Detector developments at ESRF

M. Ruat on behalf on the Detector Unit and the Instrumentation Services and Development Division

APS 3-Way Meeting, Detector Workshop, July 31st 2013
Outline

The Detector Unit at ESRF

Overview of current developments

Beamlines Upgrade program (UPBL)

Warning: this is a non-exhaustive and subjective presentation....
The Detector Unit is part of the **Instrument Services and Developments Division (ISDD)**
The Detector Unit at ESRF

The Detector Unit is composed of:
- 9 Engineers
- 7 Technicians (Detector Technical Support Team (DTST))
- 1 visiting engineer from ALBA
- 1 PhD student
- 1 Administrative assistant

Spread into 5 laboratories

A balanced combination of:
- **Services:**
  Advice, test, commissioning, loan, BL operation, administrative support (CFT, RFQ, EU project, ...)
- **Instrument development:**
  Detectors and control electronics
- **Production**
  Mainly of in-house developments
Detectors @ ESRF: overall picture and foreseen evolution

- High energy diffraction
- Soft Condensed Matter
- Inelastic Scattering
- Coherent beam
- X-ray Imaging
- Fluorescence Spectroscopy

- LARGE AREA INTEGRATING
- PHOTON COUNTING 0D/1D 2D
- SMALL PIXELS
- 2D IMAGING
- ENERGY DISPERSIVE

- CURRENT DETECTORS
  - a:Si Flat Panels
  - Large Field CCDs
  - APD
  - MAXIPIX, PILATUS
  - Direct Detection CCDs
  - FReLoN (CCDs)
  - Commercial CMOS
  - SDD, Multielement Si, Ge

- NEW DETECTORS
  - Mini Flat Panel
  - New MAXIPIX
  - EIGER
  - Very small pixel detector
  - Fast imaging Camera
  - Next generations
  - Custom FReLoN

- UNDERLYING KEY TECHNOLOGIES
  - High Energy Scintillators
  - MEDIPIX3 Edgeless sensors
  - High Z Semiconductors
  - Optics
  - High Resolution Scintillators

- Fast Data Acquisition and Management

M. Ruat - 3-WAY Meeting Aug. 2013 - APS
**The Detector Unit at ESRF**

**PRODUCTION**

Regular production of devices (figures for 2012):

- Maxipix (4 systems delivered)
- FReLoN (3 cameras delivered)
- High resolution scintillators / SCF (~60 crystals produced)
- Electronic modules (MoCo, BCDU8, ...)
- A large number of customized I/O Boxes (WAGO)
- Beamviewers (focus on micro & nano beams, white beam)

Contract for the manufacturing of **2560 IcePAP axes** (over 3 years)

**Sales of equipment** to external labs:

- 2×2 Maxipix system (Soleil)
- 3 Monochromator controllers, MoCo (ALBA)
- 22 SCF scintillator crystals (Diamond, BNL, Australian Synchrotron, LBNL, Cornell, Max Plank, Carnegie Mellon, Korea, Bruker)

→ Production and R&D scintillator programme affected by an **accident in the LPE lab**
The Detector Unit at ESRF

DEVELOPMENTS : Examples of Know-How and associated projects

- Beam diagnostics
  - New Beamviewers (Diamond) & UPBLs
- OD photon counting (APD, scintillator + PMT + fast electronic)
  - XNAP Project
- Hybrid pixel detector (MAXIPIX)
  - Medipix 3 & SMARTPIX
  - Edgeless Si sensors
  - High-Z semiconductor sensors (HIZPAD² project)
  - PEEC (PSI-ESRF Eiger collaboration)
  - UPBLs
- X-ray Imaging (scintillator/phosphor, optical coupling)
  - Large field optical coupling
  - UPBLs
- CCD camera (FRELON)
  - UPBLs
- Spectroscopy
- Flat panel
Outline

