The University of Manchester

High-Speed, *In-Situ* Chemical Species Tomography in Reactors

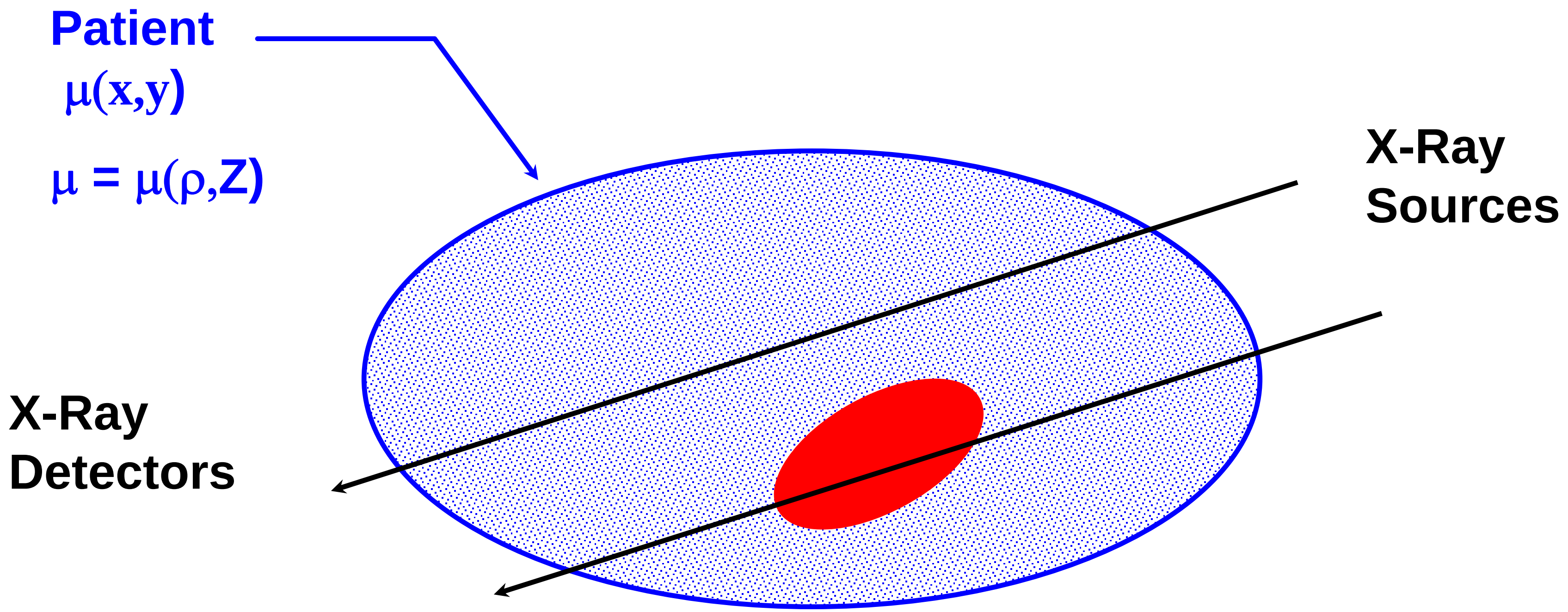
Hugh McCann
School of Electrical and Electronic Engineering
University of Manchester, UK
www.tomography.manchester.ac.uk

EUROKIN Workshop
BP Hull , 27th November 2006

Contents

- **Introduction to tomography**
  - Basic measurements
  - Image reconstruction
- **Fast non-chemically-specific tomography**
  - X-Ray CT
  - Electrical Tomography
- **Chemical Species Tomography**
  - IR Absorption Tomog.
  - Engine application
  - Scope
- **Virtual Centre for Industrial Process Tomography**
- **World Congress on IPT, Bergen 2007**
- **Conclusions**

Tomography Intro : X-Ray Attenuation



$$I_d = I_0 . \exp\left(-\int_L \mu(x,y)\, d\ell \right)$$

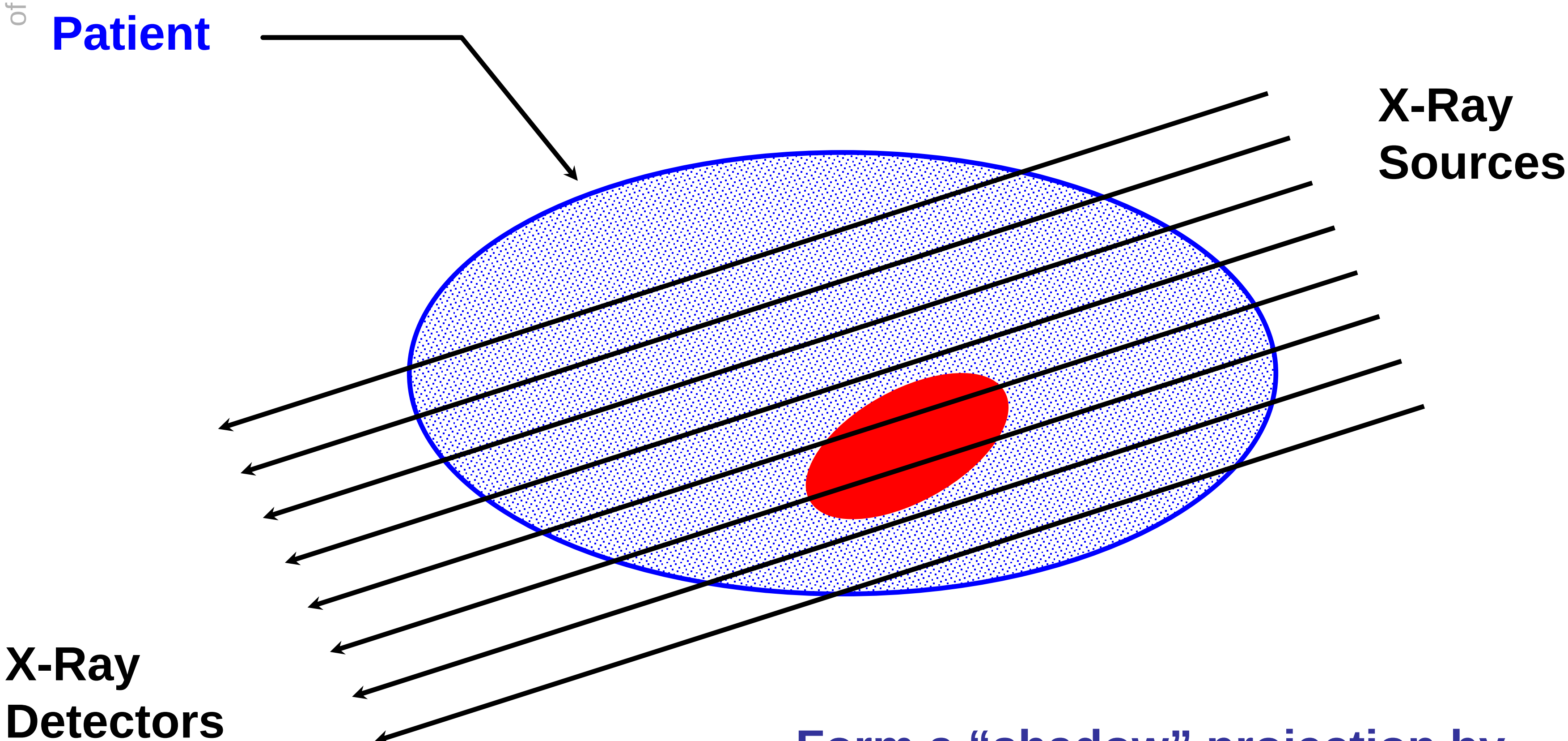
Differential absorption due to density contrast

$$-\ell n\left(\frac{I_d}{I_0}\right) = \int_L \mu(x,y)\, d\ell$$

Path density integral, PDI

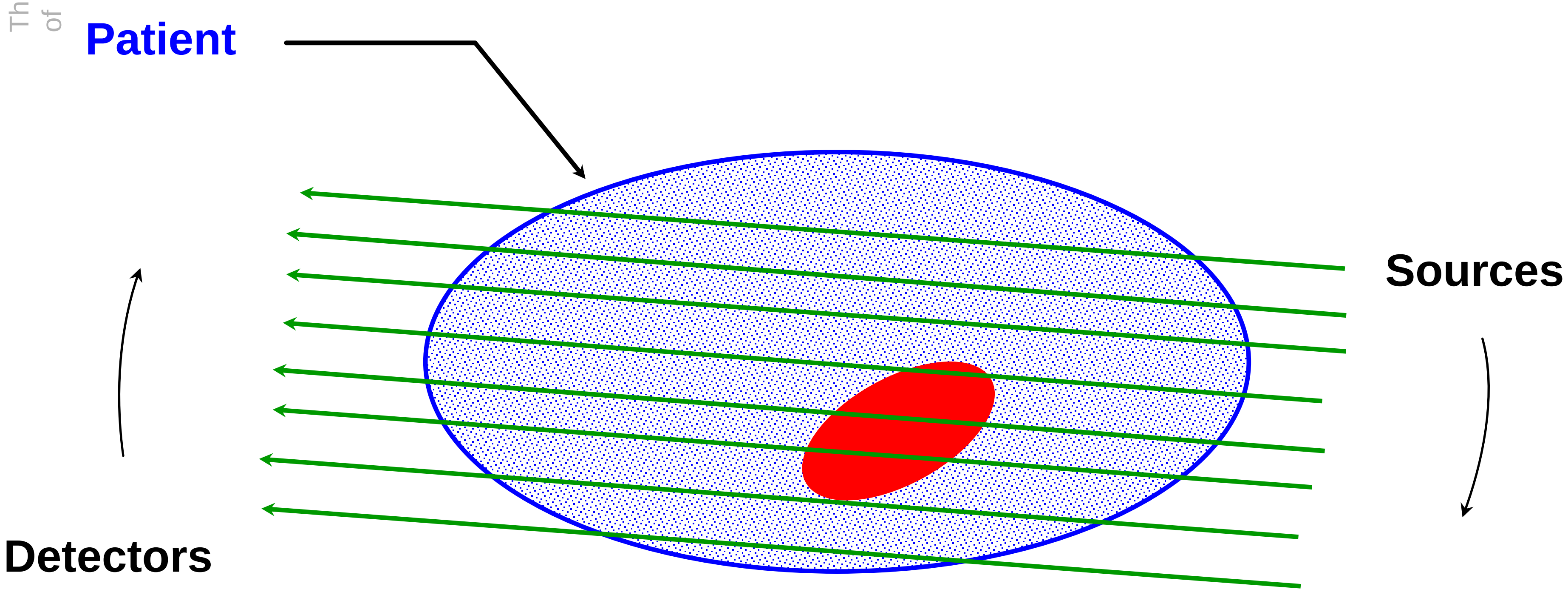
X-ray CT = Hard-field

Tomography : Projection



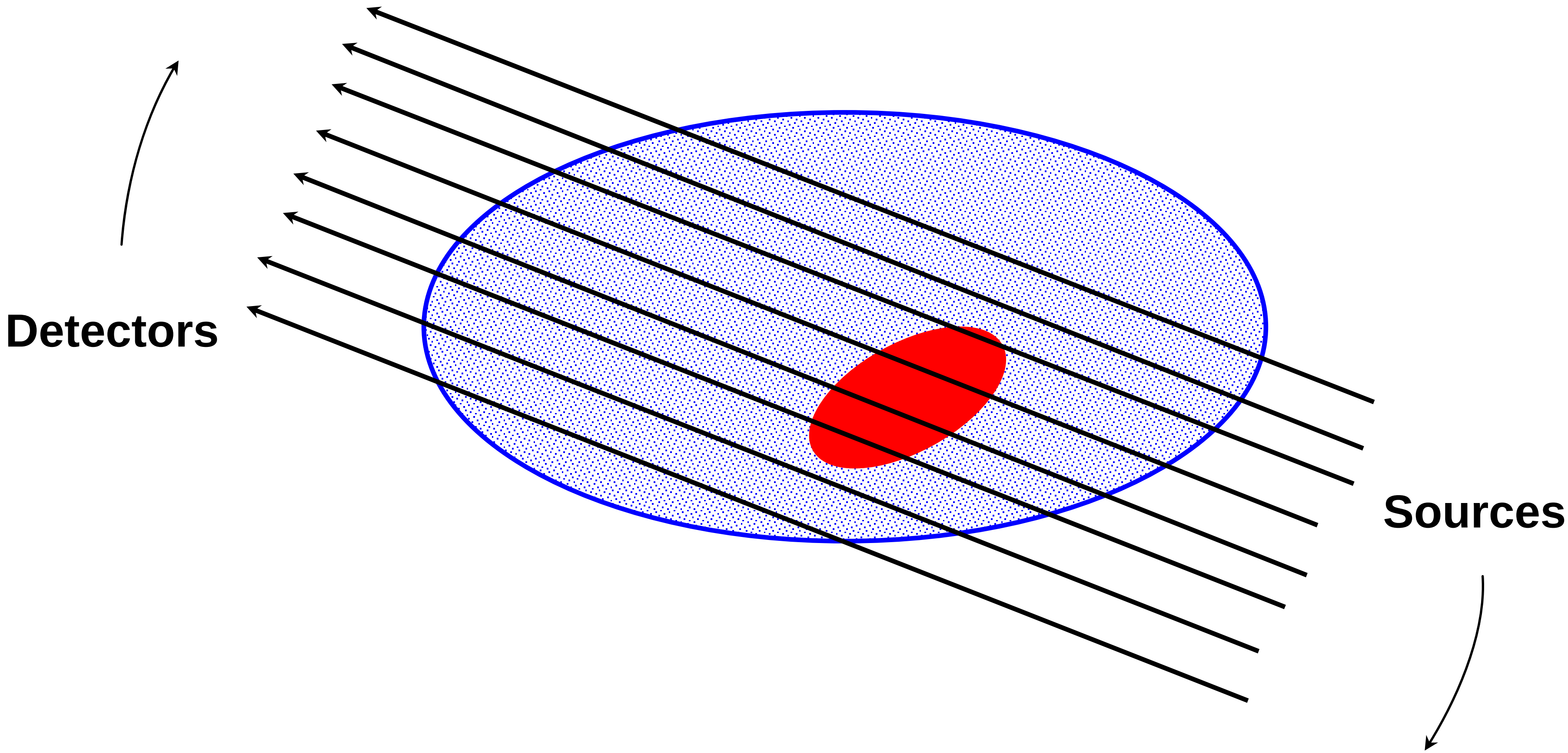
Form a "shadow" projection by measuring PDI along many parallel paths

