

Twistact Technology: Enabling More Efficient Large Scale Wind Turbines

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Presented by Brad Salzbrenner

Collaborators:

Nicolas Argibay - Jeff Koplow - Mike Dugger

Brad Boyce - Wayne Staats - Brendan Nation

Tomas Babuska - Justin Vanness - Daniel Matthew - Kent Smith



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National Nuclear Security Administration



**U.S. DEPARTMENT OF
ENERGY**

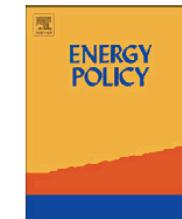
Providing all global energy with renewables by 2030 (the central role of wind power)



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Providing all global energy with wind, water, and solar power, Part I:
Technologies, energy resources, quantities and areas of infrastructure,
and materials

Mark Z. Jacobson ^{a,*}, Mark A. Delucchi ^{b,1}

^a Department of Civil and Environmental Engineering, Stanford University, Stan-

^b Institute of Transportation Studies, University of California at Davis, Davis, CA

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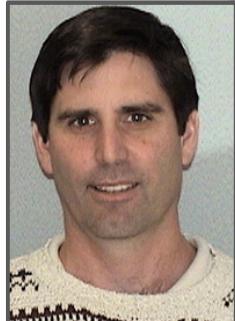
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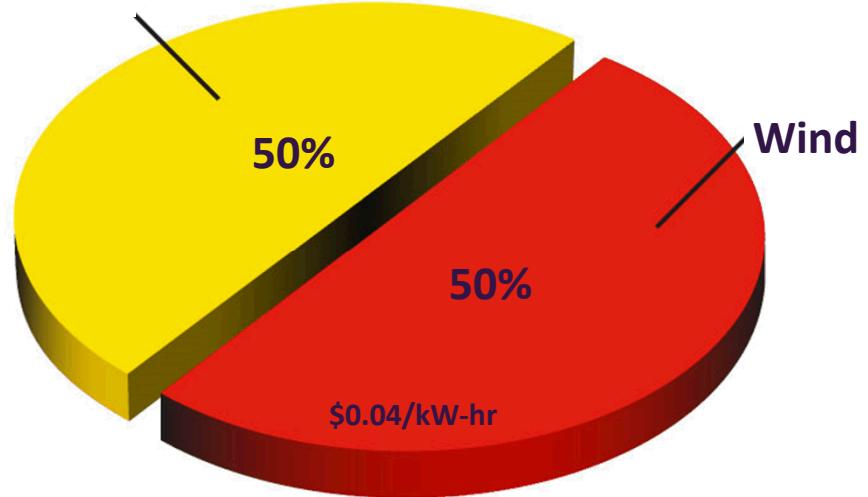
ABSTRACT



Mark Jacobson

- seasoned analyst
- technological objectivity

All other renewable
energy sources combined



15 TW global energy portfolio for 2030

Fundamentally, what is driving evolution of wind turbine technology?

- 1) **Economies of scale:** 5 to 20 MW wind turbines can achieve extremely competitive \$/kW-hr
- 2) **Criticality of offshore and remote deployment:** NIMBY & wind-resource driven

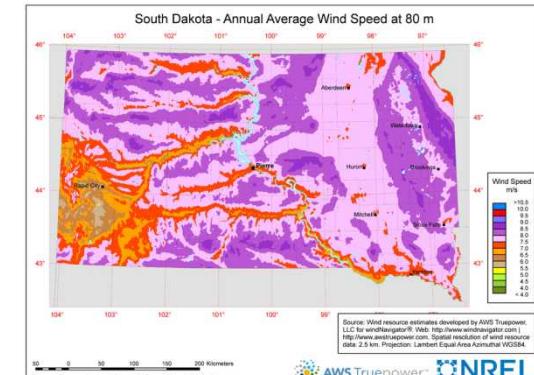
	Manufacturer name	Country of origin	Mechanical transmission	Generator rotor type	Inverter required	Turbine size (m)	Power output (MW)
1	Vestas	Denmark	Gear box Gear box ^a	Induction RE magnet	Part (DF) Full	52 – 90 112	0.9 – 3.0 3.0
2	General Electric	USA	Gear box Gear box Direct drive^b	Induction RE magnet RE magnet	Part (DF) Full Full	71 - 83 100 110	1.5 2.5 4.0
3	Sinovel	China	Gear box	Induction	Part (DF)	60 - 113	1.5 – 3.0
4	Enercon	Germany	Direct drive	Wire-wound	Full	33 - 126	0.3 – 7.5
5	Goldwind	China	Direct drive	RE magnet	Full	70 - 100	1.5 – 2.5
6	Gamesa	Spain	Gear box Gear box	Induction RE magnet	Part (DF) Full	52 – 97 128	0.9 – 3.0 4.5
7	Dongfang	China	Gear box	Induction	Part (DF)		1.0 – 2.5
8	Suzlon	India	Gear box ^b	Induction	Full	52 - 88	0.6 – 2.1
9	Siemens	Germany	Gear box Direct drive	RE magnet RE magnet	Full Full	82 – 107 101	2.3 – 3.6 3.0
10	Repower	Germany	Gear box	Induction	Part (DF)	82 - 126	2.0 – 6.0

DF: doubly fed induction generator

a) hybrid drive

b) acquired from Scanwind

c) constant-speed



Industry response: Technology down selection is now being driven by:

Power plant “scalability”

Power plant “autonomy” (reliability, service intervals)

The movement towards RE magnets (the 2nd technology down select)

- Driven by the “autonomy” requirement (brushes and slip rings have a limited service lifetime)
- Rare earth magnet rotors chosen over wire-wound rotors despite cost
- Enercon is the lone exception



But there is a big problem...

Rare earth metal supply crisis

96% of production in China

Steep price hikes

Wild uncertainty about future prices

Further uncertainty about future availability

Environmental damage of mining operations

Investor uncertainty about ROI

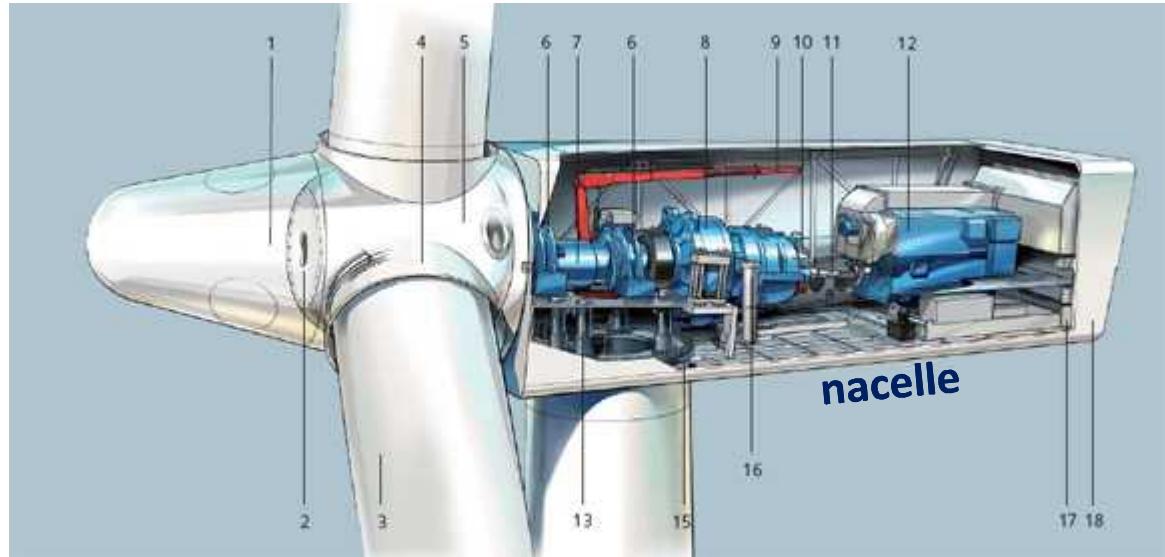
Need for contingency plan



Ref: Asian Metals

Briefing to Siemens Wind Power Group

(independent validation of the Twistact value proposition)



The purported value proposition of Twistact technology has since been verified directly by representatives of the wind turbine industry. In April of 2013, with the assistance of Hal Stillman of the International Copper Association, we engaged the Siemens Wind Power Group to gauge their level of interest in Twistact technology. The findings from this meeting were as follows:

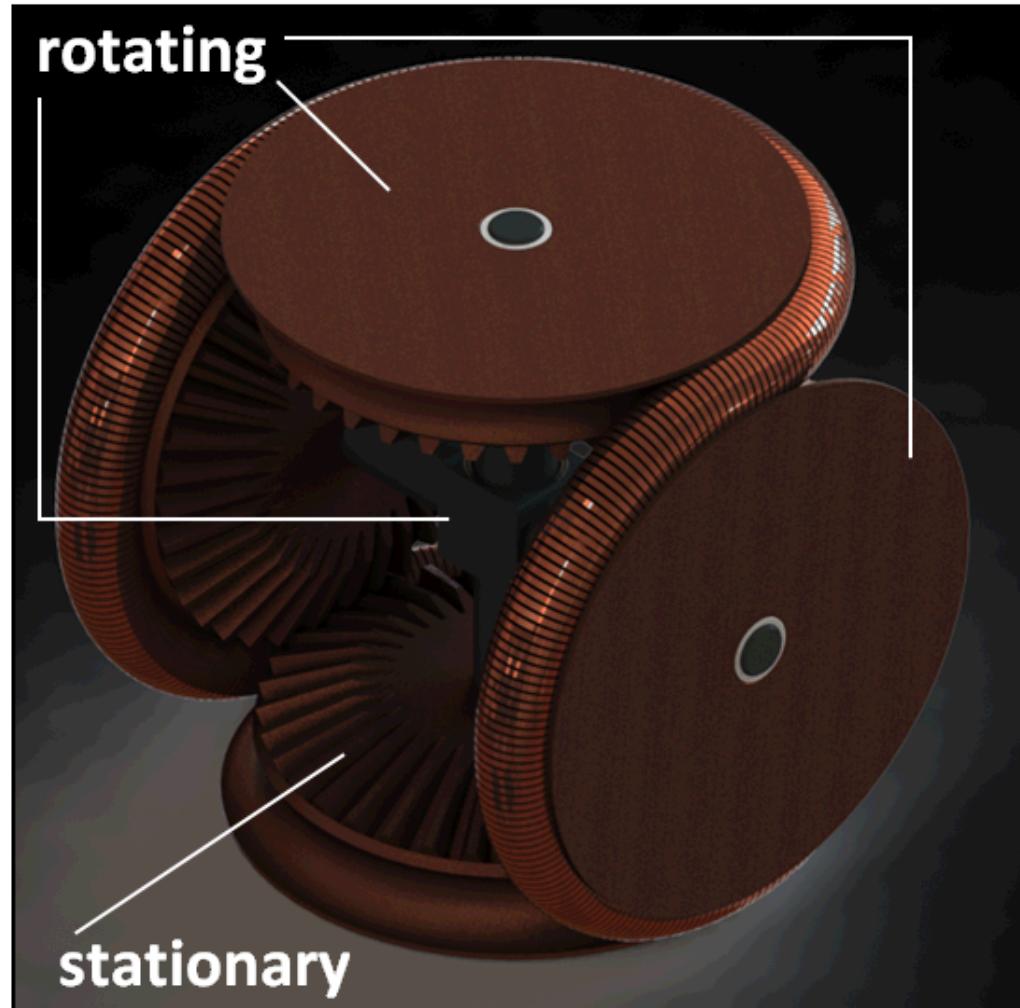
- 1) Twistact technology would allow Siemens achieve their longstanding goal of eliminating rare earth magnets in multi-MW wind turbines, which currently hinders large-scale investment in wind power because of anticipated rare earth supply disruptions.
- 2) Twistact technology would allow Siemens achieve their longstanding goal of constructing wind turbines larger than 3 MW, to realize significantly better economies of scale that exist at 10 MW and beyond.
- 3) Twistact technology would allow Siemens to **reduce the weight of their wind turbine nacelle by 50%**, thereby reducing construction costs considerably.

Twistact Technology

A fundamentally new class of rotary electrical contact device to replace brush/slip-ring hardware



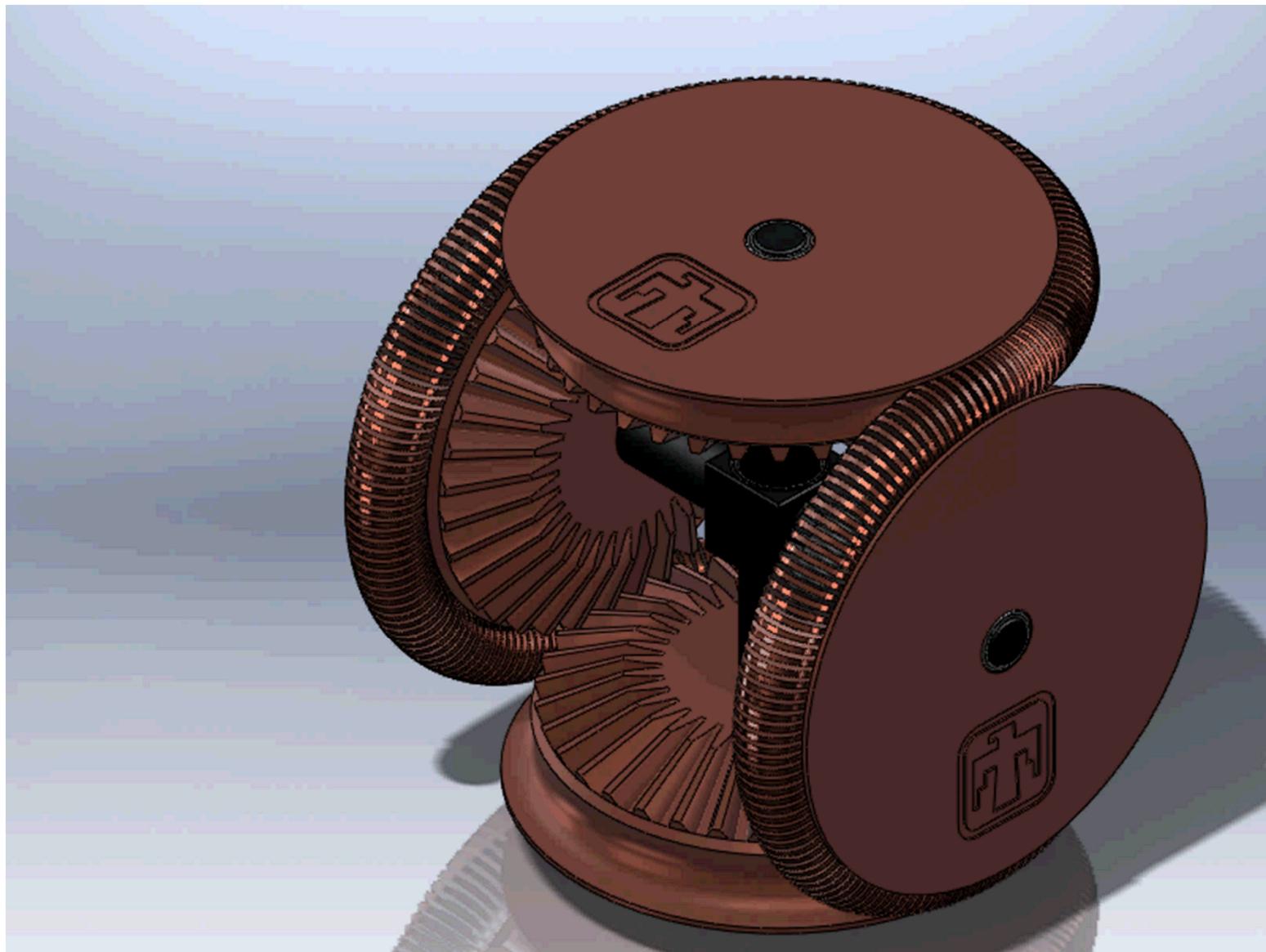
(table top demo unit)



"Rotary electrical contact device and method for providing current to and/or from a rotating member"

- US Patent 8,585,413, inventor: Jeff Koplow (Sandia Labs)
- DESIGN GOALS: current density $> 2\text{kA/cm}^2$, 30 yr service lifetime, 80M+ rotations
- Rolling contact, current spends minimal time on belt, convectively cooled

Animation of epicyclic motion that provides pure rolling mechanical contact

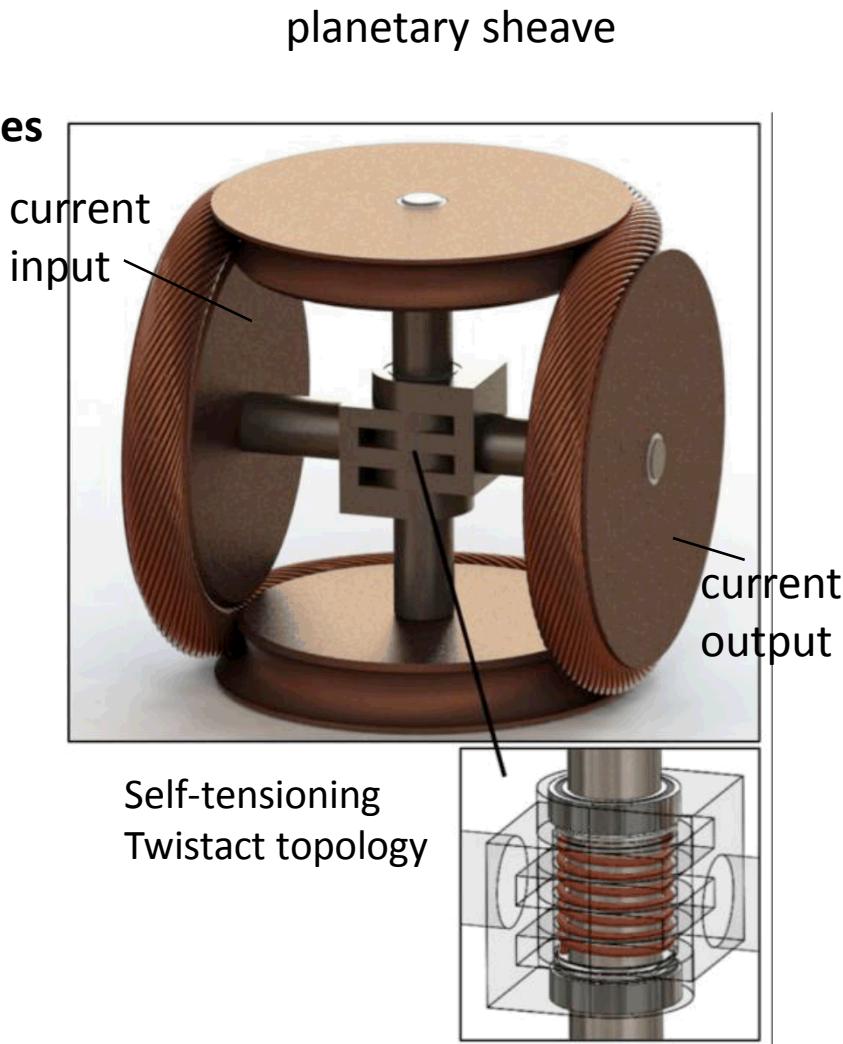


Twistact overview

- The Twistact eliminates the two physical processes by which brushes/slip-rings deteriorate: **sliding contact** and **electrical arcing**
- The Twistact consists of two elements:

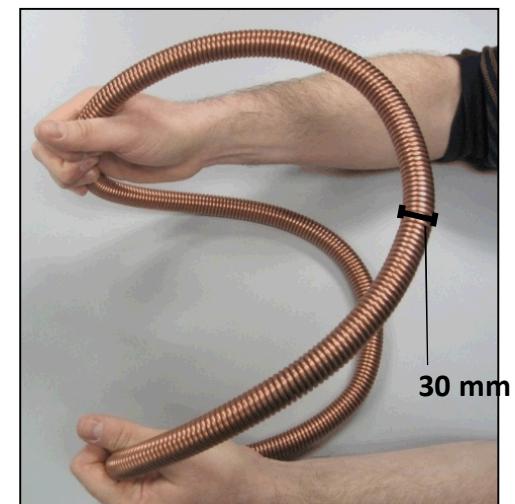
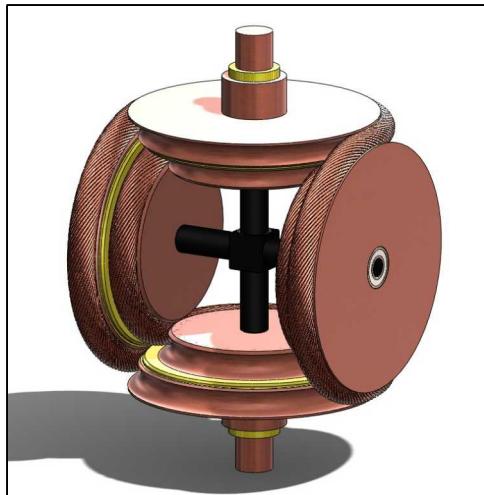
- 1) A flexible, durable, electrically conductive belt.
- 2) A unique epicyclical transmission device to provide a continuous ultra-low resistance path for current flow

- Avoids macro-scale sliding (rolling contact)
- No contact bounce means no electrical arcing
- Direct metallic contact, negligible voltage drop
- Two parallel current paths
- Current flow is principally transverse to belt
- Extremely effective thermal management

