# Controlled Magnetic Bearings for Smart Machines

Gerhard Schweitzer, ETH Zuerich

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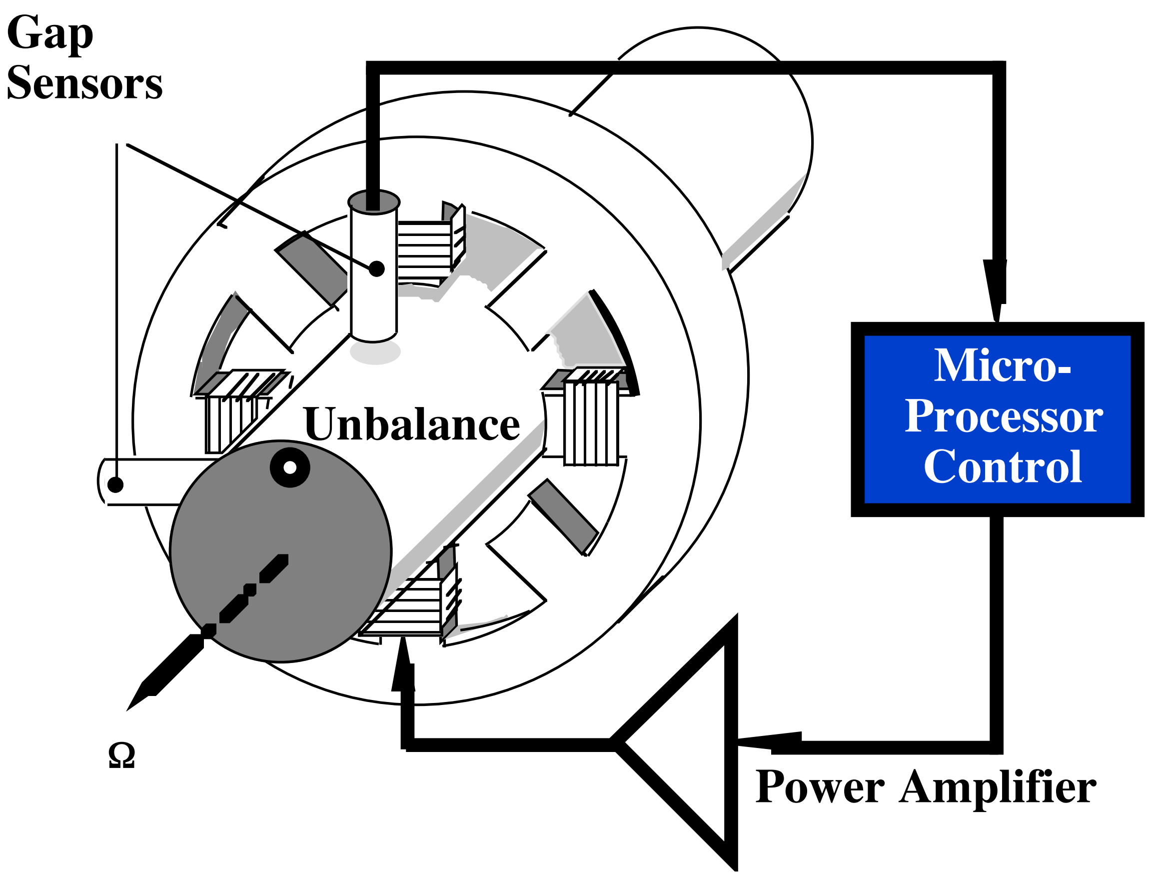
# Survey

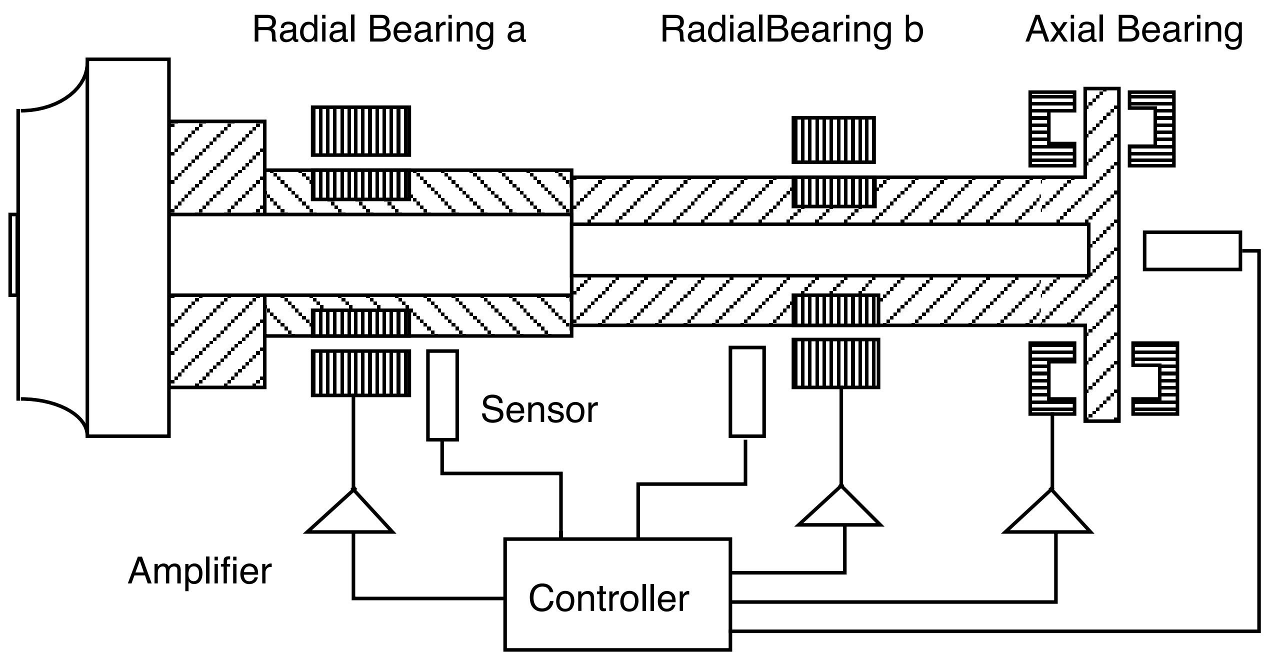
- What is a Magnetic Bearing?
- Relation to Mechatronics
- A Short Look at History
- Actual Industrial Applications
- Challenges in Control and Informatics – Smart Machines
- Future Applications and Developments

# What is a Magnetic Bearing?

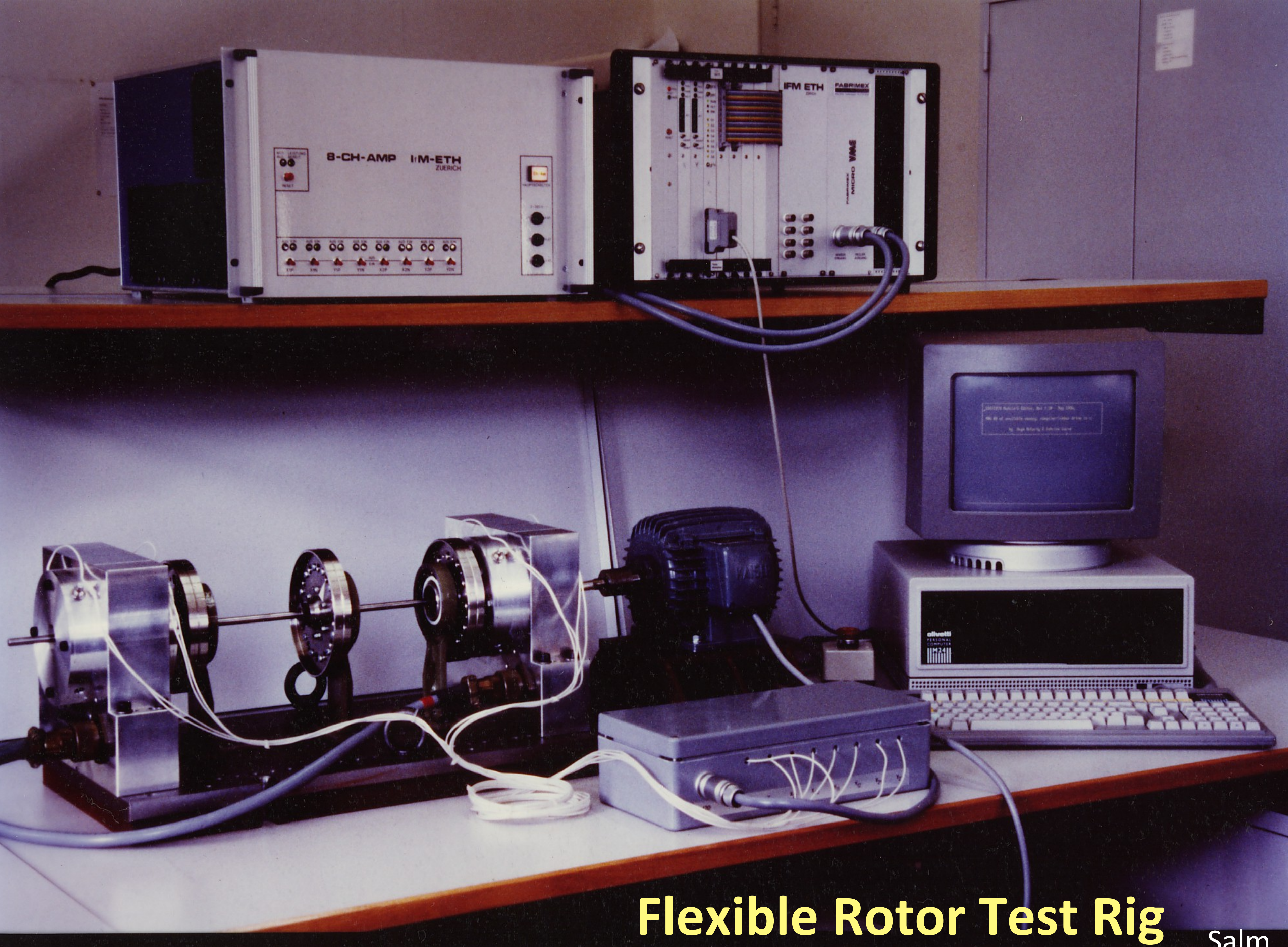
# Principle of Active Magnetic Bearing



# Main Features of AMB Rotor Suspension




- No lubrication, no mechanical wear
- Control of dynamical behavior
- Integrated software is a powerful machine element




# Flexible Rotor Test Rig

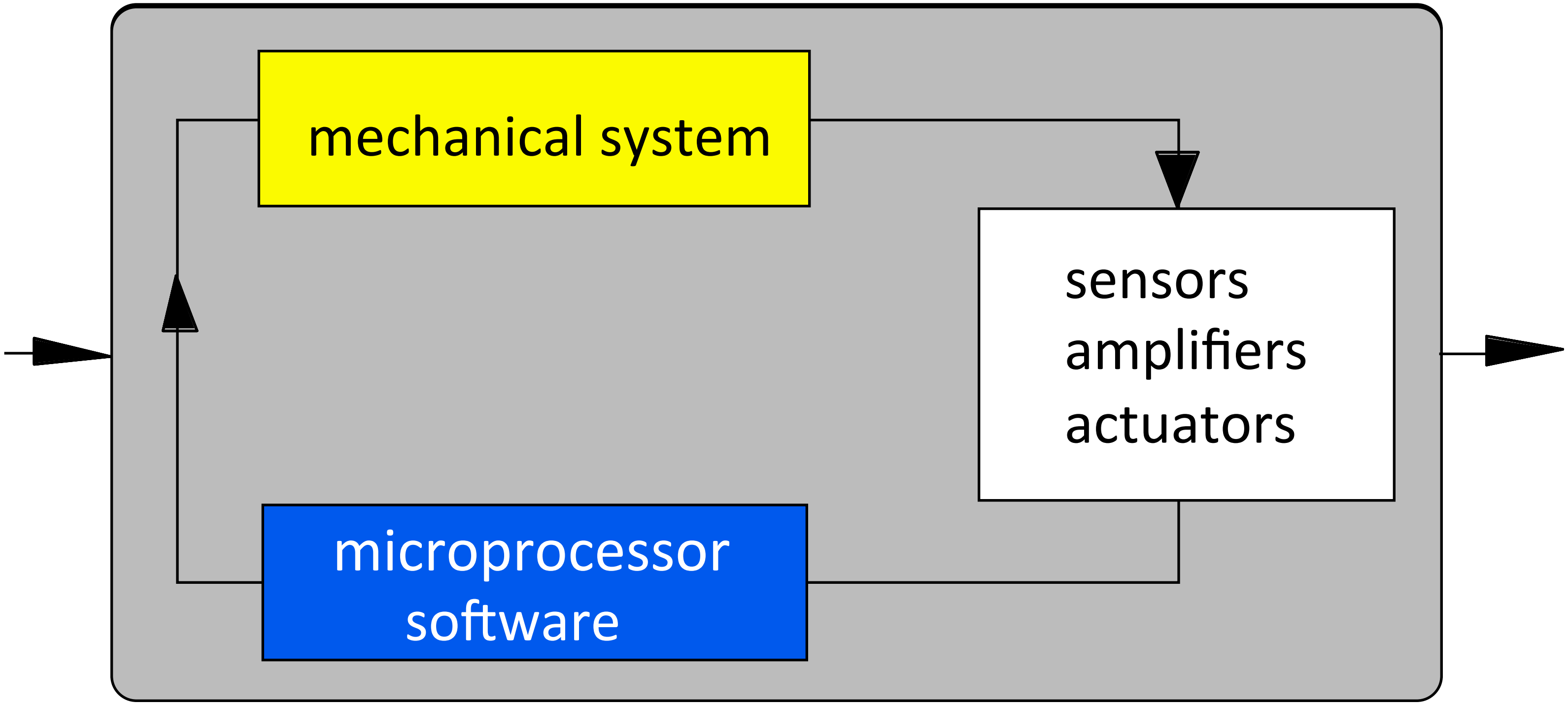
Salm

# Properties of Active Magnetic Bearings

| | |
|---|---|
| specific load | ca 25 $N/cm^2$ |
| maximal load | proportional to bearing area |
| dynamic stiffness | depending on control law |
| dynamic damping | depending on control law |
| frequency response | 100 - 1000 Hz, 3 dB |
| air gap | 0.3 - 0.8 mm |
| circumferential speed | < 300 m/s |
| losses in the rotor | eddy currents, hysteresis, gas friction |
| losses in the stator | copper losses |
| losses in the amplifier | switching losses |

# Relation to Mechatronics

# Definition of Mechatronics
(ETH, 1984)




**Hardware ./. Software**

# Examples for Mechatronic Products

Robots

Sewing machines

Car braking systems

Car drive train control

Self- tuning machine tools

Active magnetic bearings

....

