

# Theorien und Experimente zur Entstehung und Wirkung kosmischer Magnetfelder

Palitzsch-Museum  
23. März 2023

Frank Stefani

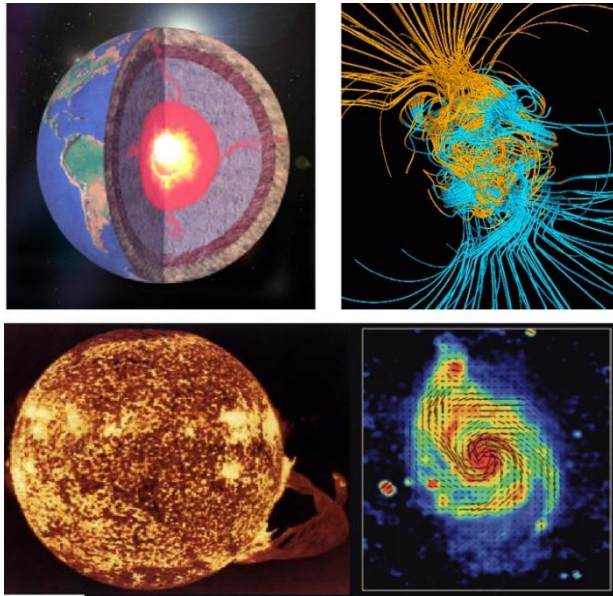


**HZDR**

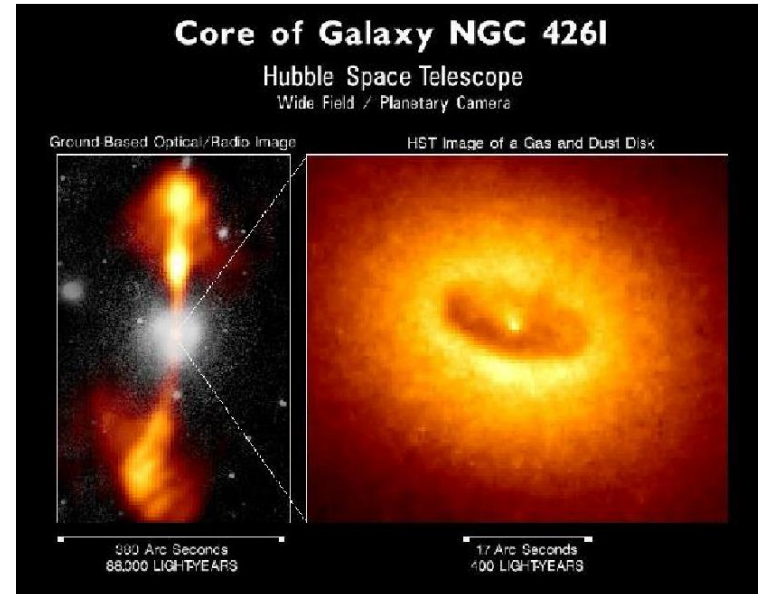
 **HELMHOLTZ**  
ZENTRUM DRESDEN  
ROSSENDORF

# Motivation: Magnetfelder im Kosmos...

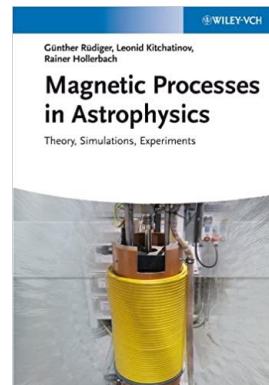
...werden durch den hydro-magnetischen **Dynamoeffekt** generiert



...spielen eine entscheidende Rolle bei der **Entstehung von Sternen und Schwarzen Löchern**



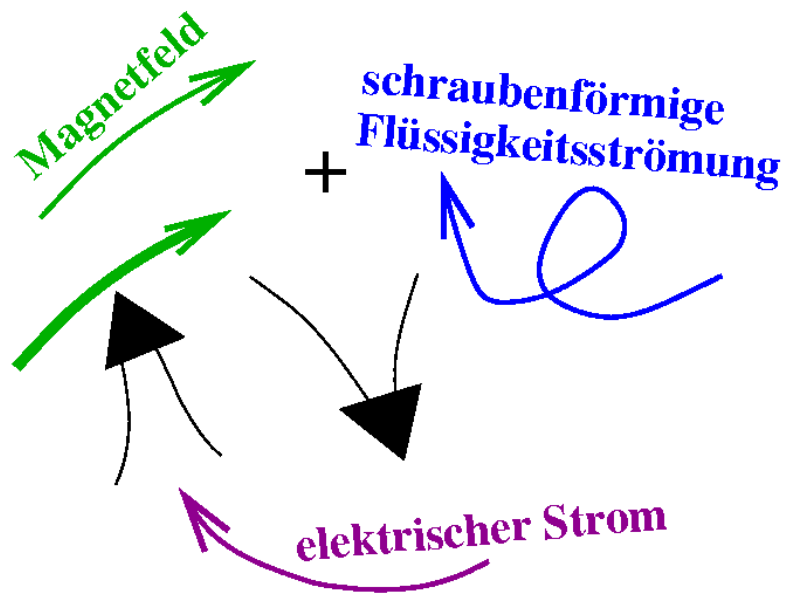
G. Rüdiger, L. Kitchatinov,  
R. Hollerbach: Magnetic  
Processes in Astrophysics  
(2013)



# Grundlagen

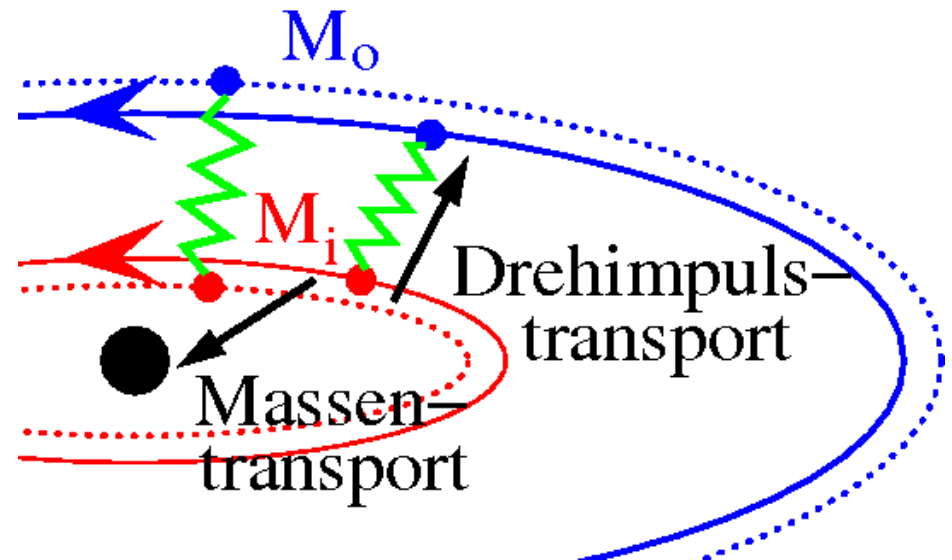
## Dynamoeffekt:

Selbsterregung eines Magnetfeldes in genügend starken schraubenförmigen Strömungen leitfähiger Fluide



## Magneto-Rotationsinstabilität (MRI):

Magnetfelder wirken wie Federn und bewirken Drehimpuls- und Massentransport in Akkretionsscheiben, aus denen Sterne und Schwarze Löcher gefüttert werden



# Magnetohydrodynamik: Die Theorie

Navier-Stokes-Gleichung:

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\frac{\nabla P}{\rho} + \frac{\text{curl} \mathbf{B} \times \mathbf{B}}{\mu_0 \rho} + \nu \nabla^2 \mathbf{u}$$

Dimensionslose Parameter:  
(Reynolds, Hartmann)

$$Re = \frac{LV}{\nu}$$

$$Ha = BL \sqrt{\frac{\sigma}{\rho \nu}}$$

Induktionsgleichung:

$$\frac{\partial \mathbf{B}}{\partial t} = \text{curl}(\mathbf{u} \times \mathbf{B}) + \frac{1}{\mu_0 \sigma} \nabla^2 \mathbf{B}$$

Dimensionslose Parameter:  
(magnetische Reynoldszahl)

$$Rm = \mu_0 \sigma LV$$

# Magneto hydrodynamik: Die Experimente

## Seit 23 Jahren: Experimente zu kosmischen Magnetfeldern

**Dynamo-Experimente:**

**Riga, Karlsruhe (1999),**

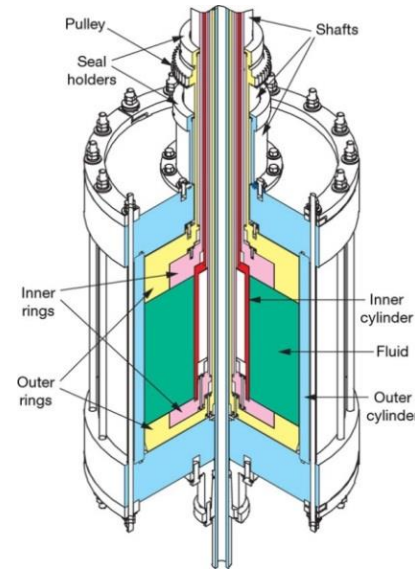
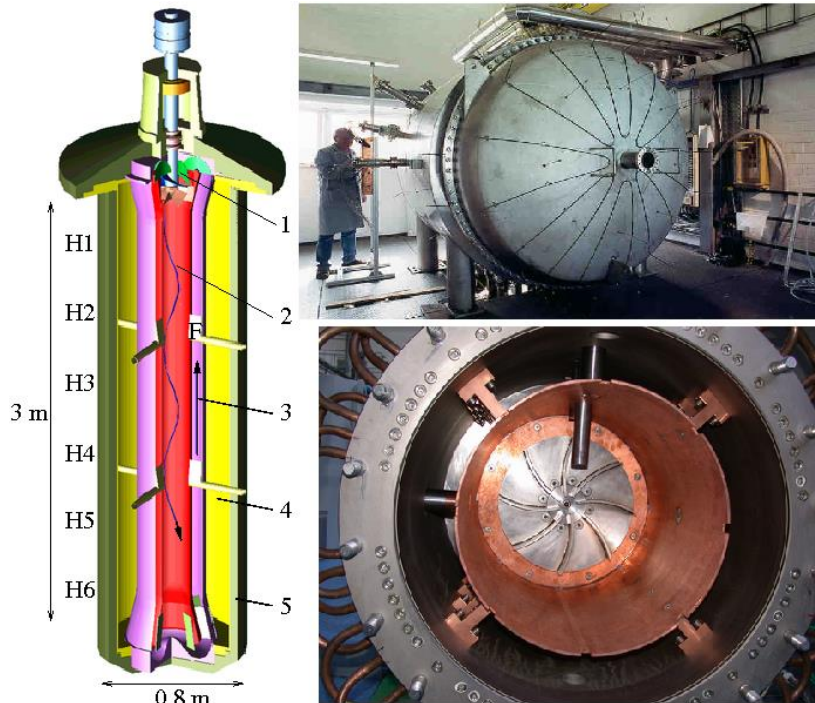
**Cadarache (2006),**

**Maryland, Madison, Perm**

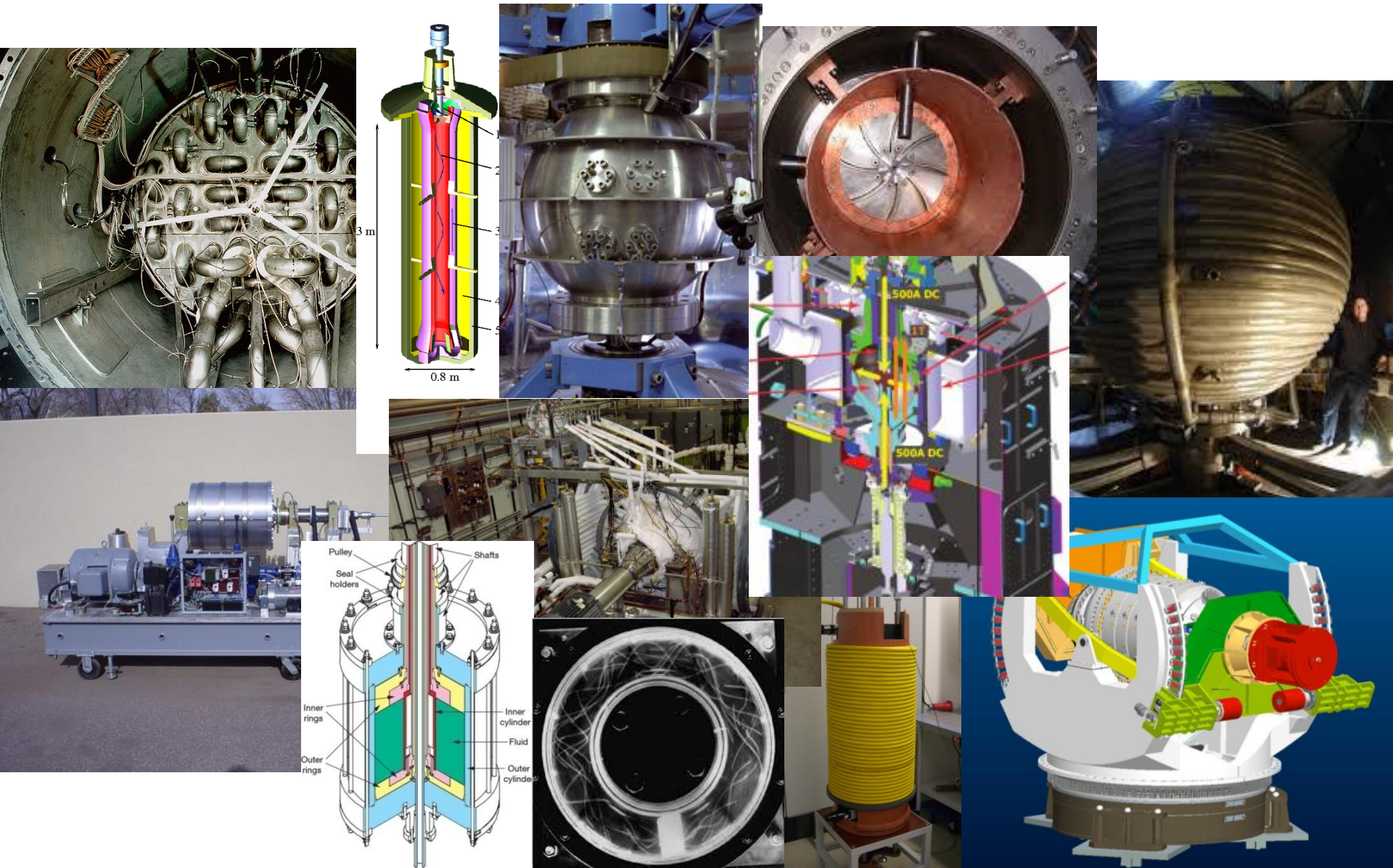
Experimente zur **Magneto-Rotationsinstabilität (MRI):**

**Dresden-Rossendorf (2006)**

**Maryland, Princeton**



# Magnetohydrodynamik: Die Experimente

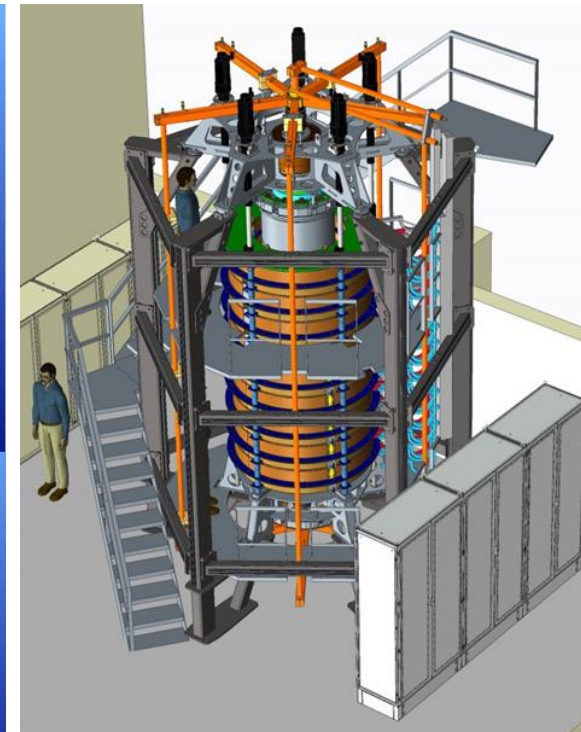
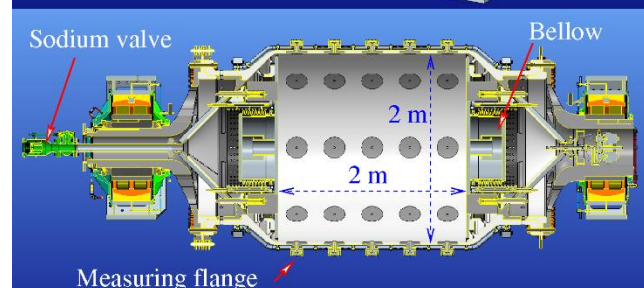
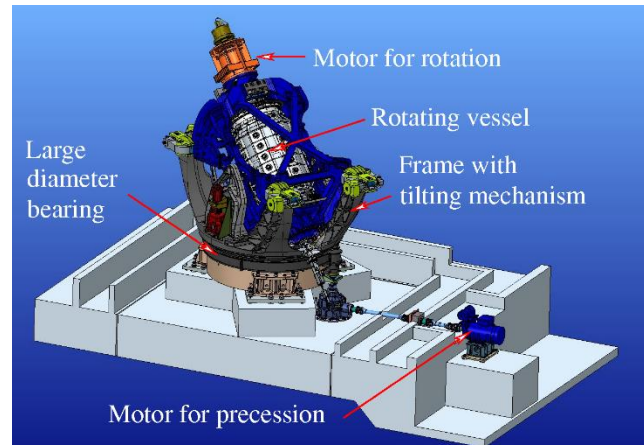


# DREsden sodium facility for DYNAmo and thermohydraulic studies

- DRESDYN-Gebäude ~500 m<sup>2</sup>
- Natriummenge: 12 Tonnen
- Präzessionsgetriebenes Dynamoexperiment mit separatem Fundament und Containment für Argonflutung
- Große Experimentierhalle für MRI/TI-Experiment (plus große Flüssigmetallbatterien)

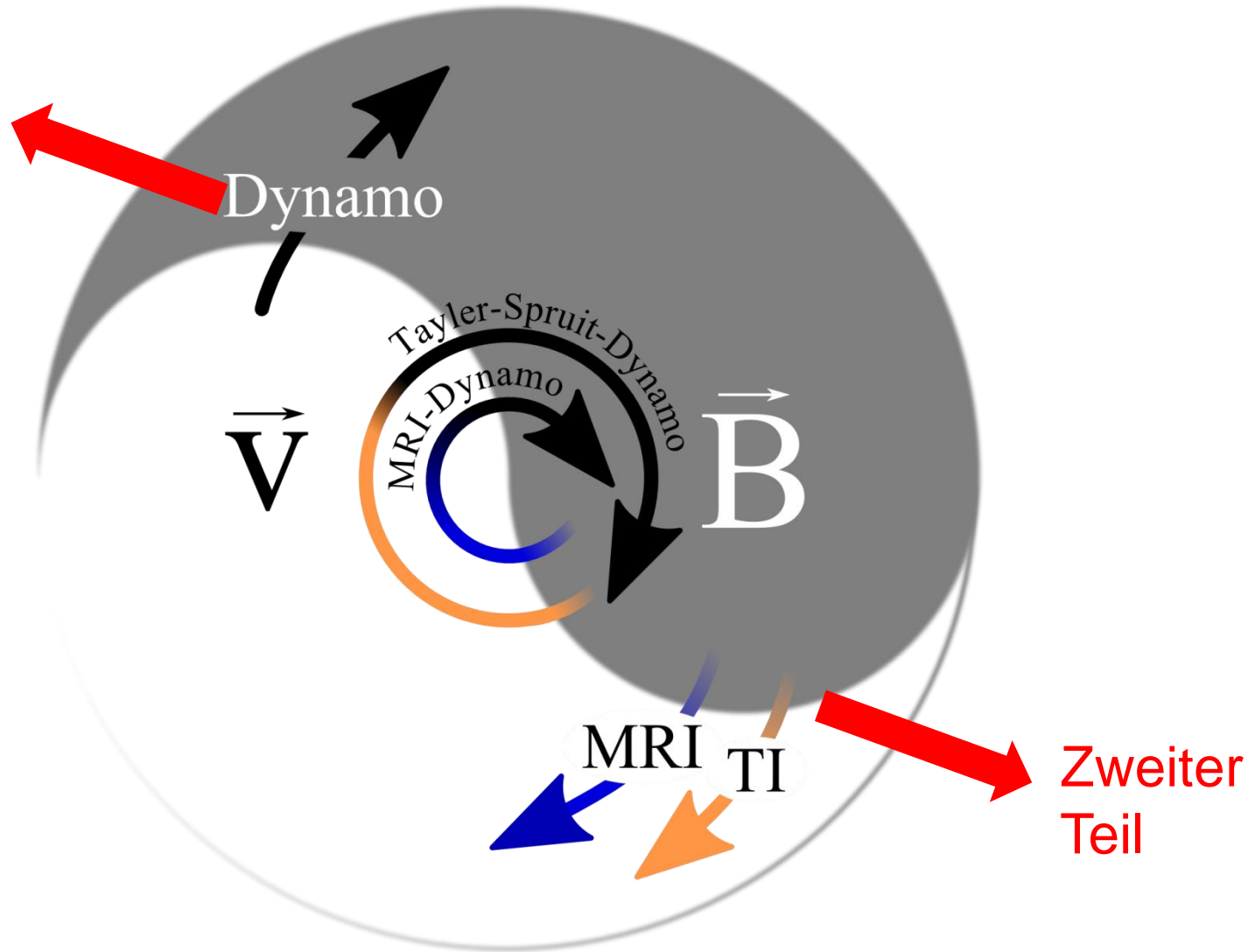


Stefani et al.: Magnetohydrodynamics 48 (2012), 103; 51 (2015), 275; Geophys. Astrophys. Fluid Dyn. (2018)



# Das Yin-Yang der kosmischen Magnetohydrodynamik

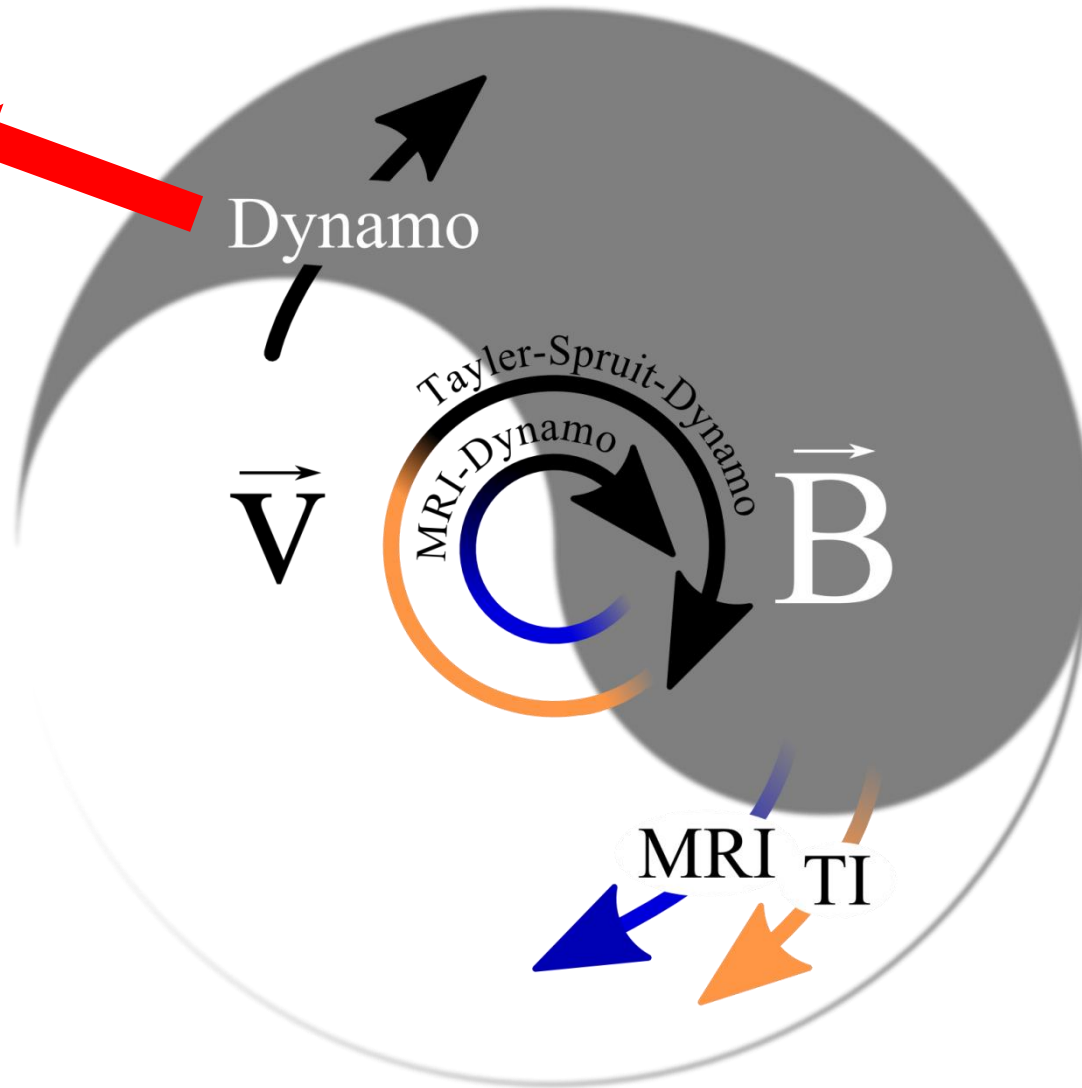
Erster  
Teil



Zweiter  
Teil

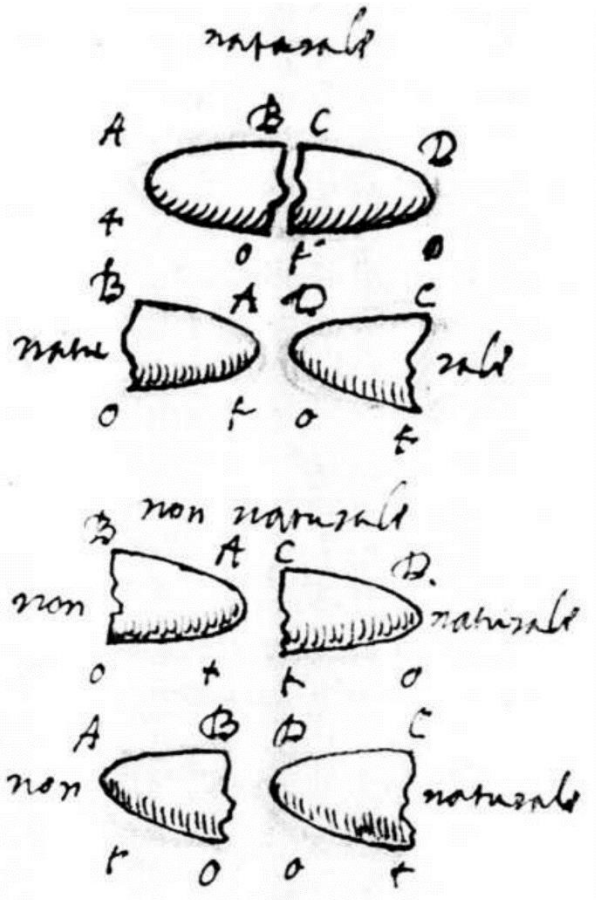


Erster  
Teil

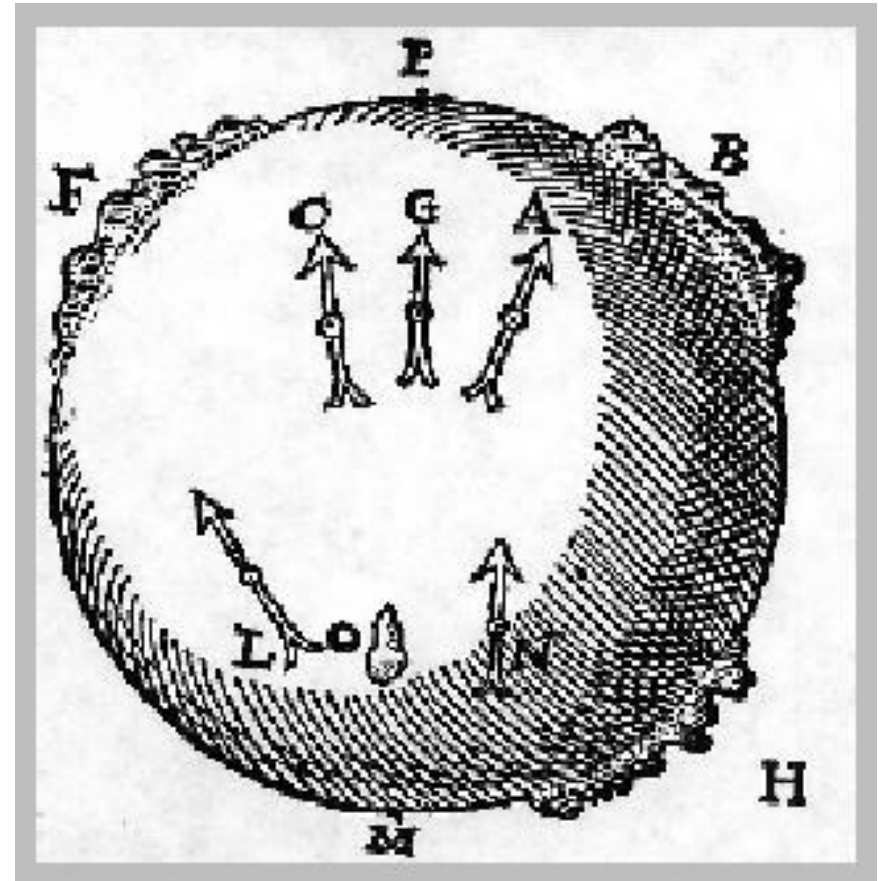


# Wie entsteht das Magnetfeld der Erde?

Petrus Peregrinus (1269):  
Entdeckung der Polarität

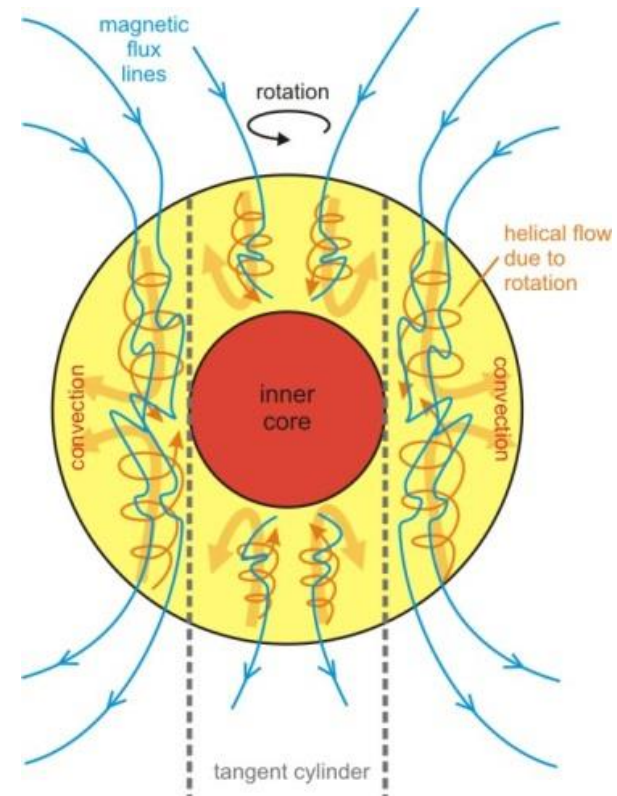
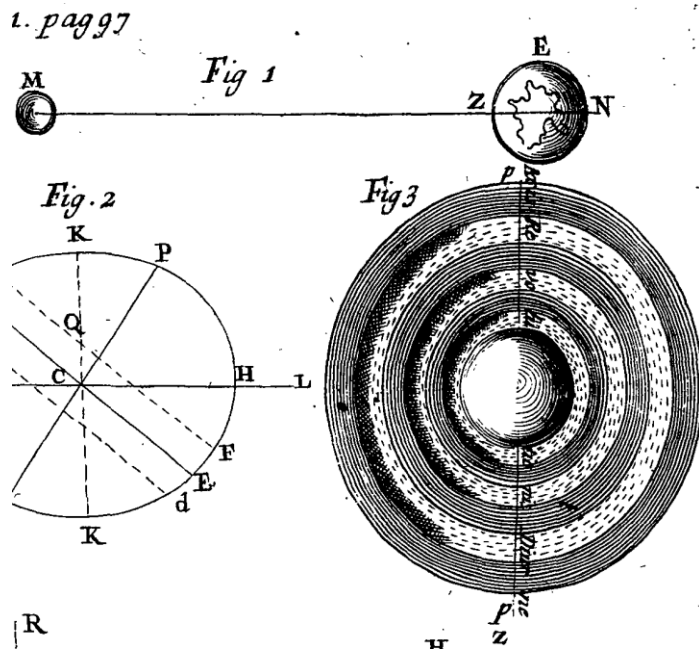


