ARIES PROOF OF CONCEPT FUND

InnoAdO – Accelerator Diagnostics using Innovative Adaptive Optics

Prof Dr Carsten P Welsch – University of Liverpool

Dr Joseph Wolfenden – D-Beam Ltd

UNIVERSITY OF LIVERPOOL

The Cockcroft Institute of Accelerator Science and Technology

D-Beam

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Overview

ARIES PROOF OF CONCEPT FUND

- Introduction
- Work Packages and Results
- Project Outcomes
- Future Goals
- ARIES PoC Experience

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Introduction: Team

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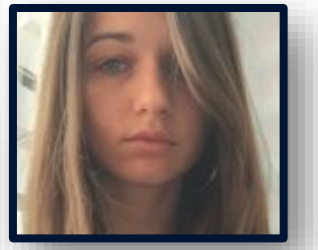
- Partnership between *QUASAR Group* at University of Liverpool (UoL), based at the Cockcroft Institute, and company *D-Beam Ltd, an STFC CERN BIC alumnus.*

Prof Dr Carsten P Welsch

- Head of UoL physics and the QUASAR Group; founder and co-Director at D-Beam Ltd.
- Over 20 years experience in beam diagnostics
- Led the largest beam diagnostics research and training networks in Europe

Dr Joseph Wolfenden

- CEO and co-director at D-Beam Ltd
- Over 5 years experience in diagnostics, specifically in target technology for InnoAdO



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Introduction: Project

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- Main goal of the Innovative Adaptive Optics (*InnoAdO*) project was to **facilitate the commercialization of a novel diagnostic systems for particle accelerators and light sources**.

- Focused on the utilization of **digital micro-mirror devices (DMDs)** in several proof of concept systems.

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Introduction: DMD Technology

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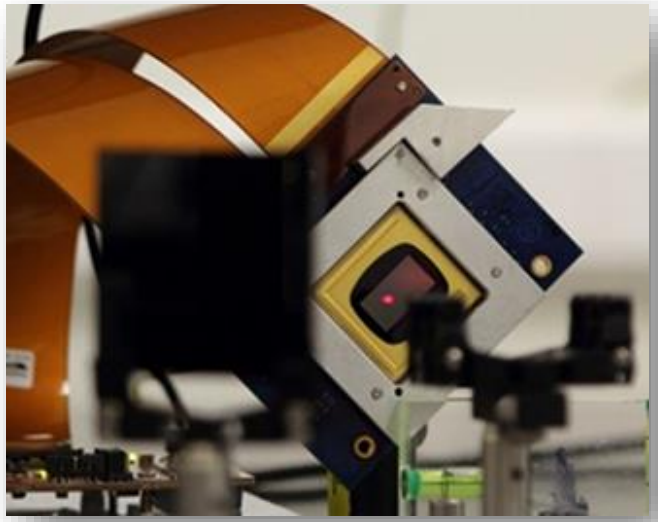
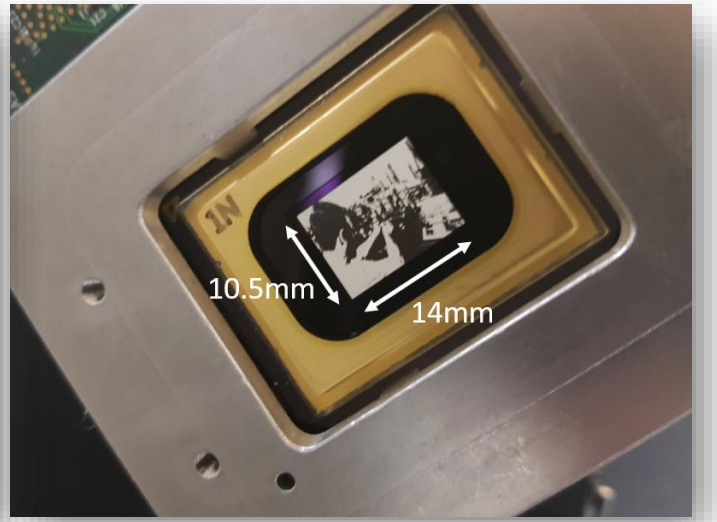
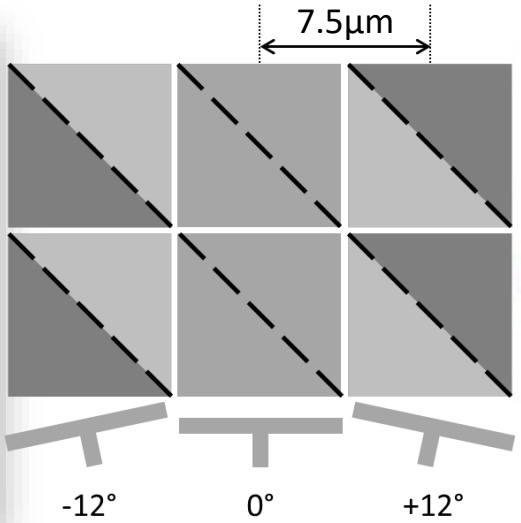
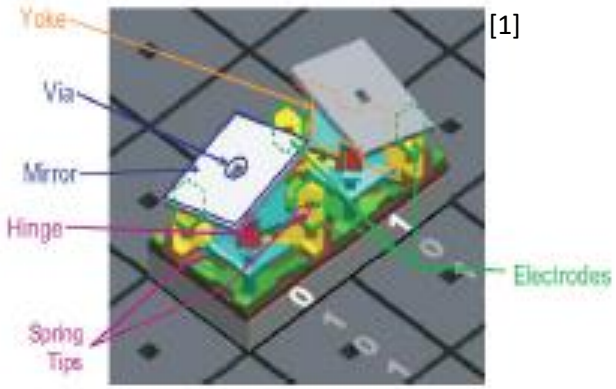
- DMDs are an array of individually controllable, micrometre-scale, mirrors.
- Each mirror can sit in one of two tilted states.
- Binary optical “masks” can be displayed and updated at ~10 kHz.









