Engineering, Operations & Technology
Boeing Research & Technology

Design, Fabrication, and Test of a 5 kWh Flywheel Energy Storage System Utilizing a High Temperature Superconducting Magnetic Bearing

Mike Strasik
Flywheel Program Manager

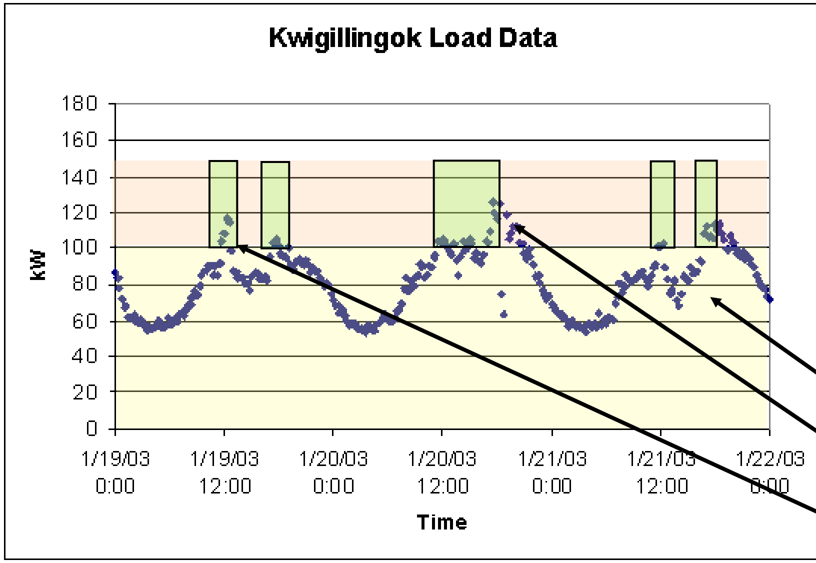
J R Hull, J A Mittleider, J F Gonder, P E Johnson, K E McCrary, and C R McIver

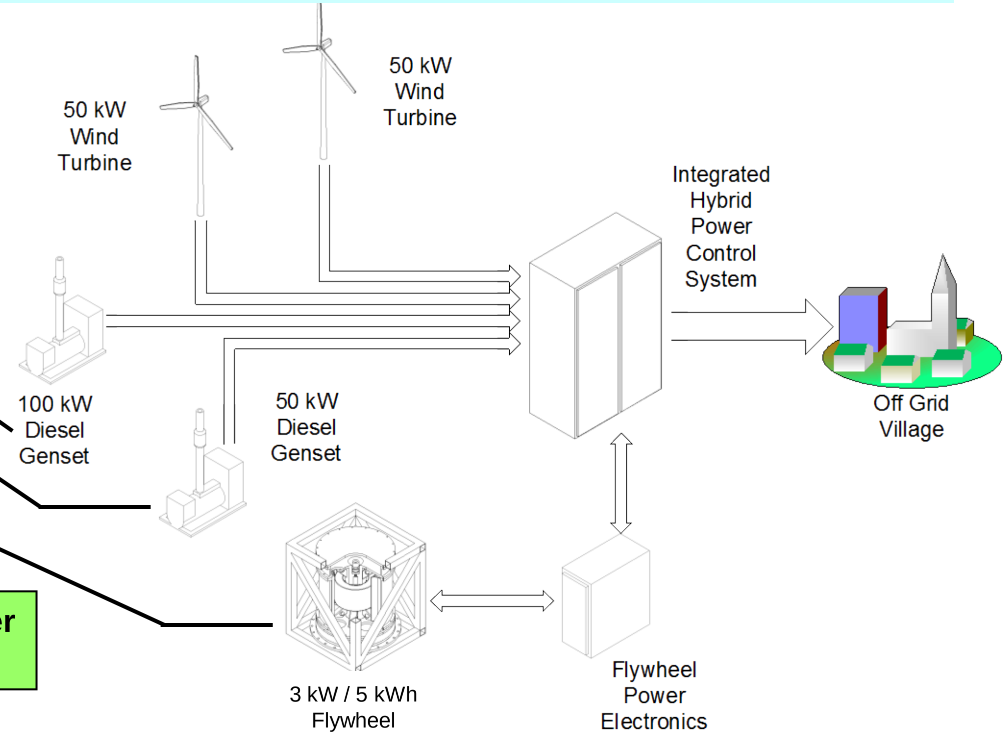
2010 Energy Storage Systems Program, November 2-4, 2010 Washington DC

This work was supported by the U.S. Department of Energy/Sandia National Laboratories Energy Storage Program Contract #598172 and #1059559 .