William Gilbert (1600):  
“Die Erde ist ein  
großer Magneteisenstein”



# Wie entsteht das Magnetfeld der Erde?

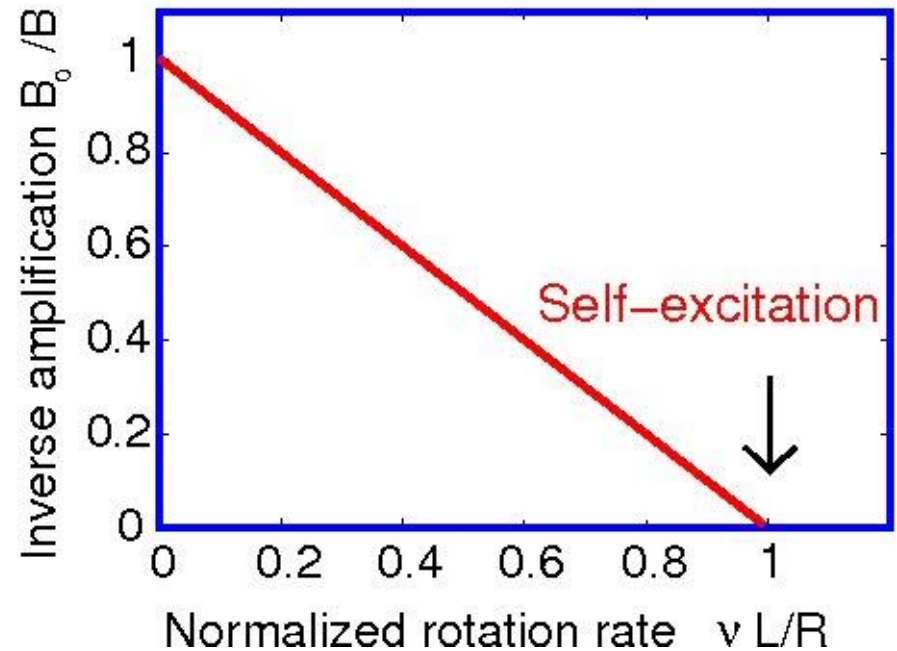
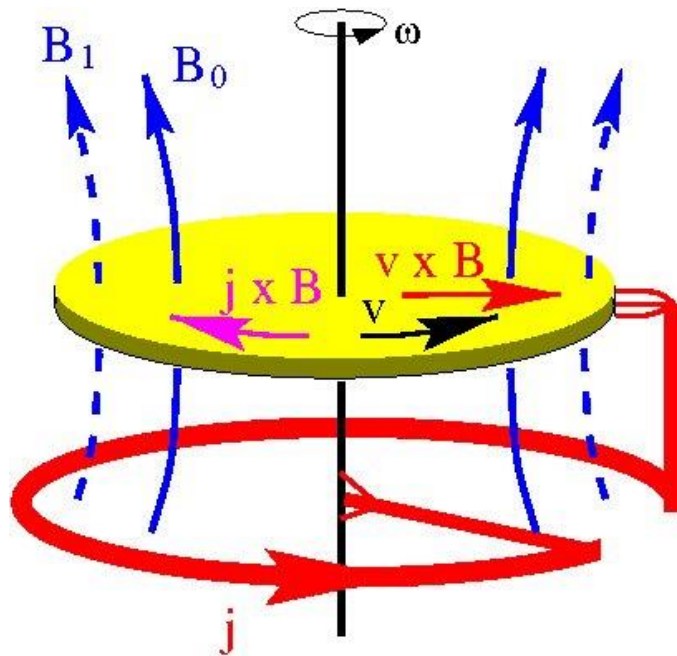
Zwischenlösung zur Erklärung der zeitlichen Variation der Deklination: Verschiedene magnetisierte Schalen im Erdinneren



Moderne Vorstellung: Erdmagnetfeld entsteht durch **Selbsterregung** in der **schraubenförmigen Strömung** des flüssigen äußeren Erdkern

E. Halley, Phil. Trans. R. Soc. London, No. 195, 1692, 563

# Mechanisches Model der Selbsterregung: Scheibendynamo



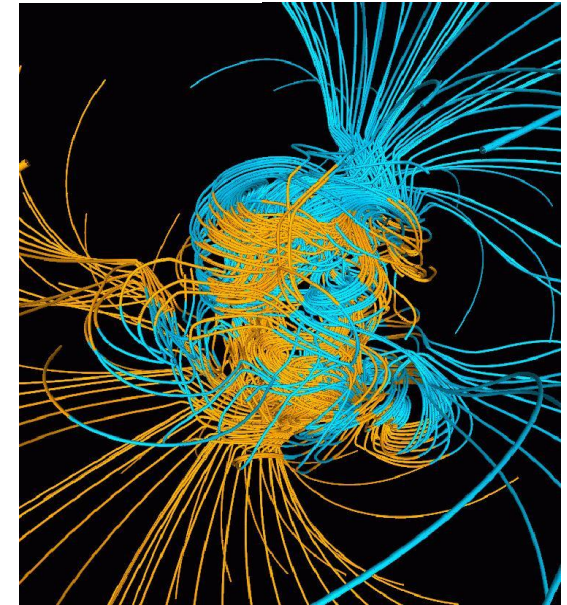
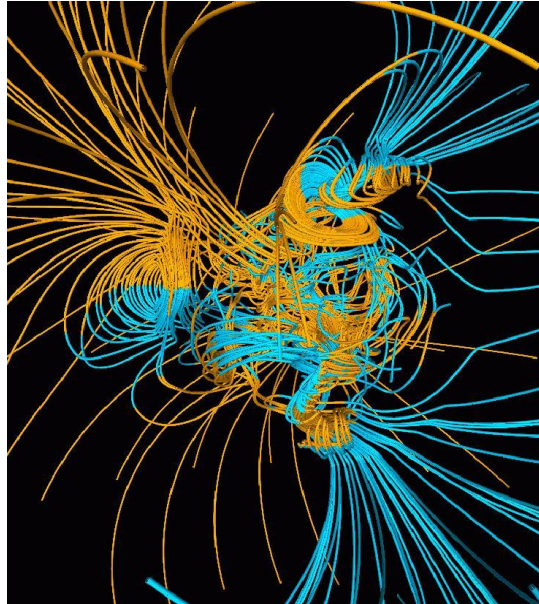
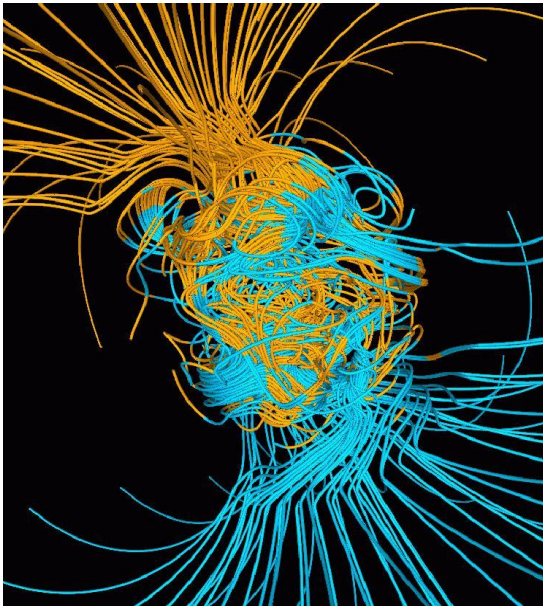
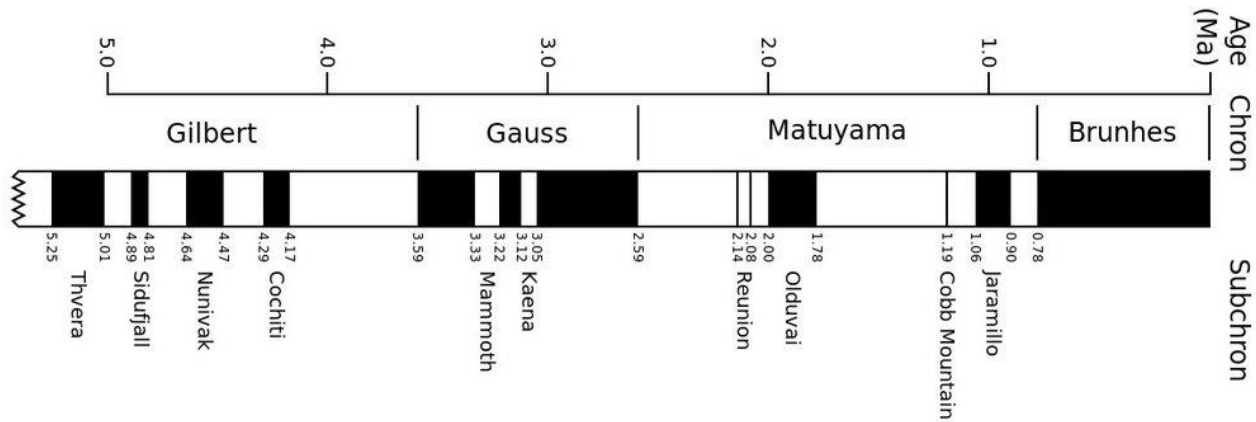
Modifizierte Scheibendynamos wurden jüngst erfolgreich in Queretaro (Mexico) und in Grenoble getestet



Avalos-Zuniga, Priede, Proc. R. Soc. A 479: 20220740, 2023

Alboussiere et al, Proc. R. Soc. A 478: 20220374, 2023

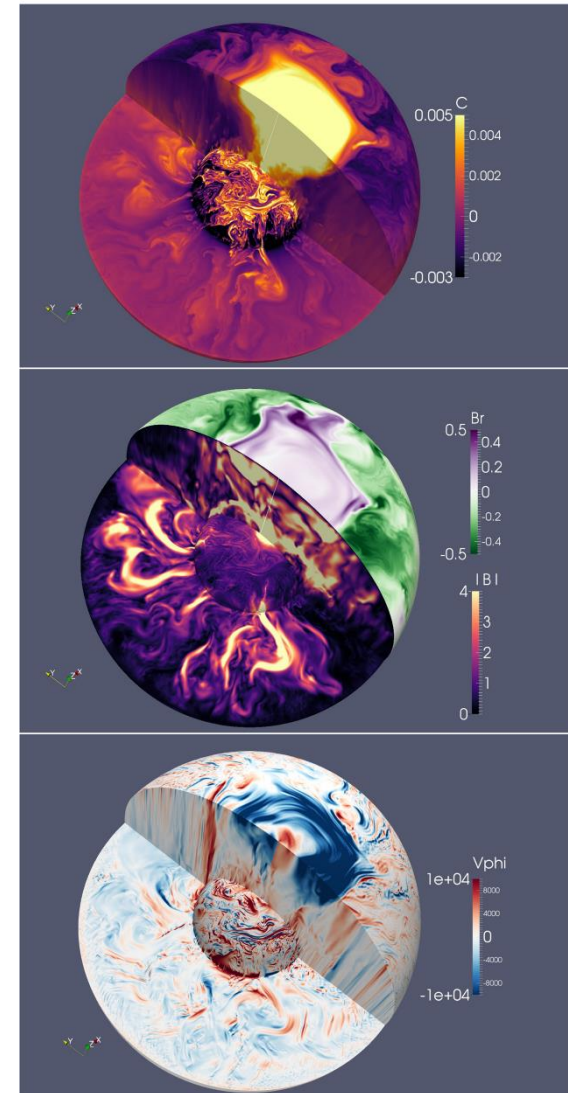
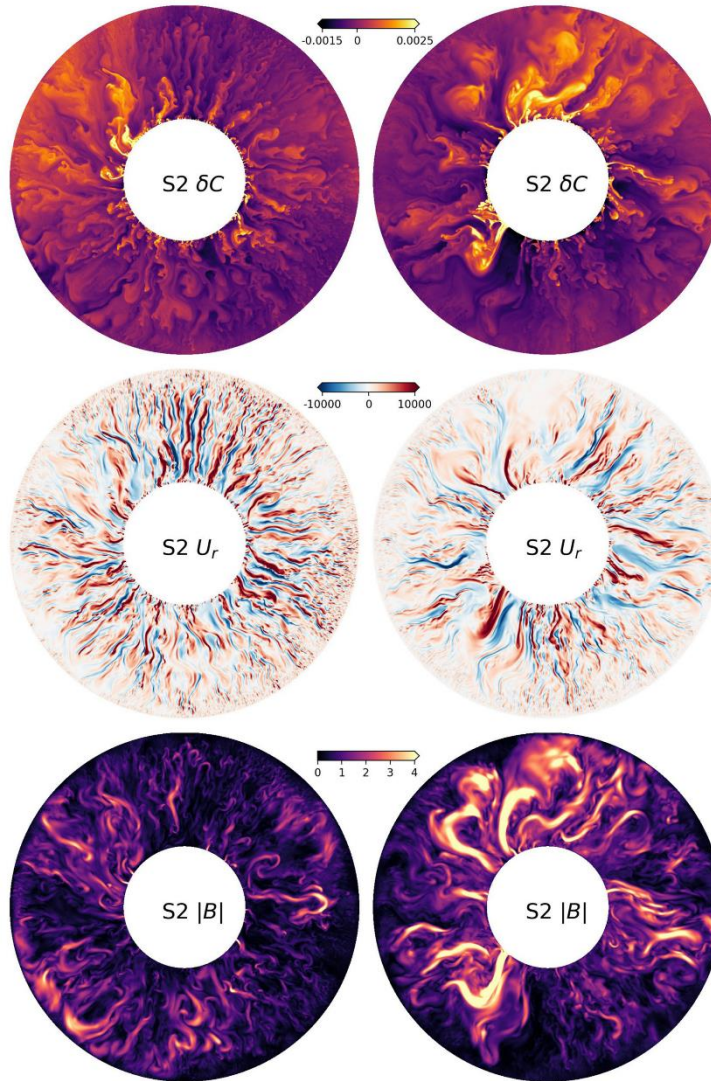
# Ein numerischer Durchbruch: Umpolungen!



Erstmalige Simulation einer Feldumpolung durch Glatzmeier und Roberts in einem erdähnlichen Dynamo-Modell

G. A. Glatzmaier, P.H. Roberts, Nature **377** (1995), 203

# Derzeitiger Stand der „Rechenkunst“



N. Schaeffer, D. Jault, H.-C. Nataf, A. Fournier, Turbulent geodynamo simulations: a leap towards Earth's core, *Geophys. J. Int.* 211, 1-29 (2017)

# Warum braucht man für Dynamoexperimente Natrium?

Bedingung für magnetische Selbsterregung: Magnetische Reynoldszahl muss größer sein als 10:

$$Rm = \mu\sigma UL > Rm_{\text{crit}} \geq 10$$

Natrium ist der beste flüssige elektrische Leiter mit  $\sigma \sim 10^7$  S/m

## Warum müssen Dynamoexperimente so groß sein?

Notwendige Leistung skaliert reziprok mit der Größe:

$$P \sim Rm^3 / L$$

Vertretbare Leistung (einige 100 kW) nur mit großen Anlagen ( $\sim 1$  m) möglich

# Erste Abschätzungen für Dynamoexperimente



Max Steenbeck  
an H. Klare 1975:



*"...daß der Aufwand für einen  
derartigen Versuch beträchtlich  
sein müsse – ein Kessel mit etwa  
10 m<sup>3</sup> flüssigem Natrium und  
einer Pumpenleistung von nicht  
weniger als 10 m<sup>3</sup>/sec."*

Prof. Dr. Dr. h.c. MAX STEENBECK

Präsident  
der Akademie der Wissenschaften  
der DDR

Herrn Professor Dr. H. Klare

10E Berlin  
Ulmer-Buschke-Straße 22/23

Sehr geehrter Herr Klare!

Dieses Schreiben enthält den Vorschlag zu einem prinzipiell und  
wissenschaftlich bedeutsamen Experiment, dessen Durchführung  
möglich ist, aber recht erhebliche Aufwendungen erfordert. Es  
wäre wichtig, dazu Ihre Meinung zu erfahren.



# Mit Kupfer geht's auch kleiner...

Siemens' Dynamomaschine



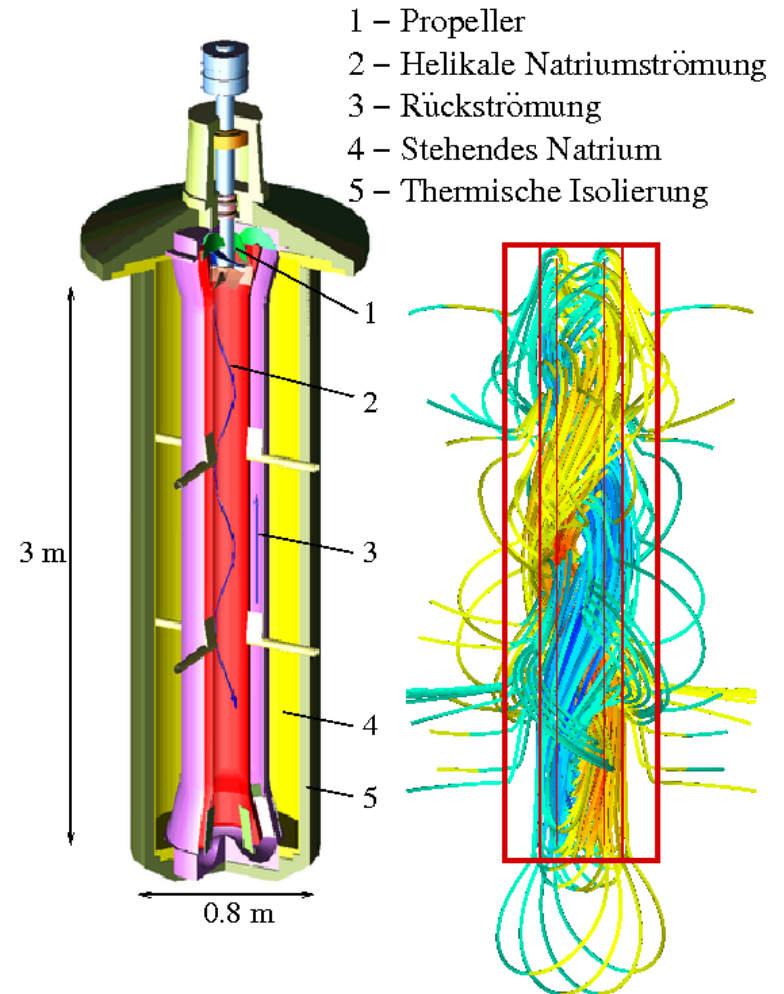
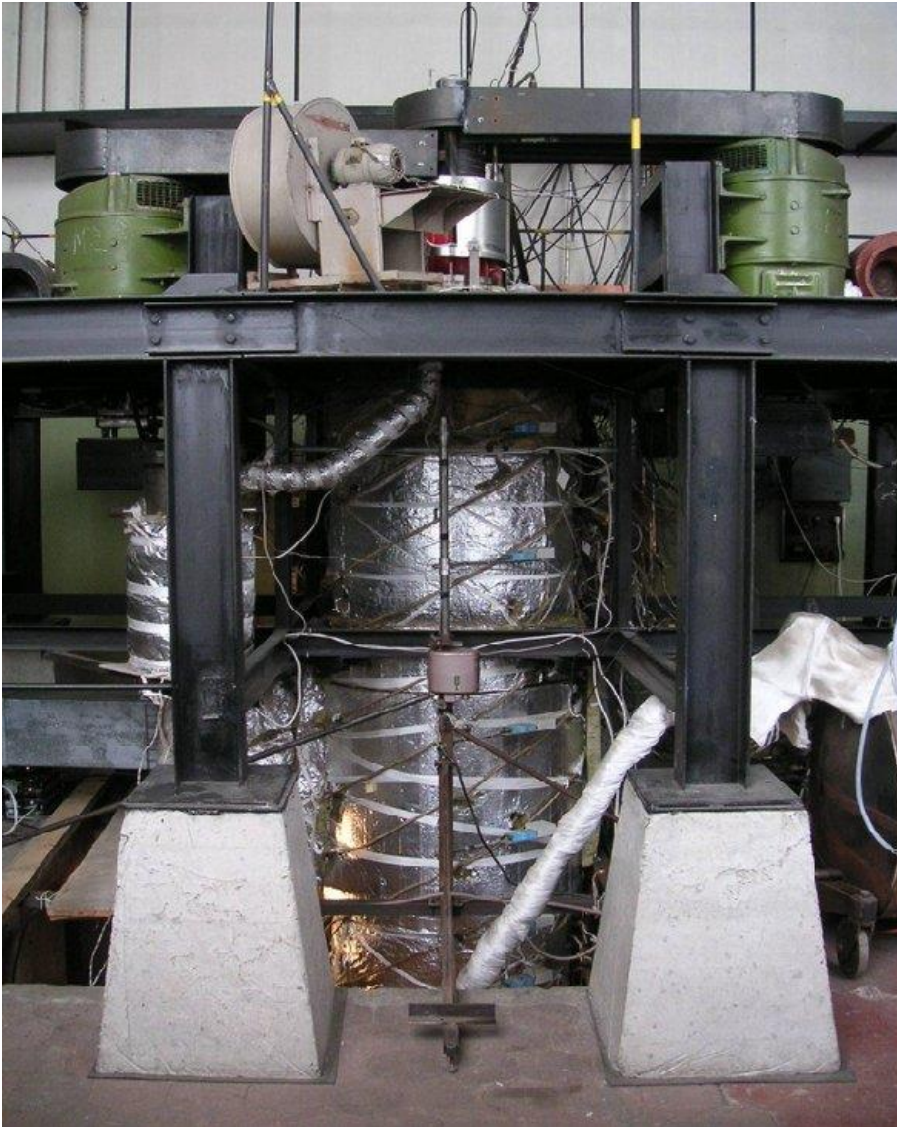
© Deutsches Museum

Stadtmuseum  
Dresden

Electricitätswerke vorm. O.L Kummer,  
Niedersedlitz bei Dresden 1894



# Rigaer Dynamoexperiment



Dynamo-  
modul

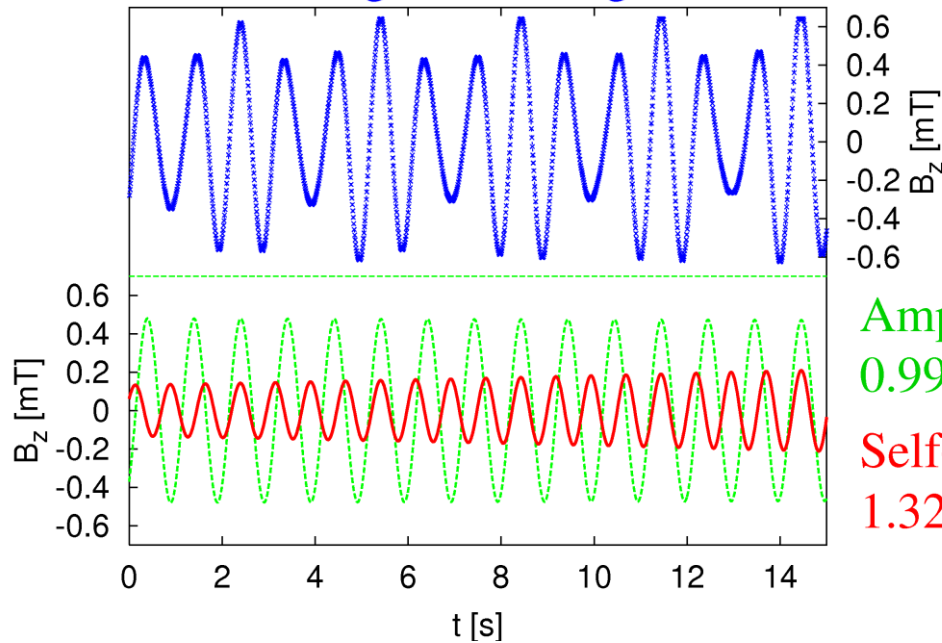
Berechnetes  
Magnetfeld

# Rigaer Dynamoexperiment

Erstmaliger Nachweis magnetischer Selbsterregung in einer Flüssigmetallströmung:

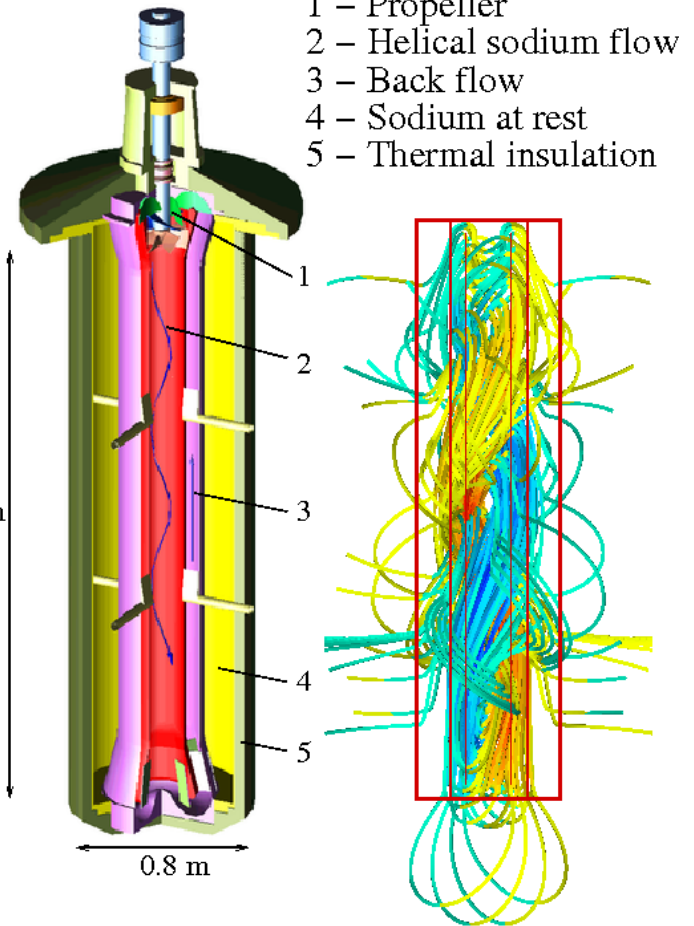
11.11.1999

Measured signal at flux gate sensor



Amplified  
0.995 Hz

Self-excited  
1.326 Hz



Dynamo  
module

Simulated  
eigenfield

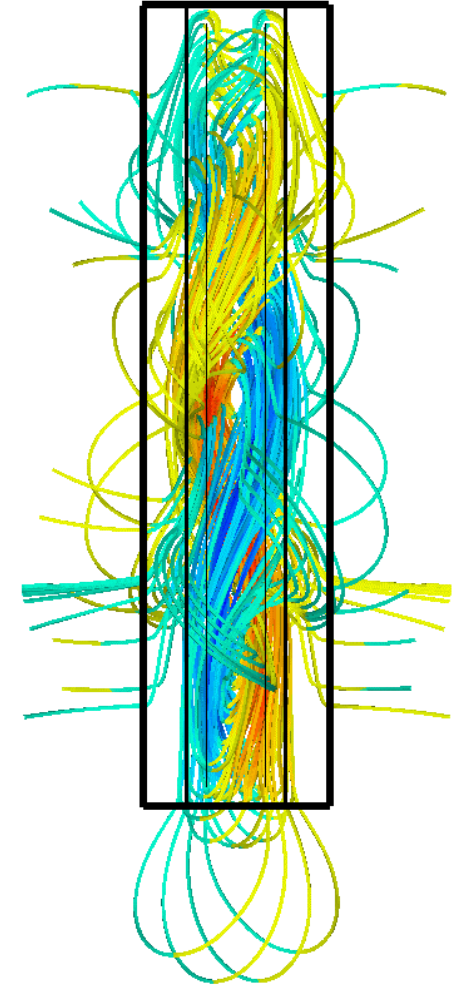
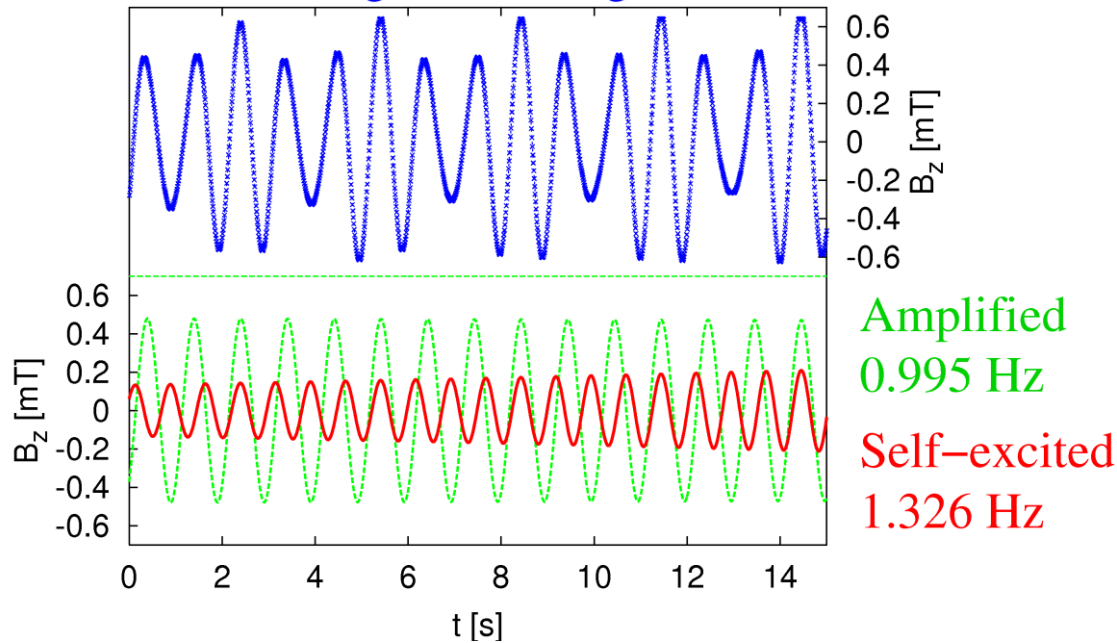
Gailitis et al., Phys. Rev. Lett. 84 (2000) 436

# Rigaer Dynamoexperiment

Erstmaliger Nachweis magnetischer Selbsterregung in einer Flüssigmetallströmung:

11.11.1999

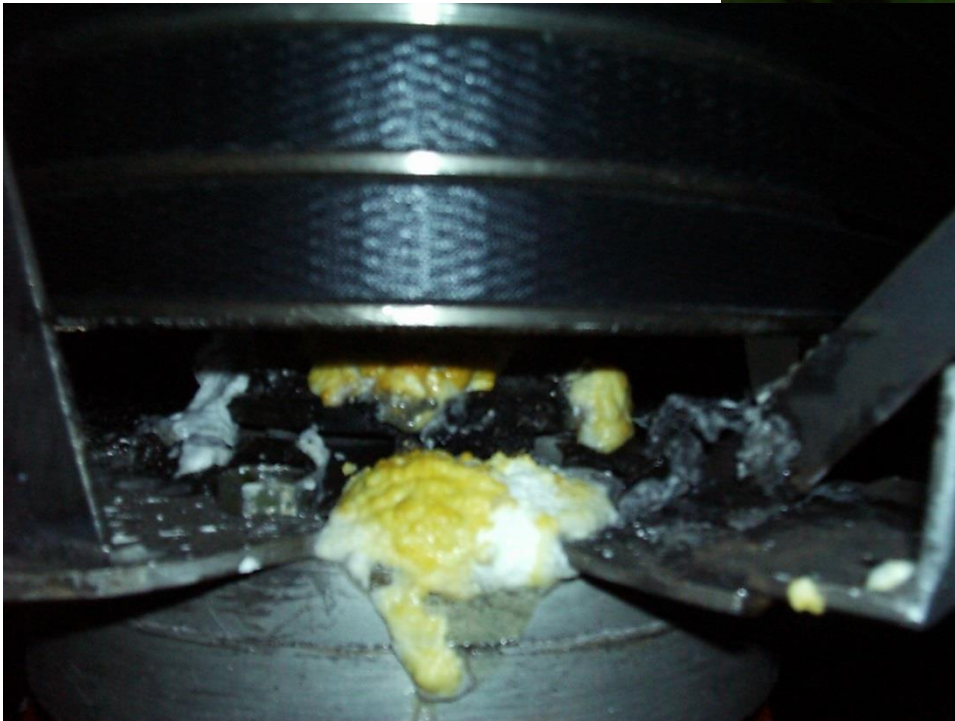
Measured signal at flux gate sensor



Gailitis et al., Phys. Rev. Lett. 84 (2000) 436

# Rigaer Dynamoexperiment – Vorsicht: Natrium!

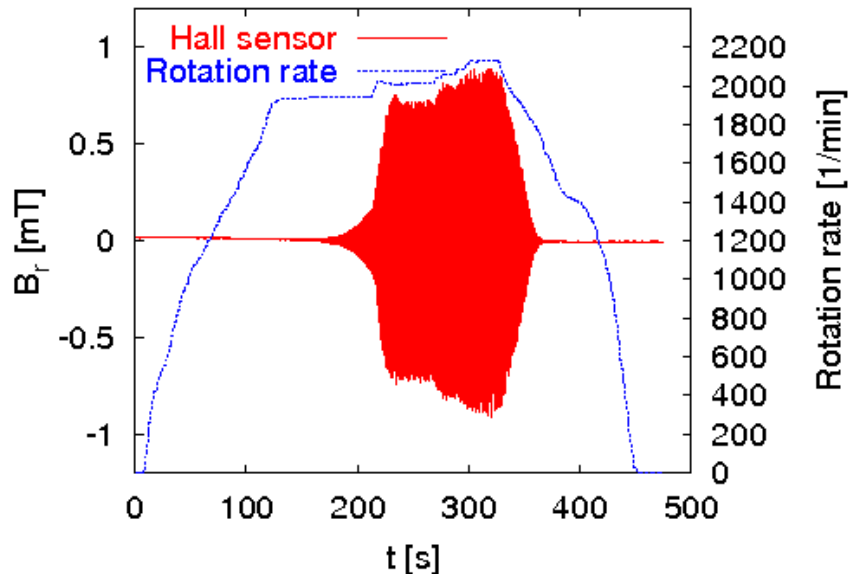
Der Abend des  
11.11.1999...



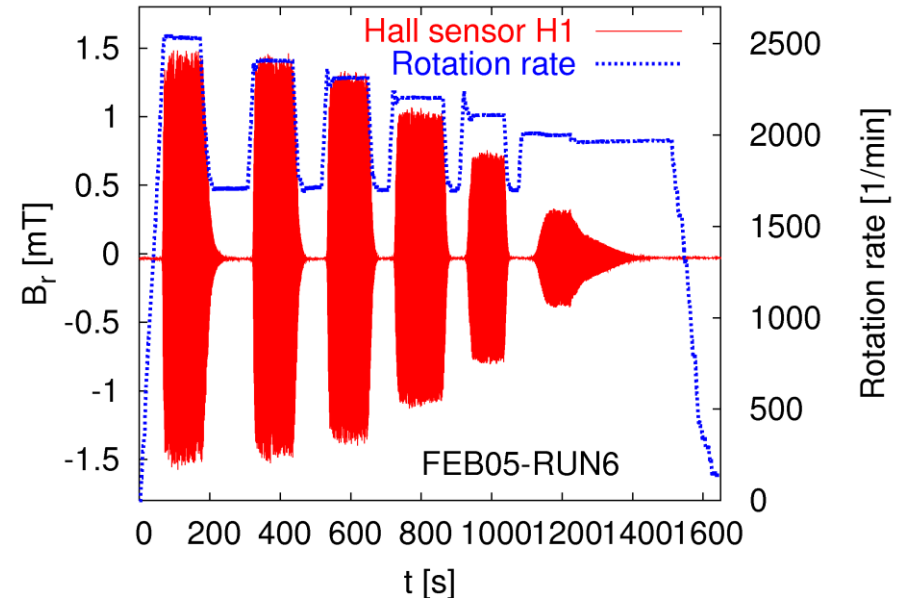
...und der Morgen  
danach...

# Rigaer Dynamoexperiment

Erreichen des Sättigungsregimes (Juli 2000)

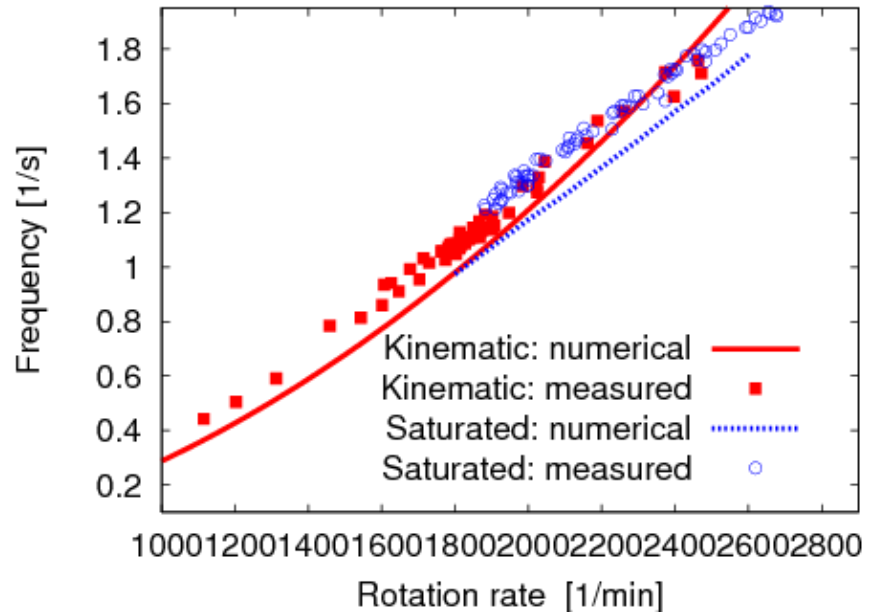
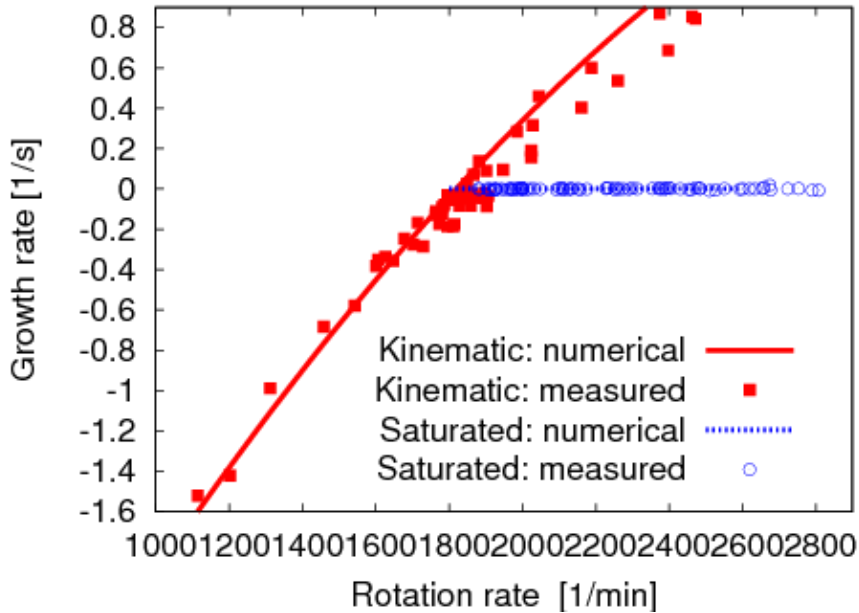


„An- und Ausschalten“ des Feldes (Februar 2005)



Gailitis et al., Phys. Rev. Lett. 86 (2001) 3024; Rev. Mod. Phys. 74 (2002) 973 ; Phys. Plasmas 11 (2004) 2838; Compt. Rend. Phys. 9 (2008), 721; J. Plasma Phys. 84, 735840301 (2018)

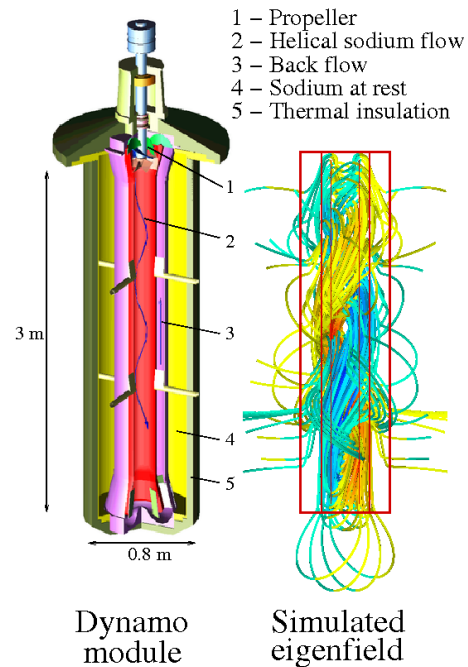
# Rigaer Dynamo: Wachstumsraten und Frequenzen des Magnetfeldes



Numerische Vorhersagen waren bis auf 5-10 Prozent genau

# Herzlichen Glückwunsch!

- Agris Gailitis erhält die Petrus Peregrinus Medal 2016 der European Geosciences Union





# Karlsruher Dynamo: Technische Realisierung eines $\alpha^2$ -Dynamos

## Der $\alpha$ -Effekt: Eine Thüringer Spezialität!

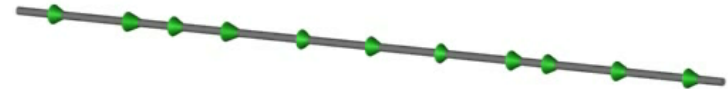
Unter dem Einfluss einer **schraubenförmigen** Strömung können elektrische Ströme entstehen, die **parallel** zum Magnetfeld sind



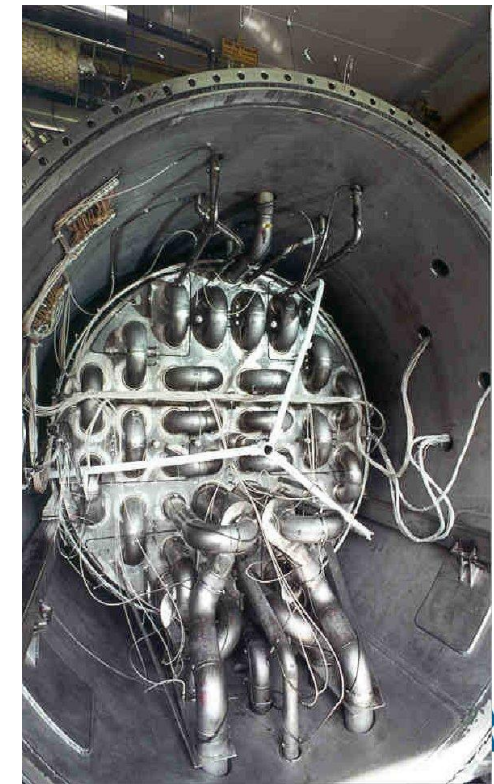
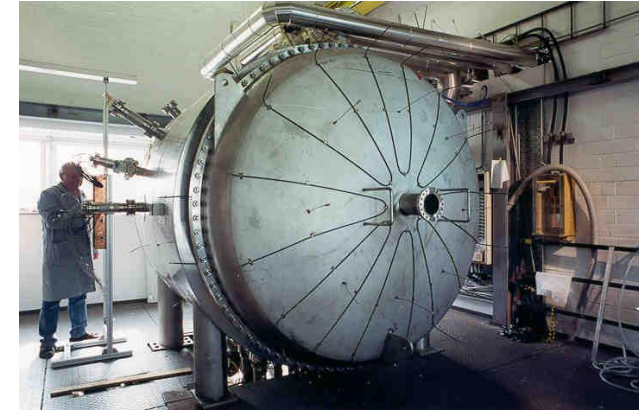
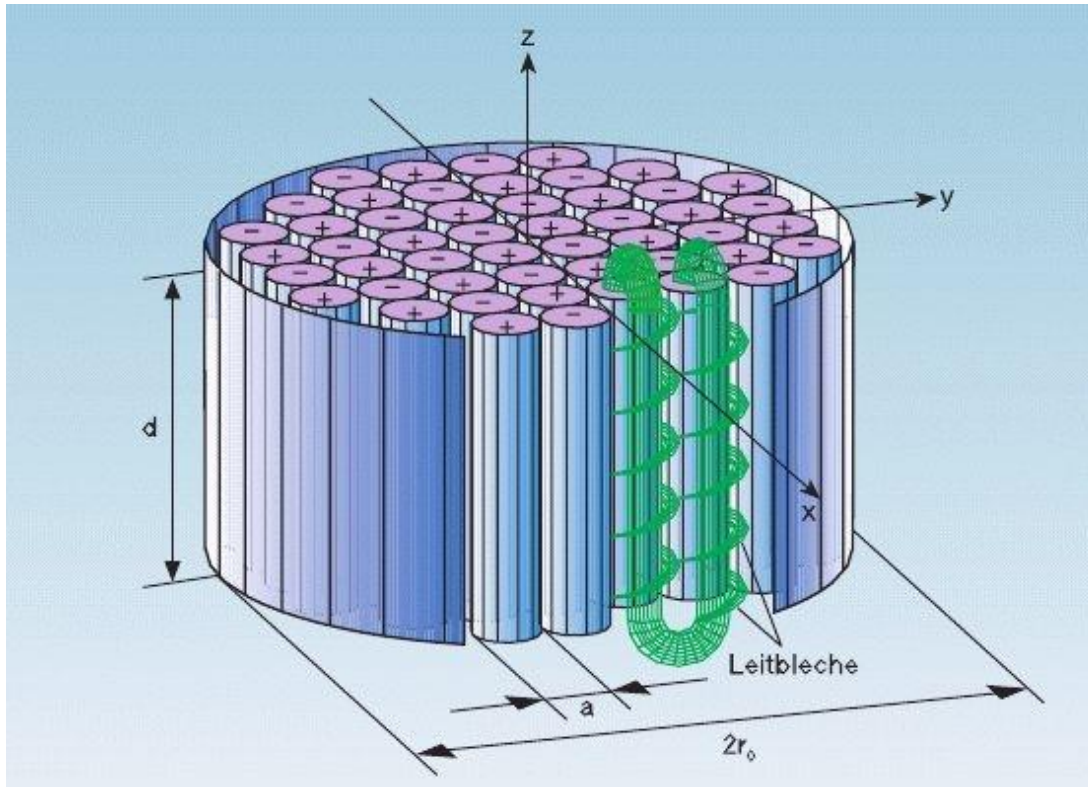
Max Steenbeck, Fritz Krause, Karl-Heinz Rädler:

*BERECHNUNG DER MITTLEREN LORENTZ-FELDSTÄRKE  
FÜR EIN ELEKTRISCH LEITENDES MEDIUM IN  
TURBULENTER, DURCH CORIOLIS-KRÄFTE  
BEEINFLUSSTER BEWEGUNG*

Zeitschrift für Naturforschung 21a, 369 (1966)



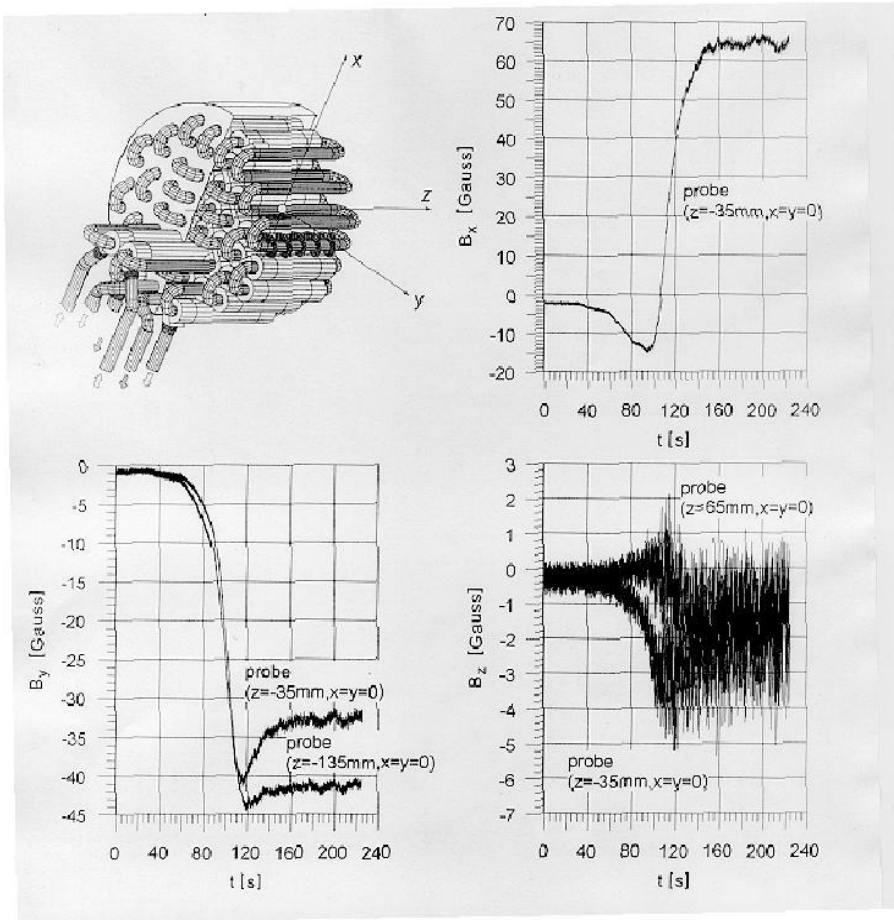
# Karlsruher Dynamoexperiment



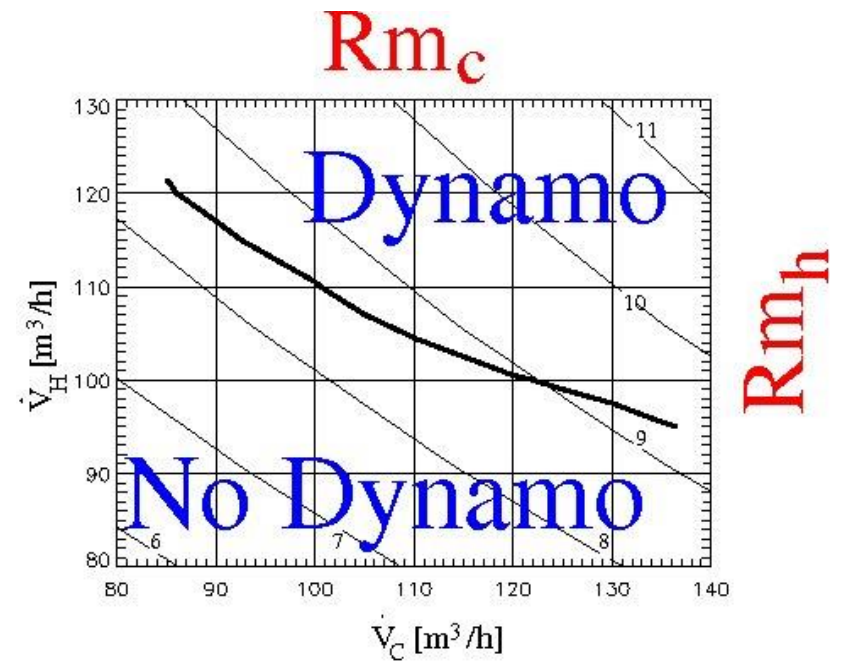
Technische Realisierung des  $\alpha$ -Effektes  
mit 52 „Spin-Generatoren“

Stieglitz and Müller, Phys. Fluids 13, 561 (2001)

# Karlsruher Dynamoexperiment



„Geheimes Fax“ von  
Karl-Heinz Rädler vom  
19.12.1999



Ebenfalls sehr gute Übereinstimmung  
mit numerischen Vorhersagen

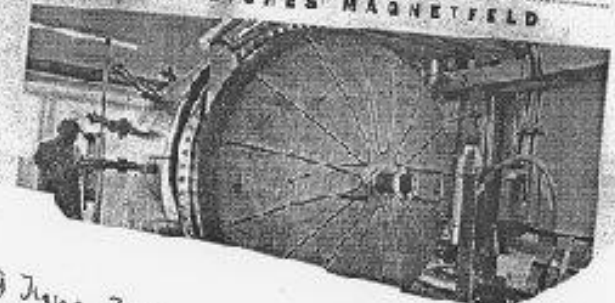


Karl-Heinz Rädler  
\* 14. Mai 1935  
† 9. Februar 2020

# „Dynamo Riga“ gegen „Dynamo Karlsruhe“

**BZ 22.10.00** **Zwei Forschergruppen streiten sich um einen ersten Platz**  
*Der Ursprung des Magnetfelds der Erde war nie nahezu zeitgleich in Riga und Karlsruhe simuliert und jedes Team will das erste ge...*

**ERDMAGNETFELD**  
**Streit um den Erdkern**  
*Bild der Wissenschaft 5/2000*  
 Zwei konkurrierende Forschergruppen haben erstmals das Erdmagnetfeld im Labor simuliert. Damit steht fest, das Erdrotations und der äußere flüssige Erdkern ein stabiles Magnetfeld erzeugen. Jetzt geht es um die Entdeckershre.

**KÜNSTLICHES MAGNETFELD**  


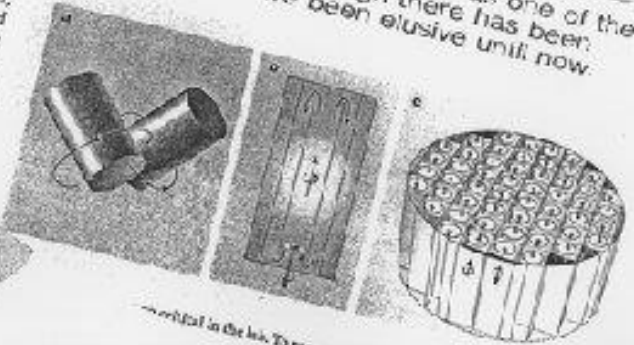
*Das Team des IZKA mit einer rotierenden Flüssigkeit selbst stabilisiertes erzeugt. Die Wissenschaftler Stieglitz plündern durch ein Rohr sind wie Luft. Das Schritt...*

*Das sich selbstnefeld ohne nicht geerd gemaint ist gendertel feld ward Labors Die Geri...*

**Frankfurter Allgemeine Zeitung**  
**FAZ 22.10.00**  
**Streit um das Magnetfeld der Erde**  
*Zwei Forschergruppen beanspruchen die erste Simulation für sich*  
 Zwei konkurrierende Forschergruppen haben erstmals das Erdmagnetfeld im Labor simuliert. Damit steht fest, das Erdrotations und der äußere flüssige Erdkern ein stabiles Magnetfeld erzeugen. Jetzt geht es um die Entdeckershre.