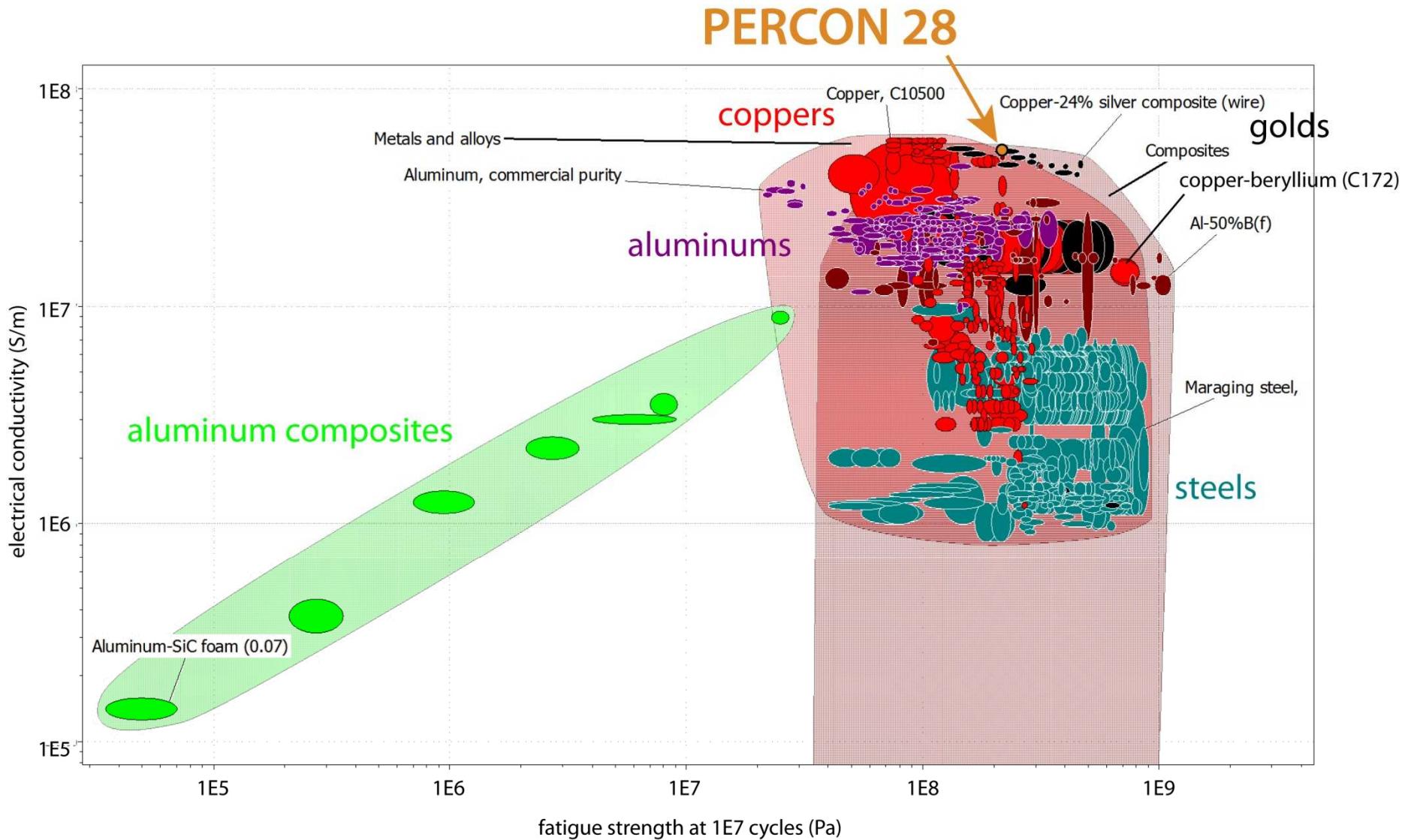


Key principles of operation

- Twistor belt carries minimal mechanical load
- Time-averaged I^2R heating is not localized (distributed over entire belt circumference)
- Twistor may be operated immersed in dielectric fluid for cooling, lubrication, and/or segregation from contaminants
- Twistor can easily be scaled up in size to increase current rating



Ashby Plot: Electrical Conductivity and Fatigue Strength

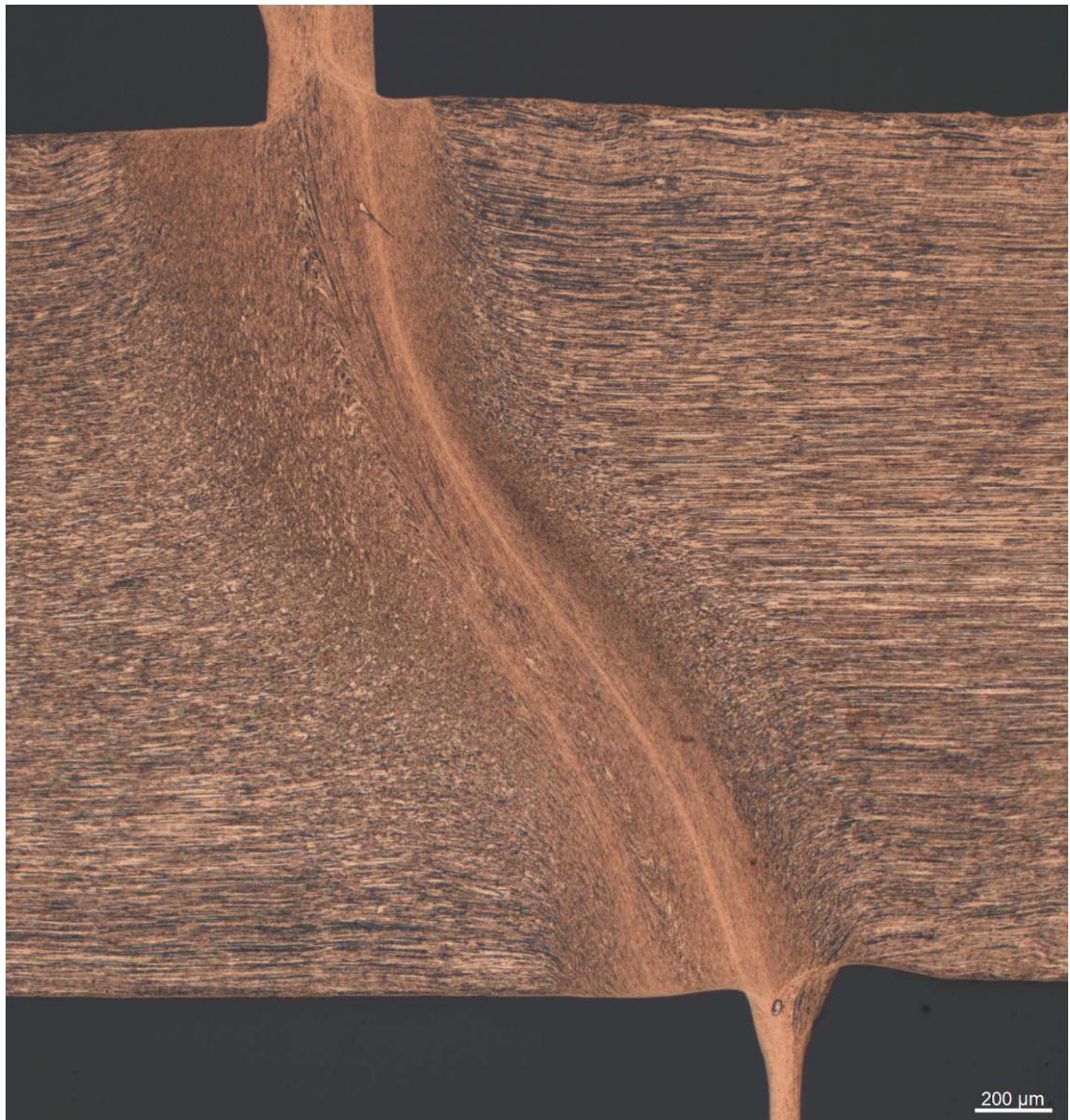


Included: copper, aluminum, iron, and gold (and their alloys)

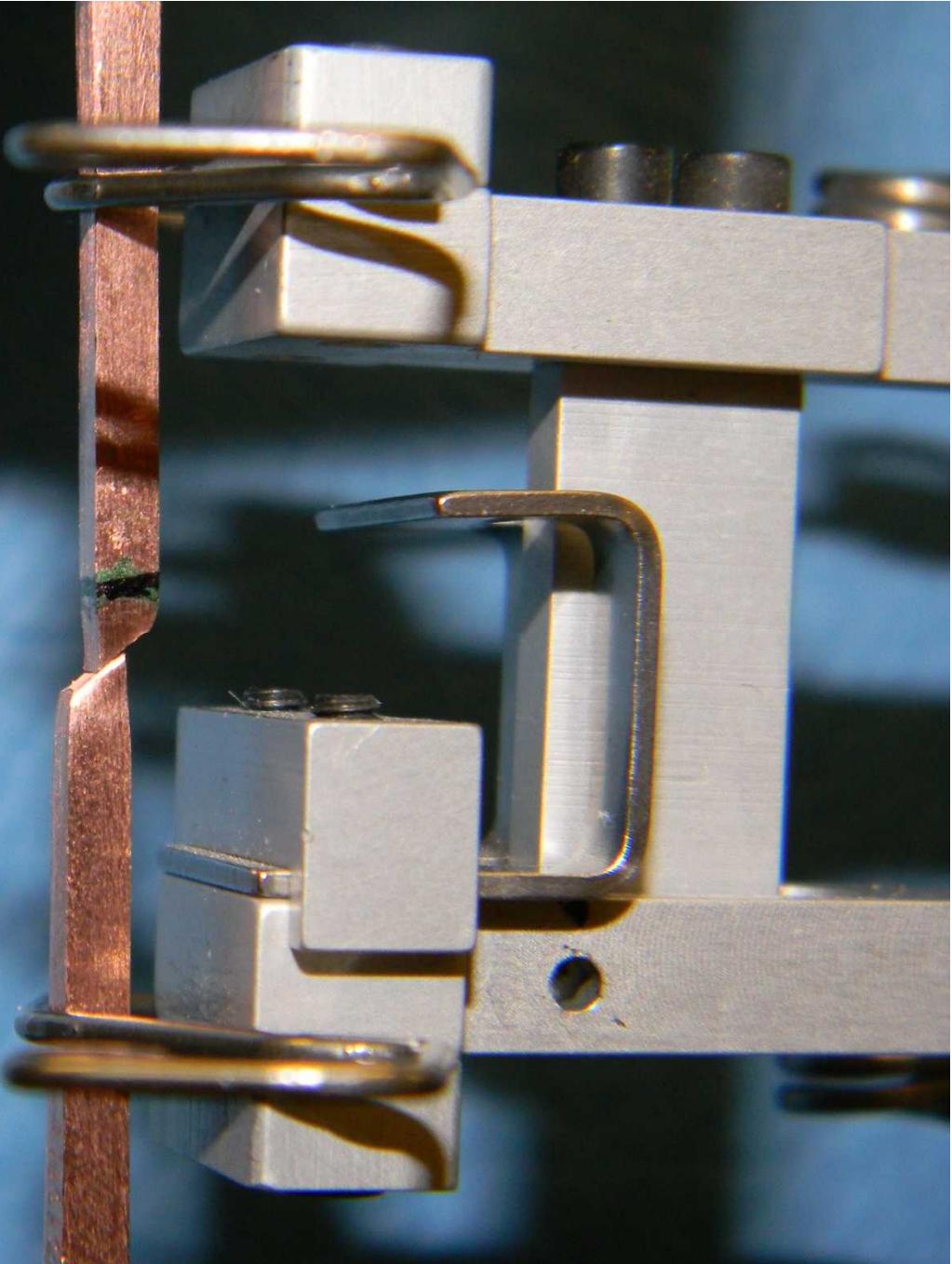
As-received cold weld joint

After hand polishing to produce a square cross-section. Note that weld location was preserved (green mark)

Cold pressure welded
junction cross-section
(Percon 28 wire)

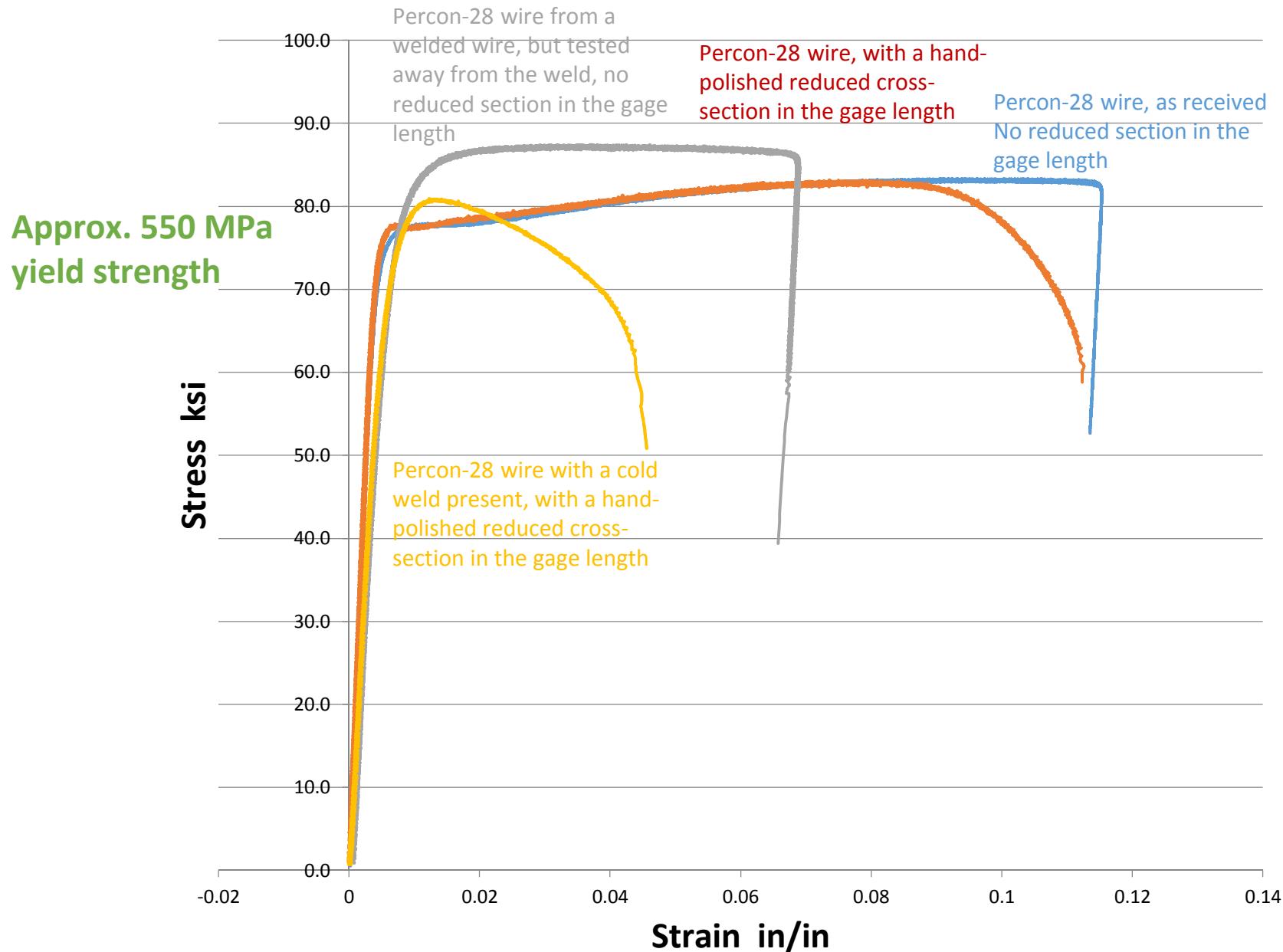


After testing, the tensile bar appeared to fail away from the welded region in a shear failure mode.



550 MPa yield strength at 1.5% strain

Stress-strain summary on first round of Percon-28 tensile tests



Contact resistance analysis

For a 12.5 mm radius belt of 2.5 sq. mm. wire:

$$R_{one \ winding} = \rho_{Percon} \frac{L}{A} \approx 0.06 \text{ m}\Omega$$

$$R_{asp. cont.} = \frac{\rho}{2a} \approx \frac{\rho_{Percon}}{2} \sqrt{\frac{\pi H}{F}}$$

Then,

$H \sim 1 \text{ GPa}$ and

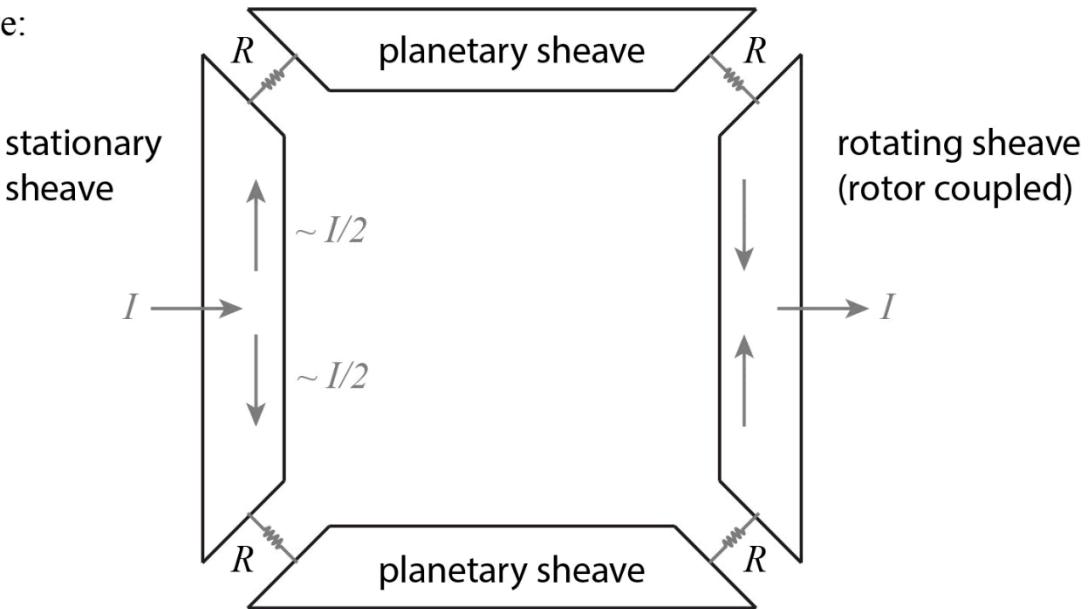
$F \sim 100 \text{ N}$ (belt tension $\sim 50 \text{ N}$):

$$R_{asp. cont.} \approx 0.05 \text{ m}\Omega$$

where F is contact force and H is the hardness of the softer sheave (work hardened, OFHC).

This corresponds to a resistance for one Twistact of,

$$R_{Twistact} \approx 0.15 \text{ m}\Omega$$

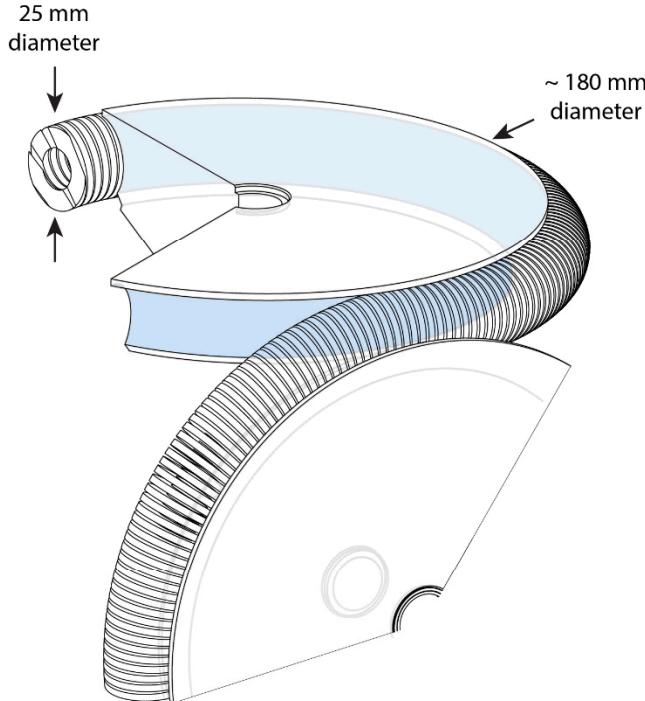


$$R_{Twistact} = \left(\frac{1}{2R} + \frac{1}{2R} \right)^{-1} = R$$

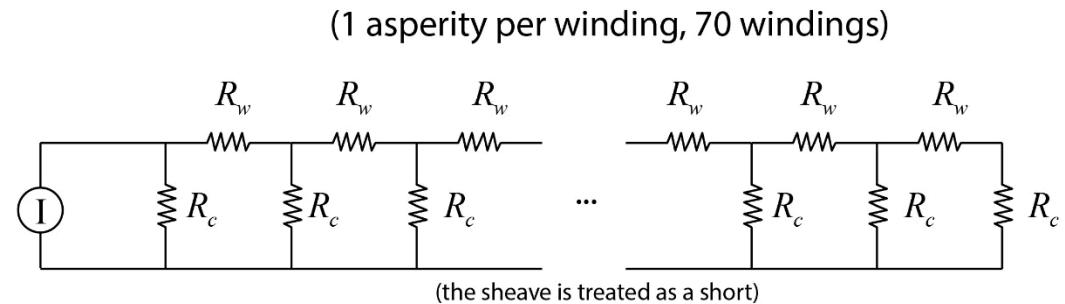
$$R = R_{one \ winding} + 2R_{asp. cont. S}$$

(negligible bulk sheave resistance)

Contact resistance analysis



the belt/sheave contact is modeled as a series of windings for which one contact point with the sheave occurs per winding, giving the following resistor network:

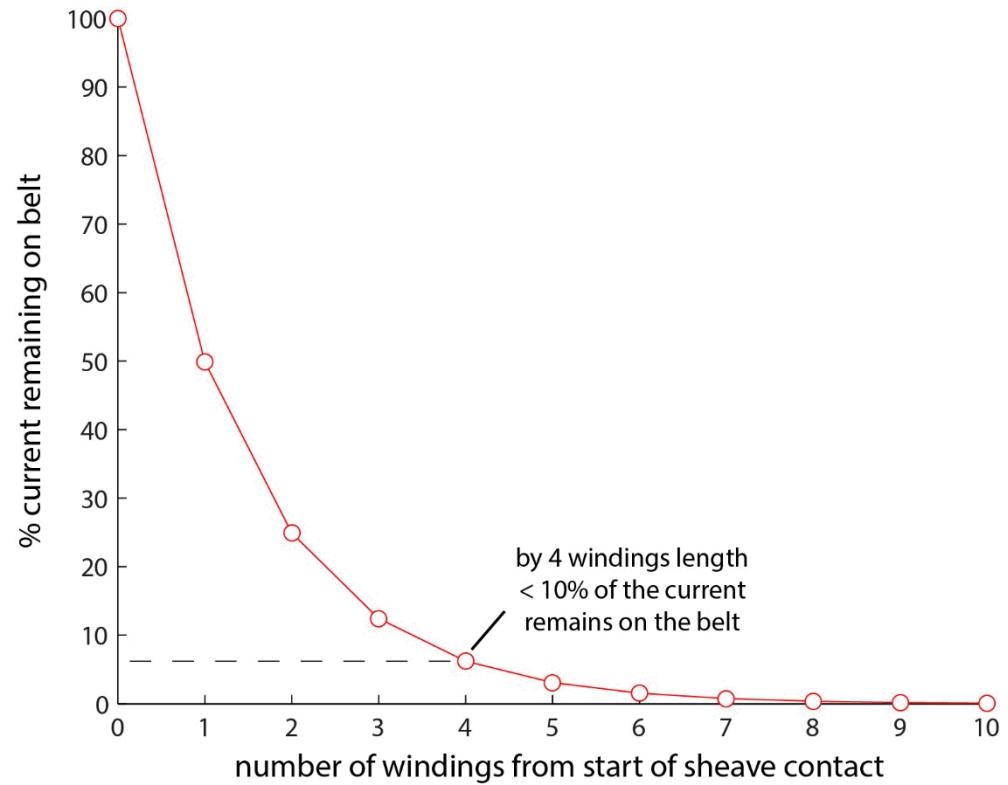
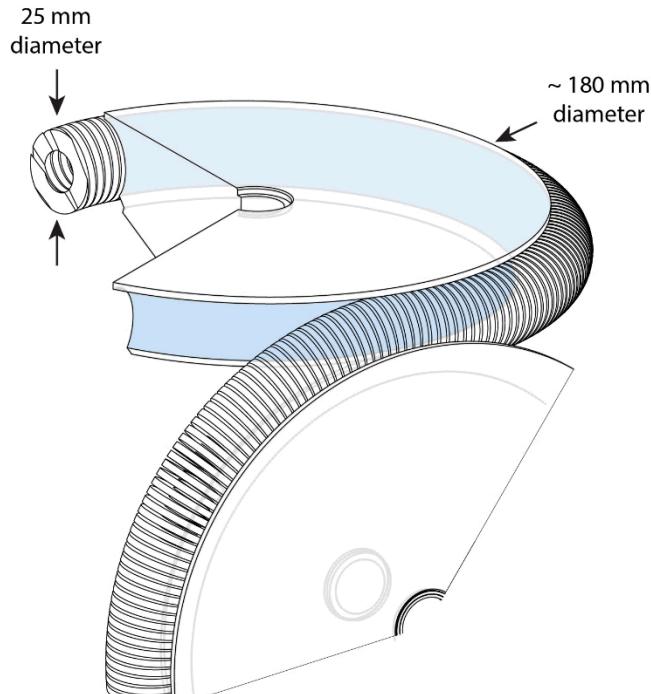


R_w is the resistance of a single length of winding $\longrightarrow R_w = \rho \frac{L}{A} \sim 0.06 \text{ m}\Omega$

R_c is the contact resistance at one asperity (1 per winding) $\longrightarrow R_c = \frac{\rho}{2a} \sim 0.57 \text{ m}\Omega$

\uparrow
calculated for a 10 lb belt tension

Contact resistance analysis



Parallel Evaluation/Development Efforts

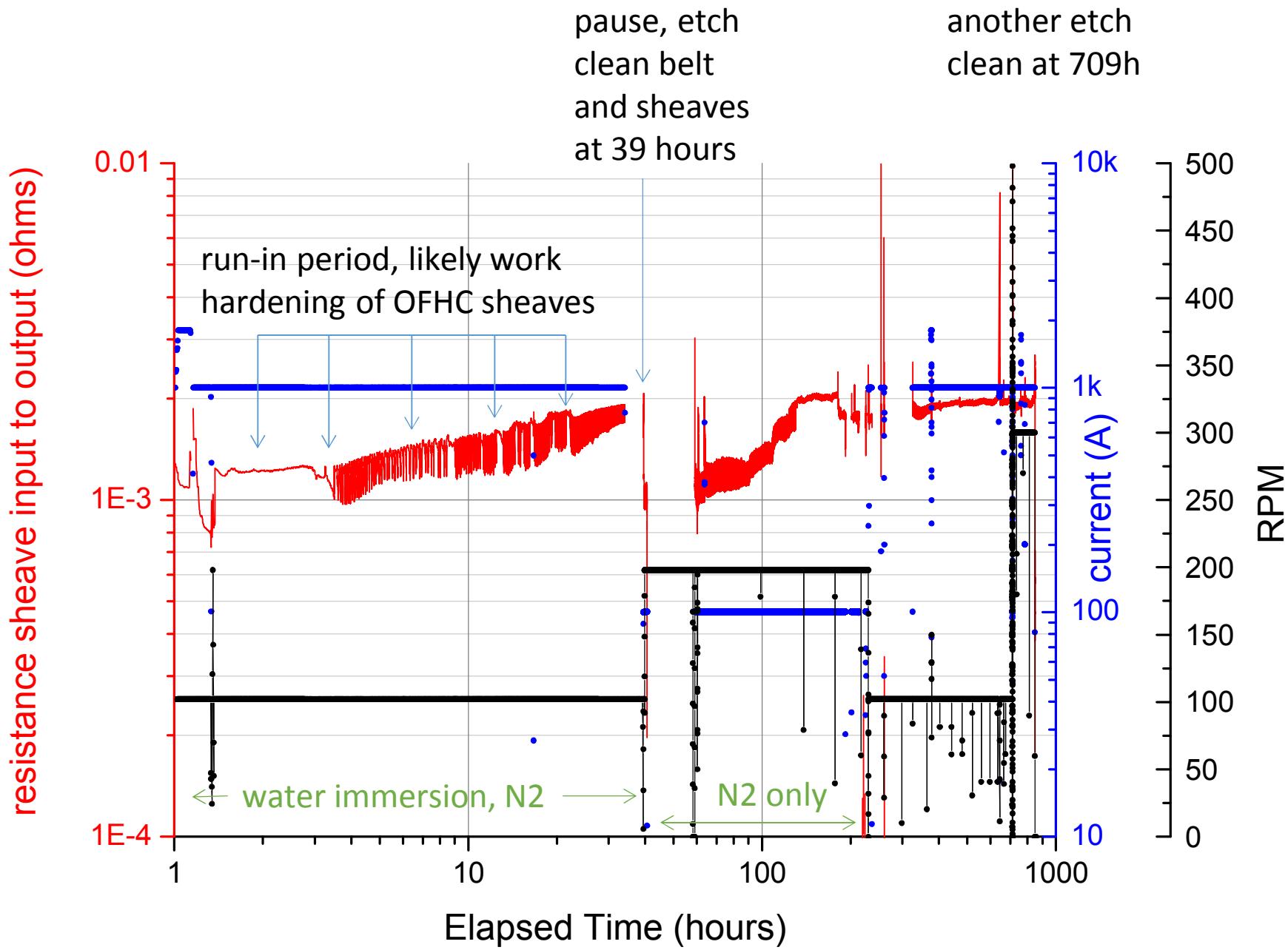
4 sheave/1 belt design --
materials aging tester
(high speed/accelerated aging)



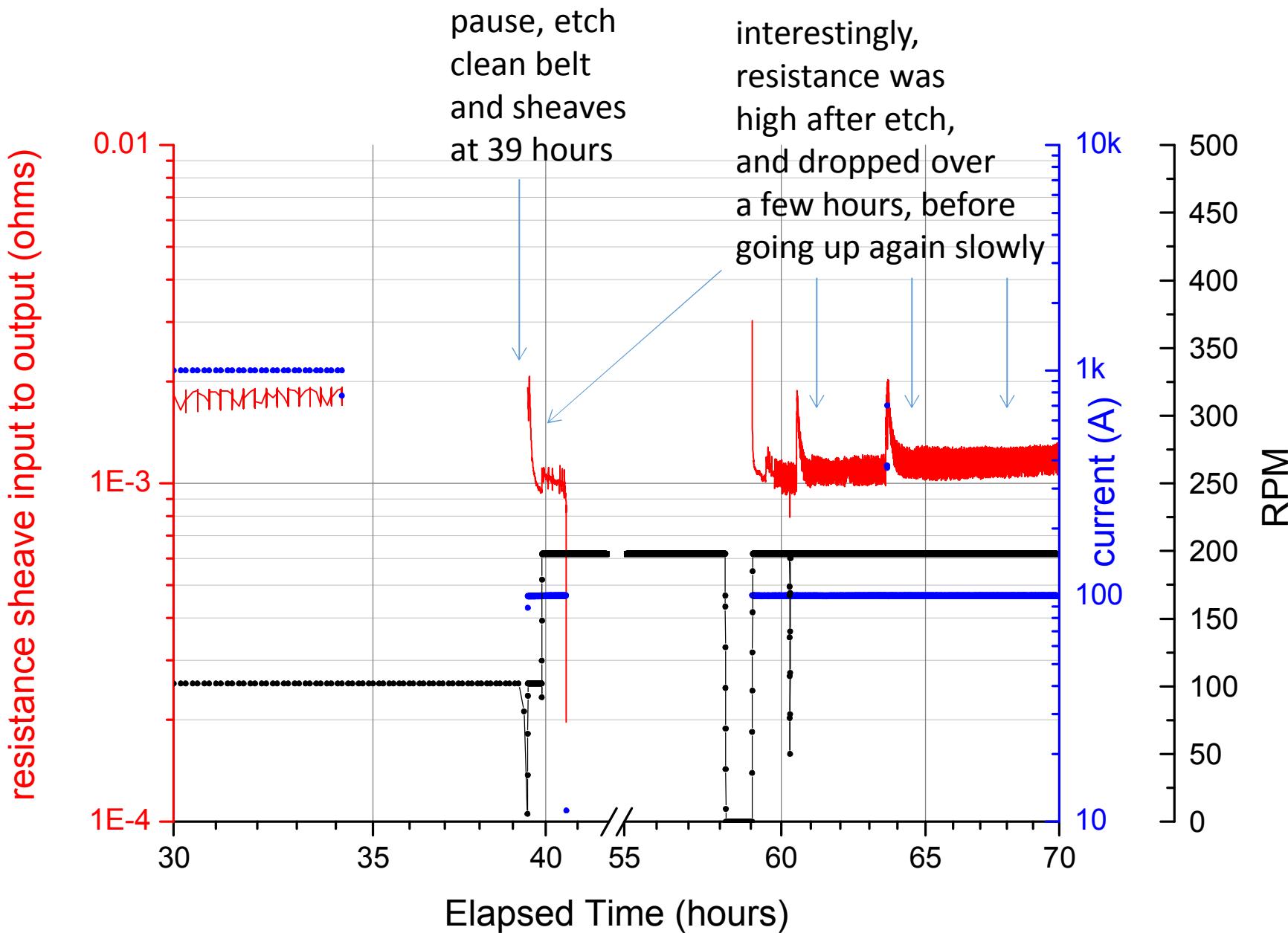
8 sheave/2-belt design --
planetary sheave design
(wind turbine architecture)



Common attributes: **1,800A DC current supplies -- 3,000 RPM capable motors --**
scalable sheave/belt geometries (including full scale/wind turbine prototype) --
environment chambers (cover gas, fluid immersion capable)



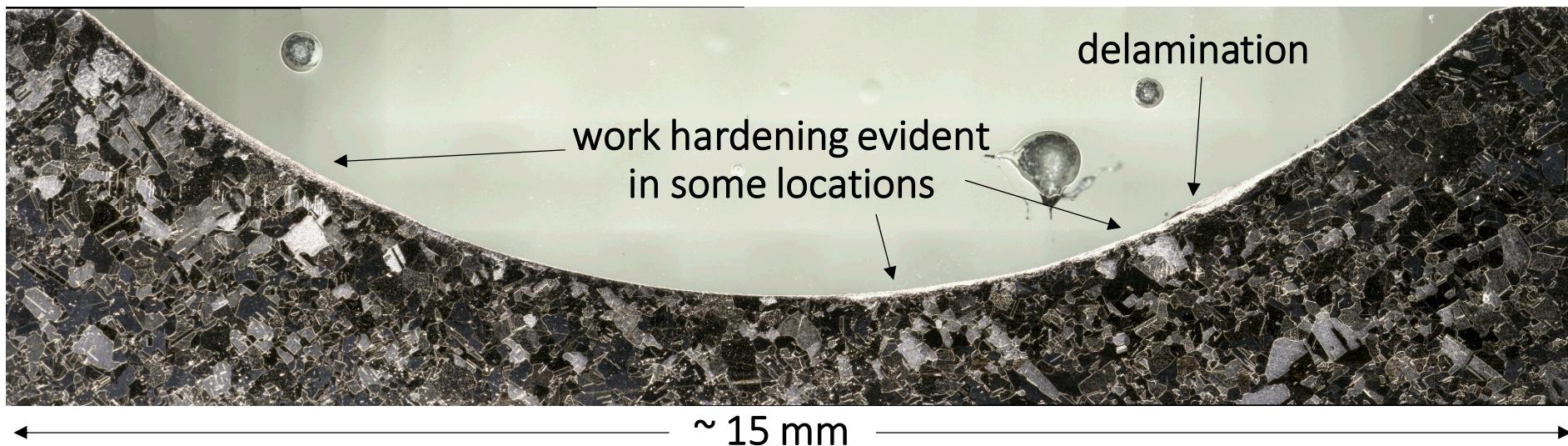
Total Belt Rotations: 7.86M



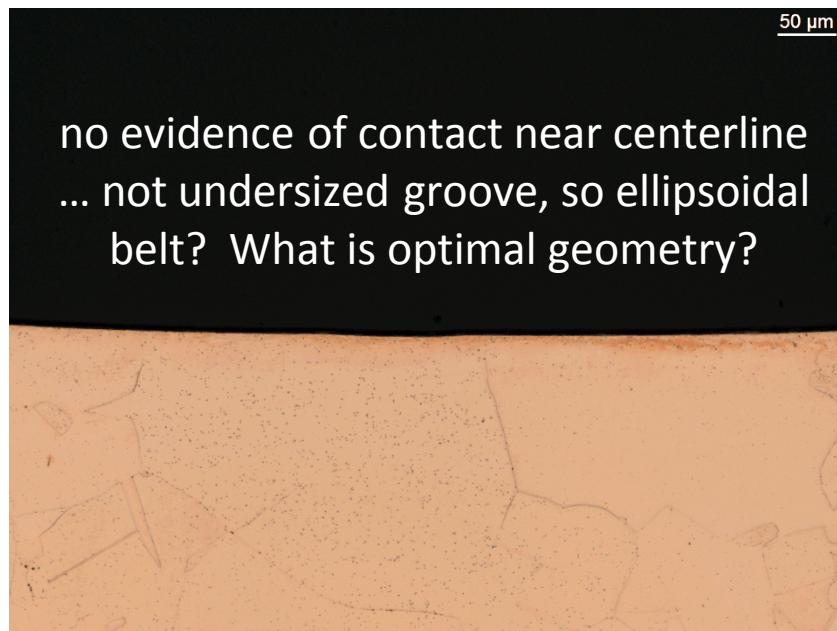
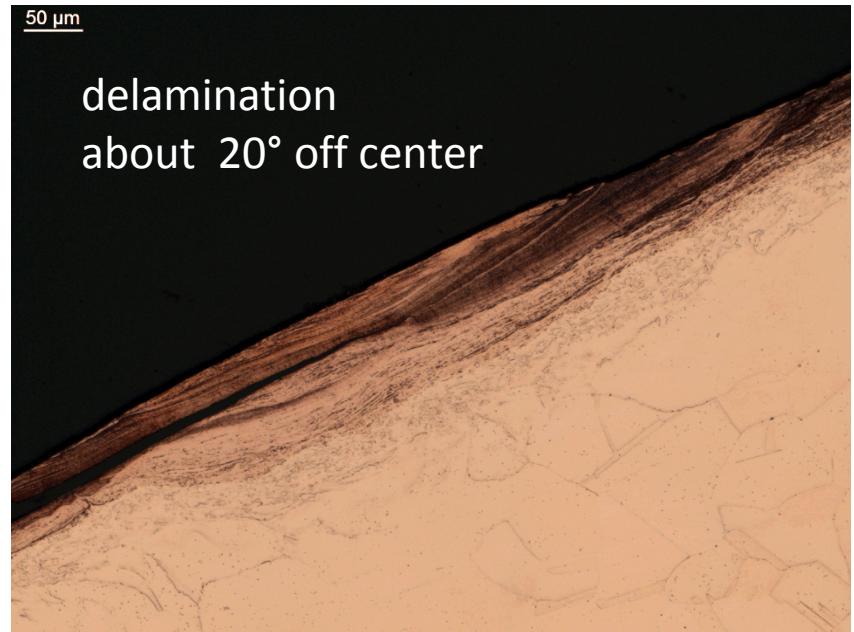


cross-section of sheave after 8M cycles

belt is undersized about 5% in radius, so the contact is nearly conformal, minimizing nominal contact stress

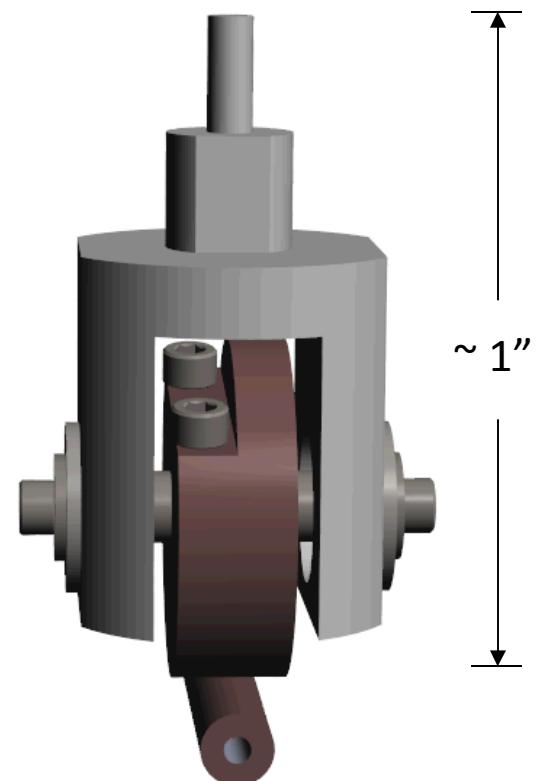


cross-section of sheave after 8M cycles



Next...

- 1) Coupon-level experiments to investigate environment effects on contact resistance
 - rolling contact over a 45° arc
 - liquid immersion cell – optimal medium?
 - propylene glycol
 - hydrofluoroether
 - water
- 2) Fabrication of full-scale geometry platform:
 - 1+ kA current, 10 rpm capable full-scale (7+” diameter sheaves) device
 - two back-to-back devices, so as to remove brushes from experiment (stationary to rotating to stationary frame)



Questions?

Most traditional generator architectures are off the table

Table 1: Pros and cons of different generator architectures in the context of multi-MW wind turbines

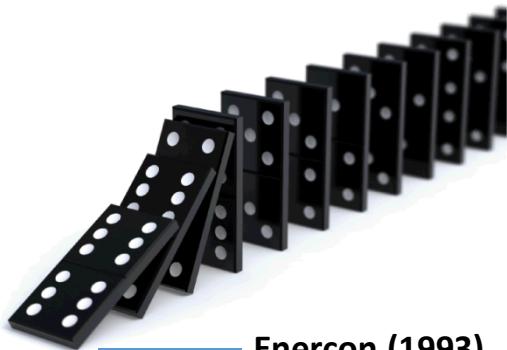
drive train	generator type	rotor architecture	advantages	disadvantages
gearbox	induction	squirrel cage	no rare earth magnets no brush/slip-ring maintenance	gear box failures <i>DFIG counterpart cheaper</i>
gearbox	induction	wire-wound	no rare earth magnets	gear box failures brush/slip-ring maintenance
gearbox	synchronous	wire-wound	no rare earth magnets	gear box failures brush/slip-ring maintenance <i>DFIG counterpart cheaper</i>
gearbox	synchronous	permanent magnet	no brush/slip-ring maintenance	gear box failures rare earth magnets (25 kg Nd /MW)
direct-drive	induction	squirrel cage	no gear box failures no rare earth magnets no brush/slip-ring maintenance	<i>poor power factor</i>
direct-drive	induction	wire-wound	no gear box failures no rare-earth magnets	<i>poor power factor</i> brush/slip-ring maintenance
direct-drive	synchronous	wire-wound	no gear box failures no rare earth magnets	brush/slip-ring maintenance
direct-drive	synchronous	permanent magnet	no gear box failures no brush/slip-ring maintenance	rare-earth magnets (250 kg Nd /MW)
direct-drive	synchronous	wire-wound+Twistact	no gear box failures no rare earth magnets no brush/slip-ring maintenance	

DFIG: doubly-fed induction generator; Nd: Neodymium

Direct drive requires some form of high-pole-count synchronous generator

The movement towards direct drive (the 1st technology down select)

- Both the “scalability” and “autonomy” requirements have driven the movement towards direct drive



Enercon (1993)

ENERGY *MIT Technology Review*

Wind Turbines Shed Their Gears

Both Siemens and GE bet on direct-drive generators.

TUESDAY, APRIL 27, 2010 | BY PETER FAIRLEY

« Audio »

Wind turbine manufacturers are turning away from the industry-standard gearboxes and generators in a bid to boost the reliability and reduce the cost of wind power.

Siemens has begun selling a three-megawatt turbine using a so-called direct-drive system that replaces the conventional high-speed generator with a low-speed generator that eliminates the need for a gearbox. And last month, General Electric announced an investment of 340

Power ring: This three-megawatt wind turbine uses permanent magnets and a design that makes it significantly lighter than a conventional geared turbine.

Overview of and Trends in Wind Turbine Generator Systems

Henk Polinder, Member, IEEE

system (illustrated in Fig. 3) is also known as the Danish concept.

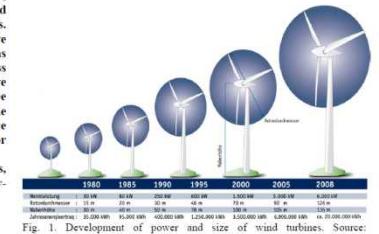


Fig. 1: Development of power and size of wind turbines. Source: Bundesverband WindEnergie e.V.

