Novel AO Act

Del Vecchio, Biasi, Riccardi, Gallieni

Background
The AO Principle
The Design Drivers
The Actuator
The Multiphysics Problem
The Model
The Application Modes
Magnetostatics
Heat transfer
Fluid dynamics
Results
Experimental Validation
Summary

Designing the Actuator for the Next-Generation Astronomical Deformable Mirrors: a Multidisciplinary and Multiphysics Approach

Comsol for Adaptive Optics

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2008 Comsol Conference Hannover, Nov 5 2008

Outline

1. Background
   - The AO Principle
   - The Design Drivers
2. The Actuator
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   - The Model
3. The Application Modes
   - Magnetostatics
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Outline

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   - The AO Principle
   - The Design Drivers
2. The Actuator
   - The Multiphysics Problem
   - The Model
3. The Application Modes
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   - Heat transfer
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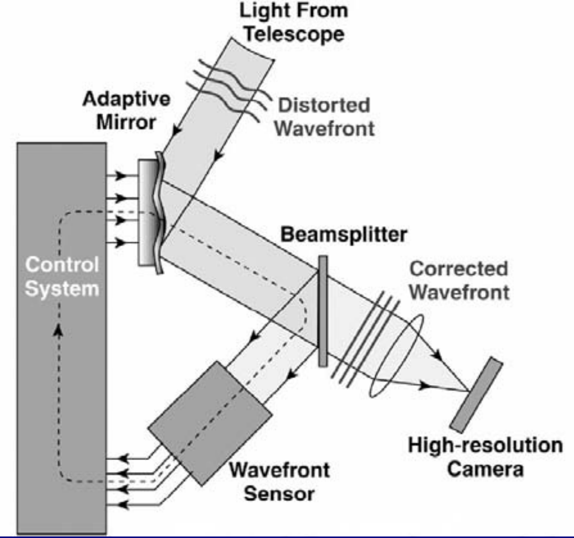
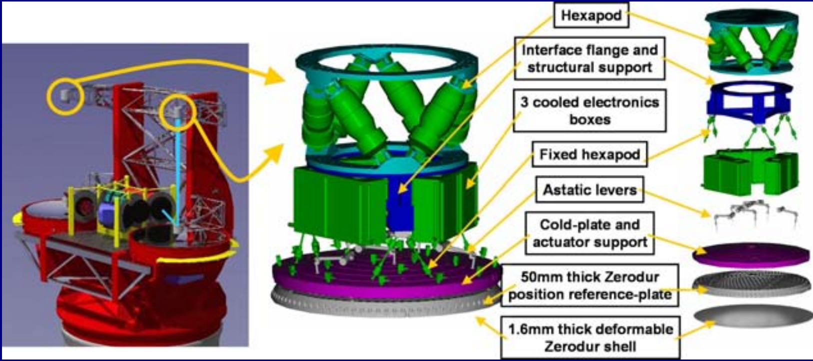
4. Results
5. Experimental Validation

Compensating the Atmospheric Turbulence
The Control System Concept



Adaptive Optics on board the Telescope
System Overview

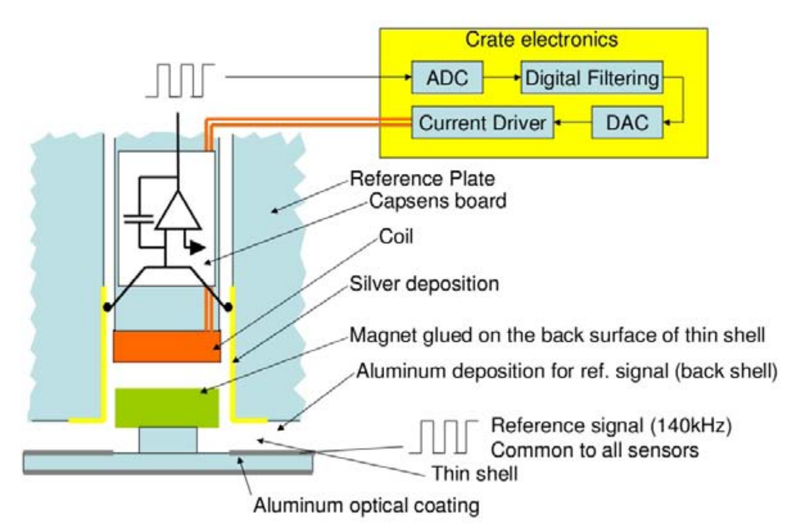


[Riccardi et al., 2004]

Background
The AO Principle
The Design Drivers
The Actuator
The Multiphysics Problem
The Model
The Application Modes
Magnetostatics
Heat transfer
Fluid dynamics
Results
Experimental Validation
Summary

Actuating the DM & Sensing the Displacements

The LBT Voice-Coil



Outline

1. Background
   - The AO Principle
   - The Design Drivers
2. The Actuator
   - The Multiphysics Problem
   - The Model
3. The Application Modes
   - Magnetostatics
   - Heat transfer
   - Fluid dynamics
4. Results
5. Experimental Validation

