Progress in Hard-Field Industrial Tomography

Packard Room 101, Engineering bldg.
Stanford university

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Outline

- Introductions: IEEE Sensors Council, The University of Manchester
- 5 minutes' excursion in Hard-Field Tomography
- Applications of Tomography sensing and imaging in Industry
- Challenges and solutions in non-medical applications:
  - ➢wavelength-sensitive modalities: IR, THz
  - ➢path integrals: kinds of image contrast, T^o-mapping
  - ➢insufficient data: sinogram recovery from limited data
-

DL sponsored by the IEEE Sensors Council

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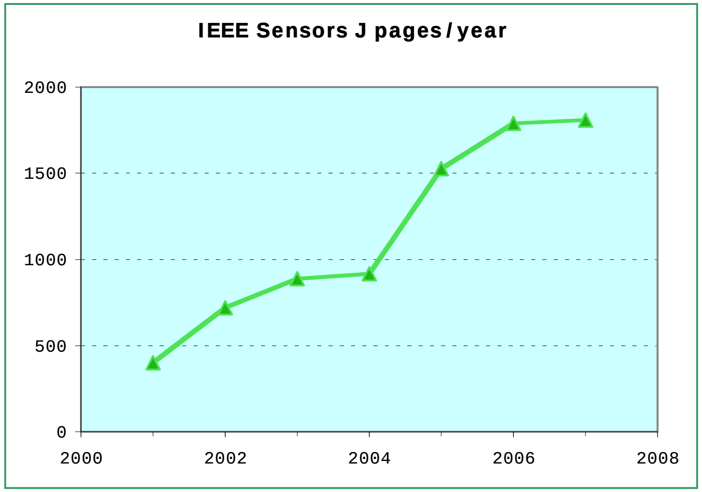
IEEE
Celebrating 125 Years
of Engineering the Future

Sensors Council

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.



Conferences: IEEE Sensors xx

2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Orlando Florida	Toronto Canada	Vienna Austria	Irvine Calif.	Daegu Korea	Atlanta Georgia	Lecce Italy	Christchurch N Zealand	Hawaii USA	Limerick Ireland

The (new) University of Manchester

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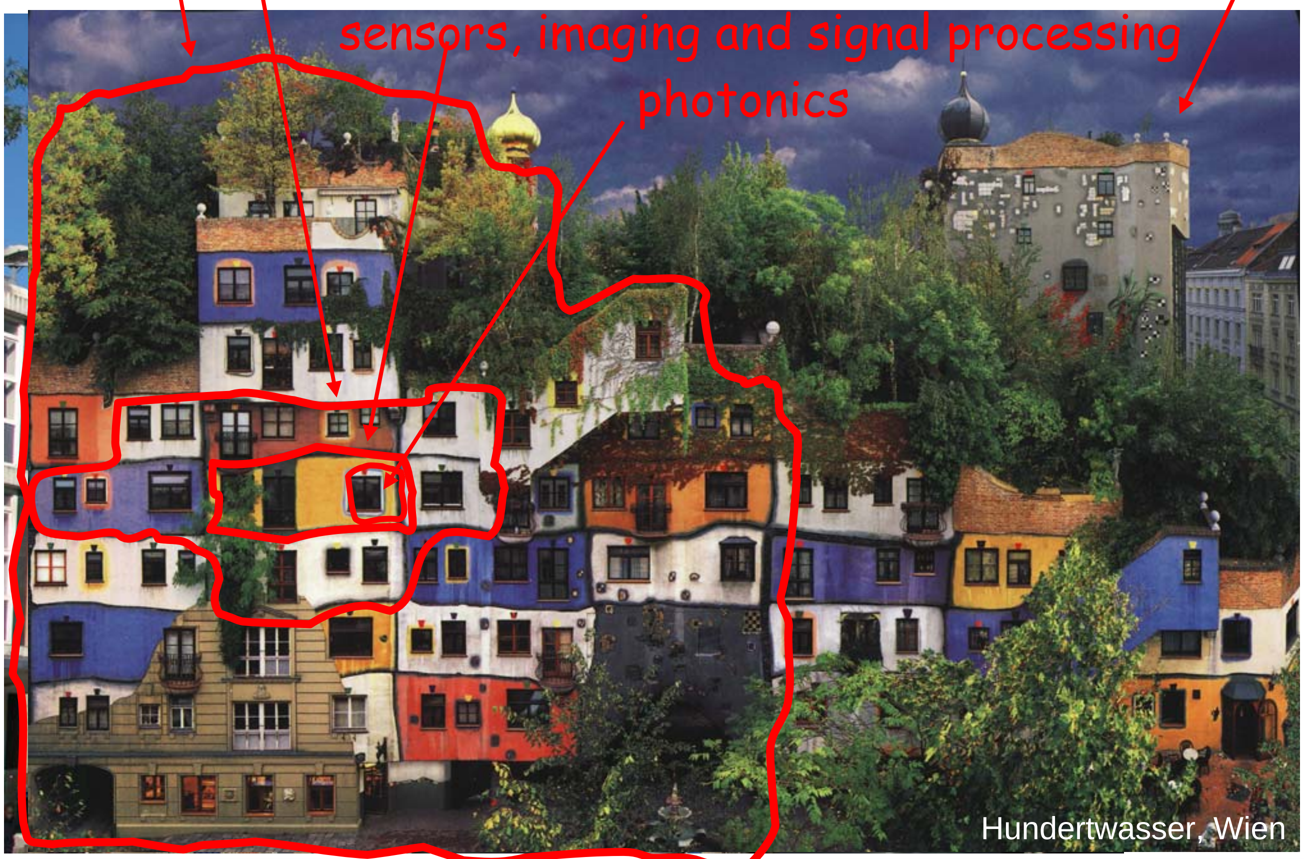

- interdisciplinarity
- research-driven
- 2015 strategy

Parallel structures: Institutes

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The Photon Science Institute

Outline

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- Applications of Tomography sensing and imaging in Industry
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-

Tomography: To see where you can't reach

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From Greek: τομή - cut

γραφός - image

The name reflects the fact that with carefully chosen measurements at the periphery of an object, one can produce without intrusion an image of inaccessible cross-sections.

How to extract images from measurements taken with a particular strategy?

Soft-field vs Hard-field Tomography

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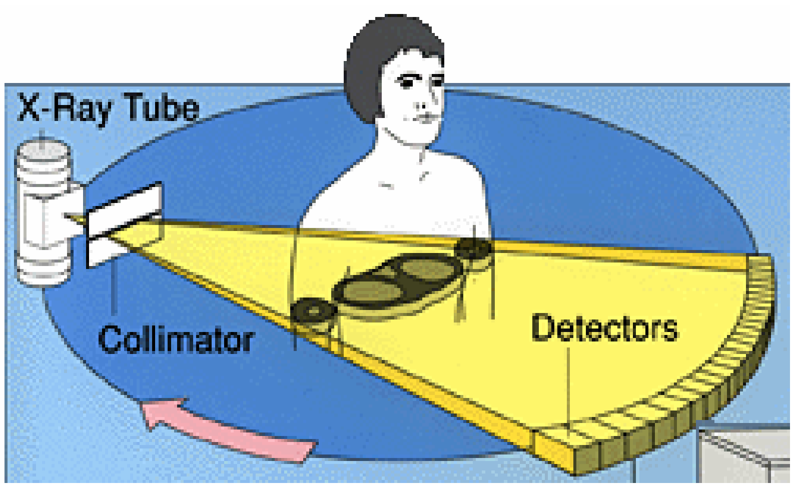
“Hard” field:

The EM field propagates along a straight line through the volume, i.e. the measurement at the volume surface depends on the values of the measured quantity only along the probed path.



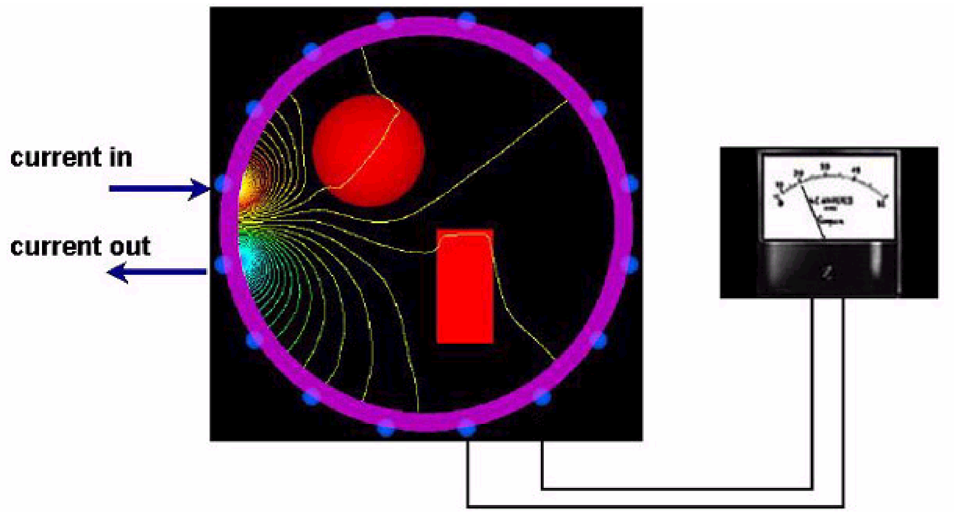
Examples:
X-ray Tomography,
Positron Emission Tomography,
Microwave Tomography
Optical Tomography
…..

typically **High-Frequency** modalities.

Soft-field vs Hard-field Tomography

"Soft" field:

The EM field propagates across the whole probed volume, i.e. the measurement at the volume surface depends on the values of the measured quantity everywhere in the volume.



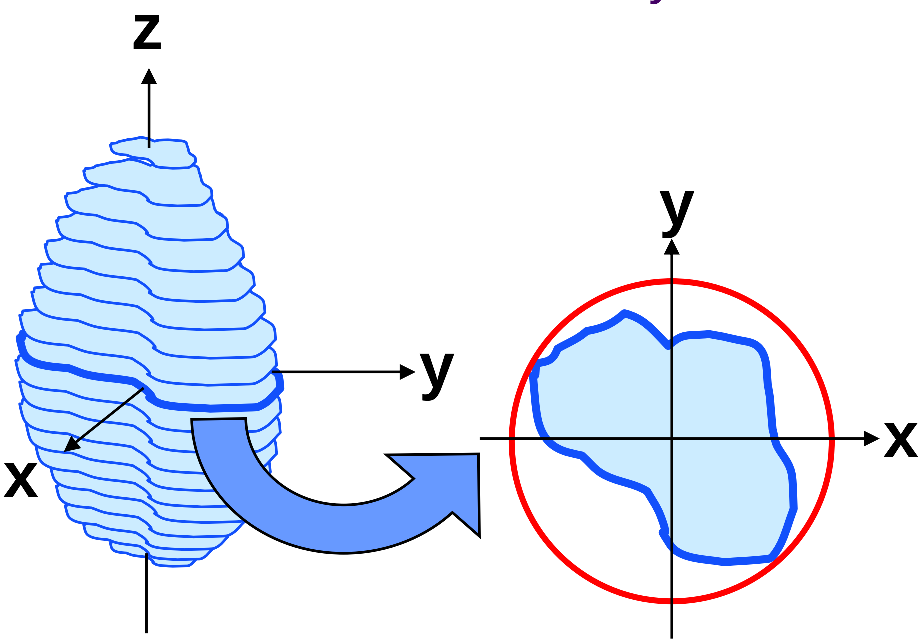
Examples:

Electrical Capacitance Tomography,
Electrical Impedance Tomography,
…..

typically **Low-Frequency** modalities.

3D stacks of 2D slices

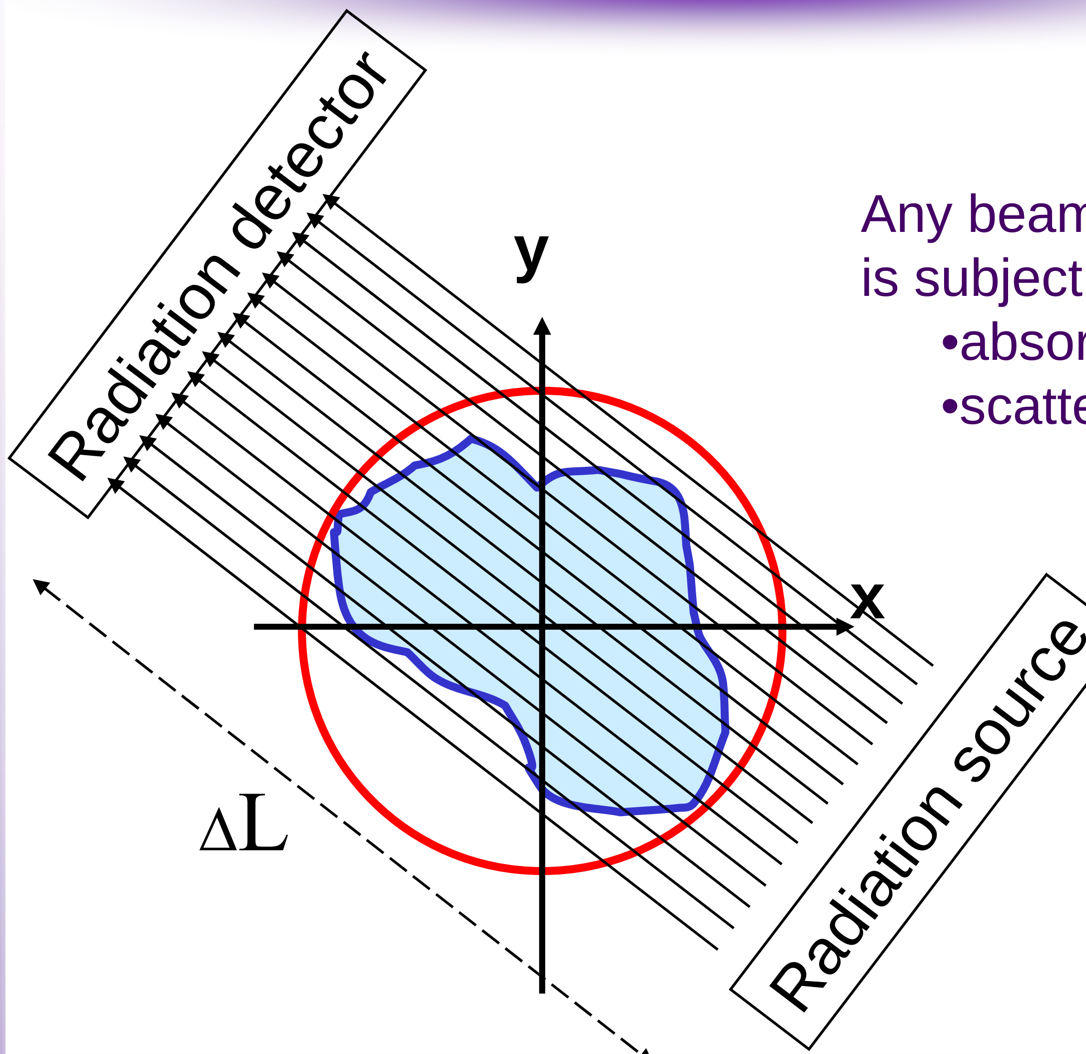
The object is 'sliced" along one of the axes (z)
(If the slices are infinitesimally thin, we have a slice for each z)



QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

If we reconstruct each slice of the object we can reconstruct the whole object by stacking of slices

X-ray CT: the modality



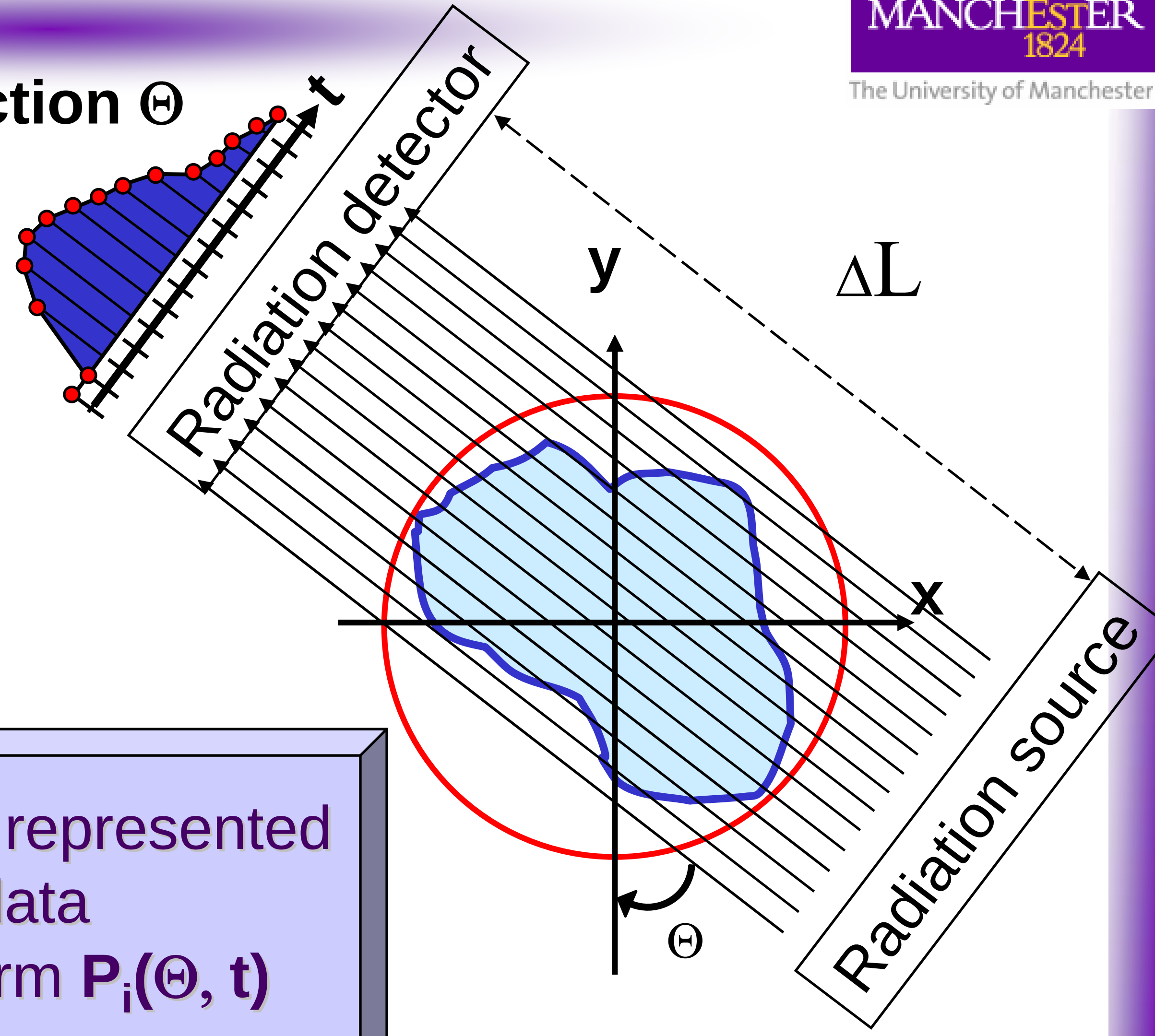
Any beam passing through the object is subject to attenuation:

- absorption
- scatter

$$\frac{N_{source} - N_{detector}}{N_{detector}} = \mu.\Delta L$$

$$N_d = N_s e^{-\int_{path} \mu(L).dL}$$

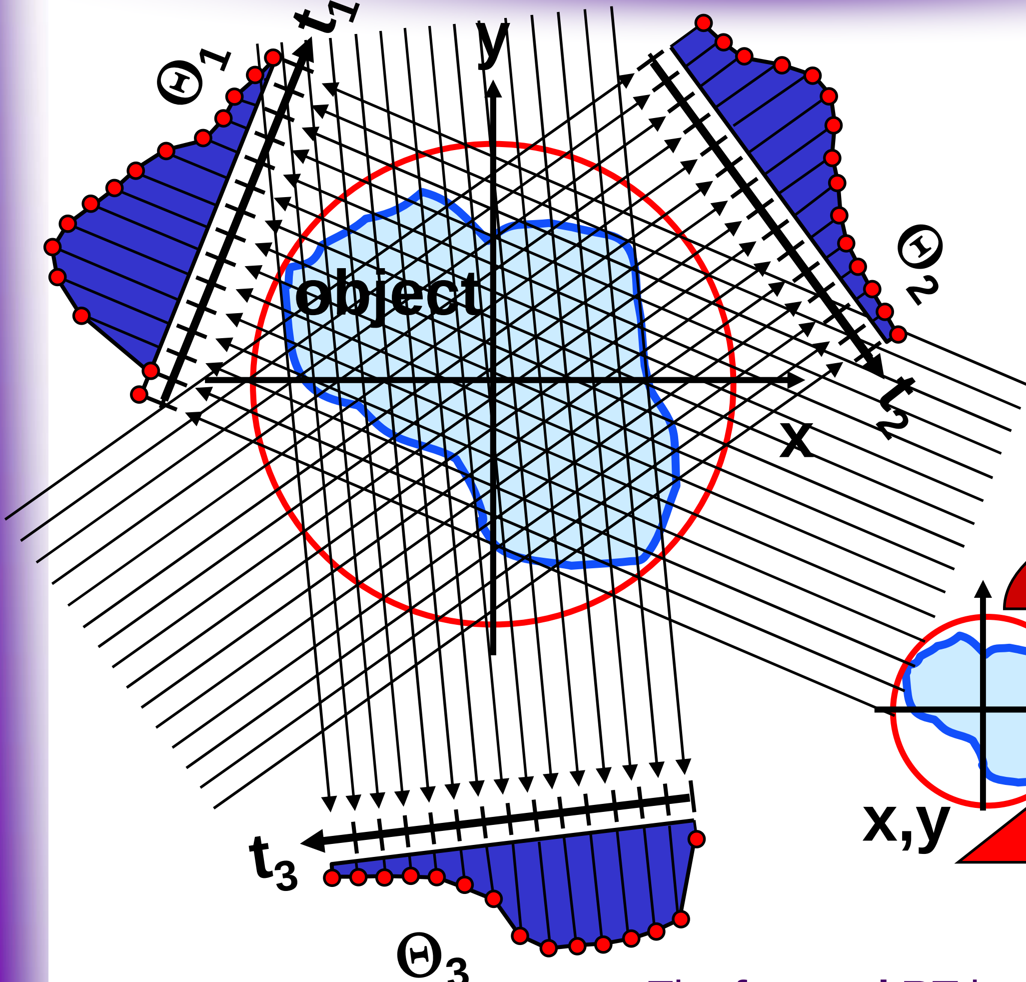
X-ray CT: the projection



For each projection angle $\Theta_1, \Theta_2 \ldots \Theta_n$ the tomograph records projections $P_i(\Theta, t)$

The object **F(x,y)** is represented by **all** the data acquired in the form $\mathbf{P_i(\Theta, t)}$

