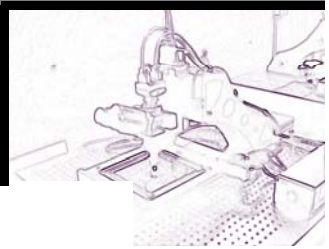
The European Scanning System for the measurement and analysis of OPERA neutrino interactions with nuclear emulsions

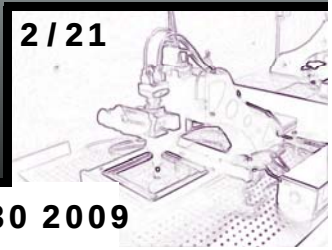
Michela Ieva, INFN-Bari

on behalf of OPERA Collaboration



Outline

- **OPERA overview**
- **Nuclear emulsion technique**
- **The European Scanning System**
- **OPERA run 2008 first results**



OPERA physics motivations

Standard Model : neutrino massless ⇨ if $m_\nu \neq 0$ new physics!

experimental methods for massive neutrino detection ⇄ direct estimation of m_ν...

⇄ phenomena allowed only if $m_\nu \neq 0$

⇩

Oscillation: neutrino flux variation of a given *flavour*

atmospheric sector

disappearance experiments :

SK I + II **K2K** **MINOS**

deficit **observed in expected fluxes**

appearance experiments

⇩

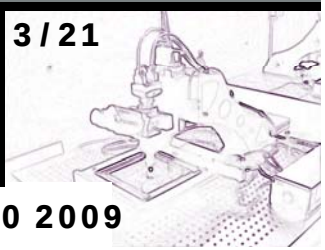
$\nu_\mu \rightarrow \nu_\tau$ oscillation final test:

ν_τ appearance in a pure ν_μ beam: OPERA

Global fit and 3σ range:

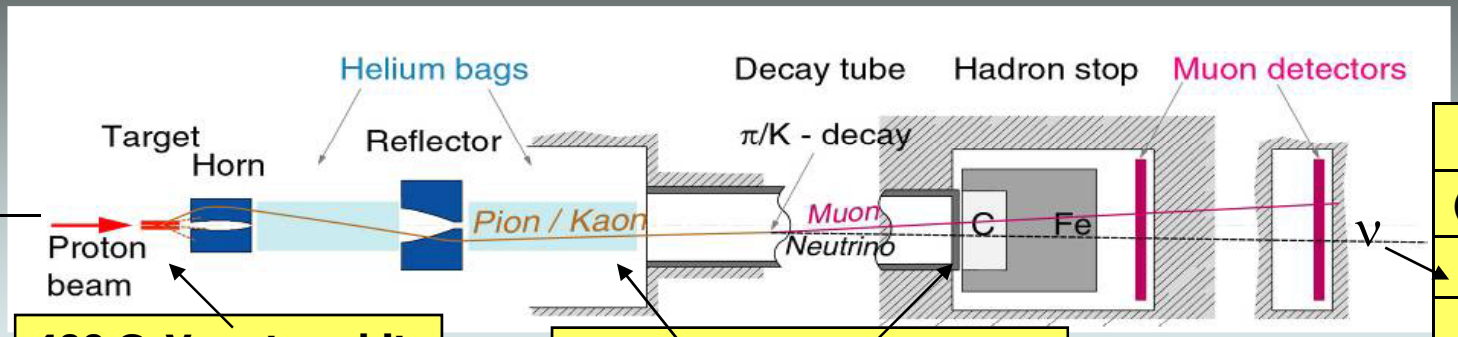
Parameter	$\sin^2\theta_{23}$	$\Delta m^2/10^{-3}$ eV^2
Best fit	0.466	2.39
1σ range	0.408 – 0.539	2.31 – 2.50
2σ range	0.366 – 0.602	2.19 – 2.66
3σ range	0.331 – 0.644	2.06 – 2.81

(G. L. Fogli *et al.*, Phys.Rev.D78:033010, 2008)



Oscillation Project with Emulsion-tRaking Apparatus

CNGS CERN neutrino beam:



$<E\nu_\mu>$	17 GeV
$(\nu_e + \bar{\nu}_e) / \nu_\mu$	< 1%
$\bar{\nu}_\mu / \nu_\mu$	~ 4%
ν_τ prompt	negligible
p.o.t. / anno	4.5×10^{19}

400 GeV protons hit a graphite target

π and K decay in flight producing neutrino beam

OPERA expected signal and background:

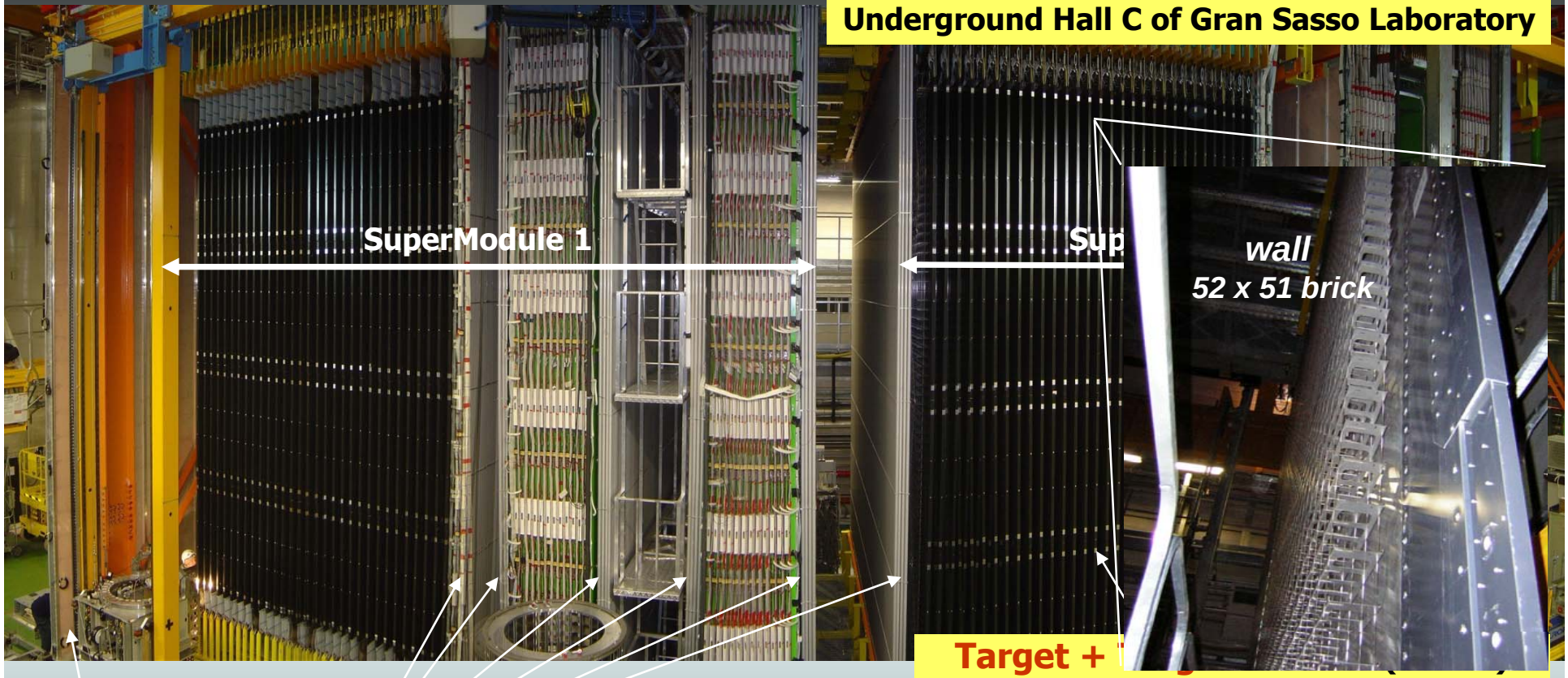
full mixing, 5 years run @ 4.5×10^{19} pot / year

τ decay channel	B.R. (%)	Signal ($\Delta m^2 = 2.5 \times 10\text{-}3\ eV^2$)	Background
$\tau \to \mu$	17.7	2.9	0.17
$\tau \to e$	17.8	3.5	0.17
$\tau \to h$	49.5	3.1	0.24
$\tau \to 3h$	15.0	0.9	0.17
Total		10.4	0.75

search for $\nu_\mu \to \nu_\tau$ oscillation in the parameters space of atmospheric neutrinos

OPERA detector

Underground Hall C of Gran Sasso Laboratory



Veto (RPC)

Muon Spectrometer (8×10 m²) :

High precision tracker
- 64-fold layers of drift tubes

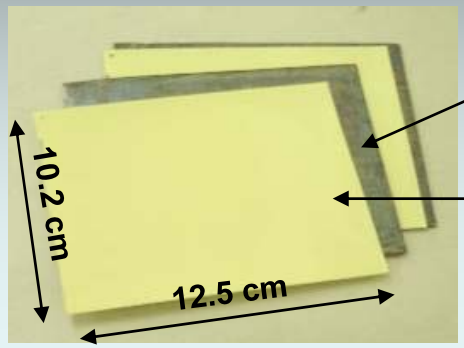
Dipole magnet
- 1.53 *T*
- 22 x 2 XY planes of RPC

Target +

- target: 2 SM, ~150000 bricks in 27 walls of SM1 and 26 walls of SM2
  Mass: ~1.25 kt
- Target tracker : doublets XY (256 plastic scintillator strips + WLS fibres+ PMT's)

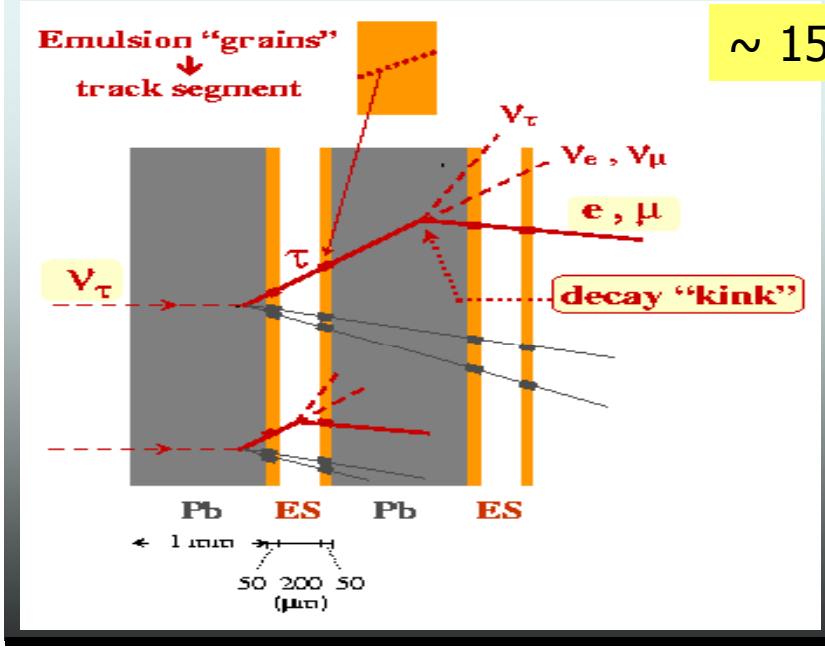
The basic element of OPERA target

A **brick** consists of a compact and modular structure made of 57 **emulsions films** (300 μm thick) spaced with **lead plates** (1 mm thick)



Pb plates

emulsion film:
2 emulsion layers (44 μm thick)
glued on a 200 μm plastic base



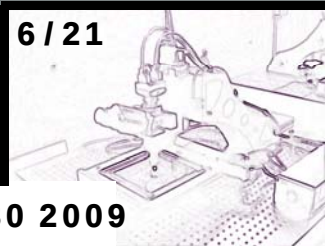
~ 150000 bricks in the OPERA target (~1.25 kton)

