IPELS-16, Garching, August 3, 2024

Paradigmatic liquid-metal experiments on geo- and astrophysical phenomena

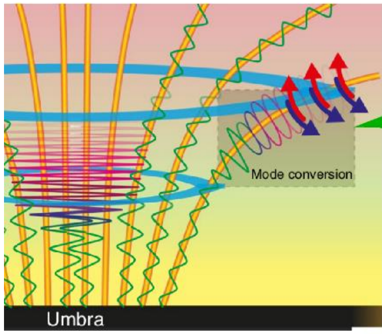
Frank Stefani

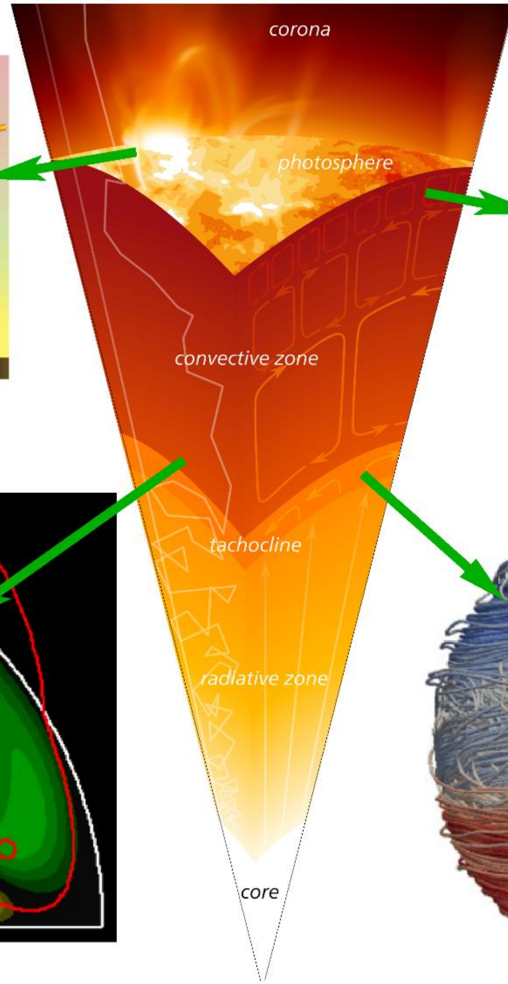
With thanks to:

Agris Gailitis (Riga), Gunter Gerbeth, André Giesecke, Thomas Gundrum, Vivaswat Kumar, George Mamatsashvili, Ashish Mishra, Jude Ogbonna, Federico Pizzi,Sebastian, Günther Rüdiger (Potsdam), Martin Seilmayer, Rodion Stepanov (Perm), Tom Weier…

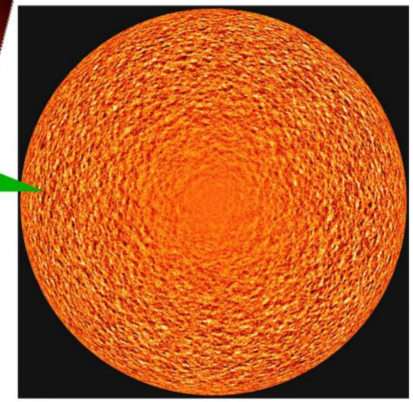
Motivation and schedule

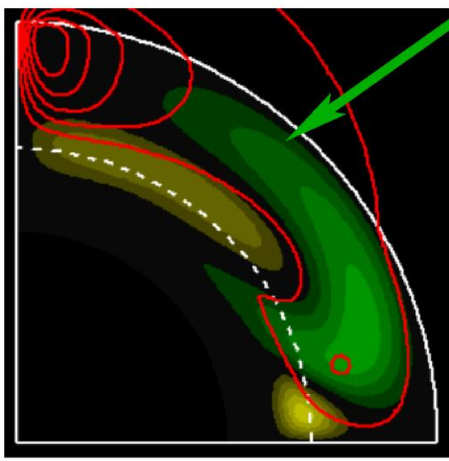
1) Alfvén waves



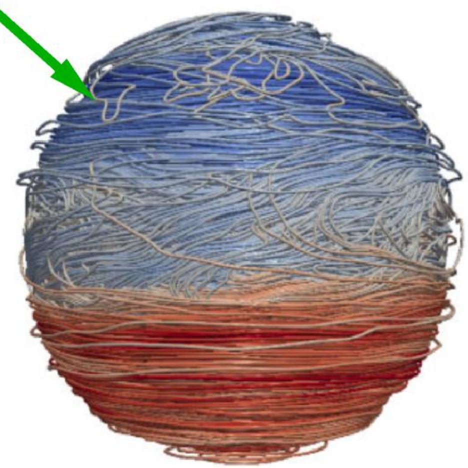


2) Convection





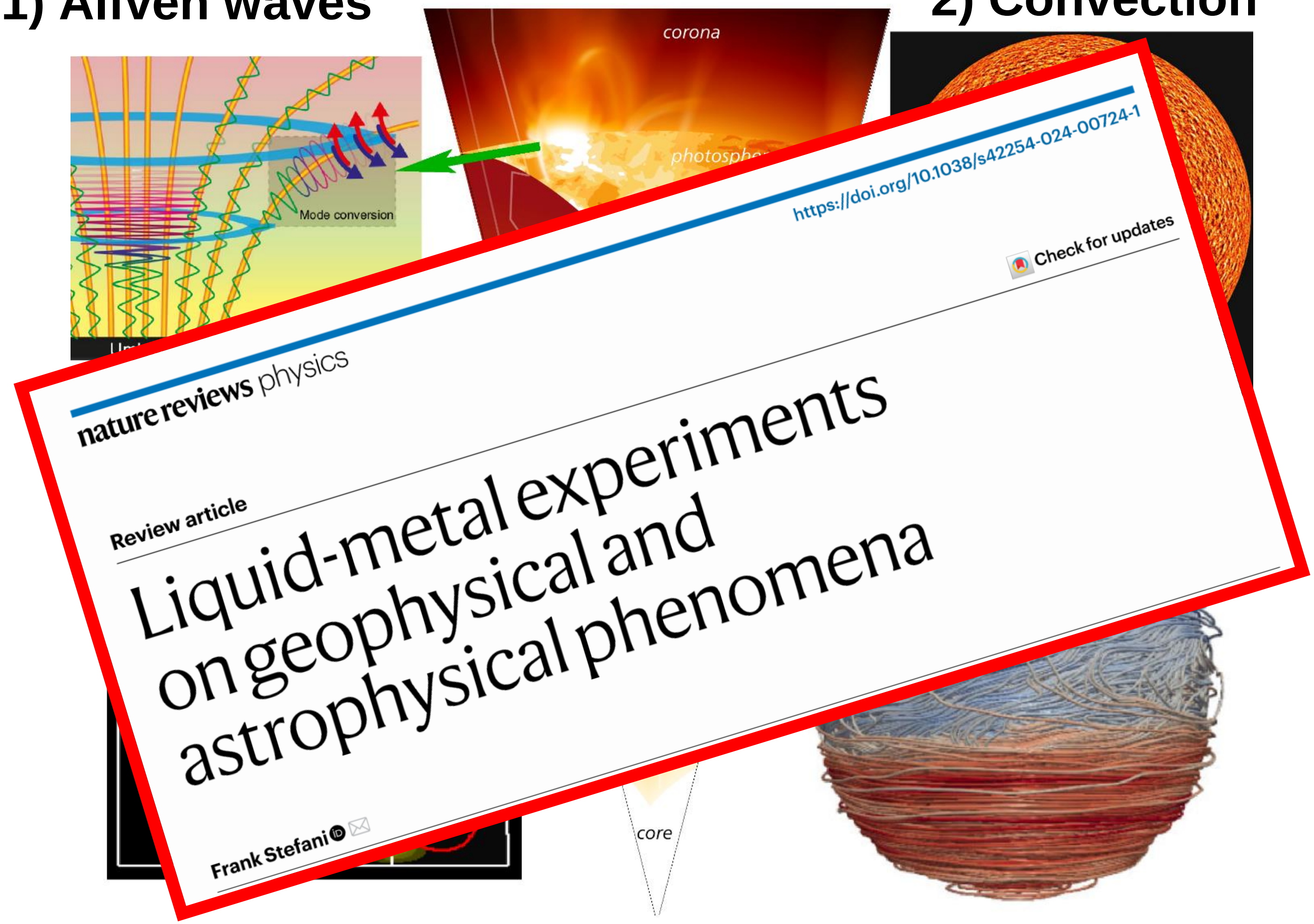
4) Dynamo



3) MRI etc…

Motivation and schedule

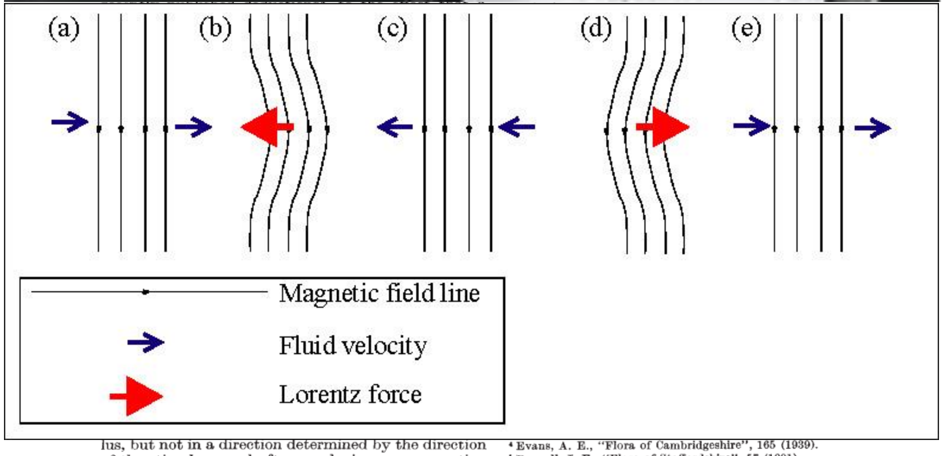
1) Alfvén waves **2) Convection**



4) Dynamo **3) MRI etc…**

Alfvén waves

Alfvén waves: Prediction by H. Alfvén 1942 (Nobel prize 1970)



lus, 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

[4] Evans, A. E., "Flora of Cambridgeshire", 165 (1939).
[5] Bagnall, J. E., "Flora of Staffordshire", 57 (1901).
[6] 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.

Thus a 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

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

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

$$B = \mu H$$

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

together with the hydrodynamic equation

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

where σ is the electric conductivity, μ the permeability, ∂ 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

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

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

$$V = \frac{H_0}{\sqrt{4\pi\partial}}.$$

Waves of this sort may be of importance in solar physics. As the sun has a general 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 $\partial = 0{\cdot}005$ gm. cm.$^{-3}$, 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 ∂ refer to a distance of about 10^{10} 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,
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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(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[3]. Controlled electron experiments suggest 9·6 [5].

The value obtained by extrapolation of the vibrational levels of the ground state is about 11, and support for this value has been given by Kynch and Penney[6]. Herzberg[7] has recently summarized evidence favouring 9·14.

At first sight, the strongest argument for 9·14 is the observation by Faltings, Groth and Harteck[8] that CO is decomposed by the xenon line at 1295 A., but not by that at 1470 A., from which they conclude that $8{\cdot}44 < D(\text{CO}) < 9{\cdot}57$. This conclusion is not based on an examination of the initial act of absorption. The only known absorption in the 1295 A. region is that corresponding to the fourth positive bands. The origins of the (9,0) and (10,0) bands lie at 76,839 cm.$^{-1}$ and 78,010 cm.$^{-1}$. The xenon line 1295 A. = 77,172 cm.$^{-1}$ 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(CO) (when the rotational energy is taken into account) a value of 79,722 cm.$^{-1}$ = 9·88 e.v. (not 9·57 e.v. as stated by Herzberg[7]). 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^{-8} sec. for $A^1\Pi$, 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

$$\text{CO}(A^1\Pi) + \text{CO}(X^1\Sigma) = \text{CO}_2 + \text{C}$$

to proceed with quantum efficiency approaching unity. The state of the carbon atom might be either ^1D or ^3P; 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(CO) less than 10 take no account of the non-crossing rule of Hund, and Neumann and Wigner[9]. 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 $D(\text{CO}) > 10{\cdot}3$, and would agree well with the predissociation limit at 11·11 e.v.

The dissociation energy of CO+ 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+ are known, namely, $X^2\Sigma+$, $A^2\Pi$ and $B^2\Sigma+$, extrapolating to dissociation limits 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(CO+) is 7·4, and D(CO) is about 10, and on the evidence of the $A^2\Pi$ state that D(CO+) is 9·2 and D(CO) is 11·8. All that may fairly be deduced from present evidence on CO+ is that D(CO) is unlikely to be much less than 10.

