ETH zürich

Power Electronic Systems Laboratory

Research in the Area of Ultra-High Rotational Speeds

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Agenda

- ETH Zurich Power Electronic Systems Lab. — 4
- General Research Approach — 5
- Performance & Technology Trends for Electrical Drive Systems — 19 Slides
- 40’000’000 rpm Spinning Ball Motor — 17 Slides
- Acoustic Levitation / Conclusion — 9

Departments of ETH Zurich

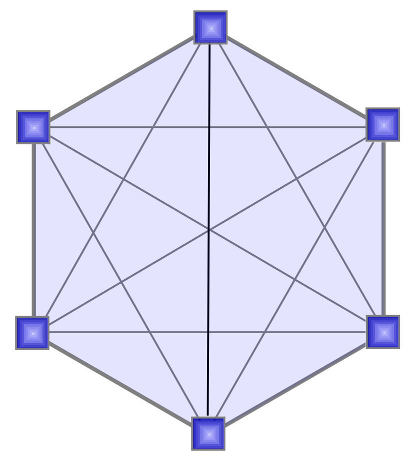
ARCH	Architecture
BAUG	Civil, Environmental and Geomatics Eng.
BIOL	Biology
BSSE	Biosystems
CHAB	Chemistry and Applied Biosciences
ERDW	Earth Sciences
GESS	Humanities, Social and Political Sciences
HEST	Health Sciences, Technology
INFK	Computer Science
ITET	**Information Technology and Electrical Eng.**
MATH	Mathematics
MATL	Materials Science
MAVT	Mechanical and Process Engineering
MTEC	Management, Technology and Economy
PHYS	Physics
USYS	Environmental Systems Sciences

21 Nobel Prizes
413 Professors
6240 T&R Staff

2 Campuses
136 Labs
35% Int. Students
110 Nationalities
36 Languages

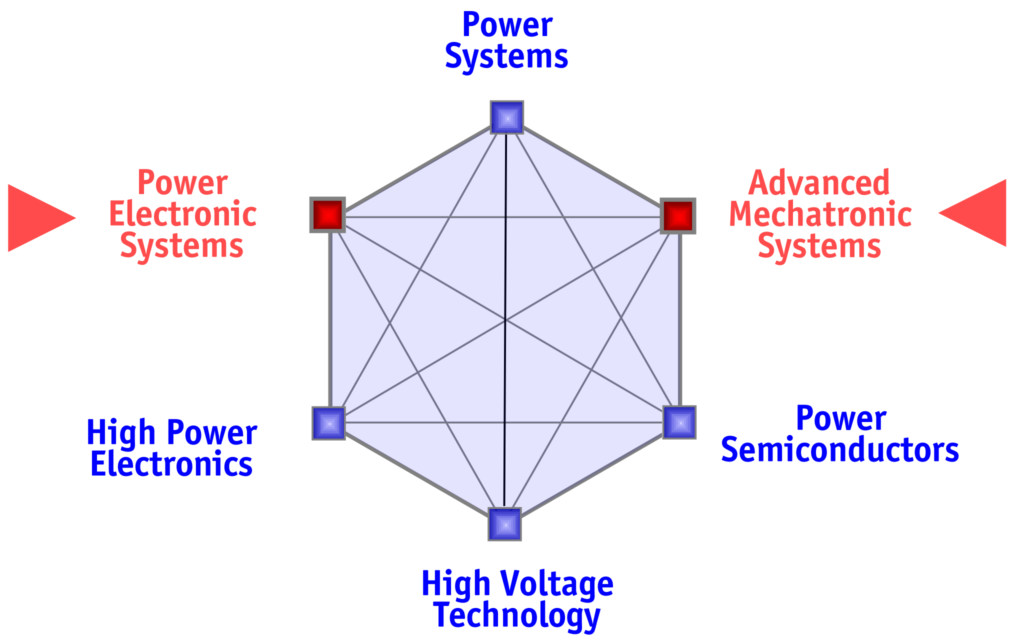
150th Anniv. in 2005

Energy Research Cluster @ D-ITET



- Balance of Fundamental and Application Oriented Research

Energy Research Cluster @ D-ITET



- Balance of Fundamental and Application Oriented Research

PES Research Scope

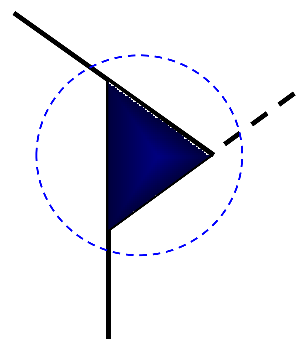
Power Electronics

Cross-Departmental

Mechanical Eng., e.g. Turbomachinery, Robotics

Microsystems
Medical Systems

Economics / Society



- *Airborne Wind Turbines*
- *Micro-Scale Energy Systems*
- *Wearable Power*
- *Exoskeletons / Artificial Muscles*
- *Hybrid Systems*
- *Pulsed Power*

Actuators /
EL. Machines

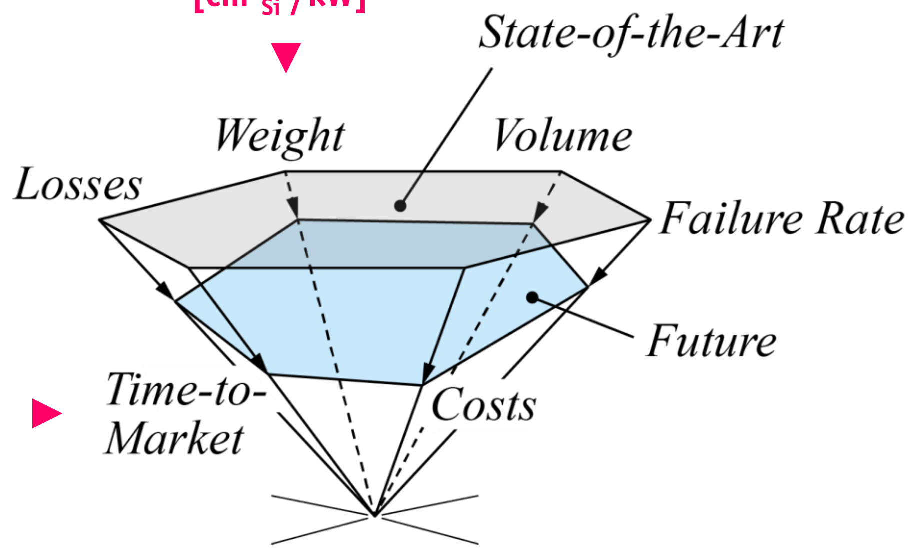
General Research Approach

Design Challenges

Mutual Coupling of Performances

Power Electronics Converters Performance Trends

Environmental Impact... [kg_{Fe} /kW]
[kg_{Cu} /kW]
[kg_{Al} /kW]
[$cm^2{}_{Si}$ /kW]

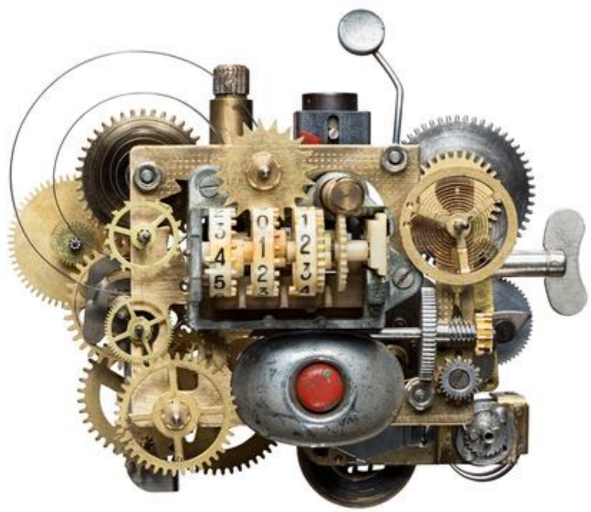


■ Performance Indices

- Power Density [kW/dm^3]
- Power per Unit Weight [kW/kg]
- Relative Costs [kW/$]
- Relative Losses [%]
- Failure Rate [h^{-1}]

► Multi-Objective Design Challenge

- Counteracting Effects of Key Design Parameters
- Mutual Coupling of Performance Indices → Trade-Offs

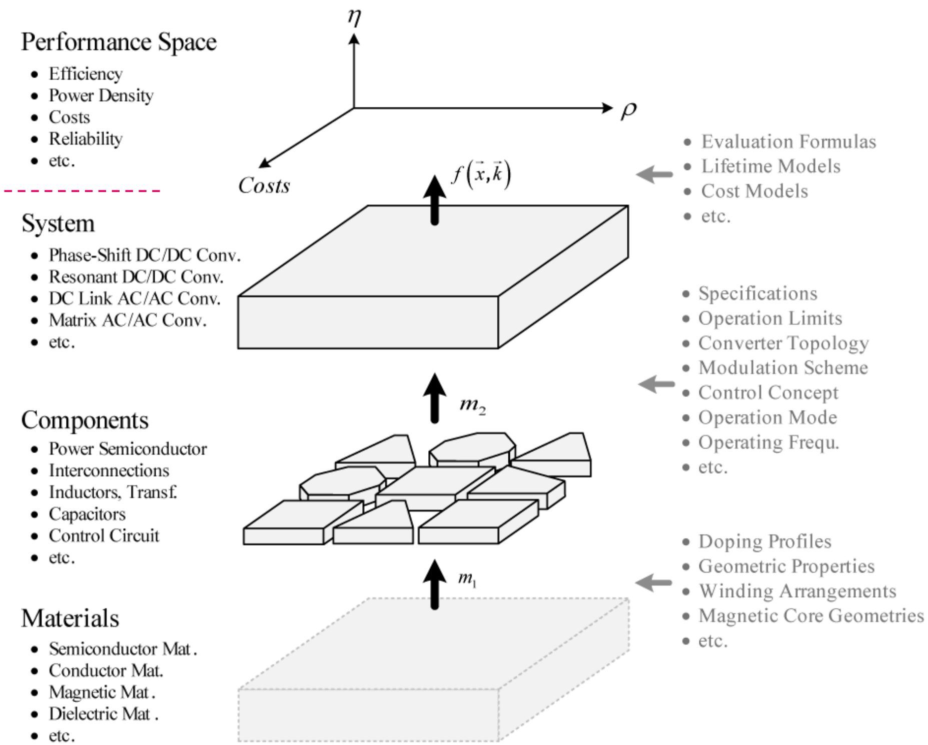


→ Large Number of Degrees of Freedom / Multi-Dimensional Design Space
→ Full Utilization of Design Space only Guaranteed by Multi-Objective Optimization

▶ Abstraction of Power Converter Design

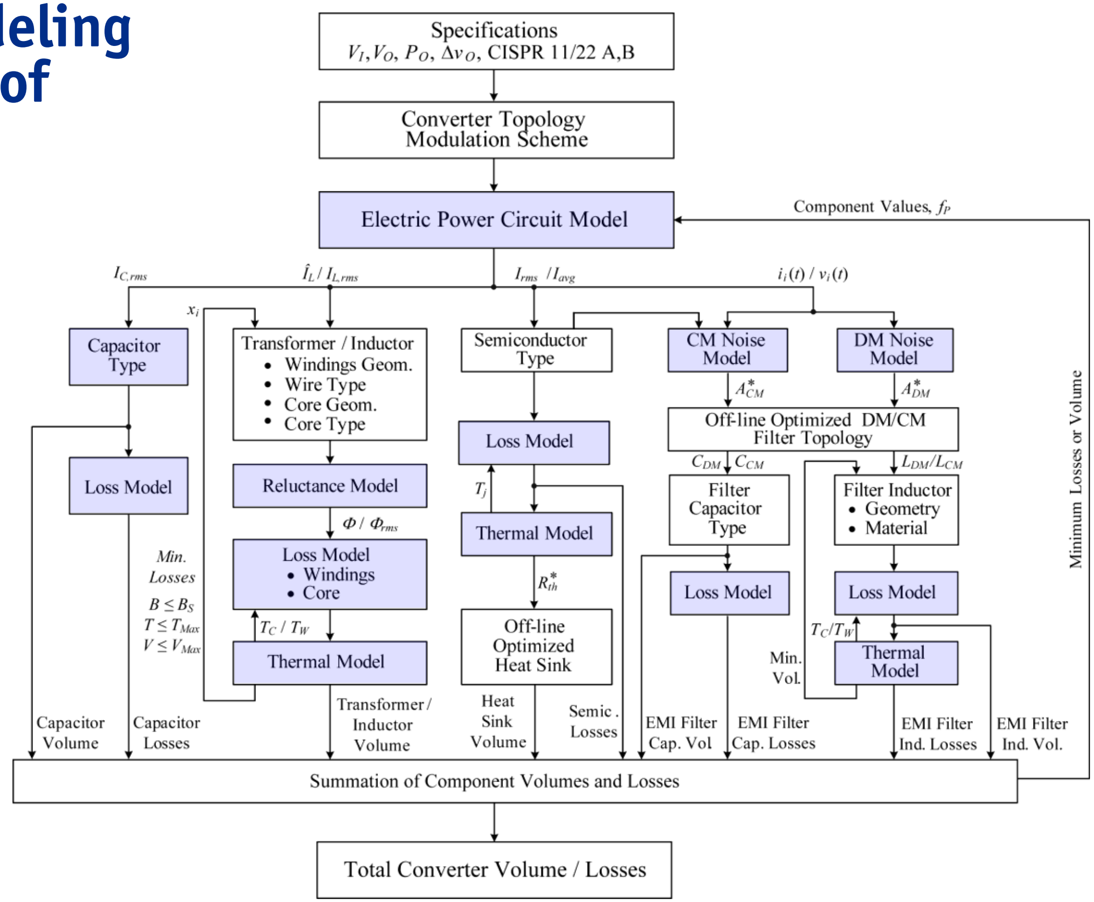
Performance Space

Design Space



→ *Mapping* of "*Design Space*" into System "*Performance Space*"

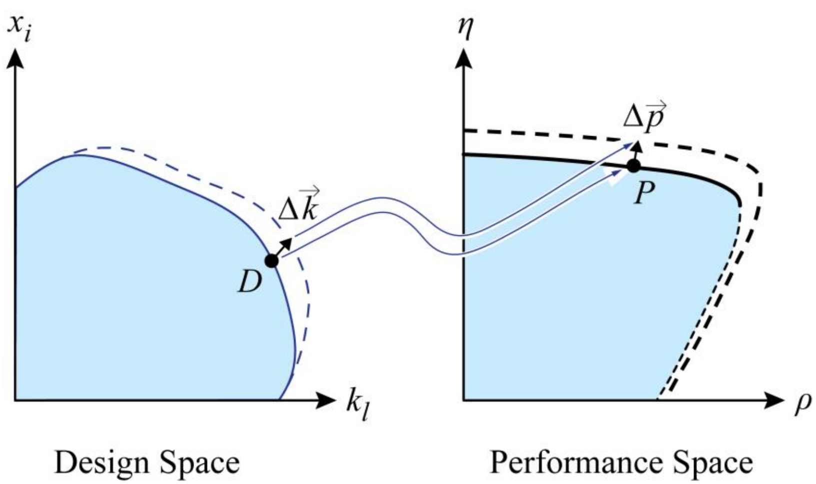
Mathematical Modeling and Optimization of Converter Design

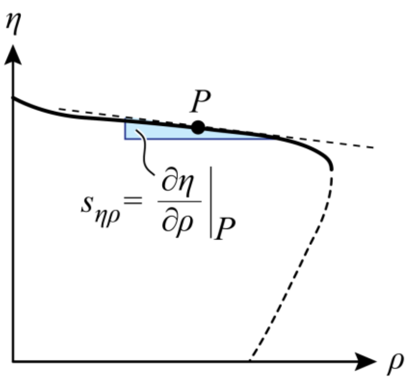


→ **Multi-Objective Optimization – *Guarantees Best Utilization of All Degrees of Freedom* (!)**

Technology Sensitivity Analysis Based on η-ρ-Pareto Front

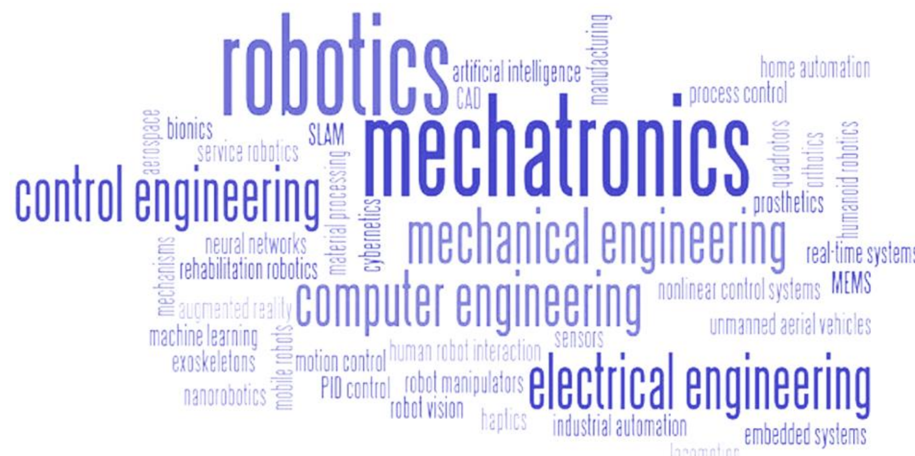
- Ensures Optimal Mapping of the “Design Space” into the “Performance Space”
- Identifies Absolute Performance Limits → Pareto Front / Surface



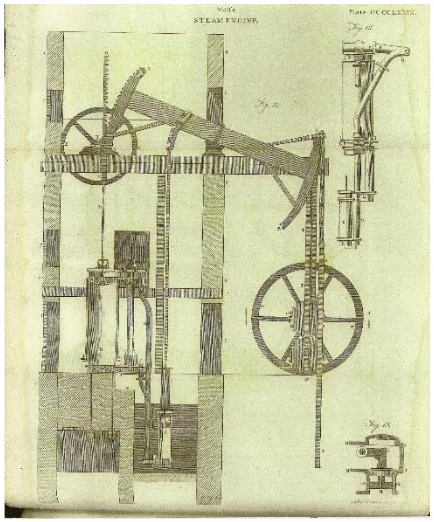


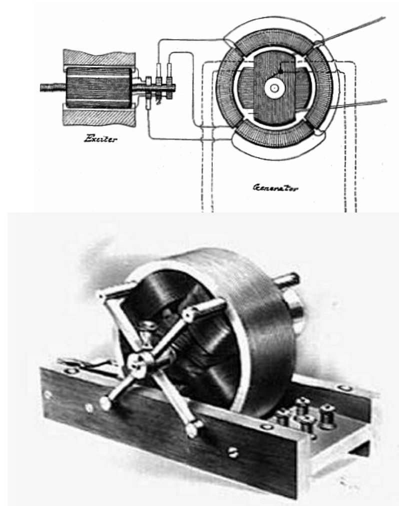
→ Clarifies Sensitivity $\Delta p / \Delta k$ to Improvements of Technologies
→ Trade-off Analysis