@4.5x10^{19} p.o.t./year, 200 days/year means

4500 ν_μ (CC + NC) /year ⇒ ~ 25 bricks/day ⇒

~ 1400 emulsion films/day have to be analyzed

need fully automatic systems
with high precision and
very high scanning speed



The nuclear emulsion technique

target ~ 8.5 millions of nuclear emulsion films

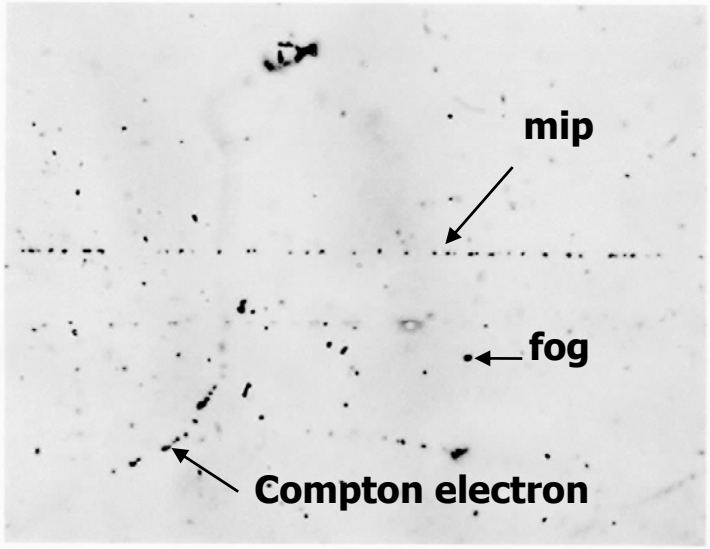
need mass production by Fuji Film

nuclear emulsion is a *special* type of photographic film made of AgBr crystals in organic gelatine and able to record tracks of charged particles with an accuracy < 1 μm

charged particles, passing through emulsions, ionize AgBr atoms that, after chemical treatments, become **black grains** along the particle track

OPERA emulsion films exposed vertically

track: sequence of grains aligned along film thickness



- **sensitivity**
  mip ionization
  ~ 36 grains per 100 μm
- **fog**
  ~ 9 grains per 1000 μm^3

- **grain dimension**
  ~ 0.6 μm

High precision tracking

Decay Kink detection, Vertex topology reconstruction

Momentum measurement

Multiple Coulomb Scattering

($\Delta p/p < 0.2$ after 5 X_0 up to 4 GeV)

Ionization (dE/dx measurement)

π/μ separation

Electron and γ identification and energy measurement

Electron-pion separation

Calorimetric energy evaluation ($\sigma/E = 40\%/\sqrt{E}$)

OPERA bricks measurement

Extracted bricks are shared among of emulsion laboratories:

Europe

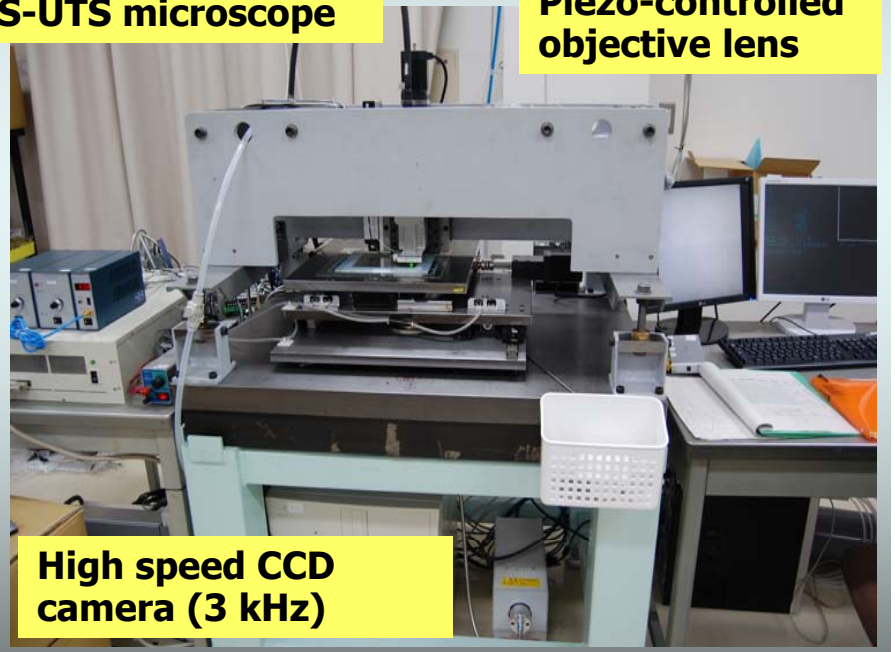
Bari (Italy)
Bern (Swiss)
Bologna (Italy)
LNF (Italy)
LNGS (Italy)
Padova (Italy)
Naples (Italy)
Rome (Italy)
Salerno (Italy)

Japan

Nagoya (Tono lab)
Toho

S-UTS microscope

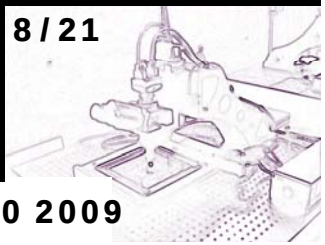
Piezo-controlled objective lens



High speed CCD camera (3 kHz)

ESS microscope

Hard-coded algorithms and custom mechanics



European Emulsion Scanning System

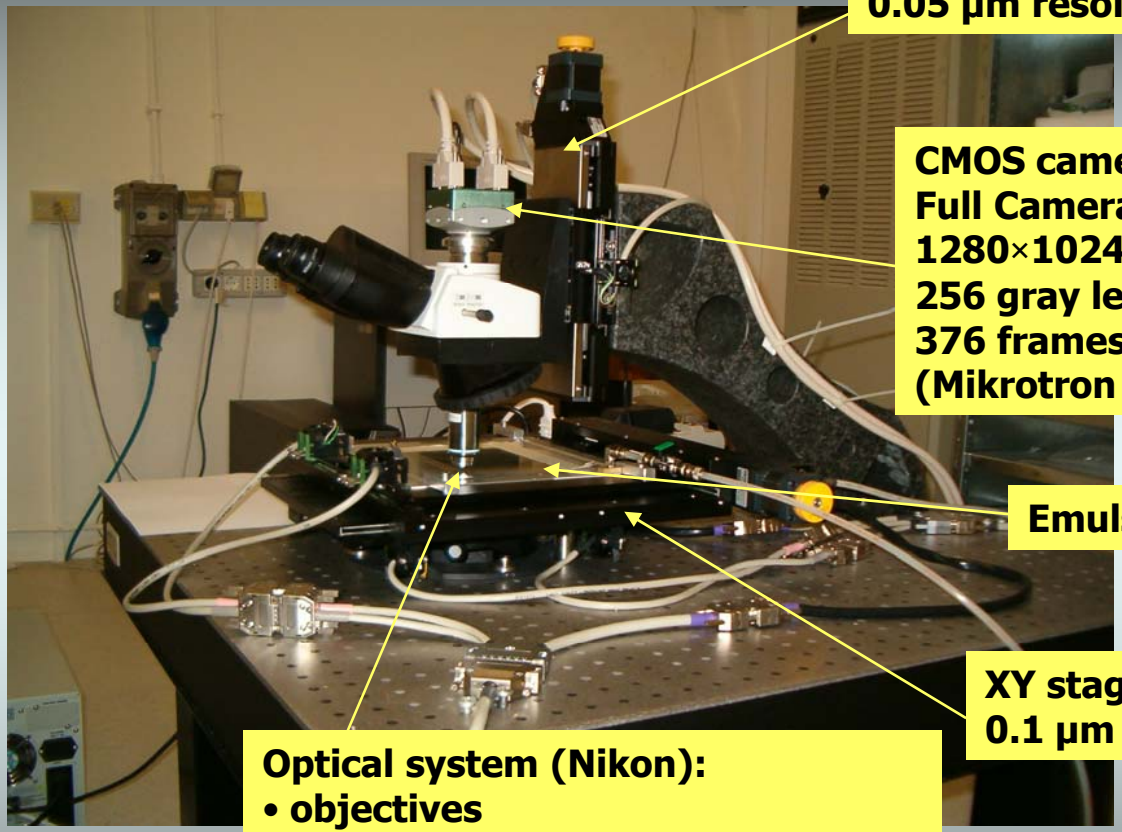
R&D of European emulsion laboratories

hardware developed in cooperation with high-technology firms

thanks to CMOS cameras, double processors and parallel processing

scanning speed: ~ 20 cm^2/h

spatial precision: ~ 0.5 μm



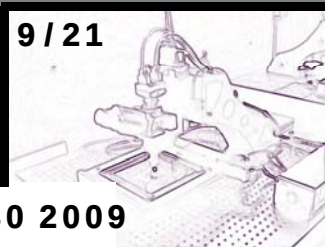
Z stage (Micos)
0.05 µm resolution

CMOS camera
Full Camera Link
1280×1024 pixels
256 gray levels
376 frames/sec
(Mikrotron MC1310)

Emulsion plate

XY stage (Micos)
0.1 µm resolution

Optical system (Nikon):
- **objectives**
  - **Oil 50× NA 0.85**
  - **Dry 50× NA 0.95**
- **optical tube:**
  - **bottom-up illumination box**
  - **collective lens**
  - **condenser NA 0.95**



Emulsion Data Taking

All microscope functionalities are handled by a remote work station **(xeon 2.8 GHz double processor)** equipped with two supplementary cards directly connected on bus PCI-X

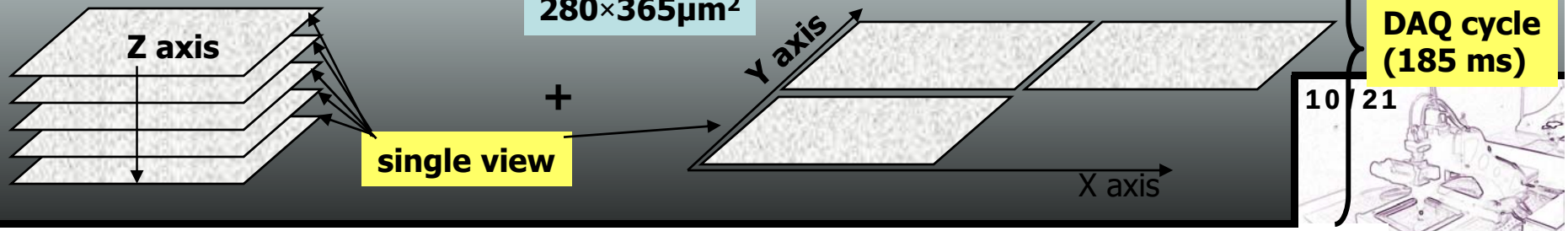
- vision processor **(Matrox Odyssey XPro)**
  image taking and analysis
- motion controller **(National Instruments Flex Motion 7344)**
  horizontal motion of the emulsion plate
  vertical motion of Z stage equipped with camera

The data taking software, written in Windows C#, C++ and Assembler, is completely object oriented and fully modular

main steps:

Z axis moving, taking tomographic sequences of 2D images spanning emulsion thickness of one field of view

