First laboratory demonstration of iEFC for high-contrast imaging at small angular separation on ELT scales

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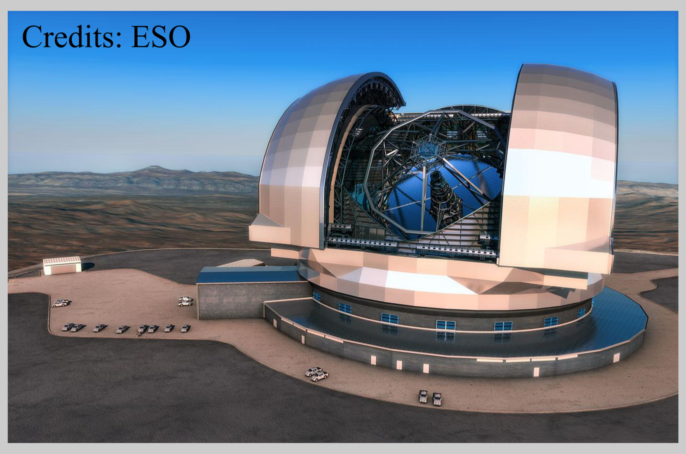
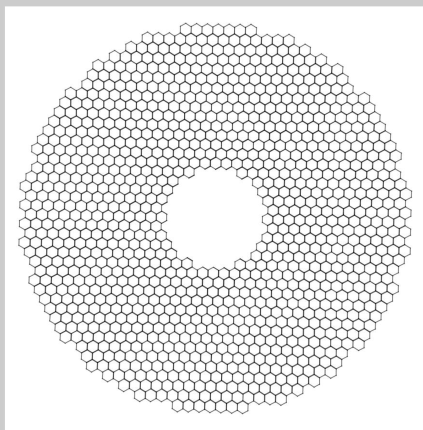
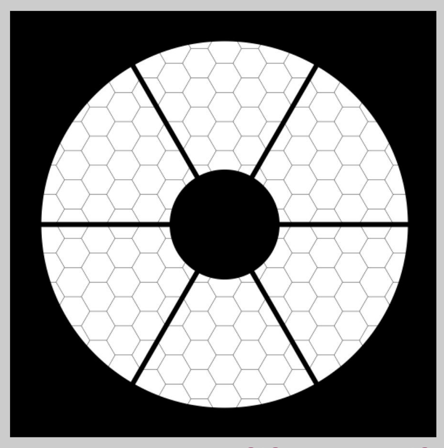
SPEED: a high-contrast imaging (HCI) testbed





ESO ELT (Extremely Large Telescope) and its pupil (composed by 798 hexagonal segments)