**Picture 29 June 2000**  
**Critical time for fluid dynamos**  
*news and views*  
 Andy Jackson  
 Einstein once cited the origin of the Earth's magnetic field as one of the fundamental unsolved problems of physics. Although there has been progress on paper, experimental models have been elusive until now.

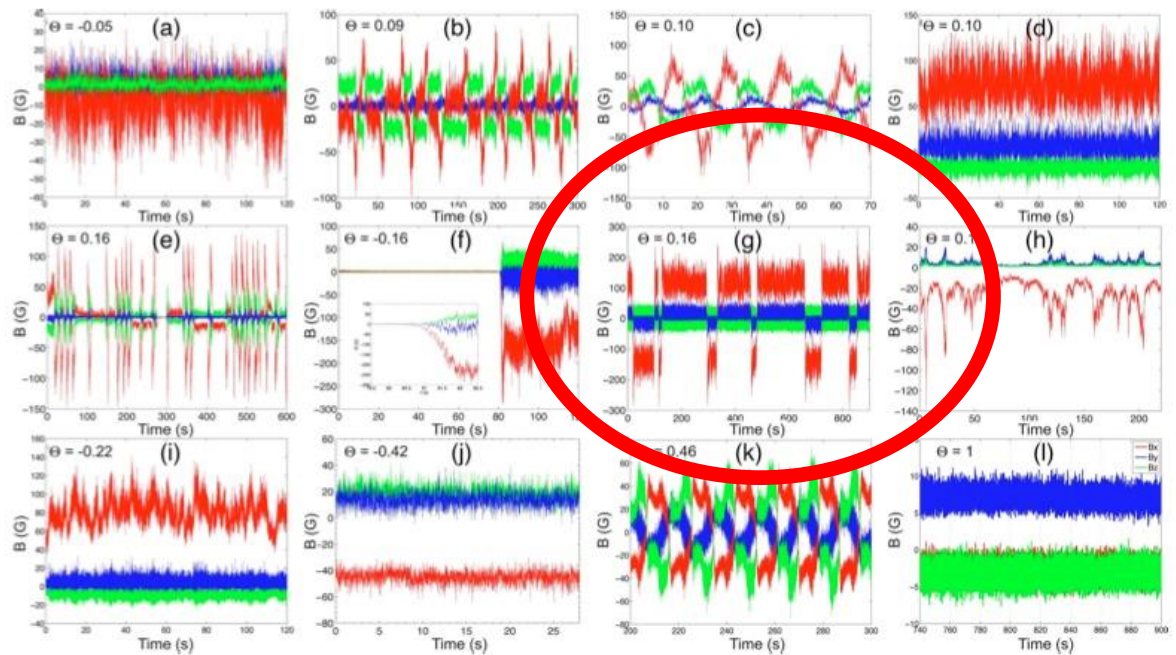
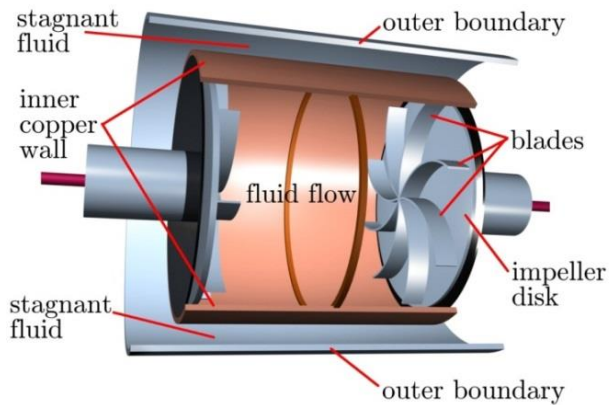
*The Earth's magnetic field originates in the liquid metallic core of the Earth, where it is sustained by complicated convection. Despite some progress on theory, attempts to recreate this story had, until recently, been largely unsuccessful. In many years of effort, reports of 'critical' conditions for the simulation of the Earth's magnetic field have been elusive until now.*



*critical in the lab to recreate the Earth's magnetic field*

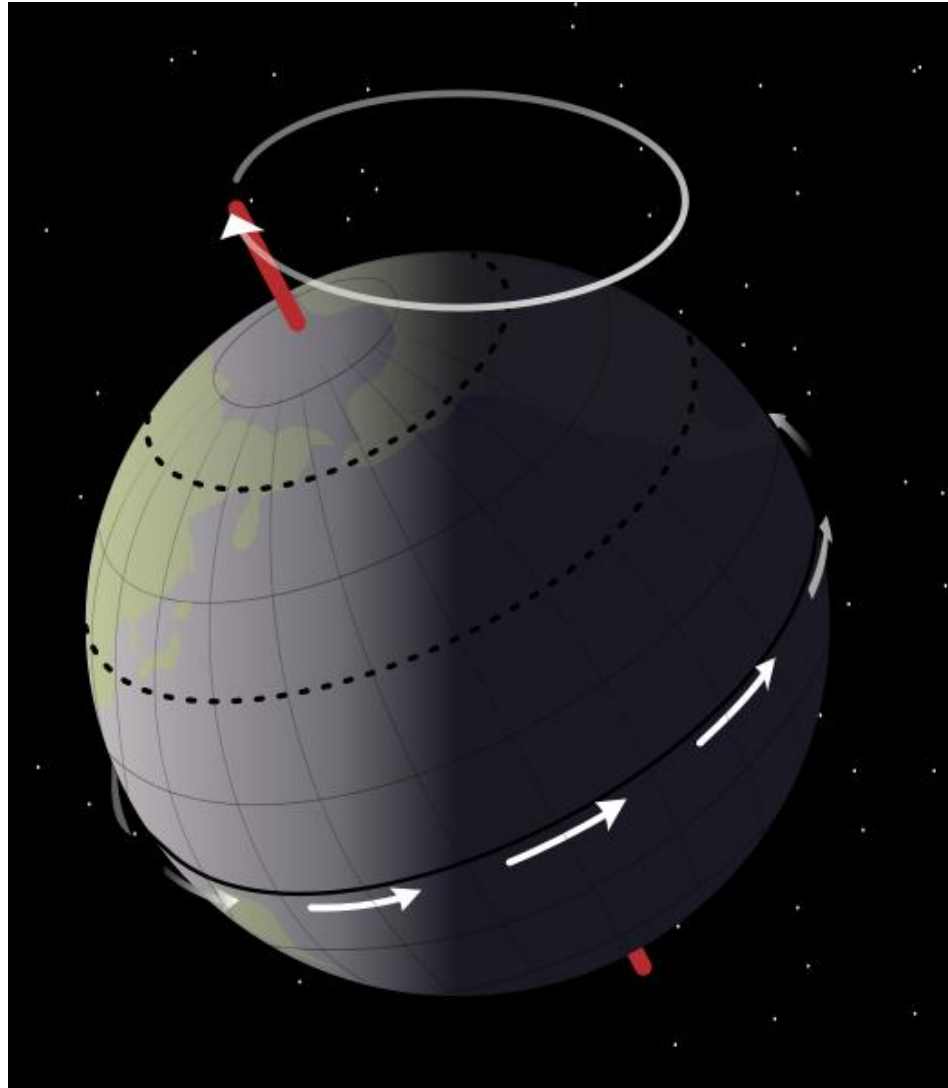
# von-Kármán-Sodium (VKS) Experiment (seit 2006)

VKS hat sowohl Selbsterregung als auch eine Reihe hochinteressanter dynamischer Effekte gezeigt (Oszillationen, **Umpolungen**, lokalisierte Felder), allerdings nur bei Verwendung magnetischen Propellermaterials...



Monchaux et al., Phys. Fluids 21 (2009), 035108

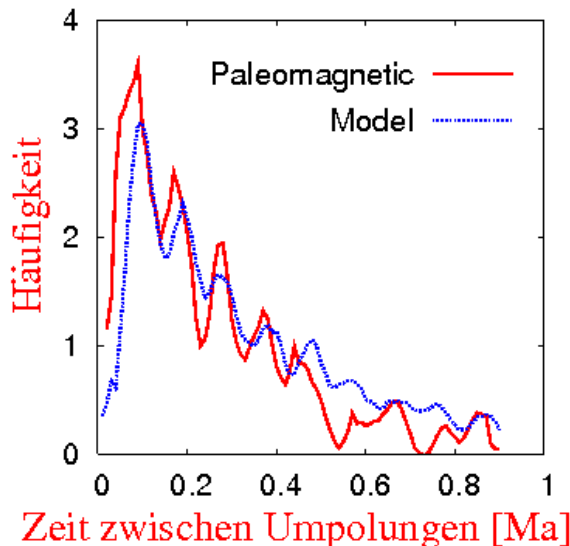
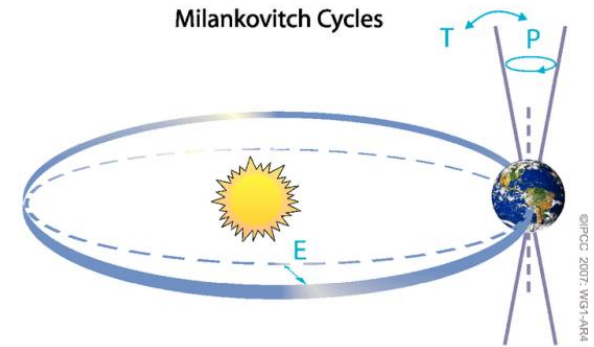
# Präzessionsgetriebener Dynamo: Was ist Präzession?



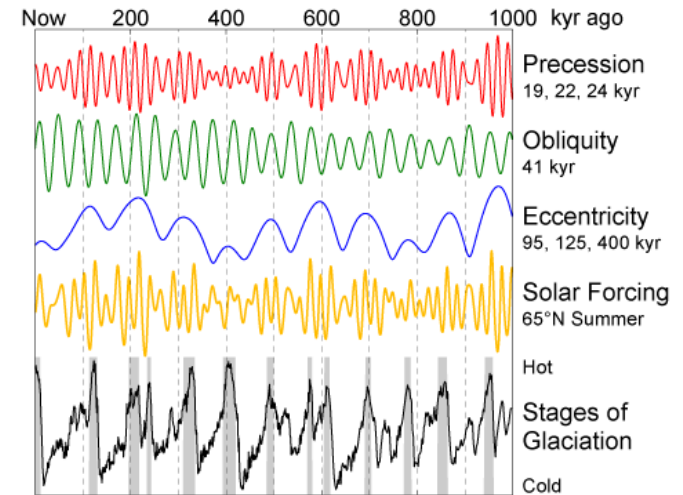
# Präzessionsgetriebener Dynamo: Geophysikalische Motivation

Häufigkeitsverteilung der Intervalle zwischen Umpolungen des Erdmagnetfeldes zeigt Maxima bei Vielfachen des Milankovich-Zyklus der Erdbahn-Exzentrizität (95 ka)

Indiz für eine wichtige Rolle von Variationen der Erdbahn für den Geodynamo



**Zusammenhang zwischen Erdmagnetfeld und Klima (Abfolge der Eiszeiten)**

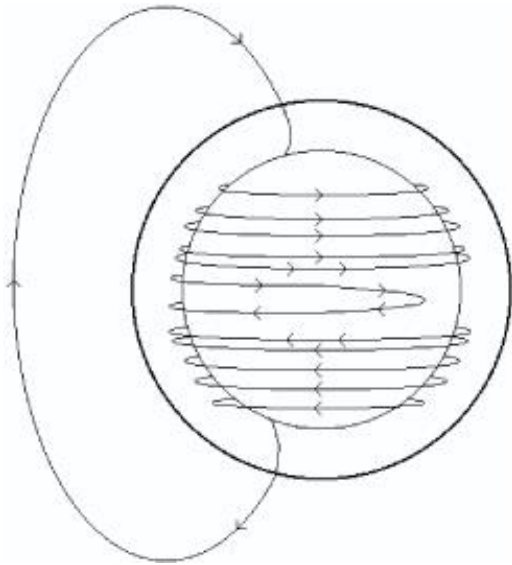


Präzession wird auch als Dynamoquelle für den frühen Mond sowie für Asteroiden (Vesta) diskutiert

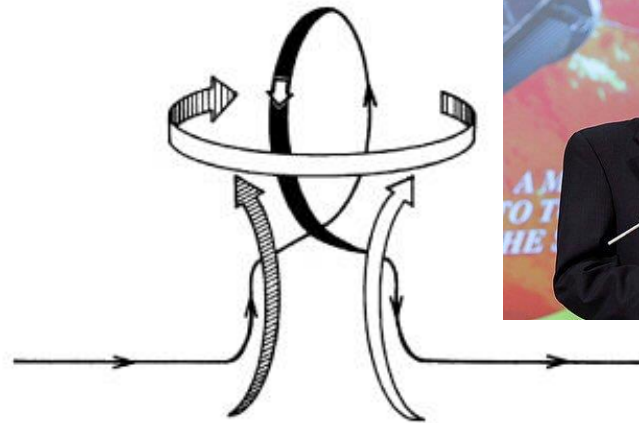
# Präzessionsgetriebener Dynamo: Astrophysikalische Motivation

Jedes Modell des Sonnendynamos benötigt:

- einen  **$\Omega$ -Effekt** zum Aufwickeln des toroidalen Feldes
- einen  **$\alpha$ -Effekt** zur Regeneration des poloidalen Feldes



$\Omega$  effect



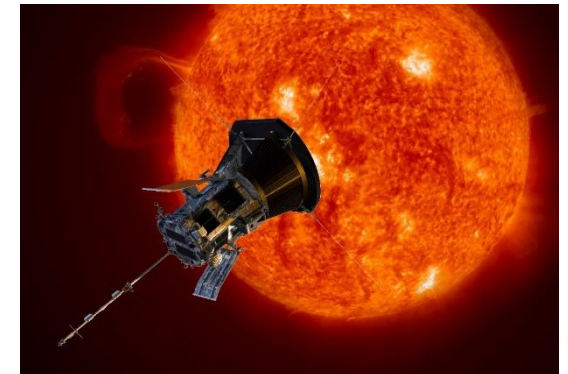
$\alpha$  effect



Eugene N. Parker

\* [10. Juni 1927](#)

† [15. März 2022](#)



Parker, *Astrophys J.* 122, 293 (1955)

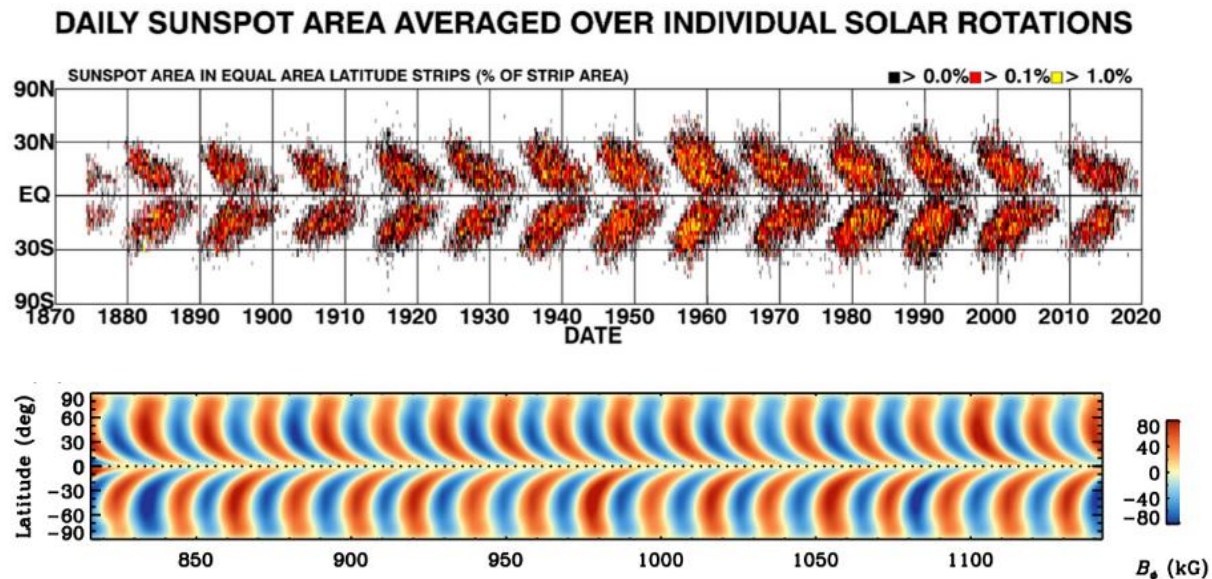


# Sonnendynamo: Konventionelle Modelle

Mit konventionellen Modellen (inklusive meridionaler Zirkulation), und ein paar angepassten Parametern erhält man problemlos

- eine vernünftige **Periode des Hale-Zyklus** (~22 Jahre)
- eine vernünftige **Gestalt des Schmetterlingsdiagramms** der Sonnenflecken

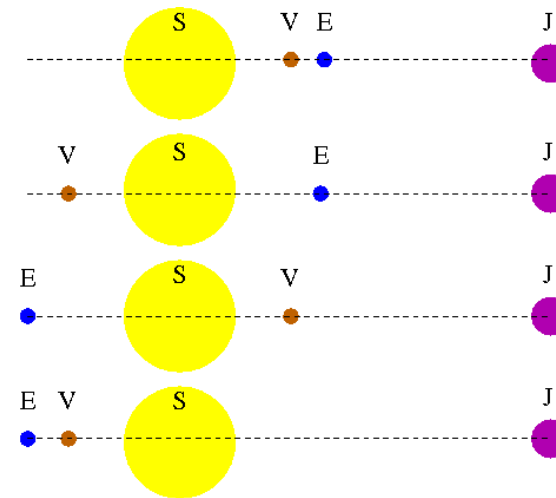
<http://www.solarcyclescience.com/solarcycle.html>



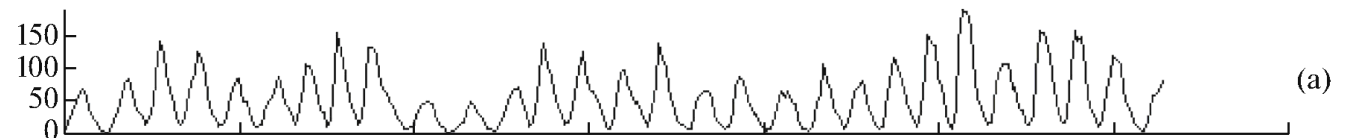
Karak, B.B., Miesch, M., ApJ 847 (2017), 69

# Aber...

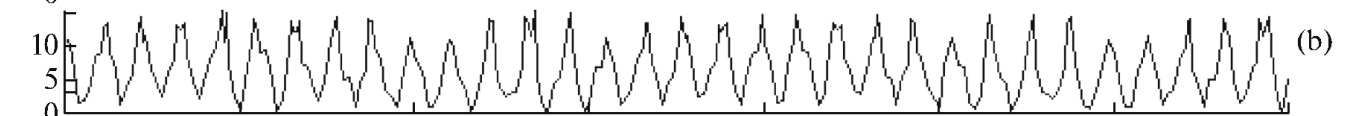
**Auffällige Synchronisierung  
des Sonnen-Zyklus mit 11.07  
Jahres-Zyklus des Venus-  
Erde-Jupiter-Systems (trotz  
sehr kleiner Gezeitenkräfte!)**



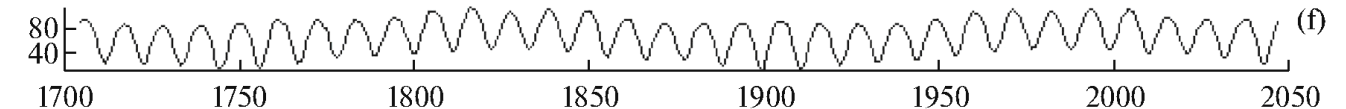
**Sonnenflecken**



**VEJ-Index**

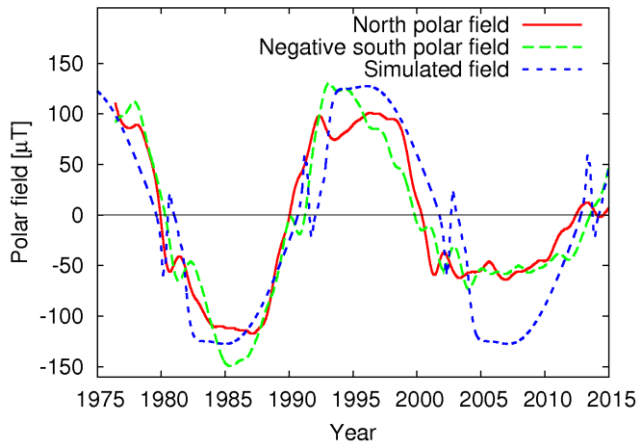
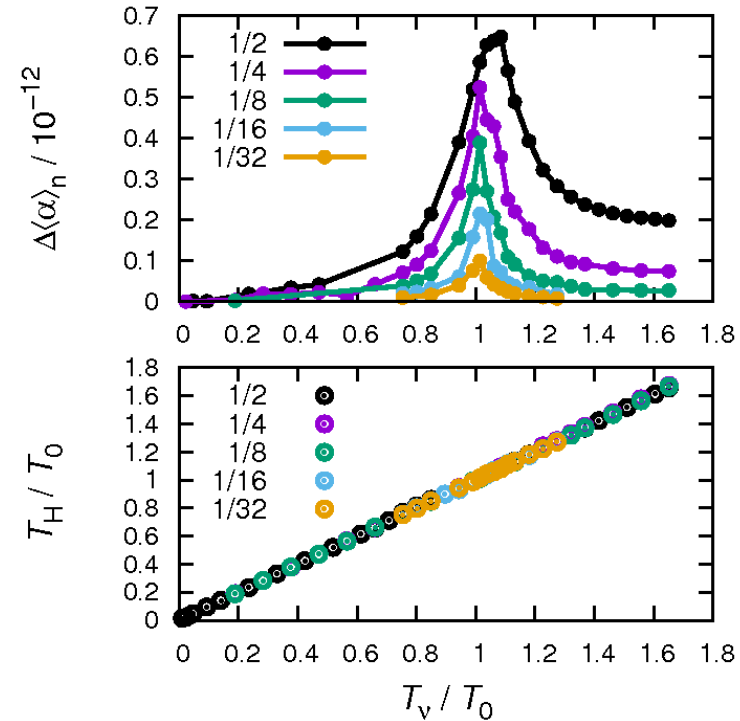
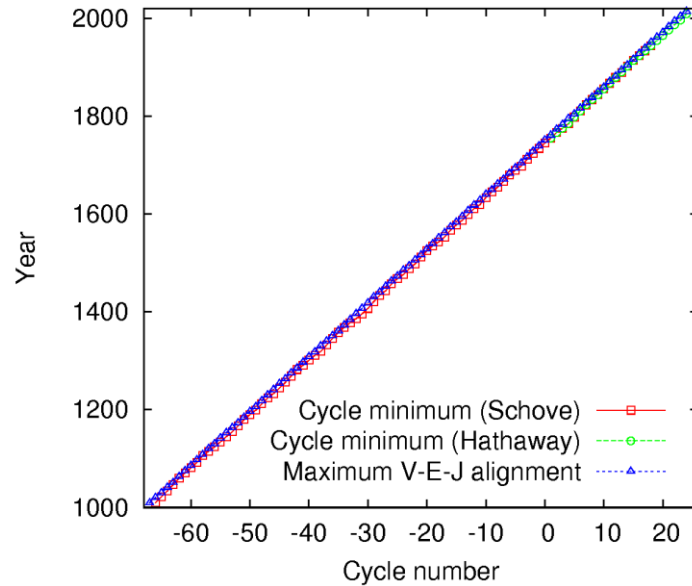


**Zufall oder Physik?**



1700 1750 1800 1850 1900 1950 2000 2050  
Years

# Synchronisierungsmodell des Sonnendynamos



1:1 Synchronisierung der Helizität der Taylor-Instabilität durch Gezeitenwirkung des Venus-Erde-Jupiter-Systems  $\rightarrow$  Sonnenzyklus mit 22.14-Jahres-Periode

Stefani et al, Solar Phys. 291 (2016), 2197; 294 (2019), 60

# Presse-Echo: Newsweek vom 4.6.2019, Editor's pick

Newsweek

SIGN IN

DOWNTIME CULTURE

**Conservatives Use Social Media to Move Agendas Much More Than Liberals Do**

DOWNTIME CULTURE

**Poor Economic Incentives Have Left Doctors Without New Antibiotics**

DOWNTIME CULTURE

**We're Running Out of Effective Drugs to Fight Off an Army of Superbugs**



**AFTER THE STORM**

**N** EDITOR'S PICK



WORLD

**Donald Trump U.K. Visit: Meet the Republicans Who Will Be Celebrating**

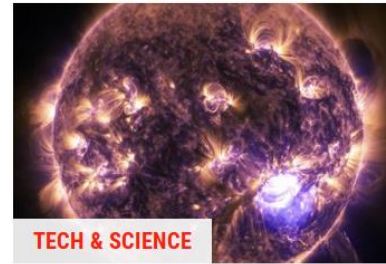
Not everyone will be waving "Dump Trump" placards when the president comes to stay.



POLITICS

**2020 Democrat: AOC's Health Care Talk Could Spell Trump's Re-Election**

Presidential candidate John Delaney and freshman Representative Alexandria Ocasio-Cortez are in a war of words over Medicare for All.



TECH & SCIENCE

**Sun's Solar Cycle Appears to Be Governed by the Alignment of the Planets**

Venus, Earth and Jupiter's tidal forces influence the solar magnetic field, according to new research.



U.S.

**Alabama Church to Show 'Arthur' Gay Wedding Episode After State TV Ban**

The First Methodist Church in Birmingham, Alabama, will host a screening and wedding party to celebrate the episode on June 15.

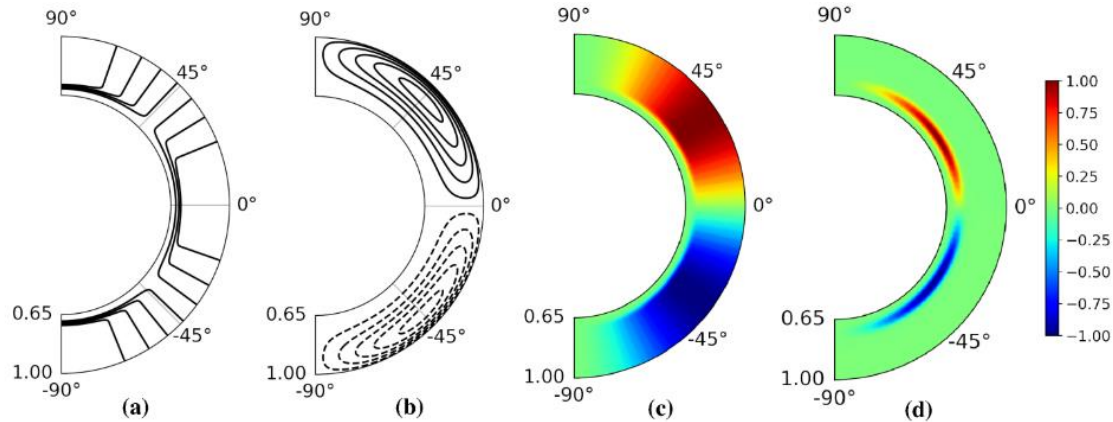
Donald  
Trump

Alexandria  
Ocasio-Cortez

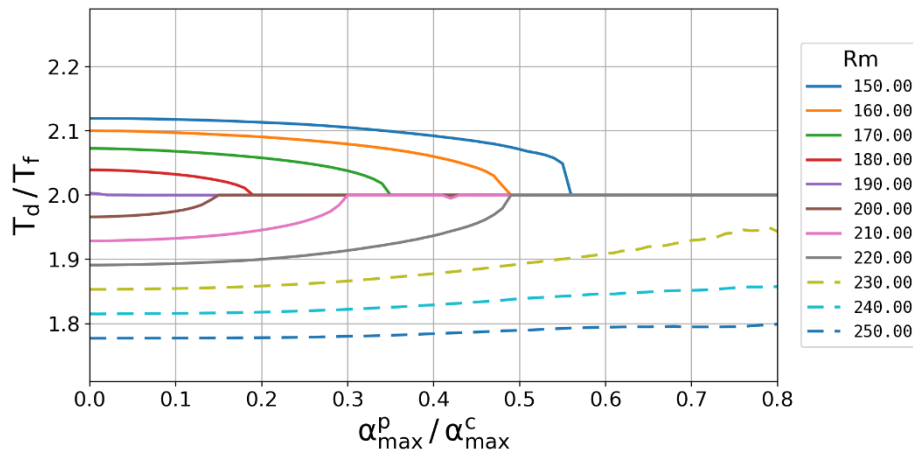
Solar Physics  
294 (2019), 60

„Arthur“

# Neu: Realistisches 2D-Modell der Synchronisierung

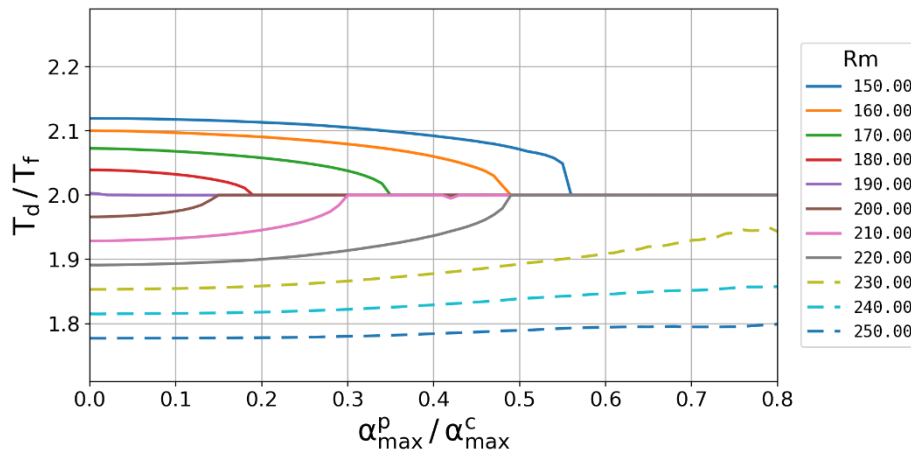
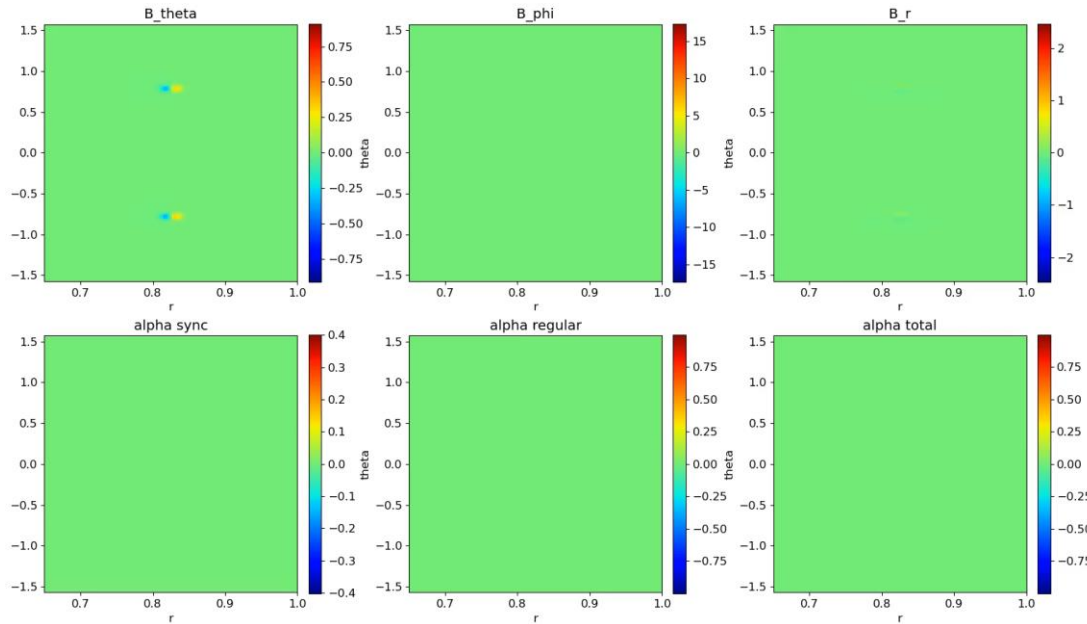


**Figure 1.** Spatial structures of the main ingredients of the dynamo model in the meridional plane. (a) Isolines of  $\Omega(r, \Theta)/\Omega_{\max}$ . (b) Streamlines of  $\mathbf{u}_p(r, \Theta)$ . (c) Constant part of  $\alpha$ , taken in the unquenched state:  $\alpha^c(r, \Theta)/\alpha_{\max}^c$ . (d) Periodic part of  $\alpha$ , with the resonance term set to 1:  $\alpha^p(r, \Theta)/\alpha_{\max}^p$ .



