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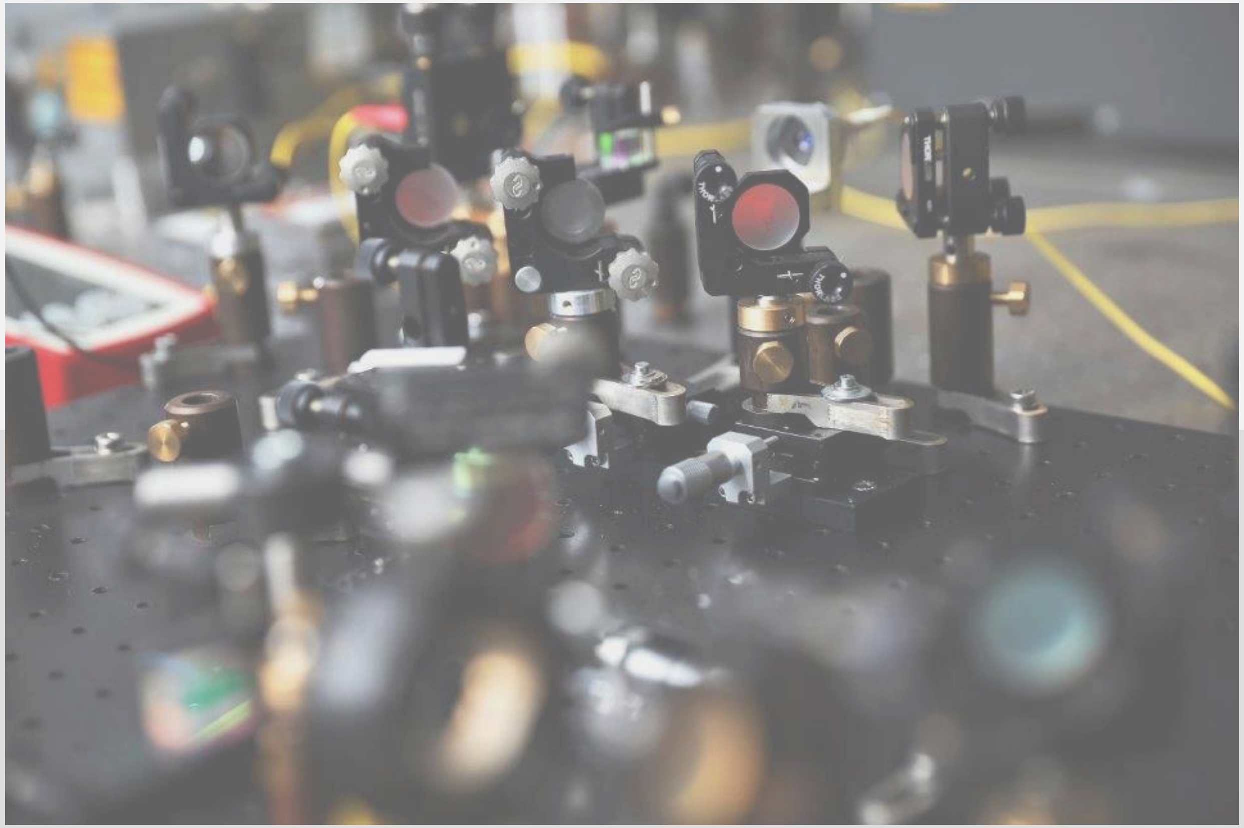
SEQUOIA

Sensing using quantum OCT with AI

Horizon Europe 101070062

https://sequoia-project.eu

SEQUOIA project introduction



Presentation outline

- **Project summary**

  Consortium | Project overview | Objectives

- Theory and principles

  OAM control | Noise reduction

  QOCT | Sustainability

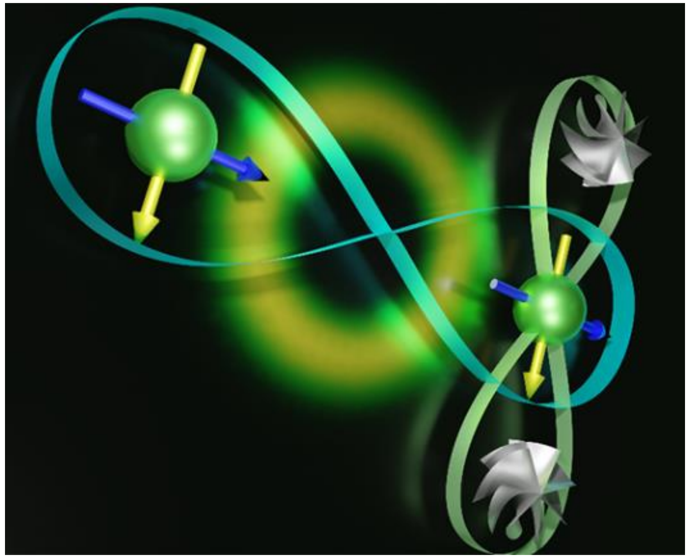
- Hardware

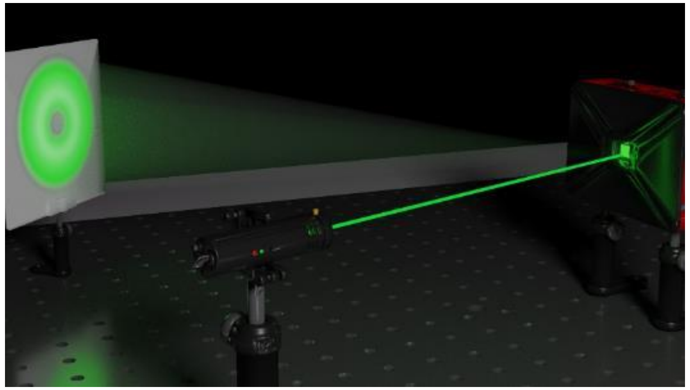
  Source | SPAD imager for QOCT

- Experiment

  Retinal studies | Characterisation and benchmarking

- Outlook





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Project summary

- Horizon Europe project to develop optical coherence tomography (OCT) using quantum techniques
  - SEQUOIA: *Sensing using quantum OCT with AI*

- OCT is a non-contact high resolution 3D imaging technology
  - Highly successful in medical (especially retinal) imaging and industry
  - State-of-the-art OCT seems to have reached its limit at ~1 µm axial resolution (δz)

Theory suggests that:

1) Quantum OCT (QOCT) could:
   - Achieve 0.5 µm δz
   - Reduce dispersion

2) Control of the quantum property of orbital angular momentum (OAM) could:
   - Reduce noise
   - Improve edge and surface profile definition
   - Aid the discrimination of chiral objects

Project consortium

No.	Name	Country
1	NKT PHOTONICS A/S	DK
2	PHYSIKALISCH-TECHNISCHE BUNDESANSTALT	DE
3	MICRO PHOTON DEVICES SRL	IT
4	NORBLIS APS	DE
5	TECHNISCHE UNIVERSITEIT DELFT	NL
6	DANMARKS TEKNISKE UNIVERSITET	DK
7	NICOLAUS COPERNICUS UNIVERSITY	PL
8	UNIVERSITAT POLITECNICA DE VALENCIA	ES
9	ARDITEC	FR
10	VIVID COMPONENTS GERMANY	DE
11	UNIVERSITY OF MÜNSTER	DE

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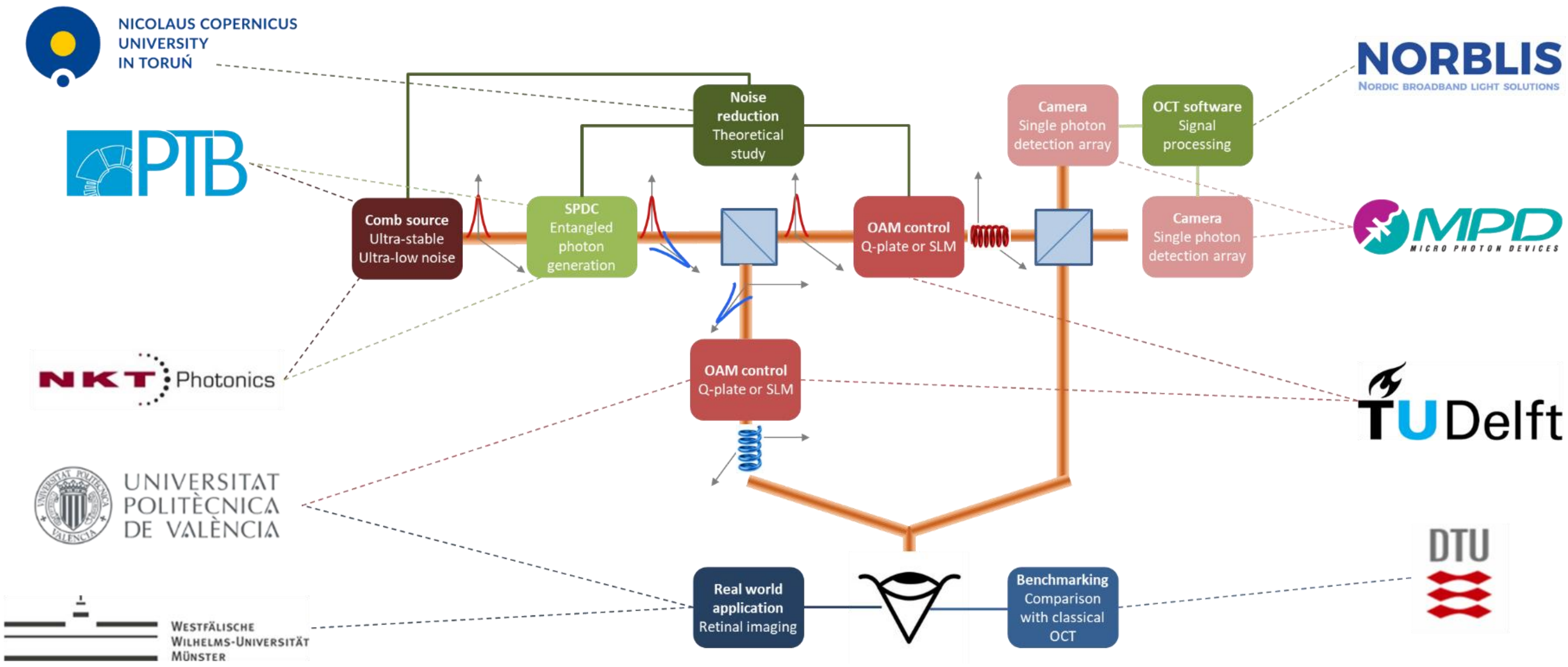
SEQUOIA overview



SEQUOIA objectives

KO-1	Overall project objective: **Demonstrate world-beating QOCT in a real world application (retinal imaging)**
KO-2	World’s most stable ultra-low noise UV comb source
KO-3	First use of ML-algorithms for high-dimensional OAM entanglement for QOCT
KO-4	First SPAD imager with high pixel count optimised for maximum coincidence throughput
KO-5	First QOCT software with OAM analysis
KO-6	First numerical simulator of SPDC process including broadband pumping and OAM
KO-7	First ever direct comparison of classical and QOCT
KO-8	Automated image analysis showing increased resolution and contrast for retinal specimens
KO-9	Quantified comparison of techno-economic and social metrics for SEQUOIA and existing solutions

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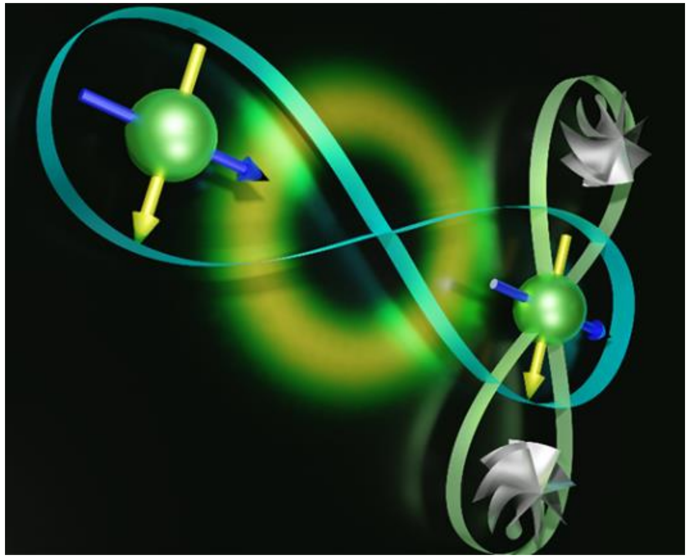
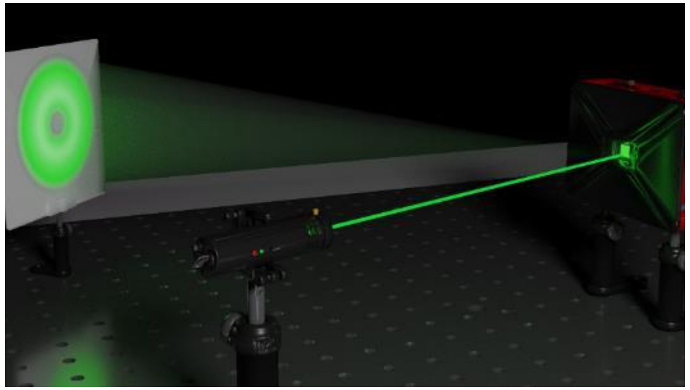




