VELO+tracker (2018/19)
- ATLAS new tracker, pixel+strip (2022)
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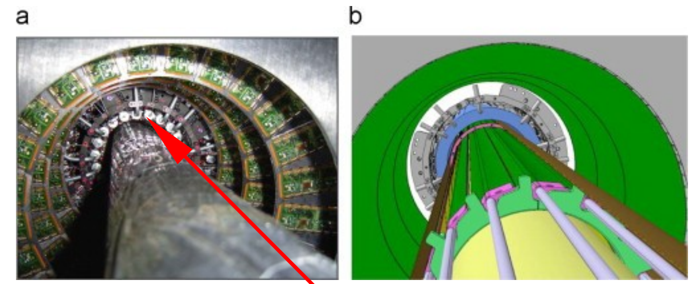
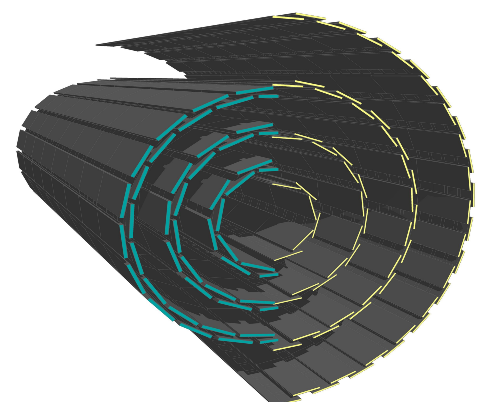


ATLAS
a. beampipe and currently innermost pixel layer (B-layer)
b. new innermost layer (IBL) on a smaller beampipe (install 2013/14)



CMS: Current 3 pixel barrel layers

new layout with 4 pixel layers

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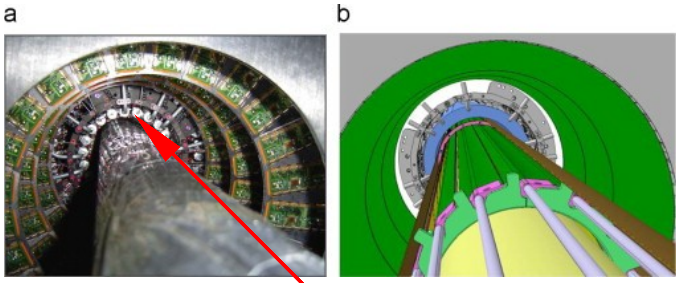

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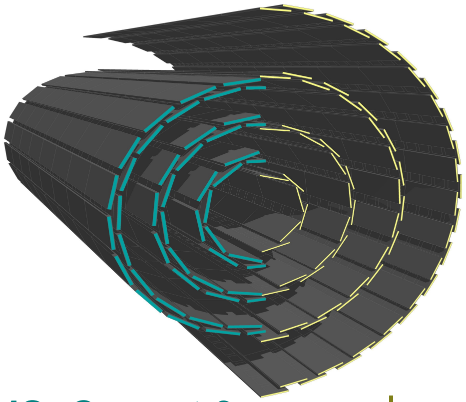
Disclaimer

the list is far from being complete



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Large Hadron Collider – a discovery machine

= aiming to discover particles which exist in our universe,
… but we know nothing about

→ so, proton collisions @ **energy as high as possible (= $)**
- → produced particles - very energetic
- → particle (=track) multiplicity per collision is high
- → bunch crossing every 25 ns (50 ns)

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For tracking detectors this means:

Segmentation: separation power of tracks from each other (in space) ...
& to measure track curvature (=particle momentum)
→ the detector segmentation should be high
(ever smaller pitch towards the interaction point)

Fast: distinguish tracks from different bunch crossings (LHC 25 ns)
→ readout of the detectors (charge collection and FE)

Radiation tolerant: inner most layers at least 10^{15} n_{eq}/cm^2
(HL-LHC → ≥ 10^{16} n_{eq}/cm^2)

Material budget: the thinner the better = less scattering in the layers

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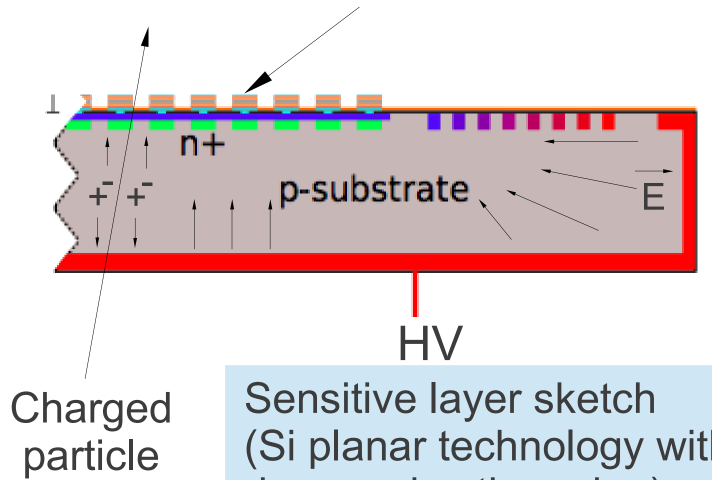
LHC, equally relevant

Sensitive layer of a HEP semiconductor detector

Highly segmented electrodes → allows to get precise position of a charged particle`s passage



Sensitive layer sketch (Si planar technology with guard rings and active edge)

Sensitive layer of a detector:

→ reverse biased diode

→ material, design of the electrodes, guard rings, operational voltage (bias HV) depend only on the application of the detector

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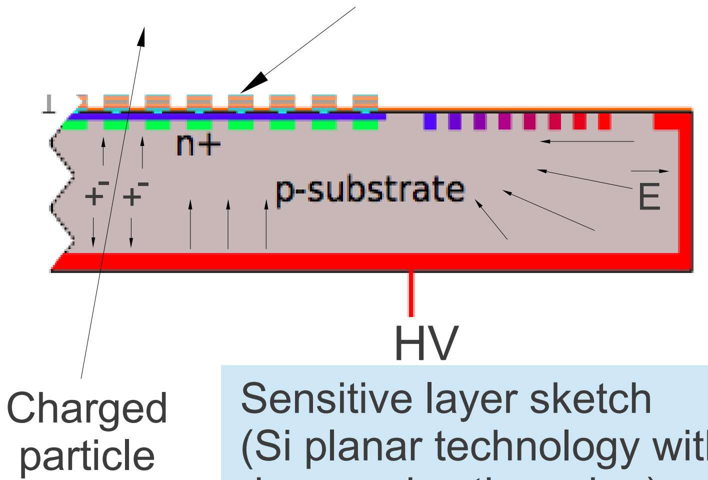

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- if assuming all particles to be MIPs (~80 e/h pairs per 1 µm in Si)

Questions to be asked (and answered!):

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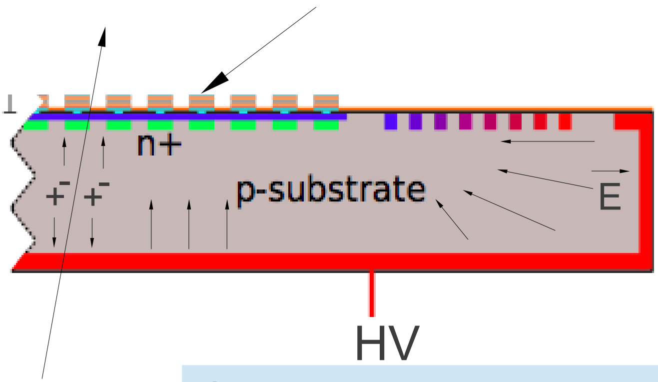

Charged particle

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- what's the Charge Collection Efficiency at different:
  - Bias Voltage, Temperature, Irradiation, track incident Point and Angle, Magnetic field, FE tuning (Threshold/calibration) → more then **6D** parameter space
  - dropping the MIP assumption → particle energy (**highly multi D** parameter space)

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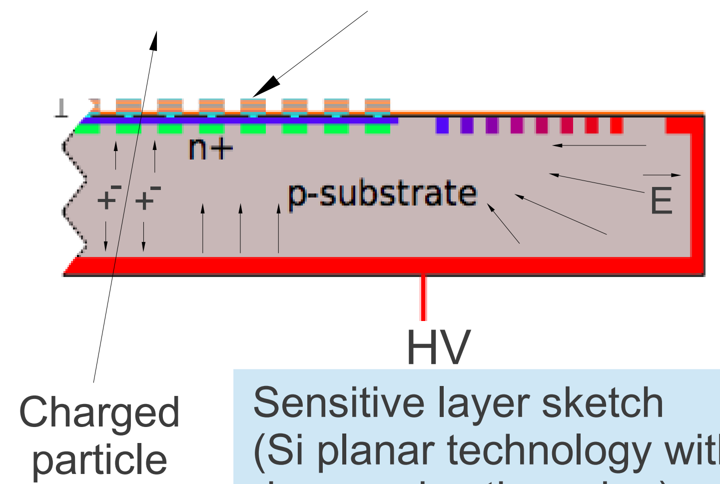

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→ systematic studies in beam tests

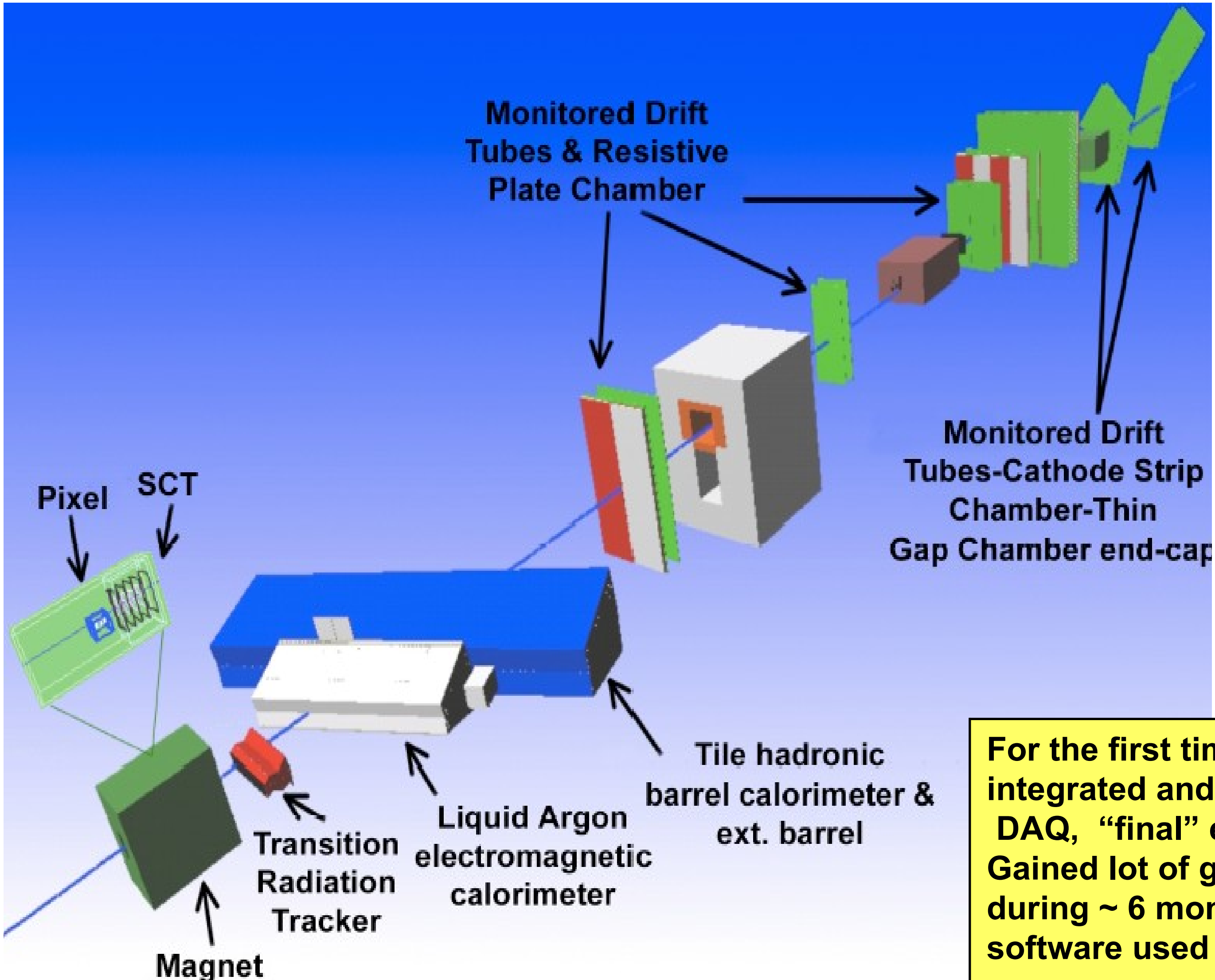
Role of beam tests in a HEP Experiment

- Conception ← Test Beams
- Conceptual design, choice of detectors/technologies ← Test Beams
- Technical design, prototypes construction and testing ← Test Beams
- Detector construction
- Calibrations ← Test Beams
- Commissioning
- Data taking ← Test Beams
- Analysis, systematics studies

… the same for all kind of particle detectors

Towards the complete experiment: ATLAS combined test beam in 2004

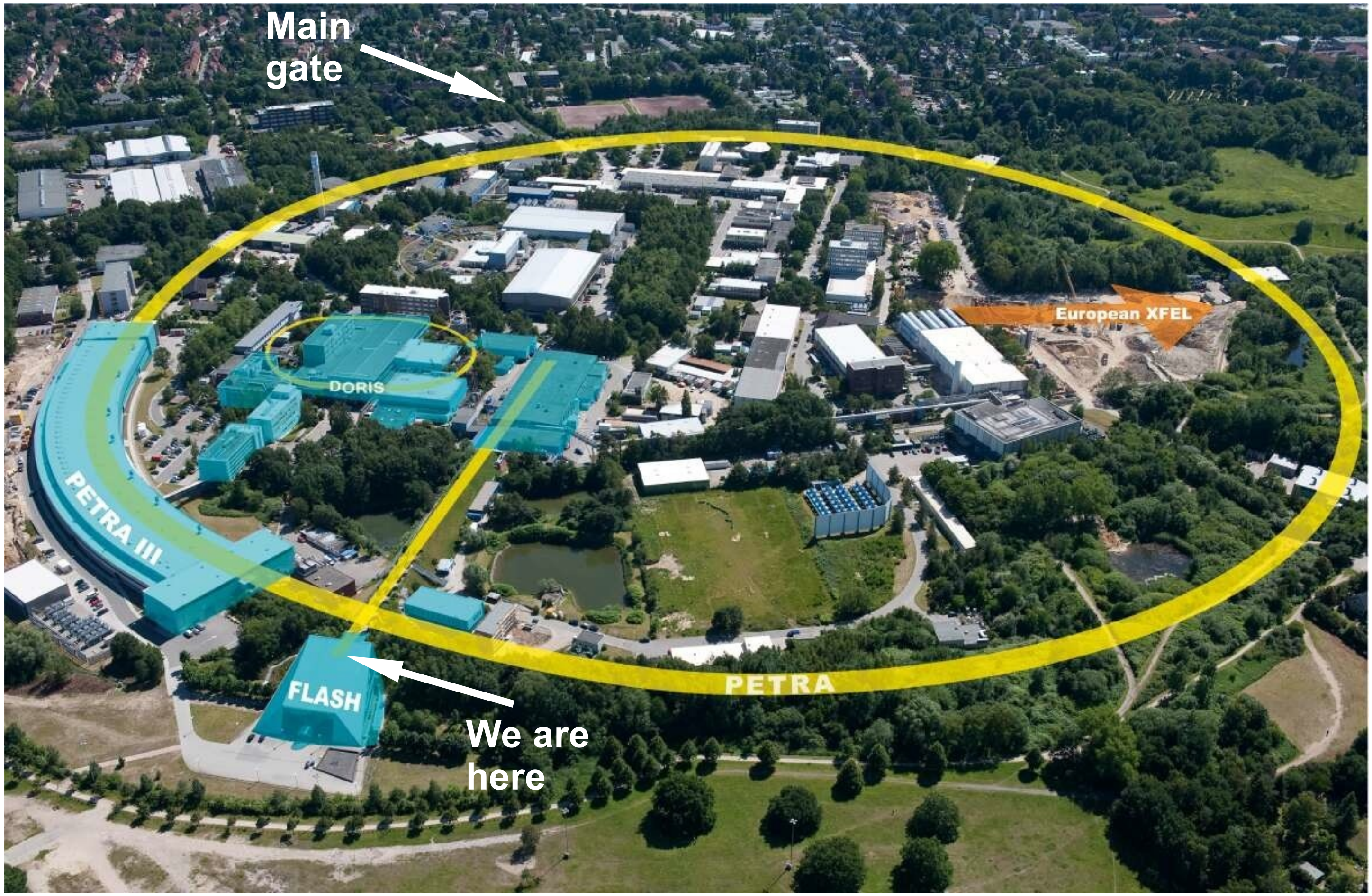
Full "vertical slice" of ATLAS tested on CERN H8 beam line May-November 2004



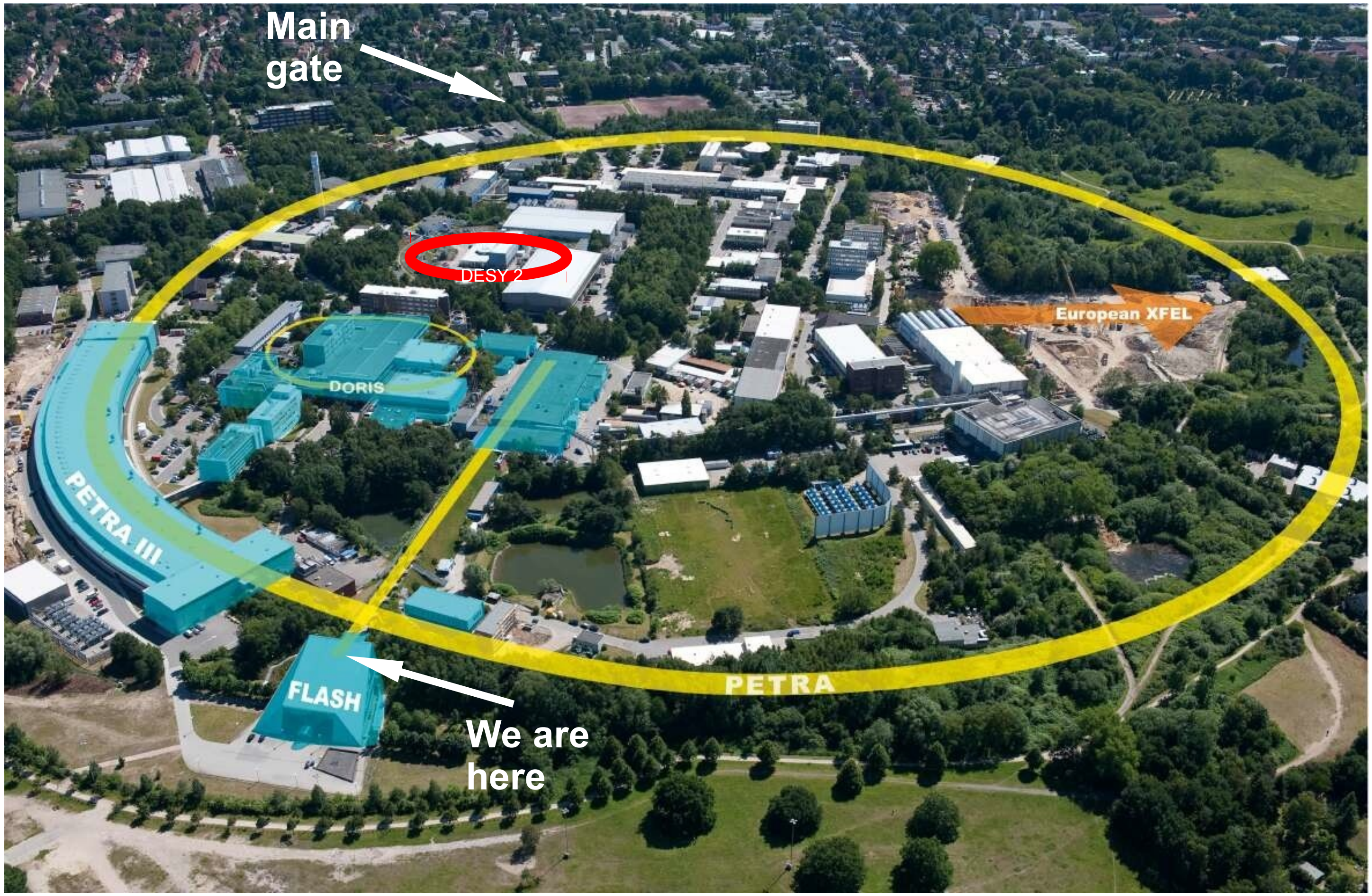
For the first time, all ATLAS sub-detectors integrated and run together with common DAQ, "final" electronics, DCS, etc. Gained lot of global operation experience during ~ 6 month run. Common ATLAS software used to analyze the data

Can you find in 10 seconds:

where is the testbeam hall on DESY site?



A hint: it's next to DESY II (6.3 GeV, e^- or e^+)



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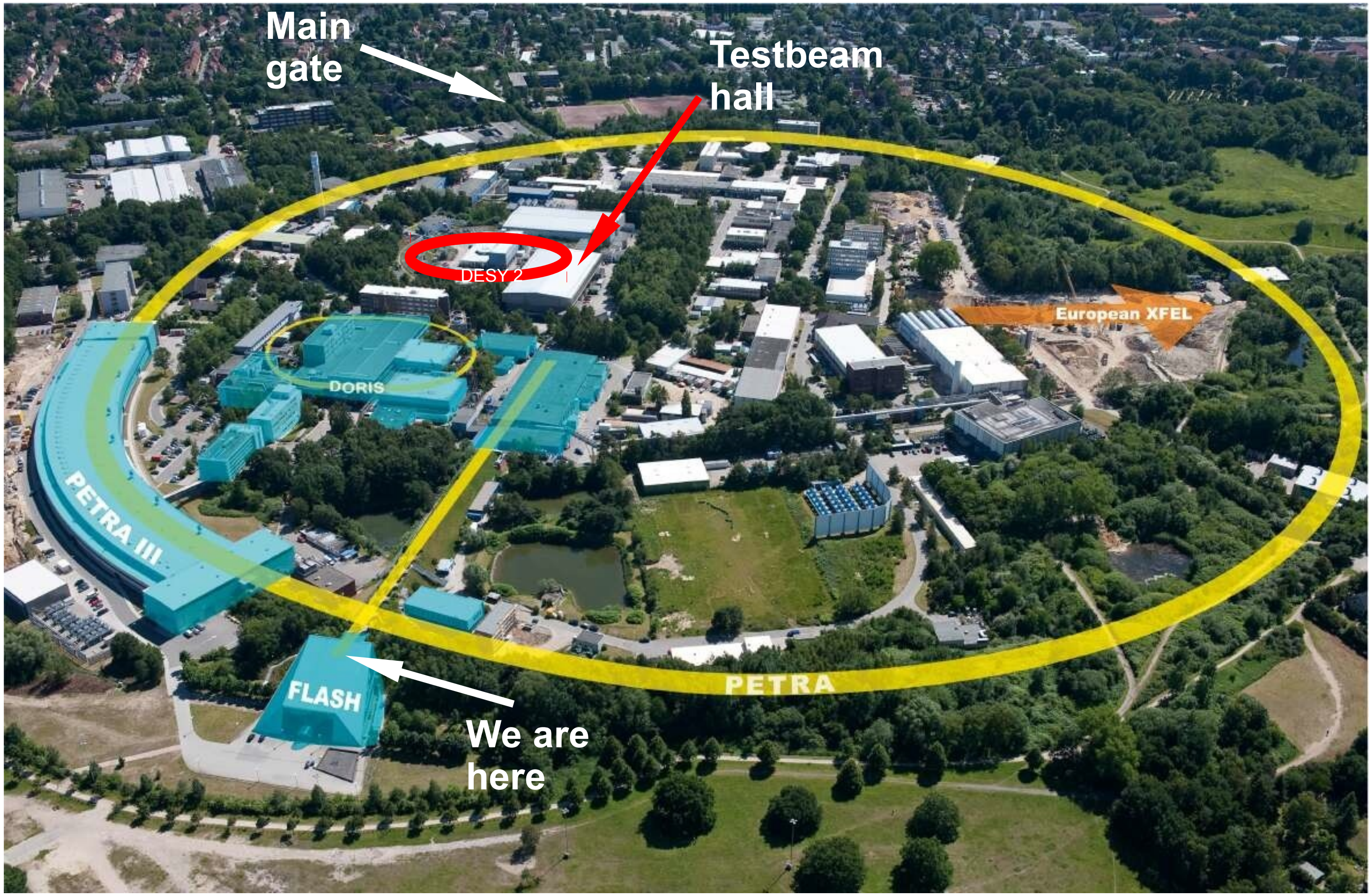
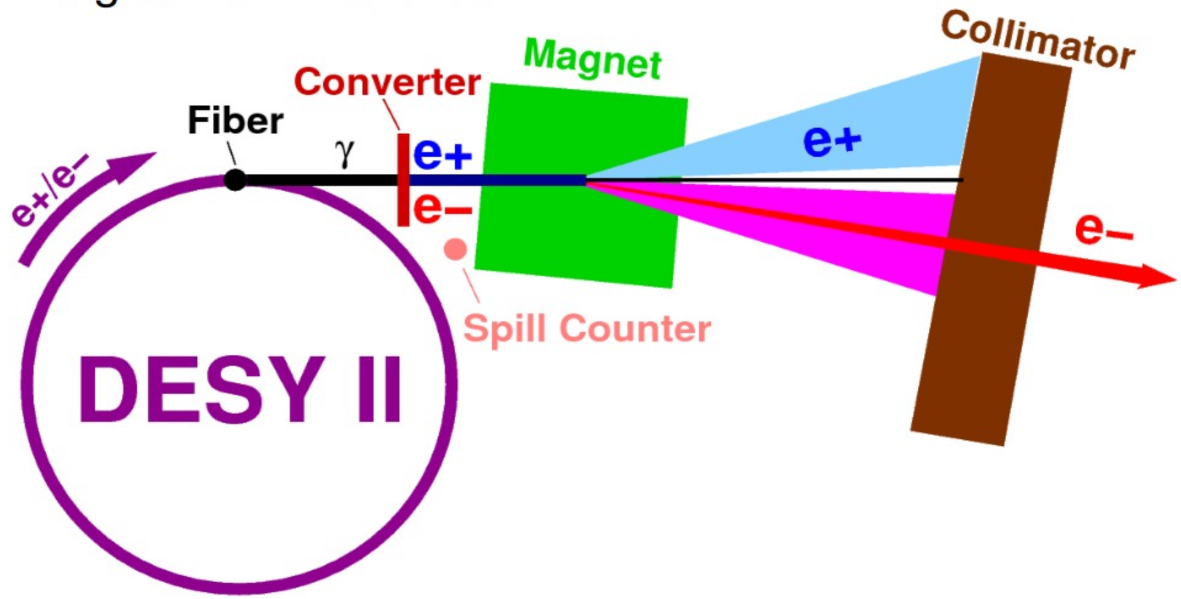
Building 27 (testbeam hall)



Beam tests at DESY

- Facility for testing detector prototypes
- Three electron/positron beam lines
- Converted bremsstrahlung

  from fibre targets in DESY II
- Typical flux around 1000 particles/cm²/second
- Energies from 1 to 6 GeV



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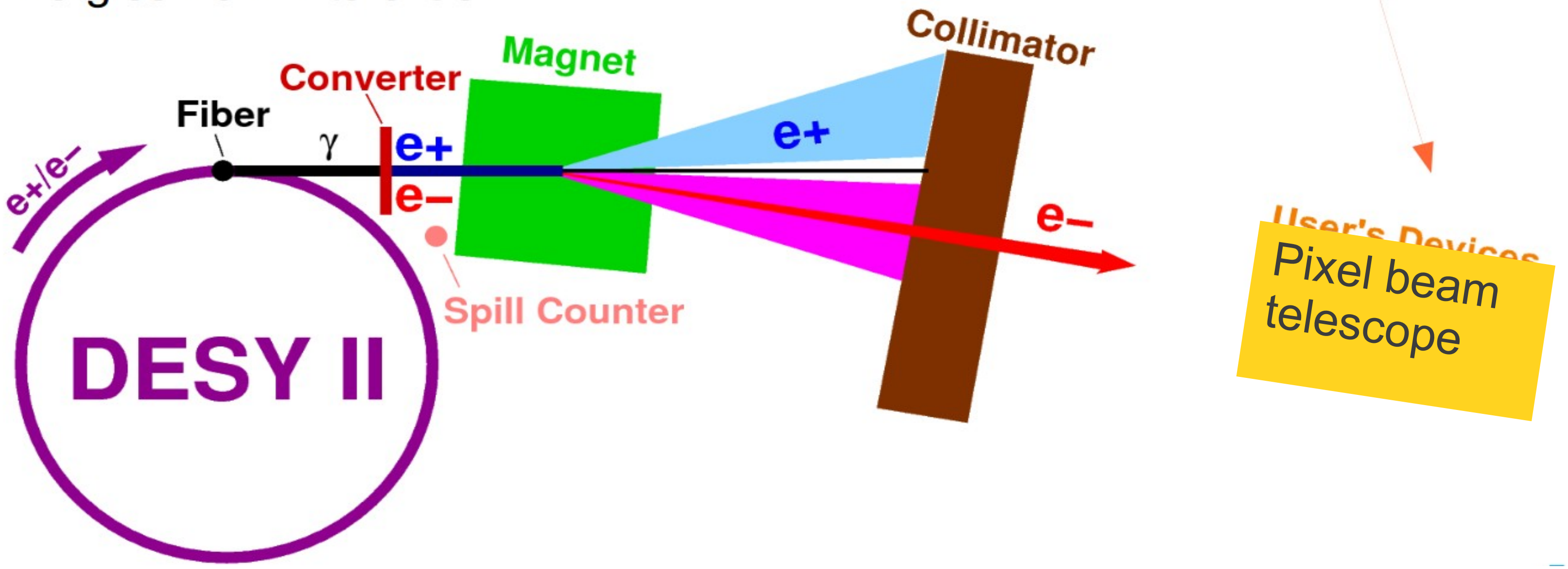


Chapter III

Pixel Beam Telescope

EUDET telescope @ DESY and CERN since 2007

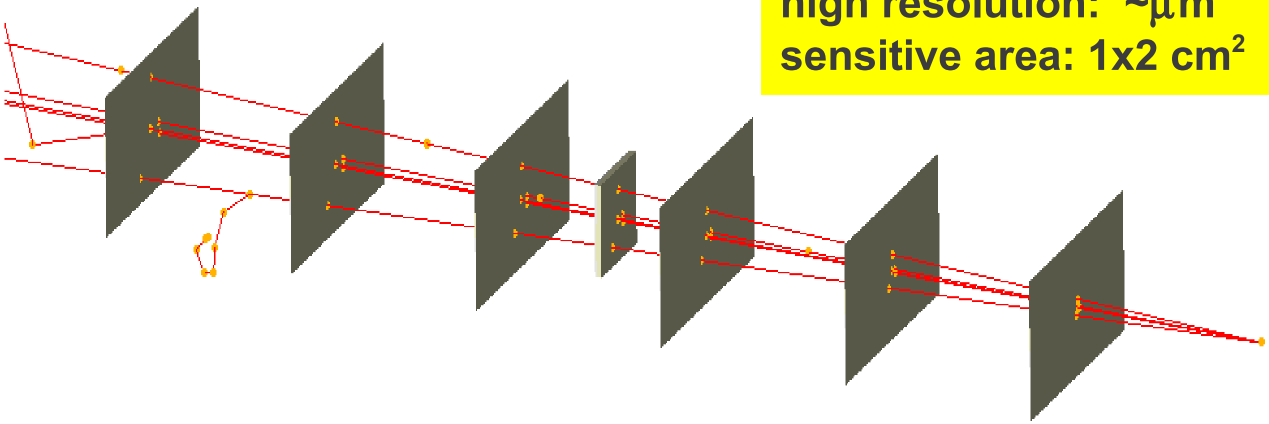
Originally developed within EUDET project (EU FP6)

Organisation and design considerations:
- certain type of Device Under Test (DUT)
  - sensors for ILC detectors
- infrastructure available for detector R&D groups
- high accuracy of track position estimation
- well defined interfaces for fast DUT integration

Pixel beam telescope: to put it simple

In order to study and develop sensors we need a tool to know where exactly a particle of known energy passed through the sensor
- lab measurements with sources useful for calibration, limited use, no info about incident point
- put a prototype into a testbeam

high resolution: ~µm
sensitive area: 1x2 cm^2



Six high resolution planes
- 2 arms with 3 sensors / each

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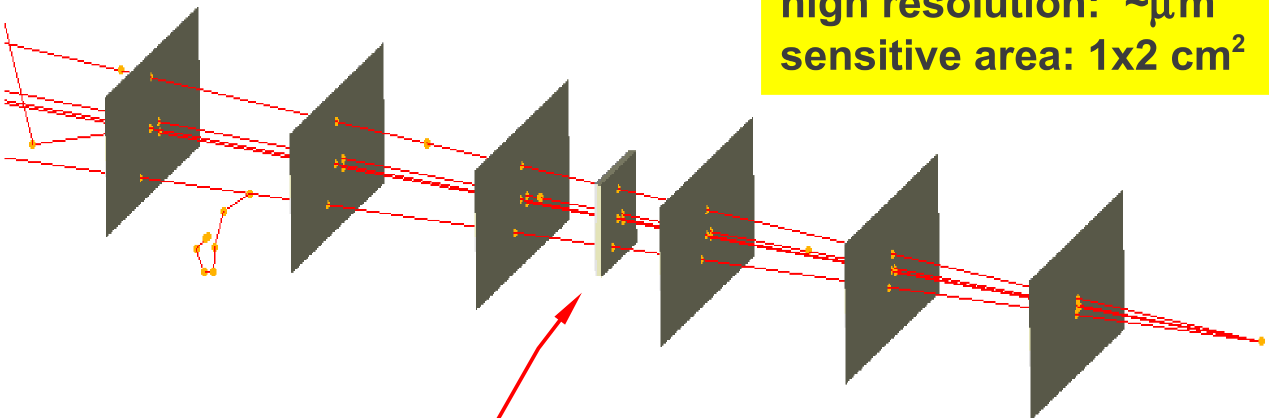

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Device Under Test (DUT)
 - placed in the center

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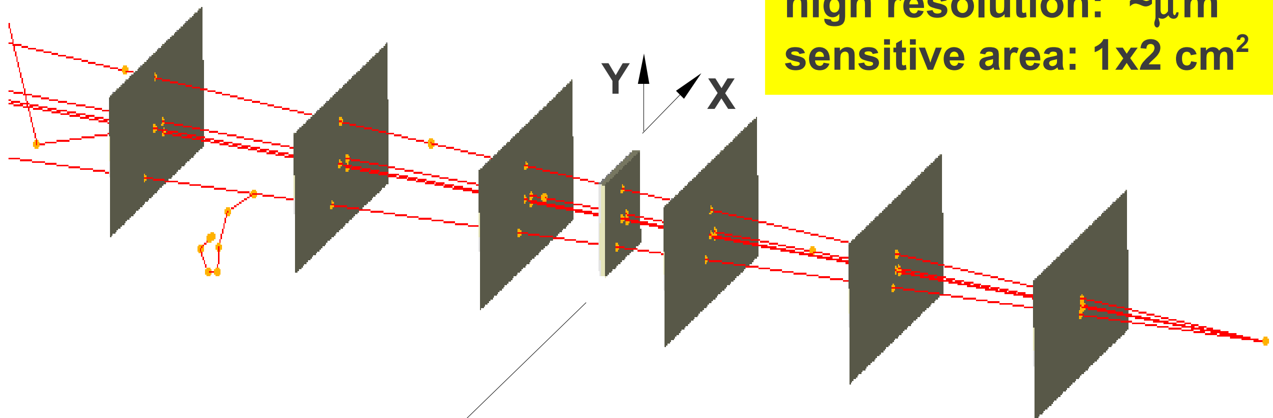

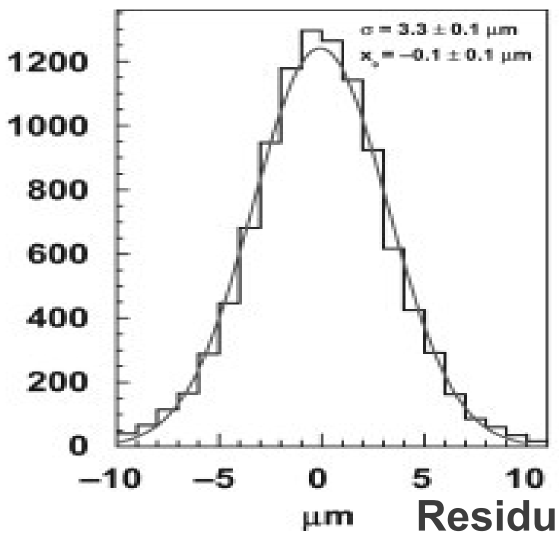

Residual = $X_{track.hit} - X_{rec.hit}$

Six high resolution planes
- 2 arms with 3 sensors / each

Device Under Test (DUT)
- placed in the center

Main feature of the telescope
- track pointing precision at DUT ~ µm (less then feature size)

Pointing resolution of a track @DUT ~2 µm
cf. smallest feature size in HEP sensors is ~10 µm
→ can map the DUT substructure perfectly!