Early adopters

The importance of eliminating the gear box amounts to common sense.

It's likely that gear box performance limitations will prove limiting to scalability and reliability.

Why not exhaustively explore options for direct drive?

Later converts

Direct drive technology has been proving itself in the field.

If direct drive succeeds, how we will be positioned among our competitors?

Both the real and perceived problems of gear boxes may amount to a competitive liability.

Hold outs

Gear box technology has yet to fully mature.

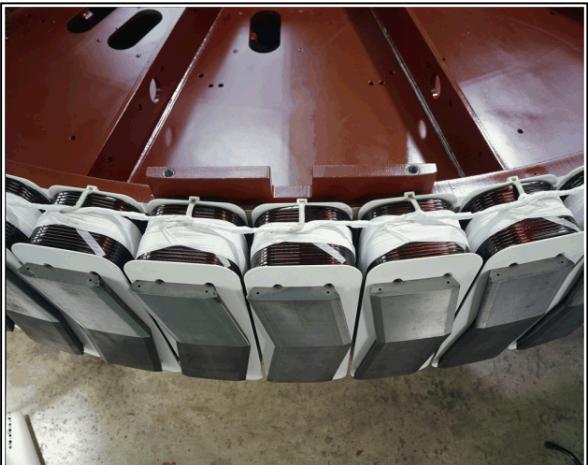
We are already heavily invested in gear box technology.

Direct drive introduces some of its own engineering challenges (e.g. mechanical rigidity).

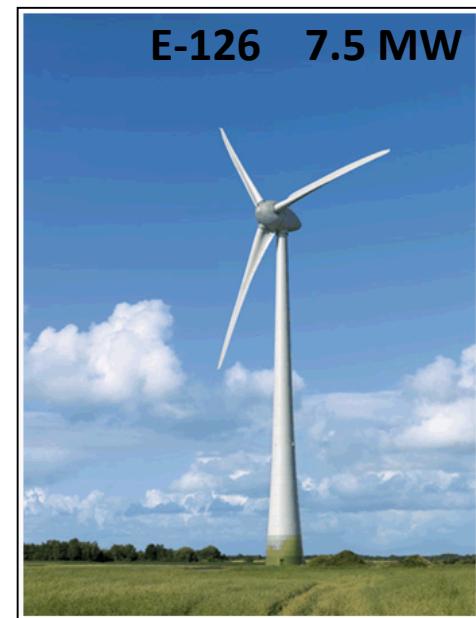
Interestingly, with regard to the rare earth crisis Enercon is once again the exception

- Since its inception in 1993, Enercon's direct-drive annular generator has been designed around use of wire-wound rotors

	E33
	E44
	E48
	E53
	E70
	E82
	E82
	E82
	E101
	E126



Enercon's wire-wound-rotor direct-drive generator has no gear box and requires no rare earth magnets but offshore deployment is hindered by the limited service lifetime of rotary electrical contacts.

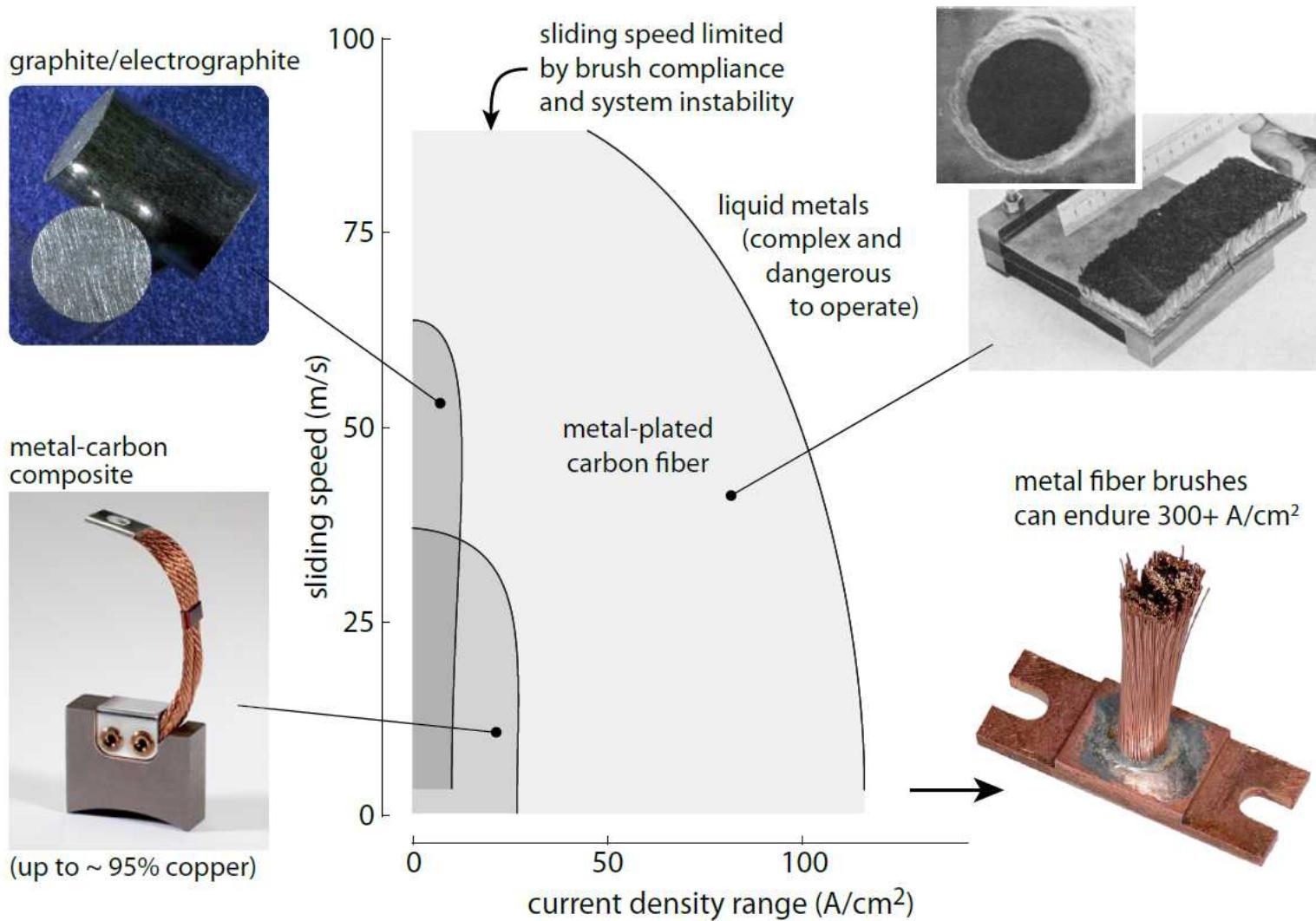


Observations about the technology path chosen by Enercon

- Decided very early that gear boxes and permanent magnets were off the table.
- Gradually scaled up and improved their original direct-drive/wire-wound rotor concept.
- Aggressive pursuit of power scaling.
- Enercon is proof positive that the direct-drive/wire-wound-rotor concept is feasible.
- Enercon has defied repeated speculation about weight and mechanical tolerance challenges.
- Reliability and service-lifetime limitations of slip-ring technology is viewed as key weakness.
- Enercon has not penetrated the offshore deployment market.

Given what Enercon has demonstrated, and given the rare earth magnet problem, what would be the impact on the industry if someone invented a rotary electrical contact technology with ideal properties?

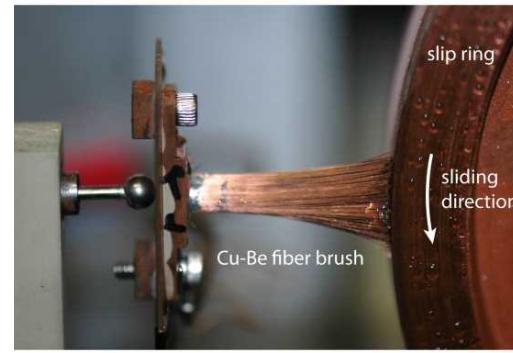
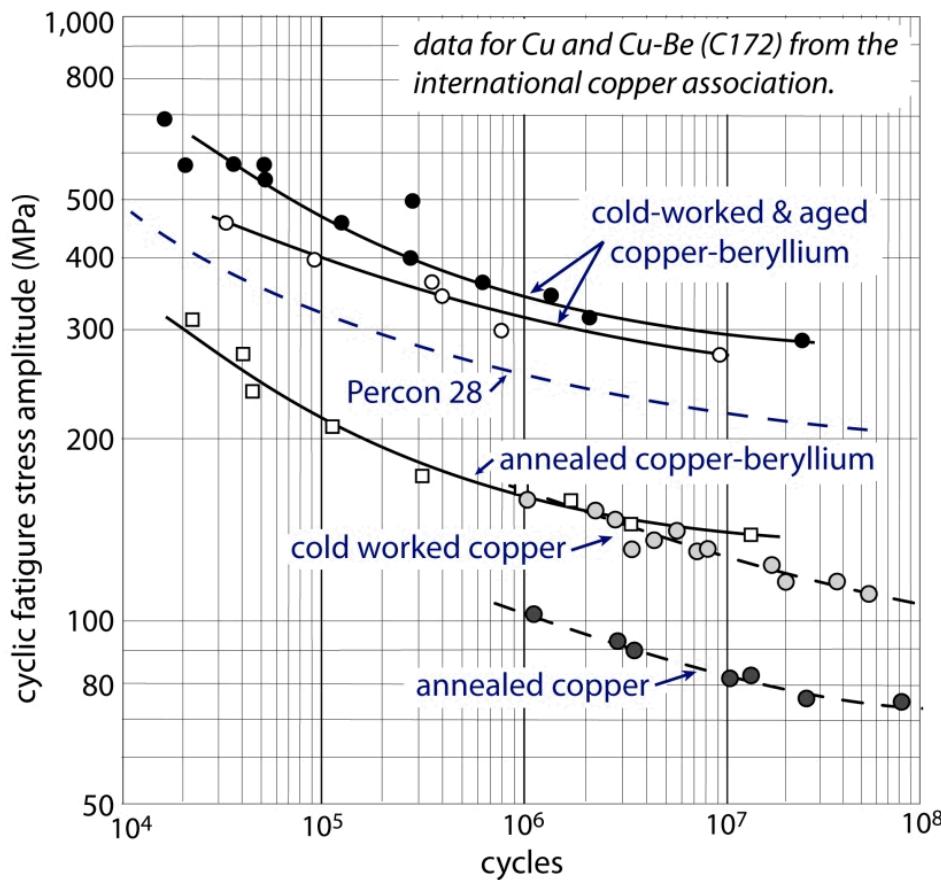
Unlike brushes, heating is distributed and thermal energy convected, and electrical conduction almost entirely transverse, so current densities of $1000+$ A/cm^2 become practical



graph adapted from: Kendall, McNab, and Wilkin, *Physics in Technology* 6 (1975)

Materials Selection: high fatigue strength and hardness are critical for longevity (both for low wear and bending fatigue life of the belt)

fatigue strength:



...hard belt/soft sheaves

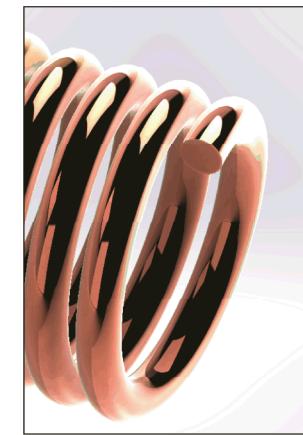
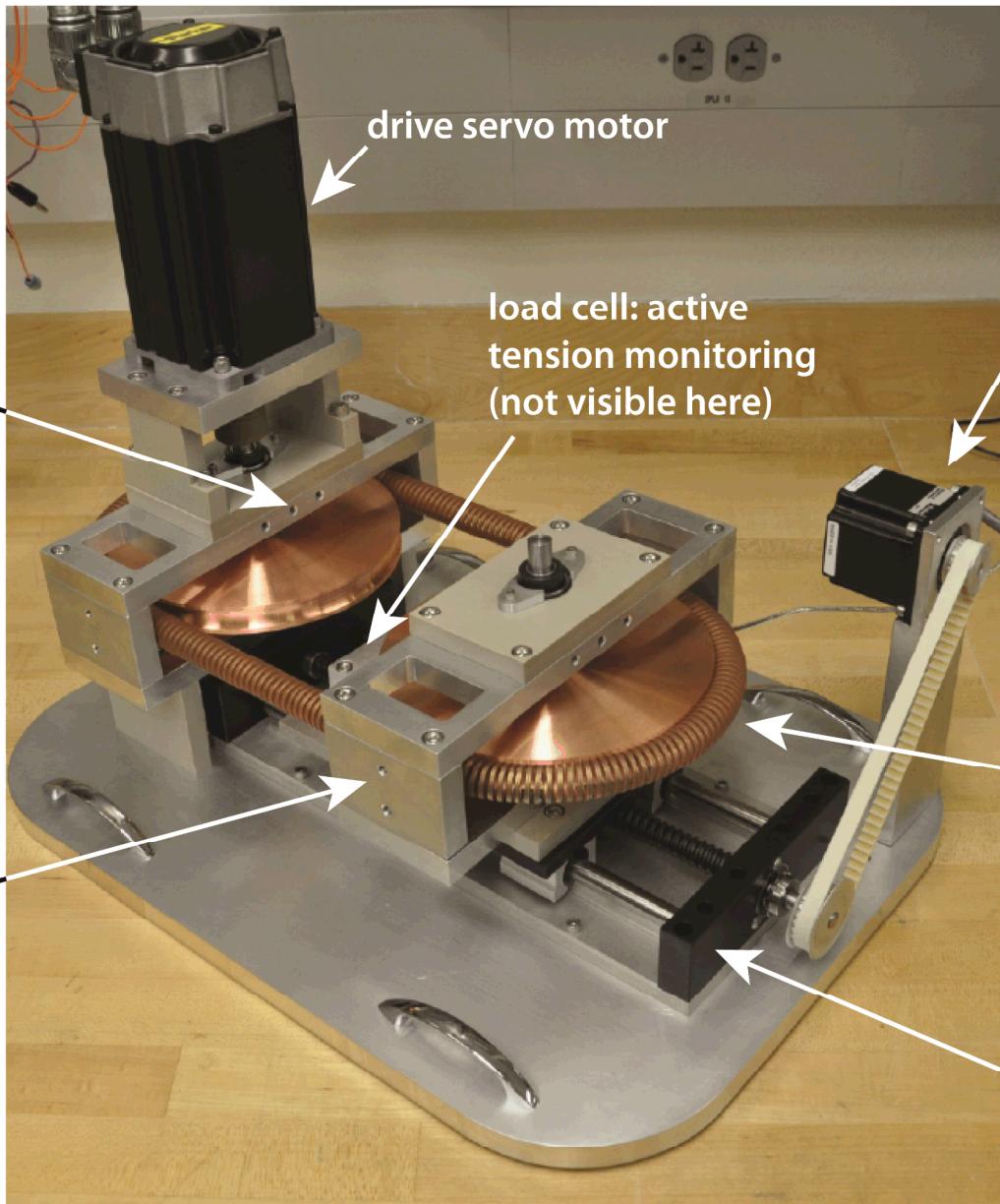
Lesson from high current density fiber brush sliding contacts: 10x wear reduction with material switch from Cu to Cu-Be running against OFHC copper slip rings

Percon 28
Electrical conductivity: 85% IACS
Tensile strength: 85 ksi (550 MPa)
Very high softening temperature

current delivery
via array of brushes

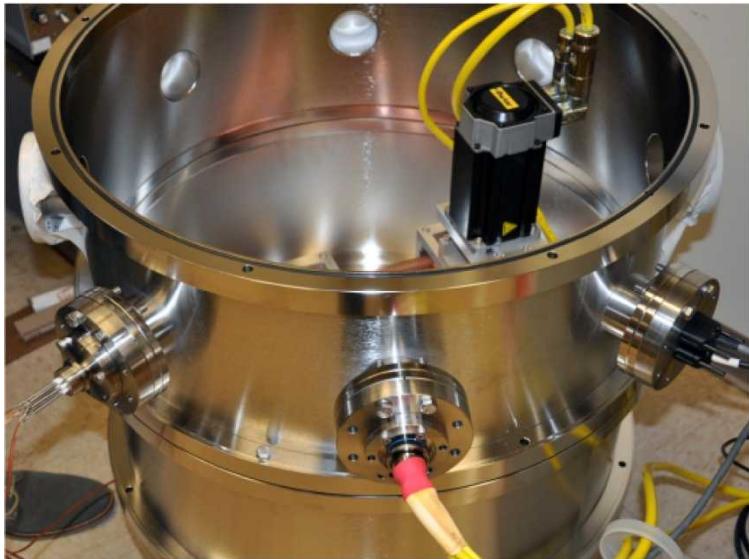


copper braids provide
current delivery to
moving carriage



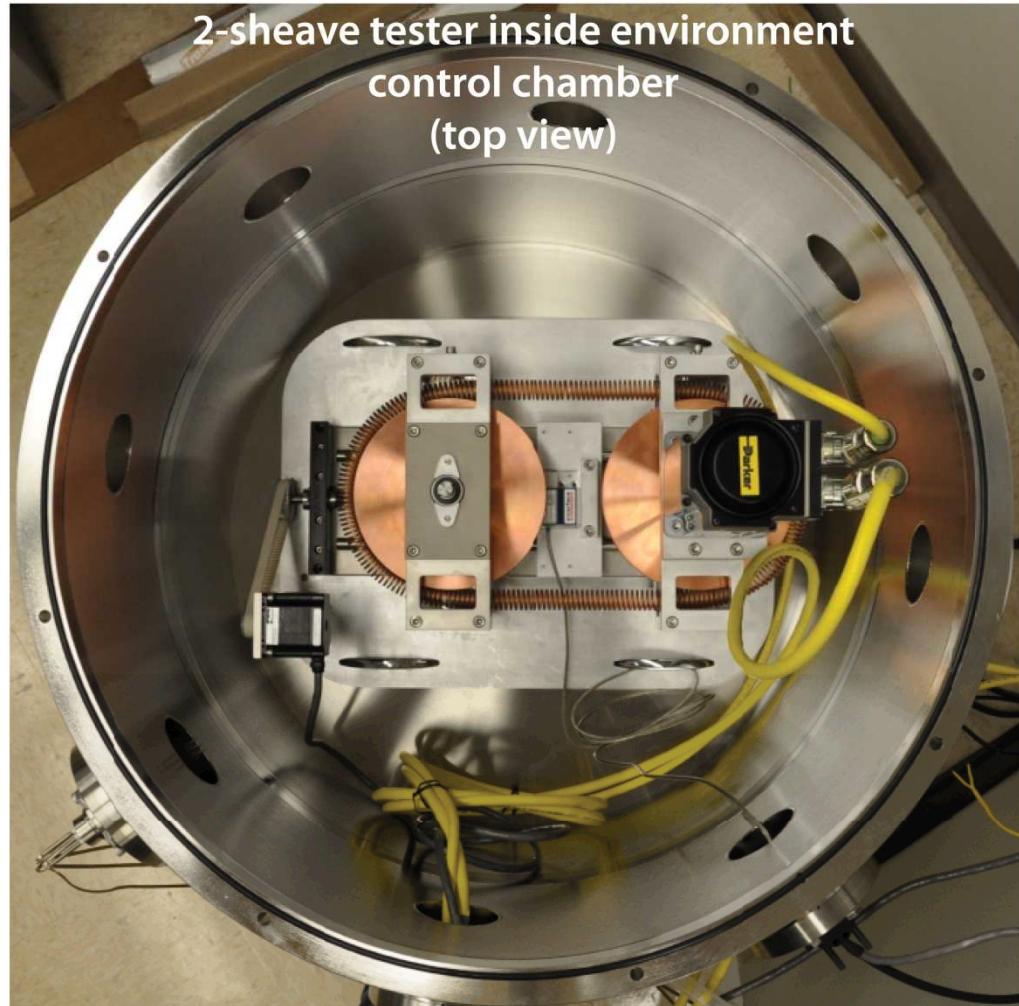
*device fits entirely in an environment chamber;
belt tension and RPM variable and continuously measured
autonomously, no breaking environment

... so we implemented environmental chambers
(cover gas control AND liquid immersion possible)

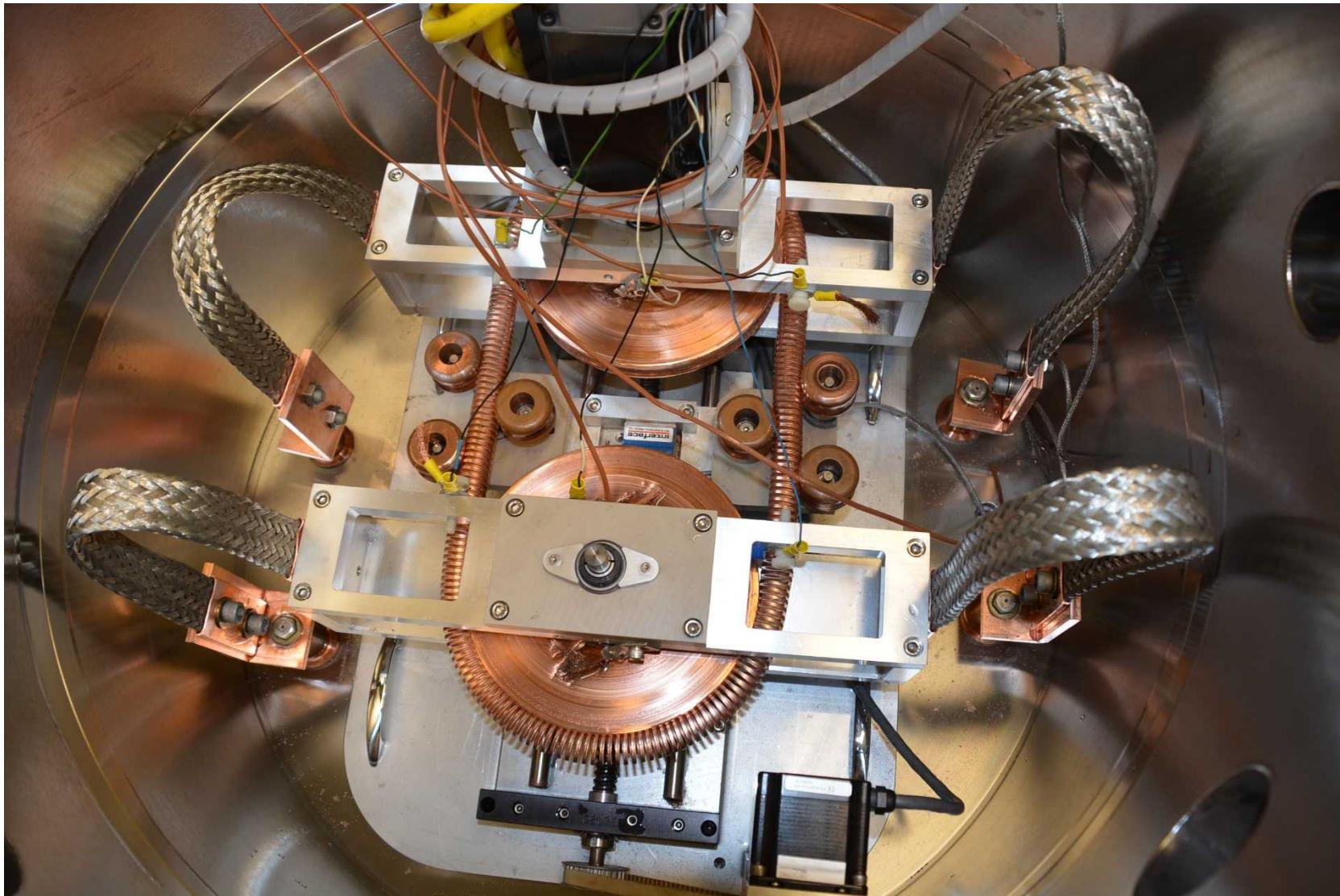


8x instrumented ports:

- 3x thermocouples
- 6x voltage taps
- motor(s) control/feedback
- force transducer
- 1,000A rated feedthroughs
- liquid and gas input/output

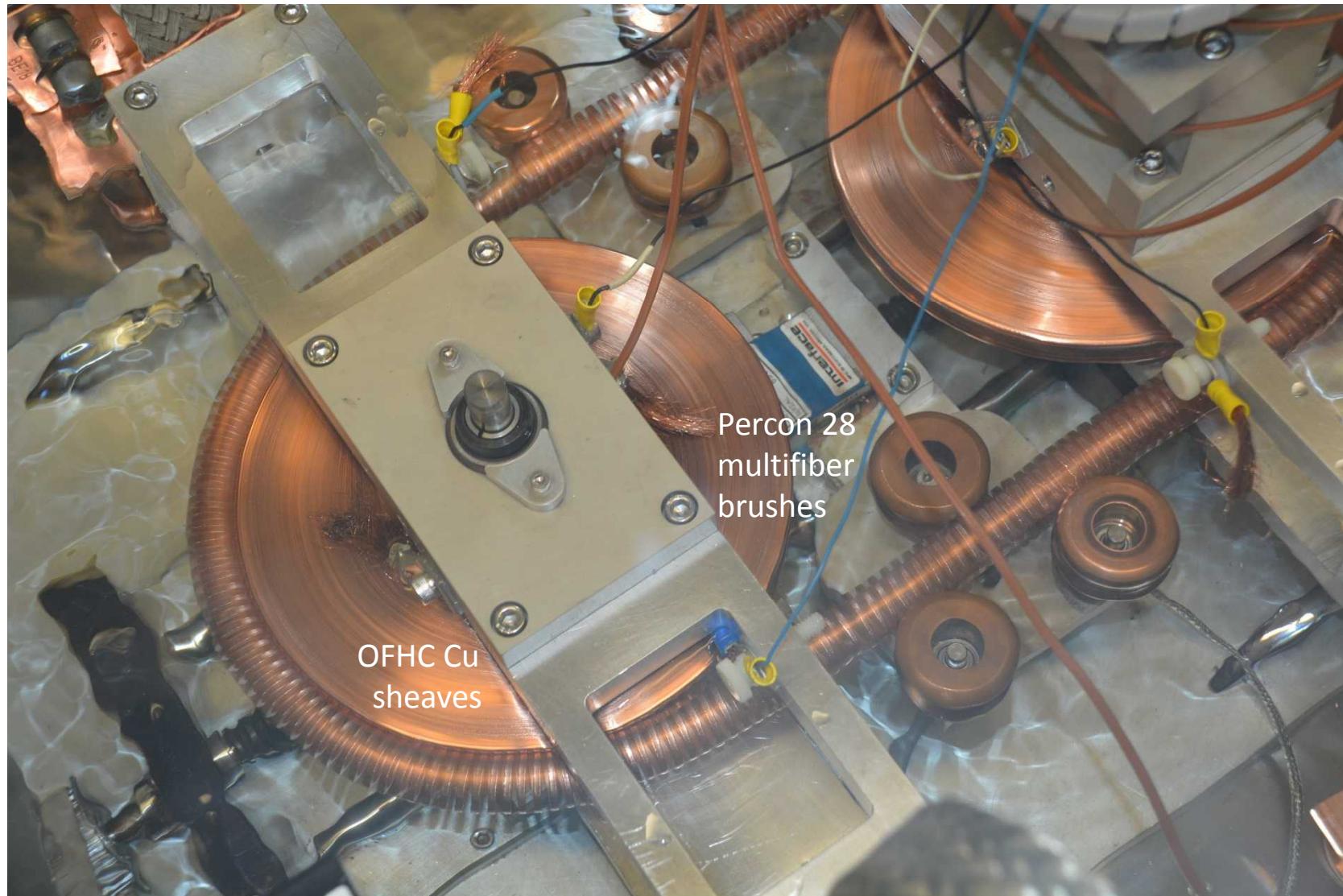


After an water/N2 gas environment (immersion) experiment



Steady-state operation at 200 RPM, 550 A, 10 lb belt tension

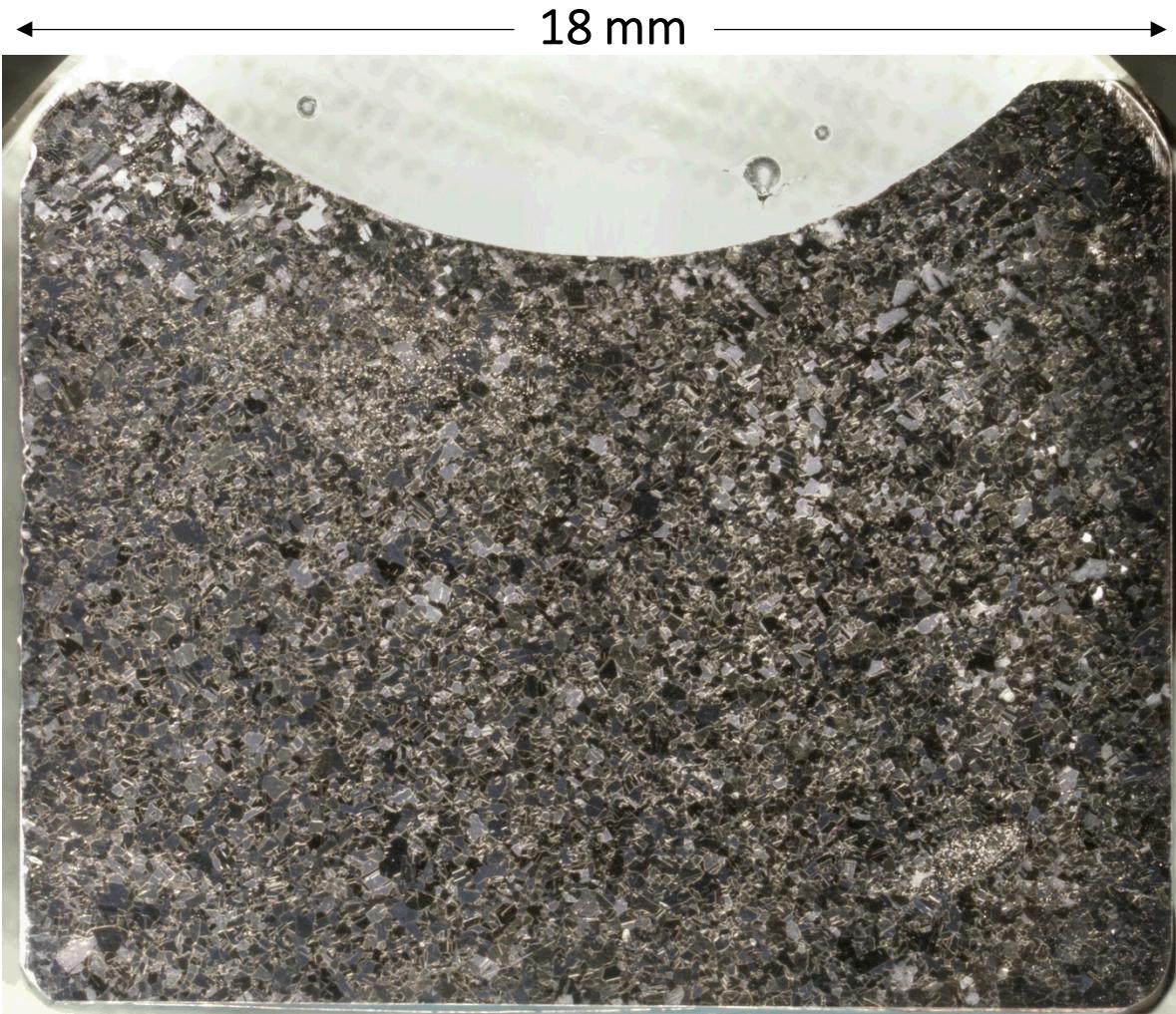
N_2 cover/water immersion, resistance from sheave to belt $\sim 1 - 2$ milliohms



this belt has 23M+ cycles at 10 lb tension, and running...

cross-section of sheave after 8M cycles

Worn-in OFHC CU sheave was sectioned, potted, polished, and acid etched to enhance grain contrast

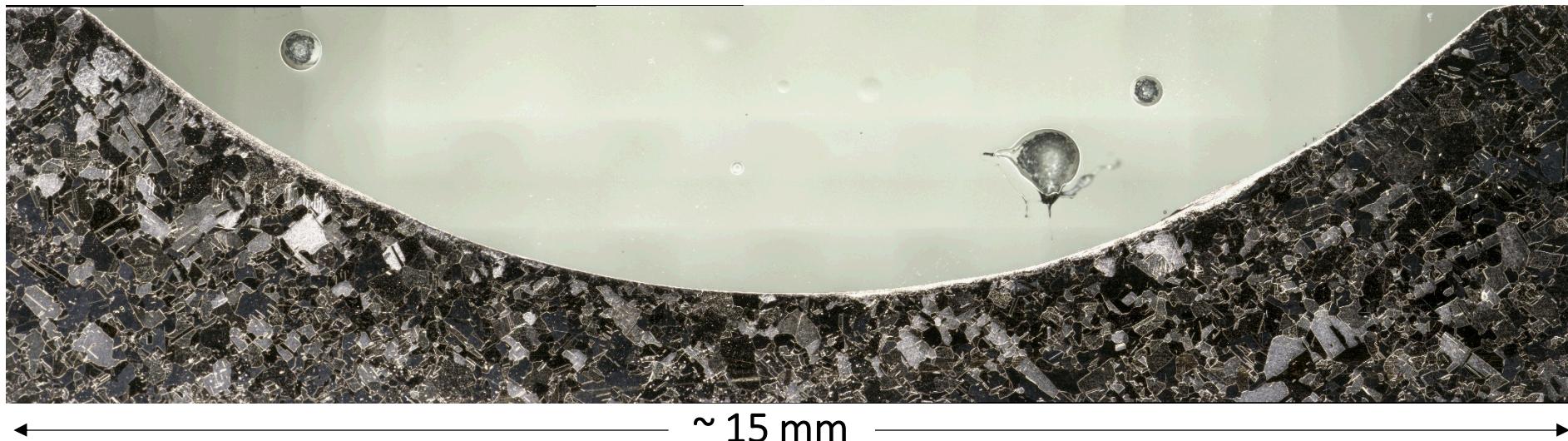


very coarse grained in bulk



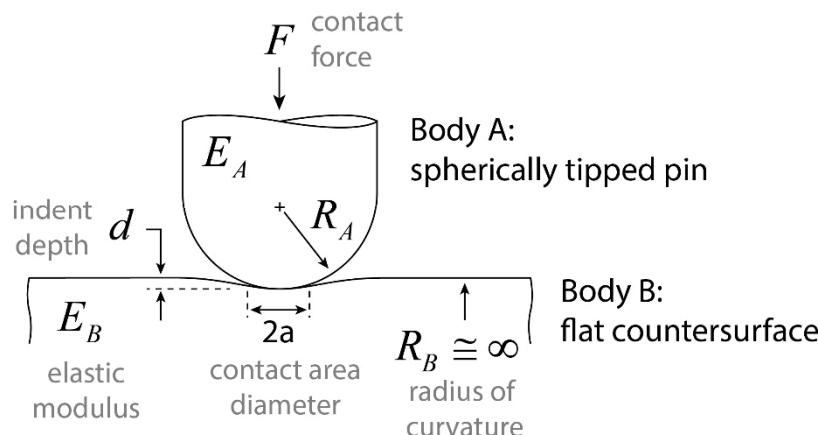
cross-section of sheave after 8M cycles

groove oversized about 5% in radius, so the contact is nearly conformal, minimizing nominal contact stress, but should occur at the centerline



How to apply Hertzian analysis as a design tool

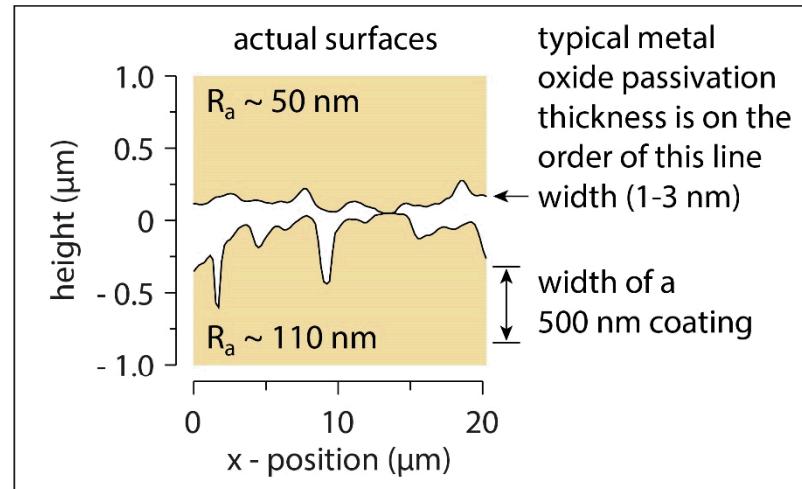
Neglecting surface roughness, the elastic half-space contact analysis is a useful predictor of long-range stress and displacement fields:



combined modulus: $E' = \left[\frac{1-v_A^2}{E_A} + \frac{1-v_B^2}{E_B} \right]^{-1}$

combined radius: $R' = \left[\frac{1}{R_A} + \frac{1}{R_B} \right]^{-1} \rightarrow R' \cong R_A$

penetration depth: $d = \left(\frac{3F}{4E' \sqrt{R'}} \right)^{2/3}$



contact diameter (fully elastic): $2a_e = \sqrt{4R'd}$

contact diameter (fully plastic): $2a_p \cong \sqrt{\frac{4F}{\pi H}}$

- both penetration depth and elastic contact area are NOT a function of HARDNESS

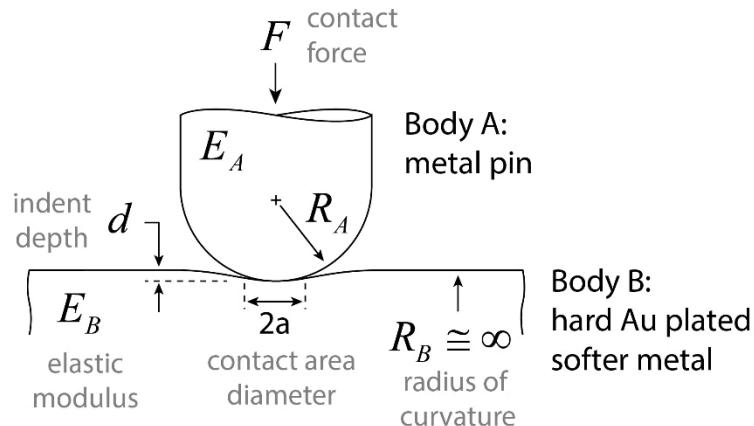
- they are a function of ELASTIC MODULUS, which is higher for most other pure metals of interest (e.g. for copper $E \sim 115$ GPa, for nickel $E \sim 200$ GPa)

For a hard Au plated contact:

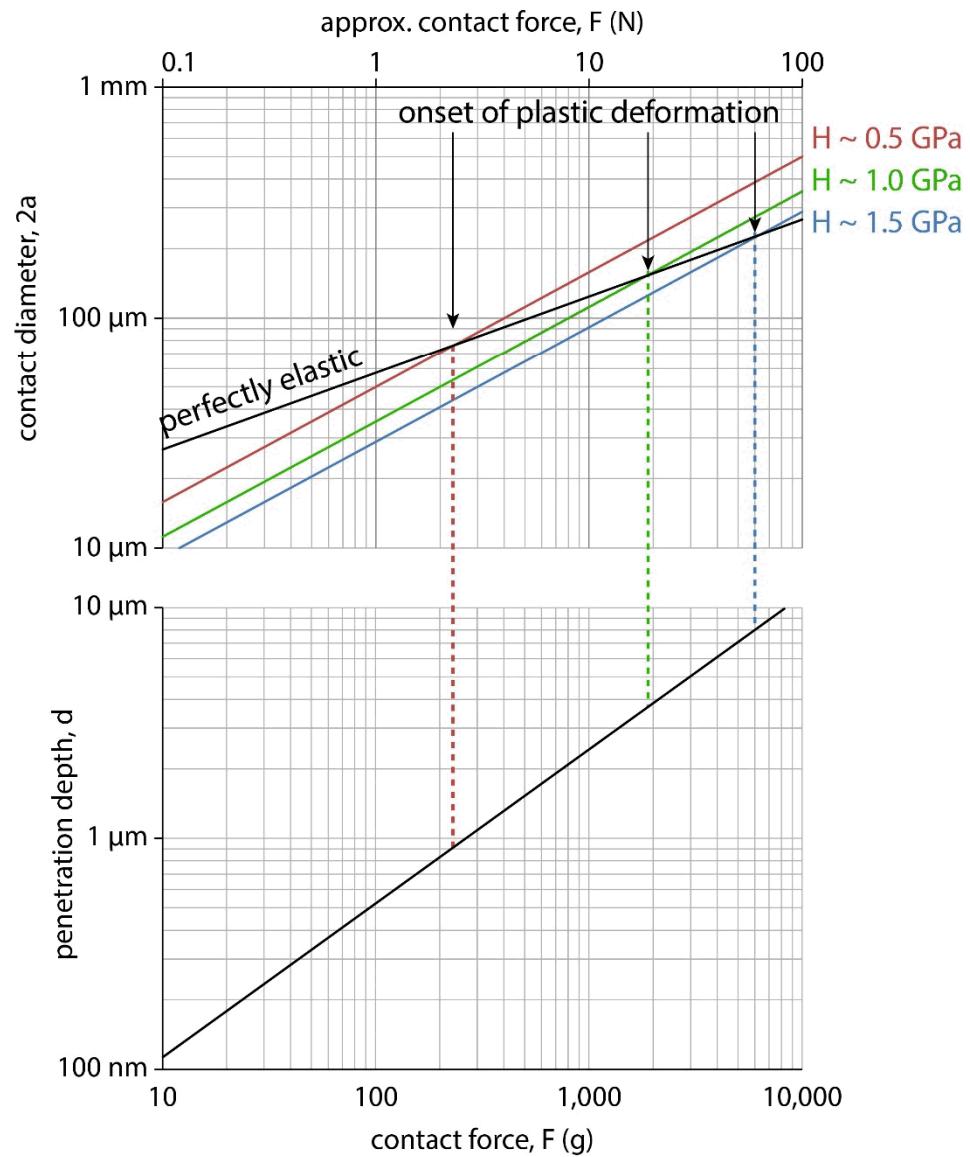
in contact with a softer (e.g. pure, coarse grain metal pin)

where, pin tip radius : $R_A = 1/16'' (\sim 1.58\text{ mm})$

elastic moduli : $E_A = E_B = E_{Au} = 79\text{ GPa}$



FOR A PERFECTLY SMOOTH CONTACT :



- note that the pin may fully yield well before the hard Au coated substrate
- most importantly: this analysis does not describe contact at the asperity level! For this we need to account for roughness...