Für einen vernünftigen Wert  $\alpha_0=1.3$  m/s, **braucht man lediglich 1 dm/s synchronisiertes  $\alpha$** , um den ganzen **Sonnendynamo zu takten**. Dieser Wert ist durchaus realistisch!

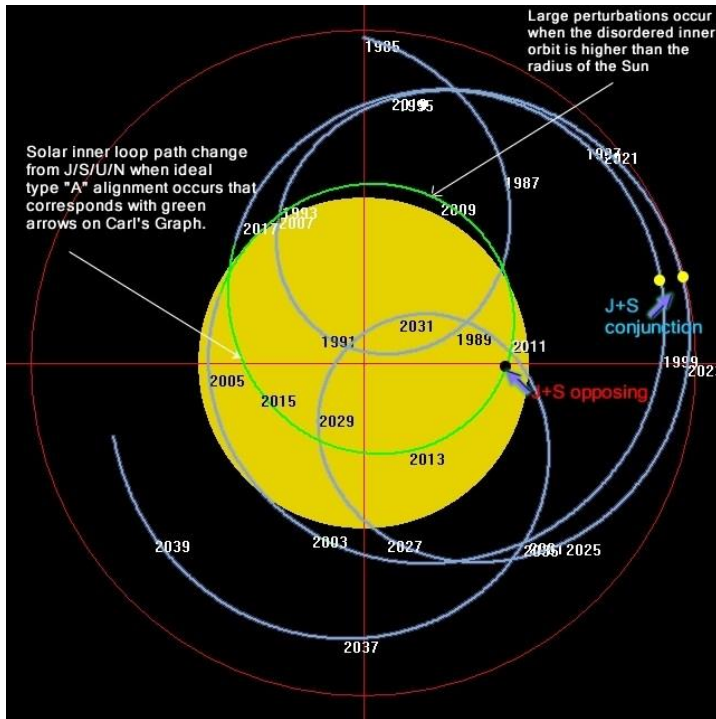
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M. Klevs, F. Stefani., L. Jouve, arXiv:3201.05452

# Inzwischen: Konsistente Erklärung kurzer und langer Zyklen



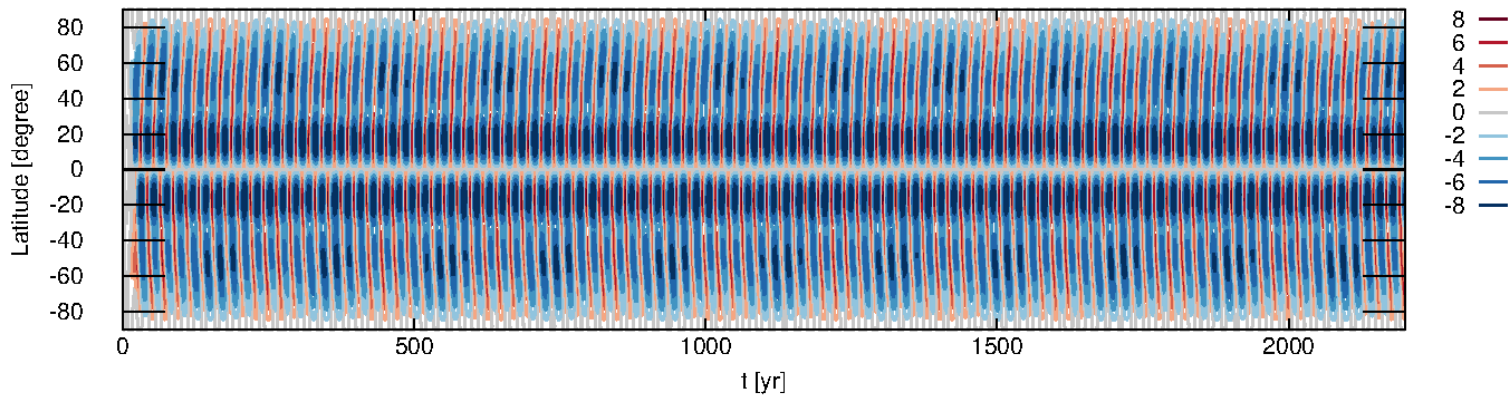
Gezeitenwirkung → **22.14 Jahre**

Sonnenbewegung um das  
Schwerezentrum des  
Sonnensystems → **19.86 Jahre**

Schwebungsperiode: **193 Jahre**

Simulation mit 19.86 Jahre Störung

**193 Jahre**



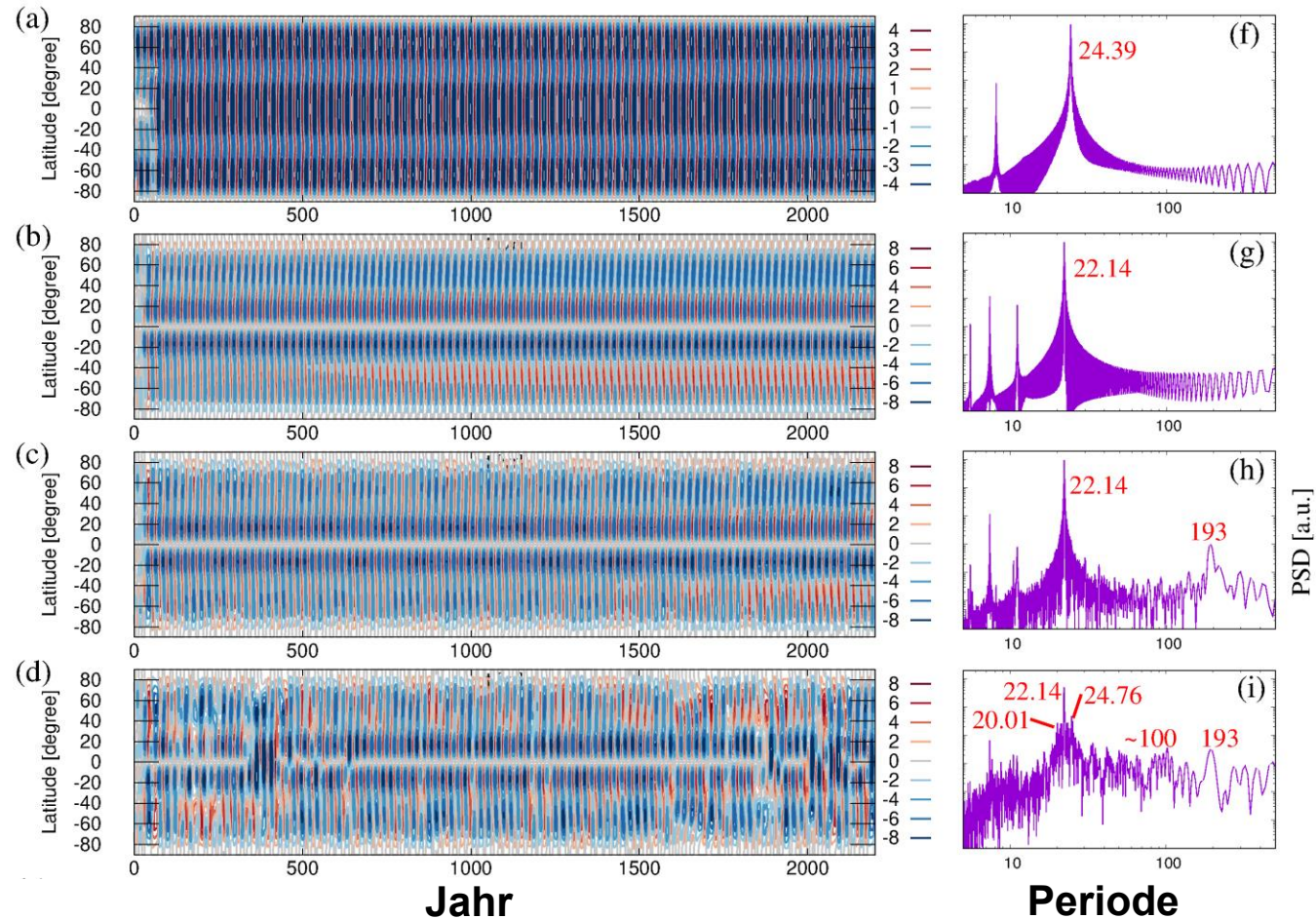
# Konsistentes Bild von Schwabe, Gleissberg, Suess/de Vries und Grand Minima!

$\alpha$ - $\Omega$ -Dynamo ohne Synchronisierung

$\alpha$ - $\Omega$ -Dynamo mit einfacher Synchronisierung (11.07 Jahre)

$\alpha$ - $\Omega$ -Dynamo mit 11.07-Jahres-Synchronisierung +  $\sim$ 19.86-Jahres-Modulation

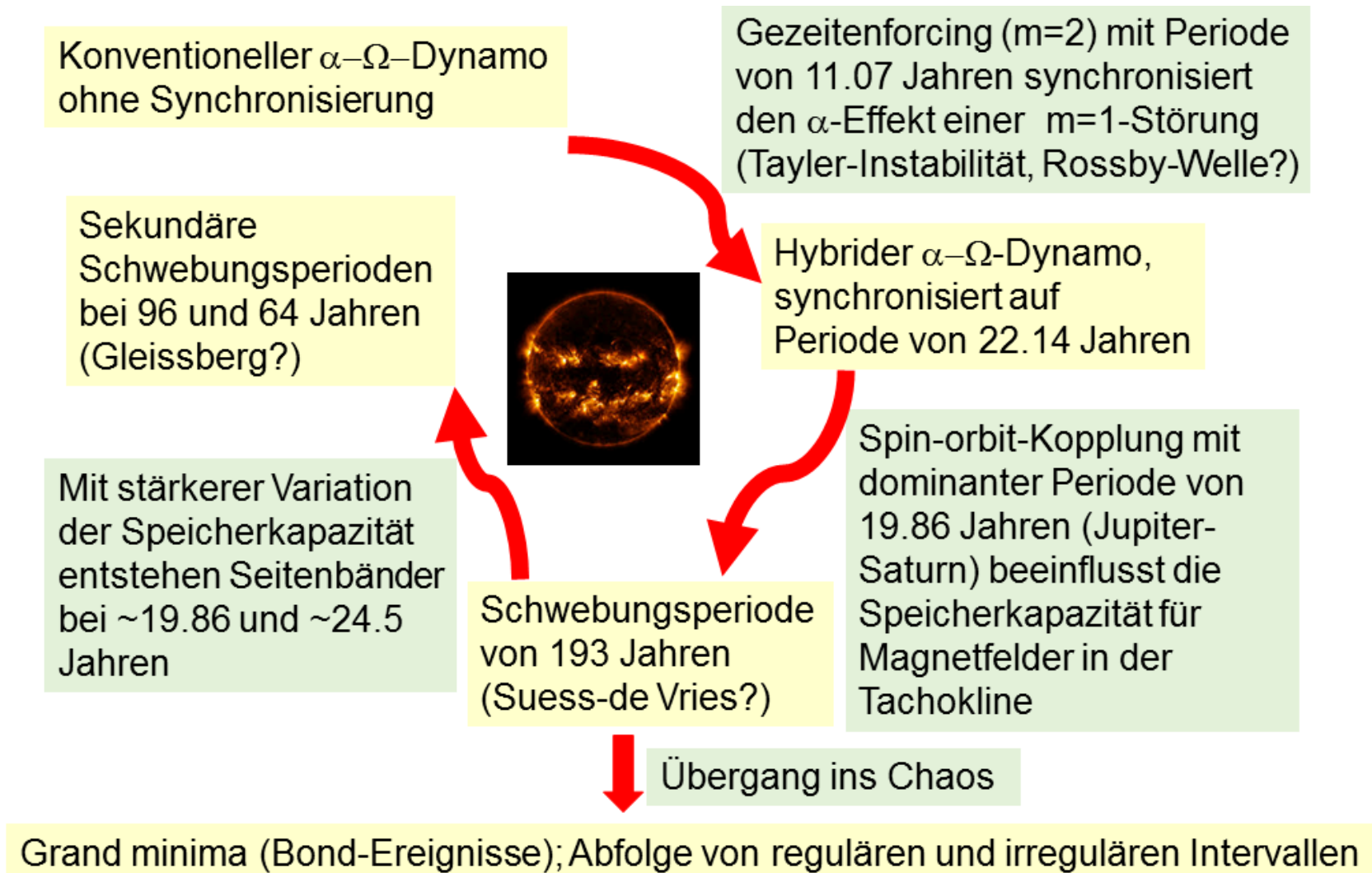
$\alpha$ - $\Omega$ -Dynamo mit 11.07-Jahres-Synchronisierung + stärkere  $\sim$ 19.86-Jahres-Modulation



Stefani et al., Magnetohydrodynamics 56 (2020), 269



# Gesamtes Synchronisierungsmodell des Sonnendynamikos

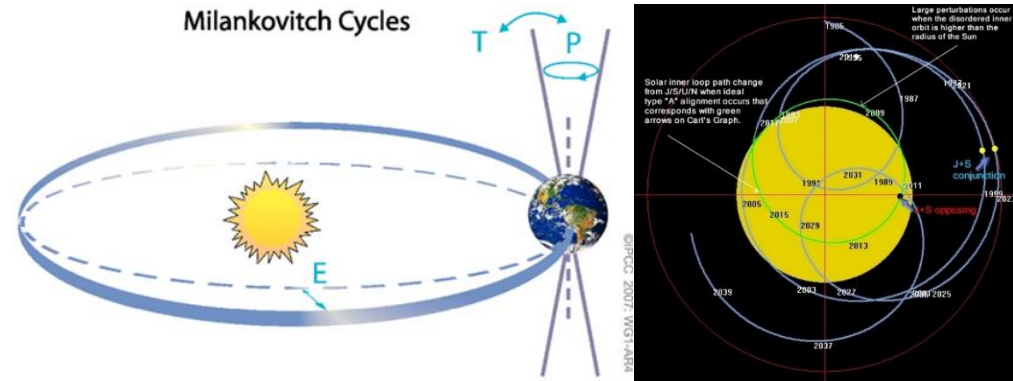


Stefani et al., Solar Physics 296 (2021), 88

# Präzessionsgetriebener Dynamo: Geschüttelt, nicht gerührt

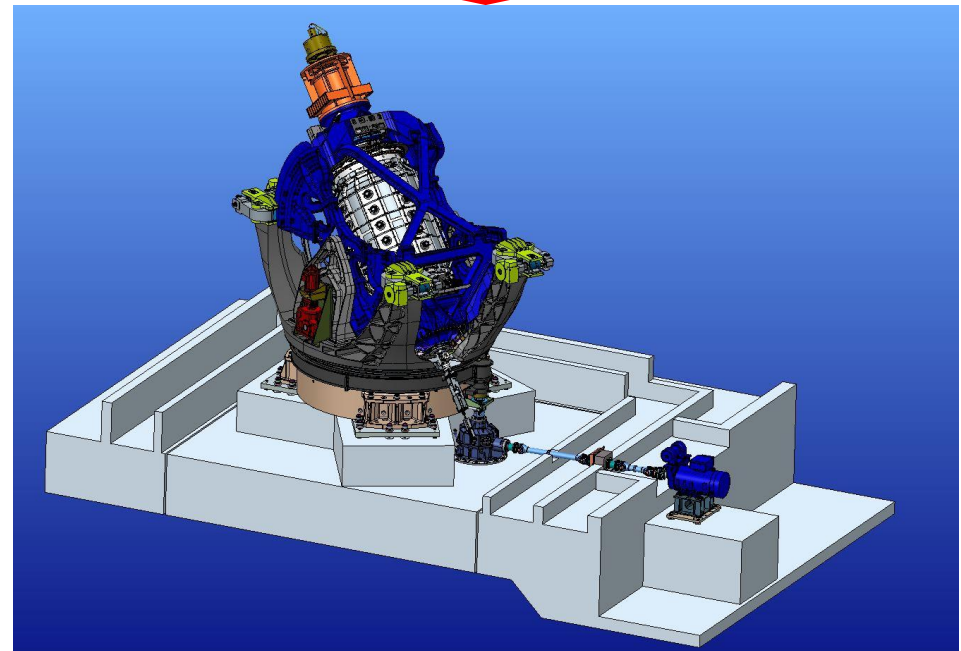
## Parameter:

- 2 m Durchmesser, 2 m Höhe, konische Endstücke,  $\sim 8 \text{ m}^3$  Natrium
- Ziel: Rotation mit 10 Hz, Präzession mit 1 Hz



## Herausforderungen:

- Sehr großes, umlaufendes Kreismoment (etwa 8 Millionen Nm)!
- Natrium ist im Havariefall nicht ablassbar!



# Präzessionsdynamo



Quelle: SBS Bühnentechnik (Zeitlupe mit Faktor 10)

# “Fundamentale” Probleme auf Grund des gewaltigen Kreiselmoments



April 2013: Bohren der 22 m tiefen Löcher für 7 Säulen

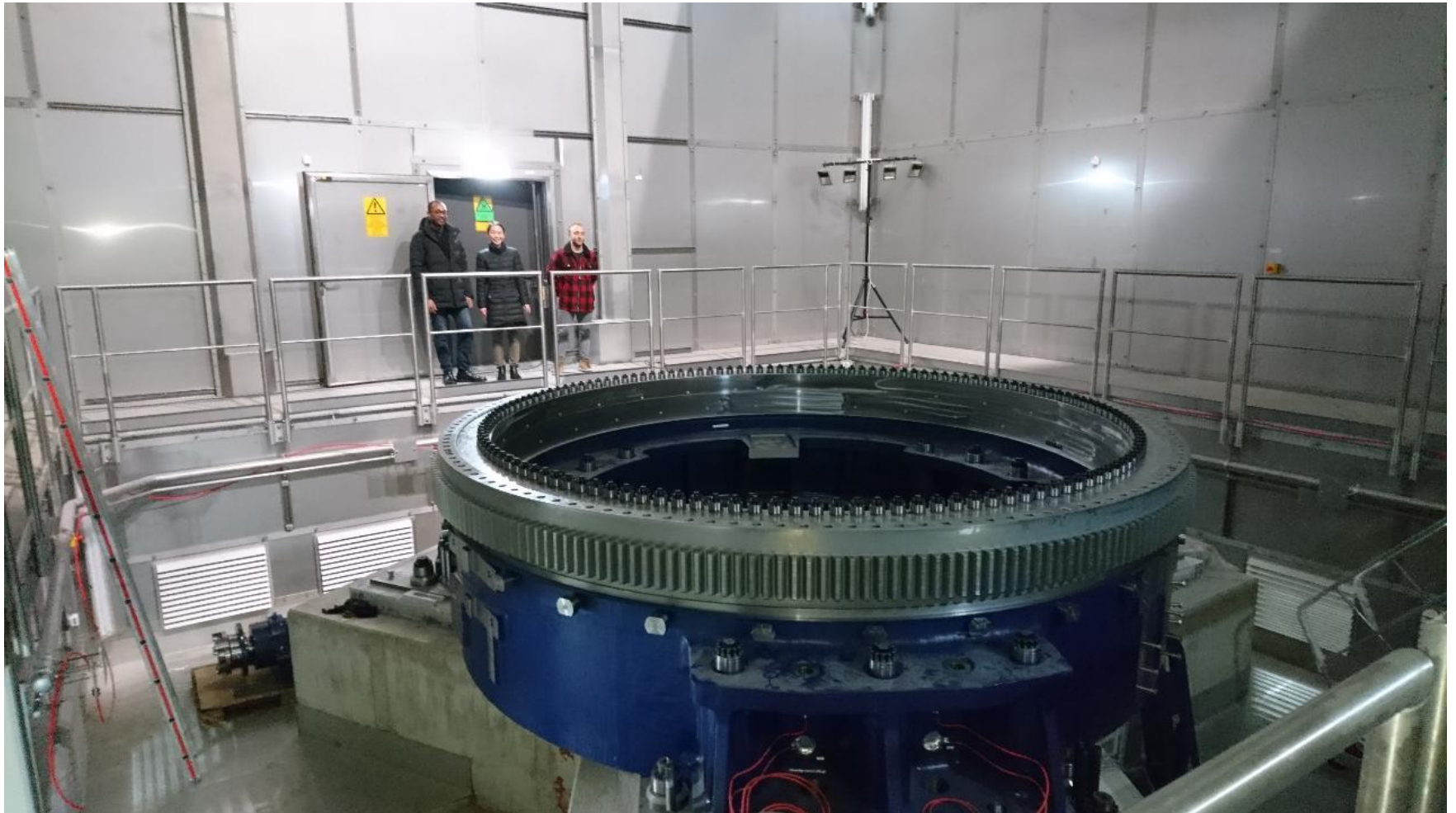


Juli 2013: Konstruktion des Fundaments



November 2014: Dreifuß für das Dynamo-Experiment innerhalb des Containments (mit “Edelstahltapete”)

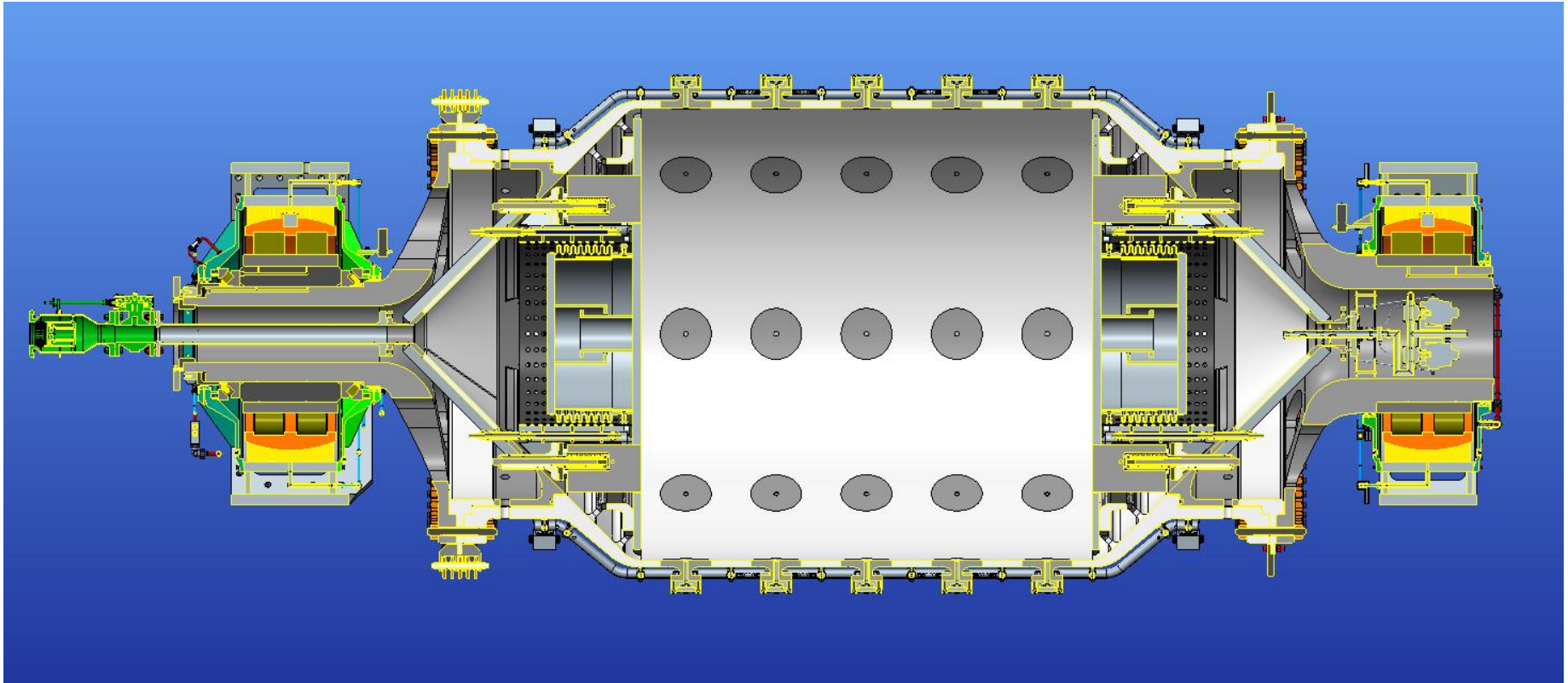
# Untergestell mit Großwälzlager (12/2018)