Basic Requirements of High Order DM's

The Specs are very Severe

Background
The AO Principle
The Design Drivers
The Actuator
The Multiphysics Problem
The Model
The Application Modes
Magnetostatics
Heat transfer
Fluid dynamics
Results
Experimental Validation
Summary

rms force (turb. corr.) [N]	.363
max force (static) [N]	.36
max force (dynamic) [N]	1.27
stroke [μm]	$\pm$150
bandwidth [kHz]	1
typical actuator spacing [mm]	25
typical mover mass [g]	≤ 10
resistance [Ω]	2 to 2.5

measuring range [μm]	$\pm$100
resolution [nm]	< 3
rms noise [nm]	< 5
drift[1] [nm]	20
bandwidth [kHz]	> 30

[1] 12 hrs base, 5°C temperature variation

Background
The AO Principle
The Design Drivers
The Actuator
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The Model
The Application Modes
Magnetostatics
Heat transfer
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Results
Experimental Validation
Summary

DM Stiffness vs. DM Thickness & Act Spacing

$K_{flex} \propto t^3 \times (1/d)^4$

- What if
  - the inter-actuator spacing is slightly reduced
  - the thickness is slightly increased

HIGHER ORDER DM	$d = 30 \rightarrow 25\,\mathrm{mm}\ (16\%)$	$\rightsquigarrow 2 \times K_{flex}$
ELT PANELS	$t = 1.6 \rightarrow 2\,\mathrm{mm}\ (20\%)$	

The Design Criterion: Avoid Thermal Pollution

The Basic Question & Two Possible Answers

reduce the *local seeing*

$\Downarrow$

reduce any local heating

$\Downarrow$

given the force, reduce the power

$\Downarrow$

maximize the efficiency, i.e. the force-to-power ratio
(while respecting the geometry and minimizing the emc)

- How getting $\Delta T \leq \pm 1$ K on any air-exposed surface?
  1. implement a cooling system
     - *active* (which $T_{coolant}$?) — SAFER BUT MORE COMPLEX
  2. rely on the natural convection
     - *passive* — SIMPLER BUT MORE RISKY

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Background
The AO Principle
The Design Drivers
The Actuator
The Multiphysics Problem
The Model
The Application Modes
Magnetostatics
Heat transfer
Fluid dynamics
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Experimental Validation
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The Actuator
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The Application Modes
- Magnetostatics
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Results

Experimental Validation

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Background
The AO Principle
The Design Drivers
The Actuator
The Multiphysics Problem
The Model
The Application Modes
Magnetostatics
Heat transfer
Fluid dynamics
Results
Experimental Validation
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Background
The AO Principle
The Design Drivers
The Actuator
The Multiphysics Problem
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Magnetostatics
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Background
The AO Principle
The Design Drivers
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The Multiphysics Problem
The Model
The Application Modes
Magnetostatics
Heat transfer
Fluid dynamics
Results
Experimental Validation
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Background
The AO Principle
The Design Drivers
The Actuator
The Multiphysics Problem
The Model
The Application Modes
Magnetostatics
Heat transfer
Fluid dynamics
Results
Experimental Validation
Summary

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Background
- The AO Principle
- The Design Drivers

The Actuator
- The Multiphysics Problem
- The Model

The Application Modes
- Magnetostatics
- Heat transfer
- Fluid dynamics

Results

Experimental Validation

Summary

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Background
The AO Principle
The Design Drivers
The Actuator
The Multiphysics Problem
The Model
The Application Modes
Magnetostatics
Heat transfer
Fluid dynamics
Results
Experimental Validation
Summary

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3. The Application Modes
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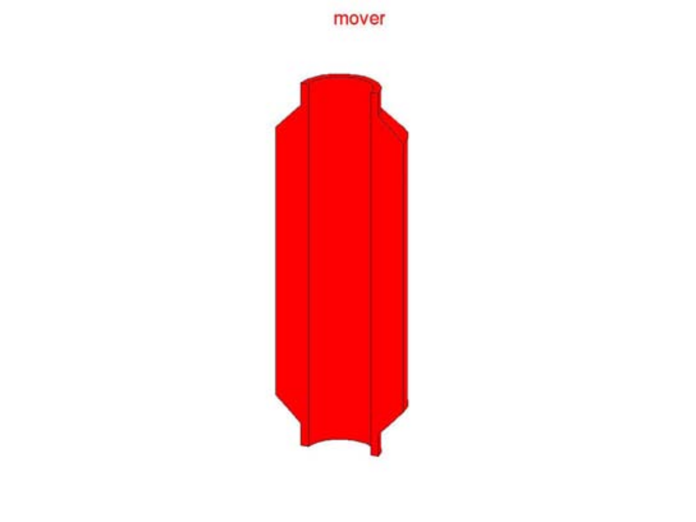
4. Results
5. Experimental Validation