Electrical Drives: General Trends



▶ Development of Motion Control Systems


James Watt's Steam Engine



Nikola Tesla's AC induction machine

Integrated drive system (AC motor + SkiN IGBT power electronics) for today's electric vehicles

■ Exponential Development

< 1900	Mechanical
1900	Mechanical + Electrical
1950	Mechanical + Electrical + Electronic → **Electronic Motion Control**
1975	Mechanical + Electrical + Electronic + Computation → **MECHATRONICS**
1985	Mechanical + Electrical + Electronic + Computation + Information/Communication

▶ Innovation in Mechatronics and Electric Drives

Key Components Available Today

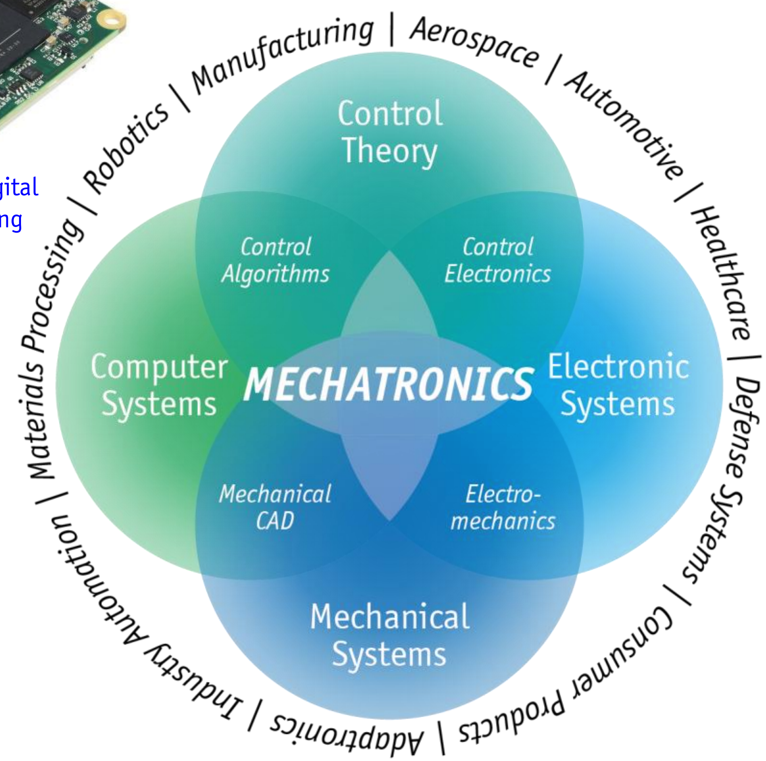
Ultra-Compact & Efficient Power Converter

Precision Sensors

High-Speed Digital Signal Processing

High-Performance Mechanical Actuators

Ultra-Compact & Efficient Electrical Machines



Extremely Wide Application Areas

- Machining
- Handling and Assembly
- Transportation (land, sea, air)
- Gas, Oil and Mining
- Water, Wastewater
- Consumer Electronics
- Computers
- Home Appliances
- Defense
- Medical
- Space Exploration

Electrical Drives: Performance Trend

Power Density

▶ Increasing Power/Torque Density

- **Esson's Scaling Law for Electrical Machines**

Machine Torque

Machine Speed

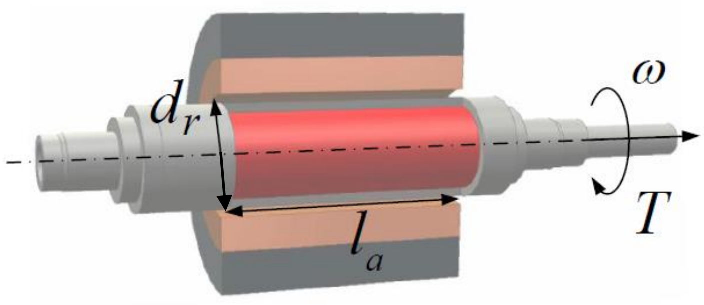
1) Mechanical Power $P_m = \omega T$

2) Machine Torque $T = c\, l_a d_r^2$

Rotor Diameter

Axial Length of Machine

Machine Size



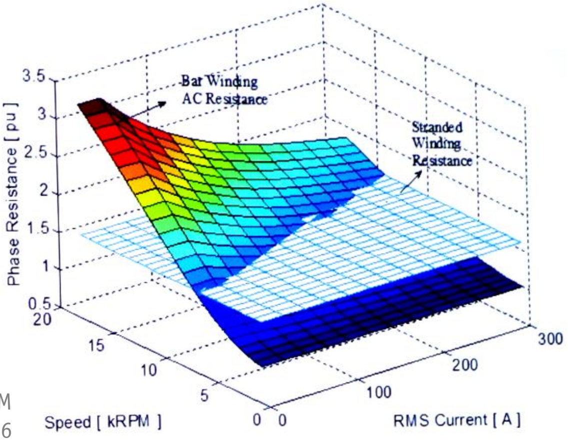
Utilization Factor
- Machine topology
- Materials
- Manufacturing methods
- Cooling

▶ Increasing the Machine Utilization Factor (1)

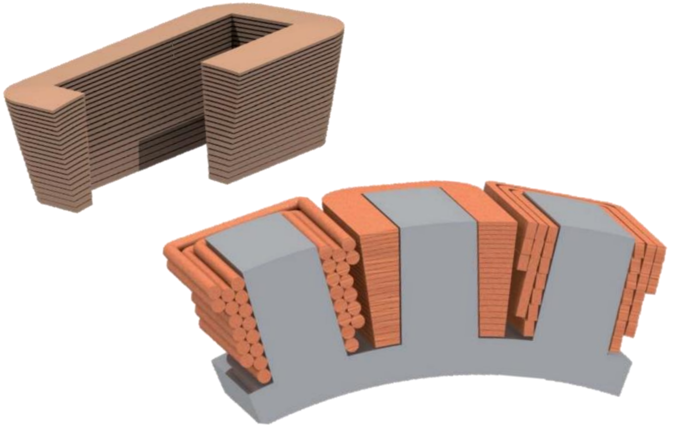
■ Degrees-of-Freedom for Improved Utilization

- Manufacturing methods
- Materials
- Cooling

– **Cast coils:**
+ Very high filling factor
+ Low-cost
+ Aluminum or copper
+ High power densities
- High-frequency losses



Source: GM Cevrolet Volt 2016



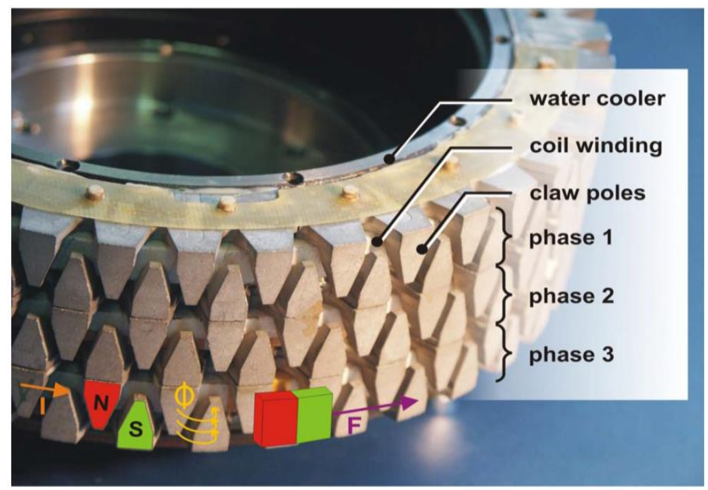
▶ Increasing the Machine Utilization Factor (2)

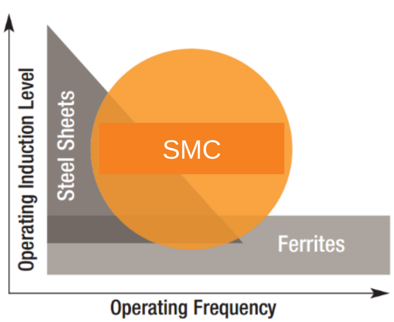
■ Degrees-of-Freedom for Improved Utilization

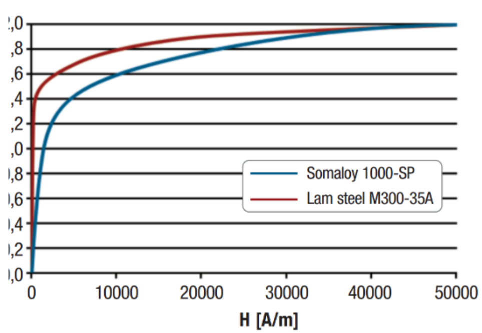
- Manufacturing methods
- Materials
- Cooling

Source: gkn.com

– **Soft magnetic composites (SMC):**
  + 3-D electrical insulation
  + Low eddy-current losses
  + Transversal- or Axial-Flux Machines
  - Mechanical strength
  - Low magnetic permeability







Source: Bauer, Kleimaier
Observer Based Sensorless Predictive Hysteresis Control of a Transverse Flux Machine

▶ Increasing the Machine Utilization Factor (2)

■ Degrees-of-Freedom for Improved Utilization

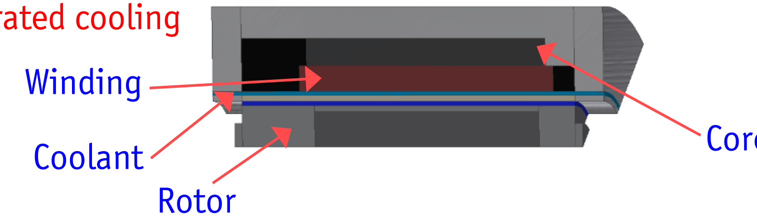
- Manufacturing methods
- Materials
- Cooling

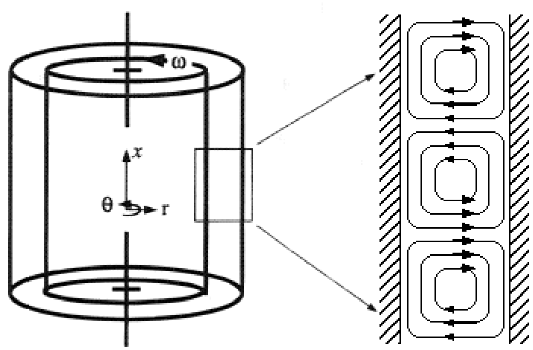
(1) Jacket cooling
(State of the art)

– **Integrated cooling (slotless machines)**

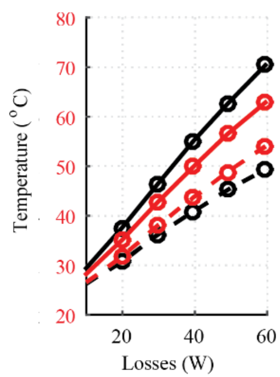
+ Smart design:
  Fast empirical models for cooling
  Magnetic ↔ Mechanical ↔ Thermal
+ > 40 °C hotspot temp. reduction

(2) Integrated cooling

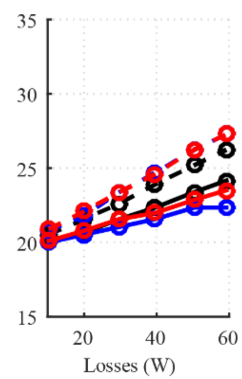




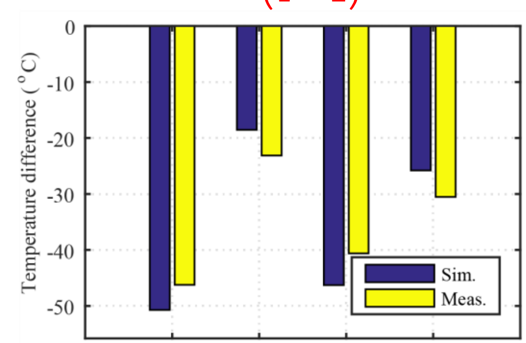
(1)



(2)



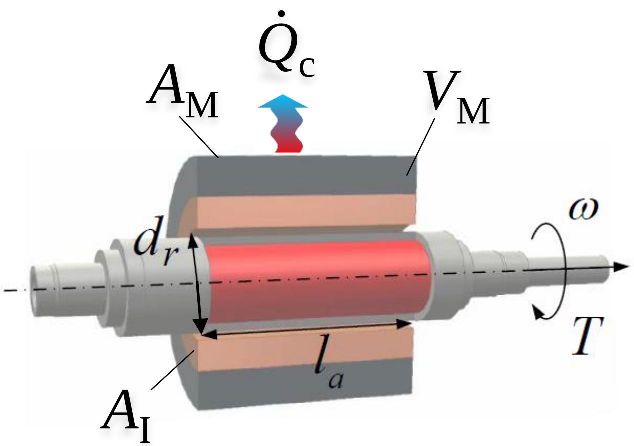
(1 − 2)



Source: Tüysüz et. al., Advanced Cooling Concepts for Ultra-High-Speed Machines, ICPE 2015

▶ Increasing the Power Density

Dimensional Scaling Factor x_d
Ratio of Dimensions Remains Constant



Machine Radius

Machine Length

Surface Area $A_M = 2\pi r_M^2 + \pi r_M l \quad \propto x_d^2$

Volume $V_M = \pi r_M^2 l \quad \propto x_d^3$

$T = B_\delta I l_a r_w \propto x_d^{3.5}$

Mechanical Power $P_m = \omega T \propto x_d^{2.5}$

$\omega = v_c / r_r \propto 1/x_d$

Copper Losses

$P_I = RI^2$ with $R = \rho \frac{l}{A_I} \propto \frac{1}{x_d}$

$P_I \leq \dot{Q}_c$ (!)

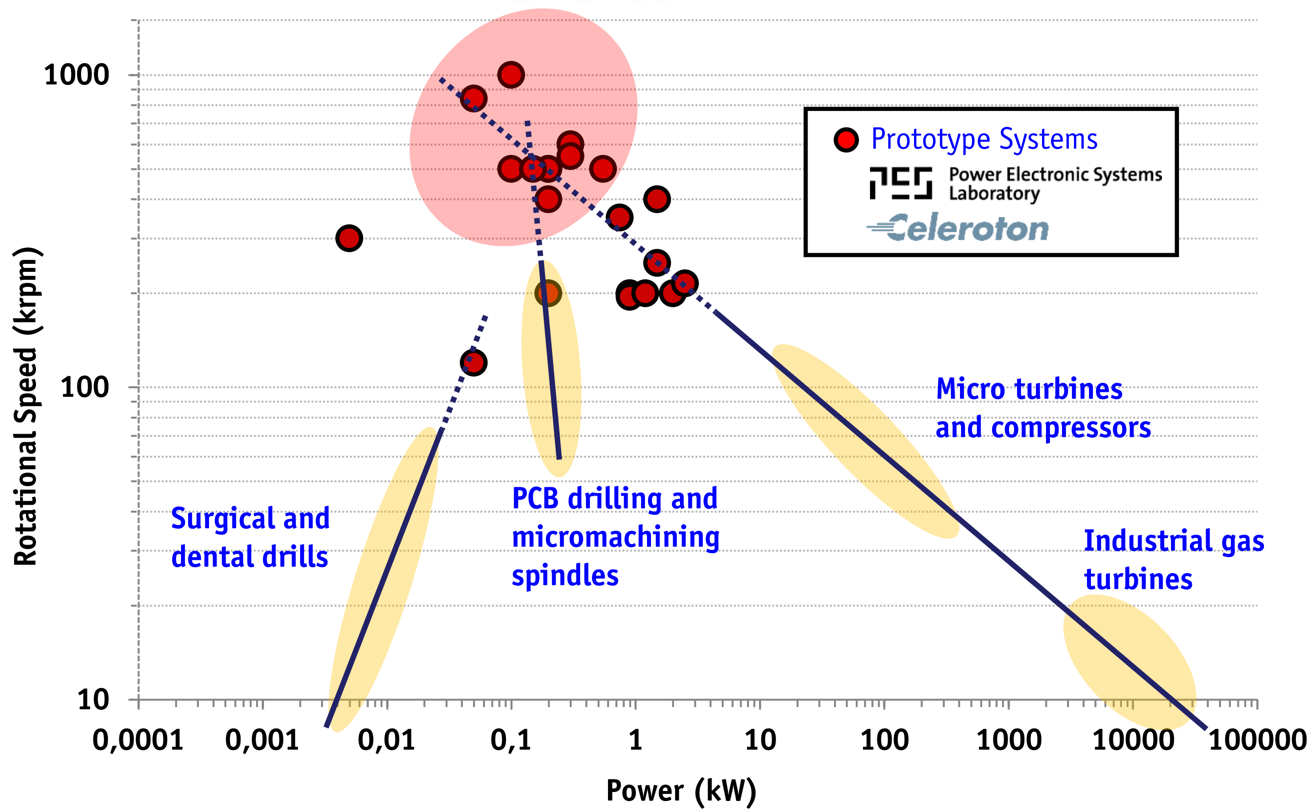
→ $I \propto x_d^{1.5}$

Power Density $p_m = P_m / V_M \propto x_d^{-0.5}$

▶ Industry Trend: High Rotational Speed for High Compactness

■ High-Speed Drives have Numerous Applications Across Industries

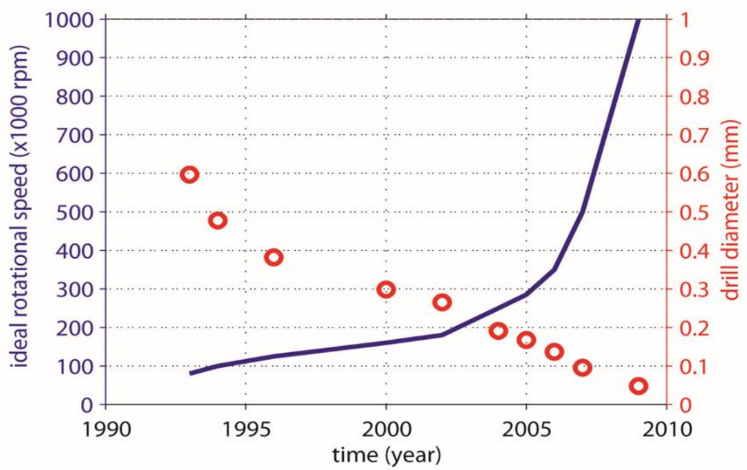
▶ Emerging Applications



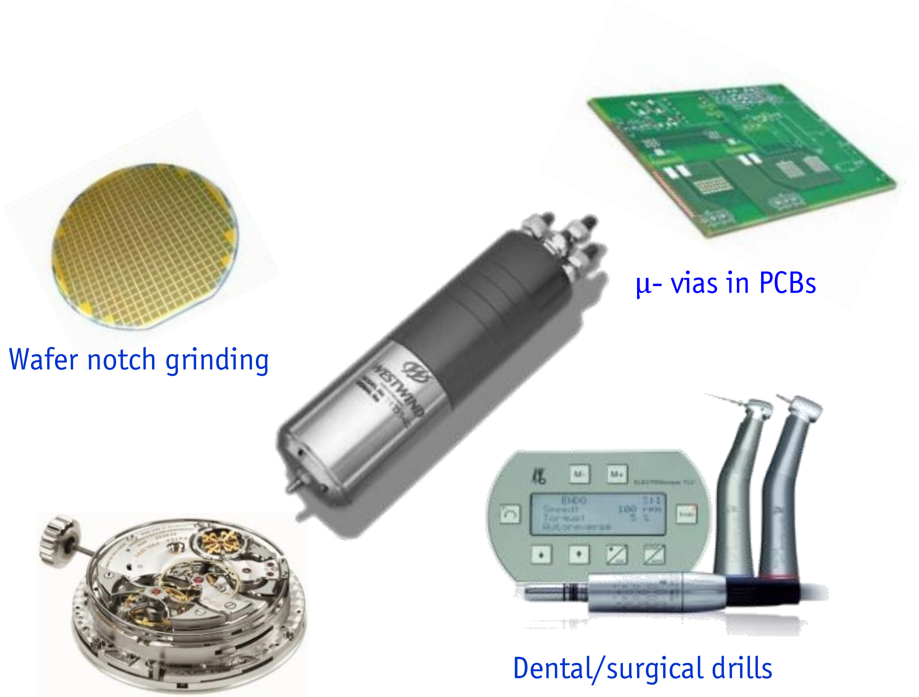
Source: Zwyssig et. al., Megaspeed Drive Systems: Pushing Beyond 1 Million r/min, IEEE Transactions on Mechatronics 2009