System Architecture for Deployment of a 3 kW / 5 kWh Flywheel Energy Storage System – DOE/Sandia Project

Objective: Design, build and deliver a flywheel energy storage system tailored for off-grid applications

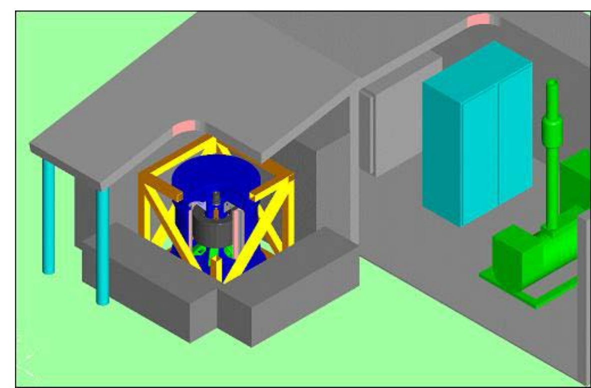




Flywheel Energy Storage System would supply power during short peak demand periods

Benefits of Using FESS Instead of Idling 2nd Generator on Standby

- **Reduce Generator Maintenance by 50% (estimate)**
- **Reduce Fuel Costs by $200k/yr (estimate)**
- **Lower Pollution**



One of three deployment options for the demo system, shown in relation to diesel genset and balance of system.

Energy Storage Program 5 kWh / 3 kW Flywheel Energy Storage System Project History and Roadmap

6/99 – 9/99

Phase I: Application ID and Initial System Specification

- Applications
- Characteristics
- Planning

5/00 – 3/01

3/01 – 11/-01 (funding interruption)

1/04 – 05/-04 (funding interruption)

Phase I: Significant Outputs

- Unit characteristics
- System specification document

11/01 – 03/07

Phase II: Component Development and Testing

- Rotor/bearing
- Materials
- Reliability

Phase II: Significant Outputs

- Prelim design complete
- HTS crystal array complete
- Material lifetime data
- Rotor upgrade complete
- Rotor qualification testing complete

04/07 – 03/10

1/09 – 8/09 (funding interruption)

Phase III: System Integration and Component Testing

- Site selection
- Detail design
- Build/buy

Phase III: Significant Outputs

- Direct cooled HTS Bearing
- Most flywheel hardware built

10/10 – 9/11

3/10 – 10/10(funding interruption)

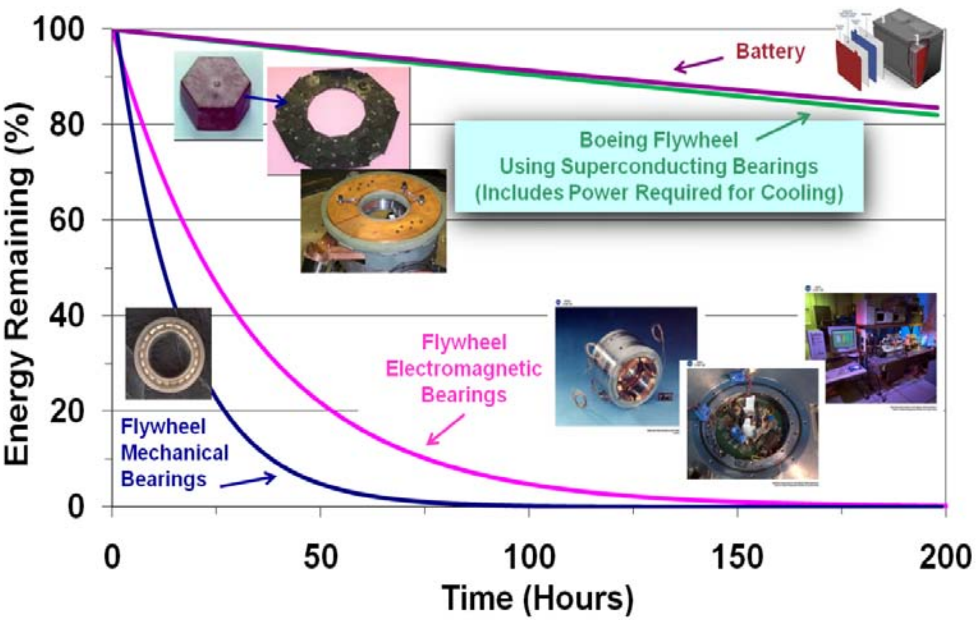
New Contract: System Integration Lab Test

- System integration
- Conduct lab spin testing
- Post-test evaluation

Flywheel Energy Storage System

- **Why Pursue Flywheel Energy Storage?**
  - Environmentally clean (green)
  - Low maintenance
  - Potential for high power density (W/ kg) and high energy density (W-Hr/ kg)
  - Can handle rapid charge and discharge rates without degradation
  - Cycle life times of >25 years
  - Broad operating temperature range