We have also re-examined nitrogen. The accepted value $D(\text{N}_2) = 7{\cdot}38$ is based on the identification of the upper state of the Vegard–Kaplan bands with the

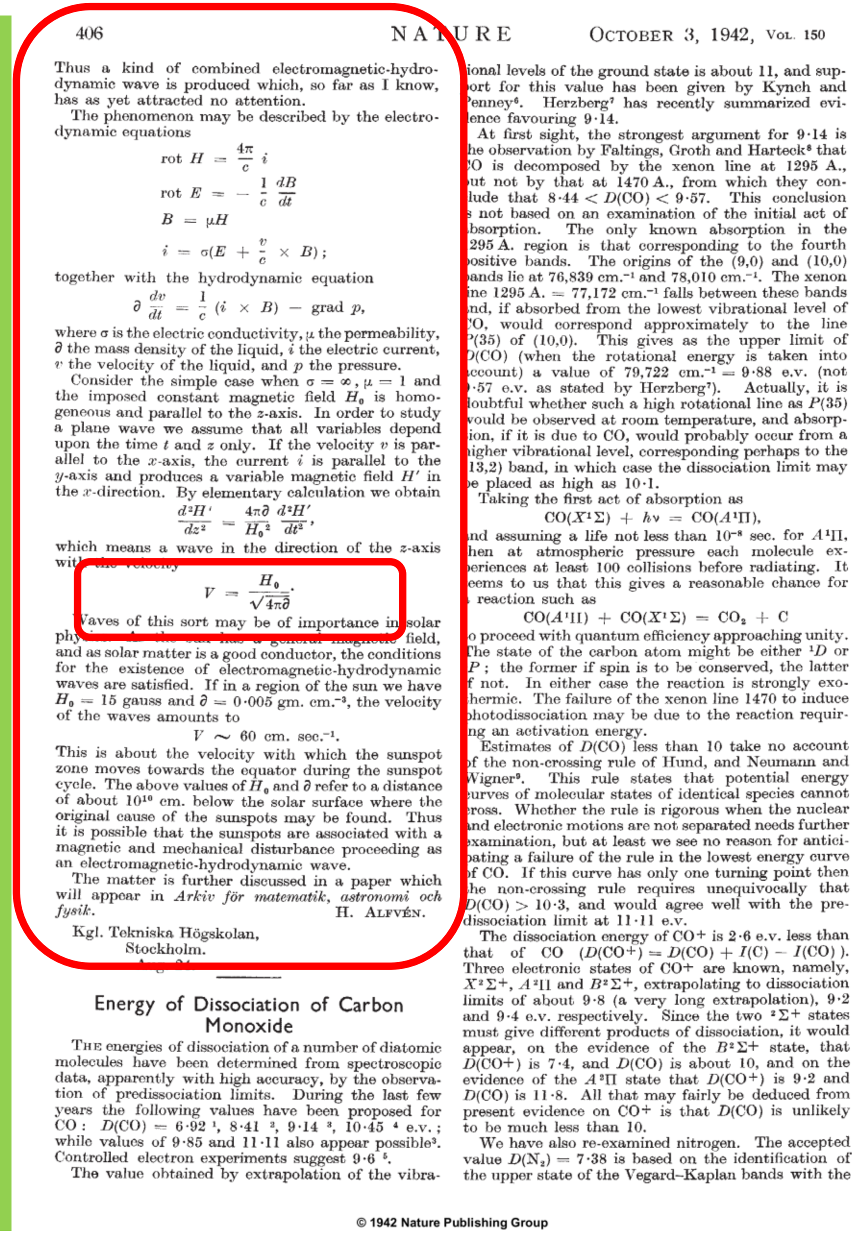
Alfvén waves: Prediction by H. Alfvén 1942 (Nobel prize 1970)

Many experiments in liquid metal and plasma

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)
T. Alboussiere et al., Phys. Fluids **23** (2011), 096601
Z. Tigrine et al., Geophys. J. Int. **219**, S83 (2019)
S. Lalloz et al., arXiv: 2405.04276

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

…and quite a number of talks at this conference!


406 NATURE OCTOBER 3, 1942, VOL. 150

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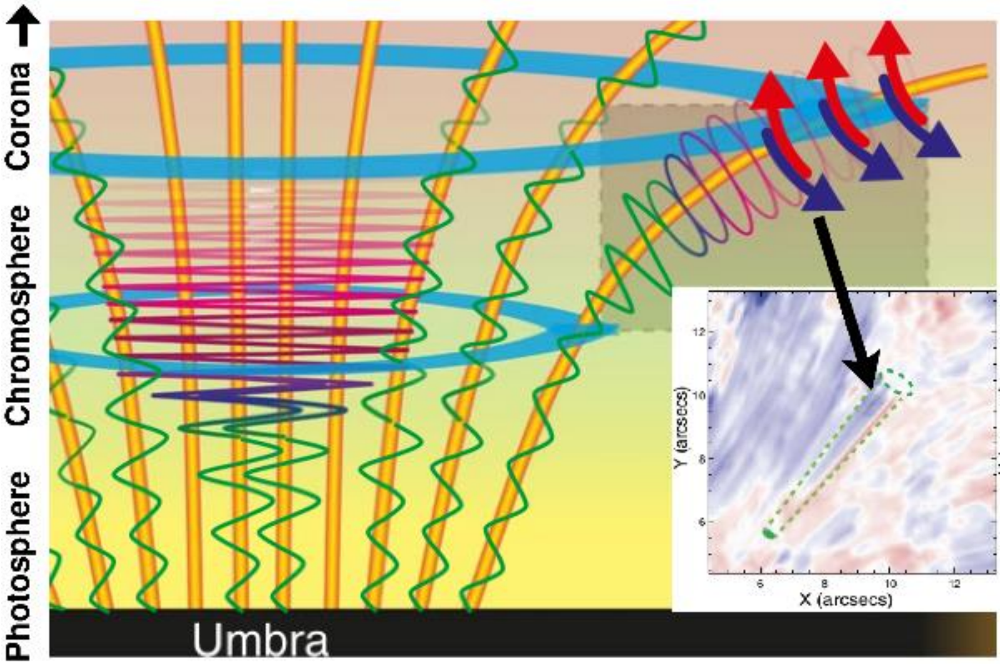
An underexplored aspect of Alfvén waves…

…is related to the heating of the solar corona which relies on transformation of sound waves into Alfvén waves via parametric resonance, or swing excitation (at a point where **sound speed = Alfvén speed**, or plasma β~1)

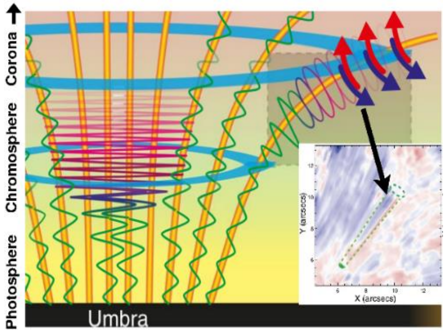
T. Zaqarashvili, ApJ 552 (2001) L81

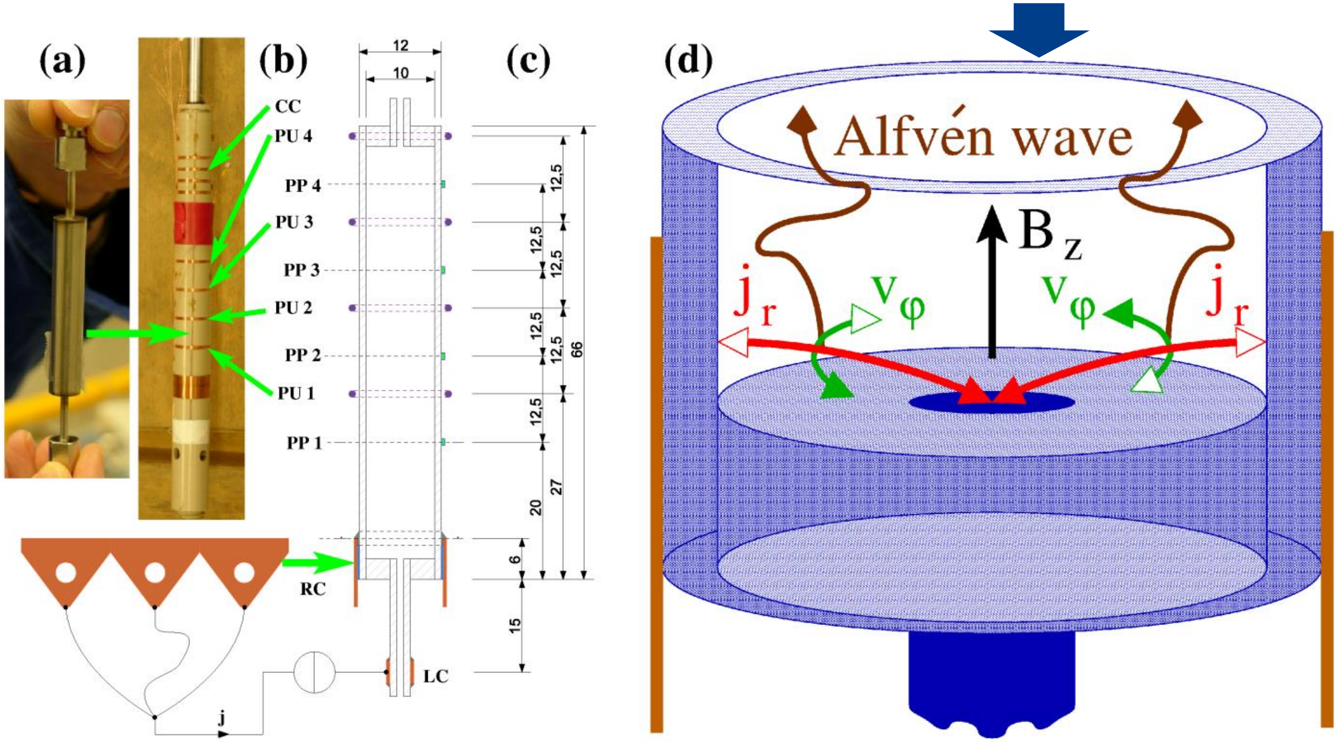


Grant et al., Nature Phys. 14 (2018), 480;
Srivastava et al., Sci. Rep. 7 (2017), 43147

Alfvén wave experiments at High Magnetic Field Lab at HZDR

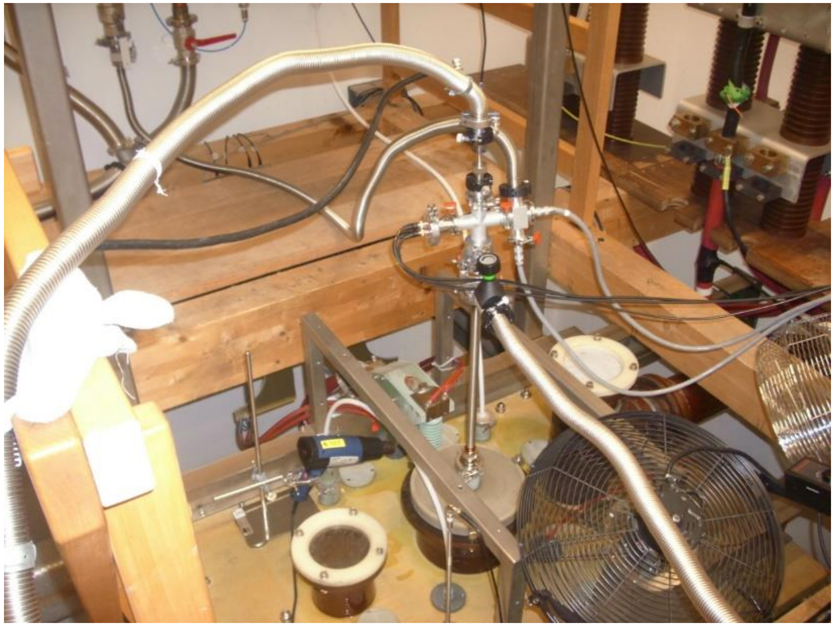
For liquid Rubidium (dangerous!!!) we obtain Sound speed = Alfvén speed (plasma β=1) at B=54 T