Orbital angular momentum: theoretical models

NICOLAUS COPERNICUS UNIVERSITY IN TORUŃ

Reducing noise through light twisting:

- Orbital angular momentum
- Propagation of OAM modes in medium
- Control and selection of correlated OAMs

SEQUOIA will:

- Develop the first **mathematical models of noise** in QOCT
- Use them to **optimise the parameters** of the SPDC

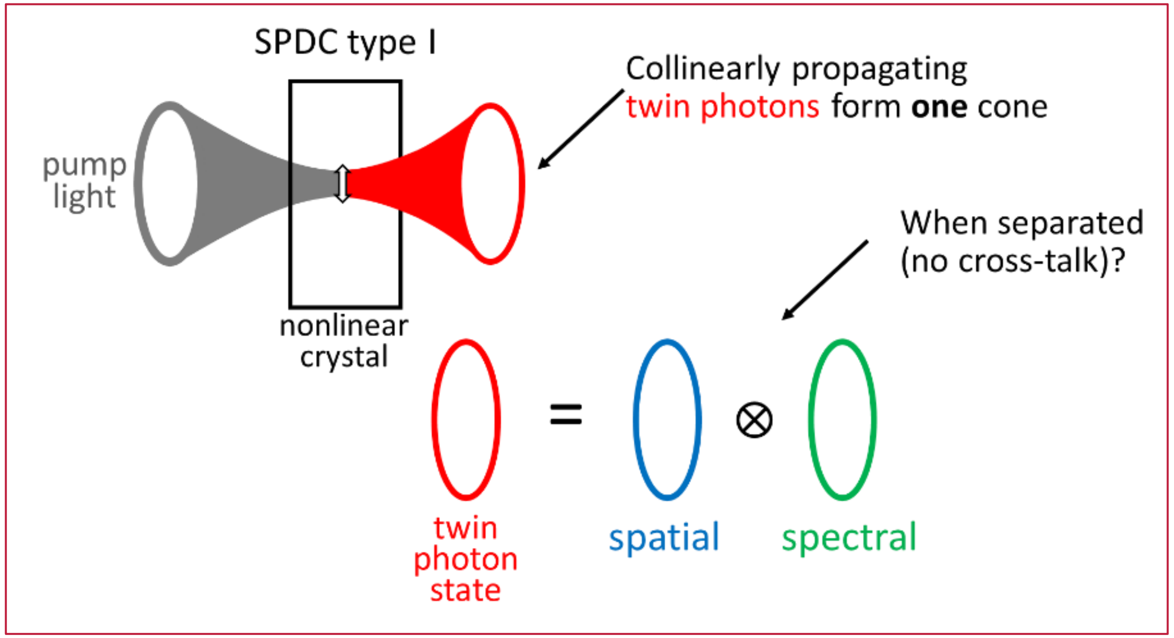
First step: getting to know the QOCT signal

- SPDC: *Spontaneous Parametric Down-Conversion*
  - Phenomenon leading to creation of entangled photon pairs

- **High-quality** QOCT signal means that there is no cross-talk between the photon pair's spatial and spectral characteristics

- What are the **experimental parameters** ensuring no cross-talk?

Type I configuration



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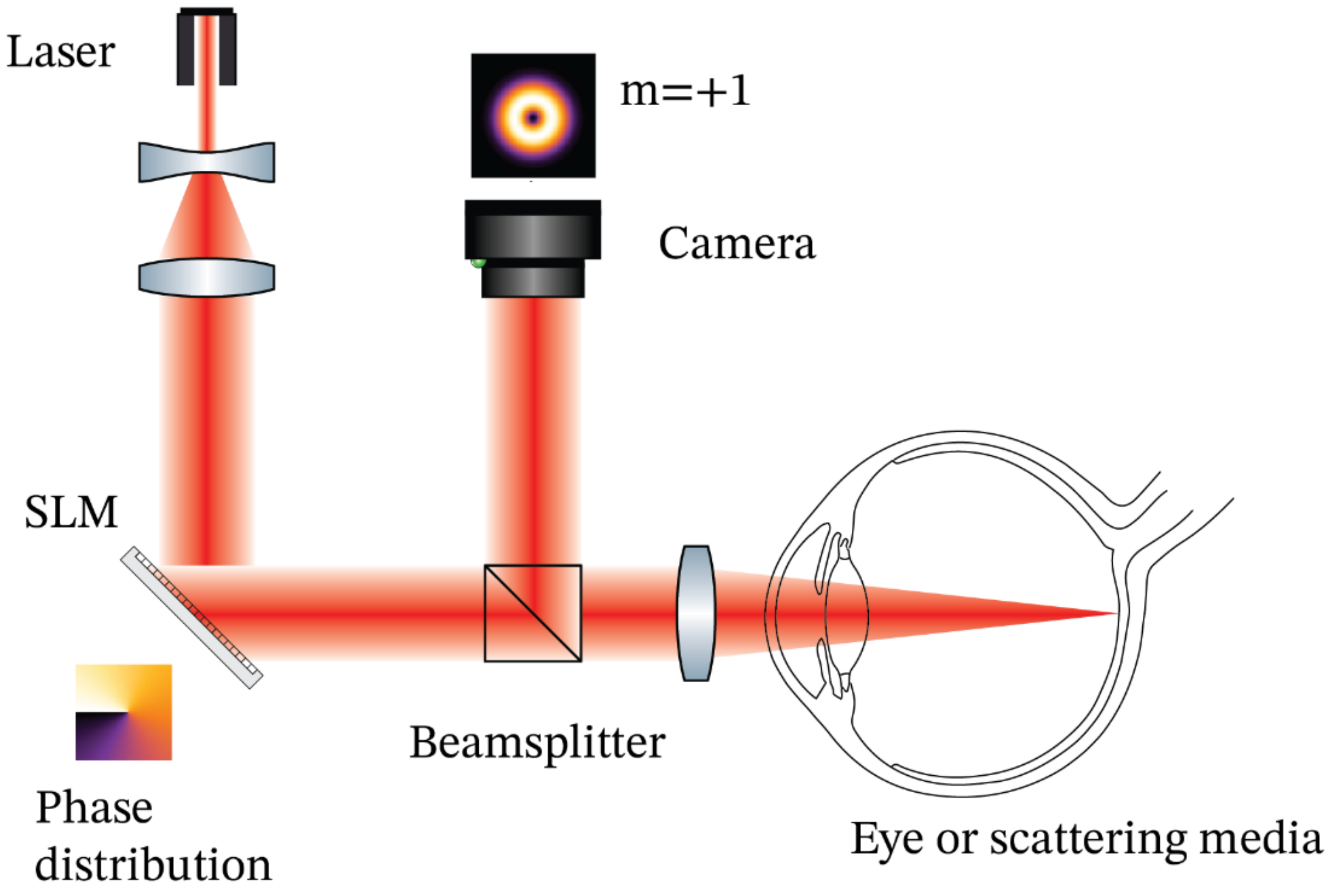
Orbital angular momentum: experiment



- Use of OAM offers protection from noise
  - It could bring other benefits:
    - Improved edge definition
    - Better surface profile distinction
    - Discrimination of chiral objects (*e.g.* in retinal structures)
- OAM is generated using a spatial light modulator (SLM)
- SEQUOIA will study the effects on OAM of propagation in a scattering media
  - Experiment and comparison with simulation
  - The eye may be approximated as a multilayer scattering media
- Train AI algorithm to recognise and control the type (order) of OAM

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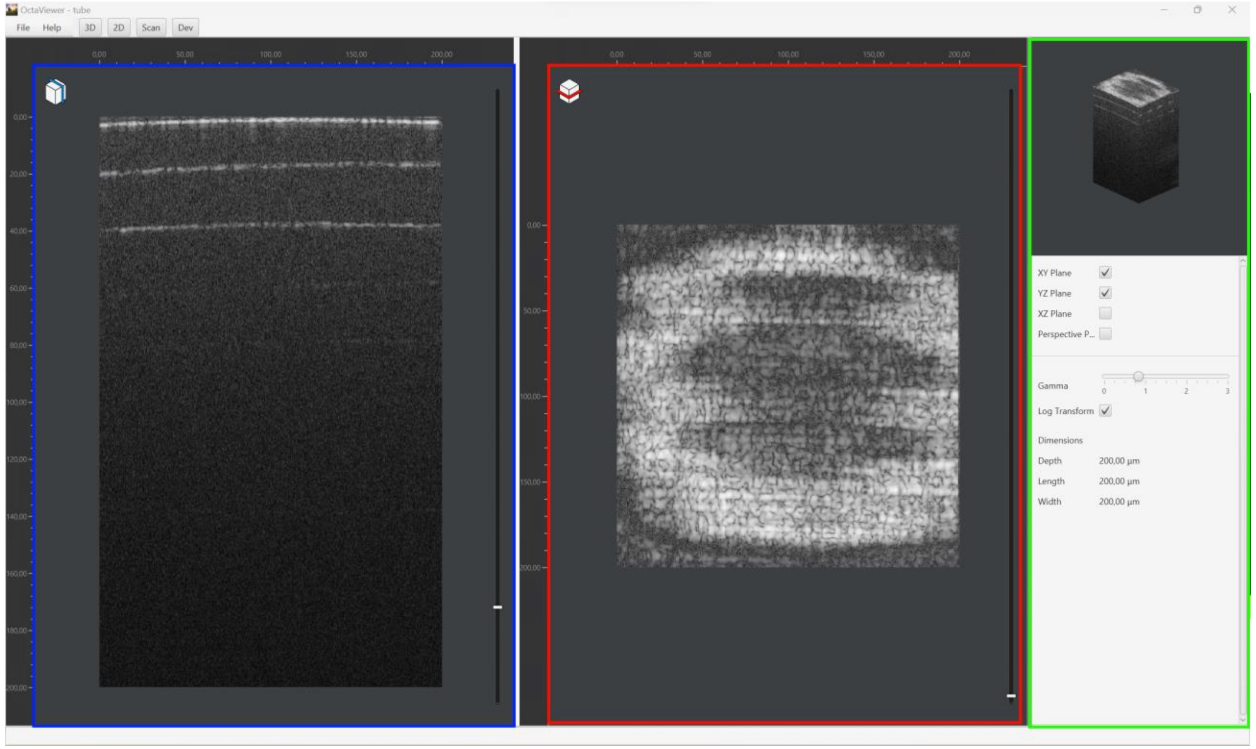
QOCT software - From classical to quantum imaging interfaces

NORBLIS
NORDIC BROADBAND LIGHT SOLUTIONS

- Tailor and optimise the existing state-of-the-art classical **spectral domain OCT** data acquisition and processing software to a **QOCT platform**
- Development of a user-friendly interface for time-domain QOCT – **single pixel** and **multi-pixel intensity correlations**
- Capability for visualisation and interactive image effects (depth, layers, *etc.*) including **spectrally resolved intensity correlations**
- Development of a novel swept source spectral domain **QOCT software supporting OAM analysis**



Example of visualisation of a volumetric scan. The blue and red regions show a B-scan and a C-scan, respectively. The green region is a control panel where the user can change how the volume is rendered.