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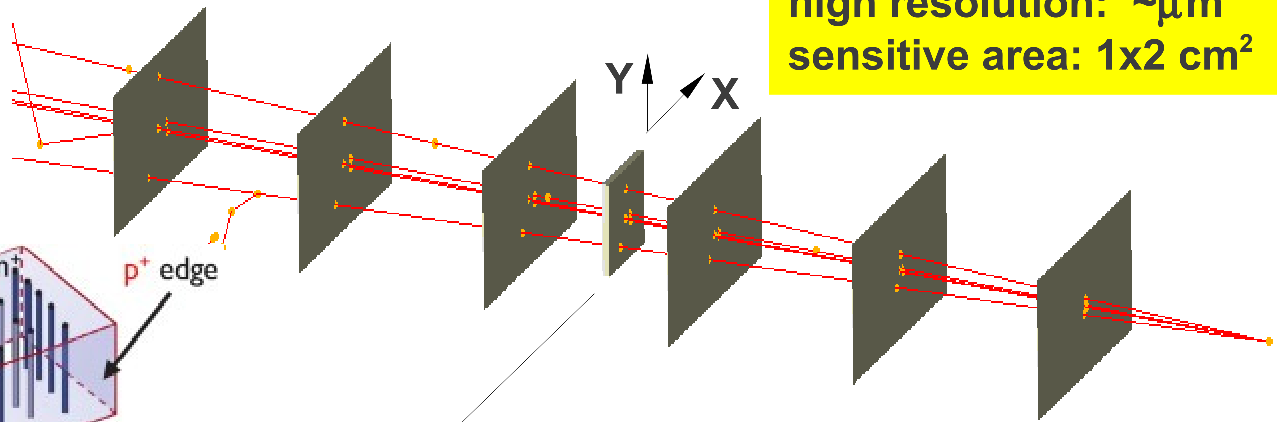
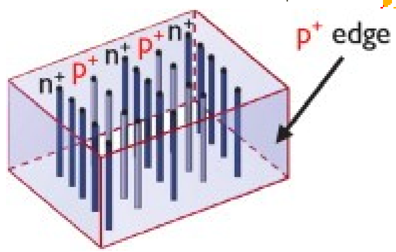
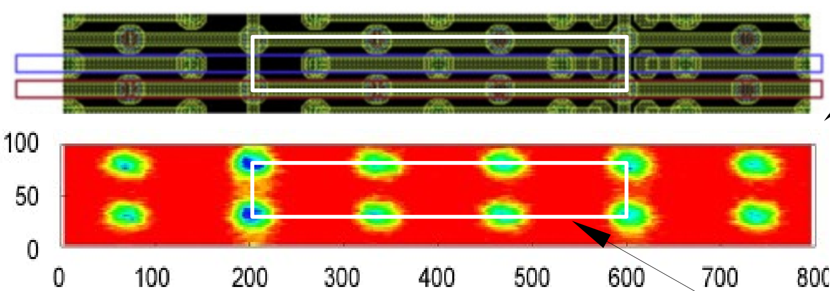


Example DUT:
3D silicon sensor
- bias and readout columns





X-ray photo

Single pixel efficiency map - drop in efficiency only if tracks go parallel to electrodes

50x400 µm (FEI3 chip) pixel contour

EUDET telescope @ DESY and CERN since 2007

Originally developed within EUDET project (EU FP6)

Organisation and design considerations:
- primary goal Device Under Test (DUT)
  - sensors for ILC detectors
- infrastructure available for detector R&D groups
- high accuracy of track position estimation

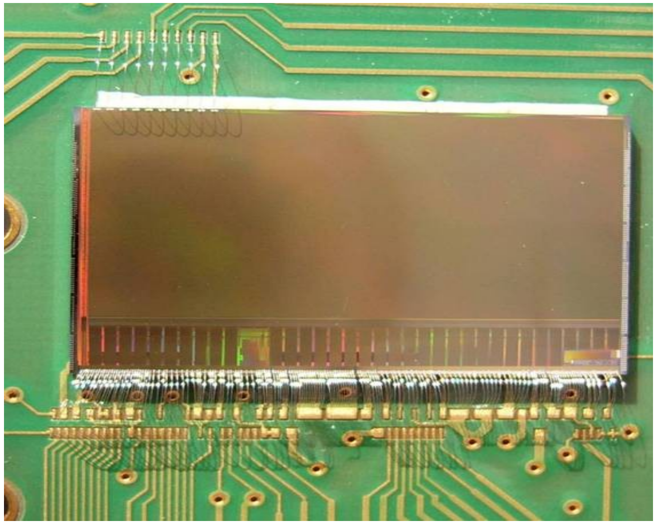
EUDET telescope – **components**:

- high resolution CMOS pixel sensors – Mimosa family (see M.Winter 6/7/2012)
- DAQ:
  - Mimosa sensors readout with VME boards (custom made) = EUDRB
  - communication and data collection protocol (C/C++, GUI) = EUDAQ
  - synchronization of detector DAQs = Trigger Logic Unit
- Mechanical frame
- DUT precision positioning in beam
  - translation (~µm) and rotation stages (10^{-4} rad) by PI

Mimosa26

High resolution plane

- MAPS = Monolithic Active Pixel Sensor
  with CMOS technology (by IPHC Strasbourg)
- pitch: **18.4 x 18.4 μm^2**
  → hit position error $\sigma_x = 3.5$ μm (intrinsic resolution)
- matrix: 1152 columns x 576 rows (~2 cm^2, **~0.7 Mpixel**)



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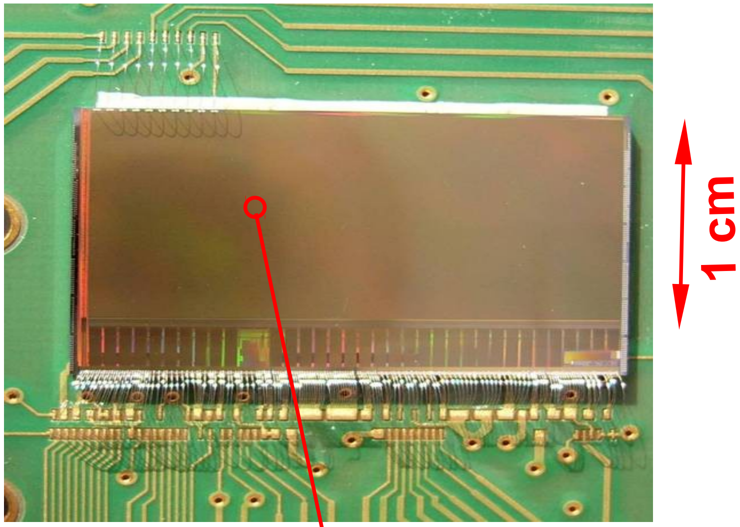
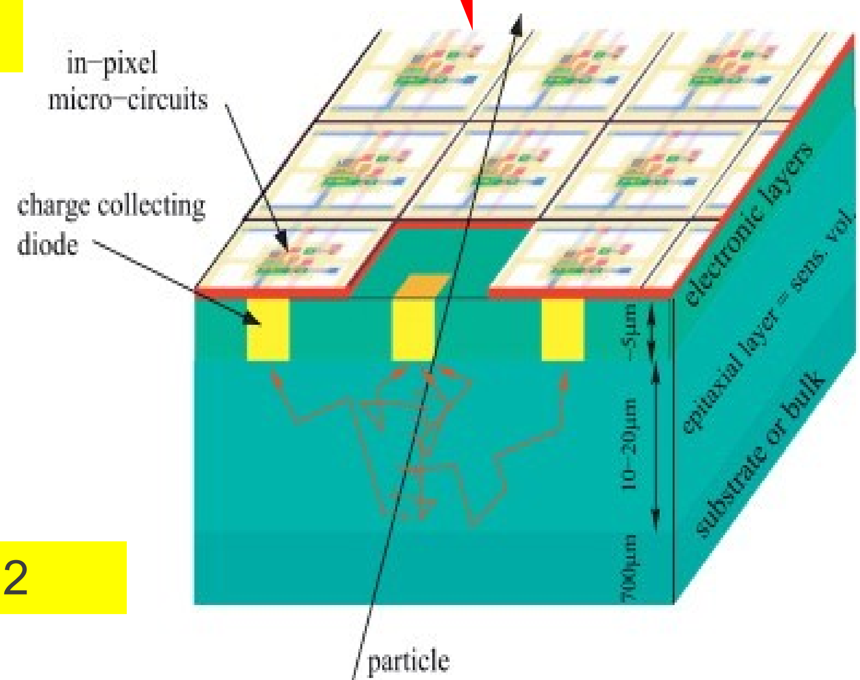
-"standard" thickness ~700 μm
"thinned" = 50 μm

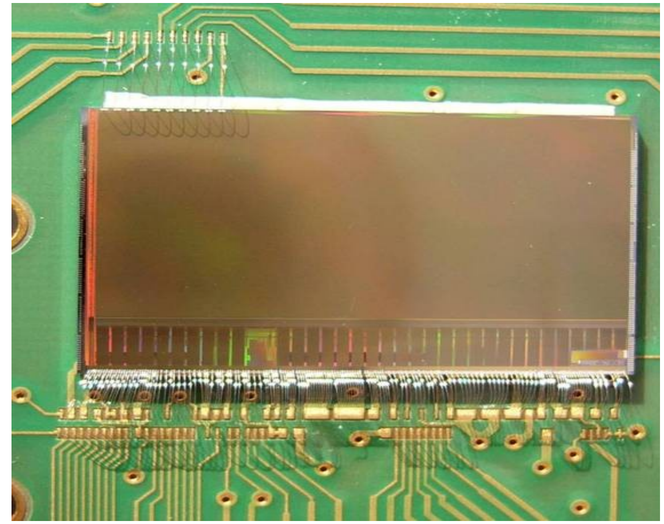


The 3 outstanding figures of Mimosa26



IS talk: Marc Winter "CMOS sensors" 06.07.12

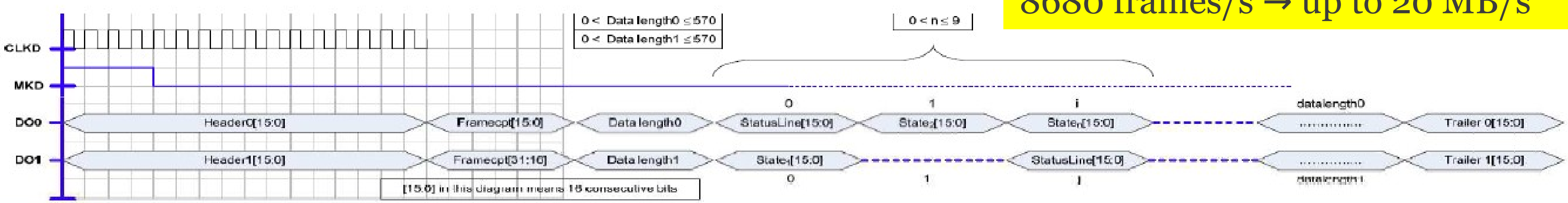
Mimosa26



- **Readout in a Rolling Shutter Mode**
  continous row-by-row readout
- **16 clocks per pixel (row)**
  readout of 1152 columns in parallel
  (=1152 CPU/GPU cores)
  x 576 rows = **9216 clocks for the whole matrix**
- **at 80 MHz**
  → 12,5 ns per clock
  → 115,2 µs per matrix (=frame)

Proprietary readout protocol of Mimosa 26

max. event size → 2 x 1152 Byte
8680 frames/s → up to 20 MB/s



4 LVDS lines for one Mimosa26 IO

6x Mi26 : bandwidth requirements ~120 MB/s

Mimosa26

- **Readout in a Rolling Shutter Mode**
  continous readout by rows (row-by-row)

- **16 clocks per pixel (row)**
  readout 1152 columns in parallel
  (=1152 CPU/GPU cores)
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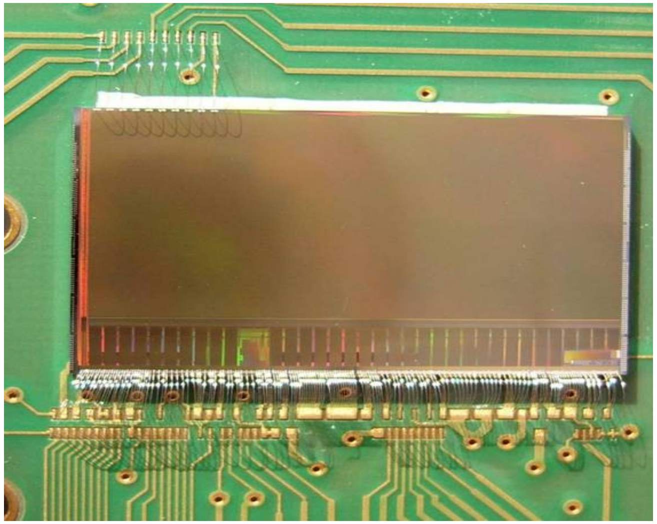
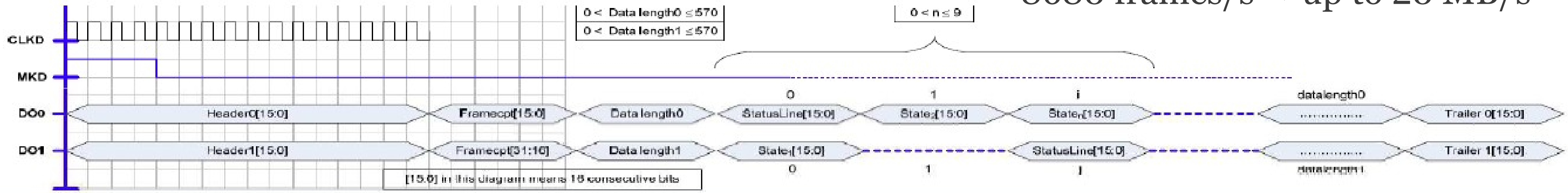
  → 12,5 ns per clock
  → 115,2 µs per matrix (=frame)



Proprietary readout protocol of Mimosa 26

max. event size → 2 x 1152 Byte
8680 frames/s → up to 20 MB/s

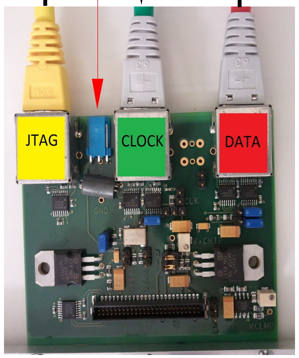


4 LVDS lines for one Mimosa26 IO

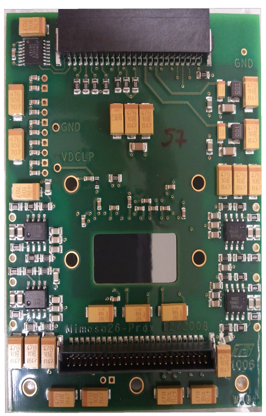
6x Mi26 : bandwidth requirements ~120 MB/s

Maximum hit occupancy: safe estimate ~100 tracks per frame (115,2 µs)
→ Mimosa26 can handle up to 1M tracks per second [just to be demonstrated in a beam test]

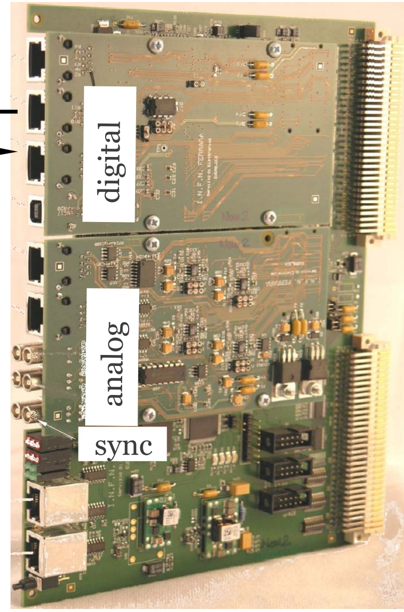
First solution within EUDET project



Auxiliary board



Mimosa26 on a single chip card
(x6 sensor sets draw 2.8A)



EUDRB = EUDET Data Reduction Board
1 EUDRB per 1 Mimosa26

Custom made (INFN Ferrara)

VME 64
6 EUDRBs
<80 MB/s

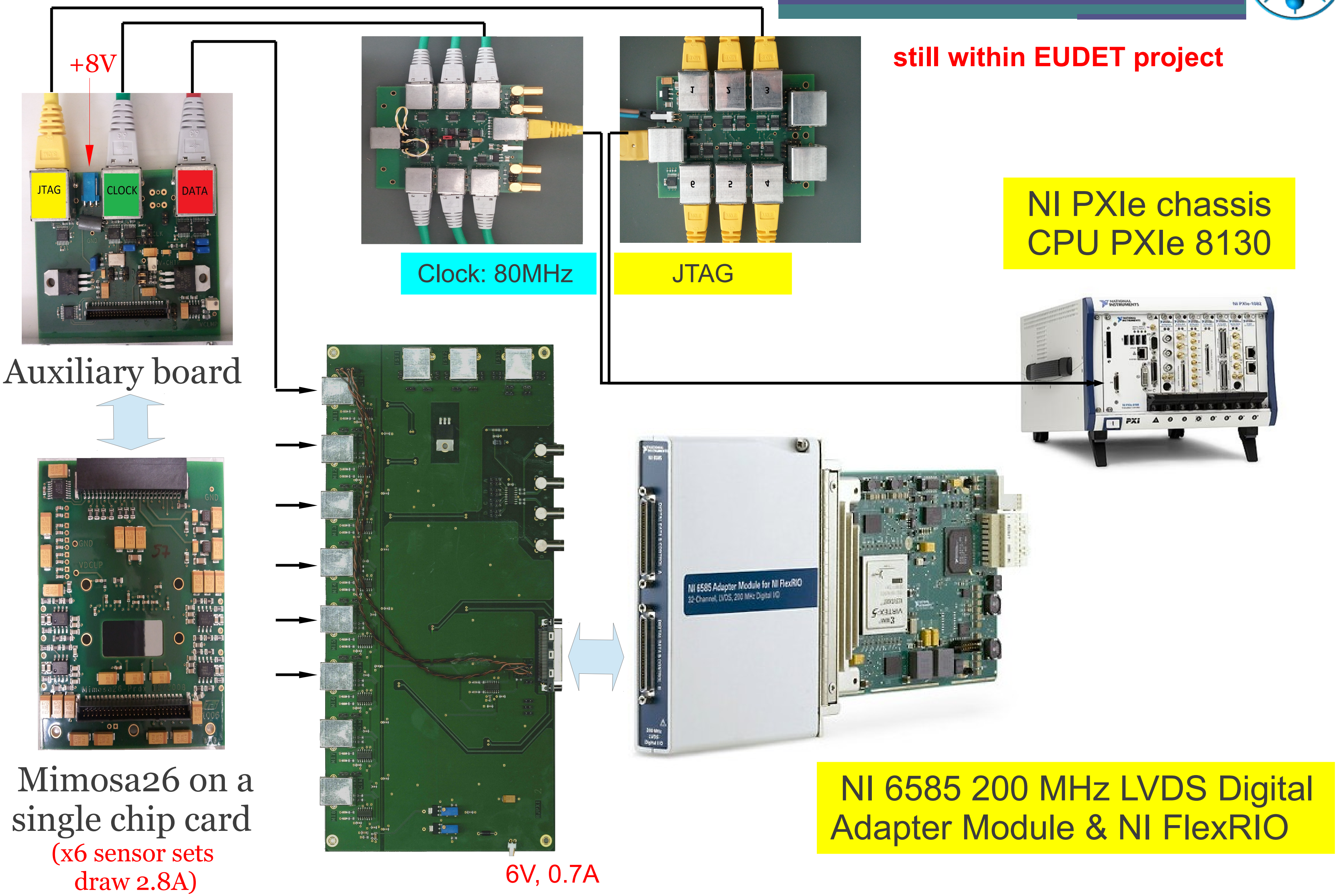
- first used for analog sensors readout (@20 MHz)
  - Mimosa 17, 18
  - “raw bit stream” or with on board noise suppression and data sparcification
- adapted for digital sensors readout with noise suppression and data sparsification on sensor (@80 MHz)
  - Mimosa 26

EUDAQ Data Collector

not easy to make EUDRB copies
→ scalability issues

..so, another way was found →

Pixel beam telescope: the building blocks

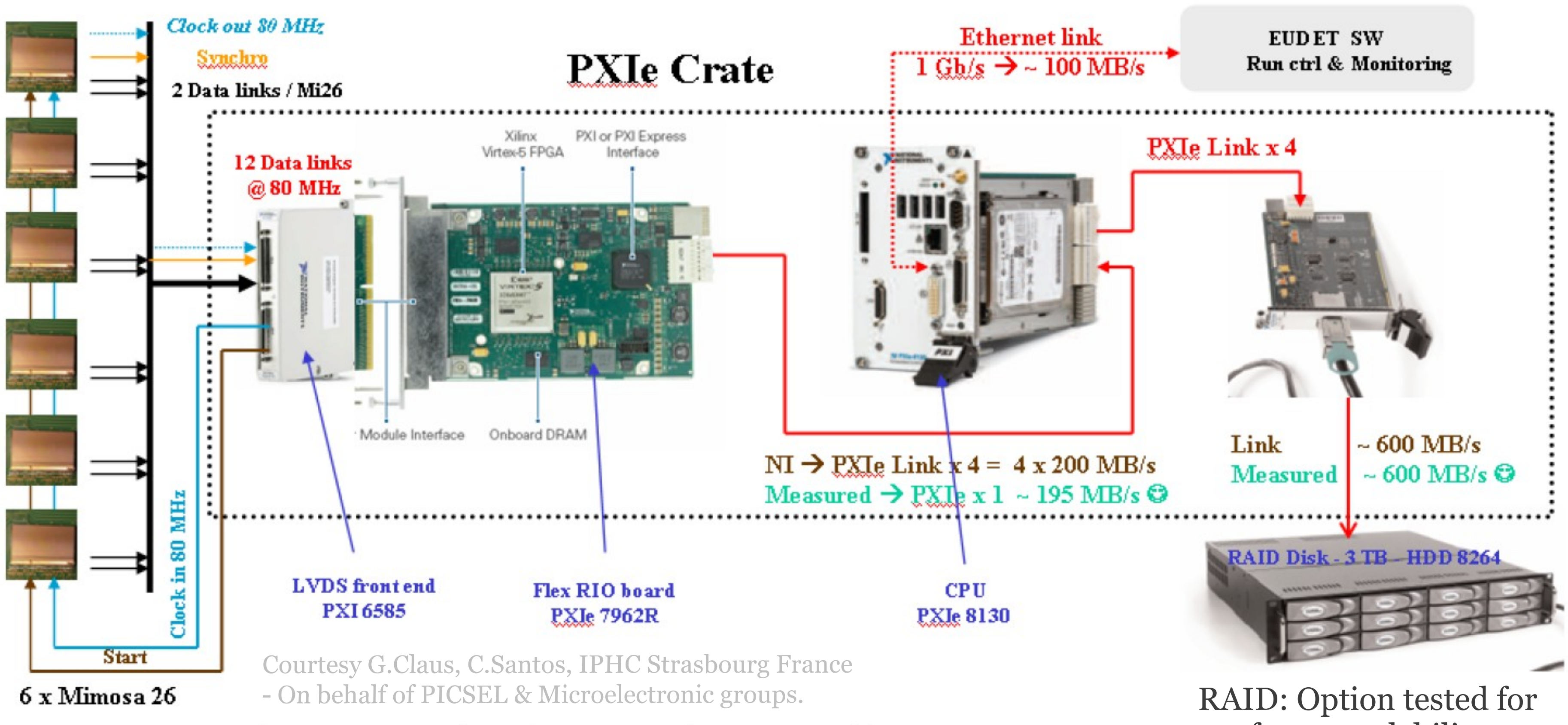


8xRJ45(2 links) →16 LVDS

Pixel beam telescope: the building blocks

High bandwidth scalable readout system:
NI Flex RIO based solution for Mimosa26 family
now Mimosa26=1x2 cm^2
→ future:: 2x2, 4x6 cm^2 area (Mimosa xx)

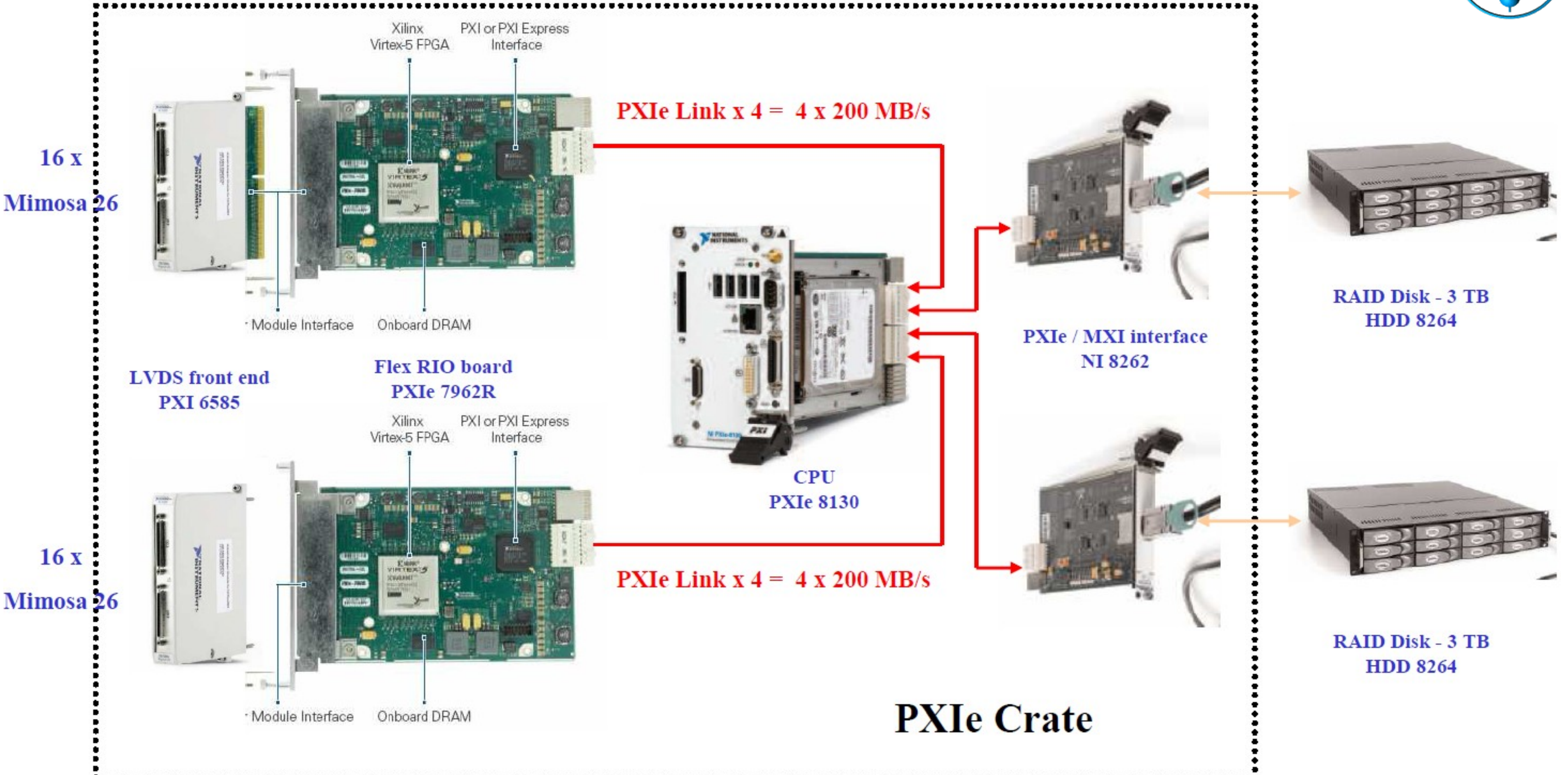
maximum readout rate achieved
= 8.68 kFrames/s
- no deadtime in the sensor DAQ chain



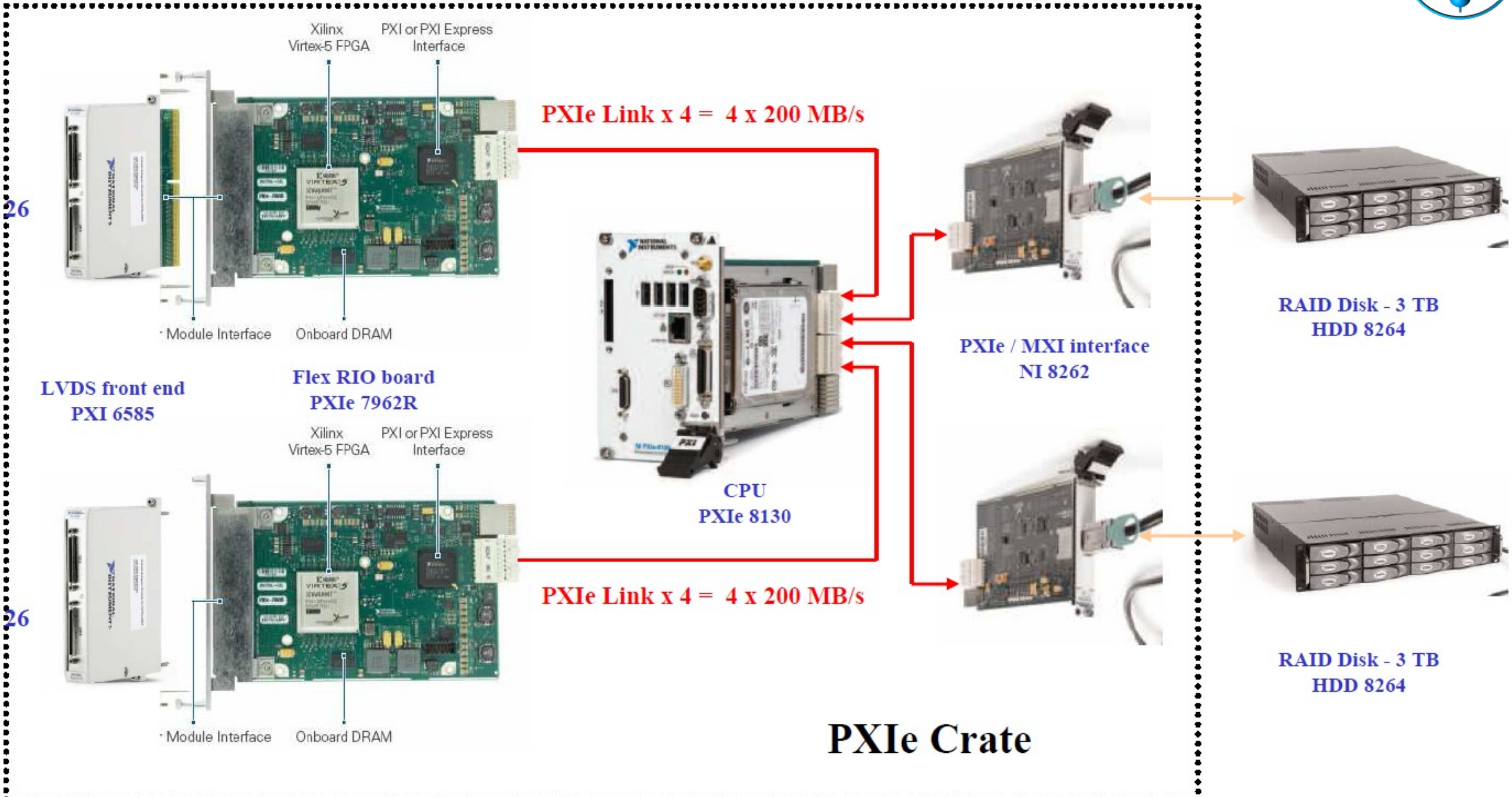
Courtesy G.Claus, C.Santos, IPHC Strasbourg France
- On behalf of PICSEL & Microelectronic groups.

RAID: Option tested for future scalability

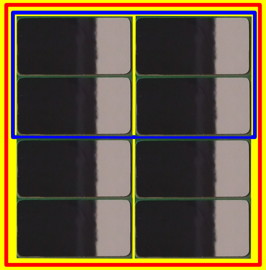
6 x Mimosa26 need < 120 MB/s, NI COTS DAQ gives 800 MB/s


Xilinx
Virtex-5 FPGA
PXI or PXI Express
Interface
PXIe Link x 4 = 4 x 200 MB/s
16 x
Mimosa 26
Module Interface
Onboard DRAM
LVDS front end
PXI 6585
Flex RIO board
PXIe 7962R
Xilinx
Virtex-5 FPGA
PXI or PXI Express
Interface
CPU
PXIe 8130
PXIe / MXI interface
NI 8262
RAID Disk - 3 TB
HDD 8264
16 x
Mimosa 26
PXIe Link x 4 = 4 x 200 MB/s
RAID Disk - 3 TB
HDD 8264
Module Interface
Onboard DRAM
PXIe Crate

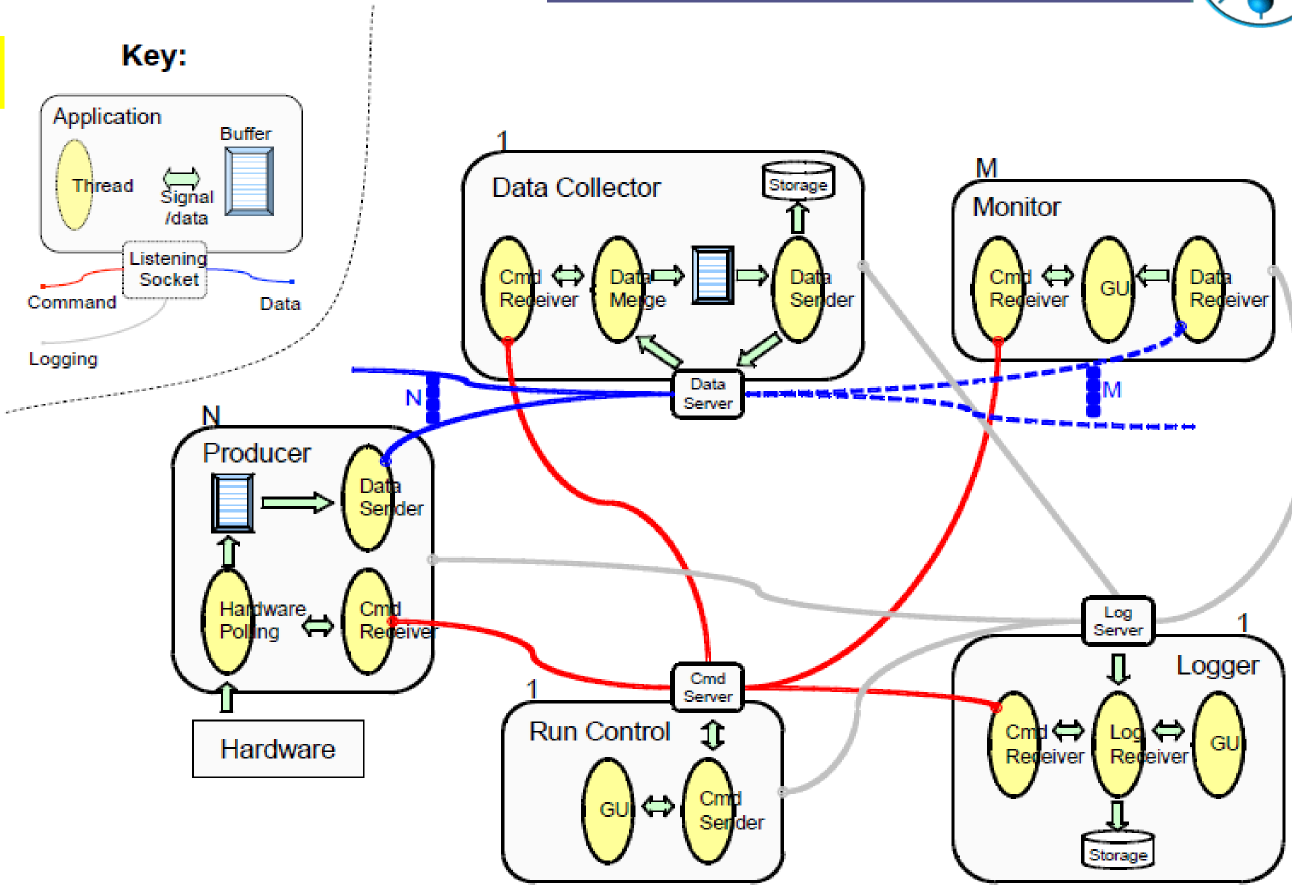
Pixel beam telescope: the building blocks



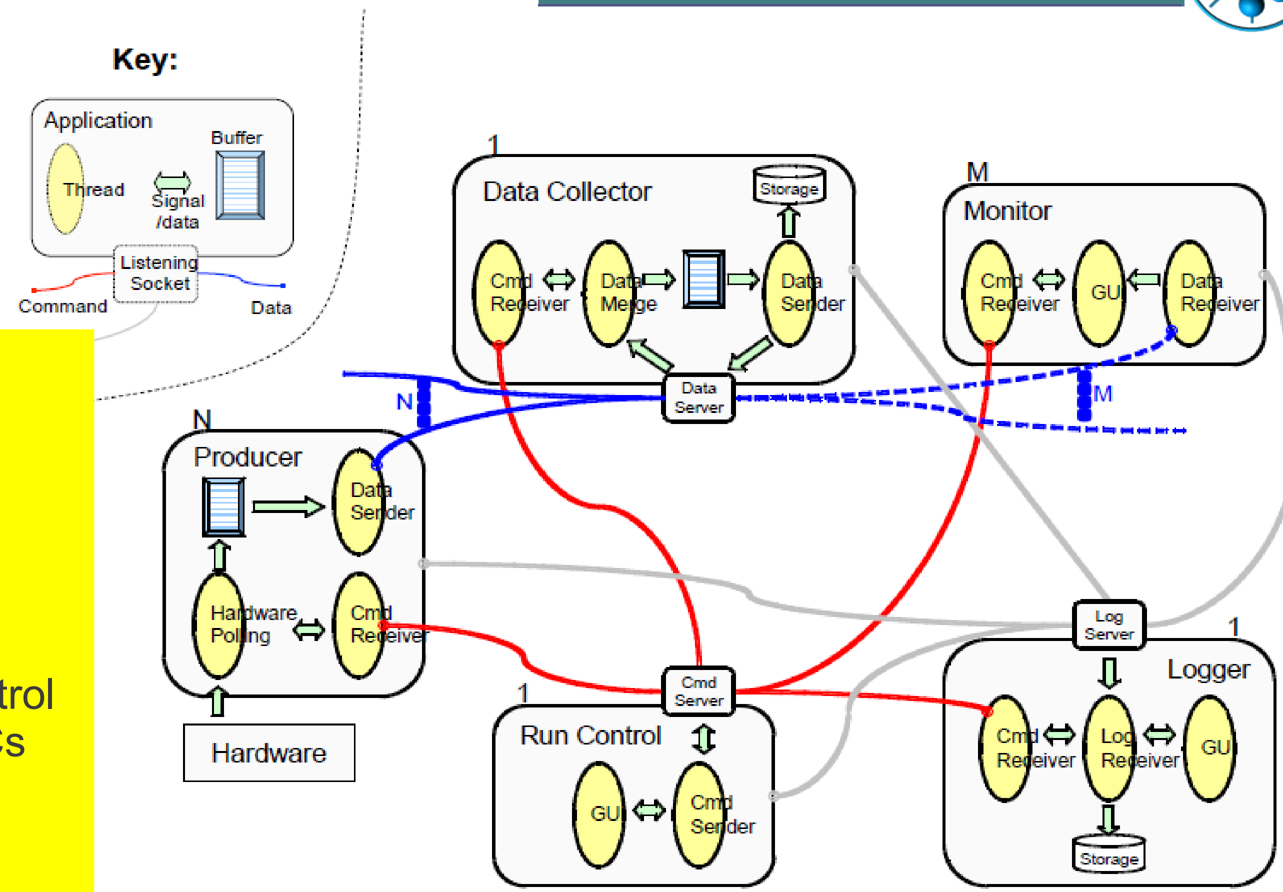
In principle can readout up to 32 Mimosa26, which is
- 4 “super”-planes x 8 Mimosa26 (1 plane = 2x4 sensors → 16 cm^2 coverage area)
- or 6 “super”-planes x 4 Mimosa26 (1 plane = 2x2 sensors → 8 cm^2 coverage)