The Detector Unit at ESRF

Overview of current developments

Beamlines Upgrade program (UPBLs)
• **White/pink beam Viewer**
  – pneumatic actuator
  – Cooled
  – pCVD diamond sensor or YAG:Ce
  – Intensity monitor
  – 20 μm pixel size

• **Monochromatic beam viewer**
  – pneumatic or stepper actuator
  – YAG:Ce screen
  – Intensity monitor
  – Accessory: diode for calibration

• **Focus beam viewer**
  – Compact, low cost
  – Standard Model: 0.8x, 1x, 2x magnification
  – under development: 4x mag., 0.9 μm pixel, 3 μm resolution

• **Semi-transparent screen**
  – 450nm thick $\text{Lu}_2\text{O}_3$:Eu on $\text{Al}_2\text{O}_3$
  – 8% absorption @15keV
  – 1s expo @ $10^{11}$ph/s/mm$^2$
  – $\sigma$=80nm on position

90 cameras are currently running for X-ray diagnostic
**Focused Beam Viewer**

**1x version:** 3.75 µm pixel size, 10 µm resolution
1280 x 960 pixels, 30 fps, 10bit DR
In 2x2 binning → VGA 50fps

**2x version:** 1.9 µm pixel size, 6 µm resolution
1280 x 960 pixels, 30fps, 10bit DR
In 2x2 binning → VGA 50fps

**Recently characterized:**
4x version: 0.9 µm pixel size, 3 µm resolution
1280 x 960 pixels, 30 fps, 10bit DR
In 2x2 binning → VGA 50 fps

**10x – 80x:** sub-micrometer resolution
Scientific grade camera, 5-20µm thick scintillator
Current developments: Beam diagnostic

4x magnification focused Beam Viewer: first characterization results

A new design

- A 90 degrees folded head with mirror
- Integration into a small, light body
- Need of motorized focus
- Radiation-hard design
- 3μm spatial resolution and 0.93μm pixel size
- Robustness and reliability under evaluation

Imaging capabilities

(1): Unfocused Image
(2): Focus Image of foam
(3): YAG 250μm 4x magnification
(4): YAG 50μm 4x magnification

Figure 7: X-ray transmission images of a foam (1) and (2) at 15KeV X-ray energy and recorded with the basler camera coupled to different scintillators. The need of motorized focus was evaluated with real images and x-ray patterns

C. Cruz de la Torre, T. Martin, D. Pothin, IWORID 2013
Current developments: Converter screens

Scintillators

- **LPE status**
  - PbO contamination (August 2012)
  - Decontamination/ neutralization of acid (Sept 2012-Dec 2012)
  - Test of all equipment (Jan-Feb. 2013)
  - Design of a new PbO extraction system with Safety and TID (Feb-March 2013)
  - Refurbishment of lab, mainly furnace room (April-May 2013)
  - Restart lab (June - July 2013)
  - Production: GGG:Tb, GGG:Eu, large LSO:Tb for UPBL4

- **Developments:**
  - **Fast garnet scintillator:** LuAG:Ce, GGG:Ce, Cr (P.A. Douissard)
  - **High-stopping power material:** LuAP:Tb (F. Riva)
  - **Large format phosphor and structured screen**
  - **Ceramics scintillator:** GLO:Eu (40µm thick)
  - **Structured scintillator:** scintillating fiberoptic plate
Current developments: Converter screens

New Phosphor screens

- **Application**: any optically coupled (lens or fibre) 2D detector with ≥ 40 mm entrance field.