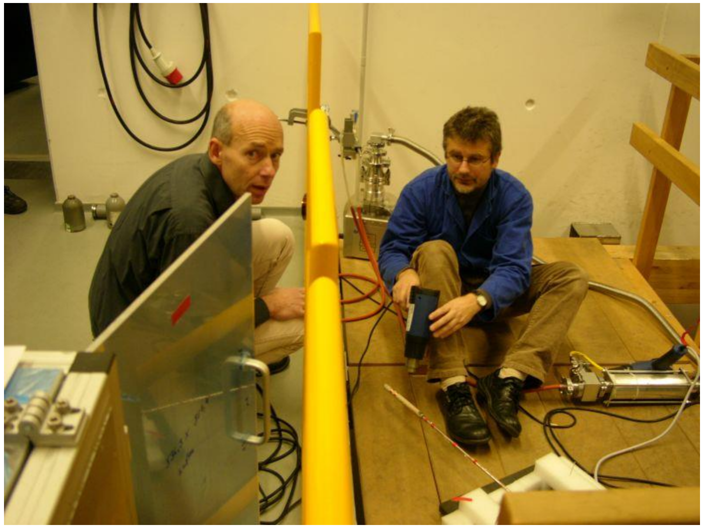




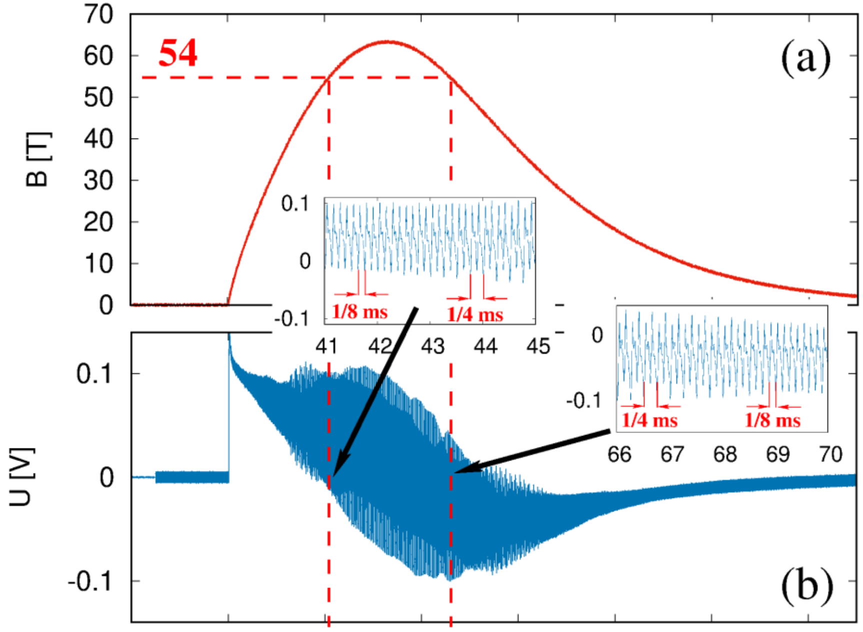
jxB excitation of torsional Alfvén waves in B up to 63 T

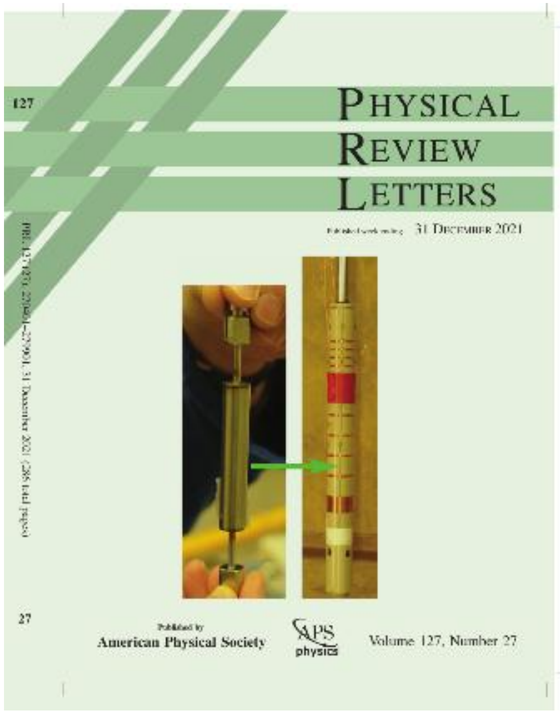
Alfvén wave experiments at High Magnetic Field Lab at HZDR





CW excitation: Voltage over bottom contact





Some rough estimates:

- Excitation current: 5 A, 8 kHz CW
- Current density: ~ 100 kA/m^2
- Azimuthal acceleration: j B/ρ ~ 3000 m/s^2
- Flow velocity: ~a T/2 ~ 20 cm/s
- Induced voltage: ~vBr~50 mV

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

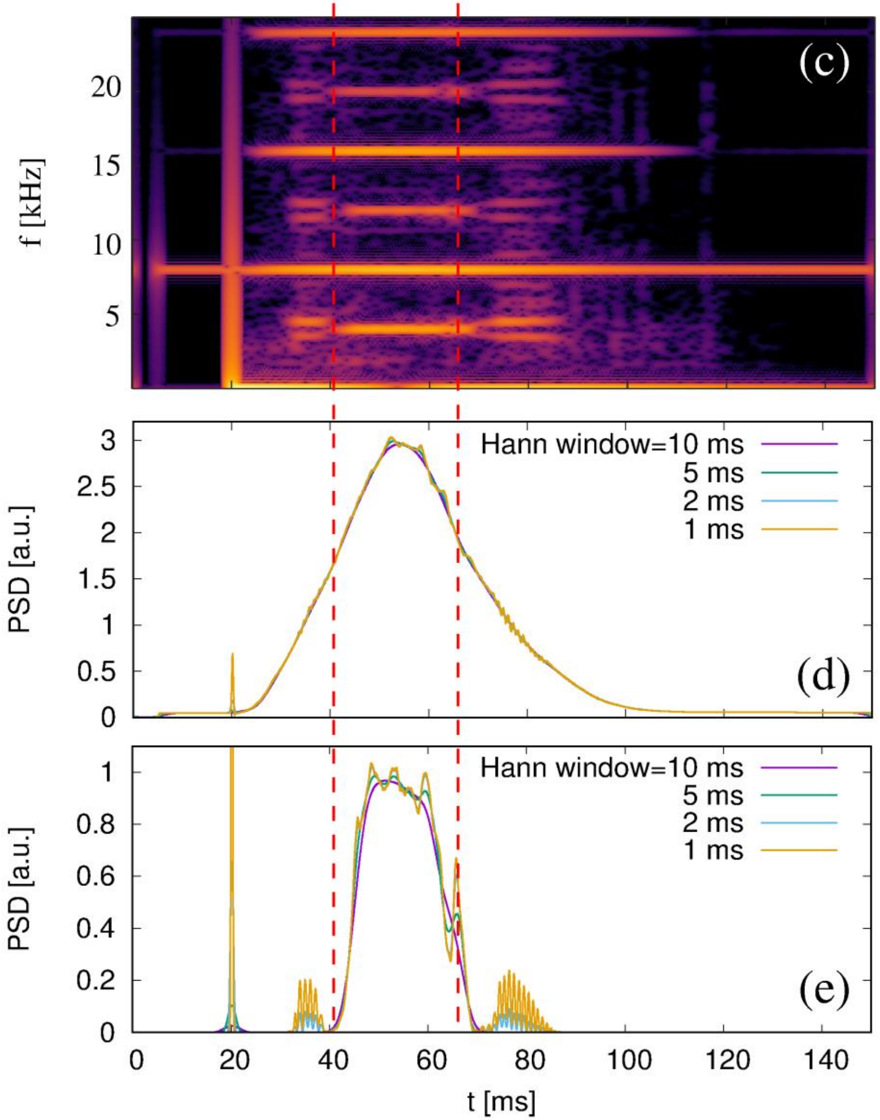
DRESDEN concept HZDR

CW excitation: Voltage over bottom contact

- Gabor transform (short time Fourier) with von Hann window 5 ms

- PSD of 8 kHz stripe is very smooth and roughly ~ B^2

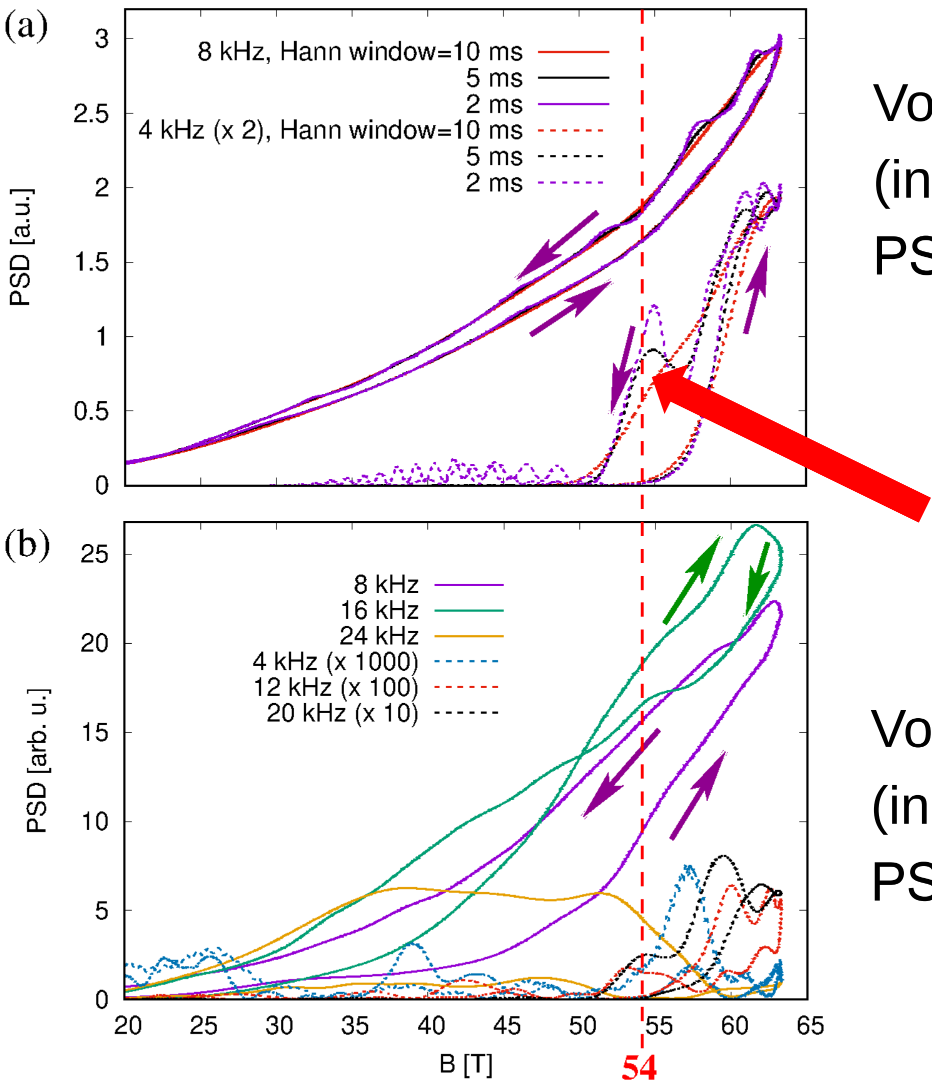
- PSD of 4 kHz stripe appears only for B=54 T (and larger)



DRESDEN concept

HZDR

CW excitation: Dependence on magnetic field



Voltage over bottom contact (indicative of Alfvén wave): PSD's for 8 kHz and 4 kHz

Period doubling due to parametric resonance (swing excitation)!!!

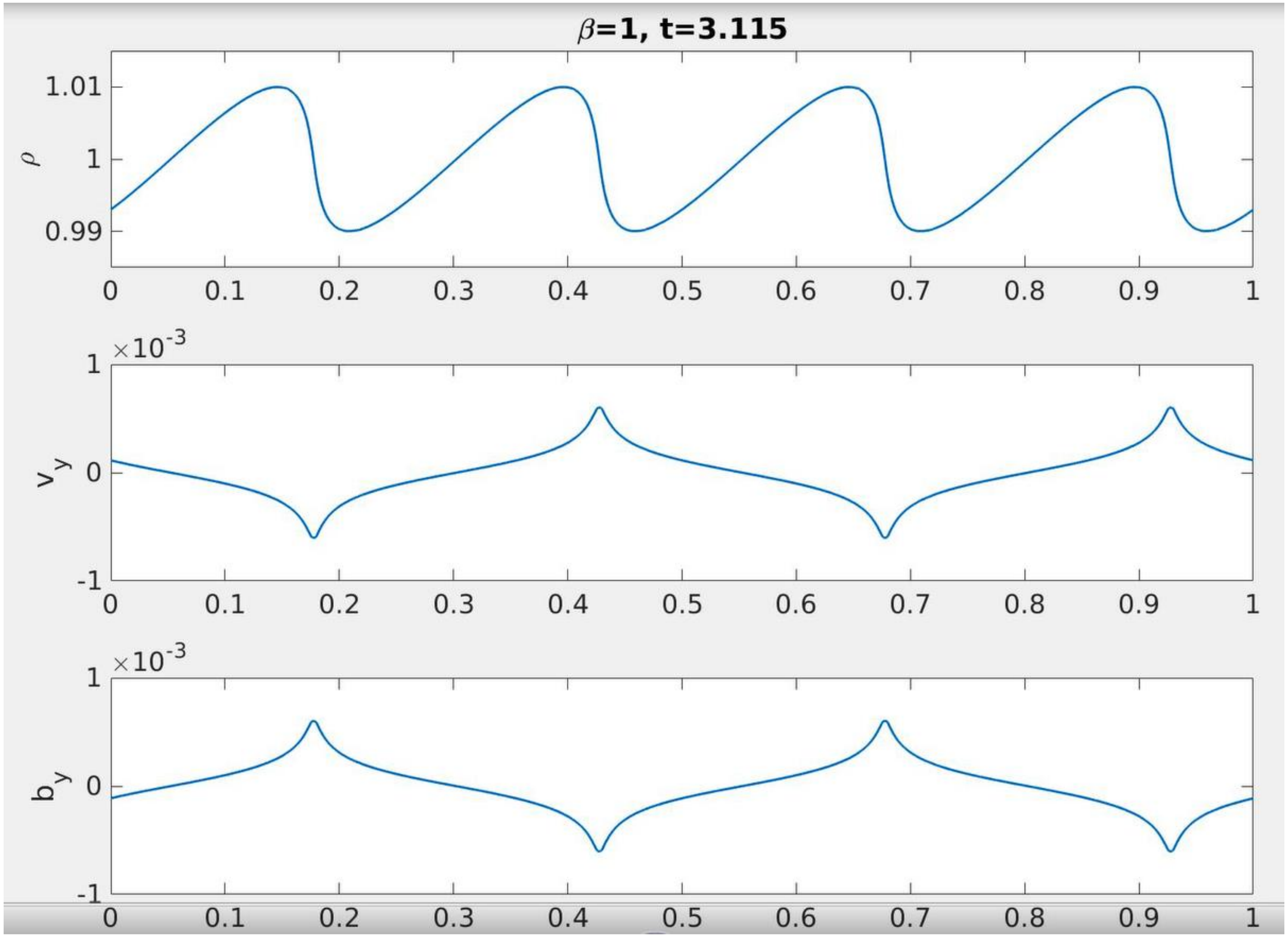
Voltage at pick-up coil 2 (indicative of magnetosonic waves): PSD's for n*4 kHz