DAQ software - EUDAQ



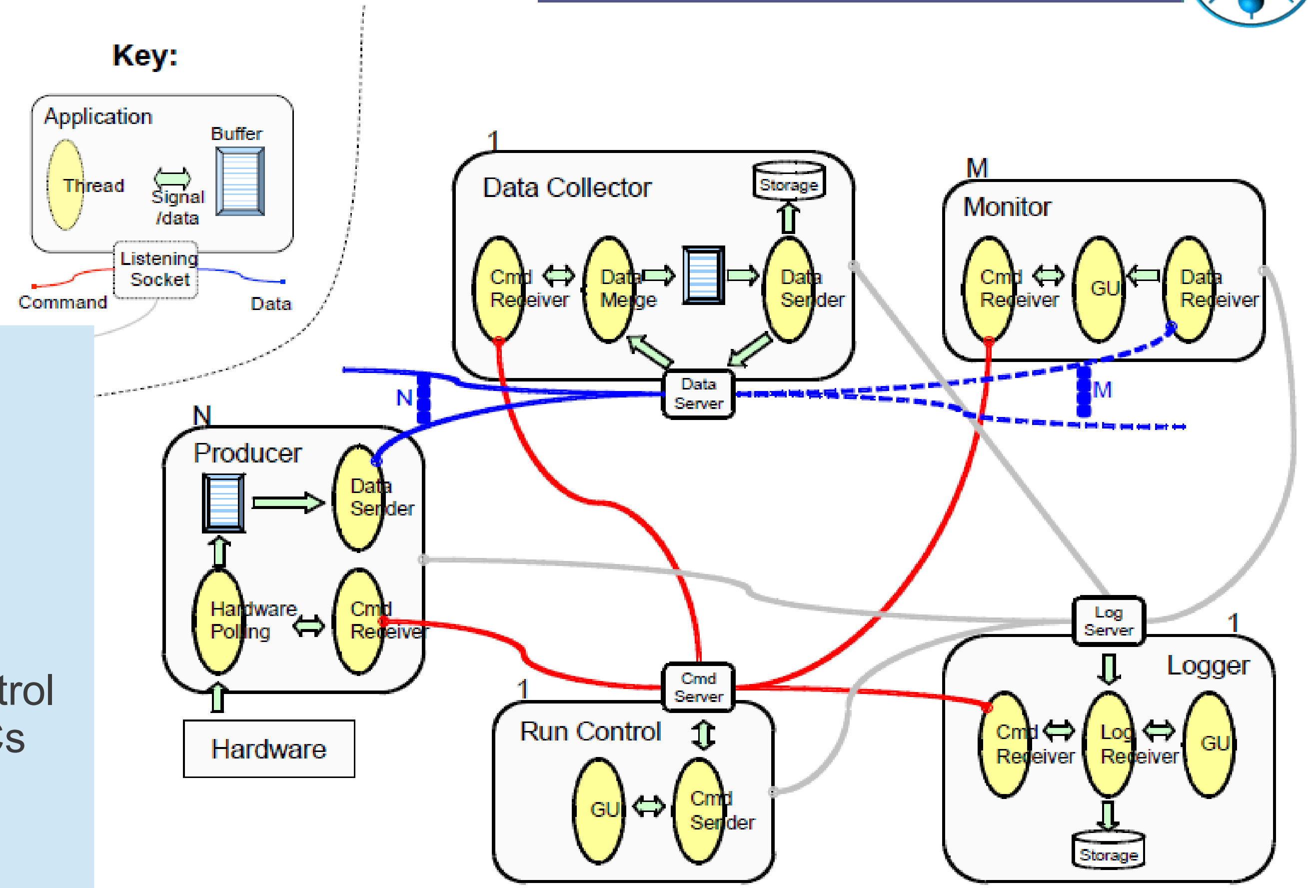
DAQ software - EUDAQ



Highly modular:
- Data Collector
- Data Logger
- DAQ Producers
  - :VME/NI Producer
  - :DUT Producer(s)
- Online Monitor (DQM)
- GUI/command line control

- can run on independent PCs
- Multithreaded
- TCP/IP sockets

DAQ software - EUDAQ



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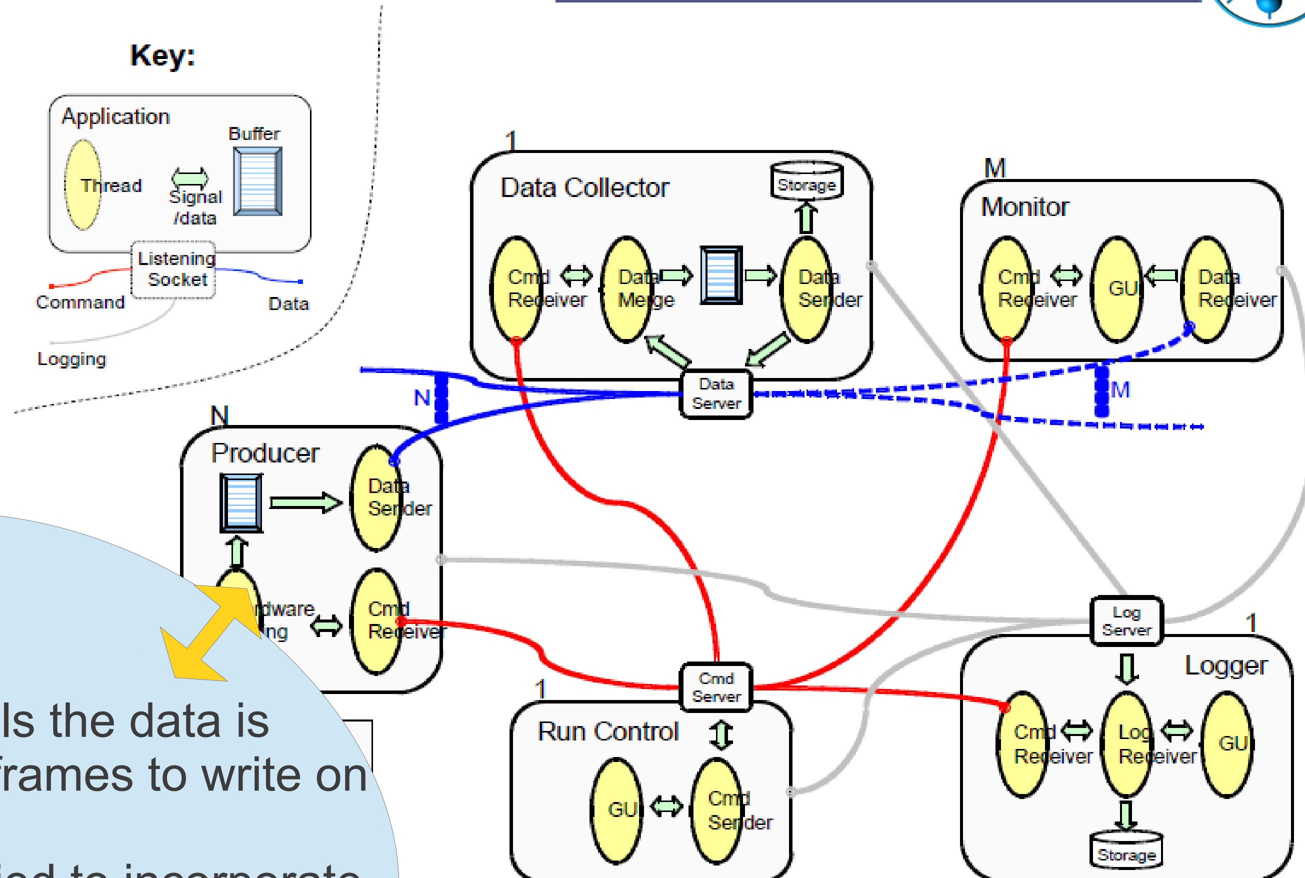
- GUI/command line control

- can run on independent PCs
- Multithreaded
- TCP/IP sockets

Platform (in-)dependence (important for DUT DAQ):
- C/C++, Qt, ROOT

Mac OSX – original implementation
Linux – easy, nearly same as Mac Os
Windows – needs some effort to have it running there

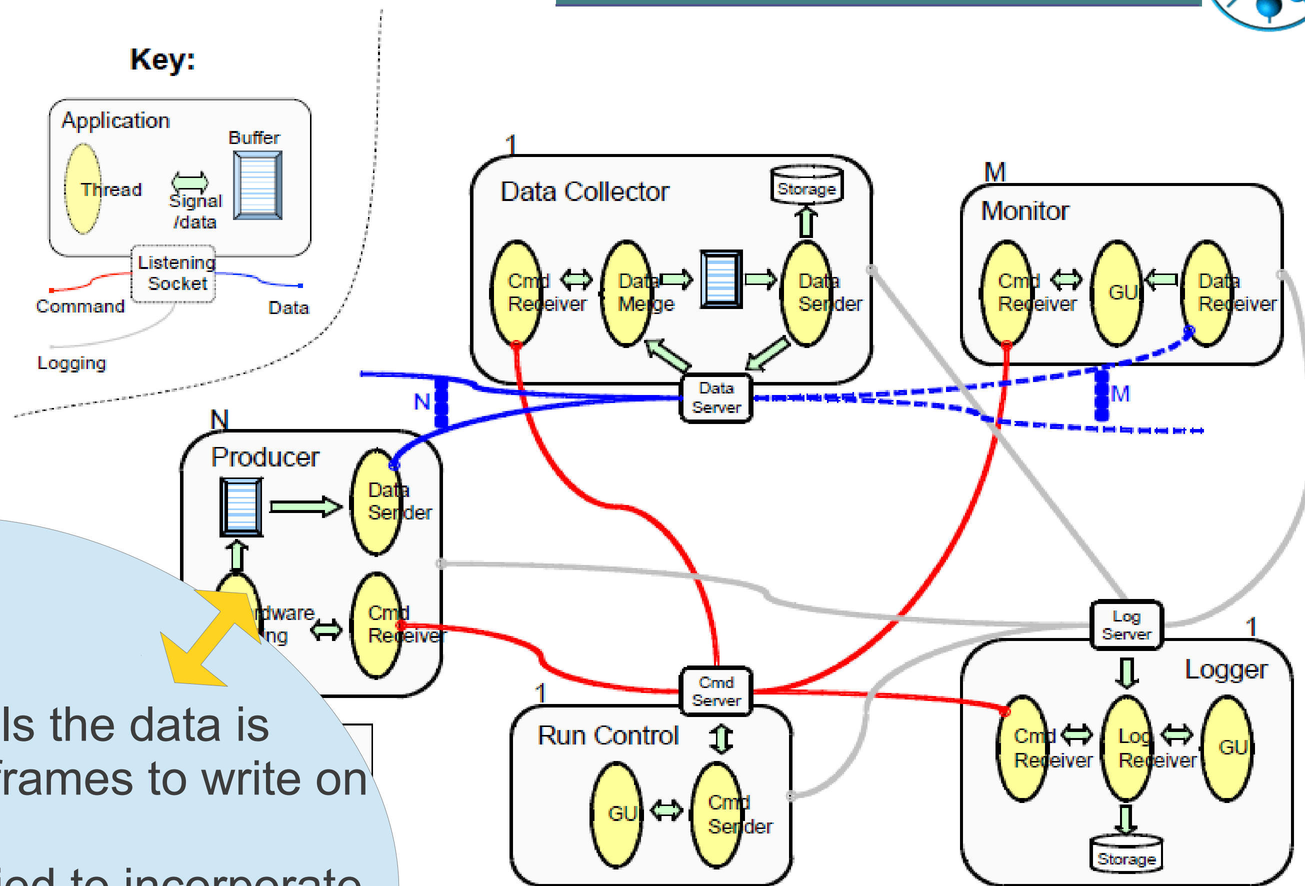
Pixel beam telescope: DAQ software - EUDAQ



DUT DAQ system:
- detector module
- readout system
- at one of the top levels the data is formed into events or frames to write on disk
- - can be easily modified to incorporate the client-server communication protocol of EUDAQ to allow the EUDAQ Run Control to take over the DUT DAQ

EUDAQ was designed having beam test applications in mind – very flexible

Pixel beam telescope: DAQ software - EUDAQ



DUT DAQ system:
- detector module
- readout system
- at one of the top levels the data is formed into events or frames to write on disk
- - can be easily modified to incorporate the client-server communication protocol of EUDAQ to allow the EUDAQ Run Control to take over the DUT DAQ

All DAQ Producers have equal rights

EUDAQ was designed having beam test applications in mind – very flexible

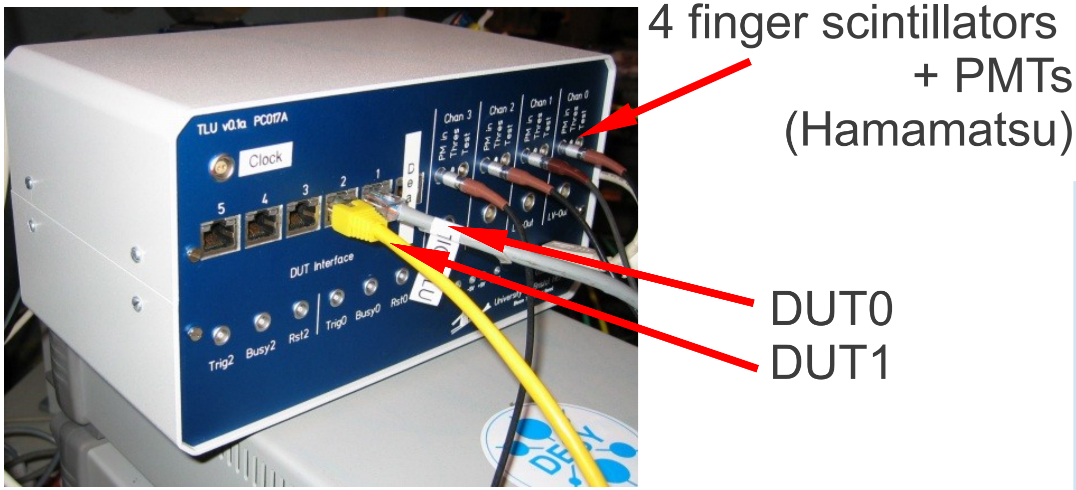
Synchronous triggering of the DAQ systems
- Trigger Logic Unit (TLU)

4 finger scintillators + PMTs (Hamamatsu)

DUT0
DUT1

TLU discriminator board
- handles negative and positive input signals (any Trigger source)
  ~100 mV, ~ns front
- need to adjust thresholds with mechanical tools (screw driver)

DUT DAQ interface RJ45 (x6) or NIM (x2) or TTL (x2)



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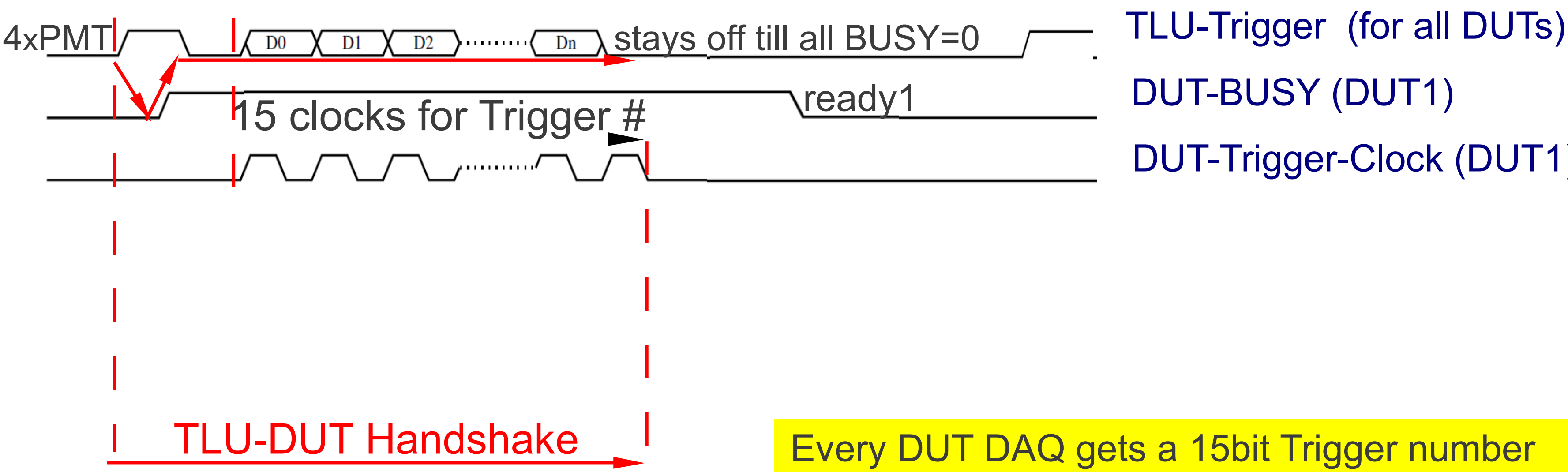
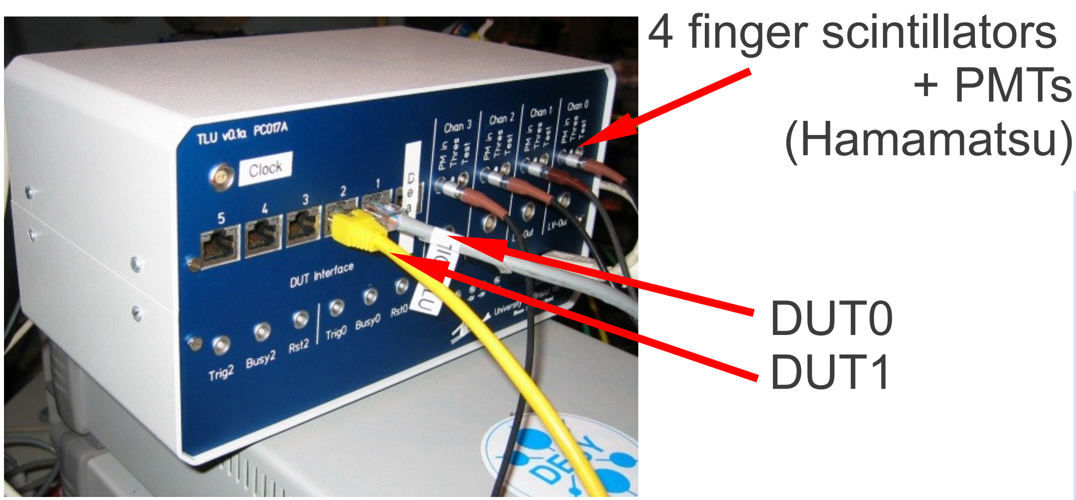


Every DUT DAQ gets a 15bit Trigger number
- for re-synchronisation between DUTs



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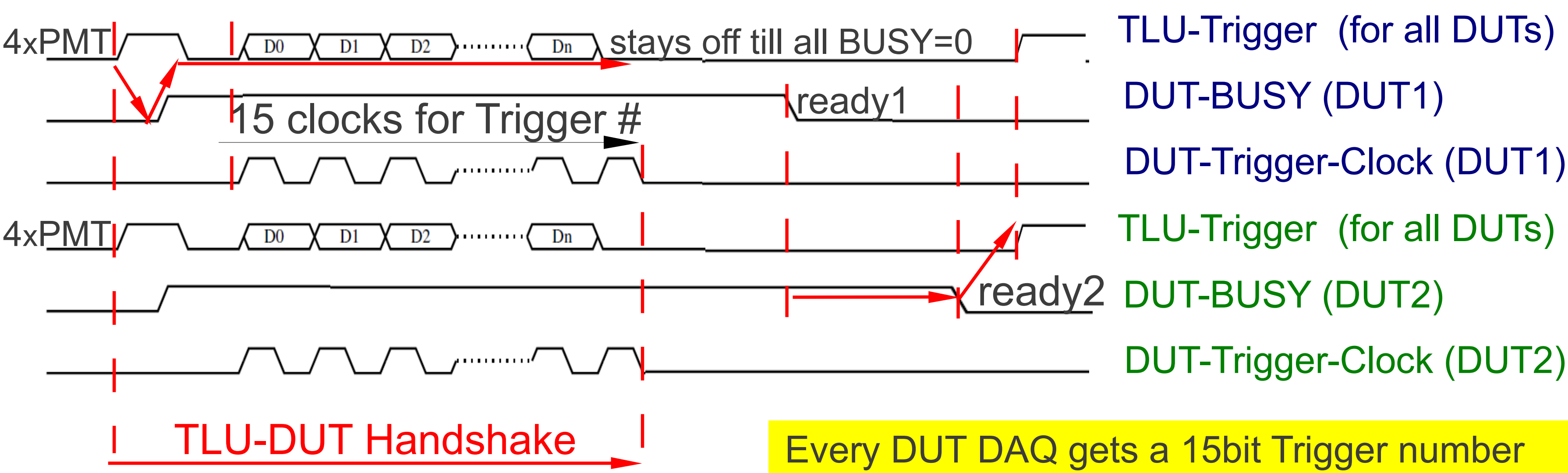

Every DUT DAQ gets a 15bit Trigger number
- for re-synchronisation between DUTs

4 finger scintillators + PMTs (Hamamatsu)

DUT0
DUT1

TLU discriminator board
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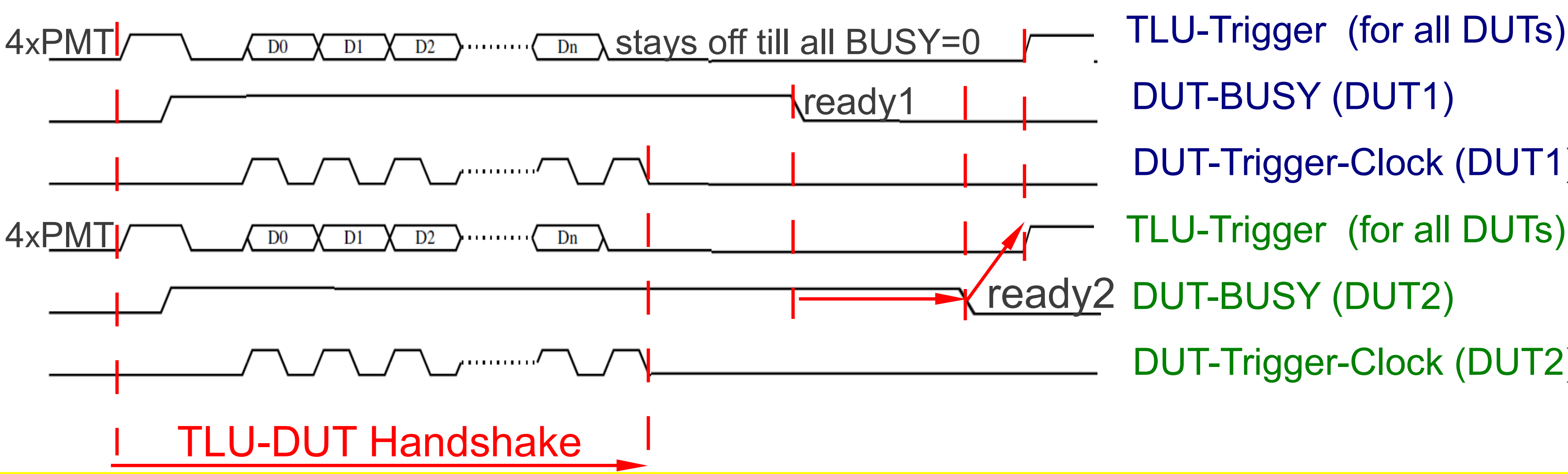
~100 mV, ~ns front
- need to adjust thresholds with mechanical tools (screw driver)



Synchronous triggering → OK for detectors with similar integration time but leads to high inefficiency for faster.vs.slower Detectors [LHC.vs.ILC]

EUTelescope software package
- track reconstruction

https://eutelescope.web.cern.ch

Most Visited | Getting Started | DESY - DESY @ BELLE ... | WebHome < Mimosa... | Datenanalyse in der P... | MayJune2012 < Atlas ...

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EUTelescope

A Generic Pixel Telescope Data Analysis Framework

View | Edit

Home

Welcome to the EUTelescope web pages.

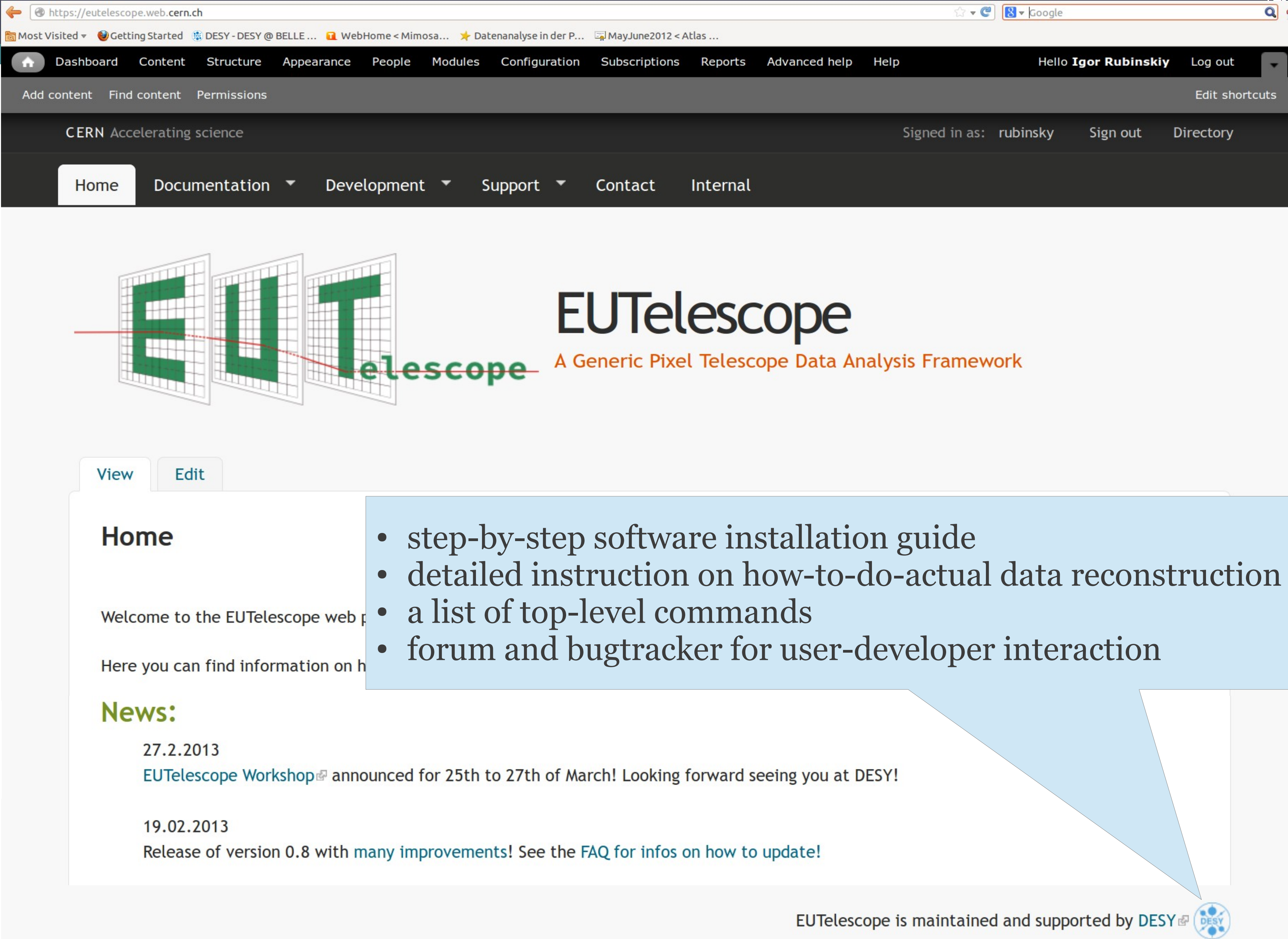
Here you can find information on how to install and run the EUTelescope software and how to get support.

News:

27.2.2013
EUTelescope Workshop announced for 25th to 27th of March! Looking forward seeing you at DESY!

19.02.2013
Release of version 0.8 with many improvements! See the FAQ for infos on how to update!

EUTelescope is maintained and supported by DESY



- step-by-step software installation guide
- detailed instruction on how-to-do-actual data reconstruction
- a list of top-level commands
- forum and bugtracker for user-developer interaction

EUTelescope – framework for testbeam data analysis

ILCSoft : = Marlin framework
- Open Source Code, easy to share by people from different collaborations
- supported by DESY IT
- under continuous development (=improvement)

ILCSoft : = Marlin framework

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Legend: Telescope + DUT data | Condition DB collections | EUTelescope library (Marlin) processors

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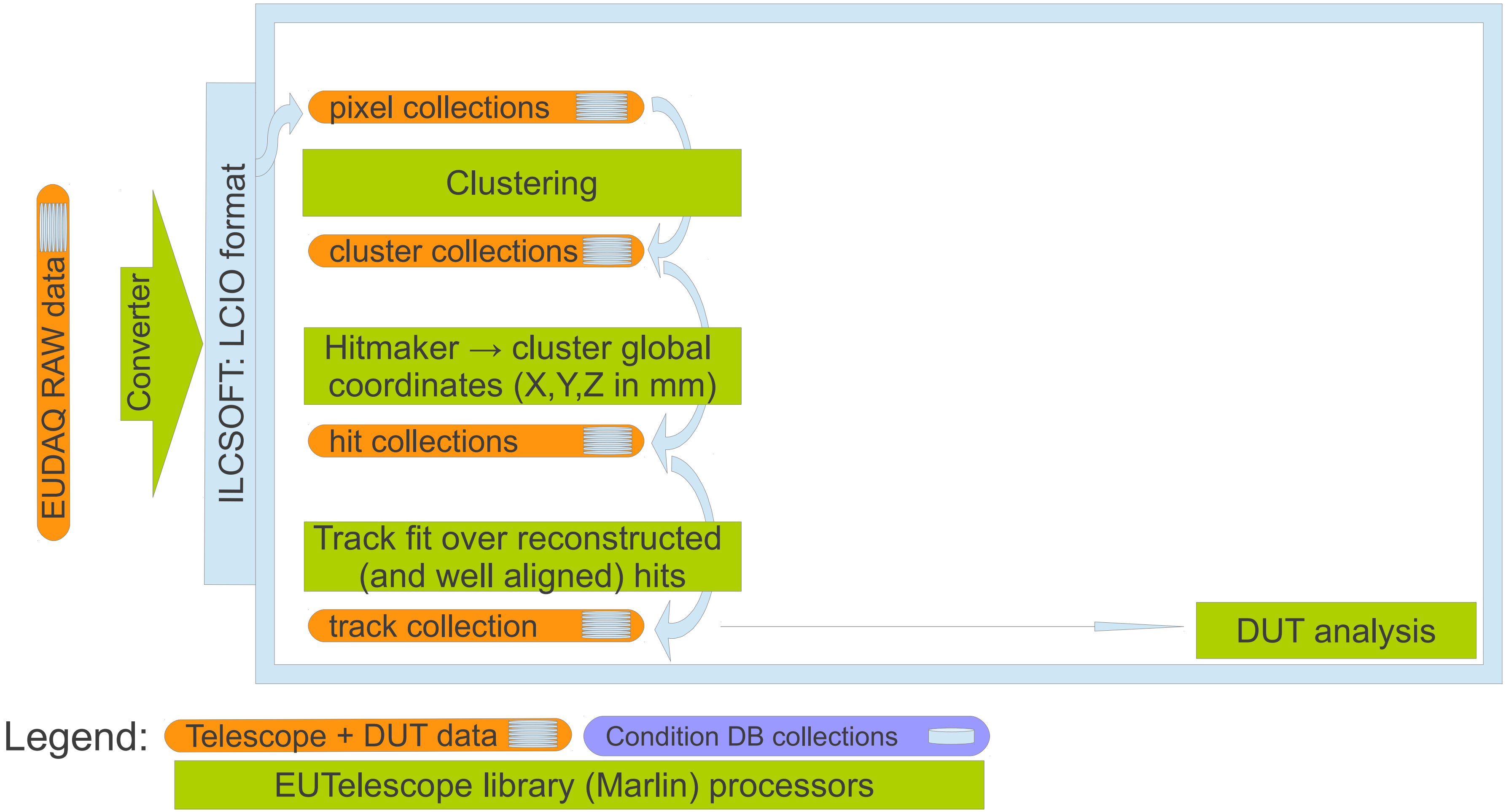

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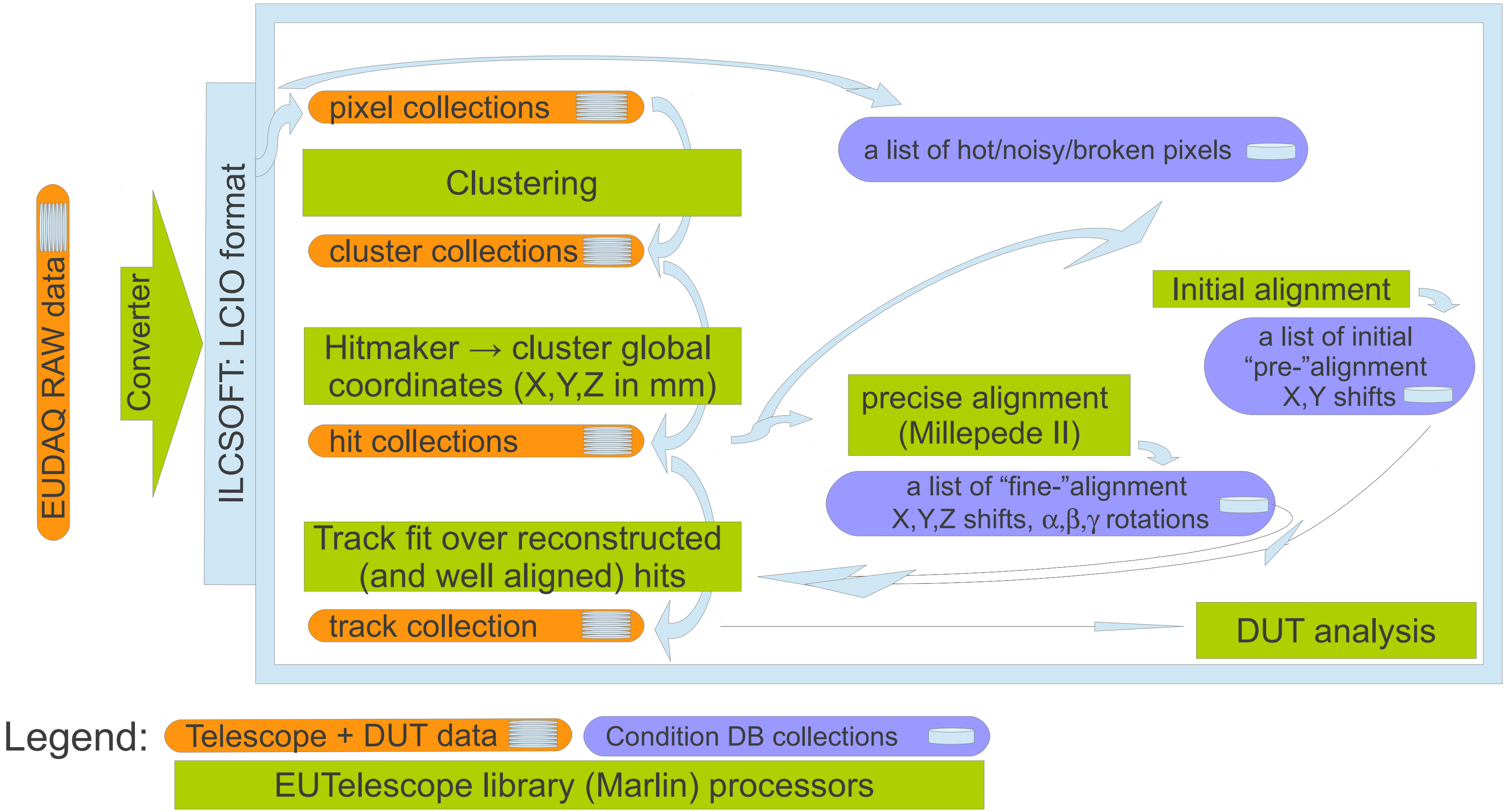

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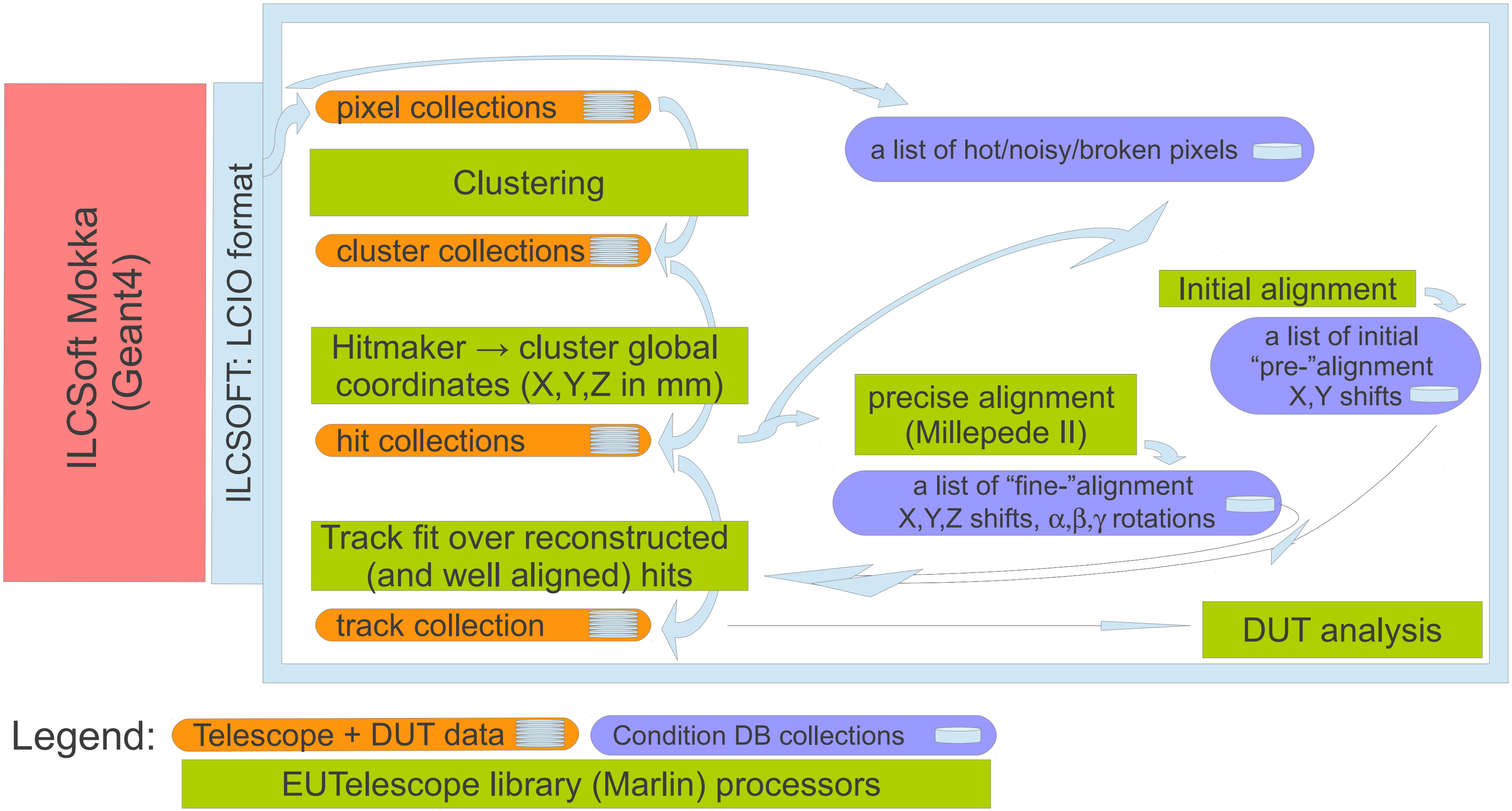