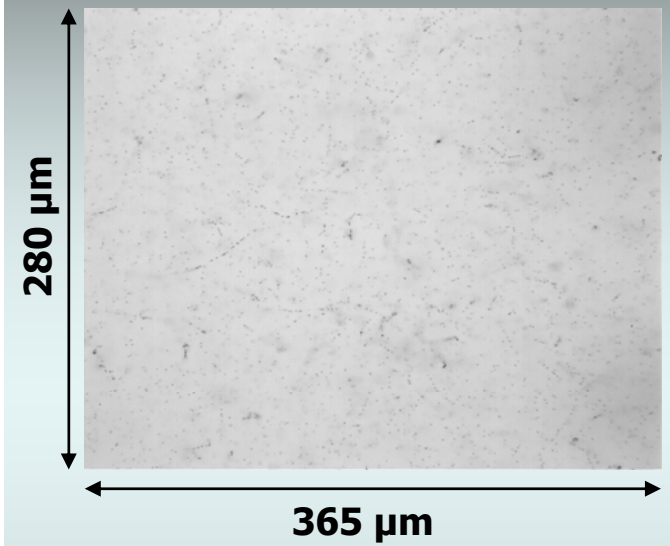
XY emulsion stage motion to next view



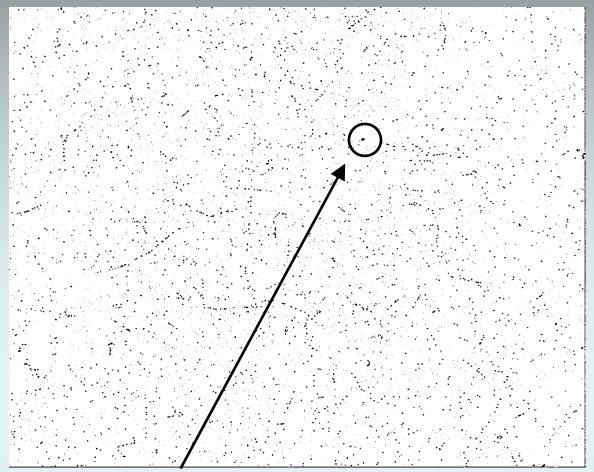
… in parallel with image taking…

15 images per view
~ 10 grains of signal/image,
~ 3000 grains of background (noise, shadows, scratches, spots)

image processing

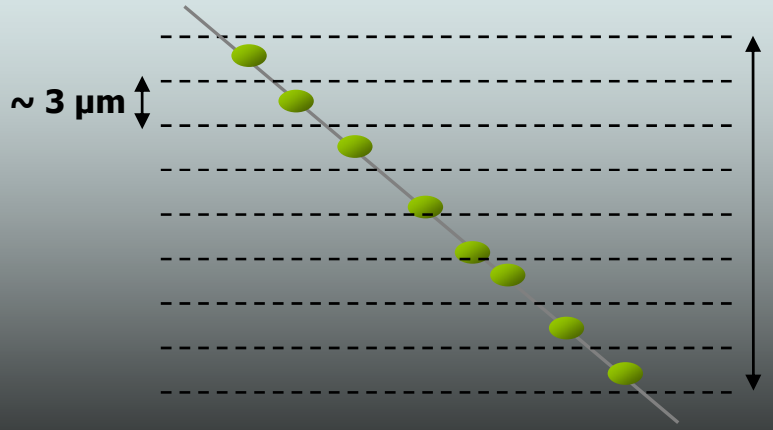


2D FIR Filter+
Equalization+
Threshold



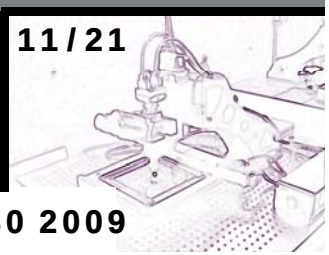
Grain recognition
(Host PC, multithreaded Assembler code)

tracking

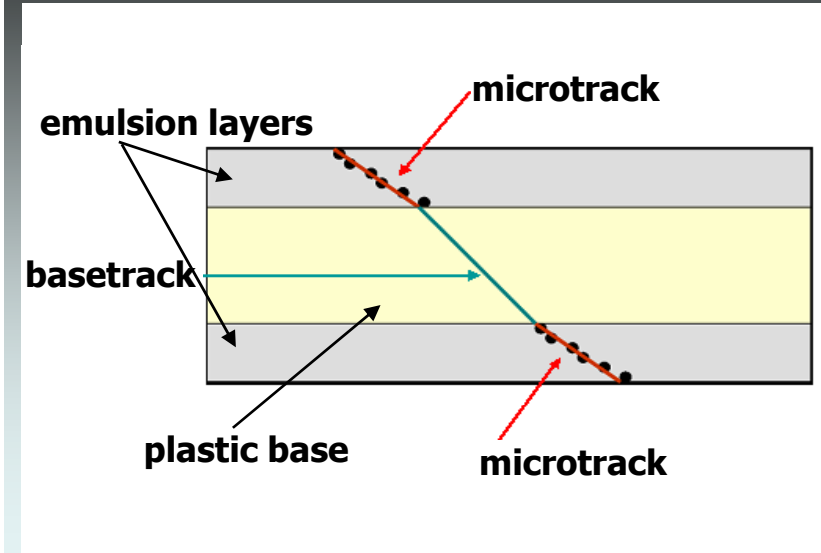


3D micro-track reconstruction
(Host PC, multithreaded C++ code):
searching for sequences of aligned grains at different Z levels

300 ÷ 3000 micro-tracks/view



Quasi on-line data analysis

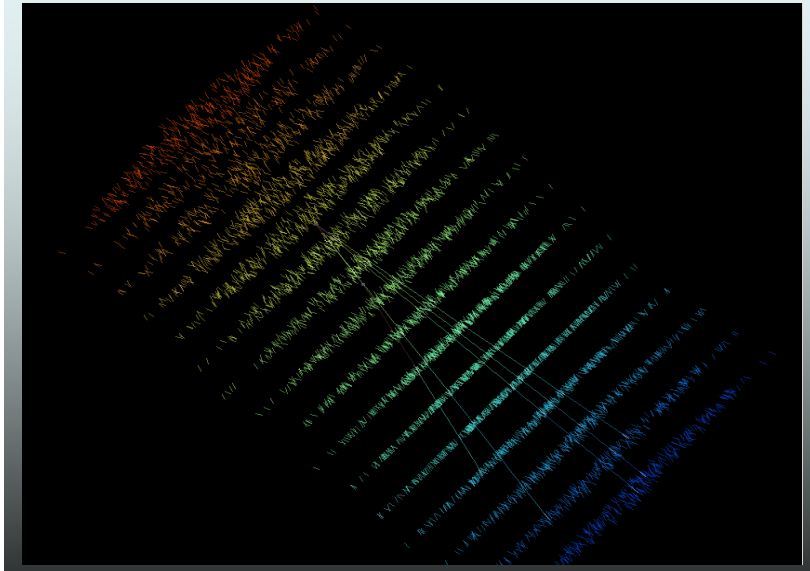


track trajectory reconstruction through a single emulsion film:

searching for matching pairs of micro-tracks within angular and position tolerances

a micro-tracks pair makes a base-track

1 ÷ 10 base-tracks/view



volume alignment:

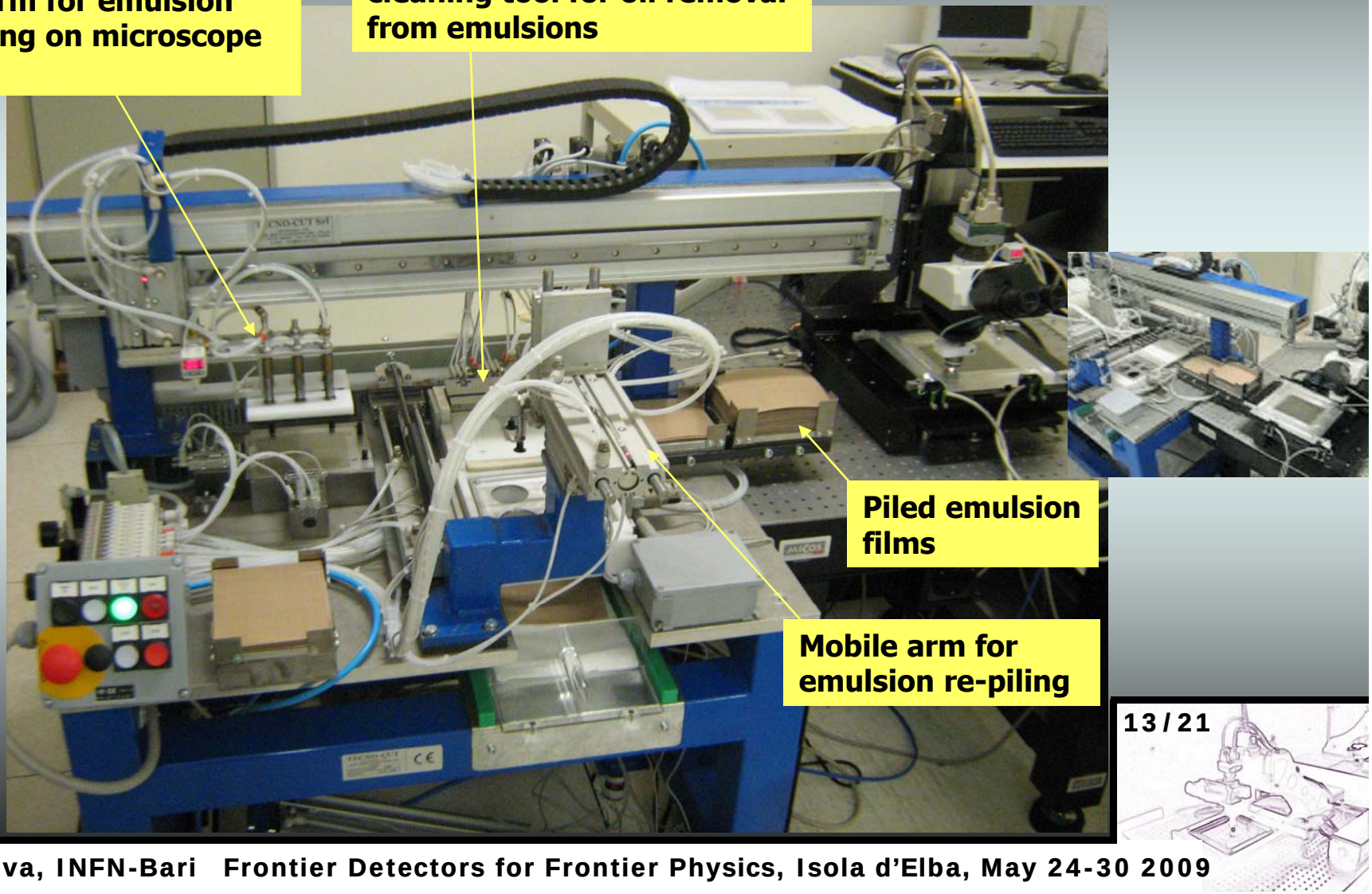
determination of affine transformation parameters for film by film alignment using pattern matching

volume tracking:

a sequence of base-tracks aligned within angular and positions tolerance makes a volume track