First simulations of parametric resonance at β=1

Density

Velocity

Magnetic field



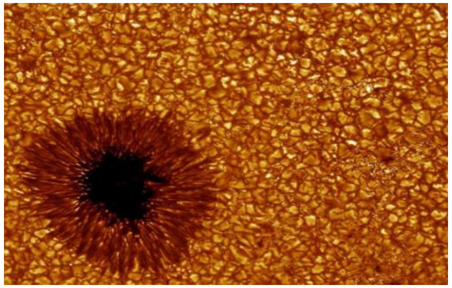
T. Zaqarashvili, ApJ 552 (2001) L81

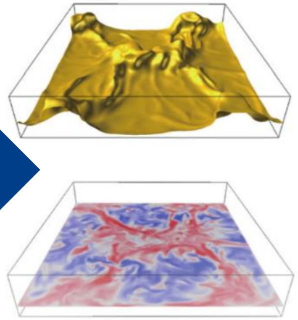
G. Mamatsashvili et al., in preparation

Convection

Convection at small Prandtl numbers

Turbulent superstructures in shallow geometry



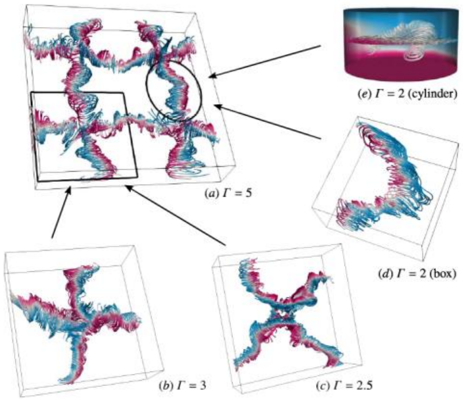


Akashi et al., J. Fluid Mech. 932, A27 (2022)

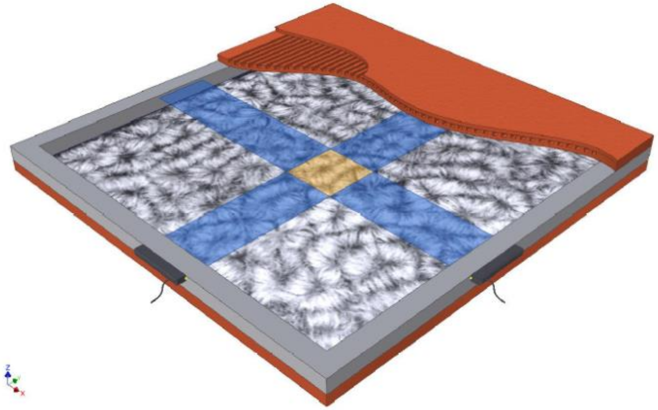
Jump rope vortex, detected first in…

Vogt et al., PNAS 115, 12674 (2018)

…turns out to be a **universal feature**

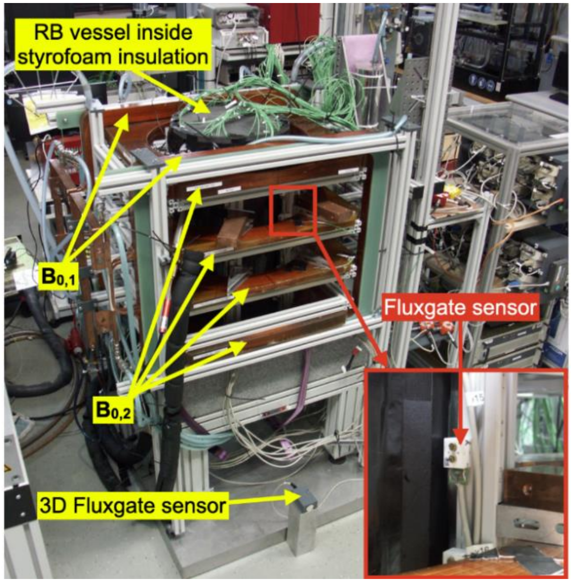


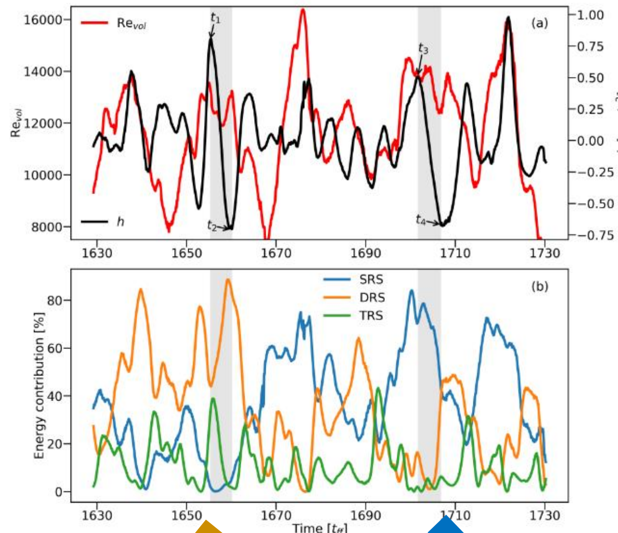
New experiment with Γ=25



Convection at small Prandtl numbers

Collaps of large-scale coherent flow in tall geometry

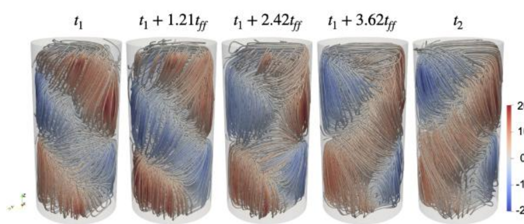


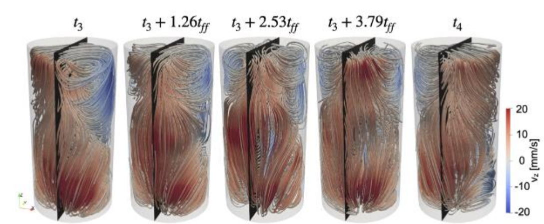


Chaotic transitions between single, double, and triple rolls

T. Wondrak et al., J. Fluid Mech. 974, A48 (2023)

Application of **Contactless Inductive Flow Tomography** for flow reconstruction



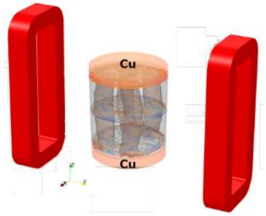


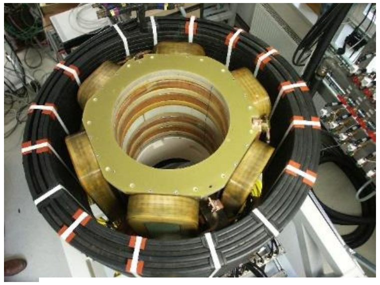
Helicity oscillations (with nearly no energy change) for Double Roll Structure und Single Roll Structure

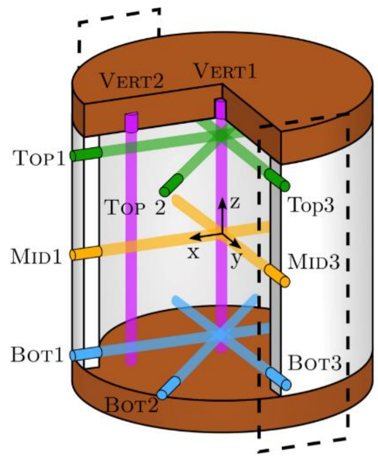
R. Mitra et al., Phys. Fluids 36, 066611(2024)

Helicity synchronization in a Rayleigh-Bénard flow

Goal: **resonant excitation of the helicity** of the sloshing m=1 mode (single roll structure) by a **tide-like** (m=2) electromagnetic force

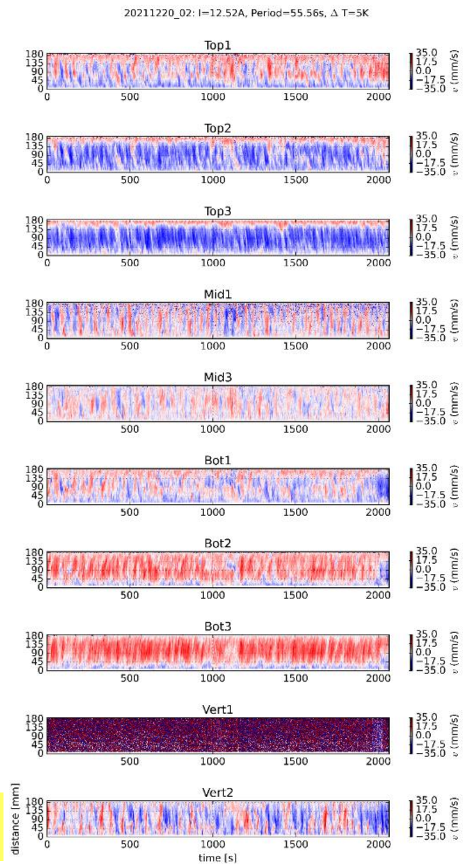


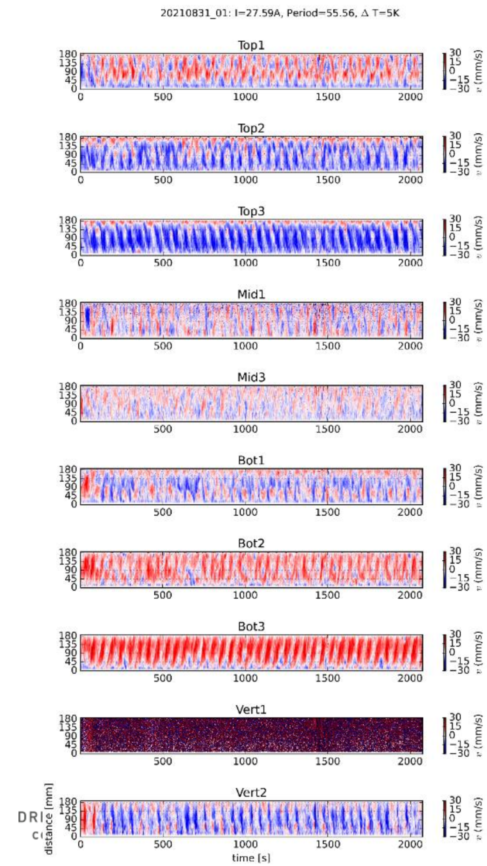


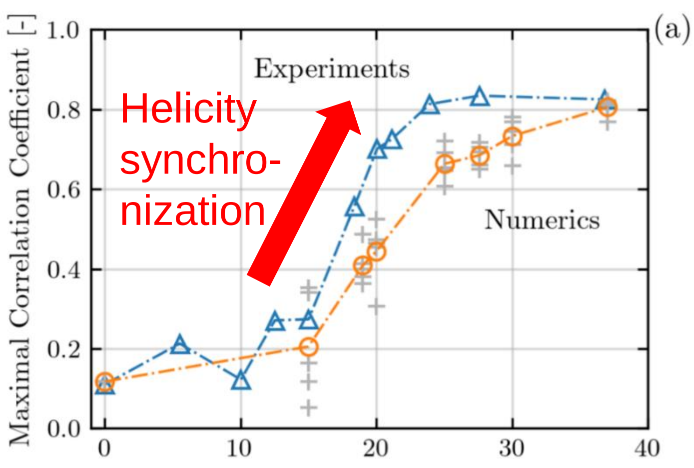


Synchronization of helicity

12.5 A → **27.5 A**







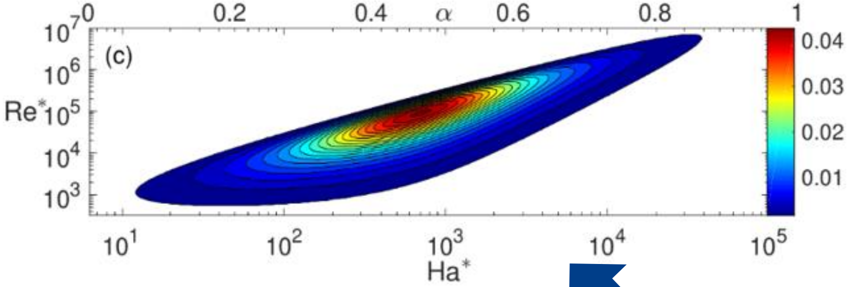
Jüstel et al., Phys. Fluids 34, 104115 (2022)