The Radon Transform

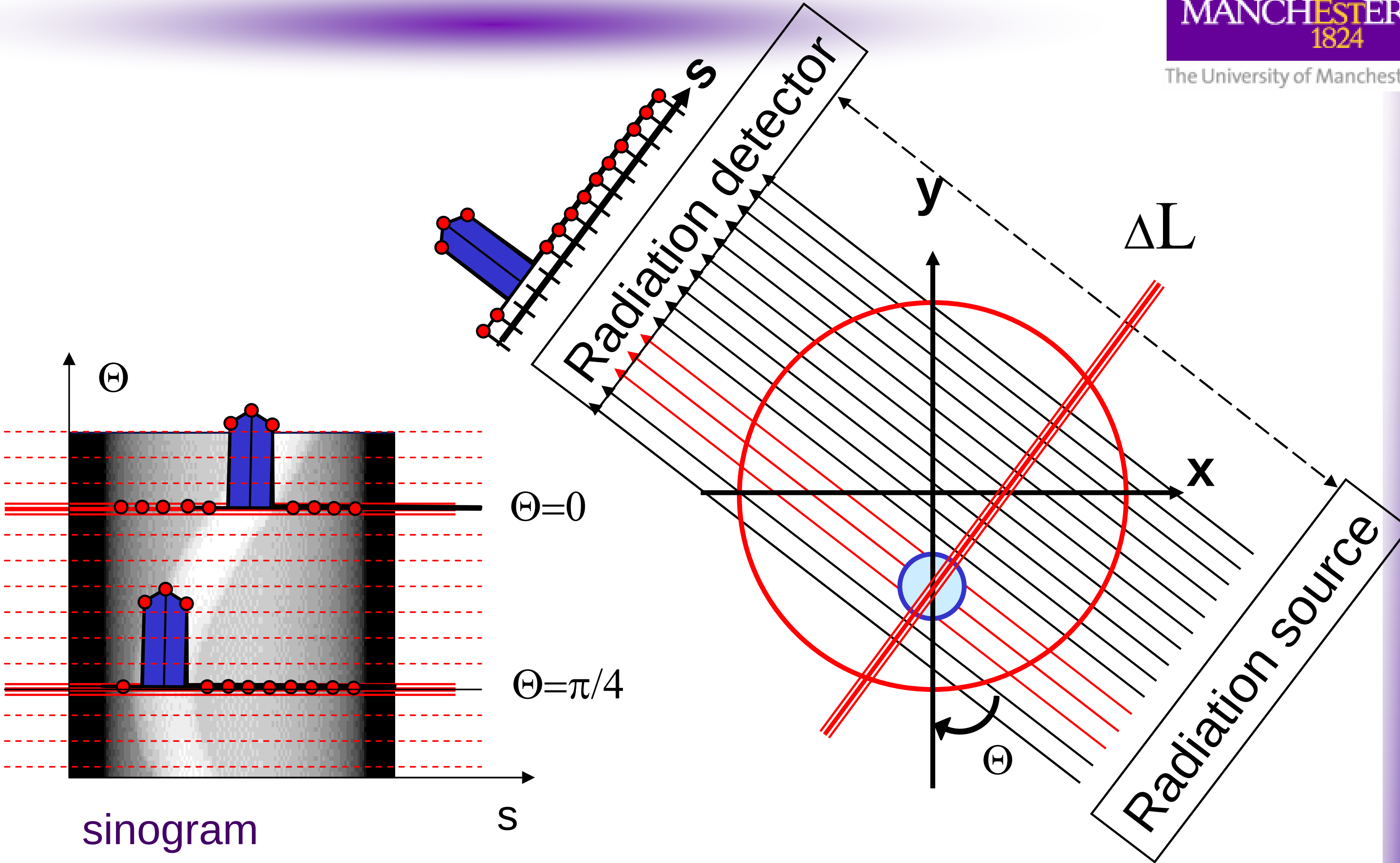


Experimental requirements:

- as many parallel beams as possible
- as many projections as possible

The **forward RT** is performed experimentally **(measurement)**
The **inverse RT** is performed mathematically **(reconstruction)**

Sinogram


Θ
Θ=0
Θ=π/4
sinogram
s
s
Radiation detector
y
ΔL
x
Θ
Radiation source

Inverse problem of Tomography

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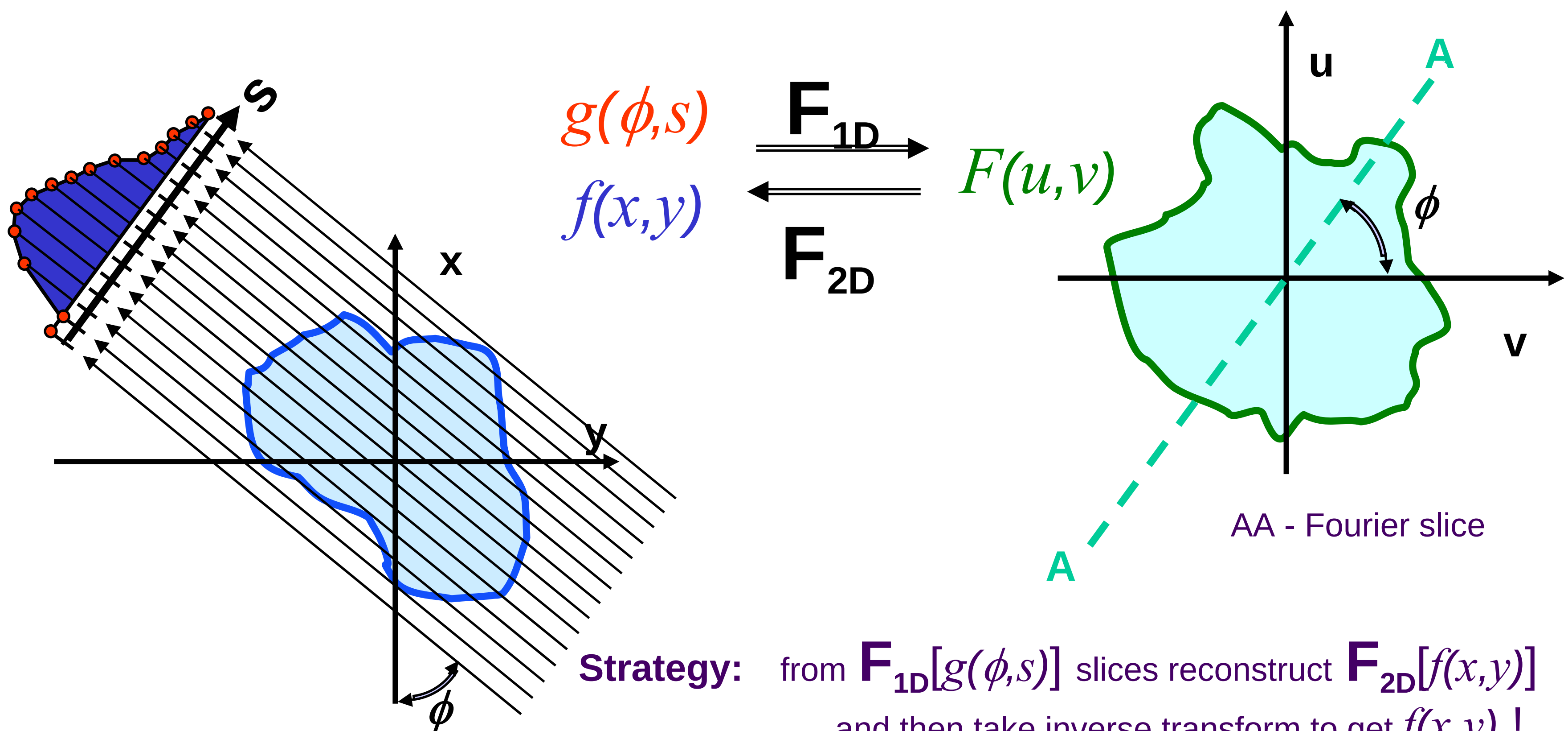
The basic problem of CT is:

Given a set of 1D projections and the angles at which these projections were taken, to reconstruct the 2-D image.

There are analytical and non-analytical (iterative) methods of solving the inverse problem, which is ill-posed and ill-conditioned.

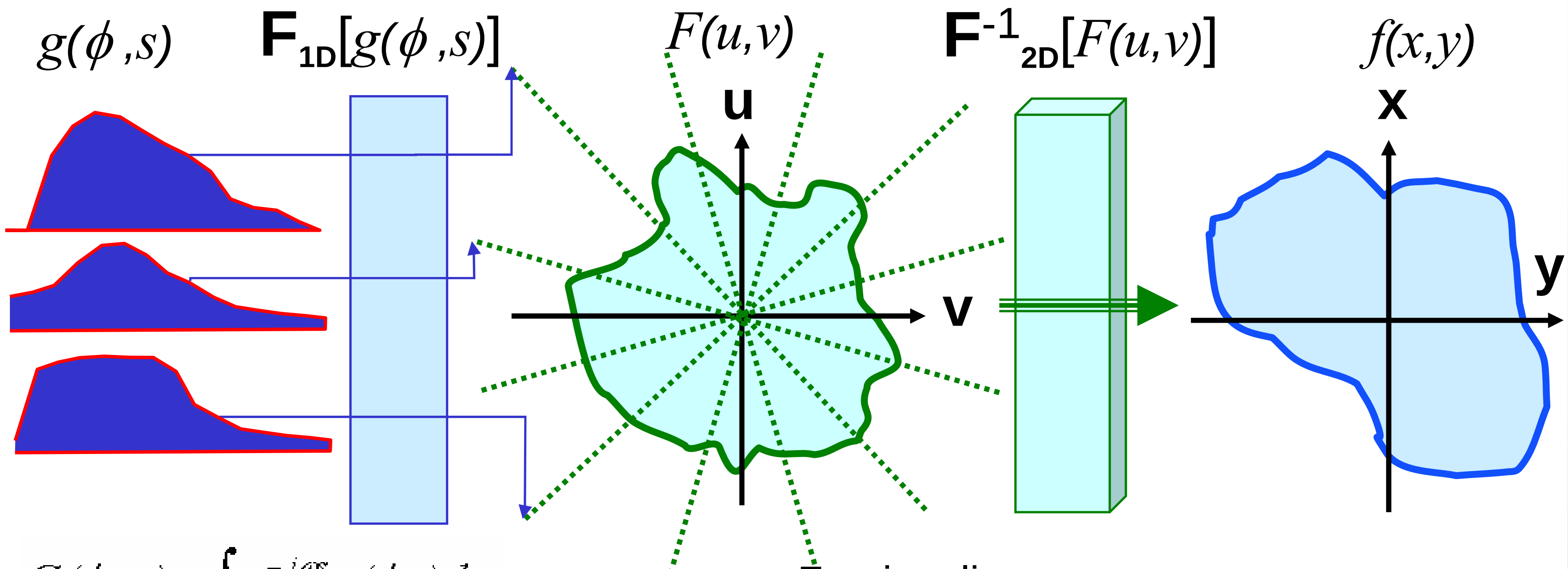
Inverse Radon Transform (iRT)

The 1D FT of the projection function $g(\phi,s)$: $\mathbf{F}_{1D}[g(\phi,s)]$, is equivalent to the slice cut at angle ϕ from the 2D Fourier Transform of the image.



Strategy: from $\mathbf{F}_{1D}[g(\phi,s)]$ slices reconstruct $\mathbf{F}_{2D}[f(x,y)]$ and then take inverse transform to get $f(x,y)$!

Direct Fourier reconstruction



$$G(\phi,\omega)=\int e^{-j\omega s} g(\phi,s)\,ds$$

Fourier slice

$$F(u,v)=\iint f(x,y)e^{-j(ux+vy)}\,dxdy$$

2D Fourier T of *f(x,y)*

$$f(x,y)=\frac{1}{4\pi^2}\iint F(u,v)e^{j(ux+vy)}\,dudv$$

Inverse 2D Fourier T of *F(u,v)*

X-ray CT in Fluidized Beds

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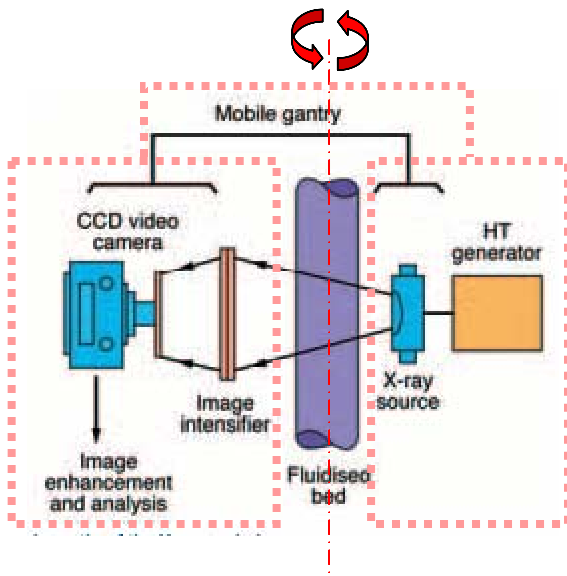
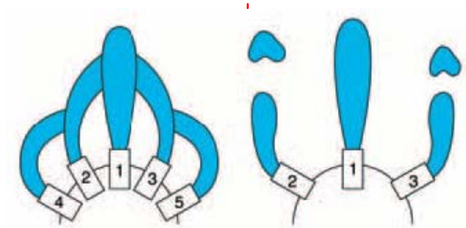
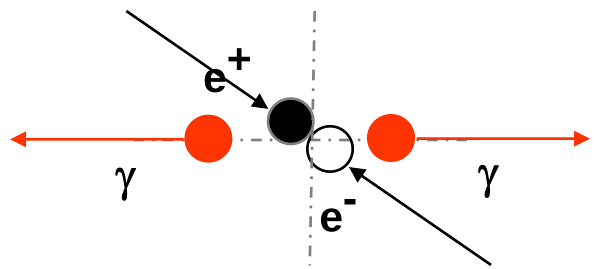


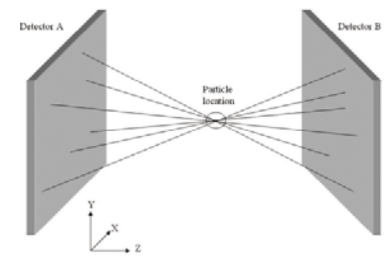


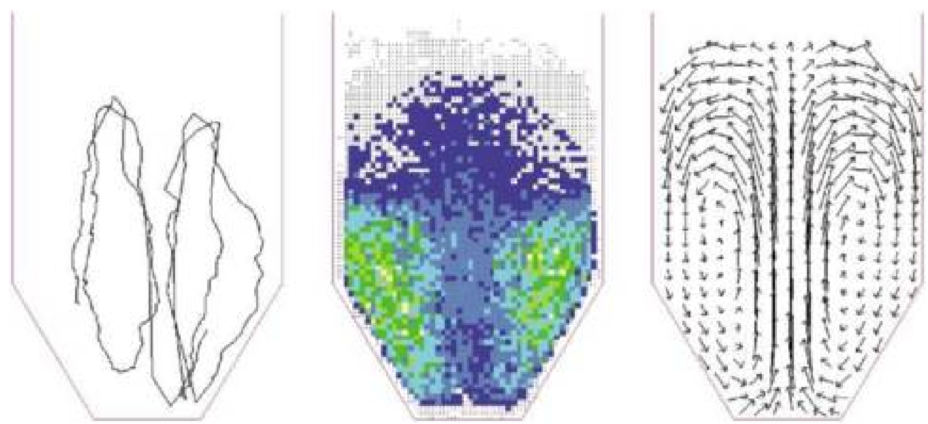
Positron Emission Tomography

Positron Emission Particle Tracking (PEPT)