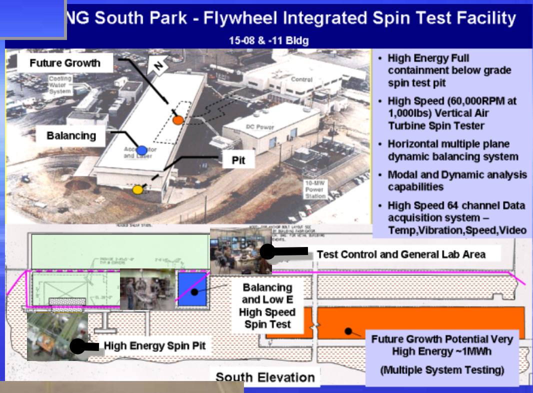
- **Why use high temperature superconducting bearings?**
  - Very low bearing losses to extend the idle mode
  - Simple passive system
  - HTS bearings will support ultra high-speed flywheels for high energy density
    - (Energy = (1/2) (Moment of Inertia) (Spin Speed)^2)



Boeing….Leading the industry by combining enabling technologies to create high energy dense electro-mechanical power systems for terrestrial and aerospace applications

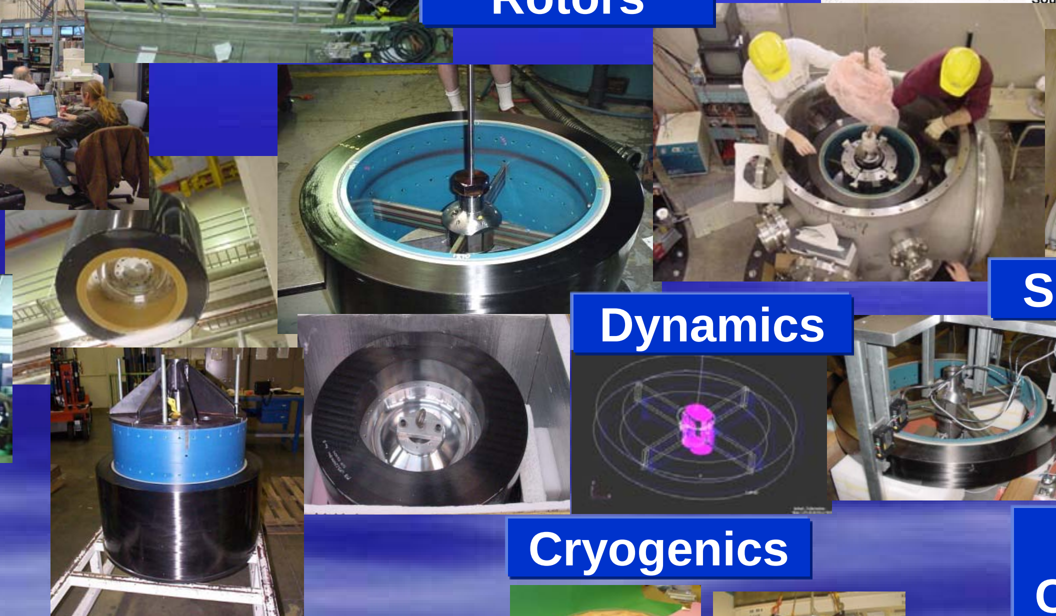
Flywheel Spin Test Facility