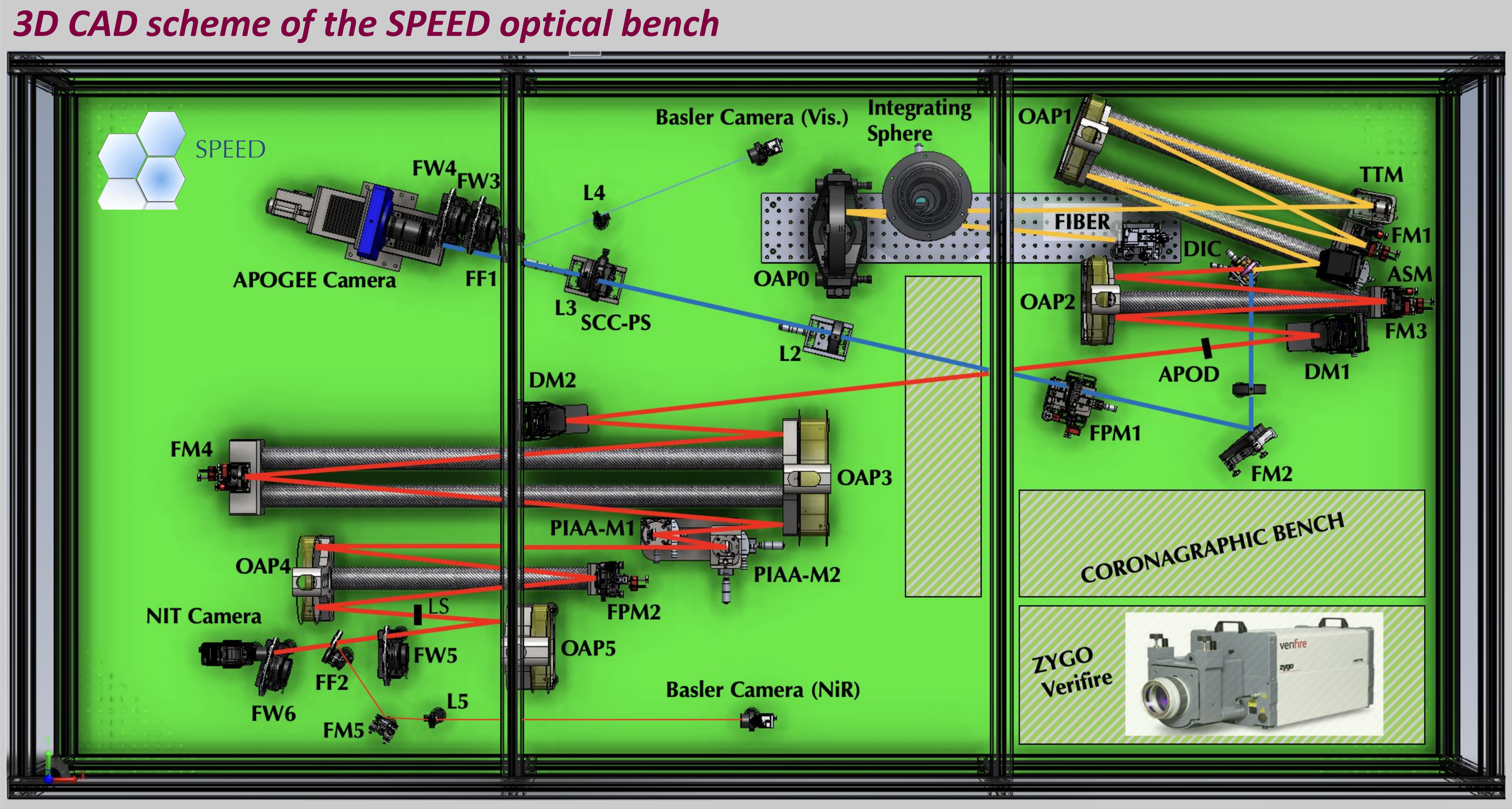


SPEED ELT-like pupil with 163 segments

SPEED (*Segmented Pupil Experiment for Exoplanet Detection*) is an experimental facility designed to study high-contrast imaging techniques for segmented telescopes.

SPEED prime objective is to achieve a high-contrast at small angular separations (~10^{-7} **within a 1-4 λ/D dark hole in the H-band**).

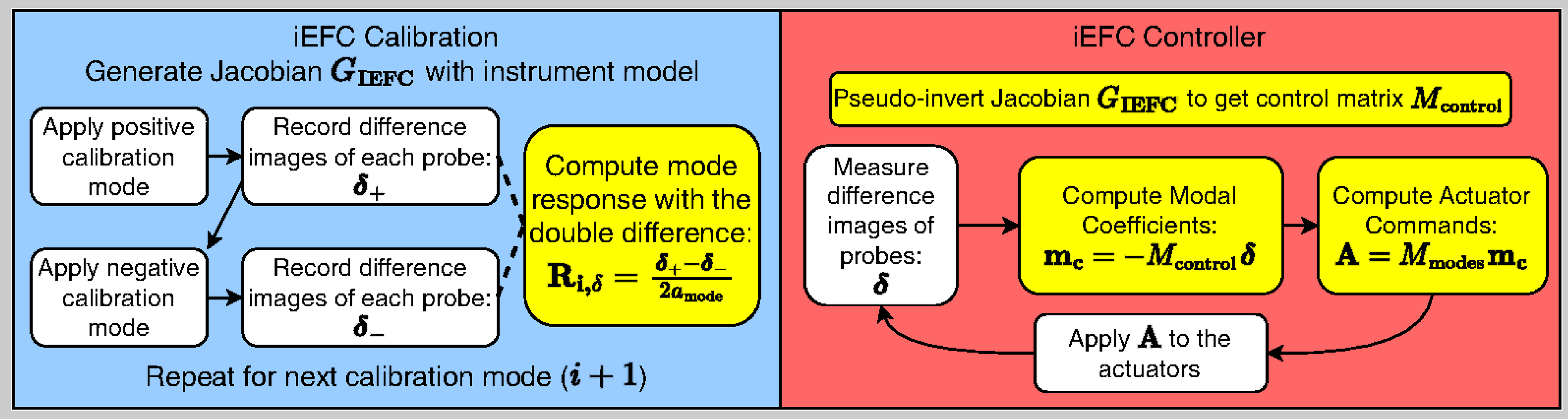
3D CAD scheme of the SPEED optical bench



