Boeing Technology
Phantom Works

Design, Fabrication, and Test of a 5-kWh/100-kW Flywheel Energy Storage Utilizing a High-Temperature Superconducting Bearing

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University of Cambridge, UK

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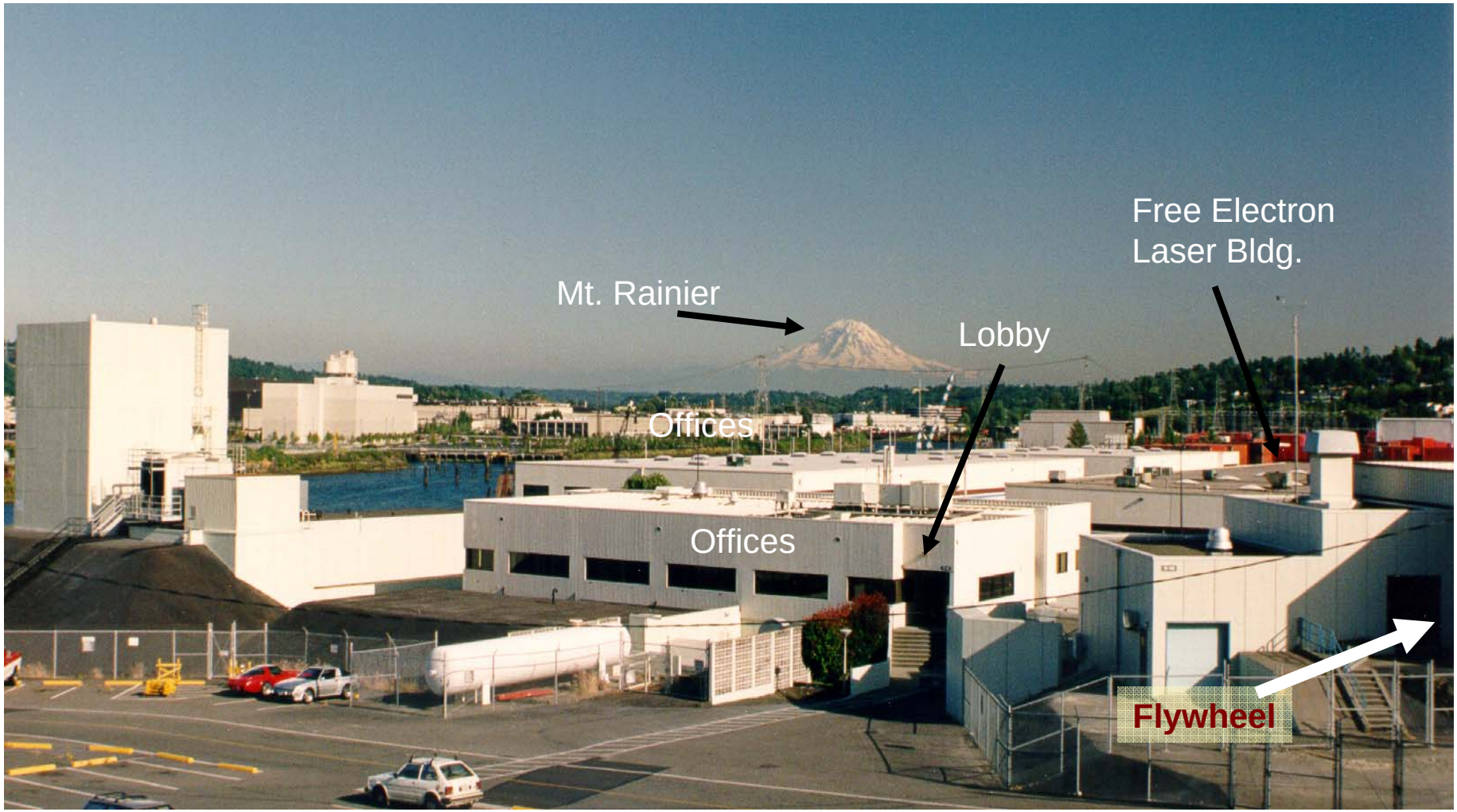
Outline

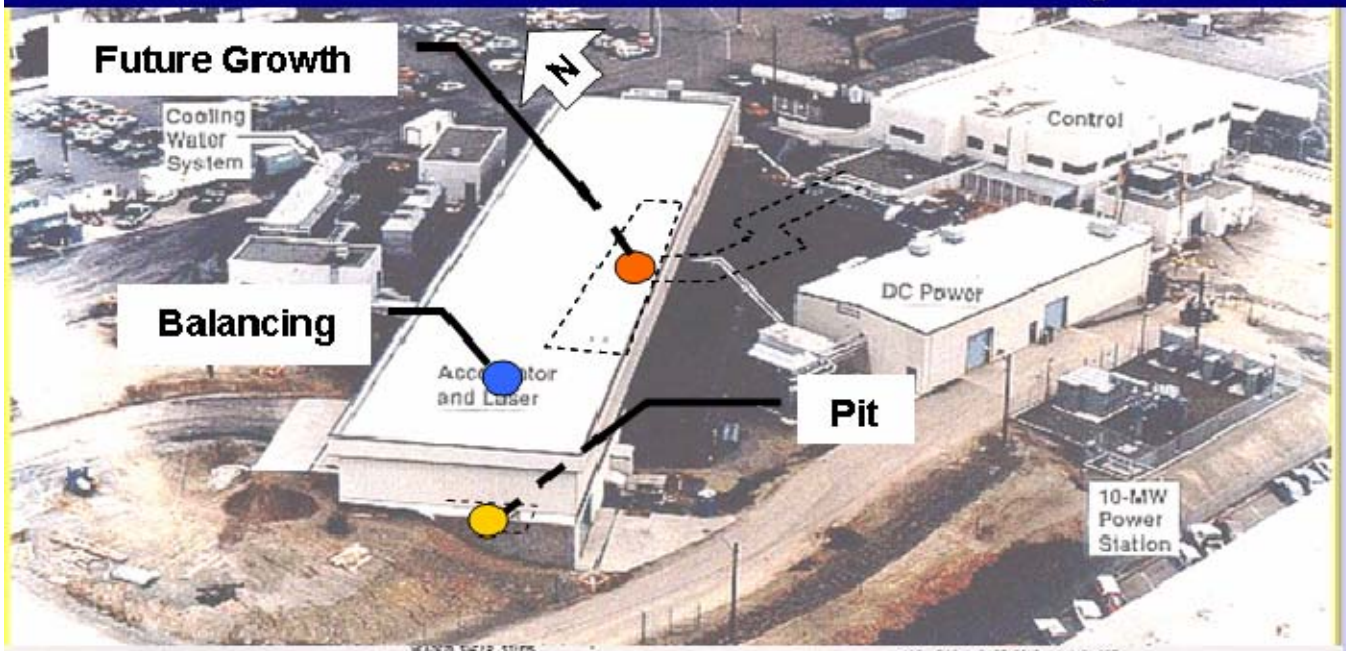
- Flywheel application description
- 5 kWh /100 kW FES design and test results
- Previous HTS bearing and cryogenic set-up and results
- Direct cooled bearing design and test results
- Description of direct cooled test set-up
- Summary

Boeing Flywheel Facility - Seattle

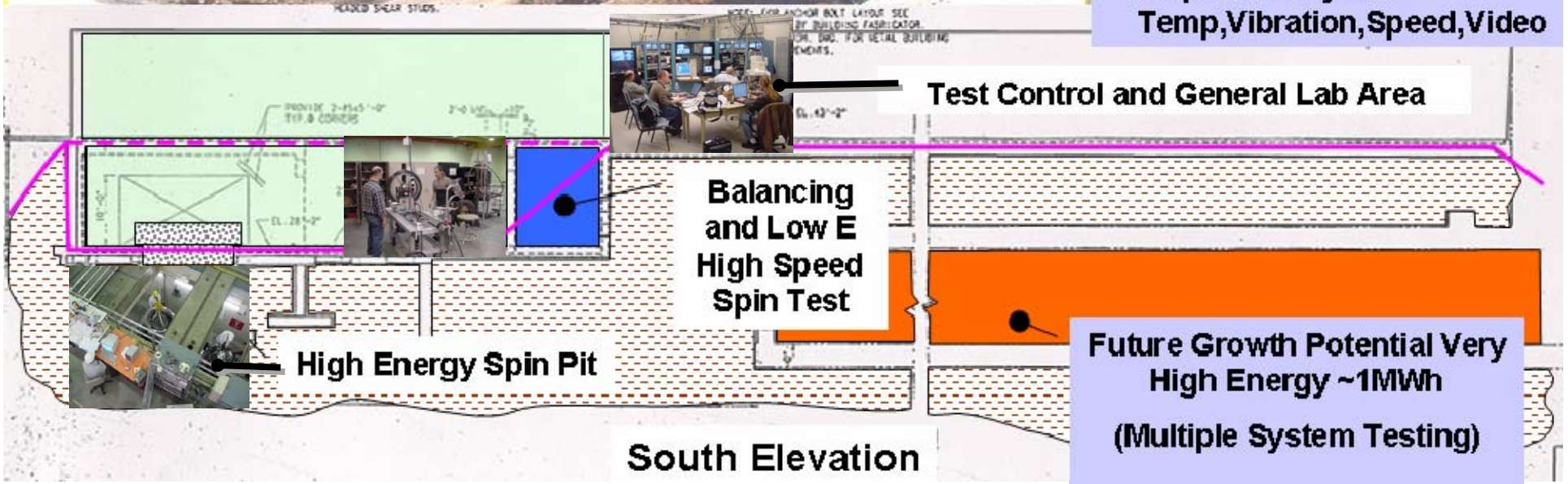


BOEING South Park - Flywheel Integrated Spin Test Facility

15-08 & -11 Bldg



- High Energy Full containment below grade spin test pit
- High Speed (60,000RPM at 1,000lbs) Vertical Air Turbine Spin Tester
- Horizontal multiple plane dynamic balancing system
- Modal and Dynamic analysis capabilities
- High Speed 64 channel Data acquisition system – Temp,Vibration,Speed,Video