[1]

[1] C.P. Welsch, E. Bravin, B. Burel, T. Chapman, T. Lefèvre, M.J. Pilon, 'Alternative Techniques for Beam Halo Measurements', Meas. Sci. Technol. 17 (2006) 2035c, CERNAB- 2006-23

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Introduction: Work Packages

ARIES PROOF OF CONCEPT FUND

- **WP1**: PoC results for optical interferometry (ODI) and optical phase space mapping (OPSM)
- **WP2**: Applications of existing DMD-techniques
- **WP3**: DMD simulations
- **WP4**: Business plan
- **WP5**: Dissemination of results

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Work Packages and Results

WP1 – PoC results for both ODI and OPSM

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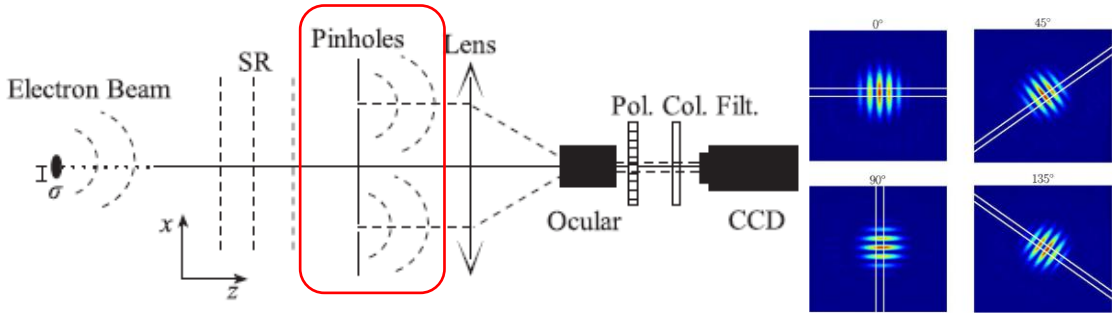
ODI and OPSM are both techniques based on “masking” optical beam radiation.

DMD to replace pinholes



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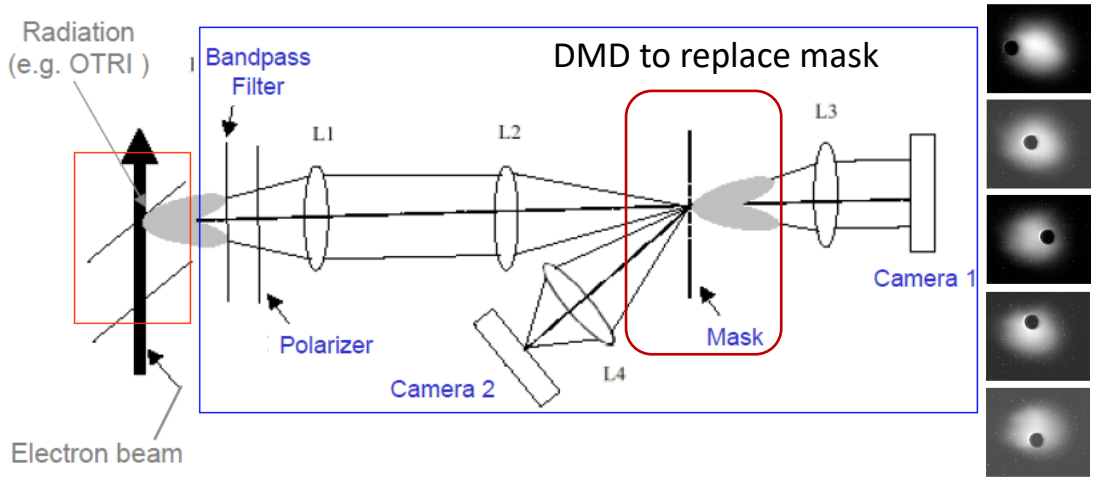

[3]

[2] L. Torino, U. Iriso, PRAB 19 122801 (2016).
[3] R.B. Fiorito et al., AIP Conf. Proc. No. 648, (2002).

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Work Packages and Results

WP1 – PoC results for both ODI and OPSM

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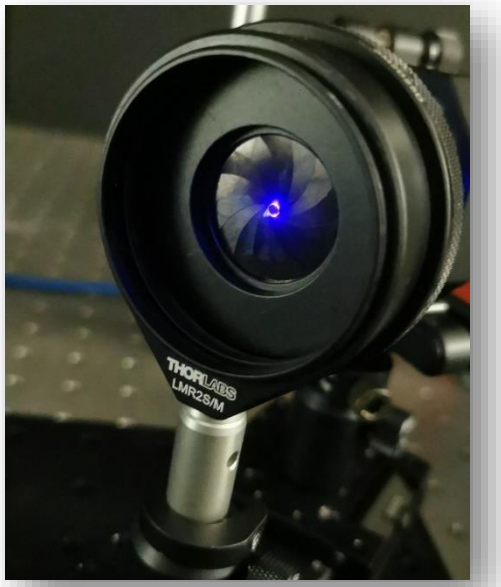
Benchmarking measurements to compare diffraction patterns produced by DMD with theory and mechanical equivalent.