Medical Tomography : Scanning

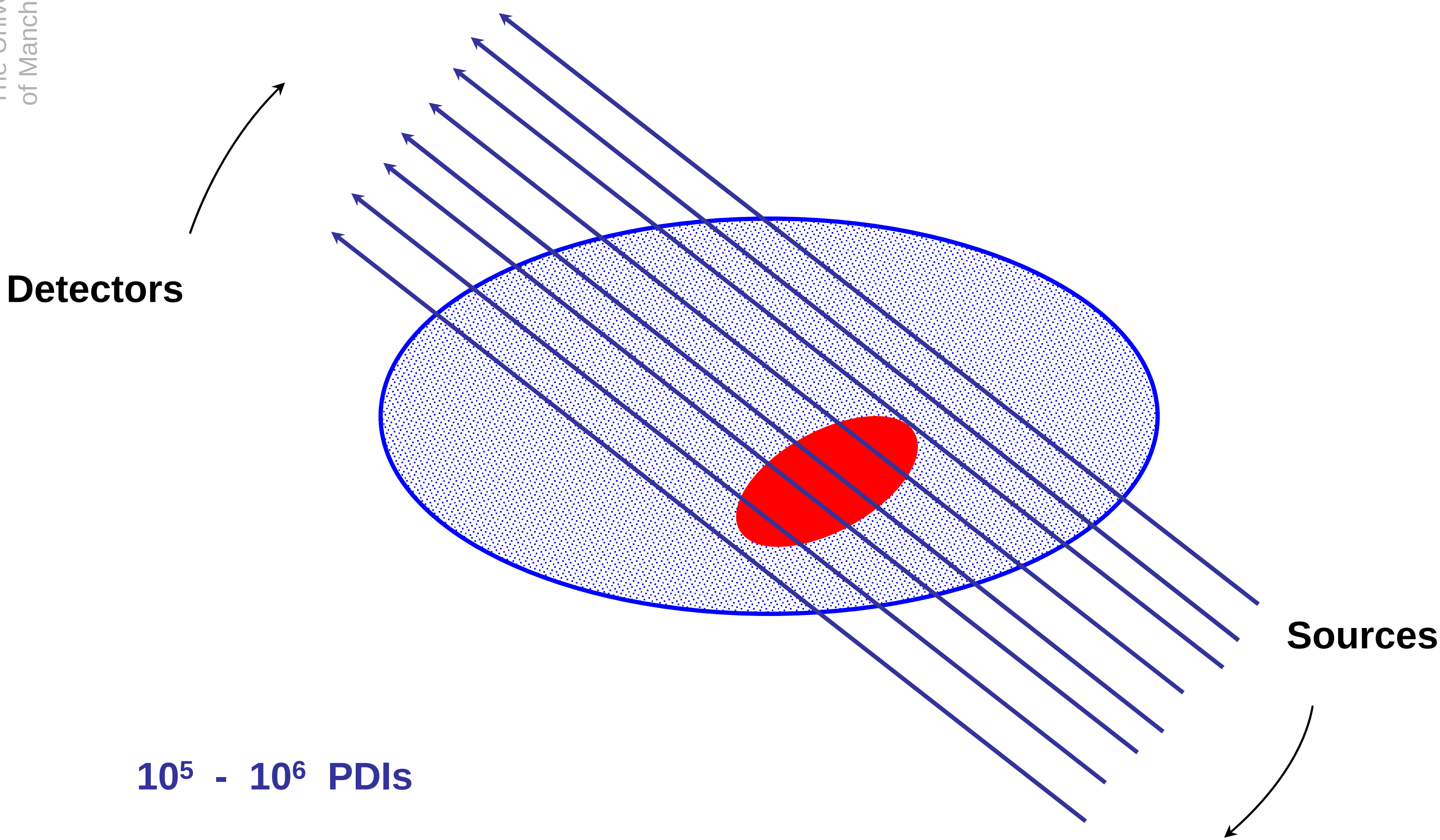


Form many projections by rotating sources and detectors around patient

Medical Tomography : Scanning



Medical Tomography : Scanning



10^5 - 10^6 PDIs

Image Reconstruction

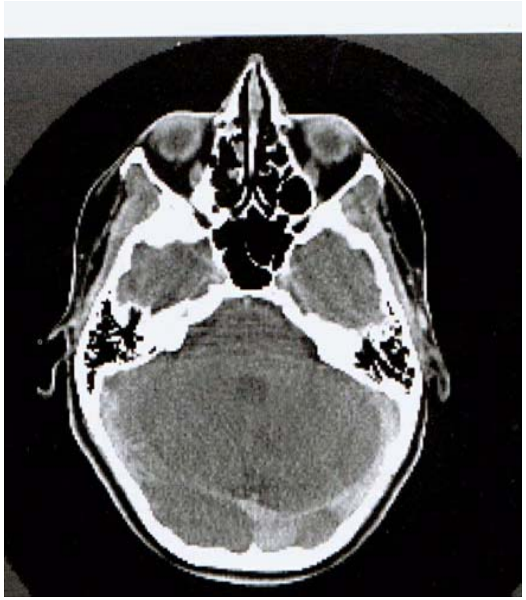
- **Data Inversion :** **- In general, ill-posed**
  - Due to limited measurement accuracy

- **Ill-posedness :** **- Non-unique solution**
  - Non-continuous dependence on data (noise)

- **Impose additional constraints from the physics of the particular case**
  - regularisation

Image reconstruction : See Bertero & Boccacci, IOPP 1998

Medical Tomography : Images



X-ray CT

MRI

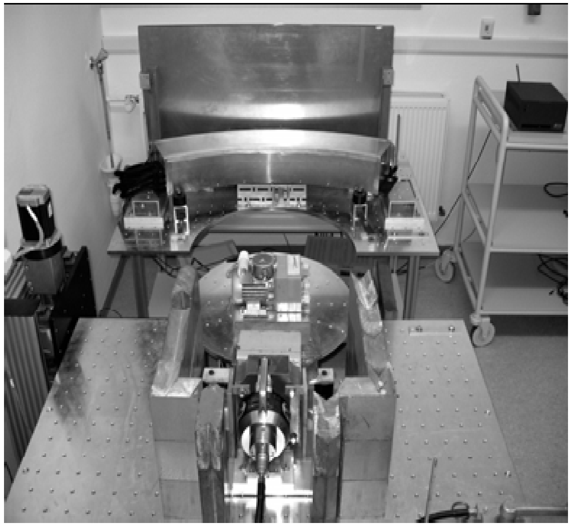
Fast in-situ X-Ray CT

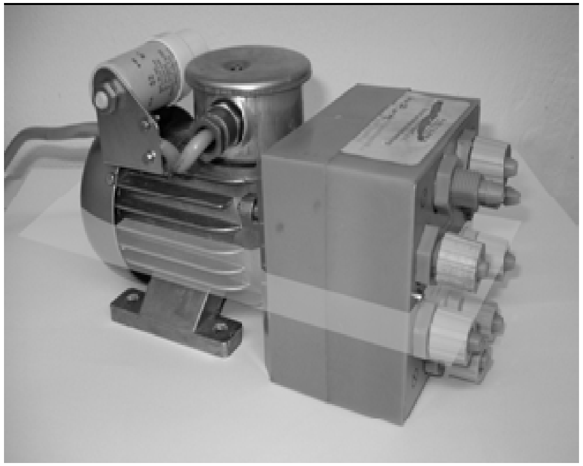
- **Sources :** - Multiplex e^- beam onto multiple fixed targets
  - Miniaturisation
- **Detectors :** - Compact, using high-density crystals
  - Improved energy resolution
  - Highly segmented detector arrays
- **Electronics :** - FPGA-based designs
  - Pulse shaping / analysis
  - Low-noise
- **Result :** - Logistics greatly improved
  - Temporal resolution in O(10 ms)

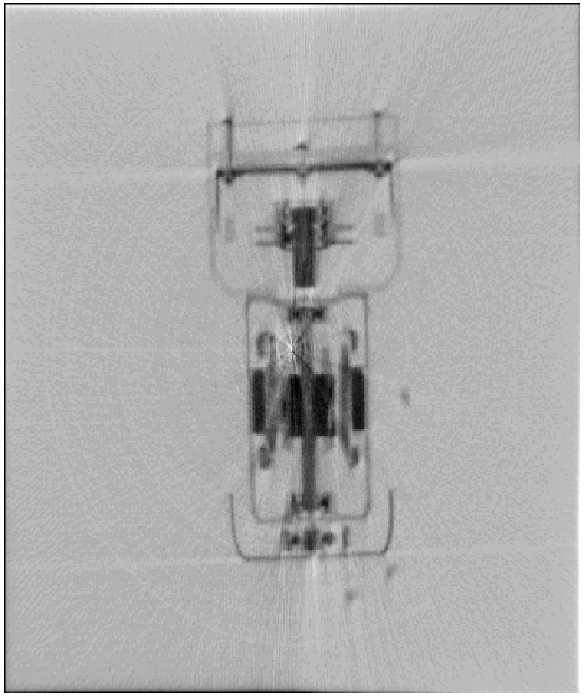
The University
of Manchester

Fast in-situ X-Ray CT

- **e.g. FZ Rossendorf group :** **- Uwe Hampel et al.**
  - See Proc. WCIPT4, 2005