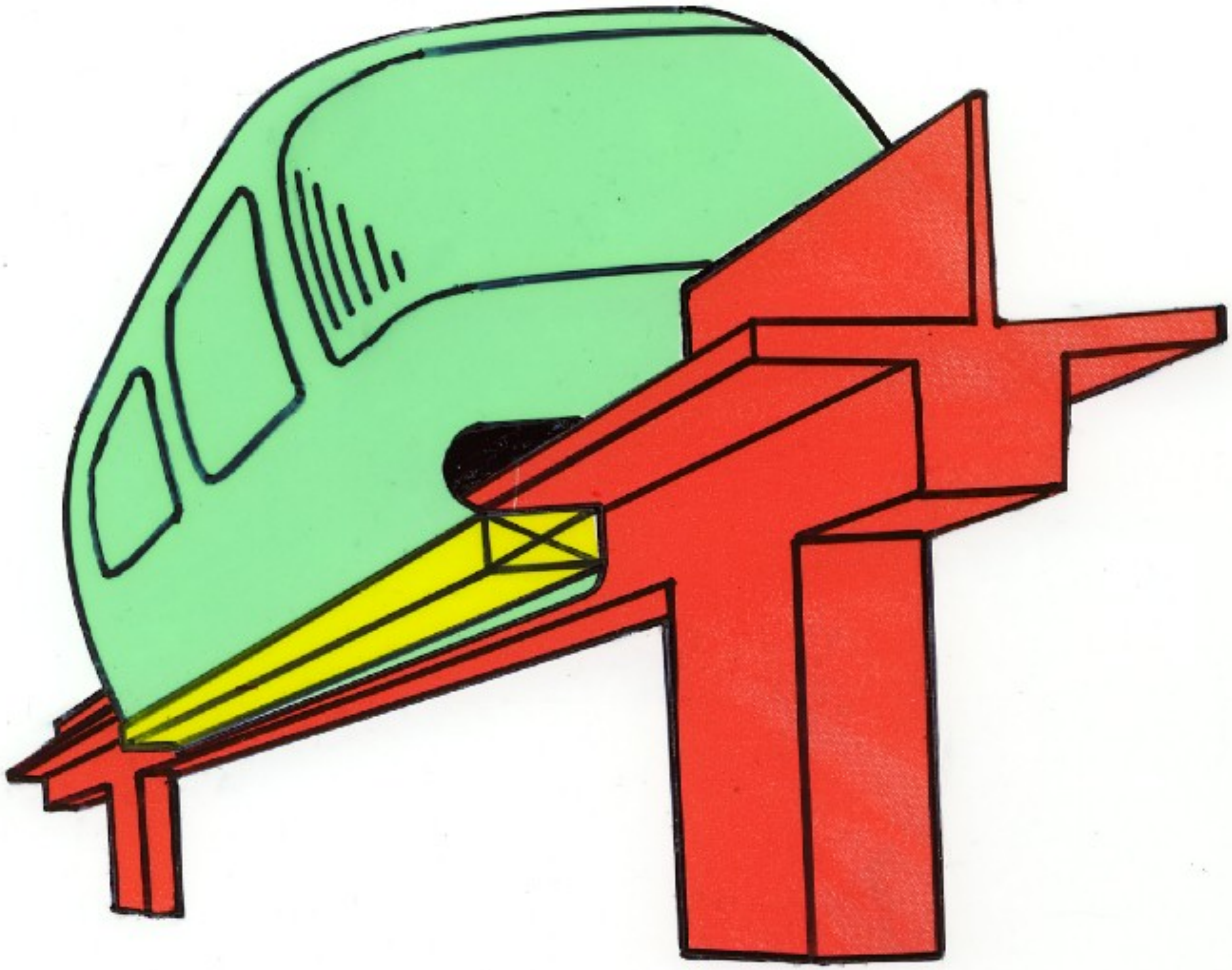
(Thermotronics, Biotronics, Domotronics, Industry 4.0, ... )

# A Short Look at History

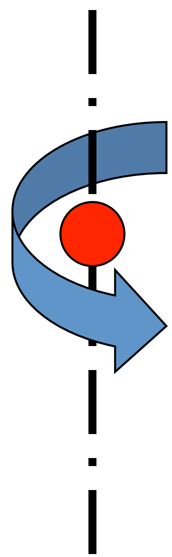
## **The magnetic bearing in transportation, physics and machinery**


**Transrapid, 1987, 500 km/h**

# Levitated Vehicle Principle



# High Speed Rotation for testing the strenght of small steel balls under centrifugal loads (Beams, Young, 1937/1946)

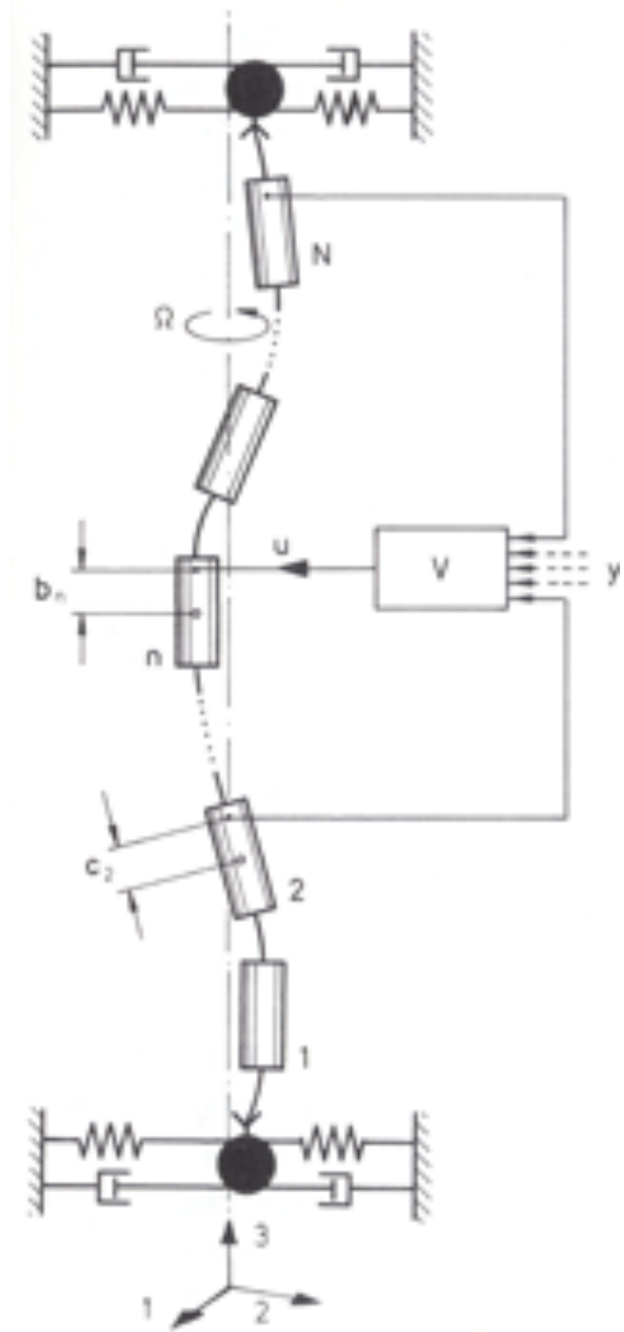


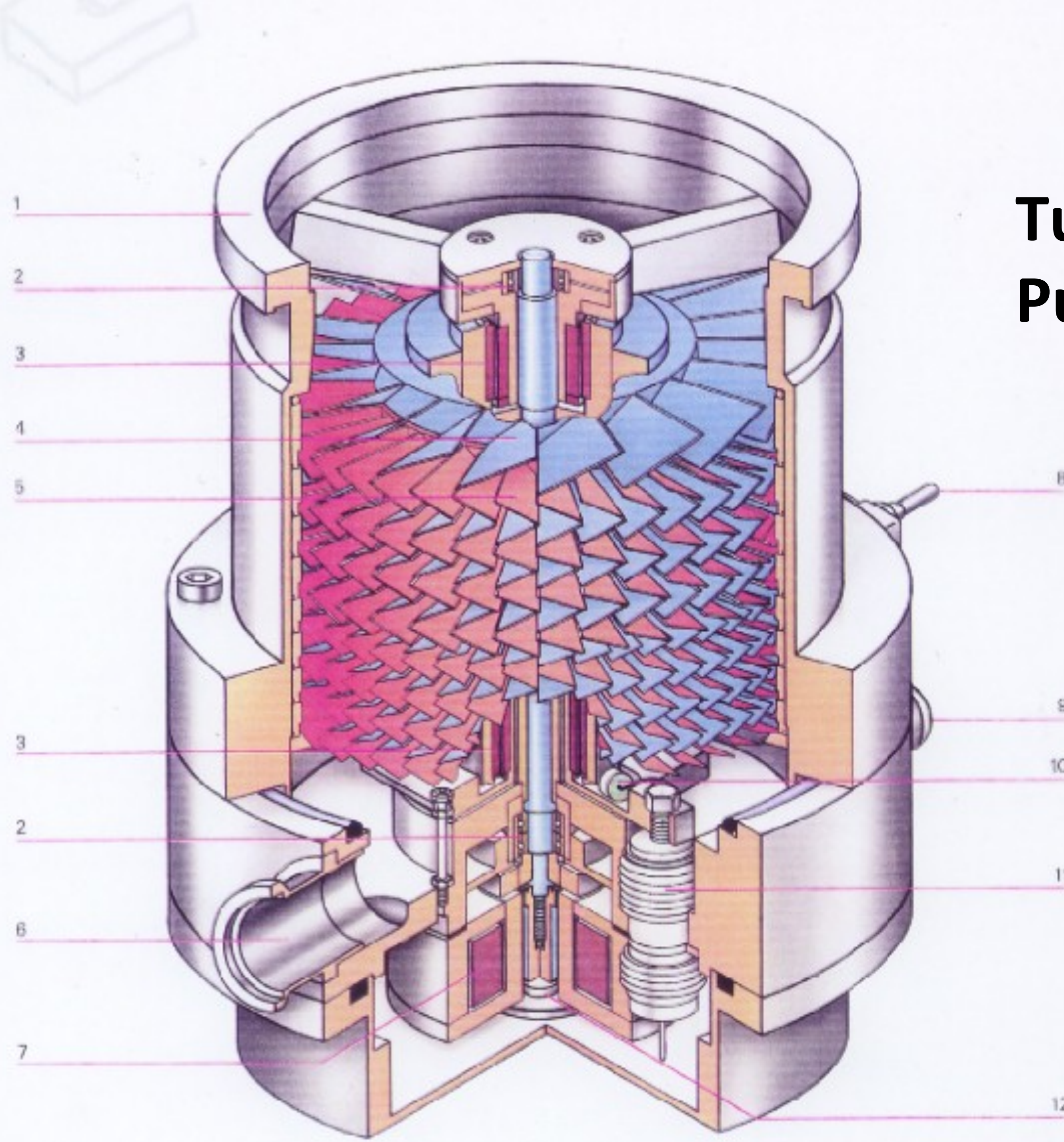
$18 \bullet 10^6$ rpm

$2 \bullet 10^8$ g

# History - 1974

Lab model of a
multi-stage gas centrifuge
demonstrating
the control and damping
of rotor vibrations
at high rotor speed
with active magnetic bearings






# Turbomolecular Pump, Balzers

1 HV-Connection
2 Retainer Bearing
3 Permanent Magnet Radial Bearing
4 Rotor
5 Stator
6 Pre-Vaccuum Conn.
7 Active Axial Magnetic Bearing
10 Radial Gap Sensor
11 Damping Element
12 Axial Gap Sensor

