Technology emphasis: tomography devices

• PSL at a glance

- Founded in 1986 by Astrophysics PhDs
- Expected Turnover 7 million Dollars in March 2011
- Over 400 detectors / year in production
- Base in UK (production) and Grenoble (Sales & Marketing)
- 25 persons, more than ½ engineers or PHDs
- Balanced activity between scientific, industrial and military market segments

MEDICAL / PHARMA

- X-ray imaging / crystallography

BIOTECH

- High Throughput screening / Confocal imaging

INDUSTRIAL

- Digital Radiography

MILITARY / AEROSPACE

- Lon range surveillance
- Night vision

PHYSICAL SCIENCE

- HR EBSD / HRTEM
• Hardware bundles for 3D reconstruction of micro & nano structures
  ❖ CT bundles, the Fundamentals
  ❖ X-ray sources
  ❖ Detectors
  ❖ Stages
  ❖ Software
  ❖ Pushing the limits
  ❖ Take away
Technology emphasis: tomography devices

- CT bundles, defining the geometry parameters
  - Energy Range: keV
  - Spatial Resolution: \( \mu \)
  - Dynamic Range: \( 2^n \)
  - Temporal resolution: msec
  - Distance Range: \( z \) in mm
  - Angular Range: in \( \mu\text{rad} \)
Technology emphasis: tomography devices

- Propagation based phase contrast imaging

✓ Recording interference fringes at phase jumps (between transmitted and diffracted beam)

![Graphite pellet, courtesy Areva, D.Tisseur](image)

Absorption

Absorption plusPropagation BasedPhase contrast

Propagation Basedholography

CoherentDiffraction

\[ n = \alpha + i\beta \]

\[ \alpha > \beta \]

Phase absorption

Phase modulation with increasing detector distance (with a coherent beam)

1µ source, cone beam geometry, 50kV, 0.2mA, magnification x25, near field regime
4k x 2.6k resolution, 9µ voxel size
Technology emphasis: tomography devices

- PSL existing bundles

- The race to the smaller spot size / highest brightness / coherence, survey of X-ray sources tested:

  - sealed tubes: 4µ 90kV
  - open tubes: < 1µ 160kV
  - enhanced open tubes < 0.5µ 160kV
  - open tubes: < 3µ 225KV
  - open dual tubes: < 70µ 450kV
  - pulsed liquid jet: 5µ 100kV

\[ U = S \times \frac{OD}{OS} \]

Reducing unsharpness + higher magnification
Technology emphasis: tomography devices

• **Detectors: X-ray / gamma & electrons**

  ❖ **Direct detection: conversion into e⁻**
  Si / GaAs / CdTe + CMOS read out
  Medium area for Si, small area for GaAs & CdTe, coarse pixel: typically 130µ, photon counting operation, color imaging thanks to built in charge sensitive amplifier / comparators / discriminator / ADC

  ❖ **Indirect detection: conversion to visible & then e⁻**
  aSi array + CsI / GdOS,
  large area, coarse pixel, 130 to 400µ
  CMOS array+ CsI / GdOS
  medium area, 50 to 100µ pixel
  CCD / low noise CMOS array + CsI
  GdOS and single crystal LuAG
  small to medium area, 10 to 100µ pixel
Technology emphasis: tomography devices

- Fine tuning X-ray CCD detector design
  - Optimizing scintillator thickness: primary absorption
  - Applying gain before read out: avoid the « quantum » sink
  - 100% duty cycle: continuous sample rotation or scanning
  - Dual slope integration: extending dynamic range up to genuine 16-bit, no artefacts during reconstruction
  - Full vertical binning: allows switching from 2D to 1D scanning with antiscattering slits

Effects of applying gain before read out: Better resolution, lower dose, no quantum sink

![CsI scintillation absorption vs x-ray energy graph](image)
Technology emphasis: tomography devices

- Fine tuning X-ray CCD detector design
  - Matching resolution of the source to the detector
    \[ M = 1 + \frac{Rd}{S} \times 1.414 \]
    \[ M = 40 \text{ with } S=0.8\mu \text{ Rd}= 22\mu \]
  - Optimizing resolution with structured phosphors

< 1\mu resolution @ 50x magnification
Technology emphasis: tomography devices

- **Precision stages**
  - Matching lateral coherence for 0D or 1D scanning
    PB-PCI
  - Matching longitudinal coherence for PB-holotography

Derived from Heisenberg uncertainty principle, Young's double pinhole

\[
\xi_t = \frac{z \Delta \theta}{2 \pi d}
\]

- 0.8\(\mu\) source, \(z=250\)mm, 90kV acceleration
  Voltage gives \(\xi_t = 1.23\mu\)

Derived from spectroscopy measurement

\[
\xi_l = \frac{\lambda}{\Delta \lambda}
\]

- 20\(\mu\) source, \(z=300\)mm, 9.15keV energy
  with \(\lambda/\Delta \lambda = 10^{-4}\) gives \(\xi_l = 1.35\mu, \xi_t = 1.29\mu\)
• Precision stages

