UCRL-TR-204664

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# A HYBRID PASSIVE/ACTIVE MAGNETIC BEARING SYSTEM

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June 11, 2004

This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

FY05 LDRD Engineering ERD Review

# A DYNAMICALLY STABLE, HIGH STIFFNESS, HYBRID PASSIVE/ACTIVE MAGNETIC BEARING SYSTEM


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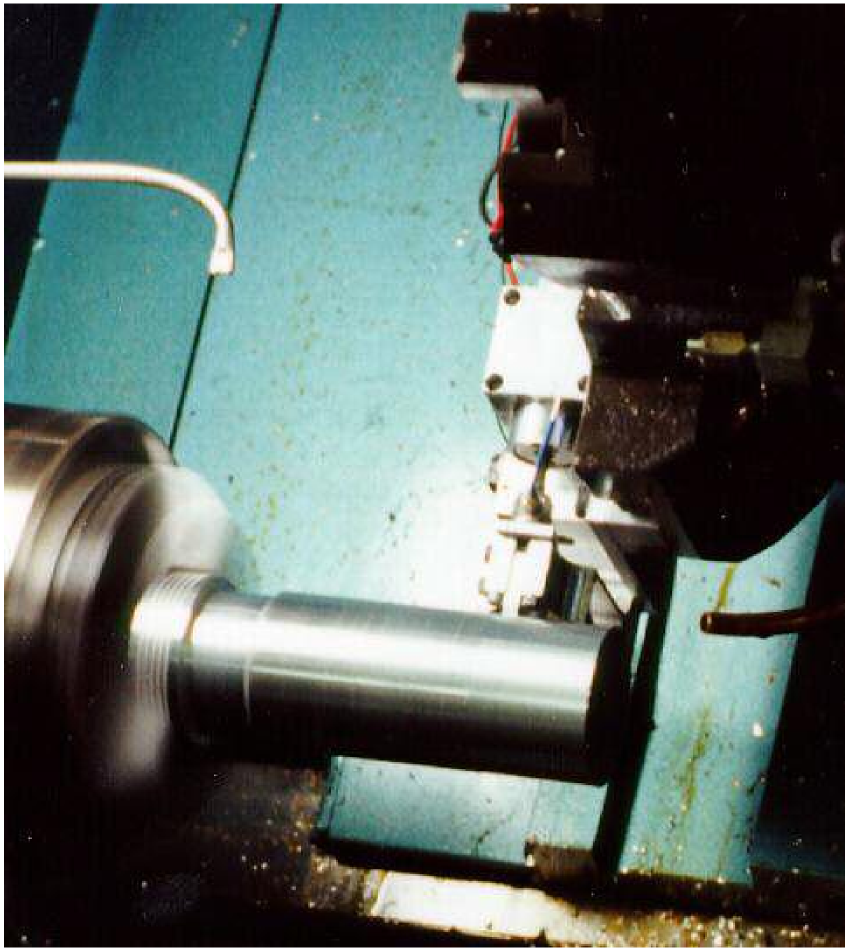
Co-Investigators: Richard Post, PhD (E&E, Energy Technology): Theoretical Physics, Magnetic Confinement of Plasmas

Steve Hunter, MS (EE): Instrumentation,Control Systems

Layton Hale, PhD (ME): Precision Engineering, Machine Design


Project Goal: R&D a novel hybrid passive/active magnetic bearing system suitable for precision engineering applications

# Precision Machining R&D Objectives



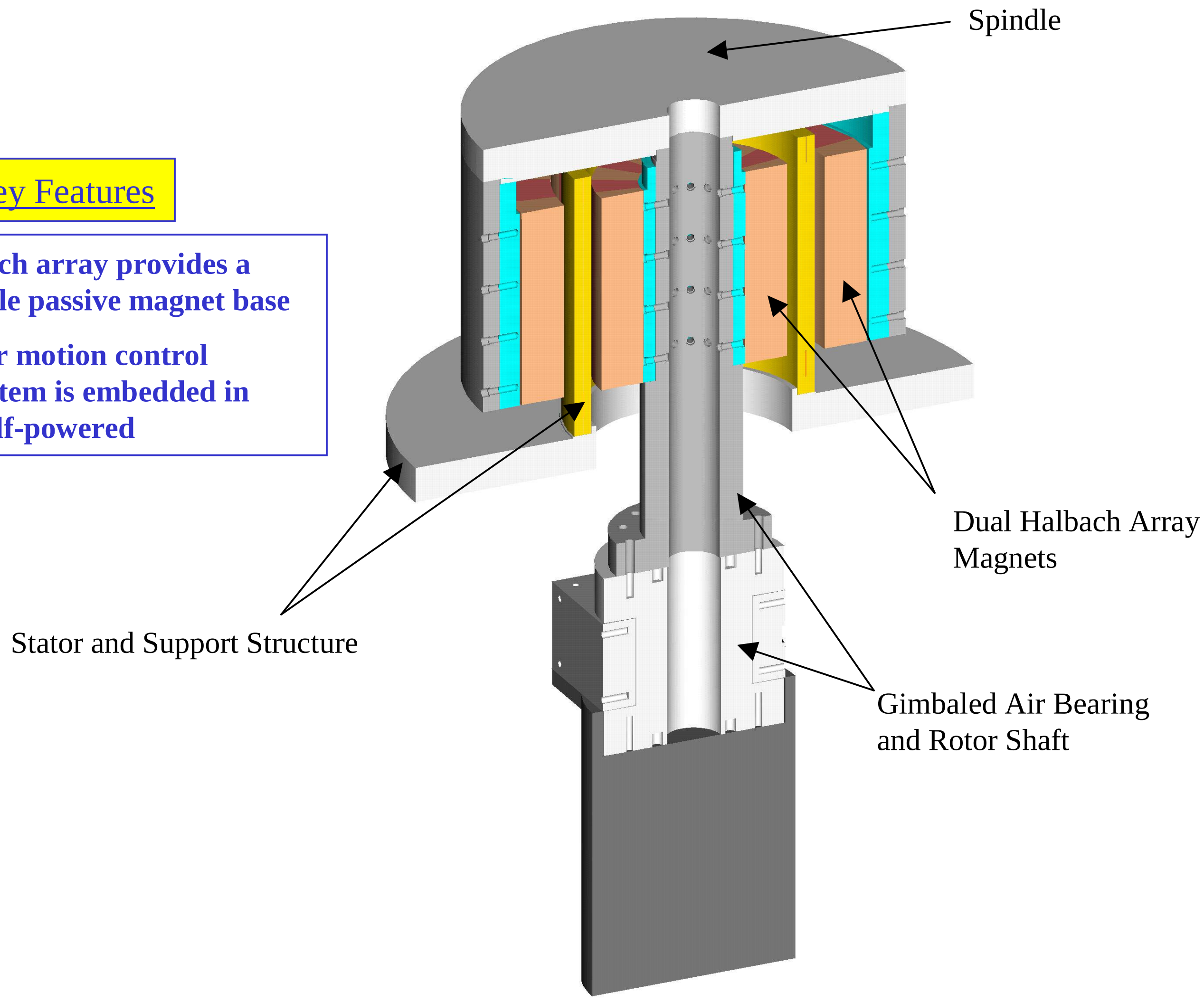
- Current precision machining relies on hydrostatic bearings for high load capacity situations and air bearings when very low error motion is a priority
    - Its difficult to get both qualities from one type of bearing
    - Air bearings are not well suited for vacuum or negative pressure applications
    - Hydrostatic bearings are susceptible to contamination when working with radioactive or otherwise hazardous materials
    - Neither can be aligned “on-the-fly”
- Our goal is to extend the “state-of-the-art” in precision machining by designing a machine with the load capacity of a hydrostatic bearing, the low error motion of an air bearing, and none of their above mentioned weaknesses
- This goal has the potential to be realized by employing a special type of hybrid magnetic bearing