# Actual Industrial Applications

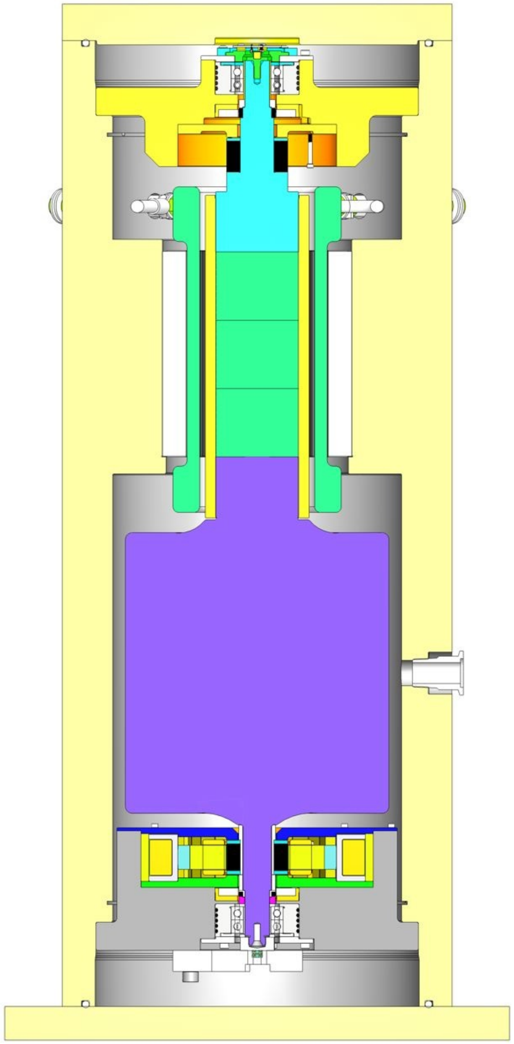
# Turbo-Blower

Cooling gas compressor for power laser of metal sheet cutting machine

speed 54000 rpm, rotor power 12 kW
rotor mass 3.6 kg


courtesy TRUMPF/Mecos

# Flywheel - Vycon

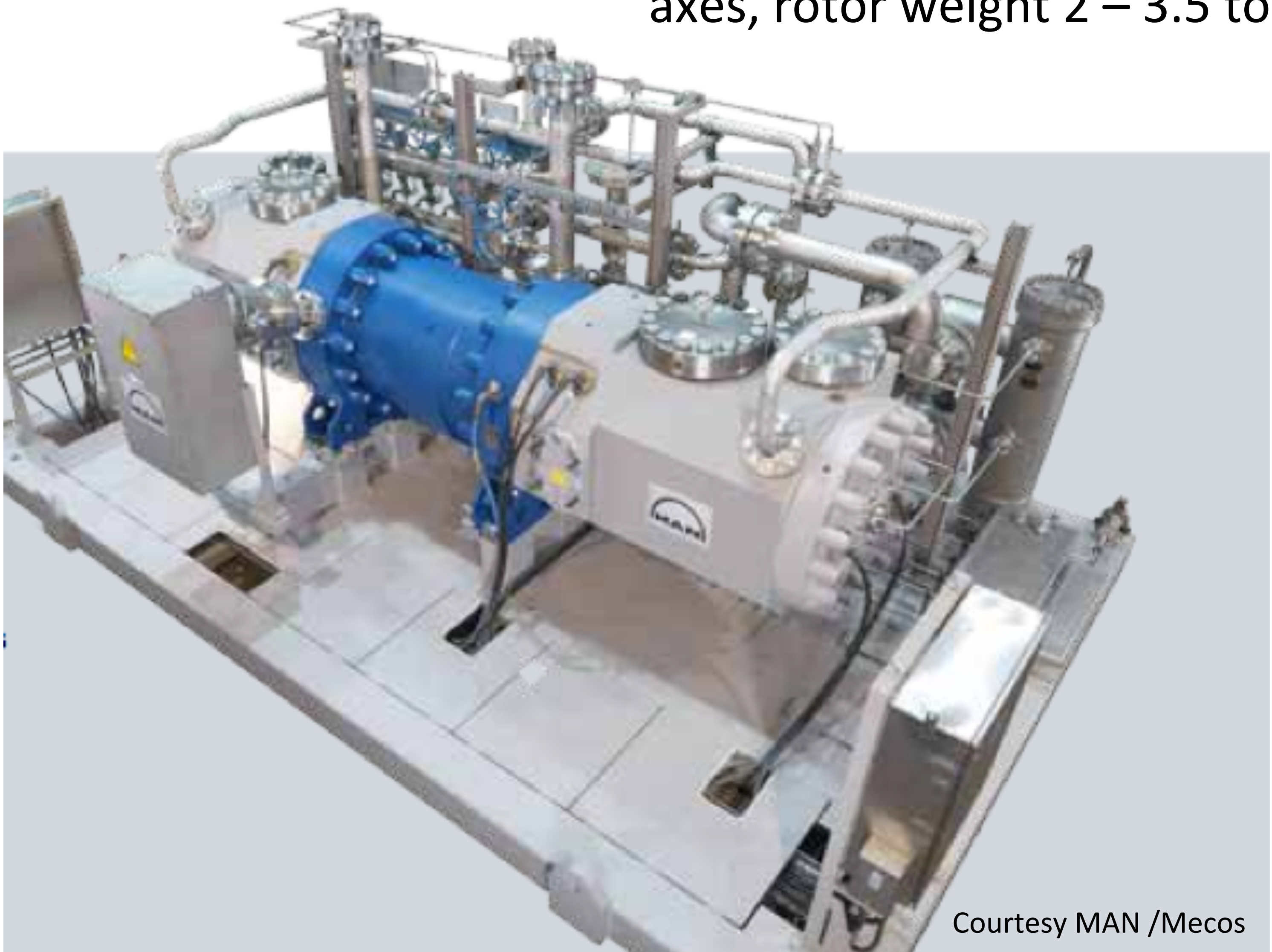


140 kW energy storage flywheel in cabinet for UPS application

Courtesy CALNETIX

# Large Turbo Compressor

20 MW, up to 12’000 rpm, control up to 9 axes, rotor weight 2 – 3.5 tons

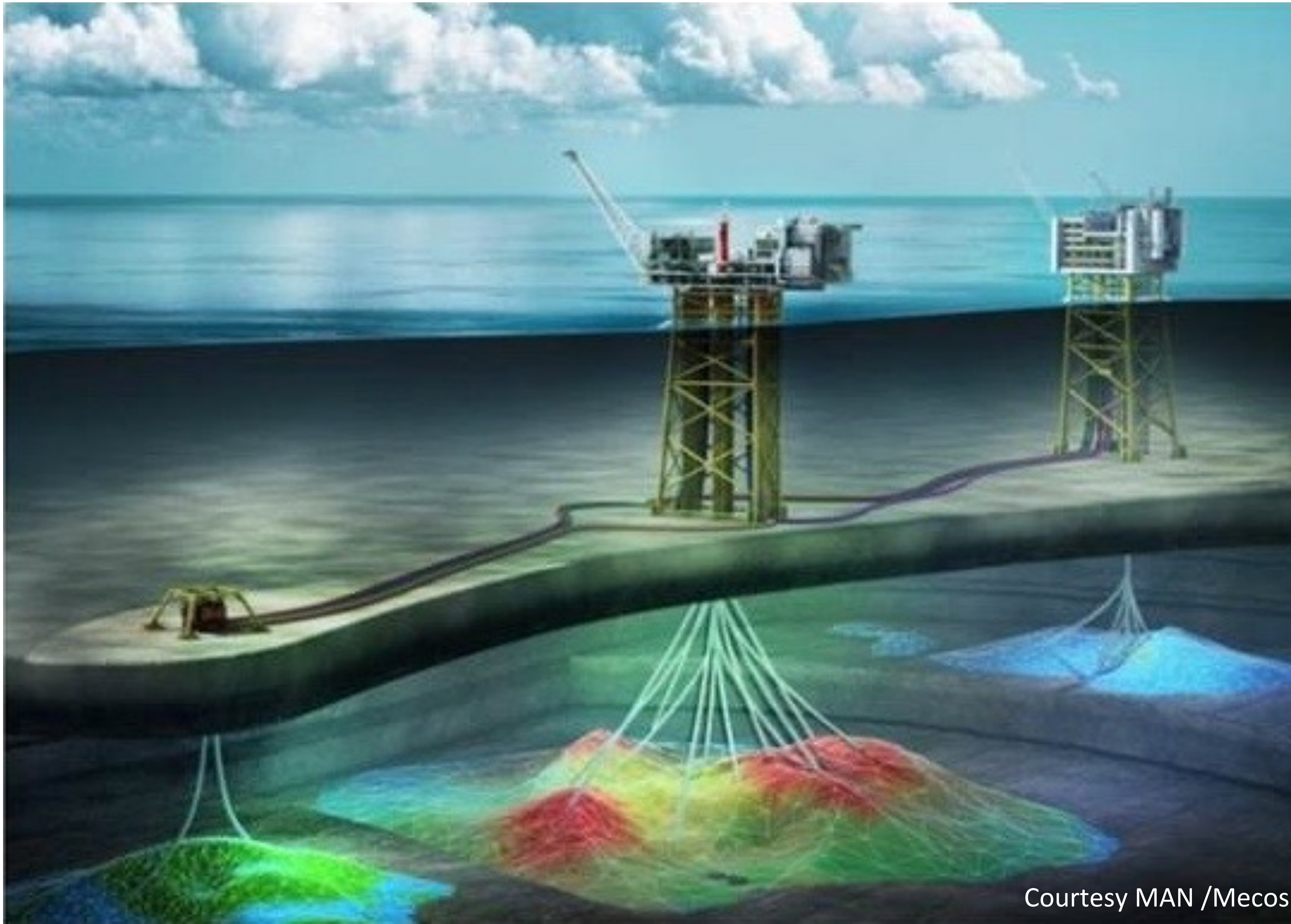


Courtesy MAN /Mecos

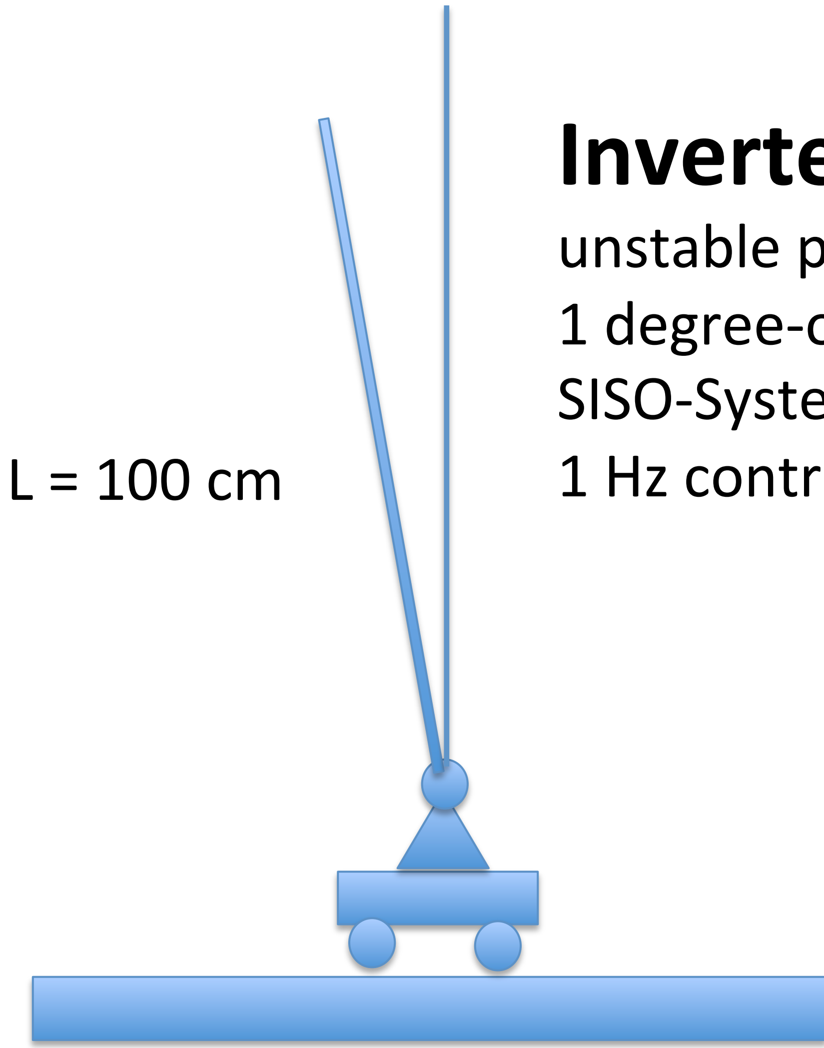
# Large Turbo Compressor – Control Cabinet

Courtesy MAN /Mecos

# Offshore Hermetically-Sealed Motor Compressor


Courtesy MAN /Mecos

# Challenges
# in Control and Informatics



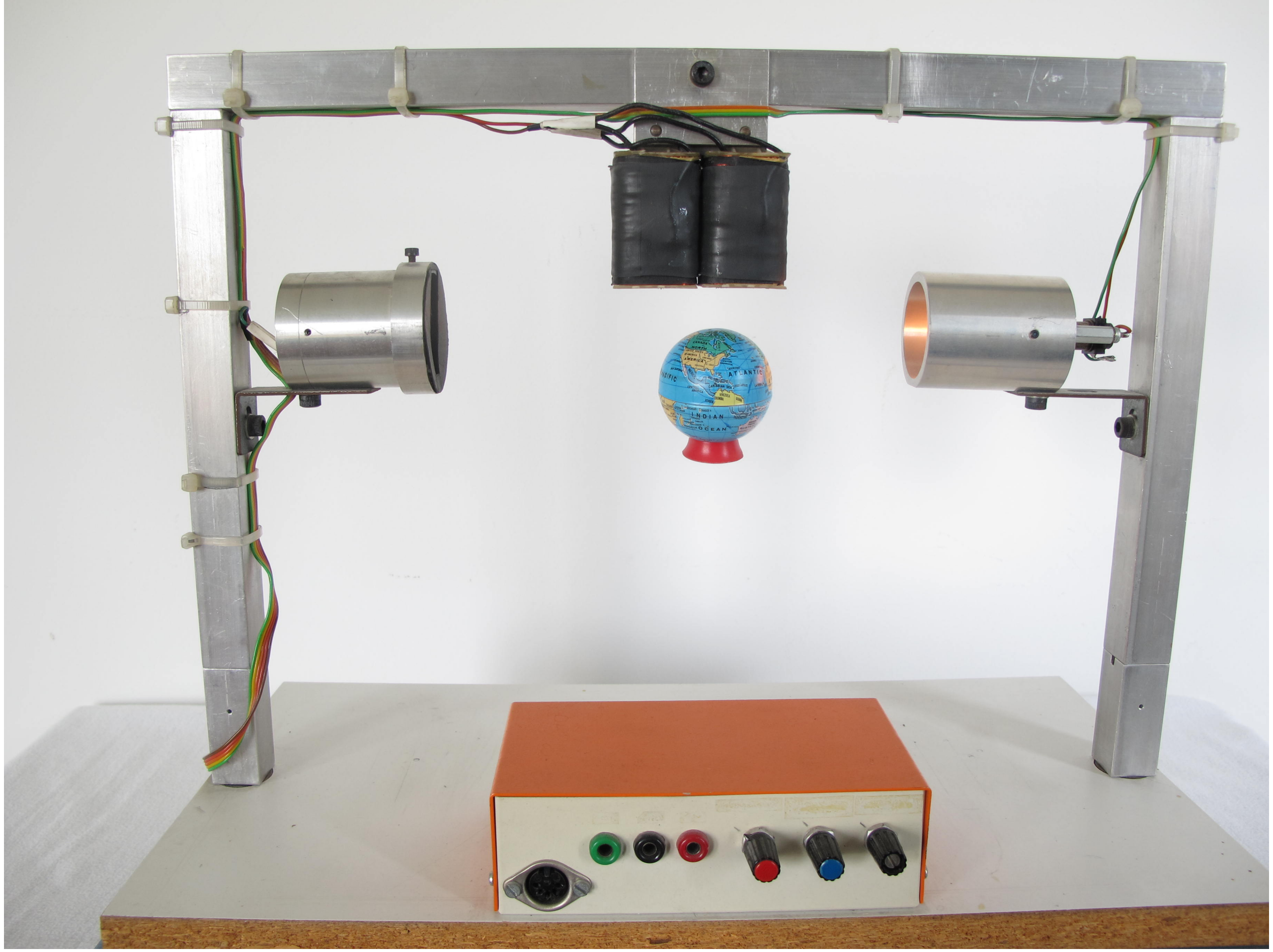

# Inverted Pendulum

unstable plant

1 degree-of-freedom

SISO-System (base displacement, inclination)

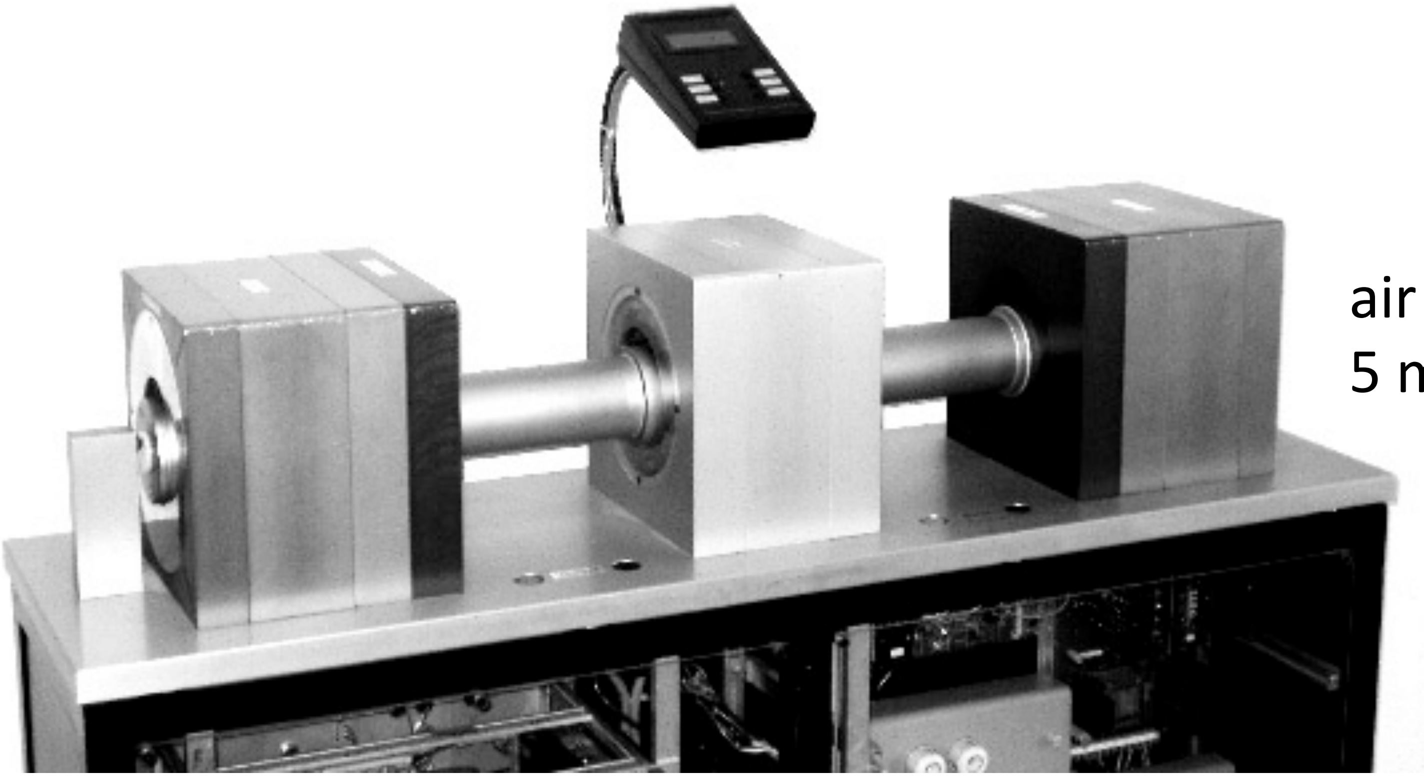
1 Hz control rate



air gap
10 mm

# Magnetic Suspension – Demonstration (1)

unstable plant
1 degree-of-freedom
SISO-System (control current, air gap)
10 Hz control rate



air gap
5 mm

# Magnetic Suspension – Demonstration (2)

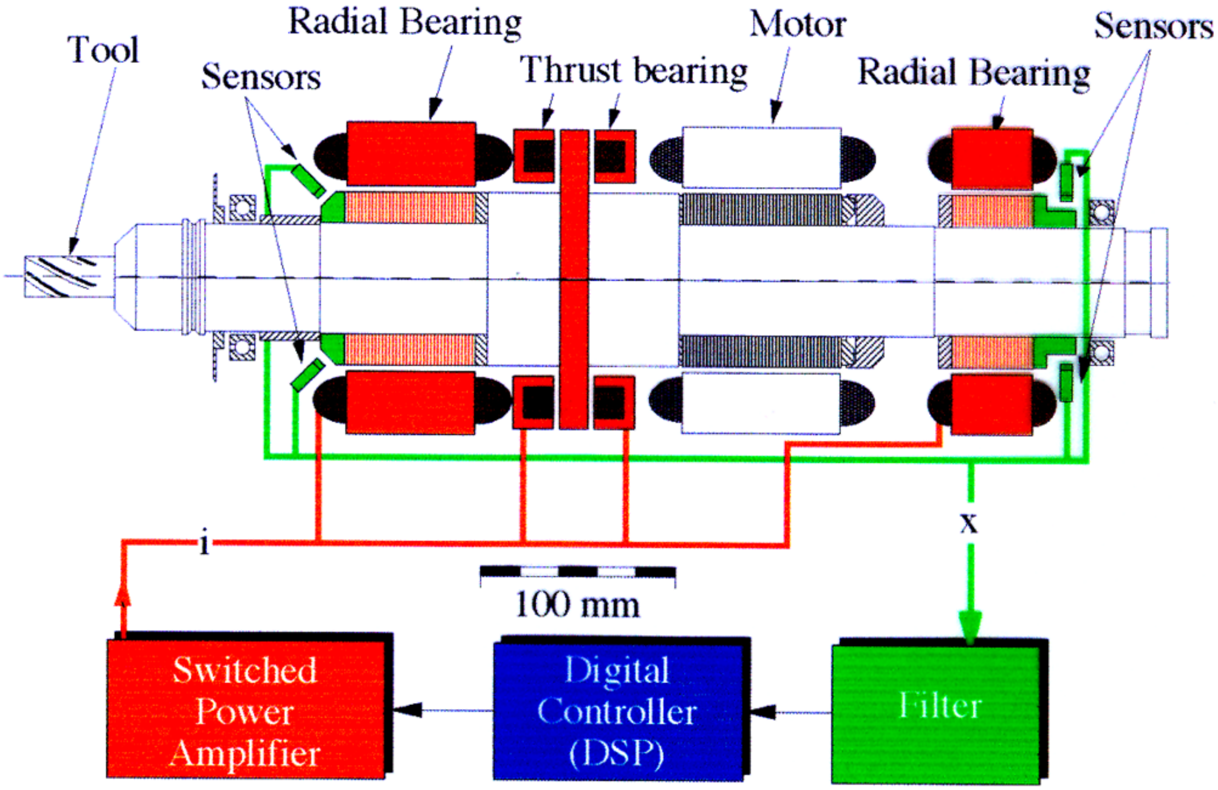
unstable plant
4 degrees-of-freedom
MIMO-System (4 currents, 4 airgaps)
Digital control, 1984, 100 Hz sampling rate

air gap
0.3 mm

# Milling Spindle in AMB for High-Speed Milling

unstable plant
5 degrees-of-freedom
MIMO-System (72 states in total)
10 kHz sampling rate