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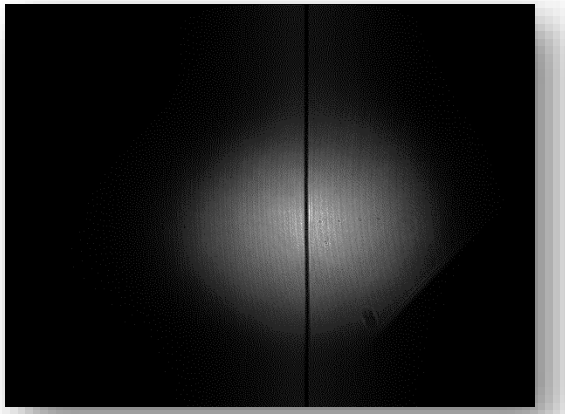
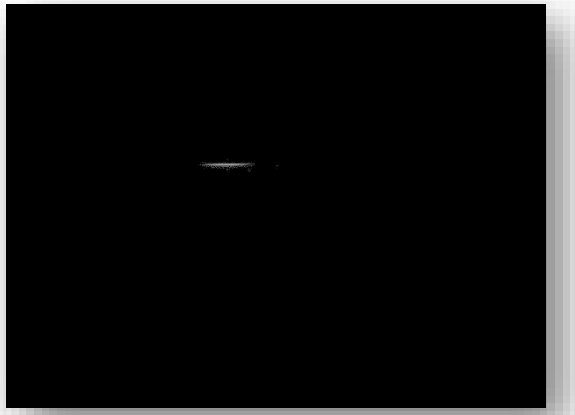
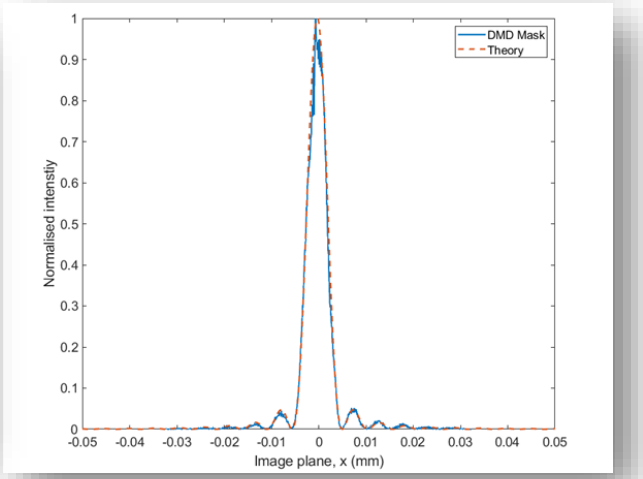
Work Packages and Results

WP1 – PoC results for both ODI and OPSM

- A 100 µm “slit” on a DMD surface, the corresponding image, the diffraction intensity distribution, and the theory/DMD comparison.







- In all instances the DMD was comparable to a mechanical device and theory;
- Results directly fed into WP3;
- Results are currently being collated into a journal article – WP5.

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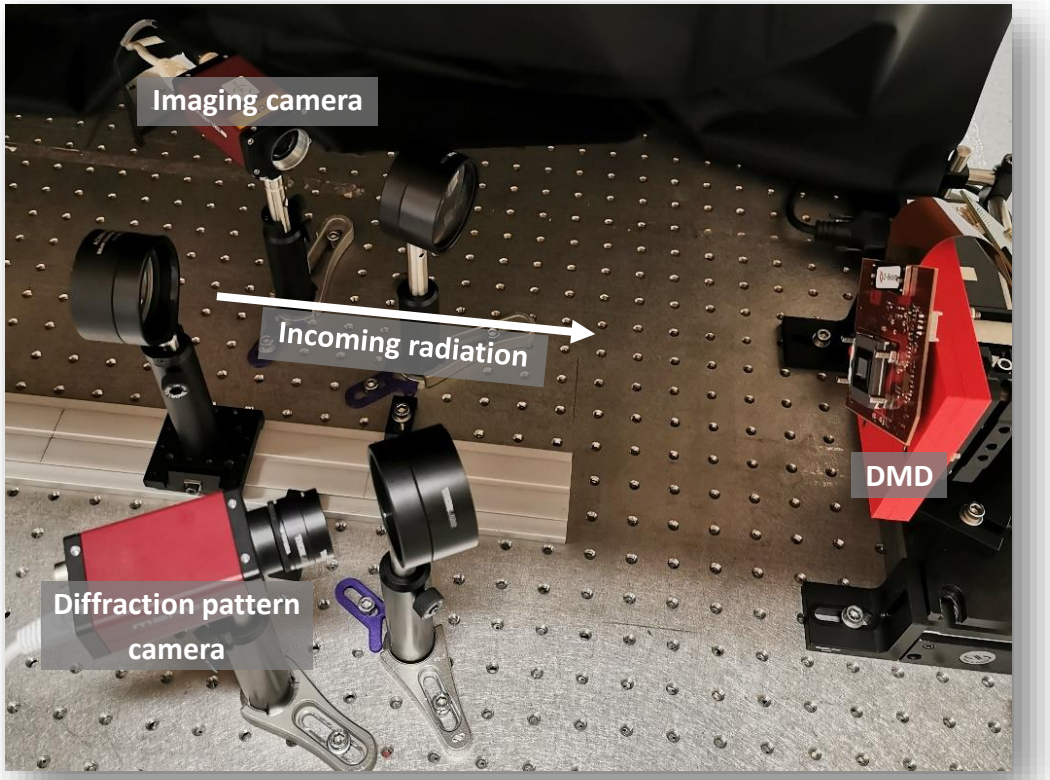
Work Packages and Results

WP1 – PoC results for both ODI and OPSM

- A PoC system was successfully developed and tested in our optics laboratory;
- Optical beam radiation enters from the left and is focused onto the DMD surface;
- A DMD mask then splits the radiation down one of two camera paths: one imaging the mask shape and position; one capturing the diffraction distribution produced;

- Important: This can be used for ODI and OPSM with very small (remotely controlled) alterations.