- **Custom development on ESRF specs**: P43 phosphor (Gd₂O₂S:Tb), mean grain size 2.5 µm. Active thickness from 10 µm to 50 µm. Any area up to 200 x 270 mm²

- Cost-effective, high light yield, quick implementation
- Burnishing under high flux

30 µm thick screen measured LSF FWHM = 30.8 µm
## Current developments: Front-End Optics

<table>
<thead>
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<th>Pixel size</th>
<th>2003</th>
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100 mm Large-field detector for ID17/ID19

Request:

- High energy tomography for medical and paleontology applications
- 100 x 20 mm² field
- 30 - 150+ keV energy range

Possible reuse of custom F300 mm lens
New mechanical design

Current system: FReLoN CCD/fiberoptic taper
- Rapid taper burnish in pink beam
- Low absorption efficiency at high energy
- Geometrical distortions

Proposal: lens-based optical front-end
Applications: X-ray imaging, X-ray diffraction (> 30 keV)

Pixel row alignment (FReLoN rotation)
Motorized iris
Motorized focusing
Lead glass protecting window
Lead shield housing
High absorption fiberoptic scintillator

Pixel size | 49 µm
---|---
FOV | 100x20 mm² up to 100x100 possible
QE @ 100 keV | > 99%
Frame rate | 40 fps
Current developments: Front-End Optics

Scintillating fiberoptic plate

undetected X-rays

X-ray conversion (phosphor screen)

light guide

phosphor screen + fiberoptic

X-ray conversion + light guide

scintillating fiberoptic
100 mm Large-field detector: First results (1)

- High resolution
- High uniformity, low image noise
- High efficiency at high energy
- 12.5 mm high-Z scintillator thickness
- Low distortion

In-vivo crocodile embryo development
Courtesy of P. Tafforeau, ID19
Current developments: Front-End Optics

100 mm Large-field detector: First results (2)

Observation in ovo de la minéralisation du squelette chez Centrochelys sulcata

Paul Tafforeau (ESRF, Grenoble, France) et Martin Kundrát (Université d’Uppsala, Suède)

45 jours  50 jours  55 jours

70 jours  75 jours  80 jours
Future: 150mm Large field, LAFIP (PALEONTOLOGY)

- **Large field fan taper optic** to replace the FReLoN-2k taper optics
- Radiation hardness, better resolution, no mechanical shutter
- First proposal: 2-3 Frelon cameras with FAN (1:1)
- Second proposal: RayoniX camera with FAN (1:1)
- Third proposal: 2 Frelon cameras with FAN (1:1)
- Fourth proposal: High resolution camera with lens optical
  - Custom lens $f=400\text{mm}$
  - $24\times36\text{mm}^2$ chip size
  - Input size: 150mm width

**Status:**
Specifications for CFT (lens) on-going

C. Ponchut, O. Hignette, T. Martin, H. Requardt, P. Tafforeau, A. Bravin
# Current developments: Hybrid Pixel Detectors

## The MAXIPIX Detector and its evolution

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<th>CURRENT</th>
<th>FUTURE</th>
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<td>SOFT X-RAYS</td>
<td>Si sensors TIMEPIX chip</td>
<td>- Edgeless Si sensors</td>
</tr>
<tr>
<td>LARGE FIELD OF VIEW NEEDED</td>
<td></td>
<td>- Medipix 3 &amp; SMARTPIX</td>
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<tr>
<td>HARD X-rays</td>
<td></td>
<td>High-Z semiconductor sensors (HIZPAD$^2$ project)</td>
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</tbody>
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Current developments: Hybrid Pixel Detectors

Development "roadmap"

- **MAXIPIX**
  - 1280x256 pix./300 fps, 256x256 pix./1400 fps
  - 14 units in operation at ESRF

- **SMARTPIX**
  - >2000 fps, energy resolution, 1k x 1k

- **Pixel sensors improvements**
  - Active edge for larger areas

- **EIGER (collab. PSI)**
  - >2000 fps, large area

- **MAXIPIX for UPBL**
  - Specific implementations

- **high-Z pixel sensors (HIZPAD, HIZPAD2)**
  - High energy applications

nb. applications
Current developments: Hybrid Pixel Detectors

Si Edgeless detectors (1)

ESRF participation in multipartner project managed by VTT research centre of Finland (2012)

- Goal: side buttable sensors on 4 sides.
- => nearly seamless large areas can be built.

- Edge leakage current is controlled by sensor edge processing.
- Enables reduction or elimination of guard rings.

