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DI PADOVA

Sviluppo di sistemi di ottica adattiva per satelliti

Lorenzo Borsoi - 39th Cycle

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Admission to the third year - December 10th, 2025



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QD-E-QKD project



«Quantum Dots for Entanglement-based Quantum Key Distribution» funded by the European «QuantERA» programme.

To develop a novel technology based on semiconductor quantum dots and test it in realistic urban communication scenario implementing point-to-point quantum key distribution using two quantum-channel approaches, a single-mode fiber and in free space.



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FSO Communication and Research Objective



FSO Communication:

- Enables very high data rates, low latency, and immunity to electromagnetic interference.
- Limited by atmospheric turbulence causing random refractive index variations.

Main turbulence effects:

- Beam wander: random displacement of the beam center due to large eddies.
- Beam spreading: beam broadening from large and small eddies.
- Scintillation: rapid intensity fluctuations from small-scale turbulence.
- Wavefront distortions: overall deformation of the optical wavefront caused by turbulence.

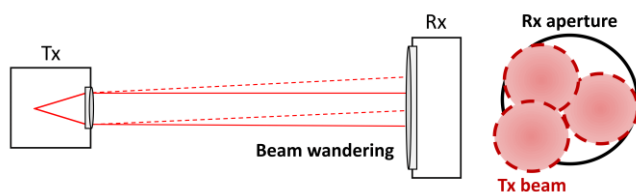
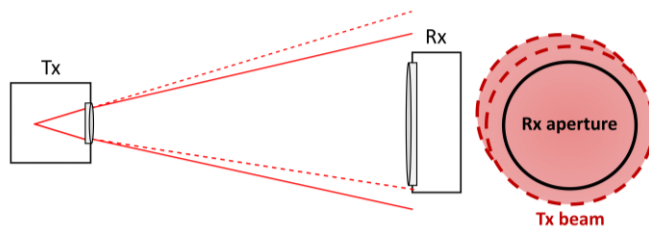
Adaptive Optics (AO) solution:

- Dynamically corrects wavefront phase.
- Compensates beam wander and restores spatial coherence.
- Improves fiber coupling efficiency.

Our Research Objective:

This study demonstrates that our novel **refractive adaptive optics** architecture can effectively optimize fiber injection in a controlled laboratory environment and in a real-urban scenario, correctly compensating for wavefront aberrations and beam wandering, thereby maximizing the collected fiber power.

Dealing with Beam Wandering



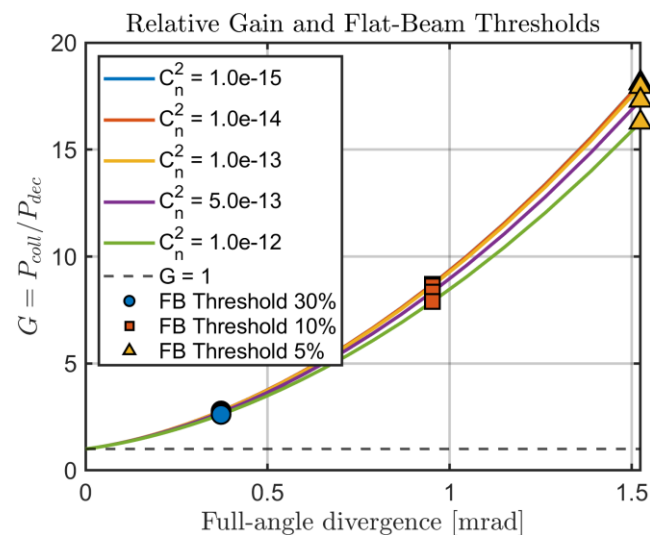
A) Decollimated beam:

- Pros: link stability, less scintillation, simpler system
- Cons: photon loss

B) Collimated beam:

- Pros: utilizes all available photons
- Cons: requires a more complex AO system

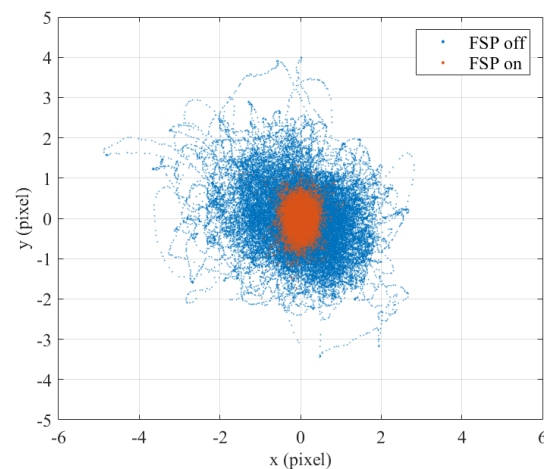
Relative Power Gain:
Collimated vs Decollimated
configurations



Parameters:

Link distance: 270 meters
Tx/Rx Aperture: 3 inch
Comm. WL: 785nm

Fast-Steering Prism (FSP) - prototype



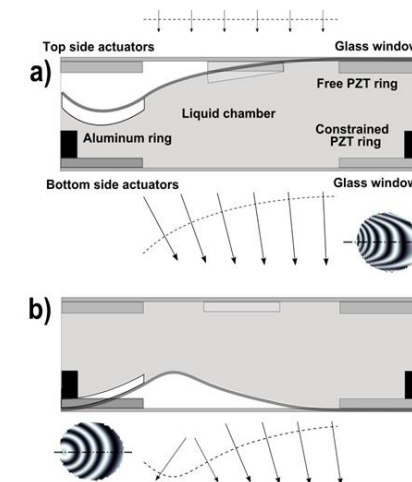
Clear aperture: 23 mm (customizable)

Number of actuators: 3

Response time: $< 400 \mu\text{s}$

Tip-tilt range: $\pm 2.2 \text{ mrad}$

Multi-Actuator Adaptive Lens (MAL)



Clear aperture: 10 mm

Number of actuators: 18

Response time: $< 2.5 \text{ ms}$

Phase modulation: up to 4th order of Zernike polynomials



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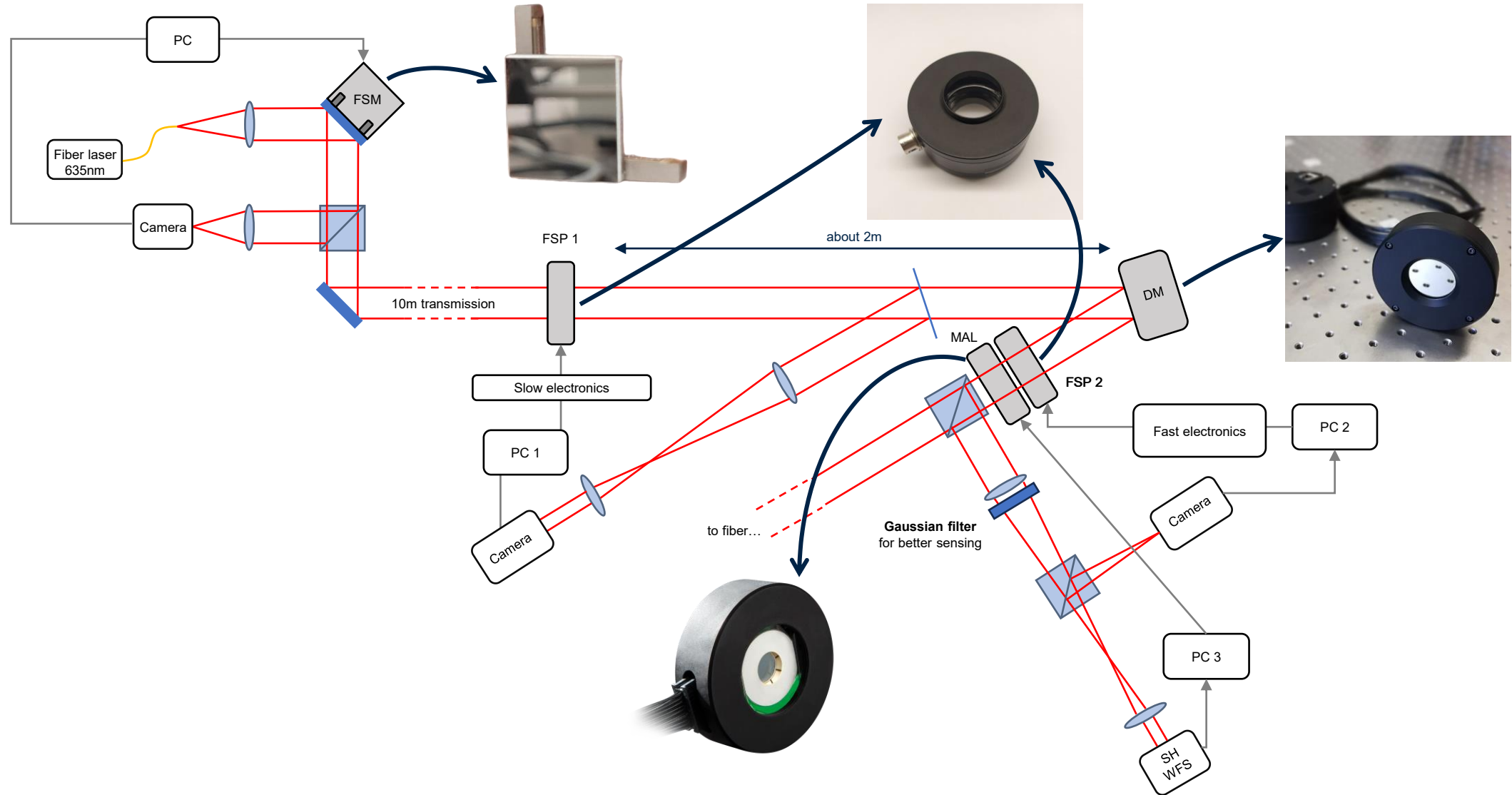
QD-E-QKD: experimental layout and laboratory tests



Laboratory tests at CNR-IFN of Padova!