Boeing Flywheel Spin Test Facility

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Flywheel Energy Storage

Test pit with concrete blocks

Flywheel test chamber

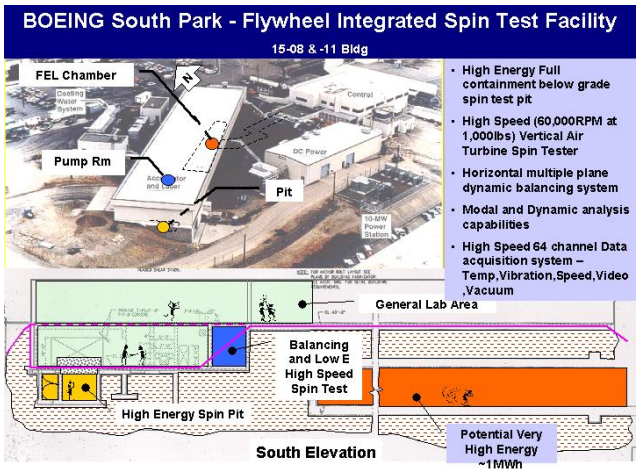
Control room

Largest Flywheel Spin Test Facility on the West Coast

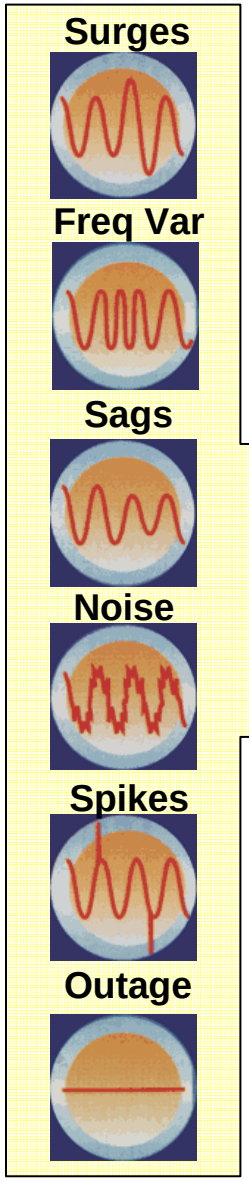
2nd Level test area

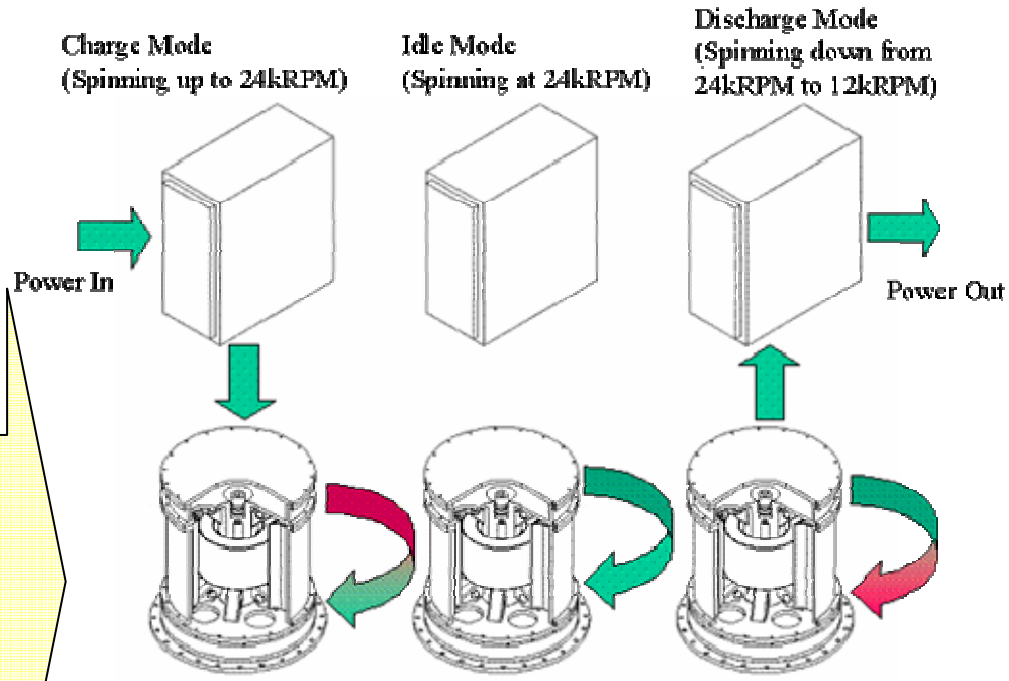
Balancing spin system

Flywheel test facility



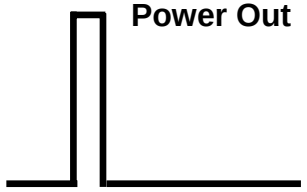
Flywheel Electricity Systems

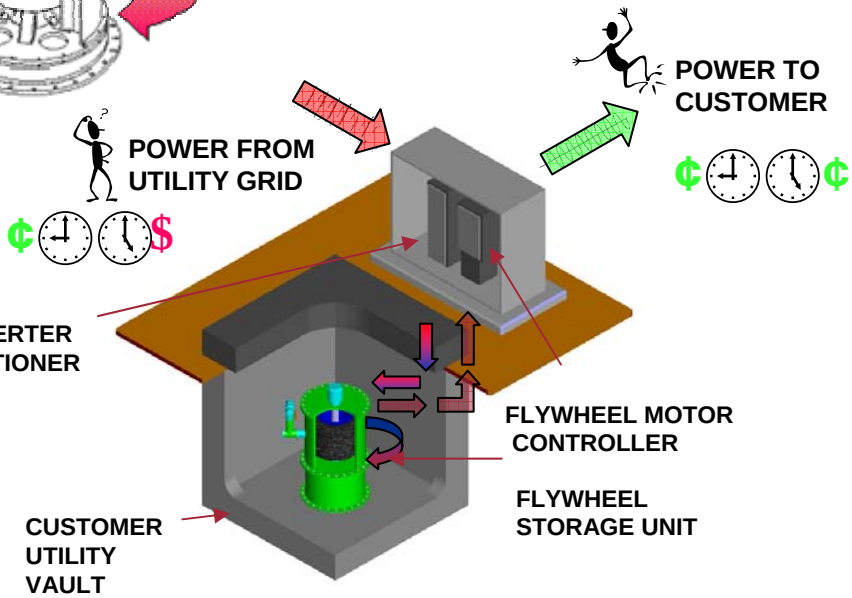




Uninterrupted Regulated (Load Leveled) Power Out

High Pulsed Power Out

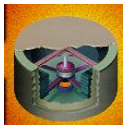




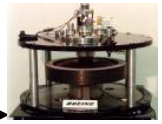
Boeing Flywheel Development History

1994 1996 1998 2000 2002 2004 2006 2008 2010

Design Concept 1 MWh FES for Commonwealth Edison



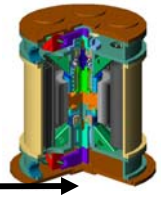
IR&D Flywheel Demonstrator 3 kW 2 kWh



DOE Phase 1 and 2 Contract ($12M)

3 kW 10 kWh

100 kW 5 kWh

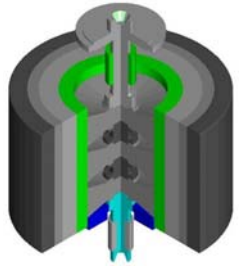


DOE/Sandia Off-Grid FES Contract ($1.5M)

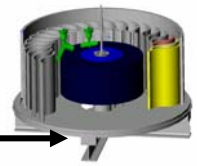
50 kW 5 kWh

New Project Proprietary Customer

100 kW 100 kWh

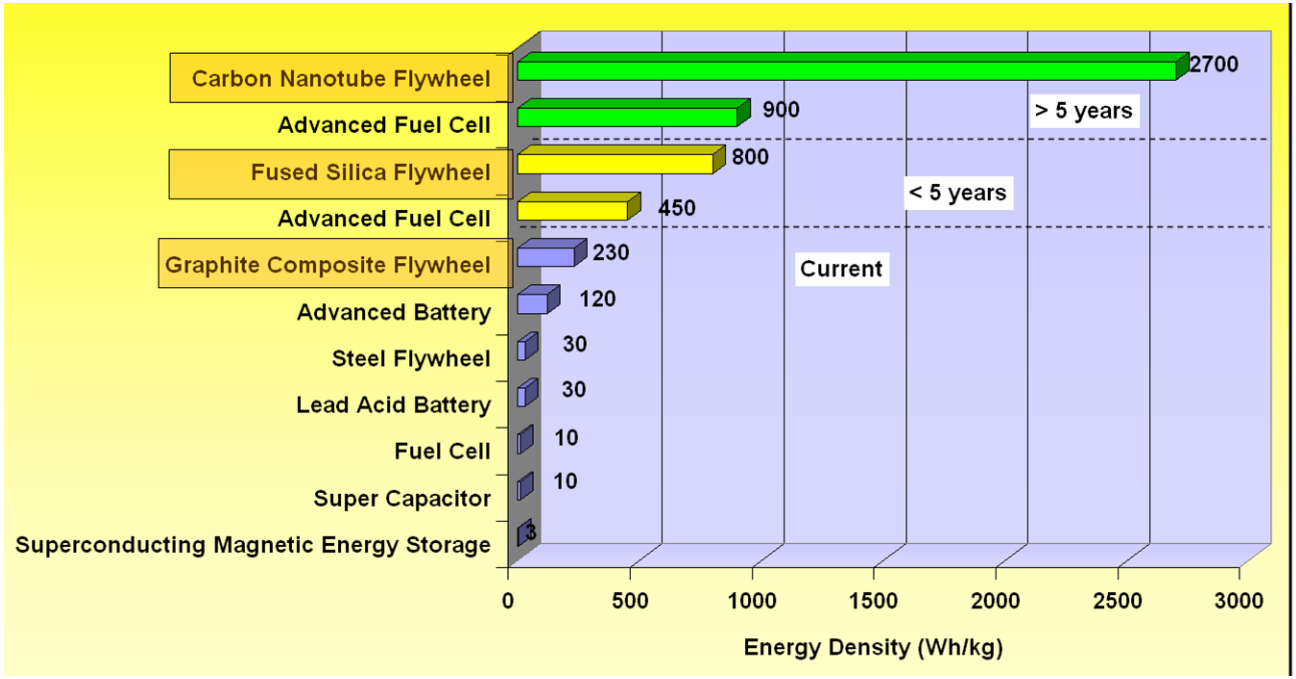


IR&D High Energy/Power Density Flywheel (Military)



Why Flywheels and Superconducting Bearings?