The Electromagnetic Core

Variable Reluctance LM: Magnetic Force = $\int_V (\mathbf{M} \cdot \nabla)\, \mathbf{B}\, dV$



[Del Vecchio et al., 2008]

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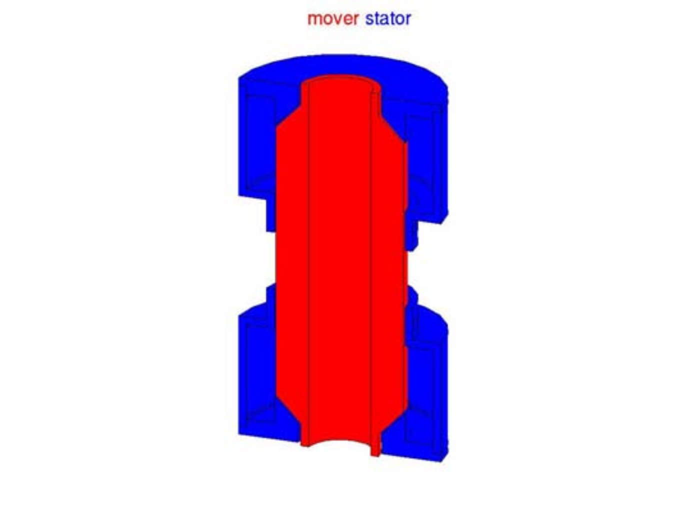

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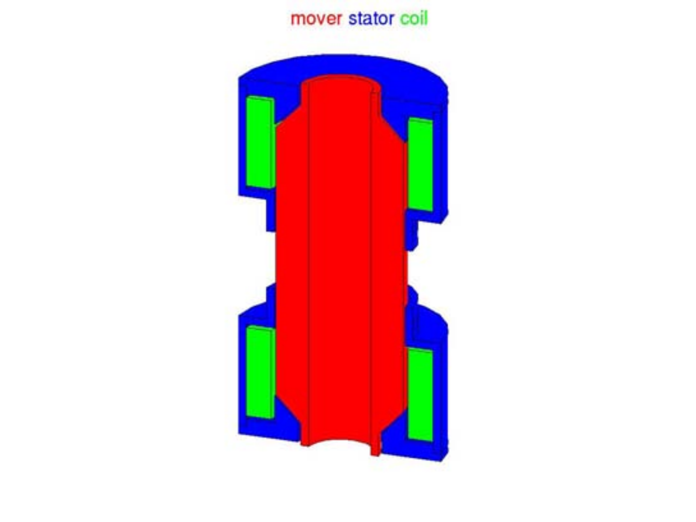

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Outline

1 Background
- The AO Principle
- The Design Drivers

2 The Actuator
- The Multiphysics Problem
- The Model

3 The Application Modes
- Magnetostatics
- Heat transfer
- Fluid dynamics

4 Results

5 Experimental Validation

The Axially Symmetric Actuator
E/M and E/S Components

Background
The AO Principle
The Design Drivers
The Actuator
The Multiphysics Problem
The Model
The Application Modes
Magnetostatics
Heat transfer
Fluid dynamics
Results
Experimental Validation
Summary

motor (statoric)

capsens (statoric)

motor (moving) & shaft

capsens (moving)

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Background
The AO Principle
The Design Drivers
The Actuator
The Multiphysics Problem
The Model
The Application Modes
Magnetostatics
Heat transfer
Fluid dynamics
Results
Experimental Validation
Summary

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Novel AO Act

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Background
- The AO Principle
- The Design Drivers

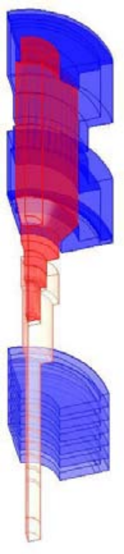
The Actuator
- The Multiphysics Problem
- The Model

The Application Modes
- Magnetostatics
- Heat transfer
- Fluid dynamics

Results

Experimental Validation

Summary



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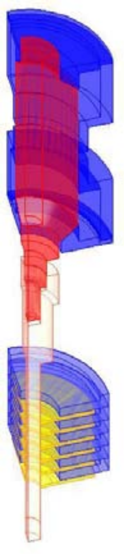
motor (moving) & shaft

capsens (moving)

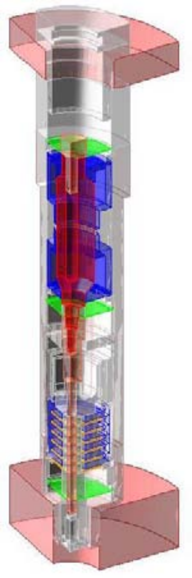
The Axially Symmetric Actuator

E/M and E/S Components



motor (statoric)
capsens (statoric)
motor (moving) & shaft
capsens (moving)

The Axially Symmetric Actuator
The Other Components



static
- motor capsens

moving
- motor shaft capsens

membranes

top/bottom plates

body (& aux)