# HIGH SPEED MILLING SPINDLE IN ACTIVE MAGNETIC BEARINGS




**Rotational speed: 40 ‘000 rpm**
**Power: 35 kW**
**Tool holder: ISO 40**

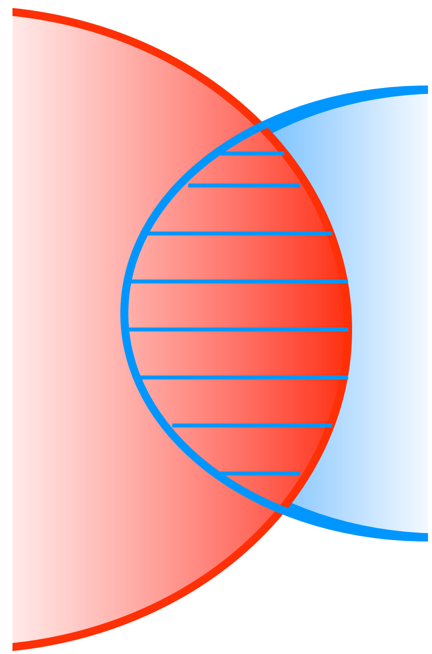
**Cutting force: 1 ‘000 N**
**Cutting speed: up to 6 ‘000 m/min**
**Digital control (10 kHz sampl. rate)**

# Objectives for Control and Information Processing

- Reliability and Safety
- Smart Machines with Better Functionality
- Communication to the Outside
  (for maintenance, to the production process, as element of “Industry 4.0”)

# Overlapping of Reliability and Safety

Safety is the quality of a unit to represent no danger to humans or environment when the unit fails (technical safety). It is investigated with reliability theory



Reliability is the quality of a unit to remain operational. It chararacterizes the probability to have no interrup-tion of operation during a certain time

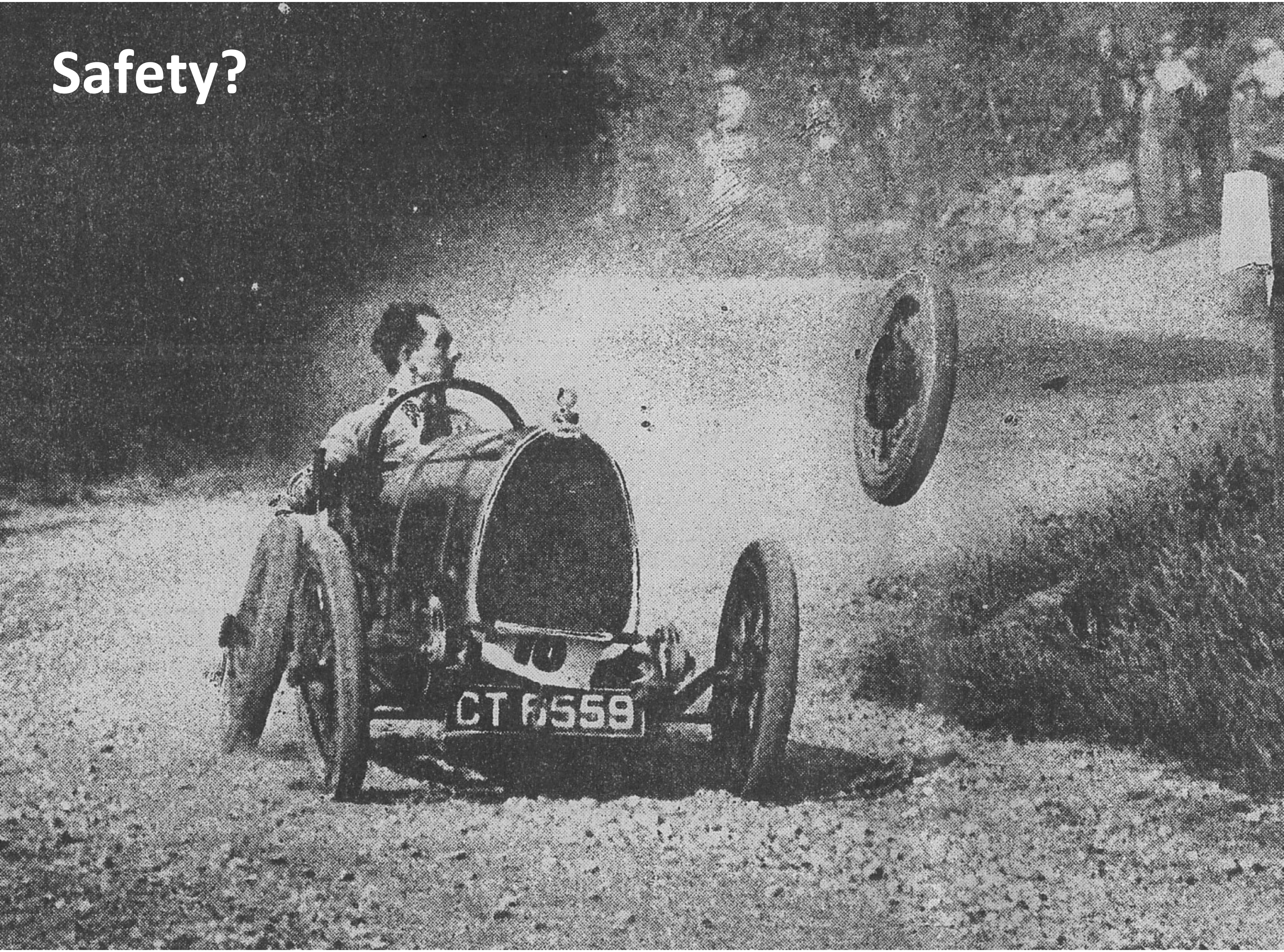
# Safety and Danger as Ingredient of Human Life

**Modern society is trying to convert danger into risk, i.e., to make it calculable and controllable**

Examples:

* hunting in the wilderness./.buying in a supermarket
* travelling with no./.with knowledge of weather forecast
* driving a car manually./.with driver assist systems

# Safety?



# Philosophical Aspects of Safety

The philosopher Karl Popper stated in his work that progress in science probably is coming from falsifying existing theories and modifying them or stating new ones that correspond better to experience than the previous ones.

As a consequence, safety appears to be an  ideal state that cannot be verified, but only - to some extent - falsified. However, there are various techniques to reduce risk, in stepwise approaches.

# Technical Aspects of Reliability

- Reliability is one of the four aspects of dependability:
  - reliability
  - safety
  - availability
  - security
- Reliability and safety are key issues in mechatronics.
- Security is of growing importance
- Mechatronics methods have to be applied to make dependable systems, out of insufficiently reliable components, using smart machine technology

# Measures for Reducing Risks of Failure

- Systematics in the design
- Software development system
- Individual measures: **redundancies**
  robust control
  exception handling
  watchdog
- Smart machine technology: diagnostics and corrections
- Complexity . /. Reliability: Biological machine ?

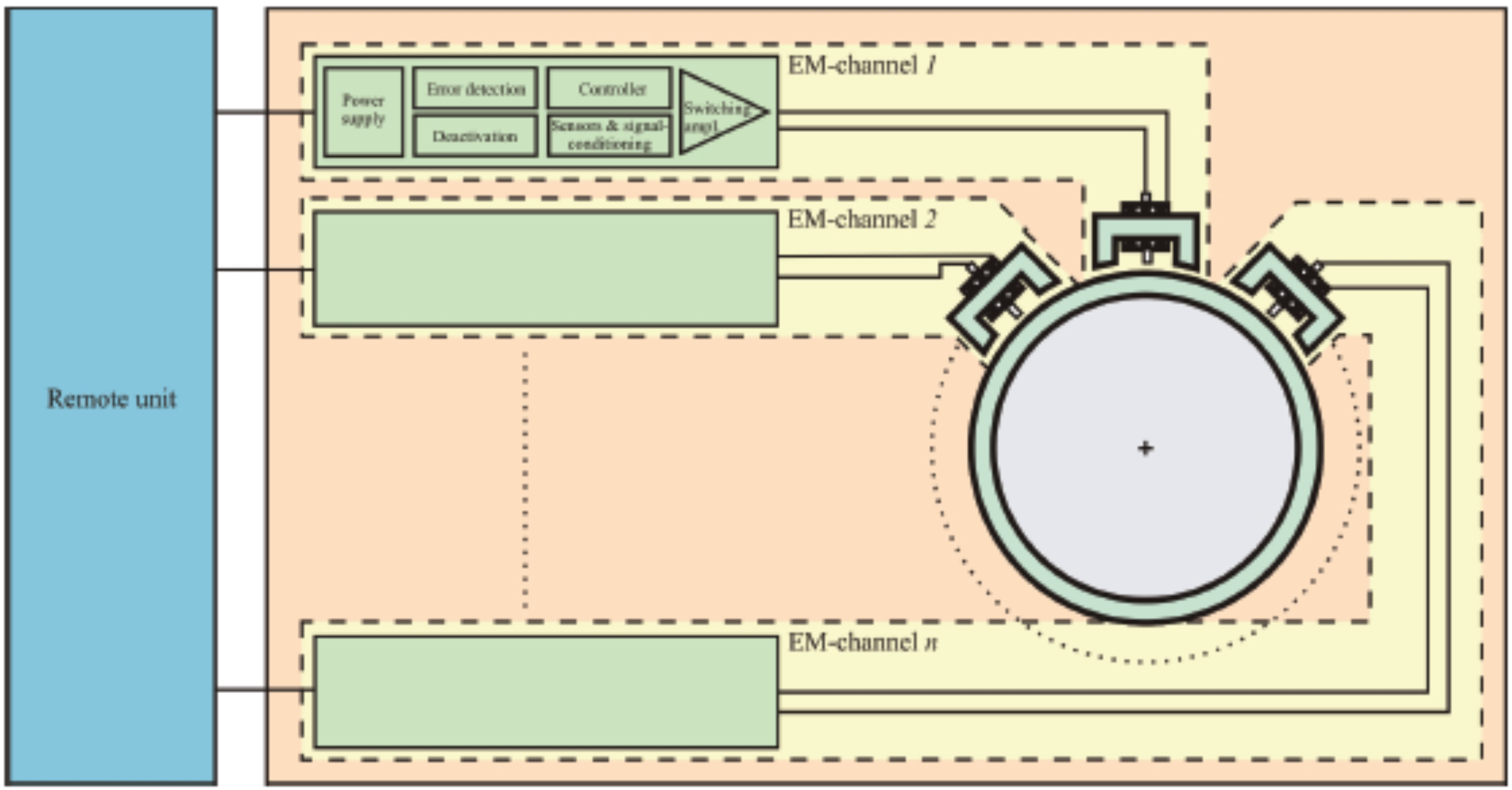
# Redundancies

## Hardware redundancy

failed components are taken out and replaced,
Examples:

redundant sensor and actuator coils, cabling, amplifiers, control system with triple modular redundant architecture with 4 processors, redundant complete and independent SISO AMB-units

# Hardware Redundancy, Example




Block diagram of an AMB system with “supreme” reliability

[Fig. from Schulz et al: A sophisticated AMB system with .., 11th ISMB, 2008 Nara, Japan]