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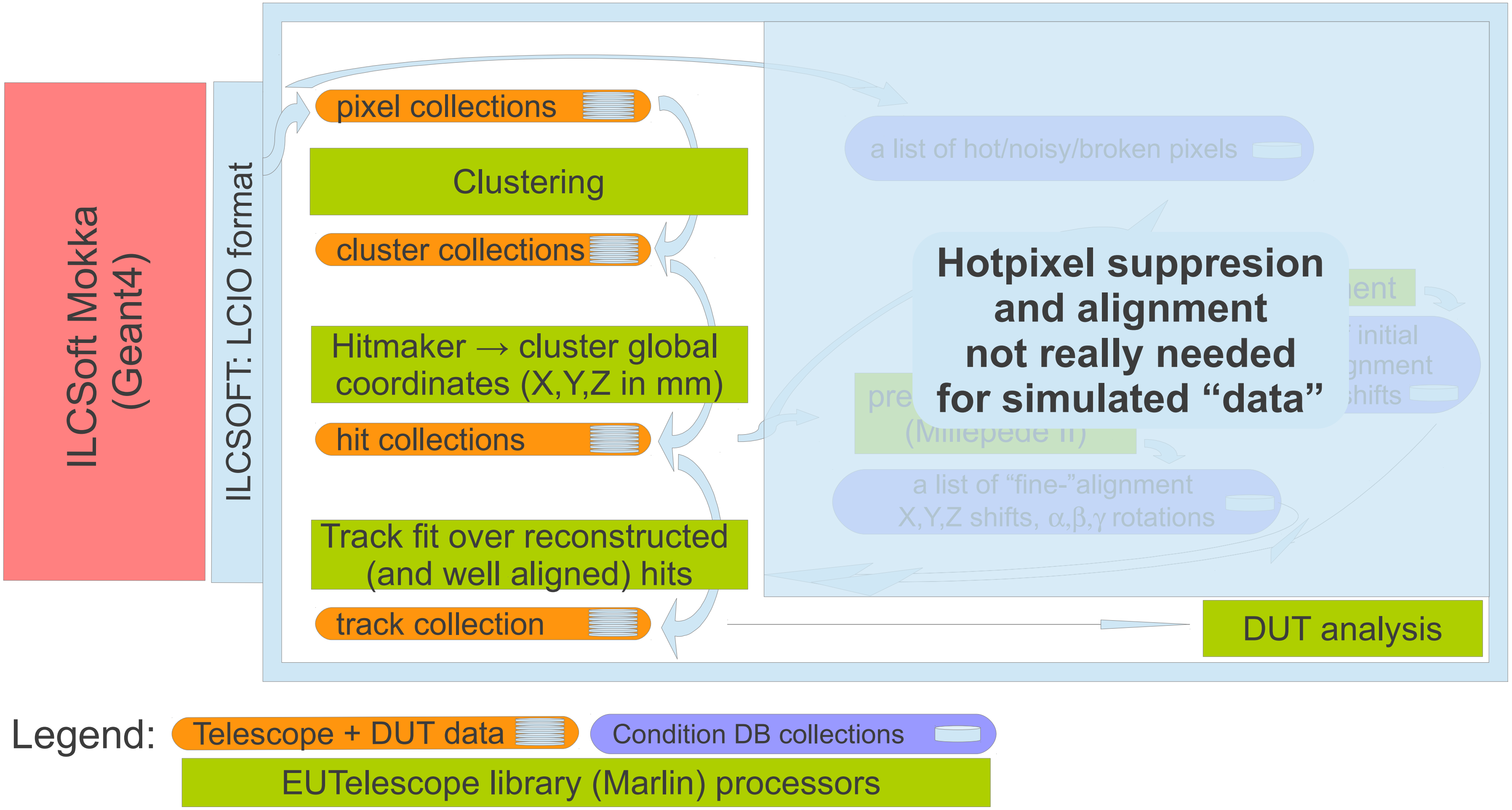
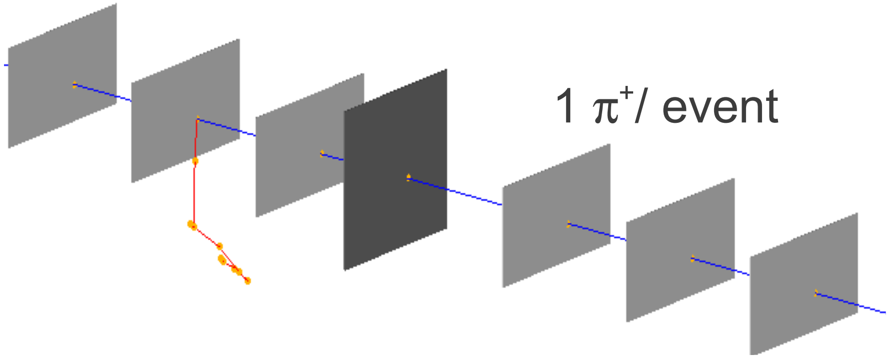


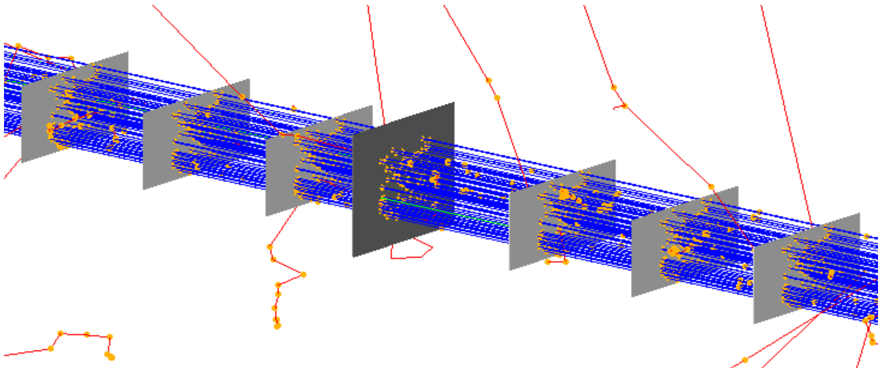
ILCSoft::Mokka - GEANT4 simulation

Tracking efficiency studies for a variaty of beam energies and multiplicity
Fixed configuration: 6 Mimosa26 (6x50 μm Si) and 1 DUT (1x500 μm Si)



1 π^+/ event

100 e^+/ event



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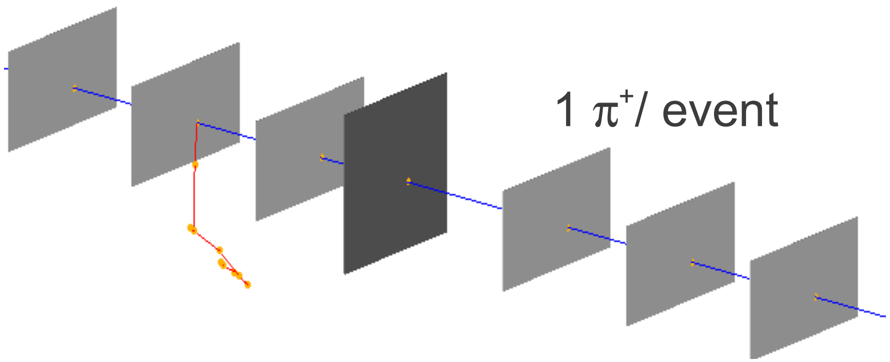

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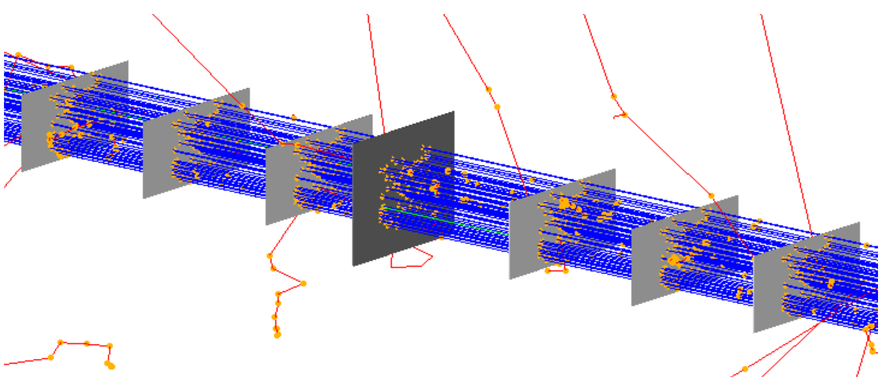

track reconstruction efficiency table: versus beam energy and multiplicity

location	particle type	beam energy, GeV	N particles per spill (=per event)		
			1	100	300
Bonn, DESY	e	1	90-95	80-95	50-90
DESY, SLAC	e	5	>98	85-95	70-90
SLAC	e	15	>98	85-95	70-90
CERN	pi	120	>98	85-95	70-90

Tracks with better χ^2 – least efficient

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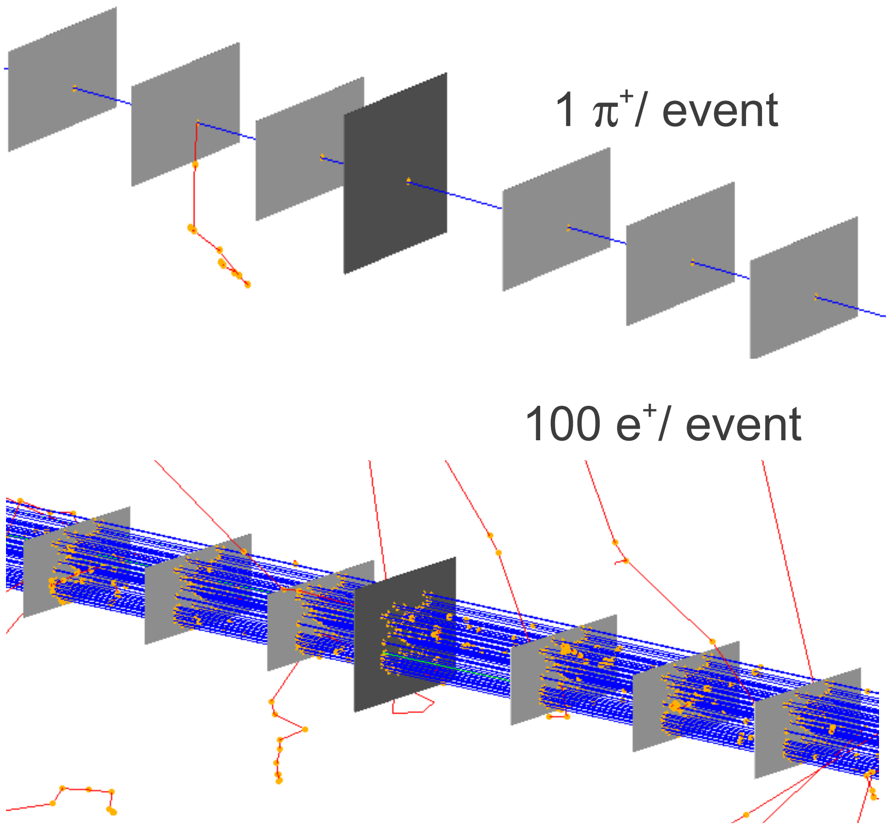

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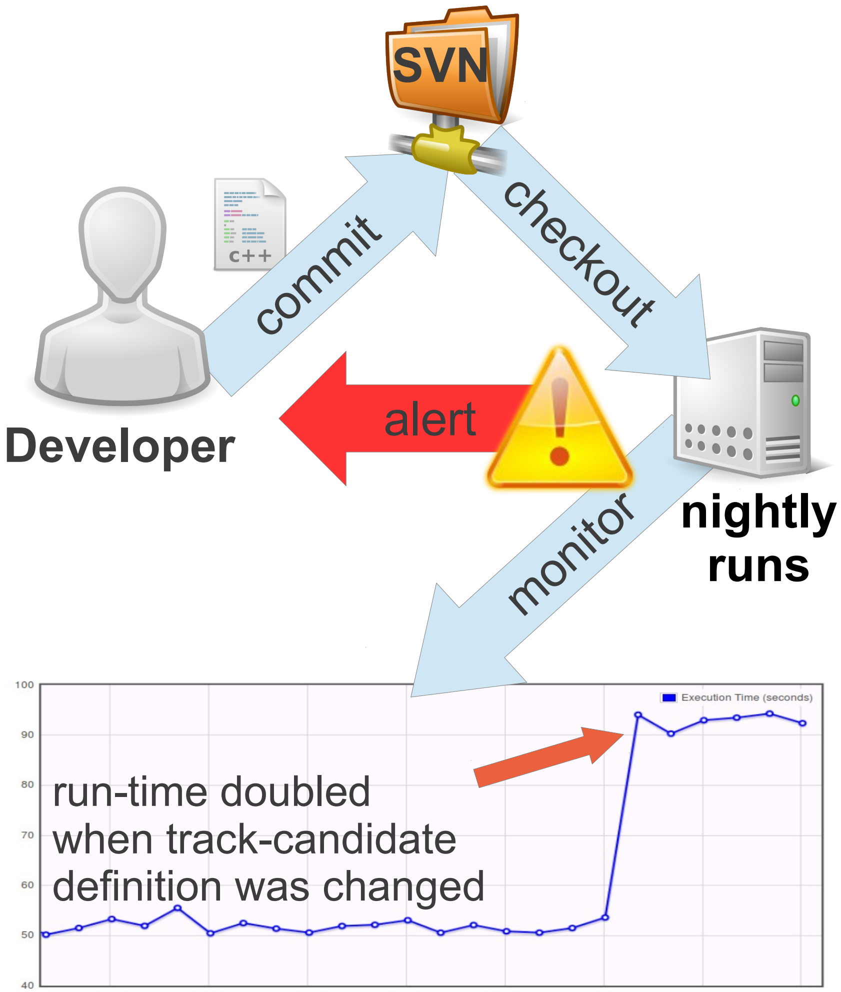
CERN	π	120	>98	85-95	70-90

Disclaimer:
only one of the track fitters was tested

Tracks with better χ^2 – least efficient

Verification & Testing

Telescopes with many usage scenarios → complex analysis software & many developers



Automated data-driven tests verify code:

- nightly builds and full analysis on "real-life" data (in CMake/CTest framework)
- tests code stability for typical usage scenarios
- automated regression testing: results compared to reference (χ^2 test)

- **If tests fail at any step:**
  - → automatic e-mail alerts sent to developers
  - → offending code can be identified through SVN history

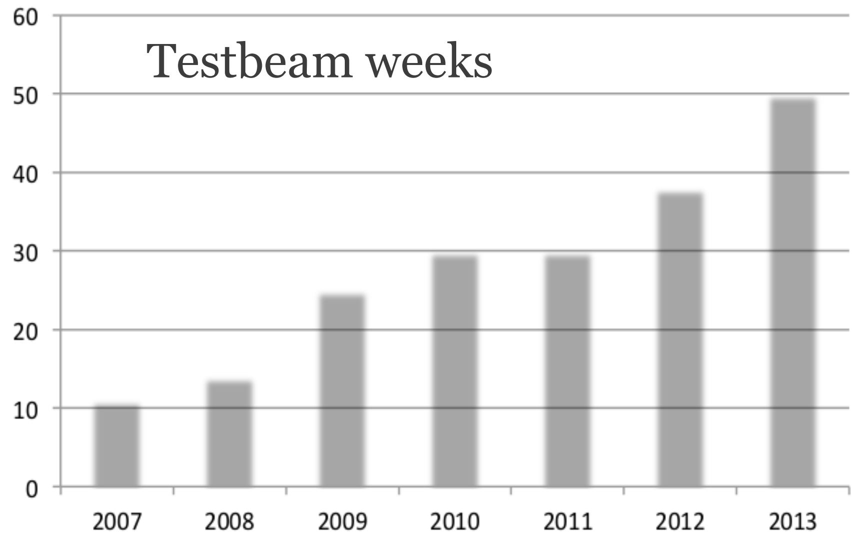
- **monitor test results in web front-end:**
  - → compiler warnings,
  - → run-time
  - → memory usage

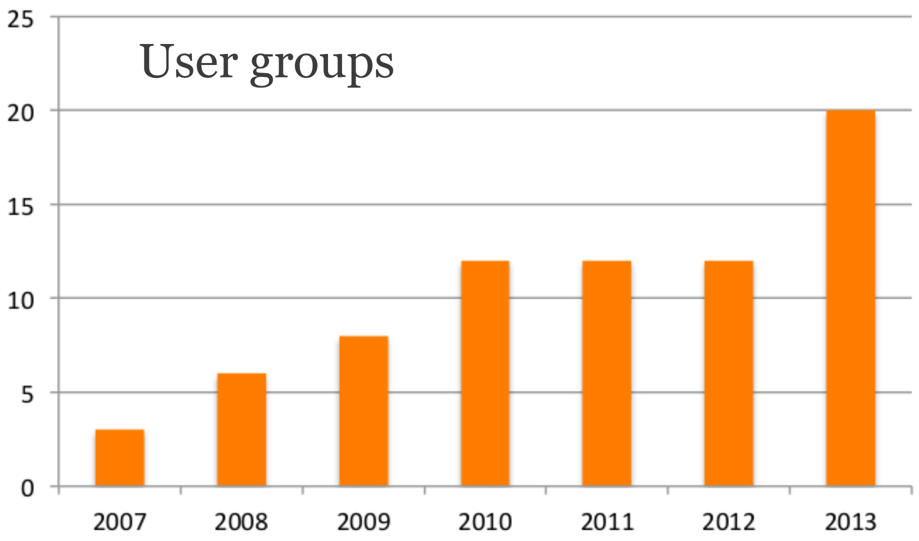
Let tests identify problems instead of the users!

EUDET telescope @ DESY and CERN since 2007

Developed within EUDET project (EU FP6)

Device Under Test (DUT) = (originally for) sensors for ILC detectors
Infrastructure available for detector R&D groups
High accuracy of track position estimation





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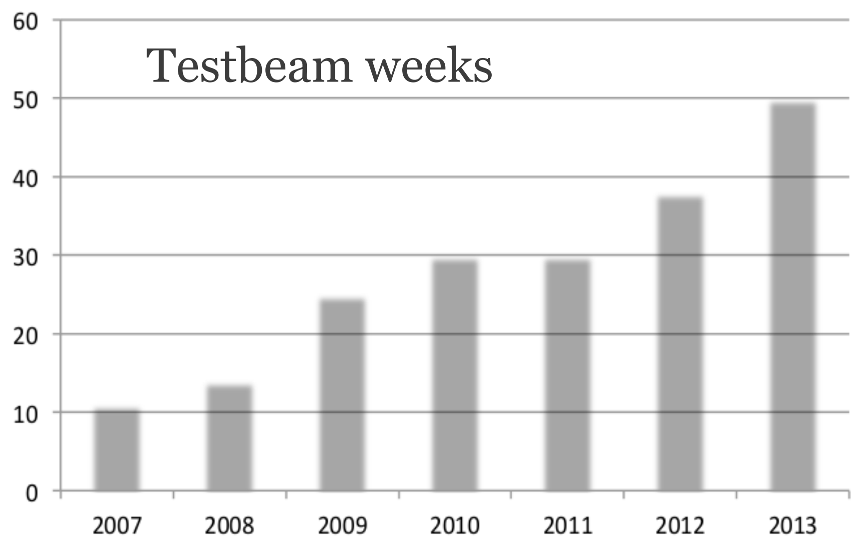

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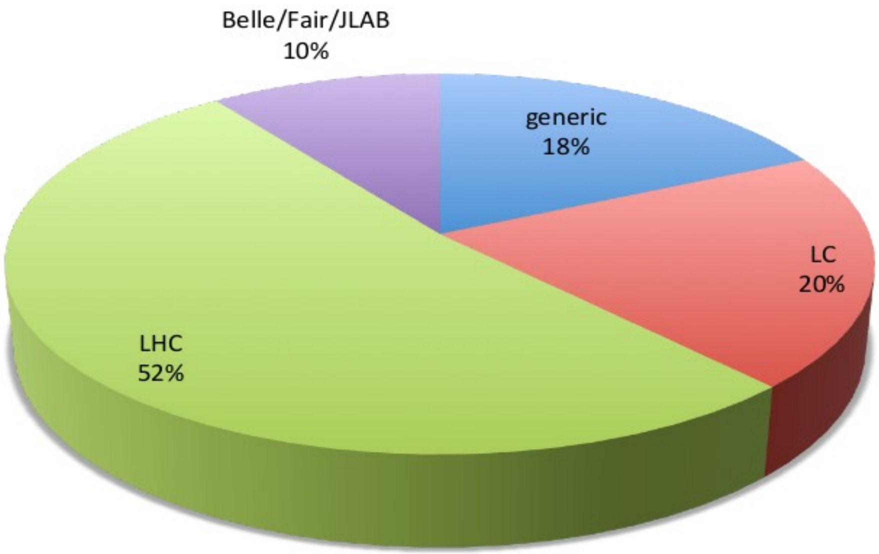


EUDET Telescope User Community

EUDET Telescope replicas

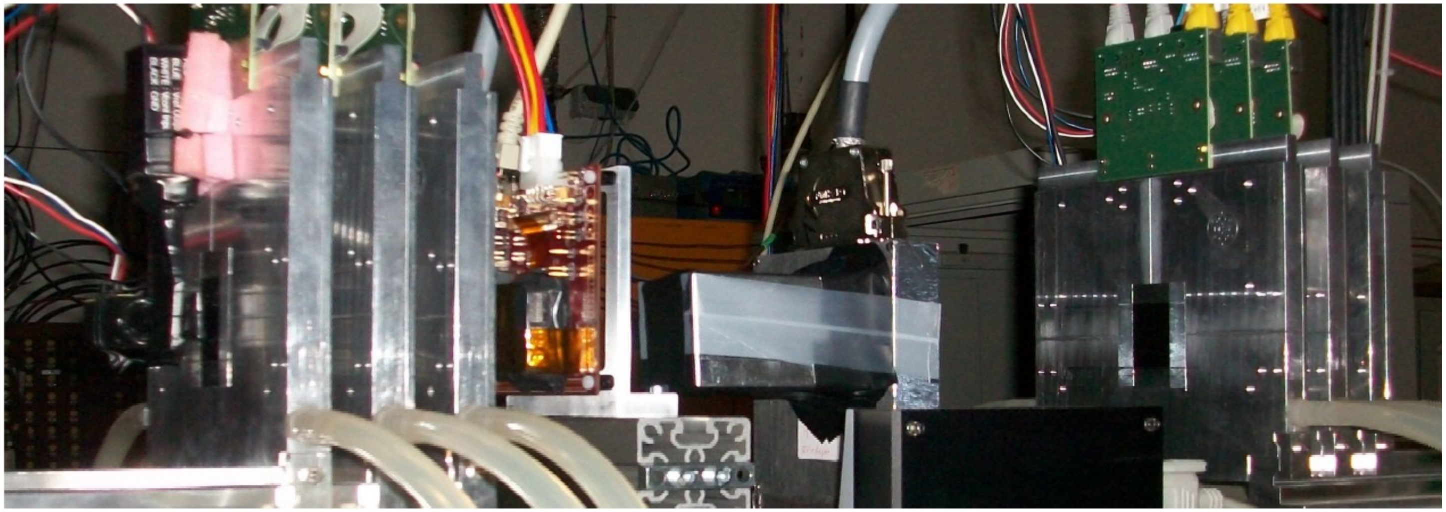
Three (identical) copies of the telescope are in operation

ANEMONE @ Bonn [ELSA, <3.5 GeV electrons]

(AlliaNz Eudet Mimosa bONn tElescope)

Vincent Van Gogh
"Vase Mit Margeriten Und Anemonen", 1887

Exact copy of the DATURA and ACONITE telescopes



Bonn University and collaborating institutes:
→ tracking detectors, sensors+FE electronics R&D for
→ Belle II (SuperKEKB, e^+e^- collider, Japan,)
→ ATLAS pixel detectors

Three (identical) copies of the telescope are in operation

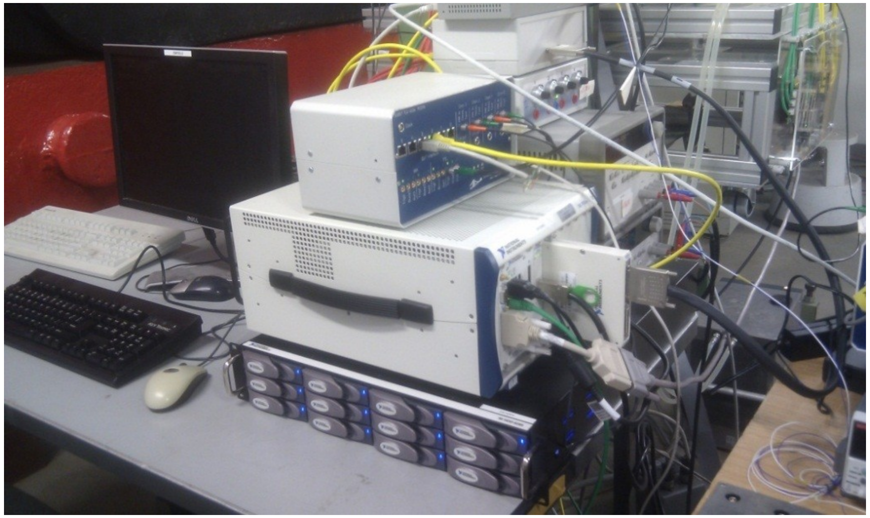
DATURA @ DESY [1-6 GeV electrons/positrons]

(Desy-Allianz Telescope with Ultrafast Readout Acceleration)

New readout based on National Instruments

- NI FlexRIO PXIe 7962R upto 200 MB/s (x4 links)

Extra: RAID disk 3 TB – maximum write speed 600 MB/s



Readout:

"Hardware hidden in software" → firmware → very cost effective maintenance

If fails or needs extention:
- buy new Off-The-Shelf

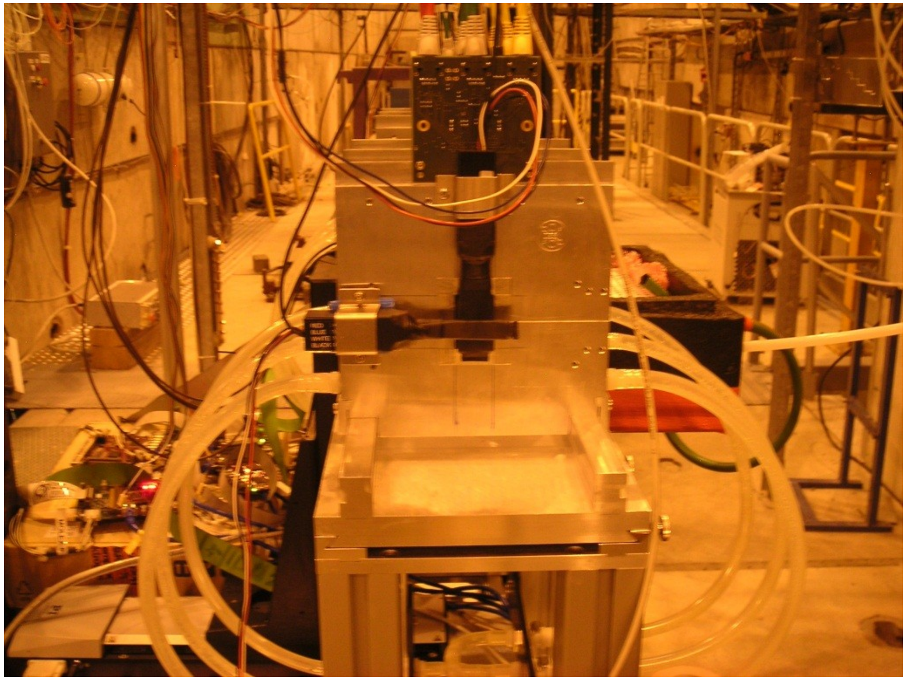
DATURA at DESY
- TestBeam hall #21
- belongs to DESY groups (ATLAS+CMS+FLC)

Currently being used a lot by the ATLAS and CMS R&D groups working on the tracking system upgrade for:
- ATLAS: Phase 0 (2013/14)
- CMS: Phase I (2017)
- Super Belle: DEPFET R&D

Three (identical) copies of the telescope are in operation

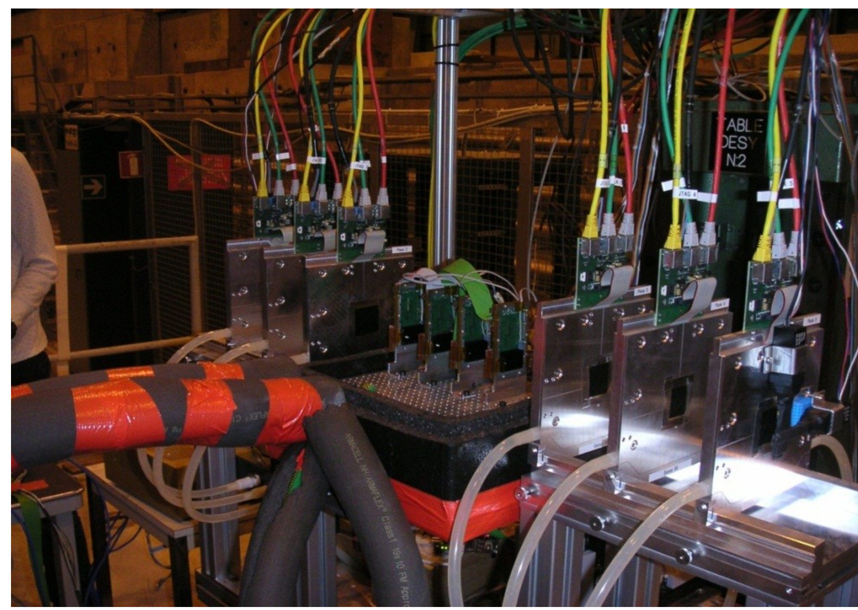
ACONITE @ CERN SPS, 120 GeV pions

(Atlas Copy of National Instruments based Telescope)



Current active ATLAS pixel groups

- Planar & 3D pixel sensor groups
- IBL (ATLAS Pixel Detector 4th Layer)
- DBM (Diamond pixel sensors for the LHC beam condition monitoring)
- Silicon strip sensors

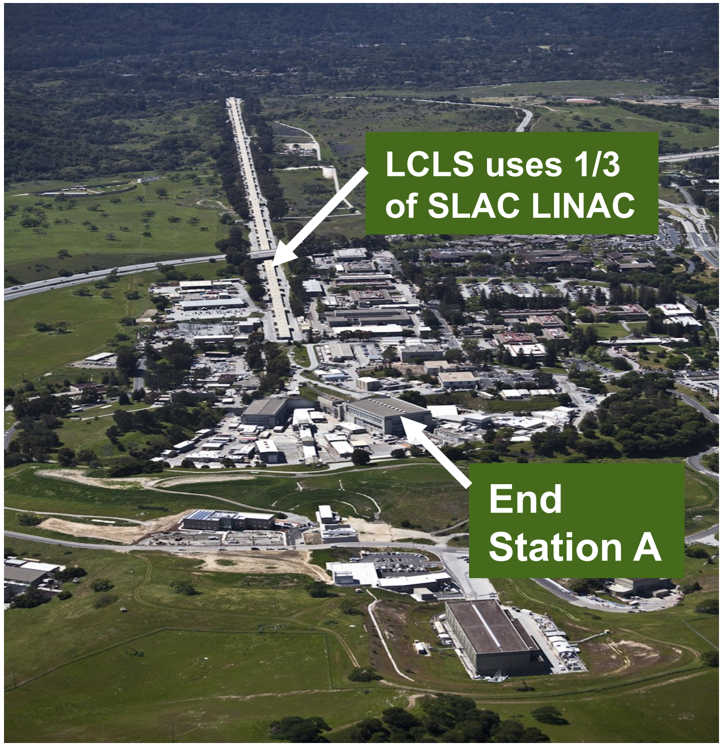


ACONITE at

- Was planned to stay at CERN H6A
  - now at DESY! [in TB22]
  - In summer → SLAC
- belongs to ATLAS collaboration & ATLAS R&D groups

...next year in North America too

This year ACONITE goes to SLAC
(until the SPS testbeam in ~2015 is back)



SLAC End Station A Test Beam (ESTB)

electron beam
- primary 15 GeV
  ~10^{10} e^-/bunch
- secondary 2.5 - 15 GeV
  10^{10} down to 1 e^-/bunch
  spill rate 5 to 120 bunches/s

This year ACONITE goes to SLAC
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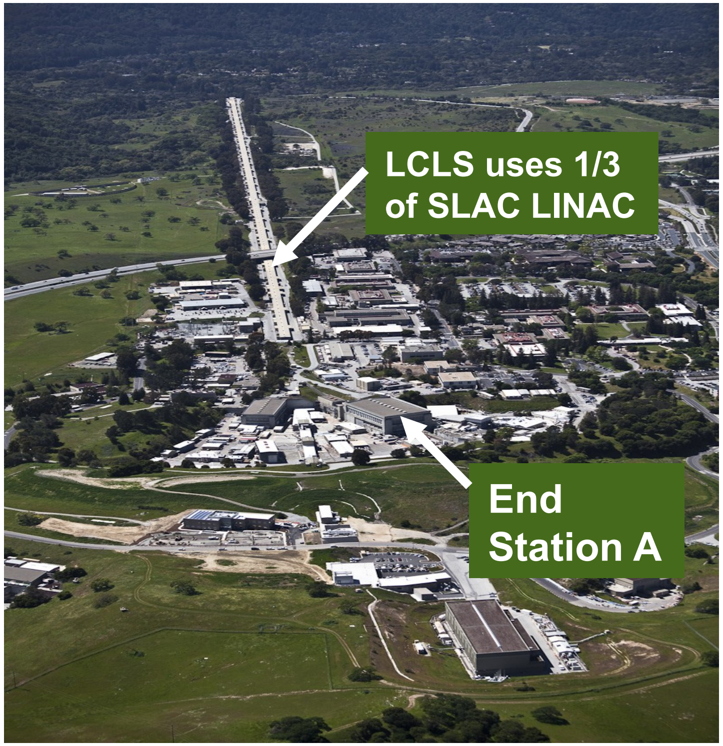

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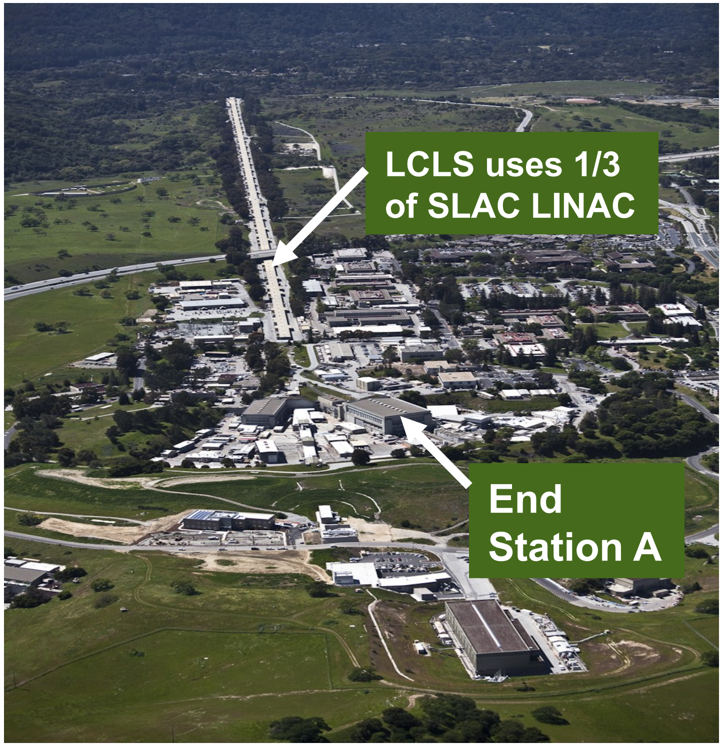
  $\sim 10^{10}$ e^-/bunch
- secondary 2.5 - 15 GeV
  10^{10} down to 1 e^-/bunch
  spill rate 5 to 120 bunches/s

The telescope sensors (Mimosa26) are able to handle ~100 (300?) tracks per frame (acc. to design specs).
Preparation tests OK: DAQ (beam) + reco (sim)
→ we are ready for final tests in the SLAC beam (~Summer 2013)

...next year in North America too

This year ACONITE goes to SLAC
(until the SPS testbeam in ~2015 is back)



SLAC End Station A Test Beam (ESTB)

electron beam
- primary 15 GeV
  ~10^{10} e^-/bunch
- secondary 2.5 - 15 GeV
  10^{10} down to 1 e^-/bunch
  spill rate 5 to 120 bunches/s

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Preparation tests OK: DAQ (beam) + reco (sim)
→ we are ready for final tests in the SLAC beam (~Summer 2013)

One more copy of the telescope goes to Canada (within next few months) → called CALADIUM

Carleton UNIVERSITY
Canada's Capital University

Carleton University:
- R&D for the tracking detector
- at the future Linear Collider

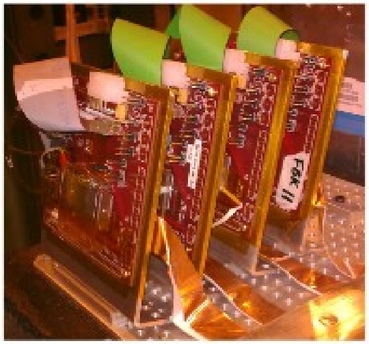
Will be shared with Canadian R&D groups:
- generic R&D