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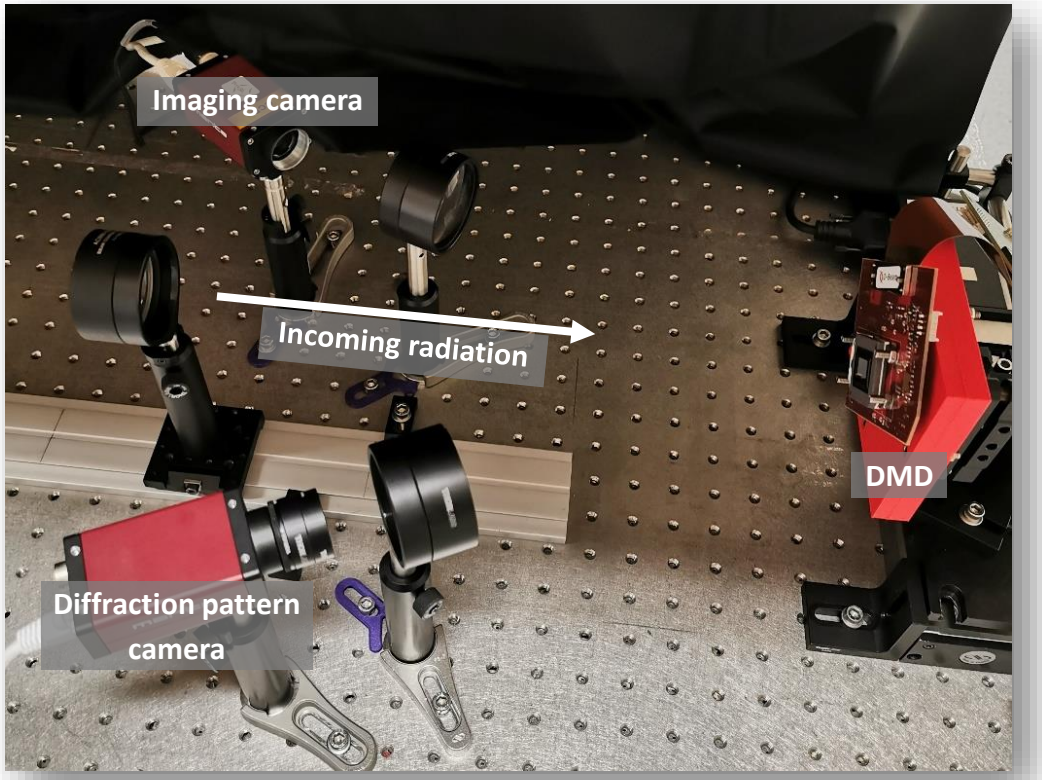
Work Packages and Results

WP1 – PoC results for both ODI and OPSM

- Arranging beam time to produce PoC measurements when first UK lockdown was announced;
- Plans to test at CLEAR (CERN) as soon as possible;
- Longer term plans for an industry-led installation at CLARA (STFC, UK) with a more compact and optimized system.



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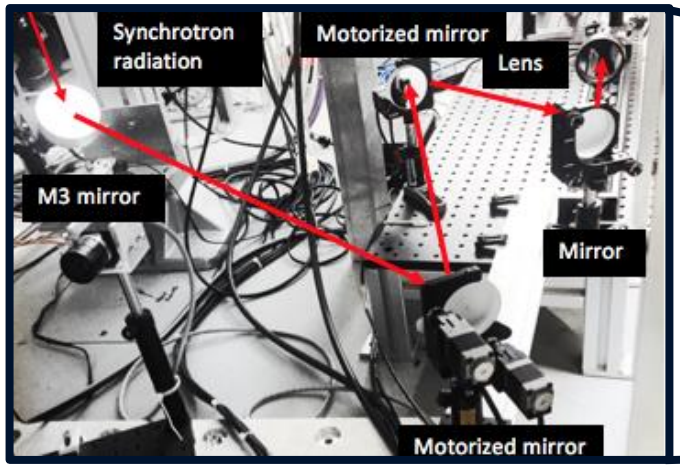
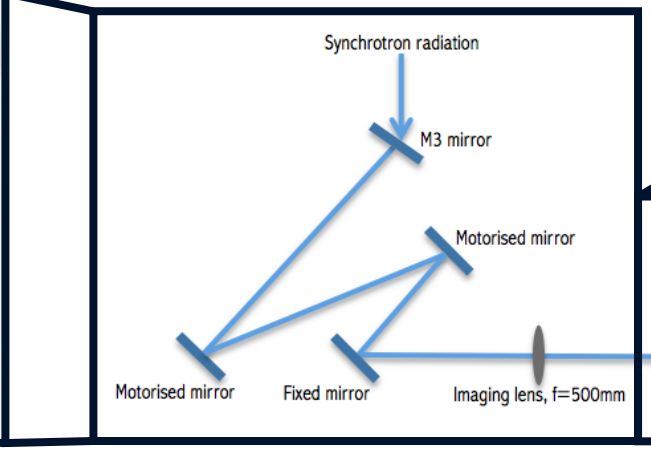
Work Packages and Results

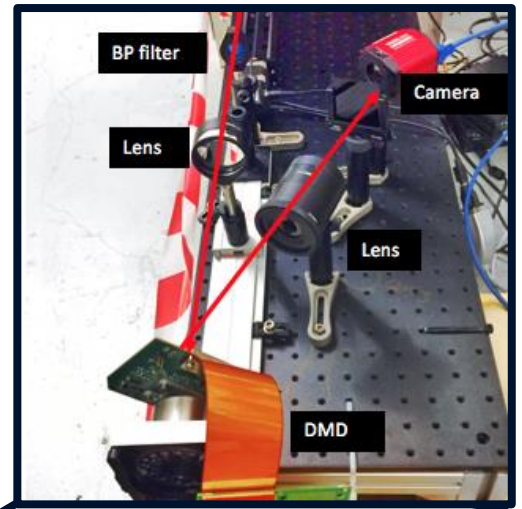
WP2 – Applications of existing DMD-techniques

PROOF OF CONCEPT FUND

- Main existing application is **DMD halo imaging.**
- Designed and installed system at Diamond Light Source (UK).
- System imaged optical synchrotron radiation onto the DMD surface.
- High intensity sections are then selectively removed from the image.
- Allows dynamic ranges of up to ~10^7.