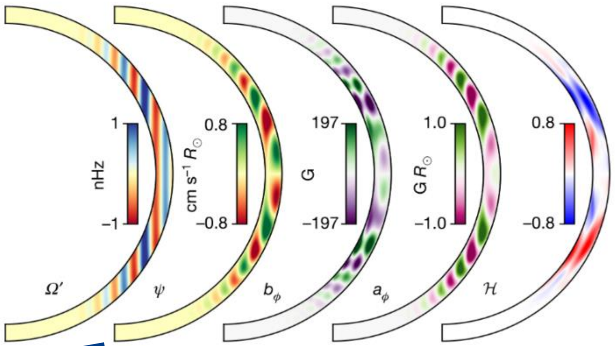
(The many facets of)

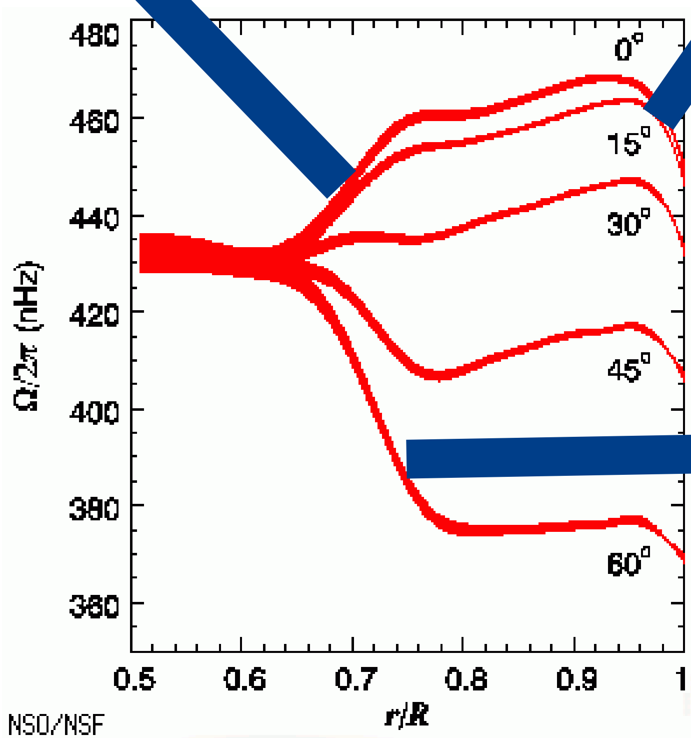
magnetorotational instability

(MRI)

MRI in the Sun?

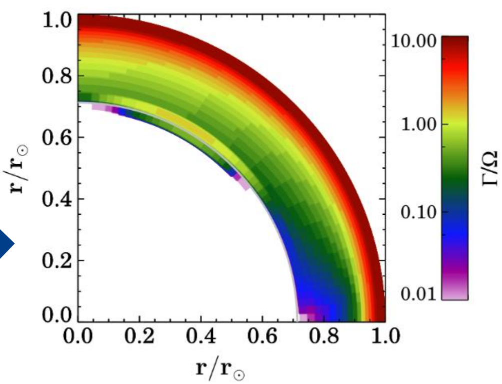






G. Mamatsashvili, F.S., R. Hollerbach, G. Rüdiger, Phys. Rev. Fluids 4 (2019), 103905

G.M. Vasil et al., Nature 628, 769 (2024)