# Hybrid Passive/Active Magnetic Bearing:

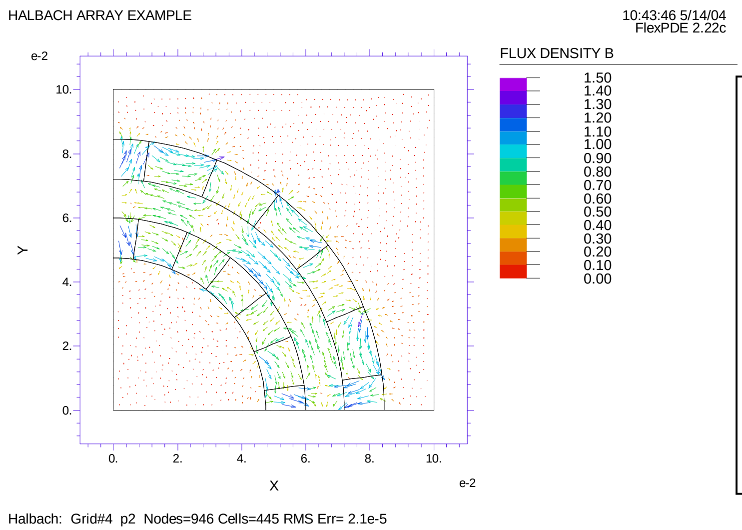
# Proof of Concept Prototype

Key Features

- Dual Halbach array provides a stiff and stable passive magnet base
- Active error motion control actuation system is embedded in stator and self-powered



# Theoretical Development




Rotor Equations of Motion

$$x'' + 2\varsigma(2x' - \lambda\theta'_y) + (2x - \lambda\theta_y) = \varepsilon\Omega^2 \cos\Omega t$$

$$y'' + 2\varsigma(2y' + \lambda\theta'_x) + (2y + \lambda\theta_x) = \varepsilon\Omega^2 \sin\Omega t$$

$$\theta''_x + 2\Omega\theta'_y + 8\varsigma(\alpha\theta'_x + \beta y') + 4(\alpha\theta_x + \beta y) = \varepsilon\gamma\phi\Omega^2 \cos\Omega t$$

$$\theta''_y - 2\Omega\theta'_x + 8\varsigma(\alpha\theta'_y - \beta x') + 4(\alpha\theta_y - \beta x) = \varepsilon\gamma\phi\Omega^2 \sin\Omega t$$