Index of Plasticity:

ref: Greenwood and Williamson, Proc. Royal Soc., 295-1442 (1966)

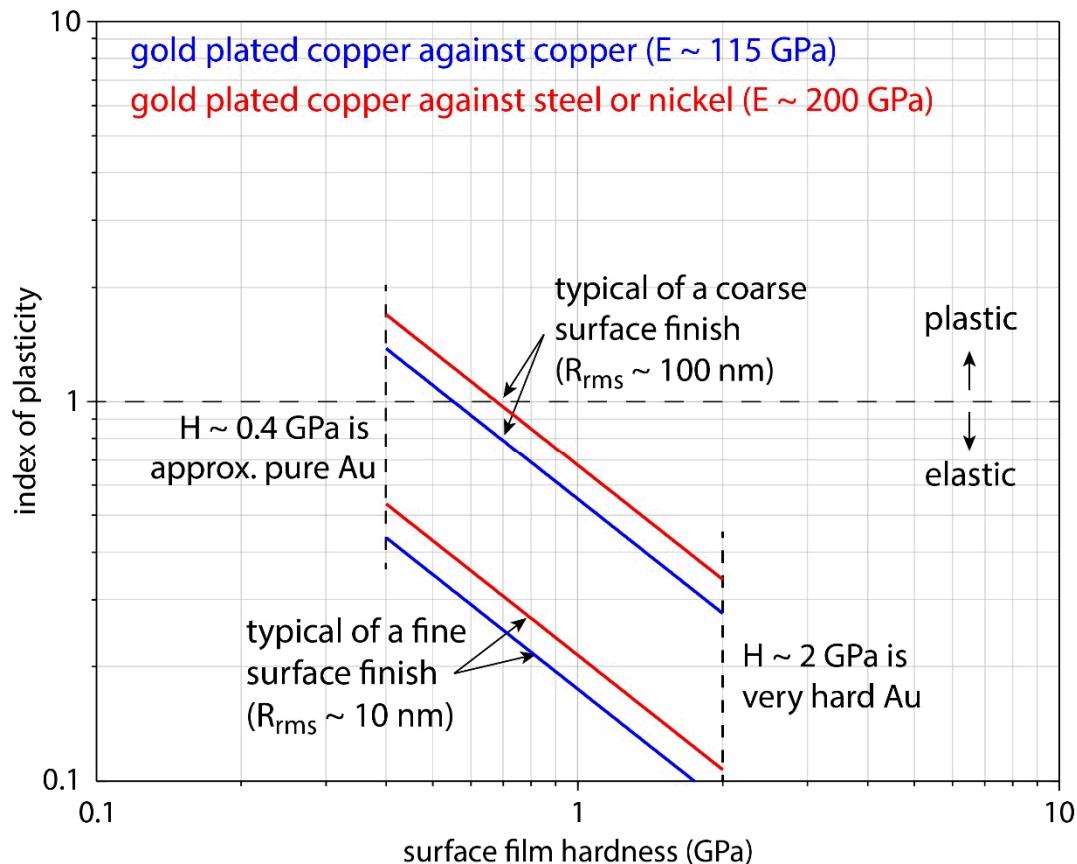
$$\Psi = \frac{E'}{H} \sqrt{\frac{R_{rms}}{r}}$$

r is the average radius of curvature of an *asperity* (typically ~ 1 mm)

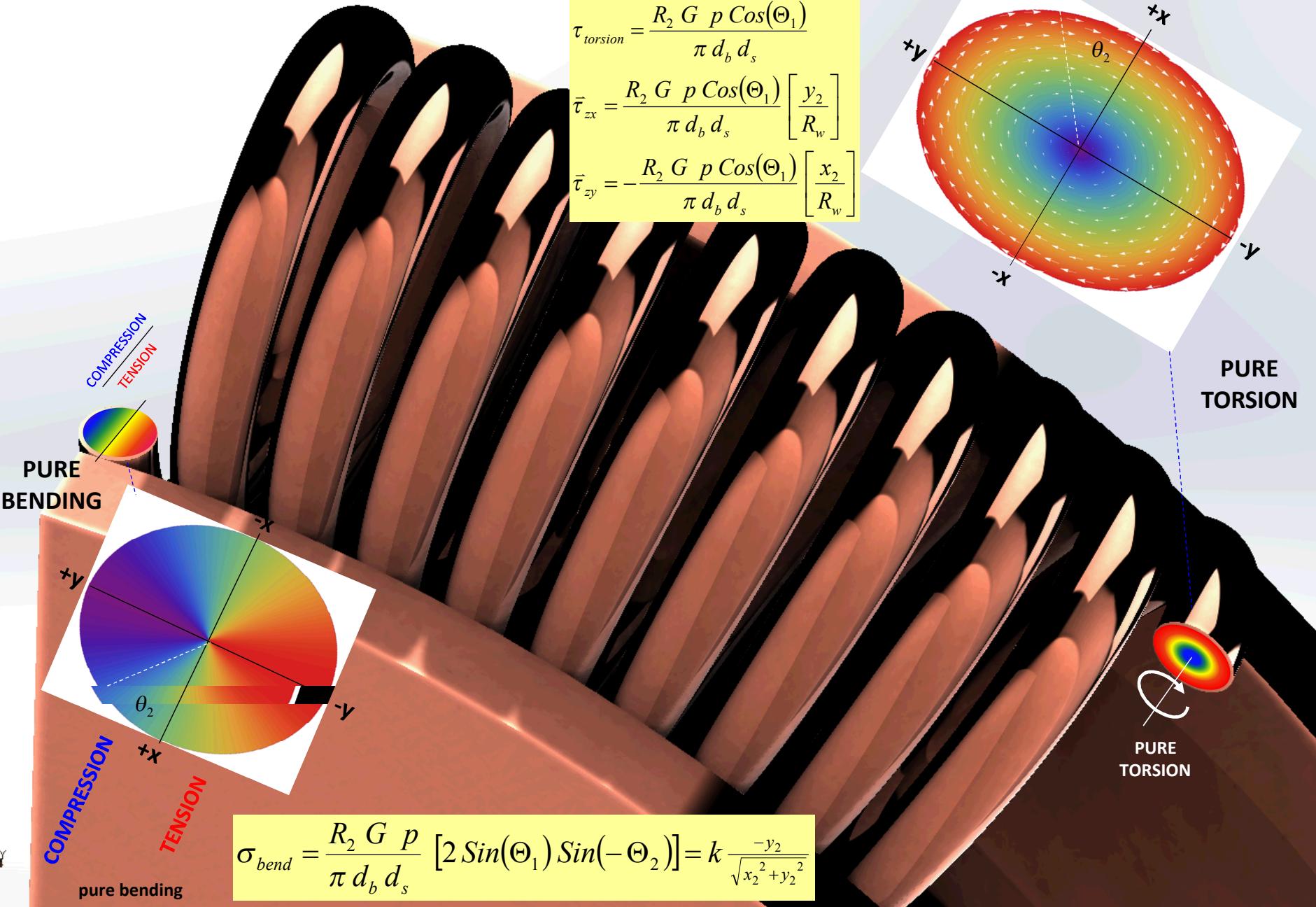
R_{rms} is the root-mean-square surface roughness (of the surface of interest)

H hardness of the surface of interest

E' combined elastic modulus

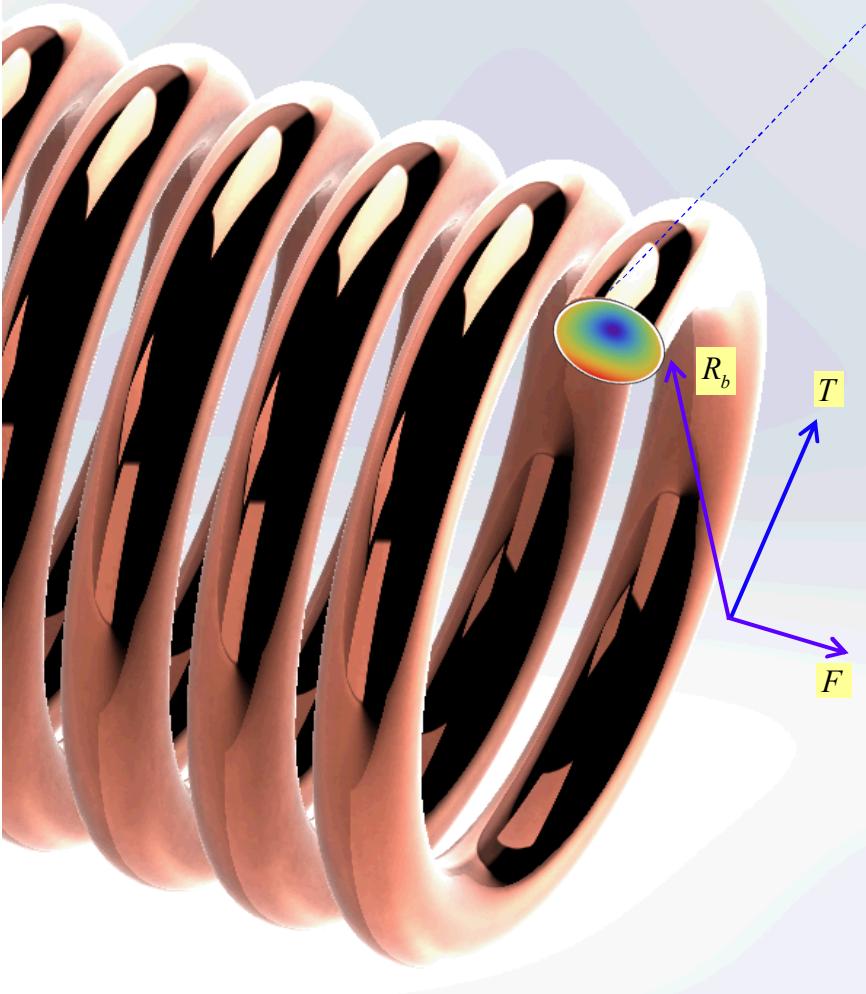


Stress fields induced by bending of spring belt:



Stress fields induced by stretching of spring belt:

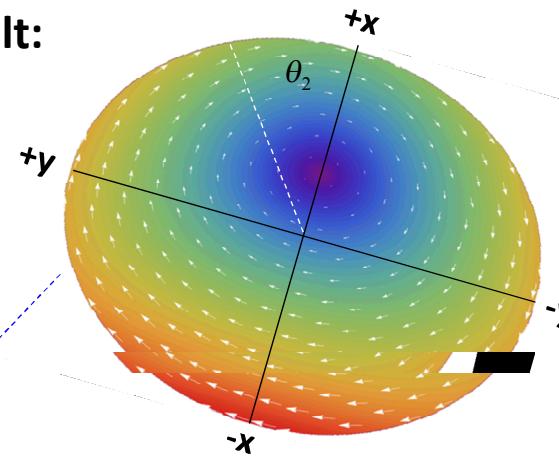
F: tension force acting on stretched spring
 T: torsional moment acting on spring wire
 J: polar moment of inertia of spring wire
 A: cross sectional area of spring wire
 x_2 : cartesian coordinate inside spring wire
 y_2 : cartesian coordinate inside spring wire
 R_2 : radial coordinate inside spring wire
 R_w : radius of spring wire
 R_b : pitch radius spring belt coil



$$T = F R_b$$

$$J = \frac{\pi R_w^4}{2}$$

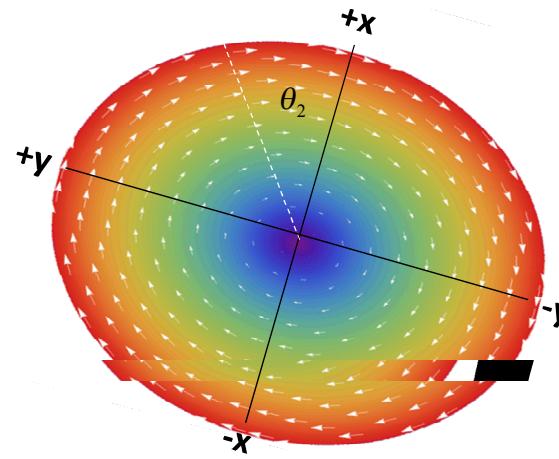
$$A = \pi R_w^2$$



combined stress induced by stretching spring belt

$$\bar{\tau}_{zx} = \frac{TR_2}{J} \left[\frac{y_2}{R_w} \right]$$

$$\bar{\tau}_{zy} = \frac{TR_2}{J} \left[\frac{-x_2}{R_w} \right] + \frac{F}{A} \left[\frac{4}{3} \left(1 - \frac{y_2^2}{R_w^2} \right) \right]$$

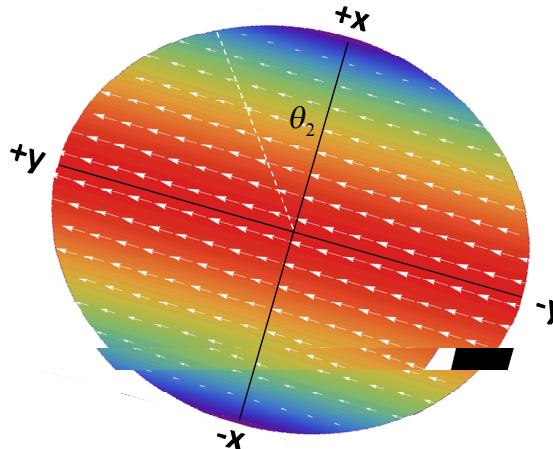


torsional stress induced by stretching spring belt

$$\tau_{torsion} = \frac{TR_2}{J}$$

$$\bar{\tau}_{zx} = \frac{Ty_2}{J}$$

$$\bar{\tau}_{zy} = -\frac{Tx_2}{J}$$



shearing stress induced by stretching spring belt

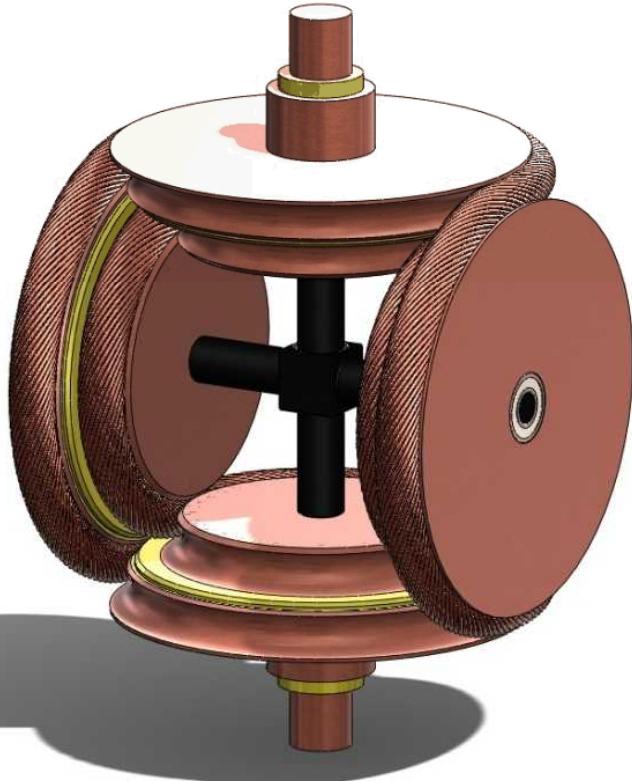
$$\tau_{shear} = \frac{4}{3} \left(1 - \frac{y_2^2}{R_w^2} \right) \frac{F}{A}$$

$$\bar{\tau}_{zx} = 0$$

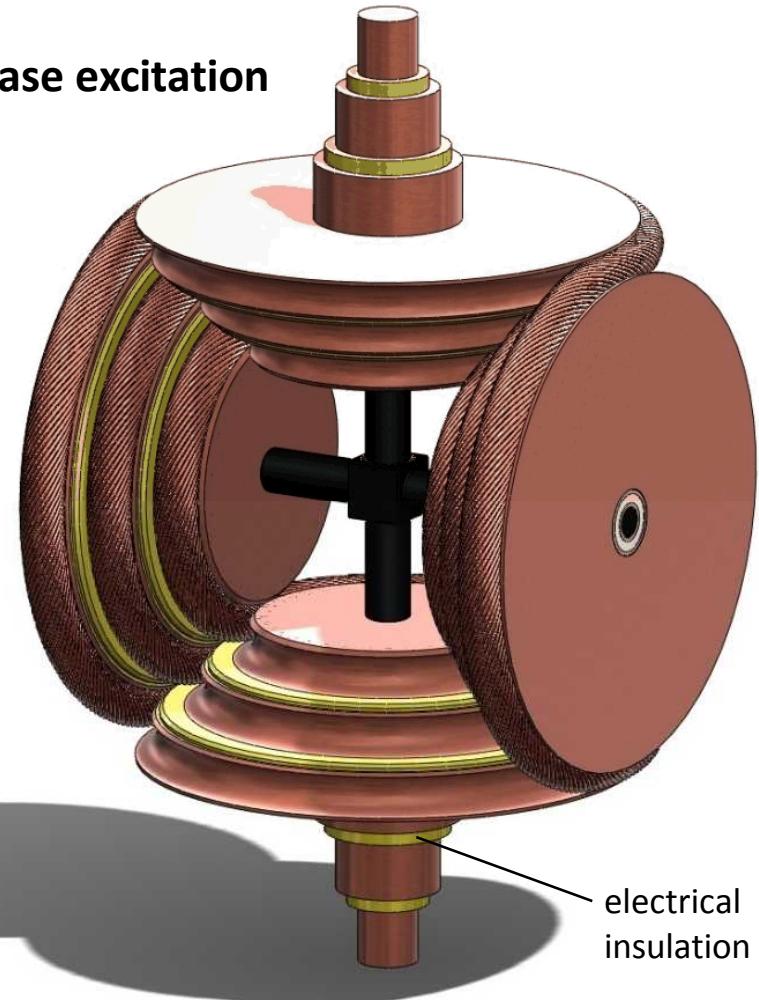
$$\bar{\tau}_{zy} = \frac{4}{3} \left(1 - \frac{y_2^2}{R_w^2} \right) \frac{F}{A}$$

Twistact variations for singly fed and doubly fed wire-wound-rotor synchronous generators

dc excitation



3-phase excitation

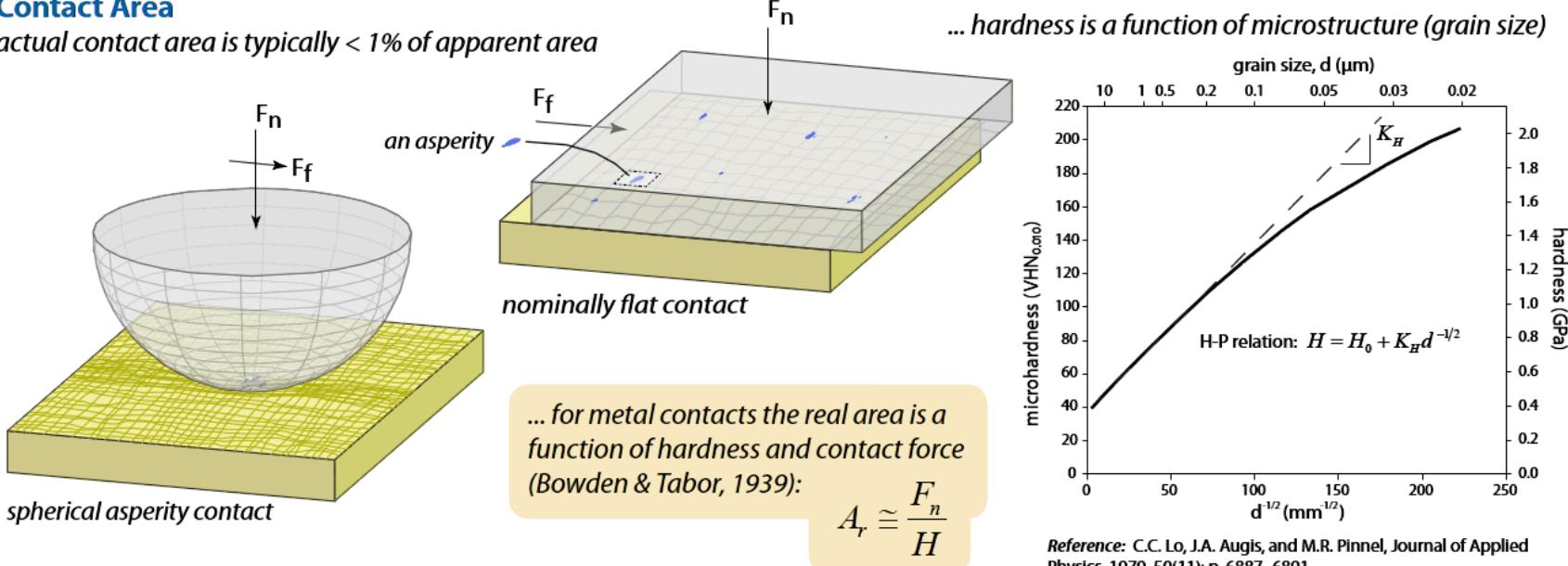


(doubly fed synchronous generators allow 3X reduction in inverter capacity)