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Background
The AO Principle
The Design Drivers
The Actuator
The Multiphysics Problem
The Model
The Application Modes
Magnetostatics
Heat transfer
Fluid dynamics
Results
Experimental Validation
Summary

- 2d geometry imported via the CAD Import Module
- Fine mesh of coil ($r_{wire} = .1195\,\mathrm{mm}$, $\delta_{ins} = 7\,\mu\mathrm{m}$) and air gaps ($\tau = 7\,\mu\mathrm{m}$)
- As a result
  - $\approx 55,000$ points and $\approx 100,000$ elements
  - .5% of which have a quality $\leq .4$
  - minimum quality = .19

From the Dwg to the Mesh
Carefully Meshing Gap & Coil Regions

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Background
The AO Principle
The Design Drivers
The Actuator
The Multiphysics Problem
The Model
The Application Modes
Magnetostatics
Heat transfer
Fluid dynamics
Results
Experimental Validation
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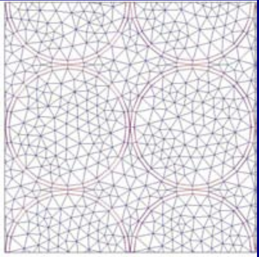

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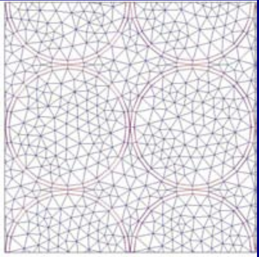

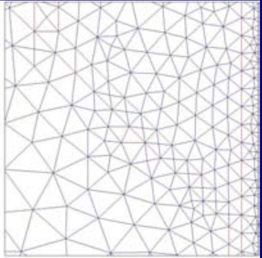

Background
The AO Principle
The Design Drivers
The Actuator
The Multiphysics Problem
The Model
The Application Modes
Magnetostatics
Heat transfer
Fluid dynamics
Results
Experimental Validation
Summary

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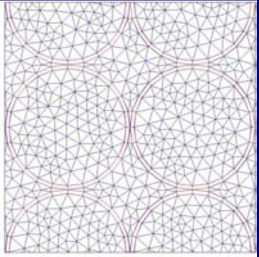

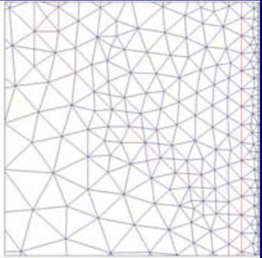

Outline

1 Background
- The AO Principle
- The Design Drivers

2 The Actuator
- The Multiphysics Problem
- The Model

3 The Application Modes
- Magnetostatics
- Heat transfer
- Fluid dynamics

4 Results

5 Experimental Validation

Setting Up the Magnetostatics

Temperature Affects the Resistive Heating

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Background
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- The Multiphysics Problem
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The Application Modes
- Magnetostatics
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- $F = \int_S -\frac{1}{2}(\mathbf{H}\cdot\mathbf{B})\,\mathbf{n} + (\mathbf{n}\cdot\mathbf{H})\,\mathbf{B}^T\,dS = \int_V (\mathbf{M}\cdot\nabla)\,\mathbf{B}\,dV$

  choose the Maxwell tensor

- $\sigma_{Cu} = \dfrac{1}{\rho_{Cu_{ref}}\,[1+0.0039\,(T-293)]} \quad \mathrm{S}\times\mathrm{m}^{-1}$

  $\rho_{Cu_{ref}} = 1.72\times10^{-8}\,\Omega\times\mathrm{m}$ Cu resistivity @ 293 K

  $T \Leftarrow$ heat transfer

Outline

1. Background
   - The AO Principle
   - The Design Drivers
2. The Actuator
   - The Multiphysics Problem
   - The Model
3. The Application Modes
   - Magnetostatics
   - Heat transfer
   - Fluid dynamics
4. Results
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Setting Up the Heat Transfer

Assumption & Restrictions

- neglect the radiative contribution
- $\frac{\partial k}{\partial T} \approx 0$ in conductive solids
- trapped air isn't convective
- convective air
  - $\rho = \frac{M}{R} \frac{p + p_{atm}}{T} = 3.484 \times 10^{-3} \frac{p}{T} \quad [\mathrm{Pa}]$ $\leftarrow pV = nRT$
    - $p \Leftarrow$ weakly compressible Navier-Stokes
    - $p_{atm} = 101325\,\mathrm{Pa}$
  - $\mathbf{u}_{air} \Leftarrow$ weakly compressible Navier-Stokes
  - boundary conditions
    - $T = T_{ref}$ @ bottom
    - thermal insulation @ vertical outer bnd
    - convective flux @ top
    - $T = T_{coolant}$ @ coolant channels bnd's (if any)

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1. Background
   - The AO Principle
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2. The Actuator
   - The Multiphysics Problem
   - The Model
3. The Application Modes
   - Magnetostatics
   - Heat transfer
   - Fluid dynamics
4. Results
5. Experimental Validation