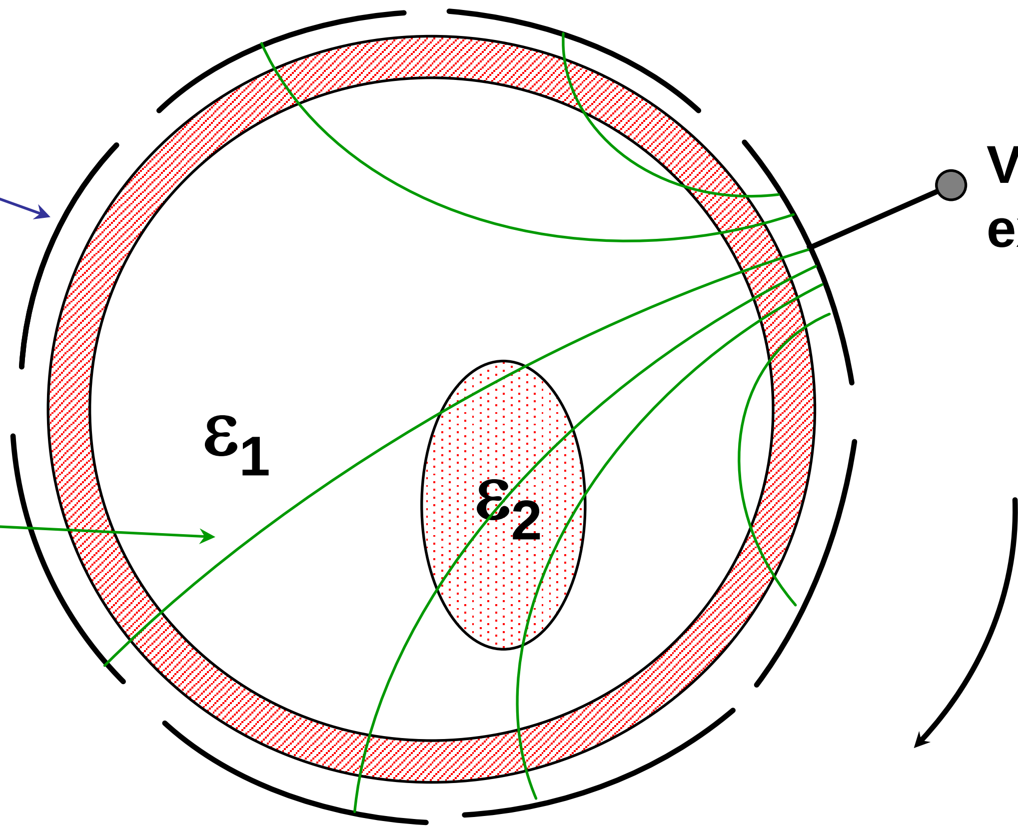




The University of Manchester

Electrical Capacitance Tomography

Charge measuring electrodes, n



Voltage excitation

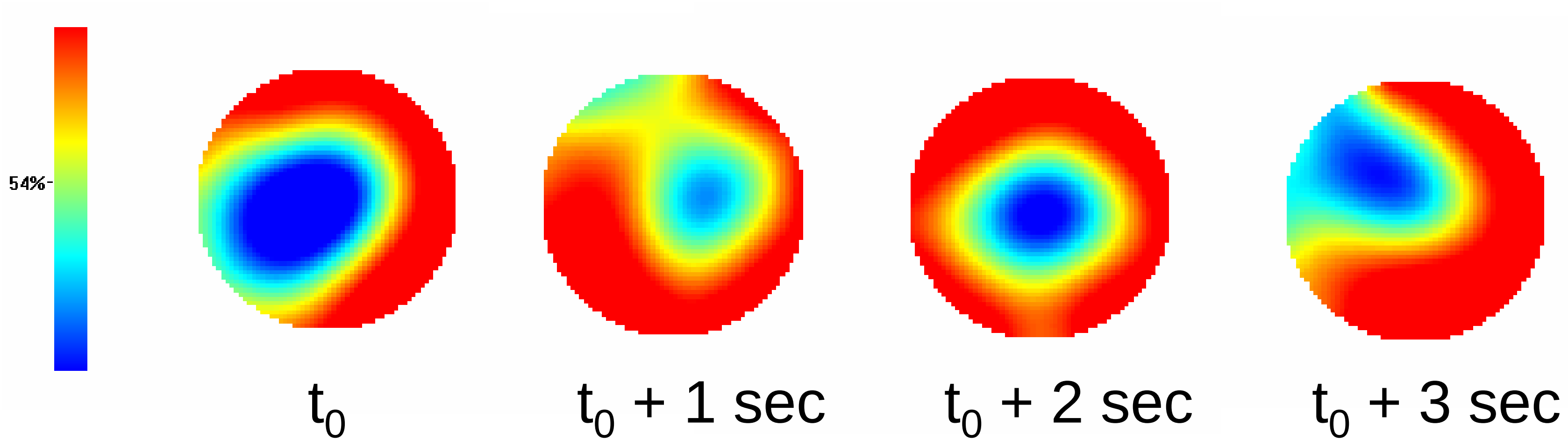
Schematic E-Field distribution

Multiplex

Max. no. of linearly independent capacitance measurements, M = n(n-1)/2

ECT = Soft-field

ECT in Fluidised Bed : Solids distribution

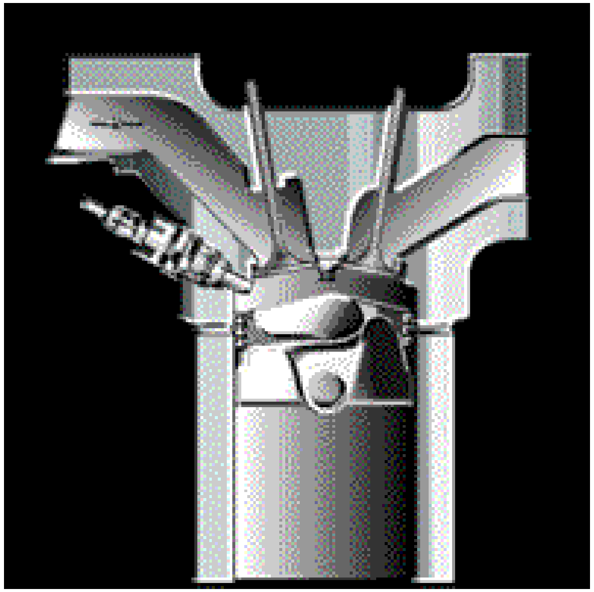


- **EPSRC Project : WQ Yang (Manchester) + S Duncan (Oxford)**
- **Objective:** **Control Fluidised Bed using ECT**
- **Needs:** **Dynamical model for solids flow**

  + State space description that links to ECT measurements

  + Actuator scheme to modify bed

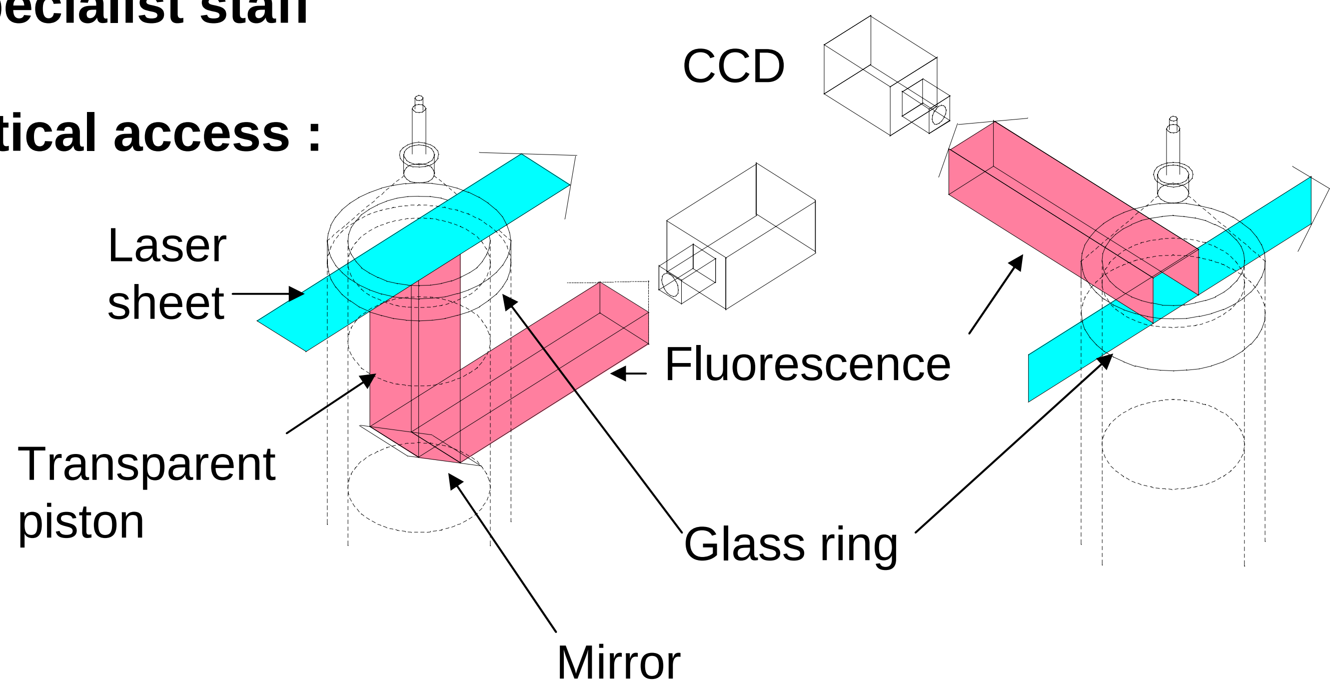
Chemical Species Tomography : Auto engine



- **Follow dynamics of fuel mixing with air, i.e. [HC](<u>x</u>,t)**
- **Why?** - **Accelerate engine development**
  - **Improve environmental performance**
  - **Research new engine concepts, e.g. HCCI**
- **Suck, squeeze, bang & blow @ ~ 50 Hz in 4-cylinder engine**
- **Critical mixing period occurs over ~ 15 ms**

What's wrong with PLIF ?

- **Indirect imaging, via dopants**
- **Model fuels only**
- **Limited laser repetition rate : can't follow cycle**
- **Needs specialist staff**
- **Large optical access :**

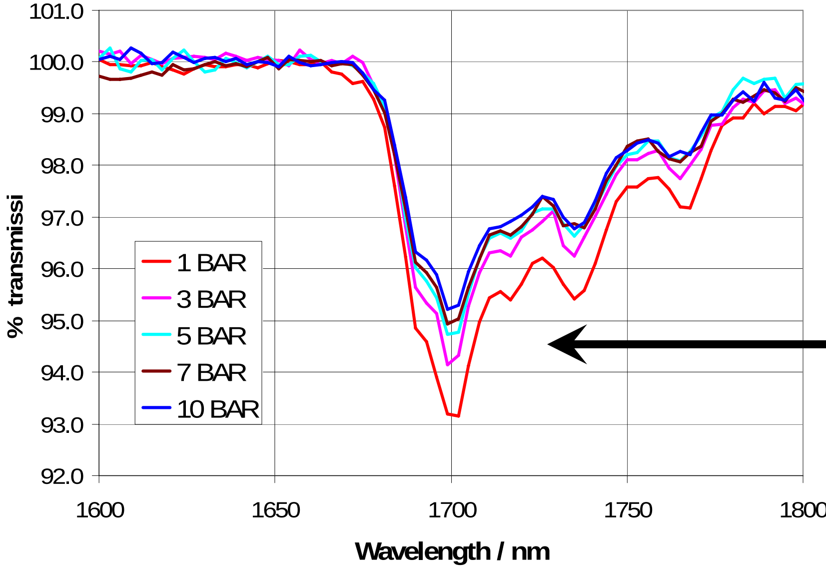


- **All but impossible on multi-cylinder engine**

Concept : Near-IR Absorption Tomography

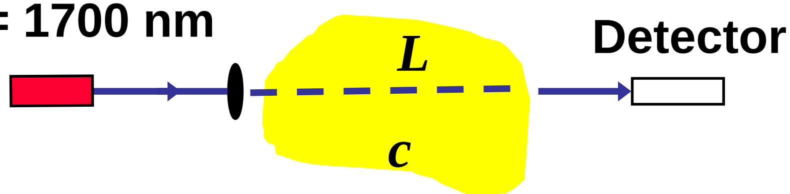
e.g. Hydrocarbons :

Stoichiometric (@10 bar) Iso-octane / air, 85 mm path length



C-H stretch vibration overtones & combinations

λ_a = 1700 nm

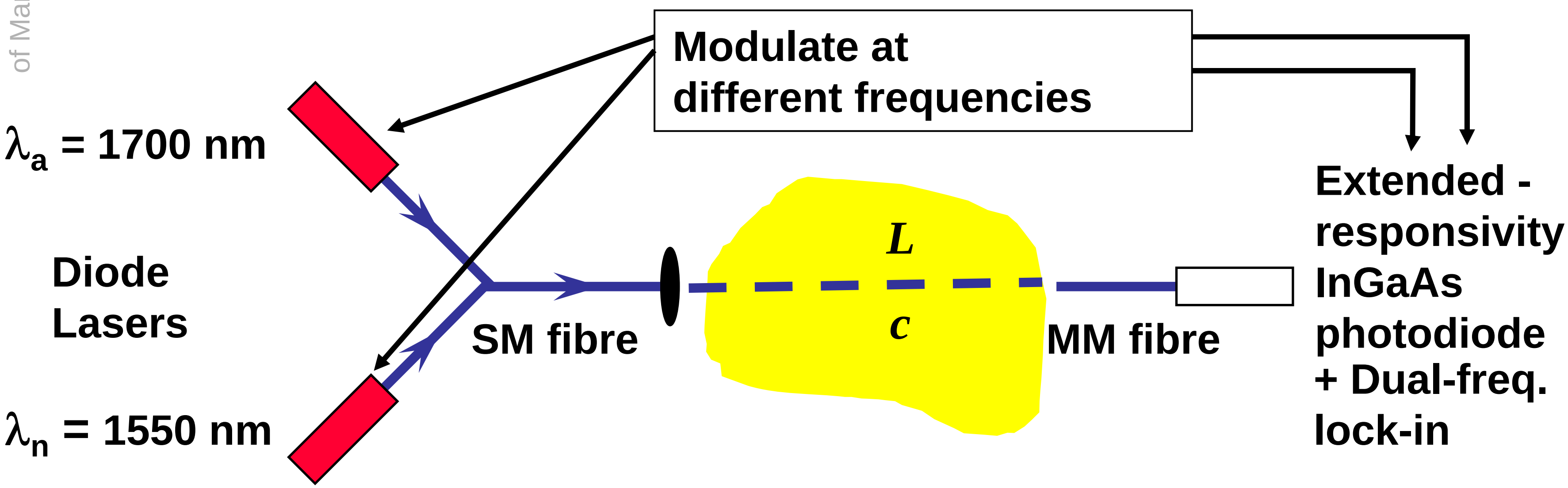


Path concentration integral :

$$-\ell n\left(\frac{I_d}{I_0}\right)_\lambda = k(\lambda).\int_L c(x,y)\,d\ell$$

- **N measurement paths ⟶ Image reconstruction yields c(x,y)**

In-cylinder fuel vapour imaging : Measurement principle



Dual- Wavelength ratio measurement accounts for :

- **Refractive index variation**
- **Scattering due to fuel droplets and soot particles**

PCI :

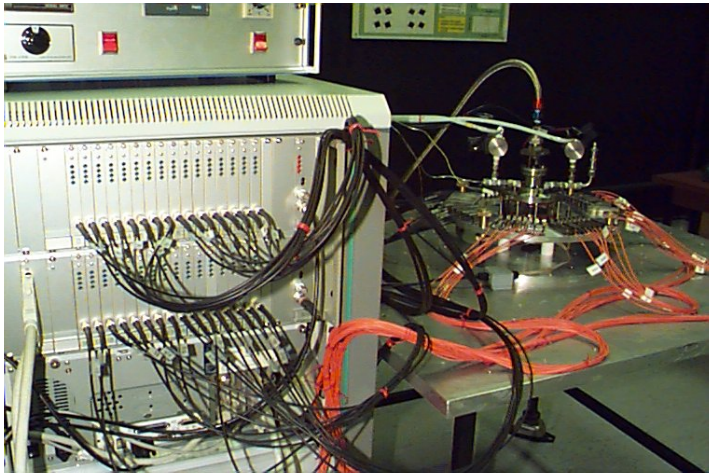
$$\int_L \mathbf{c(x,y)d}\ell = \frac{1}{\mathbf{k}(\lambda_1)-\mathbf{k}(\lambda_2)}\cdot \ell n\left(\frac{\mathbf{I_r}(\lambda_2)}{\mathbf{I_r}(\lambda_1)}\cdot\frac{\mathbf{I_0}(\lambda_1)}{\mathbf{I_0}(\lambda_2)}\right)$$