▶ High-Speed Micro-Machining Applications

- **Rotational Speed: 250’000 – 1’000’000 r/min**
  - Smaller Feature Size (µ-vias for Consumer Electronics)
  - Higher Precision in Manufacturing
  - Accelerated Manufacturing Process
  - Higher Productivity



Source: Kolar et. al., Beyond 1 000 000 rpm Review of Research on Mega-Speed Drives, COBEP 2007



Wafer notch grinding

µ- vias in PCBs

Dental/surgical drills

Watchmaking

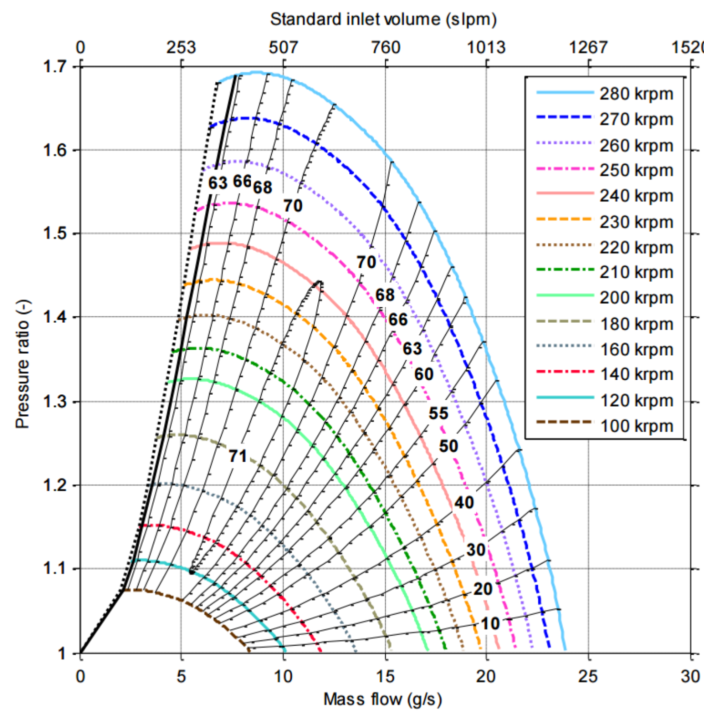
► High-Speed Turbocompressor for Portable Fuel Cell

- Reduced Weight/Volume
- Increased Pressure Ratio

Fuel cell

Celeroton

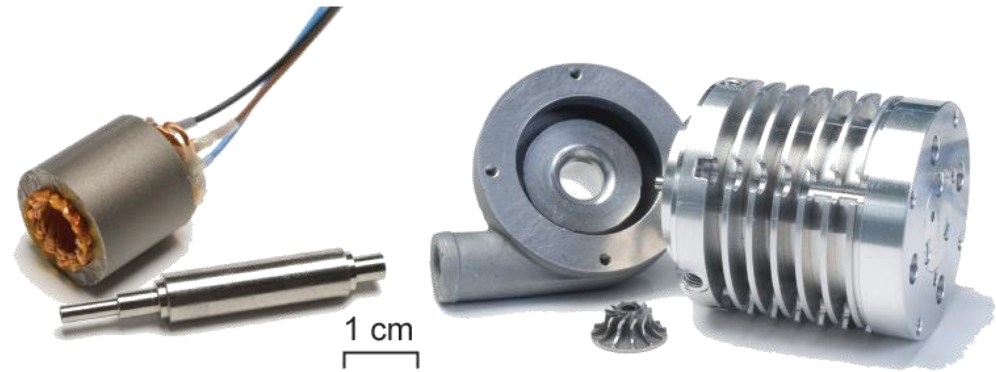
Commercially available compressors		
Speed (r/min)	280 000	18 000
Pressure ratio	1.6	1.4
Mass flow (g/s)	15	15
Weight (kg)	0.6	4



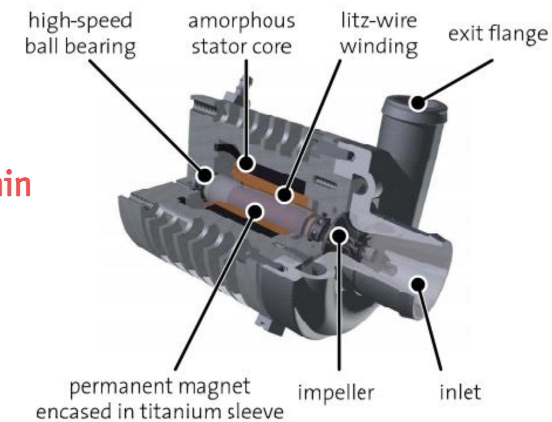
► Ultra-Compact Turbocompressor for *«Solar Impulse»*

■ Cabin Pressurization in Solar-Powered All-Electric Aircraft

- Compact machine design with 150 W



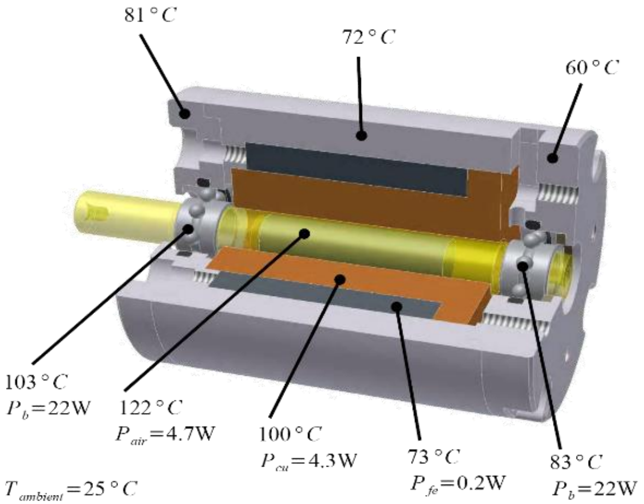
Rotational Speed	500’000 r/min
Machine Power	150 W
Mass Flow	1.2 g/s
Compression Ratio	1.8

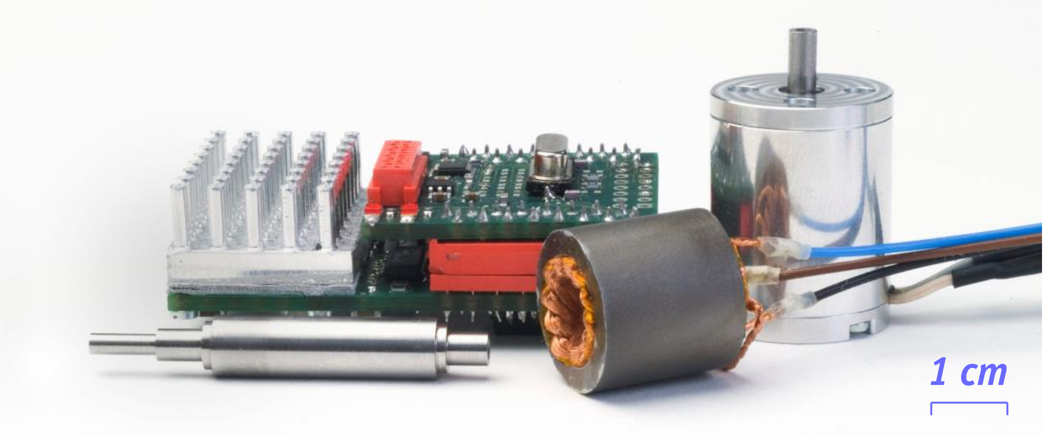


▶ 1'000'000 r/min - World Record Drive System

- Demonstration of Machine Design Principles with 100 W / 1'000'000 r/min Drive System

- P_{loss} 9W (excl. bearings)
- d Rotor PM 3 mm
- Ball Bearing Losses 44 W (!)





- ▶ µm-Scale PCB Drilling
- ▶ Dental Technology
- ▶ Laser Measurement Technology
- ▶ Turbo-Compressor Systems
- ▶ Air-to-Power
- ▶ Artificial Muscles
- ▶ Mega Gravity Science

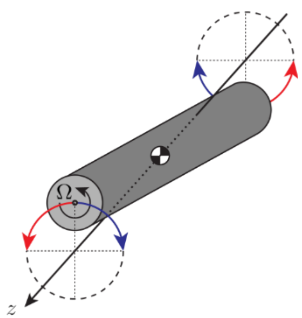
Source: Zwyssig et. al., Megaspeed Drive Systems: Pushing Beyond 1 Million r/min, IEEE Transactions on Mechatronics 2009

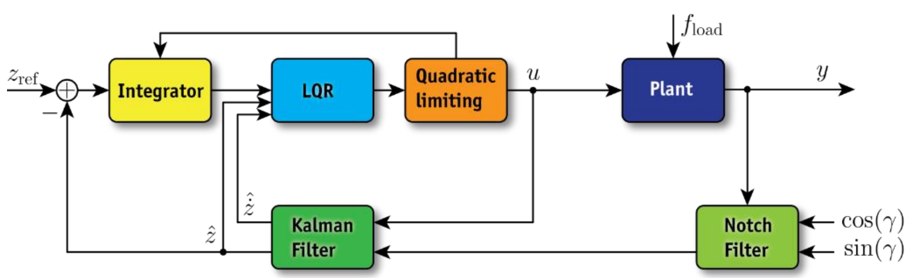
▶ Advanced Bearing Systems for High-Speed-Drives

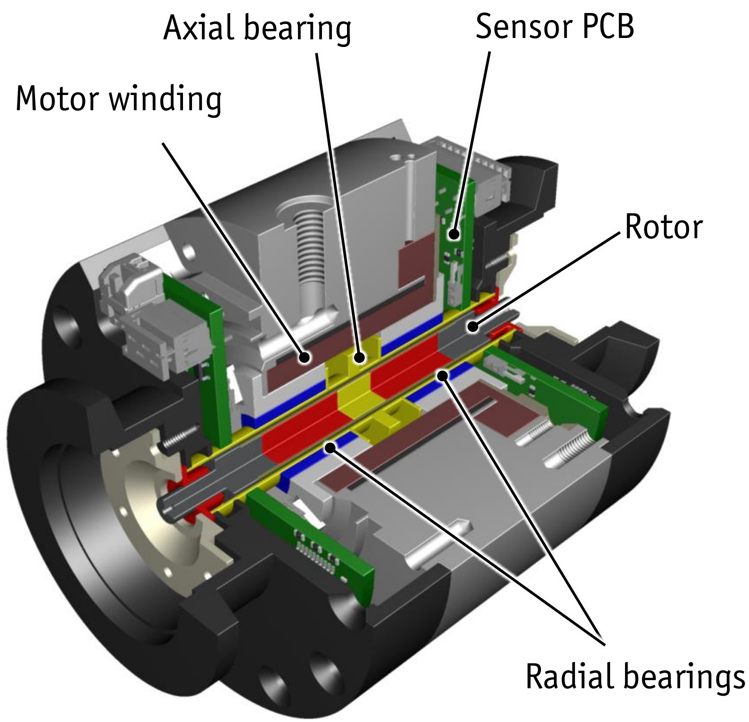
■ Lifetime of Ball Bearings Limits Rotational Speed of Electric Machine

■ Active Magnetic Bearings

+ No Wear, Long Lifetime
+ Control of Rotor Dynamics
- Limited Load Capacity
- High Bandwidth / Complex Control
- Accurate Displacement Sensing





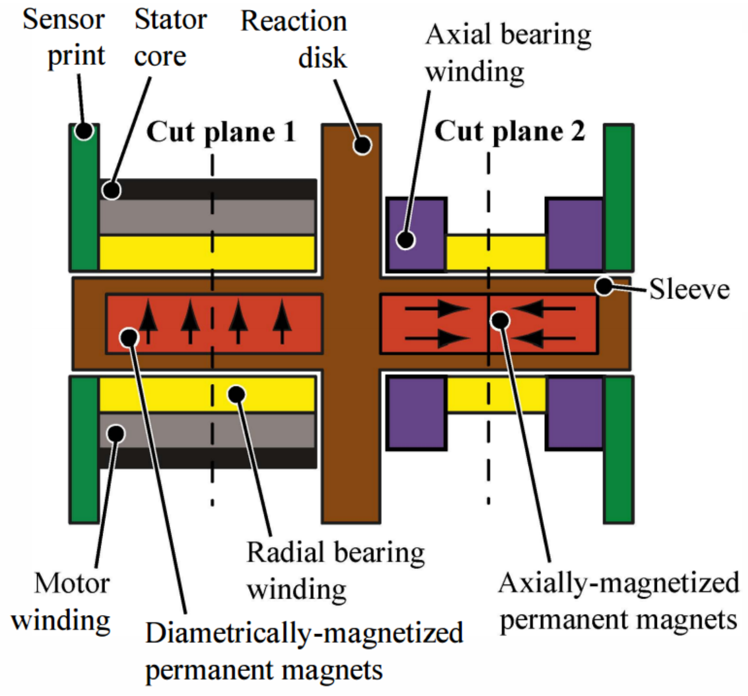


Source: Baumgartner et. al., Analysis and Design of a 300-W 500 000-r/min Slotless Self-Bearing Permanent-Magnet Motor, IEEE Transactions on Industrial Electronics 2014

Space Application: Satelite Attitude Control

- **Reaction Wheels are Widely Used for Satellite Attitude Control**
- **Currently Ball Bearings are Used Despite Disadvantages**

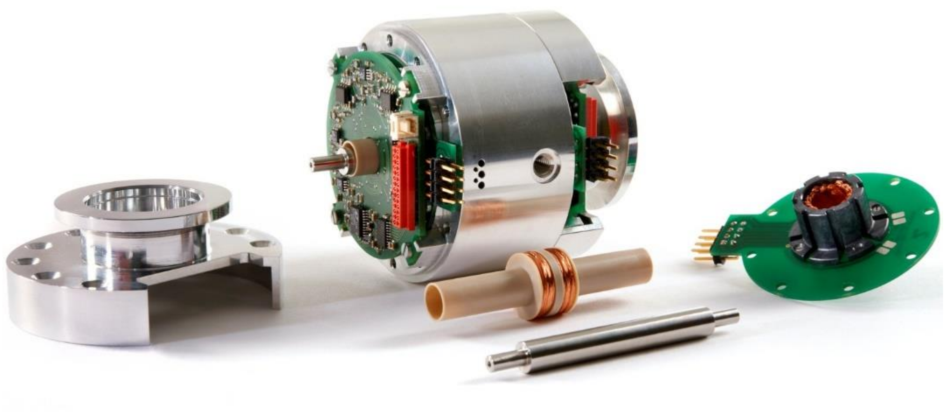
- **Magnetic Bearings Allow for**
  - Less Microvibrations
  - Higher Speed: Smaller Reaction Wheel Size