Setting Up the Weakly Compressible N-S

Assumption & Restrictions

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- $\rho = \frac{M}{R}\frac{p+p_{atm}}{T} = 3.484 \times 10^{-3}\frac{p}{T} \quad [\mathrm{kg} \times \mathrm{m}^{-3}]$ $\leftarrow pV = nRT$
- $\eta = -7.887 \times 10^{-12}\, T^2 + 4.427 \times 10^{-8}\, T + 5.204 \times 10^{-6} \quad [\mathrm{Pa} \times \mathrm{s}^{-1}]$
- $f_z = 9.81\ (\rho_{ref} - \rho_{chns}) \quad [\mathrm{N}]$
  - $\rho_{ref} = \rho$ @ $(T = T_{ref},\ p = 0)$
- boundary conditions
  - $\mathbf{u} = 0$ (wall / no slip) @ air-solid interfaces
  - $\mathbf{n} \cdot \mathbf{u} = 0$ ... (wall / slip) @ vertical outer bnd
  - $p = 0$ ... (outlet / normal stress) @ horizontal top bnd

Magnetostatic Results I

$\epsilon > 4\,\mathrm{N} \times \mathrm{W}^{-1}$

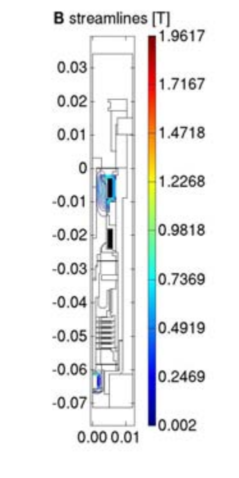
- $.57 \leq \Delta T_{Cu} \leq 3.98\,\mathrm{K}$, thanks to material optimization
- $4.05 \leq \epsilon \leq 4.1\,\mathrm{N} \times \mathrm{W}^{-1}$, thanks to geom. optimization
    1. rms turb. corr. force $.363\,\mathrm{N} \rightarrow .21\,\mathrm{A}$
    2. max dyn. force $1.27\,\mathrm{N} \rightarrow .38\,\mathrm{A}$

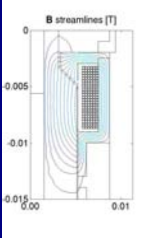
A low-order actuator vs. the current high order actuator

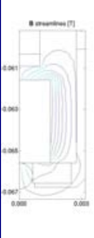
	LBT	TEC1
force	$\int_V (\mathbf{J} \times \mathbf{B})\ dV$	$\int_V (\mathbf{M} \cdot \nabla)\ \mathbf{B}\ dV$
power @ $1.27\,\mathrm{N}$ [W]	4.169	.314
power @ $.25\,\mathrm{N}$ [W]	.162	.062
mov. mass $[\mathrm{kg}\times 10^{-3}]$	2.8	14
emc	mean	negligible

Magnetostatic Results II

Shaping the Ferromagnetic Material to Focus **B**







Fluid Dynamics Results I

Computing $\Delta T = T - T_{ref}$

Background
The AO Principle
The Design Drivers
The Actuator
The Multiphysics Problem
The Model
The Application Modes
Magnetostatics
Heat transfer
Fluid dynamics
Results
Experimental Validation
Summary

- 2 force cases
  - rms turb. corr. force $f_c = .363\,\mathrm{N}$
  - max dyn. force $f_m = 1.27\,\mathrm{N}$
- *active*
  - $\Delta T_{coolant} = 0$ gives the lowest ΔT

force	max surface ΔT
f_c	$.10\,\mathrm{K}$
f_m	$.35\,\mathrm{K}$

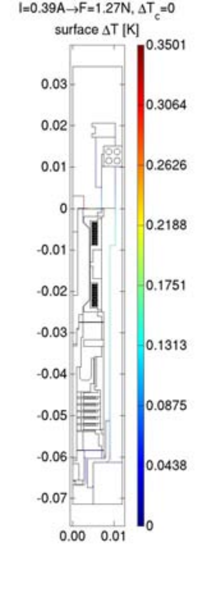
- *passive*
  - The (rare) $f = f_m$ gives out-of-specs ΔT

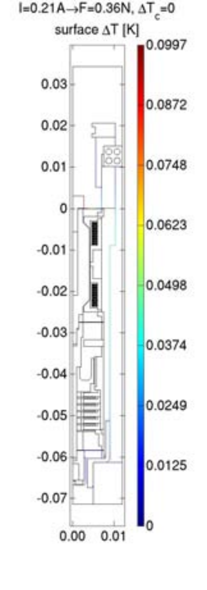
force	max surface ΔT
f_c	$.64\,\mathrm{K}$
f_m	$2.24\,\mathrm{K}$

Background
The AO Principle
The Design Drivers
The Actuator
The Multiphysics Problem
The Model
The Application Modes
Magnetostatics
Heat transfer
Fluid dynamics
Results
Experimental Validation
Summary