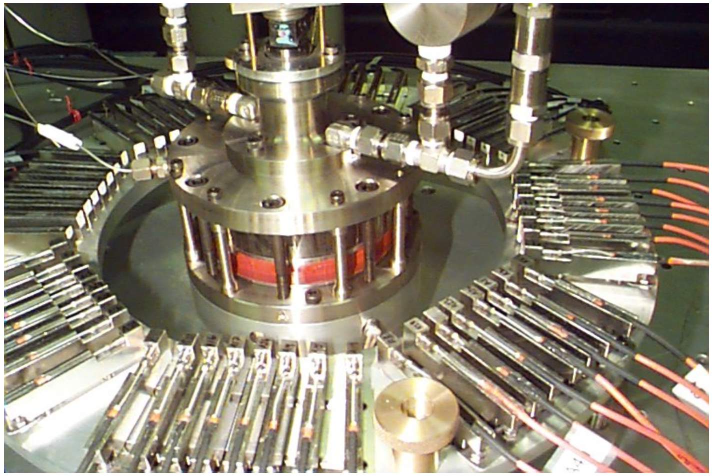
Hindle et al., *J. Elec. Im.* 10 (2001) 593

MANCHESTER 1824

The University of Manchester

In-cylinder fuel vapour imaging : 32-channel lab demo

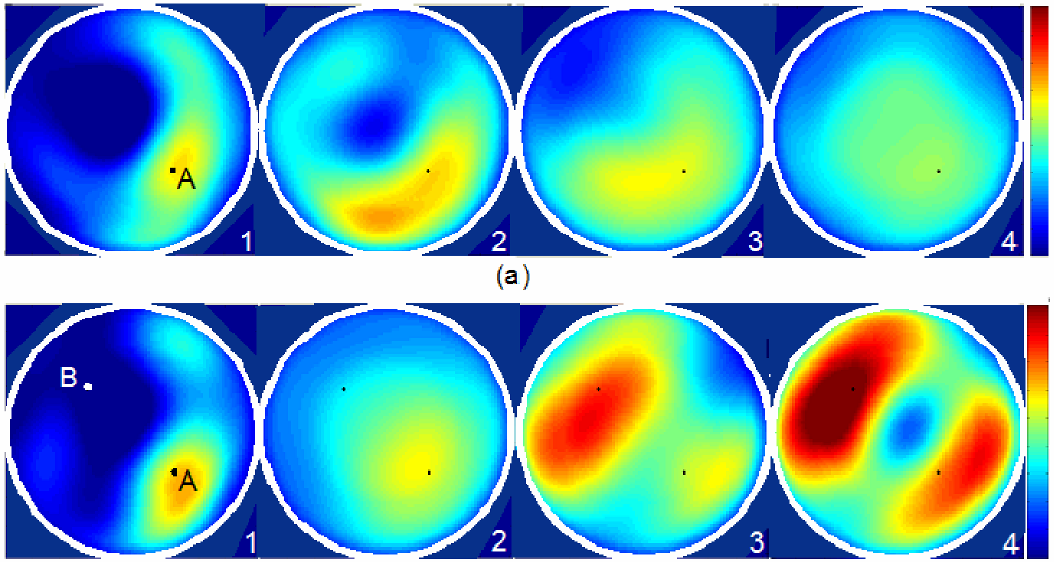




30.6 ms 51.2 ms 98.5 ms 145.0 ms

1 injection :

2 injections :



28.8 ms 98.8 ms 136.5 ms 145.0 ms

- **Imaging at up to 3,500 fps**
- **NIRAT concept established**

Wright et al., *App. Opt.* 44 (2005) 6578 - 6592

MANCHESTER 1824

The University of Manchester

DTI-EPSRC LINK project: *IMAGER*

ROUSH Technologies

AOS TECHNOLOGY

Ford

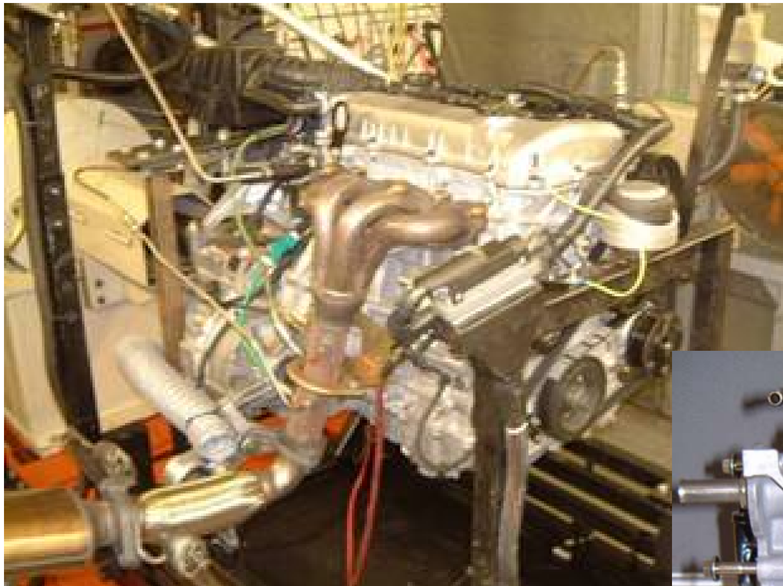
MANCHESTER 1824

The University of Manchester

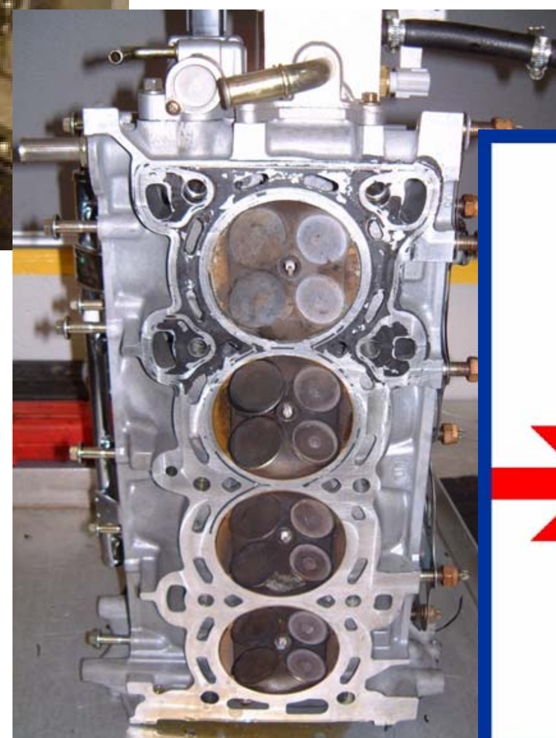
- **£1.4Million project, finished May 2006**

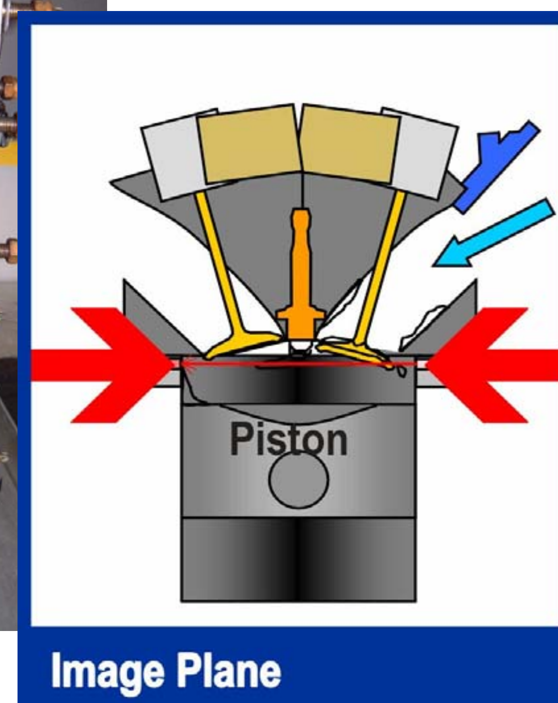
- **Achievements:**
  - **Established robust optical access in 4-cylinder engine**
  - **Discovered new design rules for tomography systems**
  - **Developed high-speed, low-noise electronic system**
  - **Customised image reconstruction algorithms**
  - **Implemented NIRAT on a 4-cylinder gasoline engine**
  - **In-cylinder imaging of pump gasoline at 4,000 fps**

IMAGER engines



- **Ford 2.0 litre engines :**
  PFI & GDI

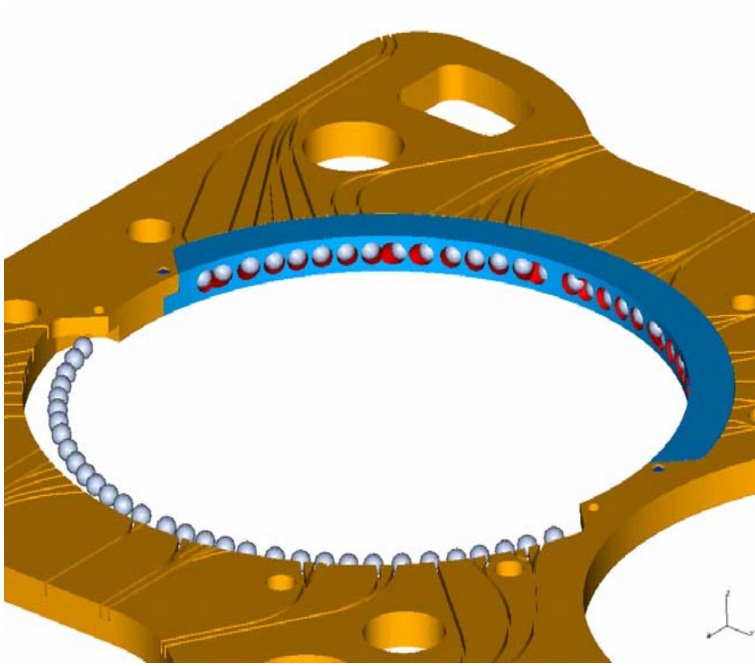




- **Modified & run at Roush, to industry standards**

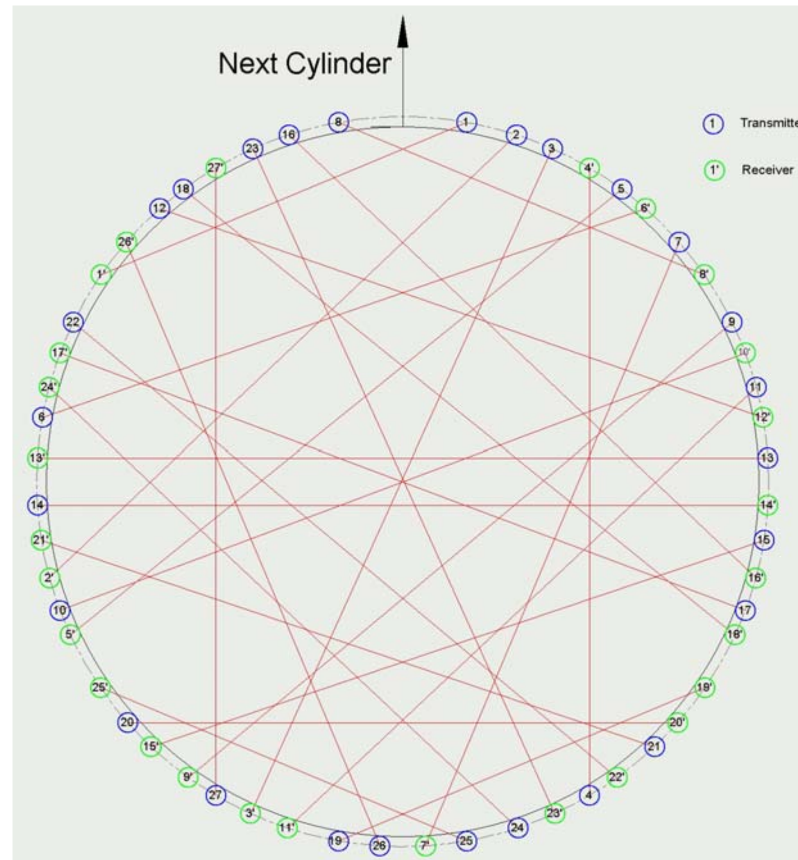
IMAGER OPtical Access Layer : OPAL

- **Critical to project success**



AOS TECHNOLOGY

ROUSH Technologies

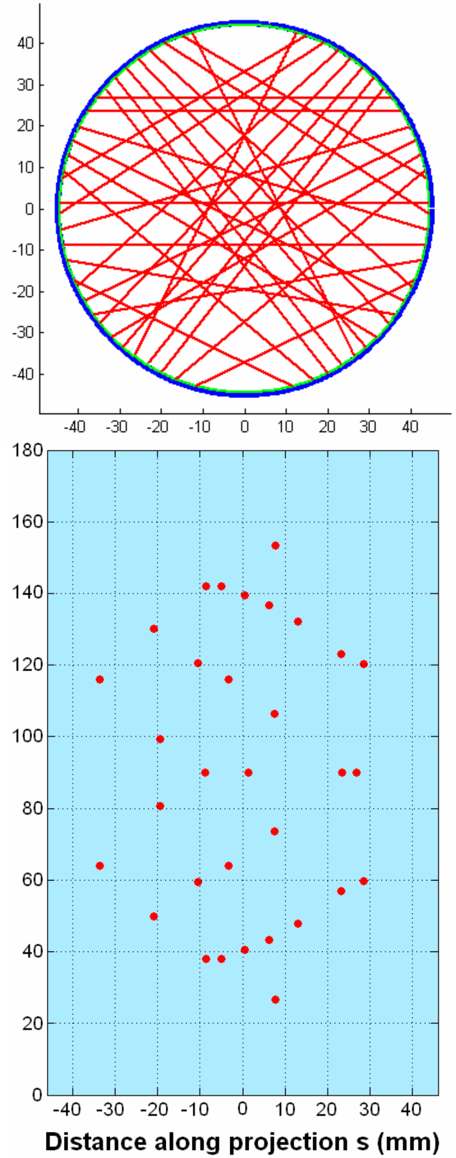


- **Constraints :**
  - Mechanical
  - Thermal
  - Optical
  - Electronic
  - Mathematical