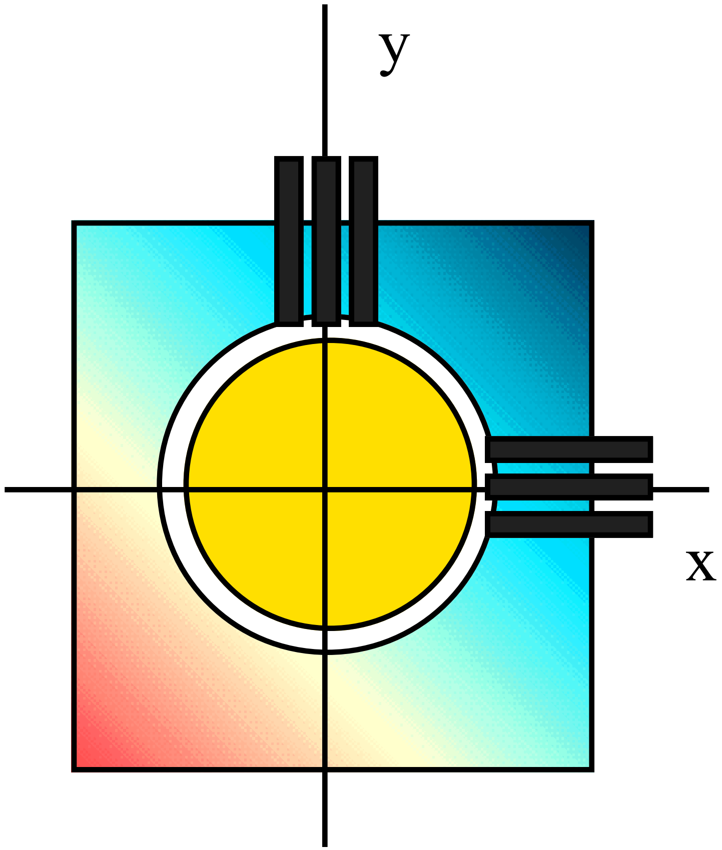
# Redundancies

**Analytical redundancy:**

failed components are computationally compensated for

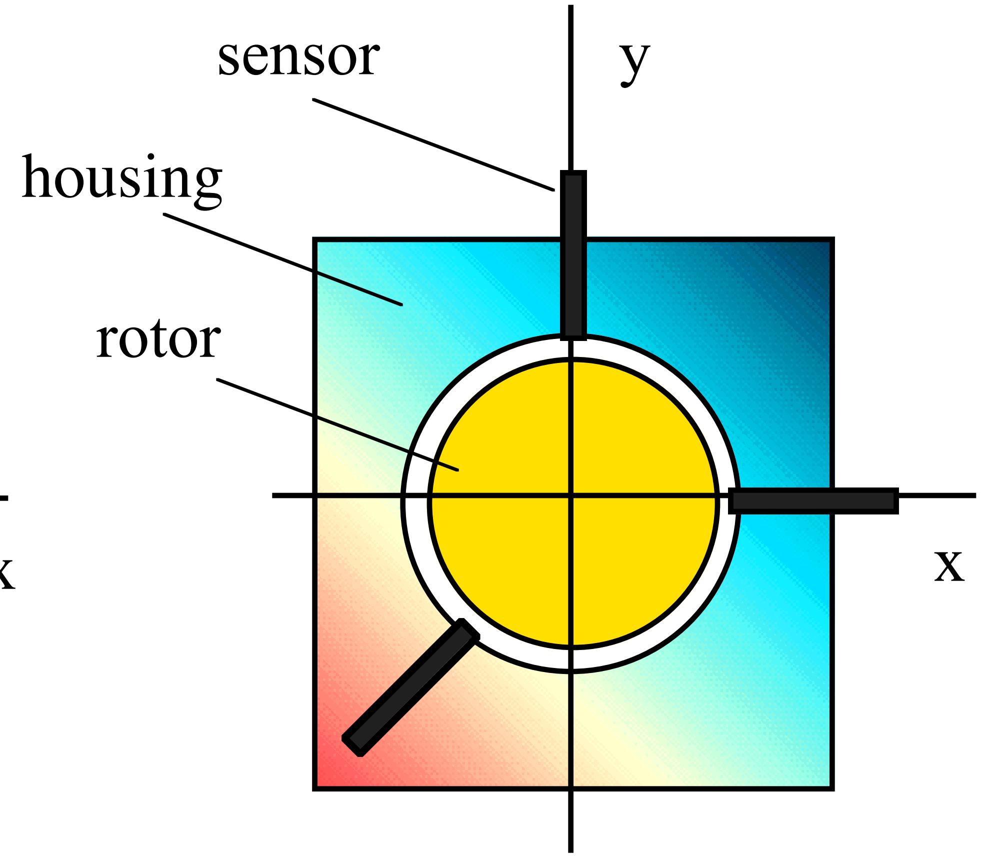
# Redundant Sensors

## Hardware redundancy




triplex sensor configuration

## Analytical redundancy




simplex sensor configuration
with one redundant sensor

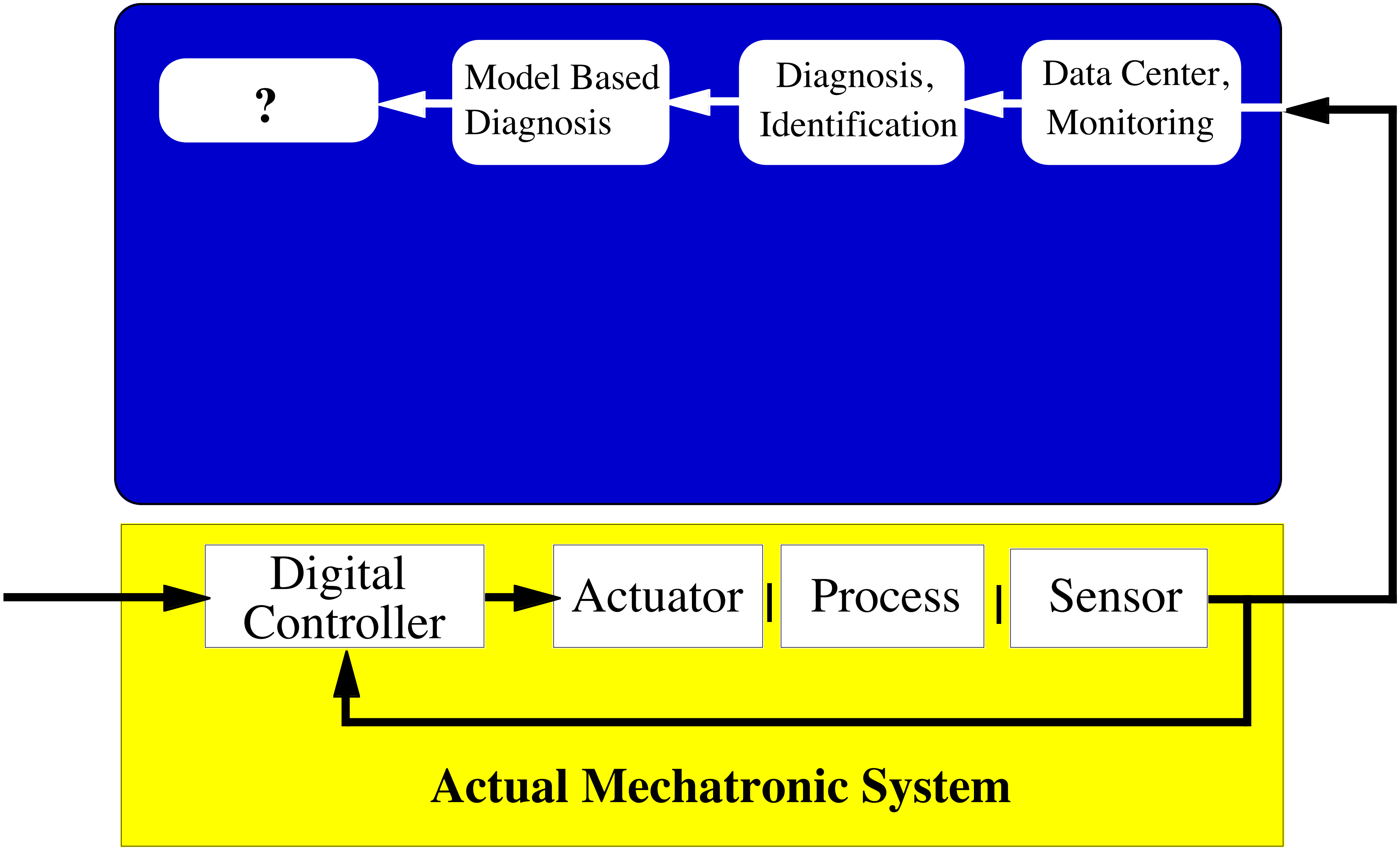
# Smart Machine Technology

# Smart Machines

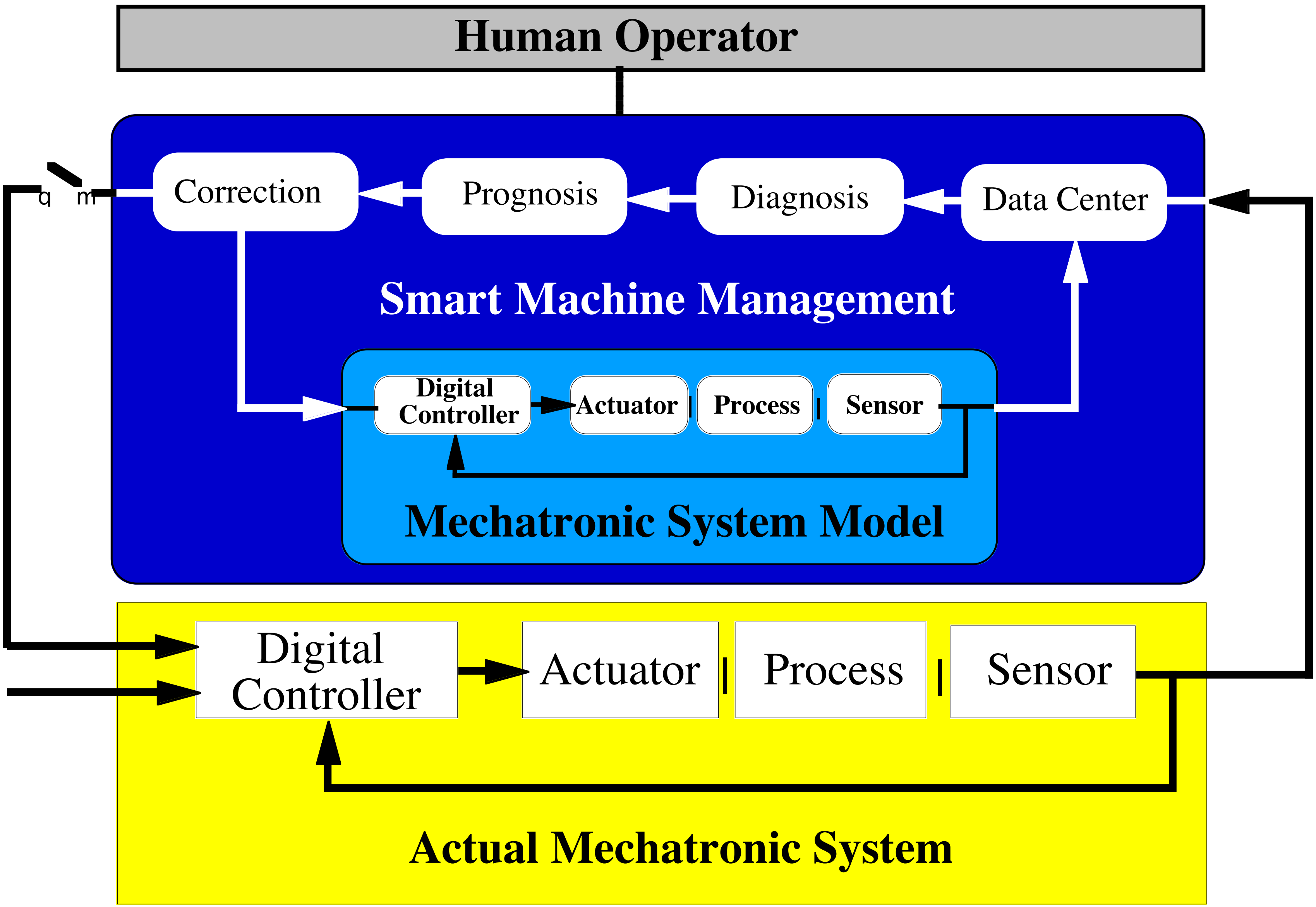
**Smart machines know their internal state and optimize it by internal information processing**

- Better functionality (self-calibration, self-diagnostics, self-tuning, self-corrections)
- higher reliability and safety, less maintenance
- potential to easily connect to the outside production world („Industry 4.0“)

# Monitoring and Identification



# Smart Machine Technology



# Diagnostics

## From data collection to cognition

- Monitoring
- Diagnostics as classification of data
- Diagnostics with setting up hypotheses
- Active diagnostics by generating defined input signals for verifying hypotheses

# Correction - Strategies and Options

## How can the situation be improved?

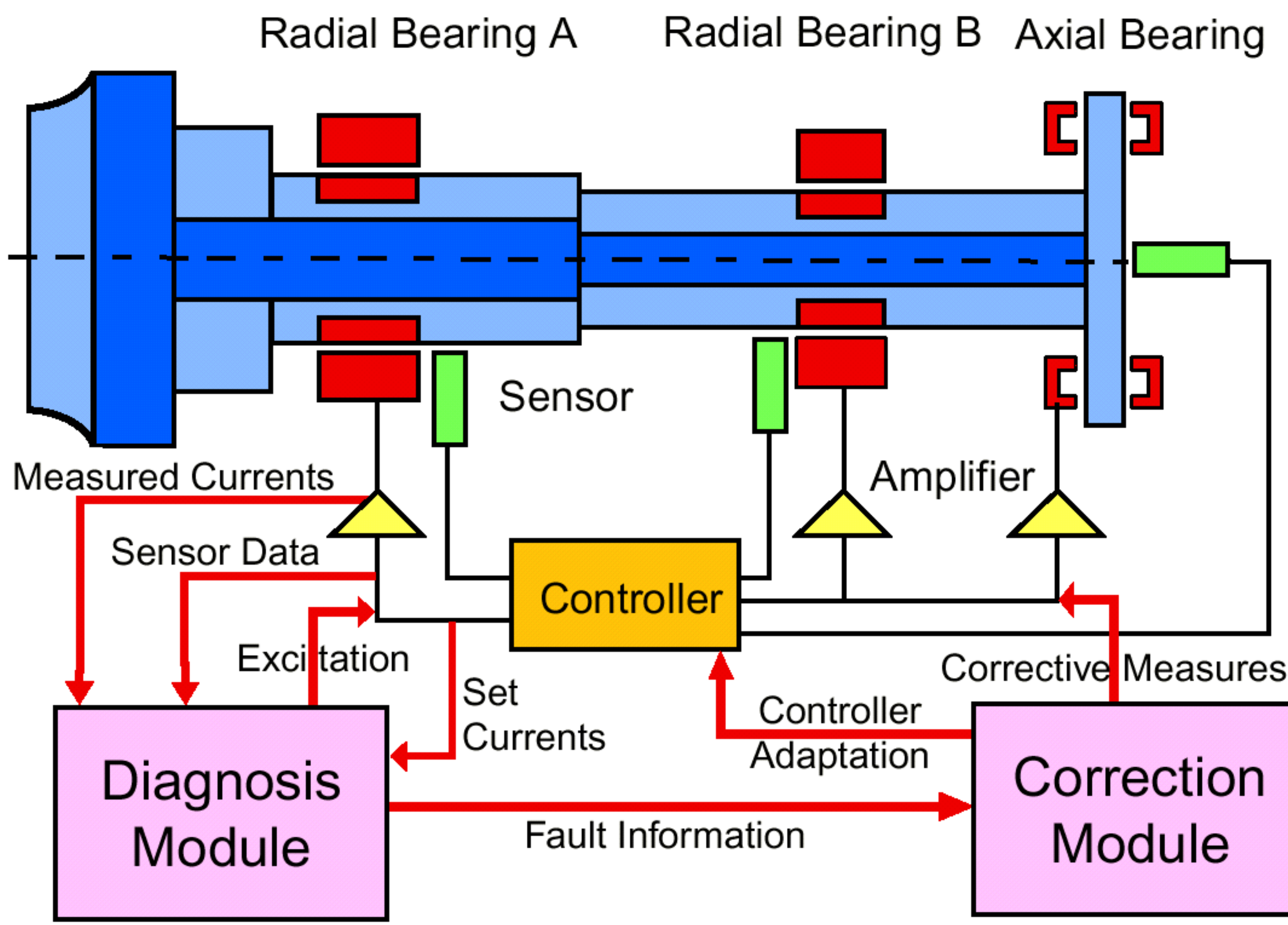
- scheduling of different operation modes
- scheduling of different controller parameters
- adaptation to disturbances
- self-calibration
- self-tuning of the controller
- management of redundancies

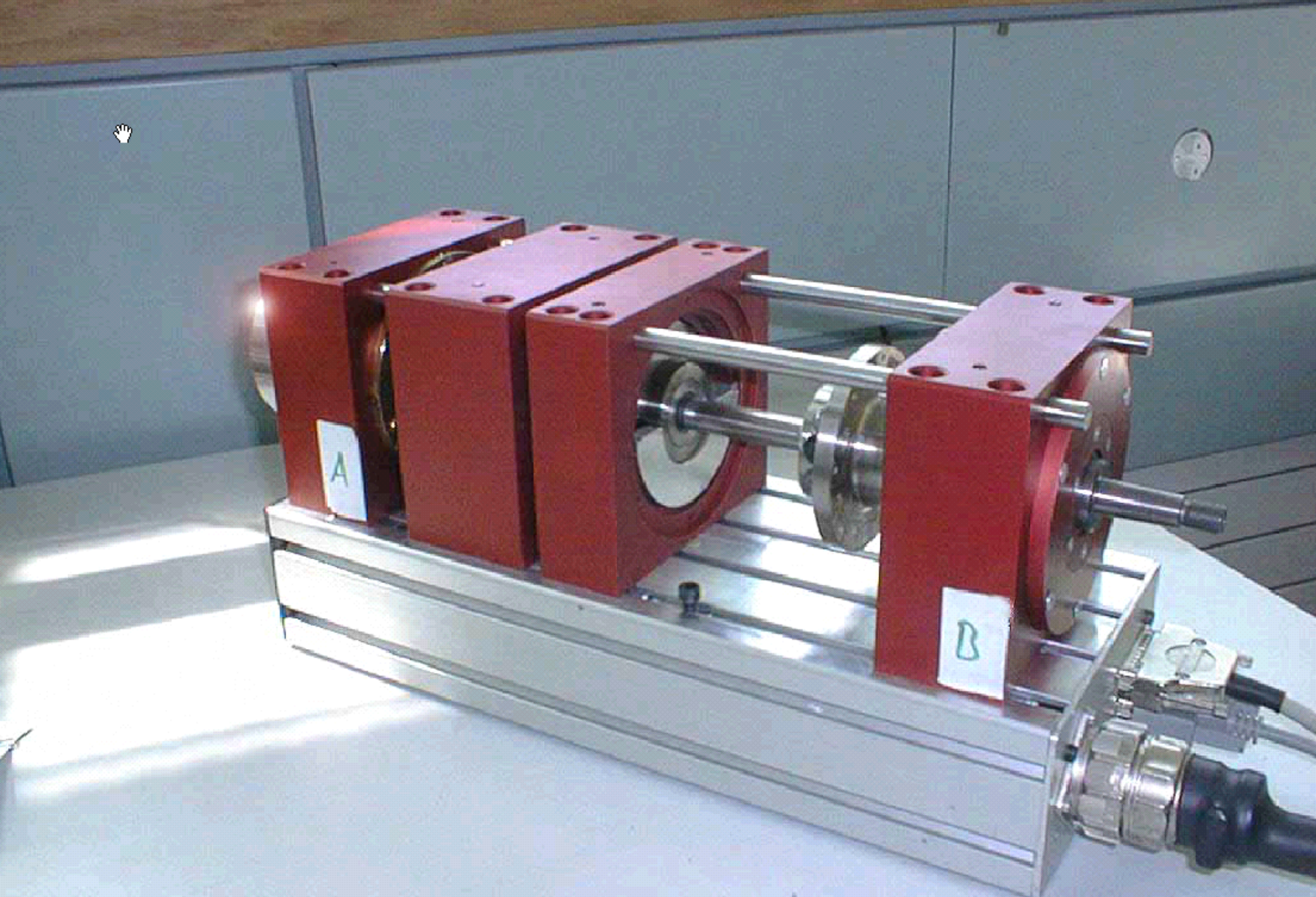
# Self-configuration of a new controller

1. Switch on full power of AMB, attract rotor to upmost position
2. Let rotor drop, measure transition function
3. Identify plant from transition function
4. Allocate automatically suitable controller for making the rotor hover, at very low frequencies
5. Generate, in addition to the control signal an excitation signal, and measure frequency response for frequencies below the first critical bending mode
6. Identify the plant in the frequency domain, derive analytical expression for frequency response
7. Allocate automatically a controller for that identified plant and that frequency range
8. Repeat in small steps from 5. until operating speed

(A priori knowledge: rotor mass, characteristic parameters of AMB)