Cutting Edge Technology for Energy Storage



Test Facility

Composite Rotors



Spin Tests

Dynamics

Shaker Tests

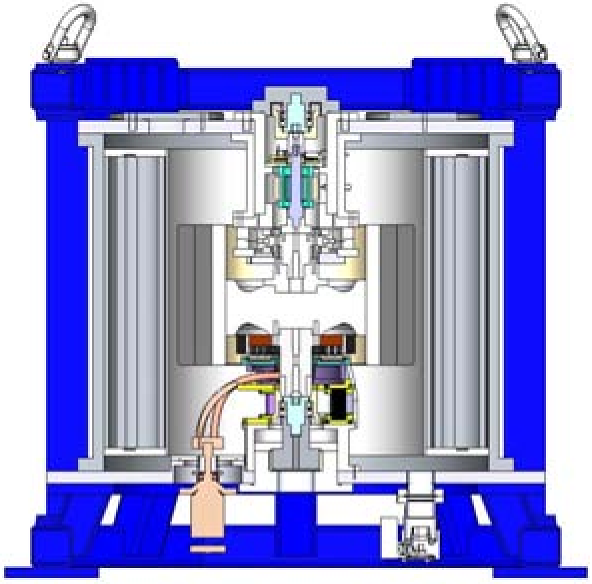
Cryogenics

Safety Containment

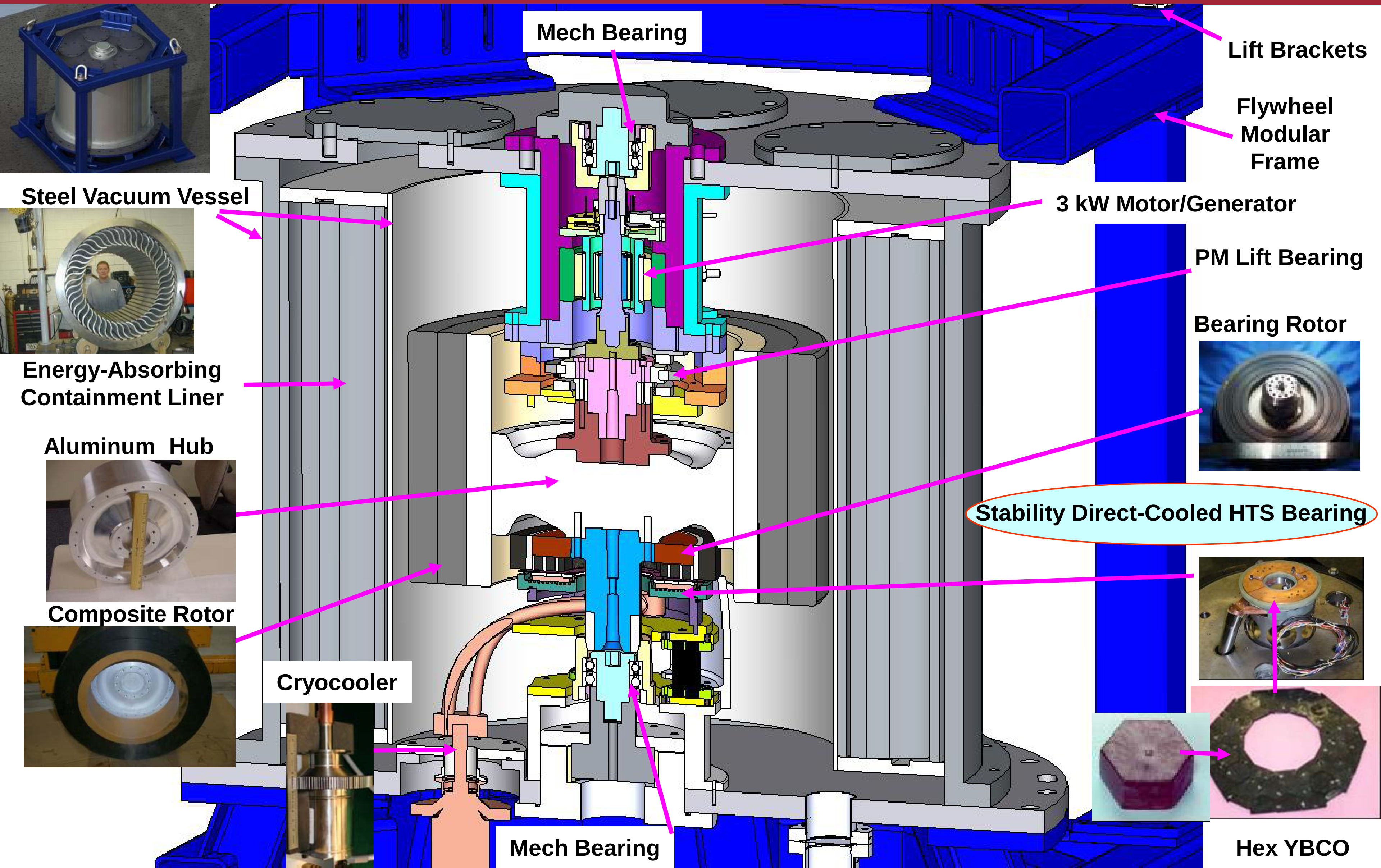
Balancing

5 kWh / 3 kW Flywheel System Design

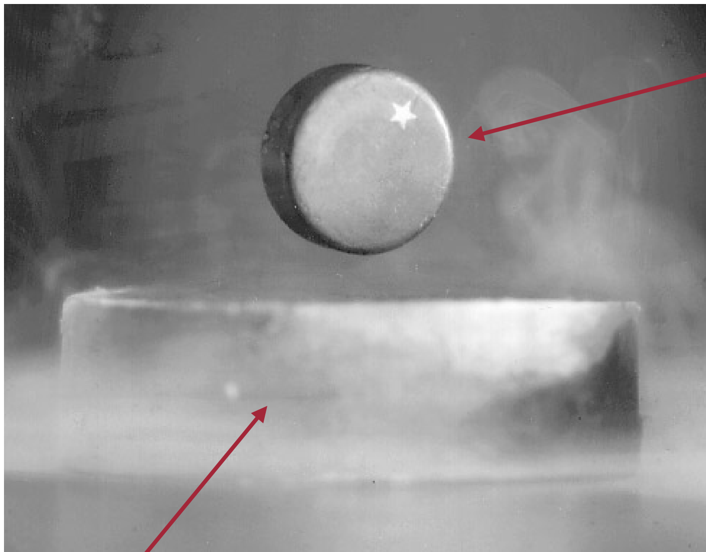
- **Design Highlights**
  - **Non-Contact Hybrid Composite Rotor with Aluminum Hub**
  - **Direct Cooled HTS Bearing with Passive Damper**
  - **Full Containment System**
  - **Redesigned Touchdown (Backup) Bearings**
  - **Custom Encoder for True Rotational Position**