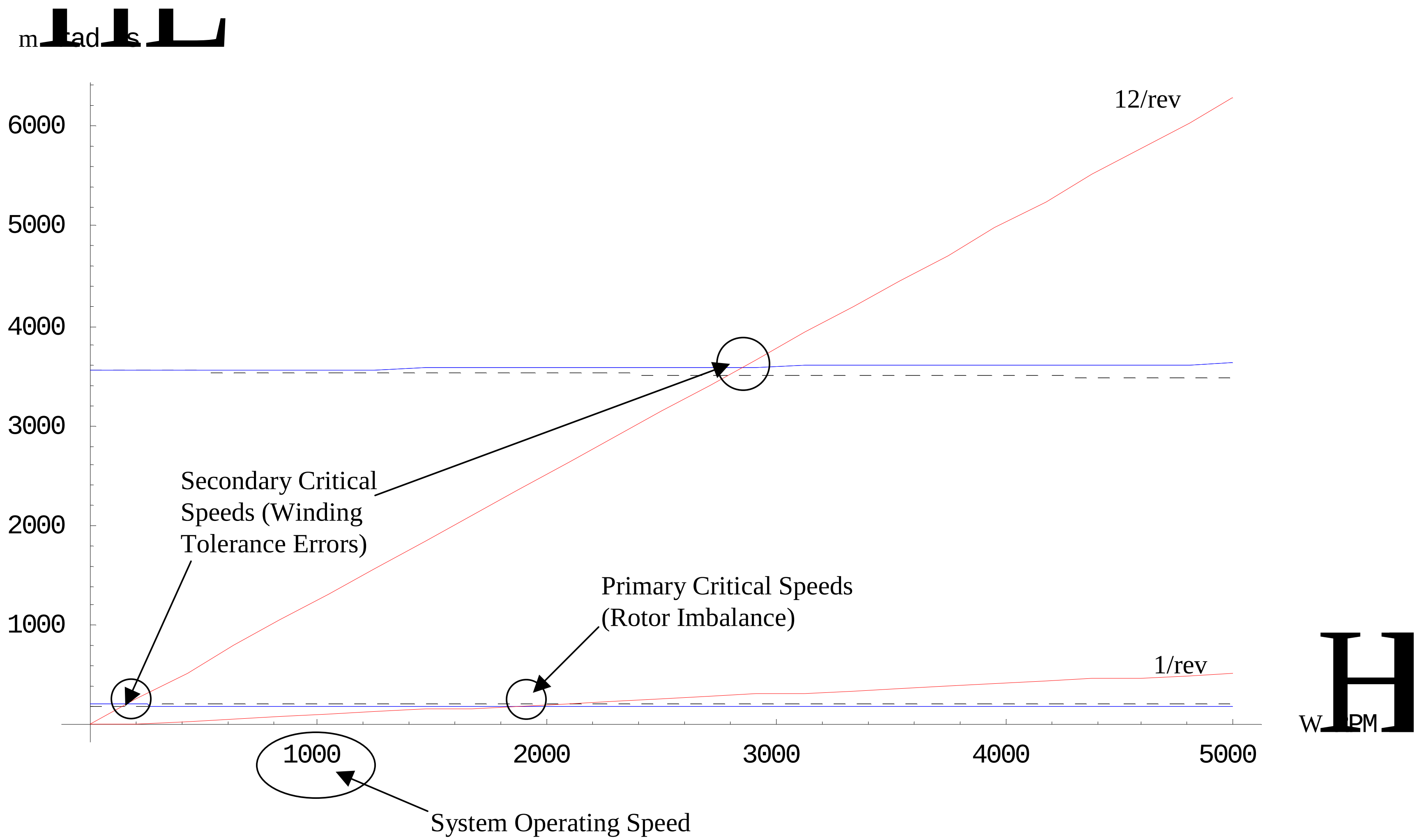
- **Theoretical development based on “First Principles”**
- **Detailed 3-D electro-mechanical calculations show only a few percent difference from 2-D assumption**
    - **2-D assumption is ideal for use in initial design and is adequate to prove concept feasibility**
    - **Current FEA agrees well with previous calculations**
- **System rotor-dynamic equations of motion derived**
    - **Dynamic response of rotor quantified**
    - **Rotor whirl mode frequencies determined**
    - **Passive component stability criteria established as a function of system parameters**
- **Bearing heat generation quantified**

# Precision Magnetic Bearing System Design Requirements

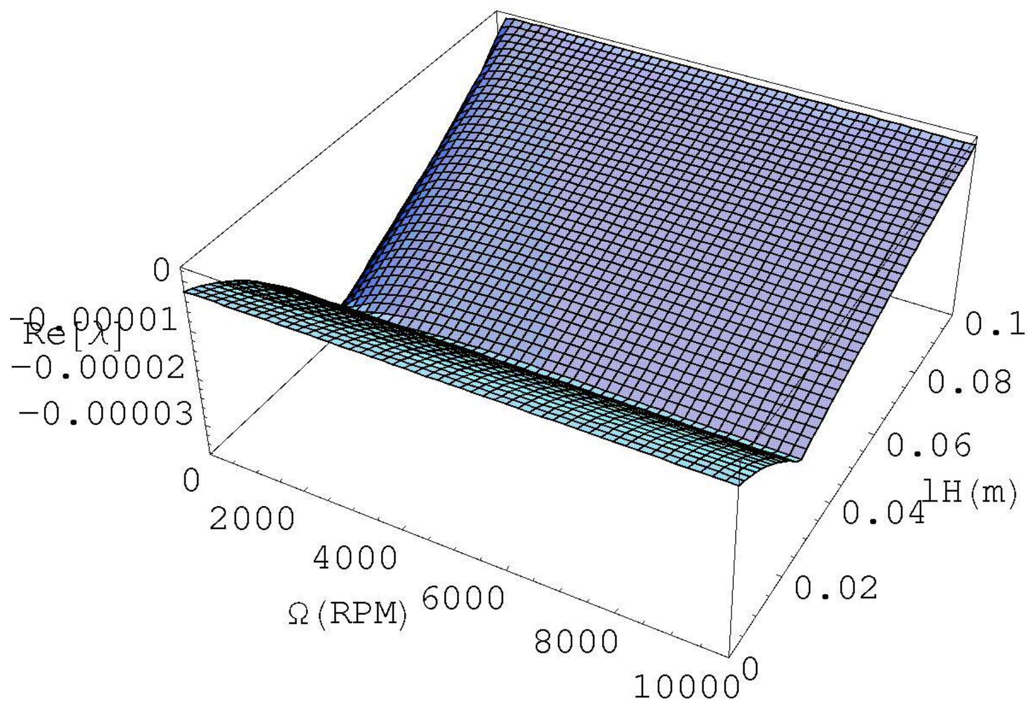
- System should be stable
  - Halbach array based system proven to be stable
- System should be initially aligned to at or below a micron
  - The system must be unresponsive to external and/or internal excitation at operating speed
    - Rotor should be balanced to micron tolerances
    - Passive component should provide the dynamic characteristics needed
  - The spindle's position and angular orientation relative to the stator must be adjustable
- Once initially aligned, the system must have the capability to perform small spindle adjustments "on-the-fly" and must be able to control residual error motions to 50 nanometer levels
  - Control system must have adequate bandwidth
  - Magnet and winding support structure must be very stiff
- The heat flow to spindle must be small
  - Gravity and operational loads should be taken up with auxiliary permanent magnets
  - Eddy current heating should be minimized
  - Control actuation forces should be small