# Concept of Smart AMB Control System



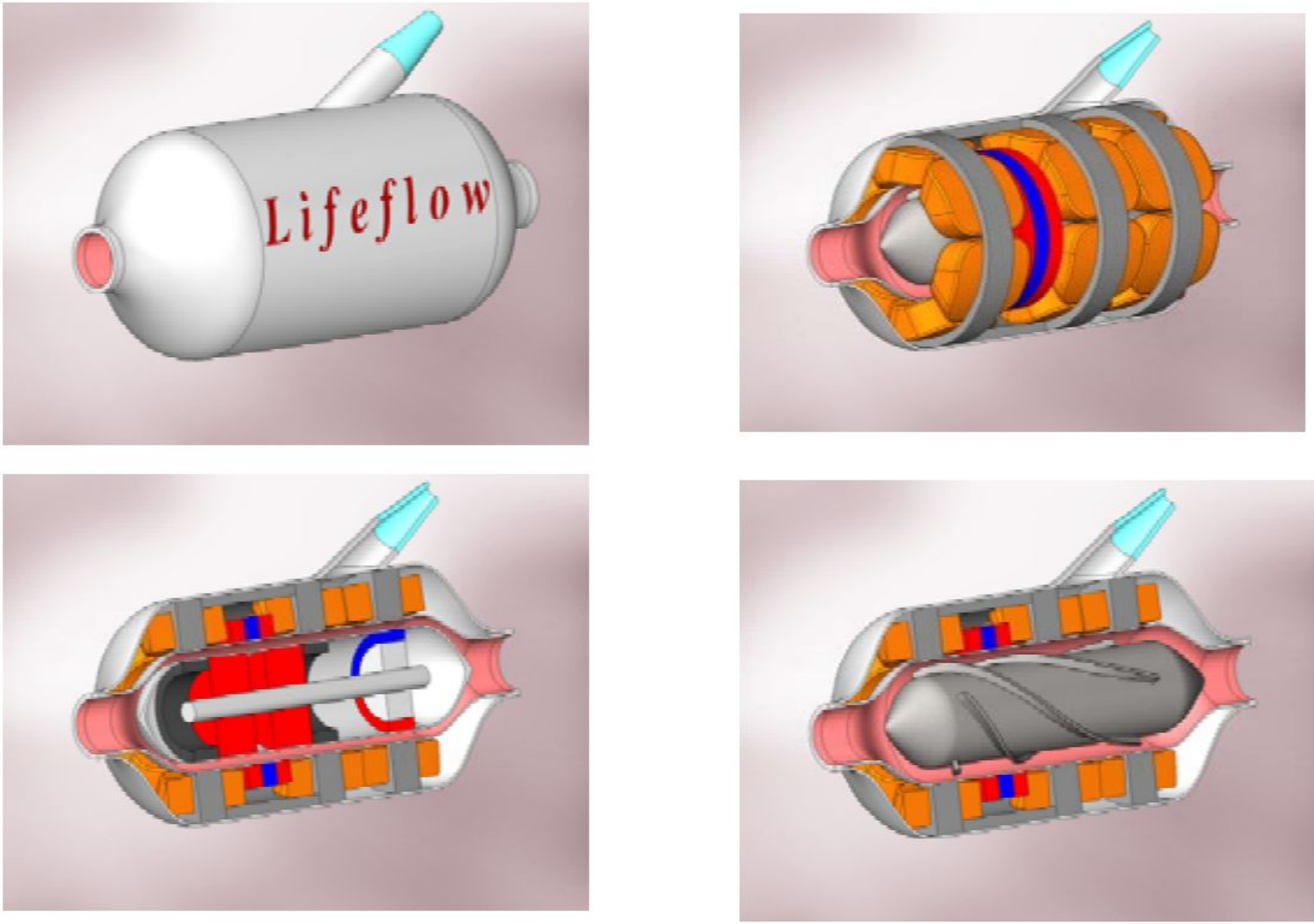



**Test Rig for Smart AMB Technology**

Lösch

# Future Applications and Developments

# Heart Assist Pump

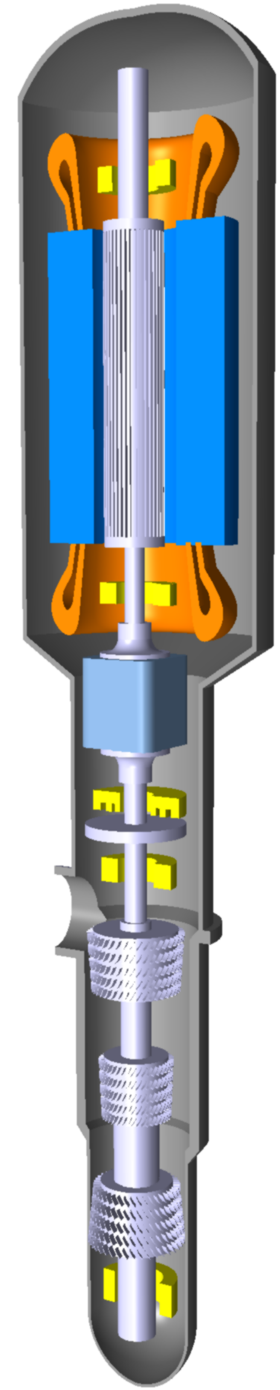



Allaire et al.

# HTR Nuclear Turbogenerator

first pebble-bed high temperature gas-cooled test reactor with the gas turbine in the direct cycle
HTR-10GT, under construction

10 MW
15’000 rpm
4 radial bearings, 2 axial
length of turbine 3.5 m
mass of turbine 600 kg



courtesy Institute of Nuclear and Novel Energy Technology INET
Tsinghua University, Beijing

Japan Rail, 2015, 605 km/

# Test Rig for Superconductive Bearing

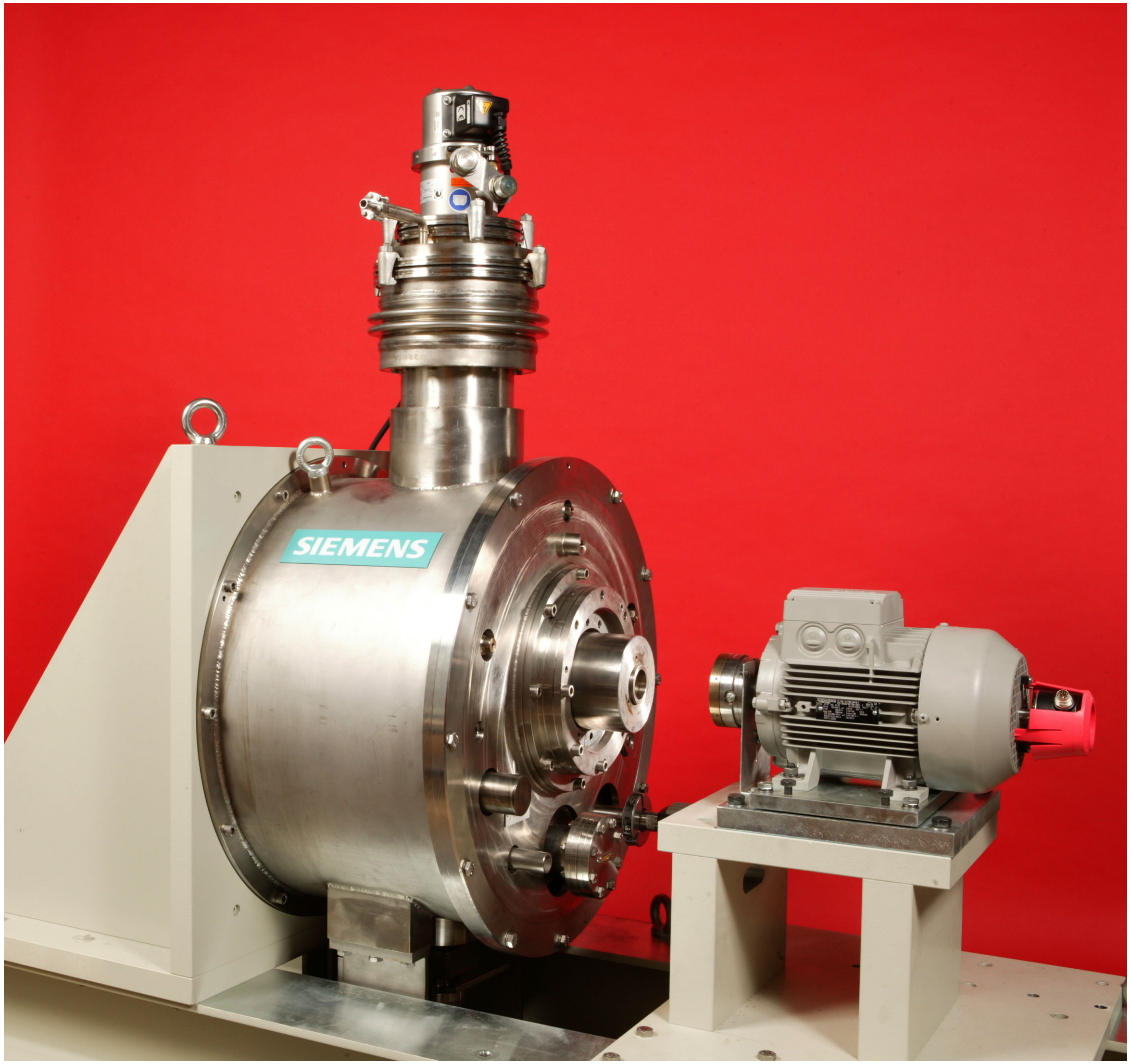
4 MVA HTS synchronous generator

bearing capacity 500 kg

maximum speed 4500 rpm

below 60 K the bearing capacity remains almost constant

bearing, initially cooled down to 28K, can still be operated for additional 2 hours without cooling




courtesy SIEMENS

# Trends and Topics in Magnetic Bearings

**Mechanics** retainer bearings (design, materials)
design for high speed (motor drive design)

**Control** elastic rotors
self-identifying rotor-bearing system
self-tuning and configuring control

**System** smart machine technology: diagnostics, reliability, safety,
information processing: interfaces to higher level monitoring or operating system, industry 4.0

**Education** Integration of Mechatronics, Control, and Structural Dynamics

# Conclusions

- **Active Magnetic Bearings (AMB) are a typical product of mechatronics**
- **AMB permit novel solutions for classical problems in rotor-dynamics**
- **AMB are a key component to smart rotating machinery**
- **Magnetic bearings allow and require an advanced level of control and information processing to make best use of its complexity and to manage risk in a smart way.**

# Thank you

# References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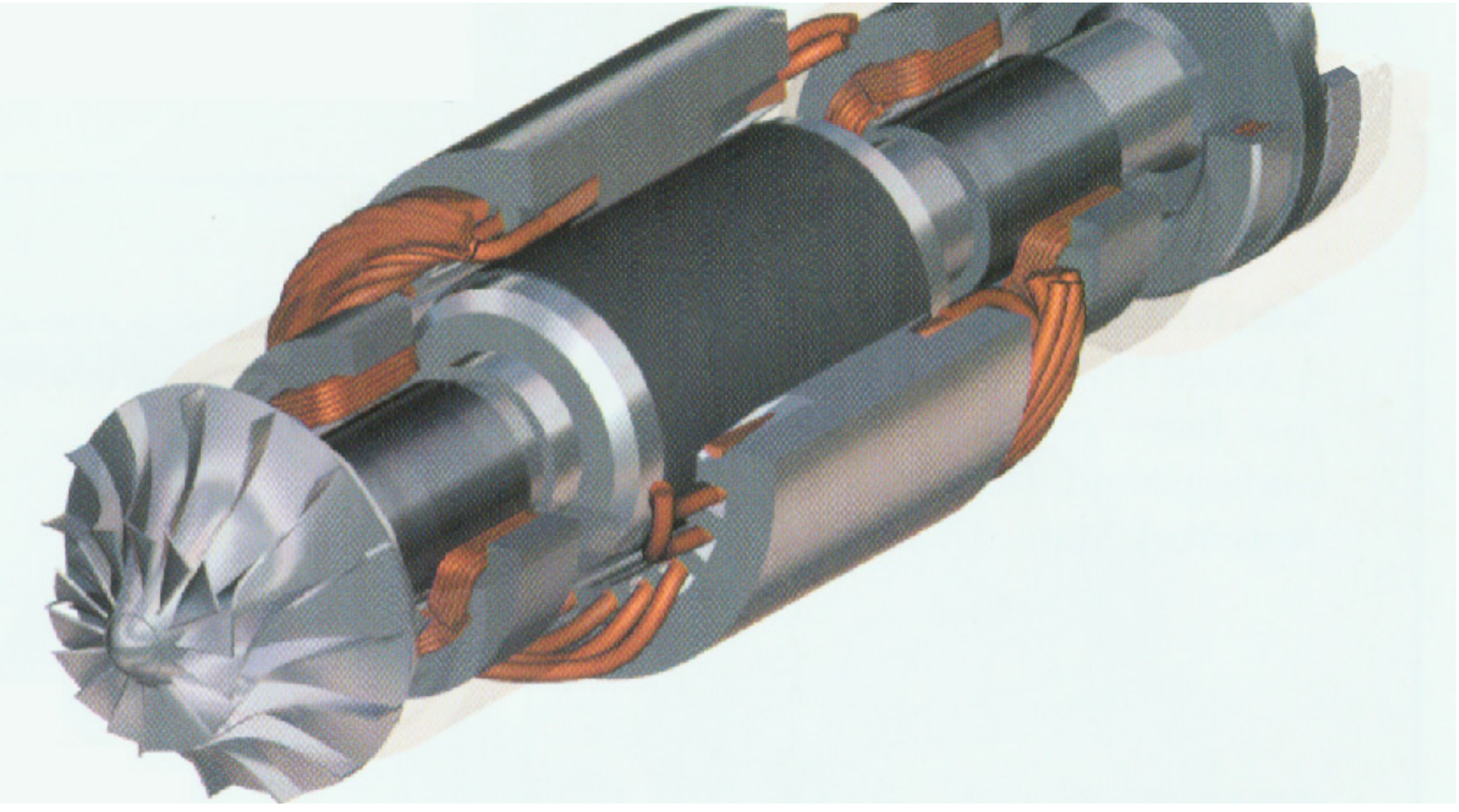
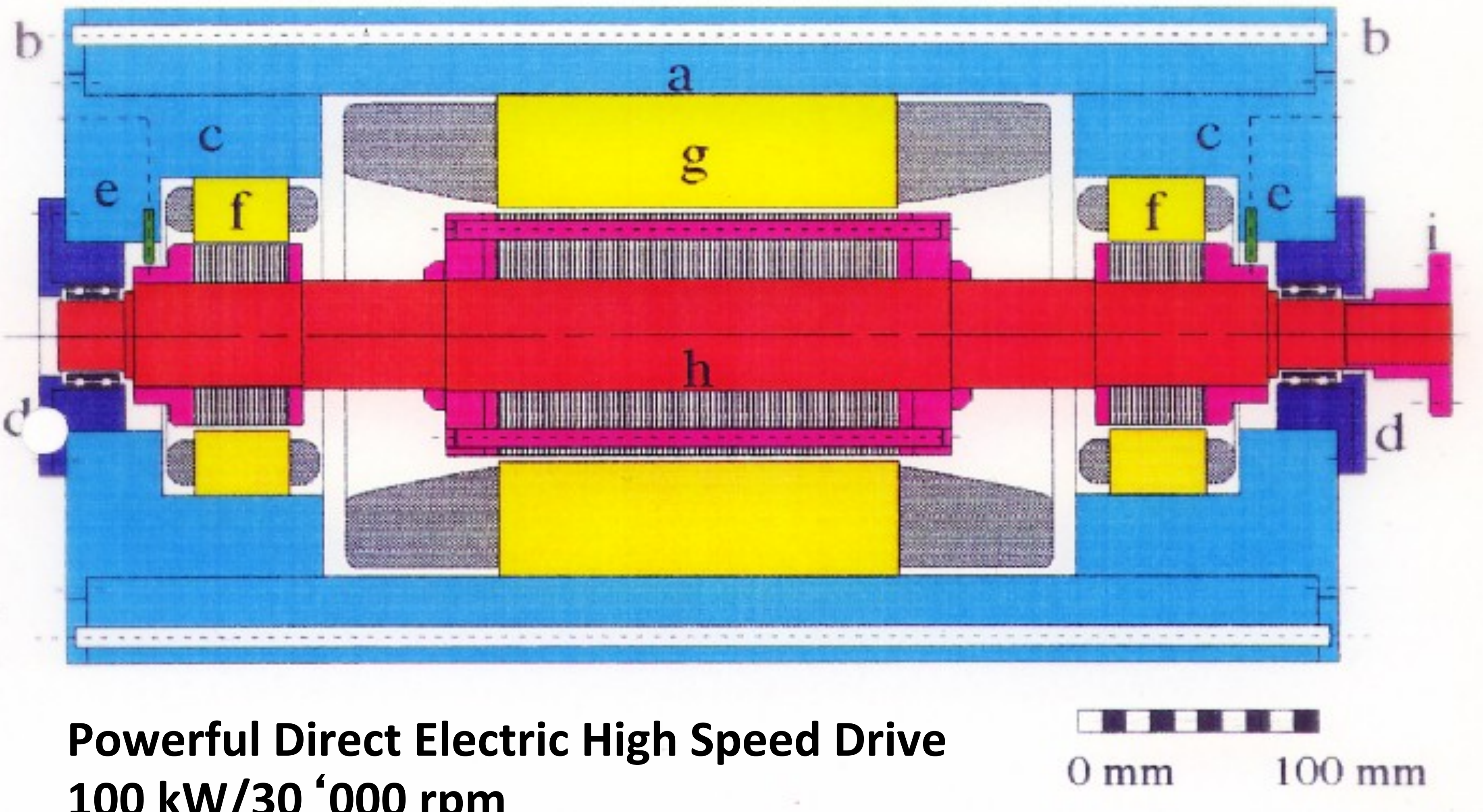
- ISO Standard 14839-2: Mechanical vibration - Vibrations of rotating machinery equipped with active magnetic bearings - Part 2: Evaluation of vibration, 05, 2004.
- ISO Standard 14839-3: Mechanical vibration - Vibrations of rotating machinery equipped with active magnetic bearings - Part 3: Evaluation of stability margin, 01, 2005.
- ISO Standard 14839-4: Mechanical vibration - Vibrations of rotating machinery equipped with active magnetic bearings - Part 4: Technical guidelines, system design (Draft), 12, 2007.