# Traverse and Pylonen (01/2019)



# Präzessionsdynamo: Rotationsbehälter mit Lagern



# Rotationsbehälter: erfolgreiche Druckprobe mit 35 bar am 14.3.19

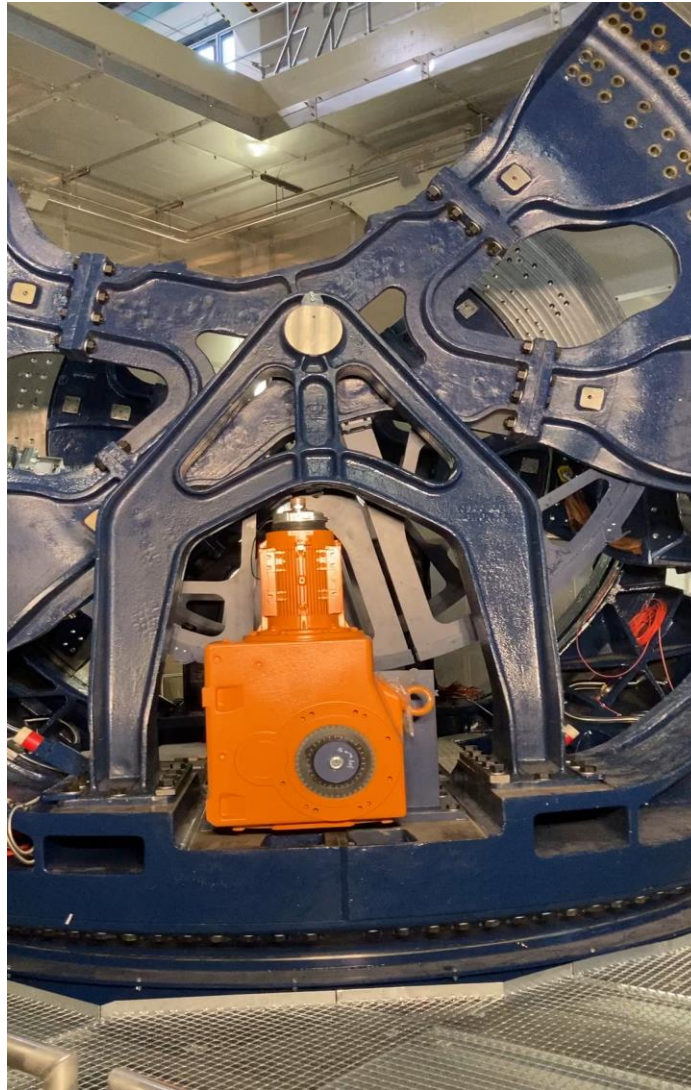




# Der Rotationsbehälter kommt in Rossendorf an (3. Juli 2020)



# Und sie bewegt sich doch!



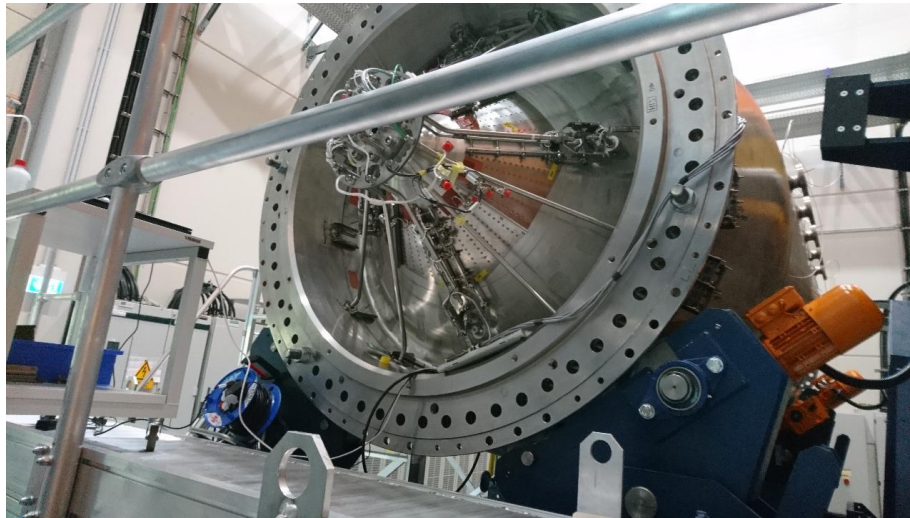
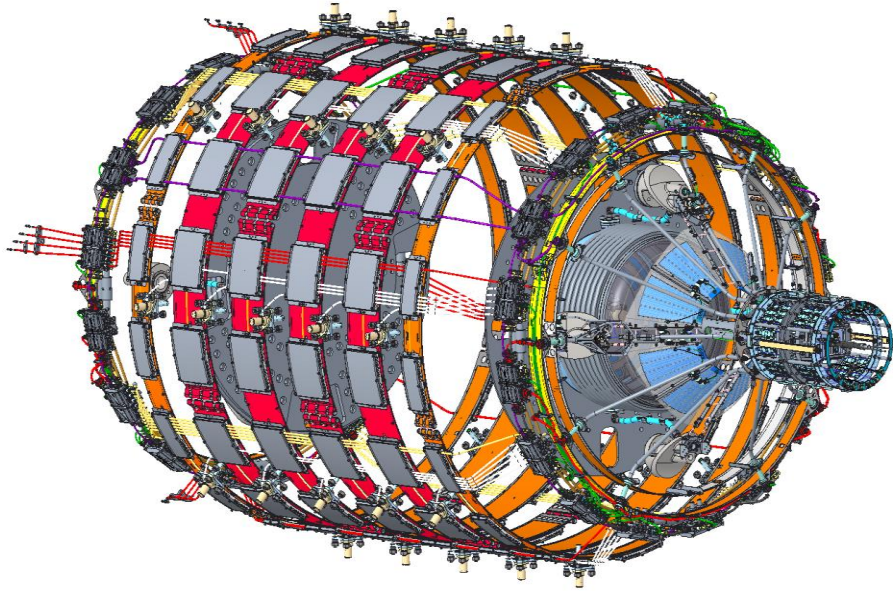
# Konische Endstücke, Aufschruppfen der Lager



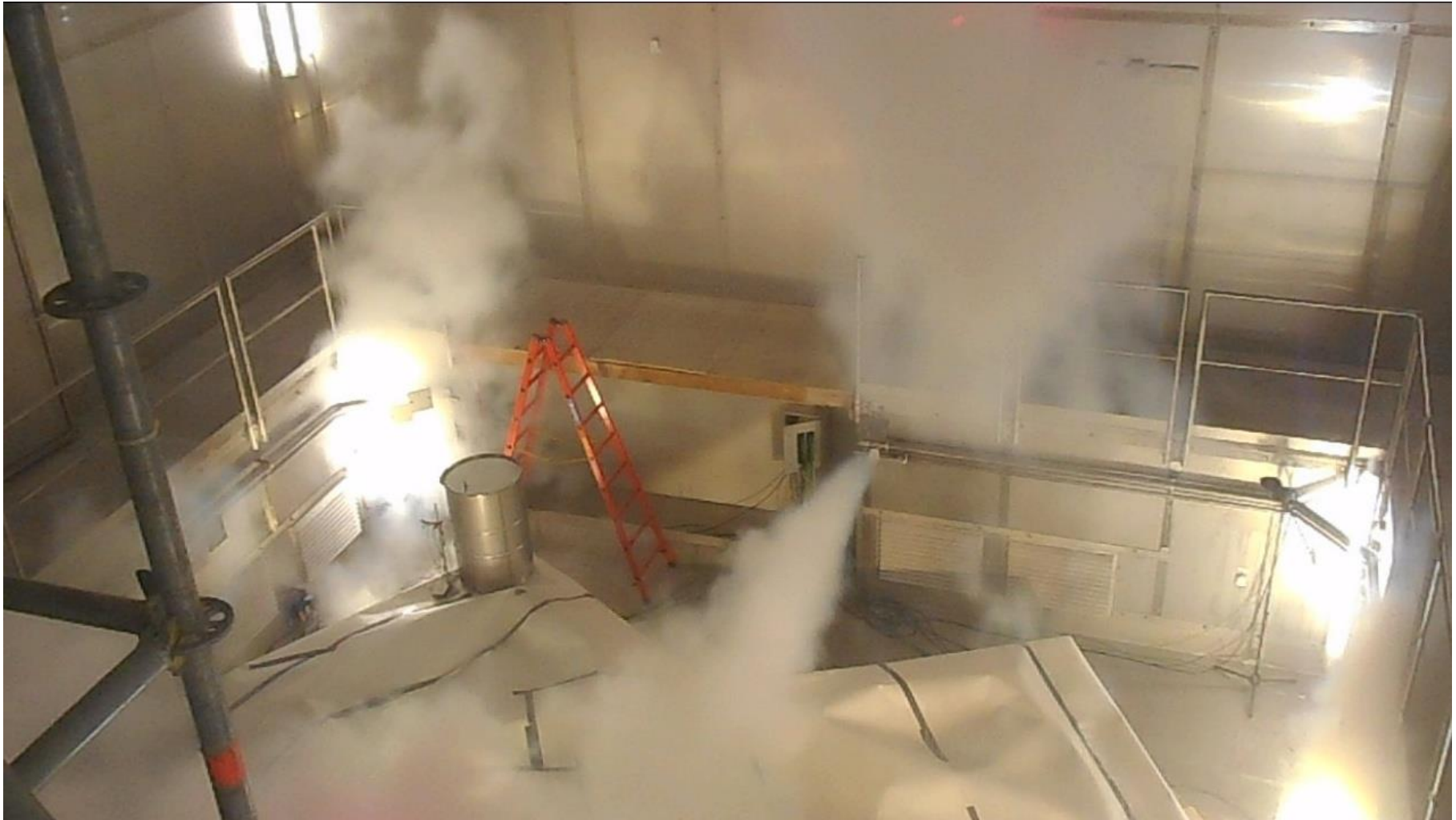
# Motor ist nach Kranschlingenriss (Mai 2022) noch in Reparatur

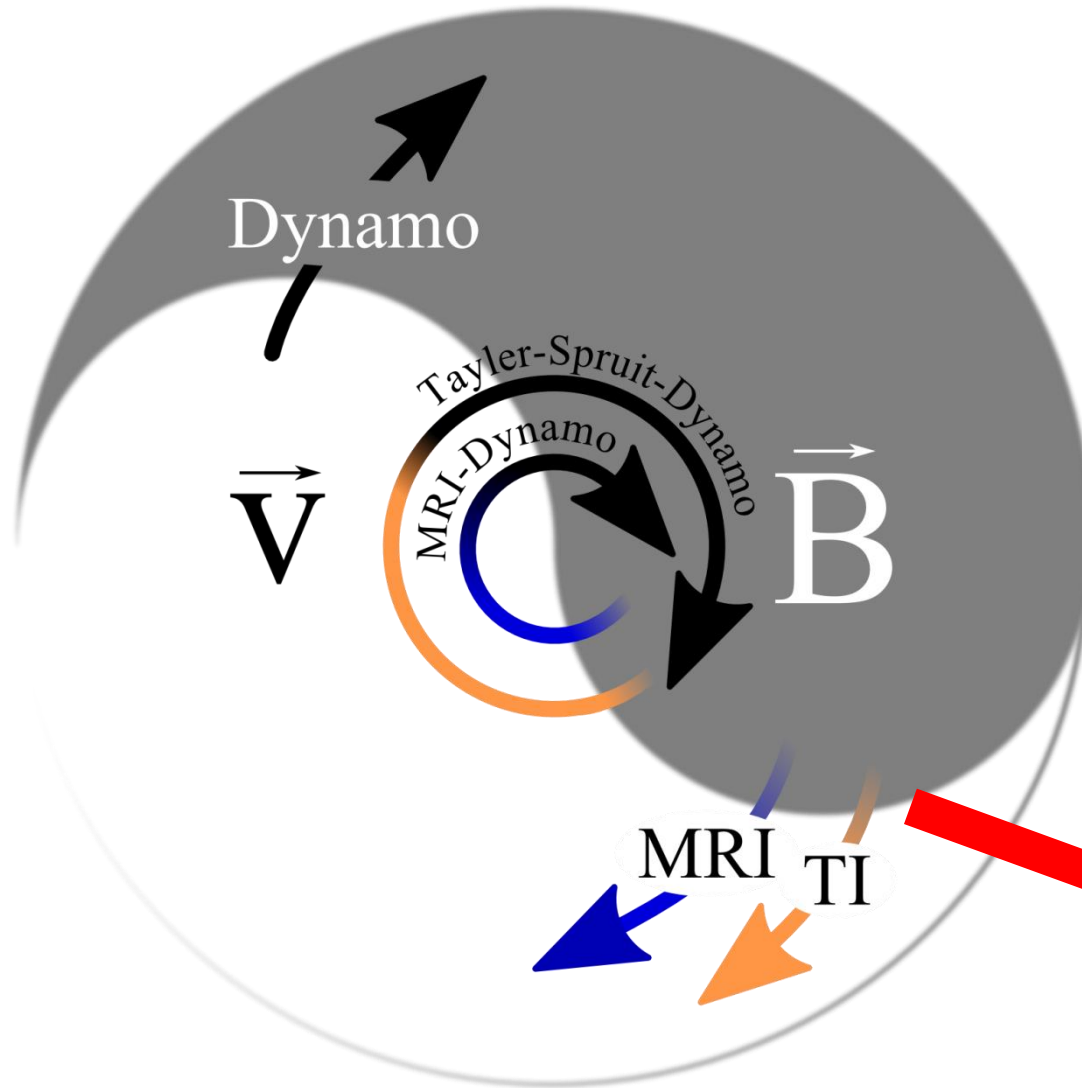


# Derzeit: Installation der Sensoren und der Heizung



# Test der Argon-Löscheinrichtung im Containment





Zweiter Teil

# Alfvén-Wellen: Vorhersage 1942 → Nobelpreis 1970

## Anemotaxis in *Drosophila*

COLE<sup>1</sup> has observed that *Drosophila melanogaster* sometimes walks against an air current. Flüggel<sup>2</sup> showed that this reaction only occurred when the air was scented, and must therefore be regarded as orientation by smell. However, reactions to air currents without smell do occur in *Drosophila*.

Comparing several species of the genus, a division can be made between those which show a distinct

stamen, for here the response is not in a direction determined by that of the stimulus. The response in these cases appears to bear a closer resemblance to the phototaxis of Oxalis leaflets and the thermotaxis of Tulipa flowers. Is one then justified (disregarding—as often becomes necessary for purposes of coherence—mere etymological niceties) in putting these responses under the heading of "thigmotaxis" (or possibly in some cases—as in Stiles's "Plant Physiology"—"seismonasty"?). By the same token



## Nomenclature of Biological Movement

HAVING read recently with very great interest Fränkel and Gunn's "Orientation of Animals", I set about making for my own clarification a classification of all the cases I know of what used to be called "tropic" movements.

It is clear that three major groupings are possible: a *taxis*, which is a bodily movement of an animal or motile plant in a direction determined by the direction of the stimulus; a *kinesis*, which is a change of rate of movement of an animal (or perhaps motile plant) in response to a change of intensity of a stimulus, but not in a direction determined by the direction of the stimulus—and often producing an aggregating effect superficially similar to that of a *taxis*; and an *orientation*, which is the placing of the body (usually if not always animal) in a direction determined by the direction of the stimulus. To these three classes many of the cases can be referred.

But the responses of sessile plant organs do not seem to be so conveniently classified. The thigmotropism of Clematis tendrils appears to warrant that name, for the response is a directional one. But the same cannot be said of the so-called "thigmotropism" of Mimosa leaflets, Mimulus stigma or Berberis

mentions records of trigonism by the independent observers, Shaw, Stokes and Brown. In Surrey, C. E. Britton<sup>3</sup> records its discovery by W. A. Todd from the Thames near Putney.

I am indebted to Mr. A. A. Dallman, of Doncaster, for certain of the references quoted.

FREDERICK BURKE.

12 Queen's Road,  
Chester.  
Aug. 29.

- <sup>1</sup> Burke, F., NATURE, 149, 331 (1942).
- <sup>2</sup> Sherlock, Mem. Geol. Survey, Mineral Resources of Gt. Brit., Rock-salt and Brine, 18, 111 (1921).
- <sup>3</sup> Belian, R., "Flora Cantabrigiensis", second edition, 145 (1902).
- <sup>4</sup> Evans, A. E., "Flora of Cambridgeshire", 165 (1939).
- <sup>5</sup> Baginall, J. E., "Flora of Staffordshire", 57 (1901).
- <sup>6</sup> Britton, C. E., J. Bot., 48, 186 (1910).

## Existence of Electromagnetic-Hydrodynamic Waves

If a conducting liquid is placed in a constant magnetic field, every motion of the liquid gives rise to an E.M.F. which produces electric currents. Owing to the magnetic field, these currents give mechanical forces which change the state of motion of the liquid.

This kind of combined electromagnetic-hydrodynamic wave is produced which, so far as I know, has as yet attracted no attention.

The phenomenon may be described by the electrodynamic equations

$$\text{rot } H = \frac{4\pi}{c} i$$

$$\text{rot } E = -\frac{1}{c} \frac{dB}{dt}$$

$$B = \mu H$$

$$i = \sigma(E + \frac{v}{c} \times B);$$

together with the hydrodynamic equation

$$\rho \frac{dv}{dt} = \frac{1}{c} (i \times B) - \text{grad } p,$$

where  $\sigma$  is the electric conductivity,  $\mu$  the permeability,  $\rho$  the mass density of the liquid,  $i$  the electric current,  $v$  the velocity of the liquid, and  $p$  the pressure.

Consider the simple case when  $\sigma = \infty$ ,  $\mu = 1$  and the imposed constant magnetic field  $H_0$  is homogeneous and parallel to the  $z$ -axis. In order to study a plane wave we assume that all variables depend upon the time  $t$  and  $z$  only. If the velocity  $v$  is parallel to the  $x$ -axis, the current  $i$  is parallel to the  $y$ -axis and produces a variable magnetic field  $H'$  in the  $x$ -direction. By elementary calculation we obtain

$$\frac{d^2 H'}{dz^2} = \frac{4\pi\sigma}{H_0^2} \frac{d^2 H'}{dt^2},$$

which means a wave in the direction of the  $z$ -axis with the velocity

$$V = \frac{H_0}{\sqrt{4\pi\sigma}}$$

Waves of this sort may be of importance in solar physics. In a region of the sun where the magnetic field, and as solar matter is a good conductor, the conditions for the existence of electromagnetic-hydrodynamic waves are satisfied. If in a region of the sun we have  $H_0 = 15$  gauss and  $\sigma = 0.005$  gm. cm.<sup>-1</sup>, the velocity of the waves amounts to

$$V \sim 60 \text{ cm. sec.}^{-1}.$$

This is about the velocity with which the sunspot zone moves towards the equator during the sunspot cycle. The above values of  $H_0$  and  $\sigma$  refer to a distance of about 10<sup>10</sup> cm. below the solar surface where the original cause of the sunspots may be found. Thus it is possible that the sunspots are associated with a magnetic and mechanical disturbance proceeding as an electromagnetic-hydrodynamic wave.

The matter is further discussed in a paper which will appear in *Arkiv för matematik, astronomi och fysik*.

H. ALFVÉN.

Kgl. Tekniska Högskolan,  
Stockholm.

## Energy of Dissociation of Carbon Monoxide

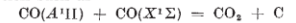
THE energies of dissociation of a number of diatomic molecules have been determined from spectroscopic data, apparently with high accuracy, by the observation of predissociation limits. During the last few years the following values have been proposed for CO:  $D(\text{CO}) = 6.92^1, 8.41^2, 9.14^3, 10.45^4$  e.v.; while values of 9.85 and 11.11 also appear possible<sup>5</sup>. Controlled electron experiments suggest 9.6<sup>6</sup>.

The value obtained by extrapolation of the vibra-

tional levels of the ground state is about 11, and support for this value has been given by Kynch and Penney<sup>5</sup>. Herzberg<sup>7</sup> has recently summarized evidence favouring 9.14.

At first sight, the strongest argument for 9.14 is the observation by Faltings, Groth and Harteck<sup>8</sup> that CO is decomposed by the xenon line at 1295 Å., but not by that at 1470 Å., from which they conclude that  $8.44 < D(\text{CO}) < 9.57$ . This conclusion is not based on an examination of the initial act of absorption. The only known absorption in the 295 Å. region is that corresponding to the fourth positive bands. The origins of the (9,0) and (10,0) bands lie at 76,839 cm.<sup>-1</sup> and 78,010 cm.<sup>-1</sup>. The xenon line 1295 Å. = 77,172 cm.<sup>-1</sup> falls between these bands and, if absorbed from the lowest vibrational level of CO, would correspond approximately to the line P(35) of (10,0). This gives as the upper limit of  $D(\text{CO})$  (when the rotational energy is taken into account) a value of 79,722 cm.<sup>-1</sup> = 9.88 e.v. (not 9.57 e.v. as stated by Herzberg<sup>7</sup>). Actually, it is doubtful whether such a high rotational line as P(35) would be observed at room temperature, and absorption, if it is due to CO, would probably occur from a higher vibrational level, corresponding perhaps to the (13,2) band, in which case the dissociation limit may be placed as high as 10.1.

Taking the first act of absorption as  $\text{CO}(X^1\Sigma) + h\nu = \text{CO}(A^1\Pi)$ , and assuming a life not less than 10<sup>-8</sup> sec. for A<sup>1</sup>Π, then at atmospheric pressure each molecule experiences at least 100 collisions before radiating. It seems to us that this gives a reasonable chance for a reaction such as



to proceed with quantum efficiency approaching unity. The state of the carbon atom might be either <sup>1</sup>D or P; the former if spin is to be conserved, the latter if not. In either case the reaction is strongly exothermic. The failure of the xenon line 1470 to induce photodissociation may be due to the reaction requiring an activation energy.

Estimates of  $D(\text{CO})$  less than 10 take no account of the non-crossing rule of Hund, and Neumann and Wigner<sup>9</sup>. This rule states that potential energy curves of molecular states of identical species cannot cross. Whether the rule is rigorous when the nuclear and electronic motions are not separated needs further examination, but at least we see no reason for anticipating a failure of the rule in the lowest energy curve of CO. If this curve has only one turning point then the non-crossing rule requires unequivocally that  $D(\text{CO}) > 10.3$ , and would agree well with the predissociation limit at 11.11 e.v.

The dissociation energy of CO<sup>+</sup> is 2.6 e.v. less than that of CO ( $D(\text{CO}^+) = D(\text{CO}) + I(\text{C}) - I(\text{CO}^+)$ ). Three electronic states of CO<sup>+</sup> are known, namely, X<sup>2</sup>Σ<sup>+</sup>, A<sup>1</sup>Π and B<sup>2</sup>Σ<sup>+</sup>, extrapolating to dissociation limits of about 9.8 (a very long extrapolation), 9.2 and 9.4 e.v. respectively. Since the two X<sup>2</sup>Σ<sup>+</sup> states must give different products of dissociation, it would appear, on the evidence of the B<sup>2</sup>Σ<sup>+</sup> state, that  $D(\text{CO}^+) = 7.4$ , and  $D(\text{CO})$  is about 10, and on the evidence of the A<sup>1</sup>Π state that  $D(\text{CO}^+) = 9.2$  and  $D(\text{CO})$  is 11.8. All that may fairly be deduced from present evidence on CO<sup>+</sup> is that  $D(\text{CO})$  is unlikely to be much less than 10.

We have also re-examined nitrogen. The accepted value  $D(\text{N}_2) = 7.38$  is based on the identification of the upper state of the Vegard-Kaplan bands with the



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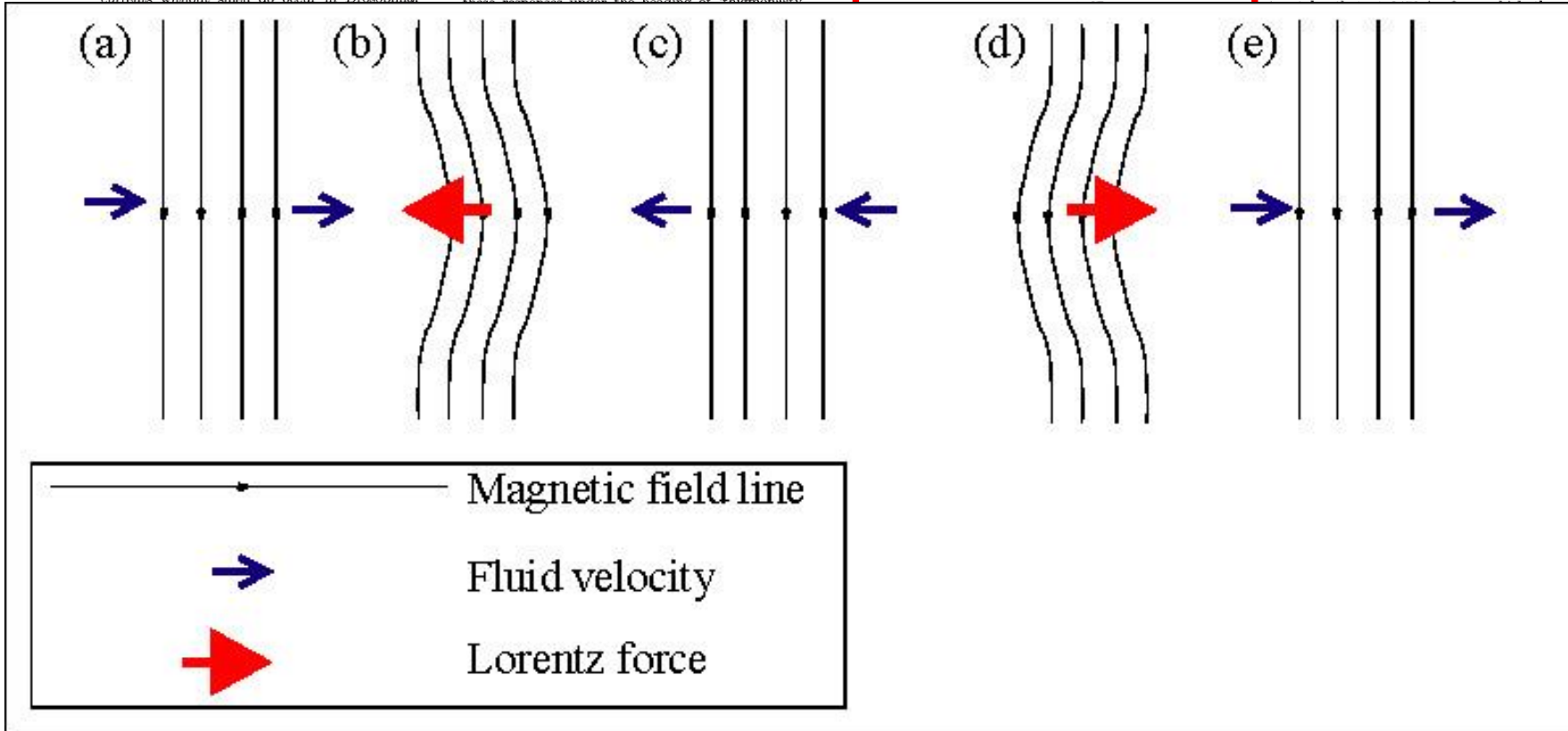
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THE energies of dissociation of a number of diatomic molecules have been determined from spectroscopic data, apparently with high accuracy, by the observation of predissociation limits. During the last few years the following values have been proposed for CO:  $D(\text{CO}) = 6.92^1, 8.41^2, 9.14^3, 10.45^4$  e.v.; while values of 9.85 and 11.11 also appear possible<sup>5</sup>. Controlled electron experiments suggest 9.6<sup>6</sup>.

The value obtained by extrapolation of the vibra-

ments of about 9.8 (a very long extrapolation), 9.2 and 9.4 e.v. respectively. Since the two  $^2\Sigma^+$  states must give different products of dissociation, it would appear, on the evidence of the  $B^2\Sigma^+$  state, that  $D(\text{CO}^+)$  is 7.4, and  $D(\text{CO})$  is about 10, and on the evidence of the  $A^2\Pi$  state that  $D(\text{CO}^+)$  is 9.2 and  $D(\text{CO})$  is 11.8. All that may fairly be deduced from present evidence on  $\text{CO}^+$  is that  $D(\text{CO})$  is unlikely to be much less than 10.

We have also re-examined nitrogen. The accepted value  $D(\text{N}_2) = 7.38$  is based on the identification of the upper state of the Vegard-Kaplan bands with the

# Alfvén-Wellen: Vorhersage 1942 → Nobelpreis 1970

No. 3805, OCTOBER 3, 1942

NATURE

405

406

NATURE

OCTOBER 3, 1942, Vol. 150

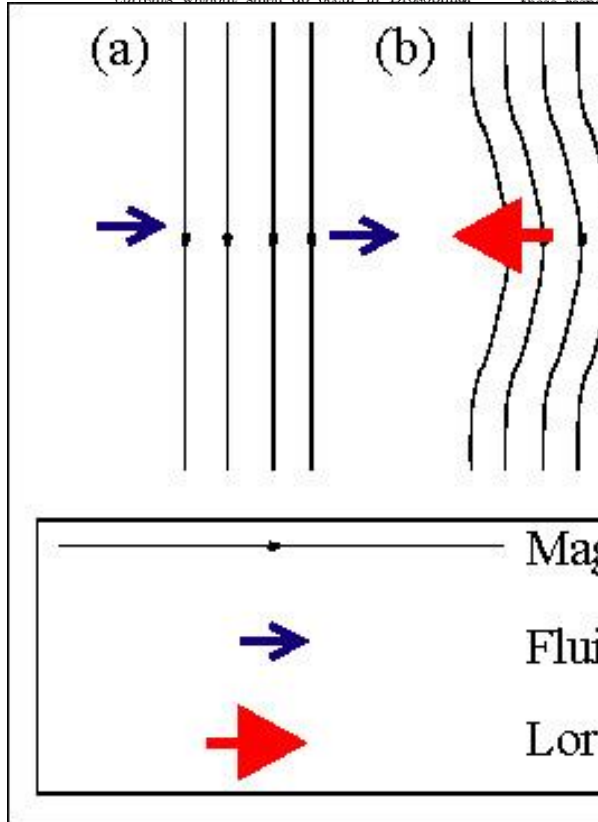
## Anemotaxis in *Drosophila*

COLE<sup>1</sup> has observed that *Drosophila melanogaster* sometimes walks against an air current. Flüggé<sup>2</sup> showed that this reaction only occurred when the air was scented, and must therefore be regarded as orientation by smell. However, reactions to air currents without smell do occur in *Drosophila*.

stamen, for here the response is not in a direction determined by that of the stimulus. The response in these cases appears to bear a closer resemblance to the phototaxis of *Opilidia* leaflets, and the thigmotaxis of *T. nemoralis*. The response is of a different nature regarding the coherence of the response.

Thus a kind of combined electromagnetic-hydrodynamic wave is produced which, so far as I know, has as yet attracted no attention.

ional levels of the ground state is about 11, and support for this value has been given by Kynch and Penney<sup>4</sup>. Herzberg<sup>7</sup> has recently summarized evi-



effect superficially similar to that of a taxis; and an orientation, which is the placing of the body (usually if not always animal) in a direction determined by the direction of the stimulus. To these three classes many of the cases can be referred.