- **Why Pursue Flywheel Energy Storage?**
  - Non-toxic and low maintenance
  - Potential for high power density (W/ kg) and high energy density (W-Hr/ kg)
  - Fast charge / discharge times possible
  - Cycle life times of >25 years
  - Broad operating temperature range

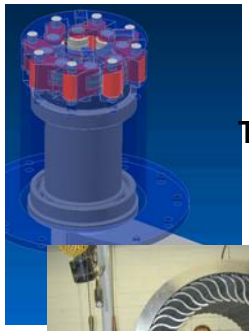


- **Why use HTS bearings?**
  - Simple passive system
  - Very low frictional loss
  - Very long lifetime
  - Low cost and maintenance
  - Lower tolerance for balancing of dynamic structures
  - High speed capability (> 500,000 RPM)
  - Adjustable stiffness and damping

Boeing Superconducting Bearing Offers Many Design and Operational Benefits Over Conventional Bearing Systems

Boeing 100 kW / 5 kWh UPS Flywheel System Design

System tested up to 15,000 RPM

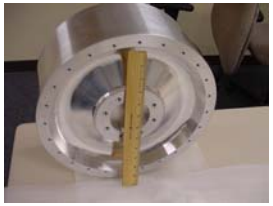


Touchdown Bearing

Steel Vacuum Vessel

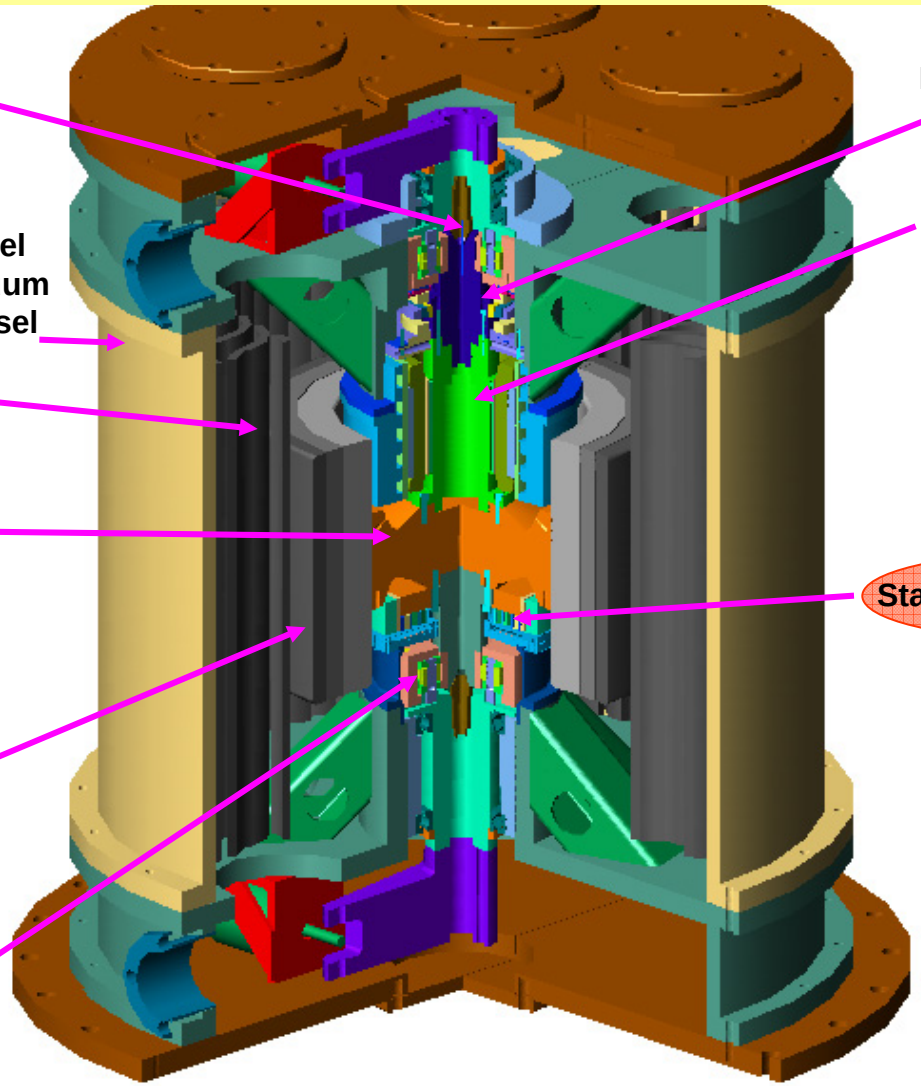
Energy-Absorbing Containment Liner

Aluminum Hub



Composite Rotor

Touchdown Bearing

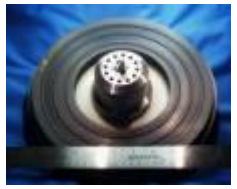


Power Electronics

Lift Bearing

Motor/Generator

Bearing Rotor



Stability HTS Bearing

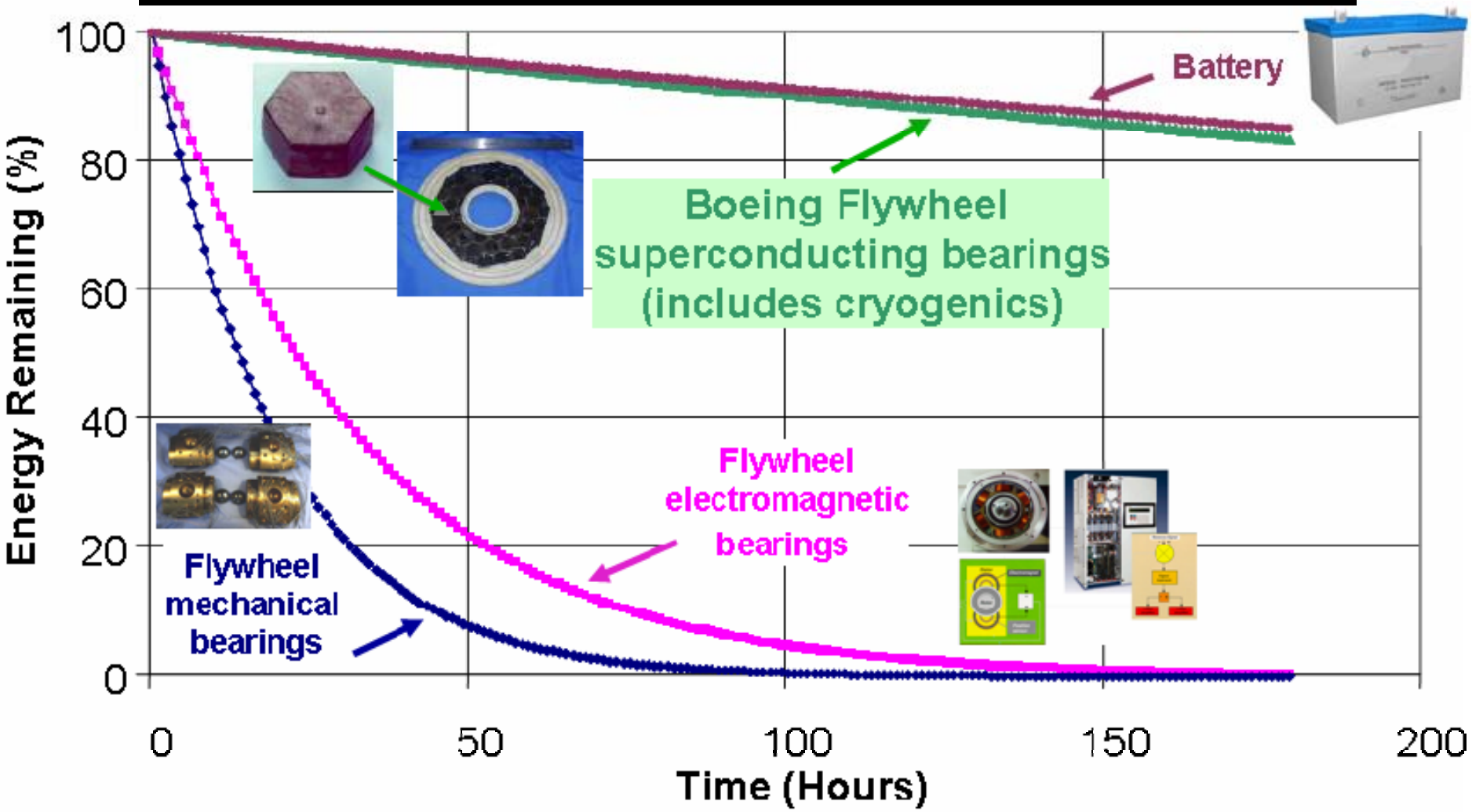
HTS Bearing

60 W GM Cryocooler

Hex YBCO

Boeing Cryogenic Bearing Enables Low Loss

Boeing-Patented Superconducting Bearing is a Unique Discriminating Technology Enabling Efficient Flywheel Systems



Superconducting Bearing System

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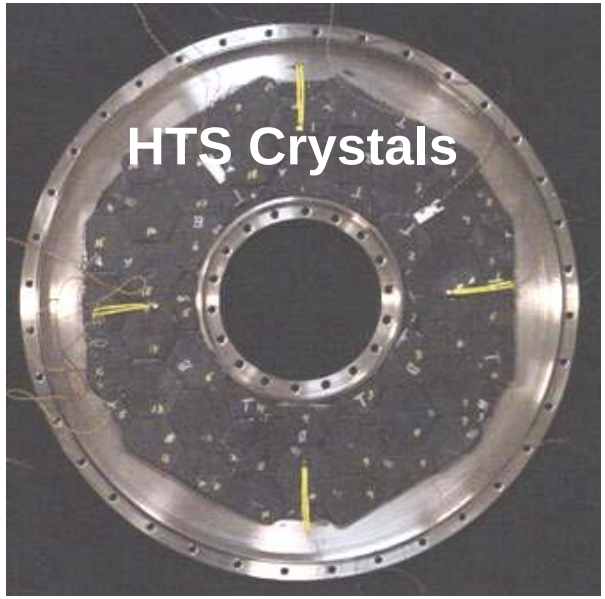
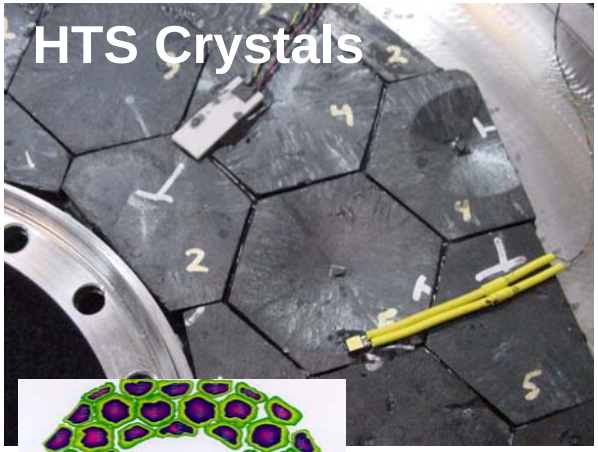
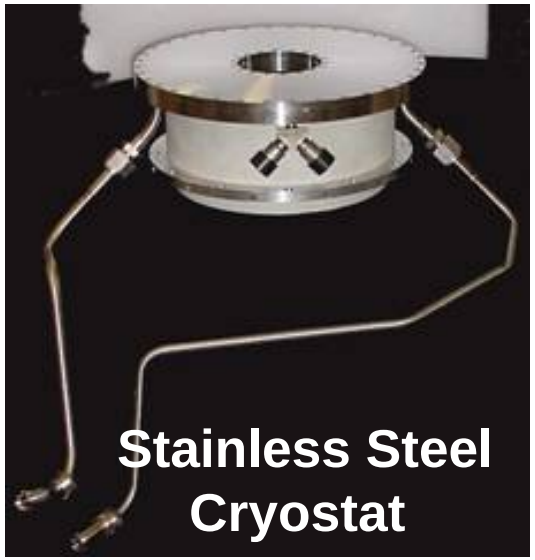
Flywheel Energy Storage