David Parker et al., Birmingham

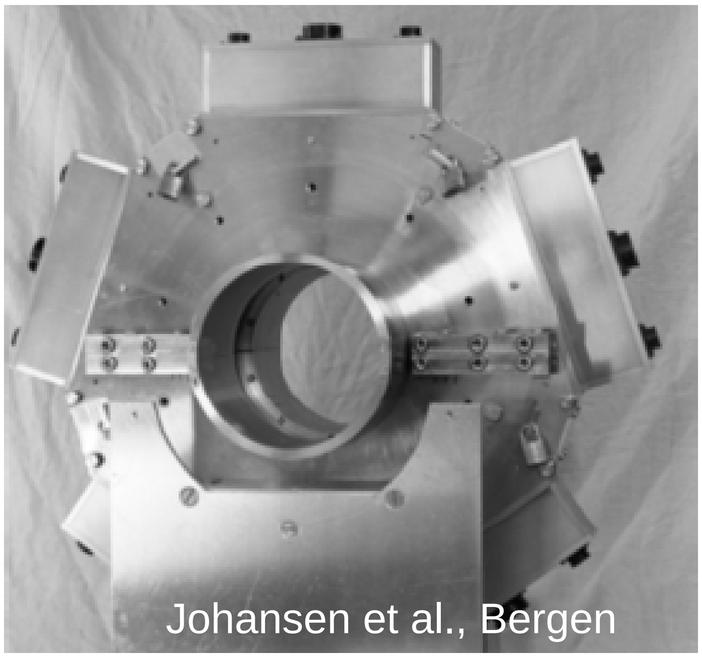




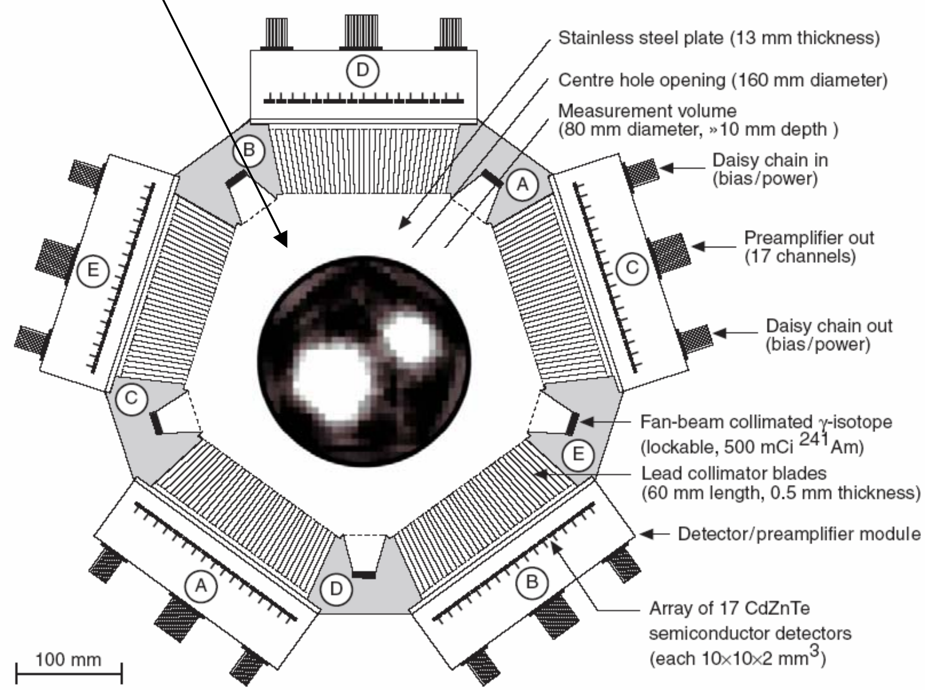

Particle tracking, occupancy and velocity field

Gamma-ray Tomography

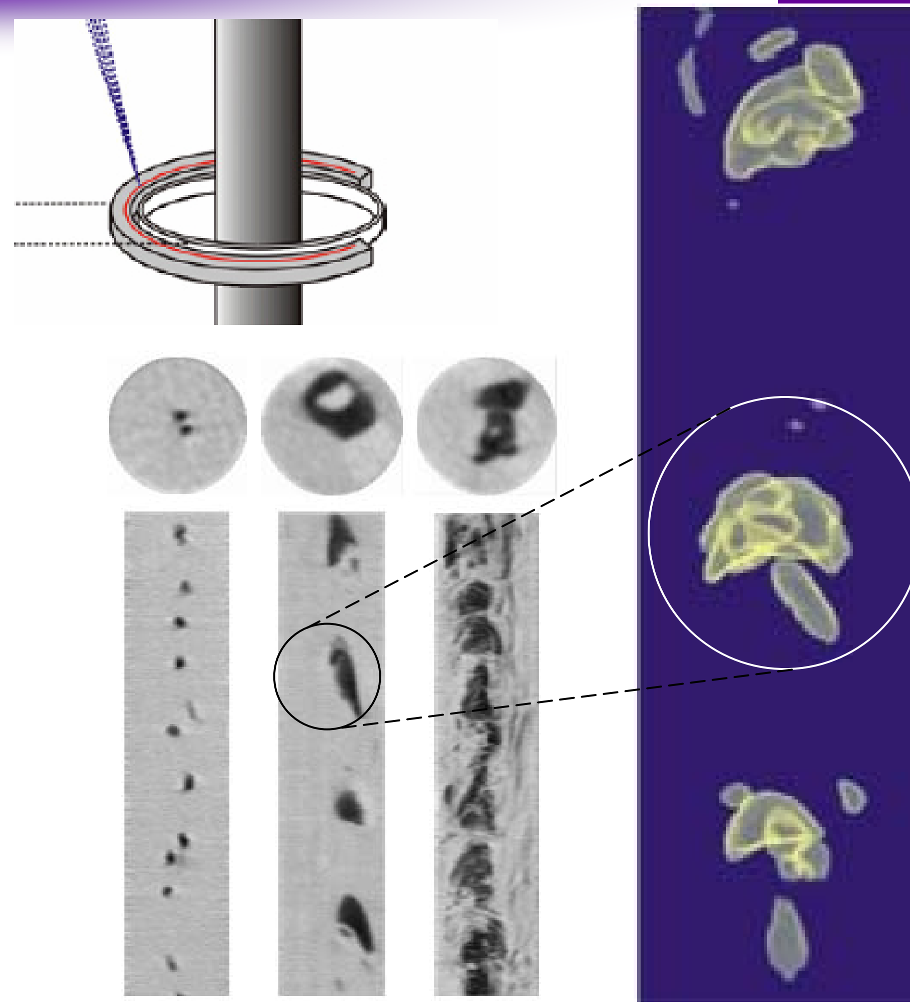
Stationary subjects



Polypropylene/air

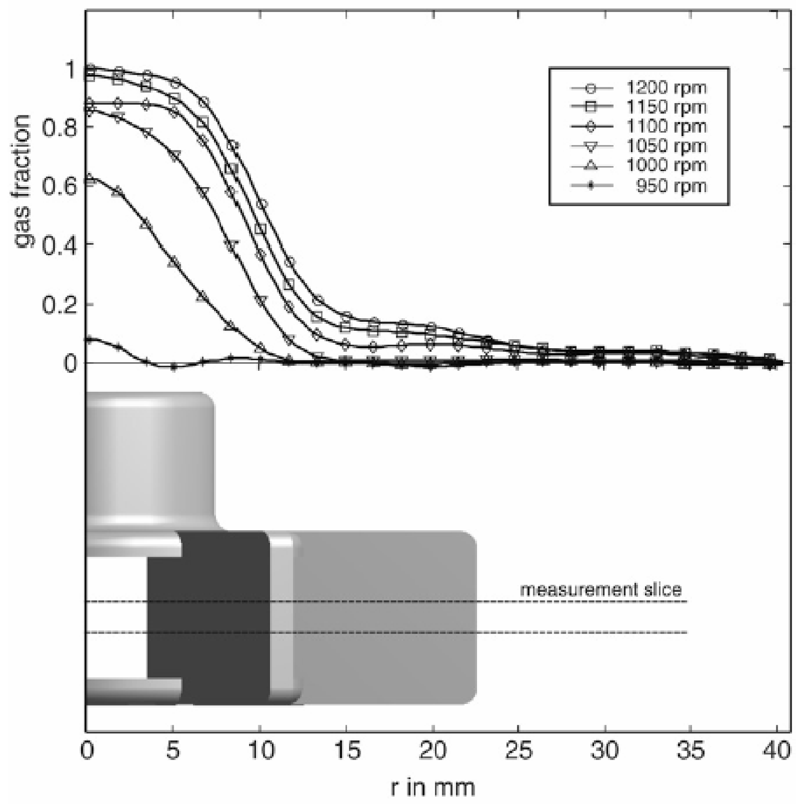


X-ray Tomography
Kinetics in bubble colmn



Gamma-ray Tomography

Fast rotating subjects - gas holdup in stirred reactor



Gamma-ray Tomography
Fast rotating subjects - pump impeller

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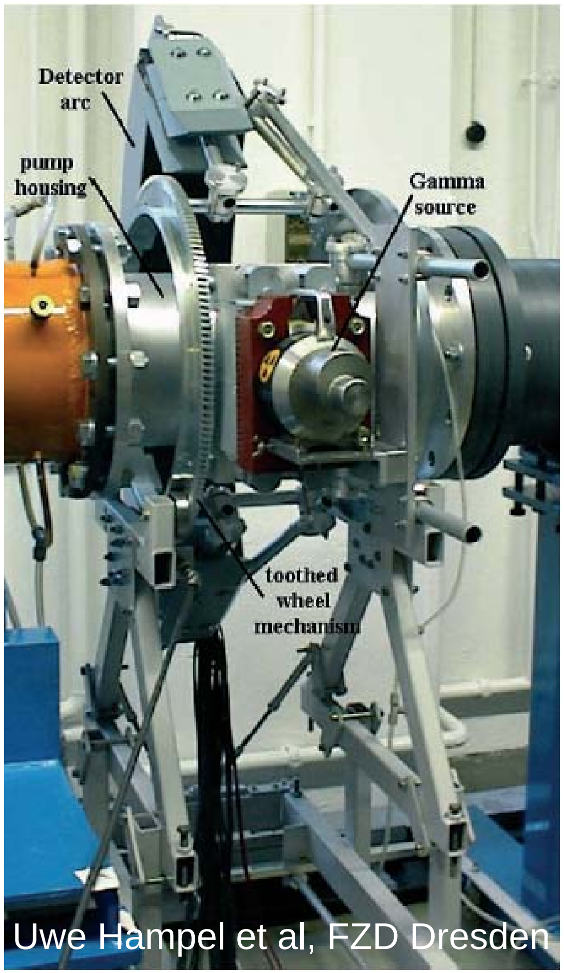
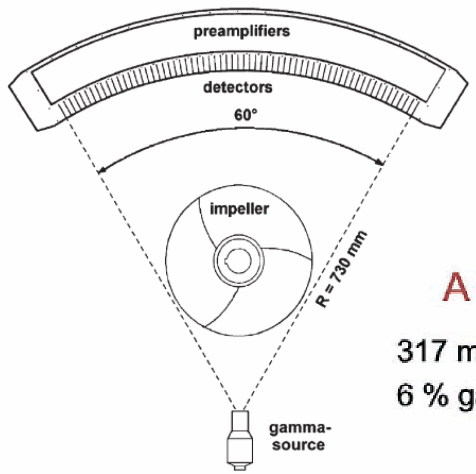
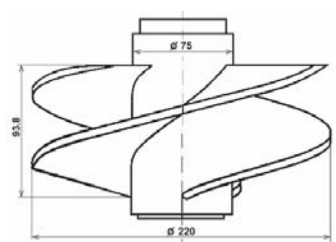
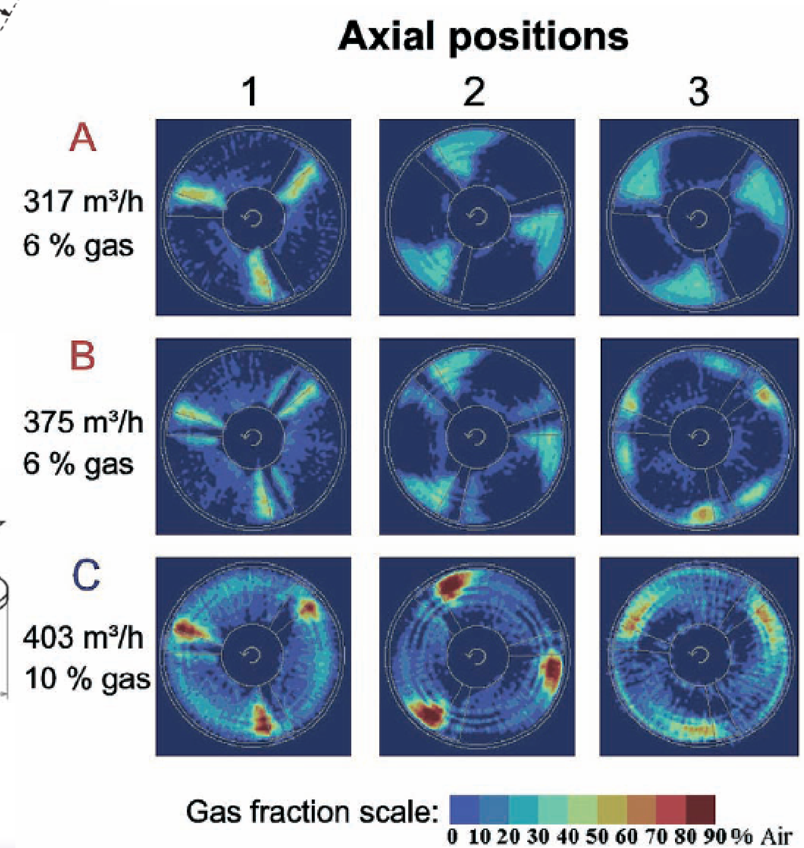


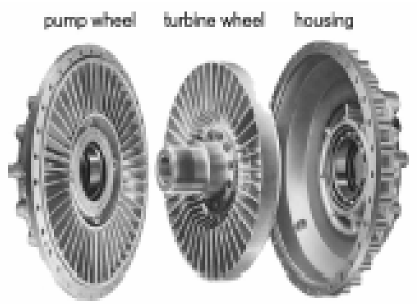


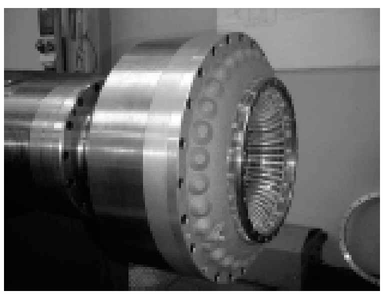


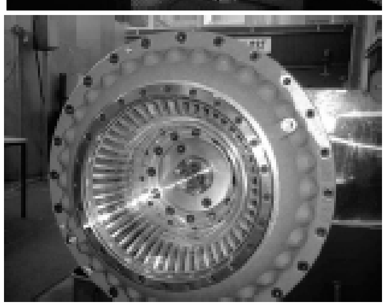


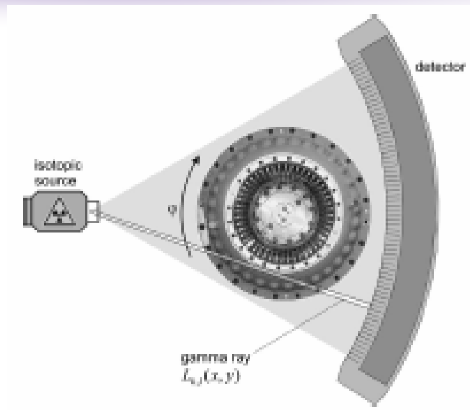
Gamma-ray Tomography

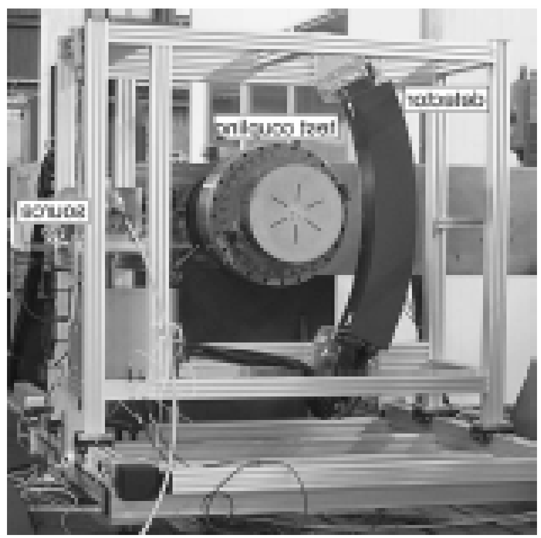
Fast rotating subjects - fluid coupling assembly

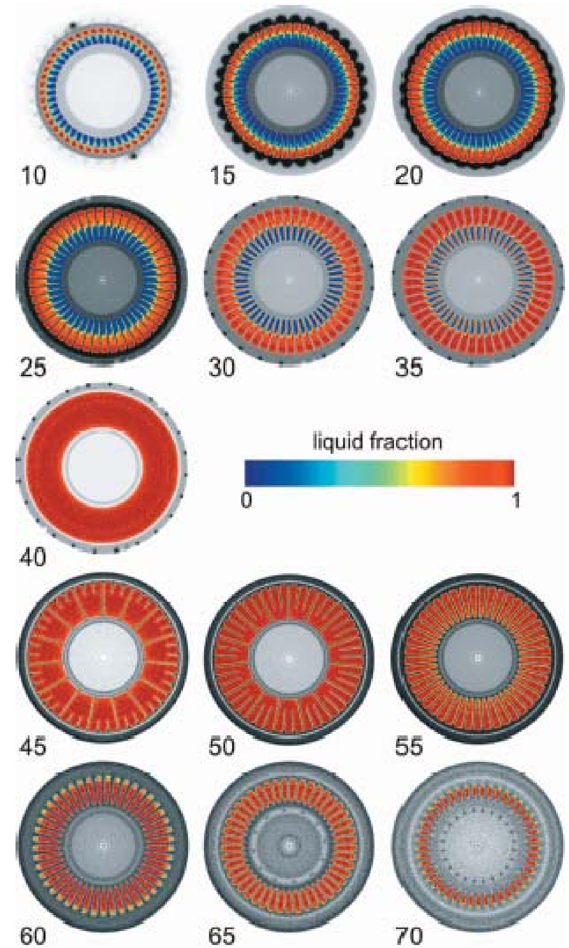








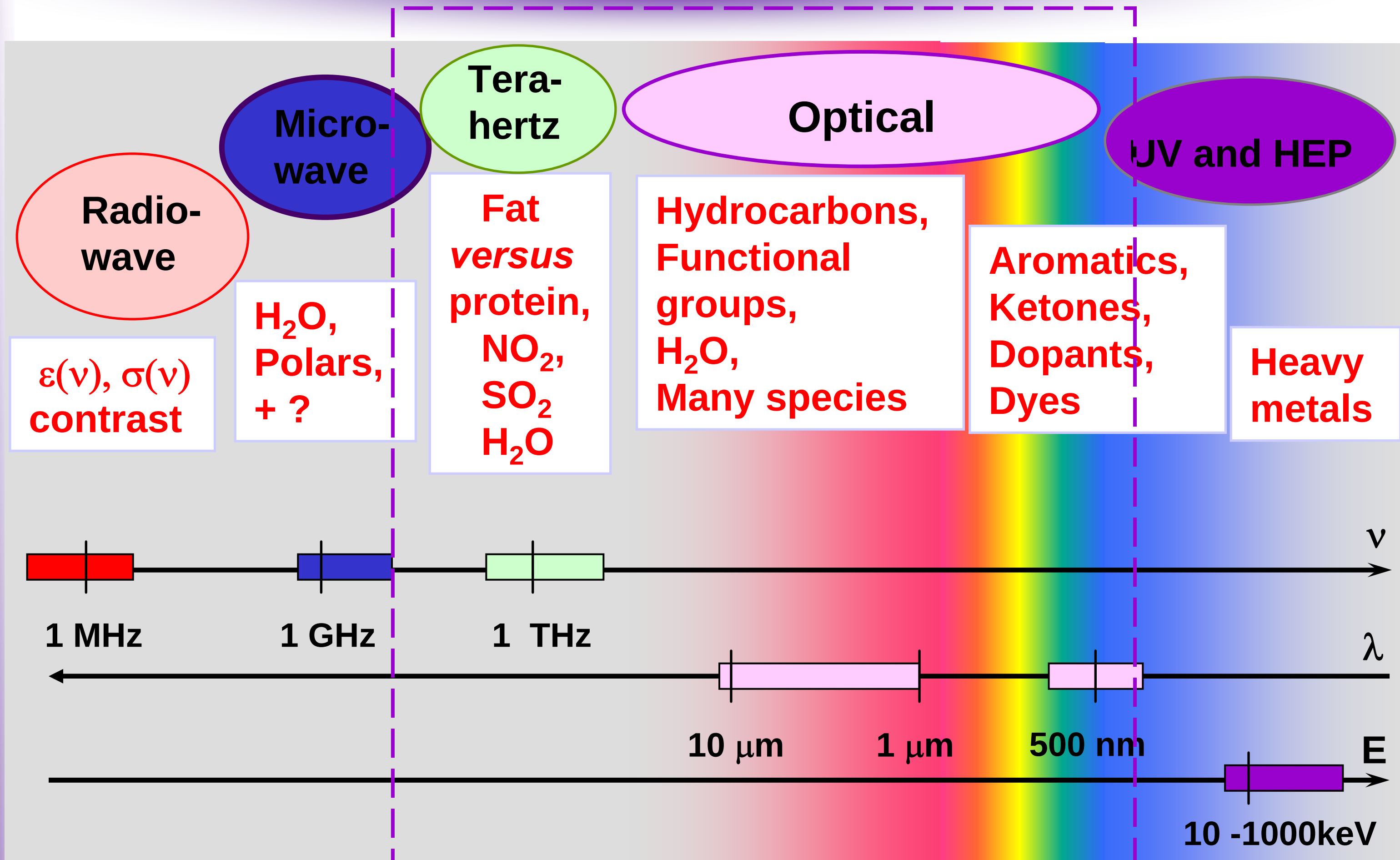




Uwe Hampel et al, FZD Dresden

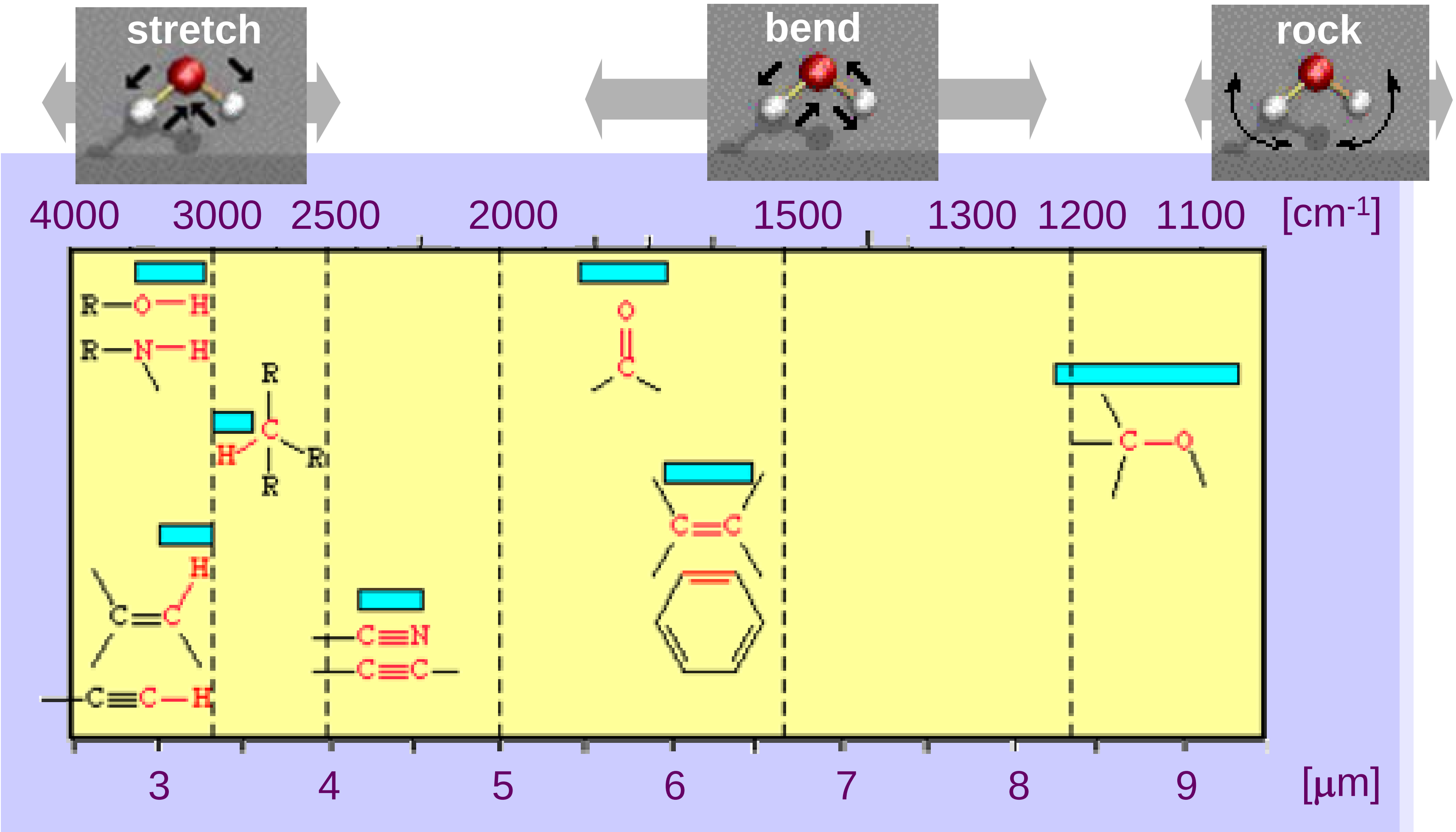
Challenge 1: ‘Spectroscopic’ Tomography

Interaction of EM field with matter



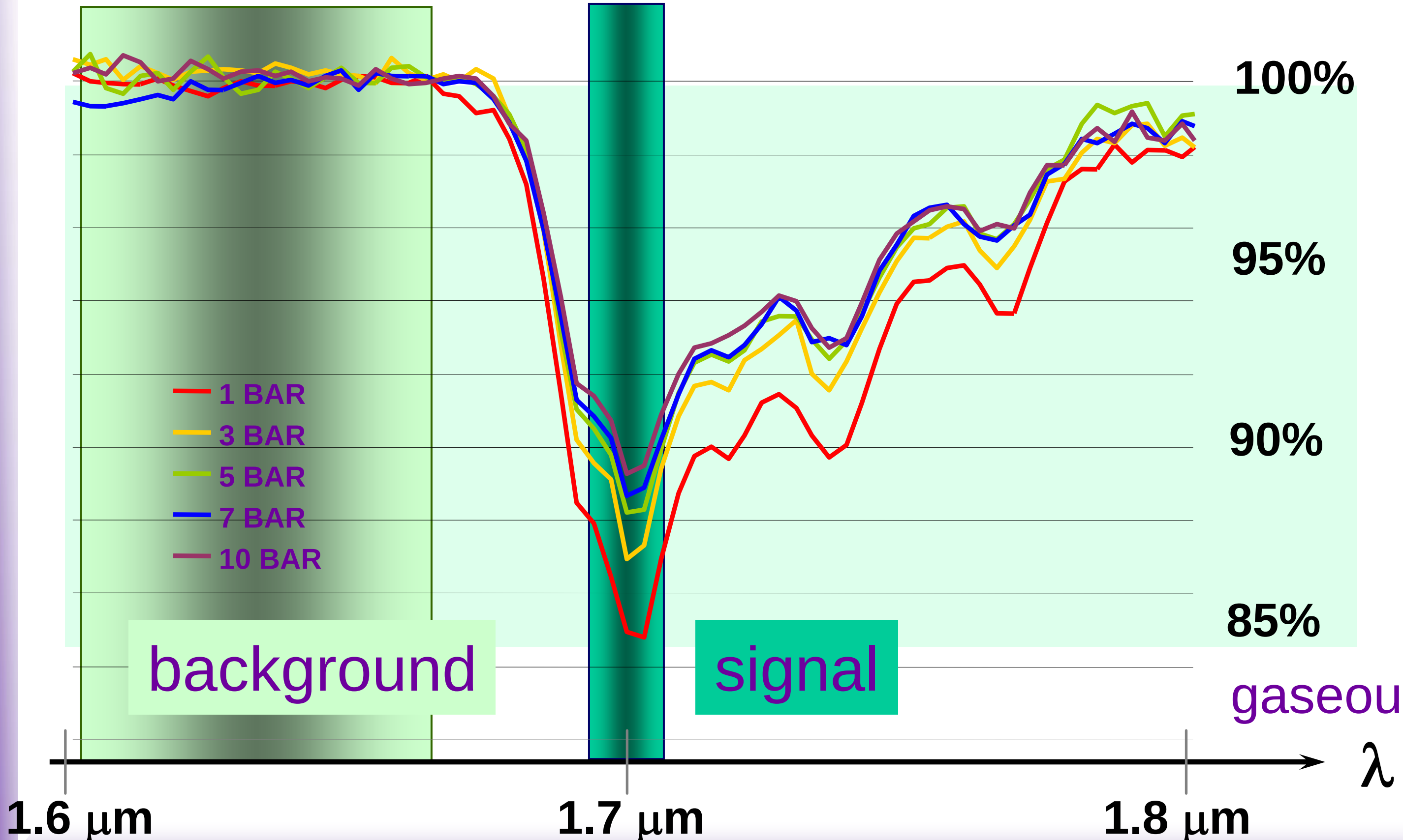
Modalities: Absorption, Scattering, Emission, etc

Mid IR optical fingerprints



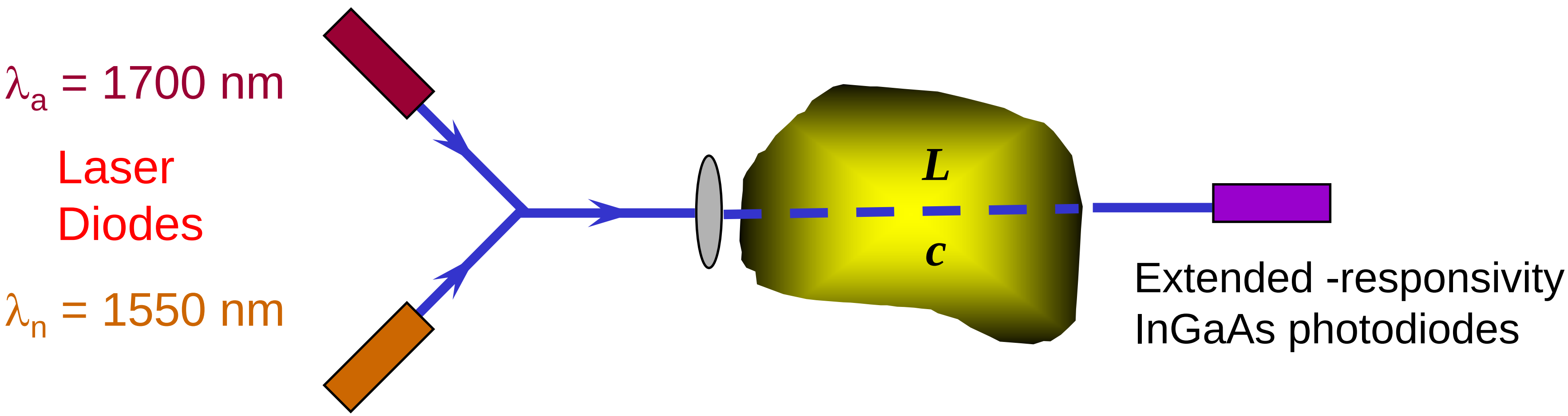
Hydrocarbon near-IR absorption (C-H bond)