Ongoing: characterizations of active edge sensor samples at ESRF
Current developments: Hybrid Pixel Detectors

Si Edgeless detectors (1)

Various doping schemes & gaps to physical edge
Assemblies mounted on 2-side edgeless ESRF chipboards with Maxipix RO
Flat-fields and edge distortions:

17.4 keV (Mo X-ray tube + Zr filter)

P on N 100 (tpxatl80)

P on N 150 (tpxatl81)

N on N 150 (tpxatl83)

C. Ponchut, IWORID 2013
Large variations in leakage currents + breakdown like behavior
Si Edgeless detectors (3)

MESH SCANS
BM05, 10 keV, threshold = 7 keV, 5 µm steps
5x5 µm theoretical beam spot size with refractive lenses; < 5 µm with Kb mirrors.

Refractive lenses, normalized to ring current
Kb mirrors, normalized to ring current
Kb mirrors, normalized to ring current

P on N 100 (tpxatl80),
top left corner
No distortion

P on N 150 (tpxatl81),
Top right corner
Stretched edge pixels

N on N 150 (tpxatl83),
Top right corner
Stretched edge pixels

C. Ponchut, IWORID 2013
Si Edgeless detectors (4)

MESH SCANS

Corner pixels - measured centers of mass

P on N 100 (tpxatl80),
top left corner
No distorsion

P on N 150 (tpxatl81),
Top right corner
Stretched edge pixels

N on N 150 (tpxatl83),
Top right corner
Stretched edge pixels

C. Ponchut, IWORID 2013
Current developments: Hybrid Pixel Detectors

Si Edgeless detectors (5)

First conclusions

• Compared polarities P on N (500 µm), N on N (300 µm)
• Compared edge structures 100, 150, G2-100
• Best edge behaviour: P on N type 100, but incomplete CCE
• Edge 100 seems better than edge 150 (less distortion)
• Correlation between low leakage current and higher edge distortions?
• Variability of image quality, leakage currents => process stability issue?
• Active edge sensors with virtually no edge distortion can be produced.
Current developments: Hybrid Pixel Detectors

Medipix 3 and SMARTPIX Project

Integration of Medipix3:

Medipix3 chip = Medipix2 +

- Analog charge summing mode (charge sharing correction)
- Continuous read-write (no dead time)
- Configurable pixel counters 1, 6, 12, or 24 bits
- 1 to 8 thresholds/pixel
- Frame rates up to 6 kHz with 6 bit counters
- Compatible with 4-side stitching
- Same geometry as Medipix2: 256x256, 55x55 µm² pixels

- Readout electronics (NIMAD) are under test
- Small modules to be characterized
- Long-term development for large area detectors

→ SMARTPIX

Courtesy L. Tlustos, CERN
Current developments: Hybrid Pixel Detectors

Medipix 3 and SMARTPIX Project

Bulrush flower X-ray image collected in charge summing mode
Current developments: Hybrid Pixel Detectors

Medipix 3 and SMARTPIX Project

is based on the use of Through silicon Vias (TSVs) for the Medipix 3 chip output
an implementation of Medipix3RX photon-counting chip for ESRF beamlines.

**Target specification:**
- 60 x 60 mm² detection field (1k x 1k pixels), scalable to larger (or smaller) areas
- 30 x 30 mm² unit modules, dead gaps < 0.5 mm
- 55x55 µm² pixel size
- 6000 fps frame rate
- No dead time (continuous read/write)
- 3 keV energy threshold
- Vacuum compatibility

**Development challenges:**
- Active edge sensors
- Vertical connections (TSV)
- Fast readouts

Current developments: Hybrid Pixel Detectors
SMARTPIX benefits

= evolution of maxiPix with:

• higher frame rate
• larger areas possible
• enhanced energy resolution
• lower energy threshold

A medium-term project

2013 2014 2015

detector module
readout electronics
data acquisition
detector integration
start module testing
detector available