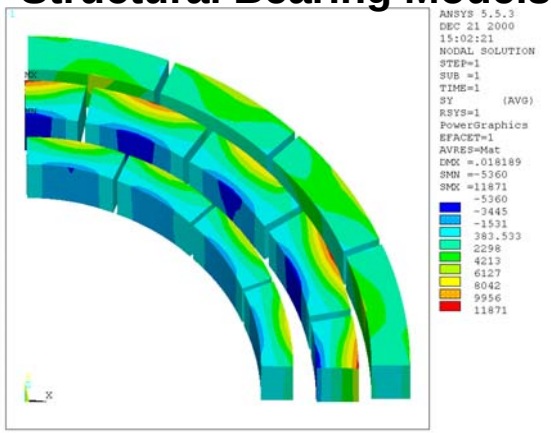


Trapped Field Profile

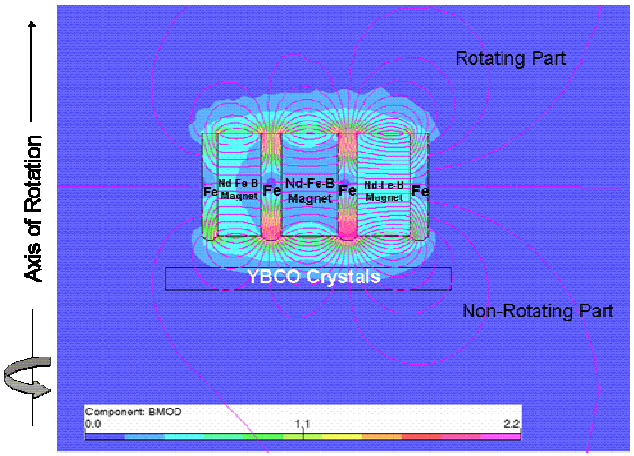
10”



Structural Bearing Models

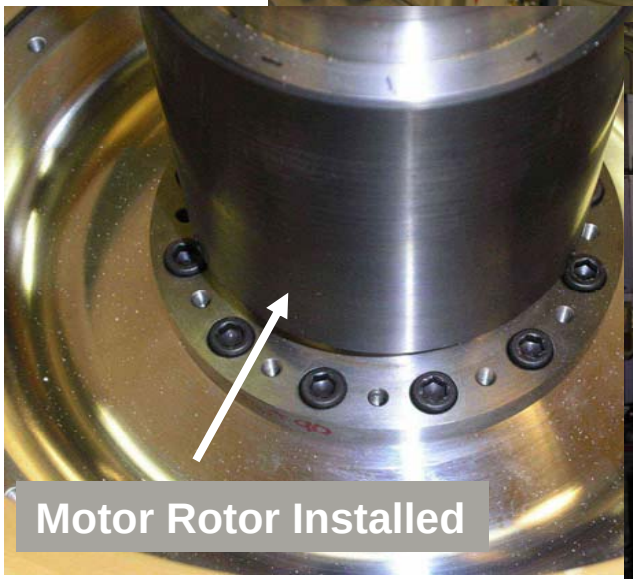


Electromagnetic Models

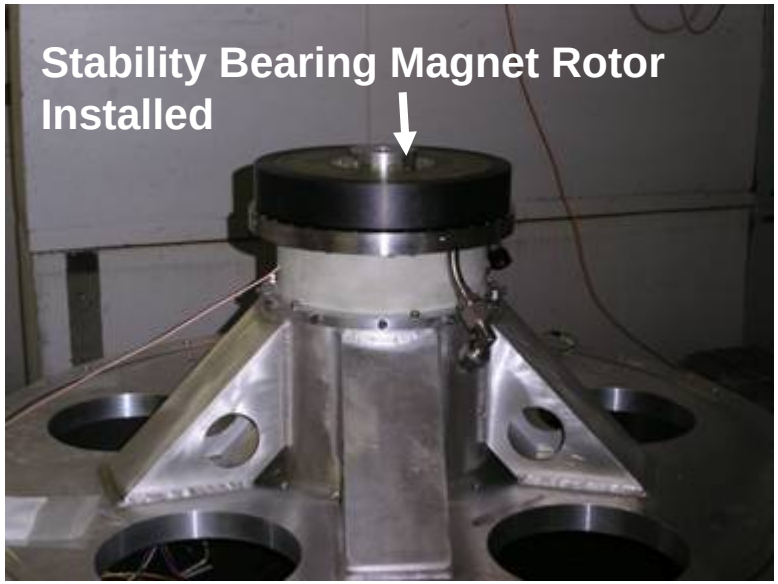


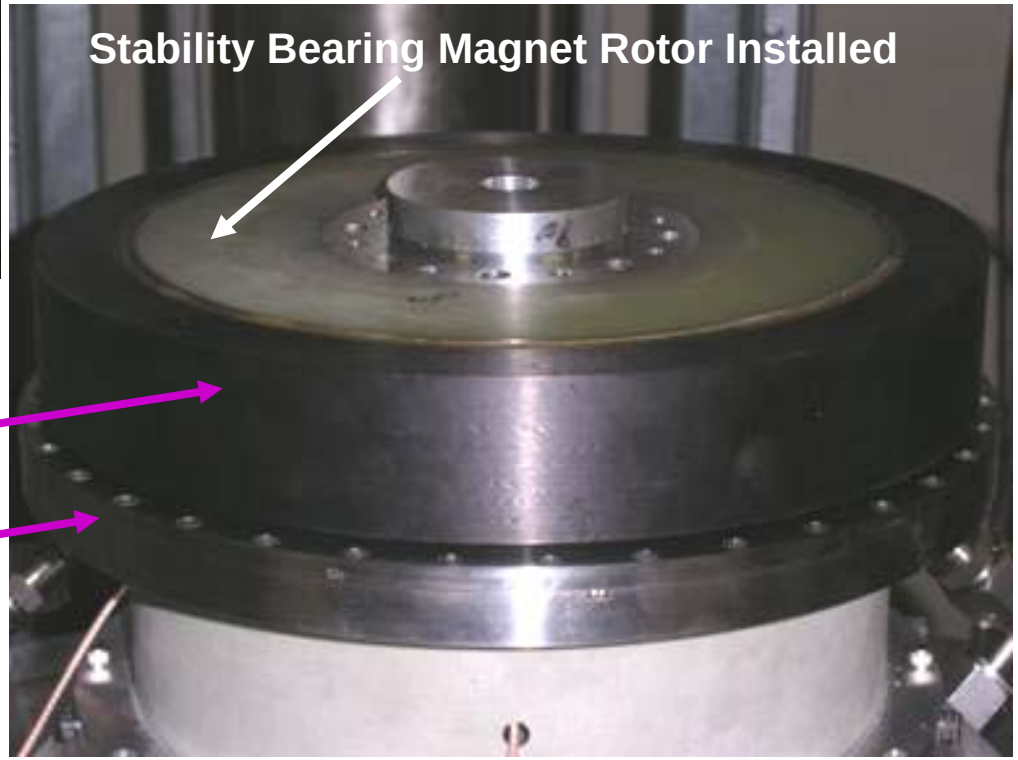
Flywheel Rotor Assembly

- The flywheel team has successfully tested a composite flywheel system weighing 360 lbs and supported by HTS bearing up to 15,000 RPM
- Superconducting bearing performance confirmed estimate of < 0.2% per hour