Electrical contact micro-morphology

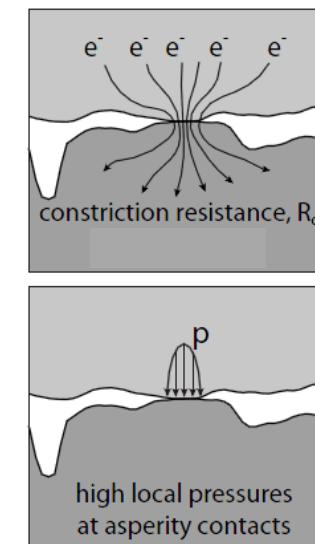
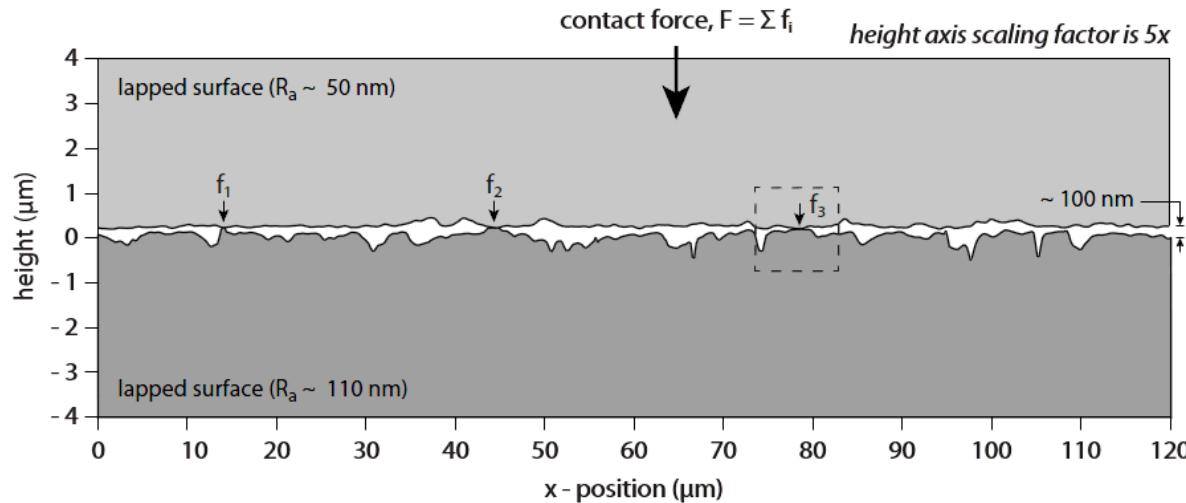
Contact Area

actual contact area is typically < 1% of apparent area



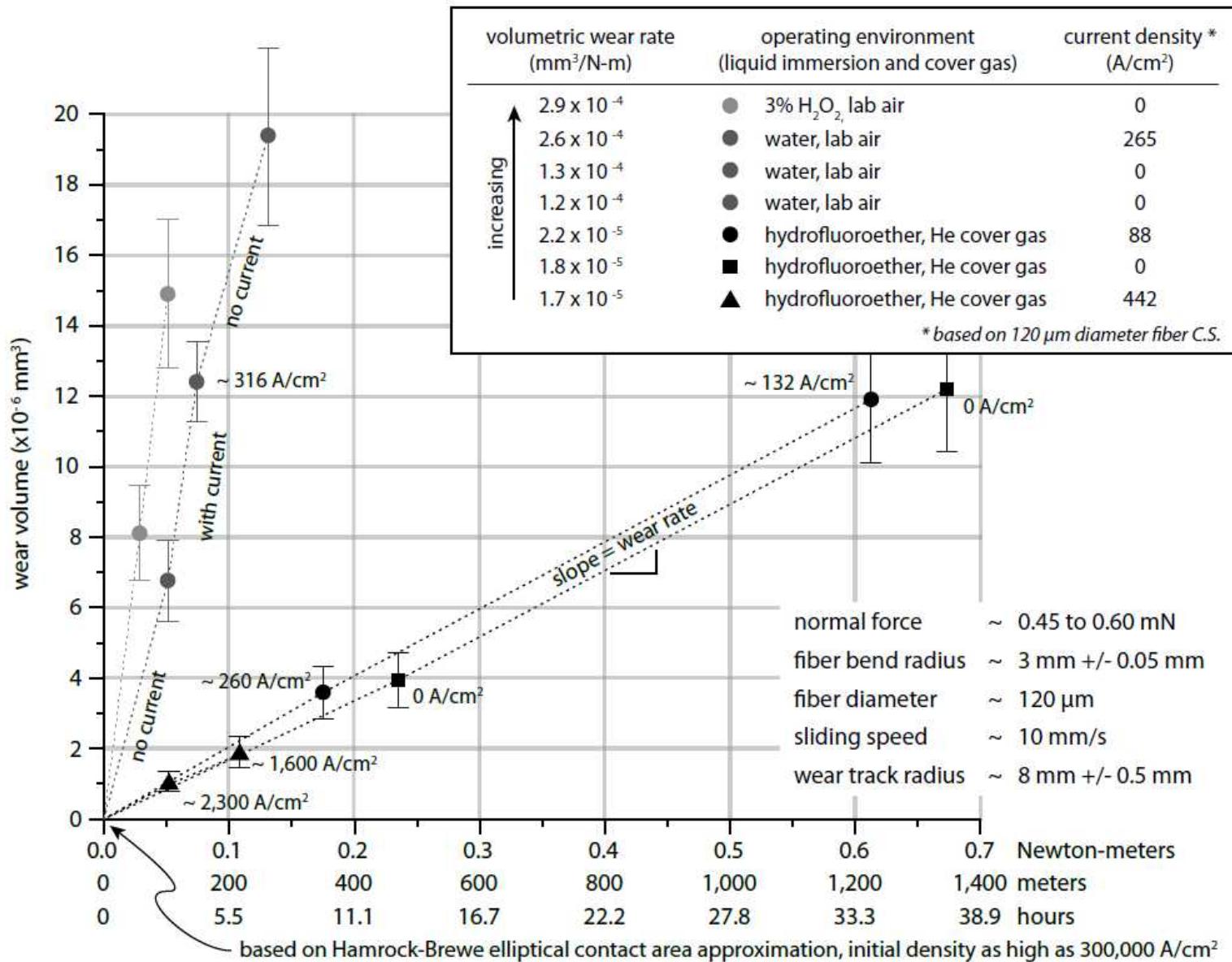
Surface Roughness

real contact area and electrical constriction



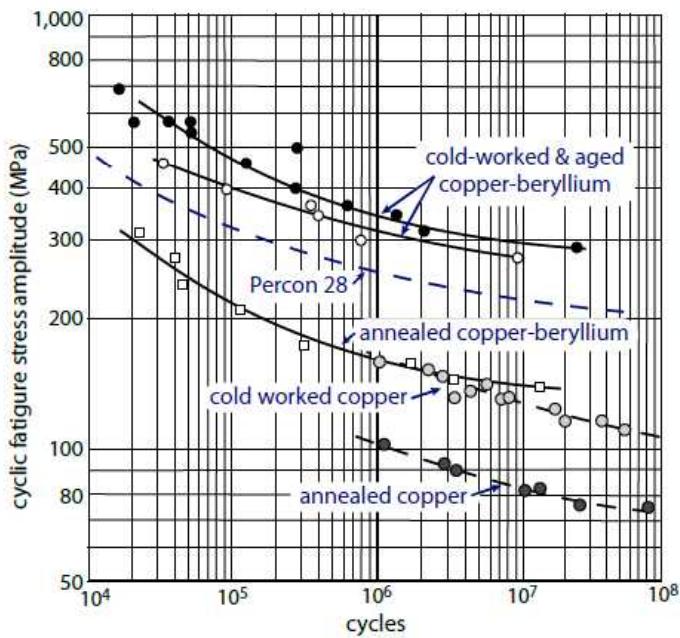
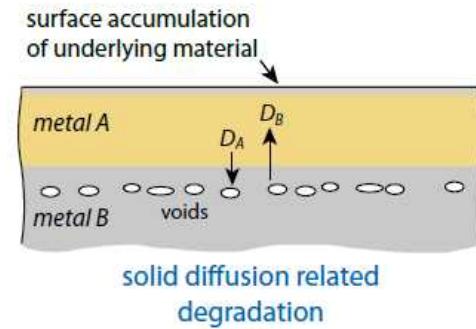
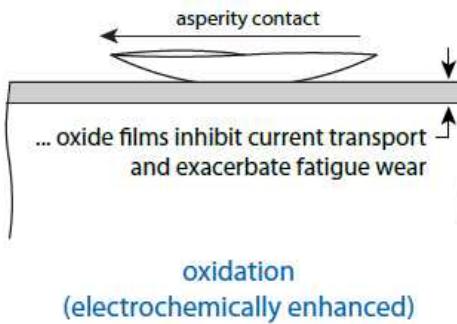
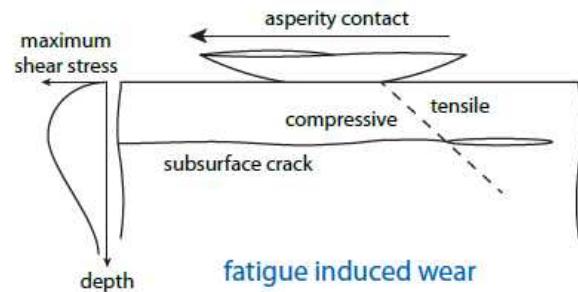
The role of the operating environment

The wear rate of a Cu-Be fiber sliding against a copper substrate was insensitive to electrical current density with the inhibition of oxidation and adequate thermal management.

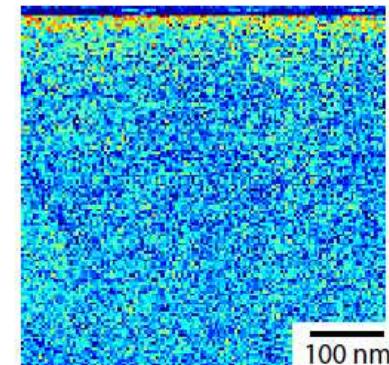
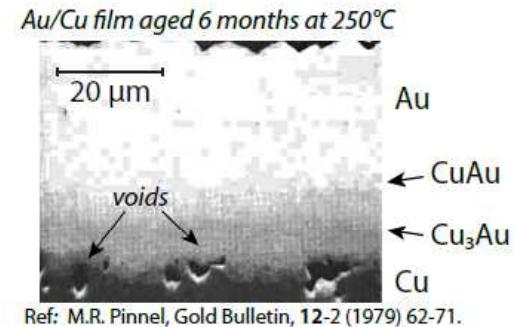
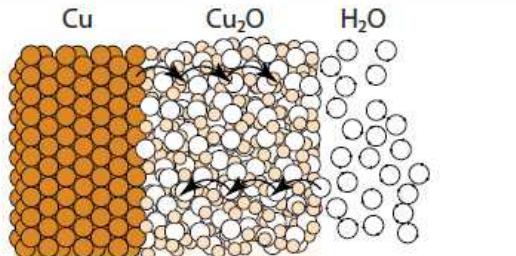
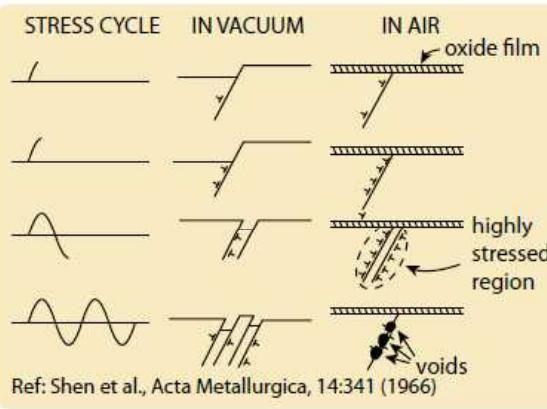


Materials challenges & experience from sliding contacts

The principal materials challenges may be broken down to fundamentally correlated atomic and micro scale processes.

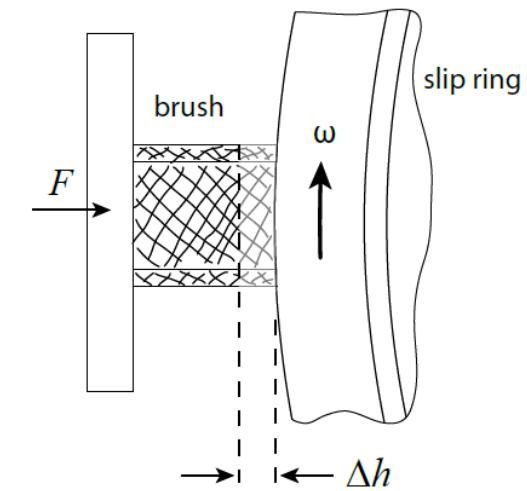
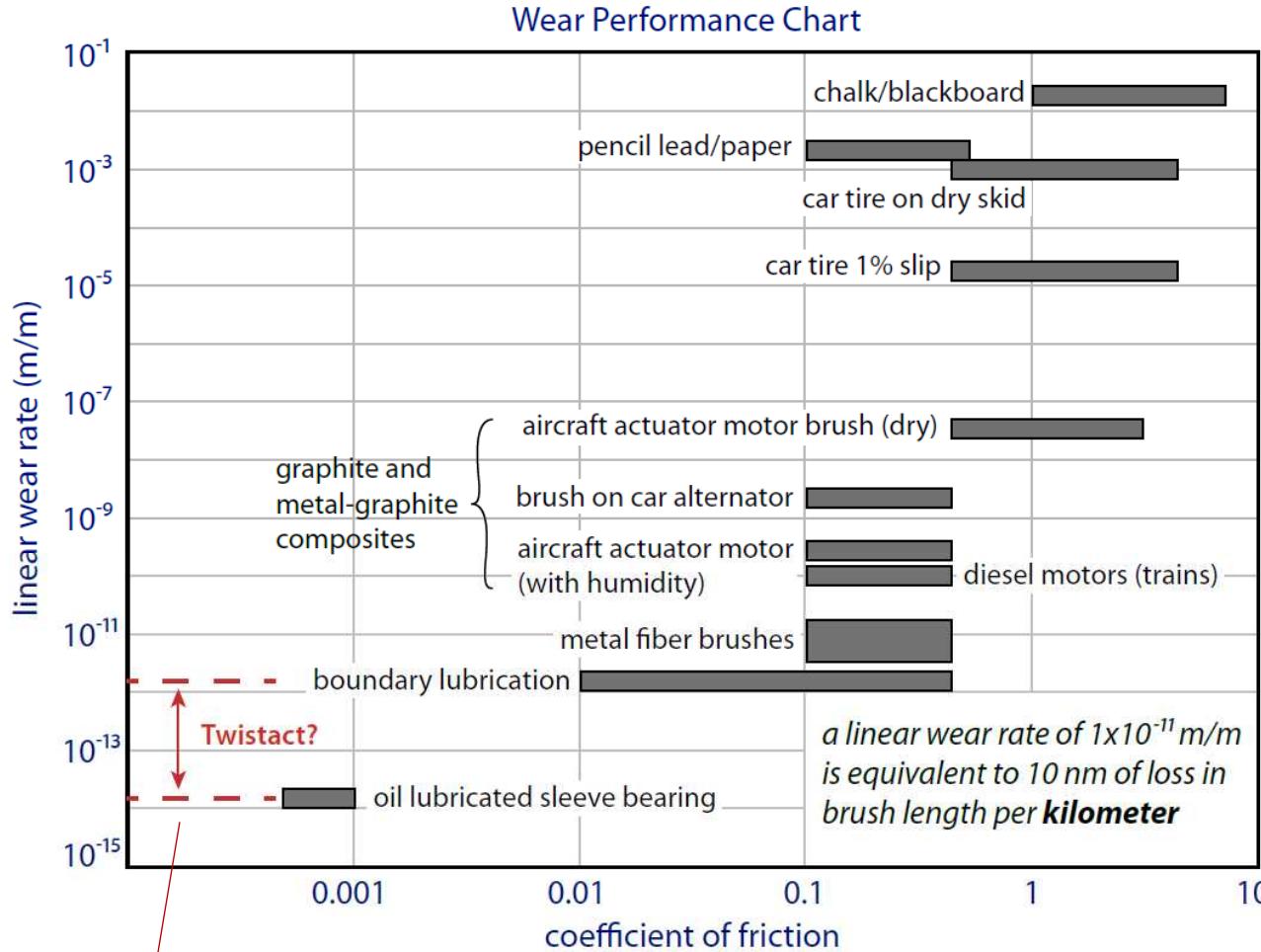


NOTE: hardness and fatigue strength are positively correlated



relative Ni concentration in a hard Au film aged at low temperature (electron microprobe/TEM)

Quantitative aspects of contact wear



linear wear rate:

$$K_{lin} = \frac{\Delta h}{d}$$

where,

Δh is brush wear (m)

d is sliding distance (m)

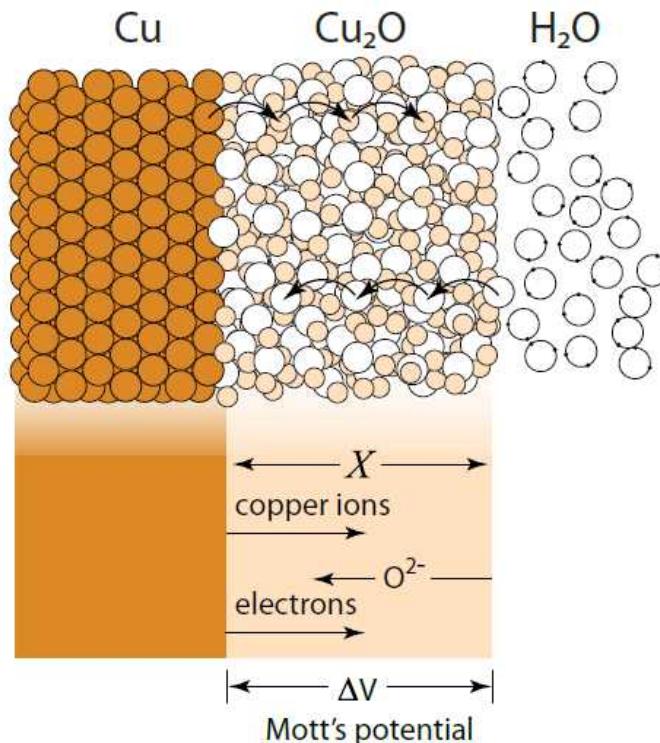
a comparison to specific wear rate, in units of $\text{mm}^3/\text{N}\cdot\text{m}$, is achieved by dividing the linear wear rate by the nominal contact pressure:

$$K_s = \frac{1}{p_0} K_{lin}$$

avoidance of sliding contact
moderate contact pressure
excellent thermal management

Oxidation phenomenon

A) Cabrera-Mott oxidation model



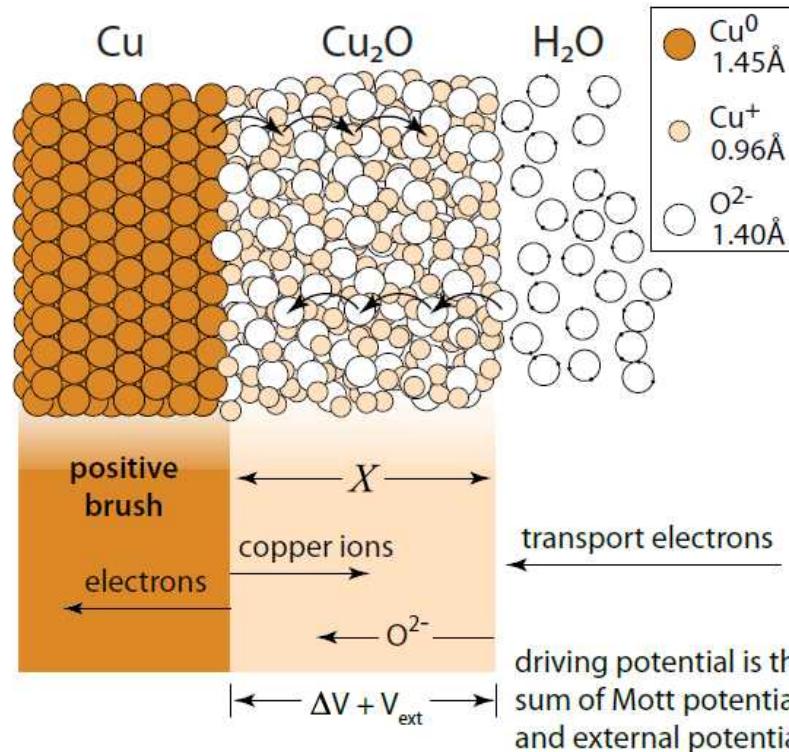
activation energy for a metal ion to jump into the oxide

$$\frac{dX}{dt} = av \exp\left(\frac{-W}{kT}\right) \exp\left(\frac{qa\Delta V}{2kTX}\right)$$

rate of oxide formation

in the absence of an externally supplied potential this is the ratio of the limiting film thickness and the current film thickness

B) electrochemically enhanced oxidation model



an externally supplied potential

$$\frac{dX}{dt} = av \exp\left(\frac{-W}{kT}\right) \exp\left(\frac{a\Delta V}{2kTX}\right) \exp\left(\frac{qaV_{ext}}{2kTX}\right)$$

definitions:

a lattice parameter

v jump frequency

k Boltzmann constant

T temperature

q unit of electric charge

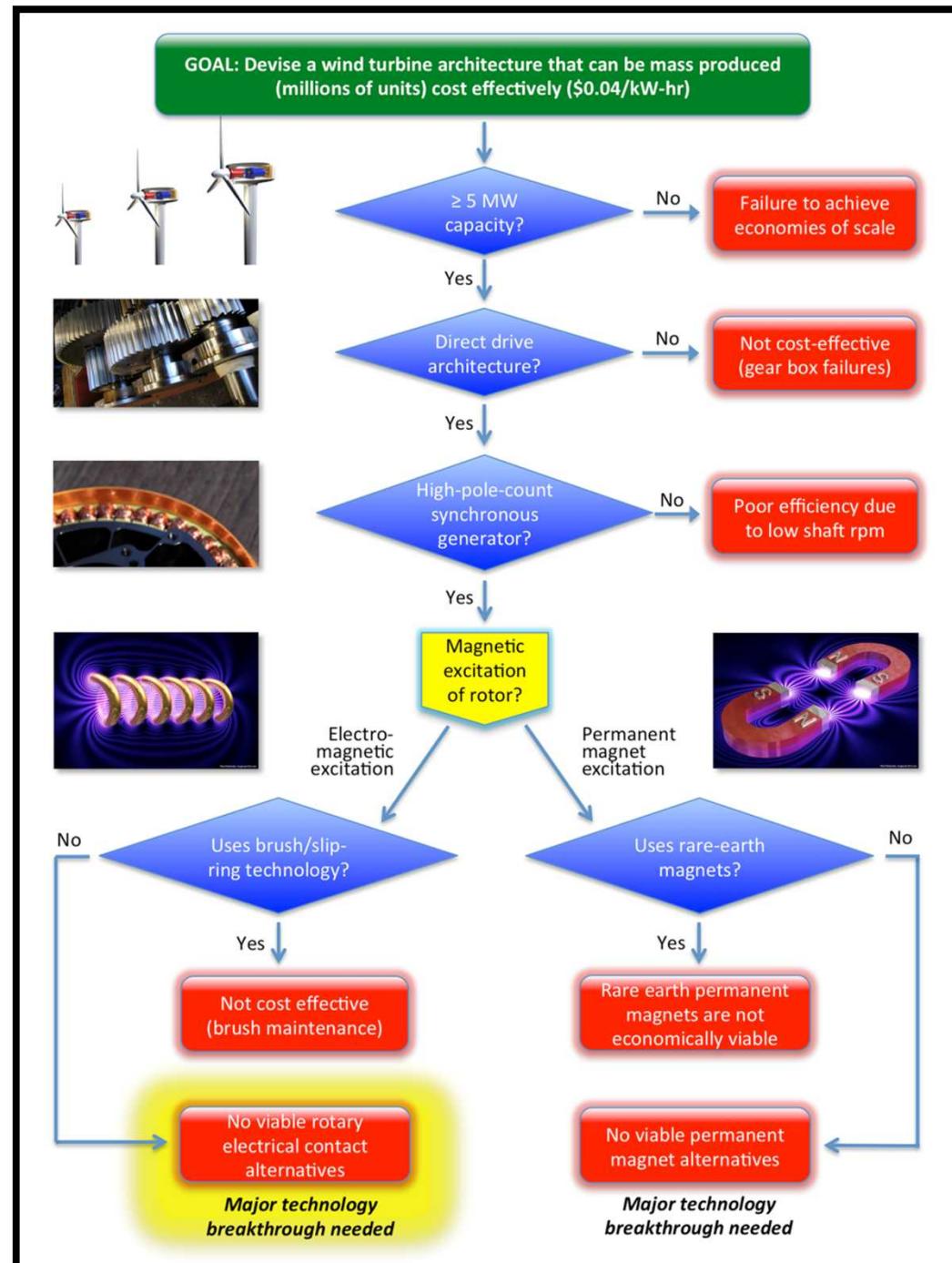
For wind power to displace fossil fuels, wind turbines must be redesigned to be cash cows with large and predictable ROI.