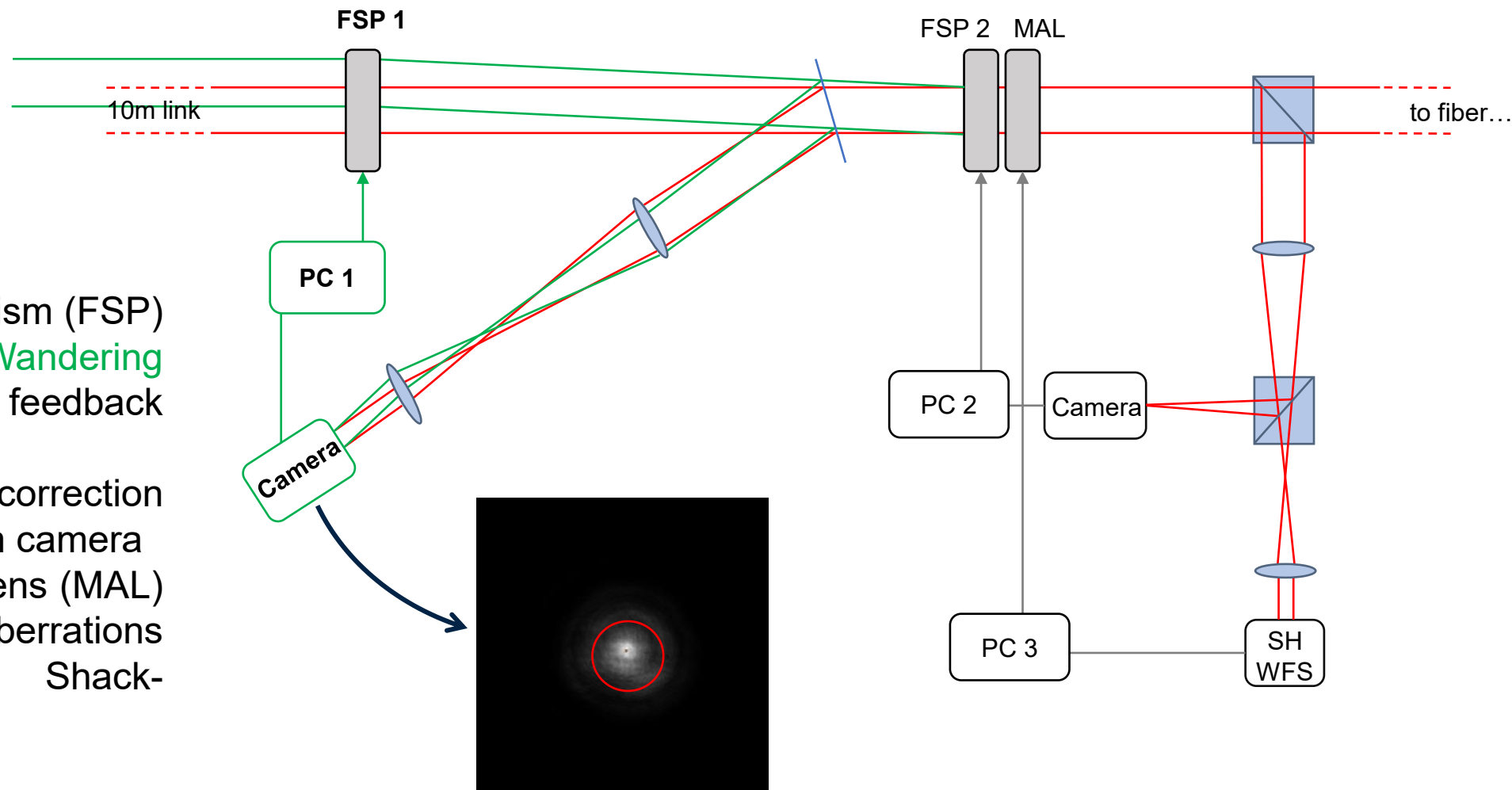


QD-E-QKD: experimental layout



Receiver

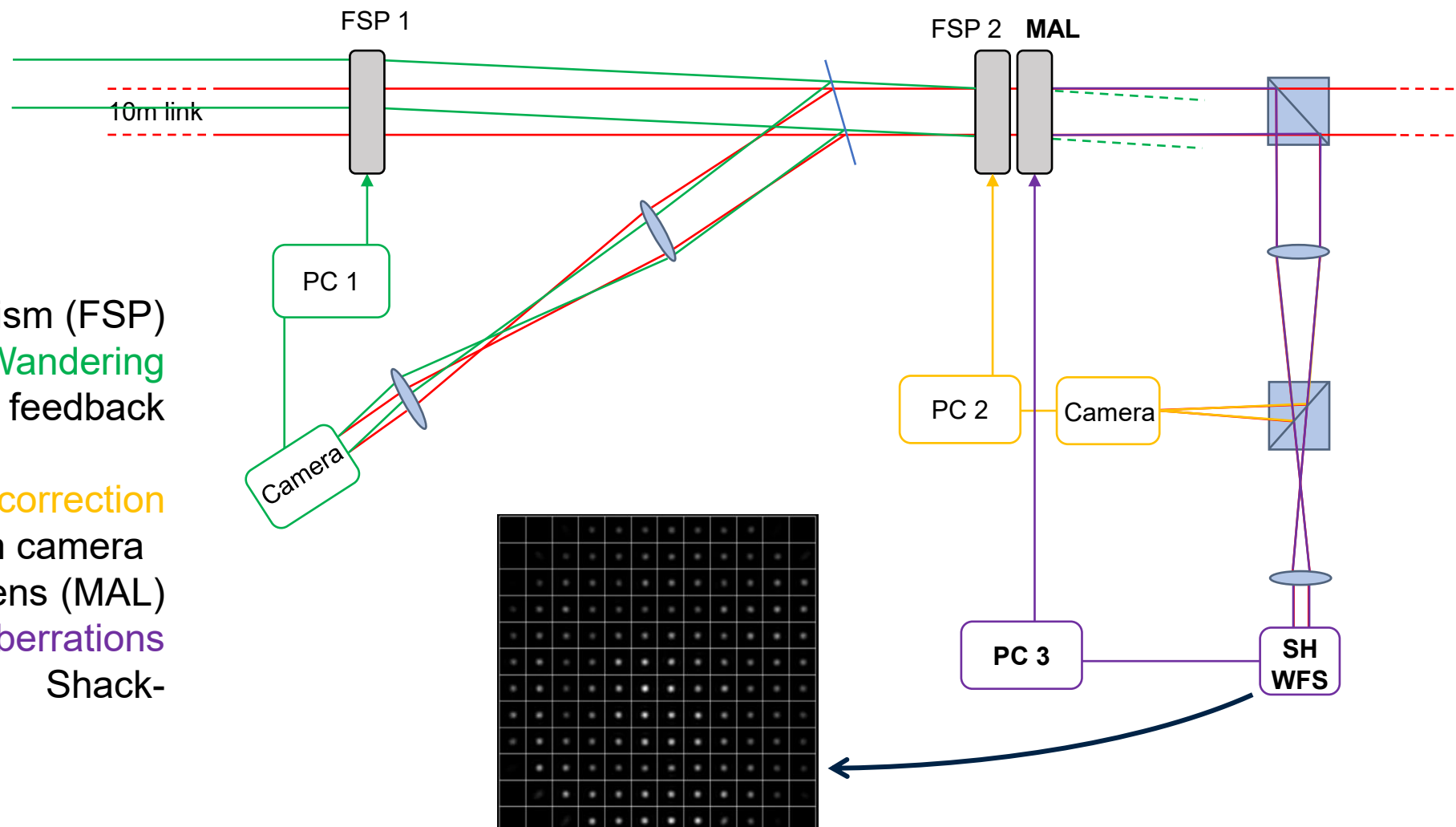
- 1 Fast Steering Prism (FSP) for **Beam Wandering correction** with feedback from camera
- 1 FSP for tip tilt correction with feedback from camera
- 1 Multi Actuator Lens (MAL) for high order aberrations correction with Shack-Hartmann WFS