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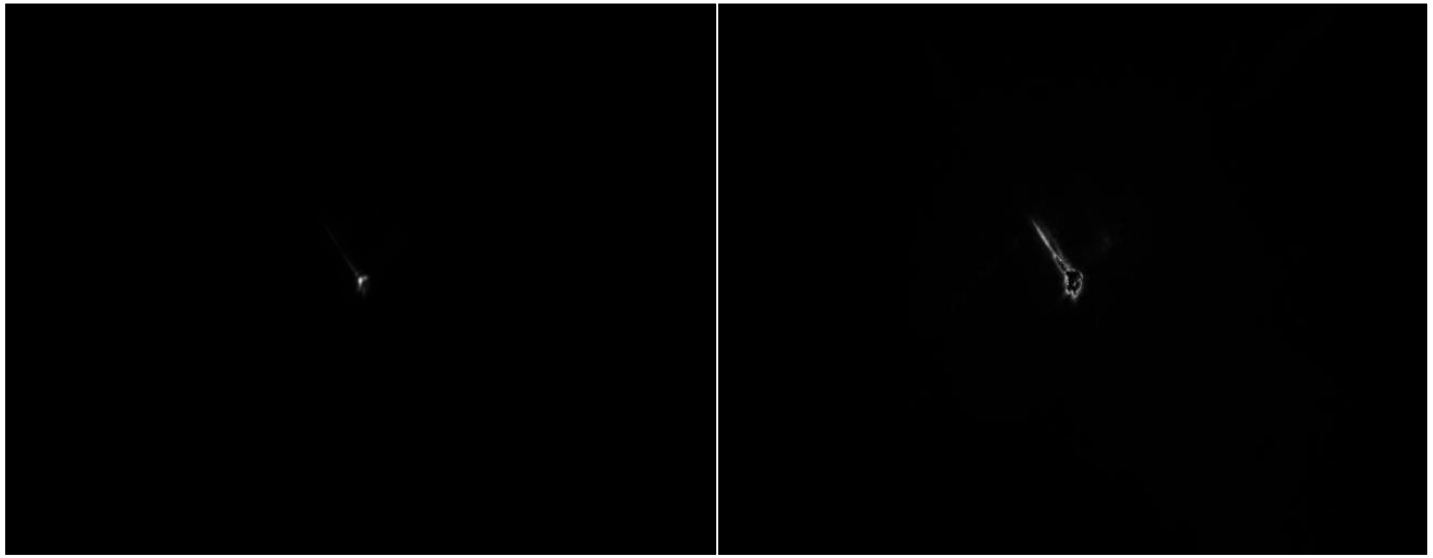
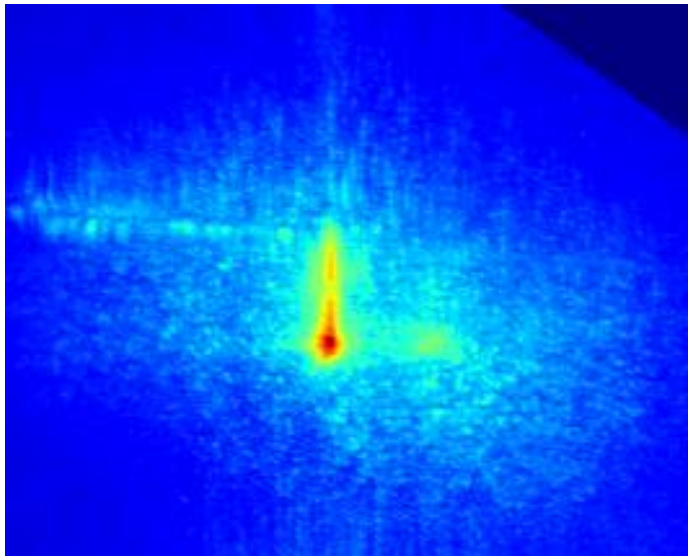
Work Packages and Results

WP2 – Applications of existing DMD-techniques

- Despite UK lockdown, early installation and remote access allowed measurements to be conducted.
- Dynamic range of 10^6 was demonstrated, limited only by camera specifications.
- Diffraction tail from extraction mirror visible, alongside up-stream sources.





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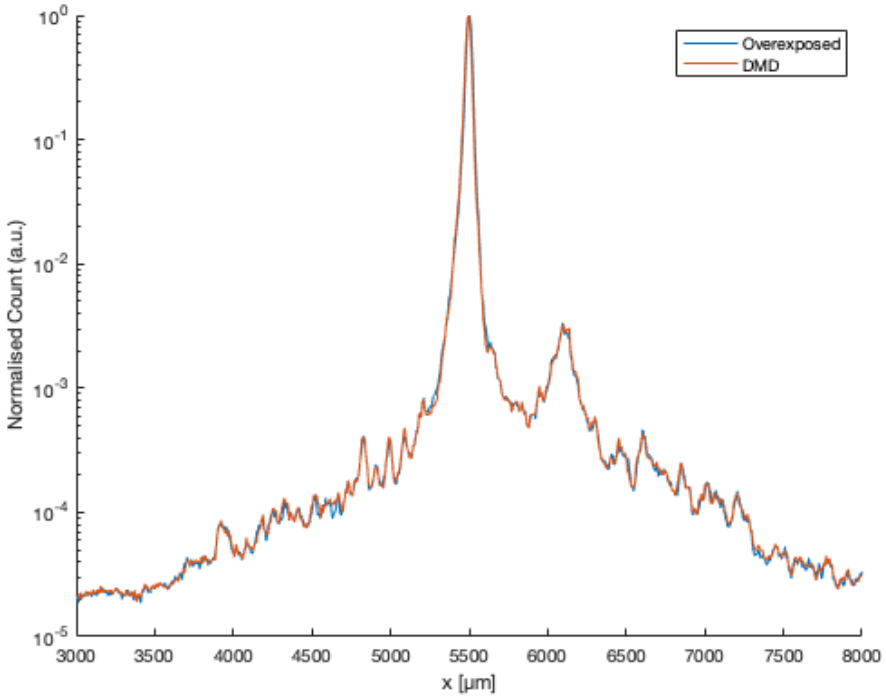
Work Packages and Results

WP2 - Applications of existing DMD-techniques

- Also demonstrated: DMD “mask” does not degrade system resolution.
- Cropped normalized log plot below is a comparison between an overexposure-style technique and a DMD.
- No significant differences were found.
- Data acquisition and control software were all optimized during the measurements program.