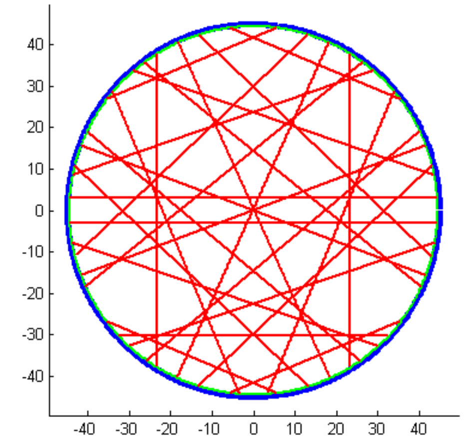
Crossley et al., *Proc. OFS18* (2006)

IMAGER OPAL array

Maximise N (32) :



Optimise angular spread (27) :



Davidson et al., *Proc. Photon '06* (2006)

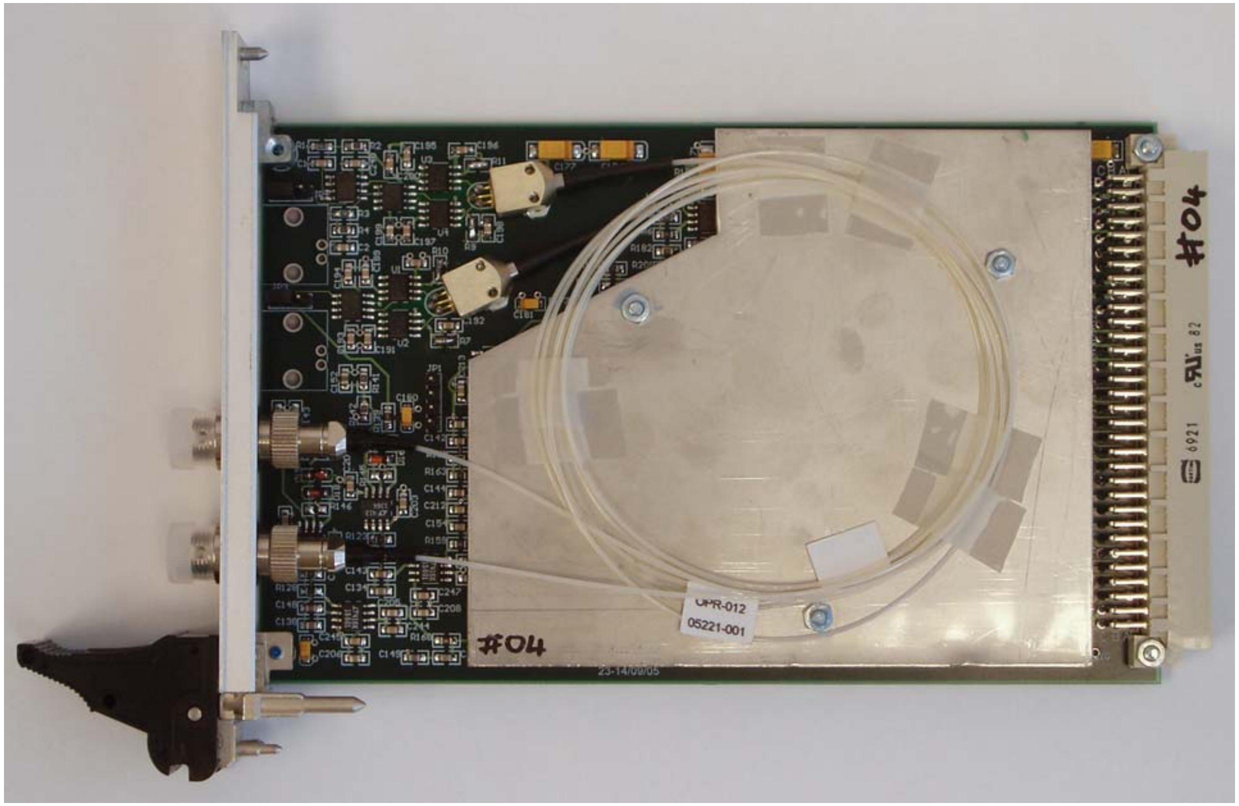
MANCHESTER 1824

The University of Manchester

IMAGER Electronics

- **Second-generation : High-speed, low-noise**

e.g. Two-channel, dual-wavelength receiver & de-multiplexer



- **Excellent "manufacturability"**

Wright et al., *IEEE Sensors J.* 5 (2005) 281 - 288

IMAGER Lab tests

- **Low-pressure steady propane flow from D/5 'pipe' :**

'pipe' positions 1 2 3

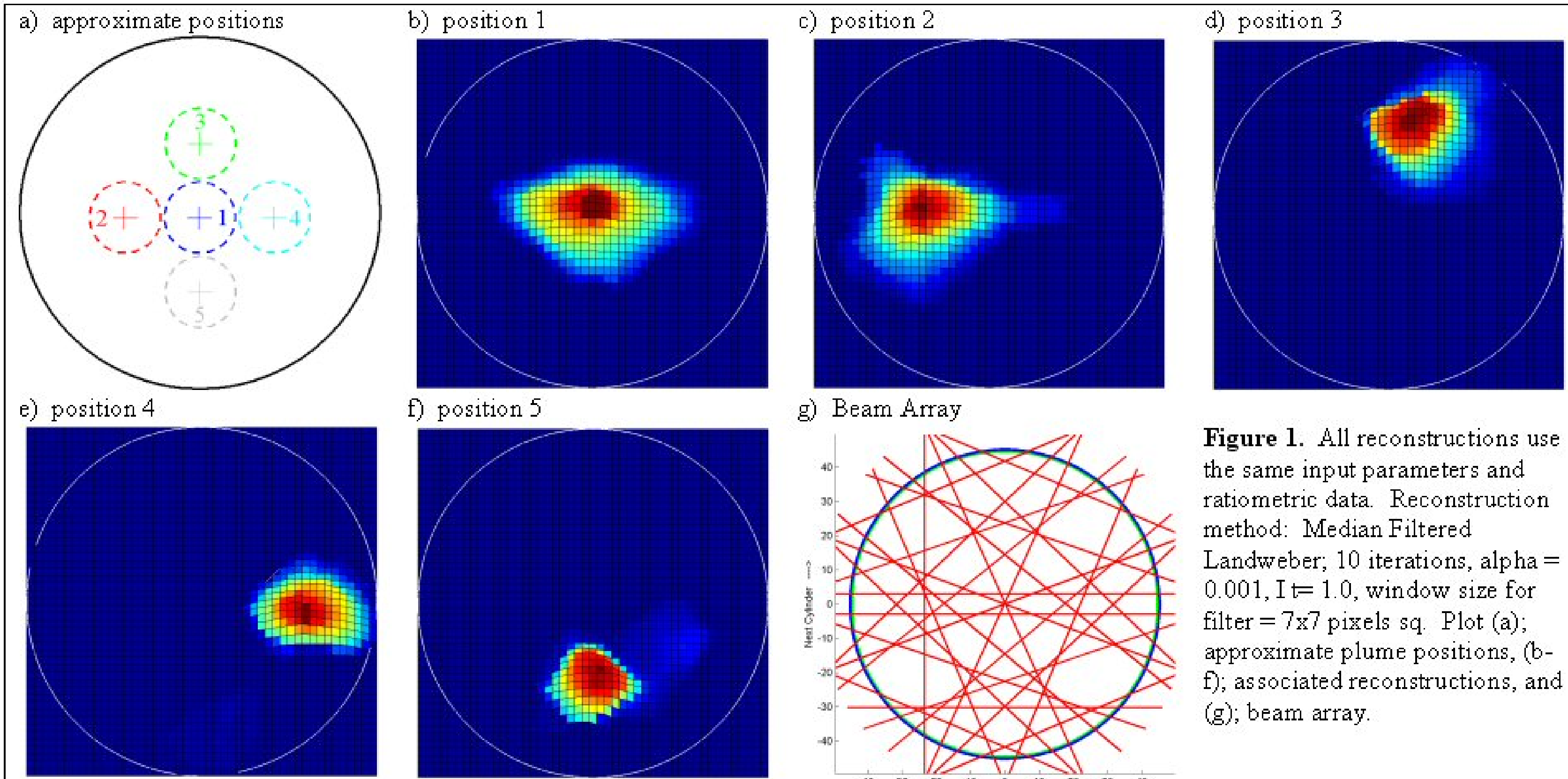
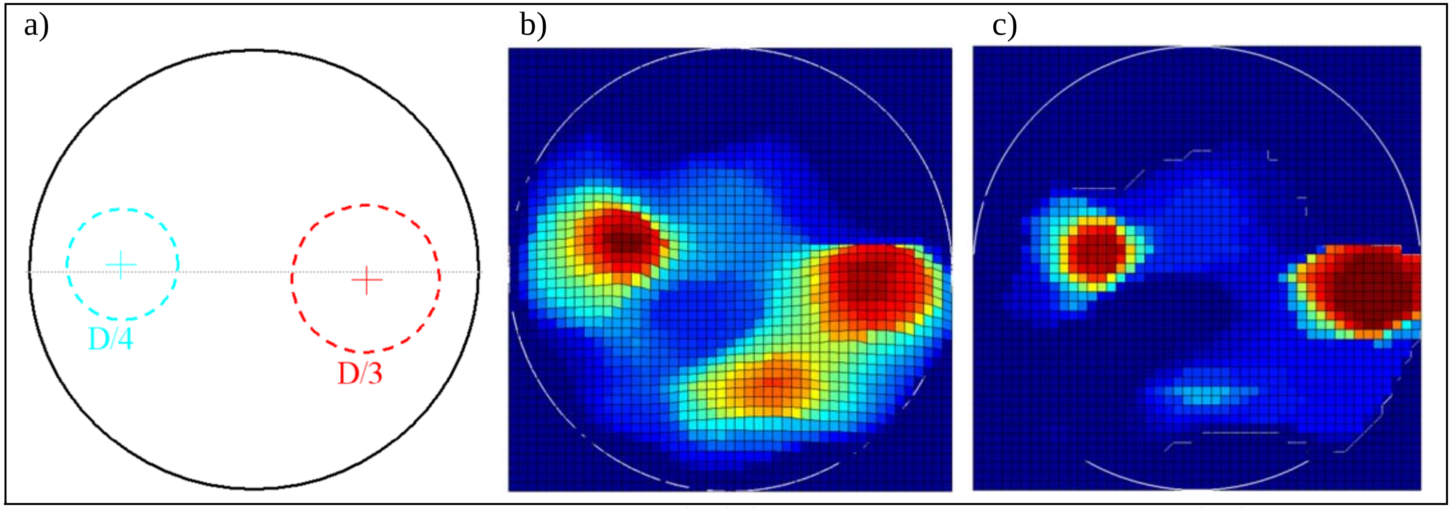


Figure 1. All reconstructions use the same input parameters and ratiometric data. Reconstruction method: Median Filtered Landweber; 10 iterations, alpha = 0.001, I t= 1.0, window size for filter = 7x7 pixels sq. Plot (a); approximate plume positions, (b-f); associated reconstructions, and (g); beam array.