Fluid Dynamics Results II

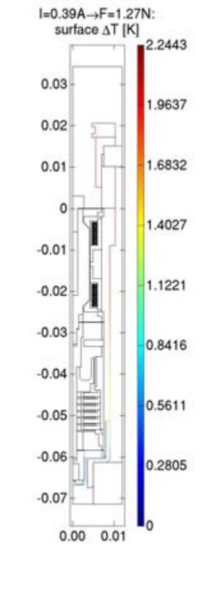
The *Active* Surface ΔT

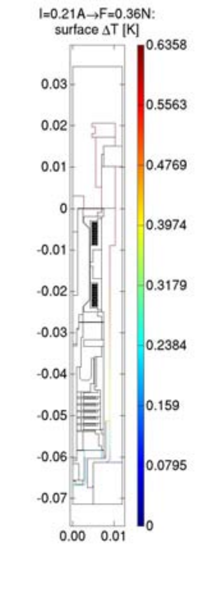




Fluid Dynamics Results III

The *Passive* Surface ΔT





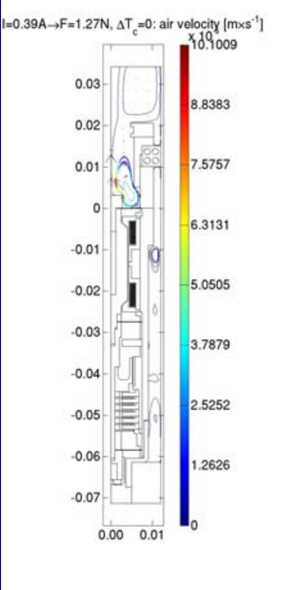
Fluid Dynamics Results IV

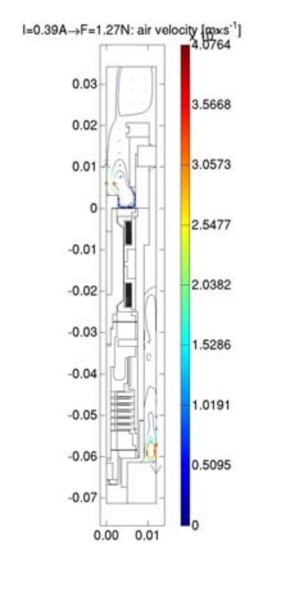
$f = f_m$: the *Active* and *Passive* Air Velocities

Novel AO Act

Del Vecchio, Biasi, Riccardi, Gallieni

Background
The AO Principle
The Design Drivers
The Actuator
The Multiphysics Problem
The Model
The Application Modes
Magnetostatics
Heat transfer
Fluid dynamics
Results
Experimental Validation
Summary





Novel AO Act

Del Vecchio, Biasi, Riccardi, Gallieni

Background
- The AO Principle
- The Design Drivers

The Actuator
- The Multiphysics Problem
- The Model

The Application Modes
- Magnetostatics
- Heat transfer
- Fluid dynamics

Results

Experimental Validation

Summary

- Running the preliminary tests
  - The mechanics is OK
  - $\epsilon \approx \frac{1}{2}$ of the design value (maybe a bad coil filling factor and stator part mismatching)

Lessons Learned & Future Work

- $\epsilon_{\mathrm{Iron+Copper}} > \epsilon_{\mathrm{PM+Copper}} \ldots$
  - but (Cons)
    - larger moving mass — DM dynamics may degrade
    - mechanical contact — tighter tolerances
    - much larger statoric mass — just higher costs
  - and (Pros)
    - low flux leakage — negligible emc
    - heat removal by natural convection — simpler design
- On the way & Still to do
  - 2d SM
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  - 3d Multiphysics — actuator interaction
  - 3d E/M & E/S

Del Vecchio, Biasi, Riccardi, Gallieni

Background
The AO Principle
The Design Drivers
The Actuator
The Multiphysics Problem
The Model
The Application Modes
Magnetostatics
Heat transfer
Fluid dynamics
Results
Experimental Validation
Summary

Lessons Learned & Future Work

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  - 3d Multiphysics — actuator interaction
  - 3d E/M & E/S

Background
The AO Principle
The Design Drivers
The Actuator
The Multiphysics Problem
The Model
The Application Modes
Magnetostatics
Heat transfer
Fluid dynamics
Results
Experimental Validation
Summary

Lessons Learned & Future Work

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  - 3d Multiphysics — actuator interaction
  - 3d E/M & E/S

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  - 2d Multiphysics — add $\dot{Q}$ from electronics boards
  - 3d Multiphysics — actuator interaction
  - 3d E/M & E/S

Background
The AO Principle
The Design Drivers
The Actuator
The Multiphysics Problem
The Model
The Application Modes
Magnetostatics
Heat transfer
Fluid dynamics
Results
Experimental Validation
Summary

Lessons Learned & Future Work

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  - 3d Multiphysics — actuator interaction
  - 3d E/M & E/S