Conceptual layout: Rx (3)

Receiver

- 1 Fast Steering Prism (FSP) for **Beam Wandering correction** with feedback from camera
- 1 FSP for **tip tilt correction** with feedback from camera
- 1 Multi Actuator Lens (MAL) for **high order aberrations correction** with Shack-Hartmann WFS

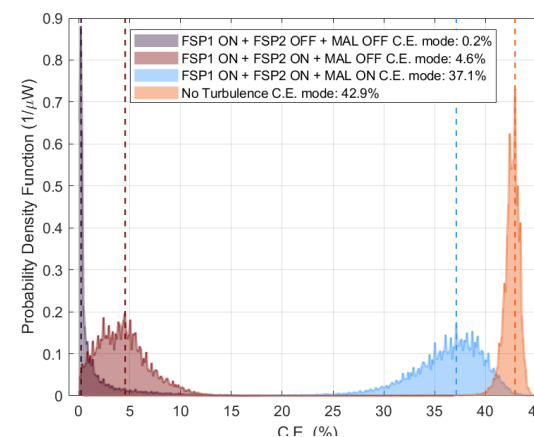
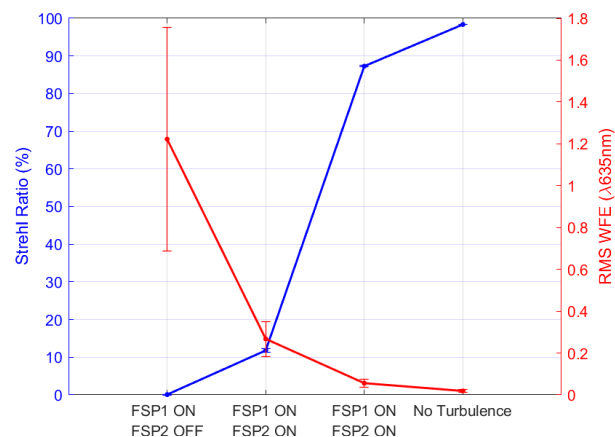


Data Acquisition:

- Shack-Hartmann Wavefront Sensor (SH-WFS) for estimating Strehl Ratio and RMS WFE.
- Fiber coupling efficiency (C.E.) measured using a single-mode fiber, photodiode, operational amplifier, and DAQ system.

Configurations Tested:

- FSP 1 ON + FSP 2 OFF + MAL OFF:** FSP 1 activated to mitigate beam wandering.
- FSP 1 ON + FSP 2 ON + MAL OFF:** FSP 1 and FSP 2 activated for tip-tilt correction.
- FSP 1 ON + FSP 2 ON + MAL ON:** Full correction using FSP 1, FSP 2, and MAL to compensate for high-order aberrations.





Conclusions



- **Key Findings:**

The results demonstrate significant improvements in optical performance by correcting beam wandering and wavefront aberrations, with:

- **Strehl Ratio:** Up to 87% on average (ideal case: 98%).
- **Coupling Efficiency:** Up to 37.1% on average (ideal case 42.9%).

- **Impact:**

These advancements are relevant for improving the reliability and stability of optical communication links that use collimated beams while maintaining system compactness.

- **Publication (First Author):**

High-efficiency free-space optical communication link with refractive adaptive optics – Accepted for publication in *Optics Express*



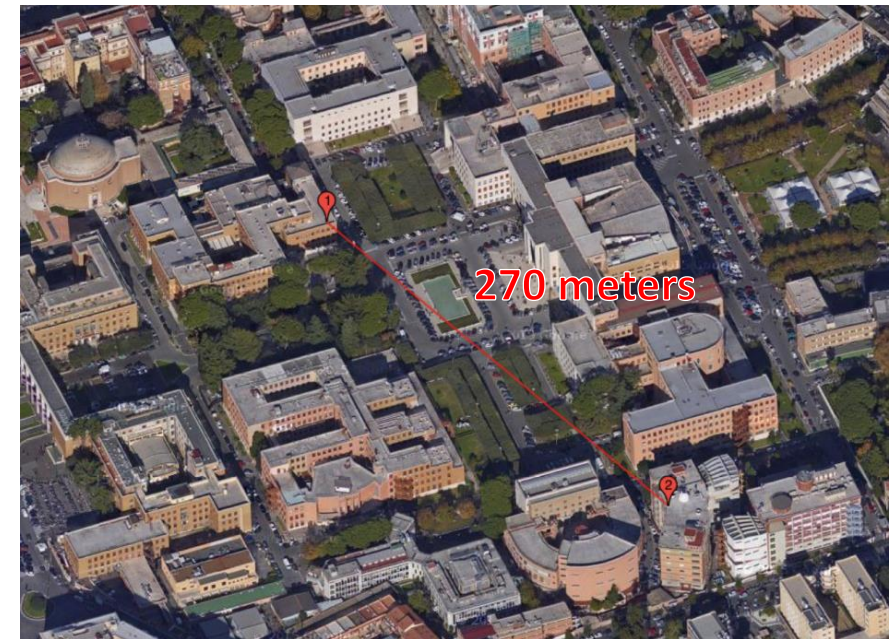
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QD-E-QKD: measurements campaign in Rome



20/03/2025

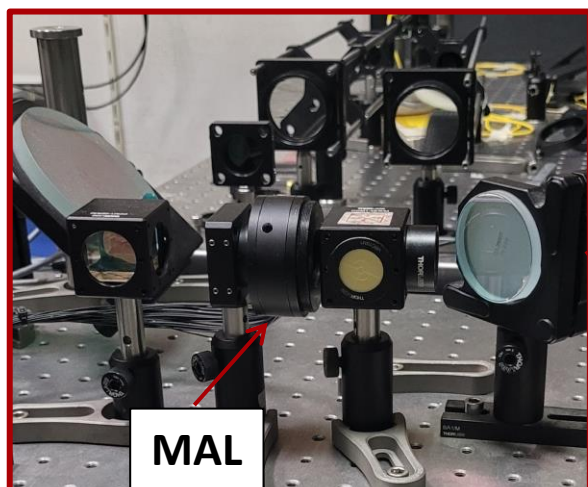
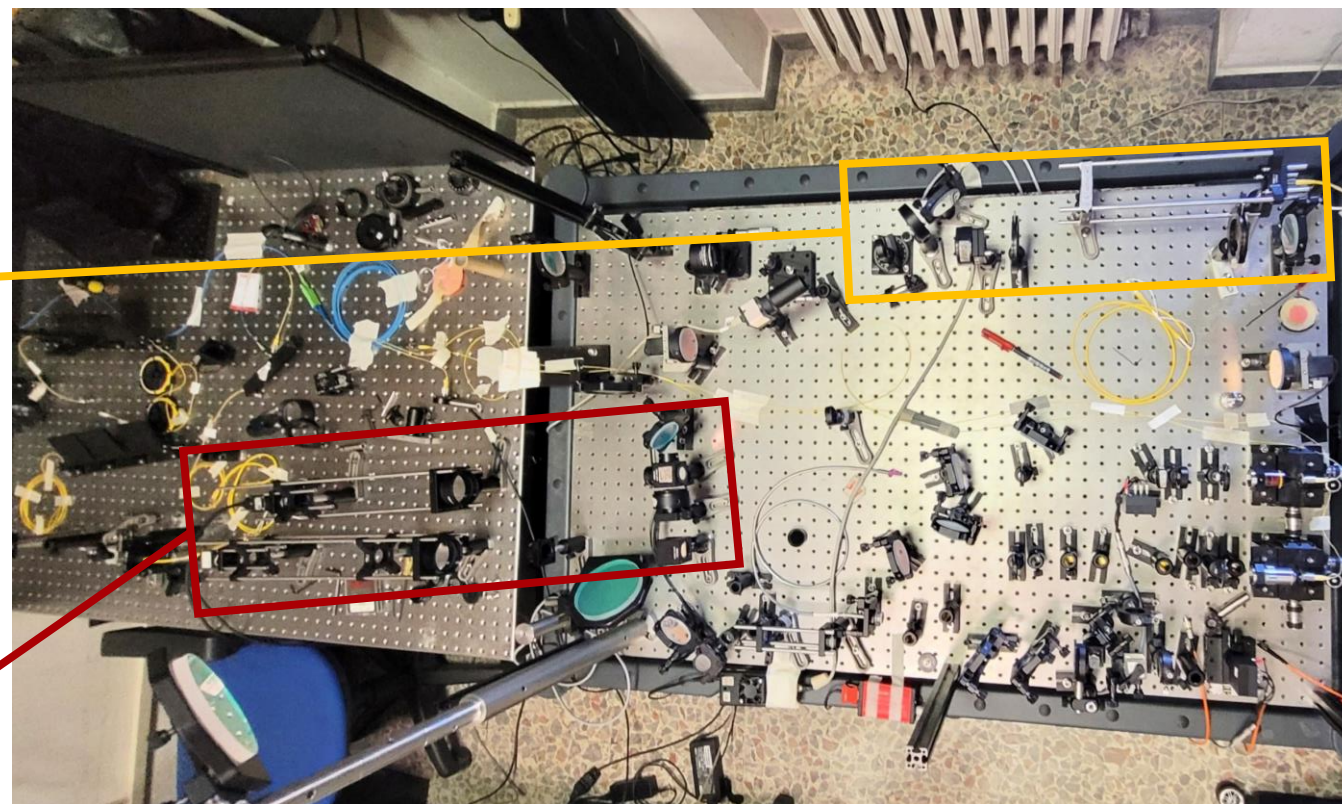
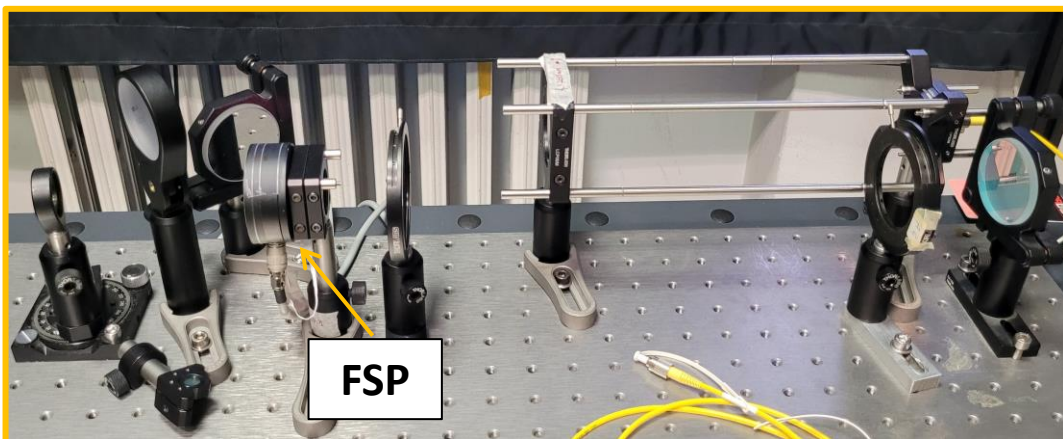
Tests and measurements campaign at
University 'La Sapienza' of Rome!