Color code: telescope simulator and common path (orange), visible path (blue) and near-infrared path (red). Acronyms: TTM - tip/tilt mirror, OAP - off-axis parabola, ASM - active segmented mirror, DM - deformable mirror, FM - flat mirror, DIC - dichroic, L - lens, SCC-PS - self-coherent camera-phasing sensor, FPM - focal plan (mask), PIAAM1 & PIAA-M2 - phase induced amplitude apodization mirror 1 & 2, LS - Lyot stop, APOGEE - visible camera, NIT - near-infrared camera, Basler - pupil camera (Vis. and NiR), FF - flip flop mirror, FW - filter wheel.

Implicit Electric field conjugation (iEFC)

iEFC is a *model-free* algorithm introduced in 2023 by S.Y. Haffert [1], combining wavefront sensing (WFS) and wavefront control (WFC).

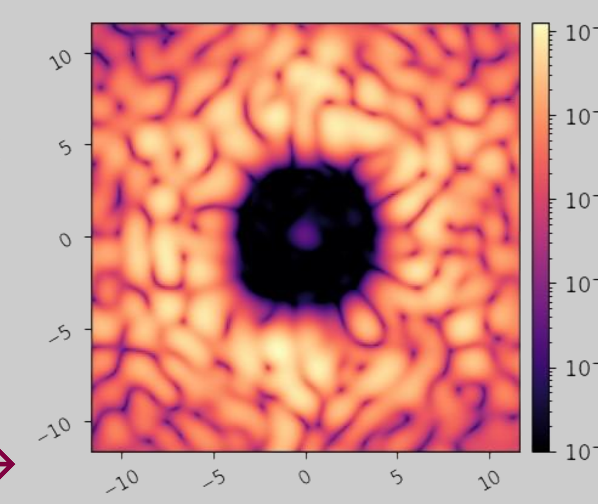


Functional steps for model-free iEFC (from Milani et al, 2024 [2]).

Principle: Rather than minimizing the difference between the estimated and measured electric fields (as EFC does), iEFC minimizes probe-induced image differences to infer the deformable mirror (DM) commands directly.

Steps:

1. Apply a calibration mode to the DM and acquire probe images
2. Compute probe image difference to construct the Jacobian (response matrix)
3. iEFC controller:
    1. Measure the probe difference image
    2. Minimize the discrepancy between the measurement and the Jacobian
    3. Compute and apply the corresponding DM command
    4. Iterate steps 1-3 until the target contrast is achieved



Example of dark-hole generated with iEFC simulation on the SPEED facility →

References:

[1] S.Y. Haffert, J.R. Males, K. Ahn *et al*, "Implicit electric field conjugation: Data-driven focal plane control", A&A 673, A28 (2023)

[2] K. Milani, E. S. Douglas, S. Y. Haffert, K. Van Gorkom, "Modeling and performance analysis of implicit electric field conjugation with two deformable mirrors applied to the Roman Coronagraph," J. Astron. Telesc. Instrum. Syst. 10(2) 029001 (15 May 2024)