5 kWh Boeing Modular Flywheel Design (DOE/Sandia)



Basic Bearing Construction



permanent magnet

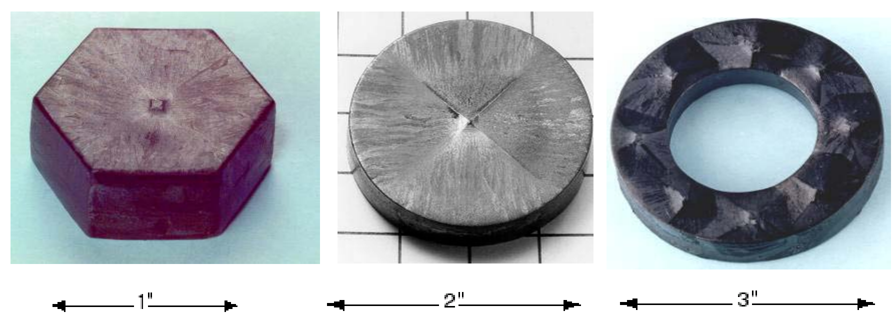
high-temperature superconductor

Relevant Properties of Superconductors:

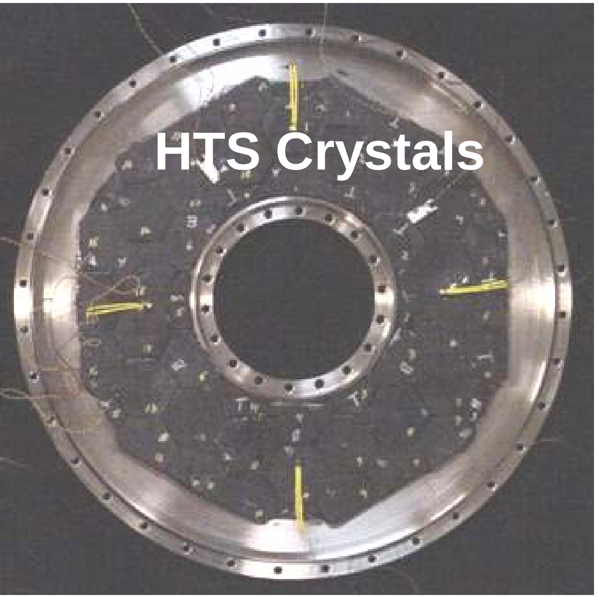
1. Zero resistance to dc current flow
2. Strong diamagnetism, keeping applied magnetic flux from entering the superconductor

The permanent magnet levitates with passive stability, rotating freely while maintaining position

Bulk crystal form (not wire) is preferred for bearings



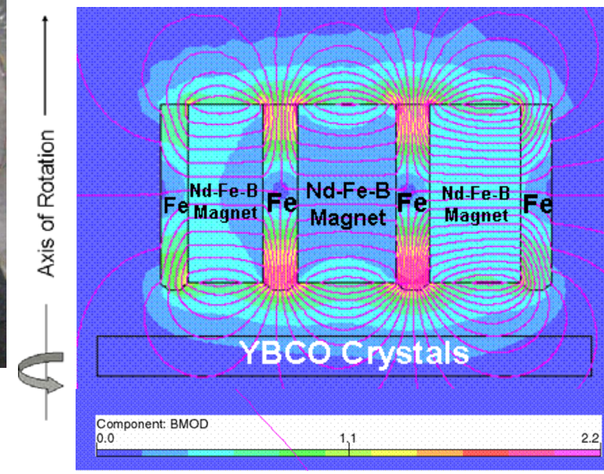
Superconducting Bearing System

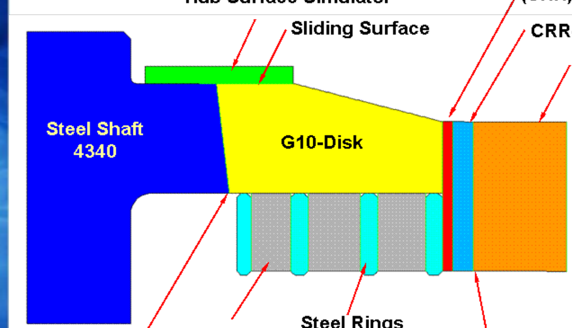


Trapped Field Profile

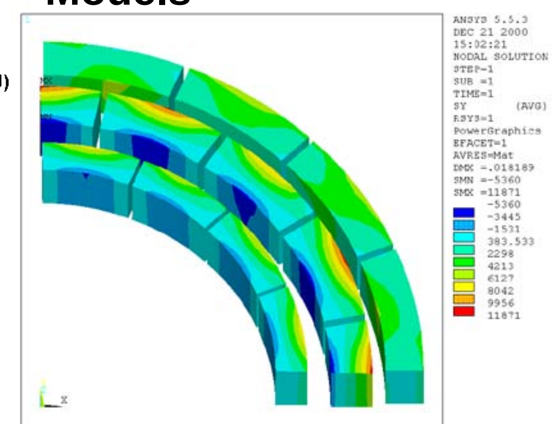
10”