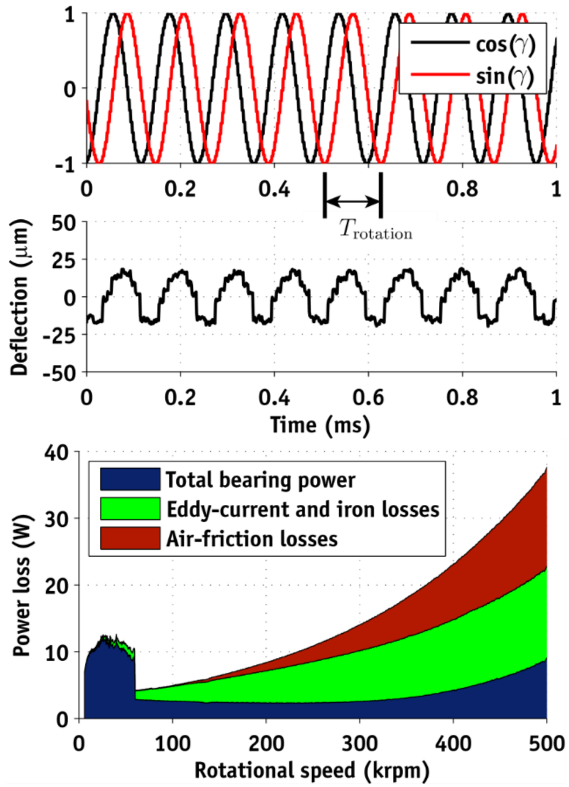


Source: nasa.gov

▶ World Record Magnetic Bearing with 500’000 r/min

- Demonstration of Active Magnetic Bearing Concept at World-Record Speed

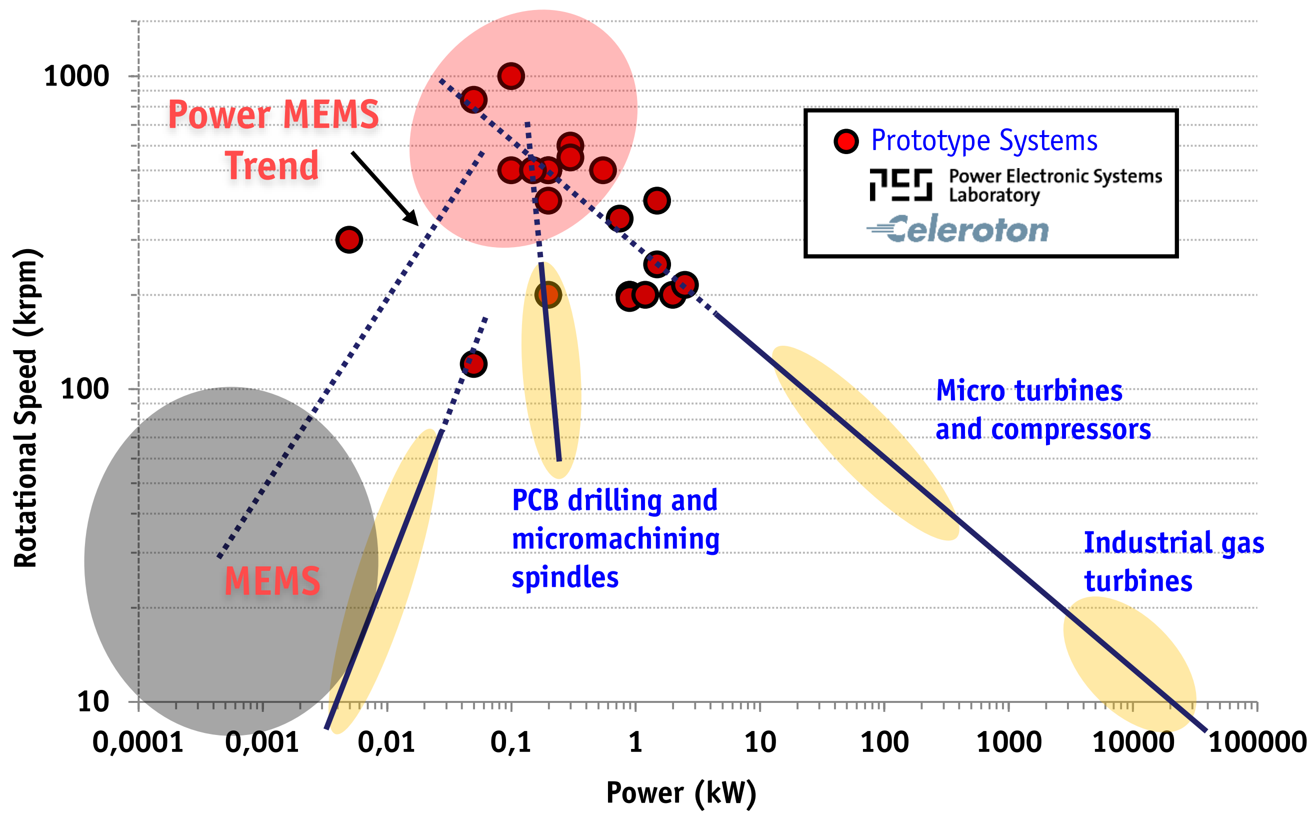




Source: Baumgartner and Kolar, Multivariable State Feedback Control of a 500 000-r/min Self-Bearing Permanent-Magnet Motor, IEEE Transactions on Mechatronics 2015

► Technology Trends for High Rotational Speeds

■ Emerging MEMS and Power MEMS Technology

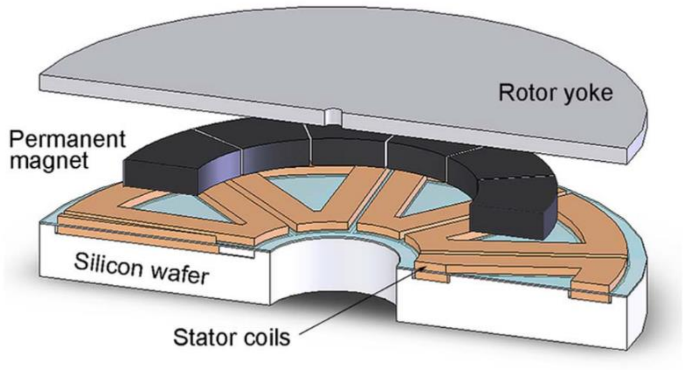


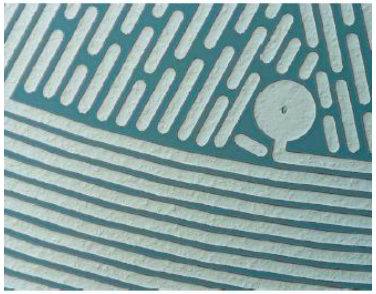
Adapted from: Zwyssig et. al., Megaspeed Drive Systems: Pushing Beyond 1 Million r/min, IEEE Transactions on Mechatronics 2009

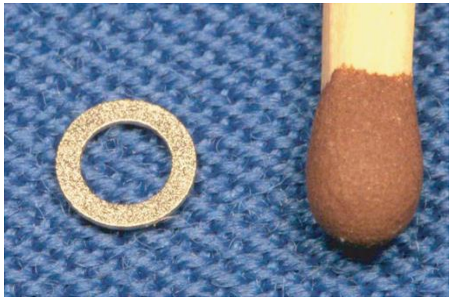
► Example 1: MEMS Brushless-DC Micromotor

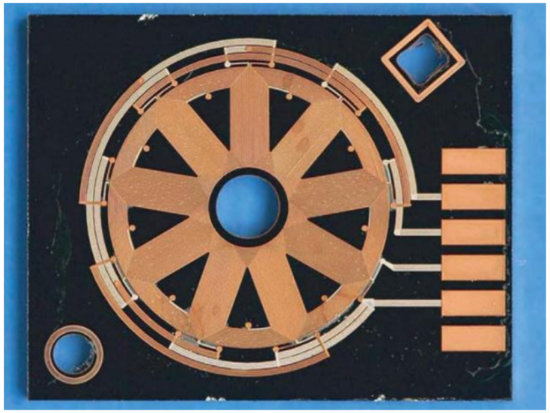
- **Main Application: Watch Industry**

- **Stator Manufactured in Clean Room** (CMOS technology)
- **310 nW at 300 r/min**
- **42% Efficiency (Open-Loop Drive)**




Stator Coil Structure


Permanent Magnet

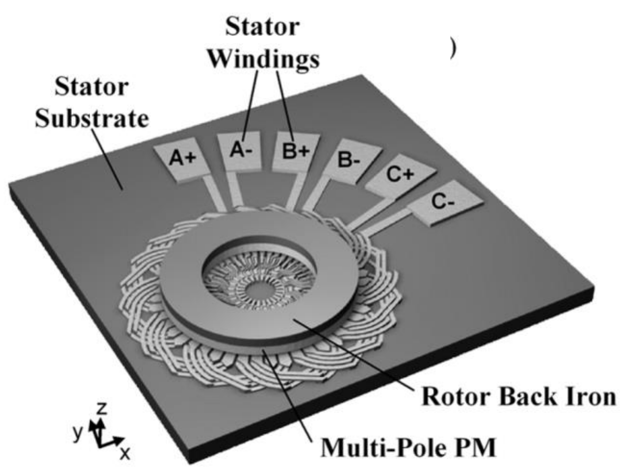

MEMS BLDC (top view)

Source: Merzaghi et. al., Development of a Hybrid MEMS BLDC Micromotor, IEEE Transactions on Industry Applications 2011

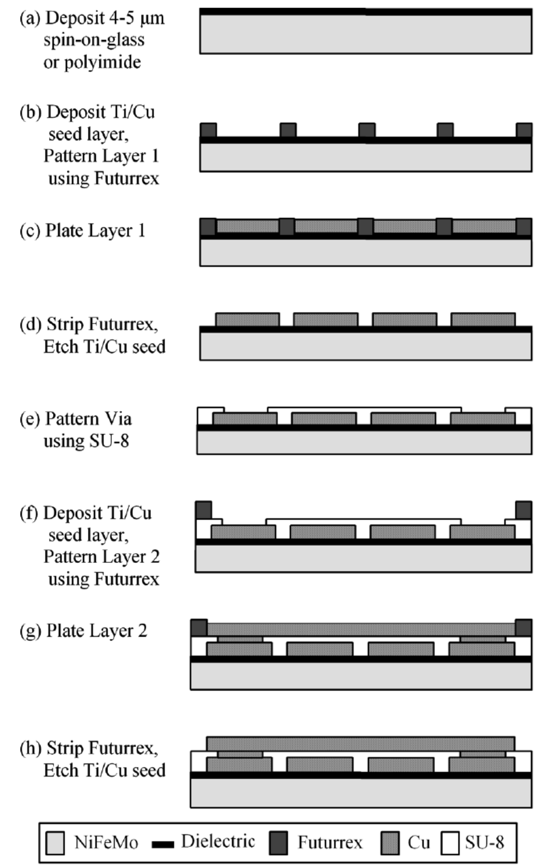
▶ Example 2: Microfabricated Axial-Flux Generator

- **Intended Application: Portable Power Generation**

- **Permanent Magnet Rotor**
- **Stator Manufactured in Clean Room** (CMOS technology)
- **2.5 W Power Conversion at 120'000 r/min**
- **43% Efficiency**



Concept



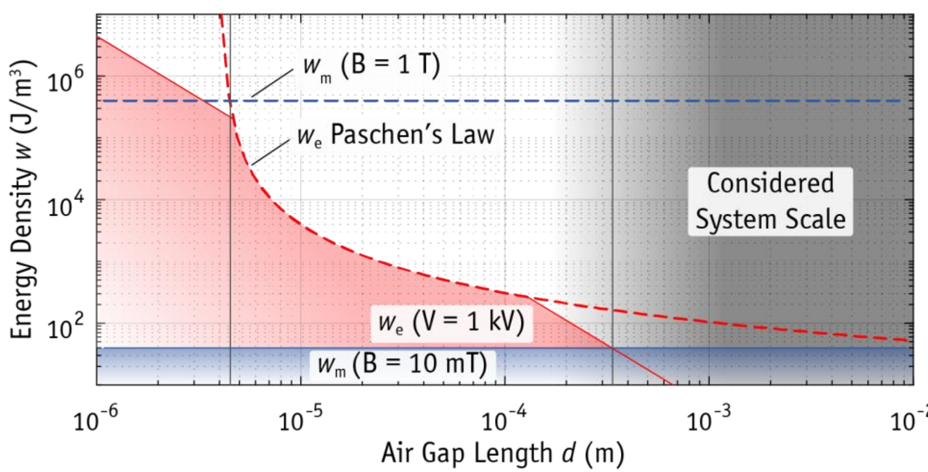
Winding Fabrication Process

Source: Arnold et. al., Microfabricated High-Speed Axial-Flux Multiwatt Permanent-Magnet Generators—Part II: Design, Fabrication, and Testing, IEEE Journal of Microelectromechanical Systems 2006

▶ Technology Selection for Ultra-High-Speed Rotation

Source: Chapman & Krein, Smaller Is Better? [Micromotors and Electric Drives], IEEE Industry Applications Magazine 2003

- Difficult Manufacturing of Inductive Components Using CMOS Processes
- Significantly Higher Energy Density with Magnetic Fields at Millimeter Scale
- Active Magnetic Bearings well Suited for Ultra-High-Speed Rotation

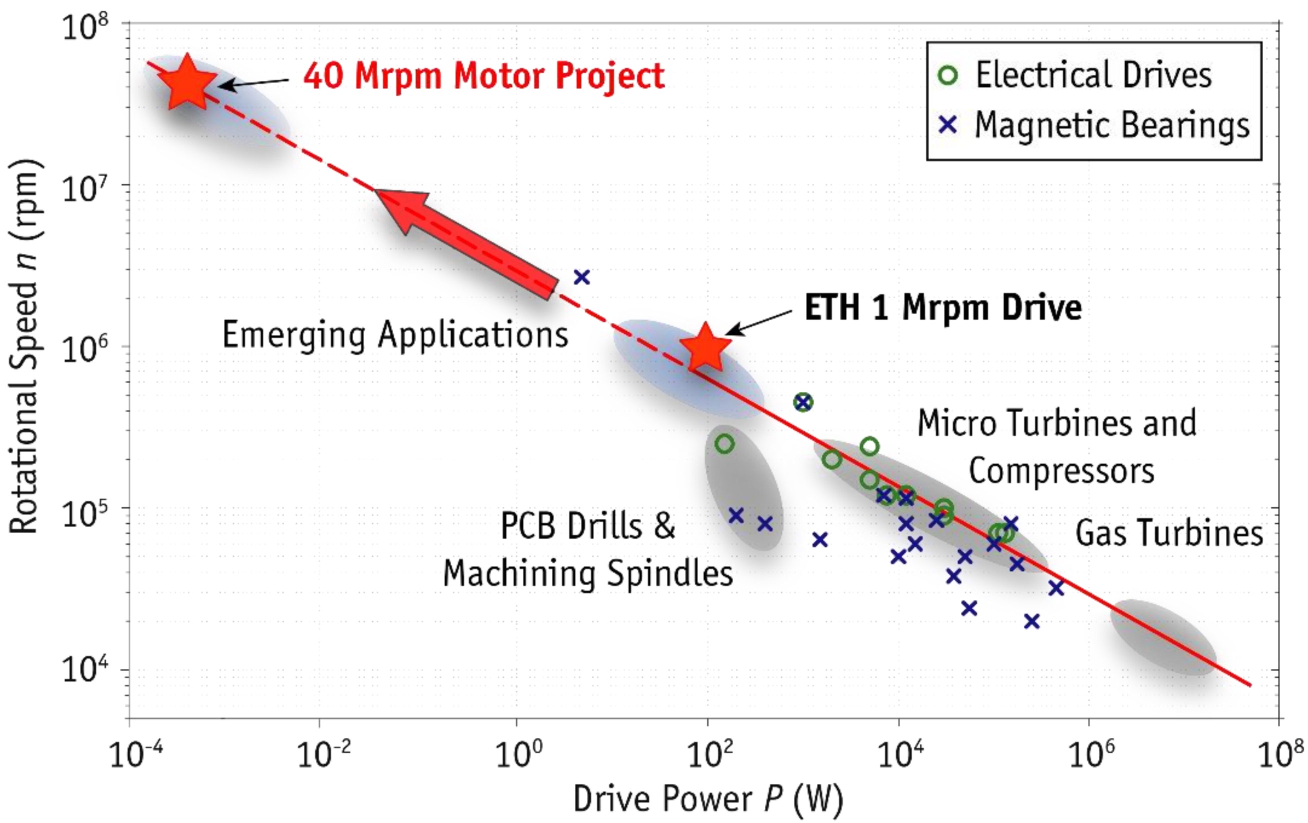


Strategic Research Project

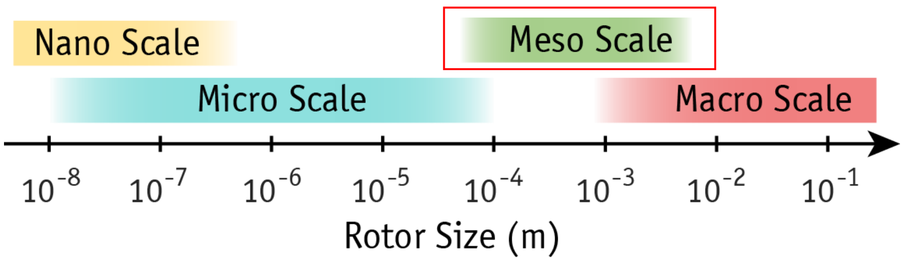
40’000’000 rpm
Spinning Ball Motor

▶ Exploring the Limits of Ultra-High-Speed Rotation

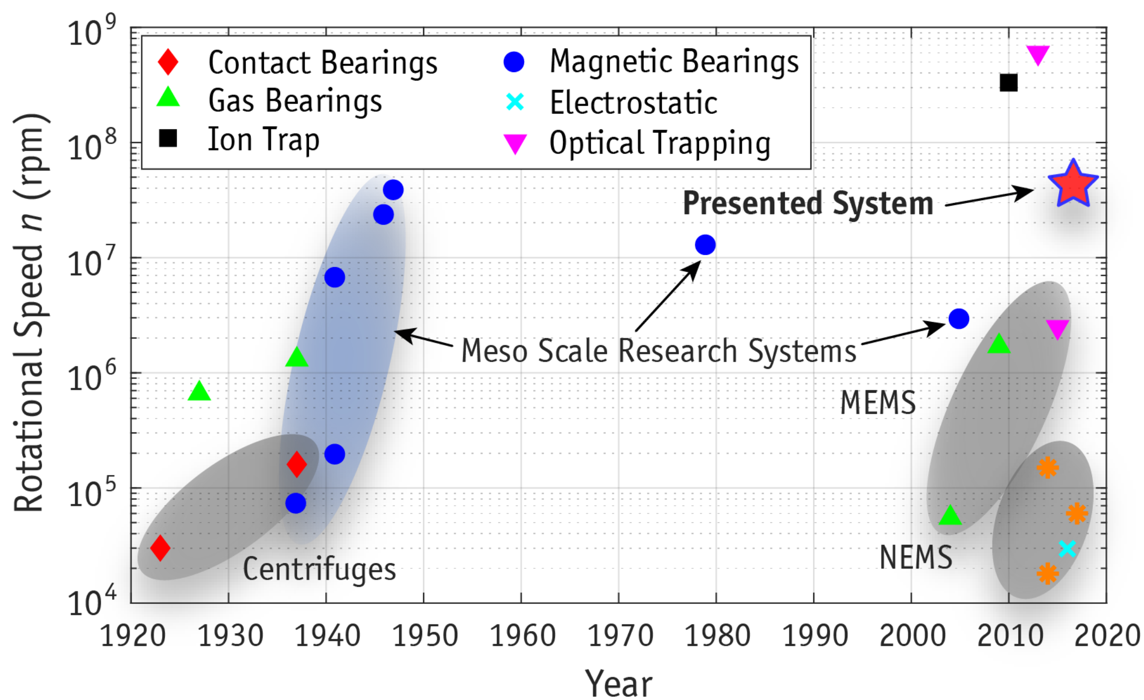
- Demonstrator System for Highest Recorded Rotational Speed for Electric Machines
- Development of Underlying Technologies for Future Drive Systems



▶ History of Ultra-High-Speed Rotation



- **Highest Rotational Speeds of Such Systems Date Back 70 Years**
- **Recently Evolved MEMS and NEMS Limited to < 3 Mrpm**

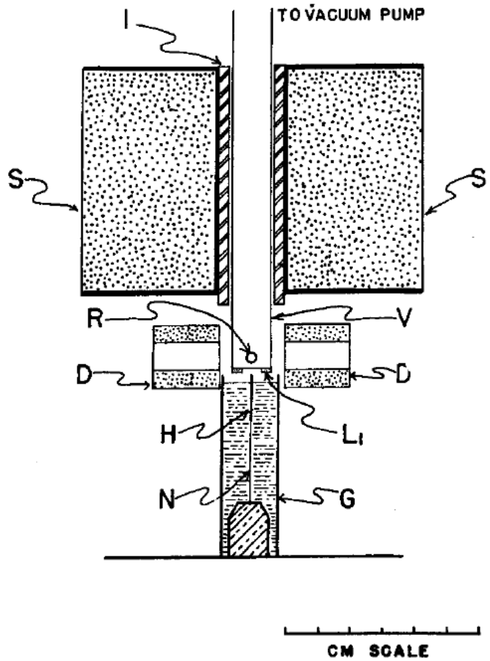


► Highest Rotational Speed of an Electric Motor

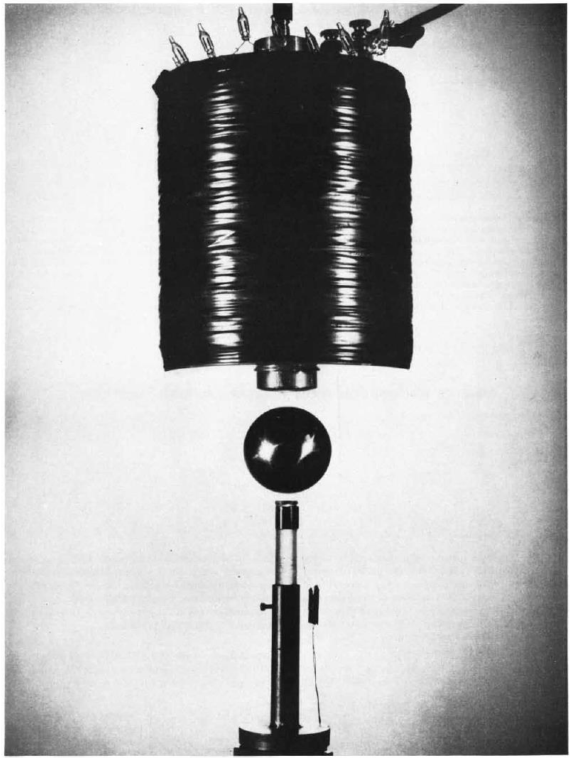
■ **J. W. Beams and J. L. Young: 37.98 Mrpm, 1947**

- R. Katano and S. Shimizu: 12.64 Mrpm, 1979
- A. Boletis and H. Bleuler: 2.88 Mrpm, 2005

► **Not Reproduced or Exceeded Since, Despite Other Attempts**



Experimental Setup Used in 1947



J. W. Beams and J. L. Young, "Centrifugal Fields," Phys. Rev., vol. 71, pp. 131–131, Jan 1947.
R. Katano and S. Shimizu, "Production of centrifugal fields greater than 100 million times gravity," Review of Scientific Instruments, vol. 50, no. 7, pp. 805–810, 1979.
A. Boletis, "High speed micromotor on a three axis active magnetic bearing," PhD Thesis, EPFL, 2005.