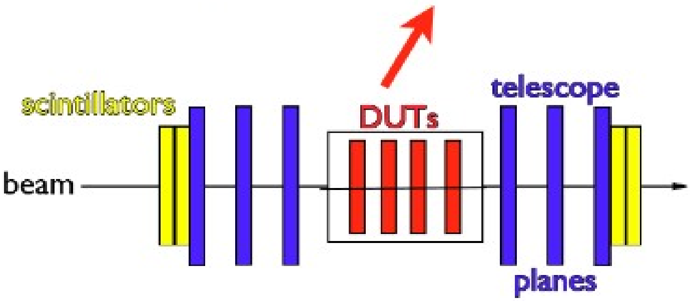
Very brief overview of the results
obtained
with the EUDET telescope (or one of the replicas)

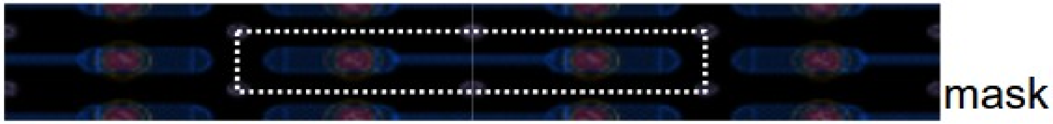
IFAE

IBL Beam Tests

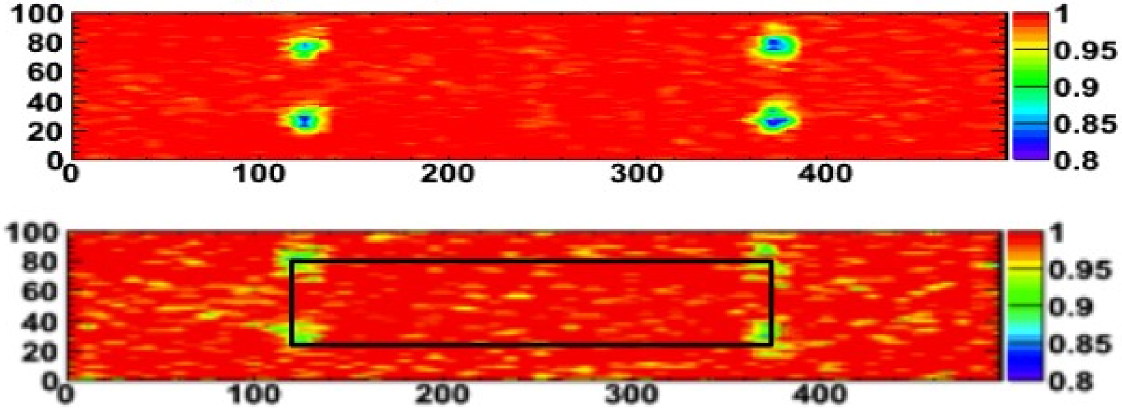
- EU Detector Telescope March-June-October:
  - 120 GeV pions from CERN - SPS (point H6b)
  - 6 planes: 660k Si pixels (18.4 μm pitch)
  - trigger: four scintillators
  - 500k events per run to have enough statistics
- Studies:
  - extrapolate tracks from telescope to DUTs. Check for a matching hit.
  - required a hit in 1 or 2 of the other DUTs (remove fakes tracks)
  - measure the efficiency (removed noisy pixel)
- Meet IBL requirement: Efficiency > 98% (with 1500e)







efficiency pixel map



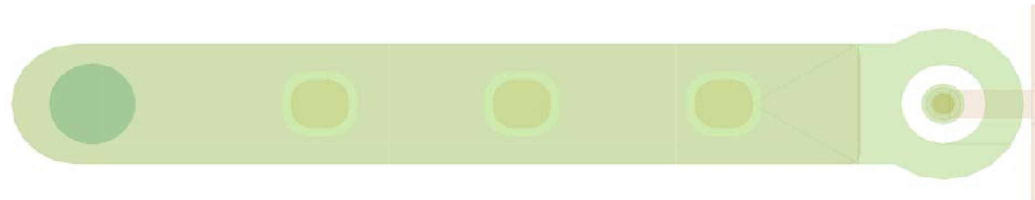
***SCC55* CNM-3D**:
un-irrad, HV=20V, **Eff.=99.4%**

***SCC34* CNM-3D**:
p-irrad, HV = 160V, **Eff.=98.96%**

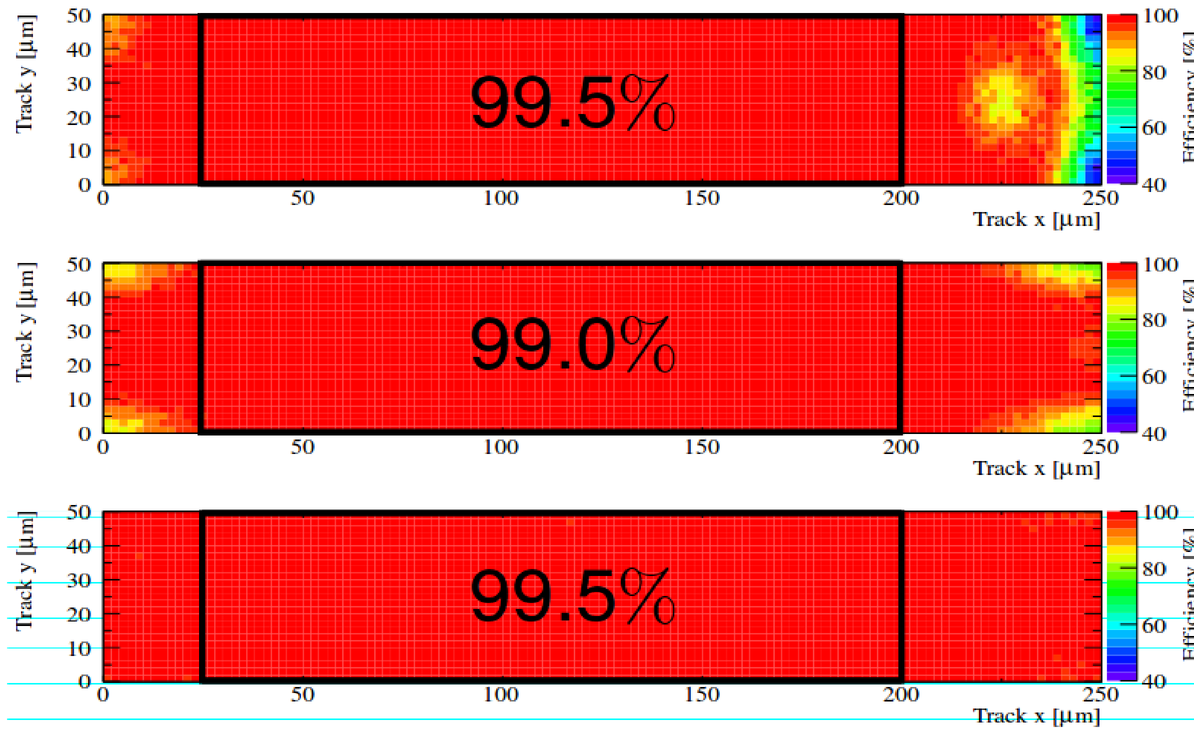
A. Micelli 7 Trento, Feb 19 2013

Pixel cell efficiency

- **FE-I4 150 μm thick, irradiated to $4\times10^{15} n_{eq}/cm^2$ in Los Alamos**
- threshold: 1.6 ke (MPV~9.5 ke)

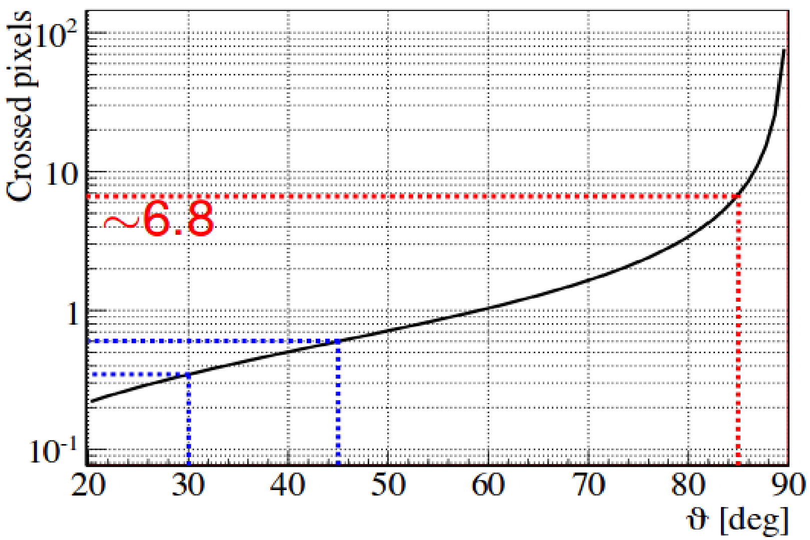


- 97.7% hit efficiency at ⊥ incidence (690 V)
- 98.4% hit efficiency at ϑ=30° (η ~0.55) (500 V)
- 99.5% hit efficiency at ϑ=45° (η ~0.88) (500 V)

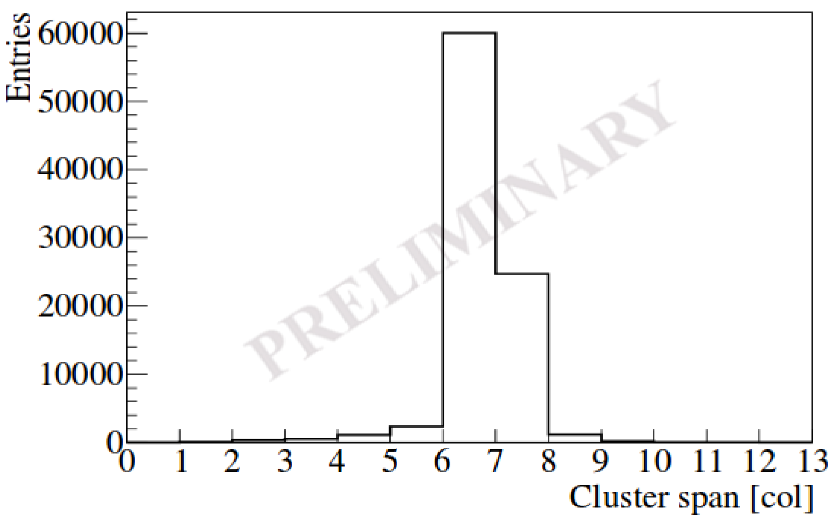


Pixel cell efficiency: high-eta

- **FE-I4 150 μm thick, irradiated to 4$\times$10$^{15}n_{eq}/cm^2$ in Los Alamos**
- ϑ=85° track incidence ($\eta \sim$3.1)
- bias voltage: 500 V
- threshold: 1.6 ke

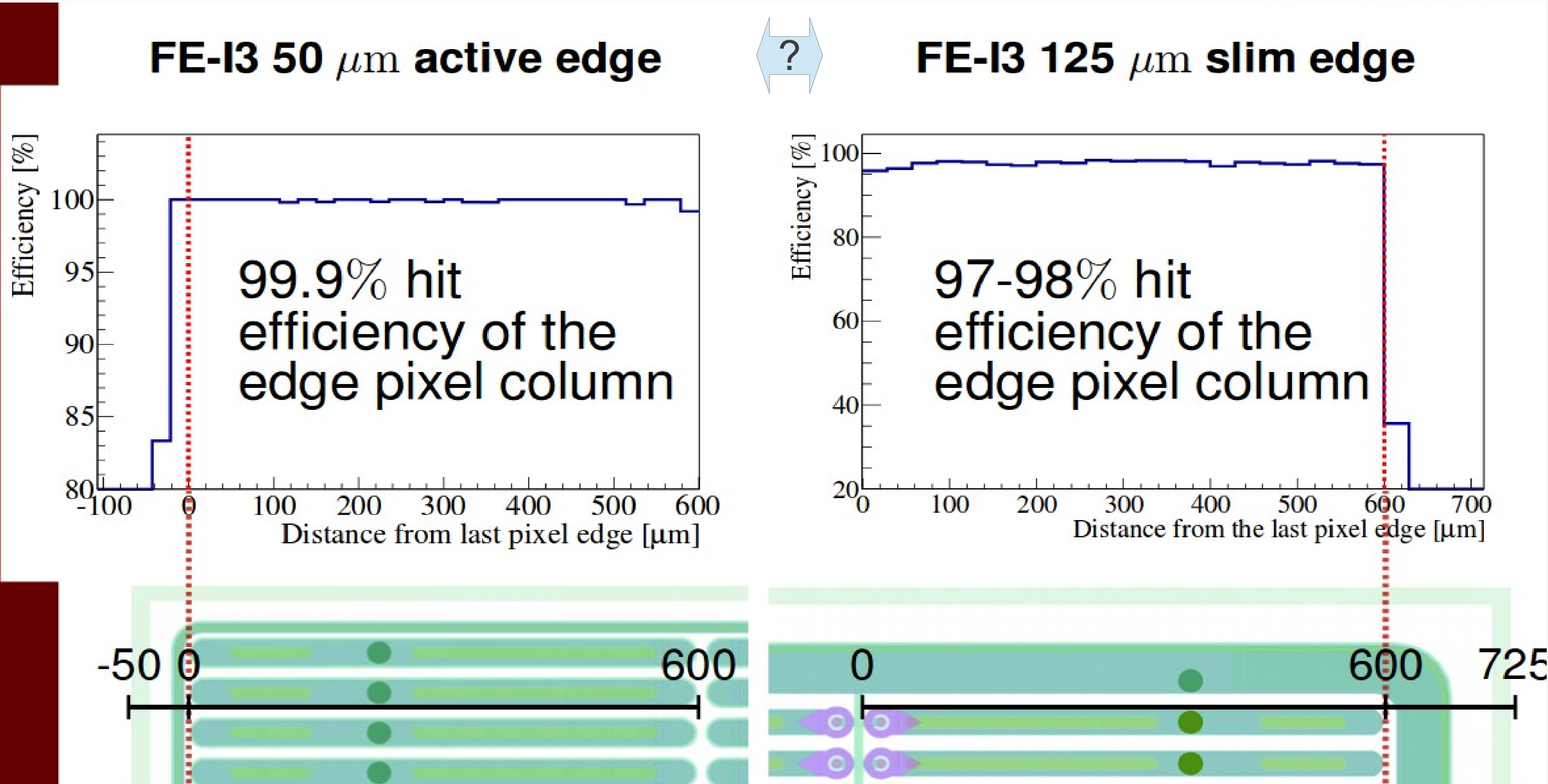


Expected number of crossed pixels along the tilted direction at different angles



Cluster distribution along the tilted direction.
Distribution mean = 6.7

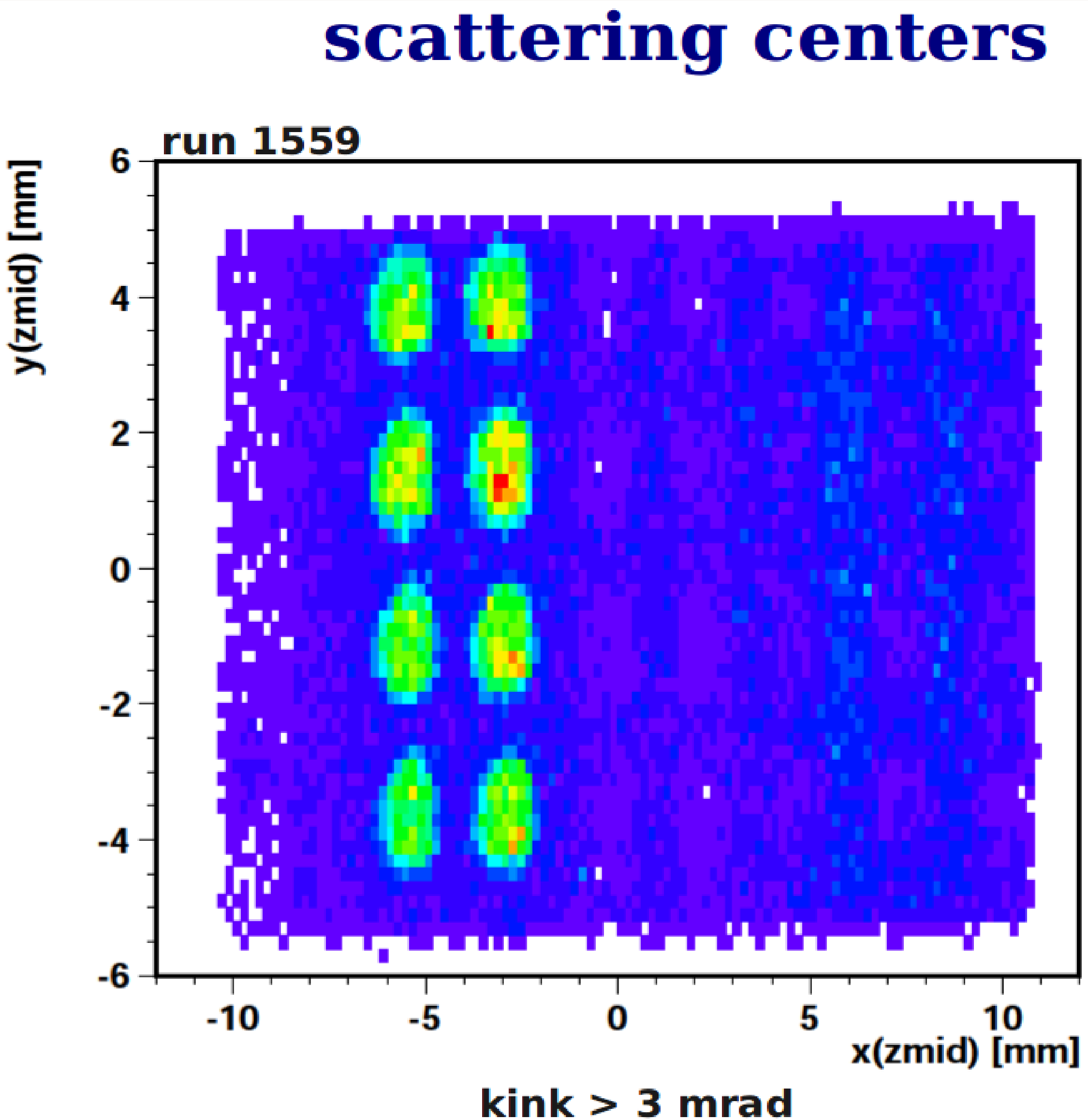
Hit efficiency for edge pixels

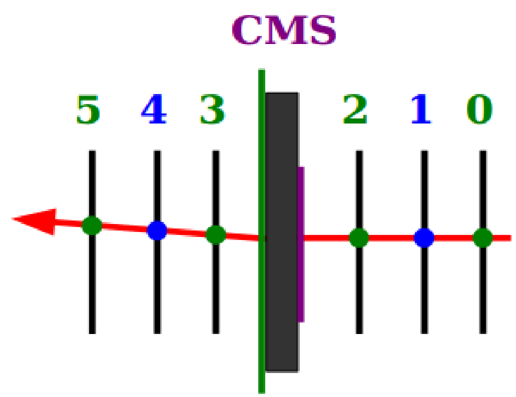


83% hit efficiency after the last pixel implant near the active edge

35% hit efficiency between the last pixel implant and the bias ring

We can also look at the amount of scattering material





DESY TB21:

- 4 GeV e^+ beam.
- tracks with > 3 mrad kink angle:
  - metal pins of the PSI chip adapter visible

D. Pitzl, DESY CMS upgrade, 20.12.2011

Improving the telescope trigger system

Improving the telescope trigger system

AIDA-NOTE-2012-005

AIDA

Advanced European Infrastructures for Detectors at Accelerators

Scientific / Technical Note

Implementation of a Configurable FE-I4 Trigger Plane for the AIDA Telescope

FEI4 as configurable Trigger Plane

Real life example:

DUT

	columns	rows	pitch [μm^2]	thickness [μm]	size [mm^2]
DEPFET	32	64	50 $\times$ 75	50	1.6 x 4.8
FEI4	336	80	50 $\times$ 250	470	16.8 x 20.0
MIMOSA26	576	1152	18.4 $\times$ 18.4	50	10.6 x 21.2

Telescope
high resolution plane

FEI4 as configurable Trigger Plane

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Real DUT is ~7 mm^2 (3% of trigger area)

Telescope high resolution plane

Default scintillators shape has fixed size 10x20 mm^2 to match the telescope planes acceptance → not easy to adjust for every DUT

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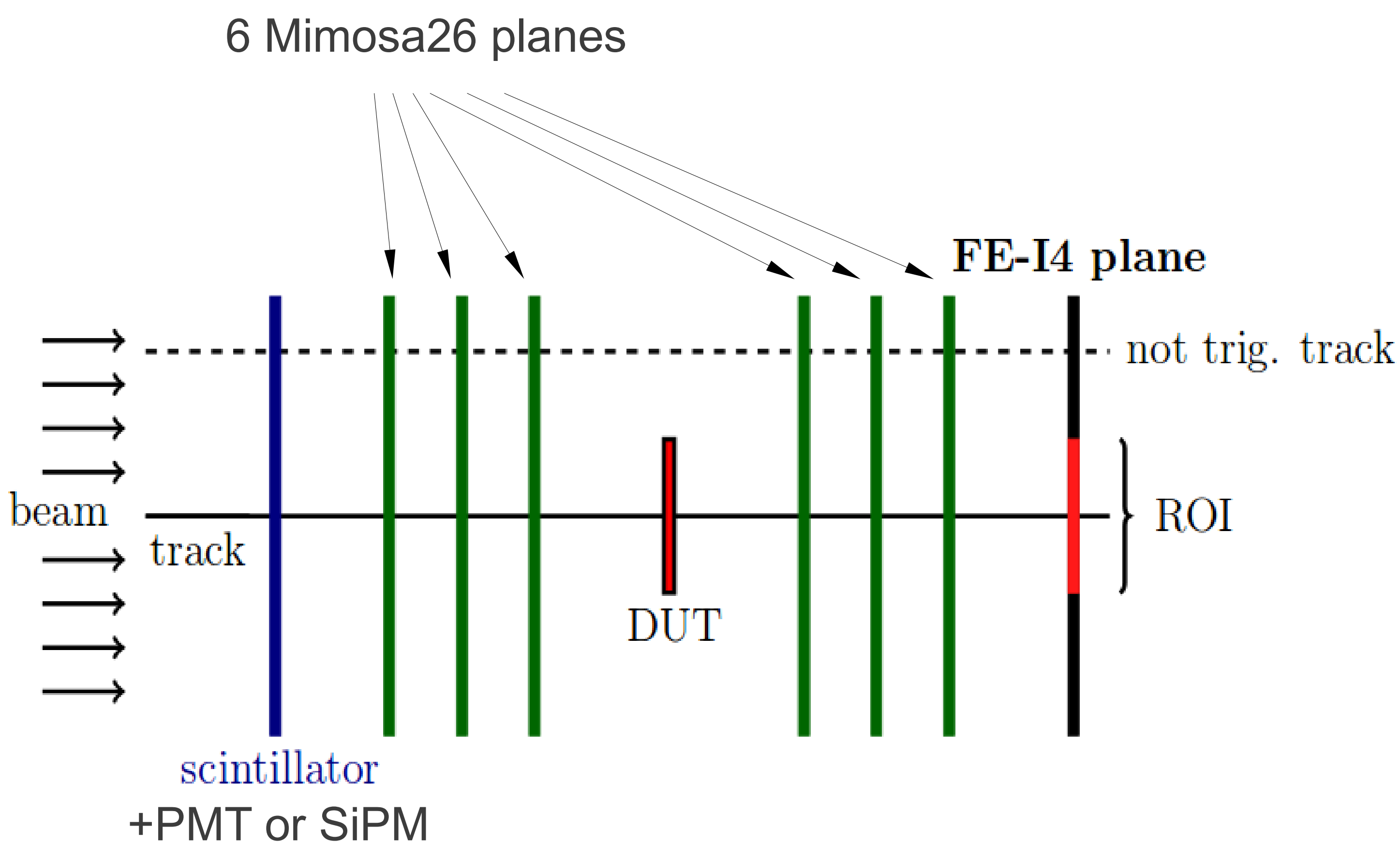
Telescope high resolution plane

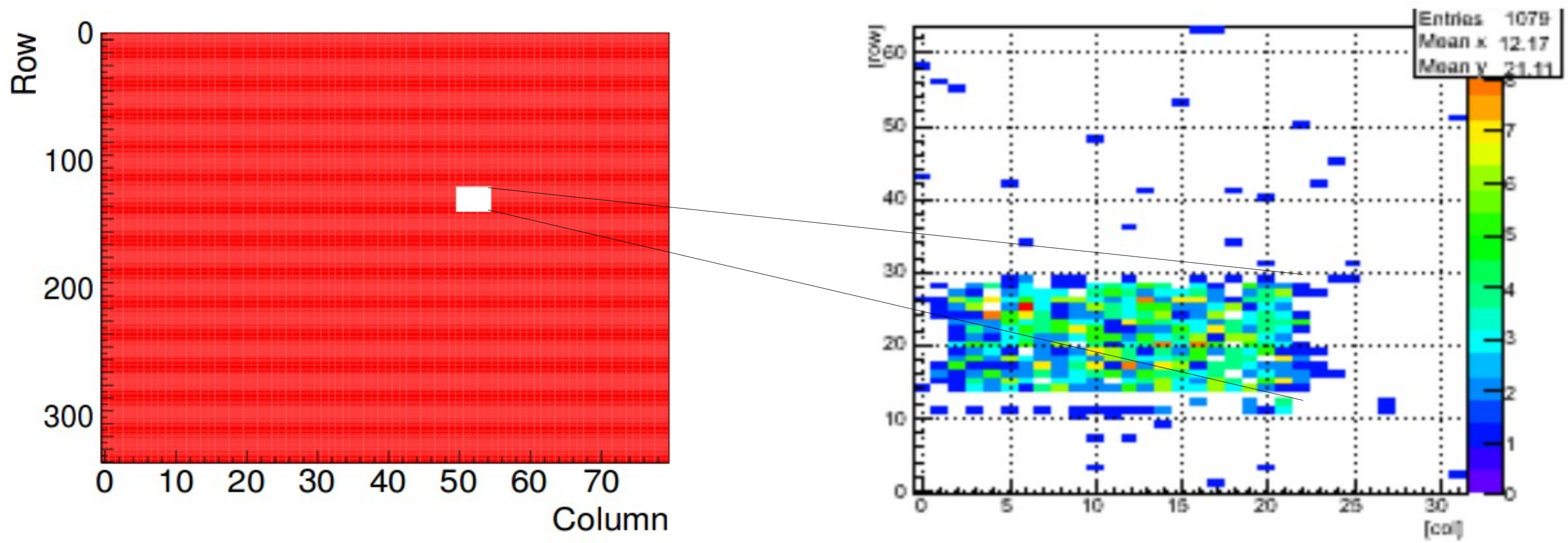
Default scintillators shape has fixed size 10x20 mm^2 to match the telescope planes acceptance → not easy to adjust for every DUT

actually ... FEI4 chip can be configured such that a (defined) group of pixels can issue a Trigger Signal (HitOr)
Thus a Region Of Interest (ROI) can be included into a triggering scheme

FEI4 as configurable Trigger Plane



DUT hitmap with FEI4 as “L1” trigger



(a) ROI of FE-I4 plane.

(b) Hitmap of DEPFET DUT.

Figure 6: Selected ROI, which is smaller than the DEPFET and corresponding hitmap of DEPFET.

Track “time-stamping” with a fast device

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- FEI4
- Timepix

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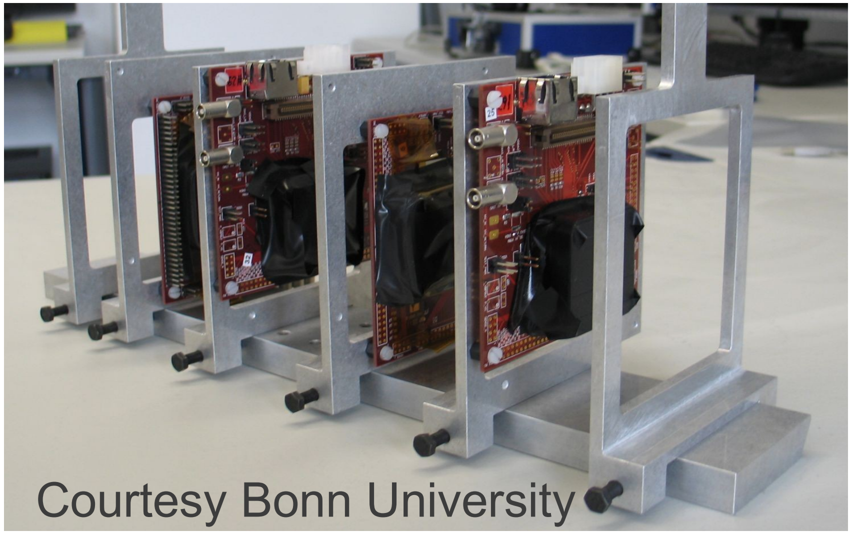
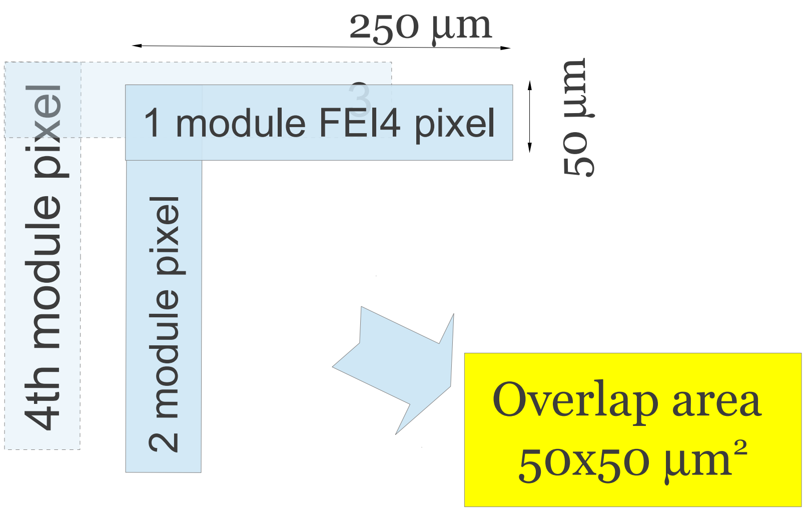
FEI4 telescope



Mutual benefits

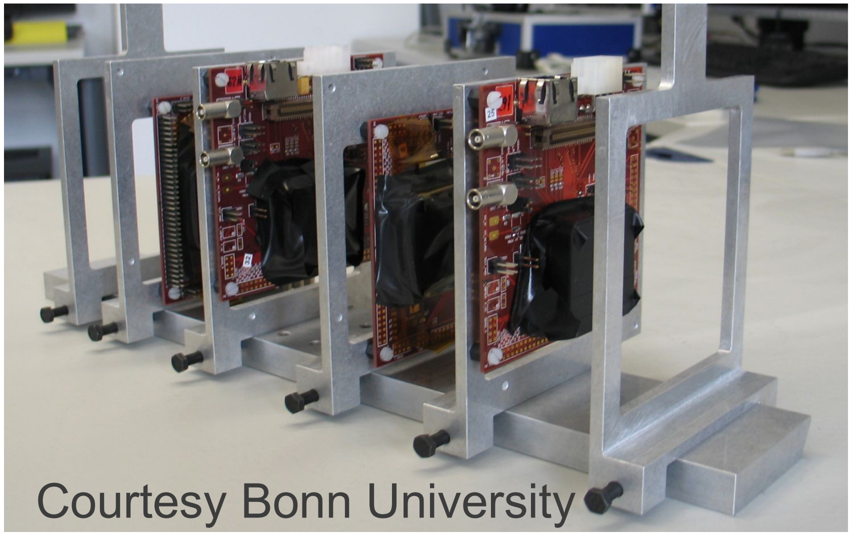
Mimosa sensors
- 3.5 μm hit position
- within 115.2 μs integration time

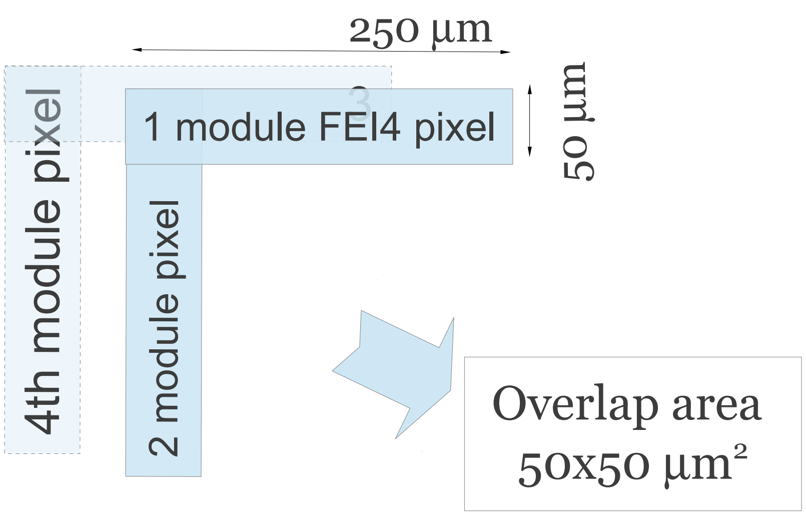
FEI4 based modules
- (relatively) low space resolution
- but 25 ns precise hit timing in a $50 \times 250\ \mu m^2$ area



work in progress

FEI4 telescope





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FEI4 based modules
- (relatively) low space resolution
- but 25 ns precise hit timing in a $50x250\ \mu m^2$ area

The FEI4 modules can be used to add timing information to track reconstruction

- current tests: disentangle ambiguity for events with more then 1 track per Mimosa frame
- high rate testbeams reconstruction

work in progress

Track "time-stamping" with a fast device

- FEI4
- Timepix

What will make it into the AIDA telescope?