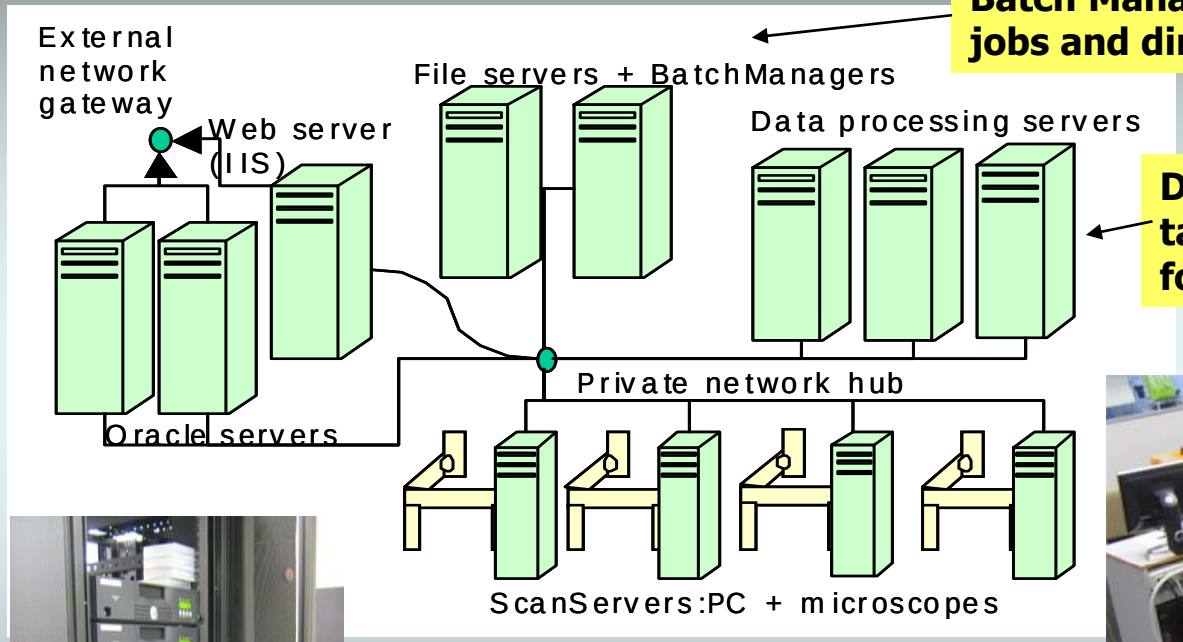
Automation improvement: the plate changer robot

To speed up the scanning procedure, a dedicated robot has been developed **(TecnoCut)** for automatic and precision positioning of emulsion films



Computing Infrastructure and Data Storage

Data taken by microscopes are sent to temporary file servers and processed using a distributed computing infrastructure **(based on .NET)** and connected with 1Gbps private network



Batch Manager coordinates jobs and directs Scan Servers

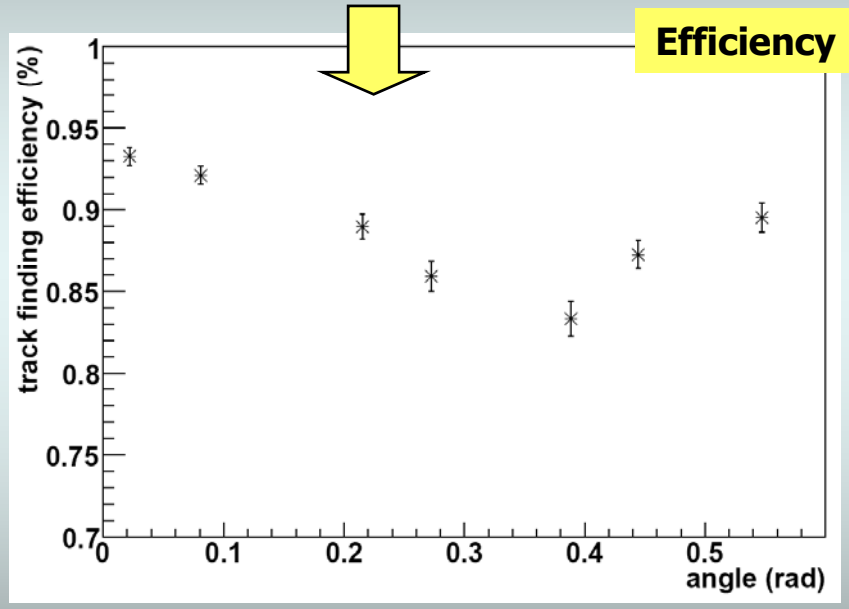
Data Processing Servers take care of heavy computing for data post-processing

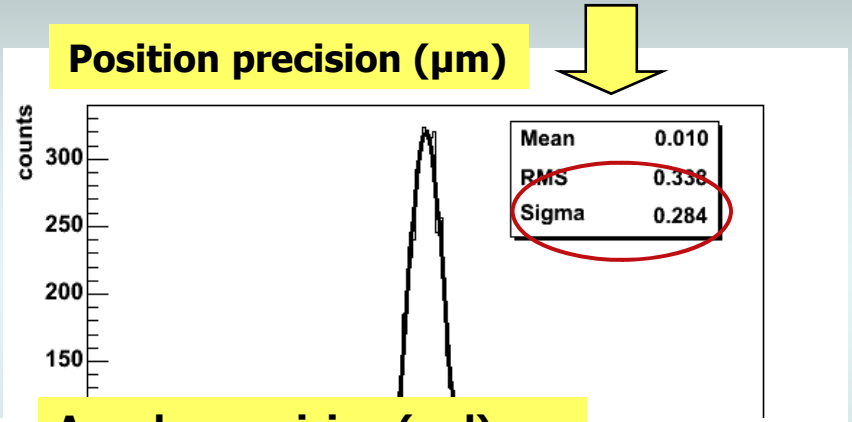
Raw and processed data are written on local Oracle DB server used also for physics analysis and data sharing

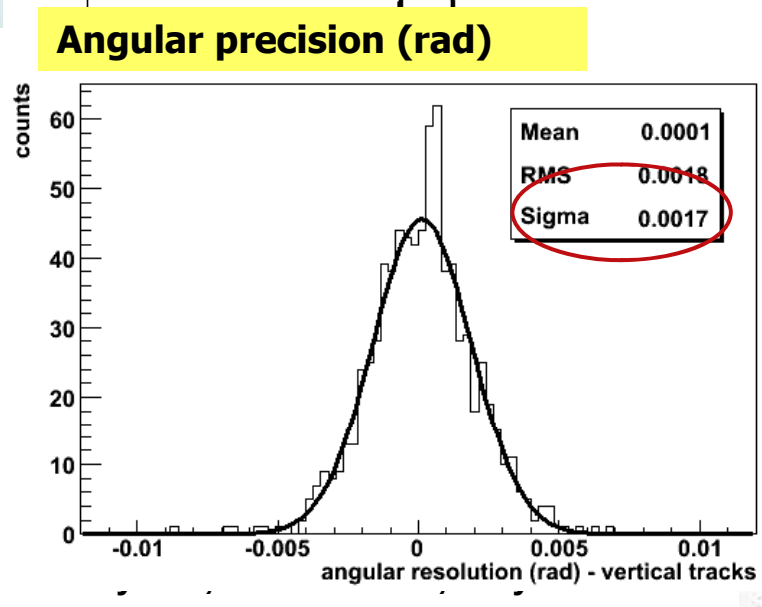
Data from different emulsion labs, **(European and Japanese)**, are collected in a Central OPERA DB **(OpIta-LNGS, OpFra-Lyon, up to 5 Tb for run 2008)**

Performance of the ESS

- **Scanning speed**: 20 cm^2/h/side (40 GB/day/microscope of raw data)
- **Purity**: 10 fake tracks/cm^2 (slope < 0.5)
- **Efficiency**: up to 95% using base-tracks ~100% using micro-tracks
- **Precision**: 0.3 ÷ 0.7 μm and 2 mrad for volume reconstructed tracks

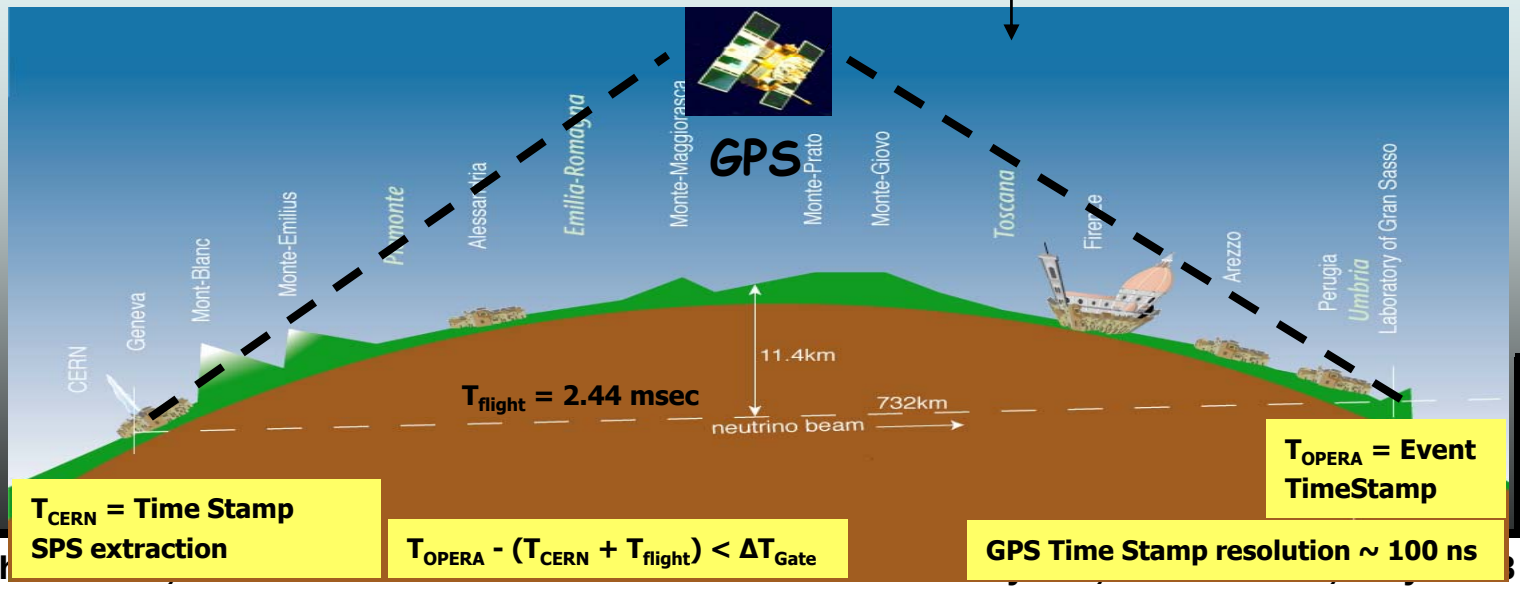






OPERA runs

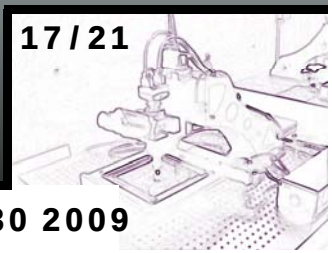
- **2006**: short commissioning run
- **2007** (24th September - 20th October):
  - ✓ 0.082 x 10^{19} pot (i.e 1.8 x 10^{13} protons/extraction)
  - ✓ ~ 3.6 effective nominal days (32±6 interactions expected in the bricks)
  - ✓ 38 interactions found
- **2008** (June 18th - November 3rd):
  - ✓ 1.782 x 10^{19} pot
  - ✓ 10100 events "on time"
  - ✓ ~1700 interactions in the bricks
  - ✓ 0.7 τ events expected