Electromagnetic Models



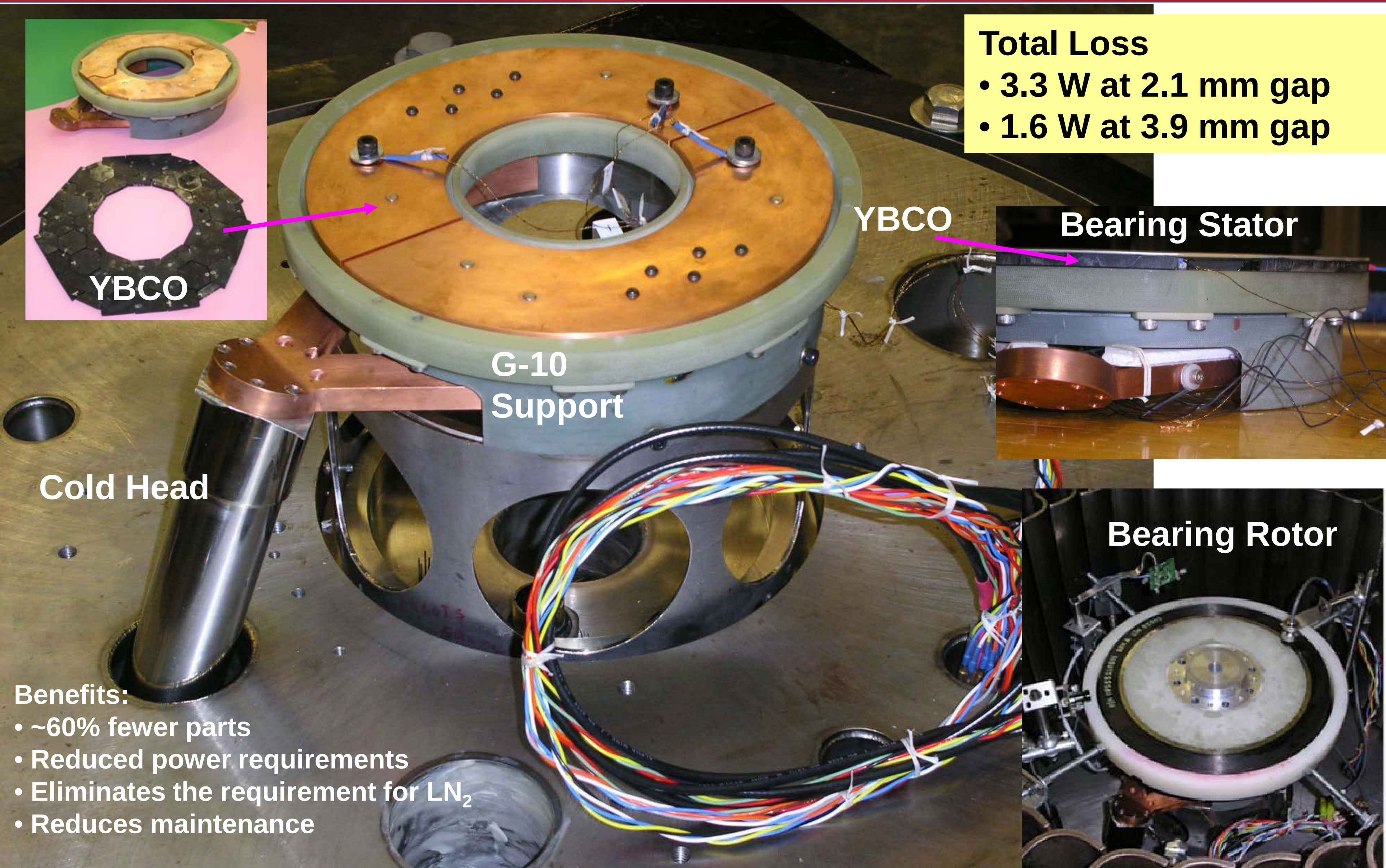


Structural Bearing Models



Direct-Cooled HTS Bearing Design – Generation 3

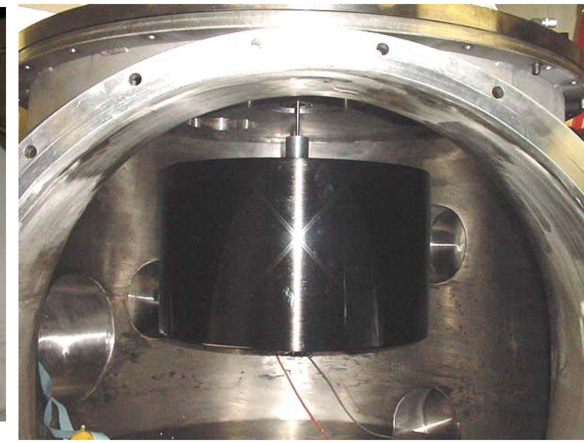
Total Loss
- **3.3 W at 2.1 mm gap**
- **1.6 W at 3.9 mm gap**