D. Kagan, G.C. Wheeler, ApJ 782, 21 (2014)

A quick guide through the MRI-zoo

HMRI

$\Omega_{out} < \Omega_{in}$

$B_{\varphi} \sim B_z$

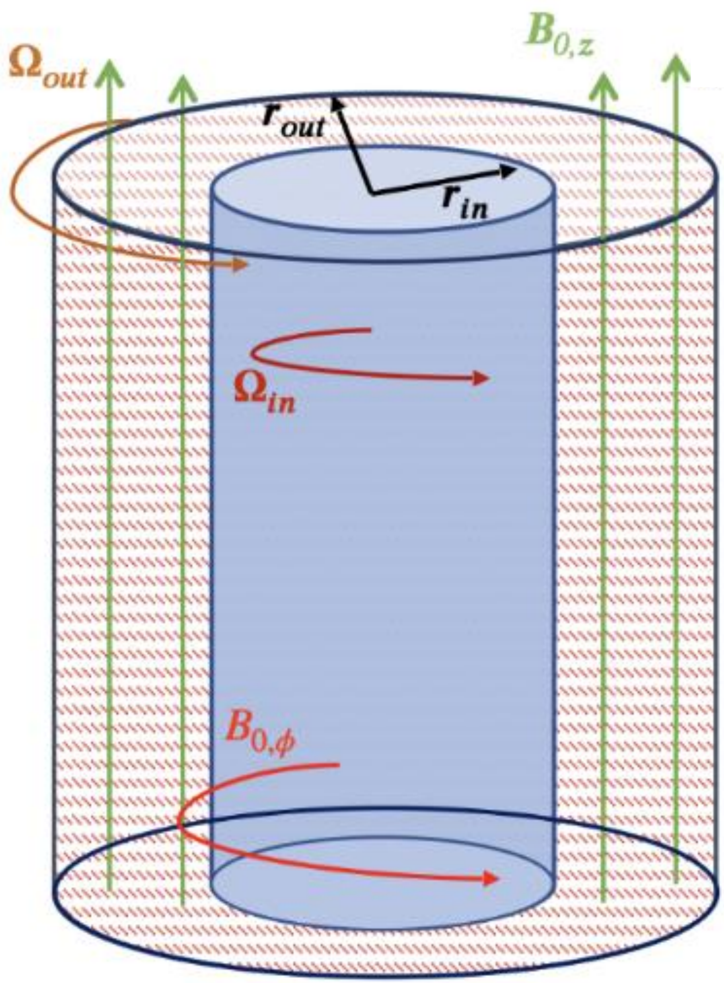
m=0

SMRI

$\Omega_{out} < \Omega_{in}$

$B_{\varphi} \ll B_z$

m=0



AMRI

$\Omega_{out} < \Omega_{in}$

$B_{\varphi} \gg B_z$

m=1

Super-HMRI

$\Omega_{out} > \Omega_{in}$

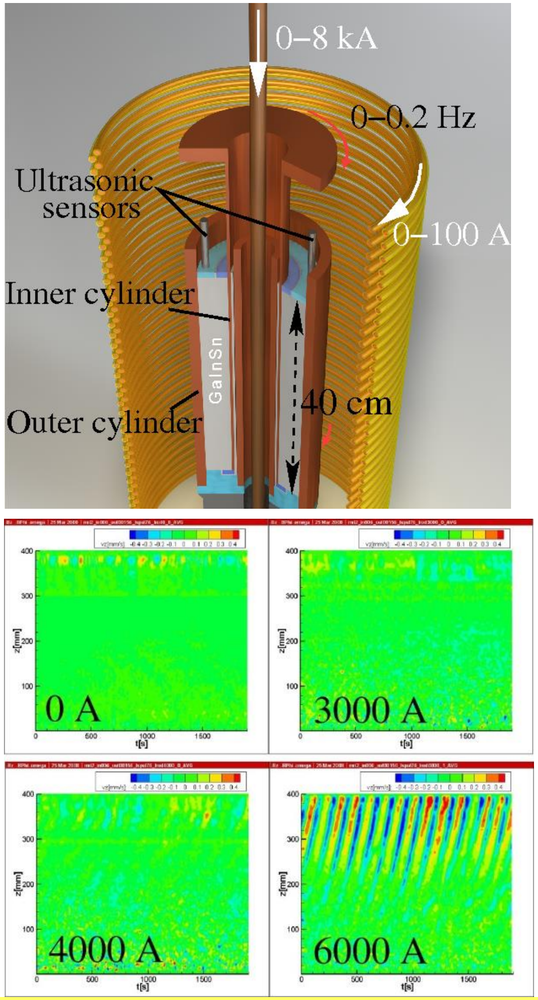
$B_{\varphi} \sim B_z$

m=0

DRESDEN concept HZDR

Helical MRI, Azimuthal MRI, Tayler instability (TI) at HZDR

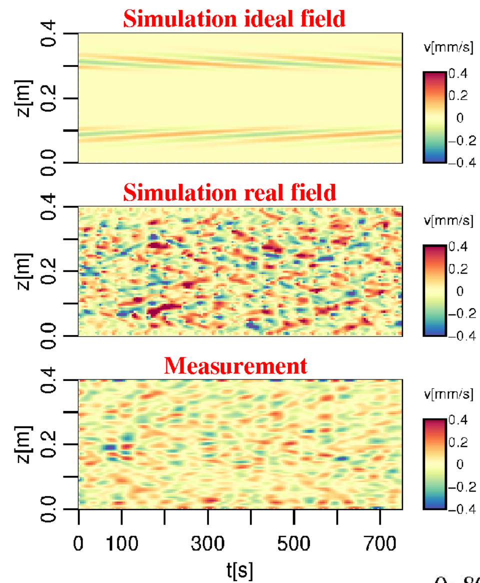
2006: HMRI

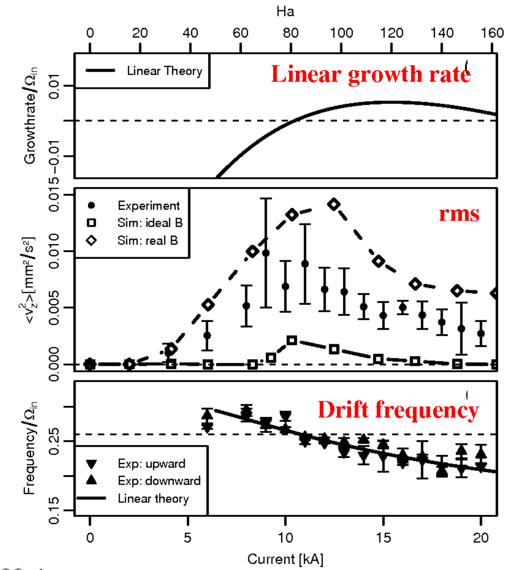


F.S. et al., PRL 97 (2006), 184502; PRE 80 (2009), 066303

2014: AMRI

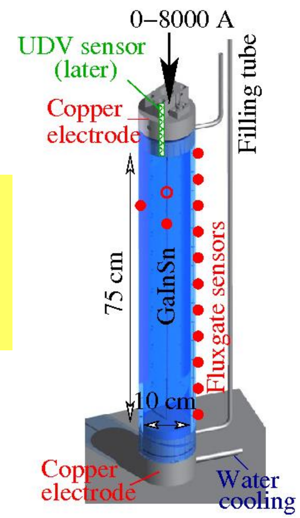
Seilmayer et al., PRL113 (2014), 024505

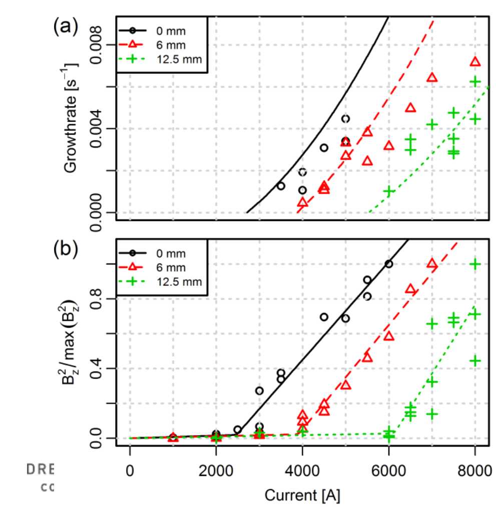




2012: TI

Seilmayer et al., PRL 108 (2012), 244501

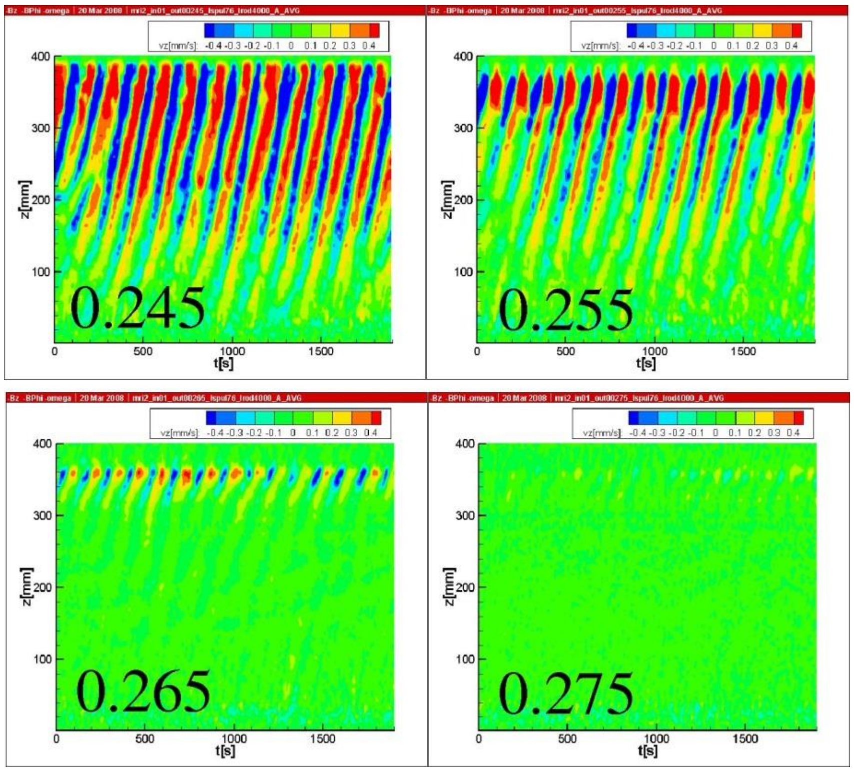


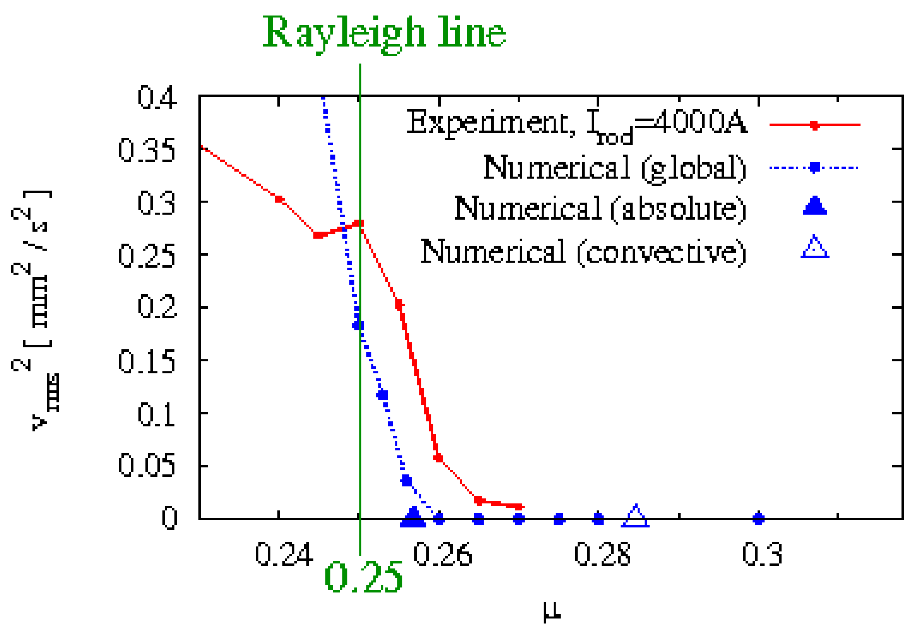


PROMISE: Selected results for HMRI

Example 1: Increase of the ratio $\mu=\Omega_{out}/\Omega_{in}$

Observed MRI is indeed an absolute (global) instability, and not only a convective one





Stefani et al., Phys. Rev. E 80 (2009), 066303

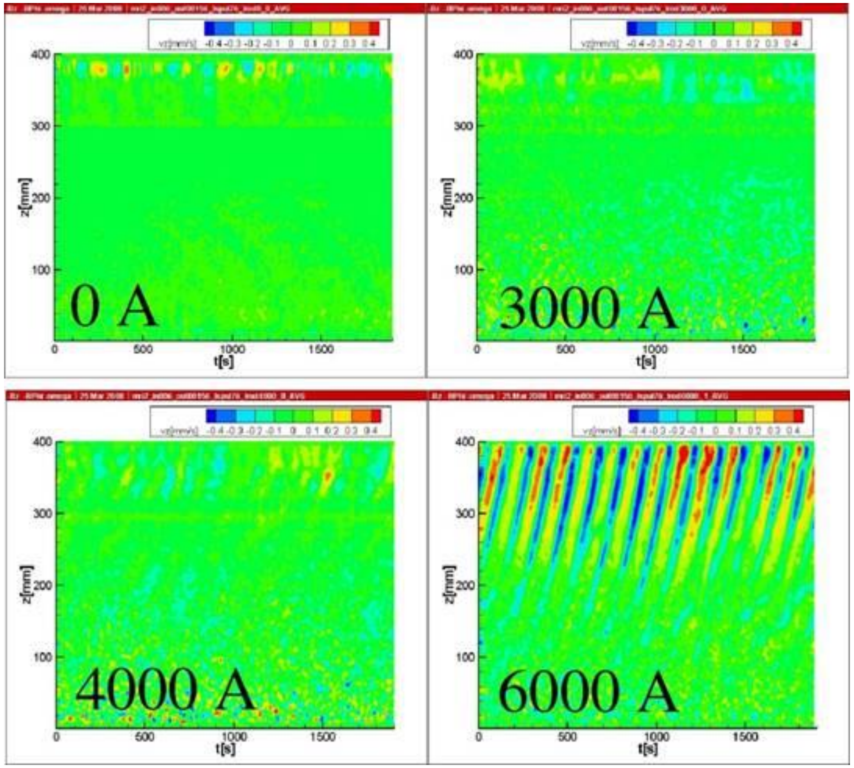
DRESDEN concept

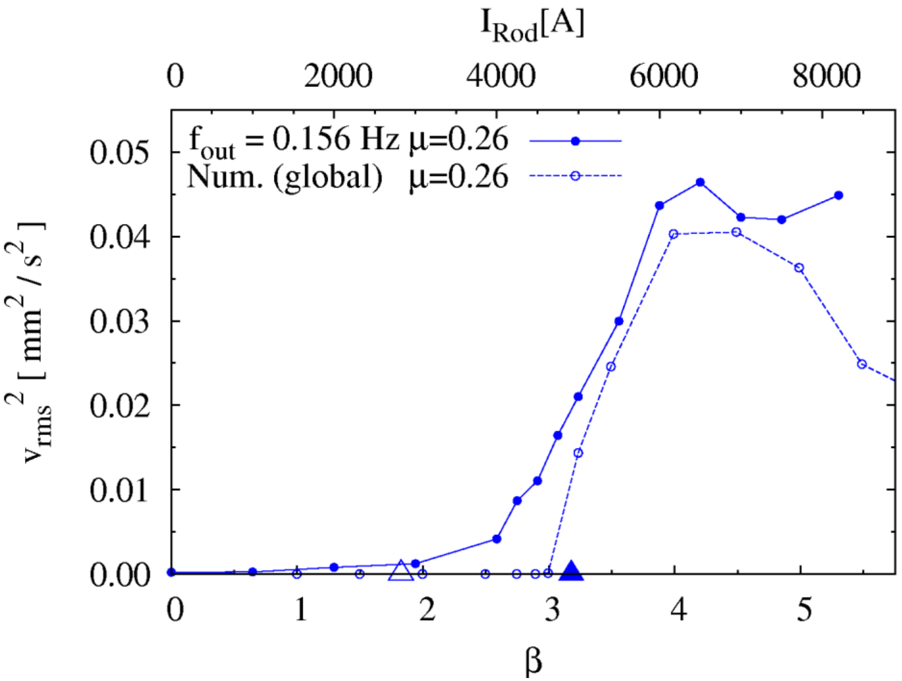
HZDR

PROMISE: Selected results for HMRI

Example 2: Increase of axial current (i.e. of the ratio $\beta=B_\varphi/B_z$)

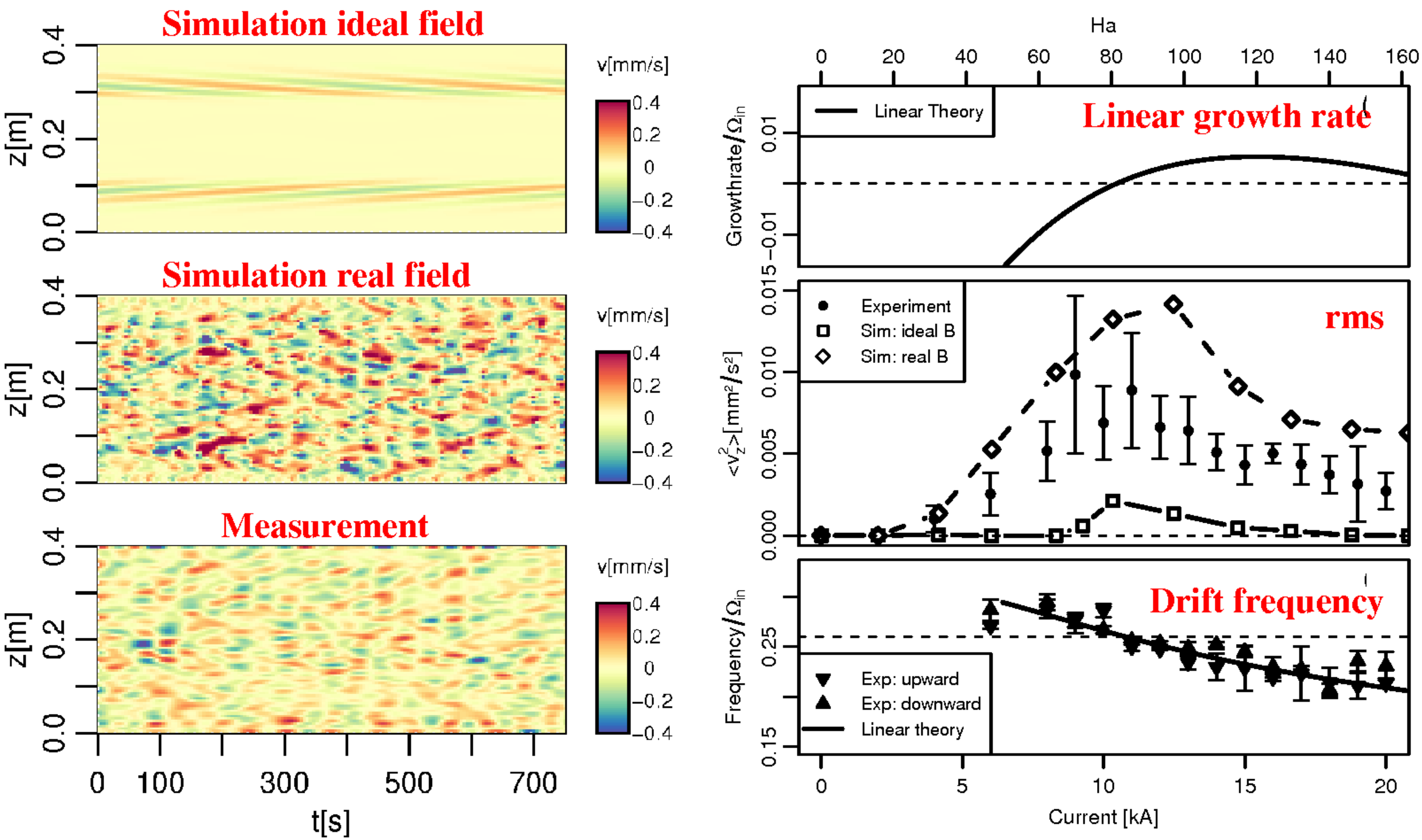
Again, observed MRI is indeed an absolute (global) instability, and not only a convective one





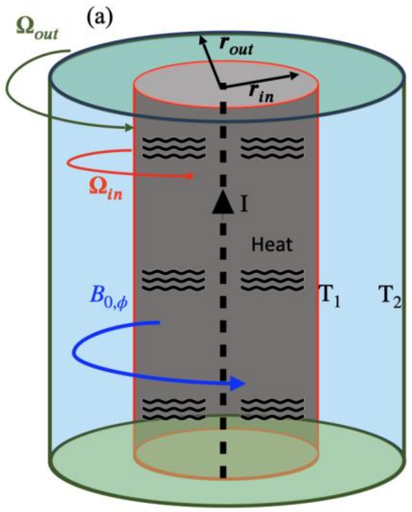
Stefani et al., Phys. Rev. E 80 (2009), 066303

AMRI: m=1 mode under influence of (pure, or dominant) B_φ

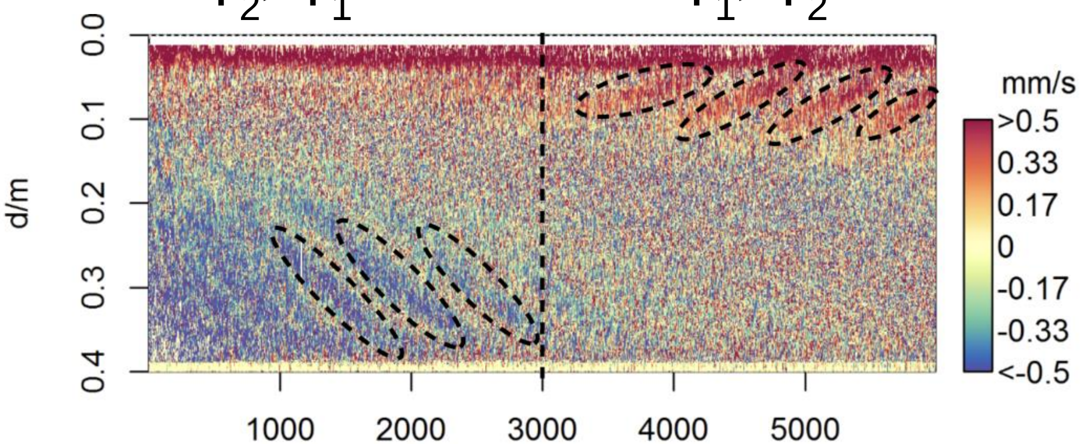


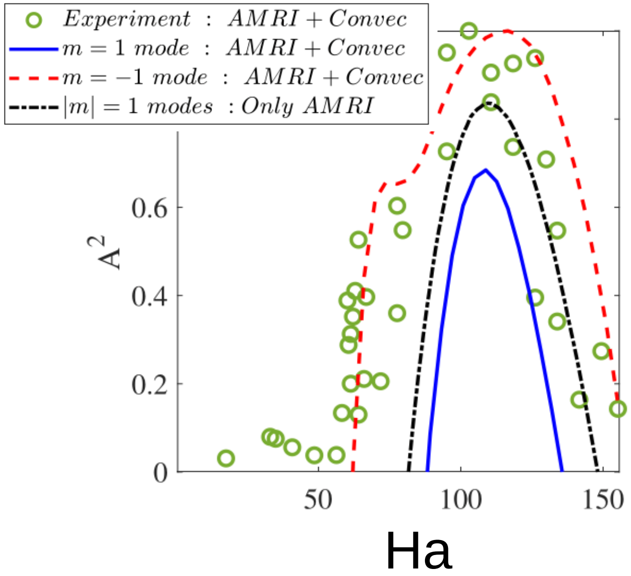
M. Seilmayer et al., PRL113 (2014), 024505