✓ Matching angular acceptance of analysers: 10µrad or less, using monochromatic or quasi monochromatic beam.
Technology emphasis: tomography devices

• Reconstruction software
  ✓ Multiplexing data input from GigE camera modules
  ✓ Beam hardening / drift corrections
  ✓ Automated, marker-less slice / rotation / tilts-series alignment
  ✓ Tiled CT (2 separated CT scans stiched after scanning)

200nm calibrated sphere slice, 200kV JEOL TEM microscope Magnification 200.000x, 100ms exposure

CT reconstruction applied HRTEM
Technology emphasis: tomography devices

**Reconstruction software**

- Raw dataset size at input: \(~10\)GB | Output vol.: \(~50\)GB possible
- Automated, marker-less tilt-series alignment on GPU technology

<table>
<thead>
<tr>
<th>Amount of data at input (Go)</th>
<th>Amount of data at output (Go)</th>
<th>Projections number</th>
<th>2D-image size at input (pixels)</th>
<th>3D-reconstructed volume at output (voxels)</th>
<th>3D-reconstruction time (per iteration) 1 GPU</th>
<th>3D-reconstruction time (per iteration) 3 GPUs</th>
<th>Acceleration ratio: 1 to 3 GPUs</th>
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<td>1.0</td>
<td>82</td>
<td>2048 x 2048</td>
<td>1024 x 1024 x 256</td>
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<td>21.3 seconds</td>
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<tr>
<td>1.3</td>
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<td>82</td>
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<td>2048 x 2048 x 512</td>
<td>270.9 seconds</td>
<td>111.6 seconds</td>
<td>2.4</td>
</tr>
</tbody>
</table>

Performance of iterative algorithm (SIRT) run on multi-GPUs mounted on a desktop PC

GPU hardware used for 3D reconstruction: one Nvidia Quadro FX5800 and two Nvidia Tesla C1060
• Pushing the limits: detectors delivering color imaging
  ✓ maintain spatial resolution
  ✓ Select energy, beam hardening all in one integrating detector

Multiple energy reconstruction:
USB-Mouseplug

Metal (strong beam hardening effect) → red
Plastic (weak beam hardening) → green
Technology emphasis: tomography devices

- Pushing the limits: detector delivering extended resolution & dynamic range for HRTEM
  - Increasing dynamic range: dual slope to 20-bit
  - Maintain spatial resolution: custom deposition of poly crystalline GdOS

<10µ resolution, no magnification

courtesy CEA ICSM, R. Podor
PtO diffraction pattern on Jeol 200kV
Technology emphasis: tomography devices

- Pushing the limits: detector delivering extended resolution & dynamic range for SEMs

✓ High resolution Kikuchi / Kossel pattern collection with custom deposition of polycrystalline GdOS

Simulation of the zero stress state. DO3 crystal symmetry with \( a = 5.8120 \) Å using Cu-Ka1 = 1.54056 Å and Cu-Ka2 = 1.54439 Å.
Technology emphasis: X-ray CCD & pixel detectors

- Pushing the limits: detector for edge enhancement / propagation based phase contrast imaging
  - Near field imaging condition
  - $\Delta$ absorption $< \Delta$ refraction index
  - Energy: 10 to 100keV
  - 2k x 1.3k, <1\(\mu\) resolution with custom GdOS scintillator, 70kV, 0.15mA cone beam, 50x magnification, pine wood splinter with fungus
  - 2k x 2k, 14\(\mu\) resolution with custom GdOS scintillator, 15keV parallel beam configuration, no magnification, Delamination of Nylon fibers in sail cloth

Courtesy: L.Mancini Elletra

courtesy U.Gent, B.Maschelle

PSL Presentation, July 16, 2008, p.16
Technology emphasis: tomography devices

• **Pushing the limits: source full coherence (transverse and longitudinal)**
  - Fresnel regime: acquiring several images at different distances along the beam path with multiple orientations
  - Recording interference fringes at phase jumps (between transmitted and diffracted beam): phase / amplitude retrieval
  - Solving electronic distribution using inverse of Radon transform
  - Very high resolution scintillator with no magnification and parallel monochromatic beam

Al –Si alloy slices, courtesy ESRF, P.Cloetens
Absorption based edge enhancement PCI holotomography
Technology emphasis: tomography devices

• Pushing the limits: monochromatic source & analyser: Diffraction Enhanced Imaging

✓ Narrow angular acceptance converts refraction variations into intensity changes
✓ No longer absorption based, Bragg conditions to be met on the analysing monochromator: contributions from ultra small angle scattering

Refraction contrast in Nylon fiber
0.55mm
0.1mm

absorption

DEI

Courtesy: Z. Zhong, Brookhaven National Lab
Technology emphasis: tomography devices

• Conclusion

- PSL drives innovation with custom design using high resolution X-ray CCD detectors & bundle systems
- From design to manufacturing, PSL offers integrated solutions
- We deliver consistent performance and quality over small volume production: from 1 off to 10s...
- Affordable pricing
- Academic references: BNL, ESRF, SLS, Elletra, Spring8, CSIRO
- Industrial references: Skyscan, XRT, SIEMENS