- Choose signal wavelength to measure attenuation+background
- Choose reference wavelength to measure background



McCann et al.
Manchester

Single channel design for 1700nm



$$I_\lambda(L,T) = Ires_\lambda(0)e^{-\alpha_\lambda cL}.S(L) + Ith_\lambda(T)$$

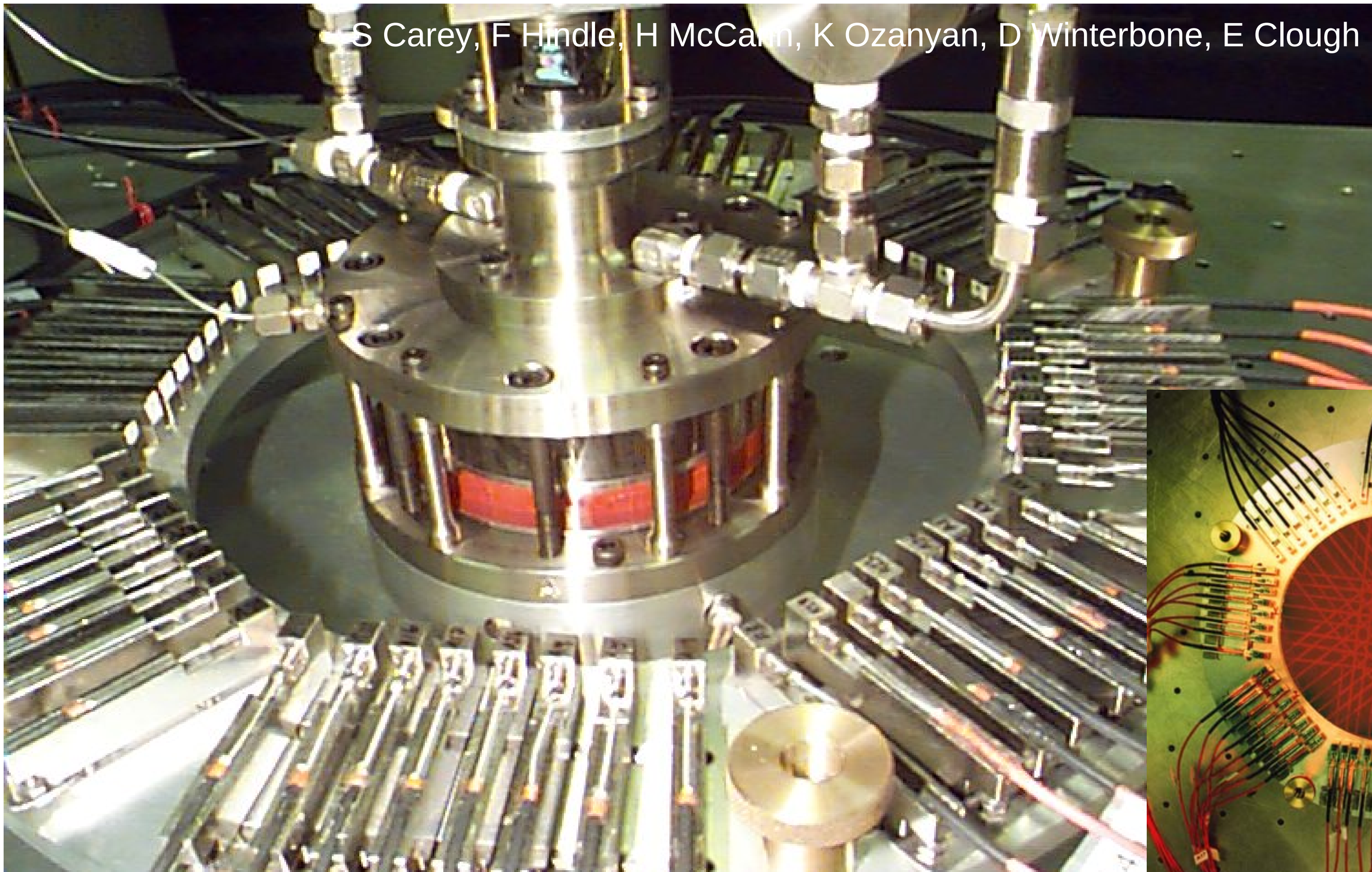
Resonant absorption

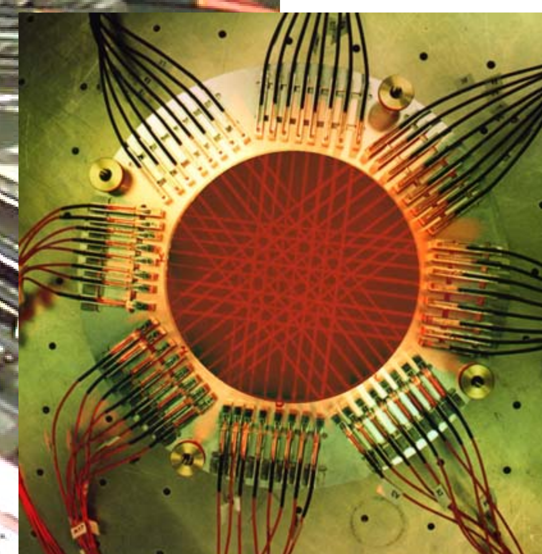
Non-resonant attenuation (scatter)

Thermal background

Engine cylinder simulator

S Carey, F Hindle, H McCann, K Ozanyan, D Winterbone, E Clough





Cost of pushing Tomography to longer λ

The University of Manchester

- NIR emitter source: several 1K£
- MIR emitter source: several 10K£
- THz emitter source: several 100K£,

…with no guarantee that a single source will be sufficient for multichannel tomography

Carefully measure this against benefit (and current funding climate)…

Relevant properties of THz radiation

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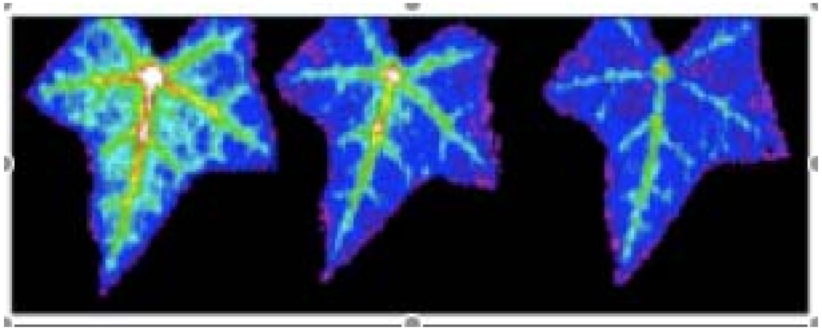
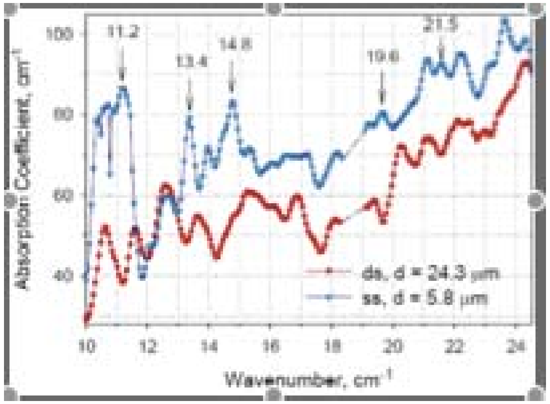


- High water absorption allows real-time monitoring of water content

- THz is suitable for long molecules: sensitive to both intermolecular and intramolecular vibrations in different chemical species:
    - Proteomics and drug discovery research proteing 3D structure, folding and characterization.
    - Very sensitive to DNA hybridization and other interactions - single and double stranded DNA

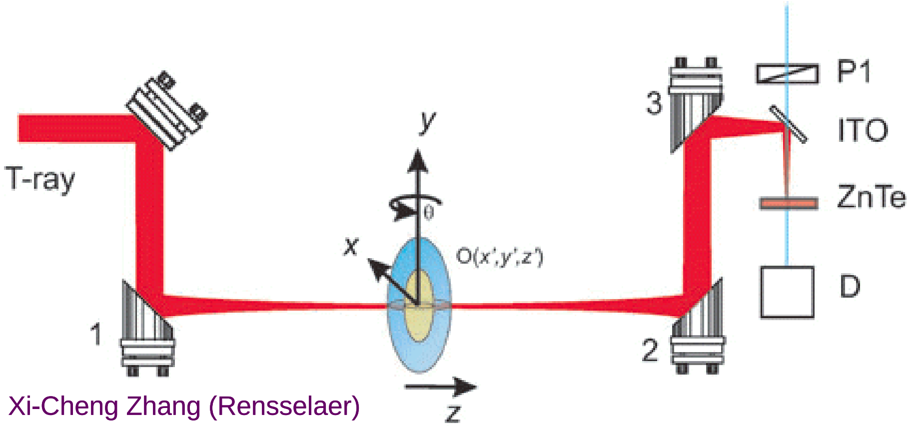


THZ Computerized Tomography

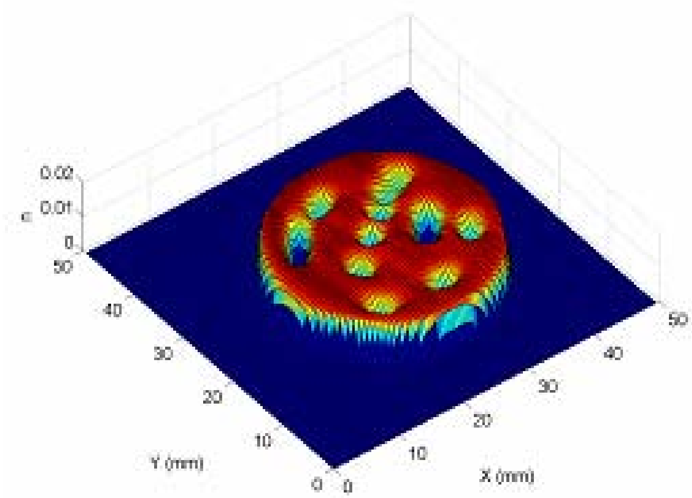
Currently THz CT is simulated only by rotation and translation of the object.

Known problems:

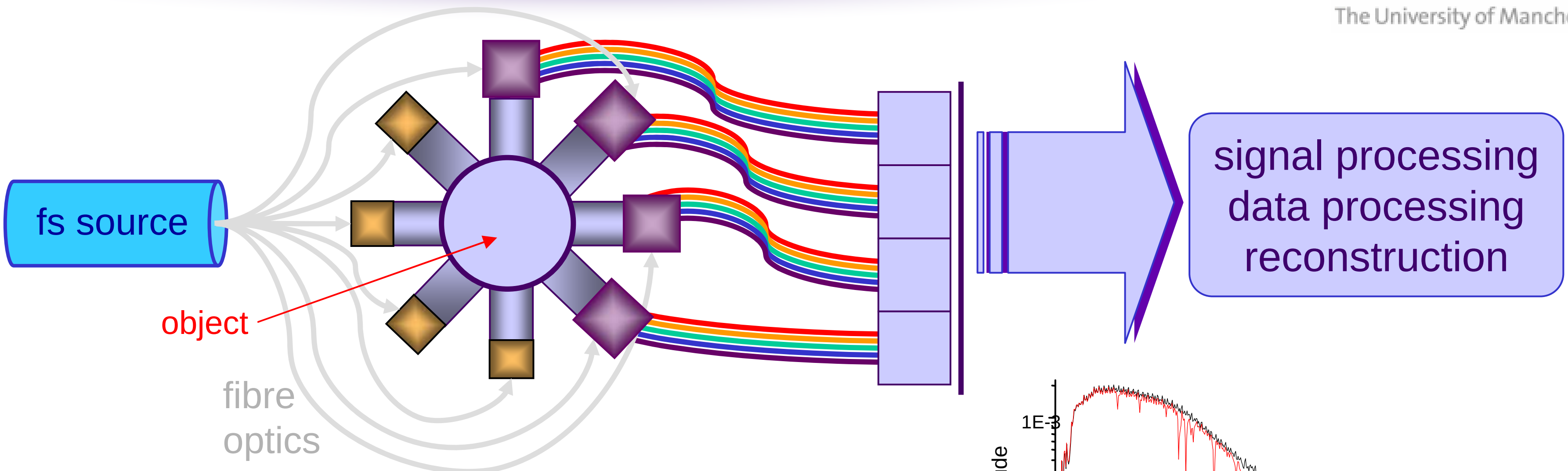
- difficulties with cost and ease to deploy
- complicated detection schemes
- “killer” applications?



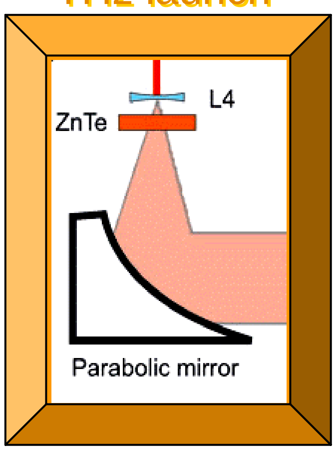
Xi-Cheng Zhang (Rensselaer)



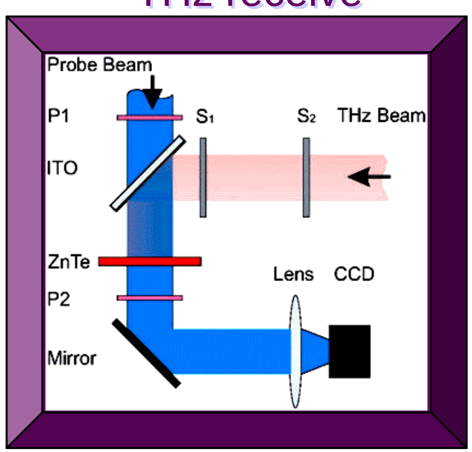
THz Tomography with ultrafast lasers

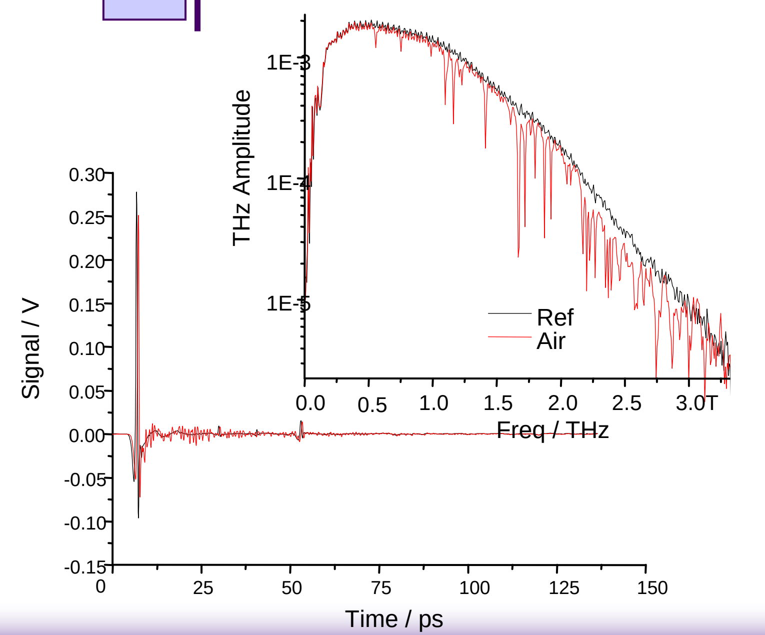


THz launch

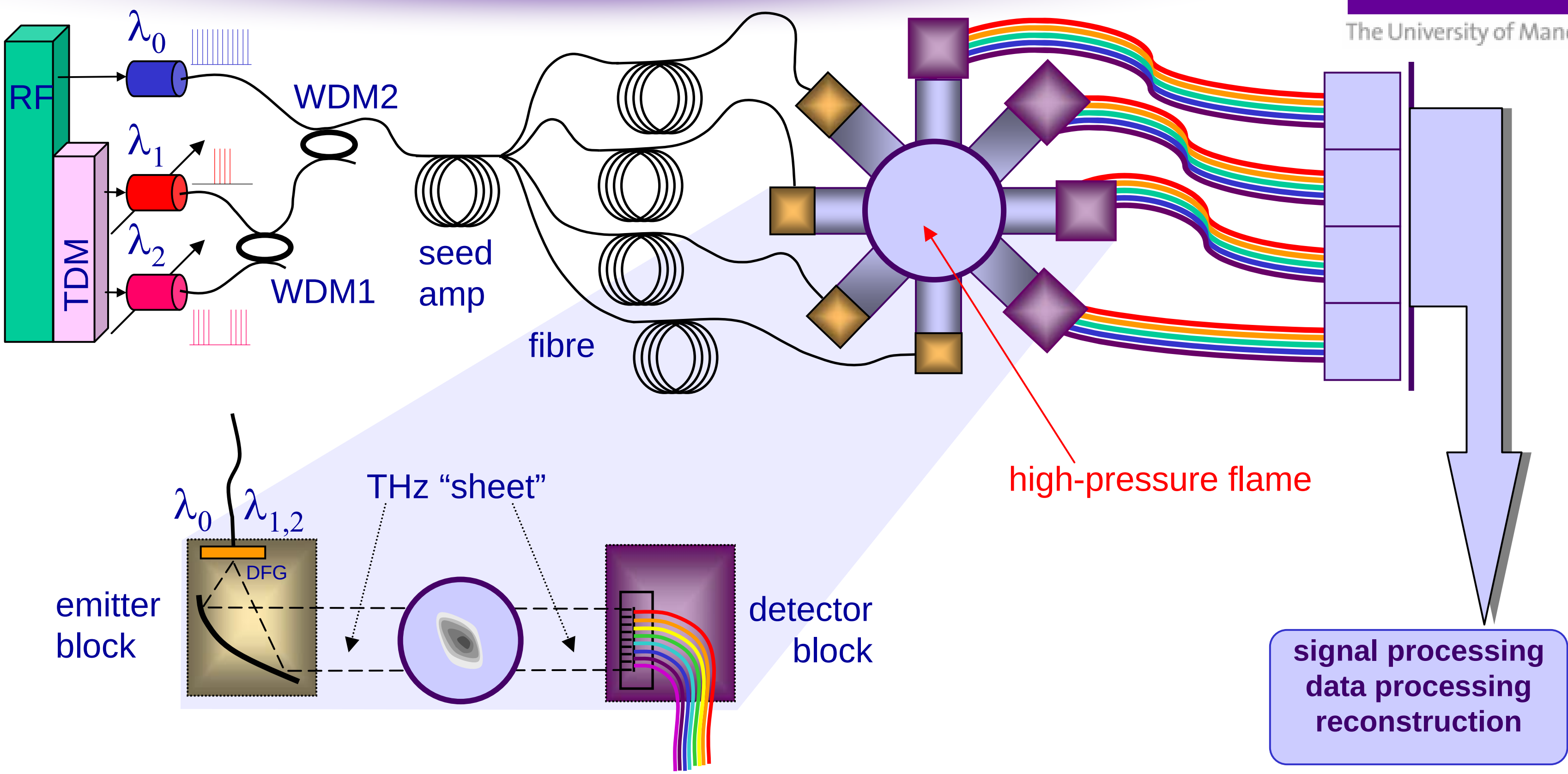


THz receive





Narrowband Tomography – system layout



- A compact desktop system, delivering high THz power by DFG with a single seed
- Pyroelectric detector arrays will be used instead of coherent detection (~20 μW per array pixel)
- Easy for access and affordable THz

THz tomography in flames

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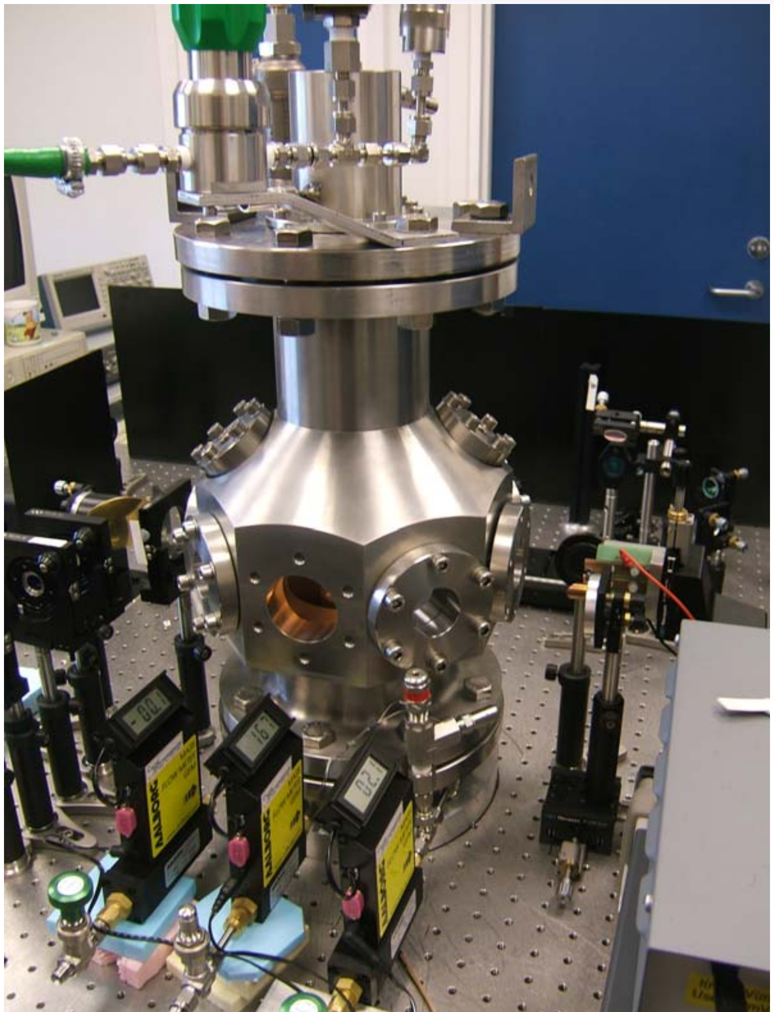