New results for AMRI+Convection: „One-winged butterflies“

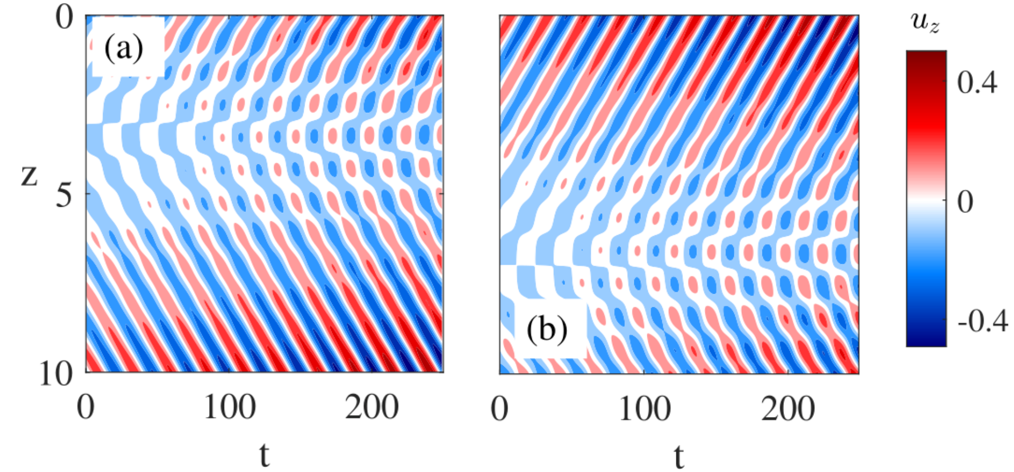


Experiment with changing radial heat flux



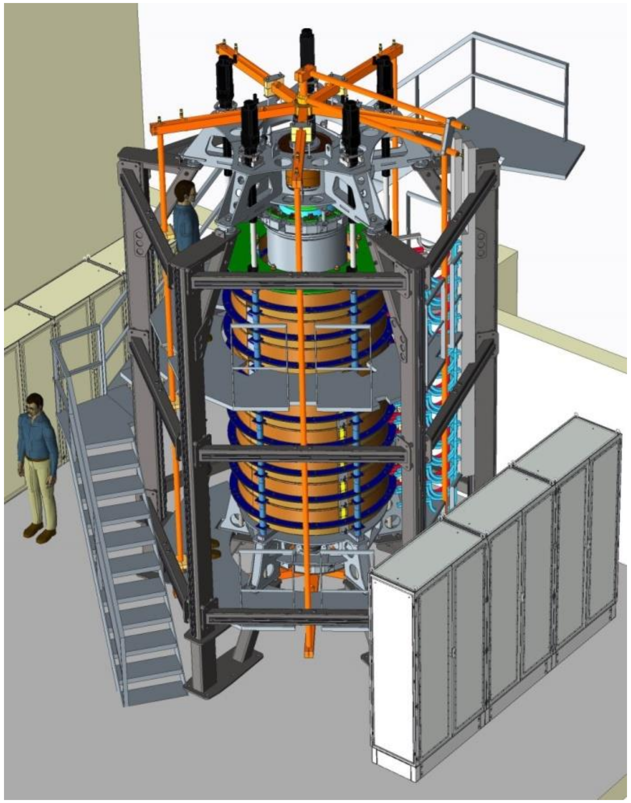


Simulation

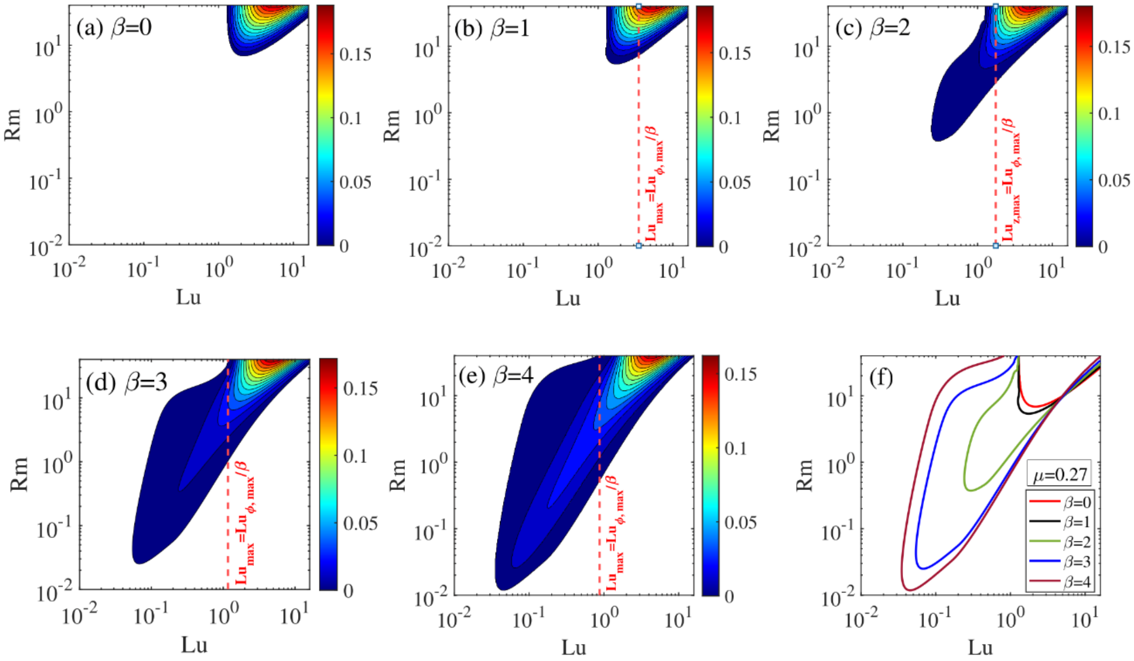


Seilmayer et al., Magnetohydrodynamics 56 (2020), 225; Mishra et al., J. Fluid Mech. (in press)

Planned experiment for SMRI, HMRI, AMRI, Super-HMRI and TI



Design of the planned MRI/TI-experiment

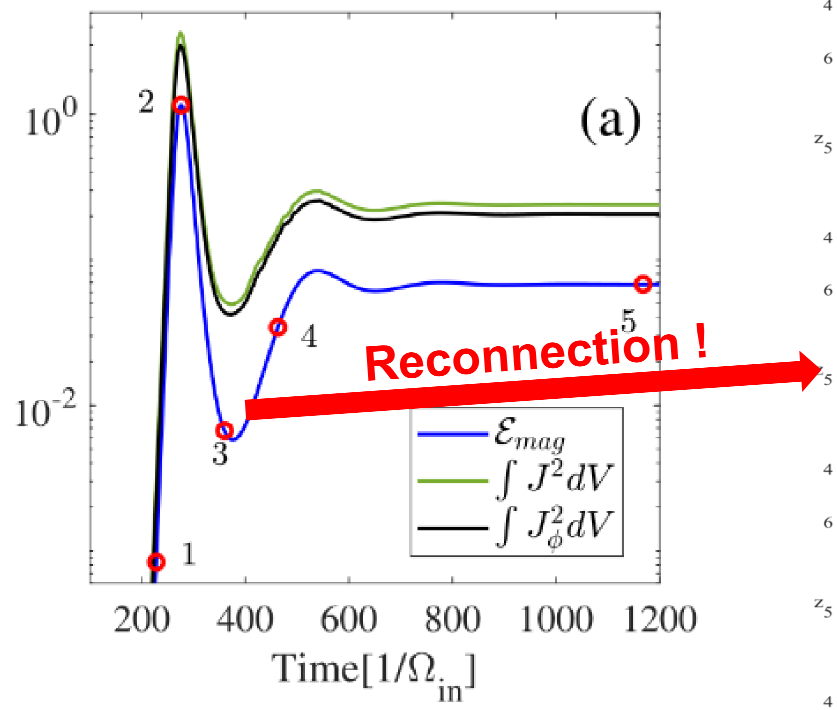


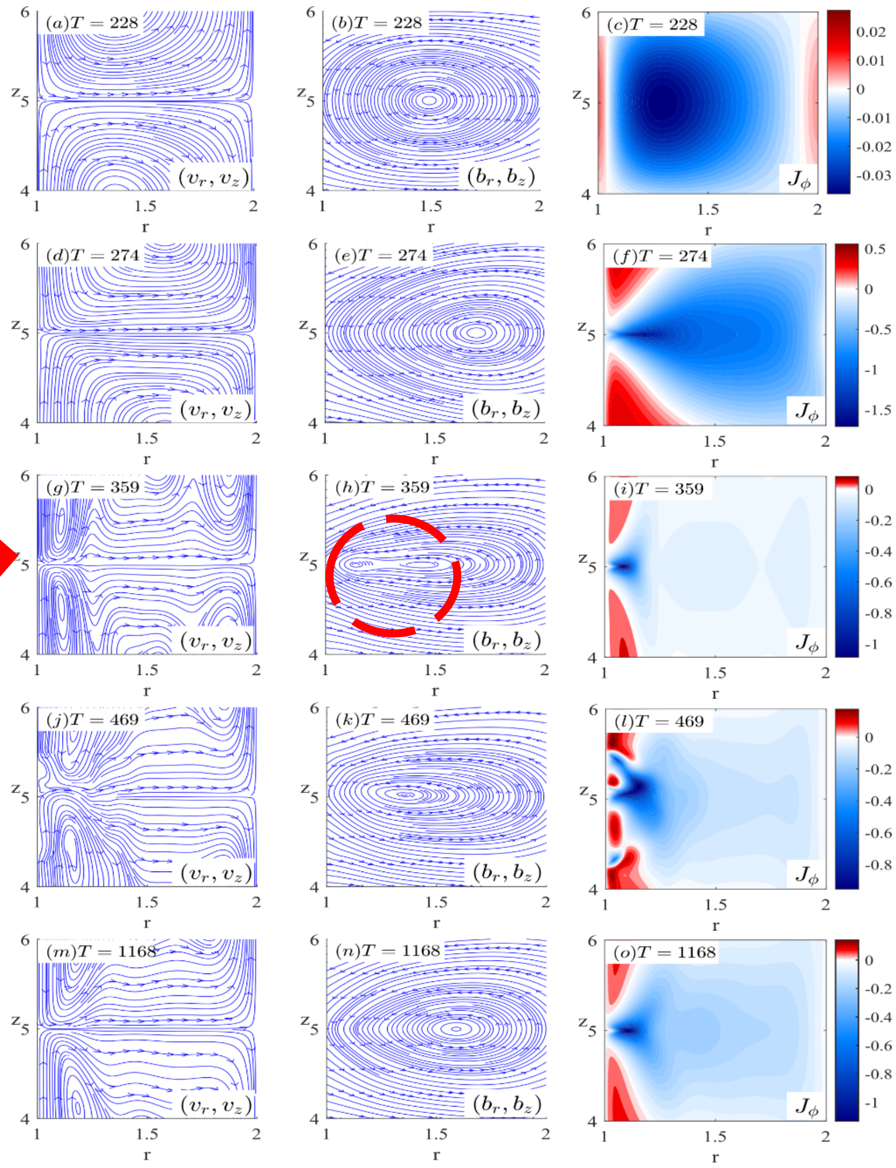
Main goal: follow the monotonic transition from HMRI to SMRI for decreasing $\beta = B_\varphi / B_z$

Mishra et al., Phys. Rev. Fluids 7 (2022), 064802

Preparations of MRI experiment: nonlinear simulations for m=0

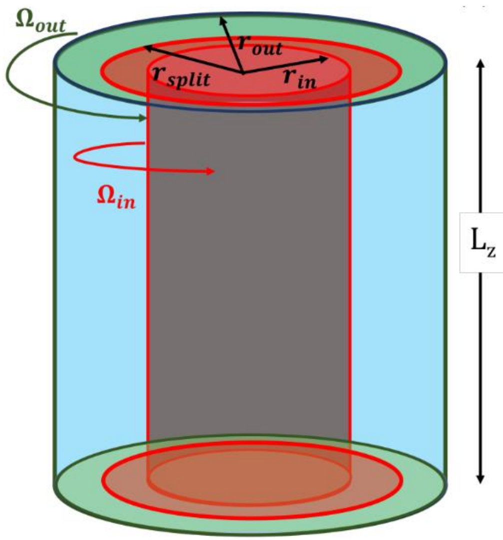
Saturation of MRI via magnetic reconnection