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FSP and MAL Integration (2)

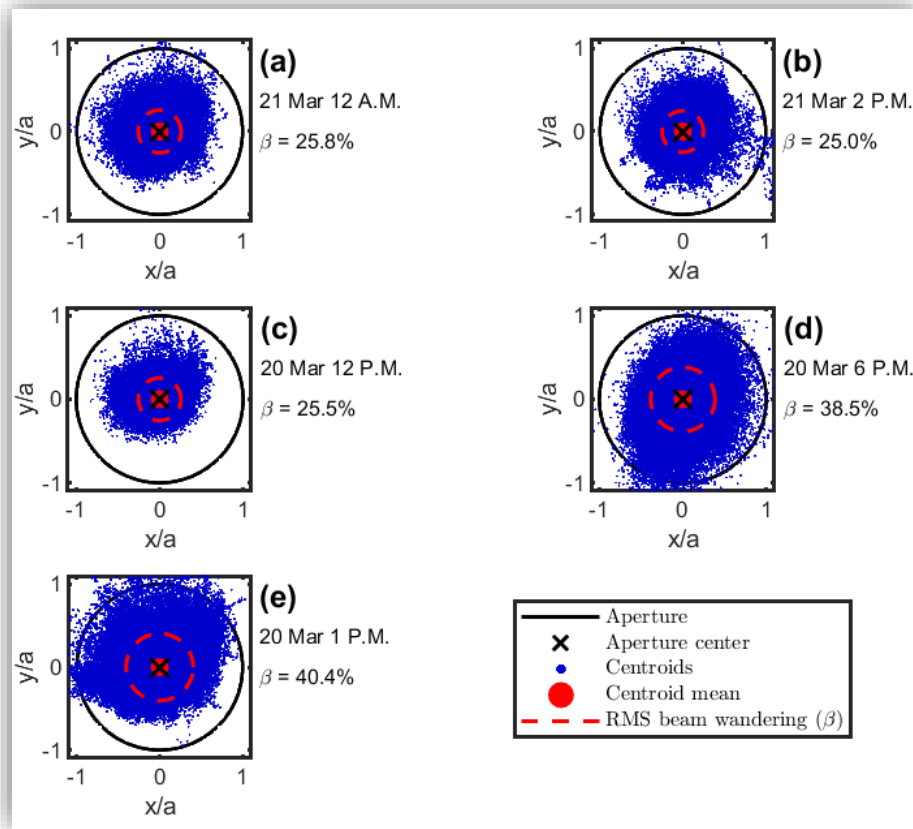


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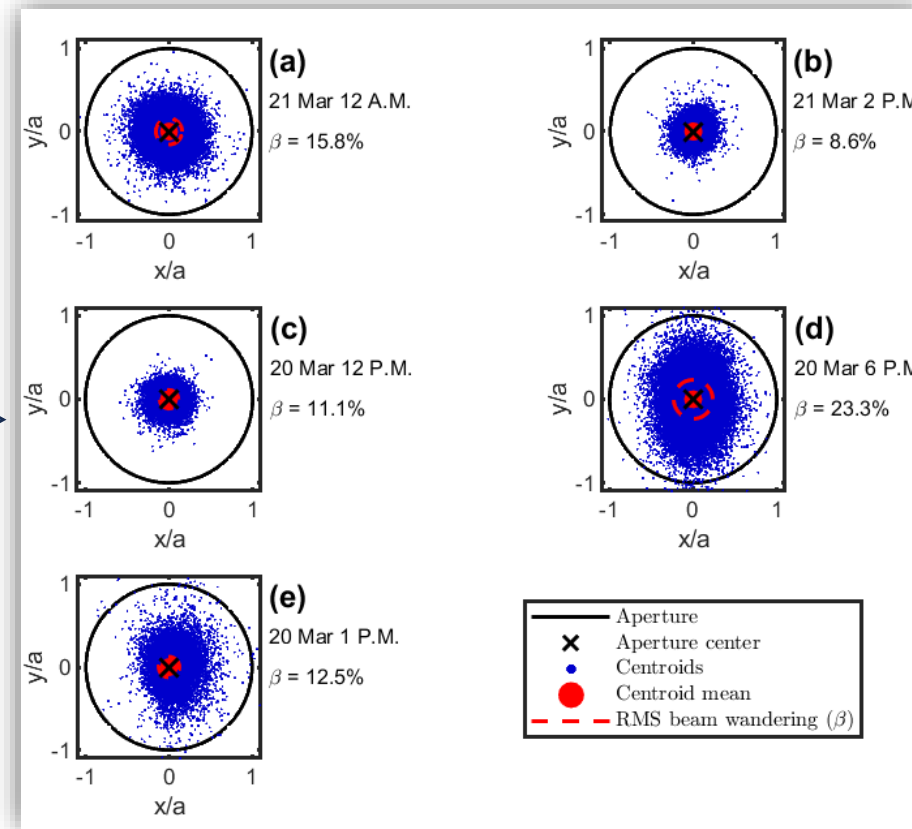
Beam Wander correction