Similar to LAMDBA (DESY) and EXCALIBUR (DIAMOND) developments
Current developments: Hybrid Pixel Detectors

High Z sensor material : CdTe (1)

Developement in the framework of HIZPAD and now HIZPAD2 European projects (started in 2009)

CdTe sensor grown by Acrorad (Japan)

FMF (Germany) bump-bonding on 2x2 Timepix chips maximum size

MAXIPIX ESRF readout system

Very simple design without cooling
Current developments: Hybrid Pixel Detectors

High Z sensor material: CdTe (2)

Quantum efficiency

Linear count rate up to $10^5$ photons/pixel/s (Timepix limited)

Yb$_2$O$_3$ nano-powder diffraction rings at 50 keV.

Comparison with FRELON CCD Camera (50 μm pixel pitch): No significant background, sharper peaks, more low intensity rings

Spatial resolution 63 μm

GOOD PERFORMANCES!!

C. Ponchut and M. Ruat, *Proceedings of IWORID 2012*
Beamline evaluations at ESRF

**ID15** – Surface diffraction: Reflectivity liquid Ga on solid Sapphire at 70 keV (Oct. 2012)

**ID15** – Surface diffraction: In-situ following of GaN growth at 70 keV (Oct. 2012)

**ID11** – High resolution diffraction imaging at 80 keV. Mechanical stability of retained austenite grains in TRIP steels studied by synchrotron X-ray diffraction during deformation (Nov. 2011)

**ID17** - Edge-Illumination phase contrast imaging for mammography at 60 and 85 keV (Sept. 2012)

**ID22** - Coherent SAXS or Ptychography experiment at 20 keV (Sept. 2012)

**FUTURE:**

**ID15** – Fast SAXS-WAXS experiment with Perkin Elmer detector for WAXS and Maxipix-CdTe for SAXS measurements

**ID17** – Detector evaluation for new tomography setup for paleontology

**ID17** – Dosimetry reconstruction for MRT
Current developments: Hybrid Pixel Detectors

High Z sensor material : CdTe (3)

GOOD PERFORMANCES....

BUT...

CdTe detectors suffer from native defects, defects induced by processing, and instabilities under irradiation

Examples to follow
Current developments: Hybrid Pixel Detectors

CdTe sensor: detector defects

Network of Lines (Native):
- Increased counts by ~10%,
- Can be FF corrected
- Sub-grain boundaries
- Next to a line of reduced counts (drift of the charges to the neighbor pixels)

Extended clusters of saturated pixels (from processing):
- Current overflow of the analog input stage of the readout chip.
- Strain in the material (From E. Hamman et al, IEEE RTSD 2012)
- Surrounded by large areas of reduced counts (gettering effect)

C. Ponchut and M. Ruat, *Proceedings of IWORID 2012*
CdTe sensors
Detector ‘aging’
Flat-Field when received (2012-02)

Soleil synchrotron 20 keV +
air scatterer

Thld 5

12 x 60 s
Temporary radiation damage (2013-03)

Phantom images of previous irradiation field
Temporary radiation damage (2013-05)

Irradiation with X-ray tube (Ag anode) at $7 \times 10^5$ photons/mm$^2$/s with a lead pattern in front of the detector.

Flat-field image after irradiation with pattern removed.

Temporary polarization = increased counts (similar to round shapes on central image).

Reset bias voltage at regular intervals in time.

Images of a lead pattern after continuous irradiation of one half of the detector surface with X-ray tube (Ag anode) at $10^7$ photons/mm$^2$/s for 3h.

(a) without bias reset.
(b) With bias reset every 10 min.
As is, after 18 months of experiments...

Ag Tube 35kVp – 25 mA
+ 100 um Ag filter

Thld 11

100 x 1 s

Chips 00, 01, 11 exhibit more extended defects + history effect.
Chip 10 is noisy and some pixels look disconnected
After 2 hours at 50°C...