The last piece of the puzzle is to eliminate the need for rare earth magnets in wind turbines.

We must rethink the unsolved brush/slip-ring problem, starting with a clean sheet of paper.

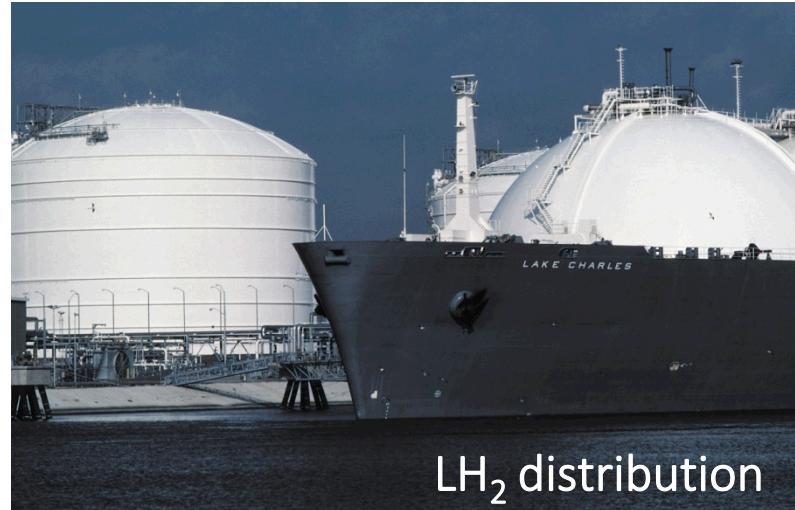
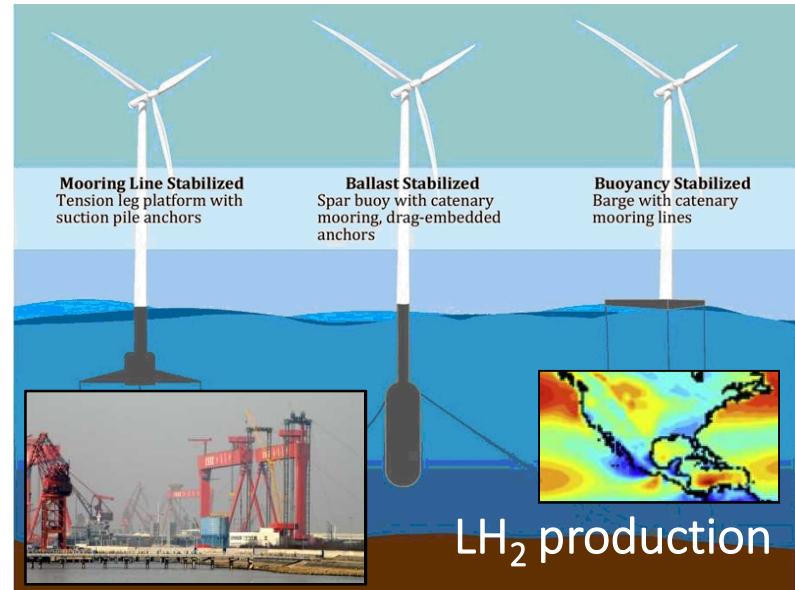
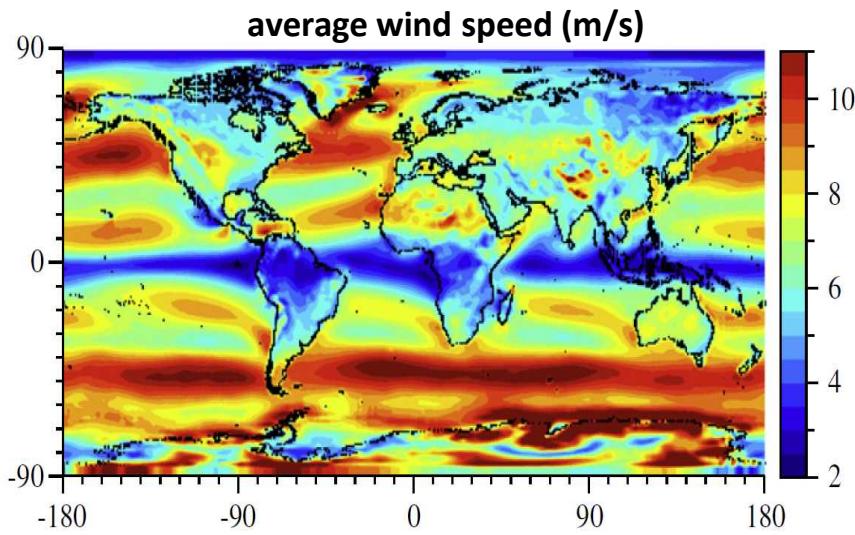
The long-awaited (190 years) breakthrough was recently invented at Sandia Livermore.



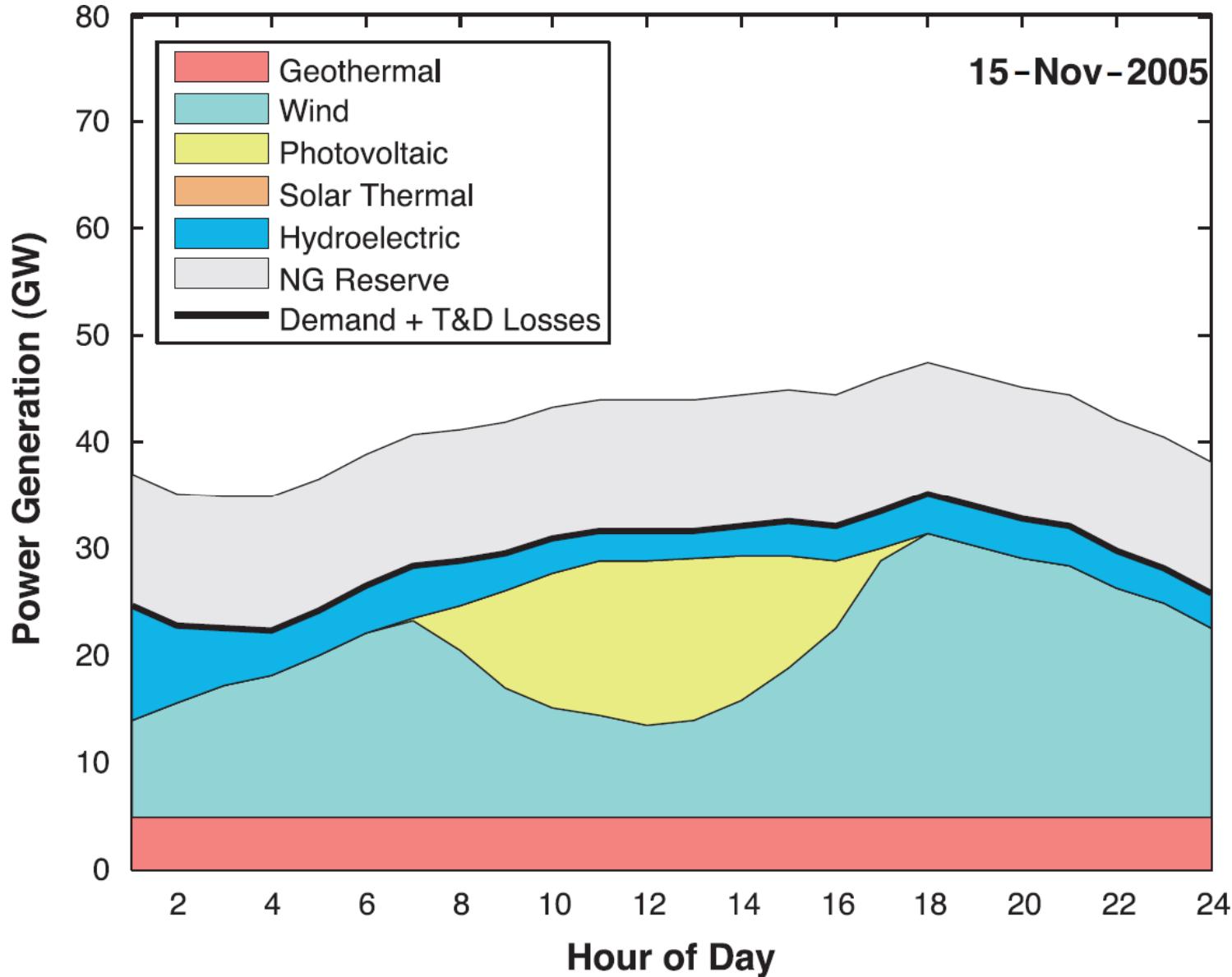
Expanding the future impact of wind power

Where the winds are: off-shore hydrogen production

(constructed at port, deployed over the horizon, not in my backyard, diurnally averaged)

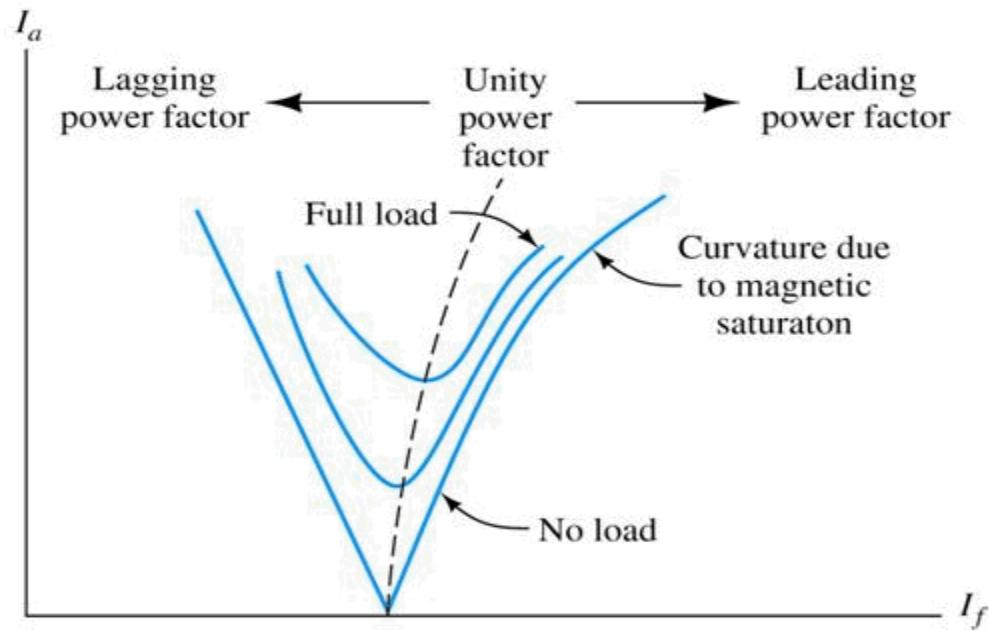
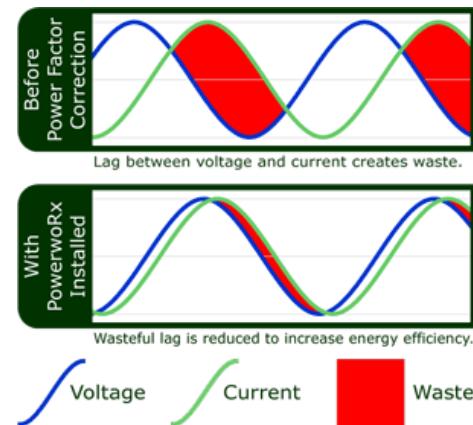
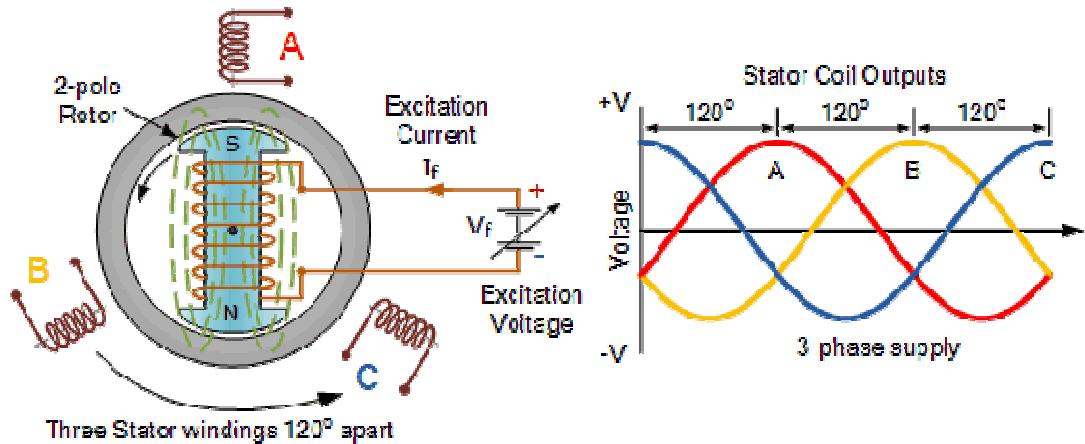


Addressing the diurnal variability of renewable power

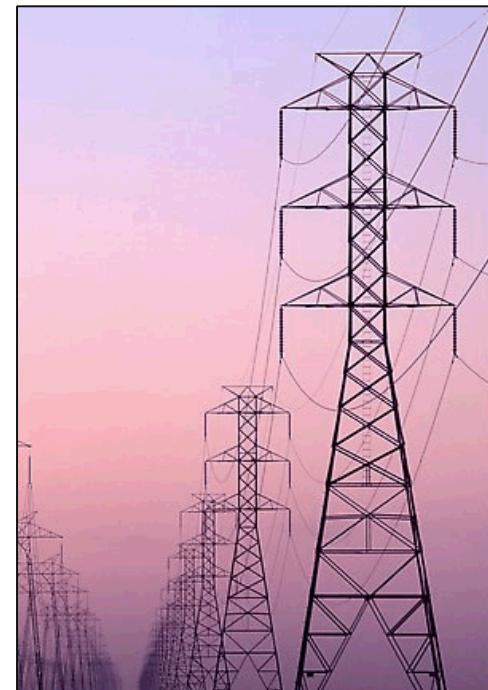


Using Twistact technology to get from \$0.04/kW-hr to \$0.03/kW-hr

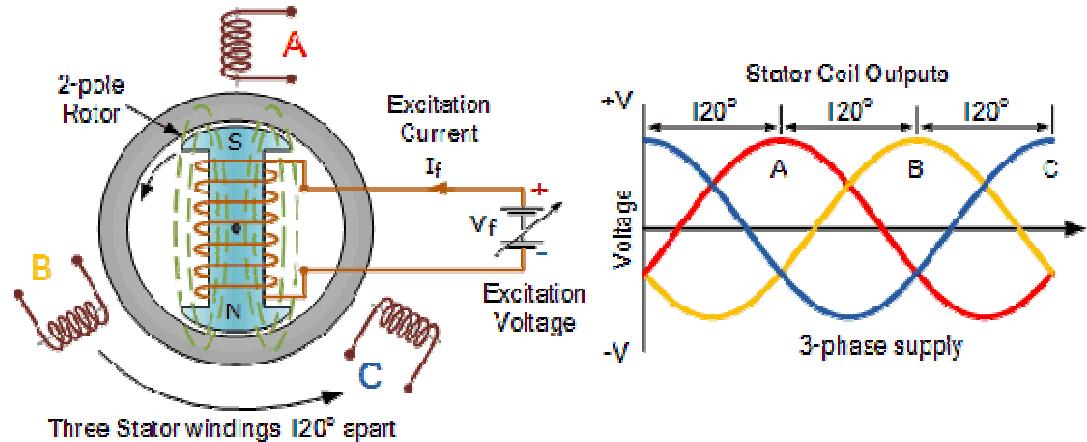
(wire wound synchronous generators enable electrical grid power factor correction)



V curves for a synchronous motor with variable excitation.

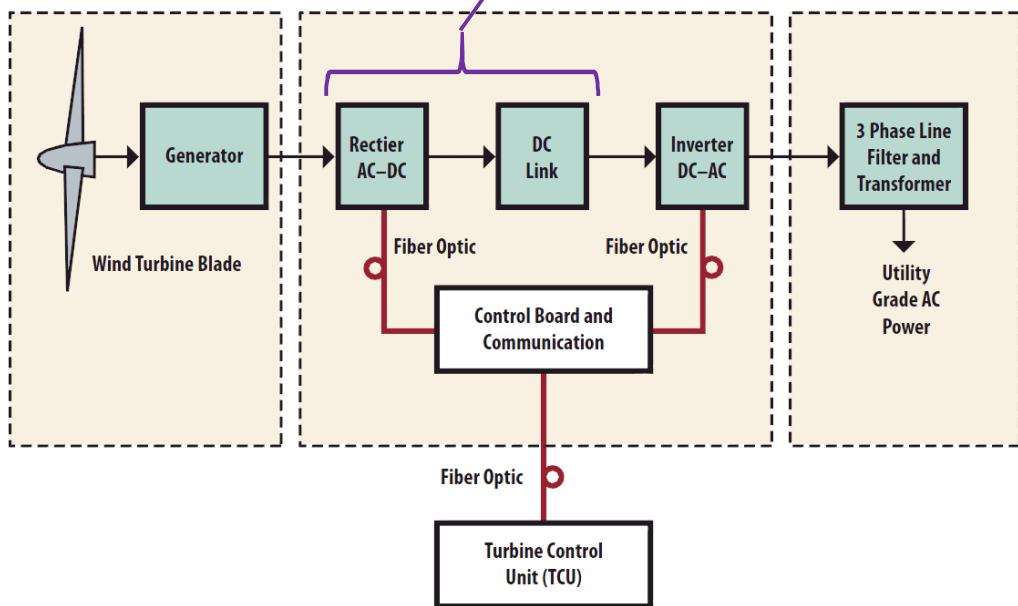


Using TwistaCT technology to get from \$0.04/kW-hr to \$0.03/kW-hr (the standard ac-dc-ac inverter topology negates the effect power factor correction)



In the case of a singly fed synchronous generator the power factor correction effect gets wiped out!

Wind Turbine Power Generation



Singly-fed
synchronized
generator

Variable
frequency
ac power

rectifier

dc power

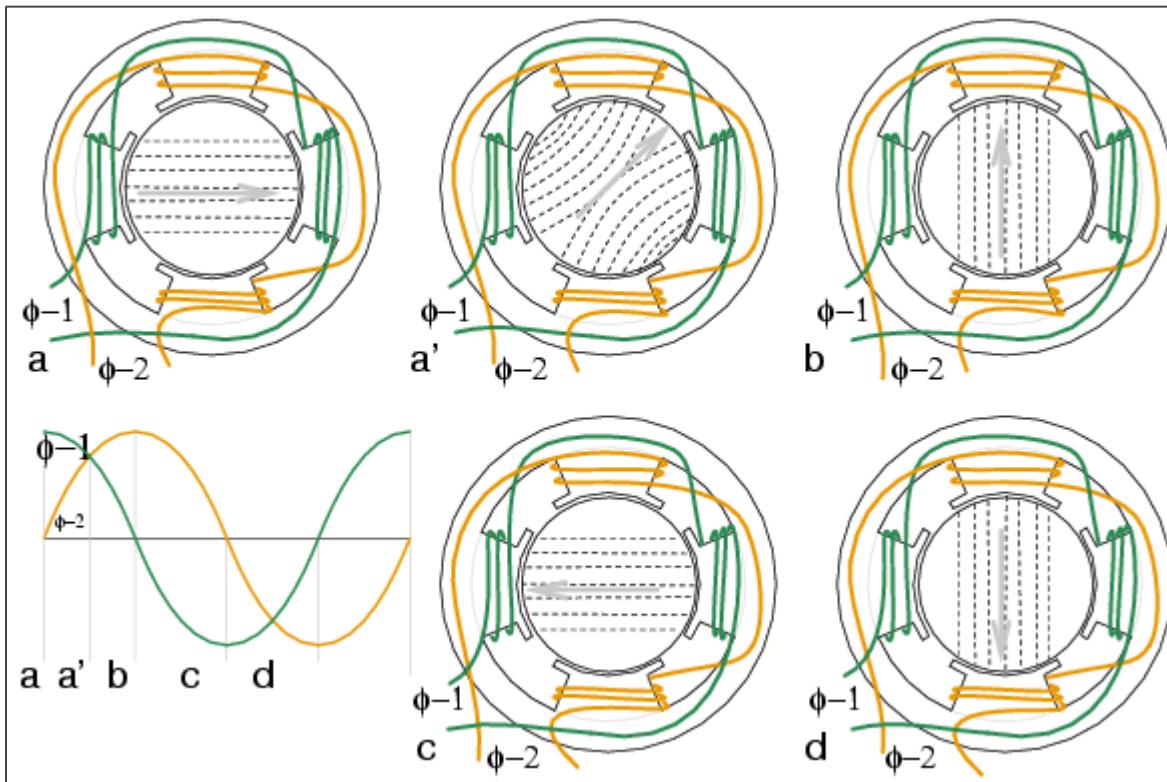
inverter

60 Hz grid
synchronized
power

Figure 1. Wind Turbine Power Generation Block Diagram

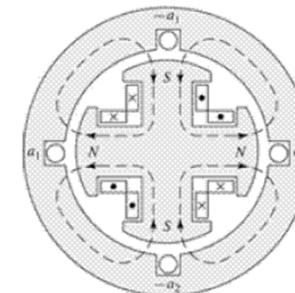
Using Twistact technology to get from \$0.04/kW-hr to \$0.03/kW-hr

- Twistact technology enables the use of doubly-fed synchronous generators
- Stator winding produces 60 Hz synchronized ac power directly (no inverter needed)
- ***This restores the power factor correction advantage***
- A 4X smaller inverter is required to generate the 3-phase rotor excitation waveform
- ***75% of ac-dc-ac inverter cost is eliminated***



The rotating magnetic field of a polyphase stator

polyphase rotor of an elementary doubly-fed synchronous generator



The rotor generates a rotating magnetic field of its own!