- Results are being collated into a journal article – WP5.



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Work Packages and Results

WP2 – Applications of existing DMD-techniques

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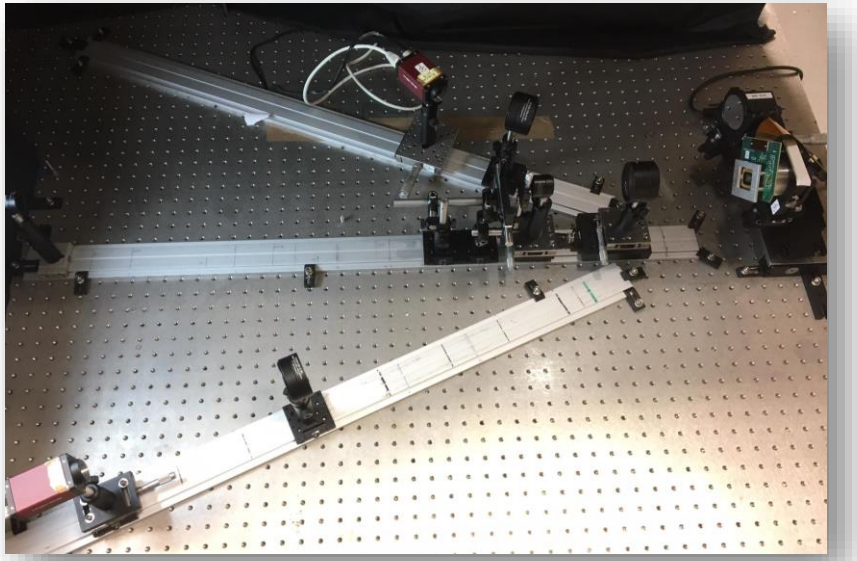
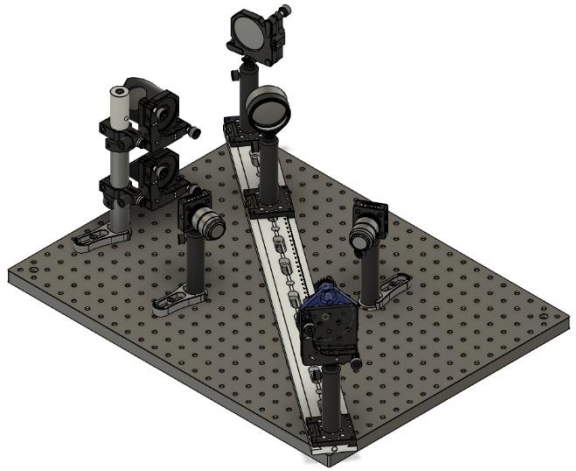
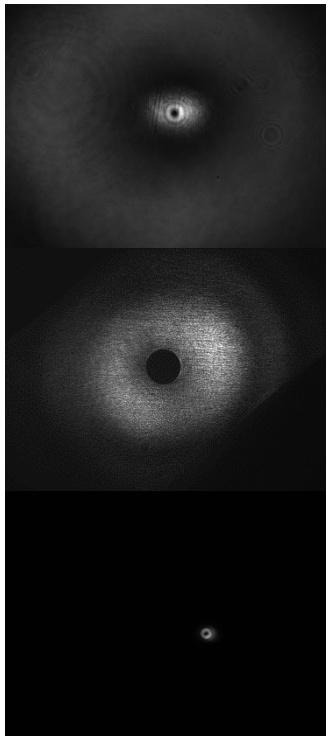
Other DMD applications under development:

- Test system built to demonstrate use of DMD as spatial filter for Lyot stop imaging.
- Follow-on: Double camera halo imaging system being installed at AWAKE (CERN).
- Follow-on: Plans to test Fourier plane filtering using halo setup at AWAKE.







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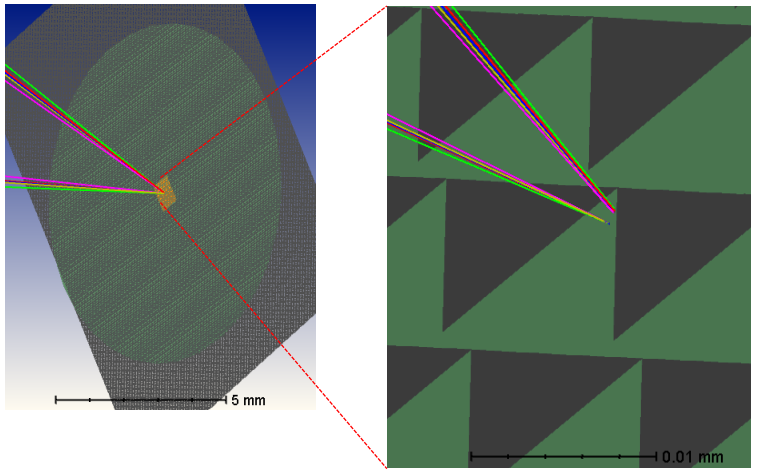
Work Packages and Results

WP3 – DMD simulations

PROOF OF CONCEPT FUND

Two candidate methods had been identified as possible solutions:

- **A Micro-ElectroMechanical System (MEMS) array object** – this worked well with ray modelling, but not diffraction;
- **A diffraction grating model –** provided diffraction effects, but was difficult to customize surface to match real DMD mask.