NOT corrected Beam Wander

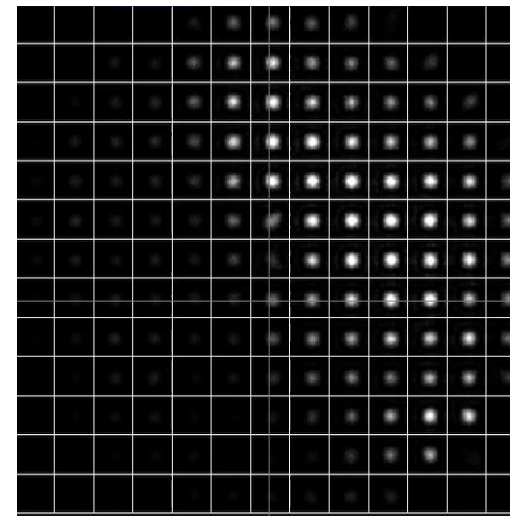
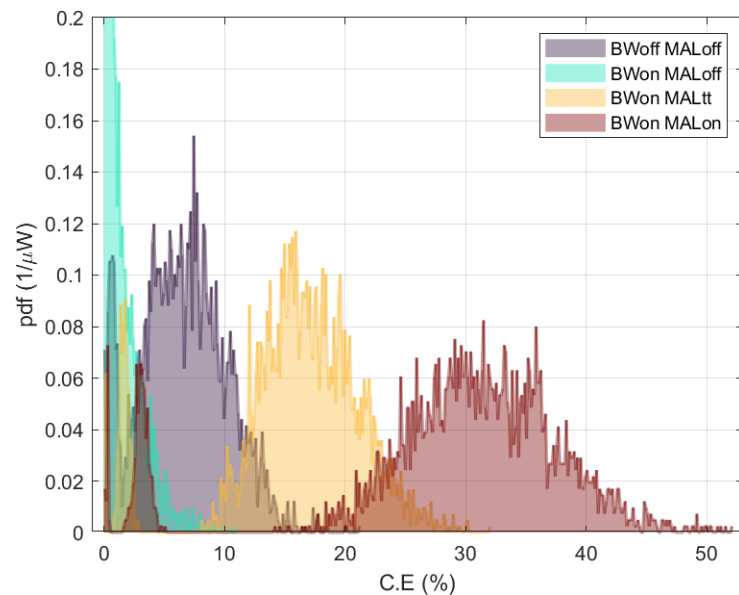
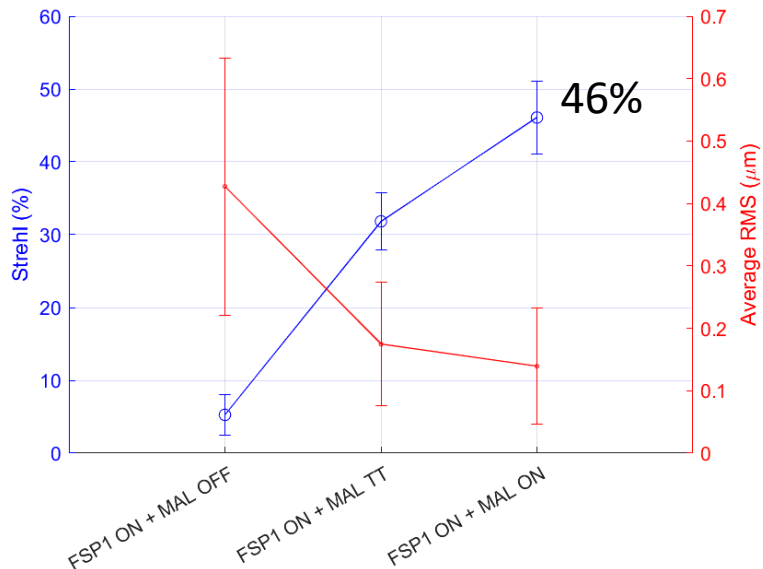
Corrected Beam Wander (FSP + MAL)



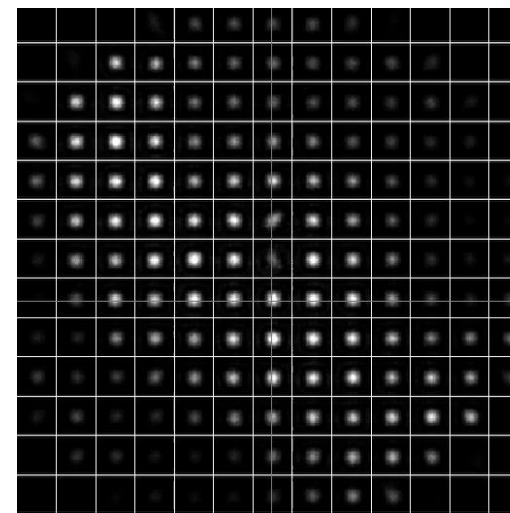
AO loop closure!



Collimated beam – Nighttime

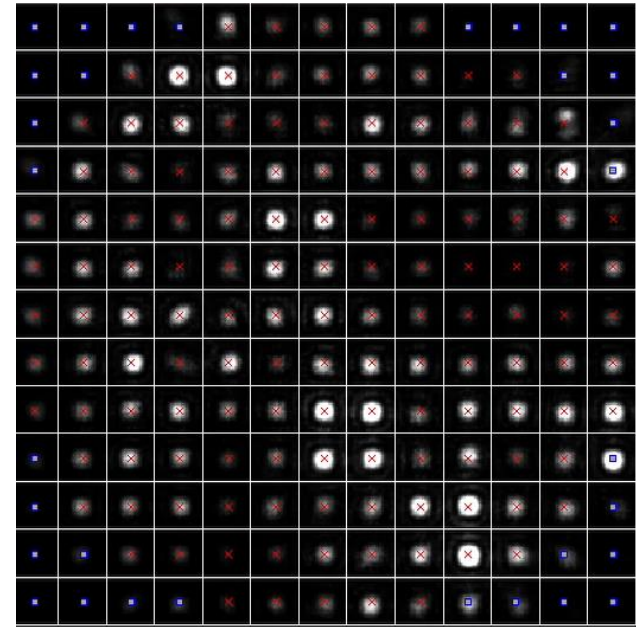
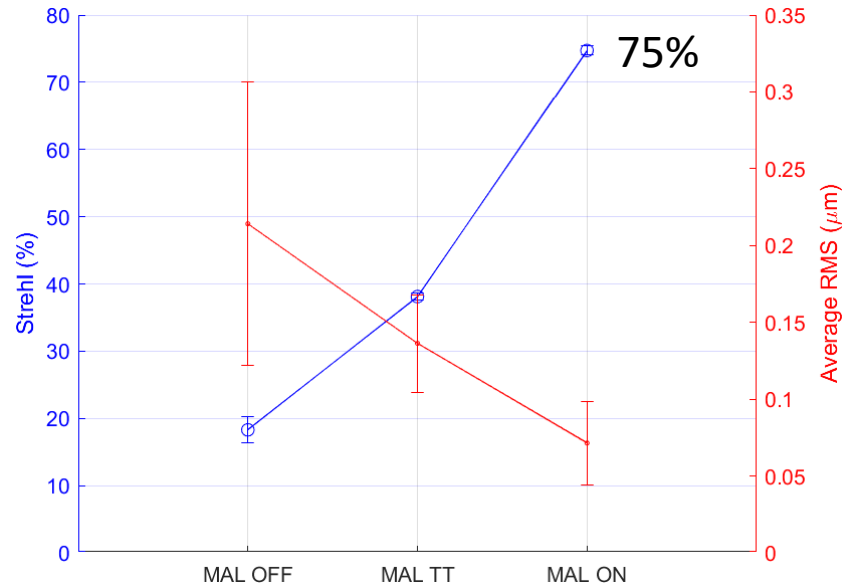


FSP OFF
MAL OFF



FSP ON
MAL ON

Decollimated Beam - Nighttime



MAL ON

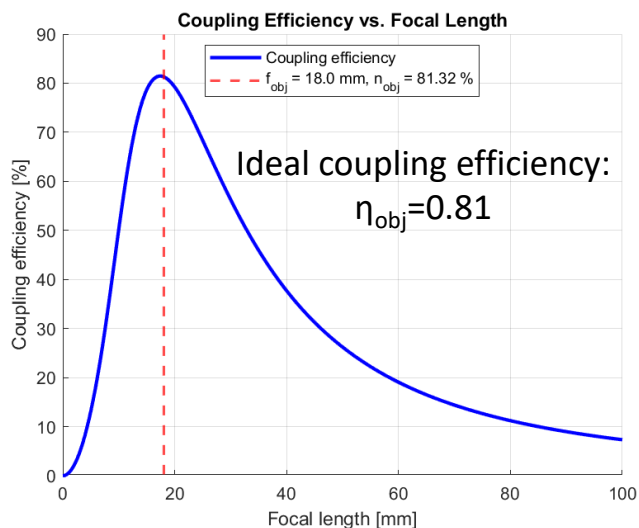
Unfortunately, we had some issues with the fiber coupling...

Collimated vs Decollimated

N.B.: Power data in μW

	COLLIMATED	DECOLLIMATED
Tx Power	863 (850nm+785nm)	863 (850nm+785nm)
Rx objective pre-fiber Power	48.9 (785nm)	21.8 (785nm)
Mean Coupled Power (full AO ON)	14.0 (785nm)	n.d.

Pre-fiber power gain:
 $48.9/21.8 = 2.2$



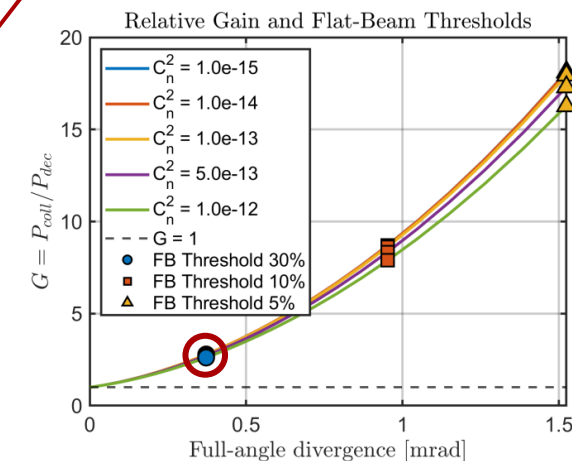
What we expect from SH-WFS data:

Coupled Power (Full AO ON): $P \approx \eta_{obj} * SR * P_{pre-fiber}$

$P_{dec} = 0.81 * 0.75 * 21.8 \mu\text{W} = 13.2 \mu\text{W}$

$P_{coll} = 0.81 * 0.46 * 48.9 \mu\text{W} = 18.2 \mu\text{W} \rightarrow$ we measured $14.0 \mu\text{W}$!