Potential applications for QOCT technologies

- Clinical applications
  - Surface imaging
    - Ophtalmology
    - Dermatology
    - Dentistry
    - Cochlear vibrometrie
  - Endoscopic imaging
    - Cardiovascular
    - Gastroenterology
    - Gynaecology Urology
    - Pulmonology
- Developmental Biology
  - Elastography
  - Cochlea Organ Tissue
  - Microvasculature
  - Skin
  - Nervous System
- Industrial application
  - Displays
  - Pharmaceuticals
  - Contact Lens Metrology
  - Packaging
  - Biofilm
  - Industrial Paints and Varnish
  - Thin Films
  - (Nano)membrane anti-fouling
  - CAD/CAM
  - 3D Printing
  - Composite Materials
  - Aerospace
  - Welding & Keyhole Mapping
  - Meat Quality Control
  - Art conservation

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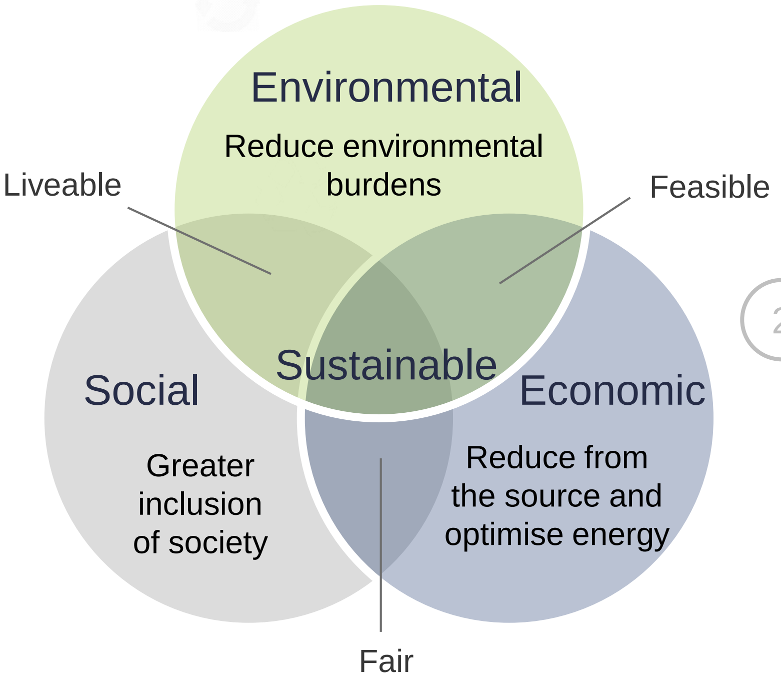
Techno-economic and social assessments of the potential for QOCT

1 Life Cycle Assessment (LCA)

3 Social Life Cycle Assessment (SLCA)



2 Techno-economic Assessment (TEA)

Life Cycle Costing (LCC)

HOLISTIC APPROACH - 3 pillars of sustainability

Tasks performed within the scope of SEQUOIA Project

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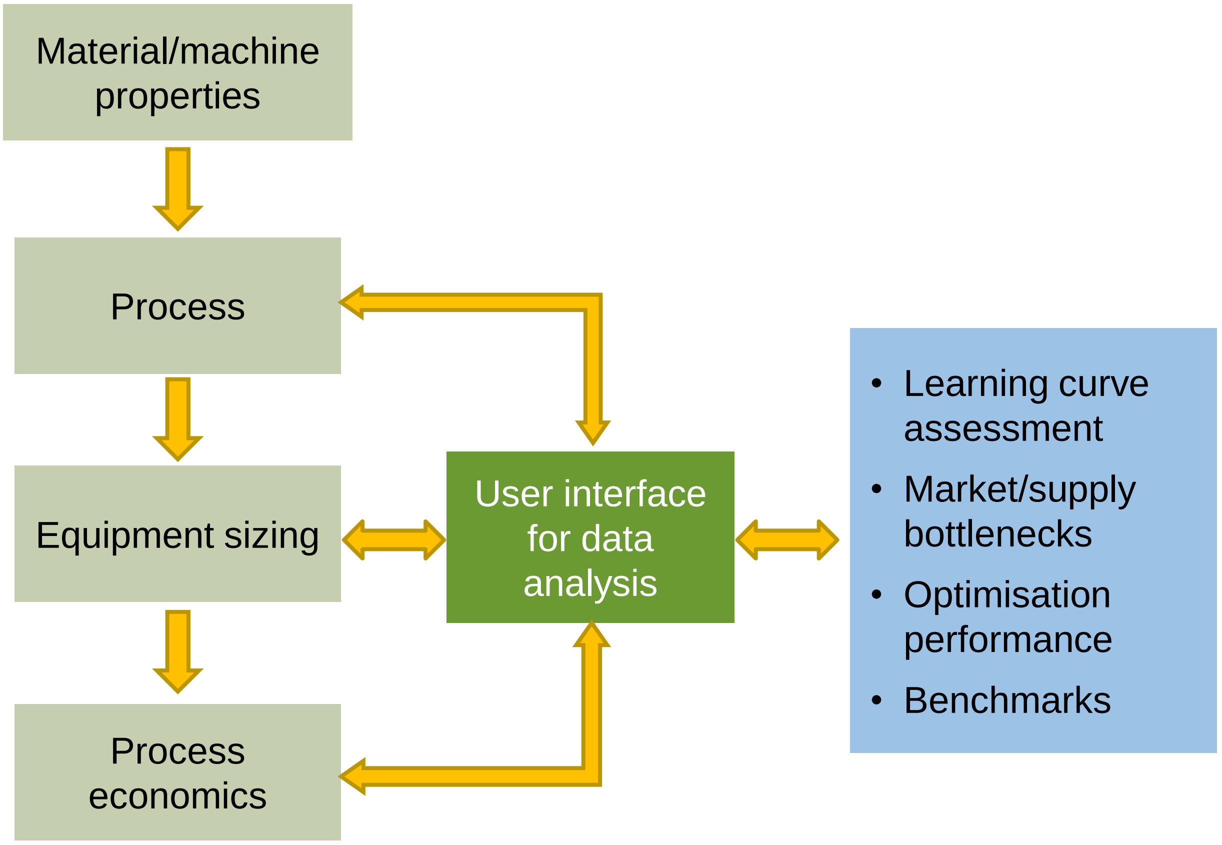
Techno-economic assessment (TEA) of QOCT technologies

- Perform a mass and energy balance, energy requirements analysis and main components sizing and rating
- **Optimise capital** CAPEX, **operational costs** OPEX and identify **cost reduction opportunities** at process level
- Carry out a **learning curve assessment** which is the representation of the costs versus the cumulative capacity or production to identify and eliminate **suply/market bottlenecks** and **material prices volatility**



TEA scheme

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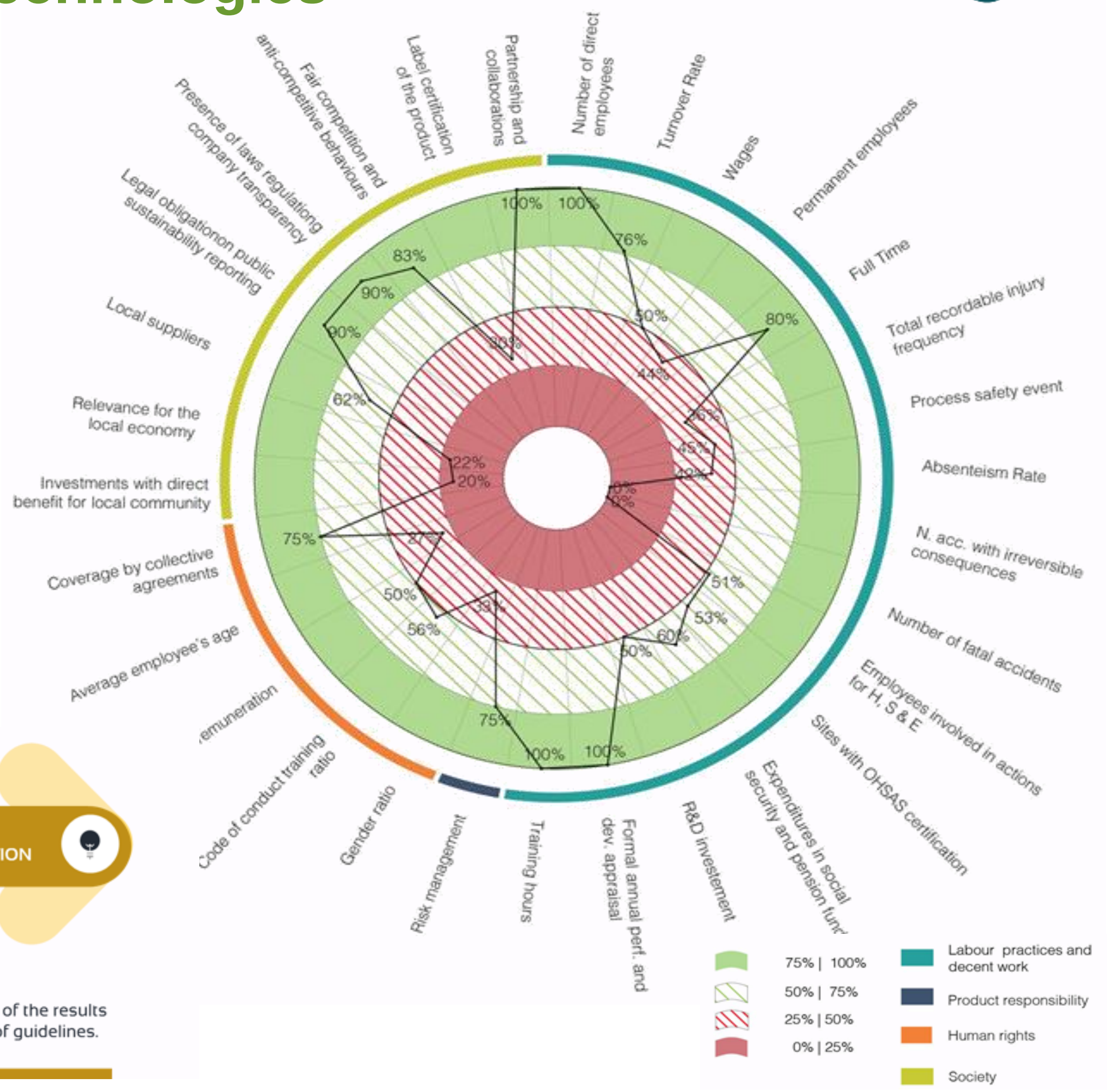
Social impacts evaluation (S-LCA) of QOCT technologies

- **Social LCA** has emerged in recent years as a methodological approach to assess the **positive and negative social aspects** in the life cycle of a product
  - From extraction of raw materials to final disposal
  - Benoit *et al*. (2010)
- This methodology can be used to identify, learn and communicate about **social impacts**, in order to support the implementation of improvement strategies
- It generally follows the **following steps**:

S-LCA development stages



Example of S-LCA results

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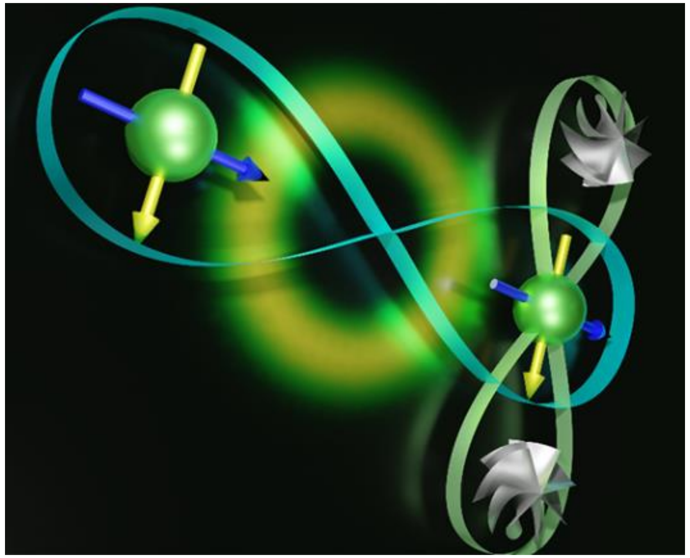
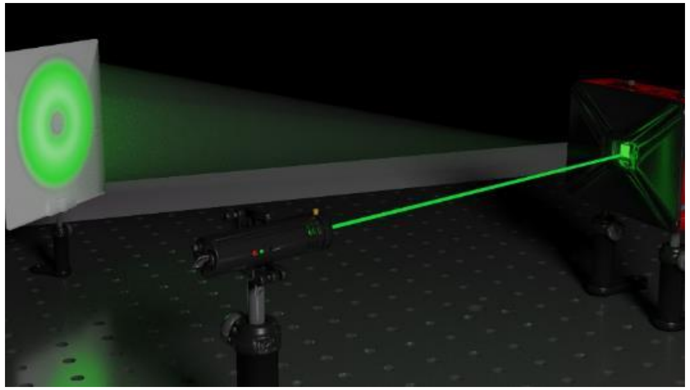
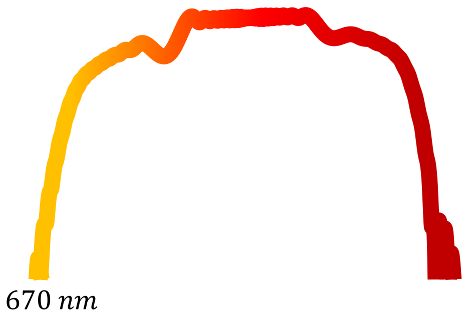