# S2M



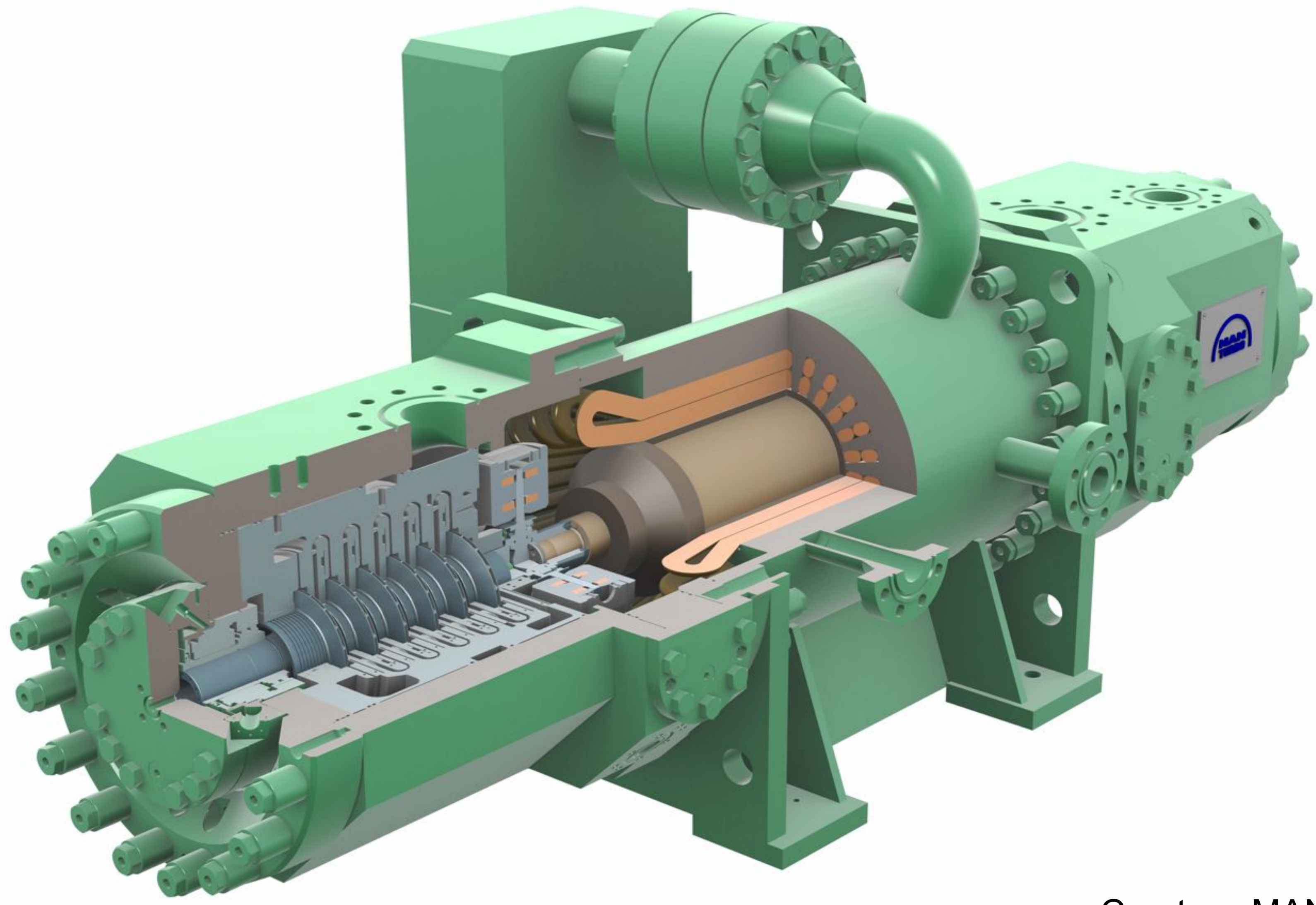



**Powerful Direct Electric High Speed Drive**
**100 kW/30 ‘000 rpm**

| | | | |
|---|---|---|---|
| **a** | **watercooled rotor housing** | **f** | **radial magnetic bearing** |
| **d** | **retainer bearing unit** | **g** | **induction machine** |
| **e** | **displacement sensor** | **h** | **rotor** |

Viggiano

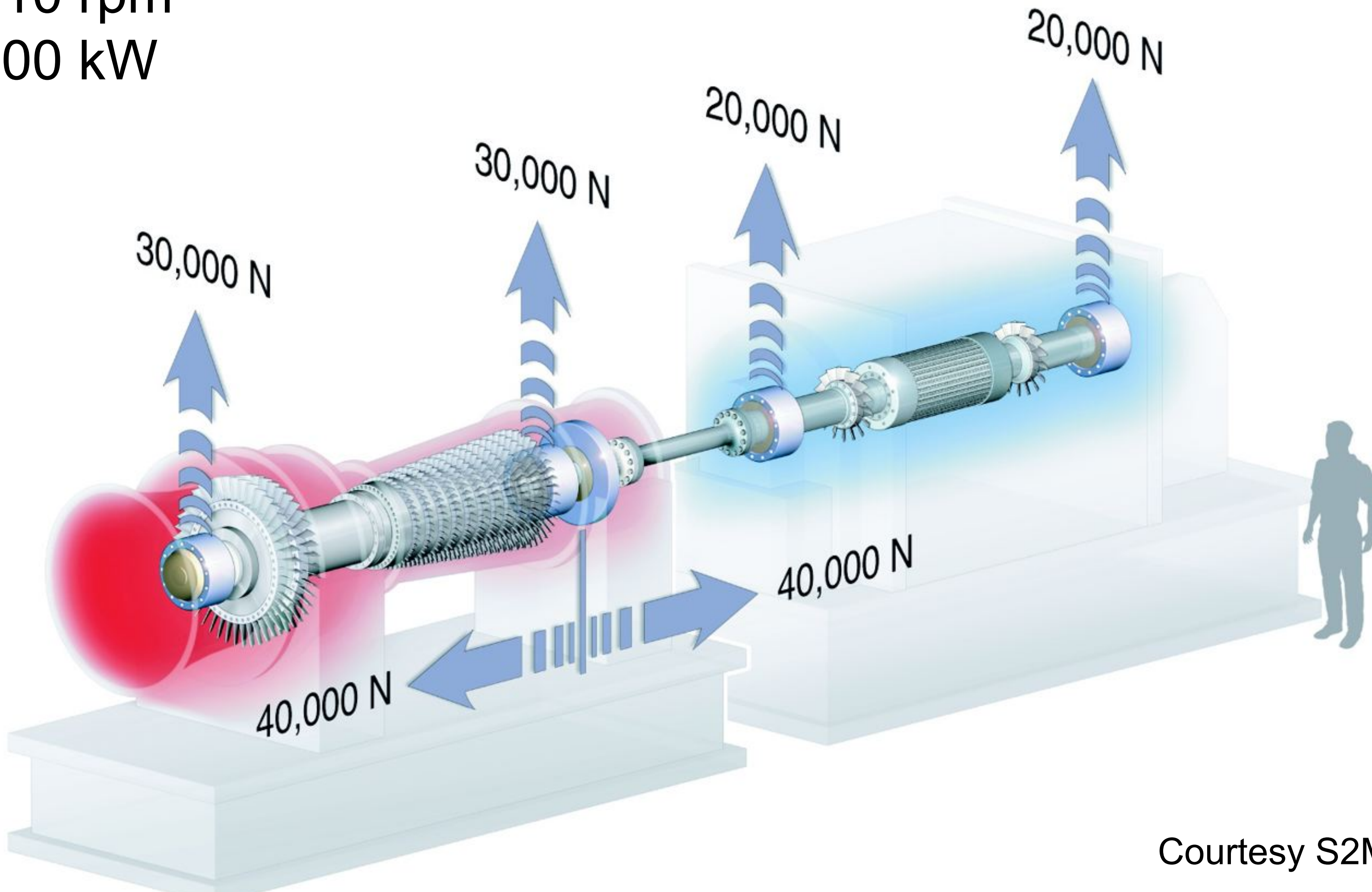
# **Pipeline Compressor** HOFIM, 6 MW, 9000 rpm



Courtesy MANTurbo/S2M

# Gas-turbine - Generator

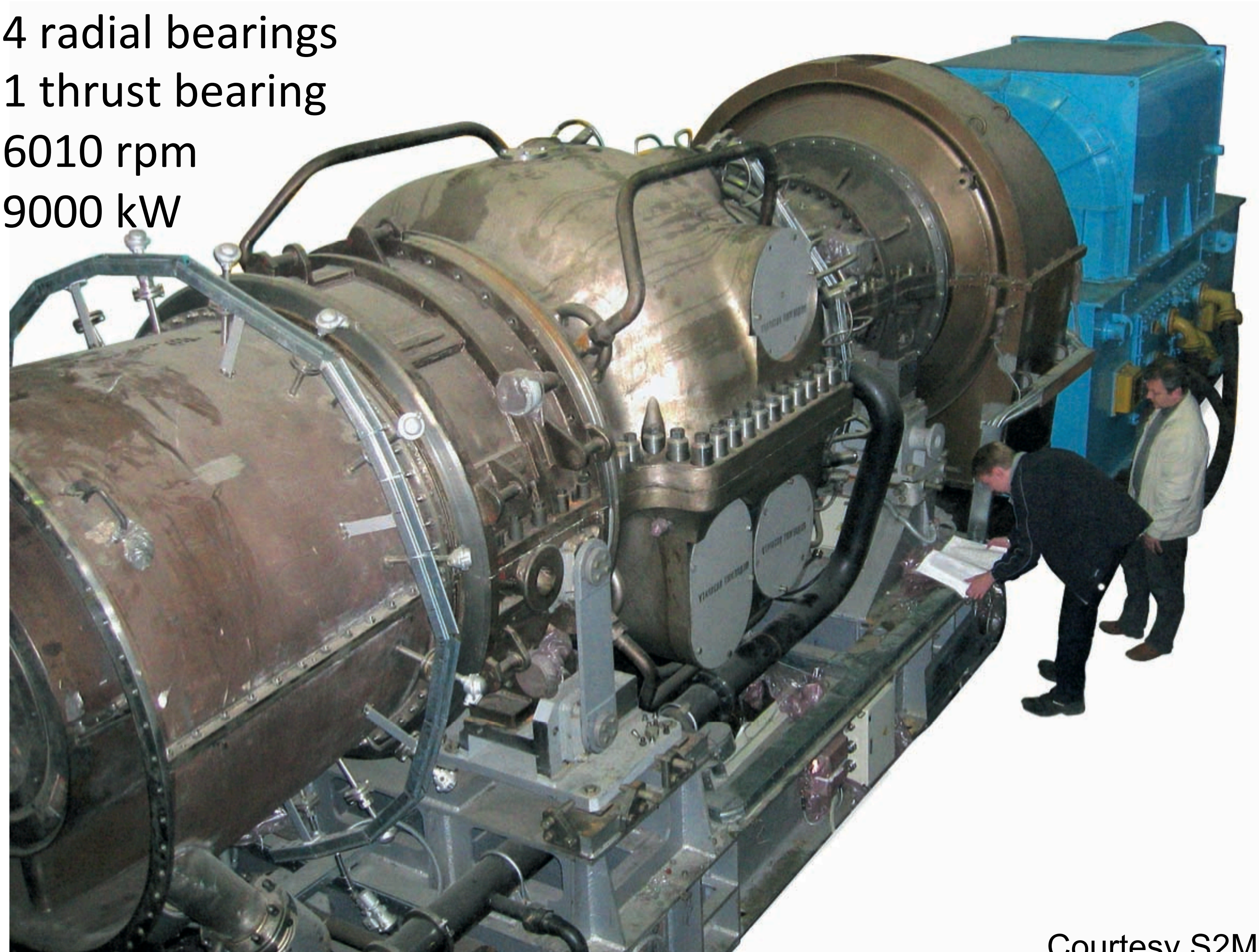
bearing diameter 400 mm
6010 rpm
9000 kW




Courtesy S2M

# Gas turbine - Generator

4 radial bearings
1 thrust bearing
6010 rpm
9000 kW



Courtesy S2M

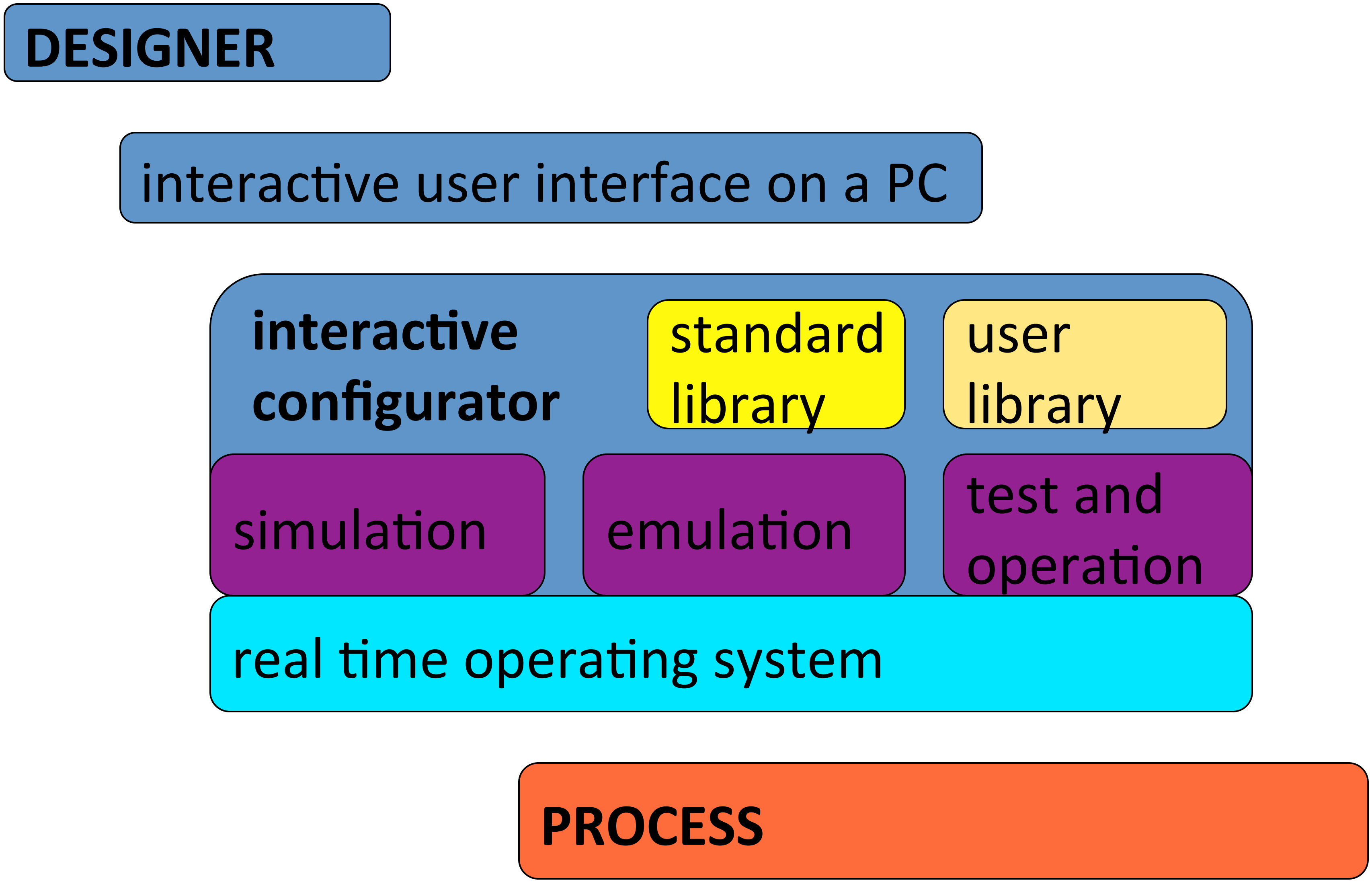
# Consequences of Failures

- Sudden failure of the rotor-bearing system with a breakdown of the rotor or of AMB function (i.e., cracking of the rotor, defect in the central controller)

- Sudden degradation of performance (i.e., blade loss, saturation effects)

- Slow degradation of performance (i.e., accumulation of unbalance, thermal effects in sensors)

# Concept of a Software Design System



# Systematics in the Design

Classical method for best practice:

FMECA (MIL-STD-1629A, ....)

**F**ailure **M**odes (what kind of failure can happen?),
**E**ffects (what are the consequences of a failure?)
**C**riticality **A**nalysis (how critical are the effects?)