▶ Fundamental Limit: Mechanical Rotor Stability

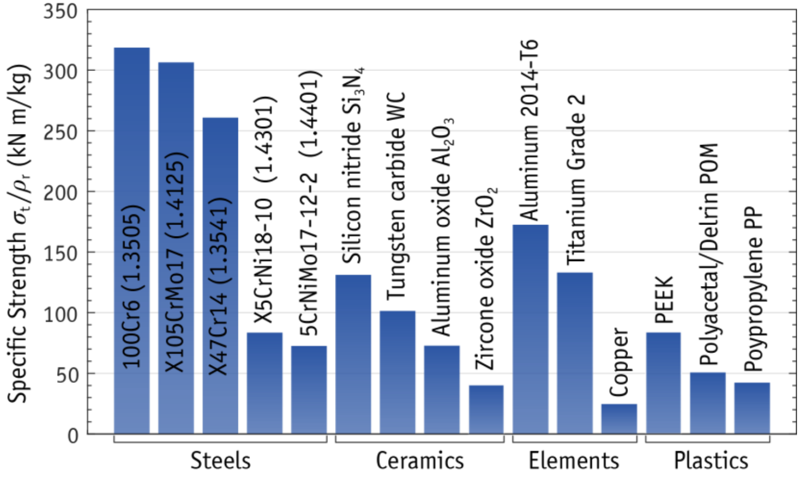
- **Withstanding Ultra-High Centrifugal Loads**
  - Steels Have Highest Specific Strengths
  - Optimal Shape Depends on Material/ Failure Criterion

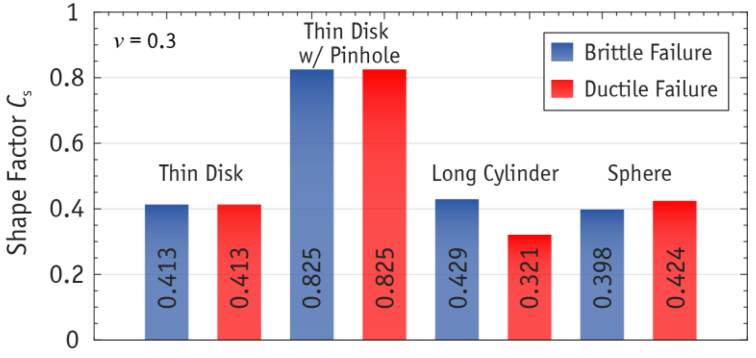
  Mechanical Stress: $\sigma_{\max} = C_s \rho_r \omega_r^2 a^2$

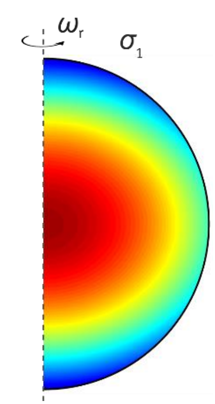
  ▶ **Rotor Diameter < 1mm Required**

- **Dynamic Rotational Stability**
  ▶ Rotation is Only Stable Around the Axis with the Largest Moment of Inertia

- **Suitable Material Properties for Magnetic Suspension**

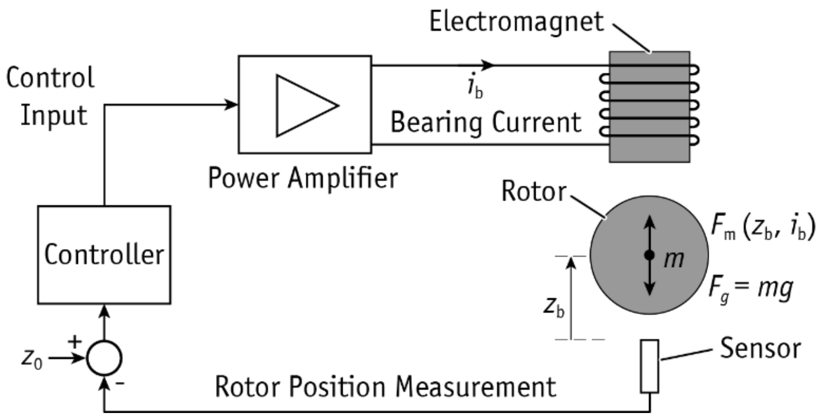






▶ Magnetic Suspension: Principle

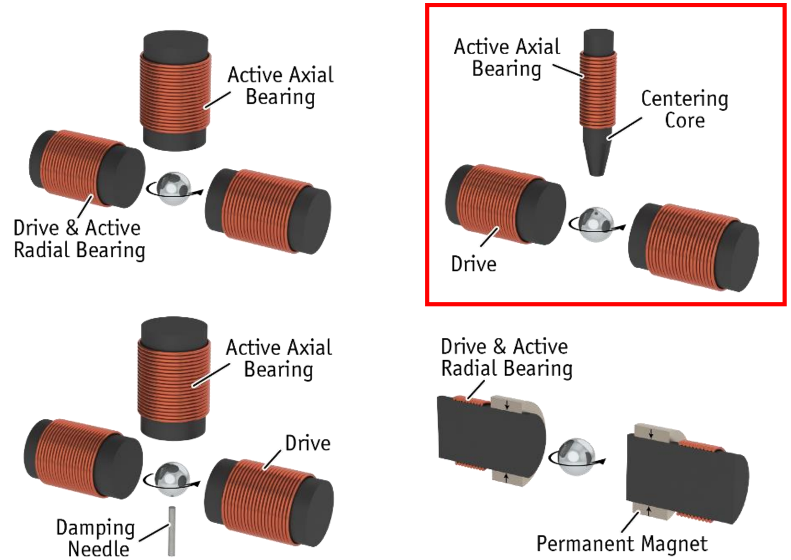
- **Levitation of the Rotor Without Mechanical Contact**



▶ Active Magnetic Suspension

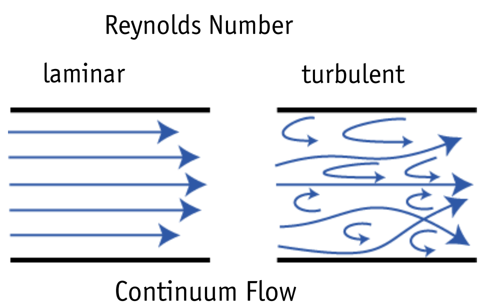
- **Stabilization of the Rotor in all DOF**
  - Insufficient Horizontal Damping Due to Low Friction

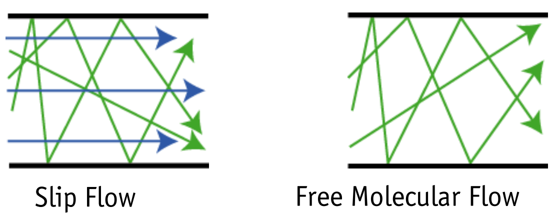
▶ Active Magnetic Damping

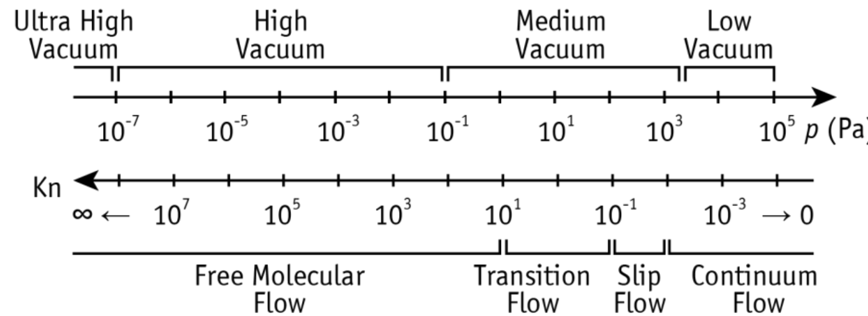


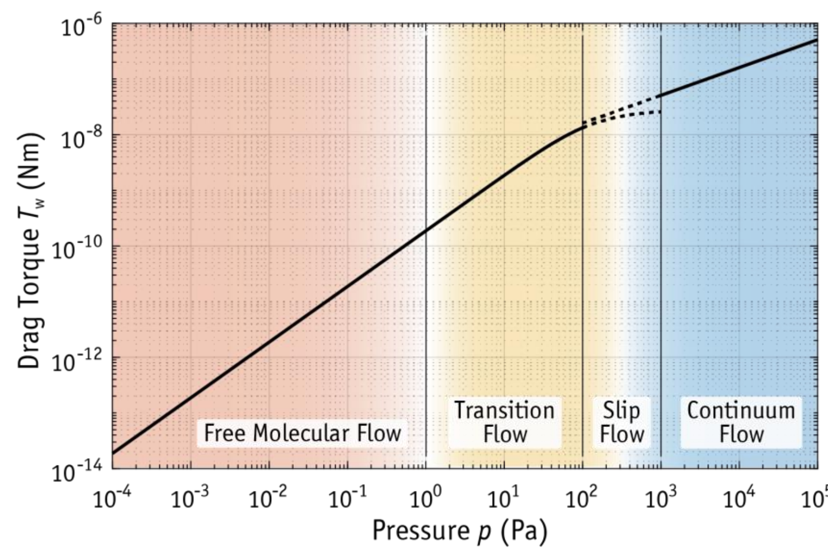
▶ Windage Losses

- **Dependent on Nature of Gas Flow**
  - Determined by Ratio of Geometry Dimensions and Mean Free Path
  - **Different Modeling Procedures**





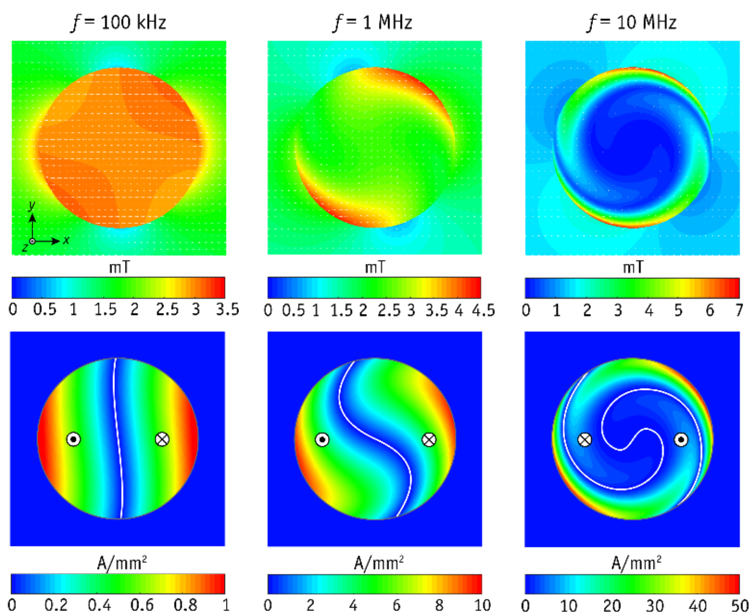




▶ Operation Under Free Molecular Conditions Necessary to Achieve Ultra-High Rotational Speeds

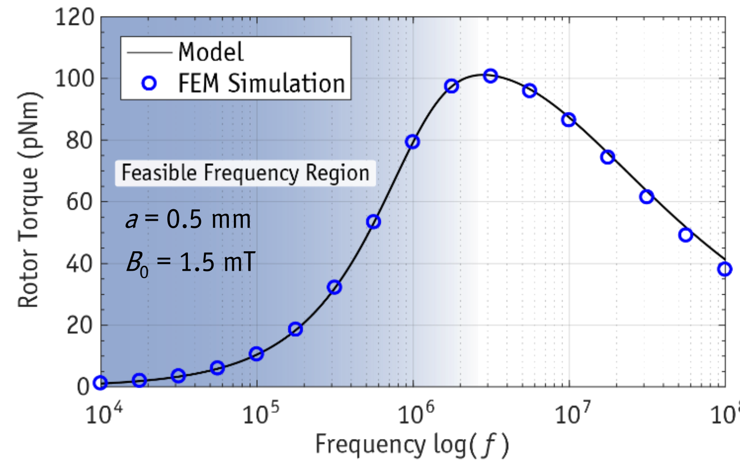
▶ Analytical Drive Model

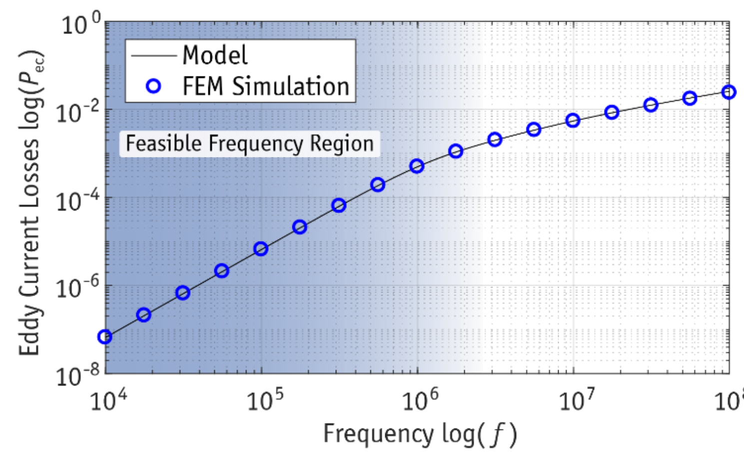
- **Solution Based on Magnetic Vector Potential**
- Conductive Sphere in Rotating Magnetic Field
  - Solid Rotor Induction Machine



◀ Flux Density

◀ Current Density

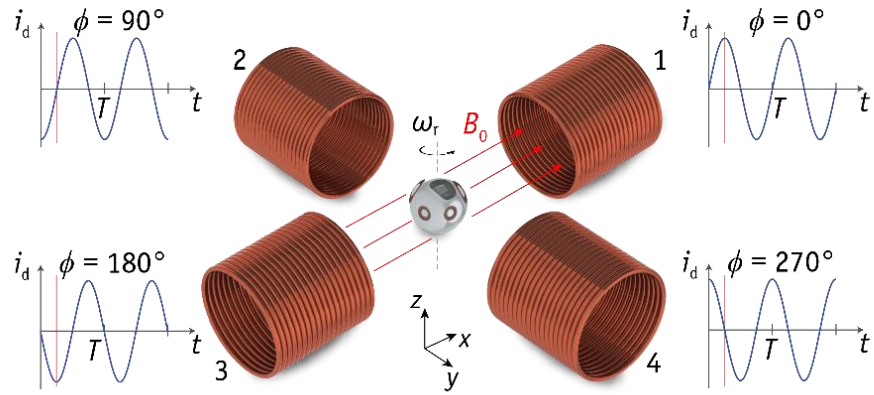




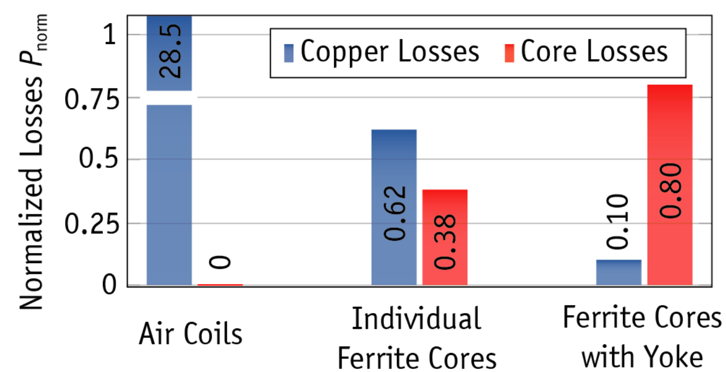
T. Reichert, T. Nussbaumer, and J. W. Kolar, "Complete analytical solution of electromagnetic field problem of high-speed spinning ball," Journal of Applied Physics, vol. 112, no. 10, 2012.