# ROTORDYNAMICS

# System Campbell Diagram

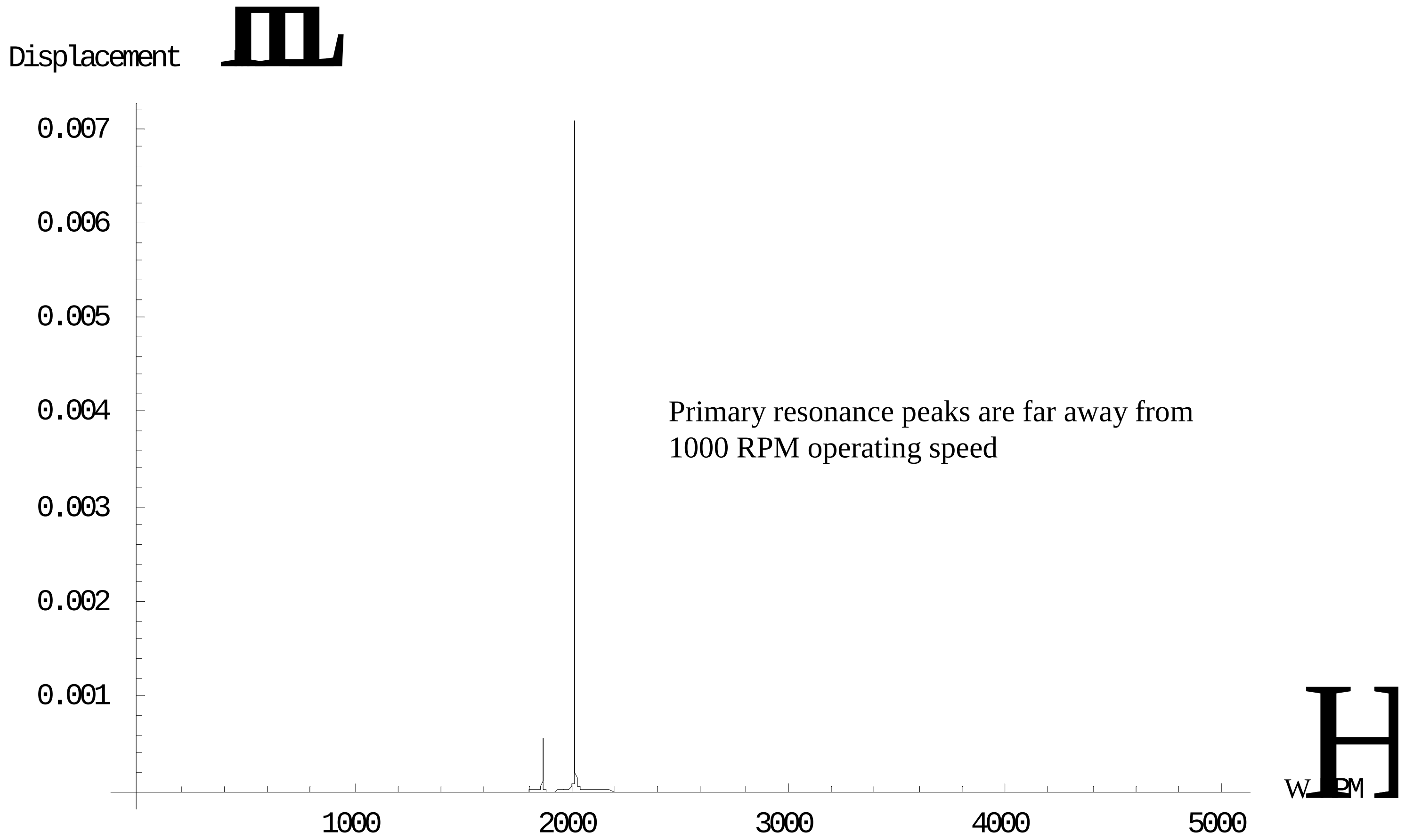


# System Theoretical Characterization: System Stability

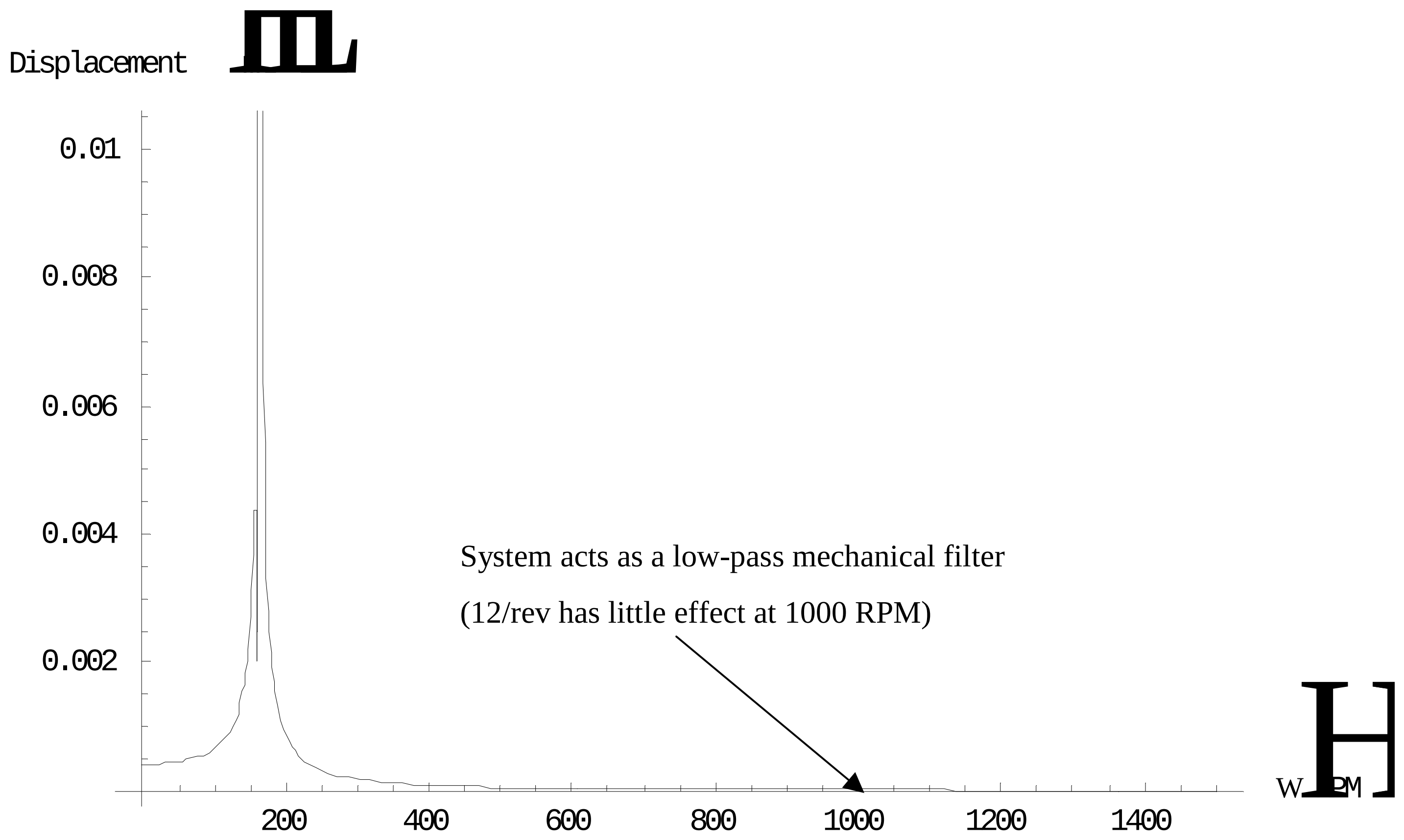



- Rotor stability as a function of operating speed and spindle overhang determined
- Passive system is stable with minimal amount of passive damping
    - Can easily be achieved with use of bleed resistor in control windings
- Passive system is stable with minimal amount of stiffness anisotropy
    - Can easily be incorporated into main windings during deposition