Theoretical fiber-coupled power gain: $18.2/13.2 = 1.4$





Conclusions



- A **pre-fiber power gain of 2.2×** was achieved by operating with a **collimated beam**, which, while more affected by **beam wandering**, enables significantly higher collected power than a de-collimated beam.
- The **theoretical fiber-coupled power gain**, derived from SH-WFS **Strehl ratio**, is estimated at **1.4×**.
- The current adaptive optics system is **limited by electronics**, unable to fully correct high-frequency **residual tip-tilt** due to beam wandering.
- Results represent a **strong proof of concept**: with optimized control hardware, gains up to **2.2×** in **fiber coupling** are expected.
- Qualitative feedback from collaborators highlights **rapid and stable fiber coupling**, suggesting enhanced beam stability provided by the adaptive receiver.
- A **new manuscript** reporting our latest measurement campaign, developed **in collaboration with Sapienza University of Rome**, is currently in the writing phase and will be submitted for publication soon.



Redesign Proposal

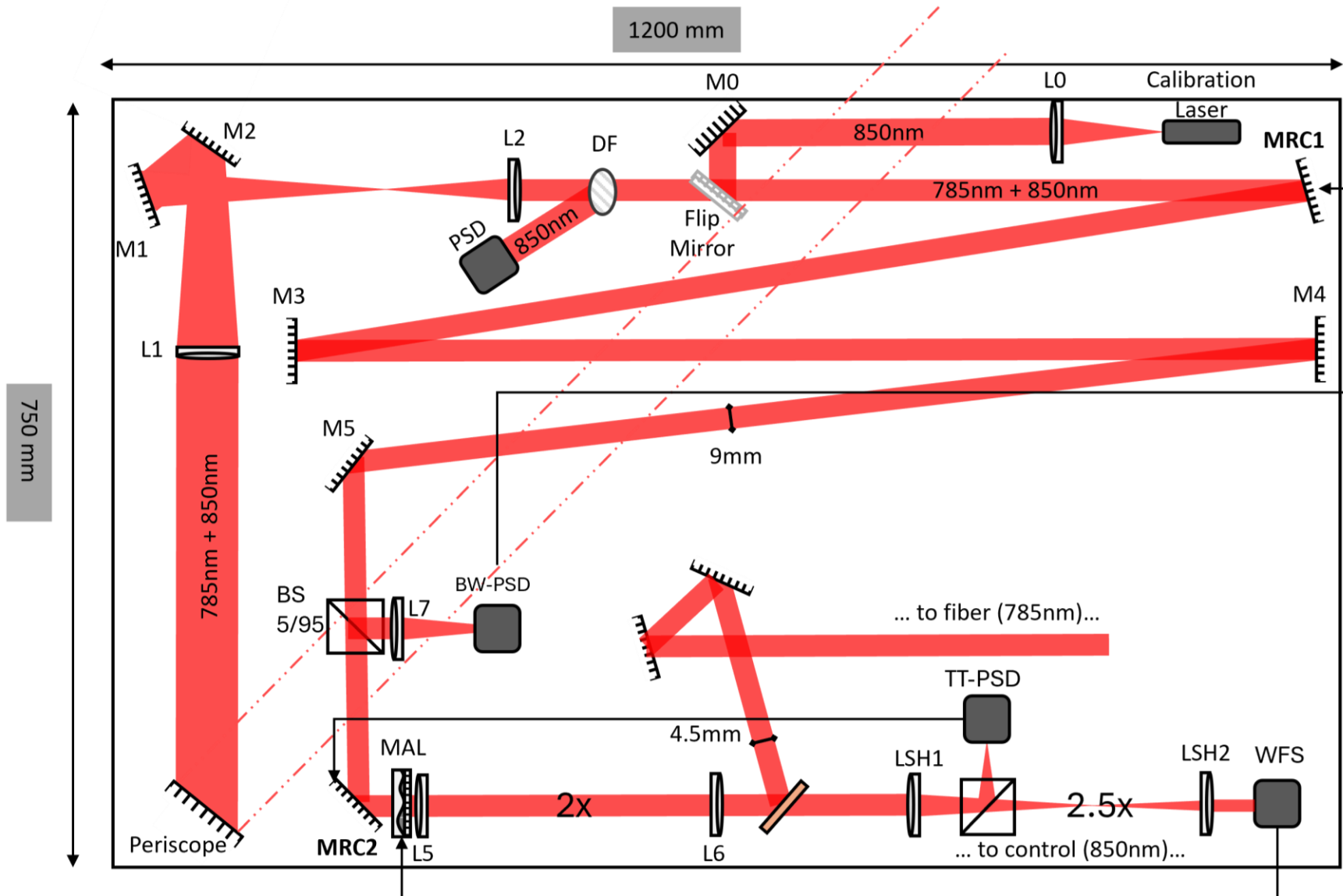


Optical Receiver in Fermi building (La Sapienza - Rome)

Communication wl: 785nm
Calibration/control wl: 850nm

Activity:
Point-to-point **quantum key
distribution** using quantum-dot
sources over free-space optical
channels

Installation scheduled for spring
2026!

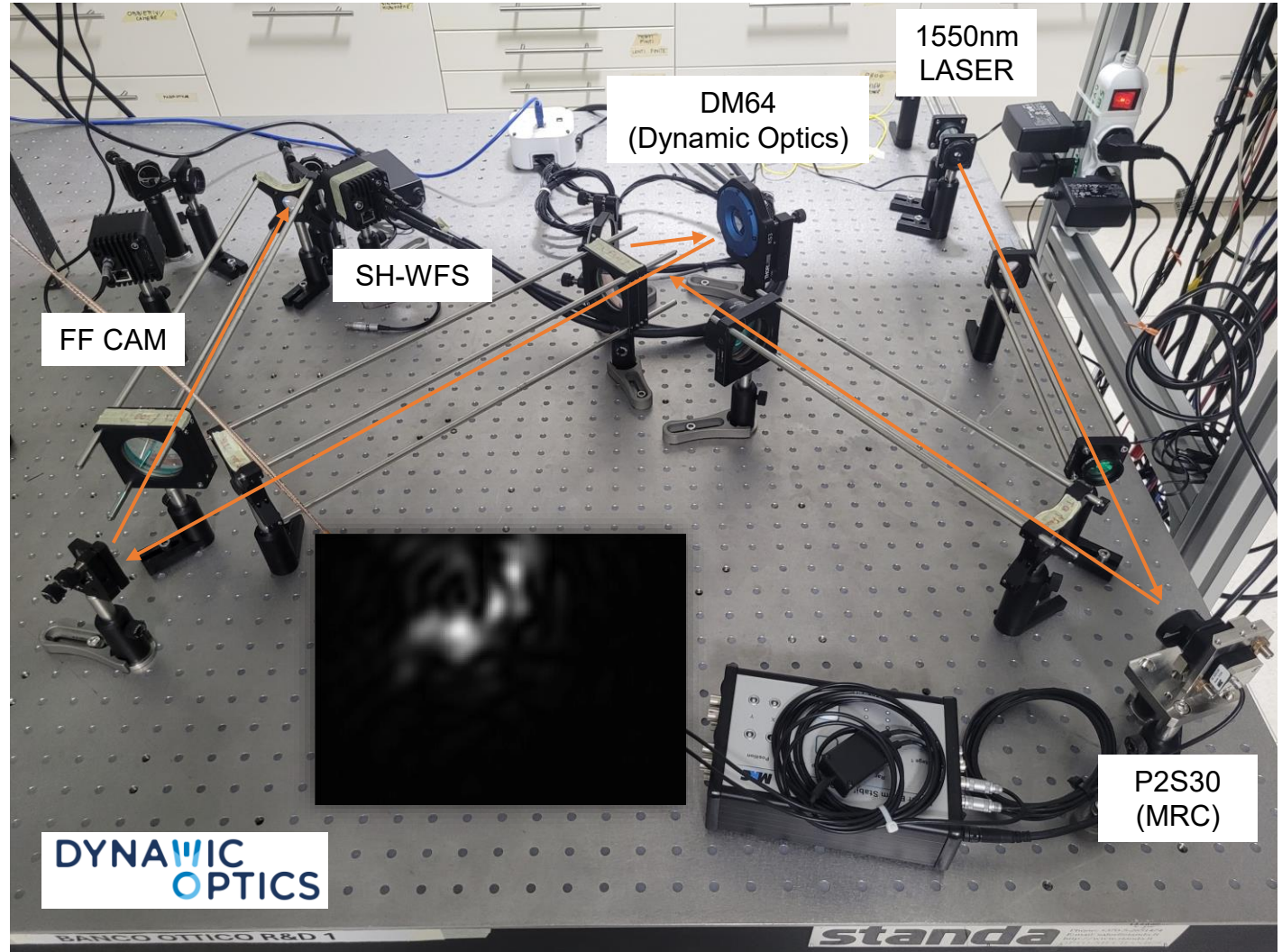
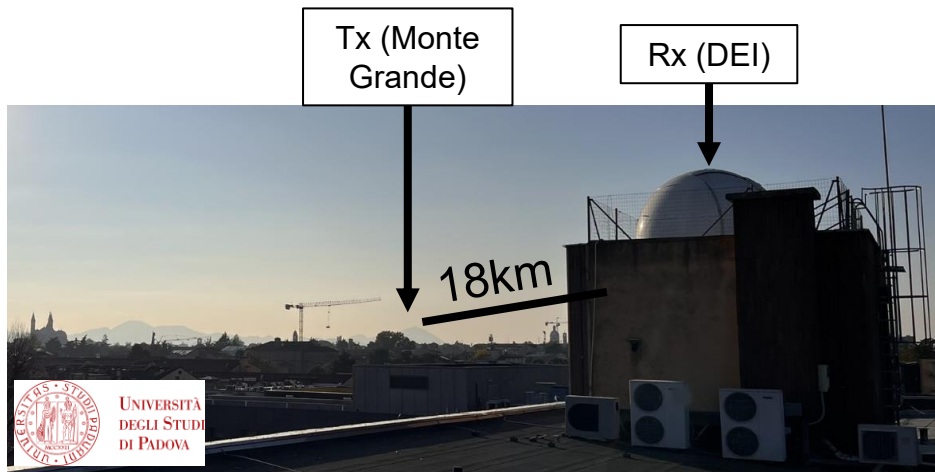