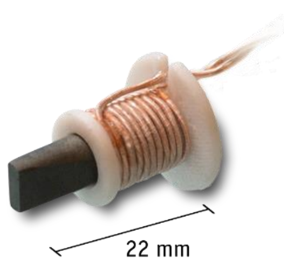
▶ Stator Design

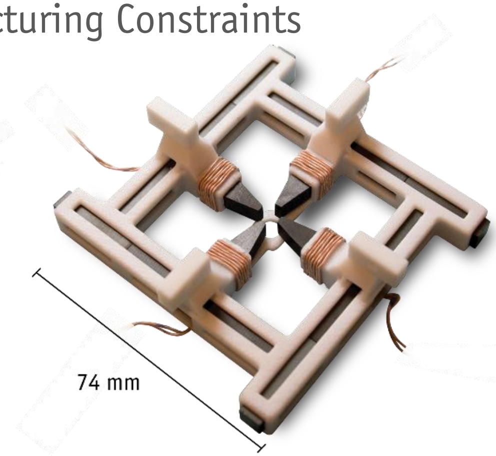
- **Drive Field Generation by Phase-Shifted Currents**
- **Air Coils**
  - Optimization for High Flux Density
    - Conical Design



- **Ferrite Core Designs**
  - Lower Losses at High Frequencies Than Conventional Materials
    - Manufacturing Constraints





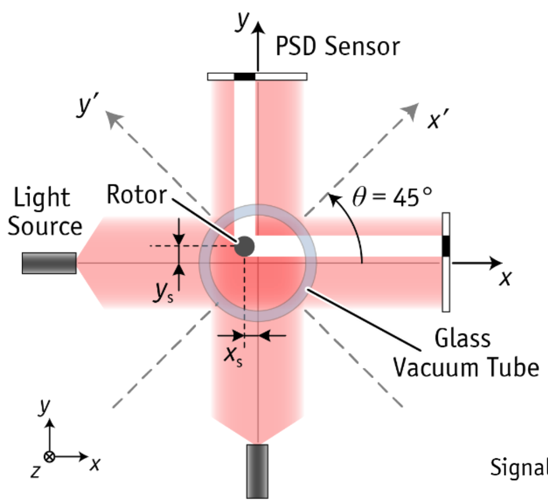


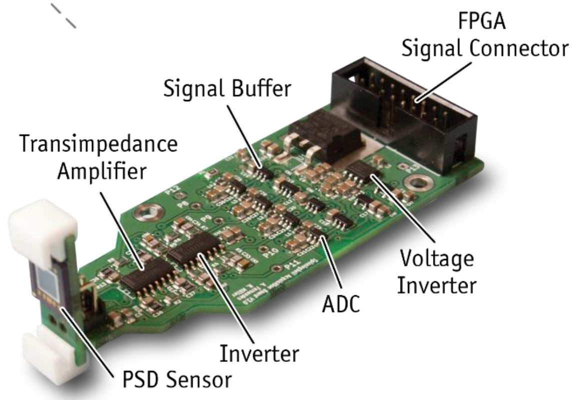
▶ Ferrite Core Designs Yield Significantly Lower Losses

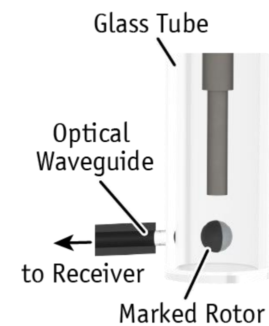
▶ Position and Speed Sensors

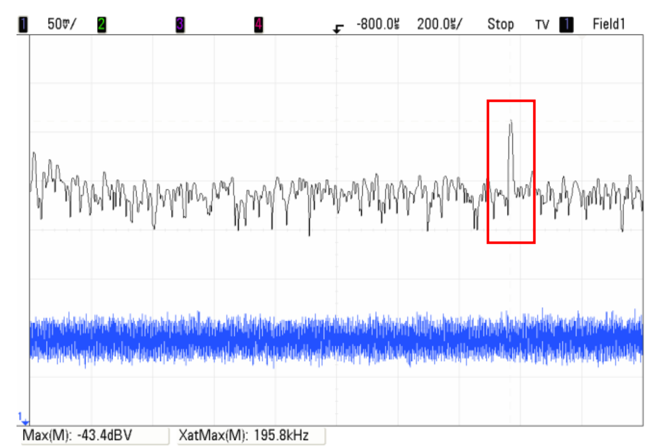
- **Rotor Shadow Projected on 2D Position Sensitive Device**
  - Distance >> Rotor Size
  - Optical Effects of Glass Vacuum Tube

- **Modulation of Light Reflected from the Rotor**
  - Rotor is Marked Prior to an Experiment
  - High Bandwidth Optical Receiver Circuit
  - Real-Time Signal Analysis Using FFT

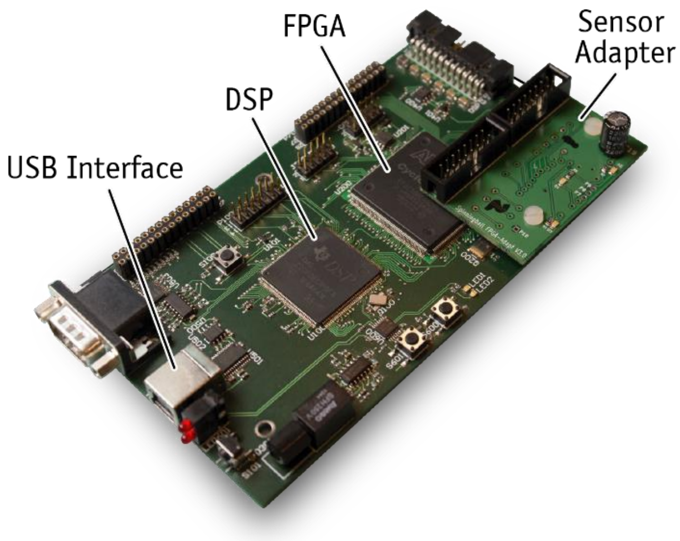


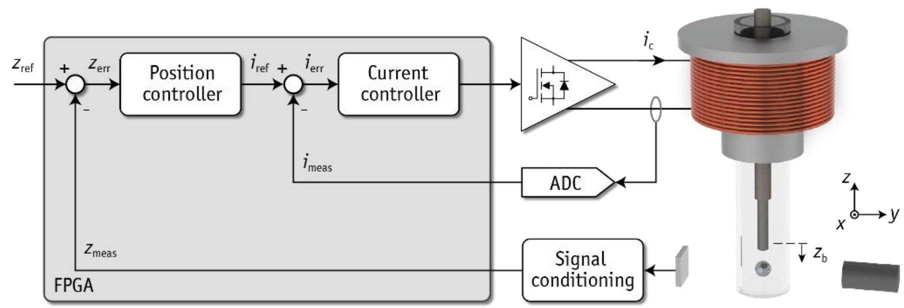


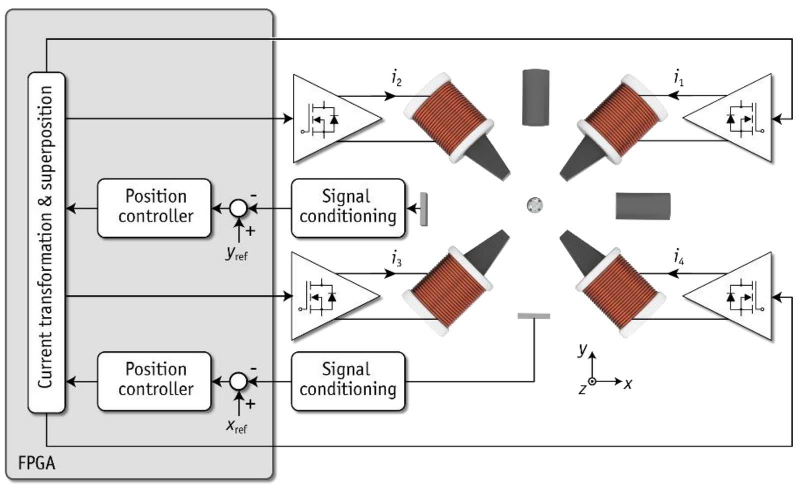




▶ Digital Control



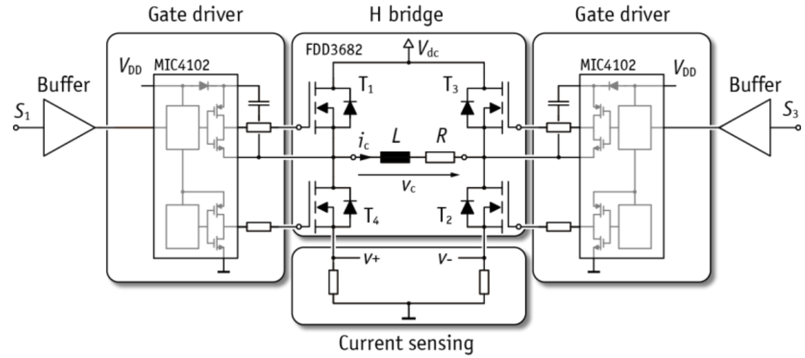


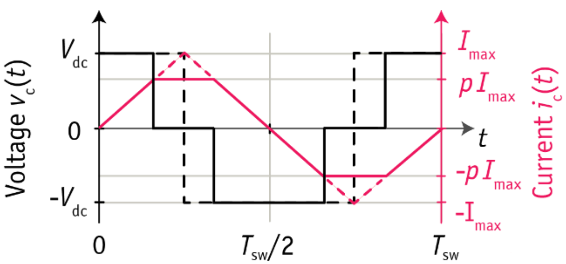


- **Controllers & Filters Implemented on FPGA (VHDL)**
  - Cascaded PID Control Structure for Axial Suspension
  - Active Radial Damping
  - Superposition of Drive and Radial Bearing Currents
  - PC Interface via DSP

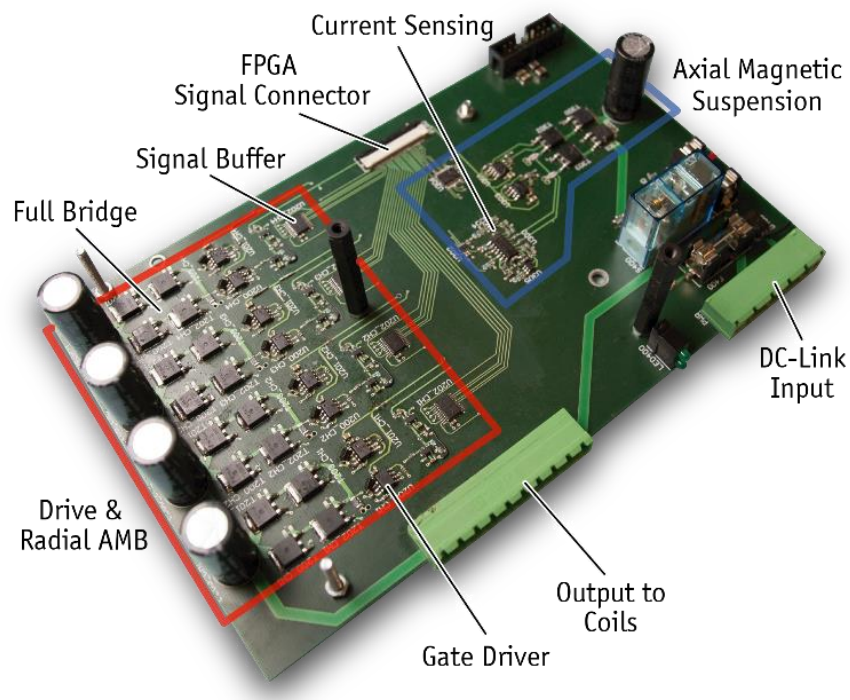
▶ Power Amplifiers

- **H Bridge Switching Amplifiers**
  - Nonlinearities due to Dead Time
    - Compensated Digitally
  - Switching Frequency up to 1.5 MHz
  - Current Sensing via Shunts for Axial Suspension



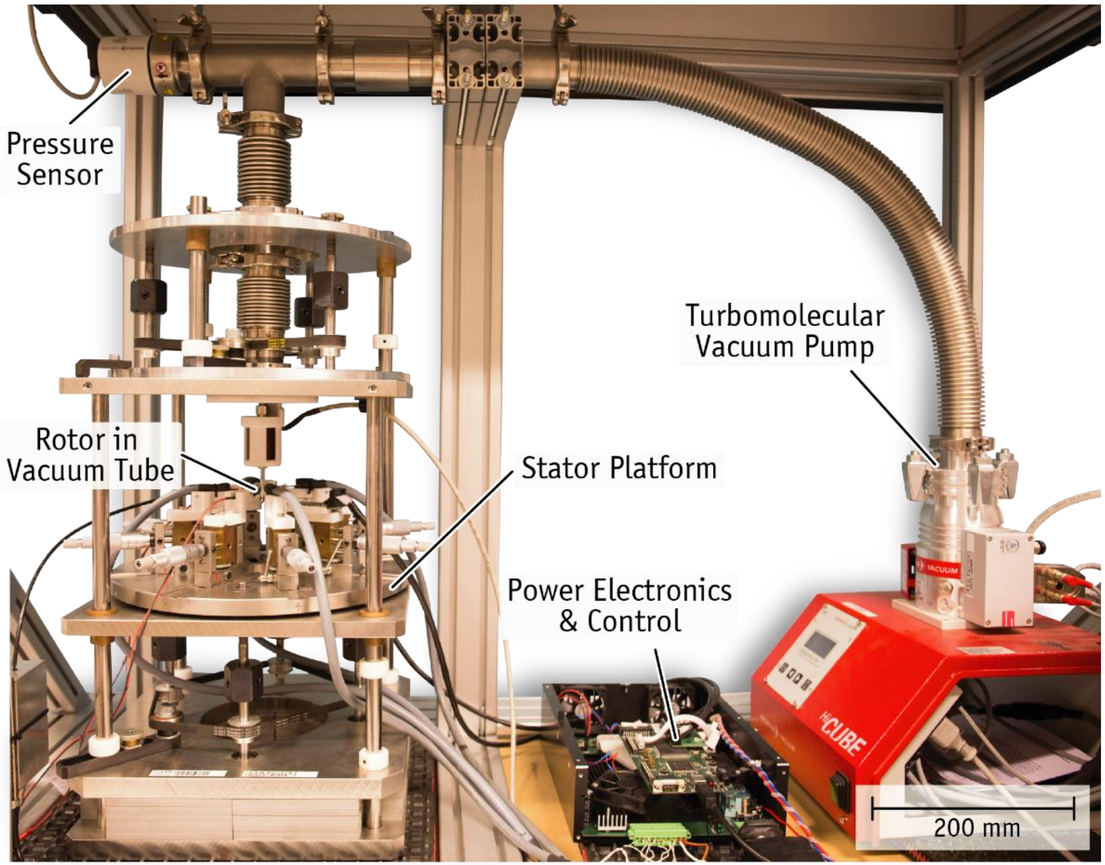


▲Fundamental Frequency Modulation of the Drive Currents



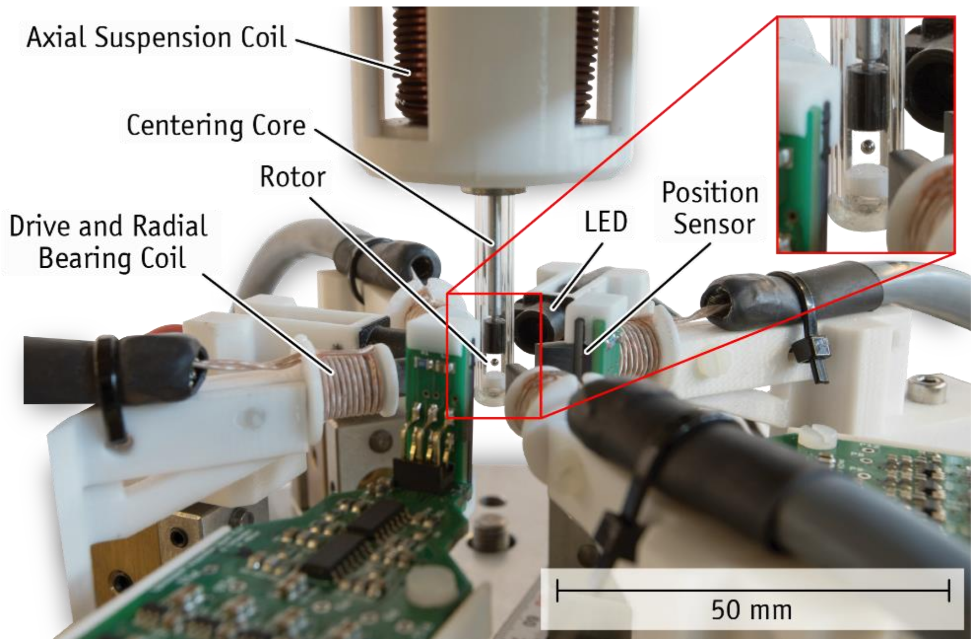
▶ Experimental Setup

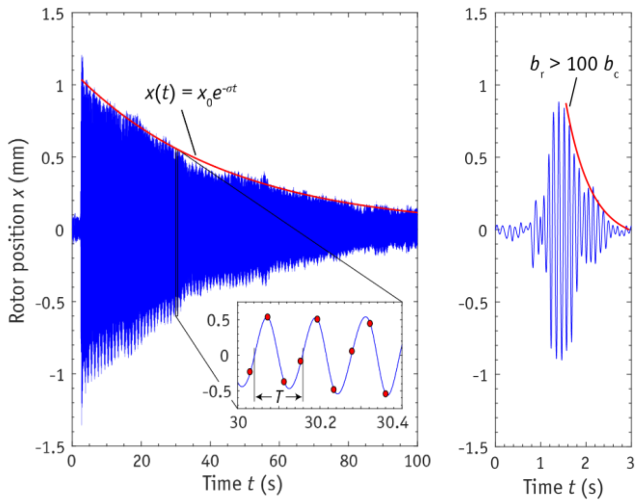
- **Integrated Two-Stage Vacuum System**
  - ISO KF DN 40 Vacuum Tubes
  - Final Pressure ~ 10^{-4} Pa
- **Adjustable Centering Core Height and Motor Platform**
- **Individual Horizontal Adjustment of Components**
- **Vibration Decoupling**