# System Rotor Imbalance Response Plot

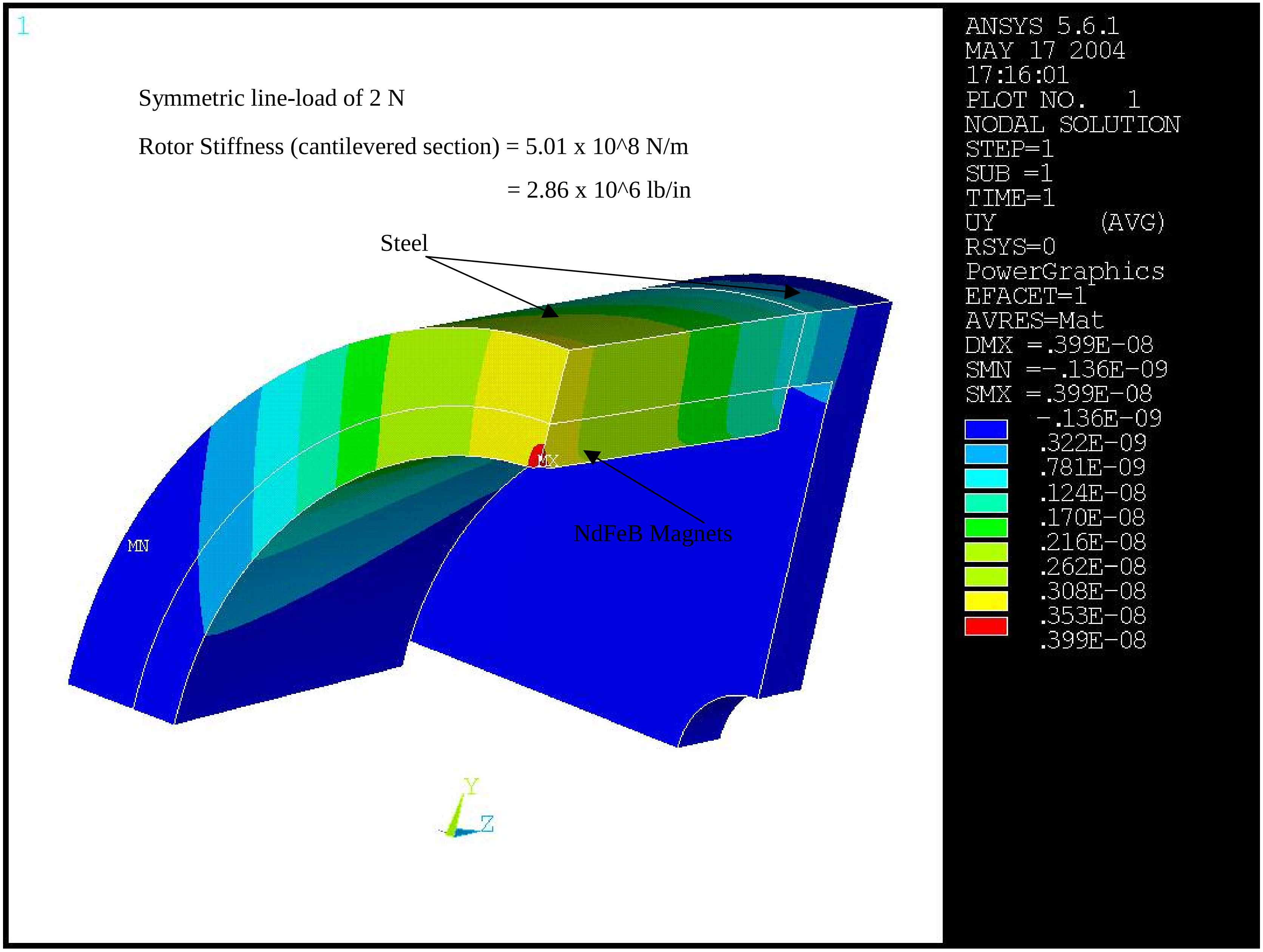


# System Response to Windings Dimensional Tolerance Errors

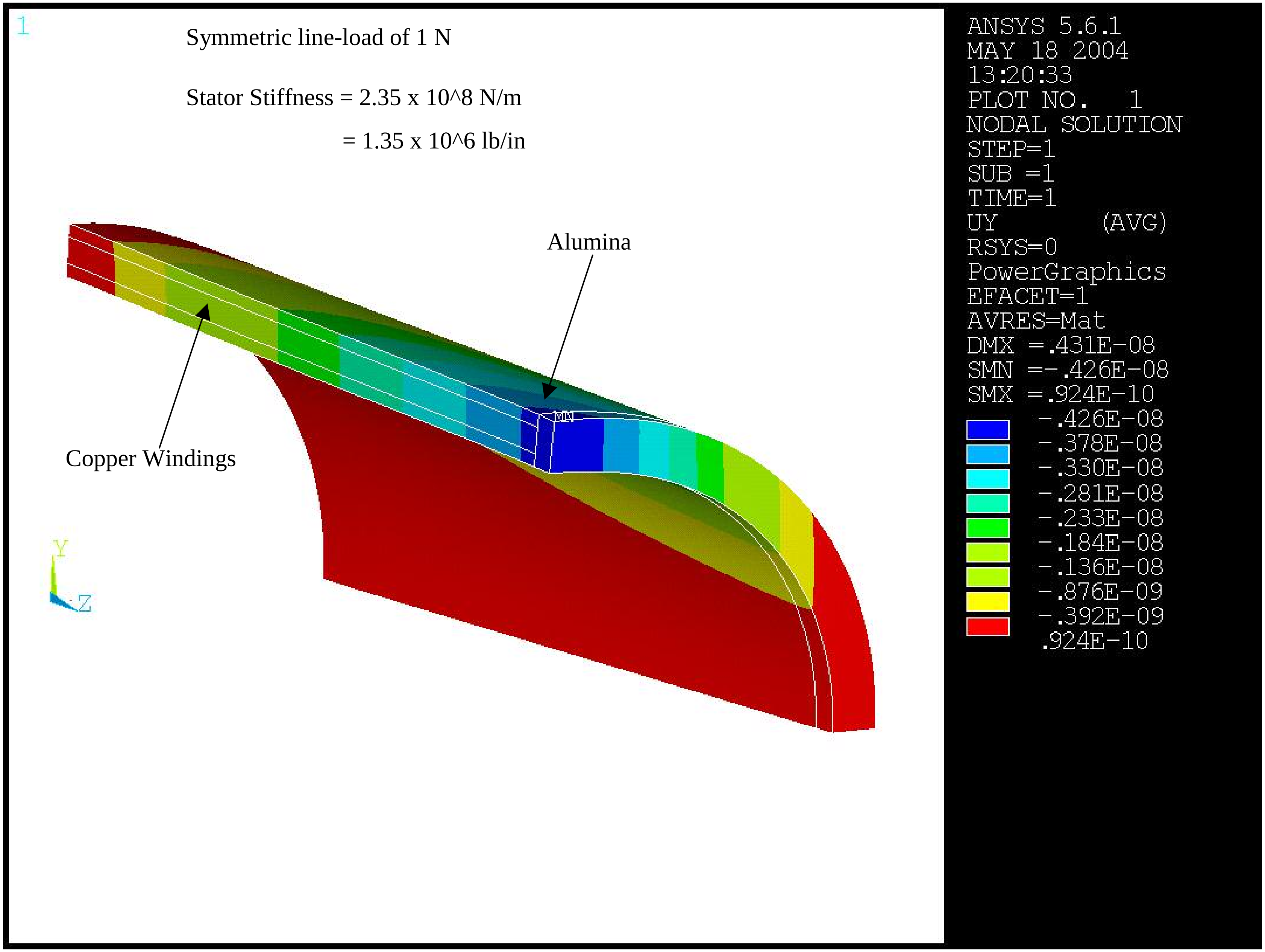


# SUPPORT STRUCTURE STIFFNESS

# Rotor Structural Stiffness

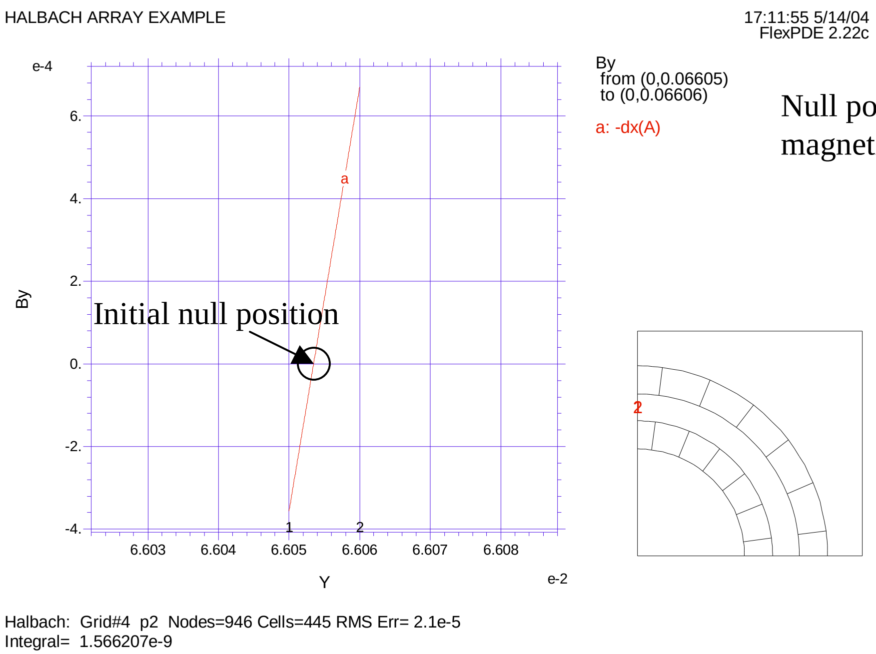