Stability Bearing Rotor Installation

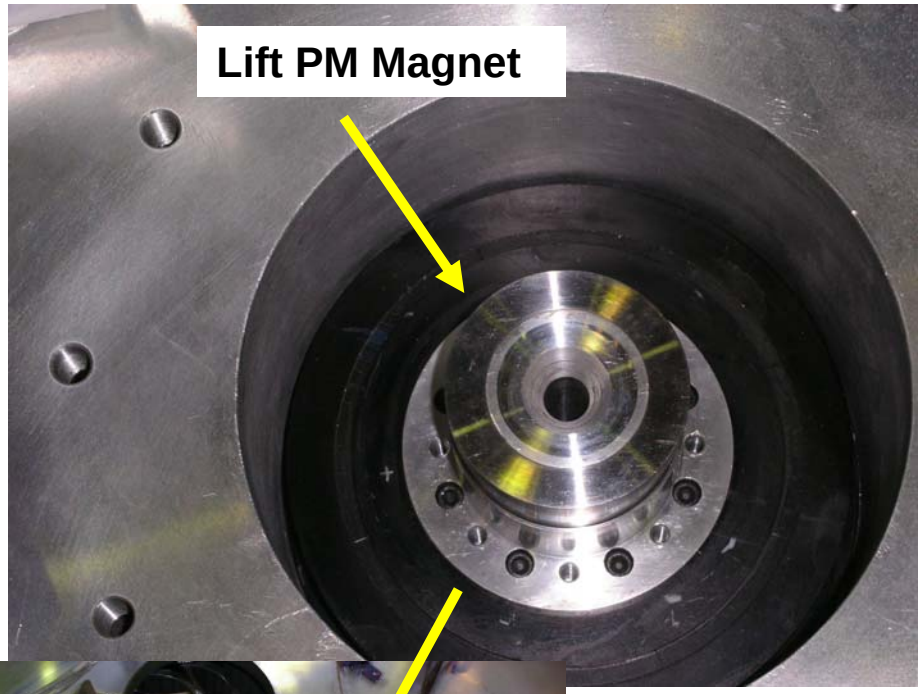


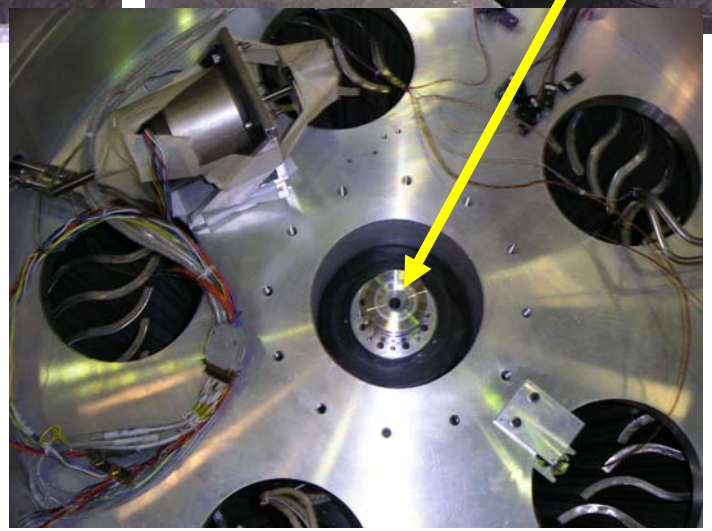


Composite Retaining Ring for Bearing Magnets

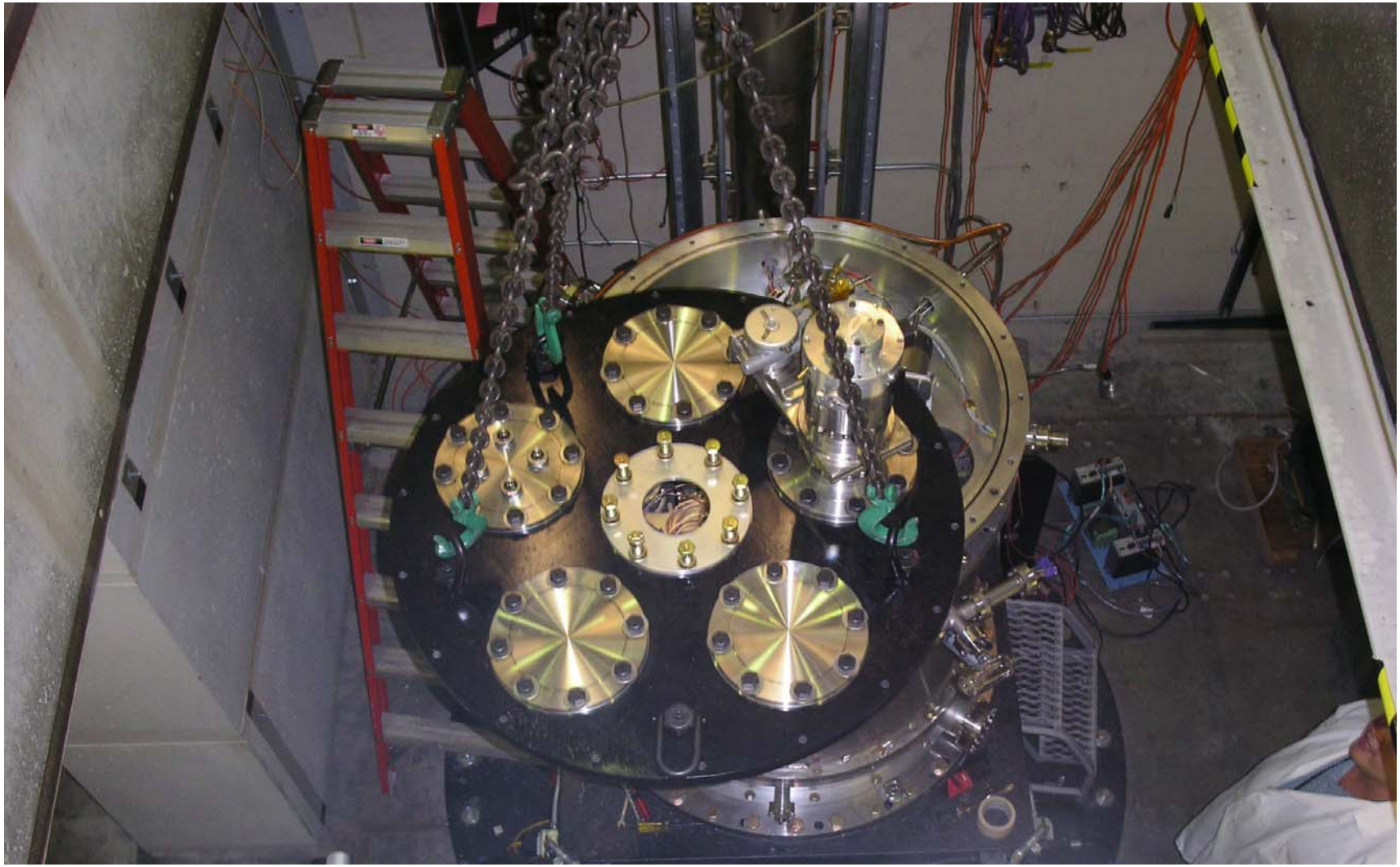
HTS Stainless Cryostat

Rotor Installation and Lift Magnet Assembly

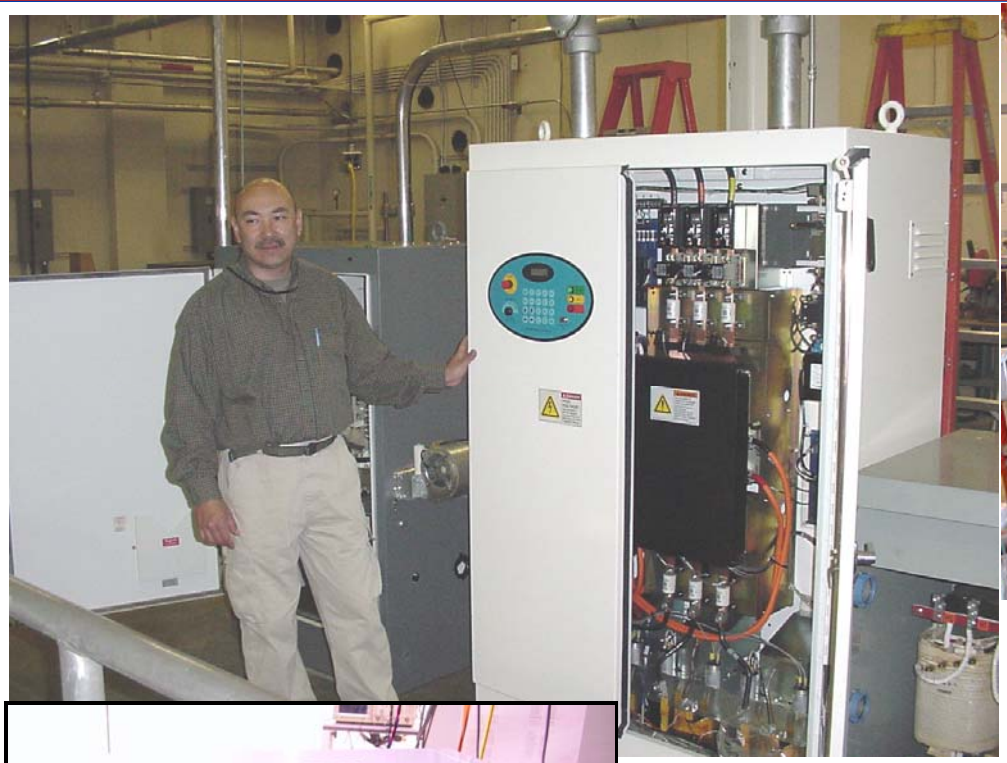


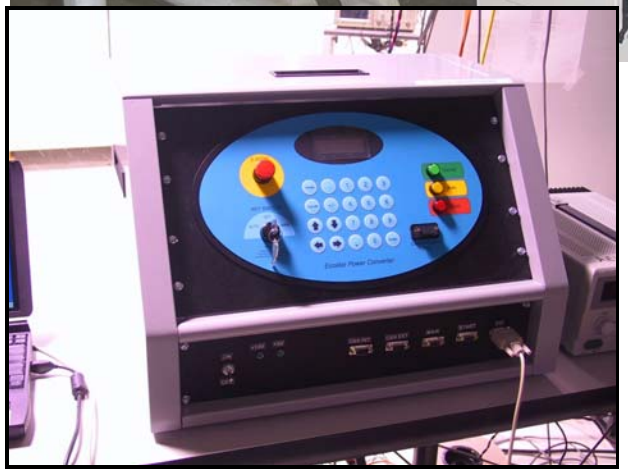


Closing Flywheel Assembly

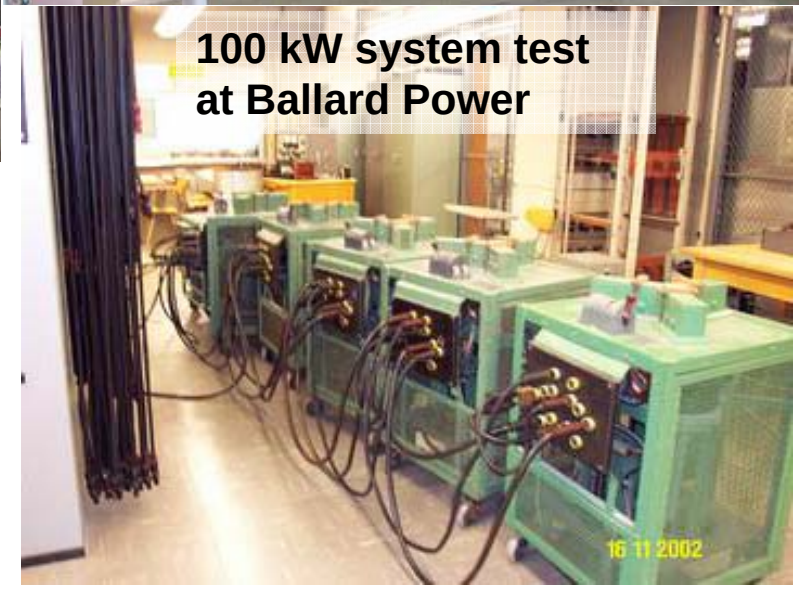


100 kW Power Electronics





Utility Remote Control Interface



100 kW system test at Ballard Power

Containment Structure for Rotor Drop/Burst - Subscale Test (after)

Dropped rotor at 41,000 rpm following quill shaft failure

Top of rotor: small scratches.

Container brackets slightly damaged,can be re-used

Bottom of rotor: lost < 1”.