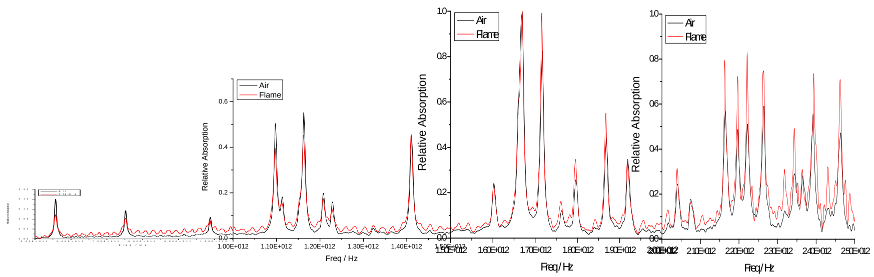

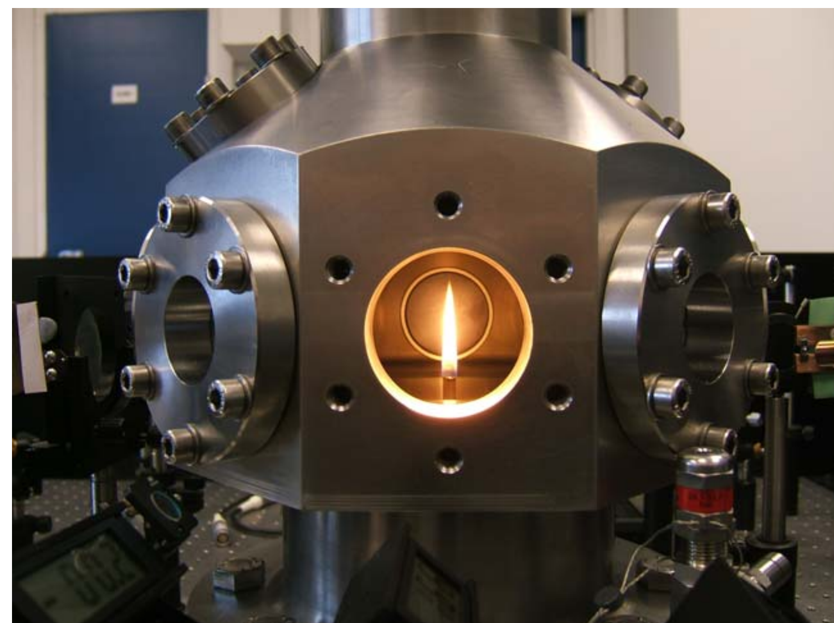

Challenge 2: Path Integrals

Similar maths, different physics

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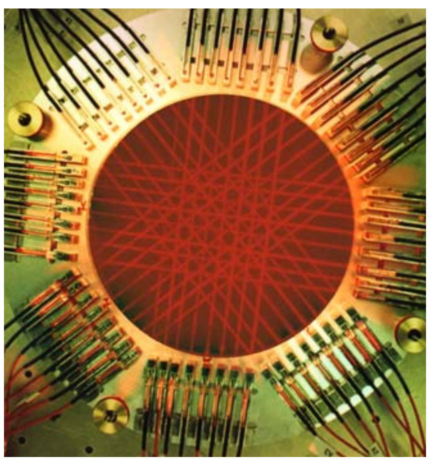
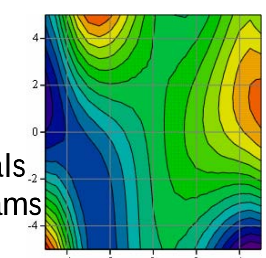
Guided Path Tomography (GPT) was pioneered in Manchester *IEEE Sensors J.*, 5 (2) 167 2005

Computer Tomography
e.g. straight propagating electromagnetic radiation

$$\Phi \approx \Phi_0 \int_0^L \mu(x)dx$$



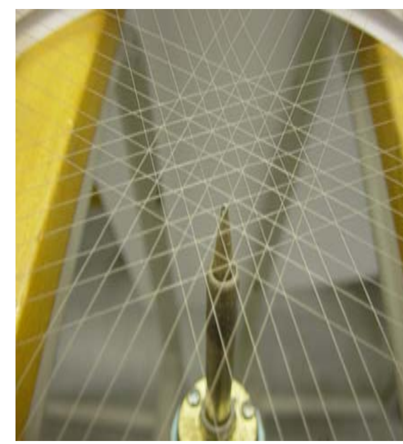
Flat 2D surfaces



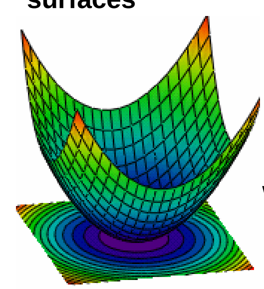
Radiation beam CT: Line integrals are along individual straight beams

Guided-Path Tomography
e.g. guided propagation of the electromagnetic field

$$R = \frac{1}{A} \int_0^L \rho(T(x))dx$$



Curved surfaces



Wire-mesh GPT: Line integrals are along wires forming a flexible "mat"

Temperature imaging with Wire-Mesh GPT

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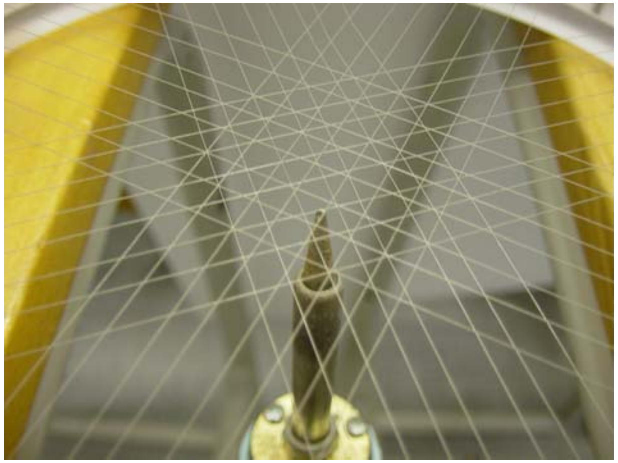
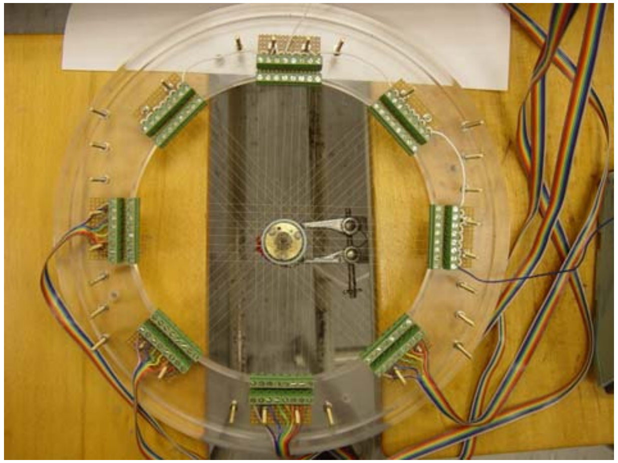
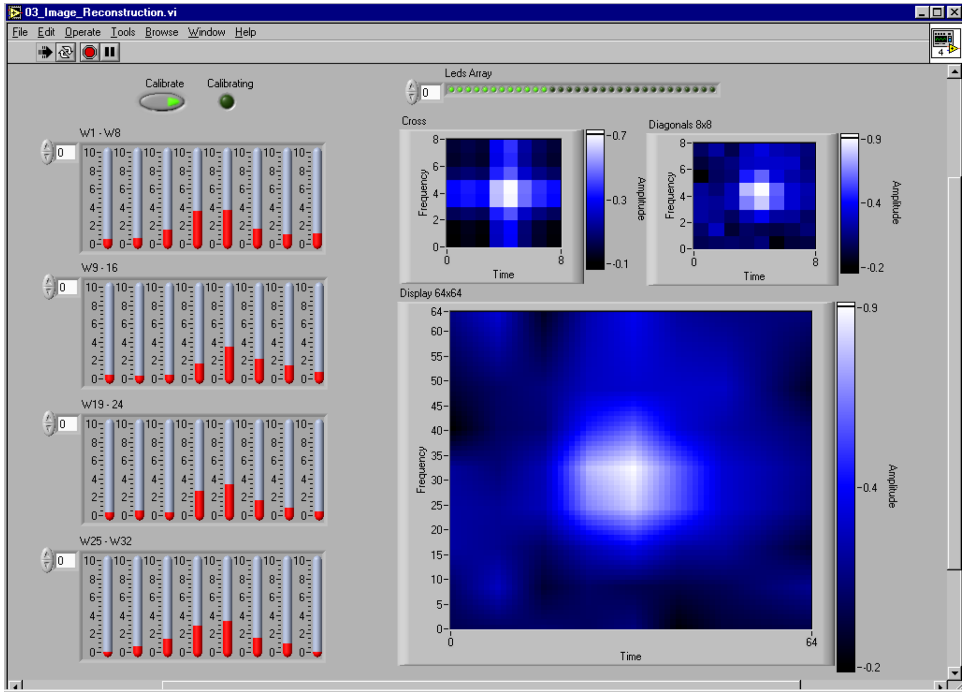
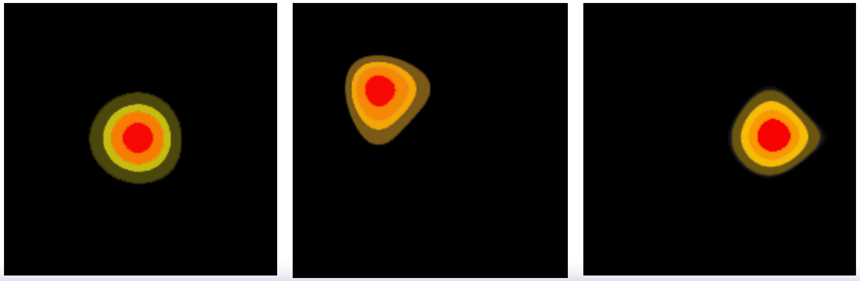






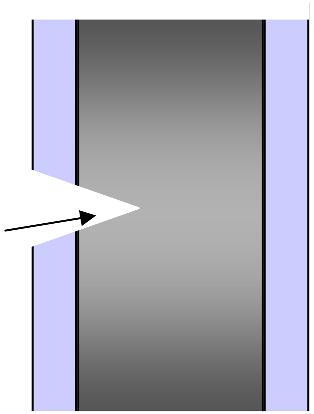


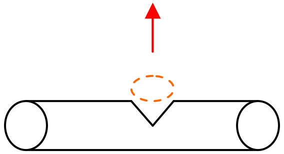
Parra-Ortiz & Ozanyan (Manchester)

Optical fibre sensing

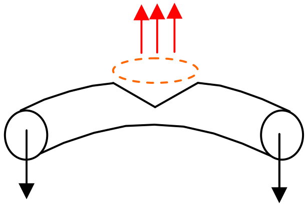
Bending loss sensing

Groove cut through cladding and into the core leads to losses as a function of bending

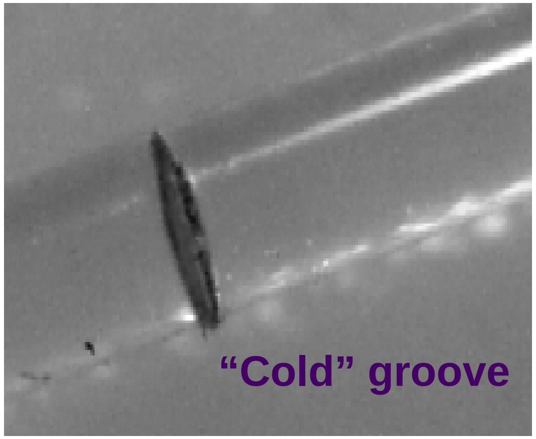


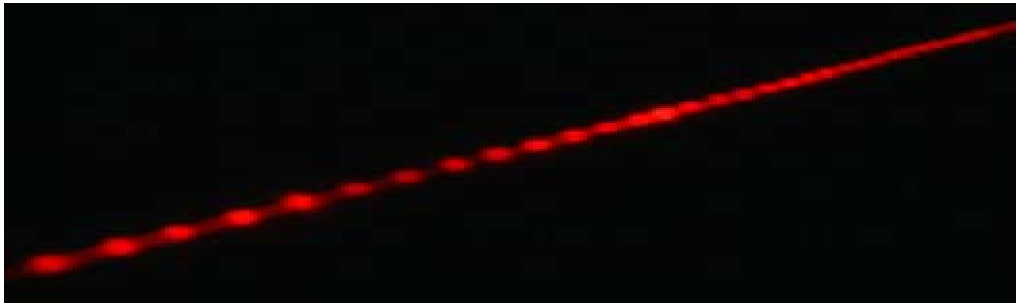


zero deformation



stretch and bend





The ‘deformation mat’

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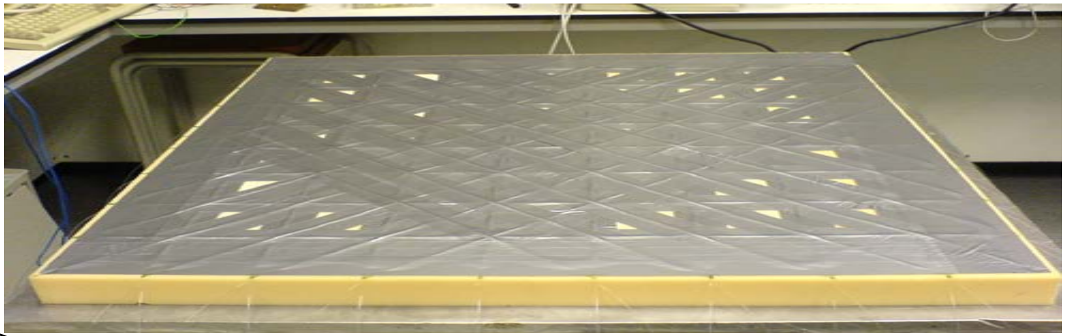
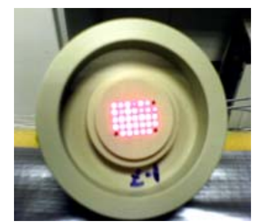
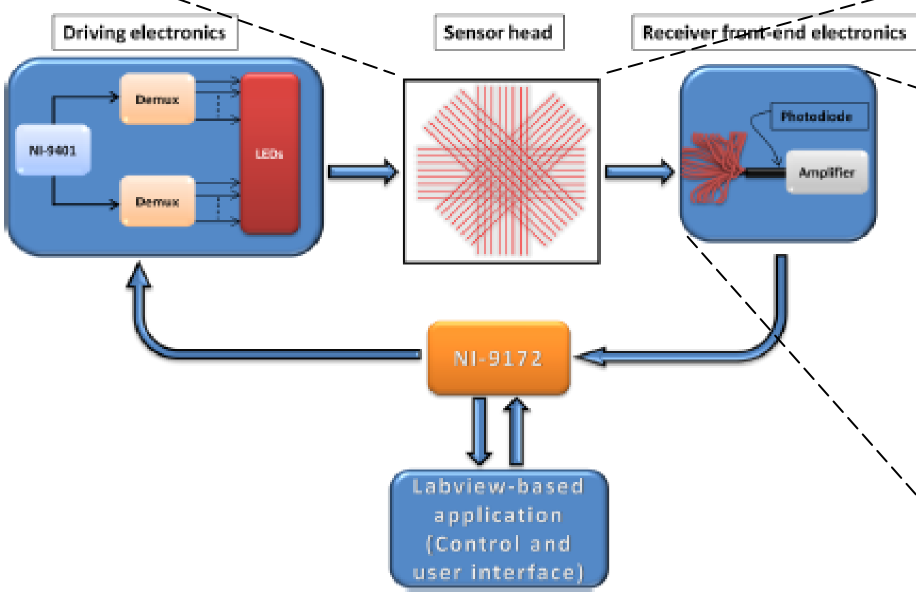
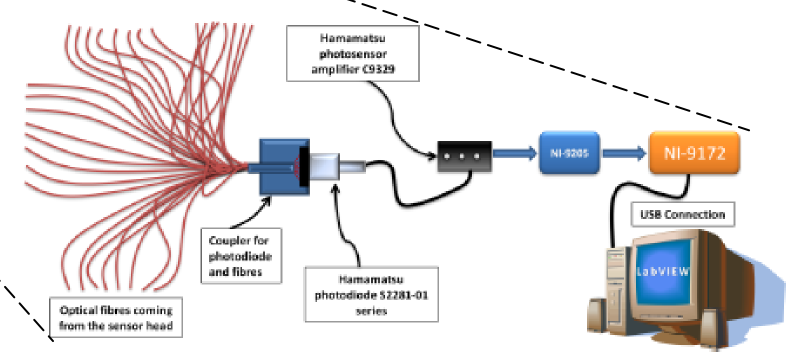


Measure intensity transmitted through a POF section







Nurgiyatna, Ceballos & Ozanyan (Manchester)

Photonic GPT algorithms and images

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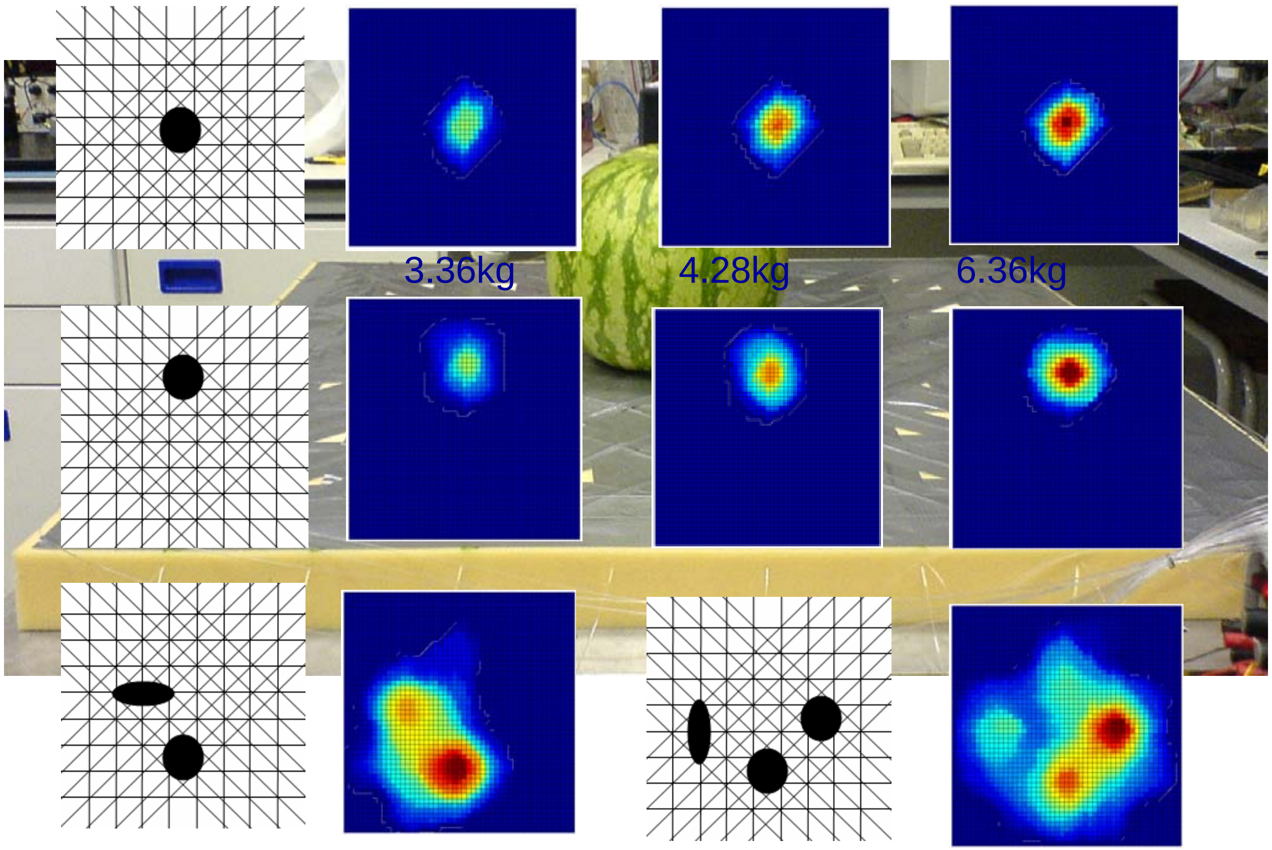

Nurgiyatna, Constantino, Davidson & Ozanyan (Manchester)

Large area monitoring by Tomography

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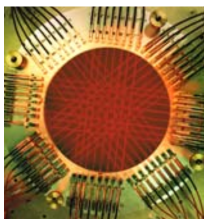
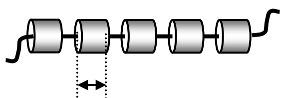
Based on Guided Path Tomography, pioneered in Manchester

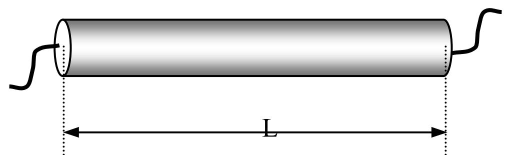
IEEE Sensors J., **5** (2) 167 2005

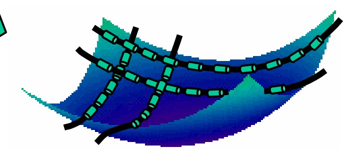
- uses analogy between the mathematics of x-ray Tomography scanners and current flowing through a wire mesh with the proper geometry.
- demonstrated for temperature with a wire-mesh sensor
- demonstrated for light propagating through fibres arranged in a near-flat plane



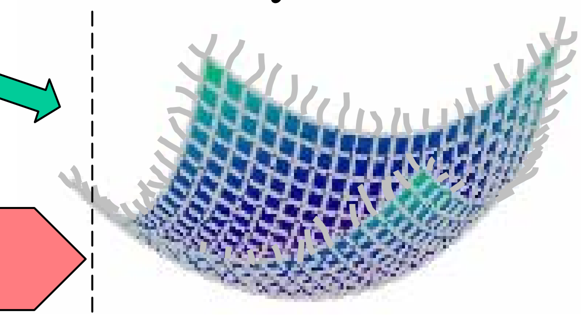


$$\varphi_i' = \varphi_0 \sum_{j=1}^{n_i} a_{ij}\lambda$$





$$\varphi(l) = \varphi_0 \int a(D(x,y,z))dl$$



LED light sources
- <£1/pc

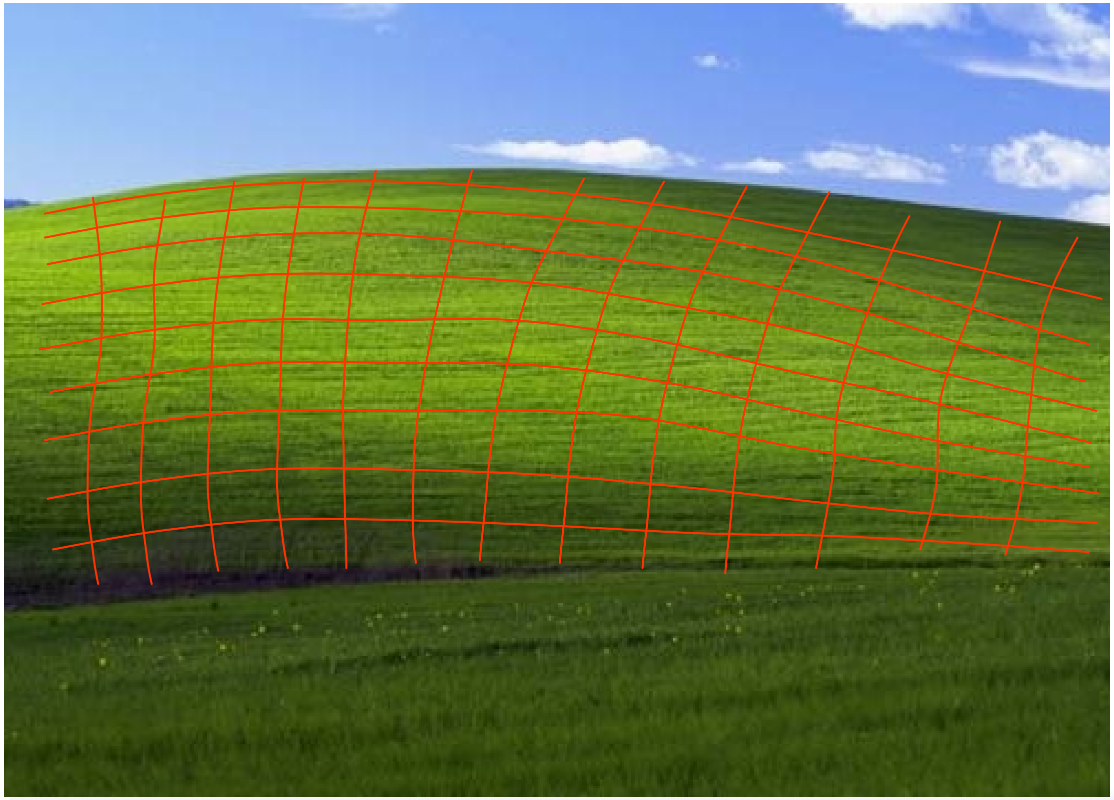
Plastic optical fibre
- £0.8/m

Photodetector, electronics, computation and display
- £1000

Only this scales with size!