Other activities: a real-time AO controller for FSO-QKD



Dynamic Optics' **real-time AO controller** will be installed in the optical receiver of the UniPd 18km FSO link used for urban quantum communication between Monte Grande and DEI.

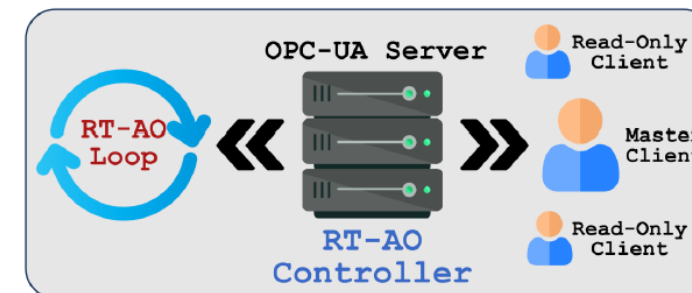




Real-Time AO Controller



- CPU-based design running on a Real-Time Linux based server
- Performs Real-Time AO closed-loop operation
 - Computational latency $<50\mu\text{s}$ and jitter $<2\mu\text{s}$.
- Responsible for Non-real-time activities:
 - send/ receive commands from/to the network
 - calibration routine
 - open loop operation based on received commands.
- Modular HW/SW architecture
 - Accepts various image dimensions and number of lenslets
 - Exhibits a Multi-Inputs-Multi-outputs AO architectures (e.g. single DM, FSM + DM, FSM + Woofer-Tweeter, WFS+TTS or WFS only)
- 19" 4U rack-mountable case (440mm (W) x 176mm (H) x 468mm (D))

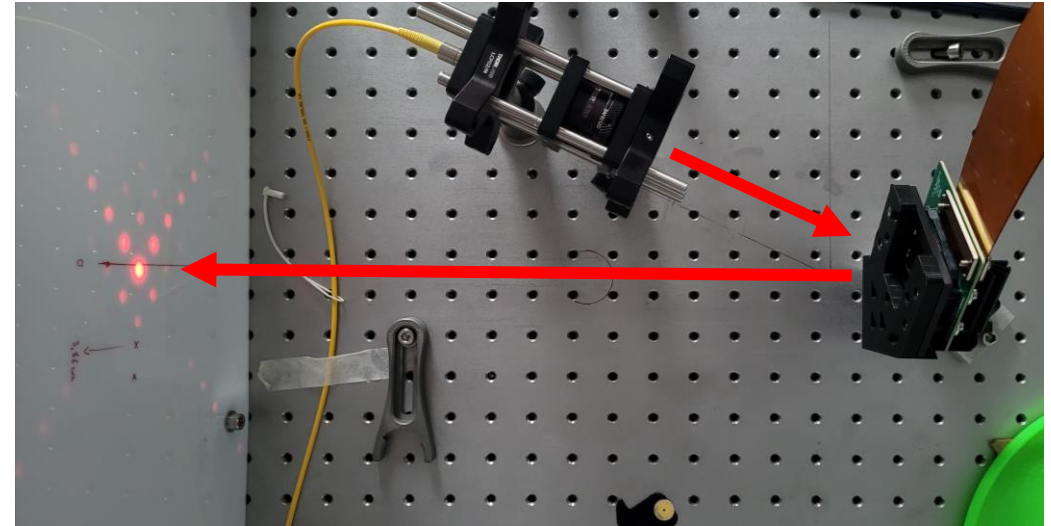


Other activities: DMD as a wavefront corrector



Vialux V-7001 technical data

Window Options	VIS, UV
Micromirrors	1024 × 768
Pitch (d_{DMD})	13.68 μ m
Blaze angle (ω)	$\pm 12^\circ$
Switching Rate 1 bit B/W	22727Hz
Controller Suite	ALP-4.3



What is a Digital Micromirror Device (DMD)?

- Array of individually controllable micromirrors -> High Spatial Resolution
- Operates as a 2D blazed grating -> diffraction orders
- Only provide a binary amplitude modulation (ON/OFF micromirror mode)
- Capability to encode a target field into a binary amplitude computer-generated hologram (CGH) -> amplitude and **phase modulated** output fields
- Applications in adaptive optics and turbulence generation

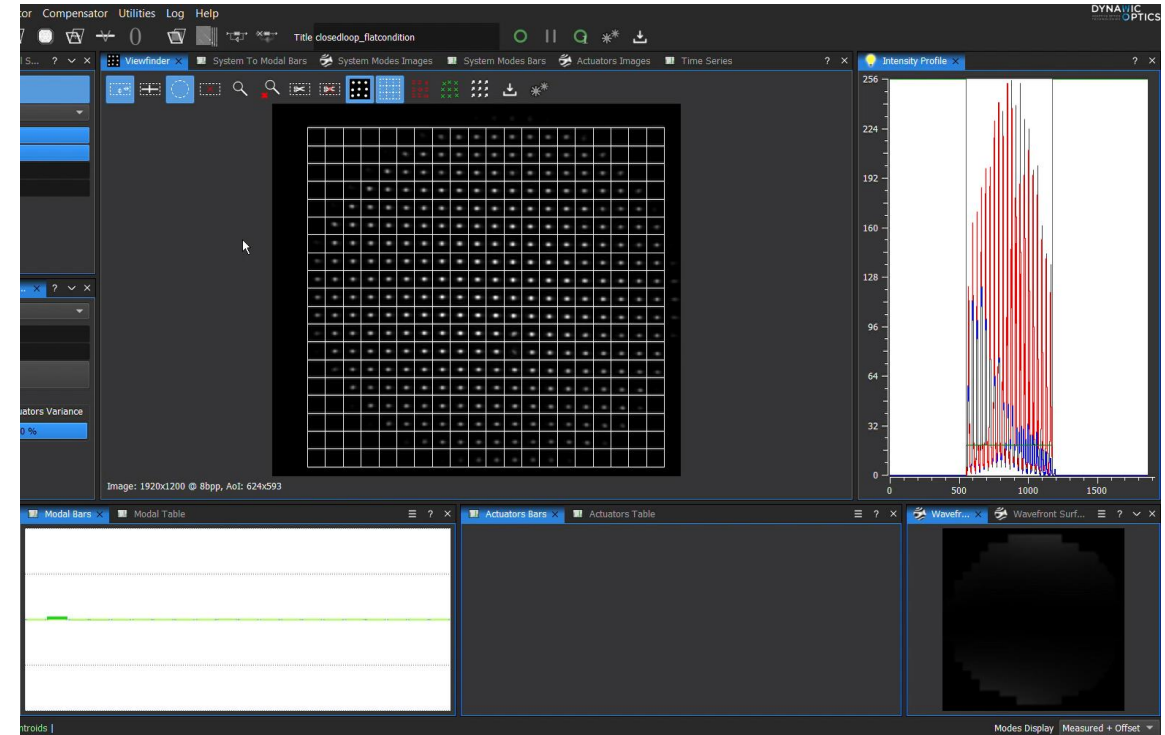
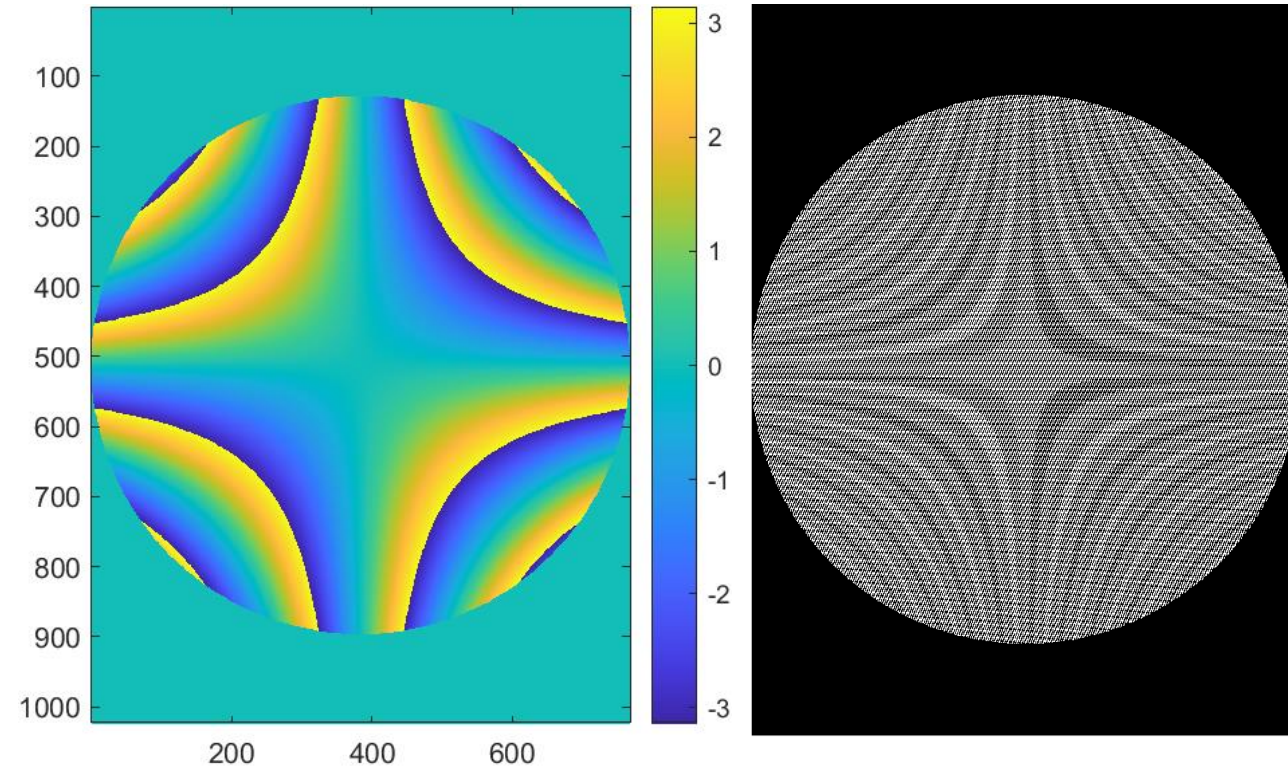
DMD Holo Phase Generation