Run 2008: vertex location preliminary results

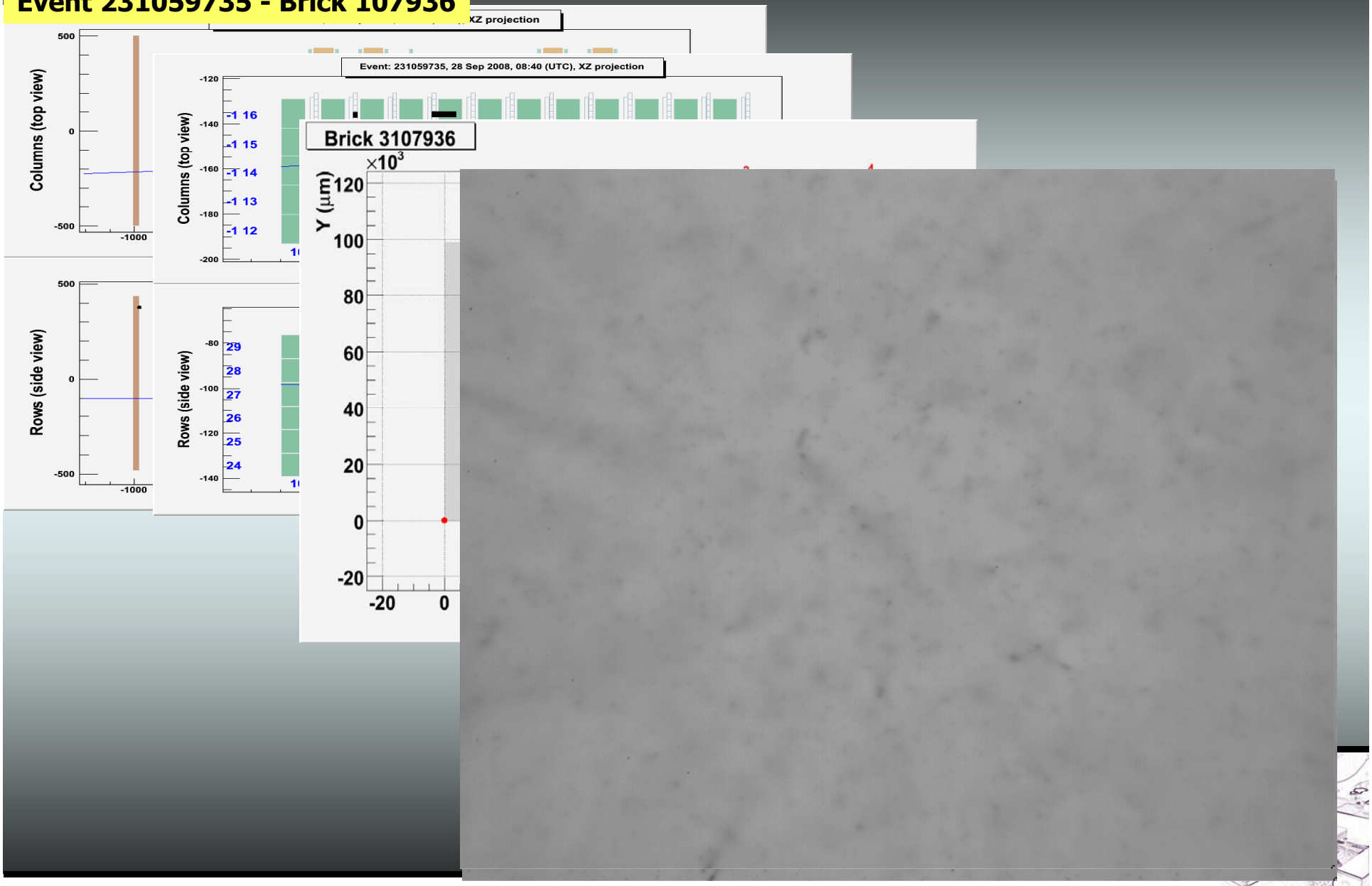
Event analysis @ 2009, May 22th

	NC	CC	Total
Bricks scanned	167	775	942
Vertices located	102	591	693
Passing through-tracks	11	38	49
Vertices in dead material	2	11	13