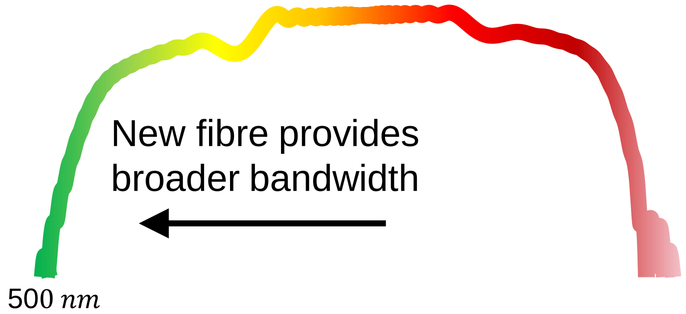


Aim: Broadband spectral coverage supercontinuum with low noise

- **Motivation:** OCT axial resolution is improved by a wider bandwidth source: spectroscopic and other functionalities can be exploited at VIS wavelengths
- **To make visible entangled photons, requires UV supercontinuum (SC):** A new fibre design will first be created and drawn at NKT Photonics to extend the SC bandwidth to reach short wavelengths
- **To make a true comb, the SC must be stabilised.** PTB will use feedback mechanisms to stabilise the repetition frequency and drift of the carrier phase



Coherent SC



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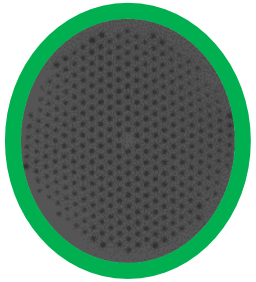
SEQUOIA ultra-stable source objective

- NKT will generate a low noise broadband comb source using coherent SC
- For the SC to be considered a comb, advanced stabilisation techniques are required
  - An octave spanning spectrum is required for carrier phase stabilisation
  - Relative intensity noise (RIN) of <0.6 % in Stage 1 and 0.2 % in Stage 2

NKTP fs laser

+

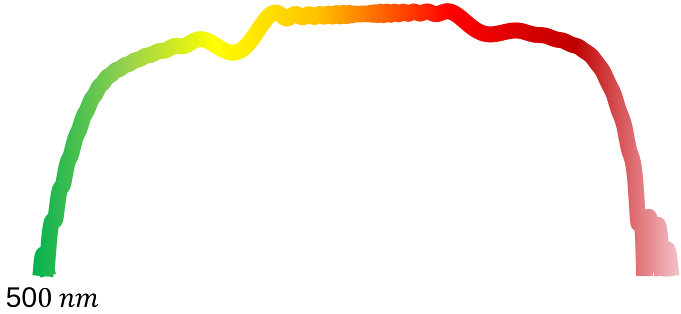


All-normal fibre

+

Advanced stabilisation with PTB

→



Octave spanning SC

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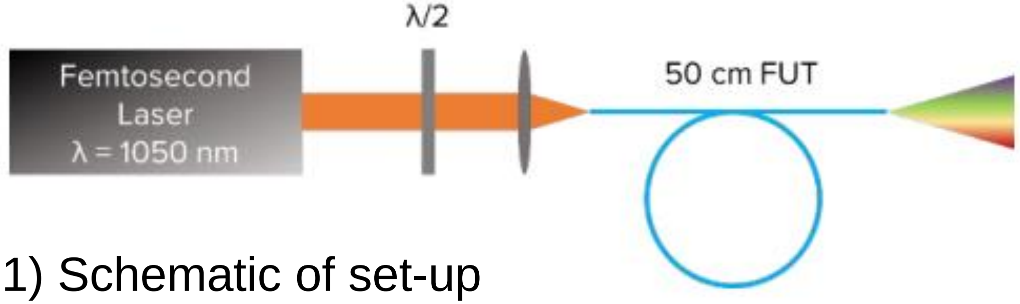
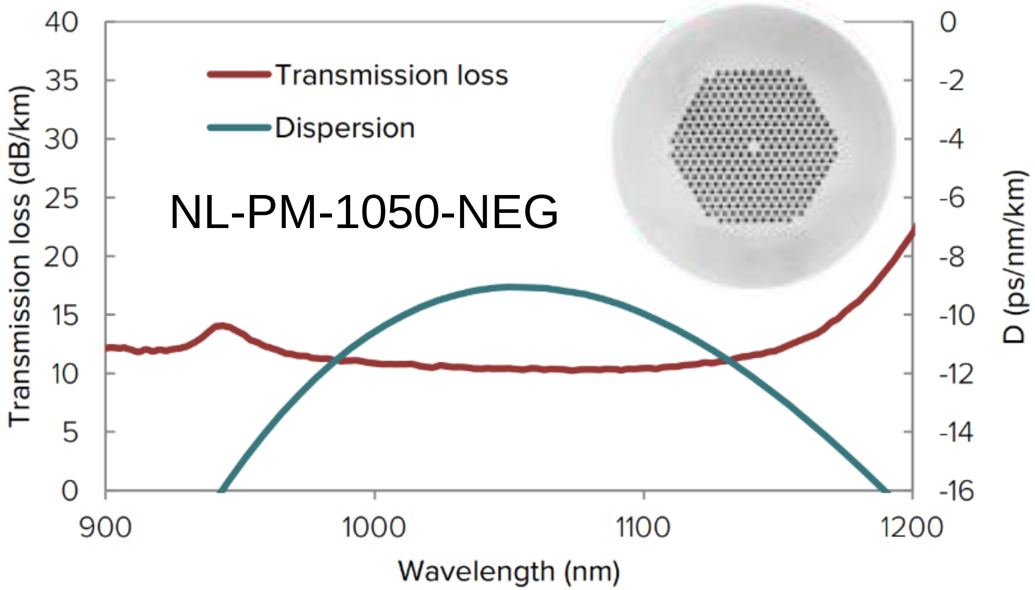
Advantage for OCT: a spectrally-flat light source

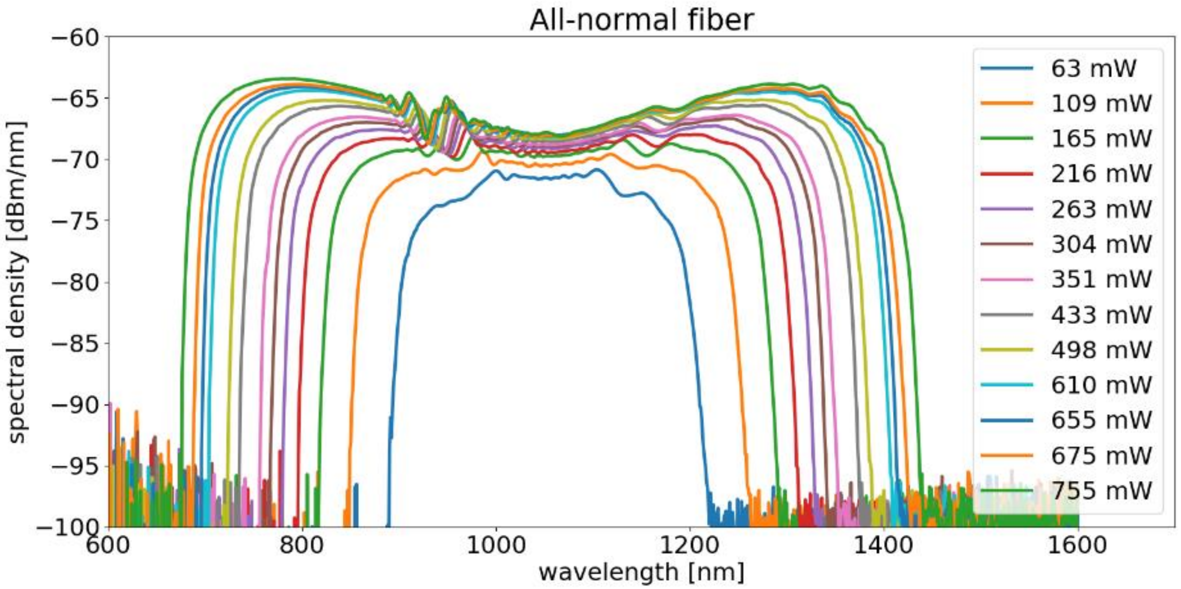
- All normal dispersion SC provides greater spectral flatness than typical SC
- The fibre is pumped using a 130 fs, 80 MHz NKTP Origami 10HP laser
- The result is an octave spanning SC, with a spectral flatness of 5 dB



1) Schematic of set-up



2) Fibre loss and dispersion



3) Spectrum at several pump powers (pumping fast axis)

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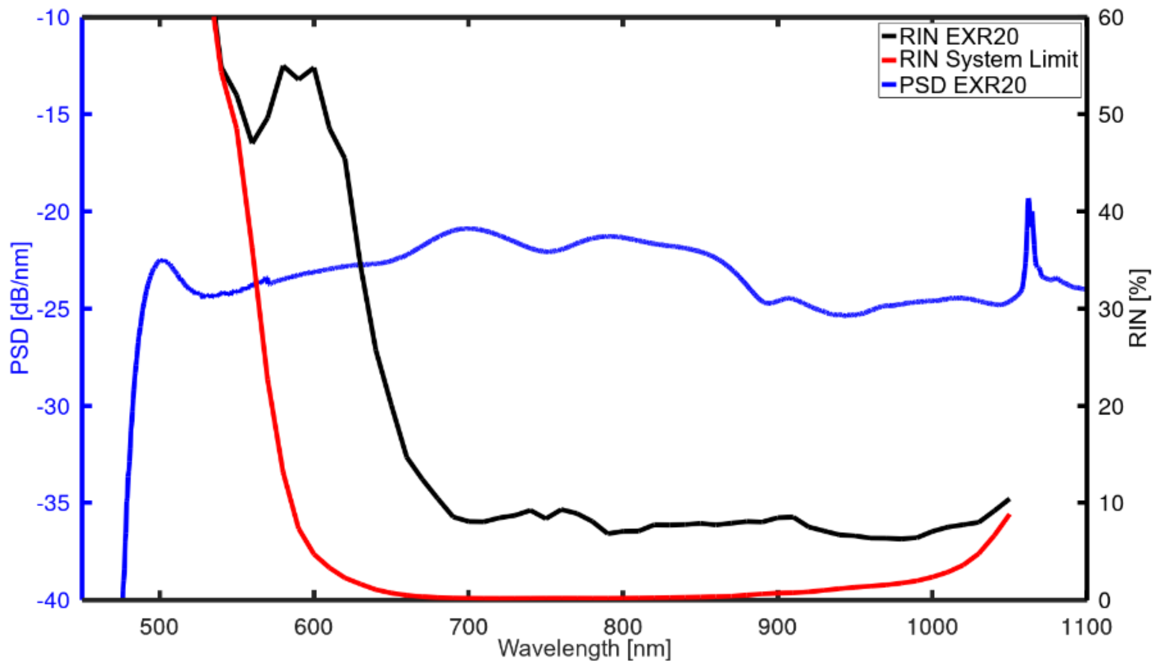
Advantage for OCT: low RIN

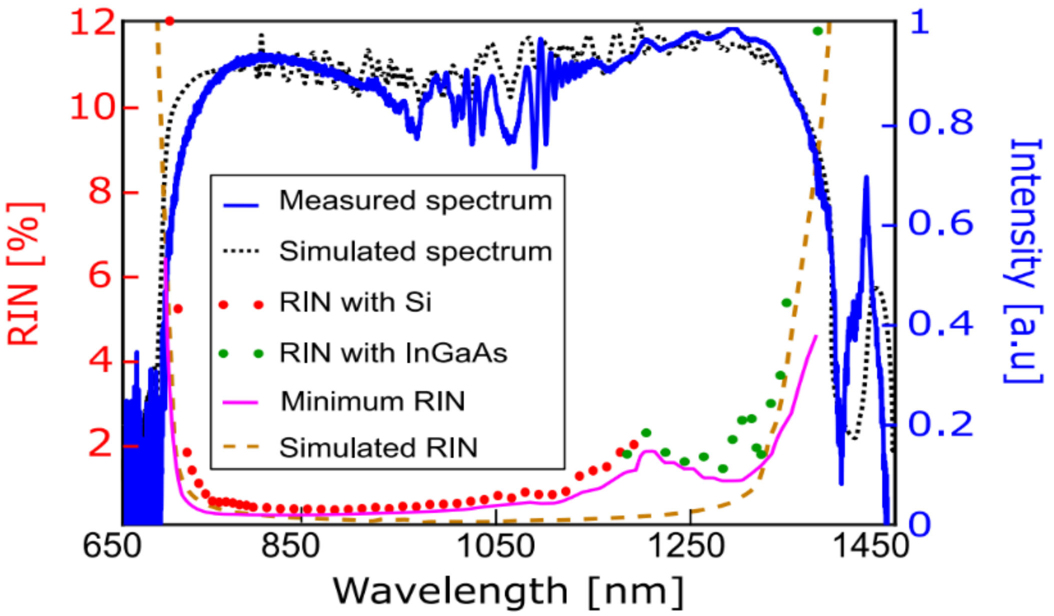
- Due to high temporal coherence, pulse-to-pulse fluctuations are very low
- Standard SC sources are characterised by RIN > 8 %
- Preliminary ANDi results suggest a possibile >10× improvement (<0.6 %)
- This can allow an OCT system to reach shot-noise limited sensitivity (>100 dB)