4 5 Beam array

IMAGER Lab tests

- **Low-pressure steady propane flows from D/4 and D/3 'pipes' :**

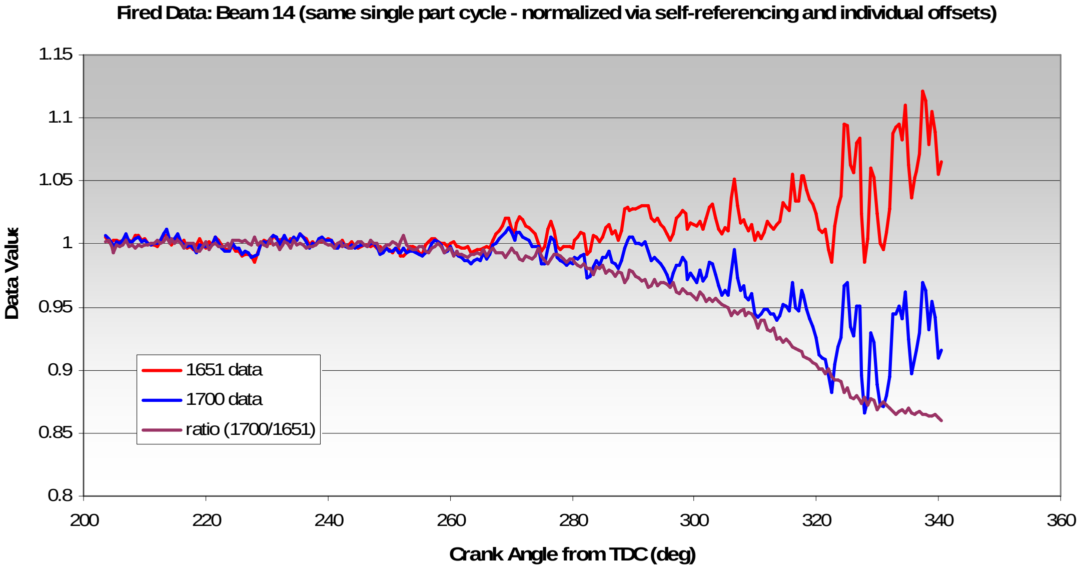


α = 0.001
10 iterations
filter window 7x7

α = 0.01
25 iterations
filter window 7x7

IMAGER Engine tests

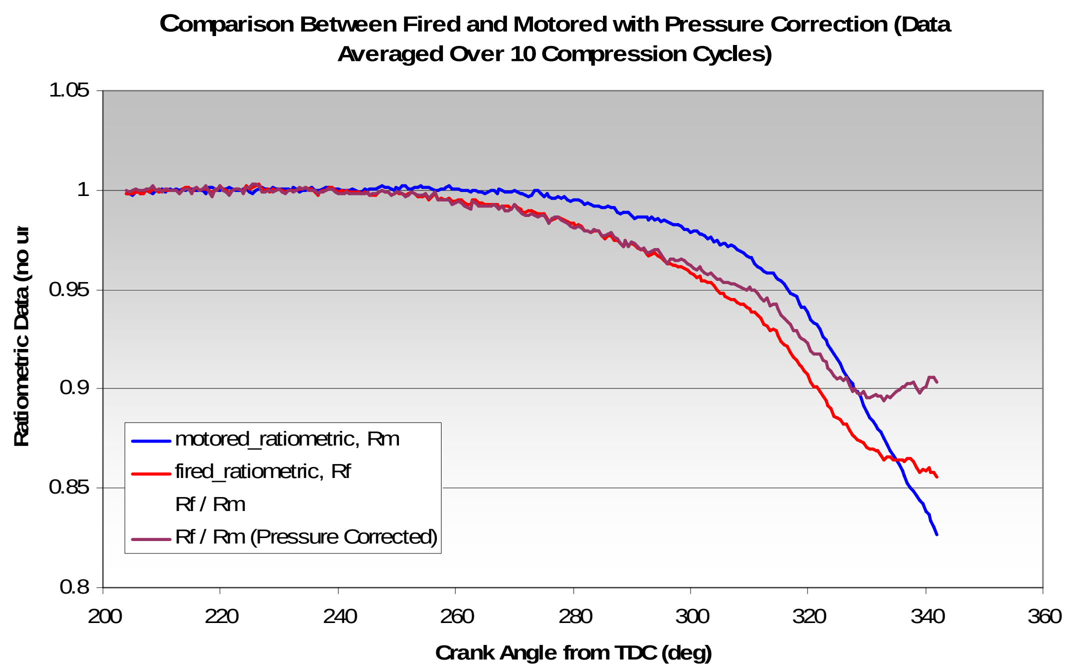
- **Late 2005 & early 2006, PFI engine**
  - **Mainly at 2000 rpm, 2 bar BMEP**
  - **27 paths (1700 & 1651 nm) simultaneously at 100 ksps**
  - **Motored**
  - **Fired with pump ULG; various End-of-Injection timings**
  - **Fired with gas**
- **Good data continues beyond 2.5 hours of ULG fired operation**
- **Raw fired data :**



- **Ratiometric approach works well**

IMAGER Engine tests

- **Calibrate fired data with motored :**



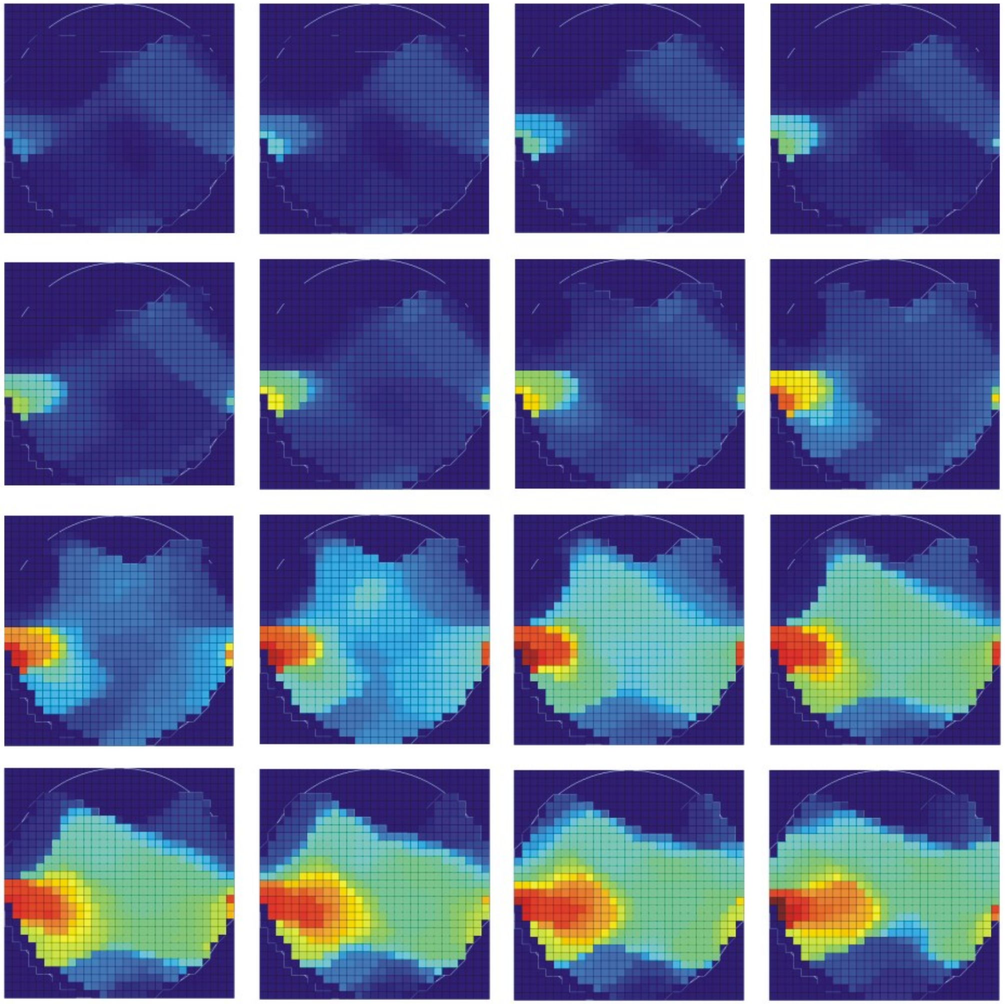
- **Physical understanding of all beams necessary**
  - at ‘consistency’ level

- **Only 12 beams used to date in image reconstruction**
  - Several more have adequate signal quality

IMAGER Engine tests

- **For illustration:**

- 2000 rpm , 2bar BMEP, pump ULG
- Single compression stroke 66º - 21º BTDC
- Image for each 3ºCA , i.e. 4,000 fps

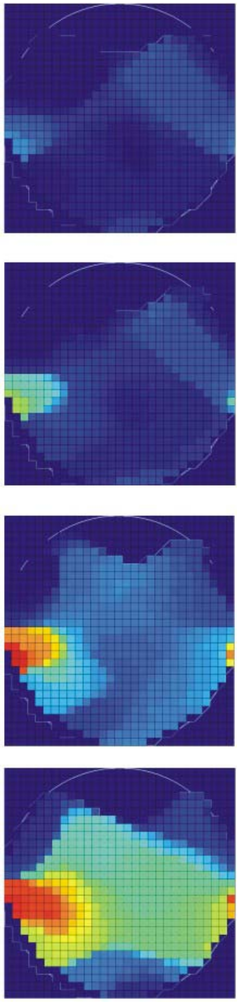


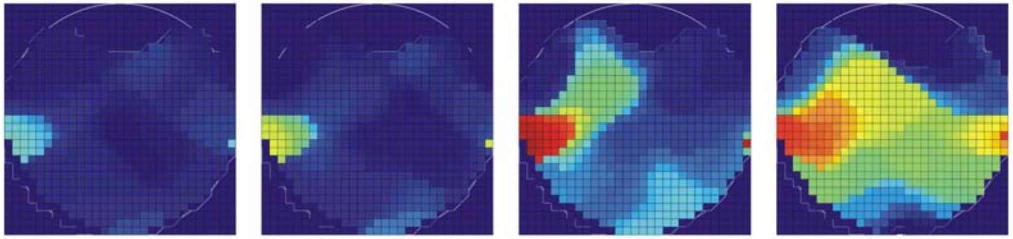
Wright et al., *Proc. Photon '06* (2006)

IMAGER Engine tests

- **For illustration:** **- Leftmost column only**

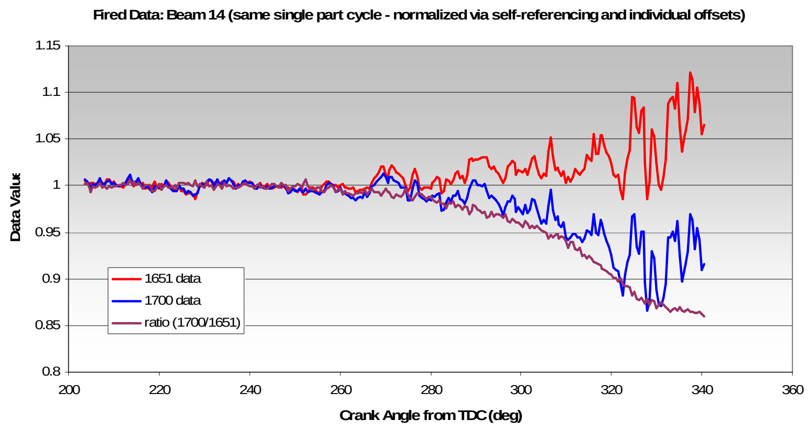
10 cycles later:





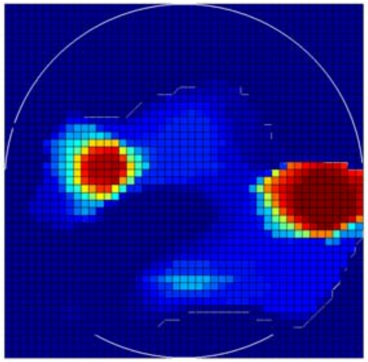
Software Bottleneck

- 27 paths, 2 wavelengths, sampled simultaneously at 100 ksps

i.e. 27 x  x 4

- i.e. ~ 10 MBytes/s, or ~35 GBytes/hr ………. Raw data!

- Raw data : 1 frame = 100 Bytes
- Image : 1 image = 10,000 Bytes



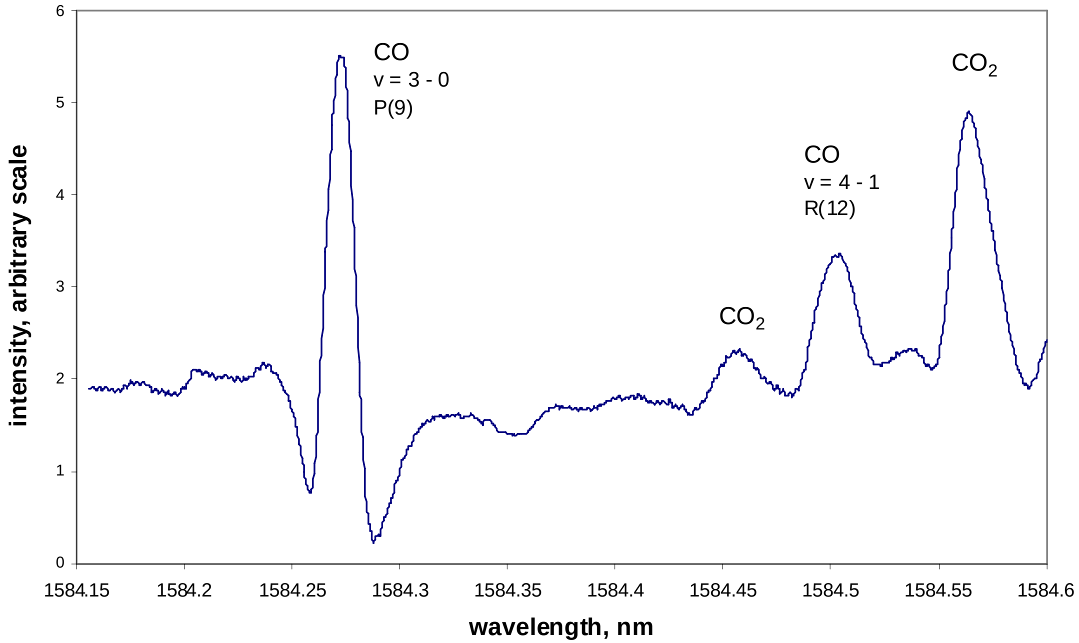
- User needs only small snatches of image data, for different engine conditions

Near-IR Absorption Tomography +

- **Lots of applications in view :**
  - **Combustion research :**
    - **automotive single-cylinder,**
    - **automotive multi-cylinder,**
    - **gas turbine**
  - **Chemical manuf. processes, e.g. catalytic fluidised beds**

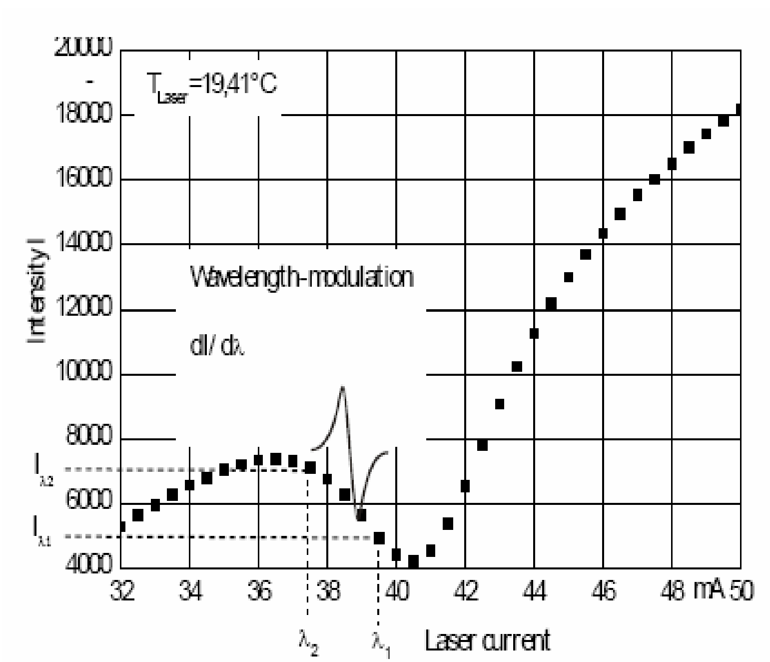
- **Extend to more species : - O_2, NO, CO, CO_2 , …….**