But the responses of sessile plant organs do not seem to be so conveniently classified. The thigmotropism of *Clematis* tendrils appears to warrant that name, for the response is a directional one. But the same cannot be said of the so-called 'thigmotropism' of *Mimosa* leaflets, *Mimulus stigma* or *Berberis*

## Electro

If a conducting liquid is placed in a magnetic field, an E.M.F. is induced in the liquid. If the liquid is to the magnetic field, these currents give mechanical forces which change the state of motion of the liquid.

## Ab 1949 viele Experimente in Flüssigmetallen und Plasmen

S. Lundquist, Nature **164**, 146 (1949)

B. Lehnert, Phys.Rev. **94** (1954), 815

A. Jameson, J. Fluid Mech. **19** (1964), 513

K. Iwai et al, Magnetohydrodynamics **39**, 245 (2003)

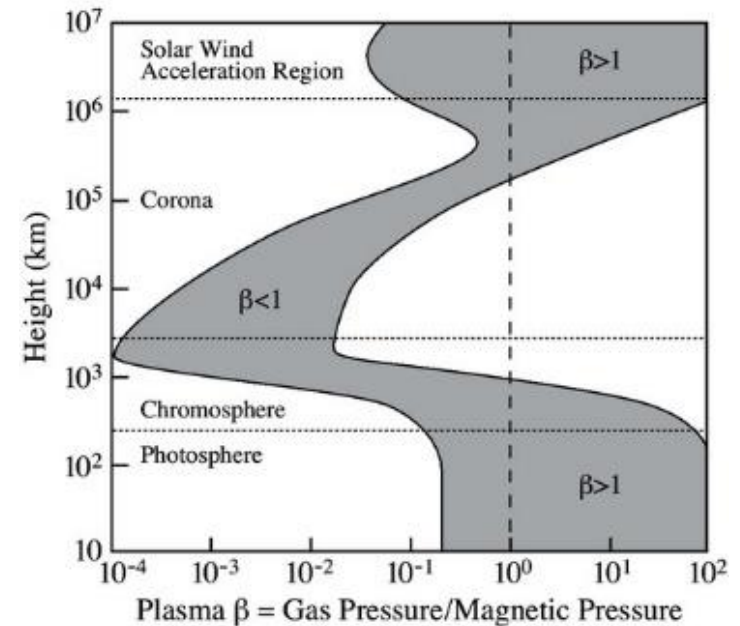
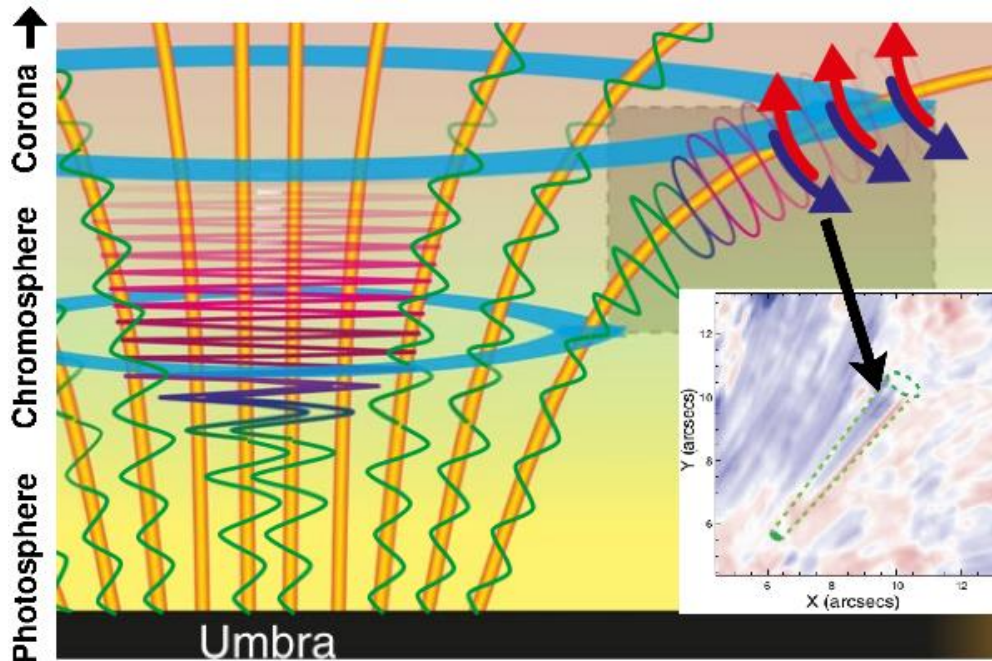
W. Gekelman et al., Phys. Plasmas **18** (2011), 055501

T. Alboussiere et al., Phys. Fluids **23** (2011), 096601

Z. Tigrine et al., Geophys. J. Int. **219**, S83 (2019)

# Alfvén-Wellen spielen eine große Rolle in der Sonnenphysik...

...insbesondere für die **Heizung der Korona**, wofür allerdings eine gegenseitige Umwandlung von Schallwellen und Alfvénwellen nötig ist



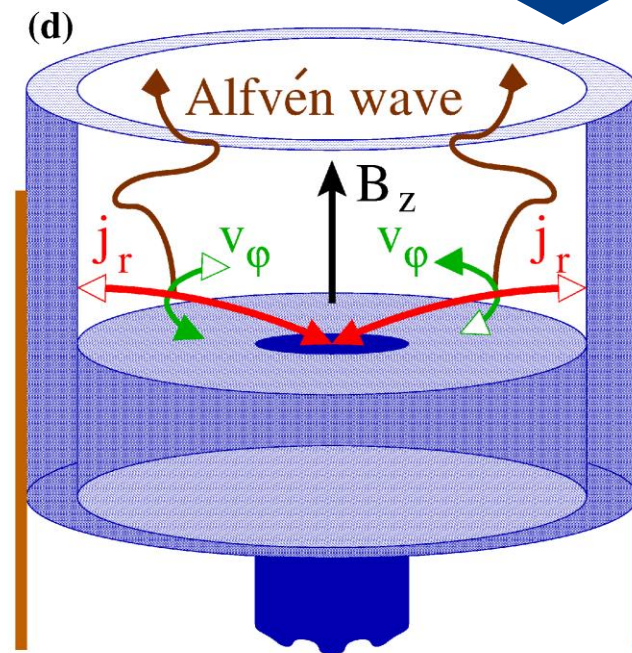
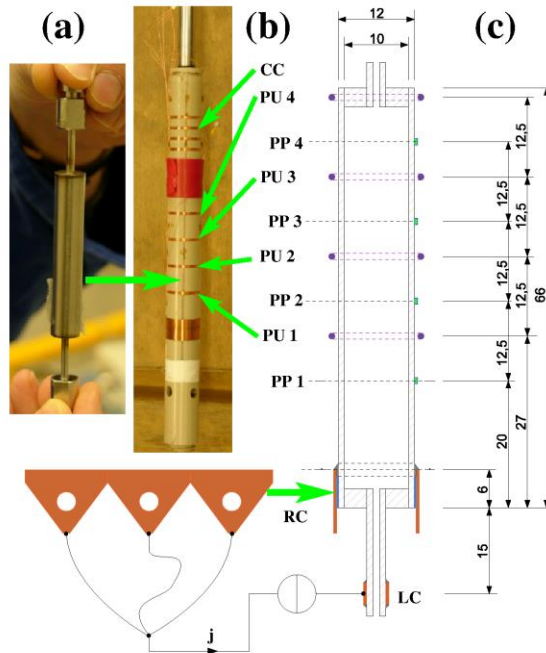
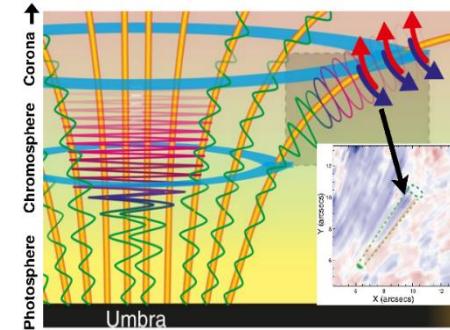
Grant et al., Nature Phys. 14 (2018), 480;  
Srivastava et al., Sci. Rep. 7 (2017), 43147

# Alfvénwellen-Experiment im Rossendorfer Hochfeldlabor

Flüssiges Rubidium:

Schallgeschwindigkeit =  
Alfvéngeschwindigkeit

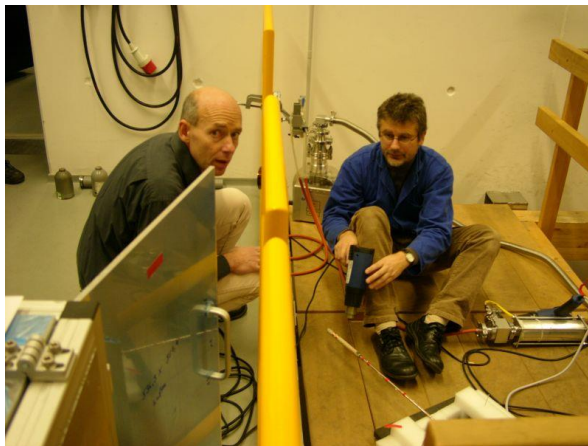
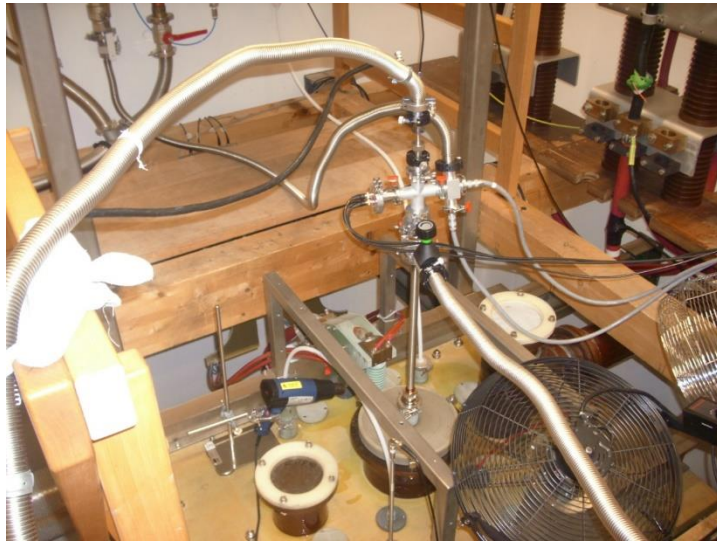
bei  $B=54\text{ T}$  !!!



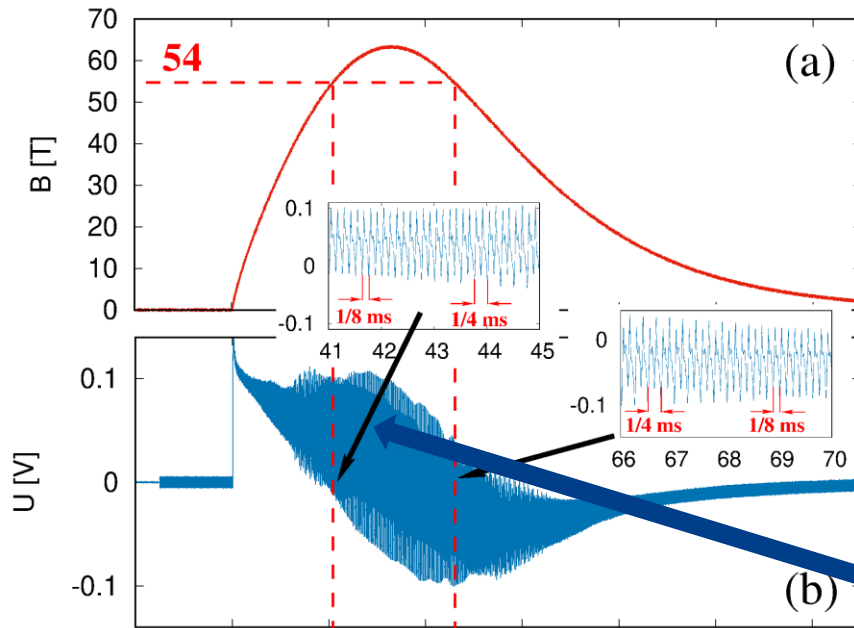
$j \times B$  Anregung torsionaler Alfvénwellen in  $B$  bis  $63\text{ T}$

# Alfvénwellen-Experiment im Rossendorfer Hochfeldlabor

Ein paar Impressionen...

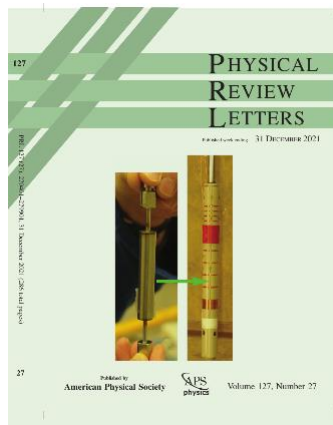


# CW-Anregung: Spannung über dem unteren Kontakt



Grobe Abschätzungen:

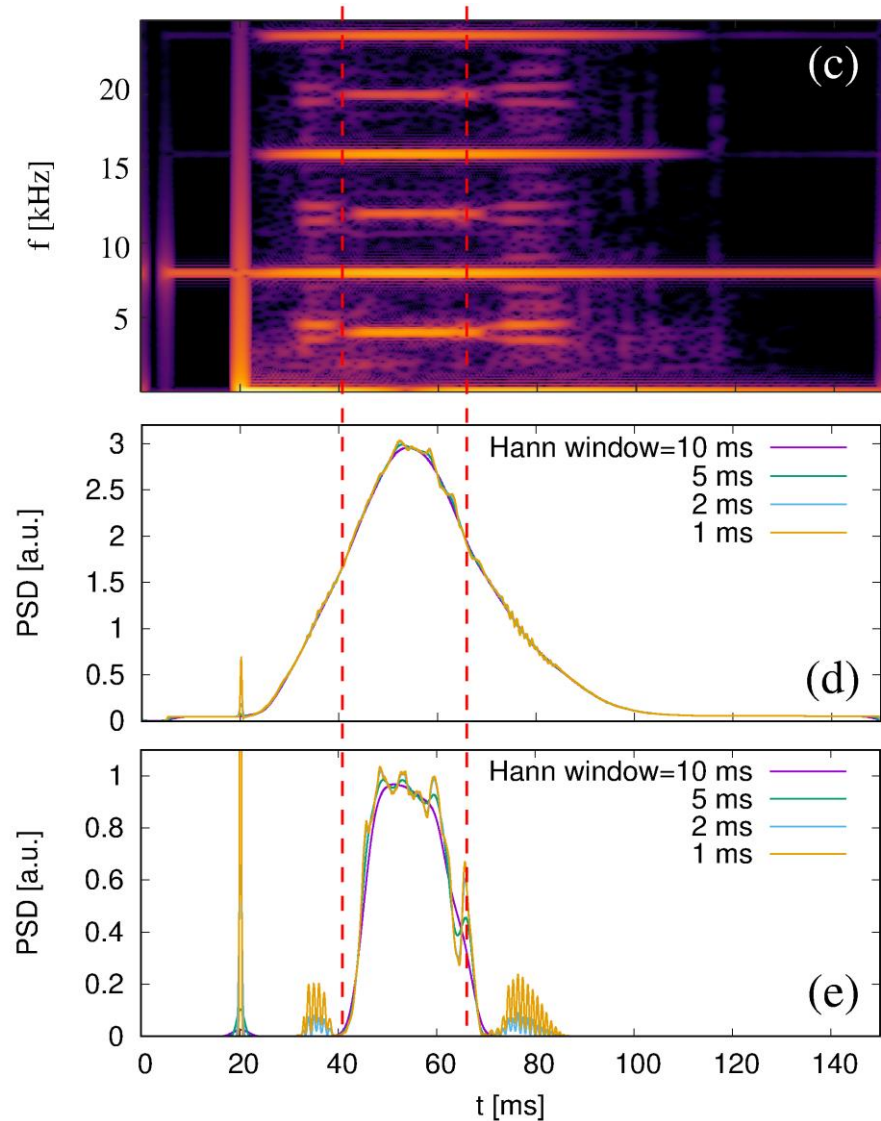
- Anregungsstrom: 5 A, 8 kHz CW
- Stromdichte:  $\sim 100 \text{ kA/m}^2$
- Azimutale Beschleunigung:  
 $j B/\rho \sim 3000 \text{ m/s}^2$
- Strömungsgeschwindigkeit:  
 $\sim a T/2 \sim 20 \text{ cm/s}$
- Induzierte Spannung:  
 $\sim v B r \sim 50 \text{ mV}$



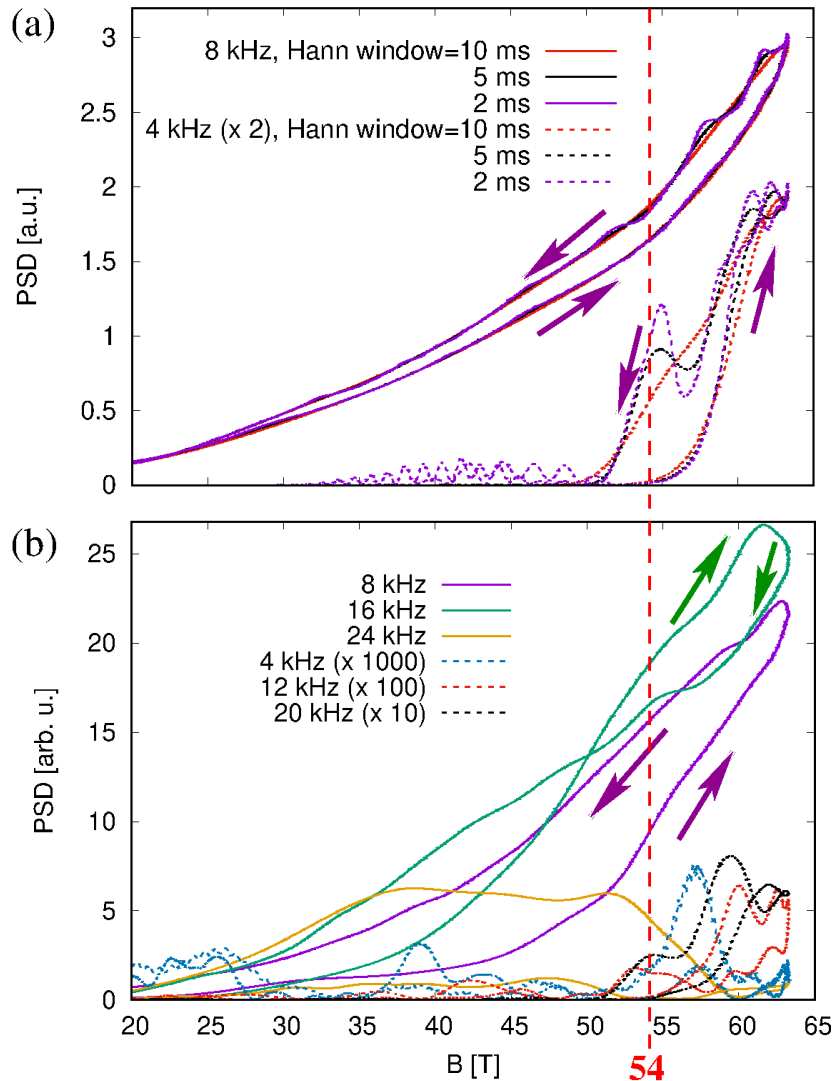
Stefani et al., Phys. Rev. Lett.  
127 (2021), 275001

# CW-Anregung: Spannung über dem unteren Konatakt

- Gabortransformation (Kurzzeit-Fourier) mit von-Hann-Fenster 5 ms
- PSD des 8 kHz-Streifens ist sehr glatt und ungefähr proportional zu  $B^2$
- PSD des 4 kHz-Streifens erscheint nur für  $B \geq 54$  T



# CW-Anregung: Abhängigkeit vom Magnetfeld

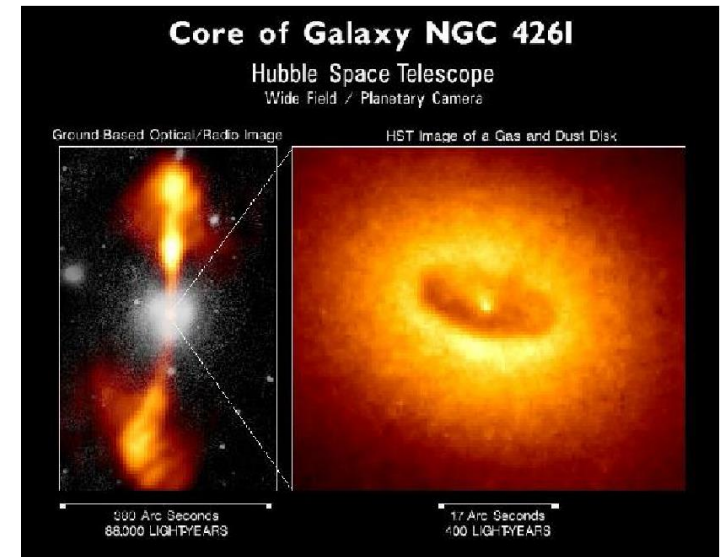
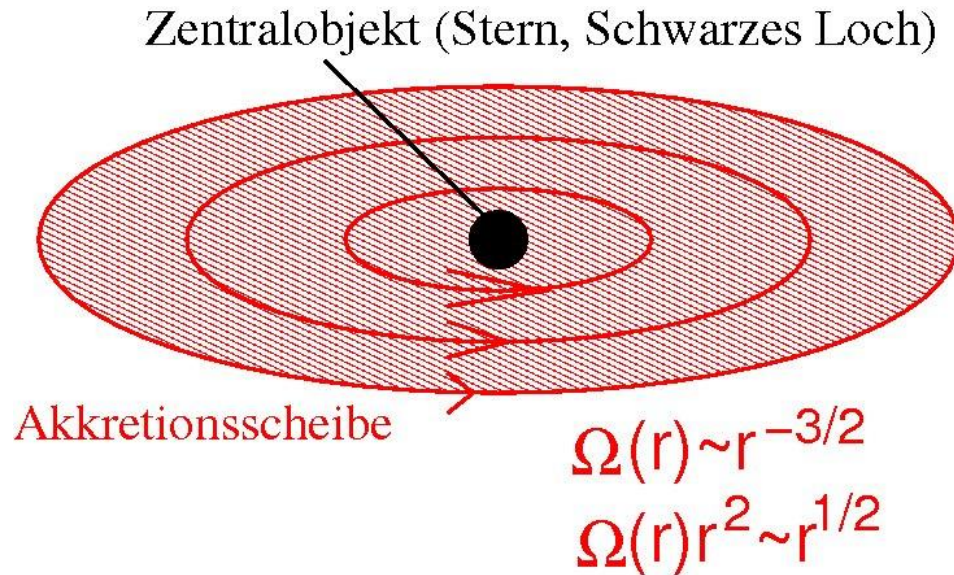


Spannung über unteren Kontakt  
(misst die Alfvénwelle):  
PSD's für 8 kHz und 4 kHz

Spannung an der Pickup-Spule 2  
(misst die Schallwelle):  
PSD's für  $n \cdot 4$  kHz



# Wie funktionieren Akkretionsscheiben?

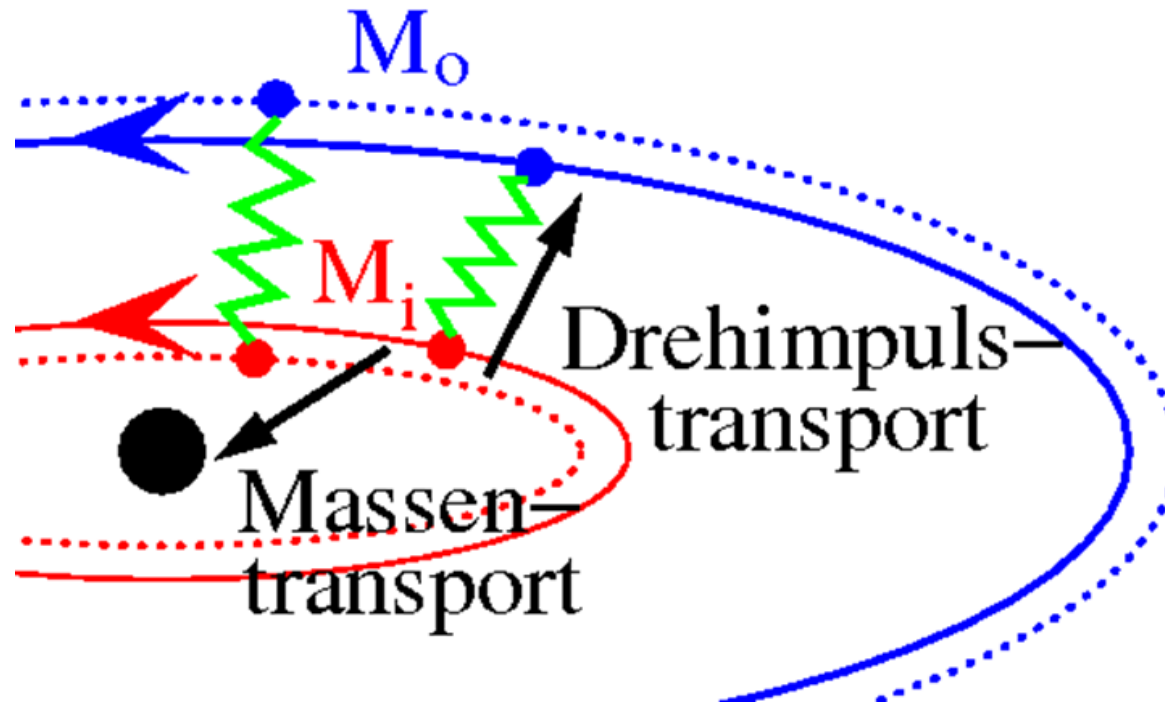


- Problem: Drehimpulstransport nach außen ist durch Viskosität nicht erklärbar.
- Turbulenz könnte helfen. Aber: **Kepler-Rotation ist hydrodynamisch stabil! Wie kommt die Turbulenz zustande?**

# Wie funktionieren Akkretionsscheiben?

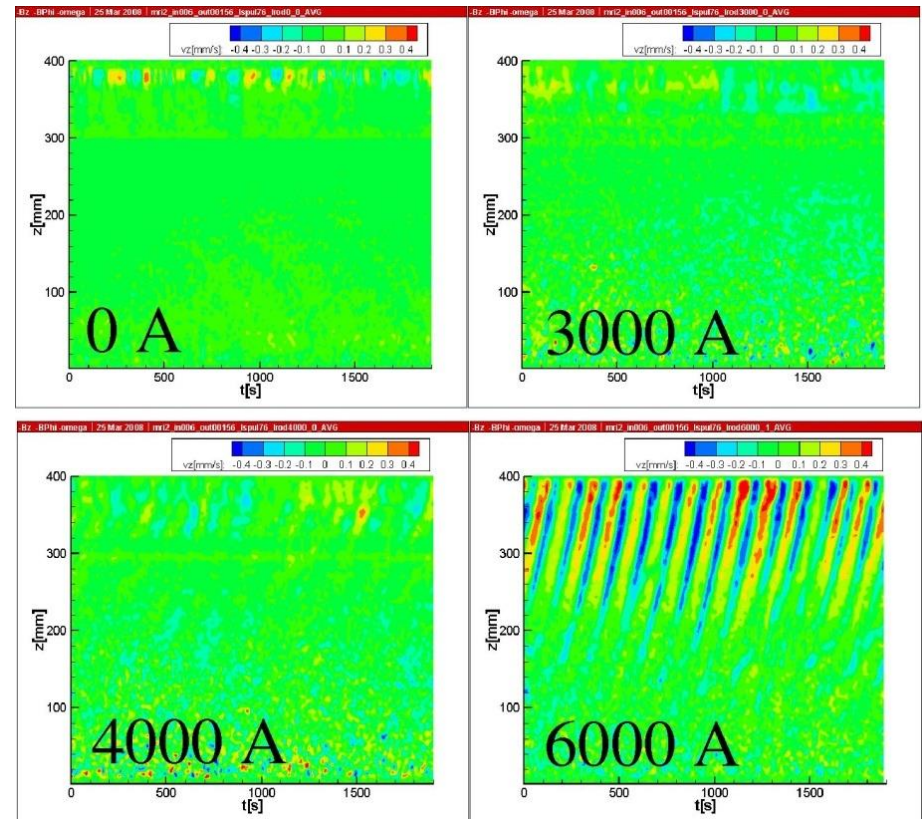
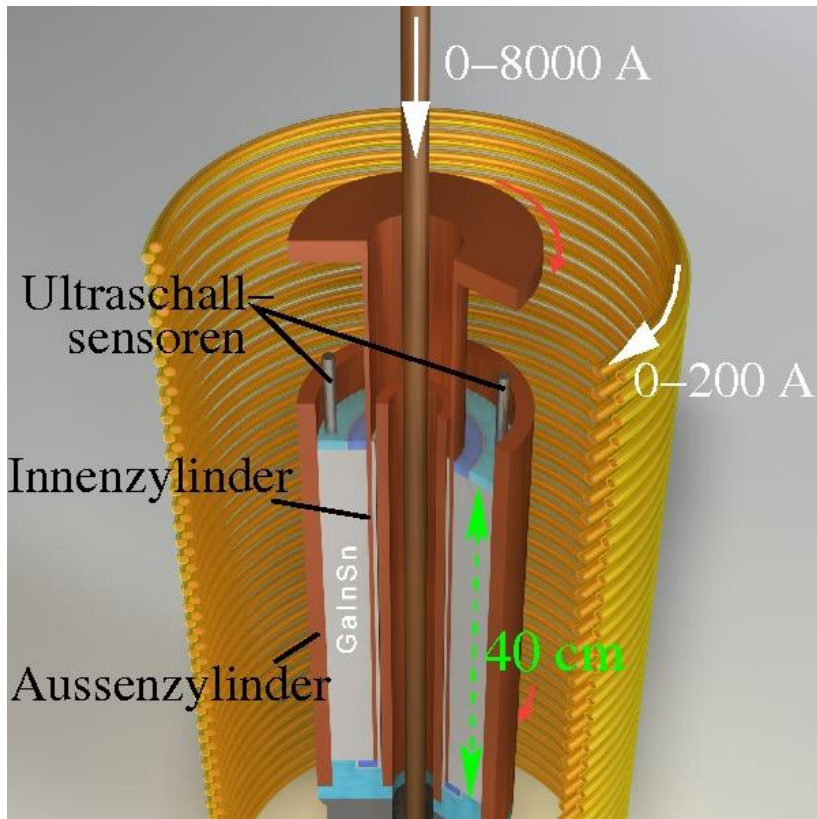
## Magneto-Rotationsinstabilität (MRI):

Magnetfelder wirken wie Federn und bewirken Drehimpuls- und Massentransport in Akkretionsscheiben, aus denen Sterne und Schwarze Löcher gefüttert werden.