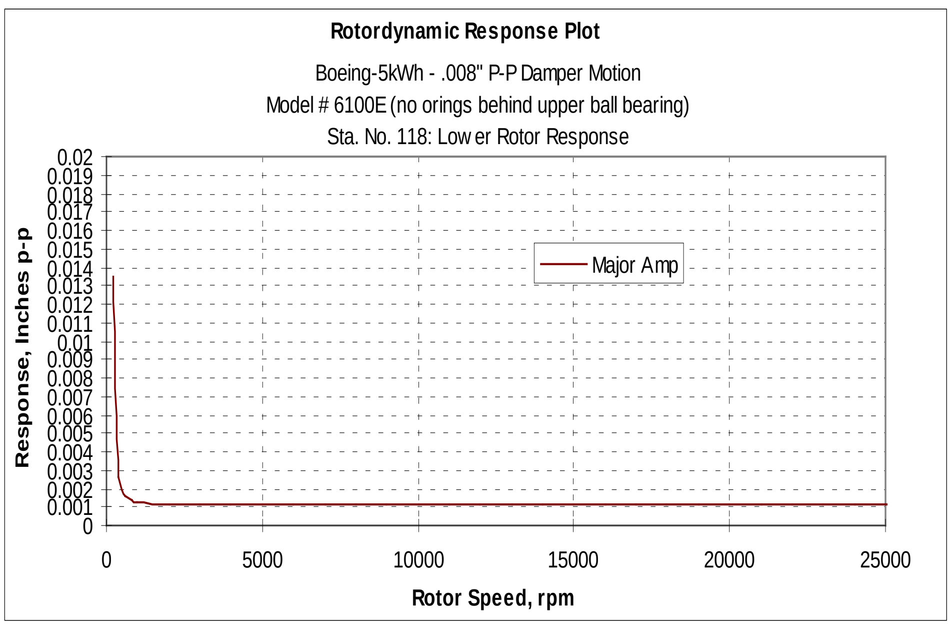


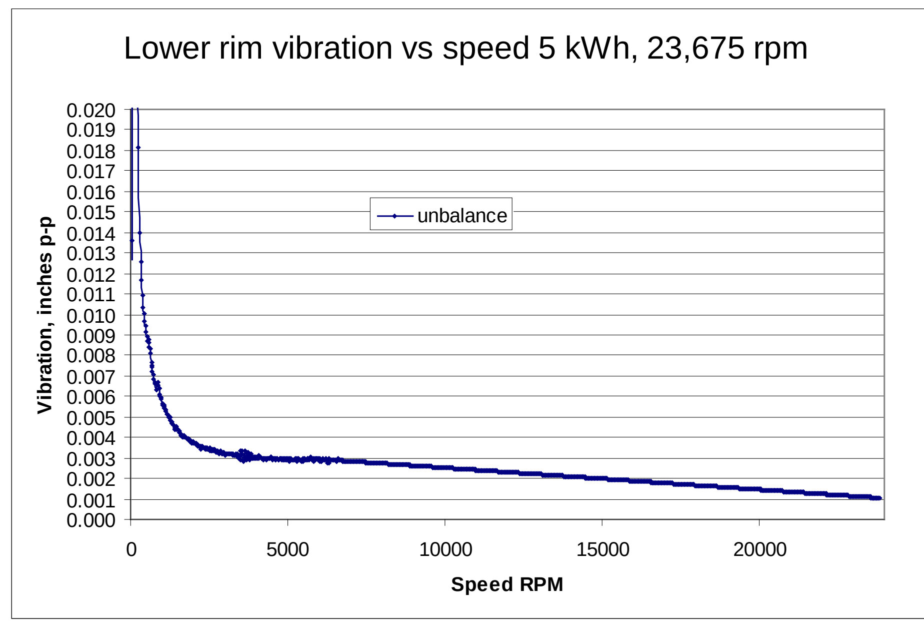
Benefits:
- **~60% fewer parts**
- **Reduced power requirements**
- **Eliminates the requirement for LN_2**
- **Reduces maintenance**

Quill Test Dynamic Model vs. Quill Test Data

- Normal max operational speed is 22,500 RPM
- Quill tested at 105% or 23,675 RPM
- Rotor Total Indicated Runout (TIR) held to 0.002” – didn’t need to balance