Background
The AO Principle
The Design Drivers
The Actuator
The Multiphysics Problem
The Model
The Application Modes
Magnetostatics
Heat transfer
Fluid dynamics
Results
Experimental Validation
Summary

Lessons Learned & Future Work

- $\epsilon_{\text{Iron+Copper}} > \epsilon_{\text{PM+Copper}} \cdots$
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Lessons Learned & Future Work

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  - 2d Multiphysics — add $\dot{Q}$ from electronics boards
  - 3d Multiphysics — actuator interaction
  - 3d E/M & E/S

Background
The AO Principle
The Design Drivers
The Actuator
The Multiphysics Problem
The Model
The Application Modes
Magnetostatics
Heat transfer
Fluid dynamics
Results
Experimental Validation
Summary

Lessons Learned & Future Work

- $\epsilon_{\mathrm{Iron+Copper}} > \epsilon_{\mathrm{PM+Copper}} \cdots$
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  - 2d Multiphysics — add $\dot{Q}$ from electronics boards
  - 3d Multiphysics — actuator interaction
  - 3d E/M & E/S

Lessons Learned & Future Work

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  - 2d SM
  - 2d Multiphysics — better bnd conditions @ bottom
  - 2d Multiphysics — add $\dot{Q}$ from electronics boards
  - 3d Multiphysics — actuator interaction
  - 3d E/M & E/S

Background
The AO Principle
The Design Drivers
The Actuator
The Multiphysics Problem
The Model
The Application Modes
Magnetostatics
Heat transfer
Fluid dynamics
Results
Experimental Validation
Summary

Lessons Learned & Future Work

- $\epsilon_{\mathrm{Iron+Copper}} > \epsilon_{\mathrm{PM+Copper}} \cdots$
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  - 2d Multiphysics — better bnd conditions @ bottom
  - 2d Multiphysics — add $\dot{Q}$ from electronics boards
  - 3d Multiphysics — actuator interaction
  - 3d E/M & E/S

Background
The AO Principle
The Design Drivers
The Actuator
The Multiphysics Problem
The Model
The Application Modes
Magnetostatics
Heat transfer
Fluid dynamics
Results
Experimental Validation
Summary

Lessons Learned & Future Work

- $\epsilon_{\mathrm{Iron+Copper}} > \epsilon_{\mathrm{PM+Copper}} \cdots$
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    - larger moving mass — DM dynamics may degrade
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  - 2d SM
  - 2d Multiphysics — better bnd conditions @ bottom
  - 2d Multiphysics — add $\dot{Q}$ from electronics boards
  - 3d Multiphysics — actuator interaction
  - 3d E/M & E/S

Novel AO Act

Del Vecchio, Biasi, Riccardi, Gallieni

Background
The AO Principle
The Design Drivers
The Actuator
The Multiphysics Problem
The Model
The Application Modes
Magnetostatics
Heat transfer
Fluid dynamics
Results
Experimental Validation
Summary

Lessons Learned & Future Work

- $\epsilon_{\mathrm{Iron+Copper}} > \epsilon_{\mathrm{PM+Copper}} \cdots$
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  - 2d SM
  - 2d Multiphysics — better bnd conditions @ bottom
  - 2d Multiphysics — add $\dot{Q}$ from electronics boards
  - 3d Multiphysics — actuator interaction
  - 3d E/M & E/S

Background
The AO Principle
The Design Drivers
The Actuator
The Multiphysics Problem
The Model
The Application Modes
Magnetostatics
Heat transfer
Fluid dynamics
Results
Experimental Validation
Summary

Lessons Learned & Future Work

- $\epsilon_{\mathrm{Iron+Copper}} > \epsilon_{\mathrm{PM+Copper}} \cdots$
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  - 2d SM
  - 2d Multiphysics — better bnd conditions @ bottom
  - 2d Multiphysics — add $\dot{Q}$ from electronics boards
  - 3d Multiphysics — actuator interaction
  - 3d E/M & E/S

Background
The AO Principle
The Design Drivers
The Actuator
The Multiphysics Problem
The Model
The Application Modes
Magnetostatics
Heat transfer
Fluid dynamics
Results
Experimental Validation
Summary

Lessons Learned & Future Work

- $\epsilon_{\mathrm{Iron+Copper}} > \epsilon_{\mathrm{PM+Copper}} \cdots$
  - but (Cons)
    - larger moving mass — DM dynamics may degrade
    - mechanical contact — tighter tolerances
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  - 2d SM — thermal deformations
  - 2d Multiphysics — better bnd conditions @ bottom
  - 2d Multiphysics — add $\dot{Q}$ from electronics boards
  - 3d Multiphysics — actuator interaction
  - 3d E/M & E/S

Lessons Learned & Future Work

Background
The AO Principle
The Design Drivers
The Actuator
The Multiphysics Problem
The Model
The Application Modes
Magnetostatics
Heat transfer
Fluid dynamics
Results
Experimental Validation
Summary