Ag Tube 35kVp – 25 mA
+ 100 um Ag filter

Thld 11

60 x 1 s

History effects have disappeared, as well as some defects on chips 00, 01, 11. Chip 10 idem → temporary :-( 
Current developments: Hybrid Pixel Detectors

CdTe sensor : detector instabilities

- Extensive use → quicker polarization, enhanced radiation damage, extra noise
- Low temperature baking (50°C) induces defects relaxation in CdTe

NEED TO CHARACTERIZE TEMPORARY vs PERMANENT or RECURRING EFFECTS
And the way to avoid or ‘anneal them’, if possible.

→ Need to improve the design by cooling and / or resetting the bias on the detector at regular interval times
Outline

The Detector Unit at ESRF

Overview of current developments

Beamlines Upgrade program (UPBLs)
ESRF Upgrade

 Longer beamlines, increased flux, new techniques → New detector solutions

Phase I examples
High resolution imaging and ptychography

- High resolution detector 16Mpixels
  - 10x custom optics (CFT)
  - 1.5um pixel size
  - Rot-C, 45° motorized mirror for 5x mag.
  - Frelon e2V 16Mp, 6.14 x 6.14 mm²
  - SVS HR16070, 7.24 x 4.81mm²
- Composite detector for cSAXS
  - Remote head Maxipix detector, 4 chips, 256x256
  - Central hole ~5x5mm

**Status:**
detector delivery planned end 2013 (! optics)
**Energy dispersive detectors**

*Two identical detectors:*
2 x PNdetector SDD 6 element arrays = 2 x 540mm\(^2\)
energy range \(\sim 2...25\text{keV}\), global *throughput* count rate to \(\sim 6\text{Mcps}\)
Fast MCA spectra readout to 1kHz, based on existing (ID22) XIA-XMAP pulse processors

**Operation in vacuum** \(\sim 10^{-7}\text{mbar}\), confined space need for \(\sim 30\text{mm}\) approach to sample for large detection solid angle.
Detector Peltier coolers and electronics are water cooled.

Detectors show in retracted position

**Status:**
- detectors delivery planned for *June 2013*
- upgrade of obsolescent ID22 DAQ (PXI--\(\to\)PXLe), testing by BCU and C Cohen completed.

Energy dispersive detectors

Operation in air

'Low energy'

Two identical detectors:
~2...25keV, total throughput count rate to ~3Mcps
2 x PN detector silicon drift-diode 3 element arrays = 2 x 270mm$^2$, detectors assembled by SGX Sensortech

'High energy'

single detector:
~2...70keV, throughput count rate to ~4Mcps
8 element germanium diode array = 400mm$^2$
low vibration, water cooled Pulse Tube cryocooler, Canberra France

Status: CFT completed, finalizing contract, delivery ~April 2014

Status: detector delivery planned for Sept 2013
In-line Germanium detector, 350µm pitch

- Spare and obsolescence issues of electronics
- Request also
  - better resolution (50µm)
  - why not 2D (151mm x10mm)
  - 10µs readout time
- Investigations are on-going
  - Ge upgrade
  - Microstrip sensors i.e. Elettra Picasso (Si microstrip sensors illuminated in the edge)
  - Flat panel
  - Pixel detectors
  - Frelon Hama + Front-end optics

T. Brochard, C. Nemoz, A. Bravin, P. Fajardo, T. Martin
ID19: High resolution detector for white beam application

- Folded head (mirror between scintillator and objective)
- Rot-C (F-mount and Frelon)
- Two motorized optics
- 5x, 10x magnification, Mitutoyo objectives
- Eyepiece for large format sensor

Status:
detector expected last year but now ready to be delivered
ESRF Upgrade phase I

UPBL6 –ID20 Raman spectrometer

Status: detector commissioned July 2013

1 single chip MAXIPIX detector per analyzer (end May 2013)

Specific chipboard with no edges along one corner enables:
- minimum back scattering angle
- tilted geometries

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see presentation by A. Homs @ 16:10

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Thank you for your attention!