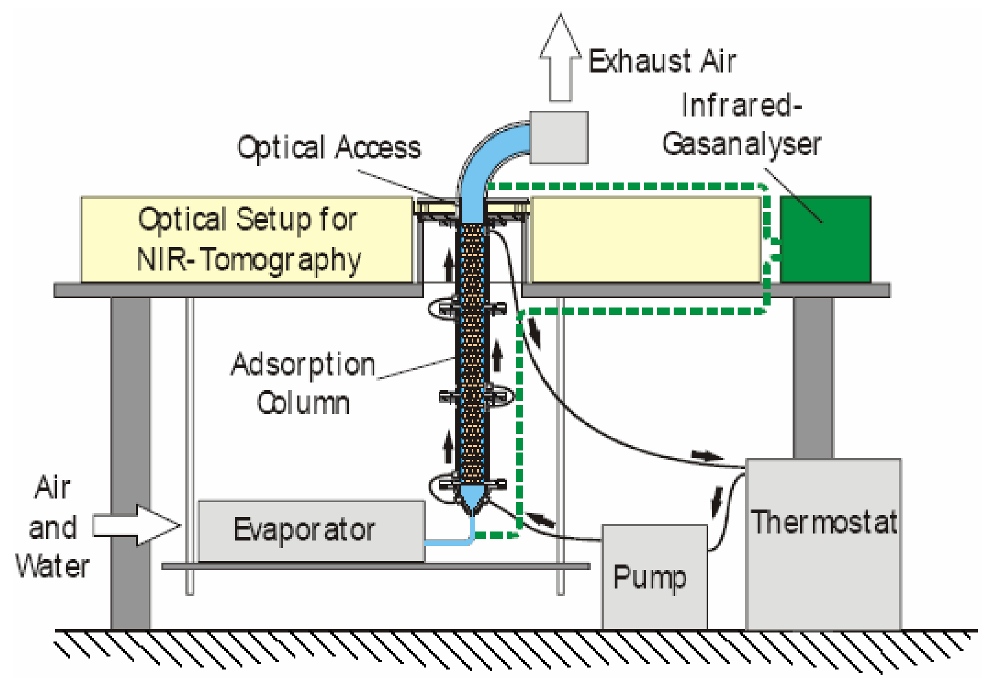
- **Use TDLAS (P.A. Martin, UoM)**



Water vapour imaging

- Water break-through in adsorption column
- Model / Improve / Control purification & separation of gases
- Single DFB laser, wavelength-modulated on 1396 nm line





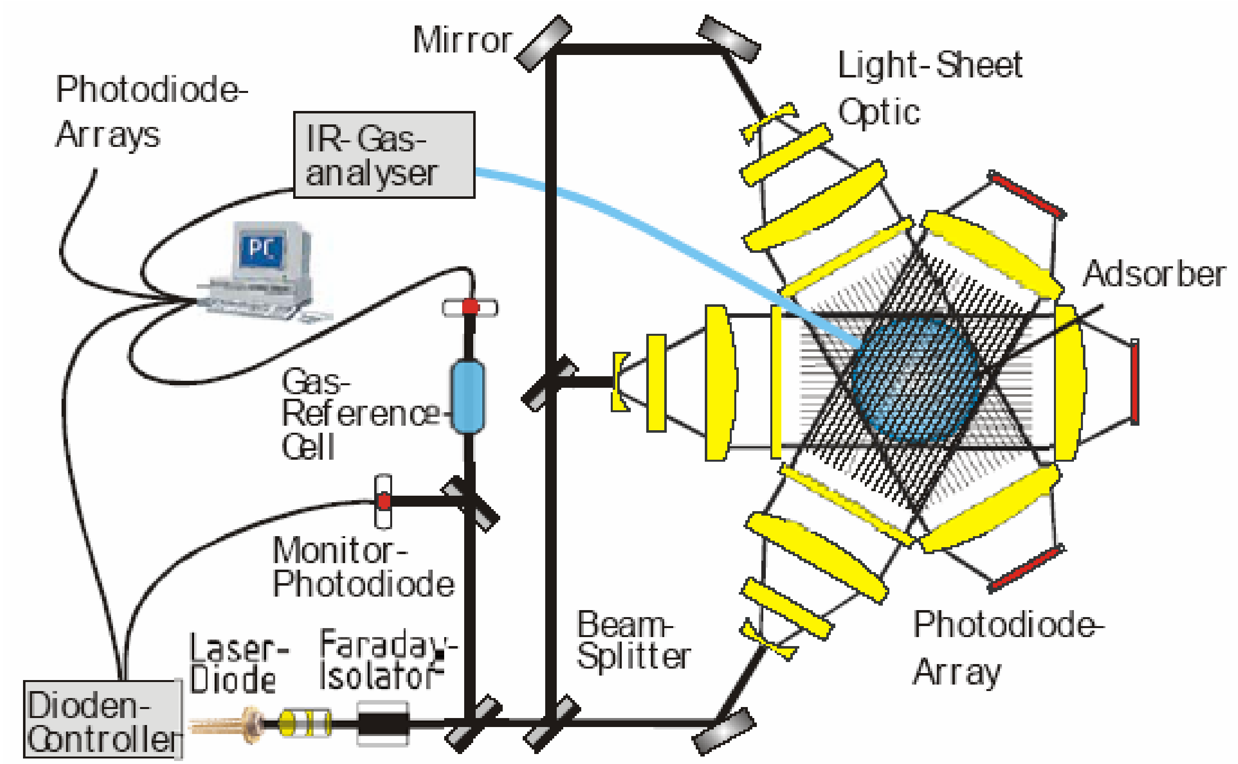
Salem, Tsotsas & Mewes, Chem. Eng. Sci. (2005)

MANCHESTER 1824

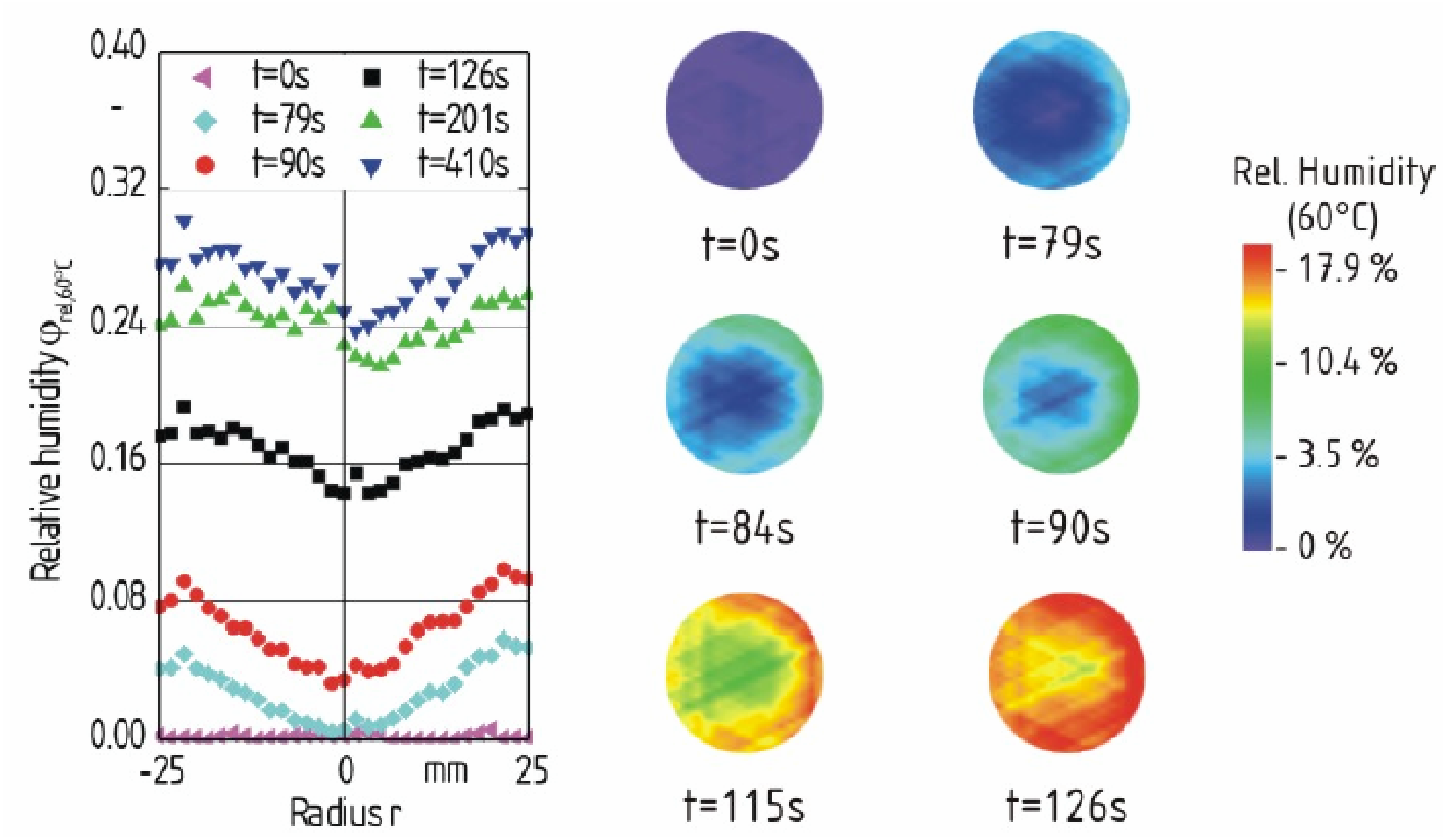
The University of Manchester

Water vapour imaging

- **Chosen λ region free of absorption by CO_2, N_2, etc.**
- **Free-space optics : - External gas reference cell**
  - 3 sheets + array detectors (3 x 128)
- **δ_t < 1s**