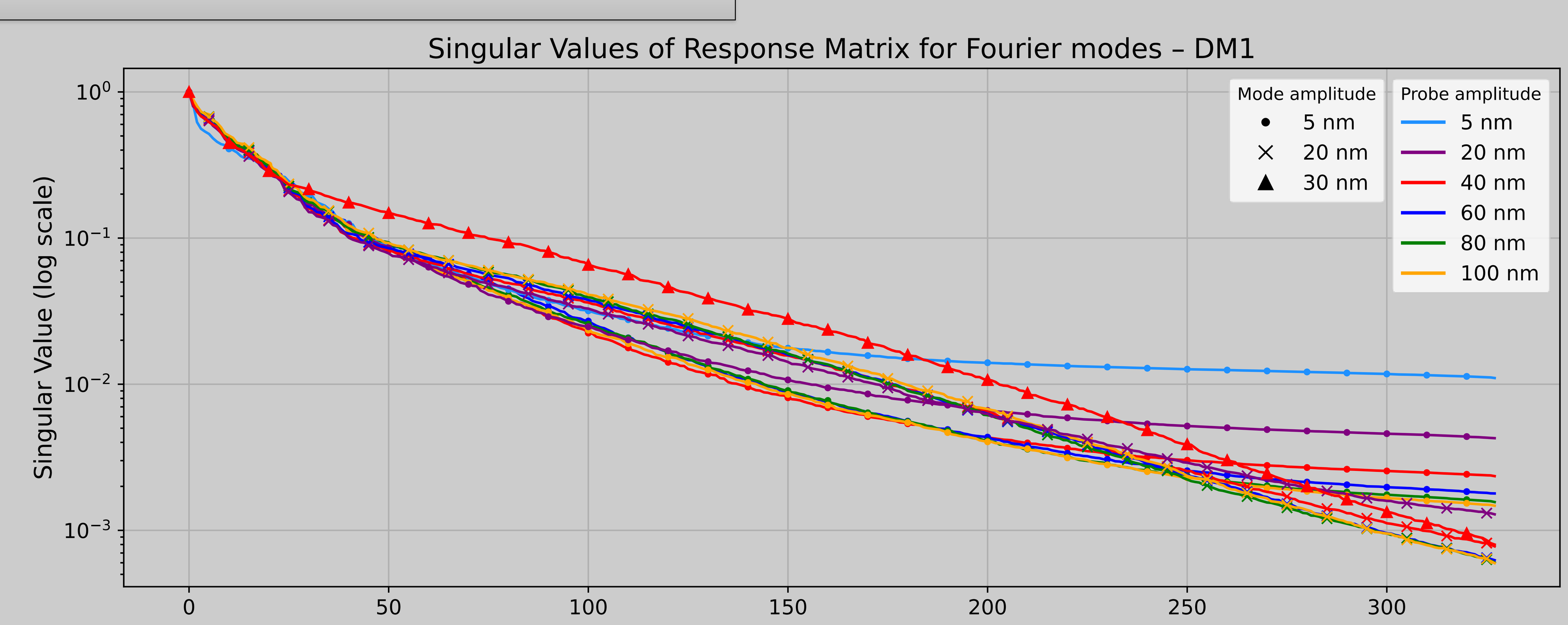
[3] E. Sidick et al., "Optimizing the regularization in broadband wavefront control algorithm for WFIRST coronagraph," Proc. SPIE 10400, 1040022 (2017).