Timepix telescope (by Medipix-LHCb collaboration)
- the first Timepix chip was requestetd and funded by EUDET

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Timepix telescope (by Medipix-LHCb collaboration)
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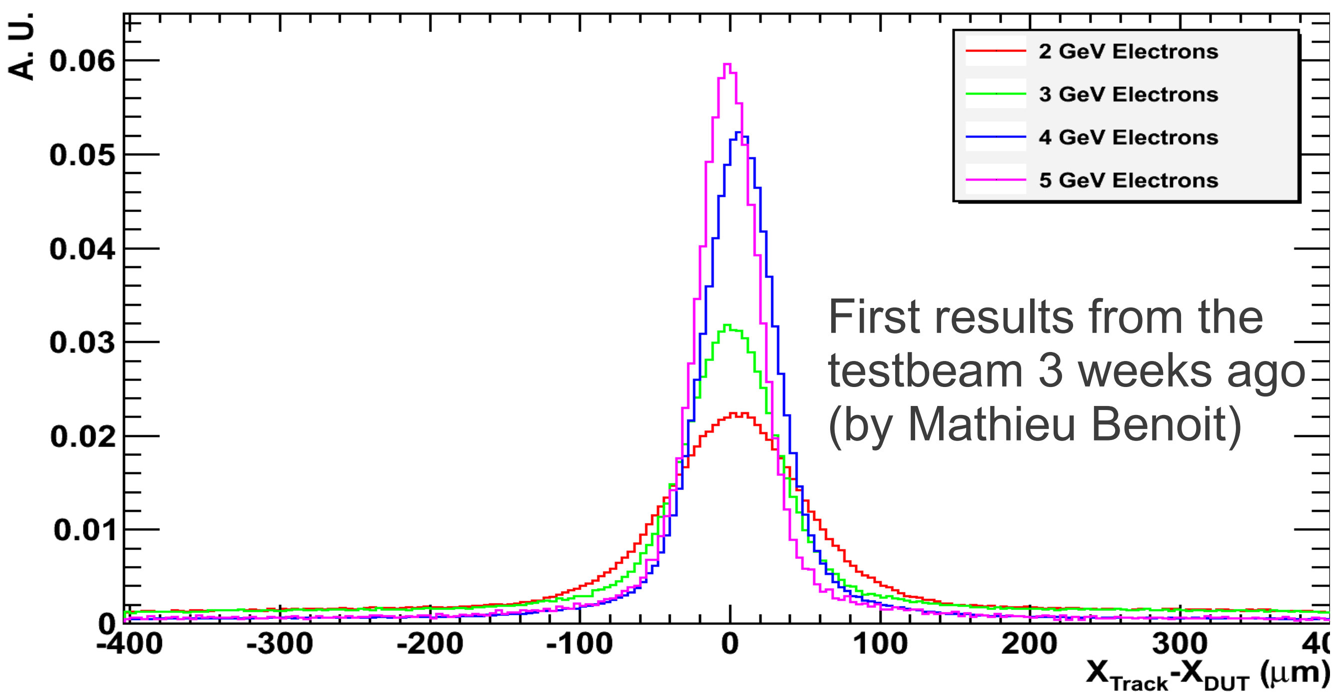
Feature list:
- 14 bit ToT or TOA resolution (range 0 – 11265)
  ~10 ns hit timing
- 55x55 μm^2 pixels
- 256x256 pixels per matrix (14x14 mm^2)
- open shutter readout mode,
  - tunable for duration from ~ns to ~s
    or for the maximum number of accumulated hits (<~100)
  - matrix readout envokes ~20 ms sensitivity deadtime

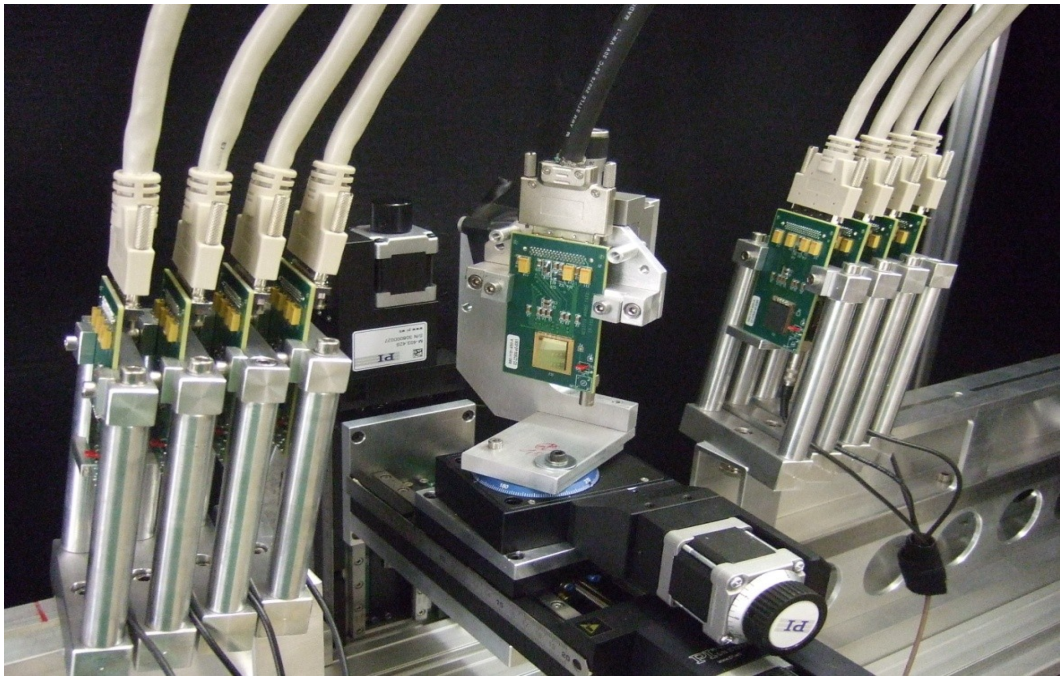
The first Timepix chip was requestetd and funded by EUDET

Timepix based modules have been tested as DUT with the EUDET telescope –
- first attemt in 2010 (by NIKHEF)
- recent results on full integration
  - with TLU full handshake
  - with EUDAQ producer integrated into the Timepix DAQ

- full integration complete and well tested (CLICPIX group)



Timepix telescope (by Medipix-LHCb collaboration)



Why tilted?
- full digital readout
- cluster size → resolution
- optimise cluster size by tilting

Timepix telescope
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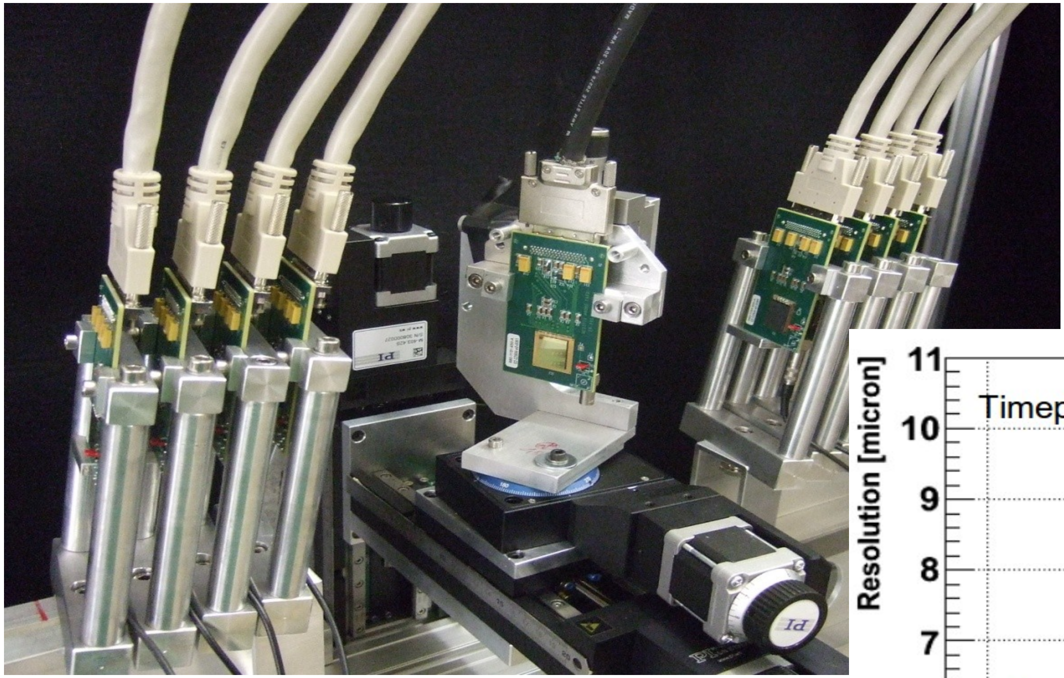

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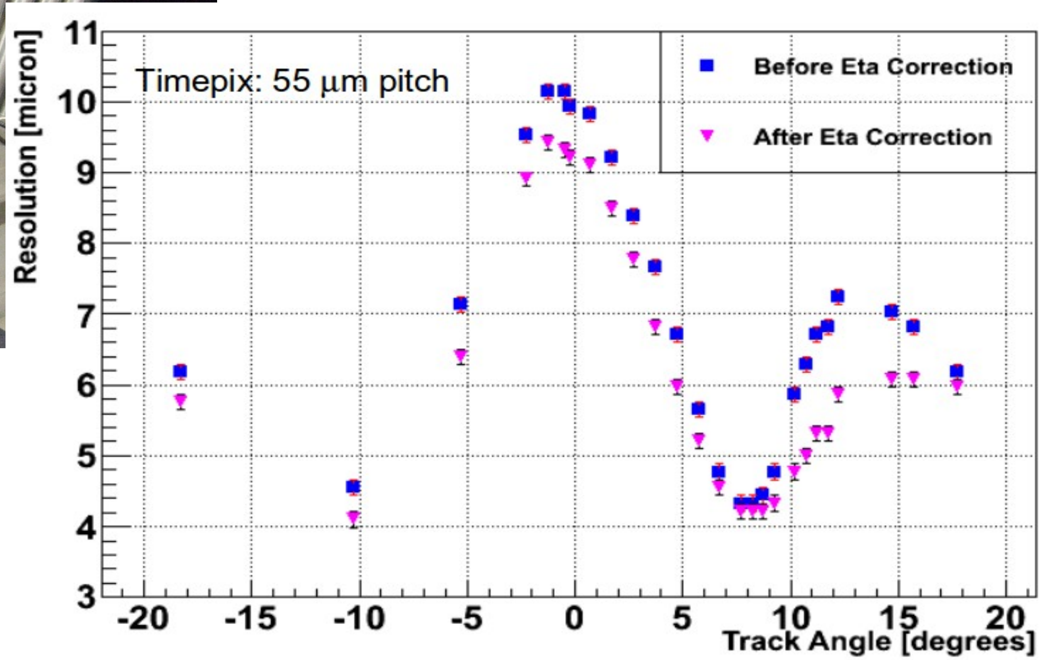


For optimal resolution :
sensors tilt (8 deg) + turn (8 deg)

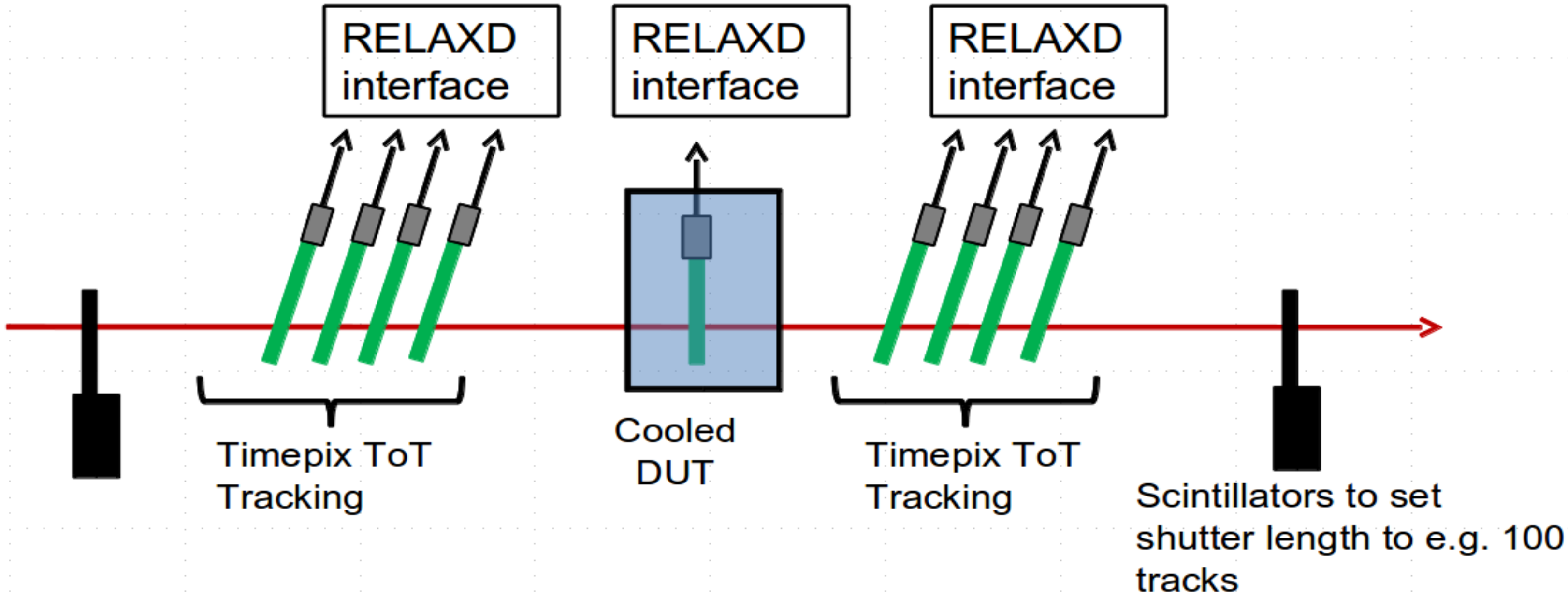
RELAXD Telescope – Timepix DUT

Optimised for resolution

Eight angled Timepix tracking planes gives a ~1.7um Track Extrapolation Error

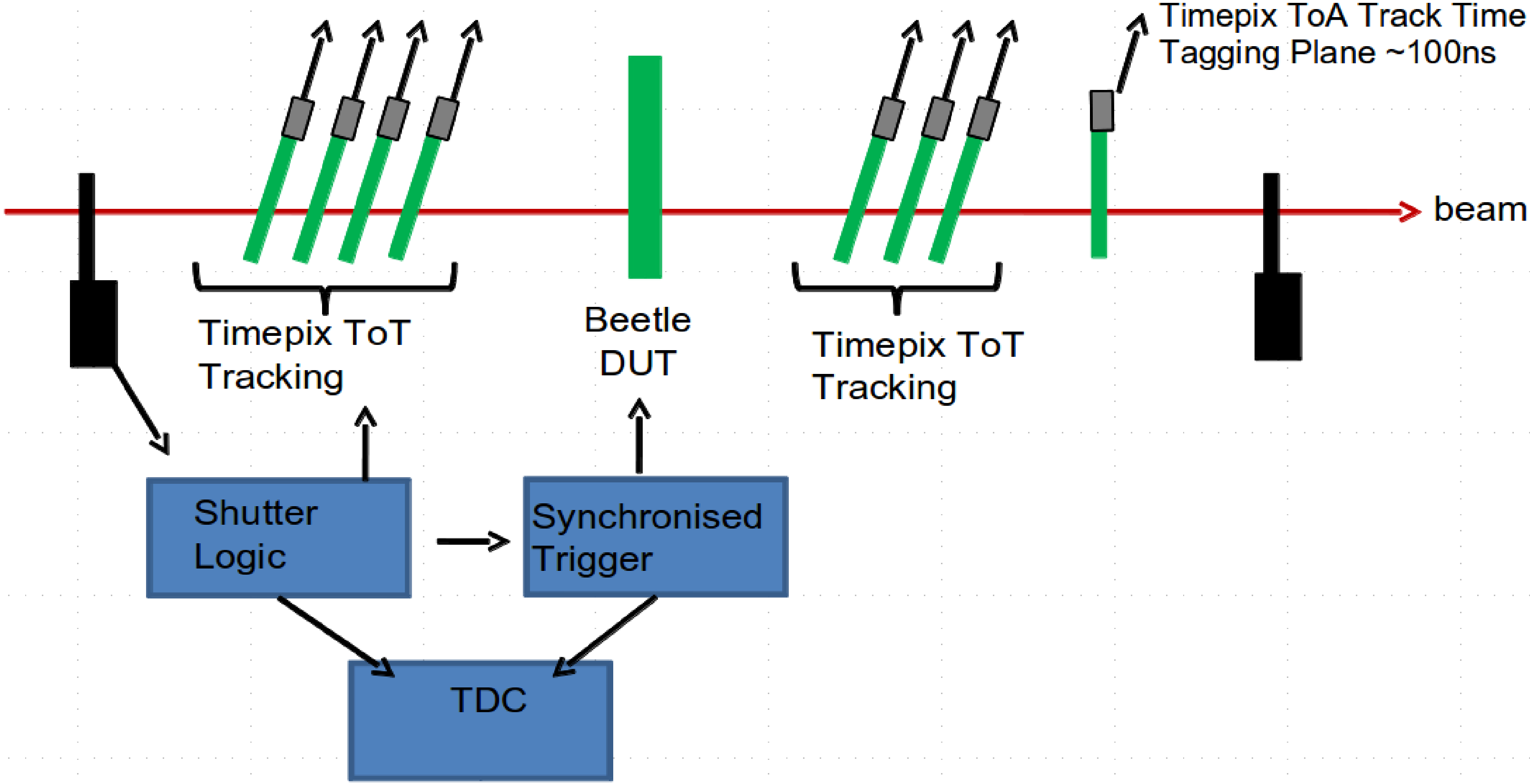
RELAXD system allowed 55 frames per second readout (~2,500 tracks per second)
Each 100,000 point measurement now takes 4 minutes at the SPS NA.

Closely spaced (~10mm) tacking planes reduce multiple scattering effects



Time Resolution for LHC readouts

- Asynchronous SPS beam not suited to LHC systems designed for 25ns bunch structure
- Implemented a TDC which with Timepix ToA mode gives us ~1ns per track time stamping
- Able to provide and record synchronised triggers to 40MHz readout systems (TELL1)
- Allows software reconstruction and analysis of asynchronous tracks



new Trigger Logic Unit “mini-TLU”

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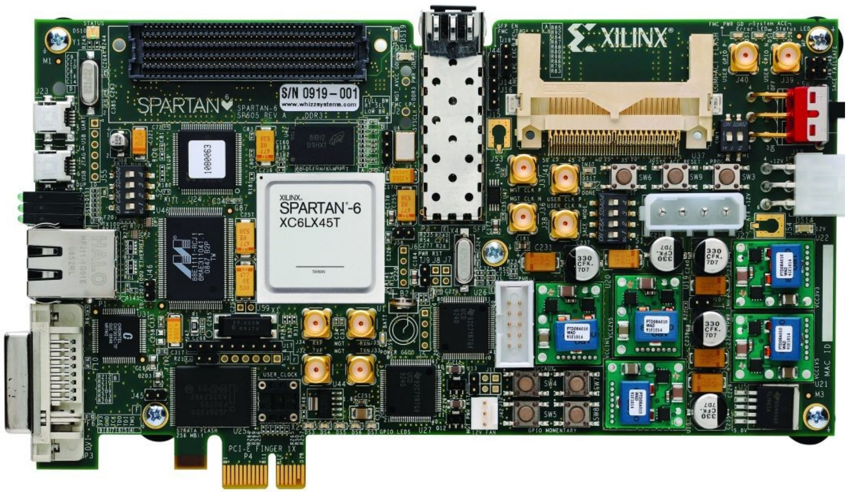
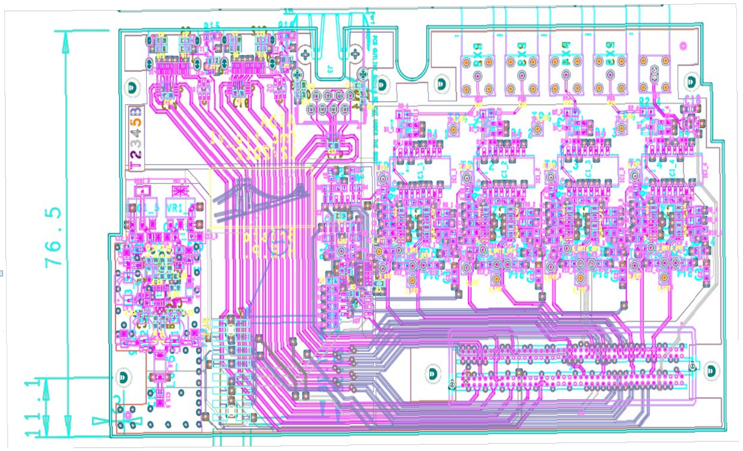


Xilinx Spartan-6 Evaluation Kit



Custom design descriminator board & DUT interface
design by Bristol U
in-production DESY,CERN

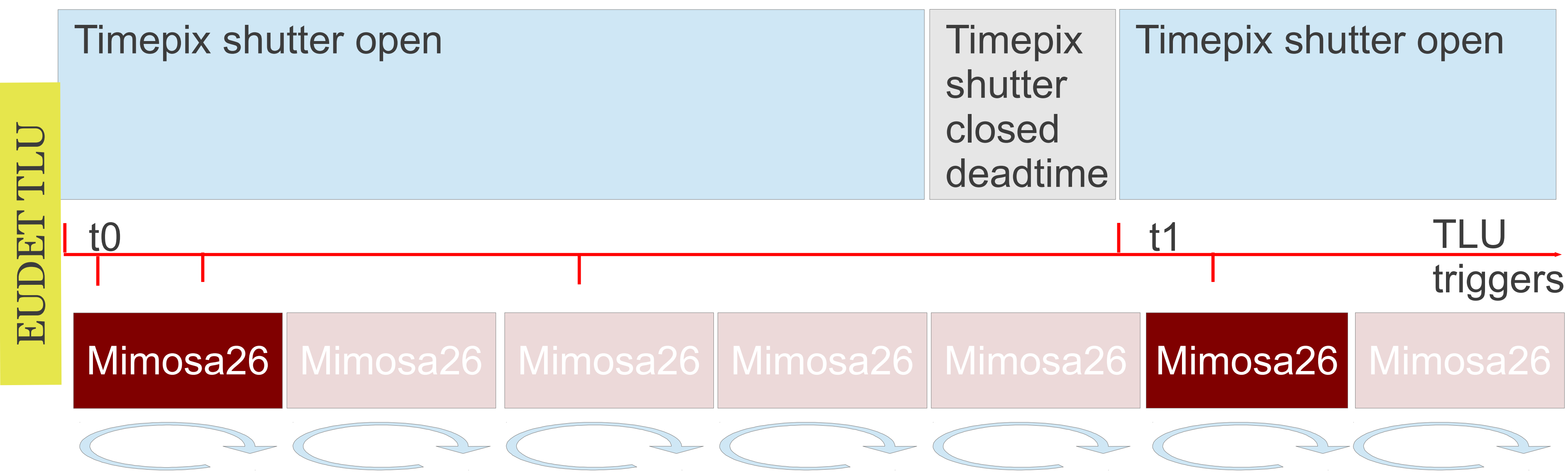
What will make it into the AIDA telescope?

EUDET TLU -

“synchronous”, no triggers issued until all detectors are ready to accept

AIDA mini-TLU

- integrating slow and fast readout into the trigger logic of the beam telescope to maximize track rate for all DAQ systems
- “asynchronous”,
  - every DAQ systems gets a Trigger and Timestamp (if not BUSY)
  - challenging for EUDAQ → merge data streams: online or offline?
  - anyway need data merging at some level for the online DQM



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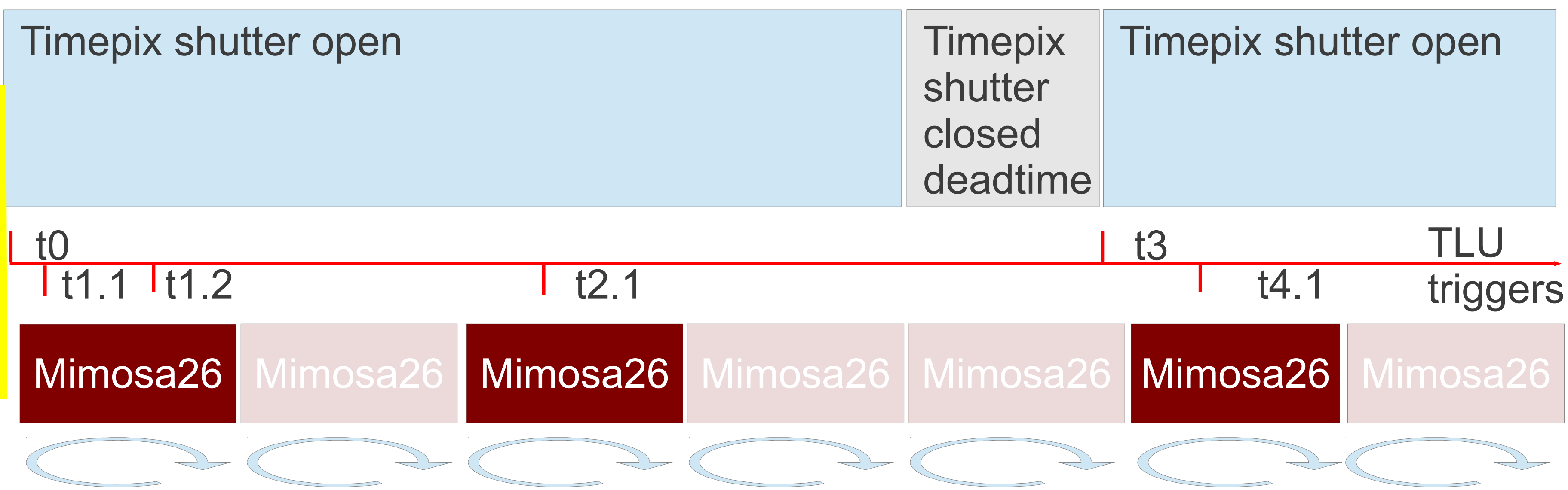
New mini-TLU



Prototype in production

Pixel beam telescope - very usefull and in high demand.

A high resolution pixel beam telescope for detector development

Testbeam is a cross road of many R&D projects

- Common Testbeam Telescope makes life easier for all of them

<u>We have achieved:</u>

- **Mimosa26** design and **NI PXIe + FlexRIO** bandwidth allows a dead time free operation of the pixel beam telescope
  - in a beam with particle rate up to 1 million particles per second per cm^2
  - with a possibility of easy extension of the telescope coverage area

<u>We anticipate by the end of the AIDA project:</u>

- a new generation of testbeam telescope
  - with 4x4 or 4x6 cm^2 large high resolution (~4 um) planes (2x2 cm^2 exist)
  - FEI4 based triggering (and timestamping) planes (4x4, 4x6 cm^2 - exist)
  - asynchronous Trigger Logic Unit with a sub-ns timing resolution will deliver close to 100% triggering efficiency (prototype board, firmware, PC driver – in progress)
  - - Common powering for LV and HV for the DUTs (already delivered)

Further plans

Planning to incorporate in the NI system for automatic scans and bookkeeping:

- PI translation and rotation stages
- Voltage, Current, Temperature, Humidity monitoring of all system elements

Further plans for track time stamping

To do tests at very high particle rates tests (~100 MHz/cm^2) we need to timestamp every particle going into the system with a fast detector:

- Short term goal us using an LHC type detector: ATLAS pixel modules are to be used as a triggering system and replace the scintillator based particle trigger, and in addition provide 25 ns resolution timestamp for a triggering particle

- Timepix family modules have a built-in capability of measuring a signal TOA (Time-Of-Arrival) or signal amplitude as TOT (Time-Over-Threshold)
  - the new generation Timepix3 chip will be able to handle rates up to 400 MHz/cm^2 and provide simultaneously TOT and TOA information for every particle

Thank you!

Back up slides

FEI4 as configurable Trigger Plane

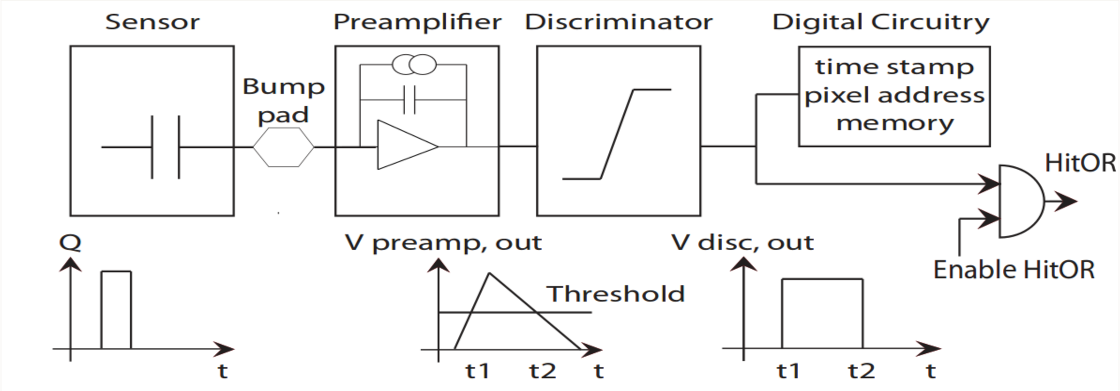


Figure 2: Simplified analog circuitry of the FE-I4 chip present on each pixel. The HitOR signal used as trigger is taken at the output of the discriminator.

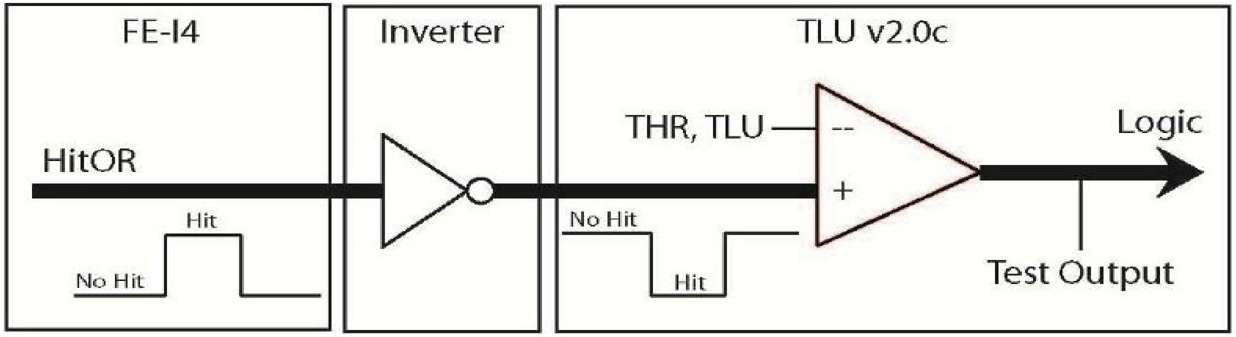
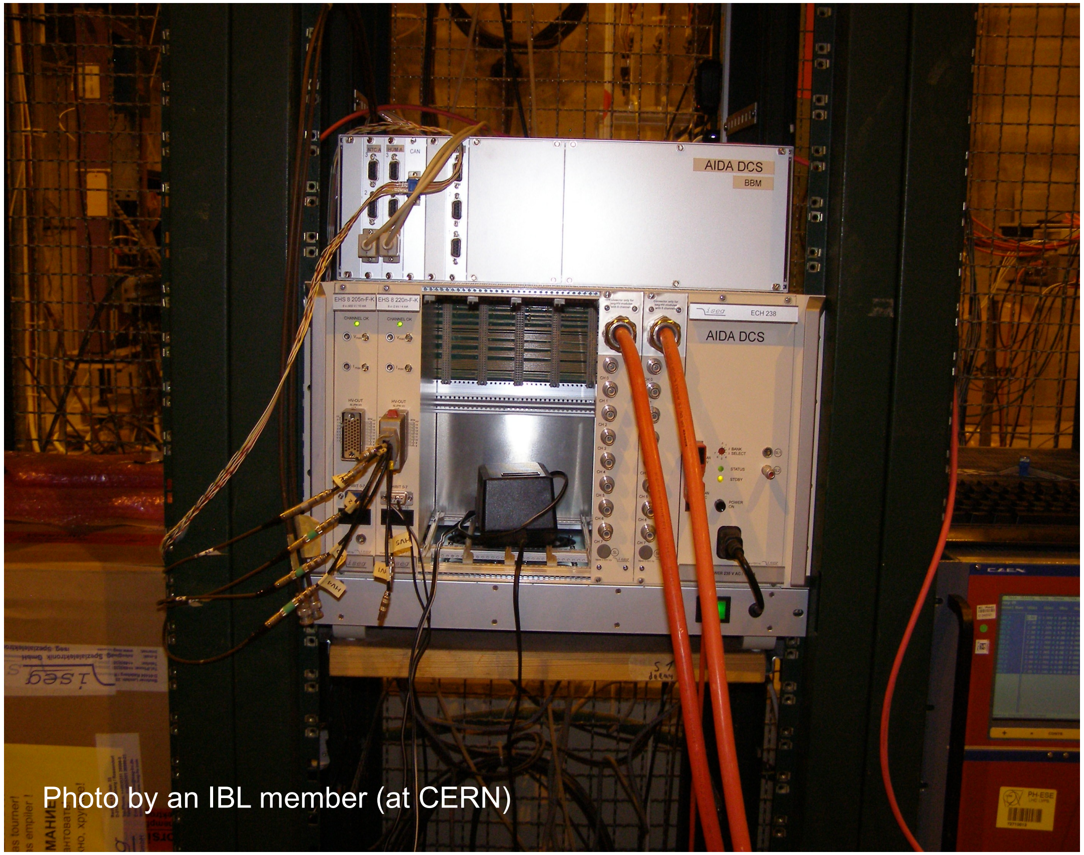


Figure 3: The HitOR signal of the FE-I4 gets inverted and then acts as an input to the TLU.

Common LV and HV powering for the DUTs as AIDA telescope infrastructure



This system is in use in ATLAS pixel detector (+IBL)

top aluminum box)
- BBM: temperature, humidity sensors
    - CANbus to PC

ISEG crate (lower one)
HV modules (left most)
    1) to 2000 V
    2) to 500 V

Lefthand modules ↔
Righthand modules (interface)

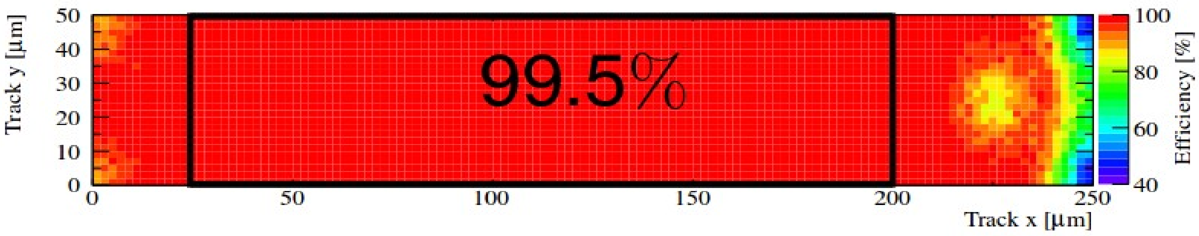
To be connected externally

Work by Wuppertal Uni

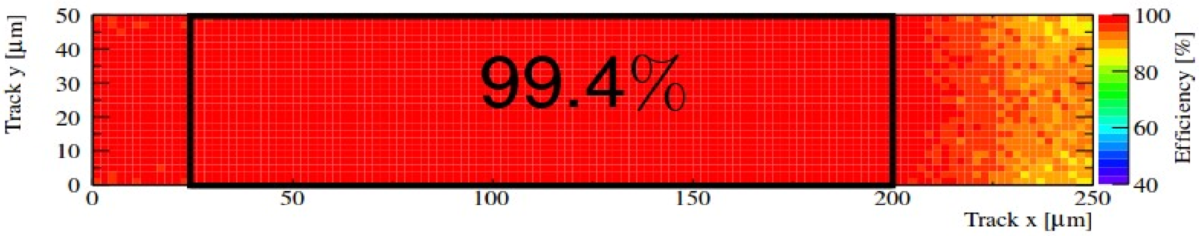
Pixel cell efficiency

- **FE-I4 150 μm thick, irradiated at 4$\times$10$^{15}n_{eq}/cm^2$ in Los Alamos**
  - test-beam at SpS, CERN with 120 GeV pions
  - threshold 1.6 ke (MPV$\sim$9.5 ke)

- 97.7% hit efficiency at $\perp$ incidence (690 V)

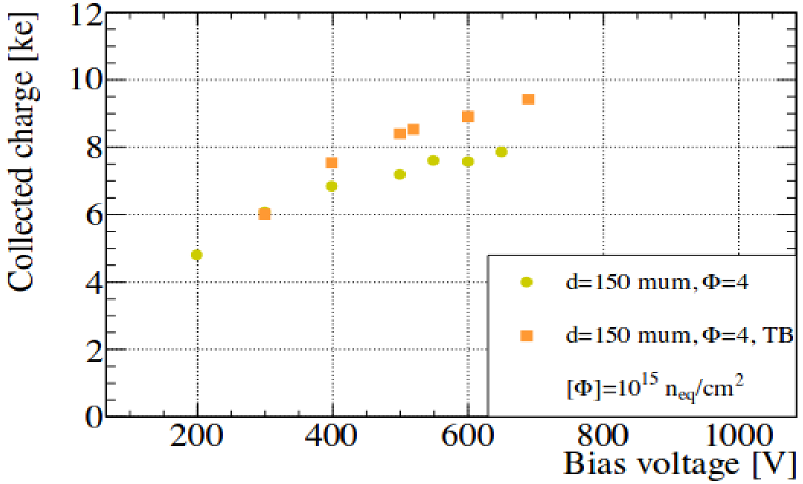


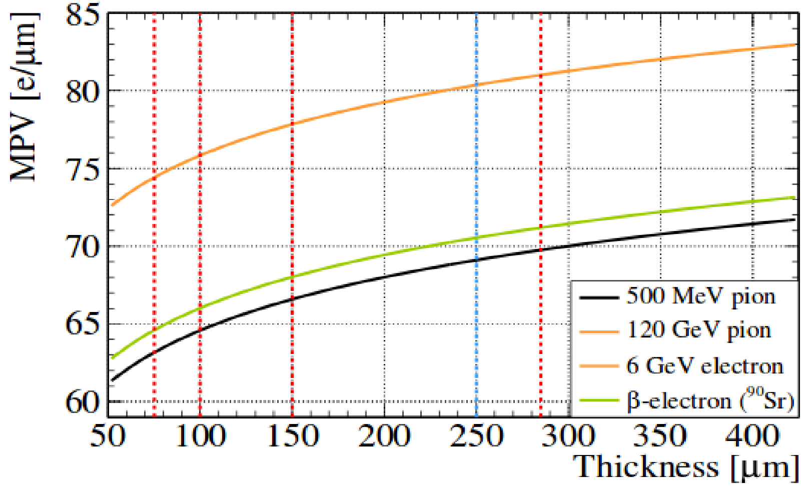
- 98.2% hit efficiency at φ=15° (650 V)



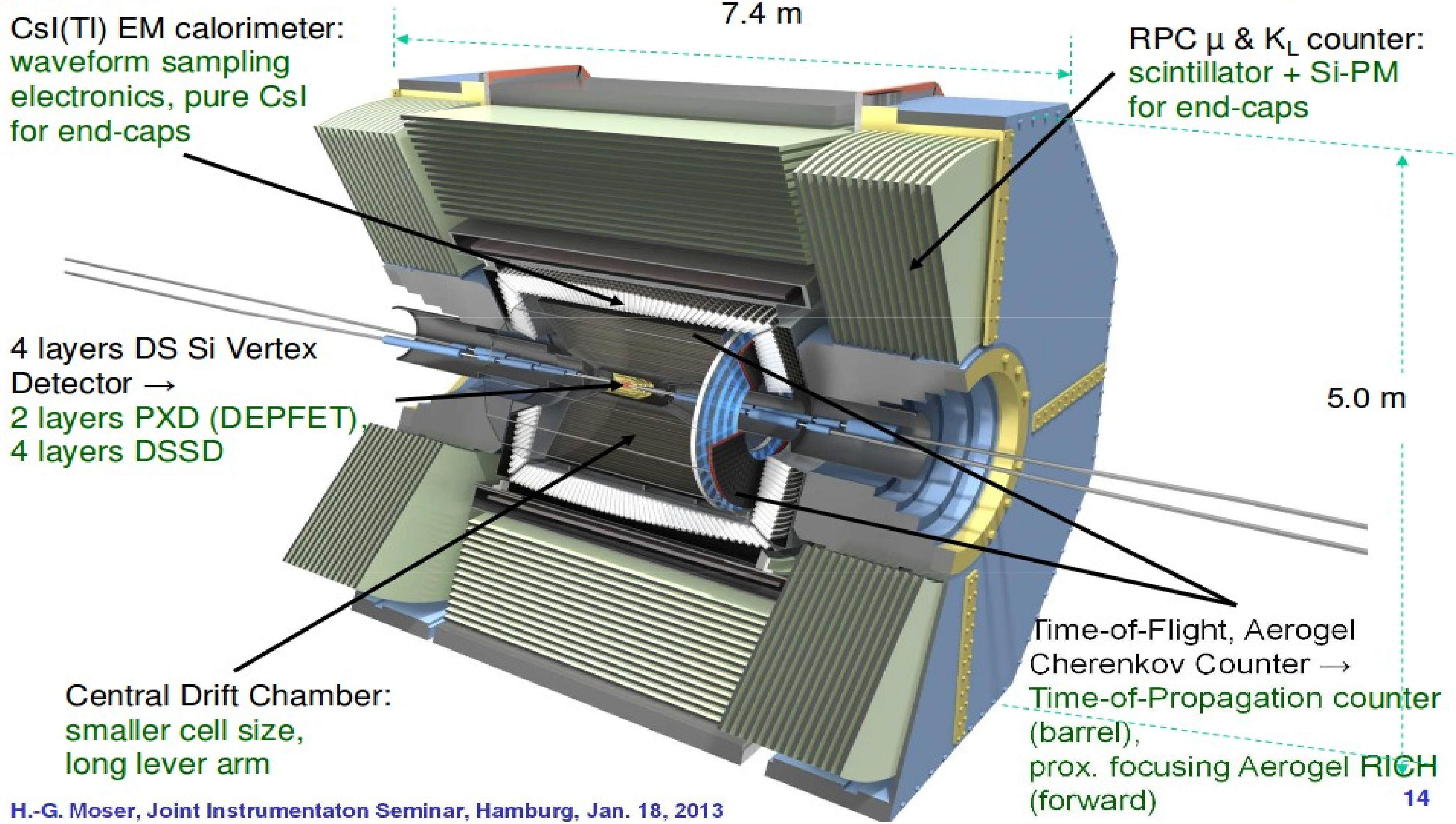
Comparison with laboratory measurements

- Collected charge is in agreement between: Test-Beam (TB, 120 GeV pions) and lab measurements (^{90}Sr)
- Small difference due to the dependence of e-h pairs generated from the particle energy ($\sim$10 e/μm)