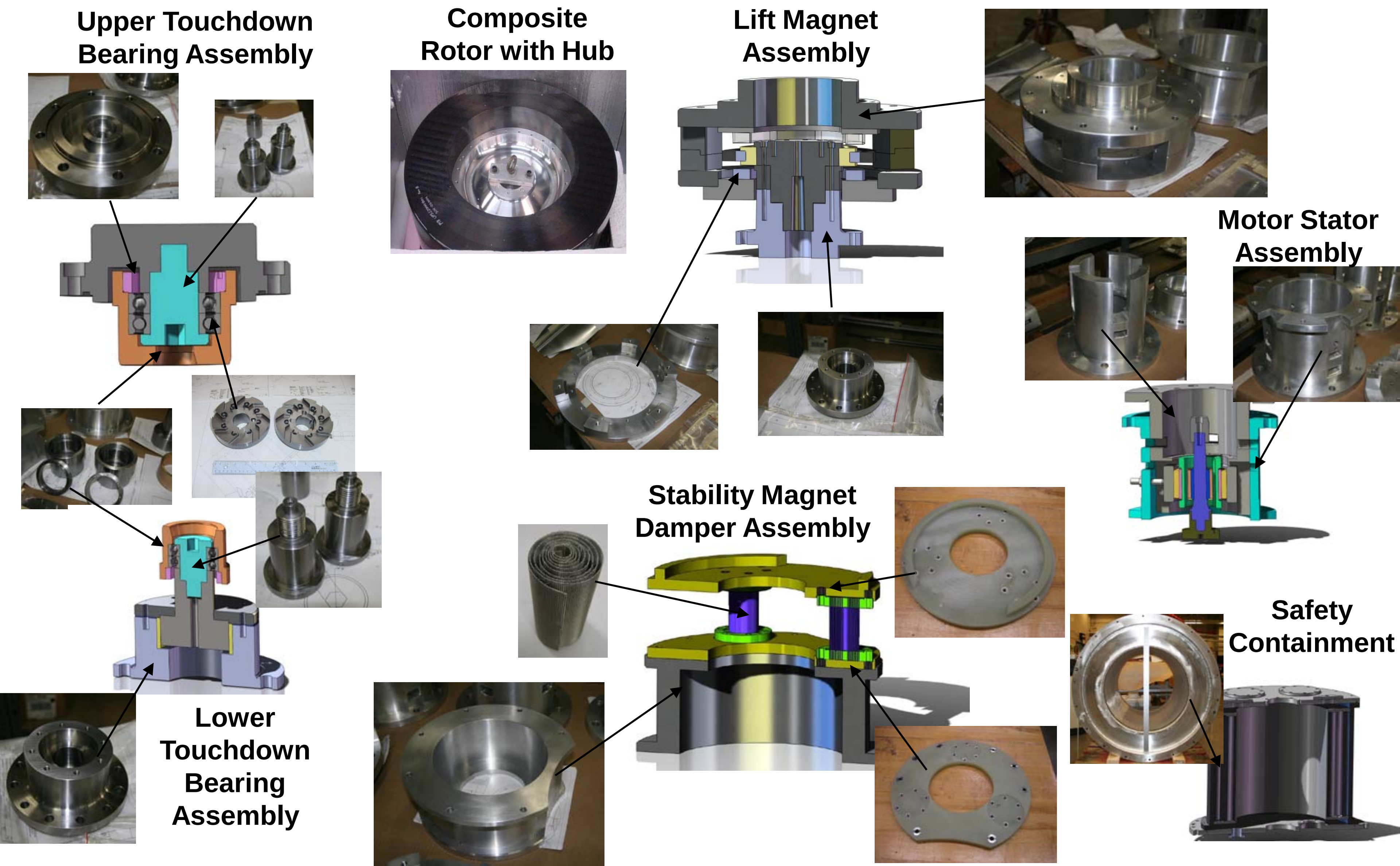




xLrotor forced response plot showing the amplitude of unbalance vs rpm

XLRotor Spreadsheet for Rotordynamic Analysis
© Rotating Machinery Analysis, Inc.

5 kWh Flywheel Hardware Completed



2010-2011 Future Tasks

Task 1: Complete fabrication of remaining components

- Fabricate or modify mechanical components of the 5 kWh / 3 kW FESS system

Task 2: Continue Integration of 5 kWhr / 3 kW FESS

- Continue integration of 5 kWh flywheel system to prepare for spin testing
- Integrate and test new flywheel damper system
- Perform motor encoder test and motor controller hardware integration test
- Integrate flywheel rotor system into one vacuum / containment system which will be mounted into a single external support structure

Task 3: Low speed testing of 5 kWhr / 3kW FESS

- Conduct and analyze low-speed testing of 5 kWh flywheel system

Task 4: Communicate program results and progress

Summary

- The 5 kWh rotor is complete and fully tested at 105% speed
- The direct cooled High Temperature Superconducting bearing was successfully tested
  - Losses measured
  - Thermal models
  - Cryocooler performance measured and verified
- System design completed
- Majority of flywheel mechanical parts built and delivered
- Remaining parts on order
- Started system integration