Water vapour imaging

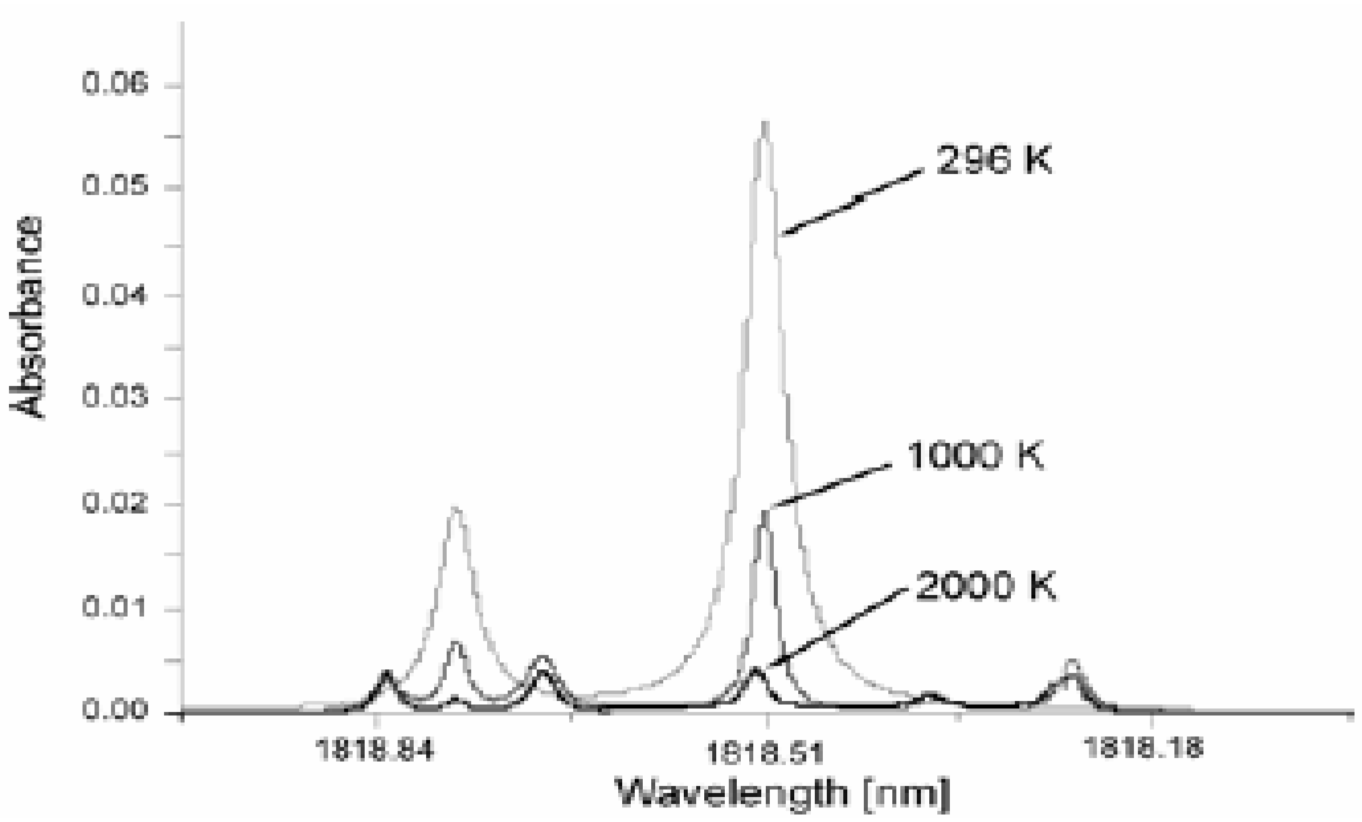


- Excellent penetration of process phenomena
- Can expect many more applications

Near-IR Absorption Tomography + +

- **Simultaneous multi-species - Reaction rates & pathways f(x,t)**

- **Temperature imaging, Krikor Ozanyan :**

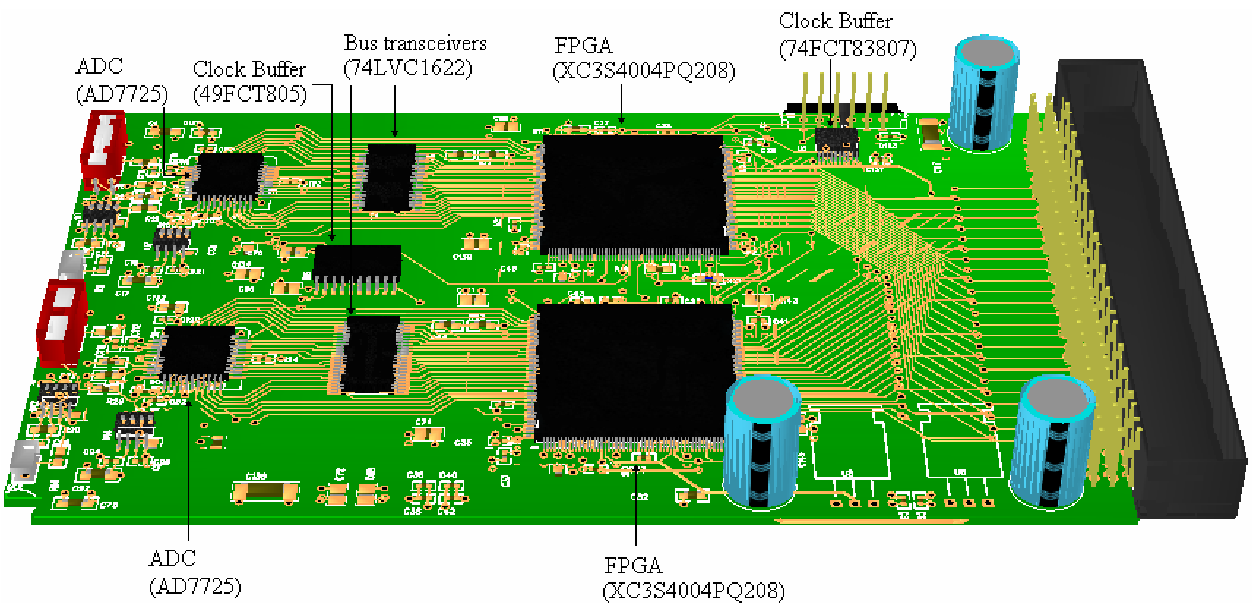


The University of Manchester

MANCHESTER 1824

Near-IR Absorption Tomography + + +

- **Exploit digital electronics** **- reliability**
  - self-calibration
  - digital lock-in & filtering : FPGA



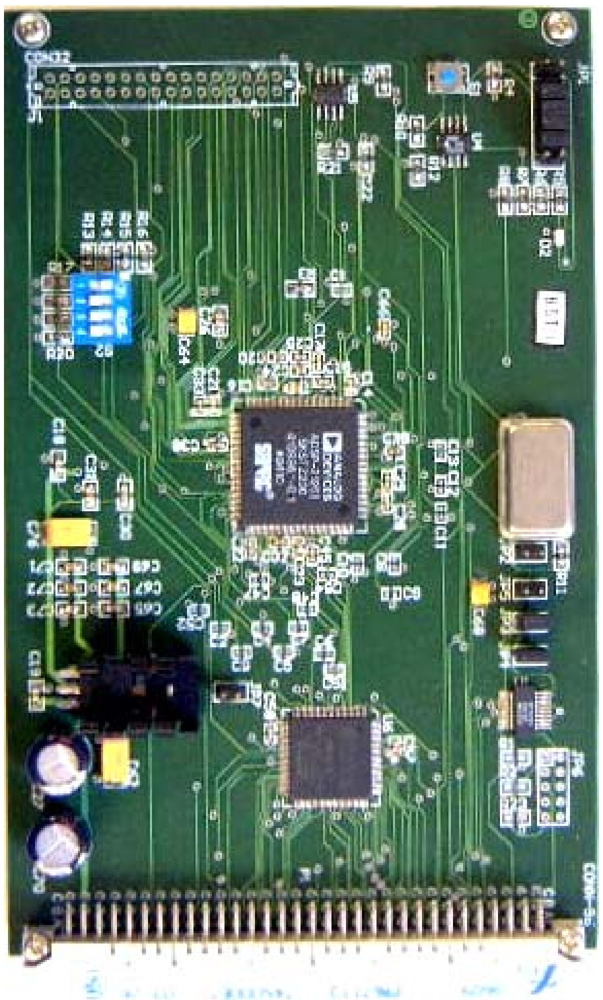
- **Increase # measurement paths, for improved spatial resolution**

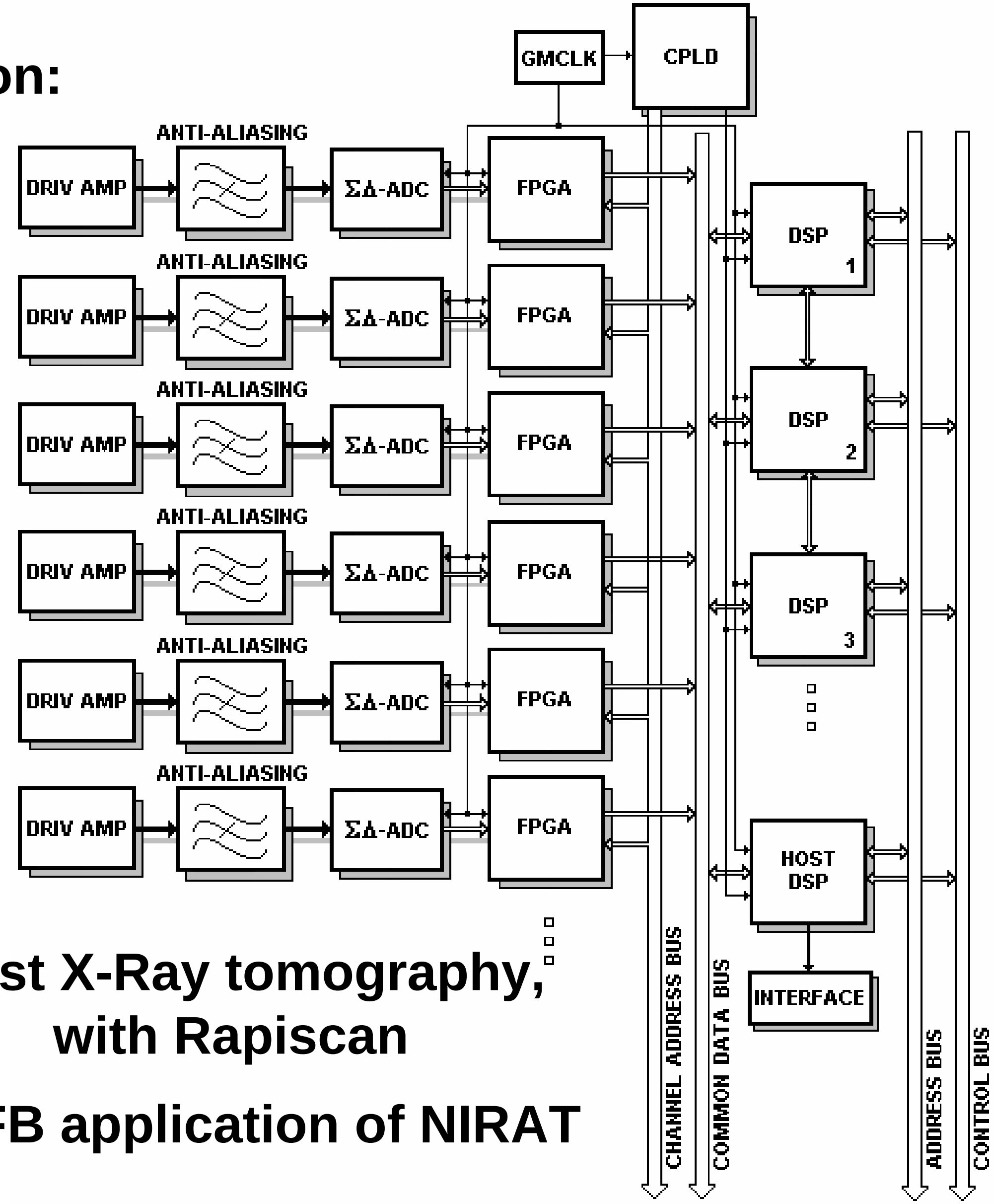
The University of Manchester

MANCHESTER 1824

Hard-Field Tomography

- **Fast multi-channel intelligent instrumentation:**





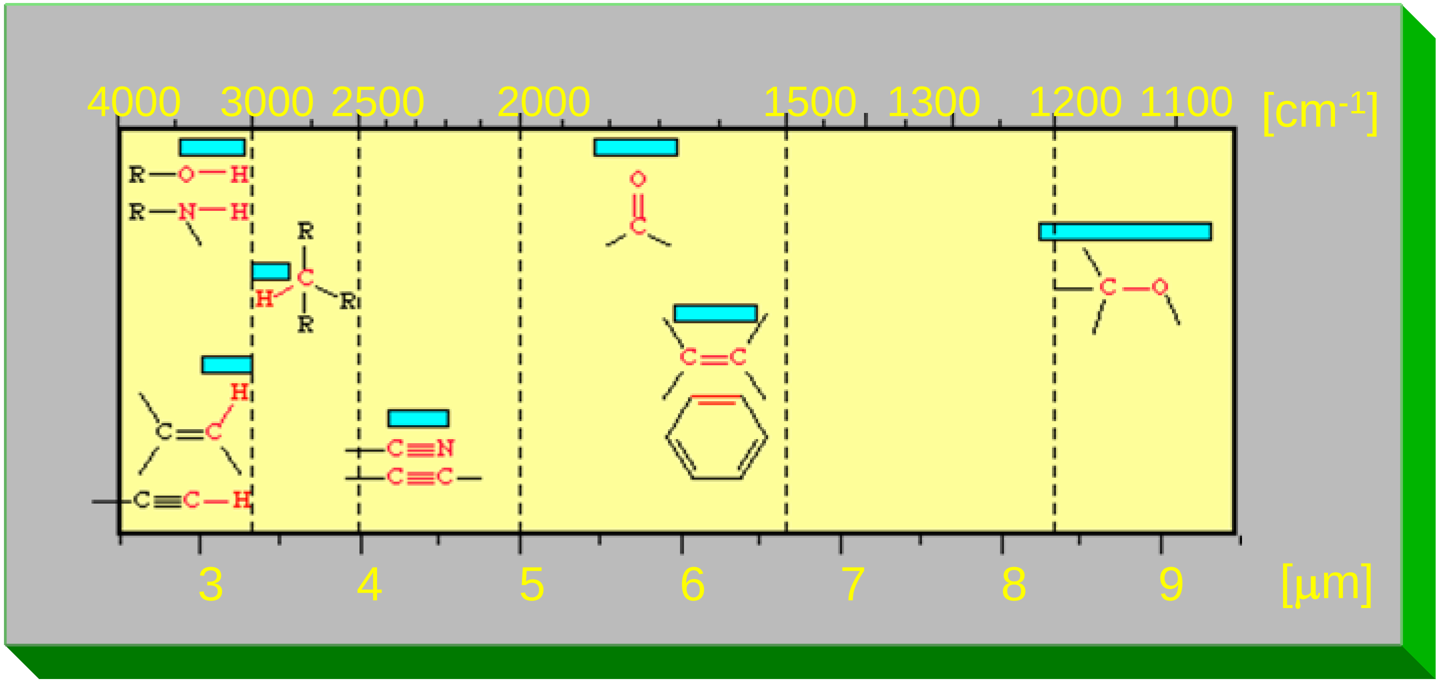
- **Fast X-Ray tomography, with Rapiscan**
- **CFB application of NIRAT**

The University of Manchester

MANCHESTER 1824

Mid-IR Absorption Tomography

- **Very strong & specific absorptions :**



- **Several new technologies (e.g. QCLs)**

- **Address minor species (< 1000 ppm)**

VCIPT

www.vcipt.org.uk

The Virtual Centre for INDUSTRIAL PROCESS TOMOGRAPHY

- **Univ. Leeds** - Particle Science & Engineering,
  - Integrated Information Systems,
  - Statistics
- **Manchester** - Chemical Engineering & Analytical Science
  - Electrical & Electronic Engineering
  - Mathematics
- **20 Academic staff & 80 Researchers**
- **8 Subscribing companies**
- **World Congress in Industrial Process Tomography**
  - 1999 UK
  - 2001 Germany
  - 2003 Canada
  - 2005 Japan
  - 2007 Norway, Bergen, 3 – 6 September

Conclusions

- **Electrical tomography is firmly established as a viable tool for *in-situ* process R&D**

- **Still lots of scope for R&D in the technique and its applications**

- **Near-IR Absorption Tomography is demonstrated in hostile systems**

- **……and the concept has huge scope for extension in a number of directions**

- **…….particularly to:**
  - **Highly scattering systems**
  - **Mid-IR and minor species**

The University of Manchester

MANCHESTER 1824

Acknowledgements

- Dr. Krikor Ozanyan (EEE), Dr. Philip Martin (UoM)
- Steve Carey, Frank Hindle, Paul Wright, John Davidson, Charles Garcia-Stewart
- Roush Technologies Ltd. - Paul Turner & colleagues
- AOS Technology Ltd. - Sam Crossley & colleagues
- Ford Motor Company - John Eade, Andy Scarisbrick, Jon Caine
- Rover, Shell, AVL GmbH
- EPSRC
- DTI (Steve Gratze)