Target Field
(Astigmatism)

Lee method

CGH -> DMD
ON/OFF pattern

Wavefront Sensor data

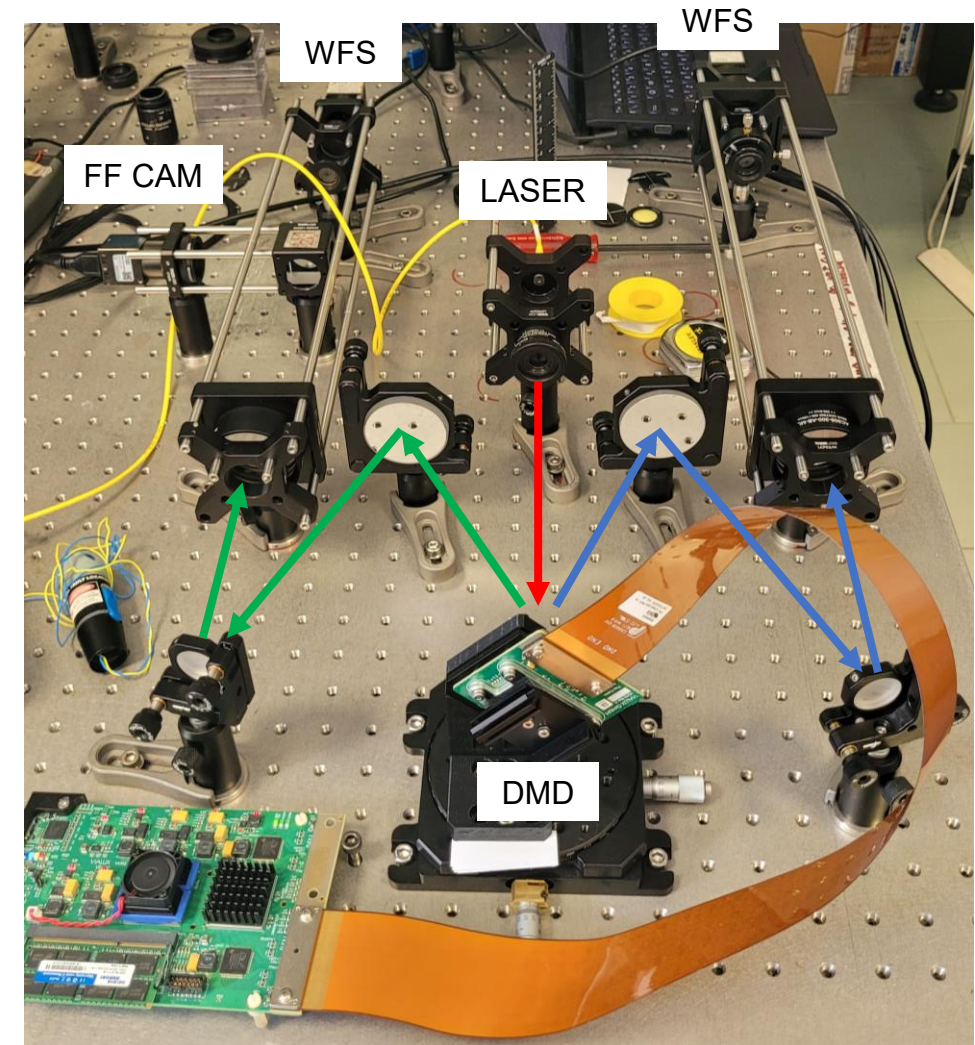


Dual-beam collection strategy: The two diffracted beams at $\pm 24^\circ$ are spatial conjugate, carrying identical phase information with opposite wavefront curvature. By collecting both beams simultaneously (e.g., via dual-fiber coupling), the available power can double while maintaining phase fidelity.

Power Budget:

1. Intrinsic DMD limit: 70% of input light (on blazing condition)
2. Single-beam hologram extraction: max 10.1% of input light (it depends on the CGH encoding method)
3. Dual-beam collection (both $\pm 24^\circ$ beams): theoretical max **~14%**
4. Additional losses: fiber coupling, wavefront residuals, feedback

Discrete phase generation: DMDs implement phase modulation through binary amplitude holograms, where continuous phase profiles are discretized into a finite number of phase levels determined by the hologram encoding scheme (e.g., Lee hologram with specific fringe width) -> quantization errors





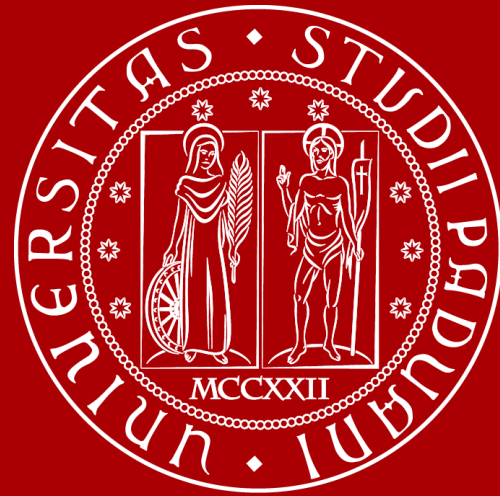
Conclusions

- The refractive adaptive optics system demonstrated strong performance in both laboratory and urban free-space conditions, achieving enhanced beam stability, higher Strehl ratios, and improved fiber-coupling efficiency.
- The combined FSP + MAL architecture proved effective for correcting beam wander and high-order aberrations, confirming the suitability of collimated-beam operation in real FSO scenarios.
- Additional activities validated the capabilities of a low-latency **real-time AO controller** and explored the potential of **DMDs** as high-resolution wavefront modulators.

Future Works

- Integration of the adaptive receiver into the 2026 QD-E-QKD free-space demonstration.
- Deployment of the real-time AO controller on the 18 km UniPd FSO-QKD link.
- Further development of DMD-based holographic phase correction, including closed-loop control algorithms, sensor selection, and laboratory testing.
- First-author publication of *High-efficiency free-space optical communication link with refractive adaptive optics* and preparation of a second manuscript based on the Rome measurement campaign.

Thanks for the attention



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