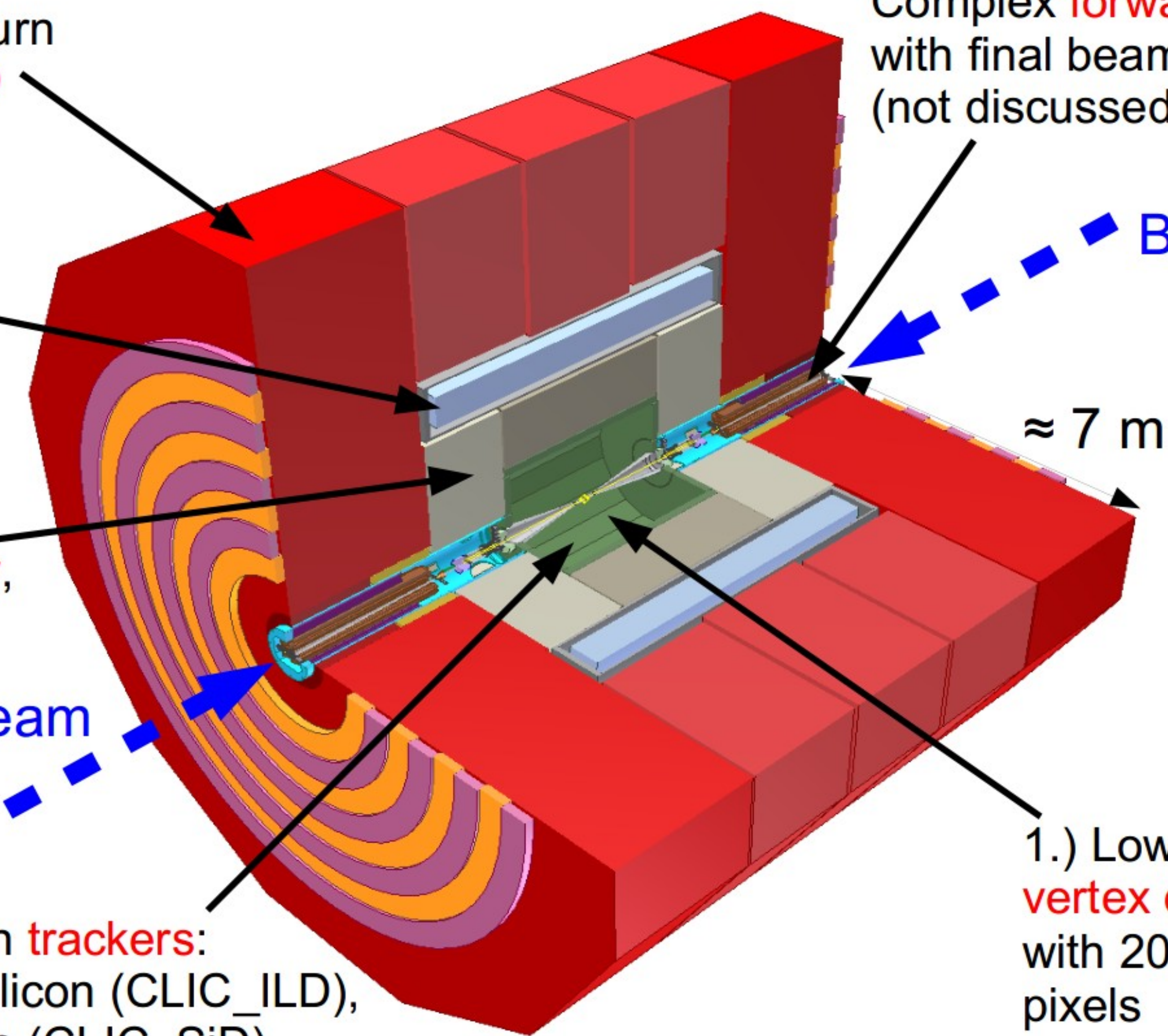




Belle II: design concept



Lepton collider detectors



Mimosa26 telescope @DESY ⇔ CERN (⇔ SLAC)

(EUDET = EUropean DETectors, FP6 project)

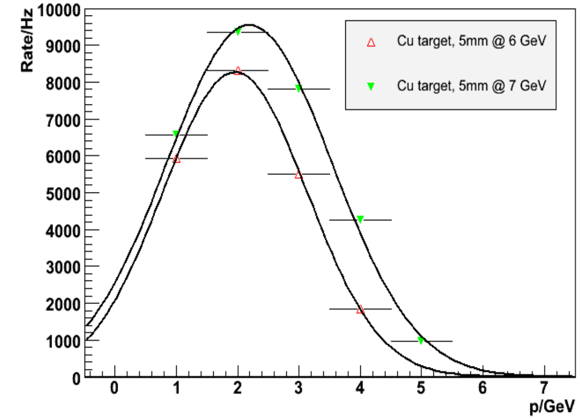
On record since 2006
- EUDET project 2006-2010
- number of groups requesting beam with the telescope doubles every year [saturating in 2011]
- in beam at DESY & CERN
  (from Nov. @DESY, from May @CERN)

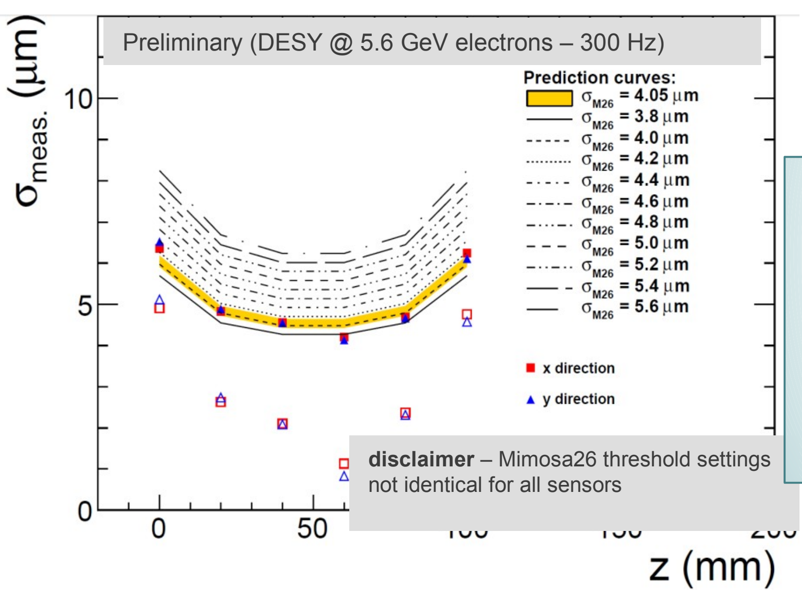
CERN
- pions @ 120 GeV
- ~0.6 Mparticles per spill
- spill ~10 sec, pause ~40 sec

DESY
- e+ or e- spectrum up to 6 GeV
- intensity depends on the beam momentum
- continuous spill
- selecting particles with dp/p ~0.01

SLAC
- e- spectrum up to 15 GeV
- beam rate/intensity ?

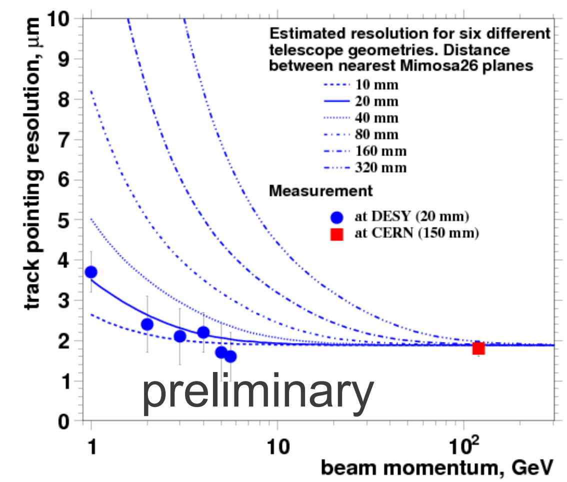
DESY (testbeam area 21, e+)





Telescope pointing resolution:
- <2 μm at CERN – for "free"
- at DESY – requires a bit of thinking on mounting to achieve same track pointing resolution
- - still true for 15 GeV@SLAC

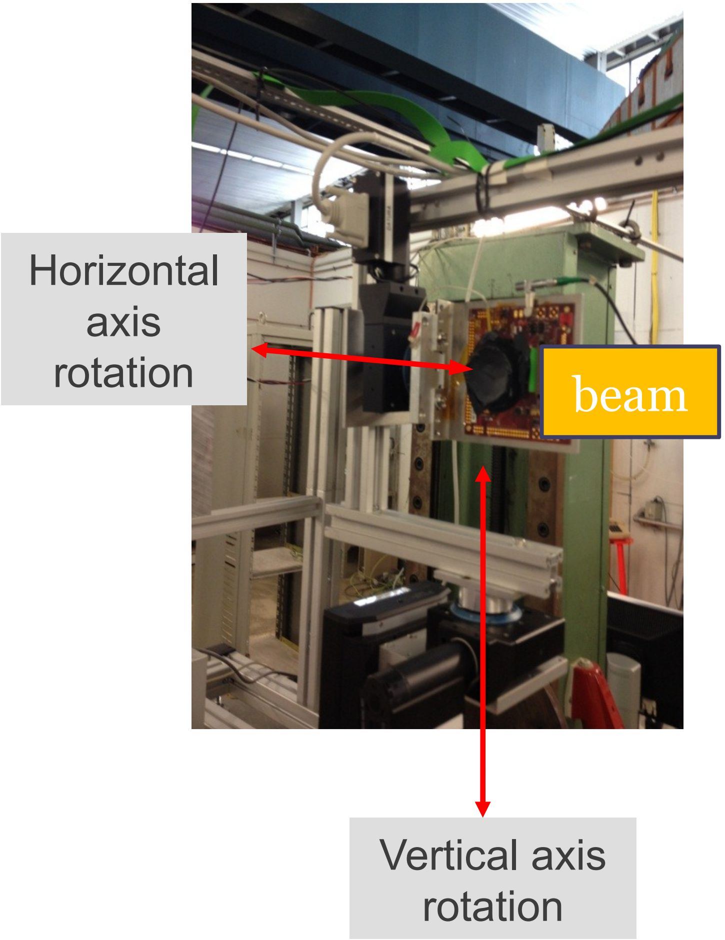
Estimated and measured resolution for equidistant setup with 6 planes



Mon Apr 16 12:22:19 2012 plot by I.Rubinskiy

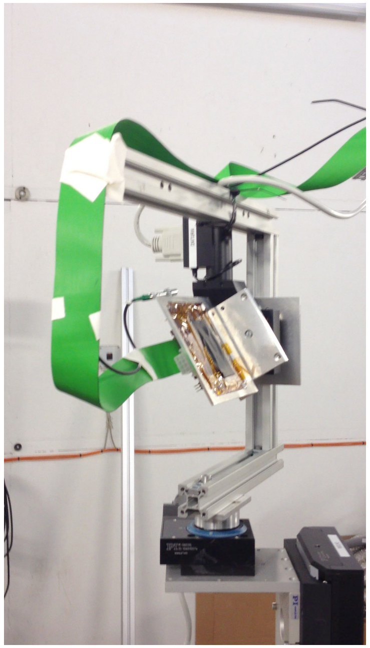
Optional feature: “Angles scans - PI rotation stage”

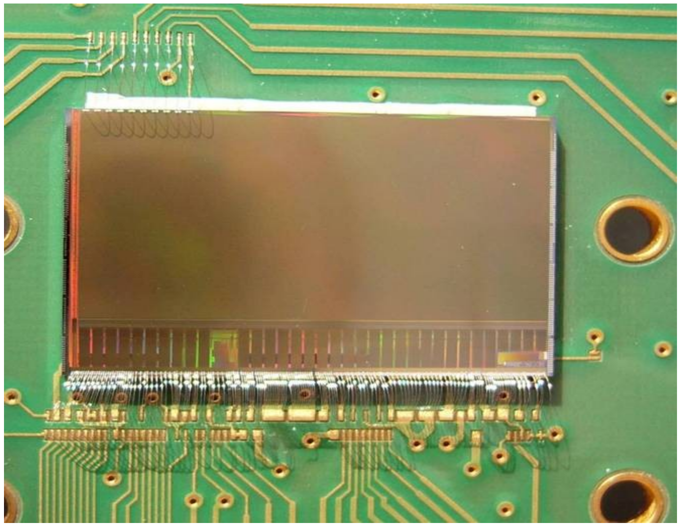
Example of a setup at DESY

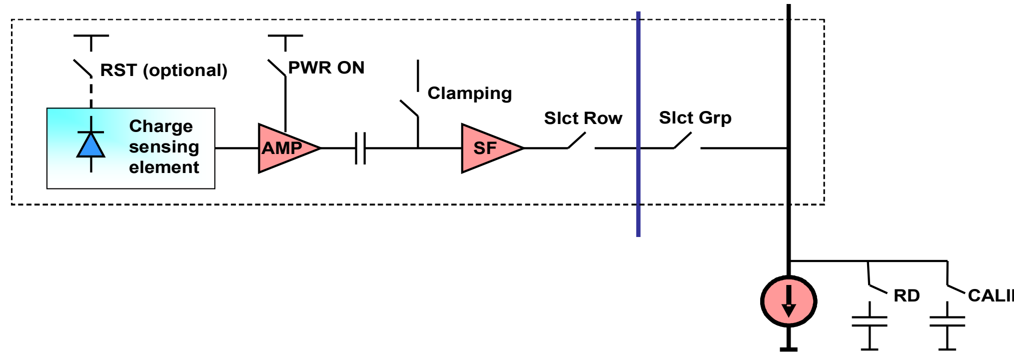


One PI rotation stage

- 32 µrad precision
- one rotation stage in
- manual control from Windows
- script control via LabView [in works]
- Unlimited rotation
  - On the photo ± 90° x ± 90 °







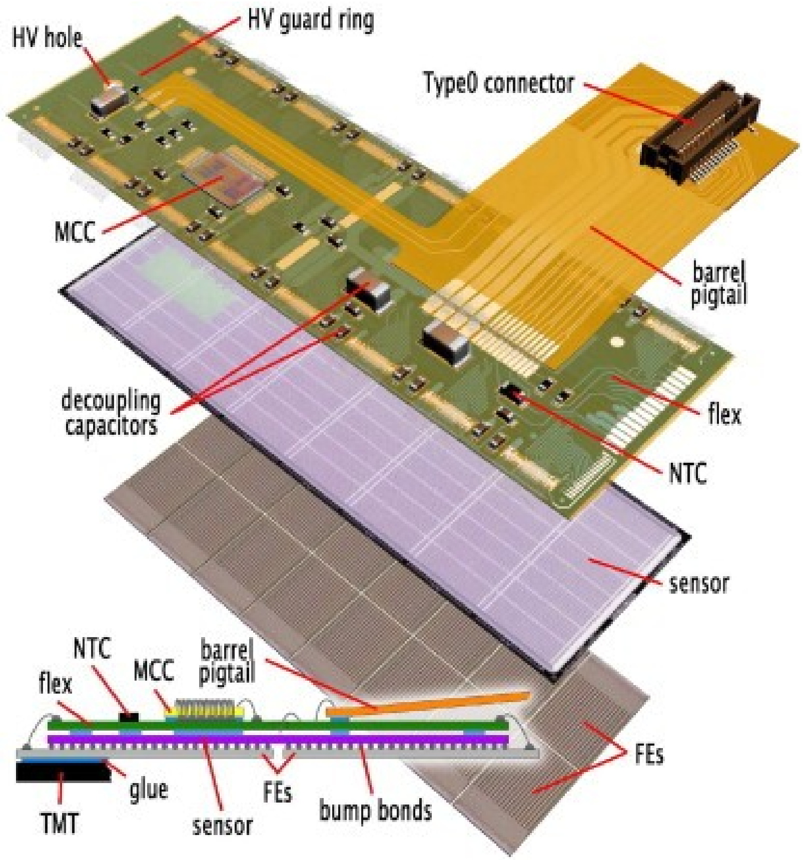
Pix level
CK
Slct_Row
Clp

Discri level
RD
CALIB
LATCH

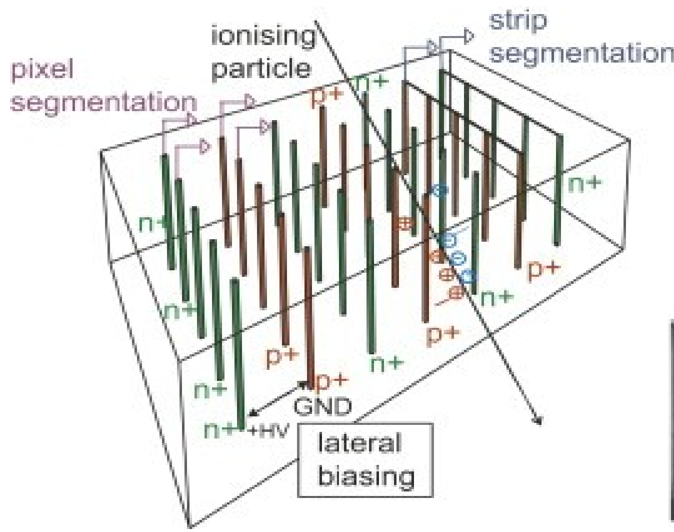
CK
PWR_On (N)
Slct_Row (N)
PWR_On (N+1)
Slct_Row (N+1)

Mimosa26
- readout in rolling shutter mode
- 3T pixel
- CDS and Zero Suppression outside of the sensitive area, at the bottom of each column

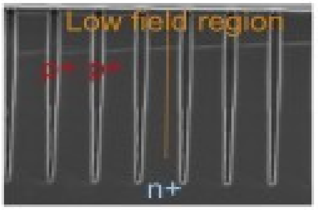
Semiconductor detectors (hybrid technology: sensor+chip)



study sensors :: novel design or new materials



3D Silicon



LHC pixel module requirements:

t (fast) charge collection (fast for shorter drift distance or higher voltage applied)
sensitive element readout should be fast (40 MHz clock)

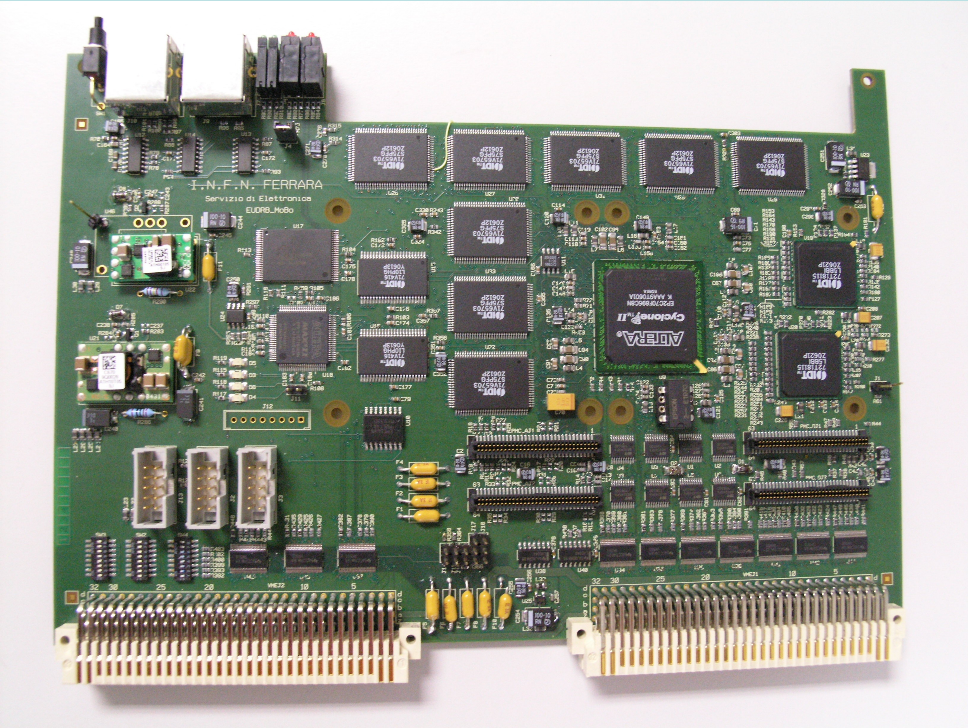
σ (resolution) pitch 50x400 μm → 14x70 μm hit position accuracy

Radiation tolerant ~10 years of operation at the LHC

E-field: are there any inefficiency spots? Where?

A VME64x-based DAQ card for MAPS sensors

Lorenzo Chiarelli, Angelo Cotta Ramusino, Livio Piemontese, Davide Spazian // Università & INFN Ferrara



mother board built around an ALTERA CycloneII FPGA (clock rate: 80MHz) and hosting the core resources and Interfaces (VME64X slave, USB2.0, EUDET trigger bus)

NIOS II, 32 bit "soft" microcontroller (clock rate: 40Mz) implemented in the FPGA for

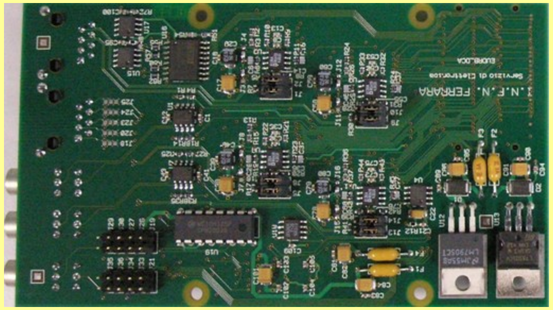
- on board diagnostics
- on-line calculation of pixel pedestal and noise
- remote configuration of the FPGA via RS-232, VME, USB2.0

Two readout modes:

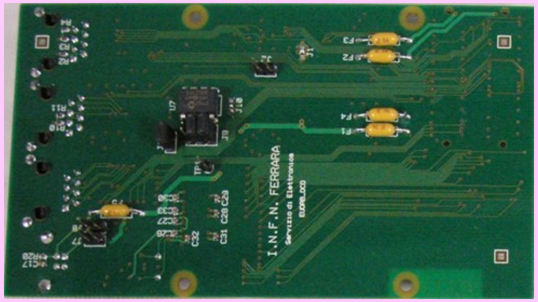
Zero Suppressed readout to minimize the readout dead-time while in normal data taking.

Non Zero Suppressed readout of multiple frames for debugging or off-line pedestal and noise calculations

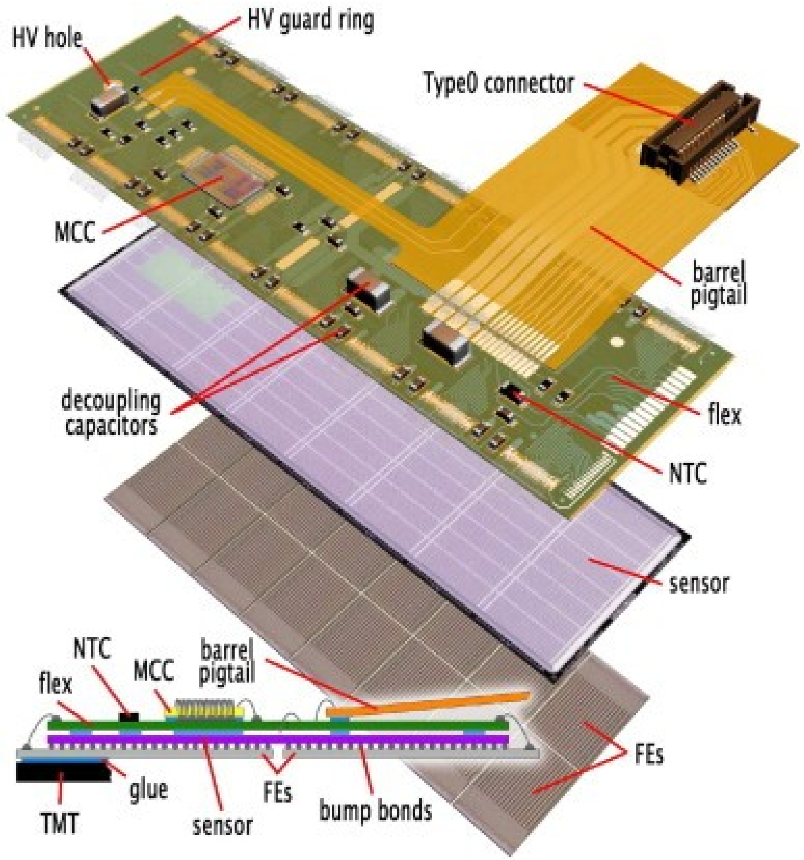
analog daughter card based on the successful LEPSI and SUCIMA designs clock rate up to 20 MHz



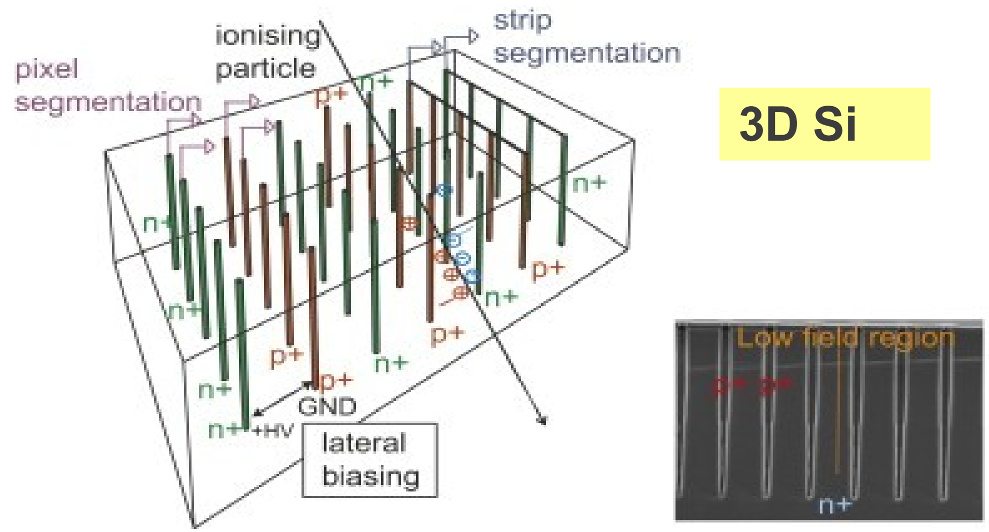
digital daughter card drives/receives control signals for the detectors and features a USB 2.0 link



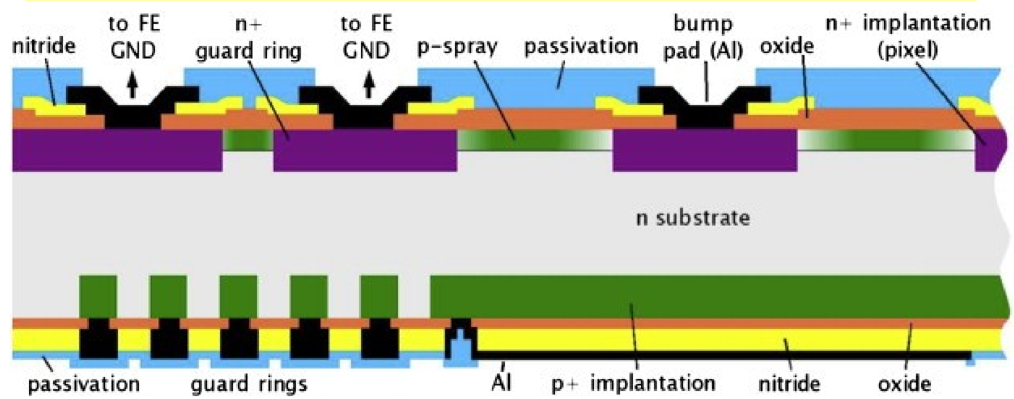
Semiconductor detectors (hybrid technology: sensor+chip)



study sensors :: novel design or new materials



Planar Pixel technology (Si or Diamond)



LHC pixel module requirements:

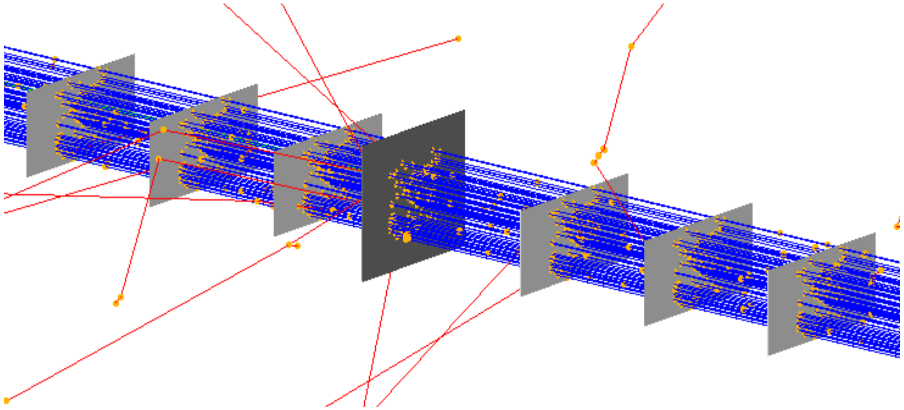
t (fast) - smaller (size) or higher voltage

σ (resolution)- σ<20 μm

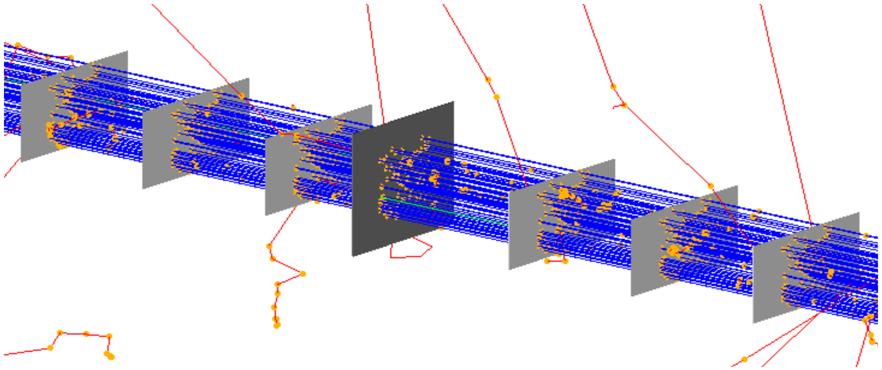
Radiation tolerant - 250 Mrad

E-field: are there any inefficiency spots? Where?

SLAC

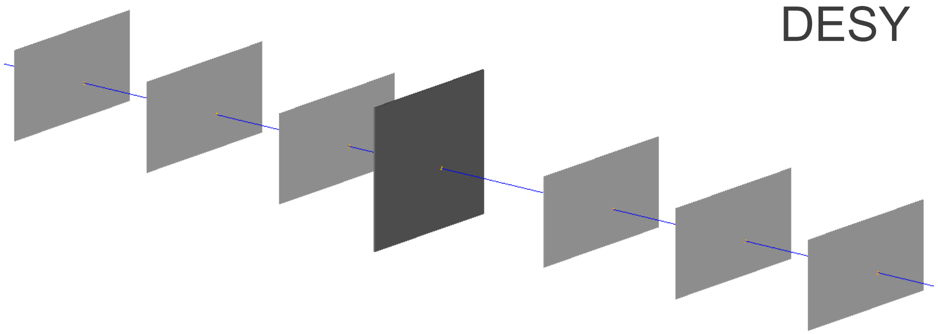


100 e^+ at 5 GeV



100 e^+ at 15 GeV

DESY



1 e^+ at 4 GeV

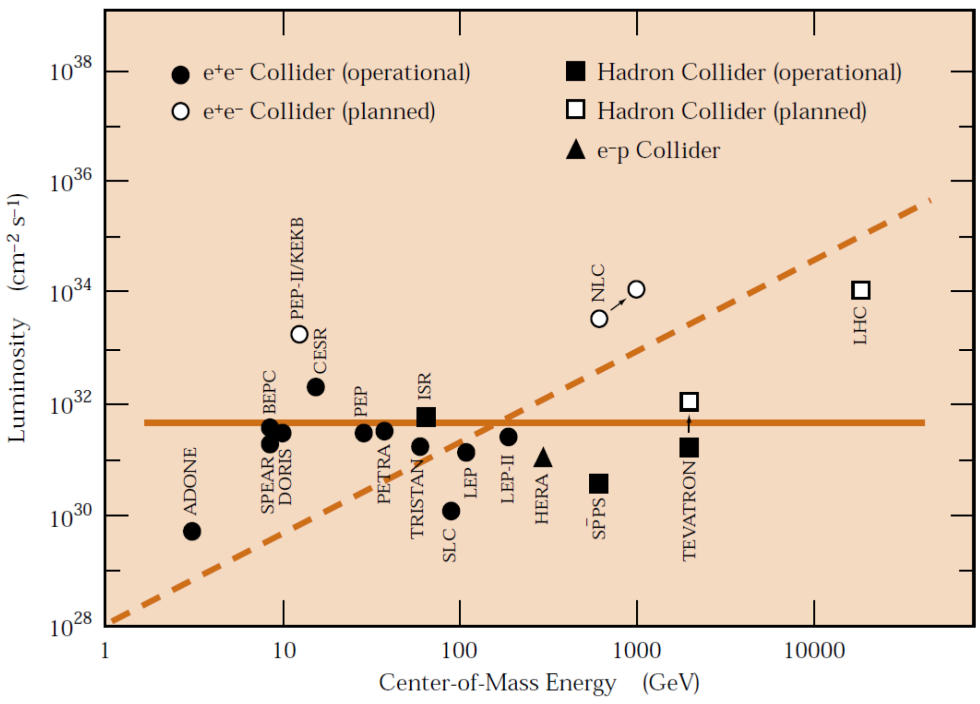
http://puhep1.princeton.edu/mumu/physics/

Comment by Fred Mills (Feb 21, 2008):

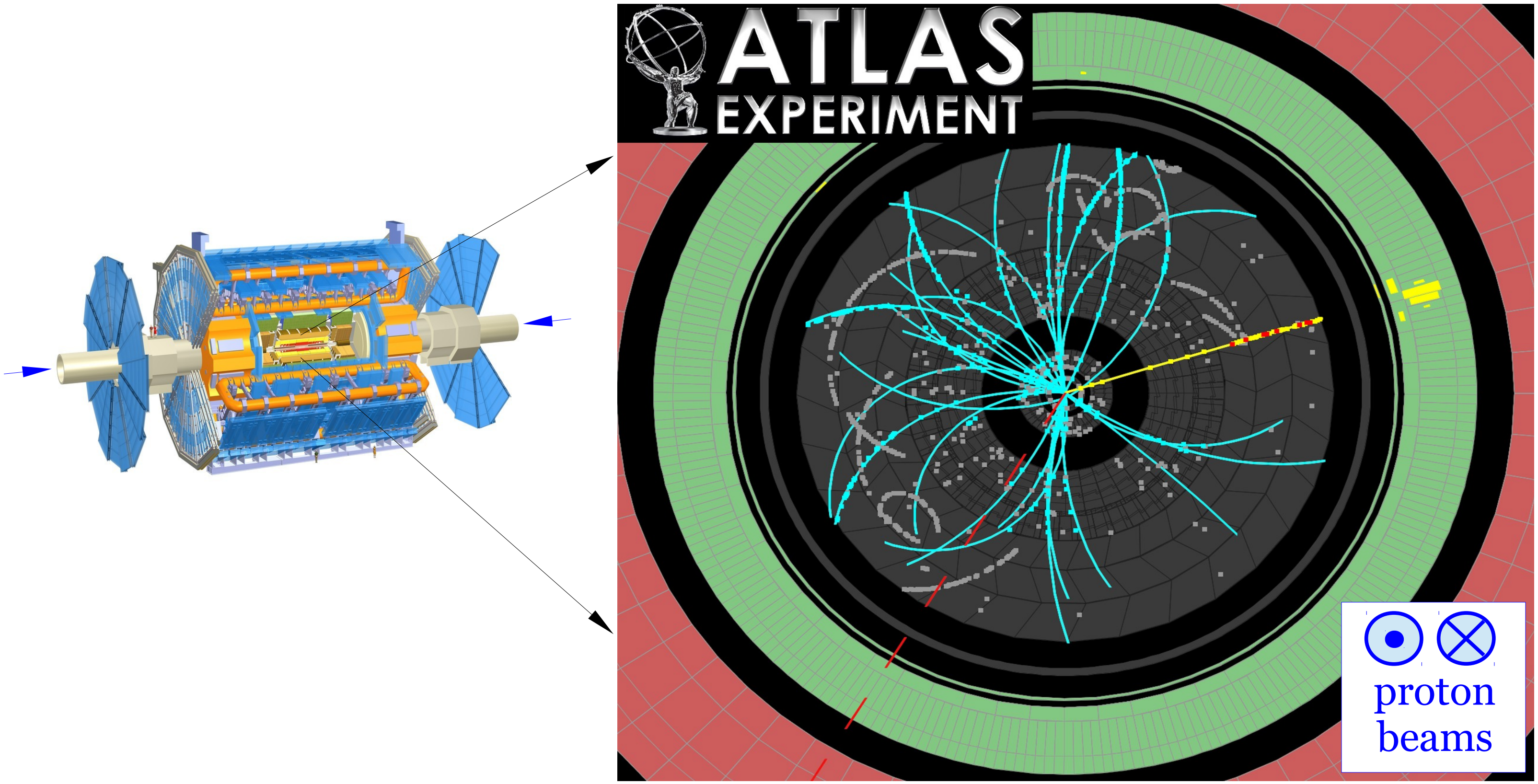
"In 1976 at Fermilab we began investigating cooling for p-pbar colliders. Shortly thereafter Milton White of Princeton, who was a member of the URA Board, told me about a need to reduce the emittance of a beam from a van de Graaff for injection into the Princeton Pennsylvania Accelerator. This was discussed at a faculty lunch and Lyman Spitzer (a well-known plasma physicist) suggested a moving electron plasma, i.e., electron beam, with which to equilibrate the proton beam. Gerry O'Neill, or a student, did some calculations which showed that the process was too slow to help.

I don't recall whether both Gerry and Gersh Budker were at the 1959 CERN conference or if so they discussed it there, but the next chance would have been in 1963 at the Dubna Conference and at Novosibirsk afterwards. Gerry, Arnold Schoch, about ten others and I visited the INP (now BINP) after the conference. On the flight back to Moscow, I was accompanied by Igor Meshkov who built the first electron cooling system for NAP. Igor had built an electron gun-collector system but had discovered that space charge caused the effective beam temperature to increase too rapidly. Three years ago Igor reminded me that I had suggested immersing the beam in a magnetic field to control it. (I had extensively studied electron beam formation and propagation when I designed and built the injector for the 50 MeV FFAG at MURA.) Thus electron cooling was already under way experimentally and theoretically (Sagdeev et al.) at INP in 1963. Budker then gave his paper at the Orsay Conference in 1966.

Since they are both deceased, we cannot ask them who came first. My own view is that while the Princeton bunch fiddled with an idea and dropped it, INP under Budker, with Meskov and Dikansky, built and tested the system which proved the method. In fact, Budker built his whole laboratory to accommodate 25 GeV p-pbar collisions, which doesn't work without cooling. He deserves to be called the inventor."