▶ Magnetic Suspension Performance

- **Prototype Hardware Realization:**

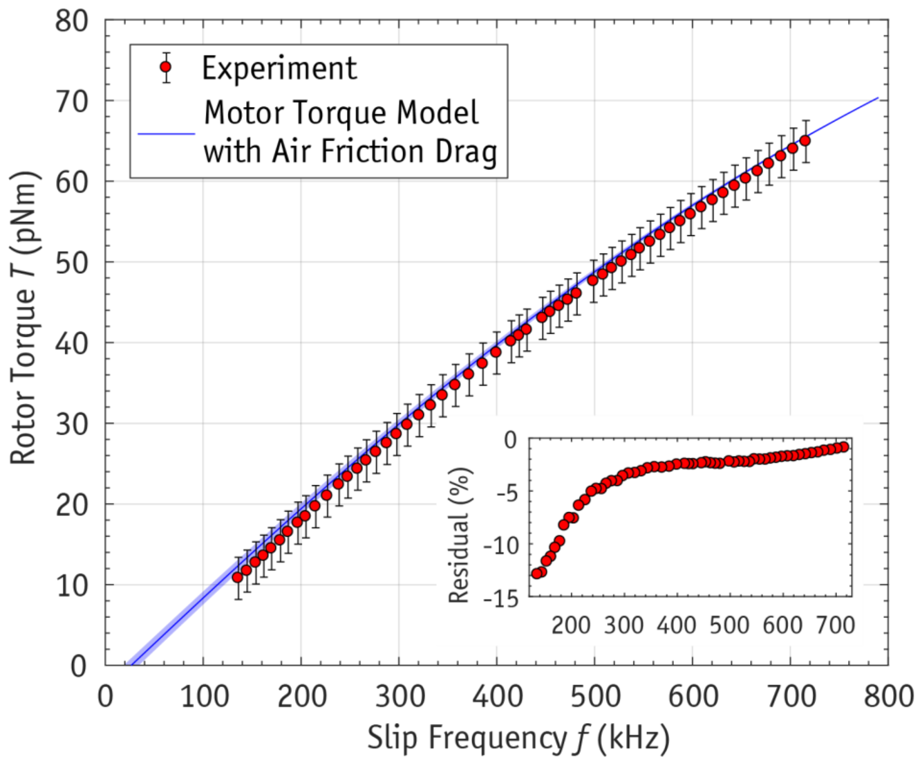




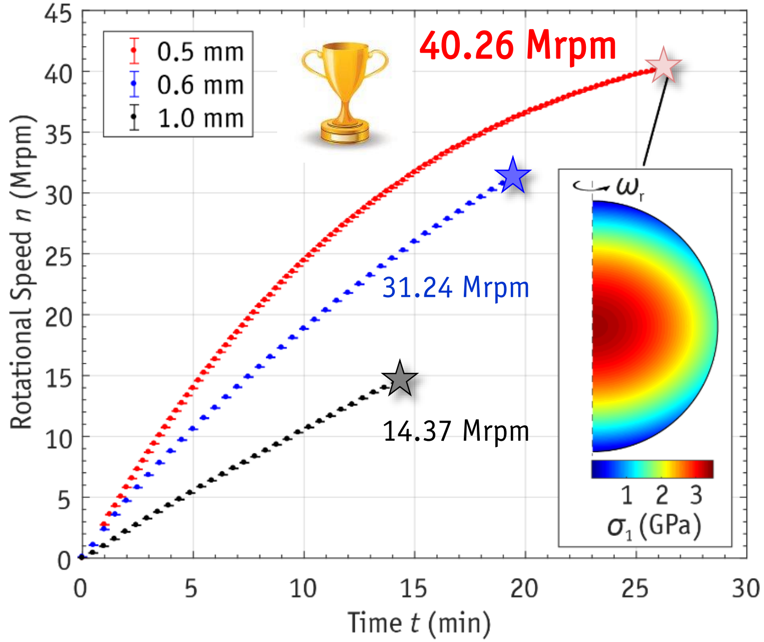
Radial Damping Increased by Factor >100

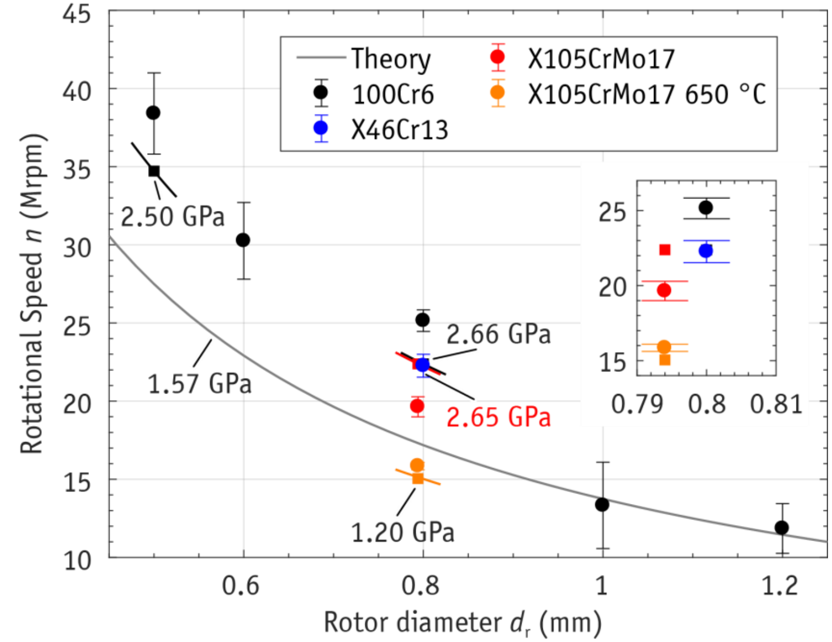
► Torque Characteristics and Rotor Temperature

- **Experimental Results in Good Agreement with Models**
  - Higher Deviations at Low Slip Frequencies due to low Absolute Torque Level
  - Rotor Temperature Approaches Ambient Temperature at High Speeds
  - Main Energy Transfer by Radiation



► Achieved Rotational Speeds

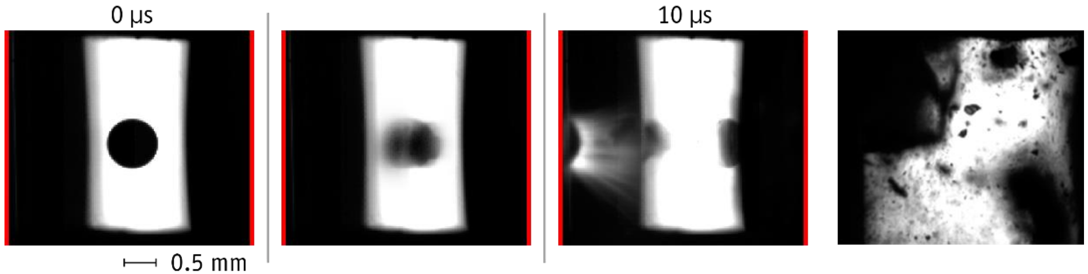


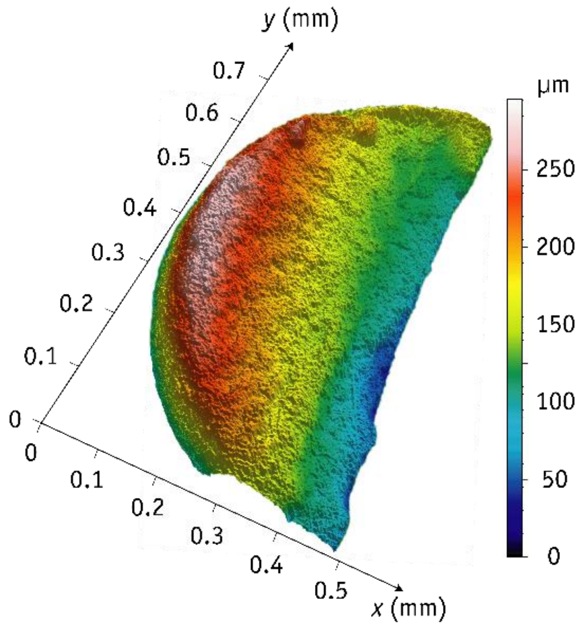


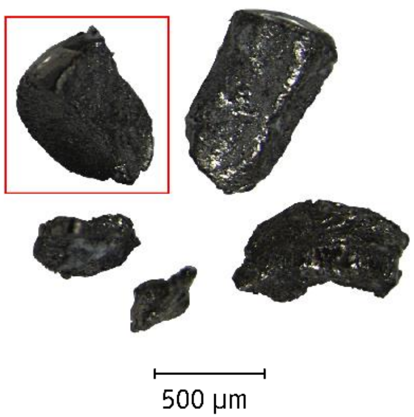
- **Highest Rotational Speed Achieved with an Electrically-Driven Rotor to Date**
  - Circumferential Speed 1047 m/s
  - Centrifugal Acceleration $4.5 \times 10^8\ g$

▶ Failure Analysis

- **Rotor Explosion**
  - Recorded at 100 000 fps
  - Spatial Resolution 23 µm
  - No Detectable Deformation



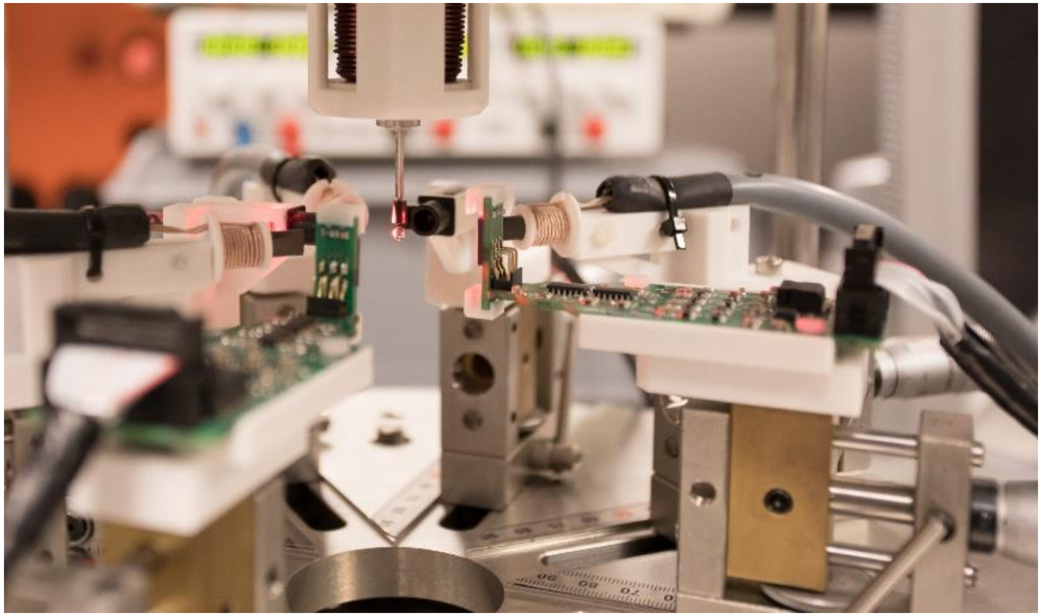




- **Microscopic Analysis**
  - 3D Imaging Using Laser Confocal Microscope
  - Brittle Failure without Apparent Voids/Defects

▶ Project Outcomes

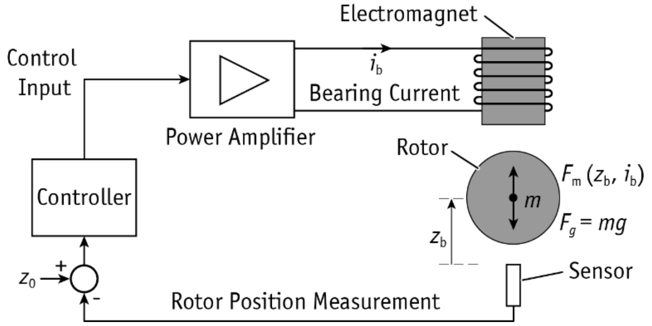
- Technologies for Micro Magnetic Beatings
- Stator Designs for Megahertz Magnetic Drive Fields
- Insights for Future Ultra-High Speed Drive Systems



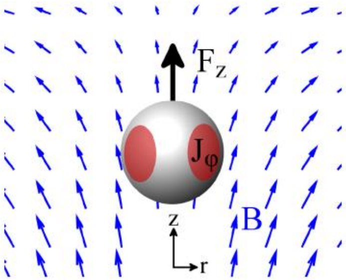
- **Highest Rotational Speed Achieved with an Electrically-Driven Rotor to Date: 40’260’000 rpm**
  - Reproduced and Exceeded World Record from 1947
  - Statistically Significant Number of Bursting Experiments

▶ High Complexity of Active Levitation

- **Active Magnetic Levitation**
  - Sensing Difficult for Small Rotors
  - High Bandwidth / Complex Control

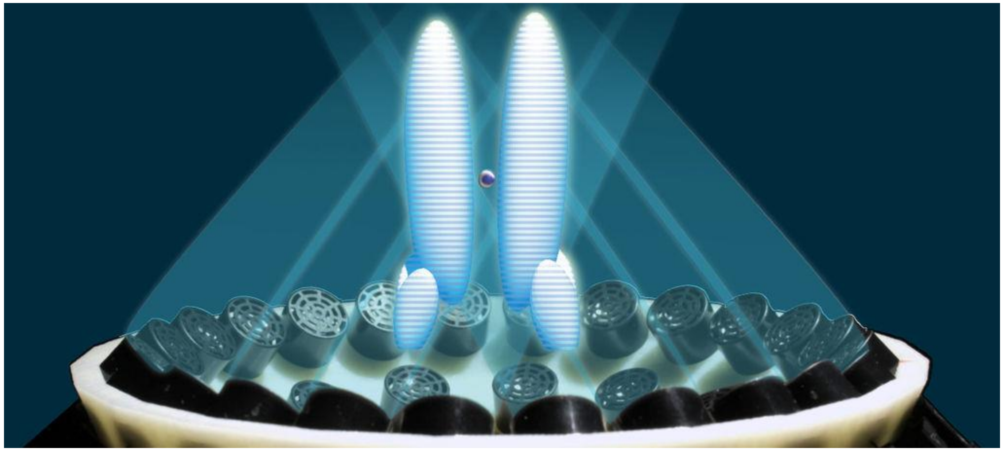


- **Passive Magnetic Levitation**
  - High Eddy Current Losses



- **Passive Acoustic Levitation**
  - **Particle < Wavelength**
  - Acoustic Pressure Field
  - Ultrasound Transducers

+ Passively Stable
+ Low Losses
- Low Load Capacity



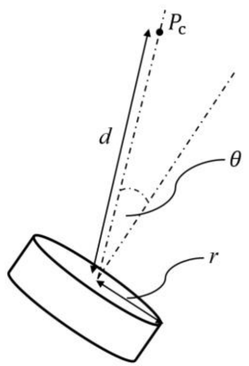
Source: https://www.instructables.com/id/Acoustic-Tractor-Beam/

Strategic Research Project

Acoustic Levitation

▶ Transducer Arrangements and Modelling

- **Individual Excitation of Many Transducers**
  - Manipulation of all Degrees of Freedom Possible
  - Achievable Force/Torque Dependent on Transducer Arrangement

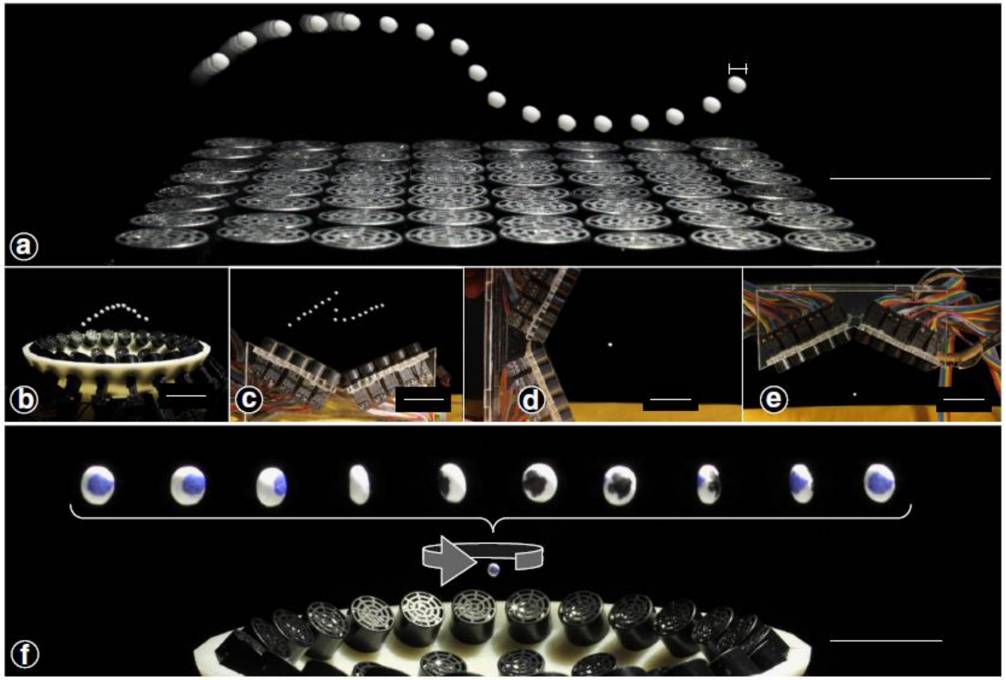


Transducer Piston Model

$$p = \sum_{j=1}^{N} p_j$$

$$p_j = \boxed{e^{i\phi}} M_j$$

$$M_j = P_0 J_0(kr\sin\theta)\frac{1}{d}e^{ikd}$$

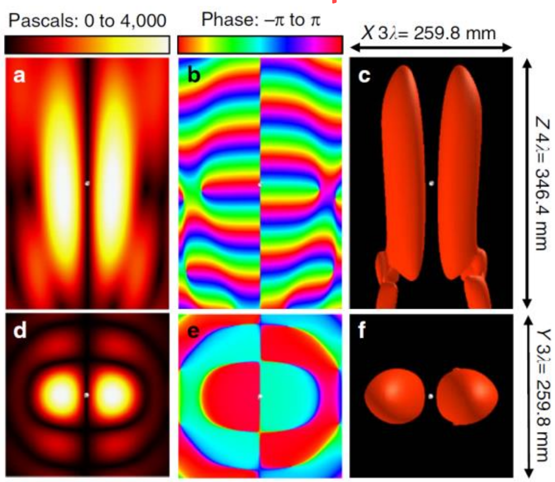


Rotational Speed ≤ 210 r/min

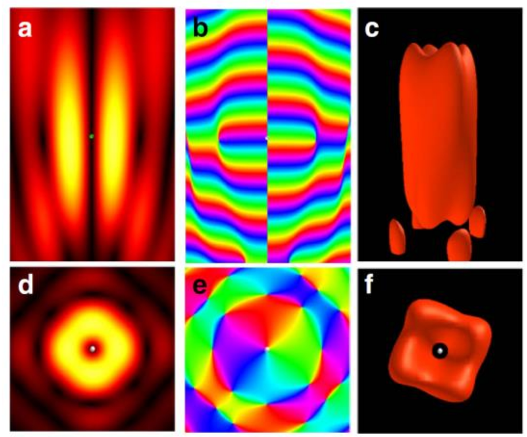
Source: Marzo et. al., Holographic acoustic elements for manipulation of levitated objects, Nature Communications 2015