Photonic GPT for large areas

Measure integrals of attenuation instead of individual sensors
Reconstruct an image of the measurand

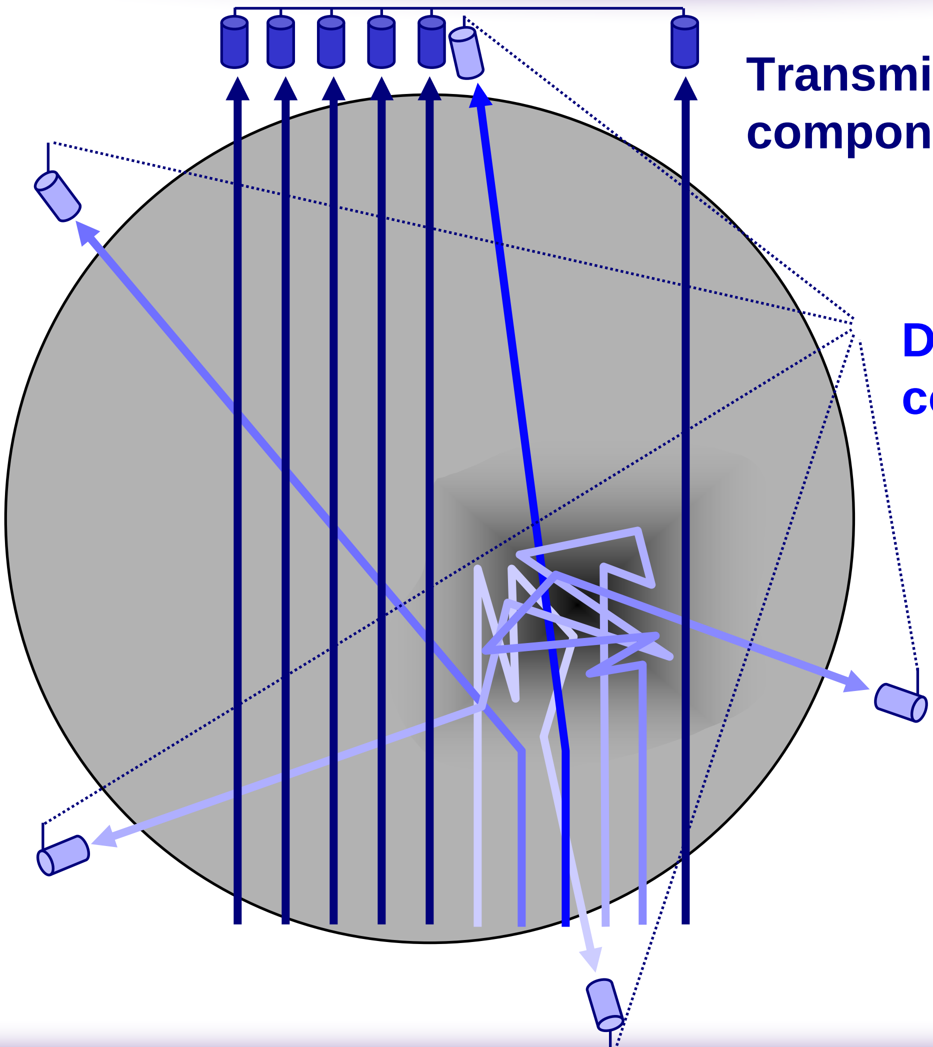


Plastic optical fibre
- £0.80/m

LEDs - around £1

Small number of photodiodes

Well-behaved line integrals?



Transmitted component

•small attenuation, trajectory unchanged.
•“hard” field, leading to Radon transform

Diffuse component

•attenuation+change in direction
•multiple “scattering” events
•forward model is based on the Diffusion Equation

General case

•both components can be essential
•forward model is based on the Transport Equation

THz hard-field tomography

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CT "line integrals" across the subject have different nature:

Amplitude contrast **vs** **Delay contrast**

Amplitude contrast

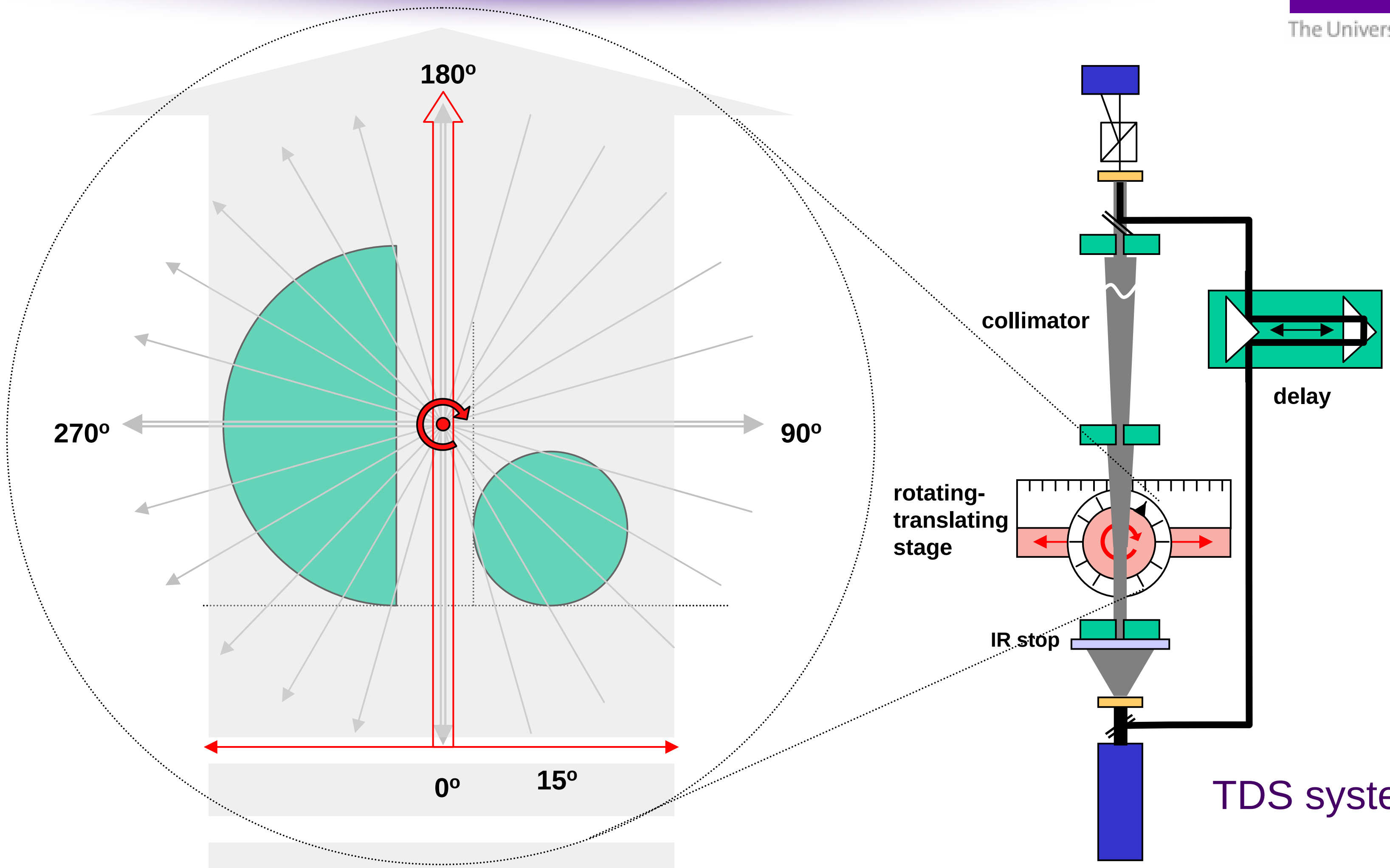
- Measured transmitted component gives line integrals of attenuation (species' c,T)
- **Images the spatial distribution of material density**
- The diffuse component eliminated by collimation, 2λ strategies, etc.
- Possible with TDS or CW

Delay contrast

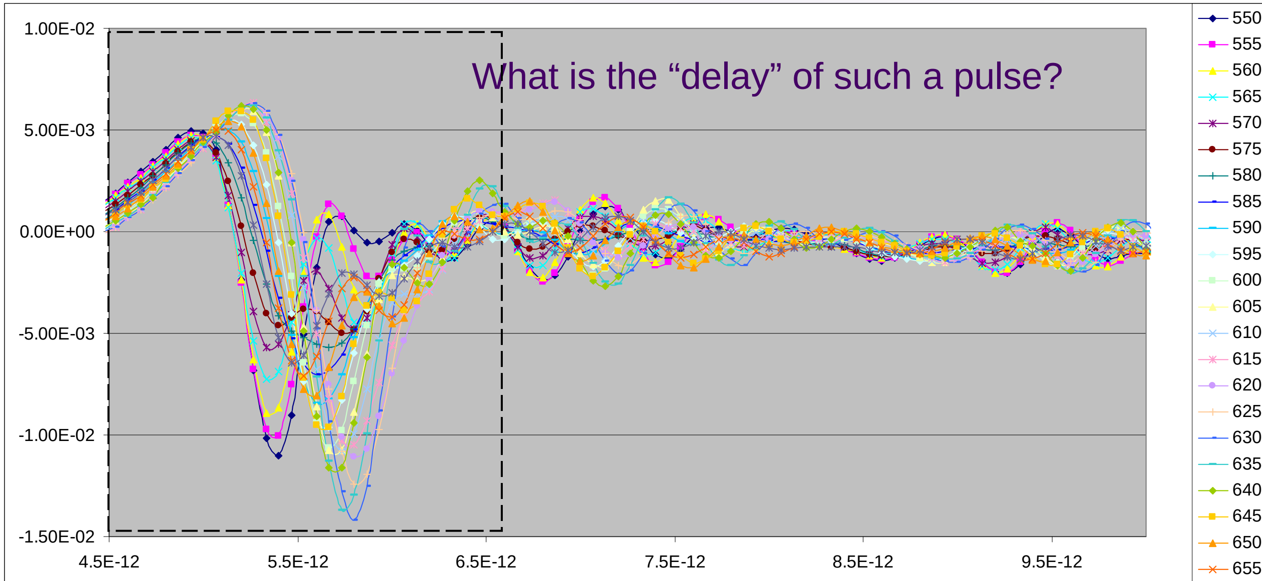
- Measured time delay gives line integrals of inverse group velocity (non species-specific n(p,T))
- **Images the spatial distribution of optical density**
- The diffuse component eliminated by taking ballistic photons only
- Possible with TDS or CW (coherent detection)

Complex phantom

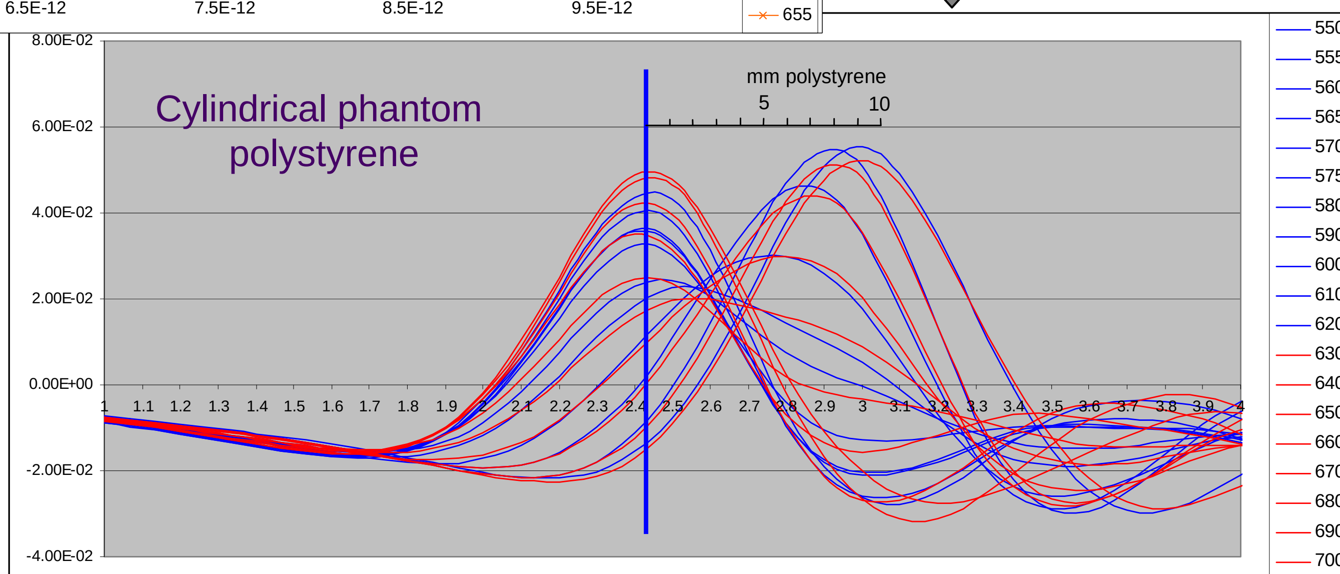
Refractive index imaging from only 12 angles



Extracting delay from waveforms



Antenna emits as the derivative of the current: Integration of the first 4ps of the THz waveform allows comparison of delays in terms of a single pulse.



The delay is calculated by a quadratic approximation of the position of the maximum of the integrated pulse

“Mirror” projections

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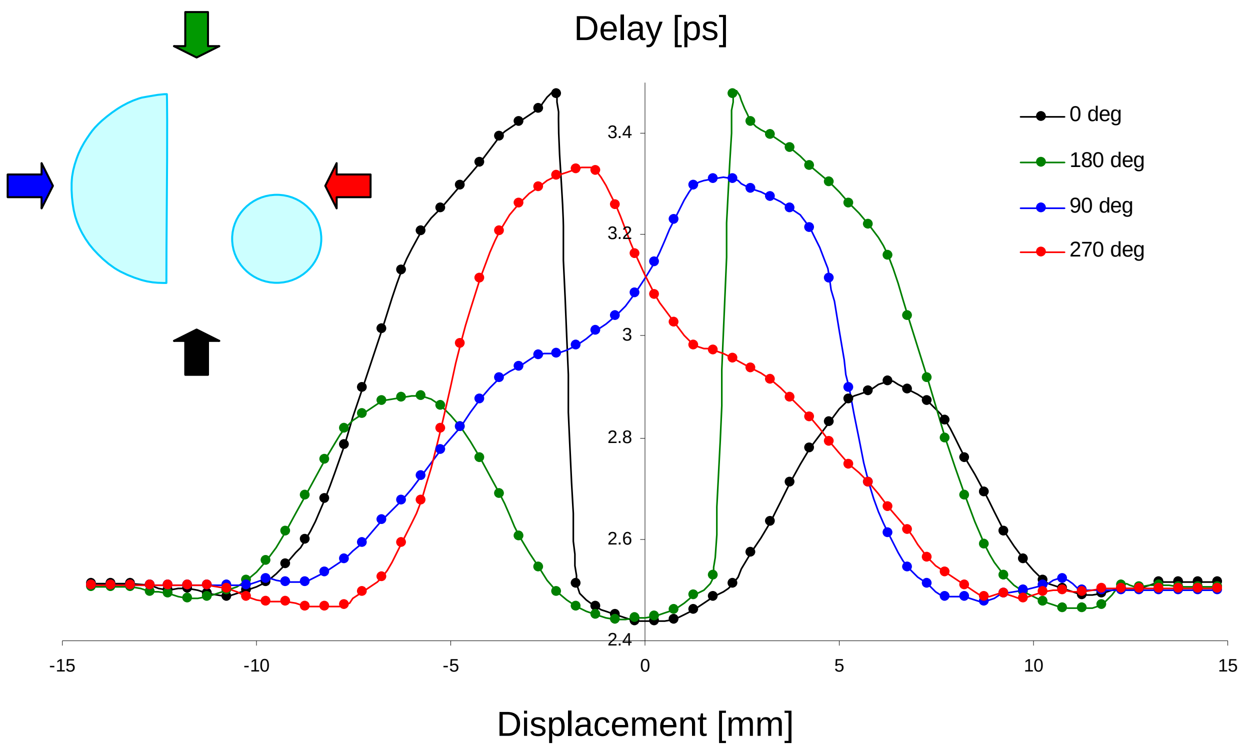
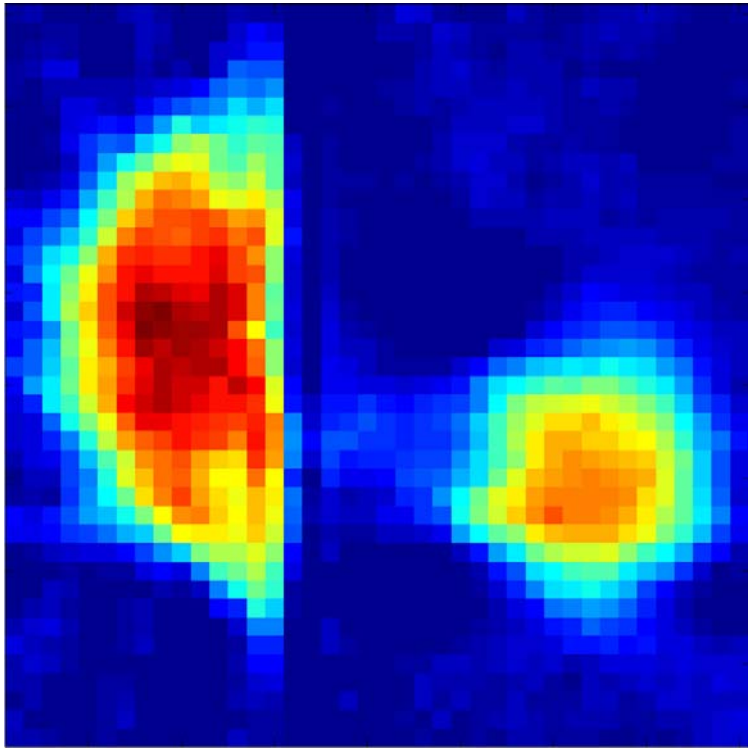
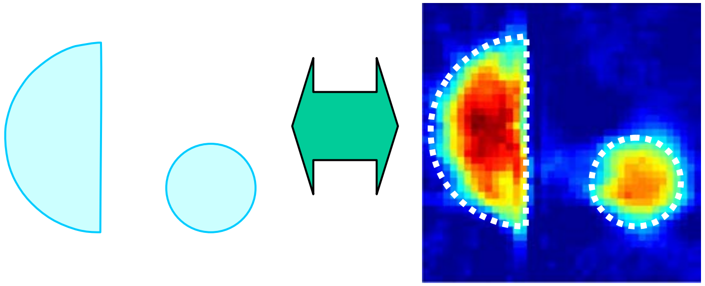


•The measured photons are “ballistic enough” – there is very little difference in which of the two objects is seen first
•Ballistic photons give us spatial resolution of the order of the wavelength

Refractive index reconstruction



Phantom with (scaled) exact dimensions on top of the reconstruction:

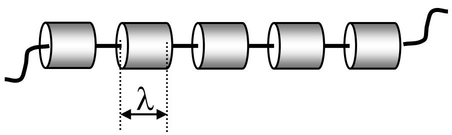


- Standard 40x40 grid, 12 projections (still limited view!)
- Standard inverse problems regularisation, such as non-zero constraints and periphery suppression
- Sharp edge is unrealistic – coincided with a line integral.
- “Glowing” sharp corners and flat result from scattering and grazing incidence reflection

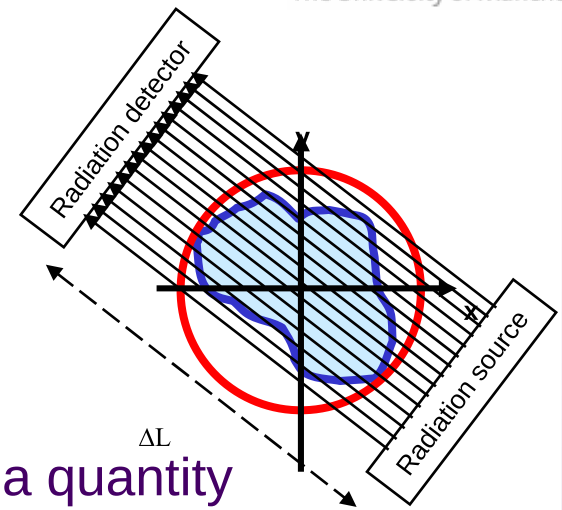
Why is temperature difficult for tomography?

- Temperature path integrals do not exist!!!

$$N_d = N_s \int_{path} \mu(L).dL$$



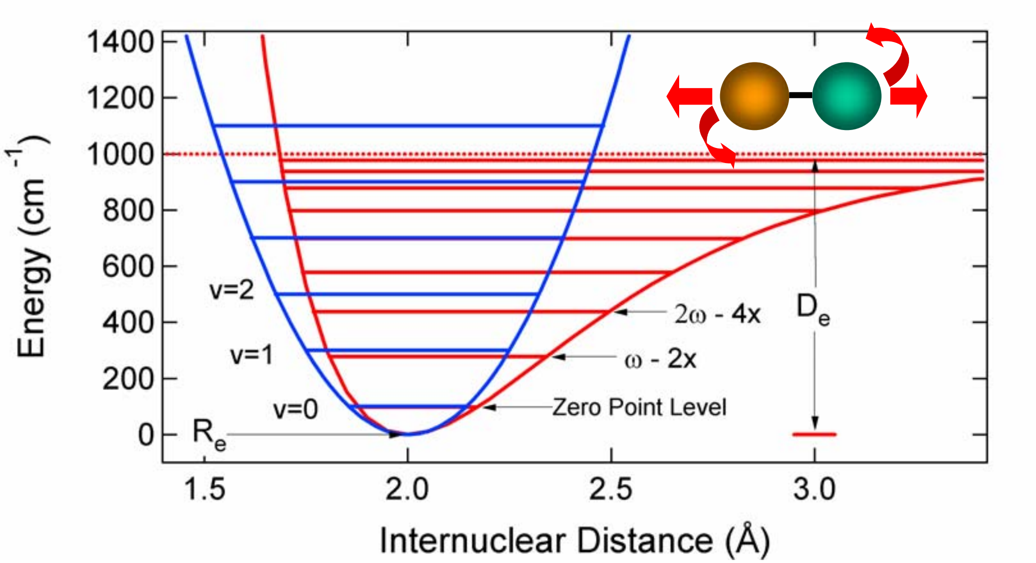
$$R = \frac{1}{A}\int_0^L \rho(T(x))dx$$

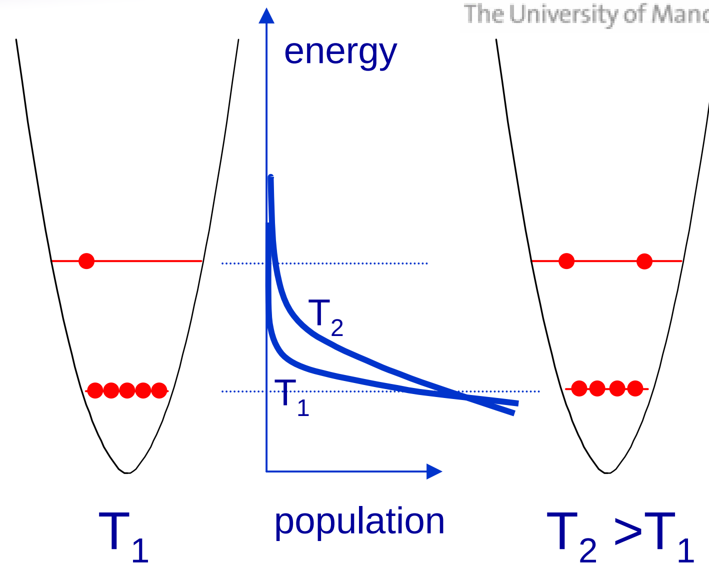


- In the case of guided-path tomography we found a quantity giving a path integral: **resistivity** (serially connected resistors). Can we find others?