Anomalous supercontinuum



1) RIN of standard SuperK sources

All-normal supercontinuum



2) RIN of the SEQUOIA all-normal SC

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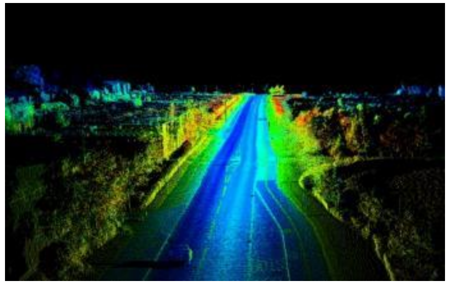
Concept: SPAD imager optimised for quantum applications



- Current SPAD imager development is driven by LIDAR:
  - High photon flux
  - Very large arrays
  - Optimised at a single wavelength (usually 905 nm)
  - TOF measurement with centroid extraction

- SEQUOIA needs SPAD imagers with:
  - Low noise
  - Good efficiency in 500 – 800 nm range
  - Coincidence detection with optimised readout
  - Thousands of pixels

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SPAD Imager for QOCT: Challenges

- Fabrication technology limitations
  - Silicon technology not driven by SPAD requirements
  - Custom technologies allows very good SPAD but limited integration
  - Standard technologies allow very good integration but usually not so good SPADs (typically high noise)
  - In recent years good SPADs in standard technologies have been reported (especially in HV-CMOS or BCD), but technology selection is still challenging (cost *vs.* quality *vs.* availability)

- Architectural challenges
  - General purpose SPAD imagers easily reach very high data throughput (moderate pixel number, high frame rate, high time-tagging/counting resolution), which are difficult to manage
  - However, in many SPAD applications (typically photon starved) a large amount of these raw data are useless (*i.e.* not coming from useful signal)
  - Clever architectures able to efficiently reduce throughput are needed

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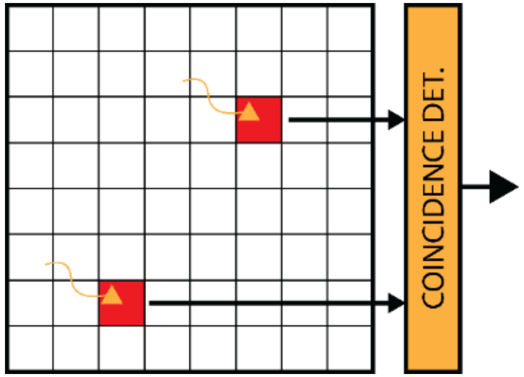
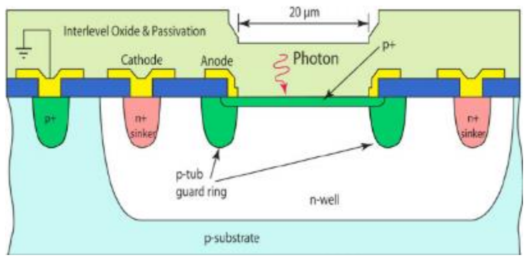
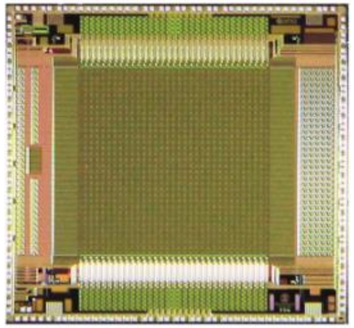
SPAD Imager for QOCT: Methodology



- Specifications (M1 - M12)
  - General purpose MPD SPAD cameras for preliminary evaluation of QOCT
  - Definition of full set of specifications for SPAD detectors, imagers and cameras
  - Selection of CMOS foundry



- SPAD structure (M1 - M18)
  - Design of new SPADs in the selected CMOS foundry
  - Fabrication and characterisation of single SPAD detectors



- SPAD imagers (M6 - M36)
  - Design and fabrication of SEQUOIA SPAD imagers
  - Design and fabrication of SEQUOIA camera
  - Characterisation and testing in QOCT set-up

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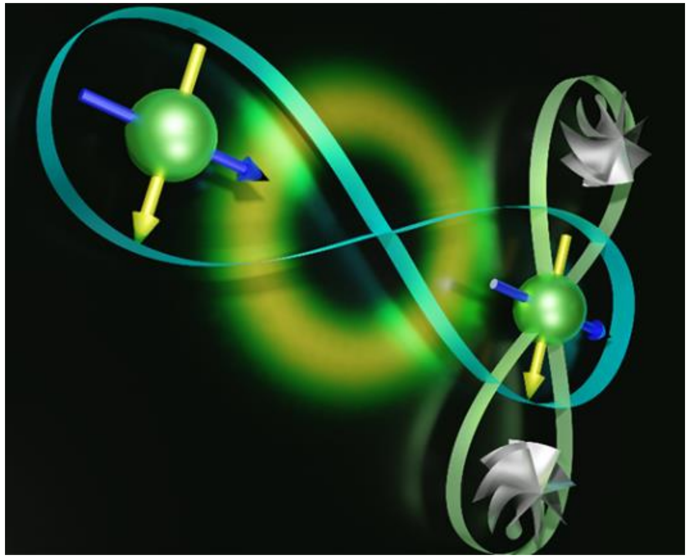

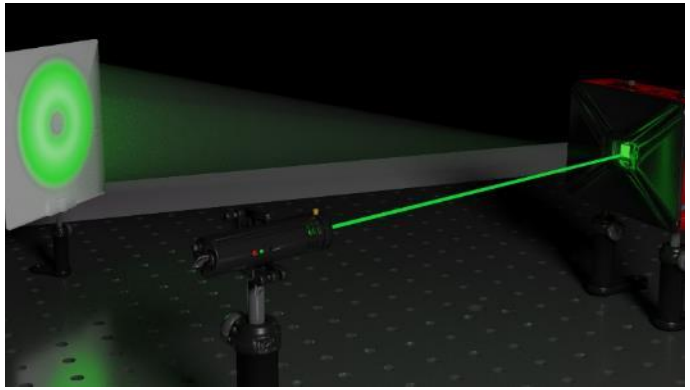

QOCT for retinal imaging

- **Key objectives:**
  - **Demonstrate QOCT** in a real-world application (retinal imaging)
  - **Automated image analysis** showing increased resolution and contrast for retinal specimens

- **Stepping stone sub-objectives**
  - Establish **durable test standards** from rodent eyes with optical properties similar to native tissue
  - Acquire **reference OCT images** for training and testing ML-based image evaluation algorithms
  - Creation of **curated QOCT retinal imaging and databases** from rodent eye test standards
  - Semantic segmentation algorithms based on deep learning for **retinal layer delineation**
    - Compare algorithm performance of QOCT and state-of-the-art OCT
  - Deep learning-based framework for the **localisation and identification** of key retinal enantiomers

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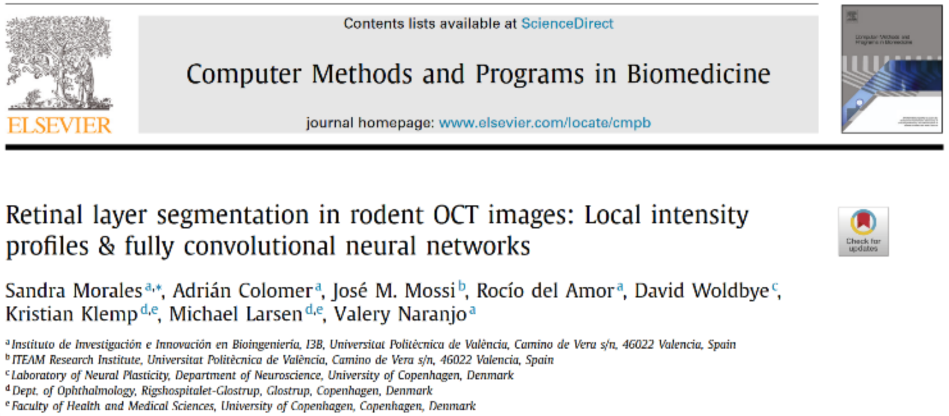
Background: H2020 project GALAHAD


Contents lists available at ScienceDirect

Computer Methods and Programs in Biomedicine

journal homepage: www.elsevier.com/locate/cmpb

Retinal layer segmentation in rodent OCT images: Local intensity profiles & fully convolutional neural networks

Sandra Morales[a,*], Adrián Colomer[a], José M. Mossi[b], Rocío del Amor[a], David Woldbye[c], Kristian Klemp[d,e], Michael Larsen[d,e], Valery Naranjo[a]

[a] Instituto de Investigación e Innovación en Bioingeniería, I3B, Universitat Politècnica de València, Camino de Vera s/n, 46022 Valencia, Spain
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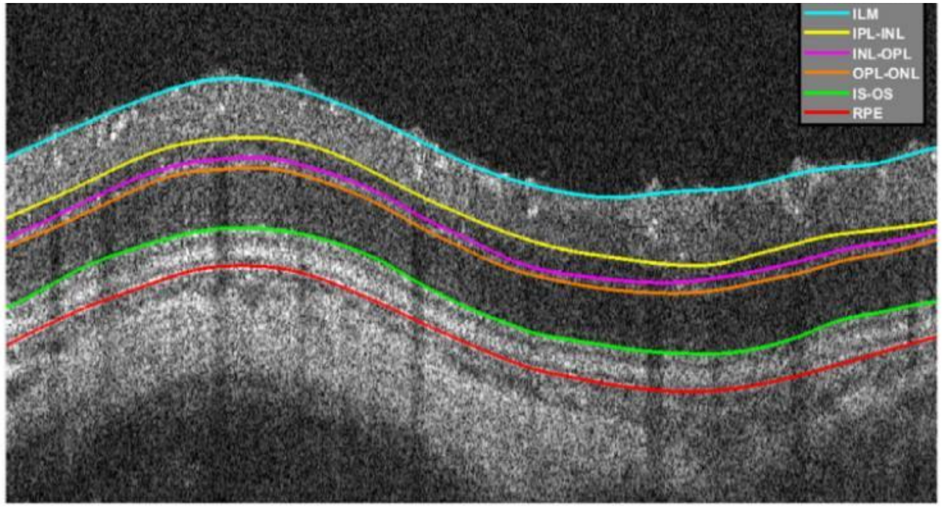
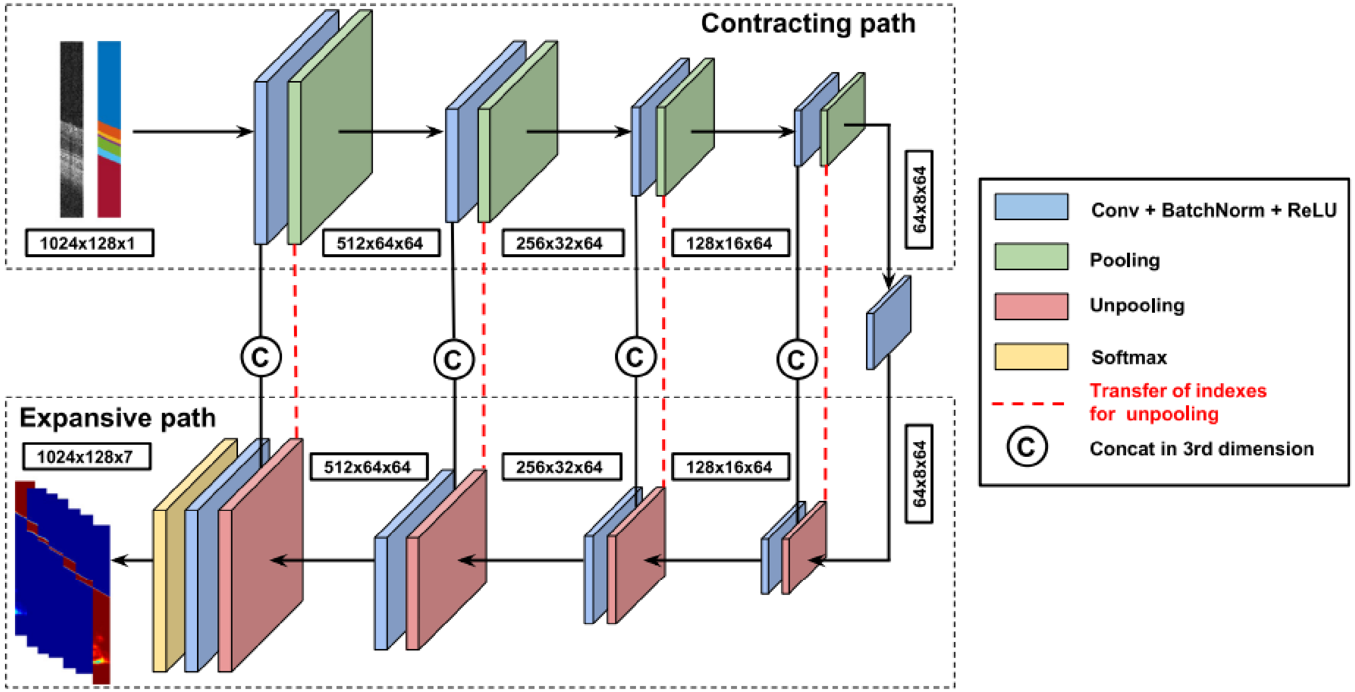
[c] Laboratory of Neural Plasticity, Department of Neuroscience, University of Copenhagen, Denmark
[d] Dept. of Ophthalmology, Rigshospitalet-Glostrup, Glostrup, Copenhagen, Denmark
[e] Faculty of Health and Medical Sciences, University of Copenhagen, Copenhagen, Denmark