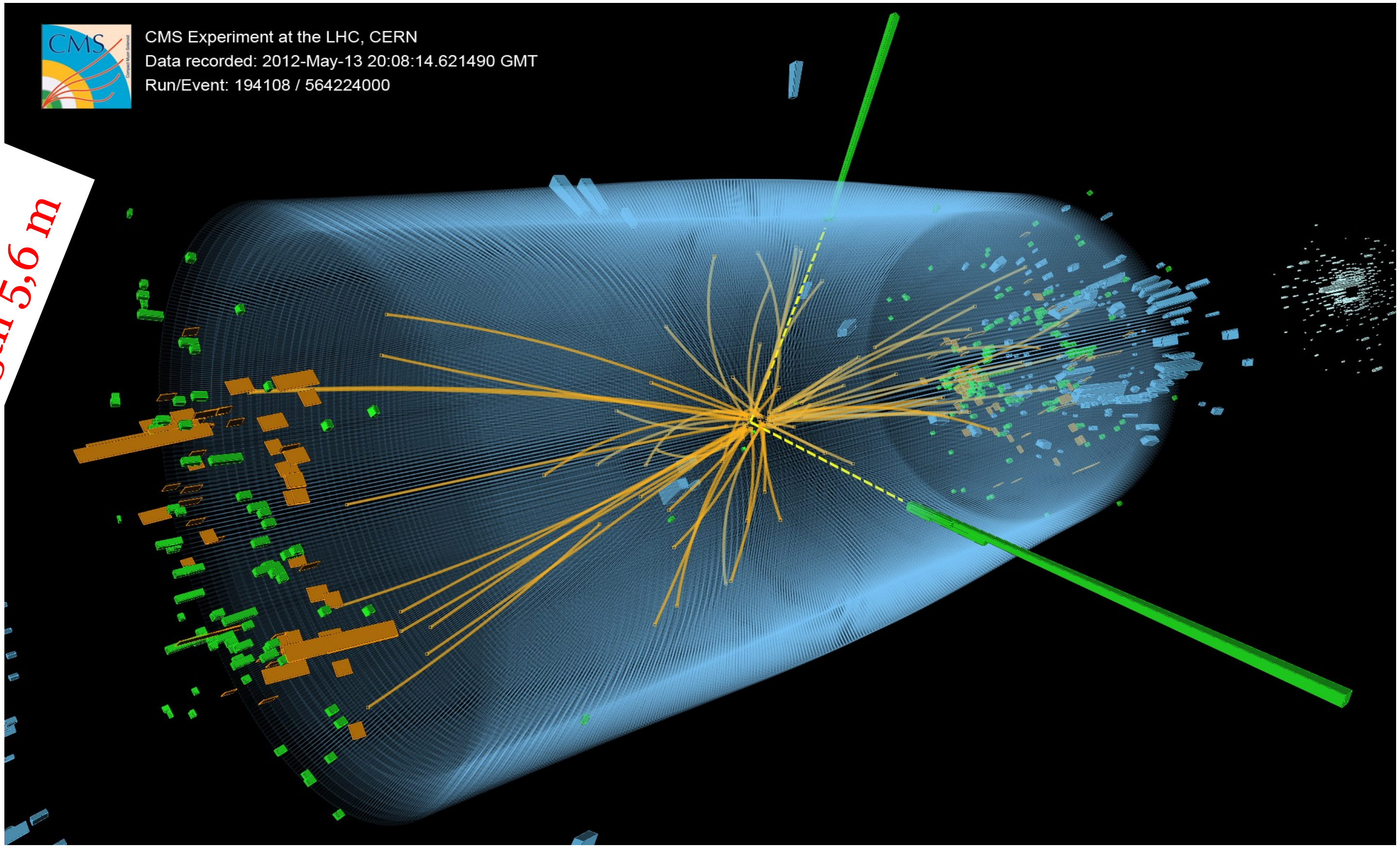

e+e- Collider (operational)
e+e- Collider (planned)
Hadron Collider (operational)
Hadron Collider (planned)
e-p Collider
Luminosity (cm-2 s-1)
Center-of-Mass Energy (GeV)
10^38
10^36
10^34
10^32
10^30
10^28
1
10
100
1000
10000
ADONE
SPEAR
DORIS
BEPC
PEP-II/KEKB
CESR
PEP
PETRA
TRISTAN
ISR
SLC
LEP
LEP-II
HERA
SPPS
NLC
TEVATRON
LHC

One more screenshot of the ATLAS inner tracker:
- detector strips or pixels are marked Grey, if a particle passed through and “fired” it.
- charged particles are seen only by their traces they leave in specially designed tracking detectors (“an invisible man footprints”).



Pattern Recognition based on strict math chains individual “hits” in “tracks”
- track curvature in the magnetic field → particle momentum (energy)
- high precision for hit coordinates needed to get track curvature precise

A screenshot of a collision event observed by CMS experiment (inner detector area)



CMS inner tracker:
∅ 2,2 m x length 5,6 m

One can see lots of tracks (colored orange) from charged particles
...two green towers without tracks (photons) [→ Higgs decay candidate]

This is one of the possible looks of a Higgs boson

Particle Colliders:

proposed & patented in 1943 (Rolf Wilderoe)

1. pioneering work 1958-1962 (Frascati and SLAC)
   first e^+e^- in 196x (Orsay and Novosibirsk),
   later In 1974 (DORIS, DESY)

   c, b quarks discovery
   $c\bar{c}$, $b\bar{b}$ spectroscopy

2. pp collider approved in 1965 (CERN)
   first pp collision 1971 (ISR, CERN)

   battle for beam stability, lumi
   - observation raising x-section
   Discovered at Serpukhov U-70

3. $p\bar{p}$ (w. electron cooling) 1966 (by Budker, Skrinski w. credits O'Neill and co)
   first $p\bar{p}$ collision 1981 (SPS, CERN)
   1983 (Tevatron, FNAL)

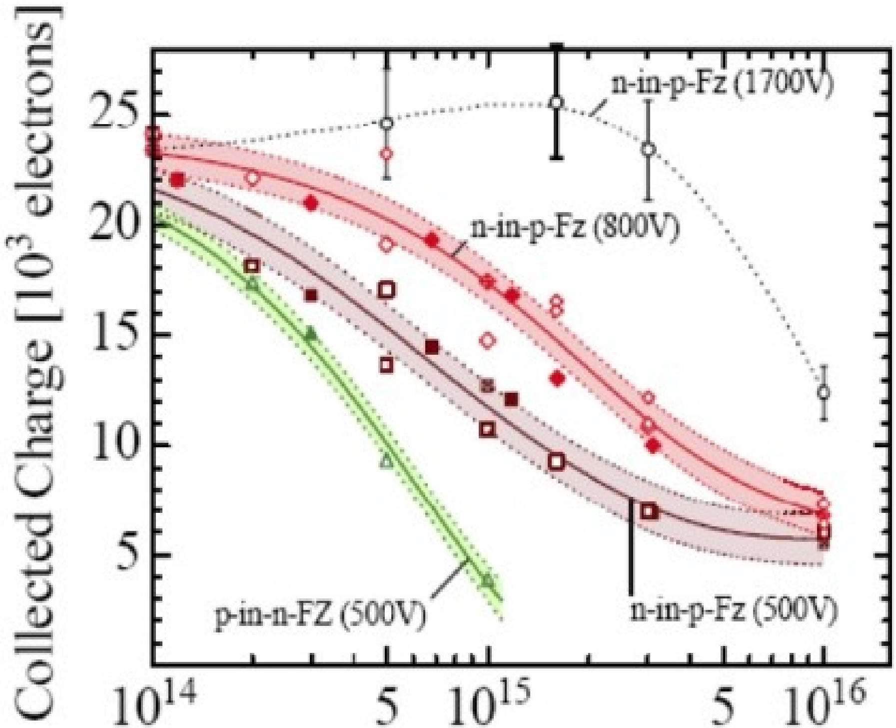
   W, Z bosons discovery
   t quark discovery

4. ep collider
   first ep 1992 (HERA, DESY)

   Indispensable proton structure insight (= discovery)

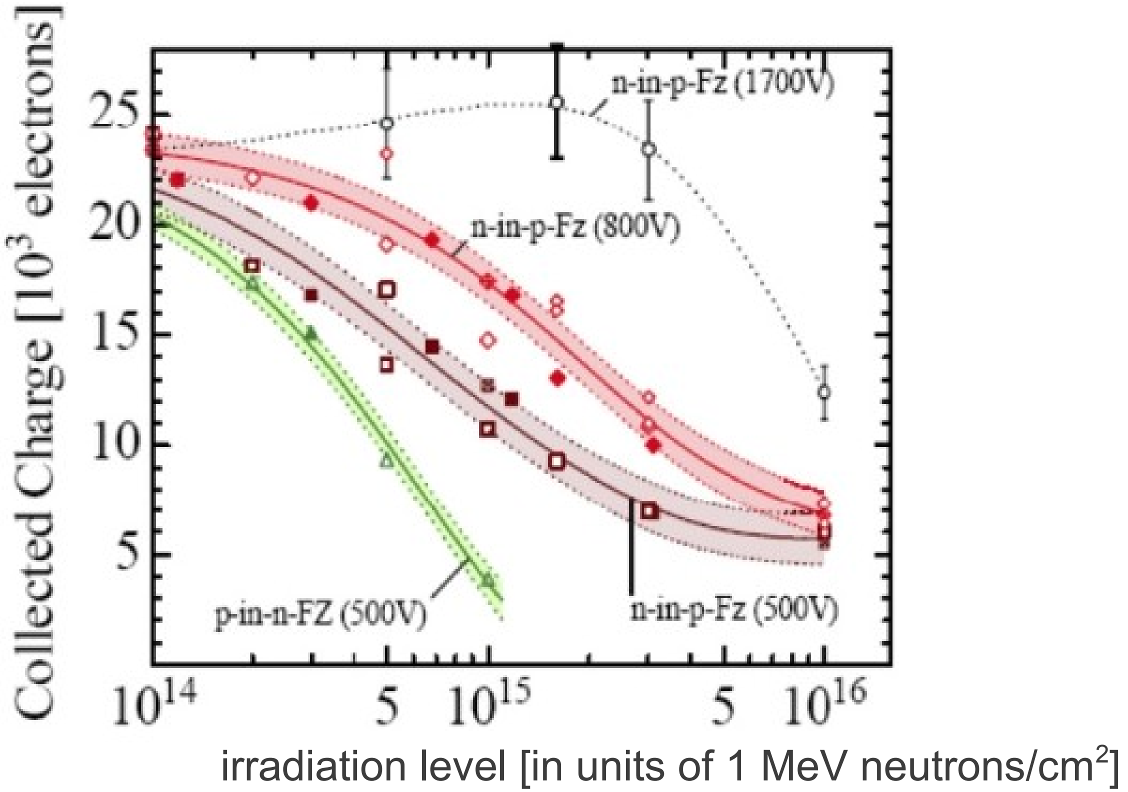
...in order to get a discovery first build a new generation machine and detectors
= sharpen a pencil to draw finer lines

Sensor performance (charge collection, efficiency) gets worse with irradiation



irradiation level [in units of 1 MeV neutrons/cm^2]

Sensor performance (charge collection, efficiency) gets worse with irradiation



Q: How does the pixel efficiency depends on the E (and/or B) field structure?
Q: How does material sensitivity depend on irradiation (also temperature, bias voltage)?

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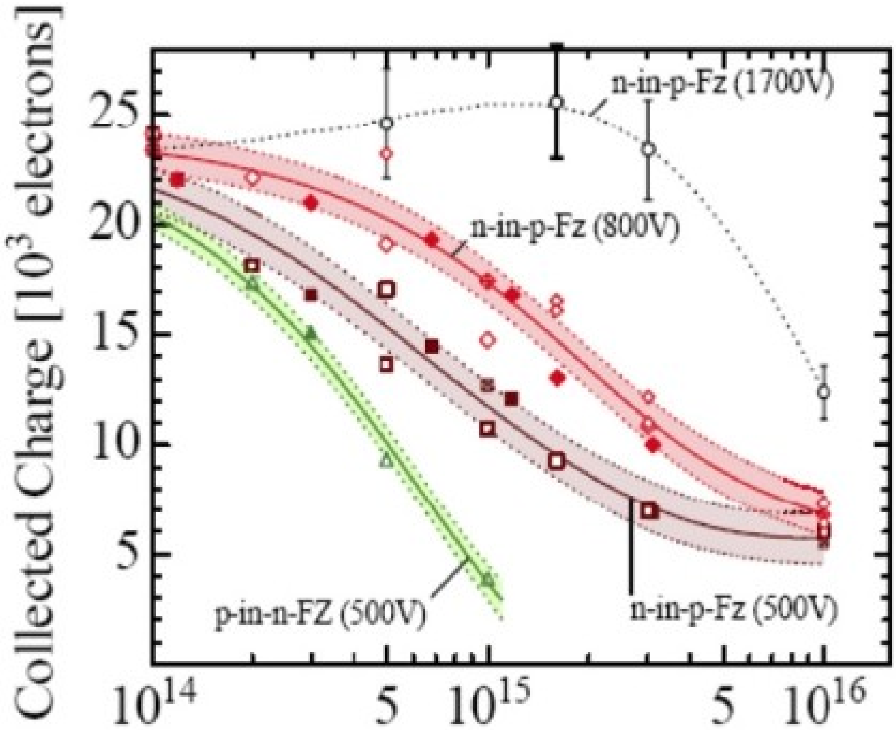

irradiation level [in units of 1 MeV neutrons/cm^2]

Q: How does the pixel efficiency depends on the E (and/or B) field structure?
Q: How does material sensitivity depend on irradiation (also temperature, bias voltage)?

The amount of parameters to be checked across is large
- need for a dedicated infrastructure to test different technologies

Typical R&D of a HEP detector ~10 years + ~10 years of exploitation → no way to improve on the "fly"

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- = too late to test detector after it has been commissioned
- detector performance tests are mandatory and testing conditions should be as close as possible to real life:
    - particle type diversity, energy, intensity
    - monitor detector efficiency and resolution

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So, we:

- test detector (sub) components in a test beam
  → during all steps of R&D
- start with one particle type (at fixed energy)
  → try different particle energy
  → try different particle type
- proceed until the whole detector module is tested

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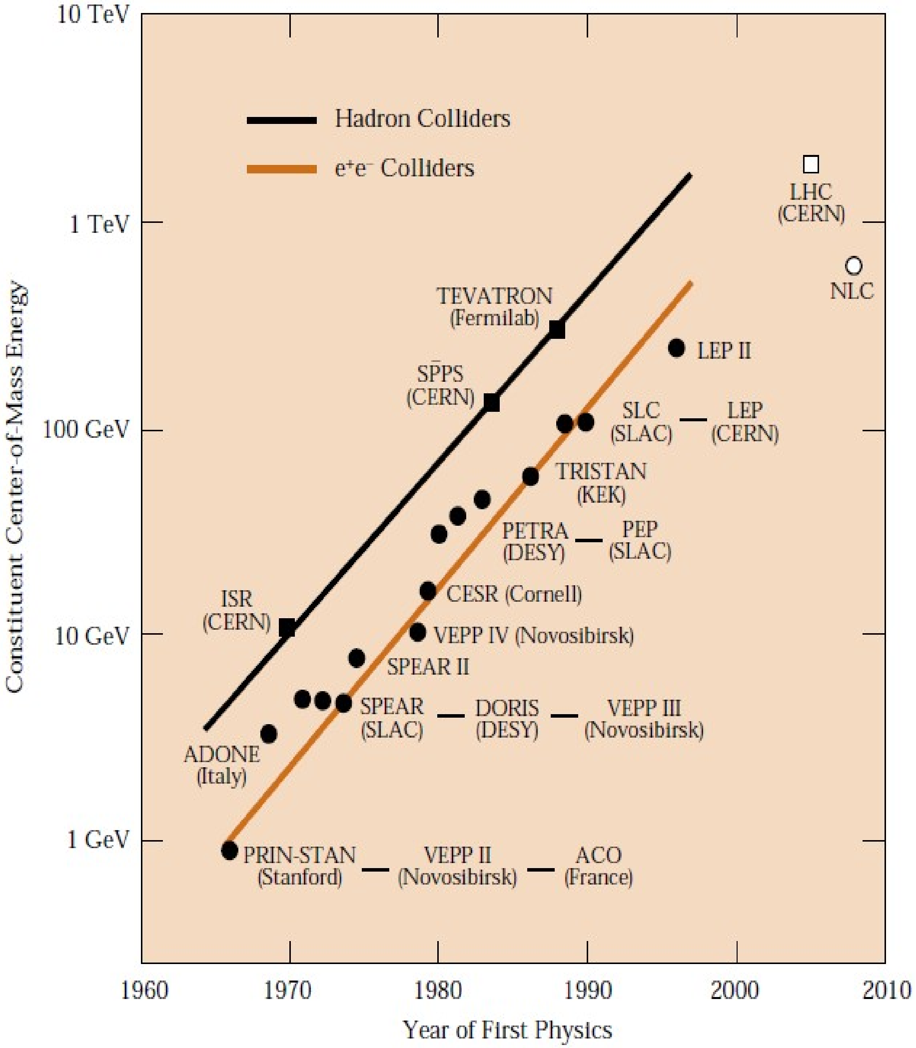
can take years of testing

Particle Colliders – 50 years of exciting discoveries



W. Panofsky “the Evolution of Particle Accelerators and Colliders” 1997

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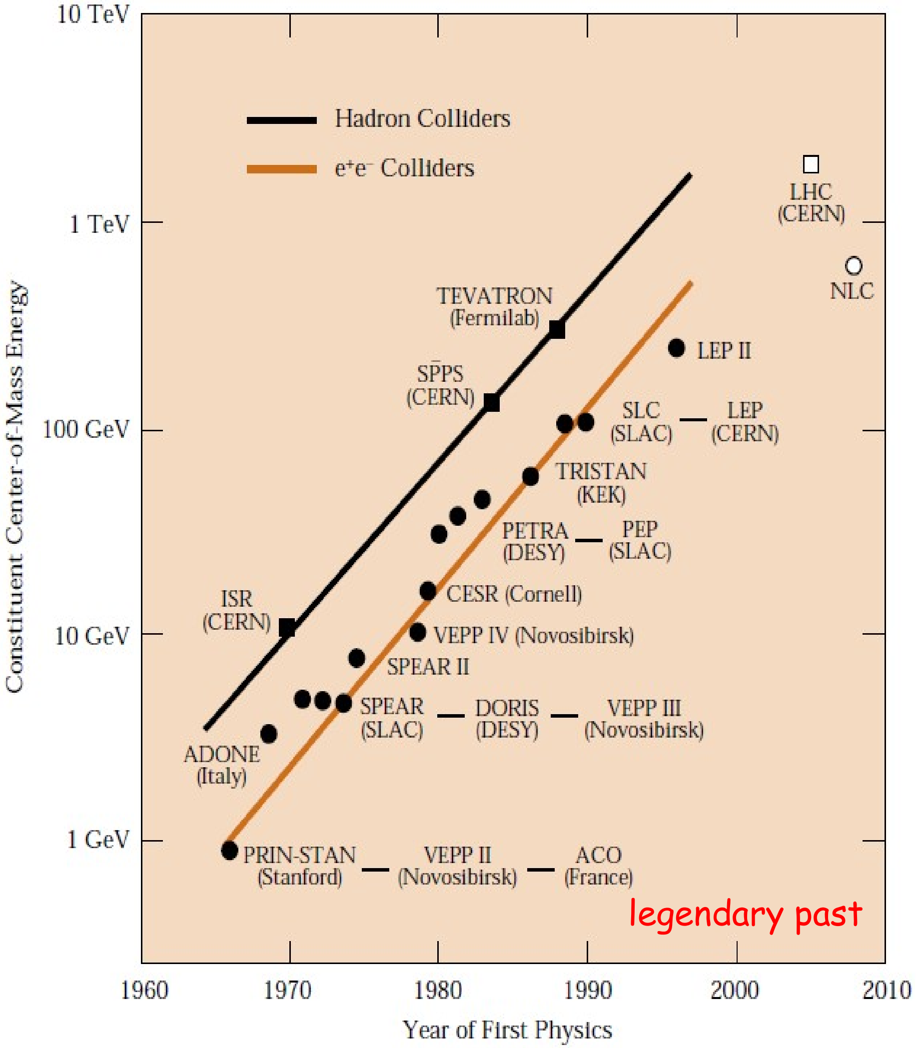

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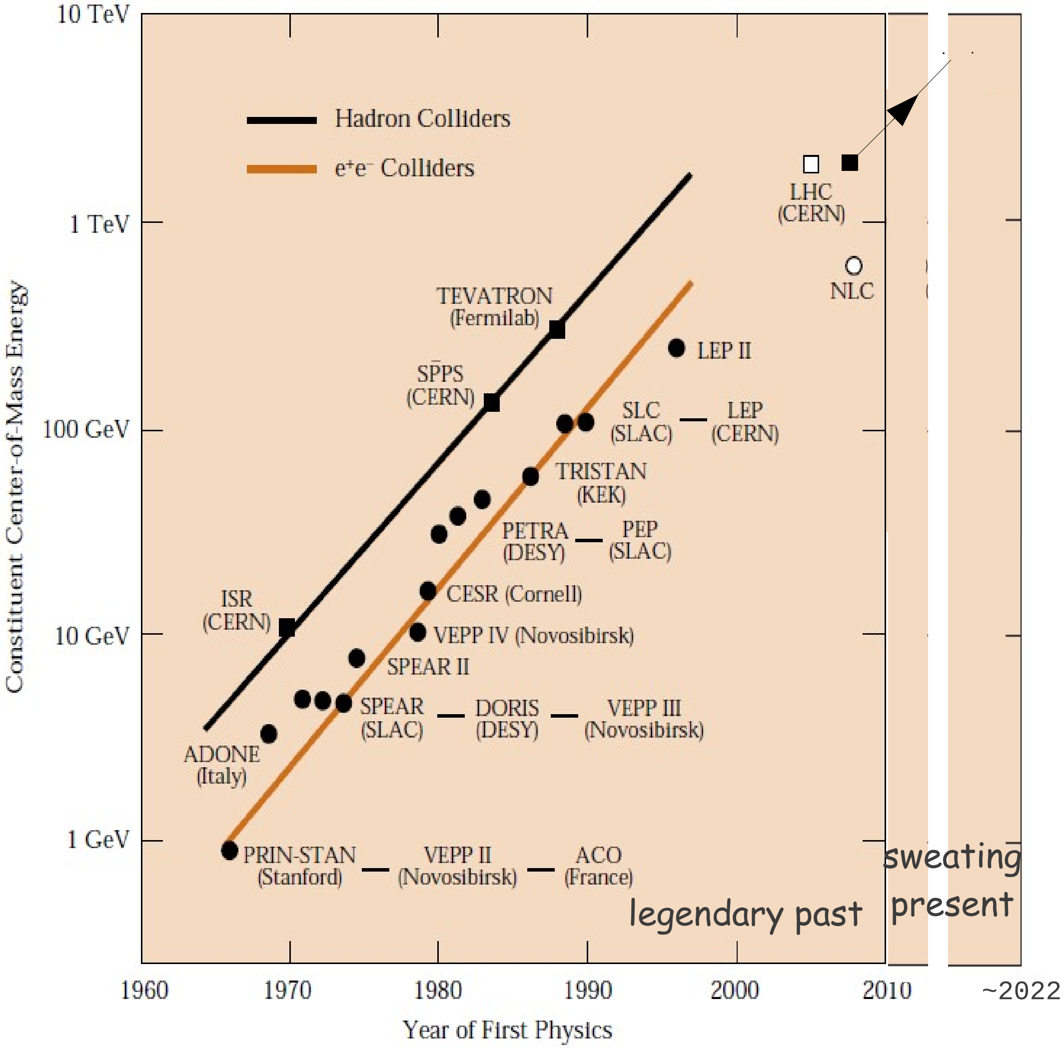

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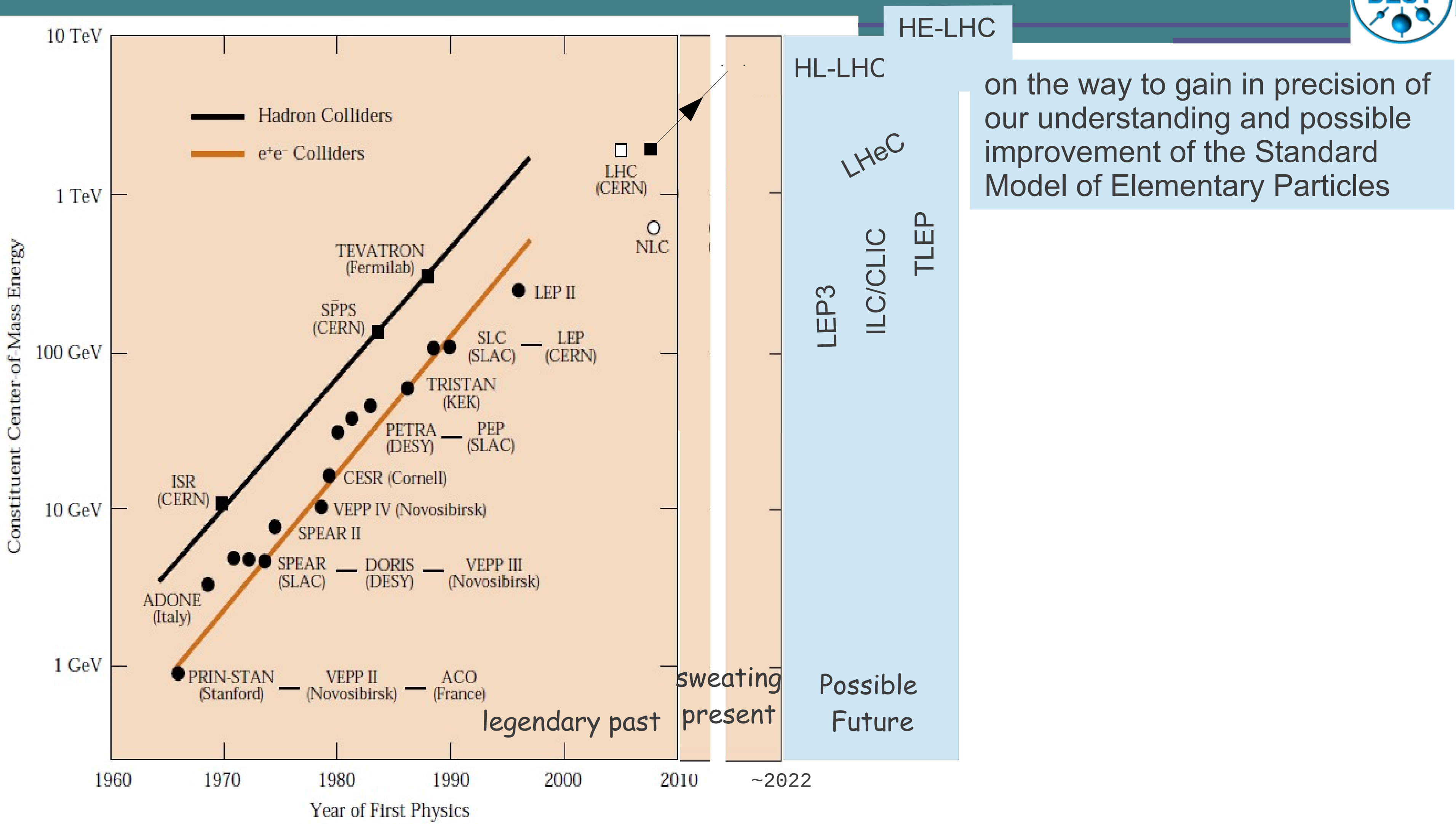
on the way to gain in precision of our understanding and possible improvement of the Standard Model of Elementary Particles

In most cases a certain way to a discovery
- build a more powerful machine



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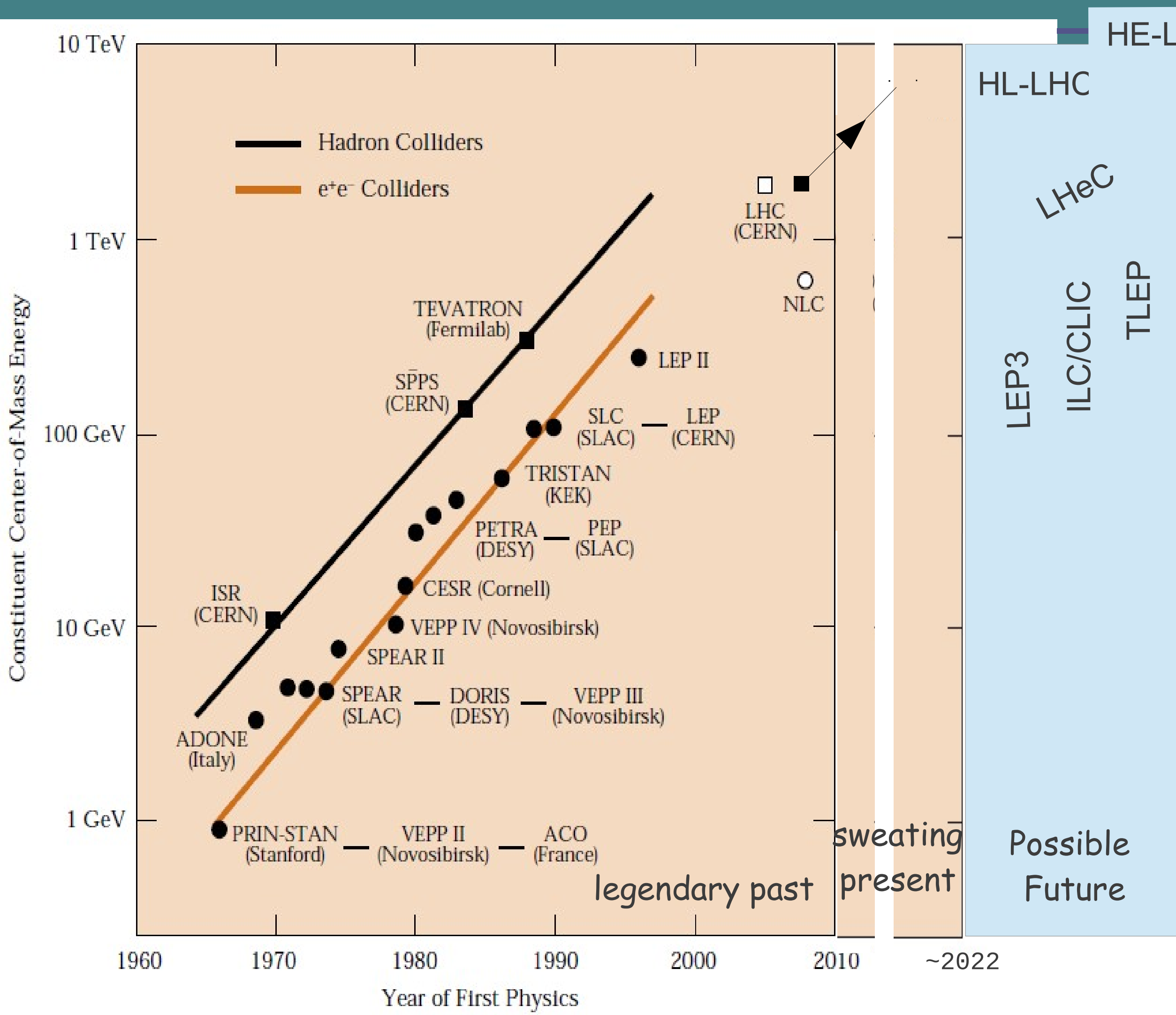
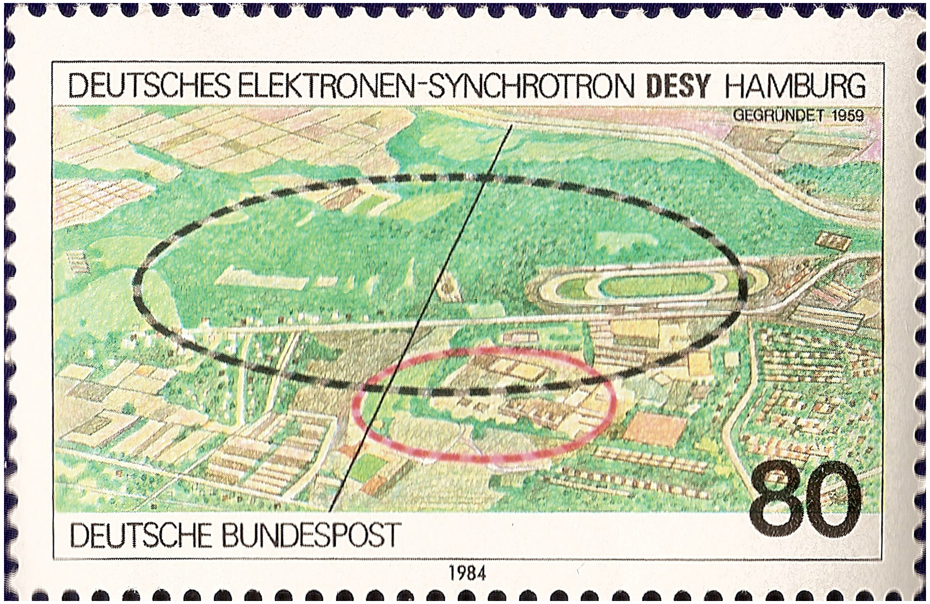


on the way to gain in precision of our understanding and possible improvement of the Standard Model of Elementary Particles

W. Panofsky "the Evolution of Particle Accelerators and Colliders" 1997

This will last until we keep our curiosity: "how does it all work?"

In most cases a certain way to a discovery - build a more powerful machine

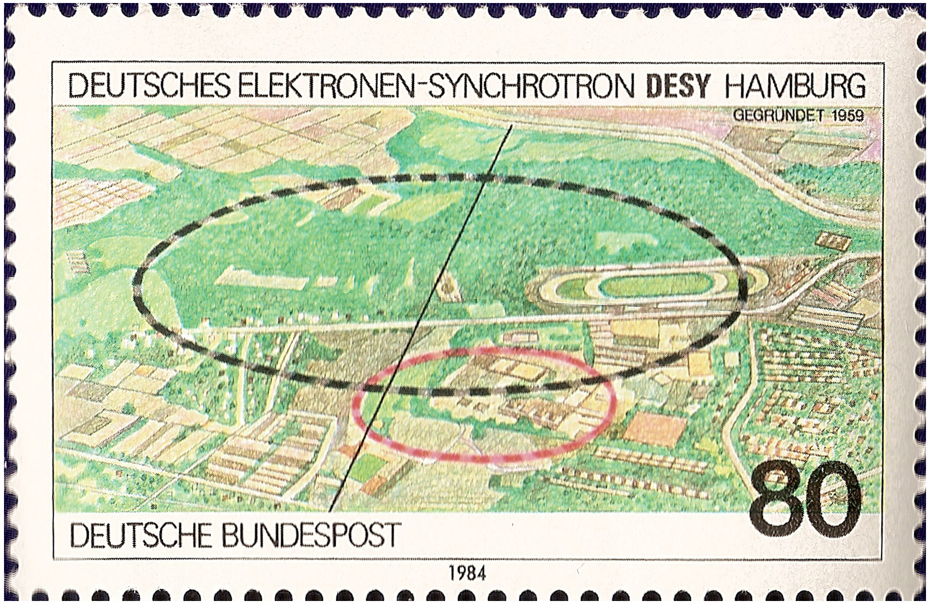


Deutsches Elektronen-Synchrotron
- in Hamburg, from 1959

- Particle Physics:
  e^+e^-:
  - DORIS ($c\bar{c}$, $b\bar{b}$ spectroscopy
    $B^0\bar{B}^0$ oscillations discovery)
  - PETRA (gluon discovery)

  $e^{-(+)}p$:
  - HERA (proton structure functions scaling violation, hard diffraction)

HEP crew: indispensable impact on the present (LHC) and future (pp or e^+e^-)



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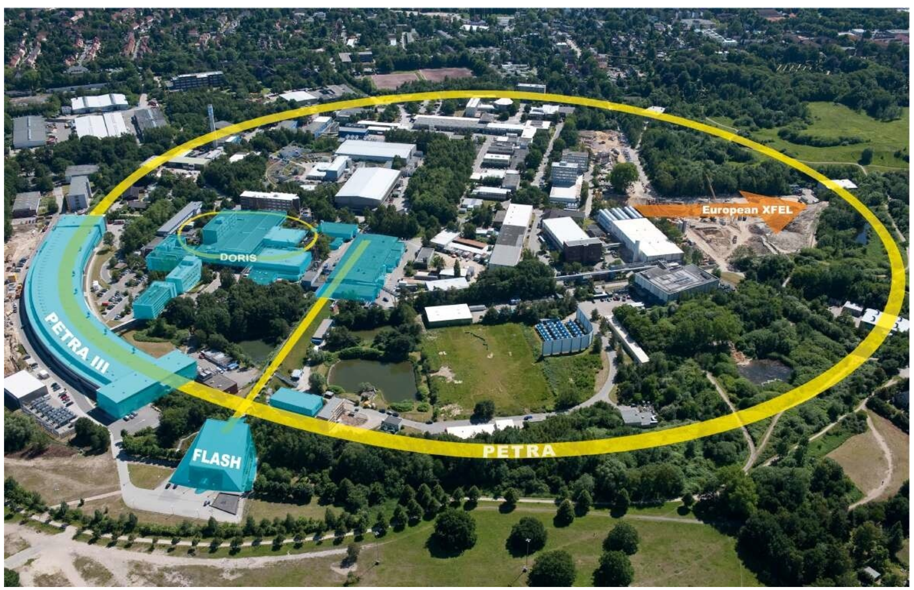
HEP crew: indispensable impact on the present (LHC) and future (pp or e^+e^-)

- Photon Science:
  PETRA III, DORISIII, FLASH, XFEL



A scientific measurement which is able to revolutionize the field is possible only with instruments, which are themselves a revolution in the field of instruments.

FEI4 feature list

- 50x250 μm^2 pixels
- 80x336 pixels per matrix (2x2 cm^2)
  - quad- and sext- modules possible
- 25 ns bunch crossing (40 MHz clock)
  - every 4 pixel group FE logic shares a buffer for 256 bunch crossings "memory"
- sensitive layer: PPS, 3D, Diamond

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- readout on trigger request
  + self trigger mode
  with tunable sensitive area

What will make it into the AIDA telescope?

Larger Mimosa planes (by IPHC Strasbourg)

- 2x2 cm^2 stiched to hold 2x2 or 2x3 sensors (covering 4x4 or 4x6 cm^2)
- double sided ladders will cover 1x12 cm^2 with a 2-hit track “pointers”

Larger Mimosa sensors as reference planes
SALAT + AID box project (by Strasbourg) ??