- Imaging has to be done in a convoluted way:
  - Bad news: additional efforts to substantiate the theory
  - Good news: opens doors to a number of control parameters

Ro-vibrational levels of molecules





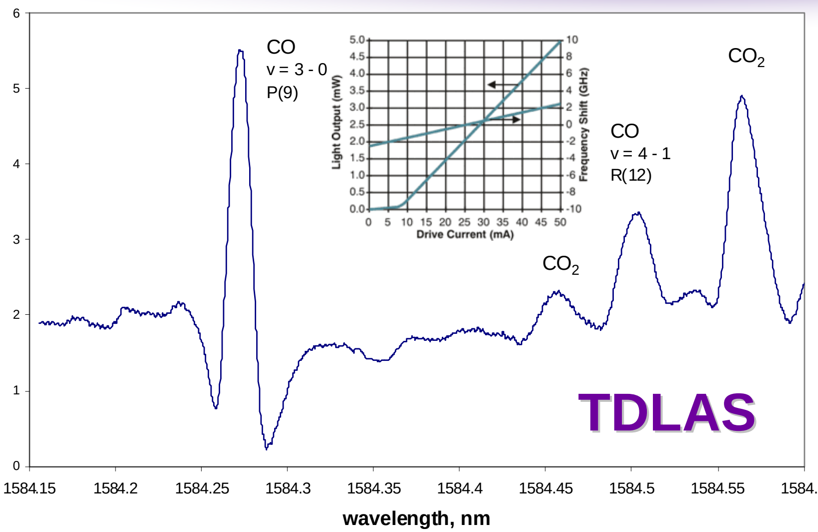
The relative population of two ro-vibrational levels and the temperature are related according to a certain law.

If we know the relative population, we can image the temperature.

Mid-IR species-specific resonances are difficult – “harmonics”?

TTOMA system

Temperature **TO**mography by **M**olecular **A**bsorption



CO:

- fundamental at 4.6 μm

sources, fibres, detectors - problematic

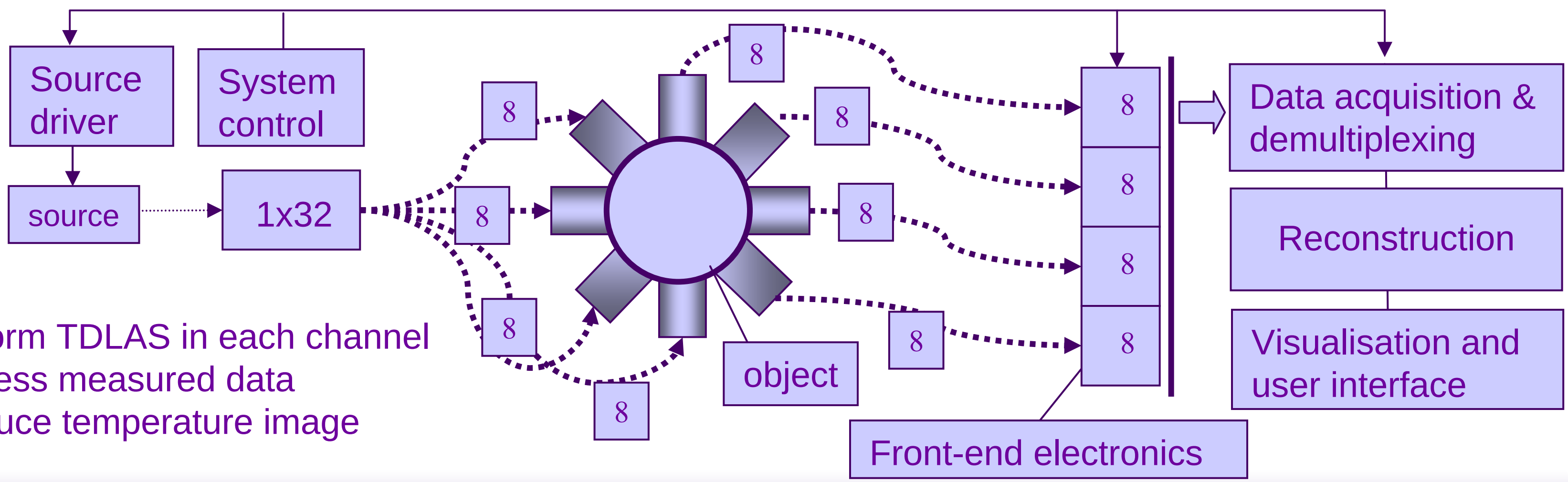
- first overtone at 2.3 μm

sources, fibres, detectors - complicated

- second overtone at 1.58 μm

sources, fibres, detectors -

easy and cheap (comms λ!!!)



- Perform TDLAS in each channel
- Process measured data
- Produce temperature image

Access to objects - hostile environments

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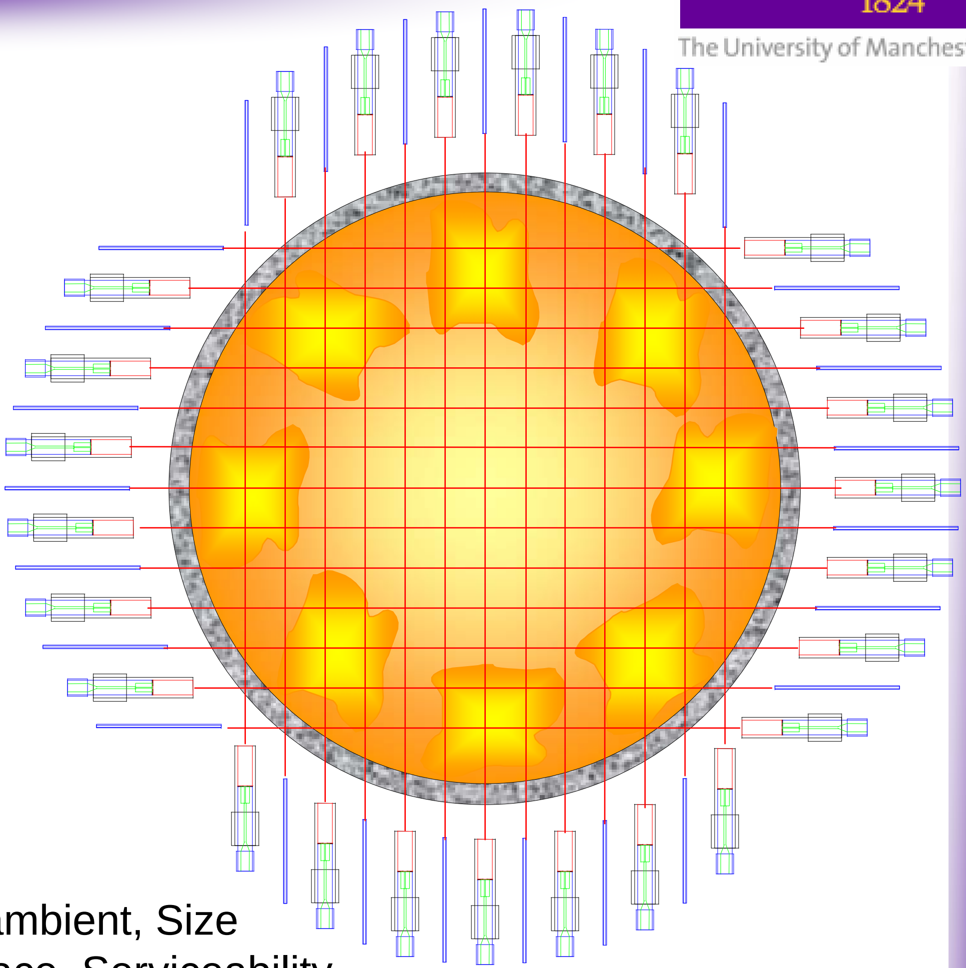
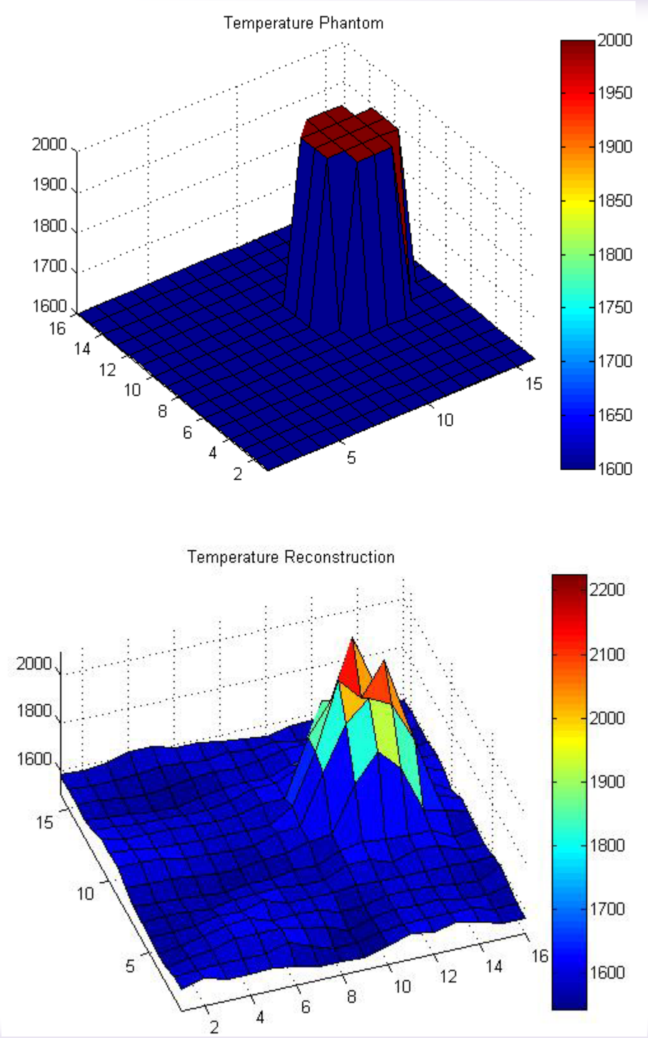
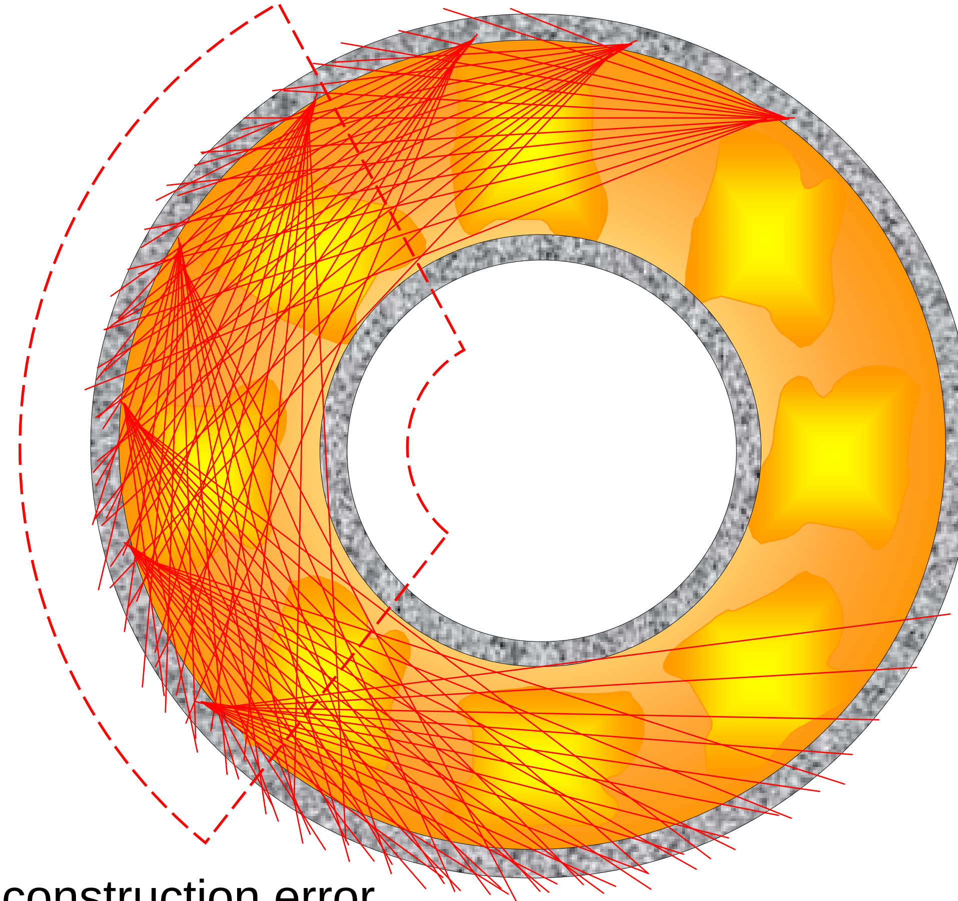


Hostile ambient, Size
Tight space, Serviceability
Alignment and calibration, Cost

Temperature Tomography in turbines





Reconstruction error
- about 17K at 2000K

Challenge 3: Insufficient data

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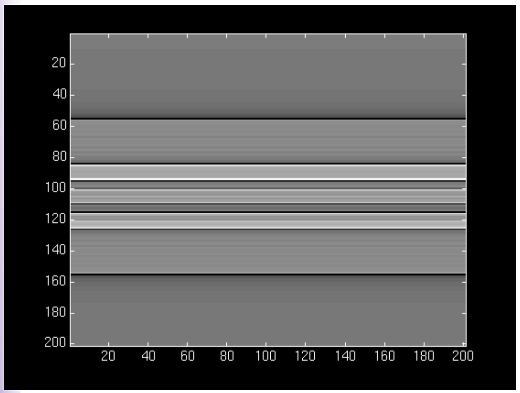
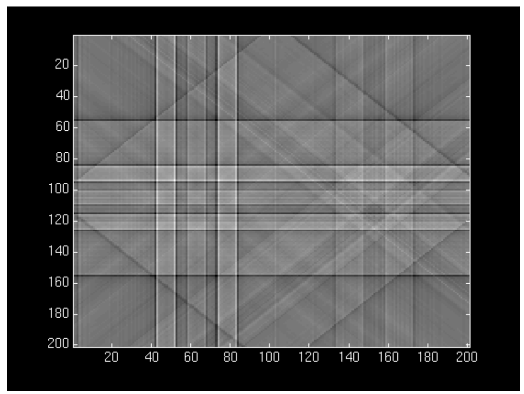
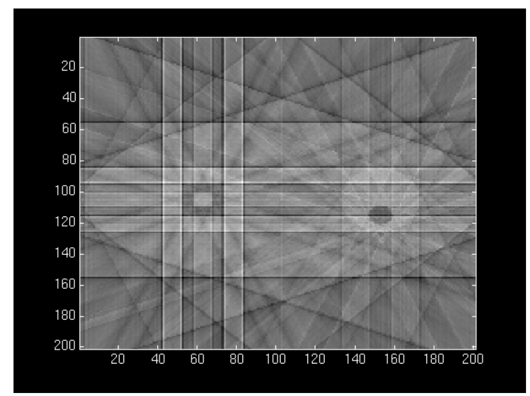
Phantom object reconstructed from 1, 4, 8, 15, and 60 filtered back projections.



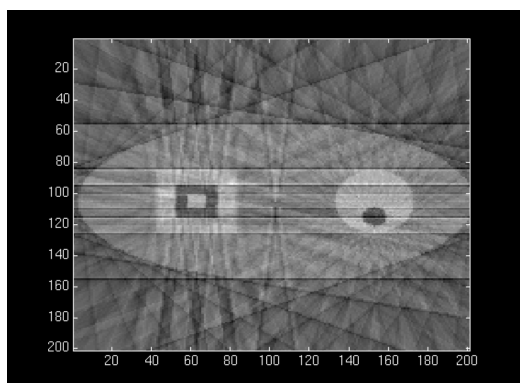
1



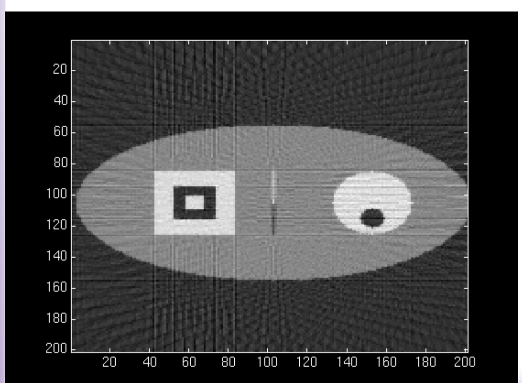
4



8



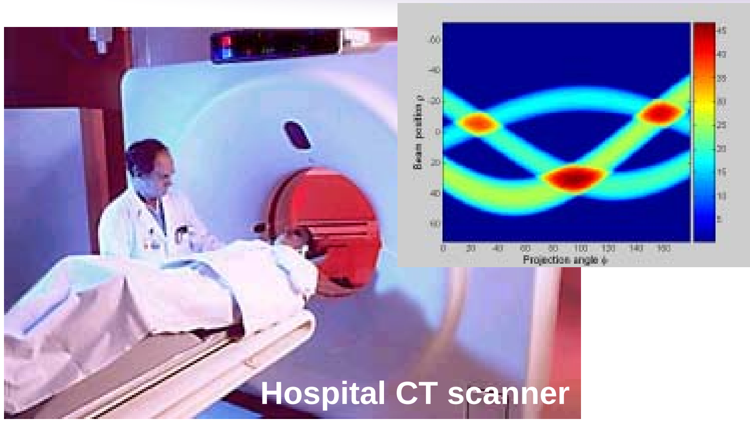
15



60

Sinograms of complex objects

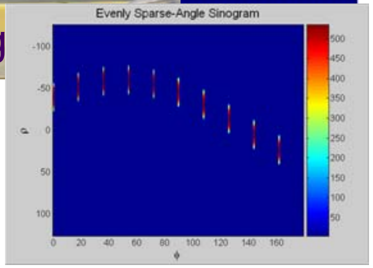
Sparse and Limited Angle Tomography

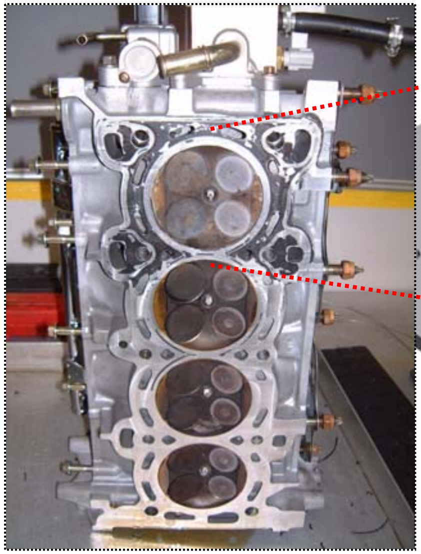


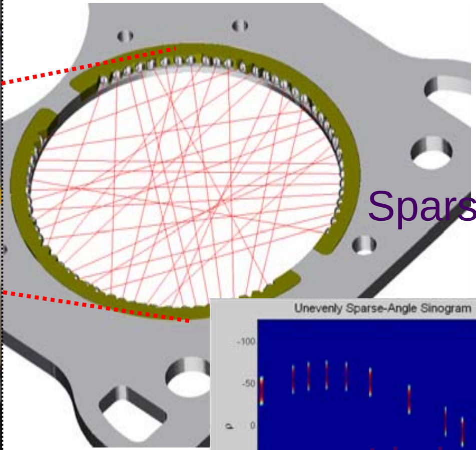
Photonic GPT, Manchester 2006 [Ozanyan et al.]

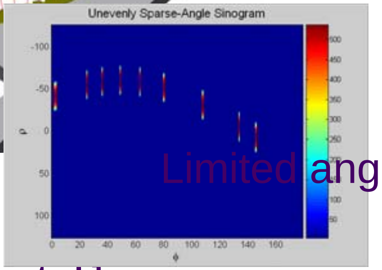
(Quasi) complete angular sampling

Sparse periodic angular sampling





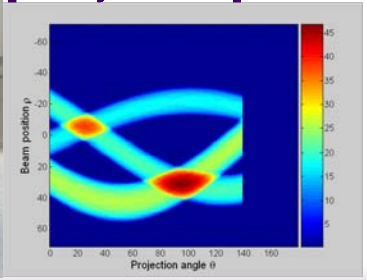




Sparse random angular sampling

Limited angle sampling

OptoFluB, Manchester 2005 [Ozanyan et al.]



IMAGER, Manchester 2002-2005 [McCann et al.]