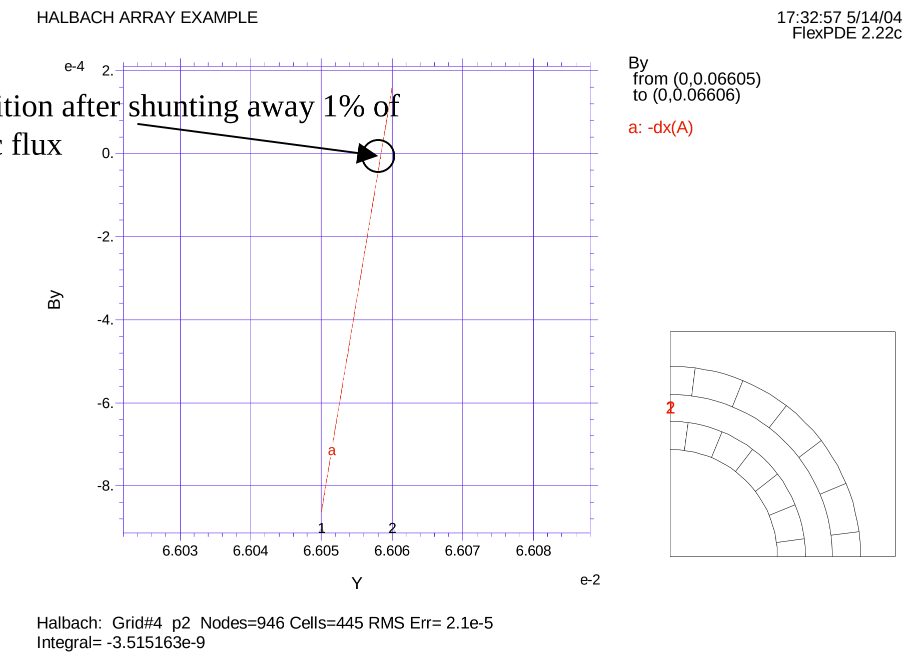
# Stator Structural Stiffness



# INITIAL ROTOR ALIGNMENT METHODOLOGY

# "Flux Shorting" Method



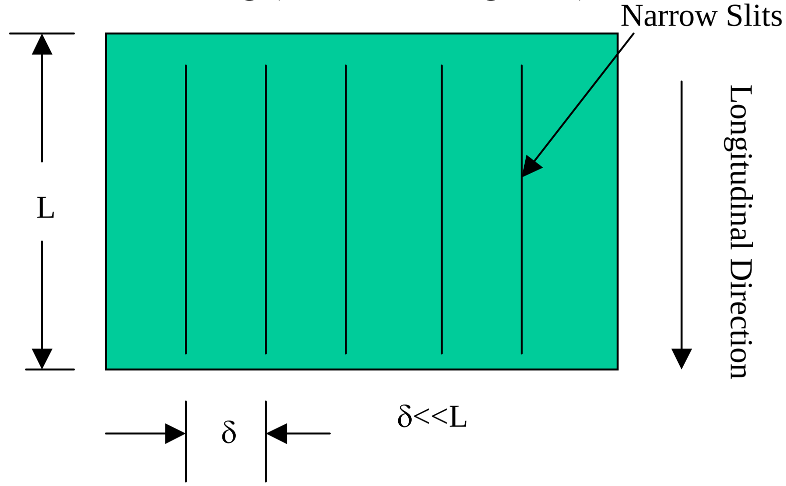




**A 1% flux reduction in the top magnet resulted in the position of the null radius being moved 4 microns in the immediate vicinity**

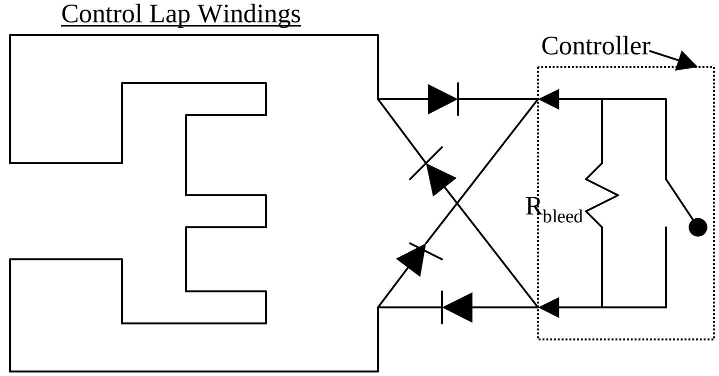
# MAIN WINDINGS AND CONTROL SYSTEM

# Main Windings, Control System, and Sensors

Main Windings(Thin Conducting Sheet)