In vivo

Encoder-decoder



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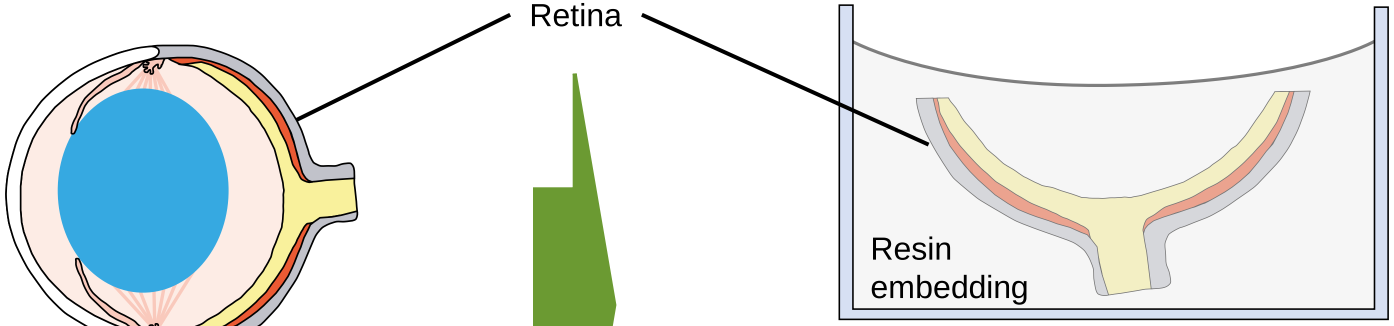
Durable test standards

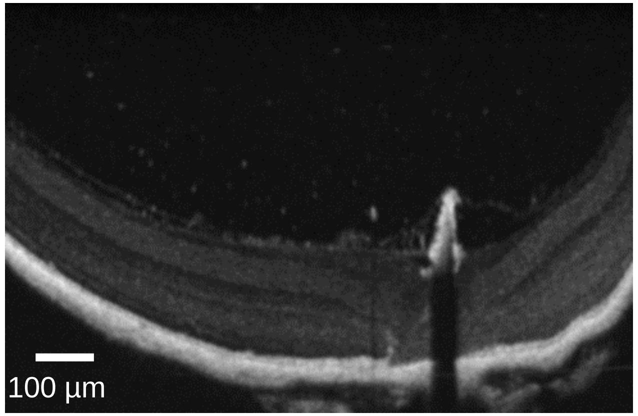
- Establishment of durable retina models for QOCT performance testing

Ex vivo rodent eye

Tissue fixation + resin embedding

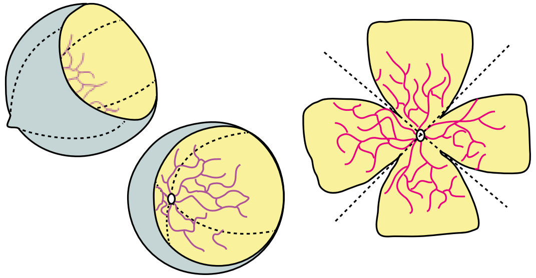
OCT measurements

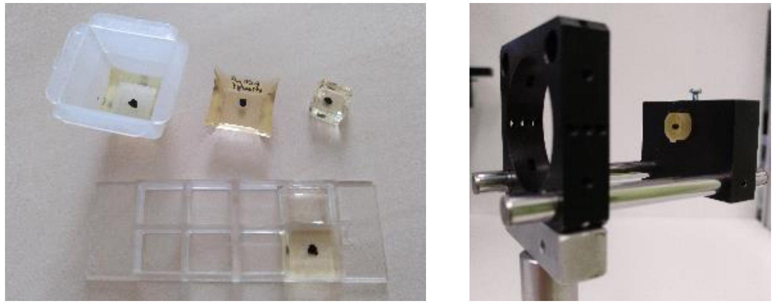




OCT B-scan (embedded mouse retina)

Dissected retina





Different embedding and mounting concepts

Á. Barroso, S. Ketelhut, G. Nettels-Hackert, P. Heidushka, R. del Amor, V. Naranjo, B. Kemper, J. Schnekenburger
Durable 3D murine ex vivo retina glaucoma models for optical coherence tomography
Biomed. Opt. Express **14**, p. 4421-4438 (2023) https://doi.org/10.1364/BOE.494271

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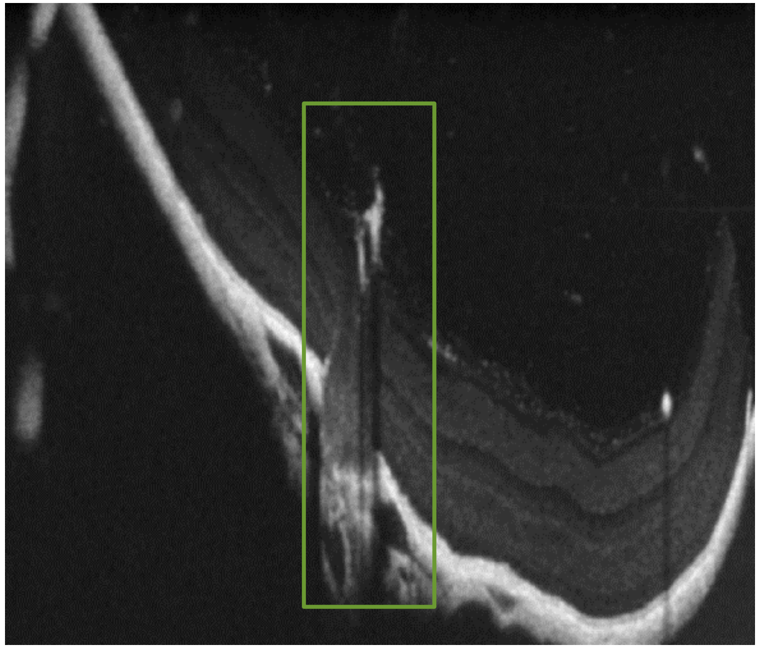
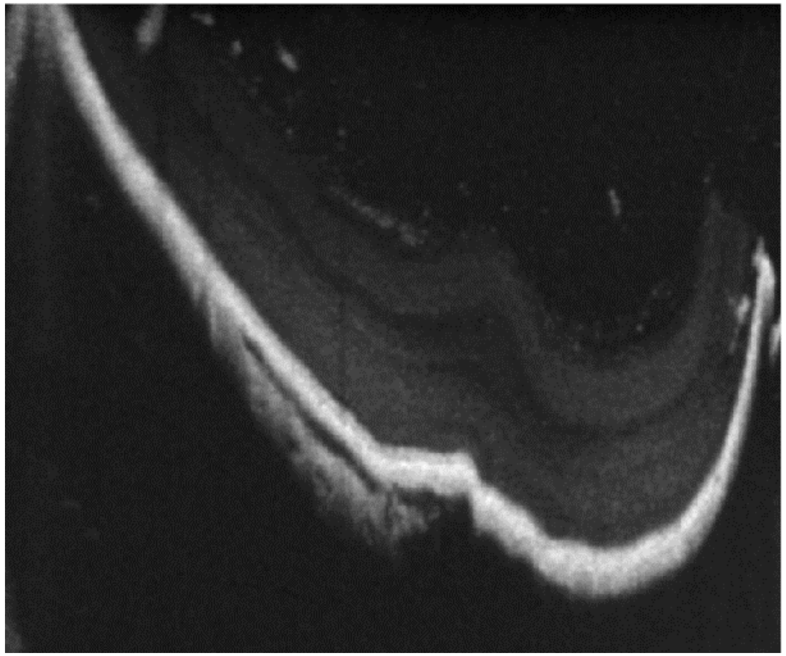
Artefact detection

- Detect the main artefacts in the *ex vivo* samples to eliminate them from the study