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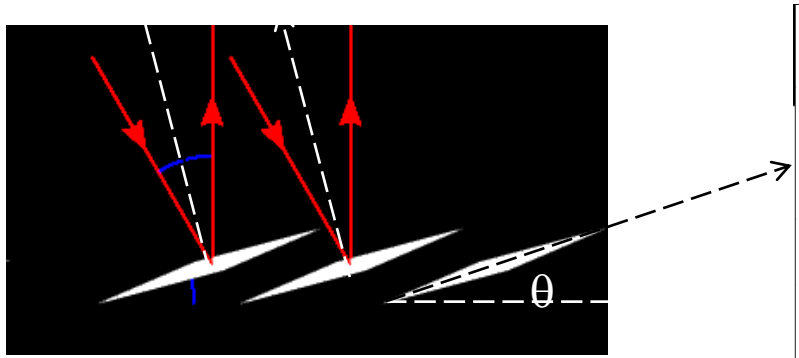

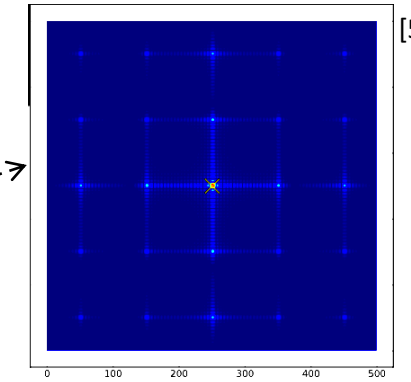

[5]

[4] Zemax OpticStudio
[5] S. Popoff, 'http://wavefrontshaping.net'

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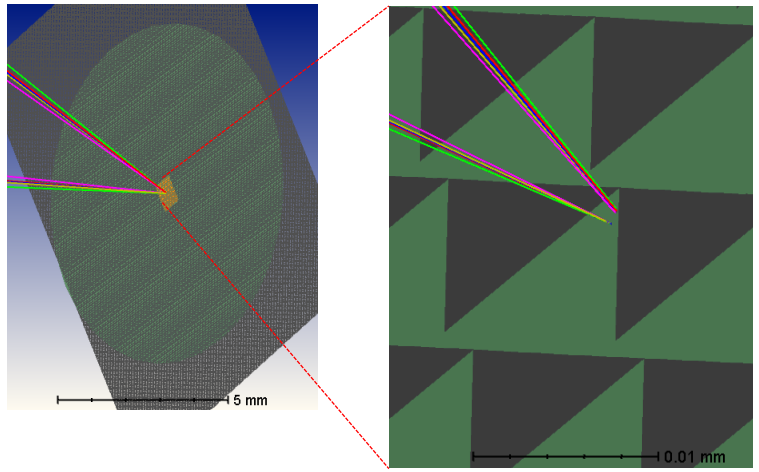
Work Packages and Results

WP3 – DMD simulations

- Existing literature demonstrates that DMD acts as diffraction grating;
- In practise, the zero-th order is only ever used to avoid aberrations;
- This, with WP1 results, demonstrates that it is not necessary to model the full DMD. Rather modelling the “aperture” a DMD mask produces is sufficient.
- Simulation capabilities will be expanded in future to cover general mask shapes.



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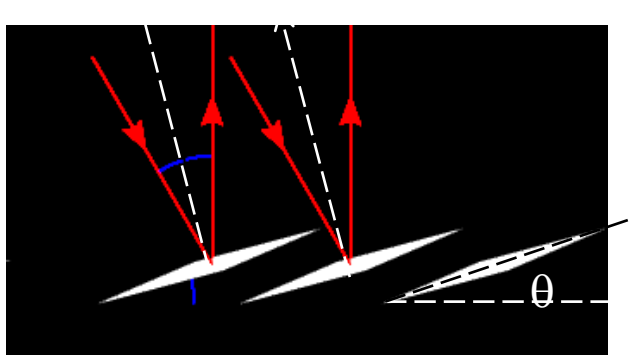

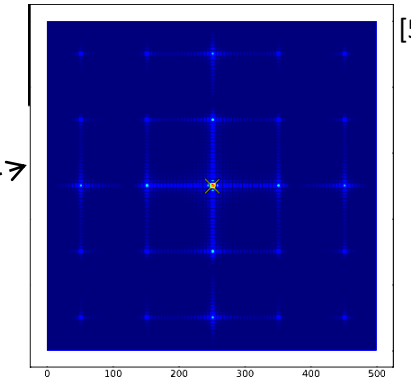

[5]

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[5] S. Popoff, ‘http://wavefrontshaping.net’