▶ Types of Acoustic Traps

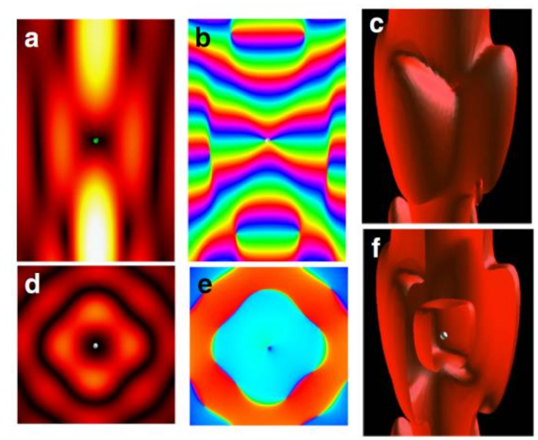
Twin Trap



Vortex Trap

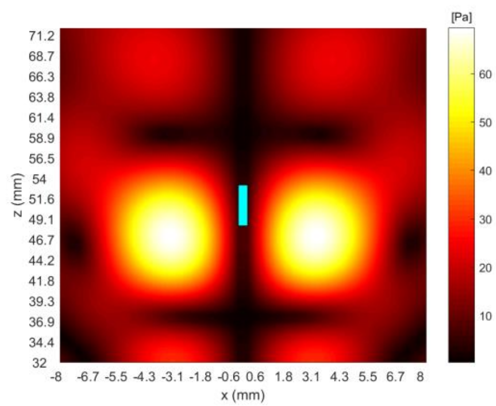


Bottle Trap

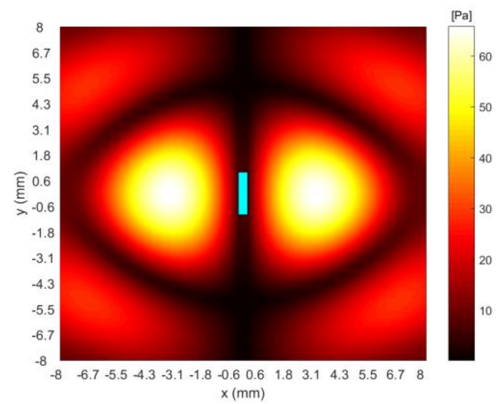


Source: Marzo et. al., Holographic acoustic elements for manipulation of levitated objects, Nature Communications 2015

- Twin Trap Provides Sufficient Load Capacity and Radial Stiffness
  - Spatial Rotation of Trap

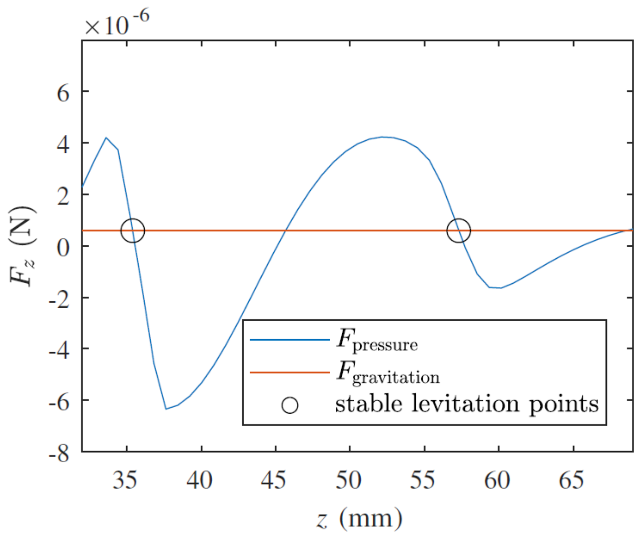


Pressure in *xz*-plane

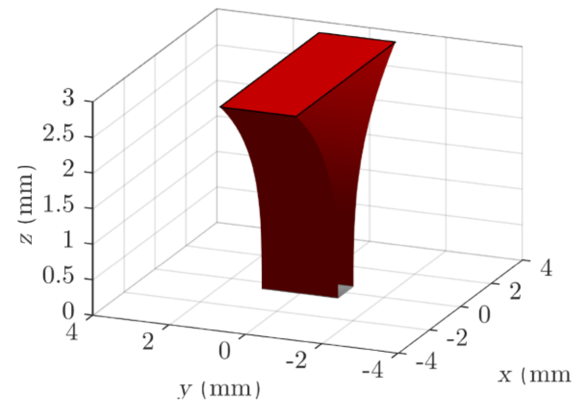


Pressure in *xy*-plane

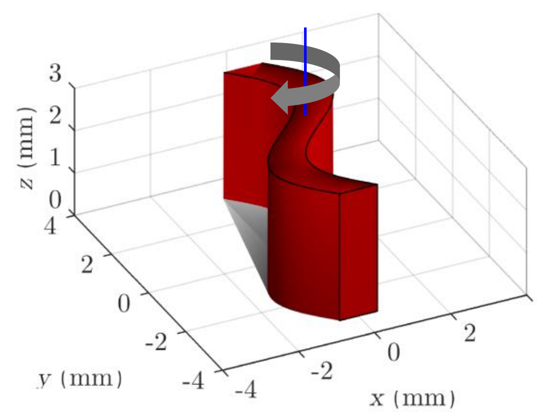
► Levitation Height and Particle Shape



- **Balance of Acoustic and Gravitational Force**
  - Negative Force Gradient Required for Stability
  - Multiple Stable Levitation Points
- **Rotor Shape Limited by Manufacturing Constraints**
  - Soft Polystyrol Material



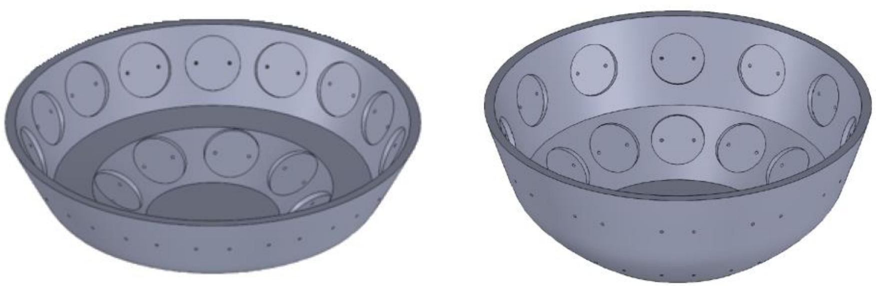
Rotor Shape for High Levitation Force

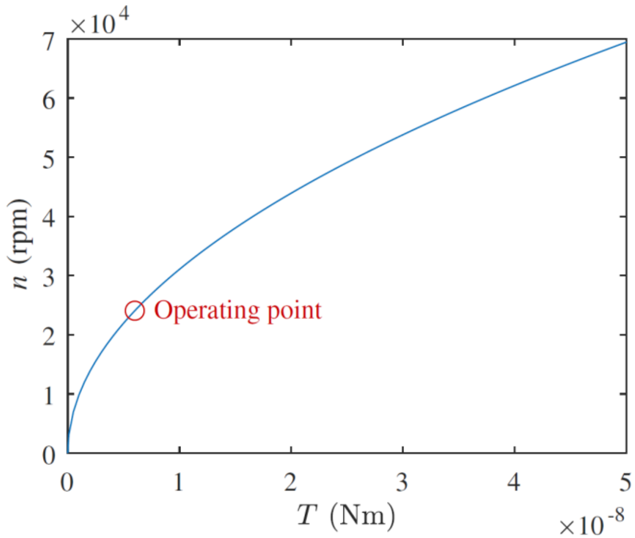


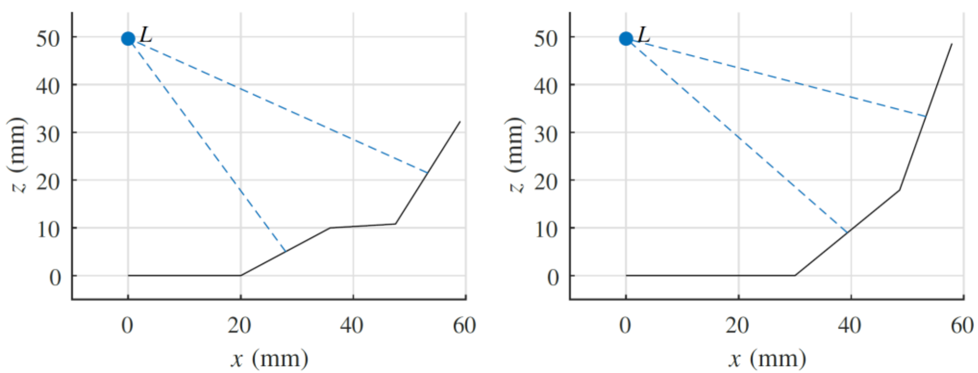
Rotor Shape for High Rotational Speed

▶ Design for High Rotational Speeds

- Rotational Speed Limited by Drag



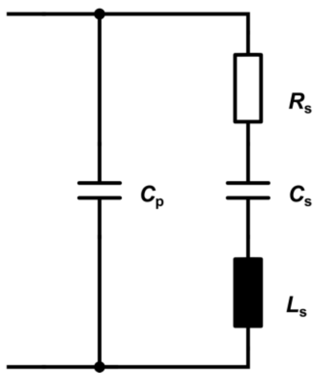


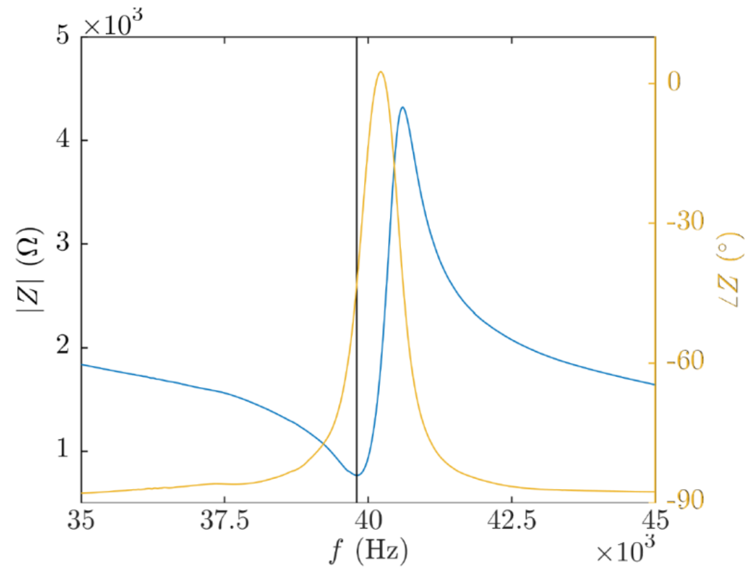


- Transducer Arrangement
  - Short Distance to Levitated Particle
  - Low Reflections (difficult to assess analytically)

▶ Transducer Properties and Excitation

Source: multicomp

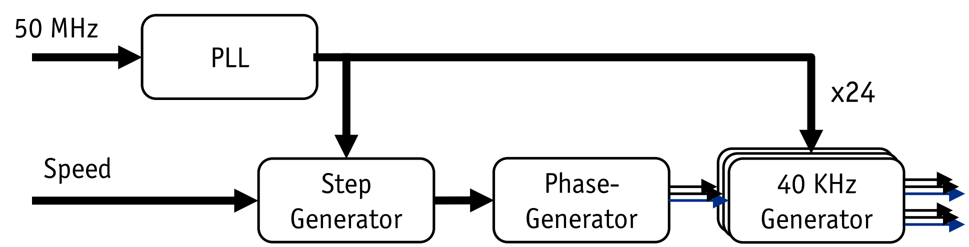




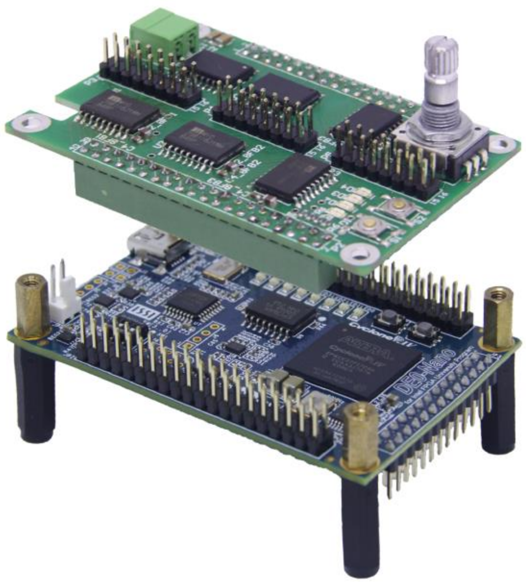
Transducer Equivalent Circuit

- Reactive Power
- Resonance Frequency ≈ 40 kHz

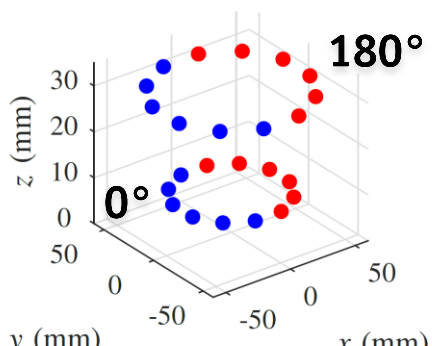
- **24 Transducers Excited by Rectangular Wave**
  - Full-Bridge Converter Topology
  - 64 V peak-peak, I ≤ 25 mA
  - FPGA-Based Switching Signal Generation



▶ System Implementation

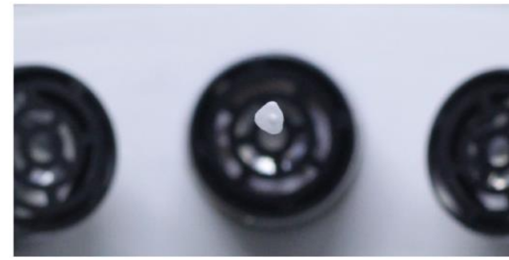


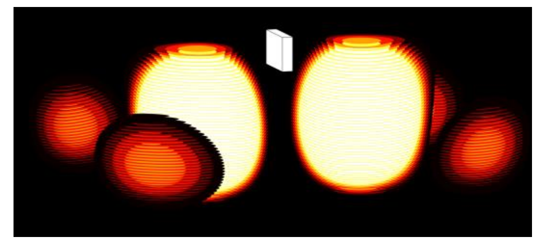
Power Electronic Converter System

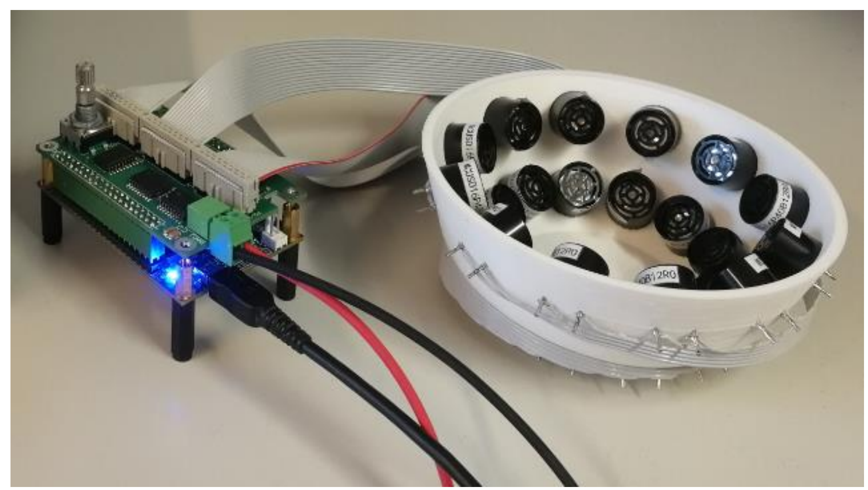


Twin Trap

- Approx. Constant Suspension Forces by Non-Linear Phase Shift
- Stability over Wide Speed Range



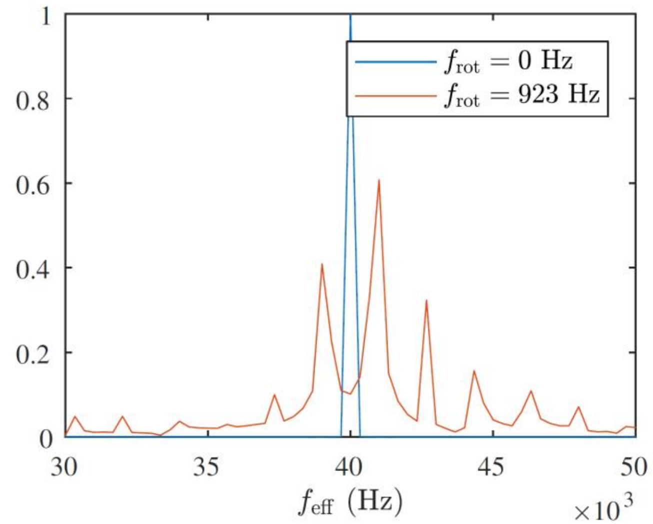




▶ Achieved Rotational Speed

Demo Video

Highest Rotational Speed: 55’410 r/min
- Limited by Power Losses
- Audible Sub-Harmonics



Increased Power in Sidebands
- High Transducer Losses
- Consideration of Transducer Properties Necessary for Higher Rotational Speeds

- **Increased Acoustic Pressure at Rotor for Higher Rotational Speeds**
  - Second Transducer Arrangement from Top

Conclusions

▶ Summary

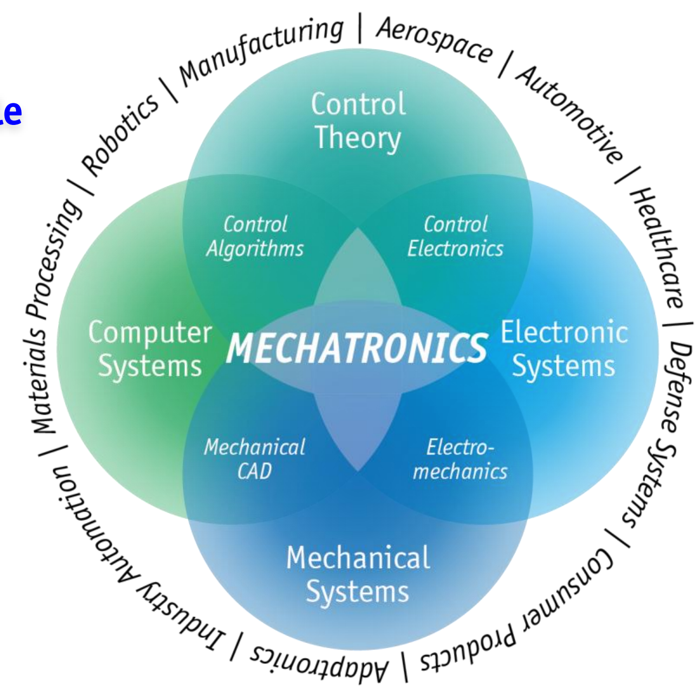
▶ Multi-Objective Design Approach Required for Power Converters and Electric Drives

▶ Ongoing Trend Towards High Power Density at High Rotational Speeds

- Miniaturization of Electric Machines
- Alternative Bearing Concepts
- Integration of Power Electronics
- System-Level Optimization

▶ Rotational Speeds of Several Million r/min Possible

- High System Complexity/Control Effort
- Future Micro Magnetic Bearings & Ultra-High-Speed Drive Systems



▶ Passive Levitation and Manipulation of Particles Possible Using Ultrasound

- Various Materials/High Flexibility
- Applications in Medical Systems, Small Robots, Material Handling, etc.

«Innovation Potential Only Limited by Laws of Physics & Imagination»

Thank You!