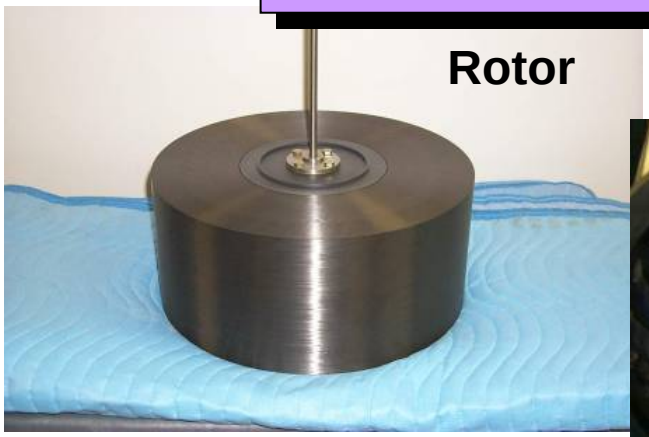
Hub broken, some melting

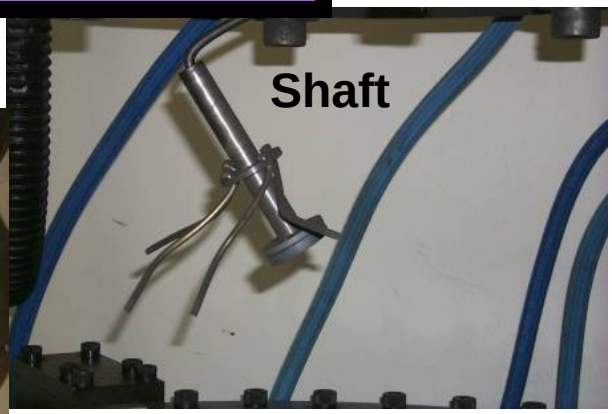
1 kWh Burst Rotor & Container Before/After

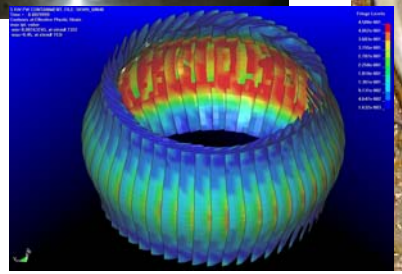
Before

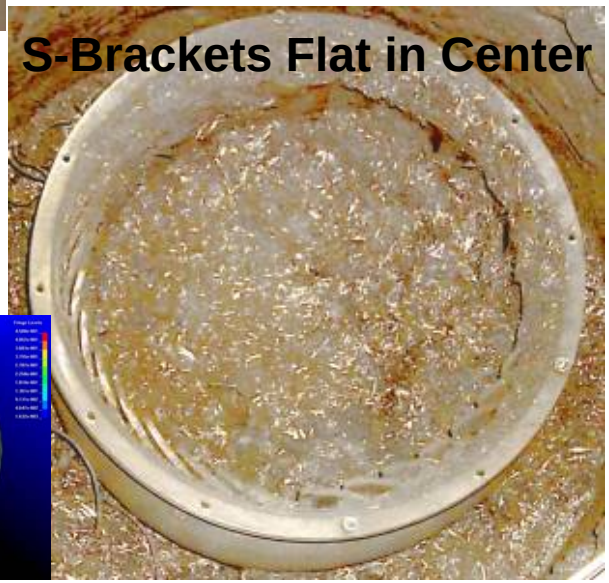
Successfully Verified Boeing Patented Safety Containment

After

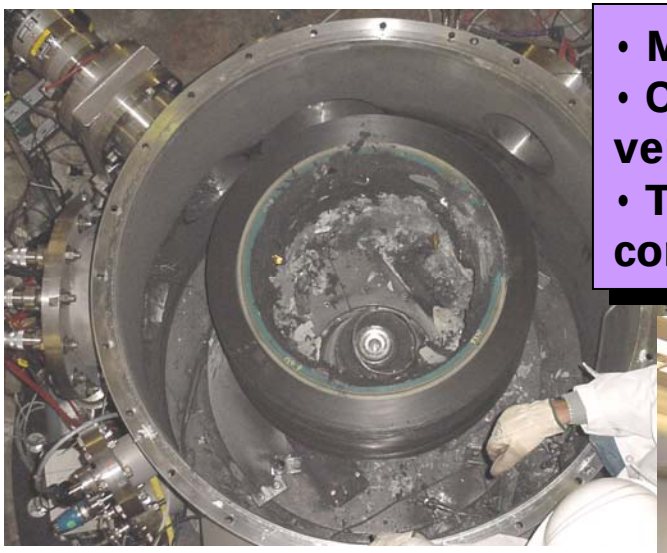




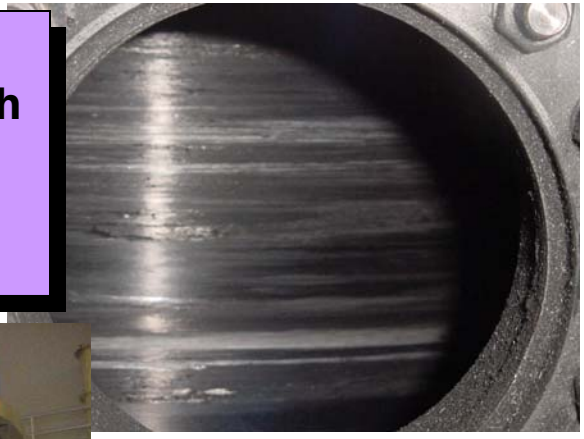




Results of High Speed Touch Down Event



- **Many lessons learned**
- **Conservative safety approach verified – no external damage**
- **Testing confirmed high risk component designs**

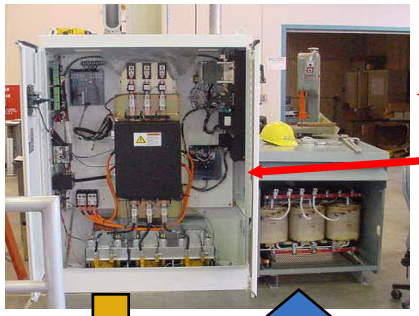


Test experience resulted in an improved modular re-design

5 kWh/100 kW UPS Flywheel Technical Issues

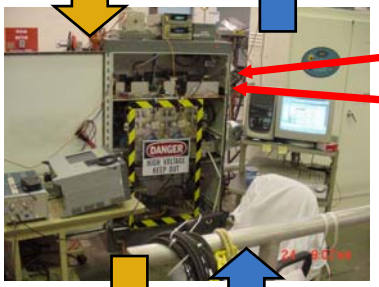
Inverter

480 VAC



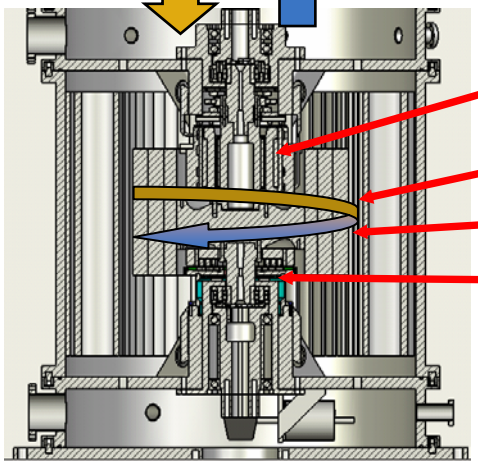
480 VAC

600 VDC



Motor Controller

Variable Freq VAC



Flywheel

Facility prepared for SCE tests

Inverter system tested and ready for integration

Motor controller over-current shutdown resolved

Motor controller algorithm

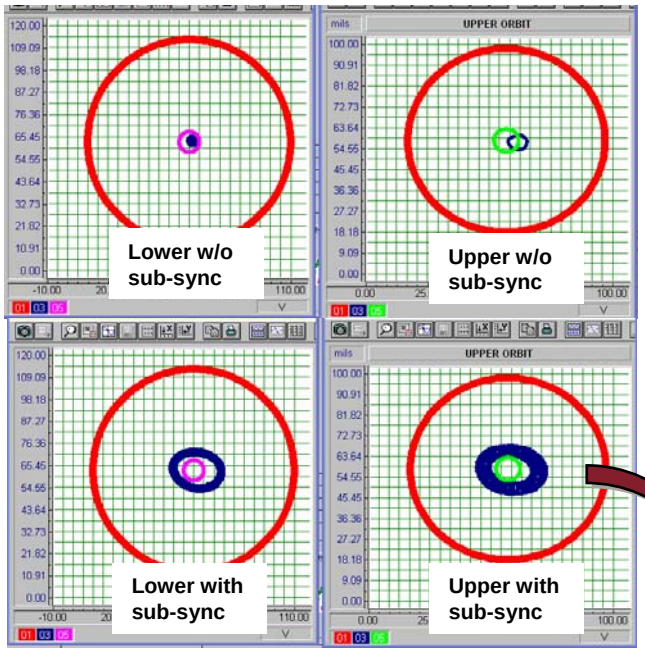
Motor stator over-heating during drive

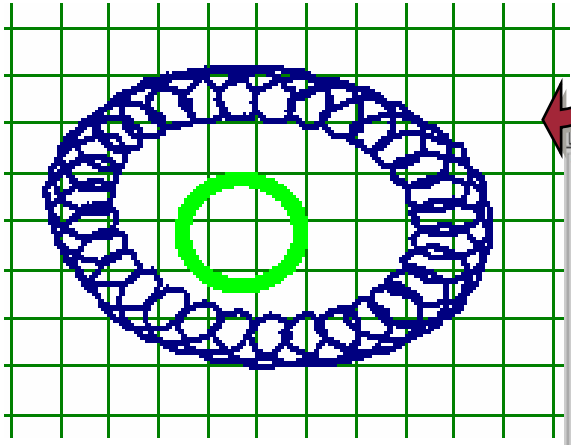
Rotor spun to 15,000 RPM non-contact

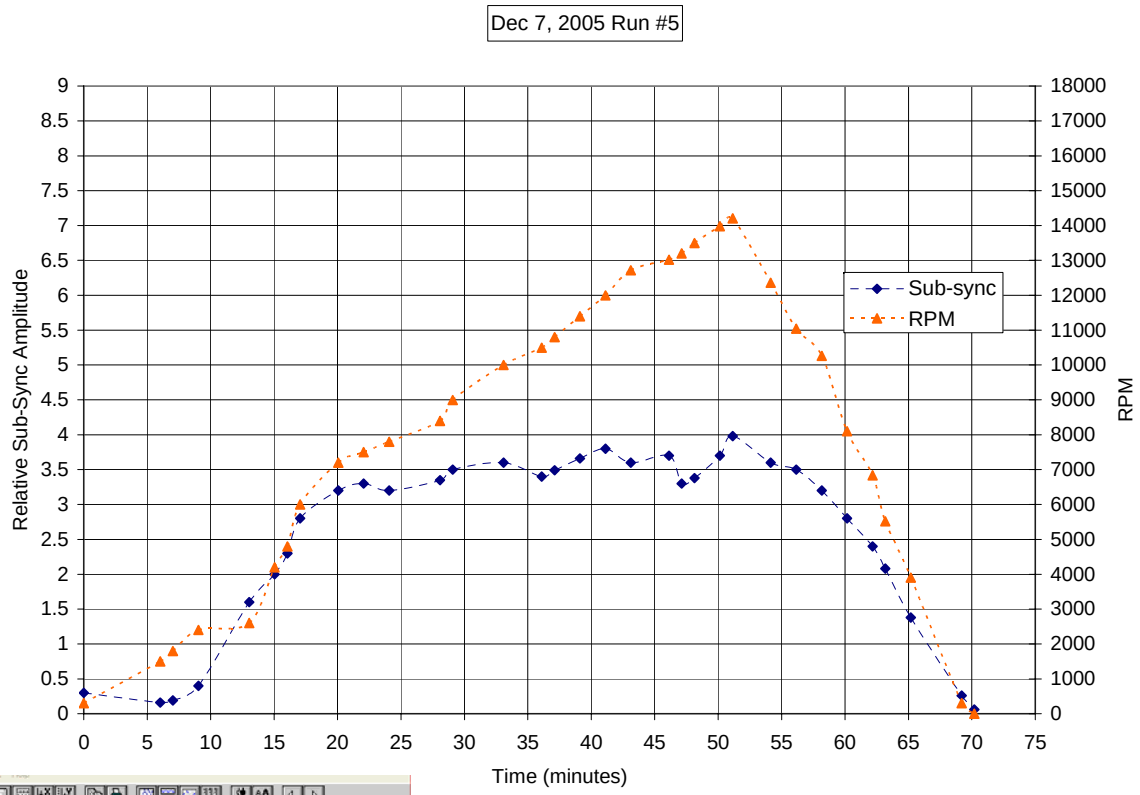
Rotor has sub-sync vibration at higher RPM