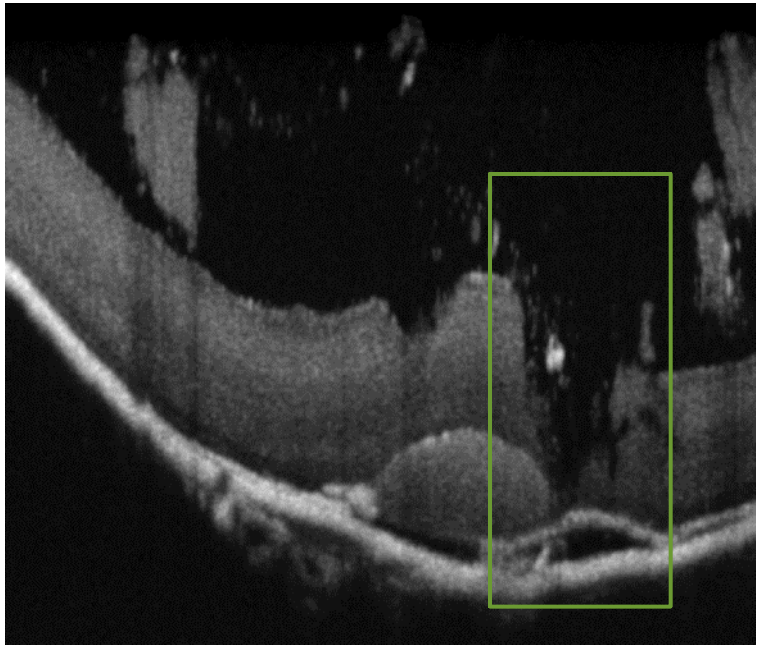
Optical nerve



Out of focus



Retina damage



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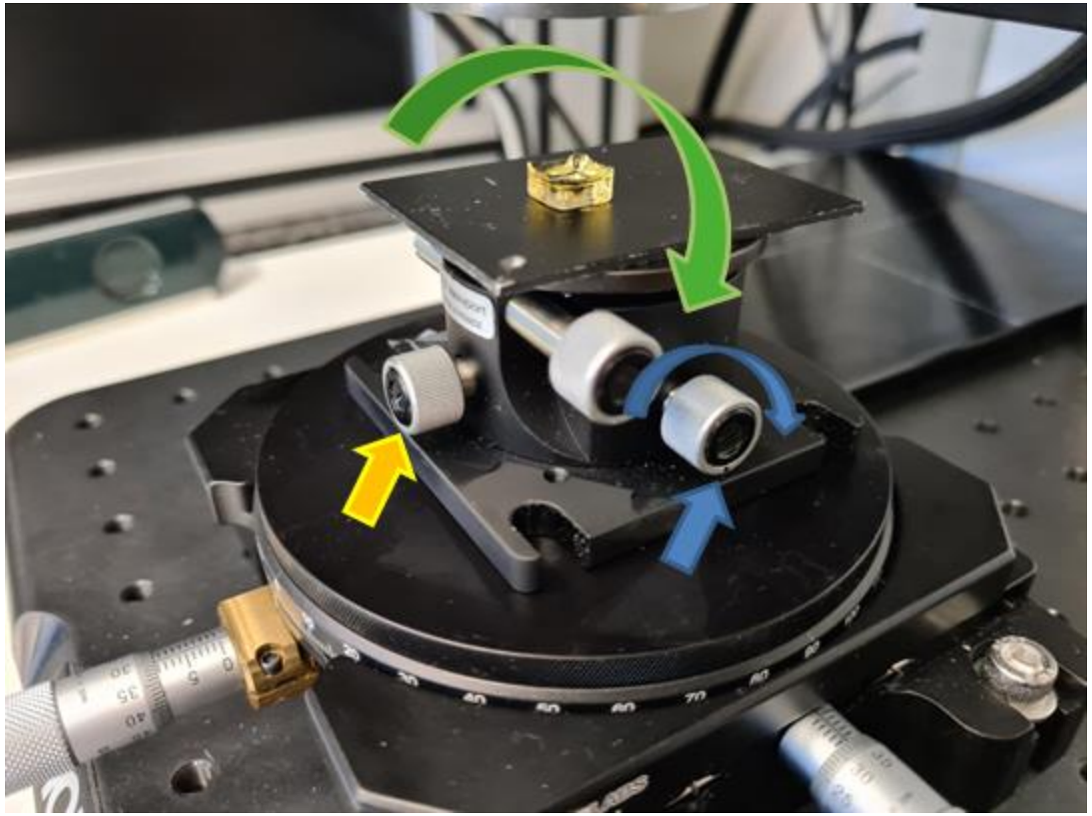
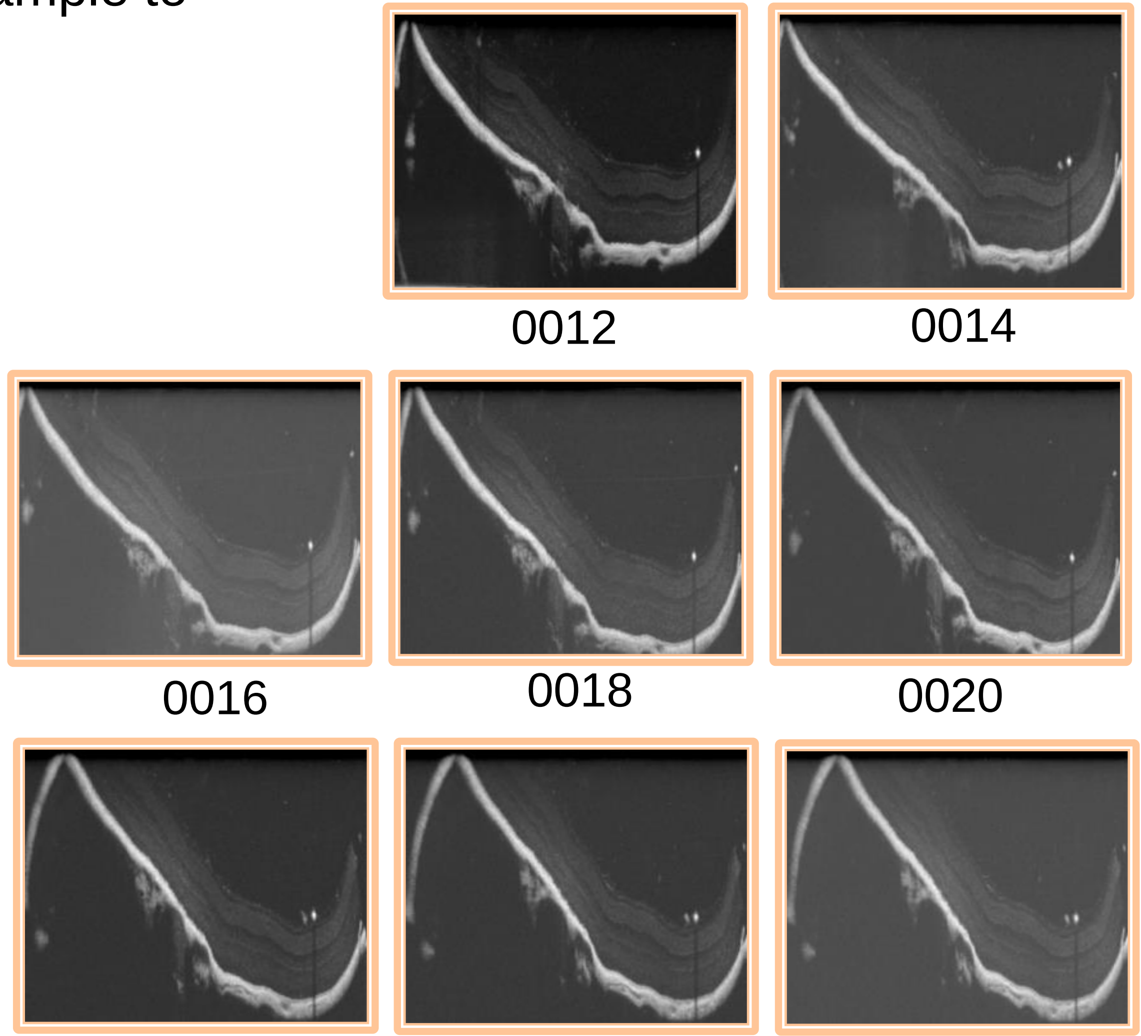
Data augmentation

- Obtain different orientations/rotations of a sample to increase the variability of the dataset





0012 0014
0016 0018 0020
0022 0024 0026

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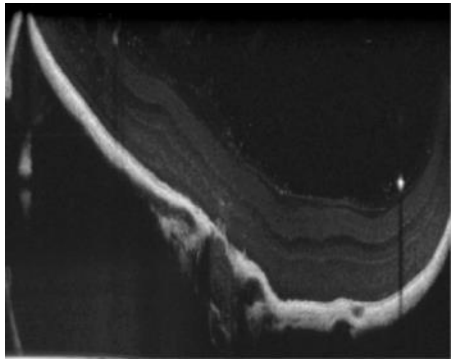
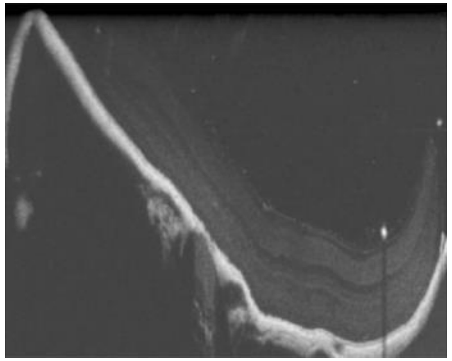
Image registration

- Objective: test the differences between the rotations of a sample using image registration

→ The samples with differences between them can be considered independent and will be included in the study

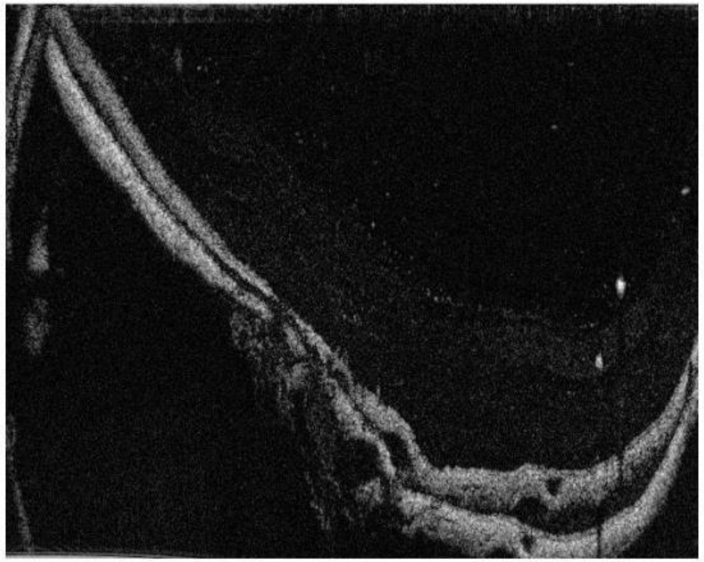


0012

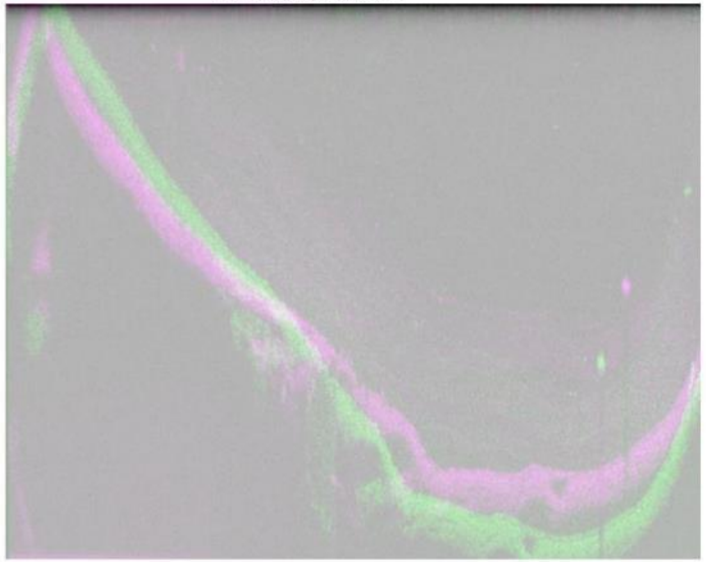


0020

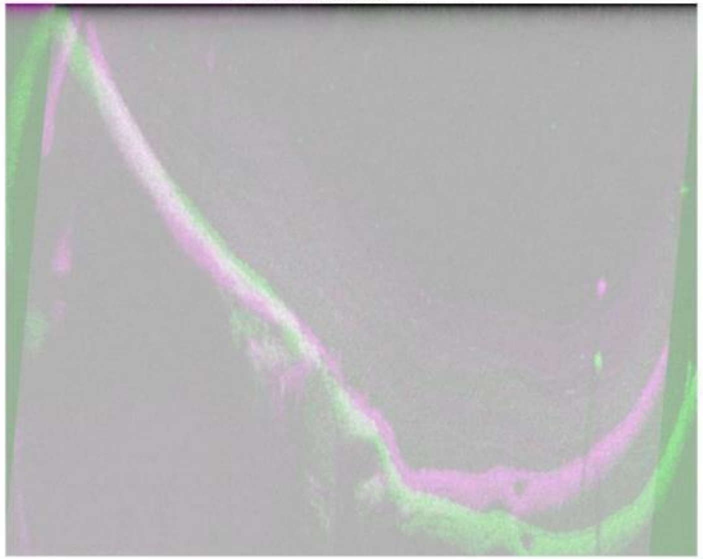
Example of image registration:



Similarity - 0020 vs 0012



Affine - 0020 vs 0012



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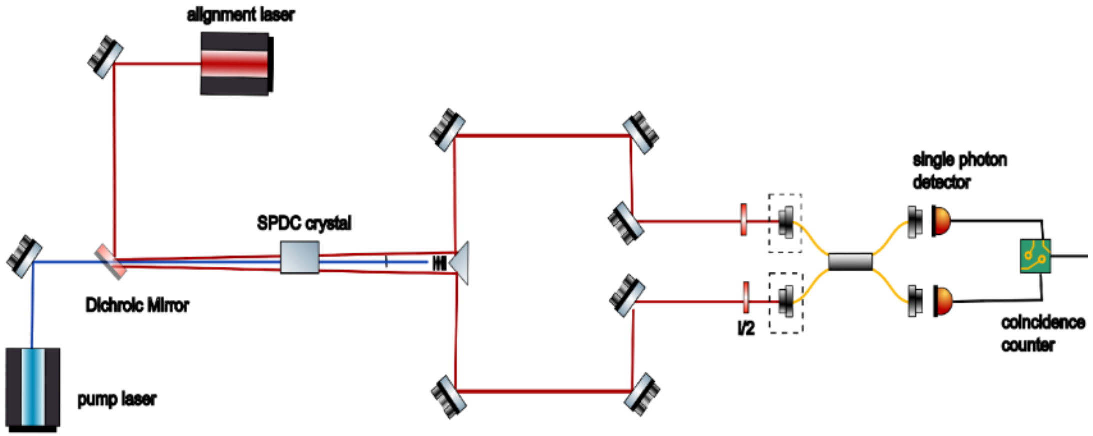
Characterisation and benchmarking