Suggested approach

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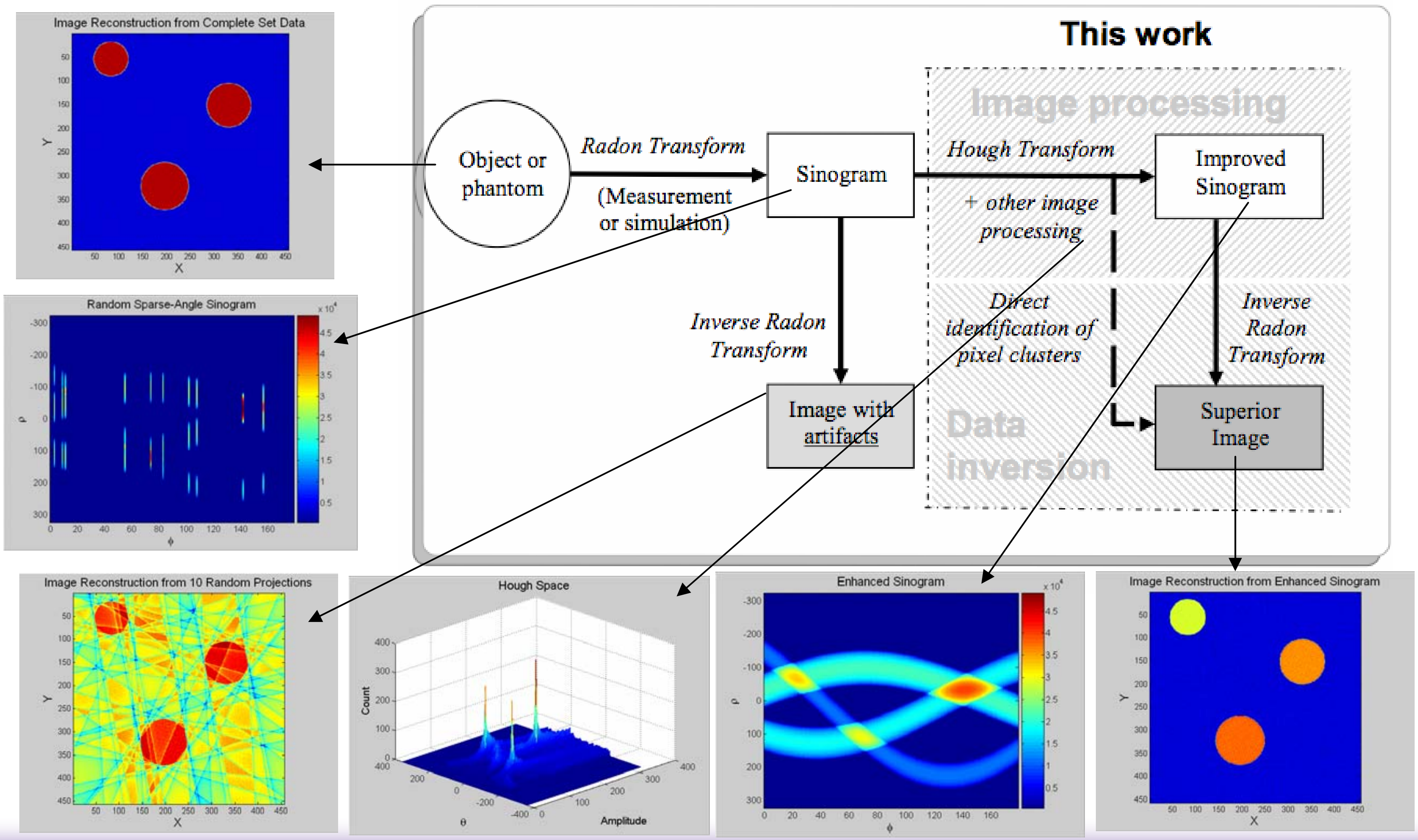


Sinusoidal Hough Transform

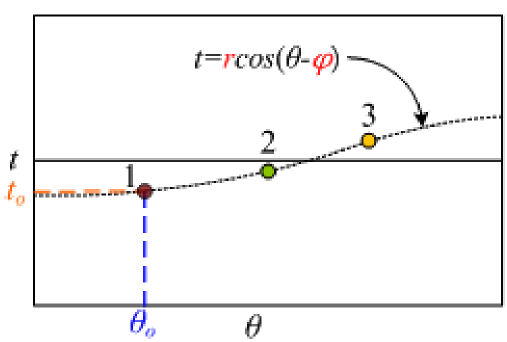
- Treat the sinogram as a pixellated image and identify sinusoidal patterns
- Use the analytical description of the patterns to calculate and fill in missing data
- Use that description for direct identification of higher intensity clusters

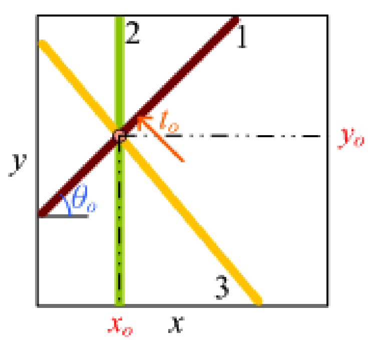
$$t = r\cos(\theta - \phi)$$

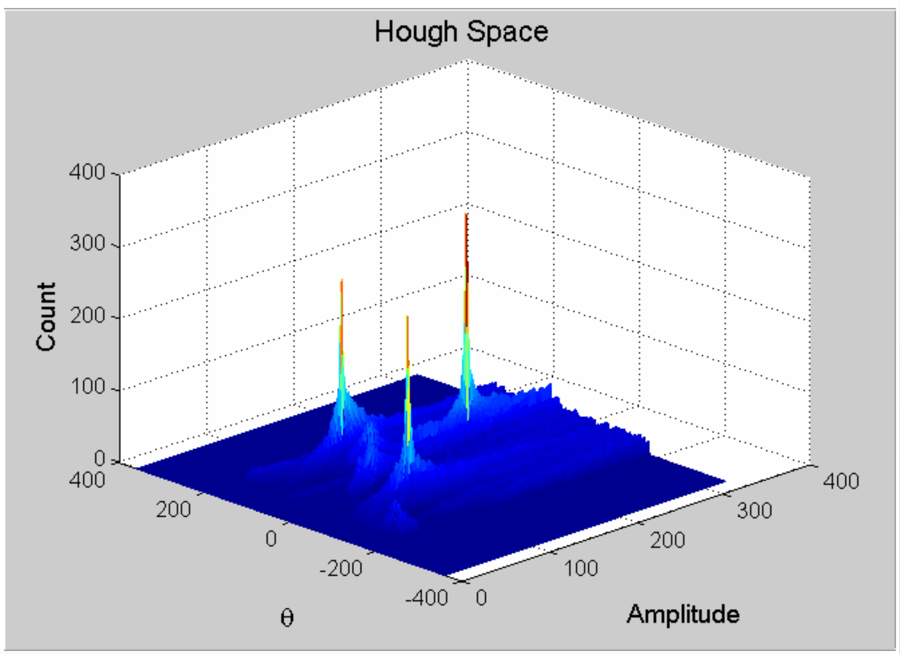
Only two variables, amplitude ***r*** and phase ***θ*** parameterise the curves which build the sinogram.

Or even better - in linear form:

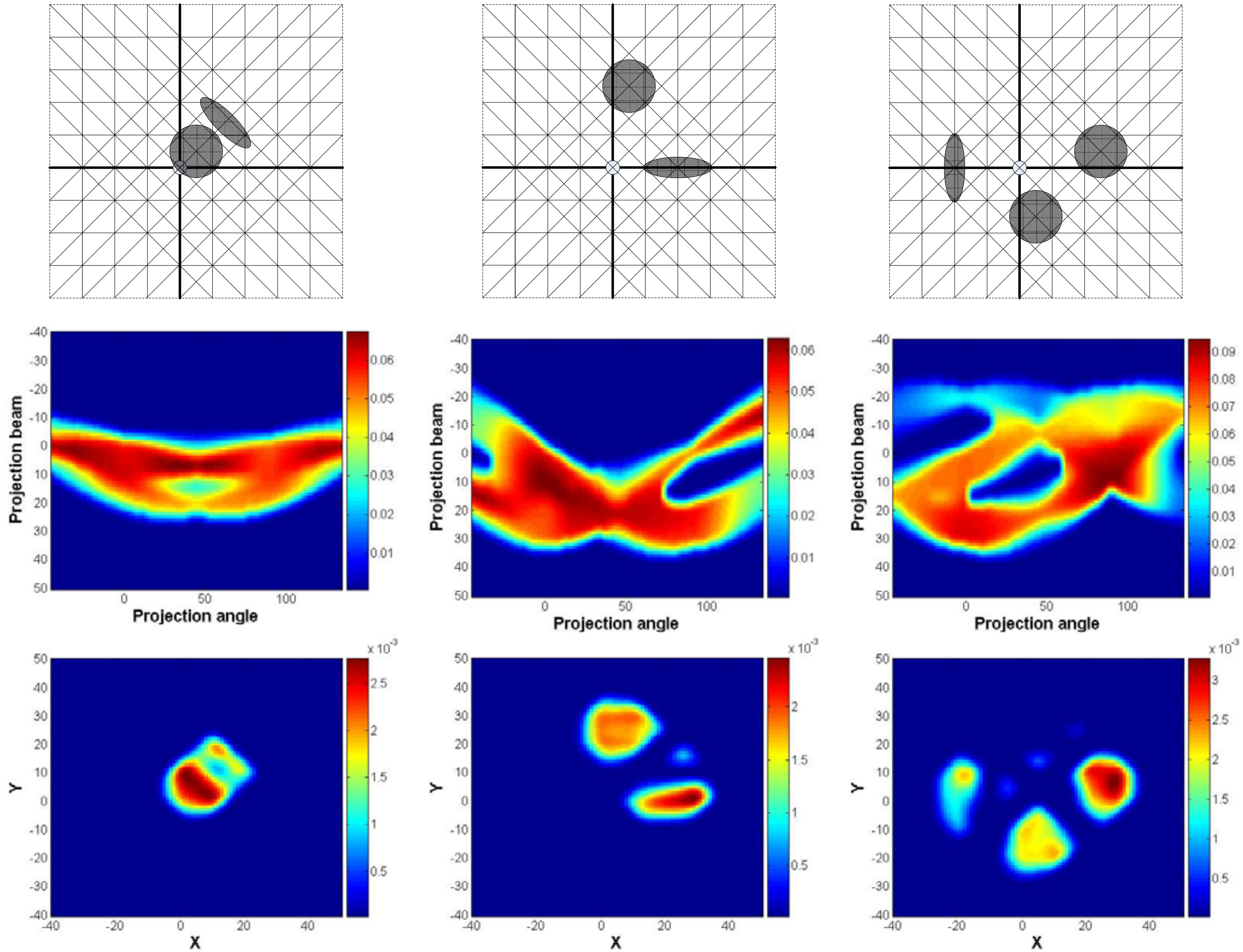
$$y = -\frac{\cos\theta}{\sin\theta}x + \frac{t}{\sin\theta}$$







Sinogram recovery - complex objects

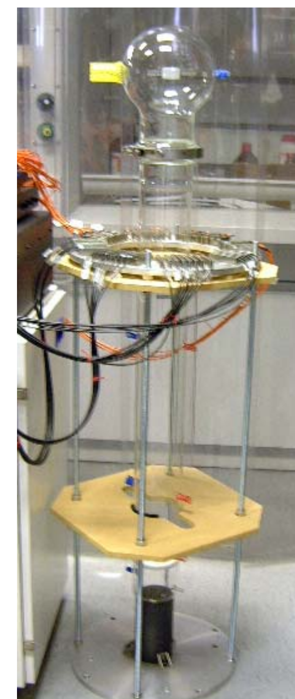


varying footprint
and position

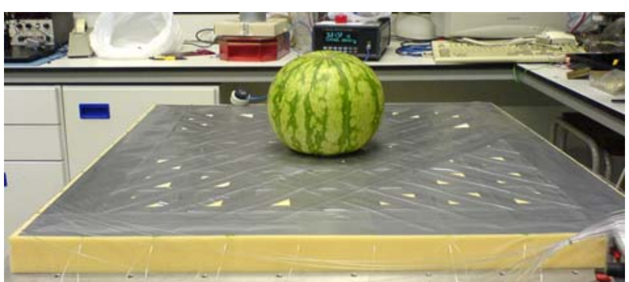
Challenge 4: Data acquisition and processing

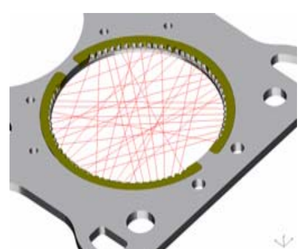
Tomography requires multichannel signal processing, tailored to each individual case :

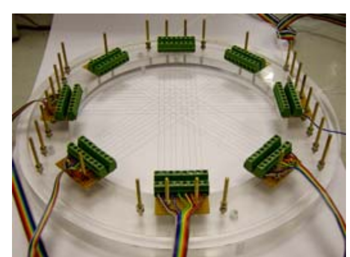
- Phase-sensitive detection (lock-in)
  - T-GPT, Optical, Electrical
- Balanced Ratiometric Detection
  - P-GPT, THz, Optical
- Photon counting
  - Optical CT, Diffuse Optical
- ...



Can analog electronics provide a solution?







Challenge 4: Data acquisition and processing

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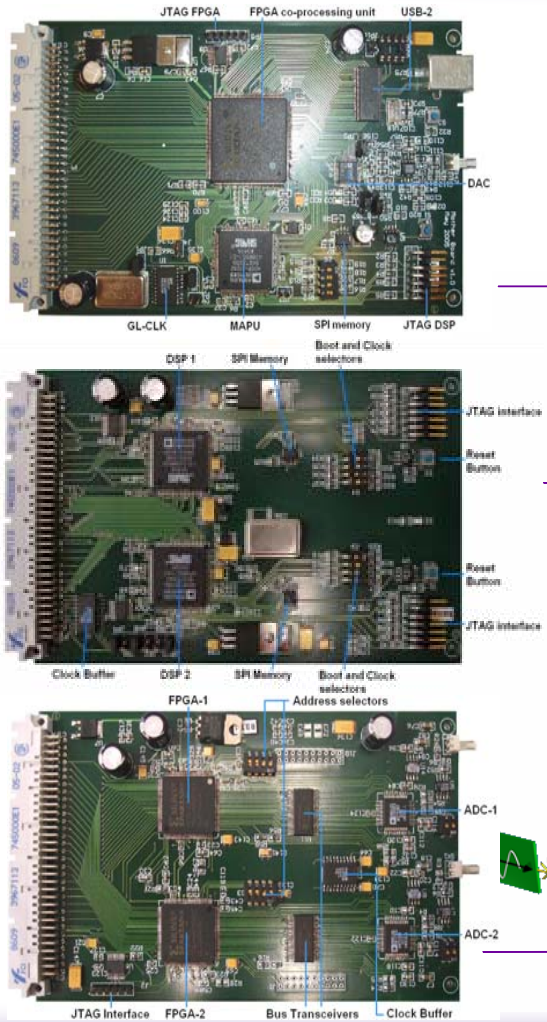
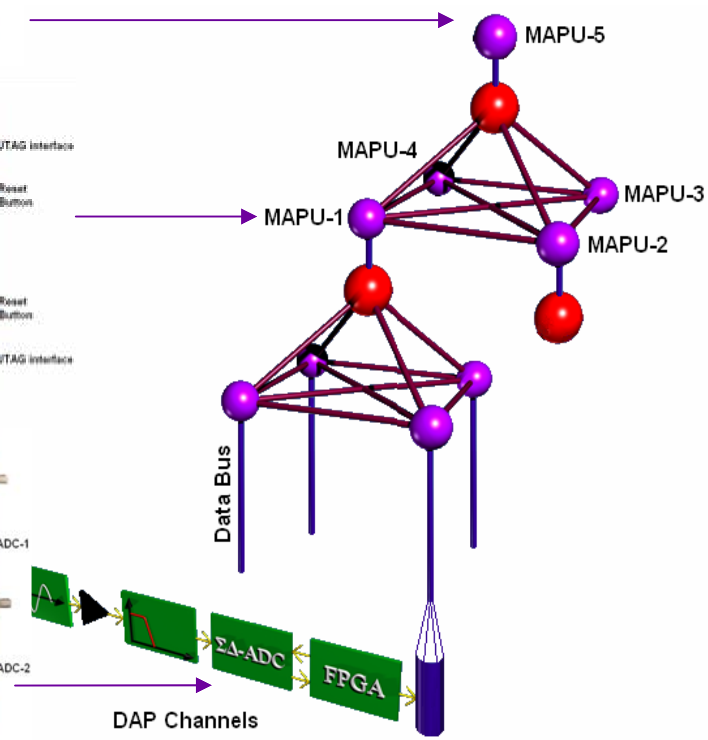
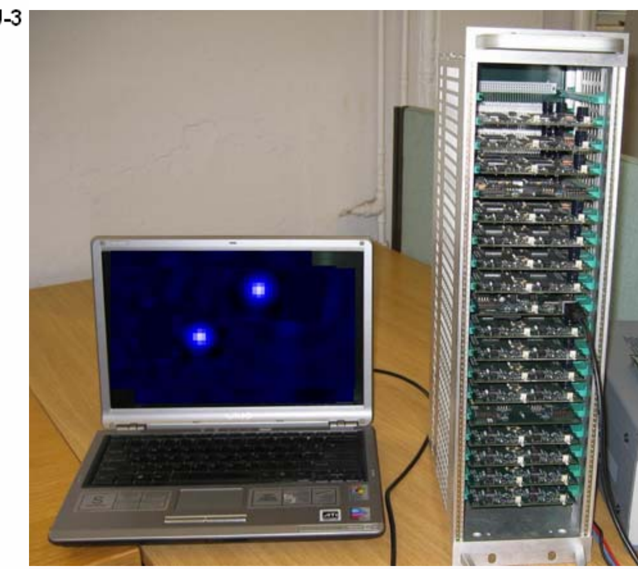
DSP/FPGA technology

- Massive parallel processing
- Expandable hierarchical architecture
- Accommodates a range of signal processing tasks



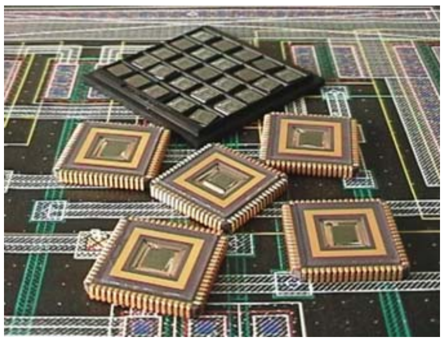




Signal processing algorithms

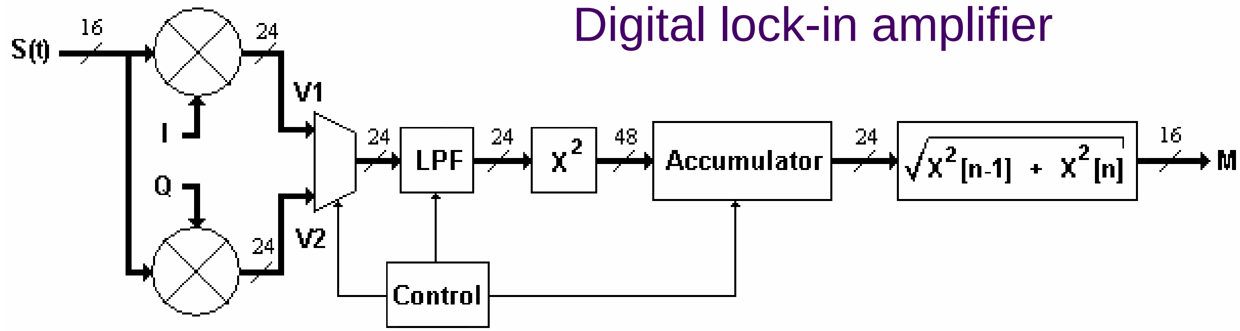
The University of Manchester

FPGA implementation

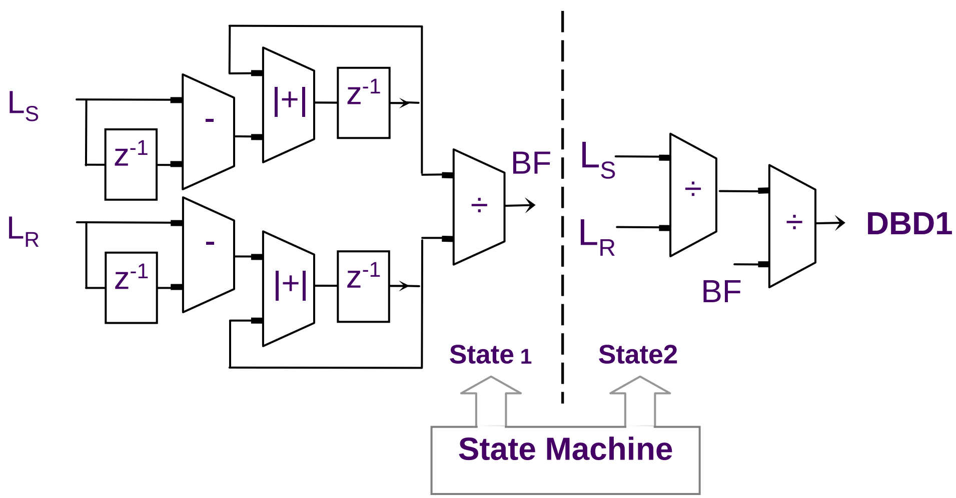


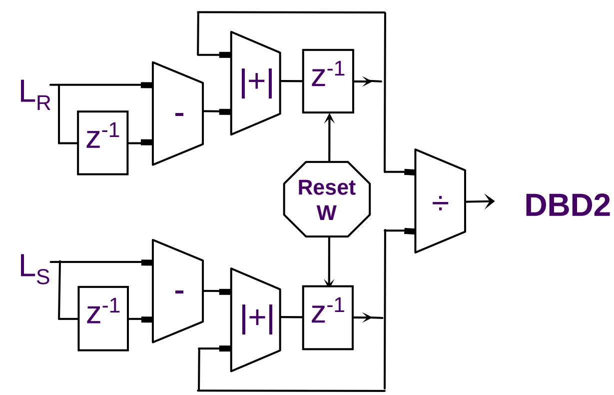
switch between algorithms
in real time

Digital lock-in amplifier



Digital balanced detector

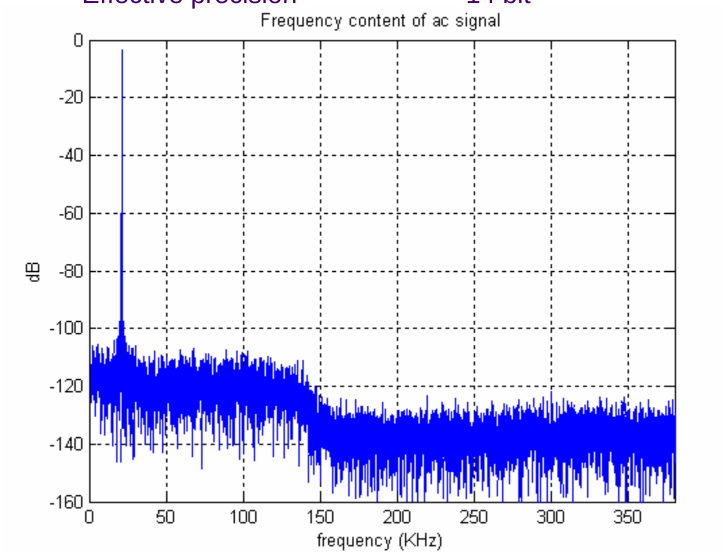




Signal processing performance

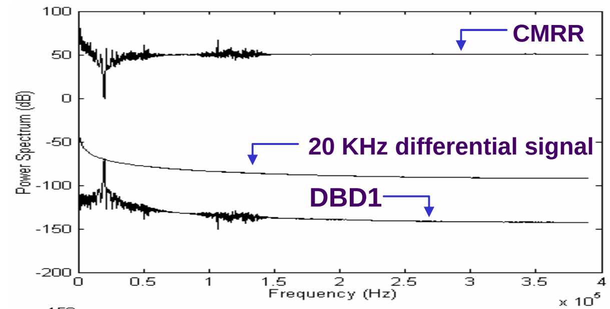
Digital lock-in amplifier

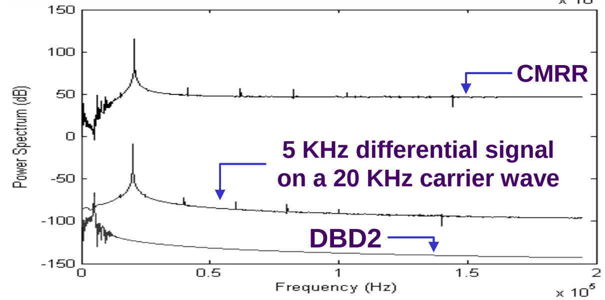
Analog signal sampling at	780 ksamples/s
Modulating frequency	180kHz
Bandwidth	50kHz
Stopband attenuation	98 dB (60 coef.)
Signal-to-noise	85 dB
Effective precision	14 bit

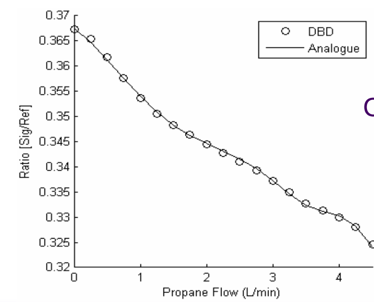


System throughput for 32 channels: ~200 Mbps

Digital balanced detector







Comparison between Analog (NIRVANA) and Digital BRD

Summary

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- Applications of Tomography sensing and imaging in Industry
- Challenges and solutions in non-medical applications:
  - wavelength-sensitive modalities: IR, THz
  - path integrals: kinds of image contrast, T^o-mapping
  - insufficient data: sinogram recovery from limited data
- Acknowledgments