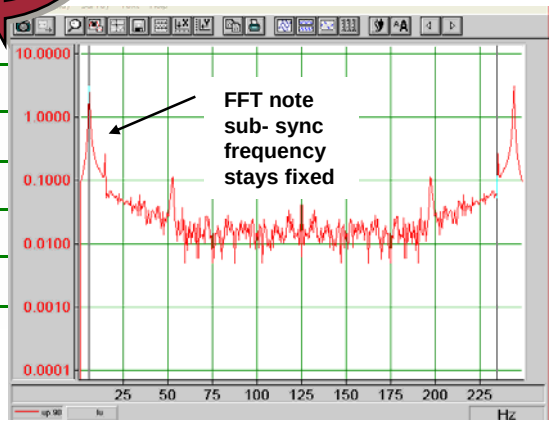
HTS Bearing nominal to 15,000 RPM

Sub-sync Whirl



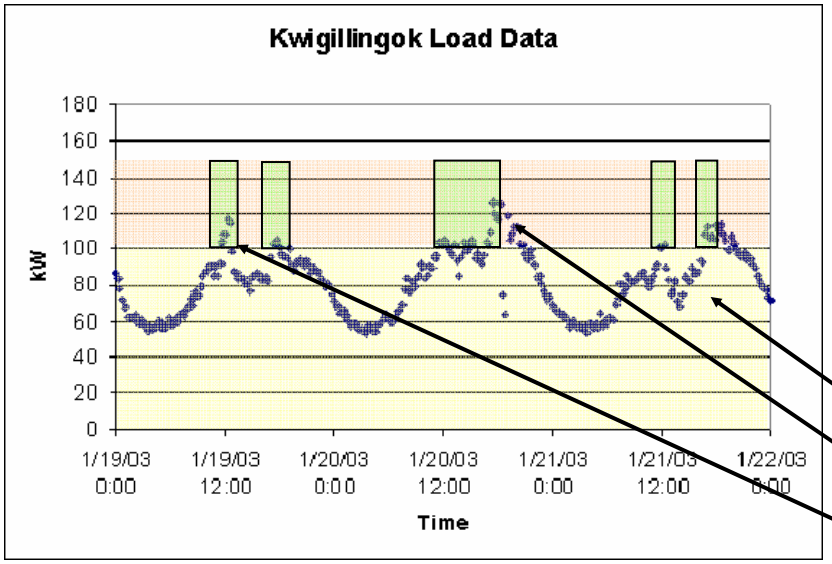


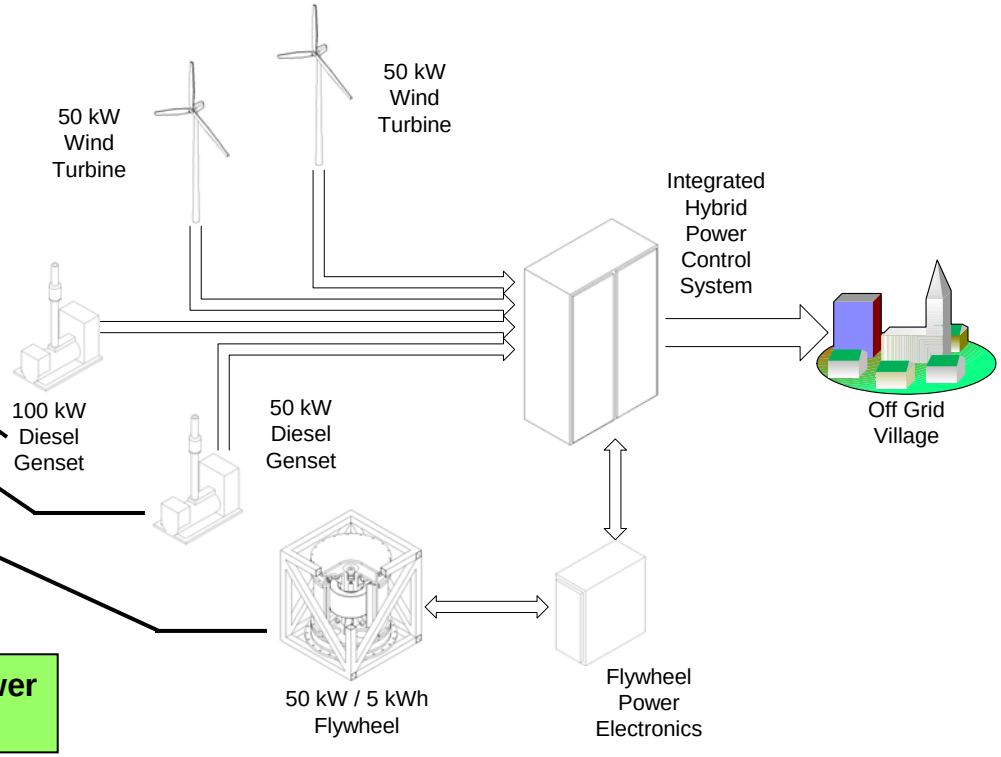




Low energy in sub-sync, but do not want to contact excursion surface

Proposed System Architecture for Deployment of a 50kW / 5kWh Flywheel Energy Storage System





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

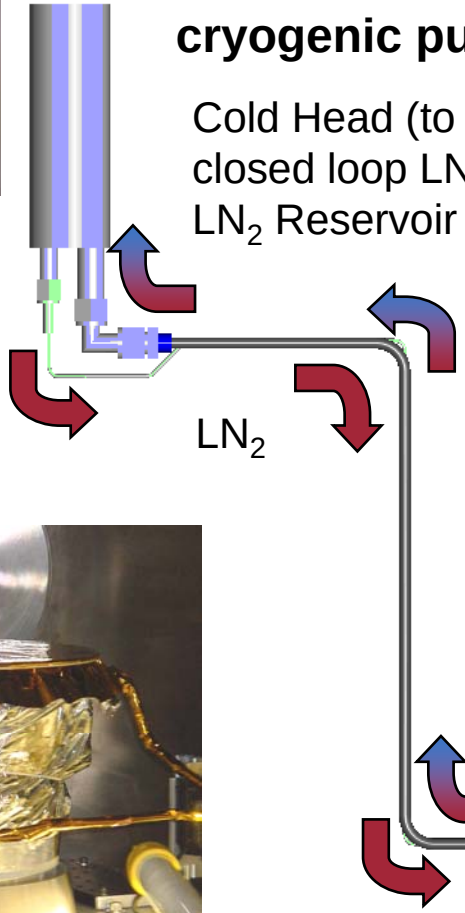
<u>Benefits of Using FESS Instead of Idling 2nd Generator on Standby</u>

- **Reduce Generator Maintenance by 50% (estimate)**
- **Reduce Fuel Costs by $80k/yr (estimate)**
- **Lower Pollution**

Key Issues for HTS Bearing Design

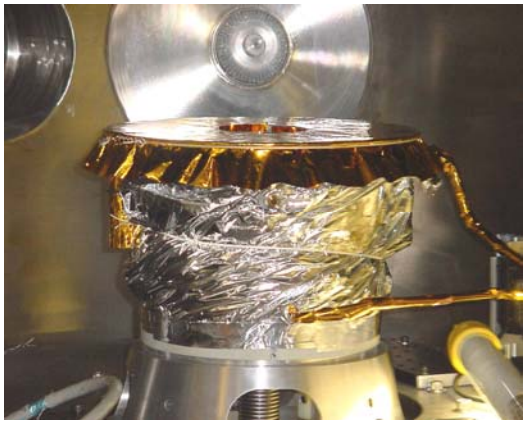
- **Overall efficiency needs to be >95% in operating range**
  - **Low loss superconducting bearing**
  - **No criticals in operating range**
- **System needs to be stiff enough to follow disturbances, yet not so stiff critical frequencies are produced in the operating range**
  - **Interactions between rotating portions (hub, spokes, & rotor)**
  - **Bearing stiffness**
  - **M/G stiffness**
  - **HTS damping – J_c and temperature dependent**
  - **Cooling type – parasitic losses, temperature**
  - **HTS samples size and superconducting properties**

Previous DOE/Boeing Flywheel Terrestrial Cryogenics



Use of a Thermosiphon eliminated a cryogenic pump requirement

HTS Stability Bearing Cryostat Installed in DOE 5 kWh Flywheel

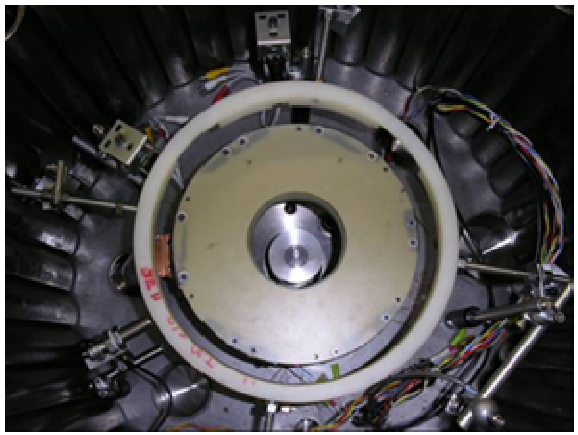


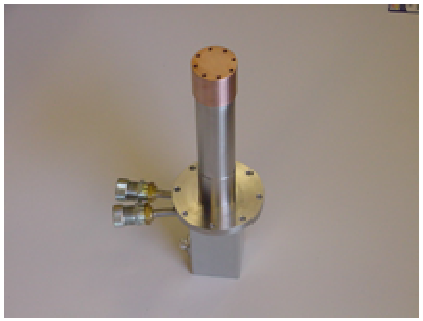
HTS Stability Bearing Cryostat Installed in DOE 10 kWh Flywheel