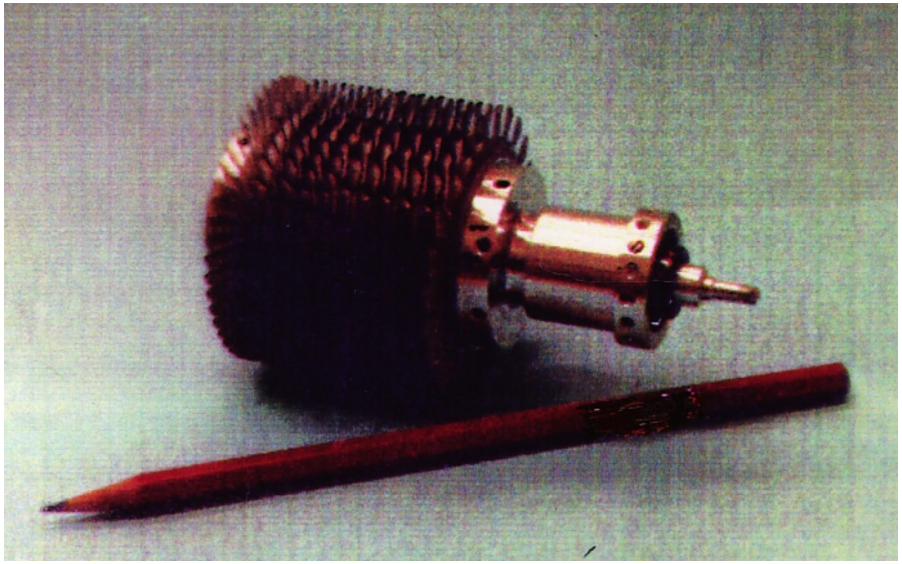
# Robust Control

„robust“ is the property of remaining within prescribed (specified, desirable) constraints under a variety of unpredictably changing conditions.

Example: blade loss

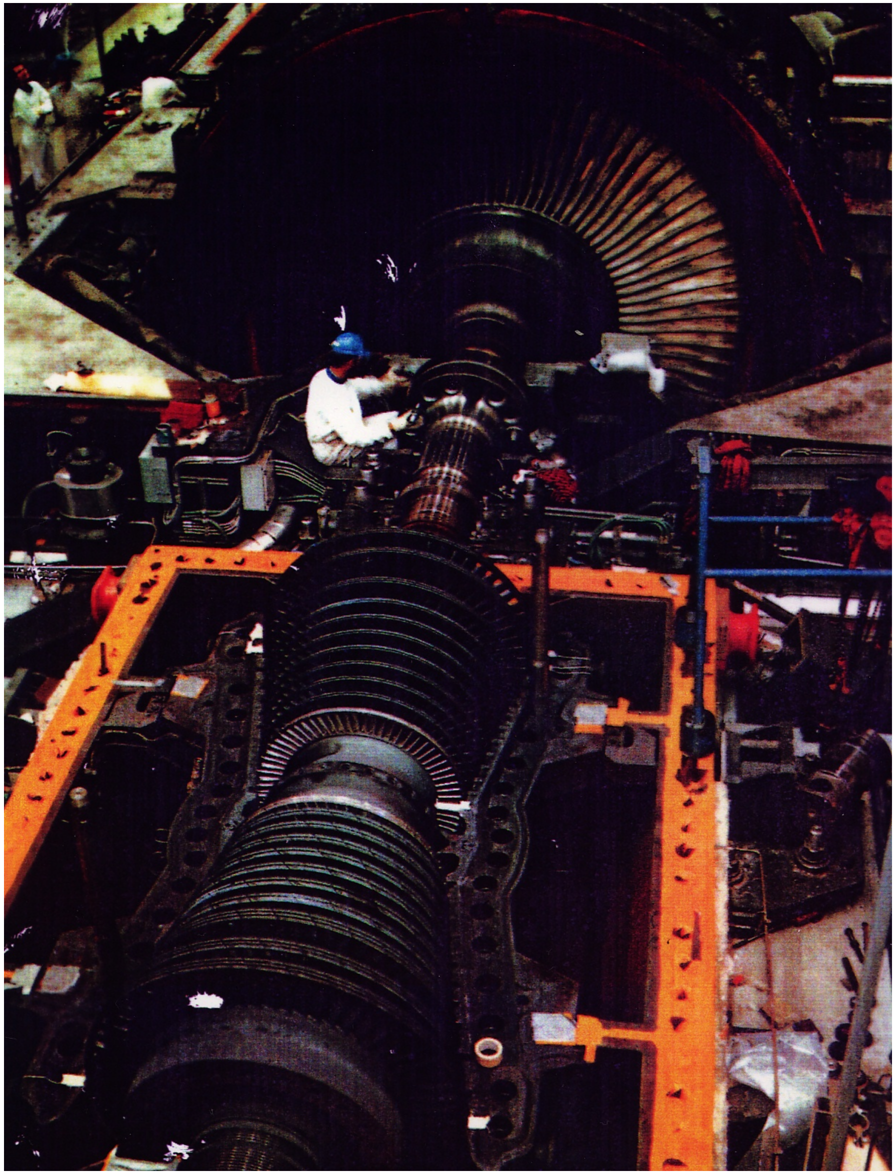
**Air gap**
**0.3 - 0.8 mm**

# Blade Loss Excitation in Turbomachines

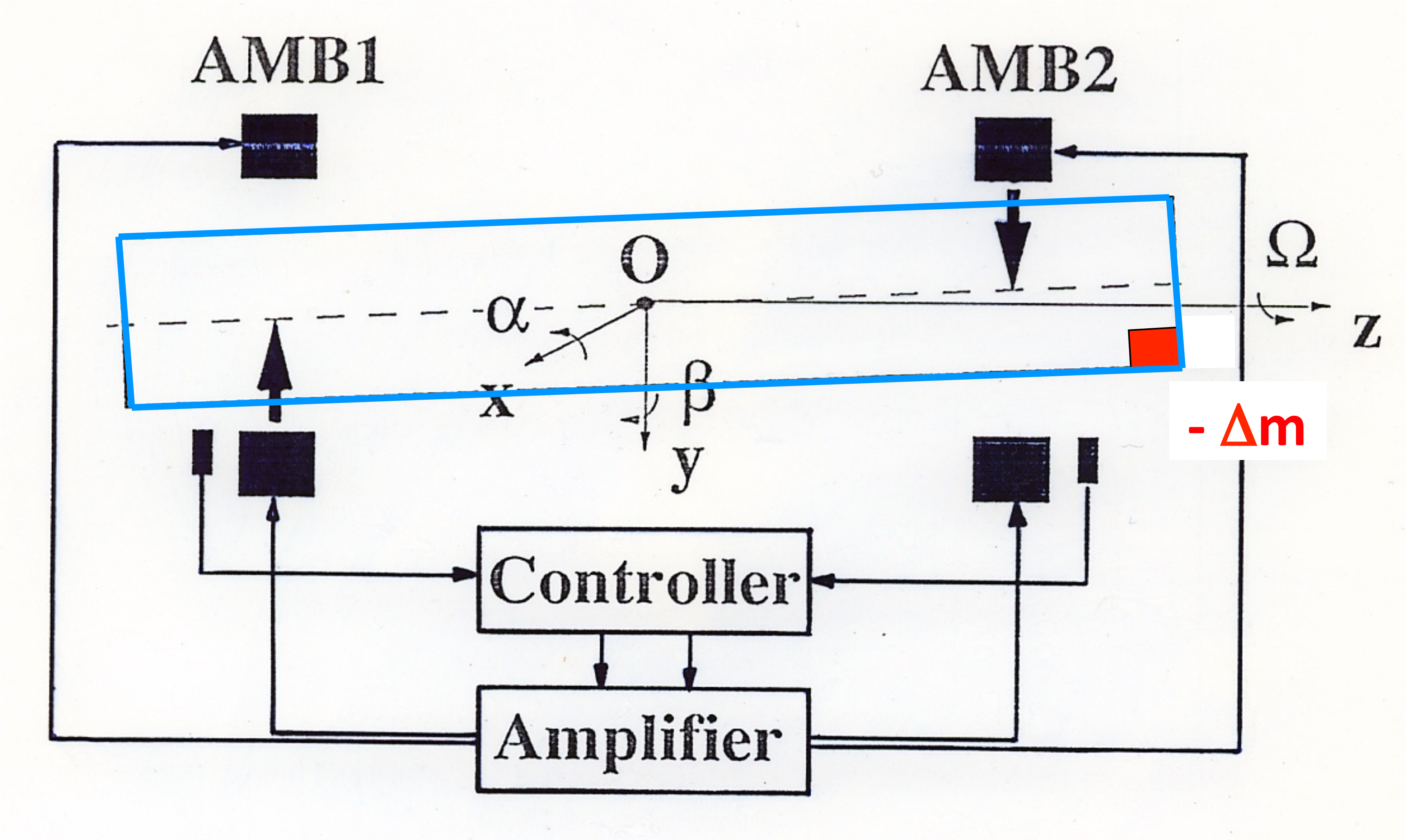


small pump for high vaccuum
80 W / 90 ‘000 rpm

large steam turbine



# Blade Loss Dynamics (1)
**rotor model**

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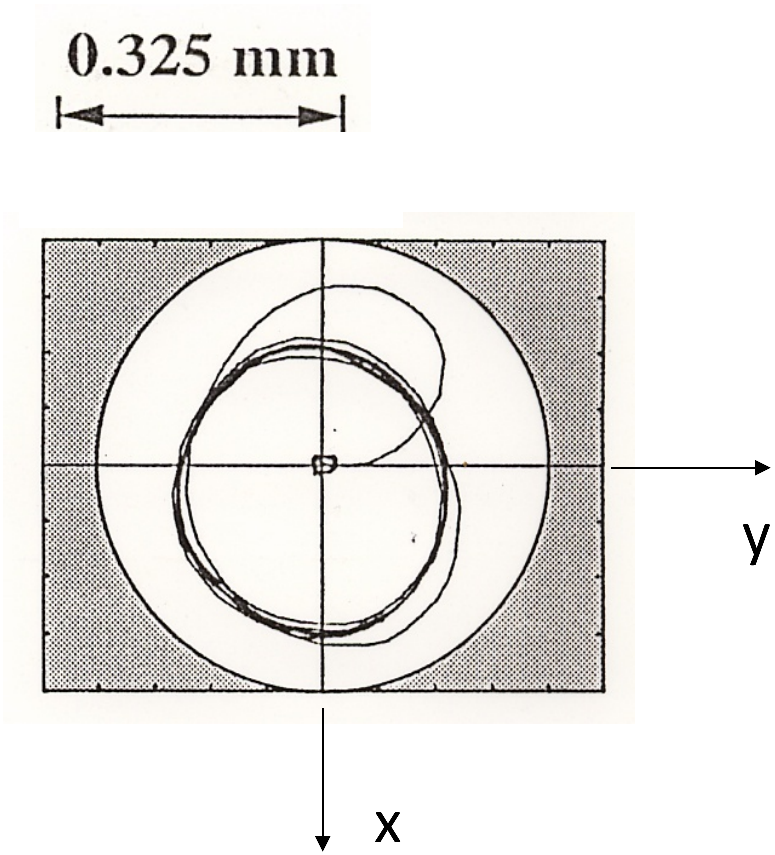
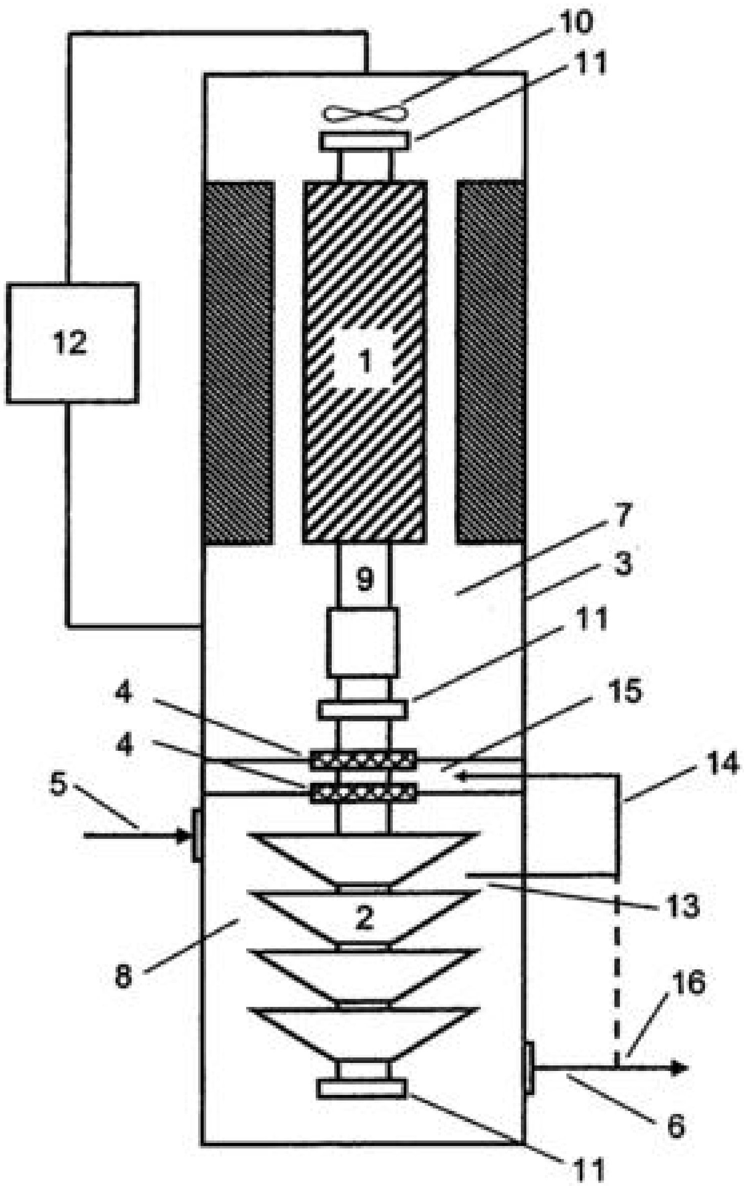
# Blade Loss Dynamics (2)
**experiments**




Unbalance: $\Delta m = 9.5$ g
Speed: $\Omega = 4000$ RPM

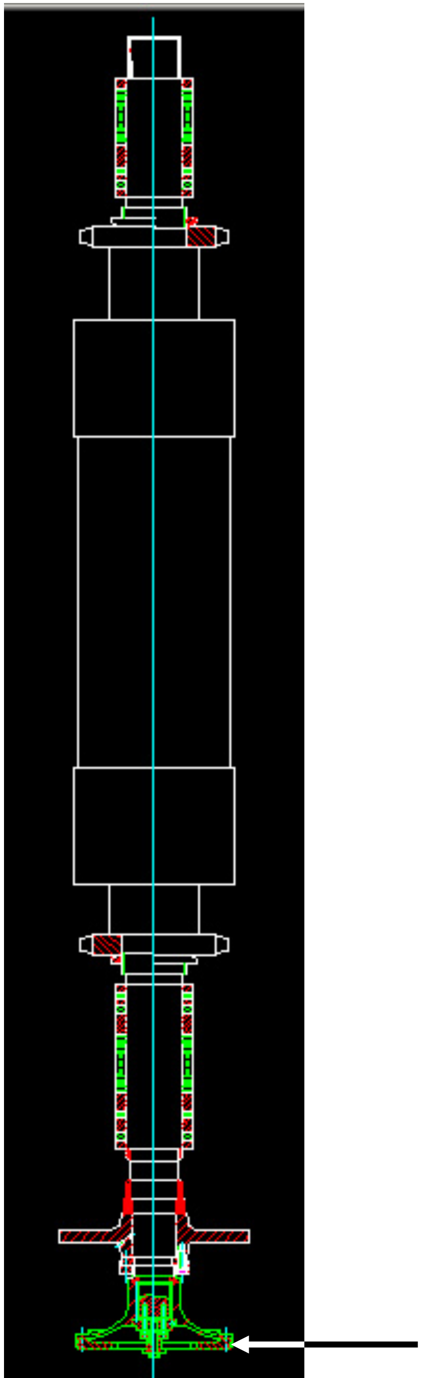
**Unbalance quality Q ≈ 80**




## Underwater Application (Natural Gas Compressor)

METHOD AND APPARATUS FOR PROTECTION OF COMPRESSOR MODULES AGAINST INFLUX OF CONTAMINATED GAS

(Norwegian Patent 2008)



# Turbo-generator for high-temperatur helium reactor (HTR)

| | |
|---|---|
| **Prototype** | **15 ‘000 rpm** |
| | **10 MW** |
| | **7 m** |
| | **4 radial AMB** |
| | **2 axial AMB** |
| **Generator:** | **1000 kg** |
| **Turbomach.:** | **600 kg** |

Tsinghua University, INET / OKBM-Russia