Control Lap Windings

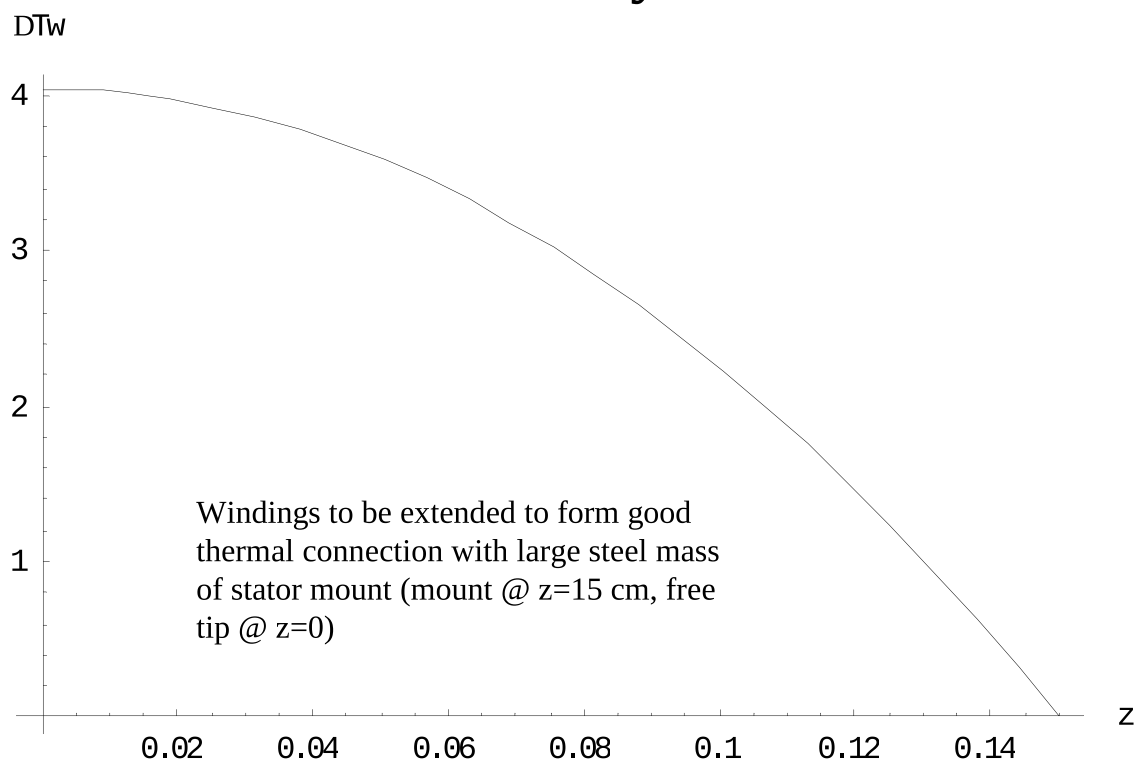



- •Main windings give passive system stiffness and stability
  - •Main windings are located on null surface
  - •Narrow slits greatly reduce parasitic eddy-currents
  - •Will consist of laminated copper layers to further limit eddy currents
  - •Anisotropy can be manufactured into windings to aid stability

- •Capacitance gauges will be used to determine position error
- •Lap windings will be deposited on the surface of the outer alumina cylinder: An off-null position
  - •This will allow for the introduction of passive damping with a bleed resistor
  - •The actuation forces are self-generated => There is no need for an external power source
- •All control algorithm needs to do is close a switch to turn on the actuator force
  - •Time constant of actuation force rise is much smaller than rotor period
- •Periodic error motions (those due to rotor imbalance, out-of-roundness,miss-alignment, and cyclic disturbance) will allow a model-based error correction algorithm to be used

# EDDY CURRENT HEAT GENERATION

# Main Winding and Spindle Heating Due to Parasitic Eddy Currents




The windings' mean temperature rise, DTw = 2.69673 C

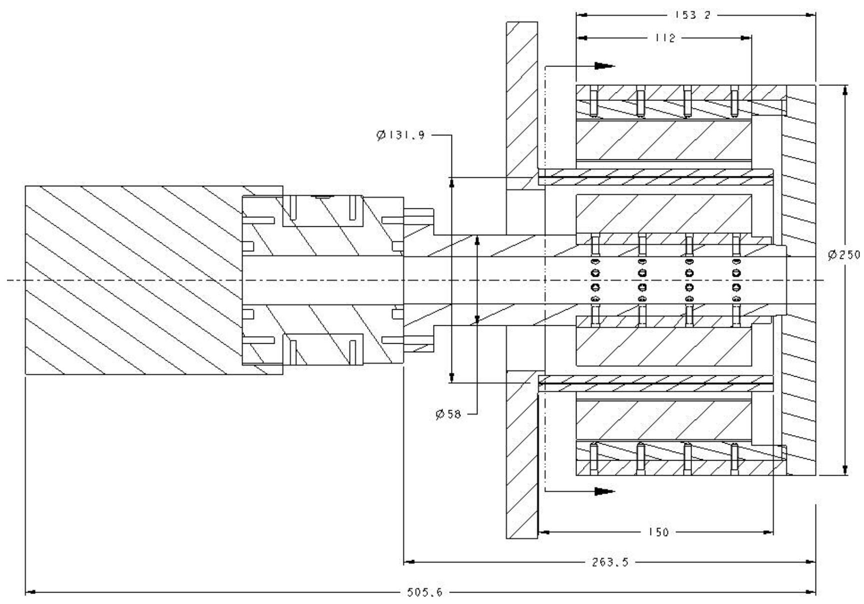
The spindle surface temperature rise, DTsp = 1.14548 C

Heat loss rate through spindle = 1.22426 Watts

# Error Budgeting

- **Total spindle radial error motion amplitude is a sum of component error motions**
  - **$E_{SRE} = E_{OR} + E_{MA} + E_{IMB} + E_{THERMAL} + E_{TOL} < 50$ nm**
    - **Where $E_{SRE}$ is the total spindle radial error motion amplitude**
  - **$E_{IMB}$ is the error motion amplitude due to rotor imbalance (dynamic miss-alignment)**
    - **This is calculated to less than 30 nm at operating speed provided rotor can be balanced to within a micron and micro-radian**
  - **$E_{TOL}$ is the error motion amplitude due to dimensional tolerance errors in the main windings**
    - **This can be eliminated by having a sufficiently large wavelength in the Halbach array**
  - **$E_{THERMAL}$ is the error motion amplitude due to bearing heat generation**
    - **This does not appear to be significant**
  - **$E_{OR}$ is the error motion amplitude due to out-of-roundness of the rotor**
    - **This error motion is predicted to be initially corrected to the sub-micron level by "flux shorting", then reduced even more by the control system**
  - **$E_{MA}$ is the error motion amplitude due to mechanical and/or magnetic miss-alignment of the rotor (static miss-alignment)**
    - **This error motion is predicted to be initially corrected to the sub-micron level by "flux shorting", then reduced even more by the control system**
- **The control system ideally should limit: $E_{OR} + ( E_{MA} + E_{IMB}) < 50$ nm using only small control forces**

# Prototype Magnetic Bearing System




- Initial prototype design will be vertical axis machine
  - Configuration will have a precision air bearing for axial load stiffness and a dual Halbach array rotor for radial stiffness
  - Simplest design that will demonstrate capability of magnetic bearing
- The stator will be two concentric alumina cylinders with the main windings between them, and located at the dual Halbach array's null radius
- Control actuation lap windings will be deposited on the surface of the outer cylinder off the null
  - This results in an embedded, self-powered control actuation system
  - An efficient, unique concept
- The dual Halbach array is a stabilizing element giving the system intrinsic stability
- Method of "flux shorting" a very unique way to initially align rotor and compensate for out-of-roundness error
- No one has ever tried to control spindle error motion employing permanent magnets with an embedded control system