- **Developing a quality metric for imaging QOCT**

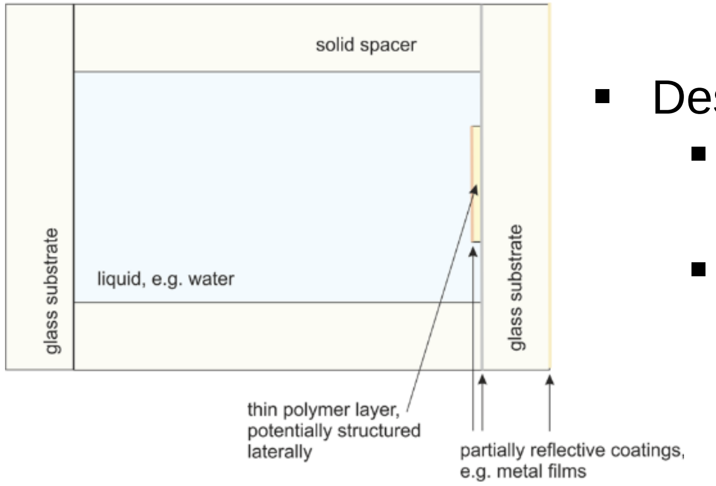
- Identification, modelling and characterisation of noise processes

→ Initial noise characterisation in a Hong-Ou-Mandel set-up

- Establish a metrological framework for entangled sources
- Benchmarking of the QOCT system against classical OCT

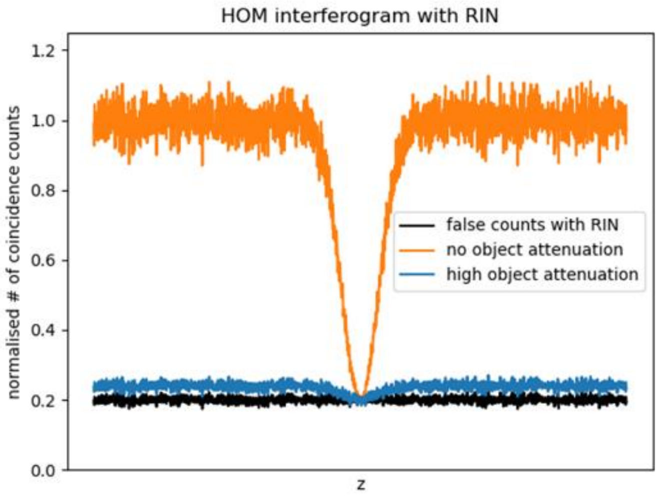


HOM set-up for noise characterisation



Multilayer sample

- Design of QOCT technical standard samples:
  - Multilayer samples with well-defined properties
  - Thickness, reflectivities, absorption, scattering and dispersion



Effect of RIN on HOM dip

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Presentation outline

- Project summary

  Consortium | Project overview | Objectives

- Theory and principles

  OAM control | Noise reduction

  QOCT | Sustainability

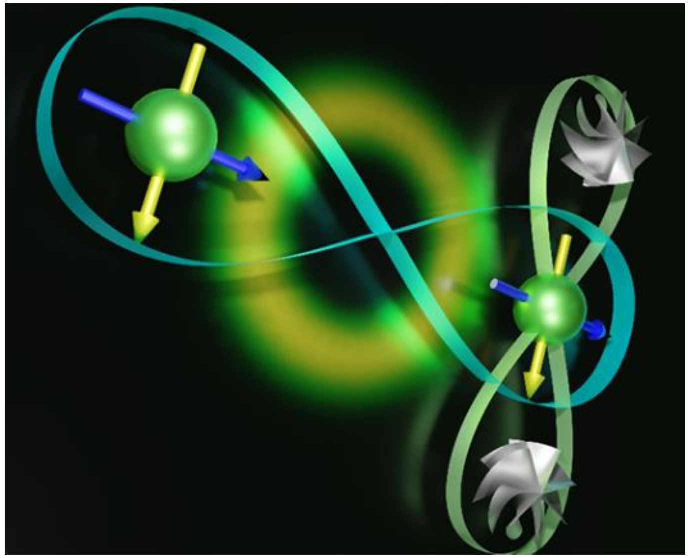
- Hardware

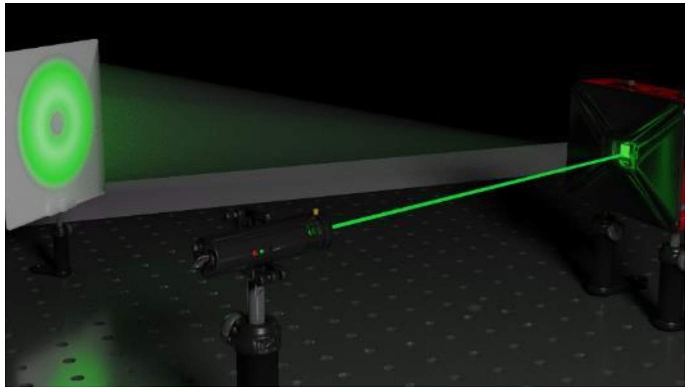
  Source | SPAD imager for QOCT

- Experiment

  Retinal studies | Characterisation and benchmarking

- **Outlook**





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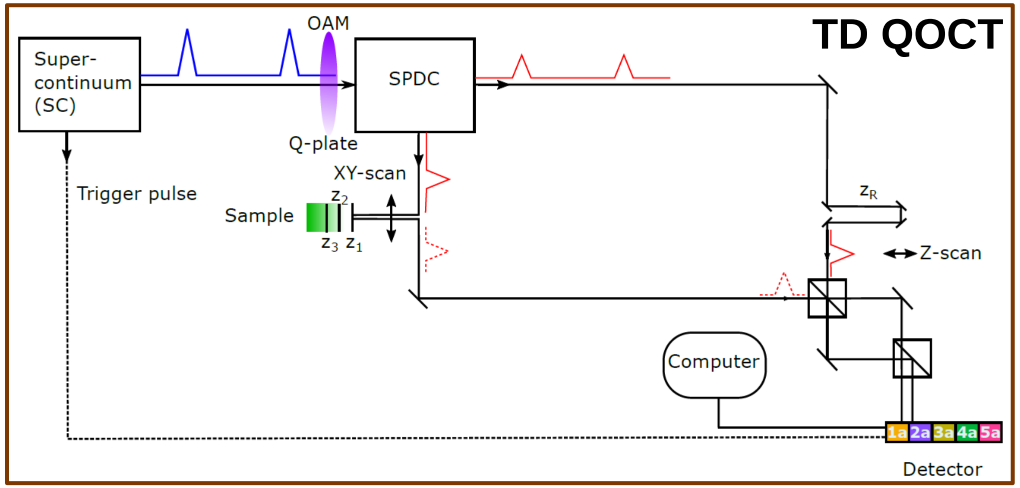
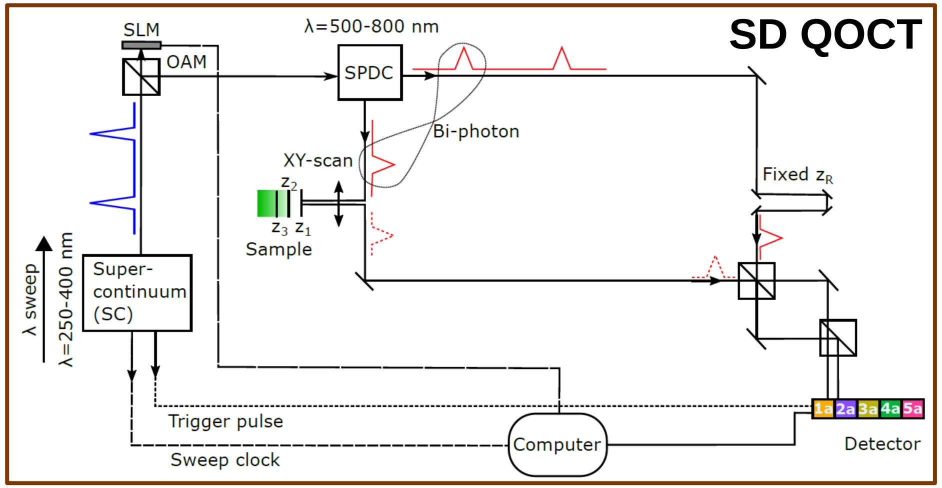
Experimental SEQUOIA goals

- **Objectives:**
  - Initial TD QOCT system for evaluation and delivery of training data for the machine learning
  - Swept source SD QOCT system using AOTF and SLMs

- **Experimental goals**:
  - Operational TD QOCT system with Q-plate and axial resolution (<1 μm)
  - 250-400 nm swept frequency comb synchronised to SLMs
  - Swept source 500-800 nm SD QOCT system with axial resolution <500 nm





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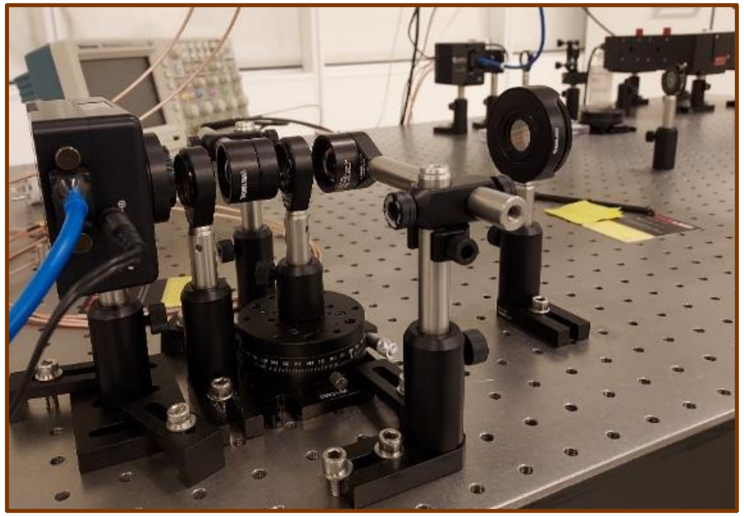
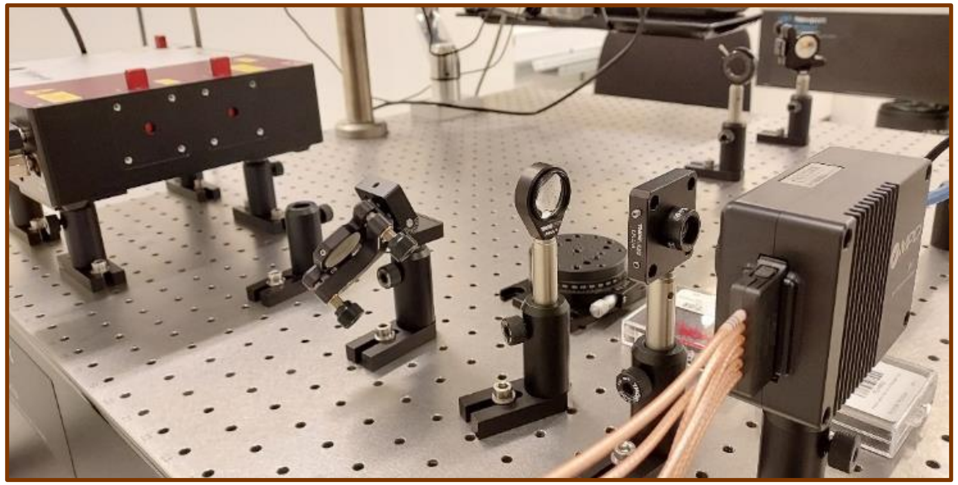
Experimental development of QOCT in SEQUOIA

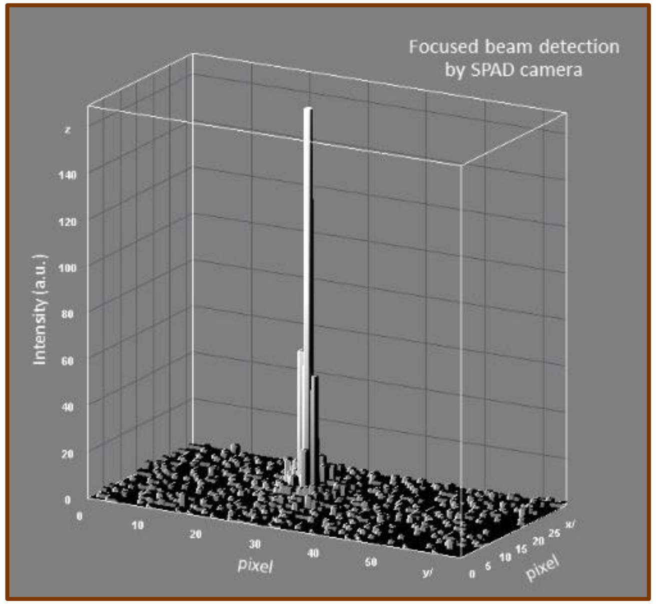
- **Status:**
  - A new Quantum Imaging Lab is established at DTU Electro
  - Focusing beam to a single pixel in an MPD SPAD camera achieved using lens combination
  - Experiment started to generate SPDC photon pairs



SPDC set-up



Set-up for focusing beam to a single pixel



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Thank you for your attention!

General enquiries to Bruce Napier; Vivid Components Germany

bruce@vividcomponents.co.uk

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