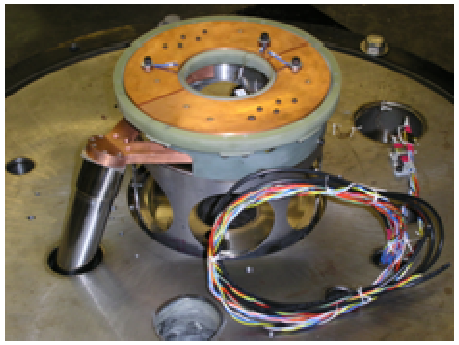
Direct Cooled HTS Bearing

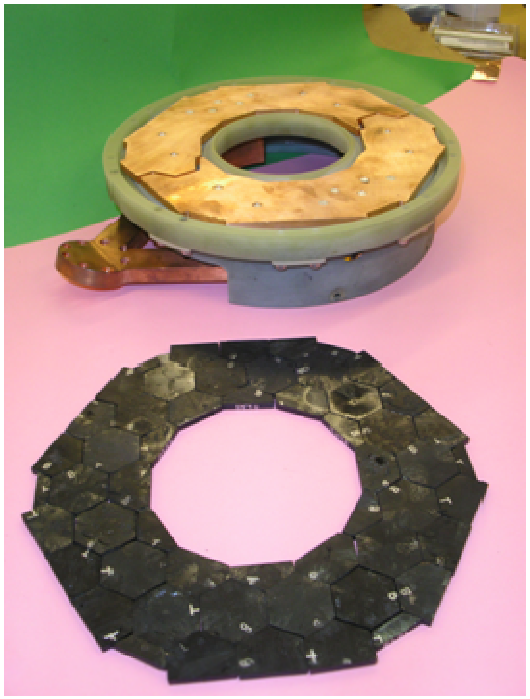
Boeing Technology | Phantom Works

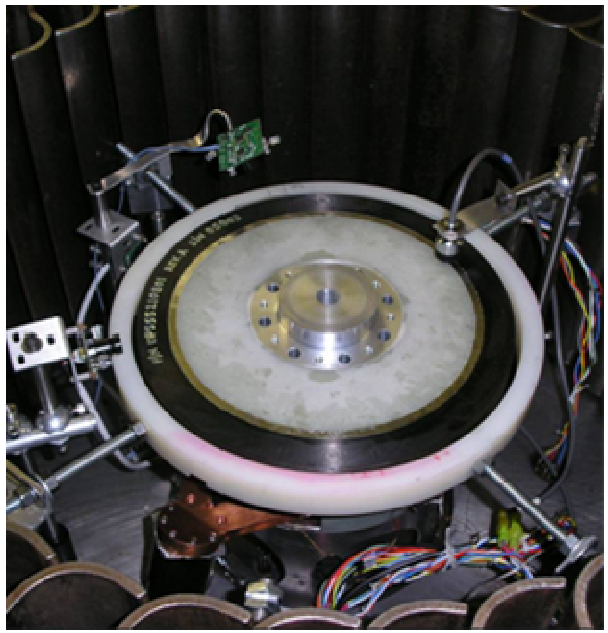
Flywheel Energy Storage



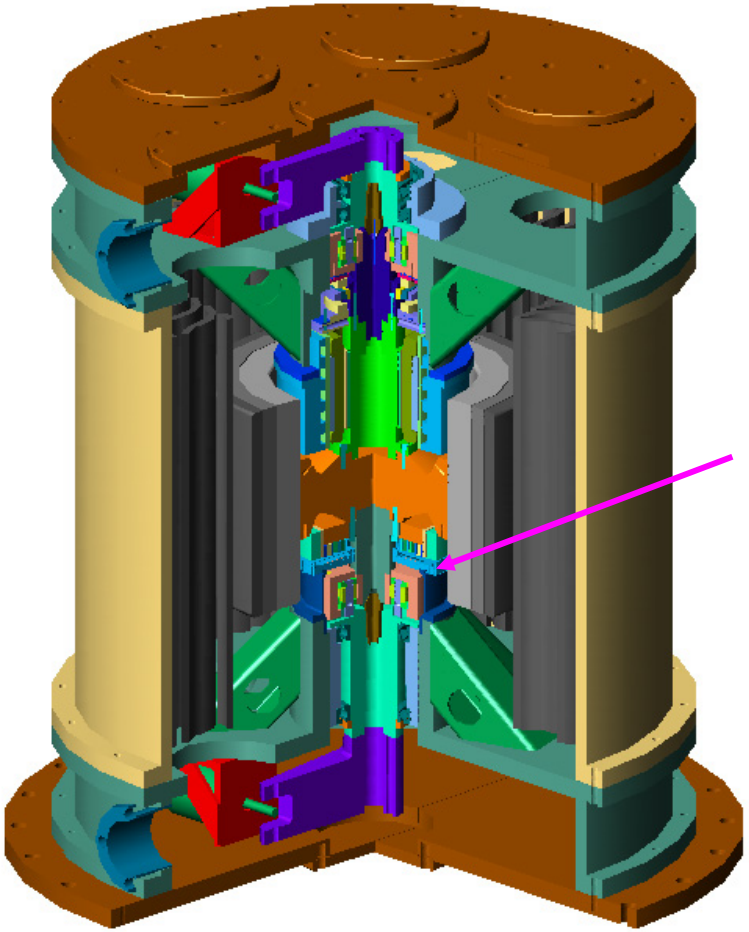




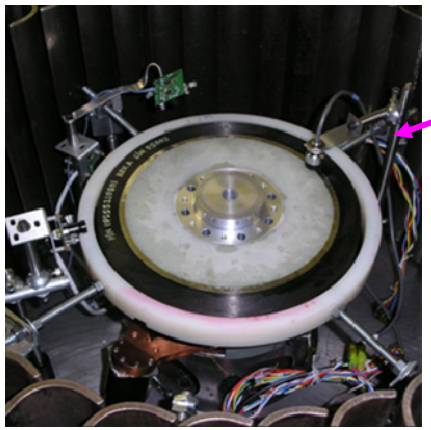


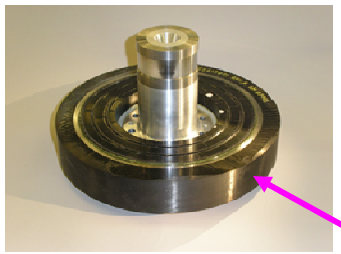


Sandia 50 kW / 5kWh Flywheel Energy Storage System 2007
Direct Cooled Bearing Tests



HTS Bearing Stator





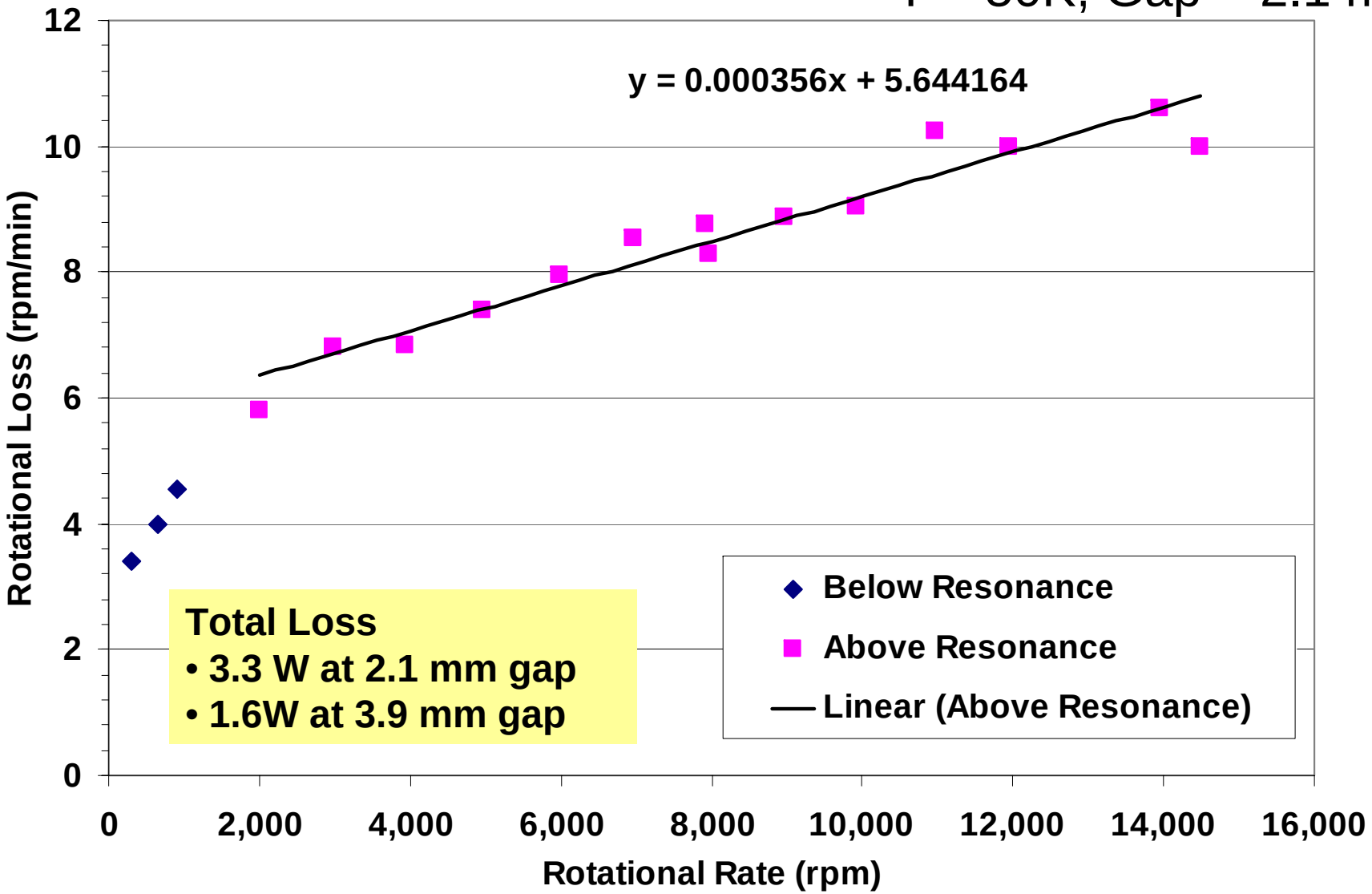
HTS Bearing Rotor

Hex YBCO

G-10 Bearing Support

Experimental Spin Down Results from Direct Cooled HTS Bearing

T = 50K, Gap = 2.1 mm



Boeing Flywheel Project Summary

- **Program goal is to design, develop, and demonstrate a 100 kW UPS flywheel electricity system**
- **Flywheel system spin tested up to 15,000 RPM in a sensorless, closed loop mode**
- **Testing identified a manufacturing deficiency in the motor stator – overheats at high speed, limiting maximum power capability**
- **Successfully spin tested direct cooled HTS bearing up to 14,500 RPM (limited by Eddy current clutch set-up)**
- **Testing confirmed commercial feasibility of this bearing design – Eddy Current losses are within acceptable limits**
- **Boeing's investment in flywheel test facilities increased our spin-test capabilities to one of the highest in the nation**