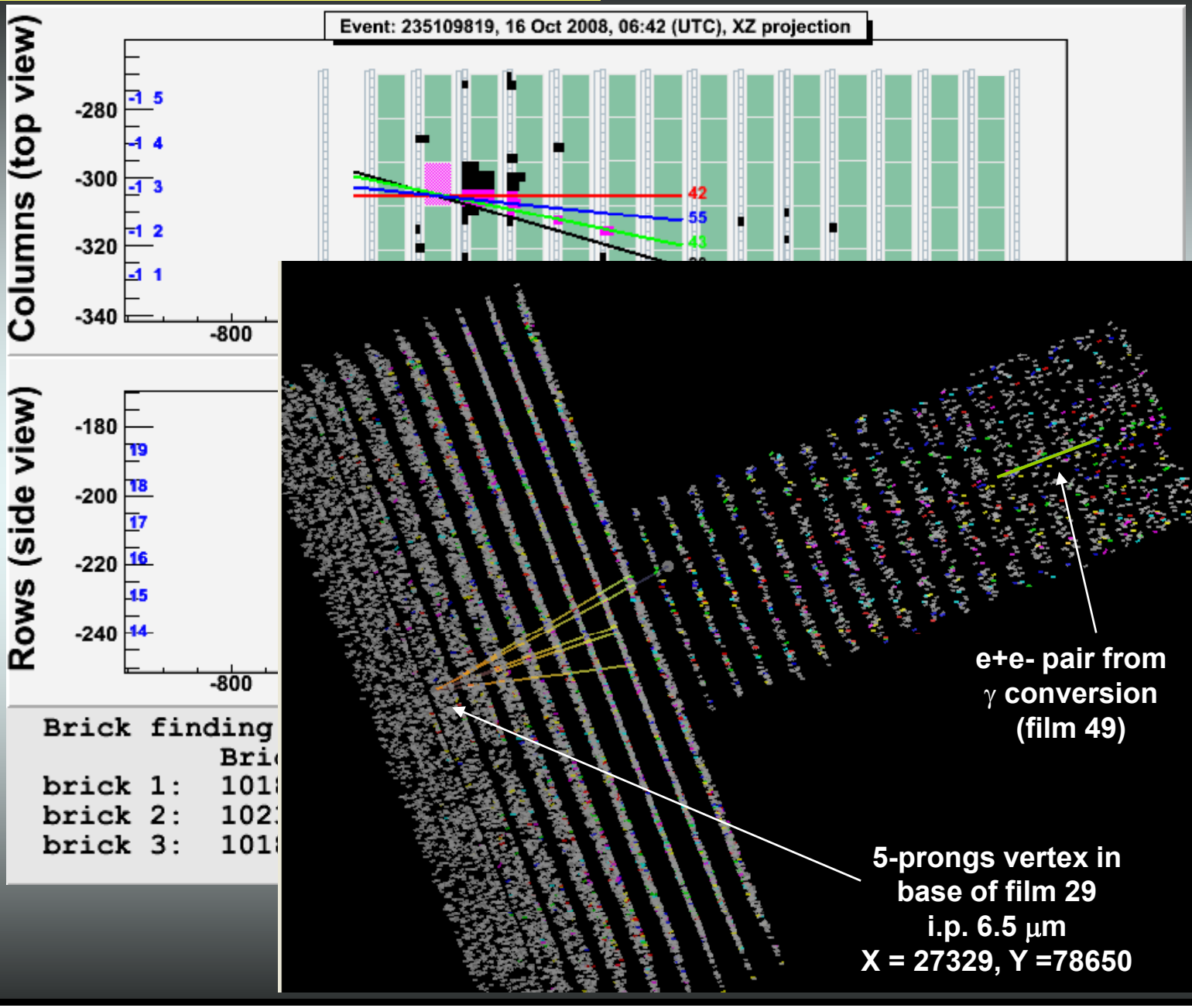


Neutrino interactions: some examples

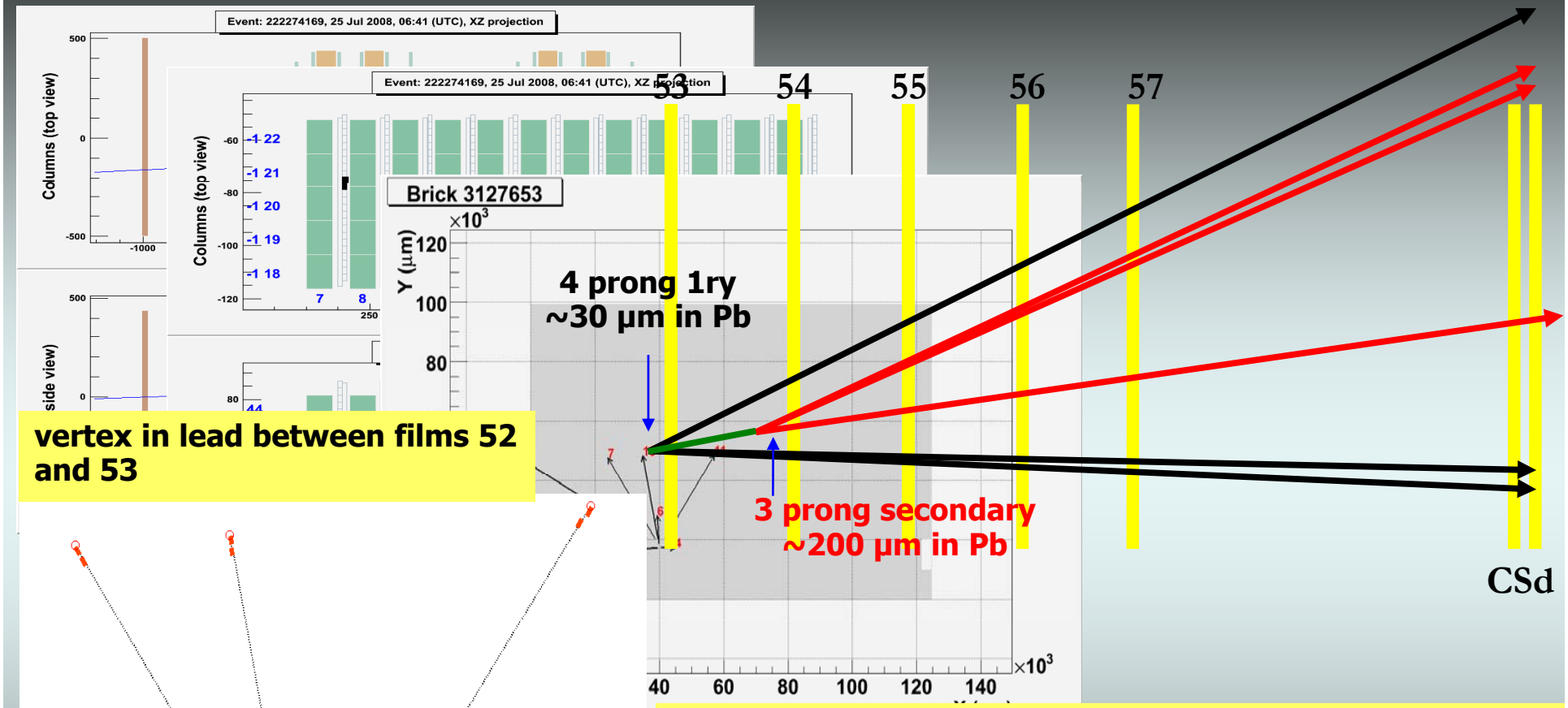
Event 231059735 - Brick 107936



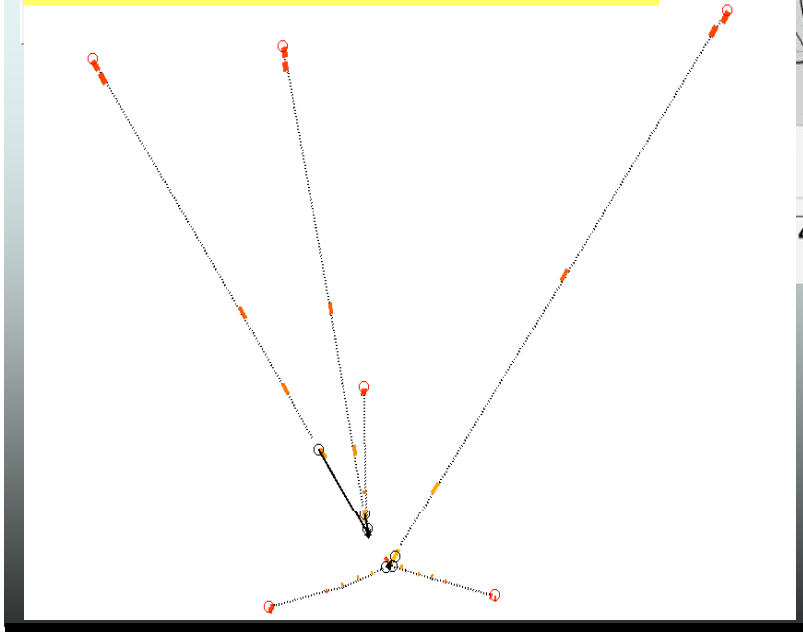
Event 235109819 (NC) – Brick 1018966



Charm candidate



vertex in lead between films 52 and 53



Charged parent path length ~ 1150 μm
$\Delta\Phi$ ~ 150° (~ back to back favour charm interpretation)
$p_1=2.4^{+1.3}_{-0.6}$ $p_2=1.3^{+0.4}_{-0.3}$ $p_3=1.2^{+1.7}_{-0.4}$ GeV/c
(evaluated by using multiple coulomb scattering)

Probability of hadron reinteraction ~10^{-6}

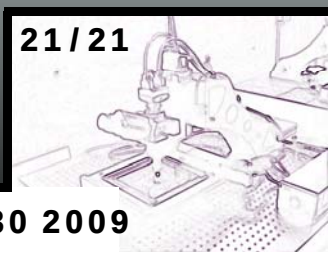
Conclusions and perspectives

- The ESS is competitive and suitable for OPERA needs.
  Moreover, thanks to the use of commercial components, the system may be improved: scanning speed, precision, tracking and image processing power could be made better.
- Emulsion scanning laboratories and infrastructures are operational.
- OPERA data taking started in 2007 with a short run.
- Analysis of RUN 2008 data is in progress:

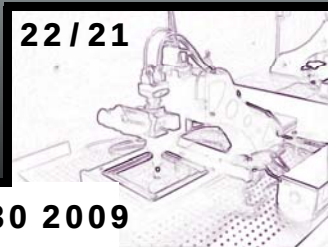
693 ν_μ neutrino interactions located
7 charm candidates events detected

next challenge:

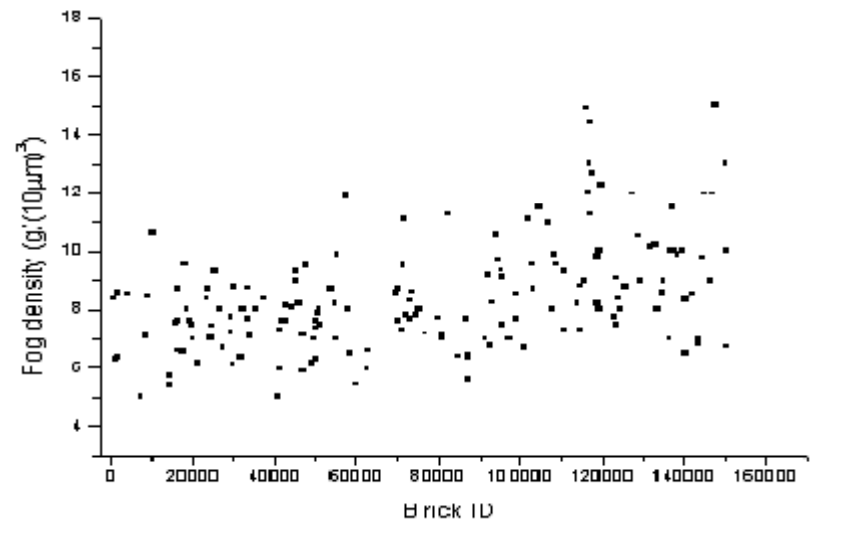
to see the first τ event!

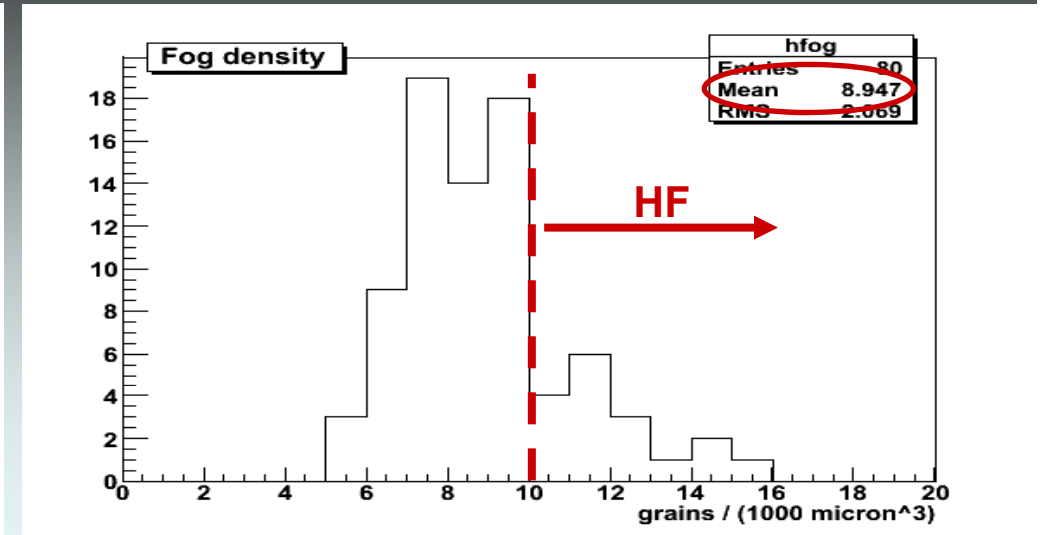


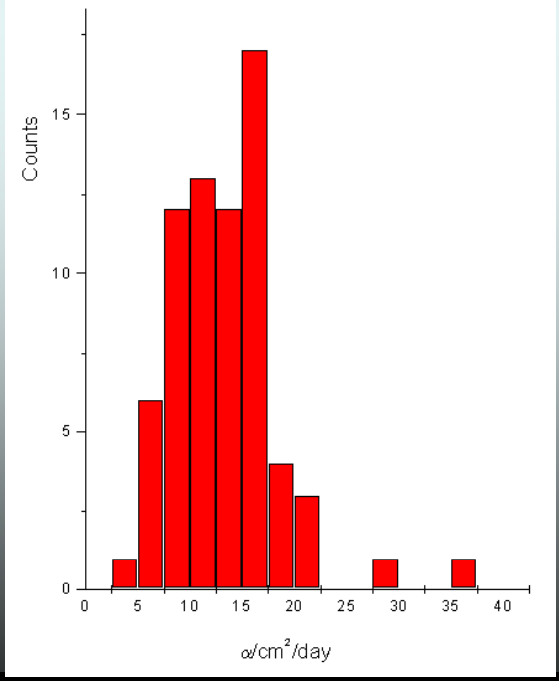
Backup slides:

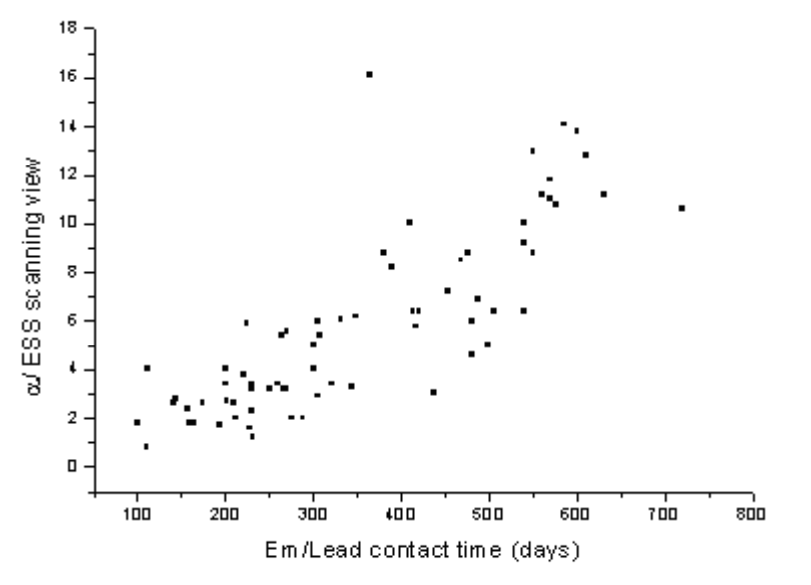


Background grains in emulsion



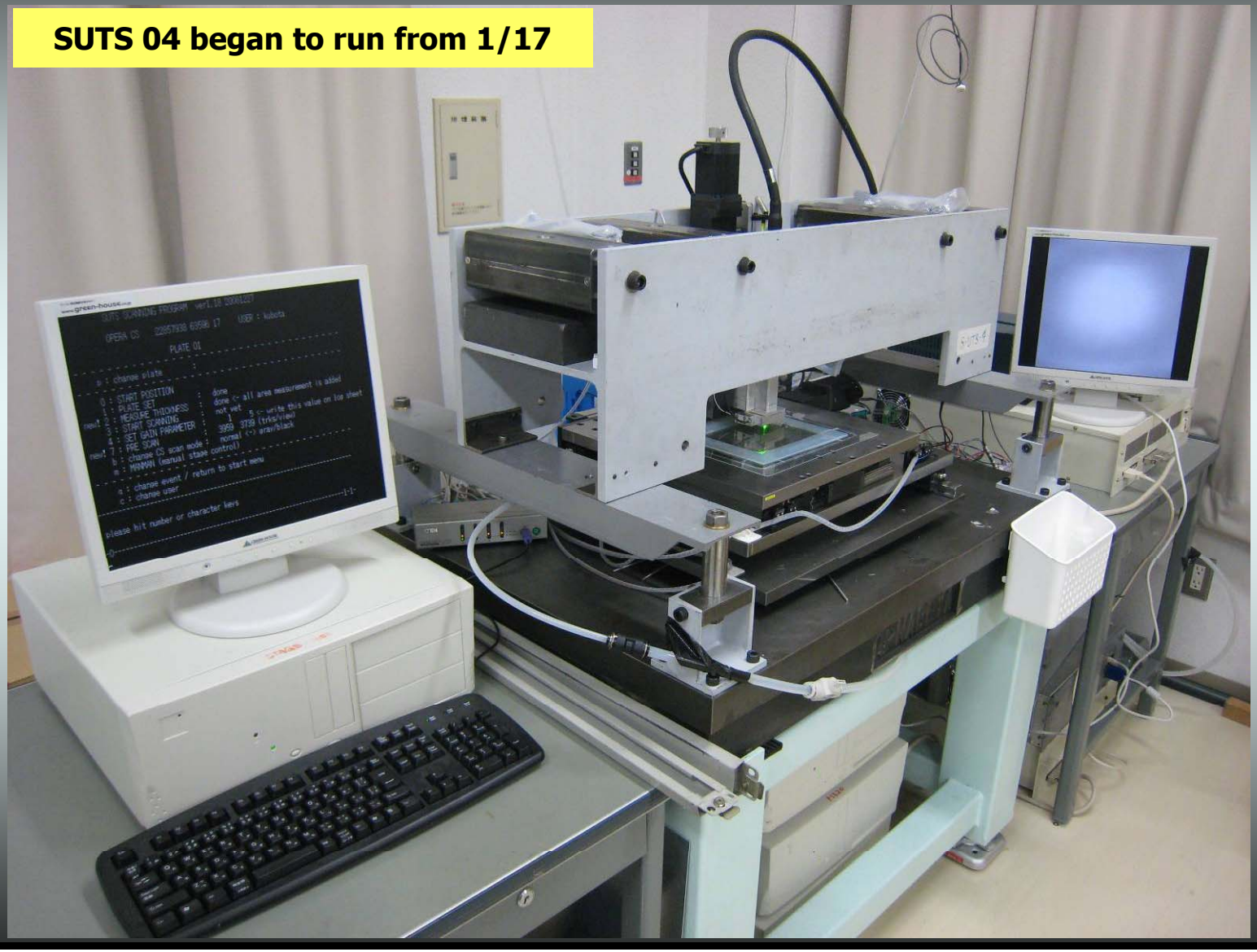


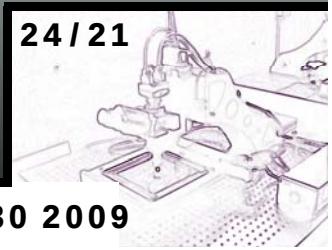




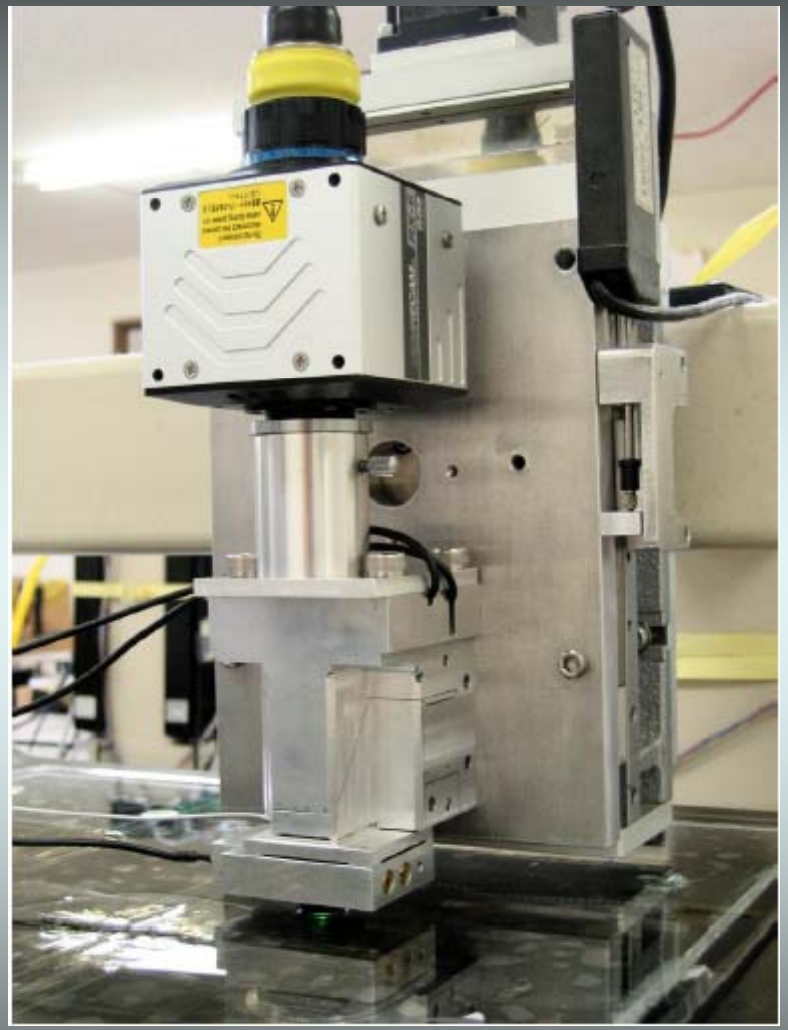
Emulsion scanning in Japan: the SUTS

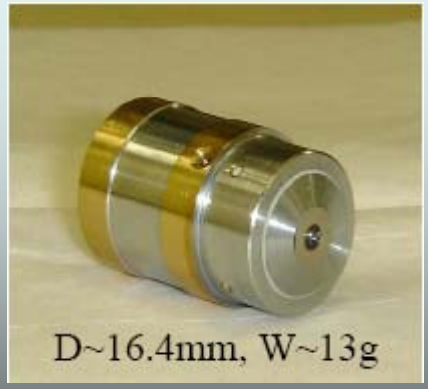
SUTS 04 began to run from 1/17





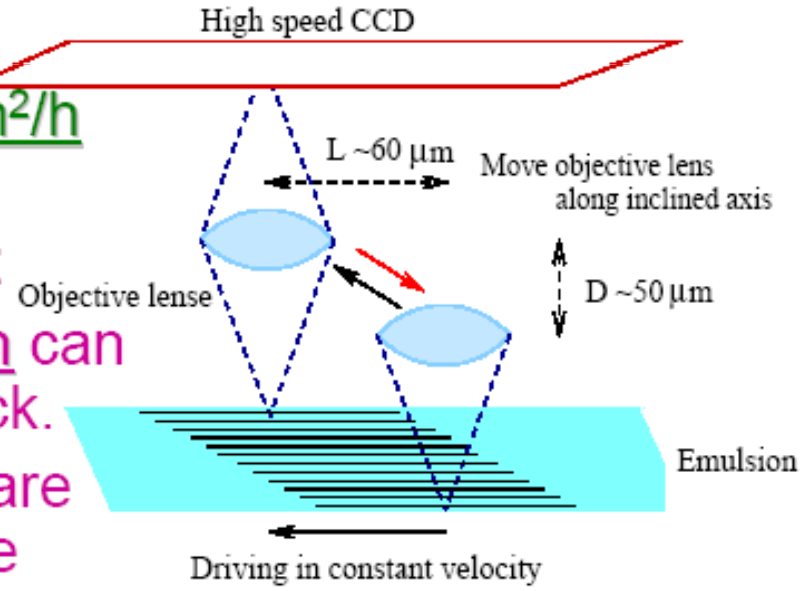
The Piezo-driven optics



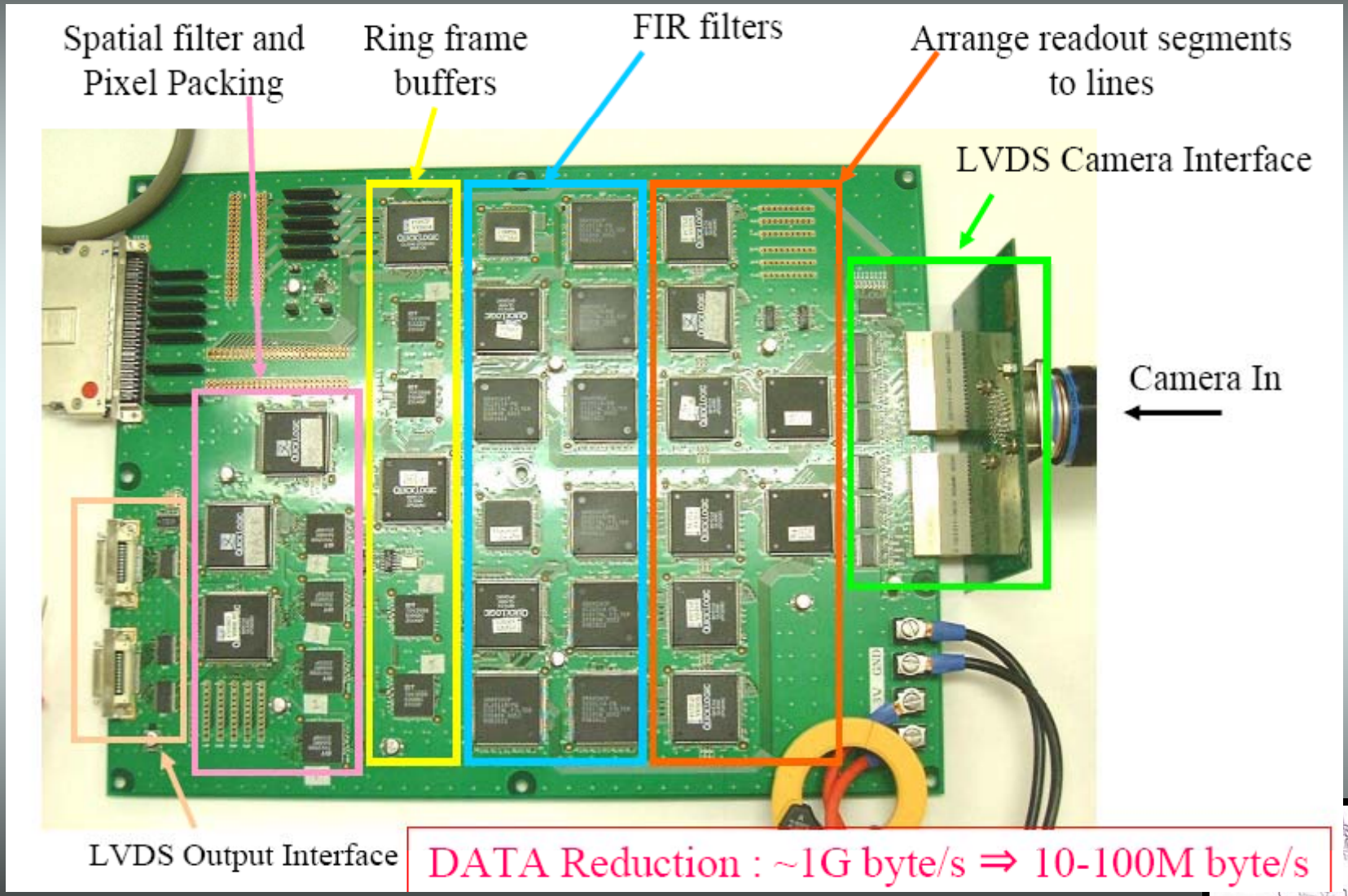


No step and repeat image taking (follow shot method)

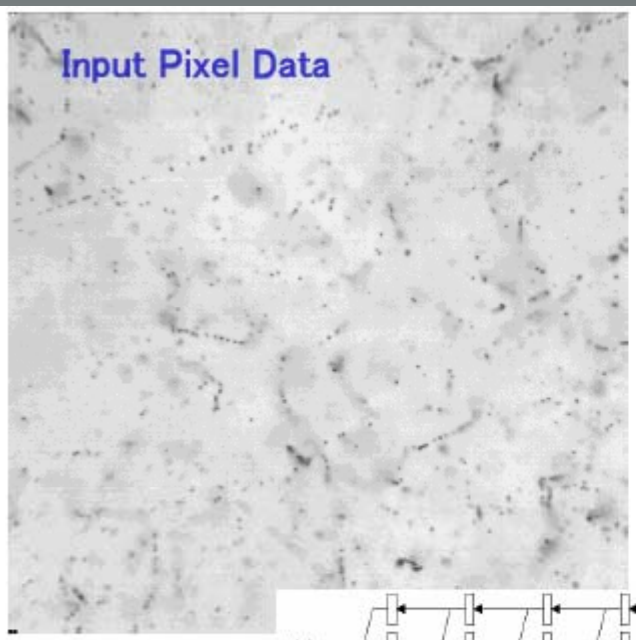
- Use Ultra High Speed Camera
  - Up to 3k frames per second.
    → Max 90views/sec~60cm²/h
- Image taking by follow shot
  - No step and repeat operation can avoid a mechanical bottleneck.
  - FOV displacement and Blur are canceled by moving objective lens