- $\epsilon_{\mathrm{Iron+Copper}} > \epsilon_{\mathrm{PM+Copper}} \cdots$
  - but (Cons)
    - larger moving mass — DM dynamics may degrade
    - mechanical contact — tighter tolerances
    - much larger statoric mass — just higher costs
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    - heat removal by natural convection — simpler design
- On the way & Still to do
  - 2d SM — thermal deformations
  - 2d Multiphysics — better bnd conditions @ bottom
  - 2d Multiphysics — add $\dot{Q}$ from electronics boards
  - 3d Multiphysics — actuator interaction
  - 3d E/M & E/S

Lessons Learned & Future Work

Novel AO Act

Del Vecchio, Biasi, Riccardi, Gallieni

Background
- The AO Principle
- The Design Drivers

The Actuator
- The Multiphysics Problem
- The Model

The Application Modes
- Magnetostatics
- Heat transfer
- Fluid dynamics

Results

Experimental Validation

Summary

- $\epsilon_{\mathrm{Iron+Copper}} > \epsilon_{\mathrm{PM+Copper}} \cdots$
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    - low flux leakage — negligible emc
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  - 2d SM — thermal deformations
  - 2d Multiphysics — better bnd conditions @ bottom
  - 2d Multiphysics — add $\dot{Q}$ from electronics boards
  - 3d Multiphysics — actuator interaction
  - 3d E/M & E/S

Lessons Learned & Future Work

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    - mechanical contact — tighter tolerances
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  - 2d SM — thermal deformations
  - 2d Multiphysics — better bnd conditions @ bottom
  - 2d Multiphysics — add $\dot{Q}$ from electronics boards
  - 3d Multiphysics — actuator interaction
  - 3d E/M & E/S

Lessons Learned & Future Work

Background
The AO Principle
The Design Drivers
The Actuator
The Multiphysics Problem
The Model
The Application Modes
Magnetostatics
Heat transfer
Fluid dynamics
Results
Experimental Validation
Summary

- $\epsilon_{\mathrm{Iron+Copper}} > \epsilon_{\mathrm{PM+Copper}} \cdots$
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- On the way & Still to do
  - 2d SM — thermal deformations
  - 2d Multiphysics — better bnd conditions @ bottom
  - 2d Multiphysics — add $\dot{Q}$ from electronics boards
  - 3d Multiphysics — actuator interaction
  - 3d E/M & E/S

Background
The AO Principle
The Design Drivers
The Actuator
The Multiphysics Problem
The Model
The Application Modes
Magnetostatics
Heat transfer
Fluid dynamics
Results
Experimental Validation
Summary

Lessons Learned & Future Work

- $\epsilon_{\mathrm{Iron+Copper}} > \epsilon_{\mathrm{PM+Copper}} \cdots$
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- On the way & Still to do
  - 2d SM — thermal deformations
  - 2d Multiphysics — better bnd conditions @ bottom
  - 2d Multiphysics — add $\dot{Q}$ from electronics boards
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  - 3d E/M & E/S

Lessons Learned & Future Work

- $\epsilon_{\text{Iron+Copper}} > \epsilon_{\text{PM+Copper}} \cdots$
  - but (Cons)

larger moving mass	DM dynamics may degrade
mechanical contact	tighter tolerances
much larger statoric mass	just higher costs

  - and (Pros)

low flux leakage	negligible emc
heat removal by natural convection	simpler design

- On the way & Still to do

2d SM	thermal deformations
2d Multiphysics	better bnd conditions @ bottom
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  - 2d SM — thermal deformations
  - 2d Multiphysics — better bnd conditions @ bottom
  - 2d Multiphysics — add $\dot{Q}$ from electronics boards
  - 3d Multiphysics — actuator interaction
  - 3d E/M & E/S

Background
- The AO Principle
- The Design Drivers

The Actuator
- The Multiphysics Problem
- The Model

The Application Modes
- Magnetostatics
- Heat transfer
- Fluid dynamics

Results

Experimental Validation

Summary

Lessons Learned & Future Work

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  - 2d Multiphysics — better bnd conditions @ bottom
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  - 2d Multiphysics — better bnd conditions @ bottom
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  - 3d E/M & E/S — tolerances $\rightsquigarrow$ run-out & tilt

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  - 2d Multiphysics — add $\dot{Q}$ from electronics boards
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For Further Reading I

Del Vecchio, C. Biasi, R. Gallieni, D. Riccardi, A. and Spairani, R.
Actuating the Deformable Mirror: a Multiphysics Design Approach
in B. L. Ellerbroek and D. Bonaccini Calia (eds), *Astronomical Telescopes and Instrumentation*, Vol. 7015, SPIE, Marseille, France, pp. 157-167, 2008.

For Further Reading II

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in D. Bonaccini Calia, B. L. Ellerbroek and R. Ragazzoni (eds), *Advancements in Adaptive Optics*, Vol. 5490, SPIE, Glasgow, UK, pp. 1564–1571, 2004.