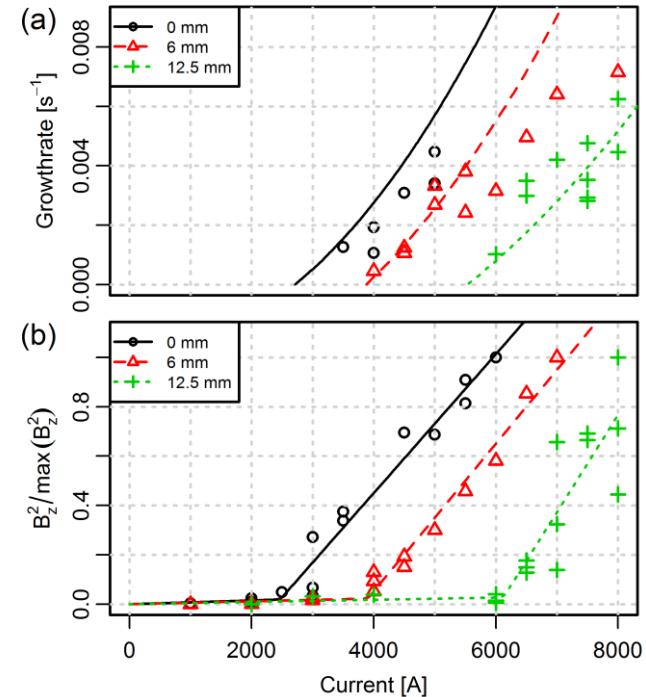
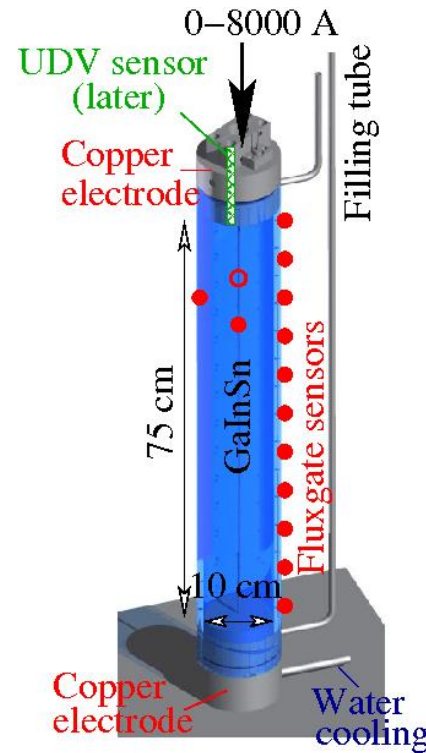
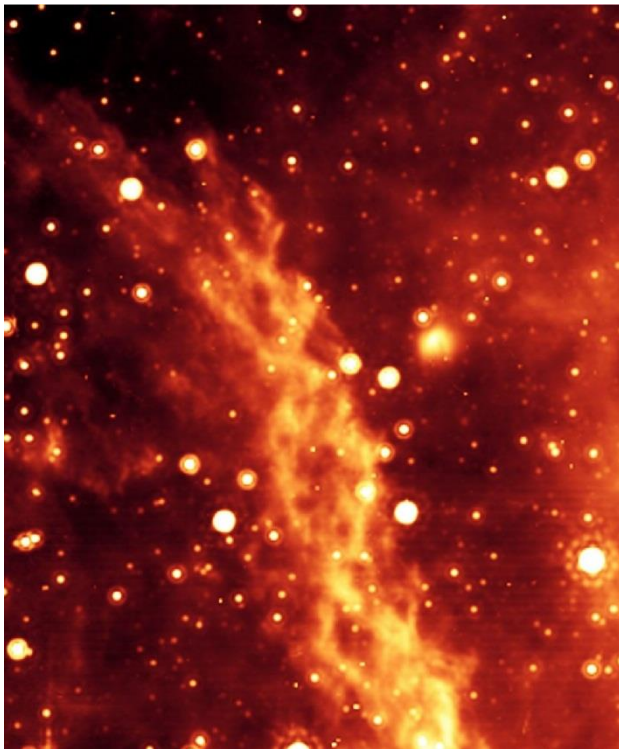
# Magneto-Rotationsinstabilität im Experiment

## 2006: Experimenteller Nachweis der helikalen MRI am HZDR



# Stromgetriebene Tayler-Instabilität (TI)

Motivation: **alternativer Mechanismus der Entstehung des Sonnenmagnetfeldes**;  
Strukturbildung in kosmischen jets

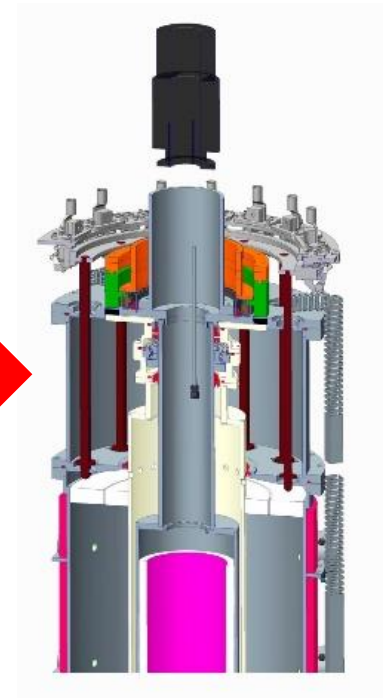
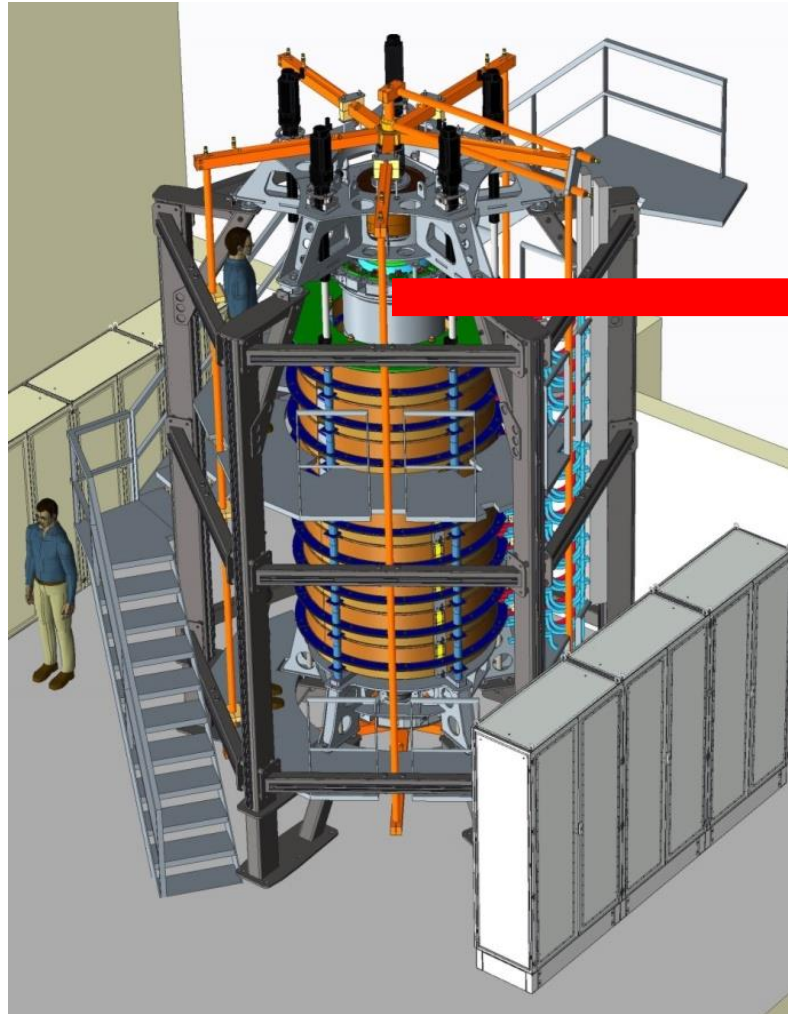


Erstes Experiment am HZDR: Gute Übereinstimmung der kritischen Ströme und der Anwachsrate für TI mit Numerik.

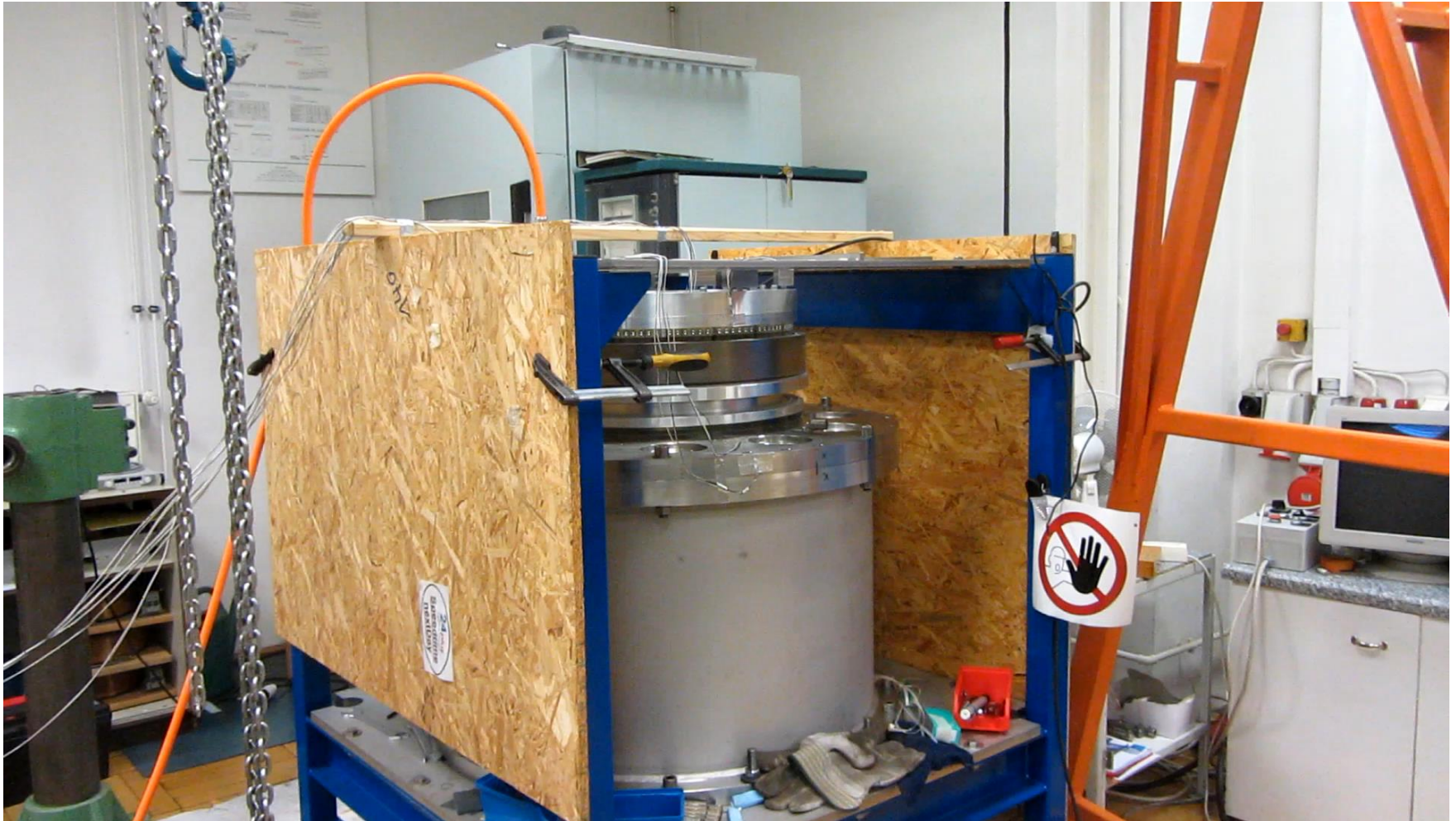
# In DRESDYN geplantes MRI/TI- Experiment

Parameter:

- $r_{in}=0.2$  m
- $r_{out}=0.4$  m
- $h=2$  m
  
- $f_{in}=20$  Hz
- $f_{out}=6$  Hz
  
- $B_z=150$  mT
  
- $R_m = 40$
- $Lu = 8$



# Erster Test ging schief!



# Erster Test ging schief! Inzwischen ist der Coupler aber da...

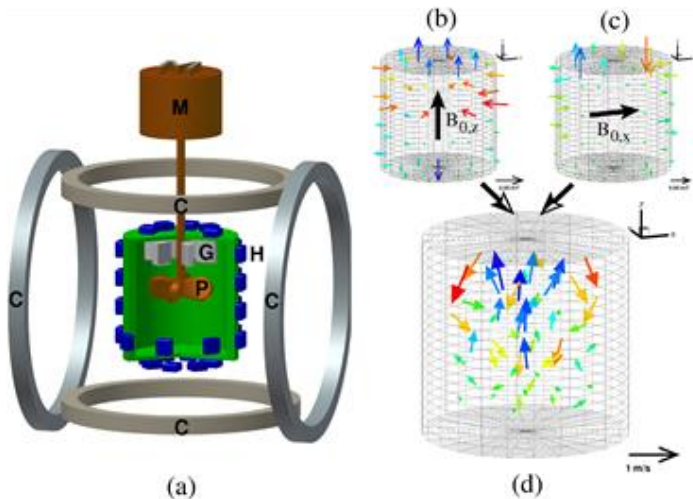


# Spin-off der Dynamoarbeiten

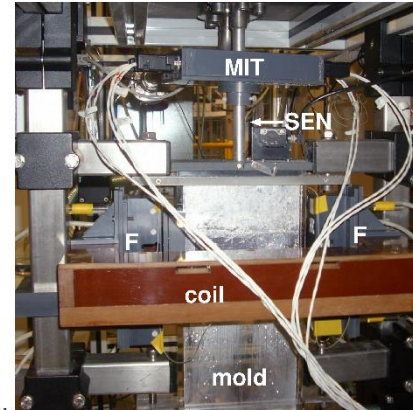
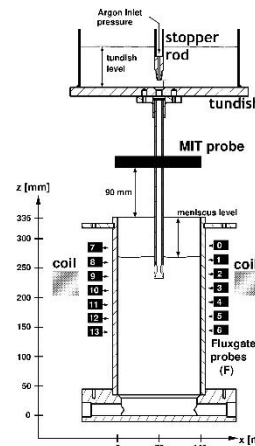
Dynamoeffekt  $\rightarrow$  Contactless Inductive Flow Tomography (CIFT)

$$\mathbf{b}(\mathbf{r}) = \frac{\sigma\mu_0}{4\pi} \int_D \frac{(\mathbf{u}(\mathbf{r}') \times \mathbf{B}(\mathbf{r}')) \times (\mathbf{r} - \mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|^3} dV' + \frac{\sigma\mu_0}{4\pi} \iint_S \varphi(\mathbf{s}') \frac{\mathbf{r} - \mathbf{s}'}{|\mathbf{r} - \mathbf{s}'|^3} \times \mathbf{n}(\mathbf{s}') dS'$$

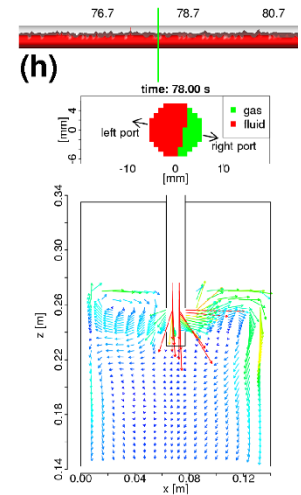
$$\varphi(\mathbf{s}) = \frac{1}{2\pi} \int_D \frac{(\mathbf{u}(\mathbf{r}') \times \mathbf{B}(\mathbf{r}')) \cdot (\mathbf{s} - \mathbf{r}')}{|\mathbf{s} - \mathbf{r}'|^3} dV' - \frac{1}{2\pi} \iint_S \varphi(\mathbf{s}') \frac{\mathbf{s} - \mathbf{s}'}{|\mathbf{s} - \mathbf{s}'|^3} \cdot \mathbf{n}(\mathbf{s}') dS'$$



Erstes Modell-Experiment



Einsatz im Stahlguss



Stefani et al.: Phys. Rev. E 70 (2004), 056306;  
Wondrak et al.: Met. Mater. Trans. B 42 (2011), 1201

DE 19922311 C2,  
DE 10026052 B4

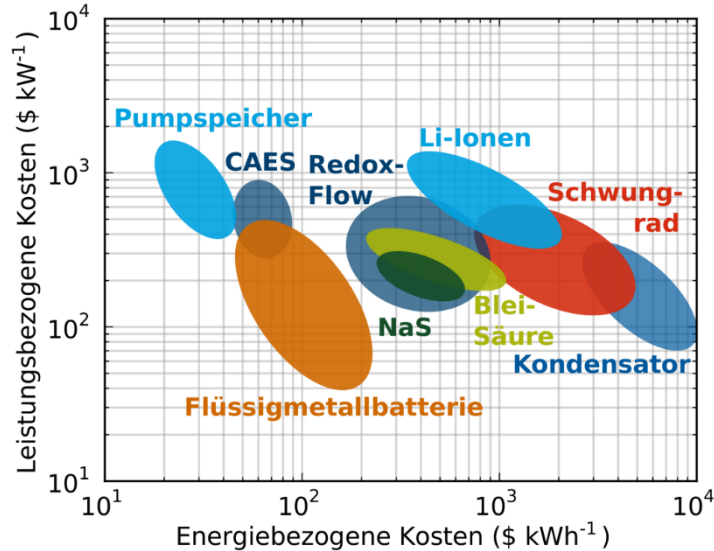


# Spin-off der Instabilitätsarbeiten

Taylor-Instabilität

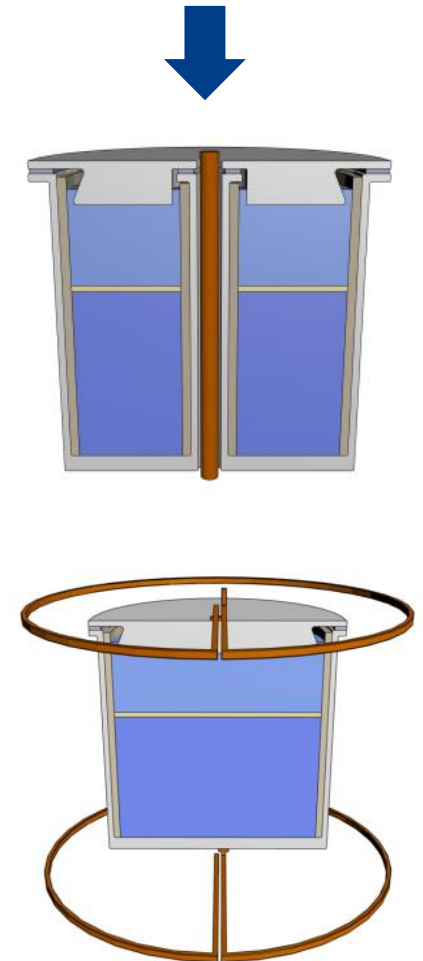
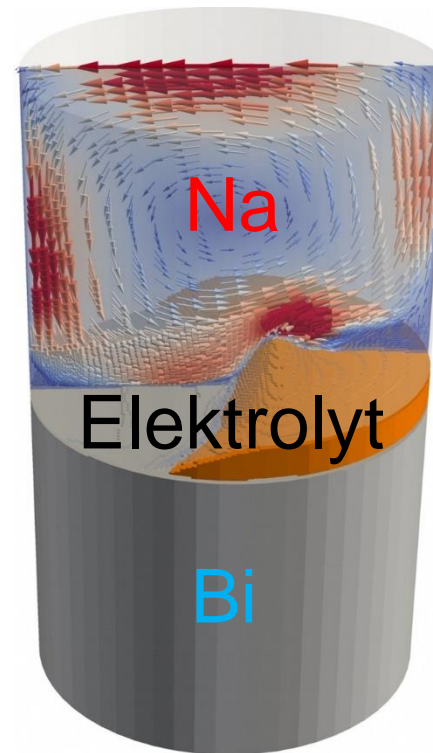


Stabilisierung großer Flüssigmetallbatterien



Große Flüssigmetallbatterien könnten sehr preiswerte Energiespeicher mit sehr hoher Zyklenanzahl sein.

Dafür muss aber die Schichtung stabil bleiben!



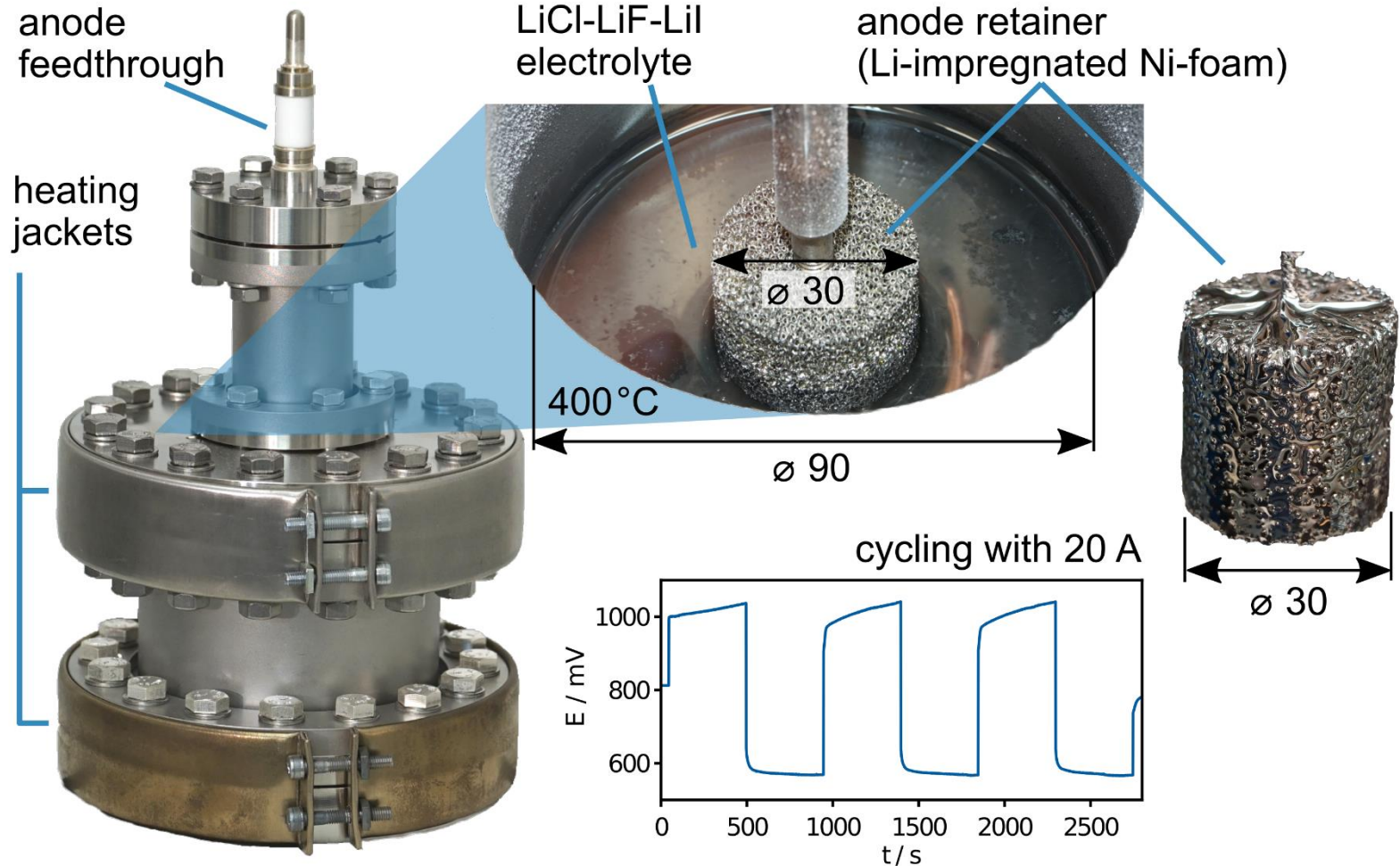
Stefani et al.: Energy Conv. Man. 52 (2011), 2982

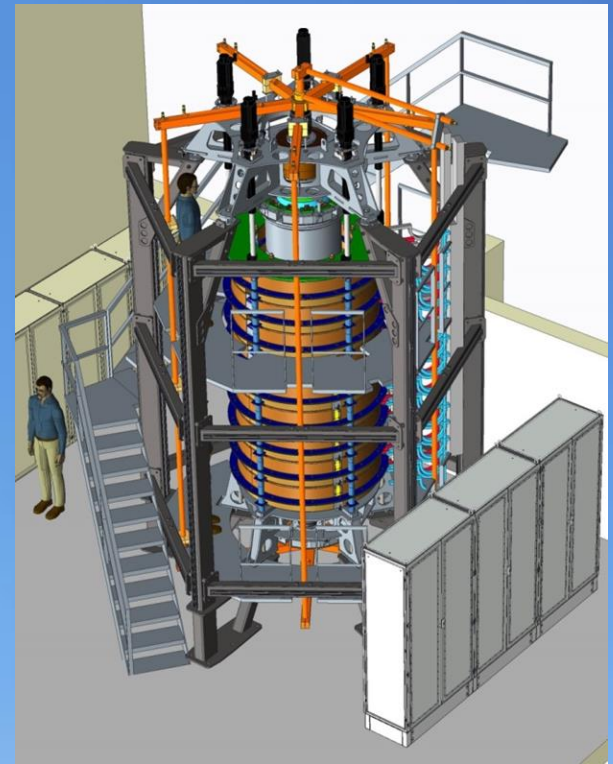
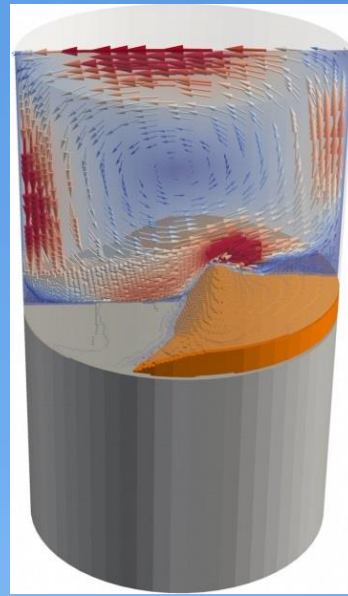
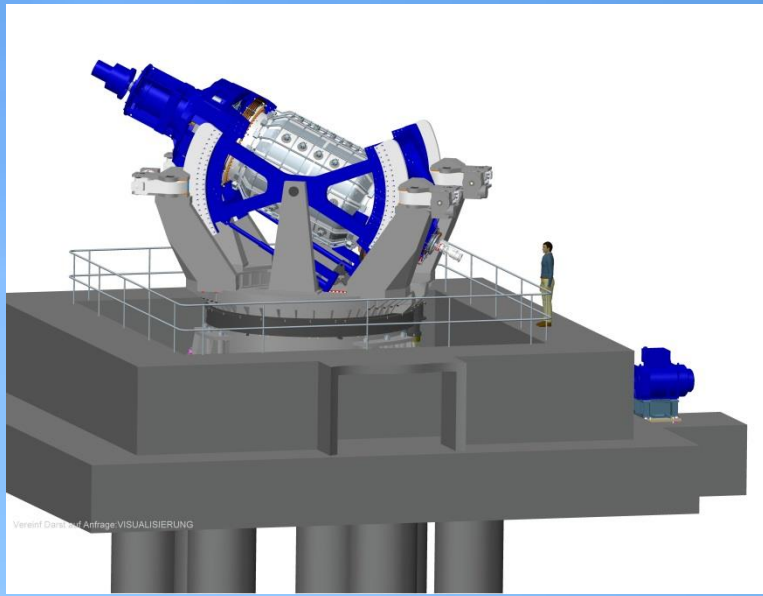
Weber et al.: J. Power Sources 265 (2014), 166

US 9,608,296 B2

DE 102013112555 B3

# Flüssigmetall-Batterien: Unser erster Demonstrator mit Li||Bi





**Vielen Dank für Ihre  
Aufmerksamkeit**