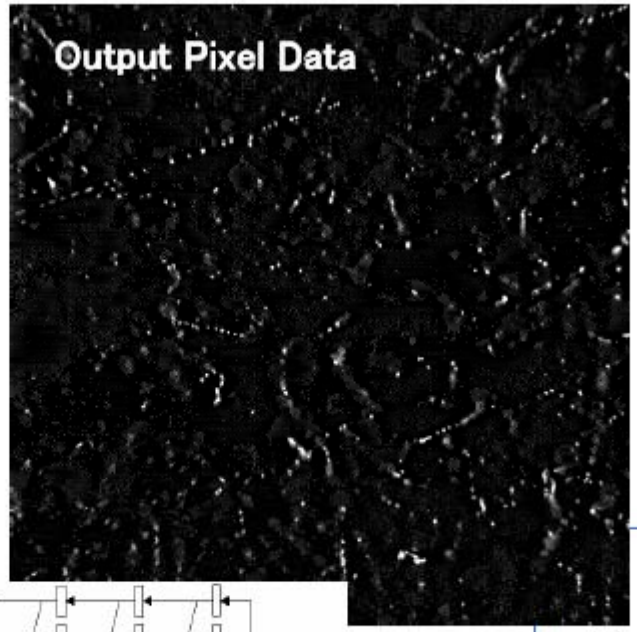


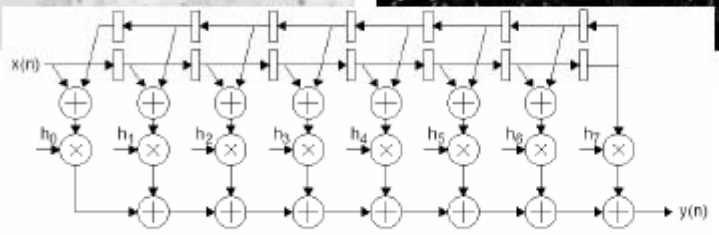
Real-time image filtering and Packing Processor



Pre-processing before track recognition

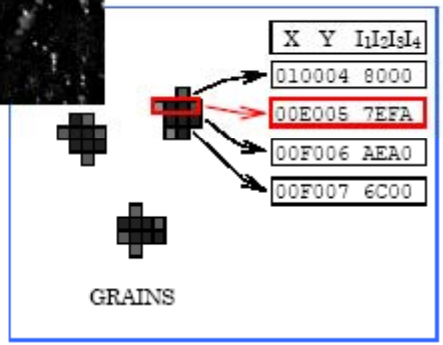






(c) 15 TAP ODD SYMMETRY FILTER

Ref. GC2011A 3.3V DIGITAL FILTER CHIP DATASHEET, GRAYCHIP, INC.



Subtract DC and LF component, like defocus grains.

Zero suppression (Record only pixels over the threshold with address)

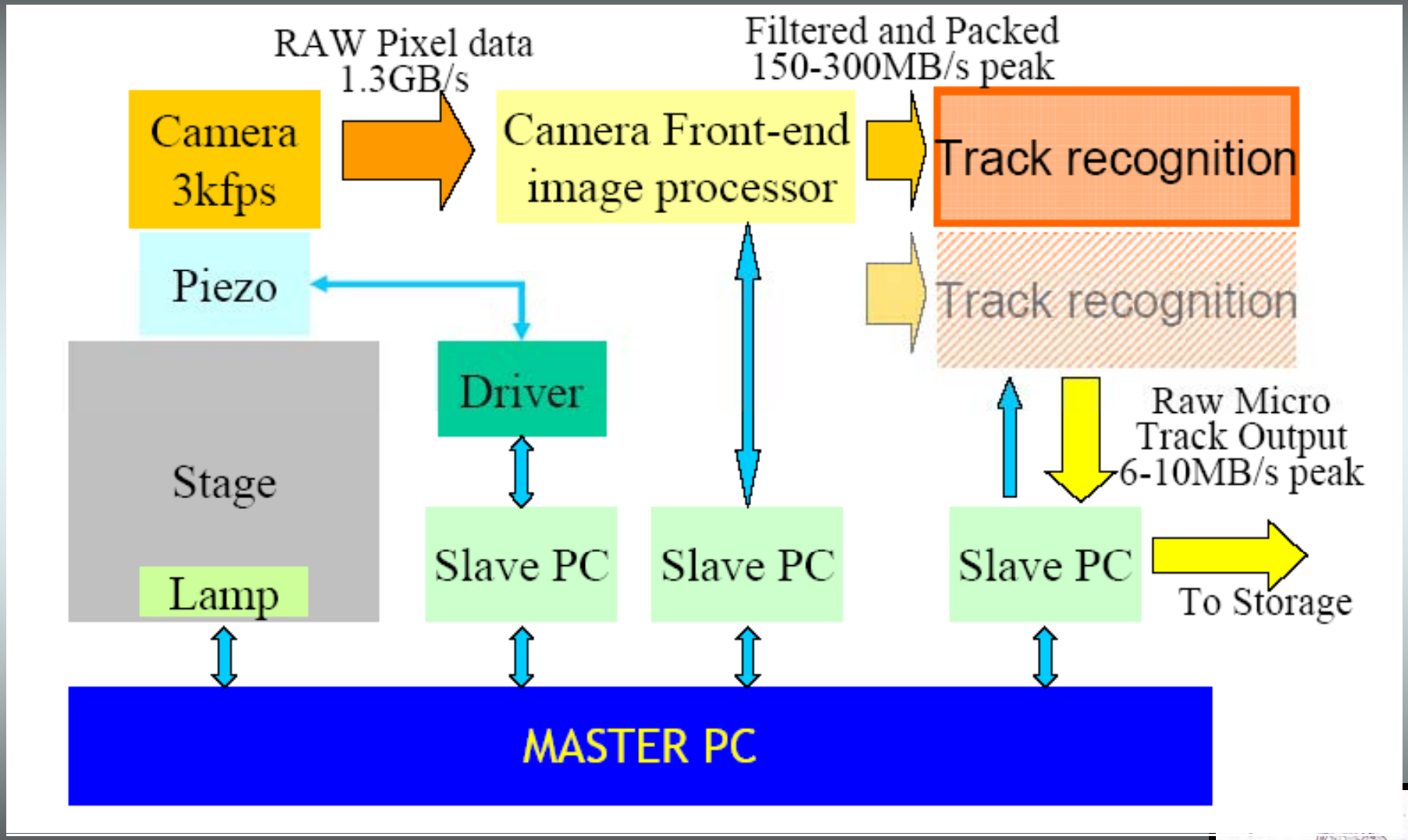
SUTS
Track recognition board

Processing speed :
>40cm^2/h/board

Internal Band width
40Gbyte/s/FPGA

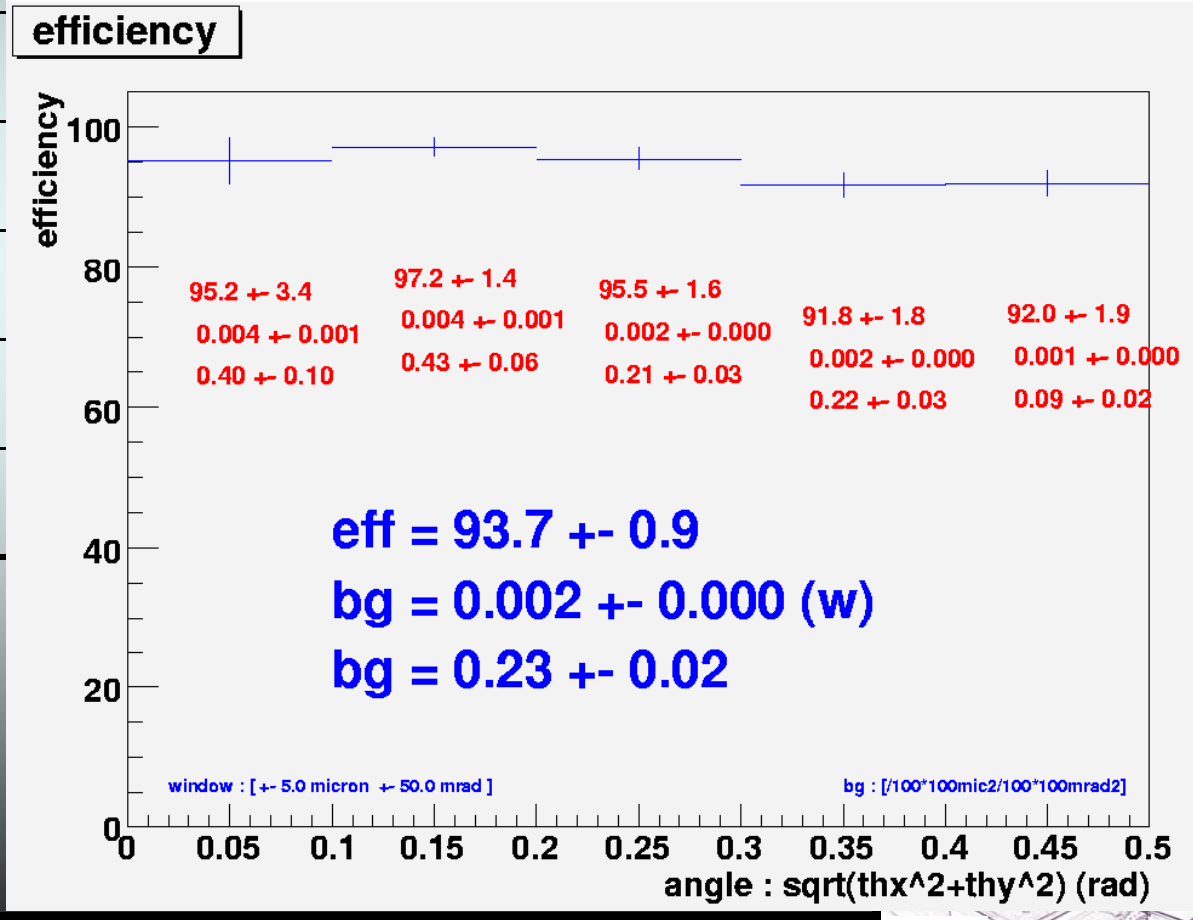
× 1

SUTS block diagram



SUTS 04 performance and efficiency

	Optical Magnitude	Speed (100cm2 area scan) (cm2/hour)	MicroTrack Angle resolution mrad (Tanθ<0.1)	
			X	Y
SUTS01	50			
SUTS02	35			
SUTS03	35			
SUTS04	35			
SUTS05	35			



Vertex location: some details

- ~ 1700 probable interactions in the bricks

Events with very low energy or very marginal

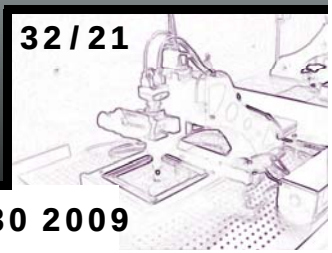
- ~ 1600 events with electronic detectors predictions

Brick finding efficiency ~ 75 %

- ~ 1100 events selected and already developed

Analysis in progress… (~ 80 % completed)

- ~ 942 events analyzed
- ~ 693 events located

Event location:

Upper limit	Lower limit	Dead material
NC: ~ 92%	NC: ~ 71%	13/693 ~ 2%
CC: ~ 94%	CC: ~ 84%