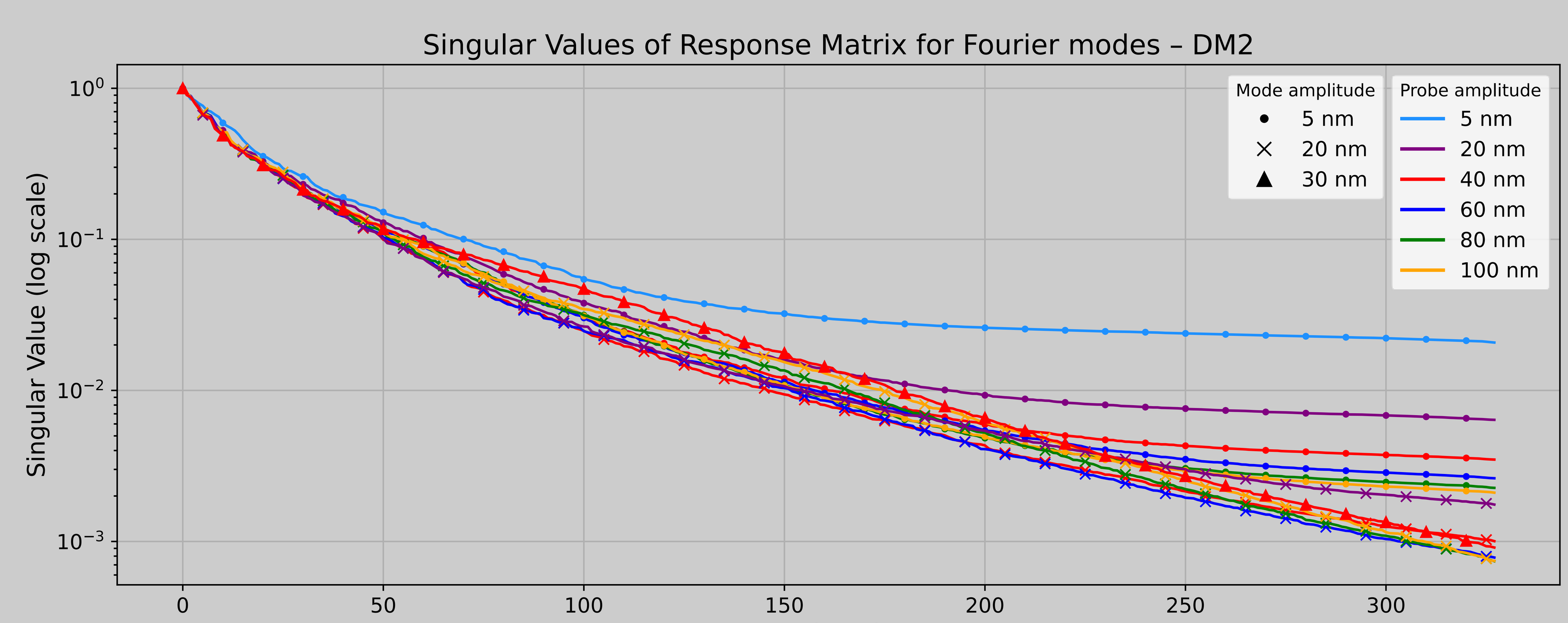
Laboratory demonstration and results

iEFC Calibration

The calibration was performed using 656 Fourier modes across the two deformable mirrors (DMs), corresponding to 164 sine modes and 164 cosine modes per DM. As an alternative modal basis, Hadamard modes were also considered; in this case, a total of 2048 modes is required, i.e., 1024 modes per DM.

The iEFC control loop is implemented using two out-of-pupil-plane Boston Micromachines (BMC) Kilo-C DMs.





Amplitude selection strategy

The selection of an appropriate stroke amplitude is critical for efficient dark-hole generation. Since the optimal amplitude depends on the instrument configuration and the relative DM positions, multiple amplitudes were tested for both calibration modes and probes. Singular Value Decomposition (SVD) was used as a first diagnostic tool to assess the impact of amplitude selection, noting that the iEFC controller relies on a different regularization scheme.

Results

The results indicate that optimizing both parameters is essential: the calibration should retain as many modes to which the system is sensitive as possible, while avoiding a rapid plateau in the singular value spectrum. Such a plateau would indicate uniform—and low—system sensitivity across those modes, implying that none of them meaningfully contribute to the calibration.

Moreover, calibration mode amplitudes exhibit a stronger dependence on the probe amplitude, highlighting the increased coupling between probing efficiency and system sensitivity in this regime.

Throughout the iEFC control loop, both the regularization parameter and the probe amplitude are adjusted to maintain optimal performance. This includes progressively relaxing the β-regularization, reducing the probe amplitude to enable finer wavefront corrections, and adapting the camera settings to preserve an adequate signal-to-noise ratio (SNR).

iEFC Controller

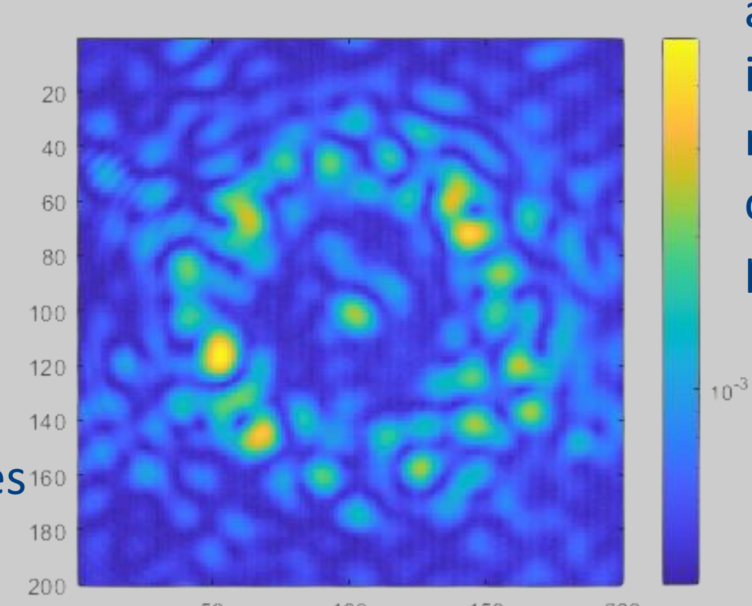
The iEFC controller implements β-regularization [3] to minimize the cost function.

The next development phase will focus on optimizing the control loop, including:

- Selecting the optimal combination of mode and probe amplitude
- Choosing an appropriate regularization parameter for efficient regularization

Future tests:

- Exploring alternative mode bases: Fourier, Hadamard and single-actuator modes



← Dark-hole generated with iEFC on the SPEED test-bed, from 1-4 λ/D

More info on SPEED →

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