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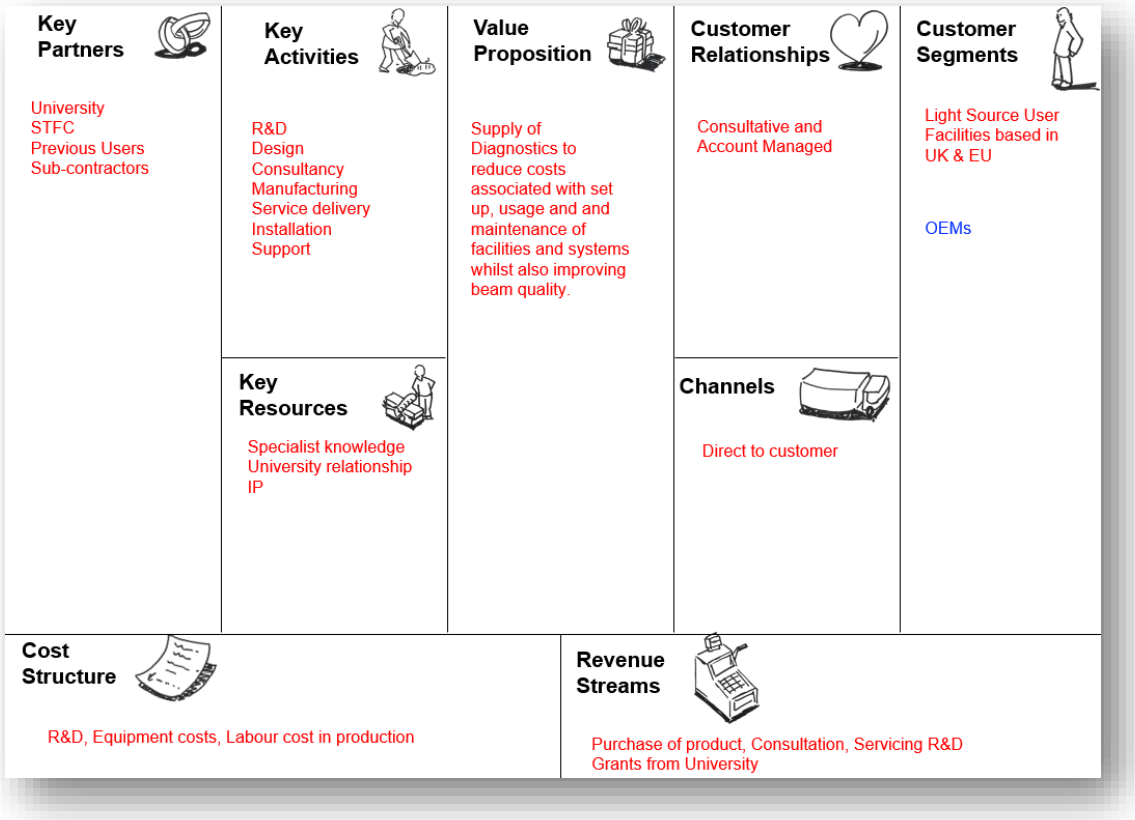
Work Packages and Results

WP4 – Business plan

- Business plan was developed throughout the project;
- Initial market of light sources was expanded to include user facilities in general – doubled target market size.
- Several potential users have been approached to carry out further measurements and prototyping.



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Work Packages and Results

WP4 – Business plan

ARIES PROOF OF CONCEPT FUND

- Discussions with UoL Business Development Manager throughout project to identify IP generated and how to be protect and utilize IP;
- D-Beam heavily involved since system design has started; provided guidance on designing market-ready and user-friendly systems;
- Several routes to market have been successfully identified, including direct offering, collaboration with OEMs, provision of system as part of consultation. This will all be pursued to reach broadest possible market.

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Work Packages and Results

WP5 – Dissemination

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- Results will be presented to international user community in a number of ways: IPAC21, established newsletters (MIRROR, OMA Express, etc). Two journal articles are also being finalized:
- **Benchmarking measurements**
  - *Targeting Optical Express to maximize impact across sectors and provide a reference for all future R&D efforts.*
- **Results from DLS measurements**
  - *Targeting Phys Rev AB to advertize results to accelerator and light source community.*

There is scope for several additional publications.

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Project Outcomes

ARIES PROOF OF CONCEPT FUND

- Fundamental benchmarking measurements completed;
- Successfully designed and built PoC systems for both, ODI and OPSM;
- Identified and established collaborations with facilities for PoC measurements;
- Identified target market of user facilities and several routes to market;
- Two articles will be submitted to high impact journals, several others to follow.
- Despite setbacks due to COVID, project has produced excellent results and will enable an important addition to company's product portfolio.
- ARIES PoC has allowed company to grow: D-Beam successful in attracting funding from a variety of other sources, e.g. STFC IPS and IAA.

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Future Goals

ARIES PROOF OF CONCEPT FUND

- Measurements with beam to complement measurements in WP1;
- Use opportunities provided by R&D in WP2;
- Approach identified users with prototype system from *InnoAdo*.
- Develop identified routes to market for off-the-shelf product, benefit from early adapter feedback, update business plan.
- Publish results whilst protecting and securing IP where useful.

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ARIES PoC Experience

ARIES PROOF OF CONCEPT FUND

- How has the PoC has helped the project?
  - *The PoC funding provided time and resources to a commercialization project that has very good potential and would not have been possible without the ARIES funding.*
  - *PoC allowed real progress to be made in a short amount of time and under very challenging circumstances.*

- What was the spin-off of the research?
  - *InnoAdo provided very good results that show the capability of DMD-based imaging systems.*
  - *Specifically, several advanced diagnostic instruments have been designed on this basis and shall now be tested with beam at various facilities.*
  - *Prototype systems shall be commercialized for identified users and markets with D-Beam as business partner.*

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ARIES PoC Experience

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- What could be the commercialization development in the future?
  - *Bringing a prototype development to an international market is something that usually falls outside of the scope of a university-based research group.*
  - *InnoAdo has identified diagnostics applications that can benefit accelerators and light sources around the world; the established partnership with D-Beam will help craft a user-friendly turn key system.*
  - *The additional support provided by UoL's Business Development Manager will help grow market position.*

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ARIES PoC Experience

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- **What you would suggest to change/modify/improve in the funding scheme?**
  - *This has been an excellent scheme which has enabled studies that would otherwise not have been possible. Requests for updates and reporting were reasonable and central support and management was excellent throughout project.*
  - *€50k is very limited to make significant progress and securing the (more-than) matching funding was a challenge – this might make other projects unviable. It might help increase level of funding to €100k, similar to e.g. ATTRACT.*
  - *It would be great if successful projects like InnoAdo could be given follow-on support, either financially to bridge TRL "valley of death" towards on off-the-shelf product or by promoting results within international partners to help market access.*

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Thank you for your attention!

Questions?

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