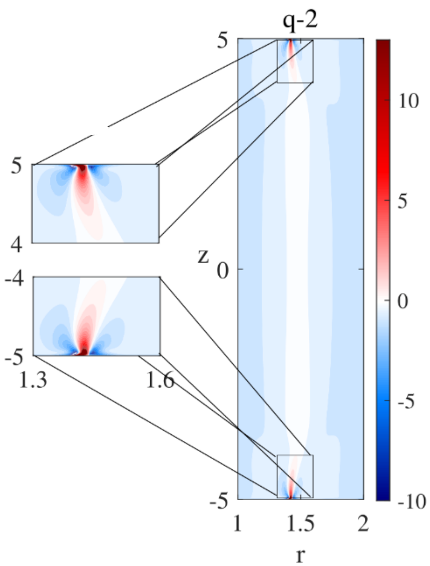


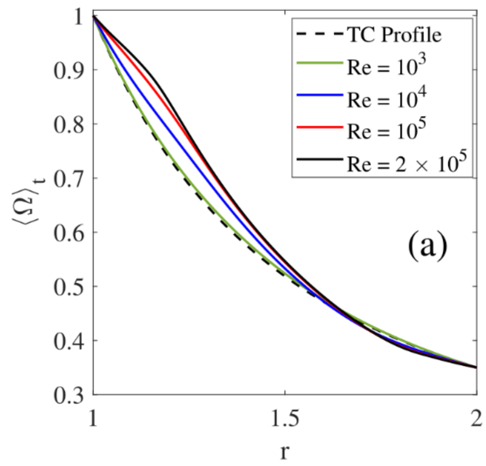


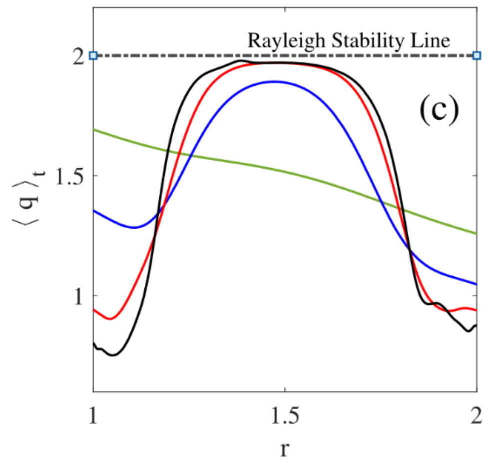
A. Mishra et al, Phys. Rev. Fluids 8, 083902 (2023)

That's all pretty nice, but what happens with real endcaps?

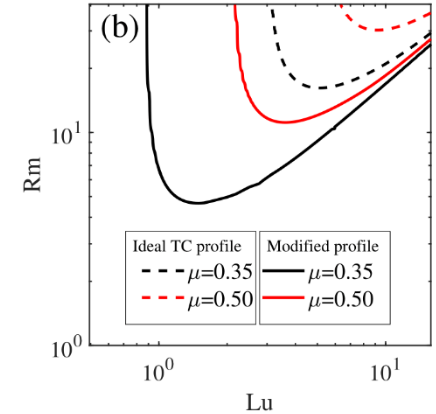




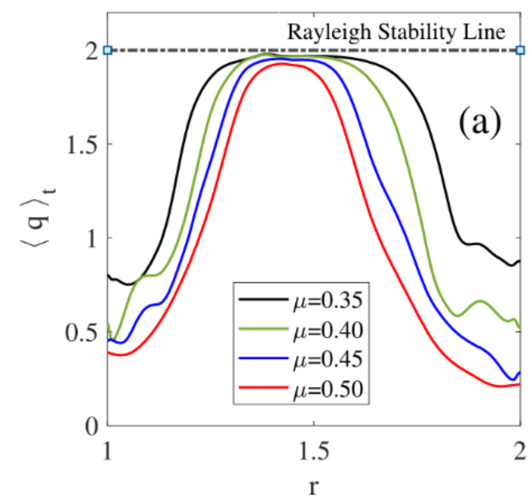




Ideal profile → real flow: **Critical Rm and Lu drop by factor of ~3**

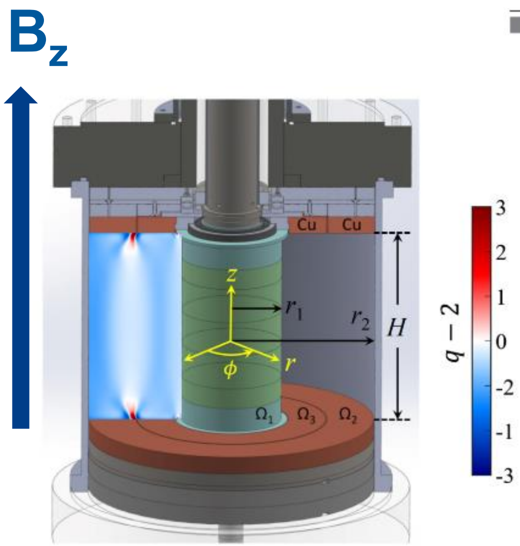


Replacing μ=0.35 by μ=0.5, the original critical values are retained



A. Mishra, Dissertation and Phys. Rev. Fluids 9, 033904 (2024)

The Princeton experiment on SMRI (talk by Y. Wang yesterday)

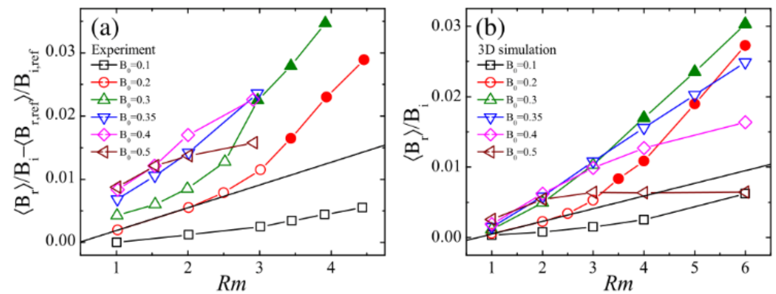


PHYSICAL REVIEW LETTERS 129, 115001 (2022)

Editors' Suggestion | Featured in Physics

Observation of Axisymmetric Standard Magnetorotational Instability in the Laboratory

Yin Wang[1,*] Erik P. Gilson[1] Fatima Ebrahimi[1,2] Jeremy Goodman[2] and Hantao Ji[1,2]
[1]Princeton Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08543, USA
[2]Department of Astrophysical Sciences, Princeton University, Princeton, New Jersey 08544, USA



nature communications

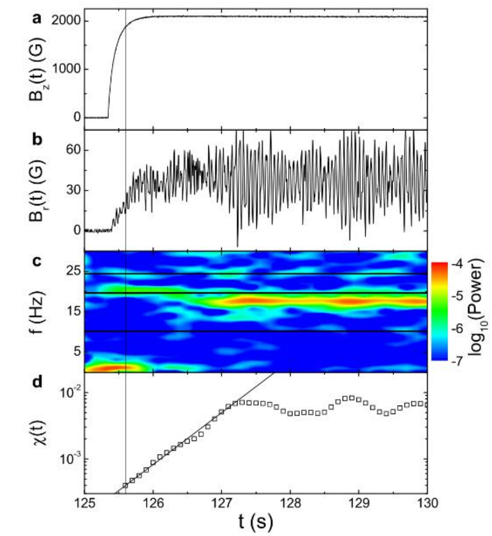
Article

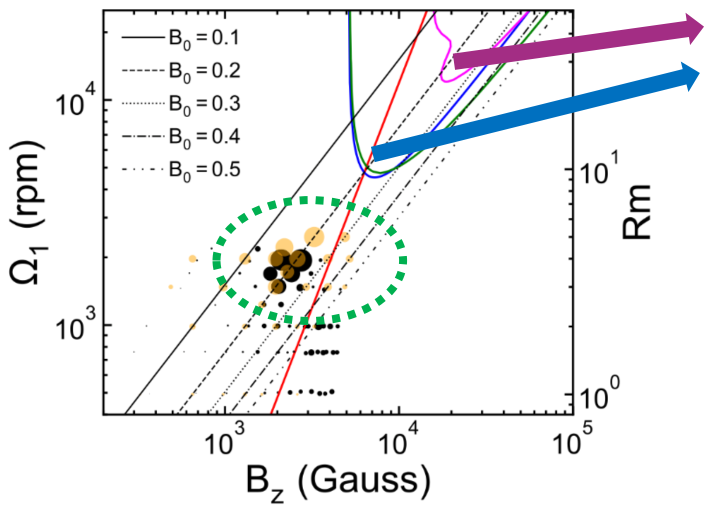
https://doi.org/10.1038/s41467-022-32278-0

Identification of a non-axisymmetric mode in laboratory experiments searching for standard magnetorotational instability

Received: 4 April 2022
Accepted: 25 July 2022

Yin Wang[1], Erik P. Gilson[1], Fatima Ebrahimi[1,2], Jeremy Goodman[2], Kyle J. Caspary[1], Himawan W. Winarto[2] & Hantao Ji[1,2]

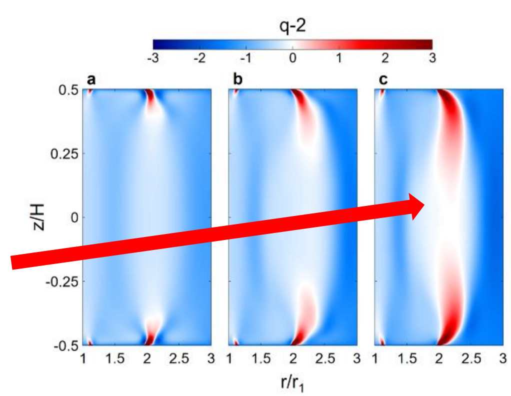




MRI detected for 10-times (m=1) or 3-times (m=0) too small values of Rm und Lu

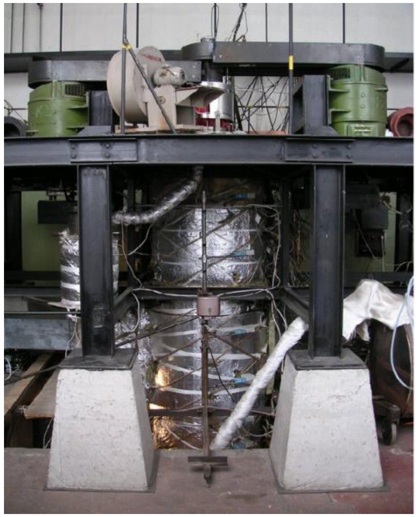
Similar problem:

Flow-induced currents in copper-lids modify the flow profile, which may become Rayleigh unstable (q>2)



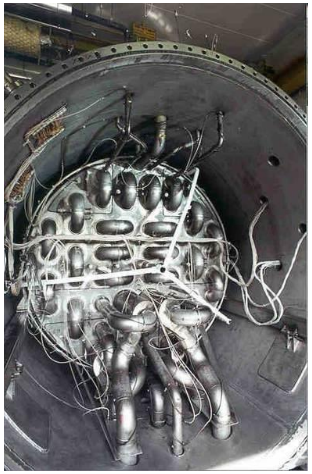
Rüdiger et al., J.Plasma Phys. 90 (2024), 905900105

Dynamos

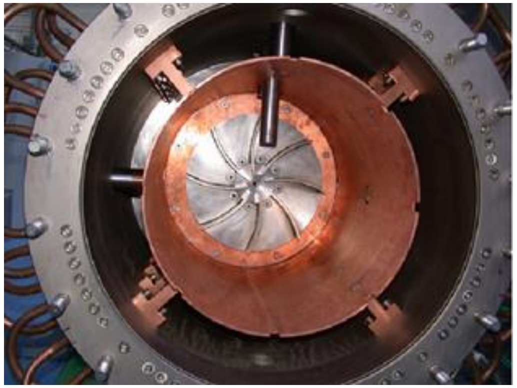


Riga

Karlsruhe



Dynamos

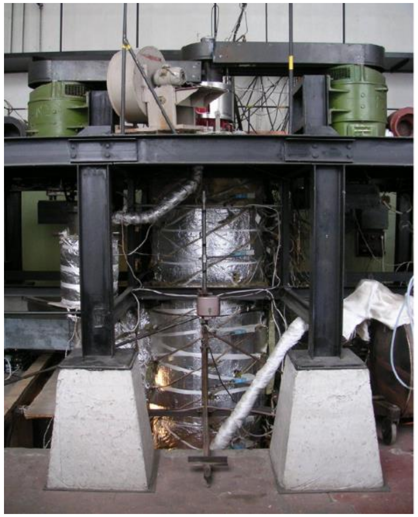


VKS

DRESDYN

DRESDEN concept

HZDR



Riga

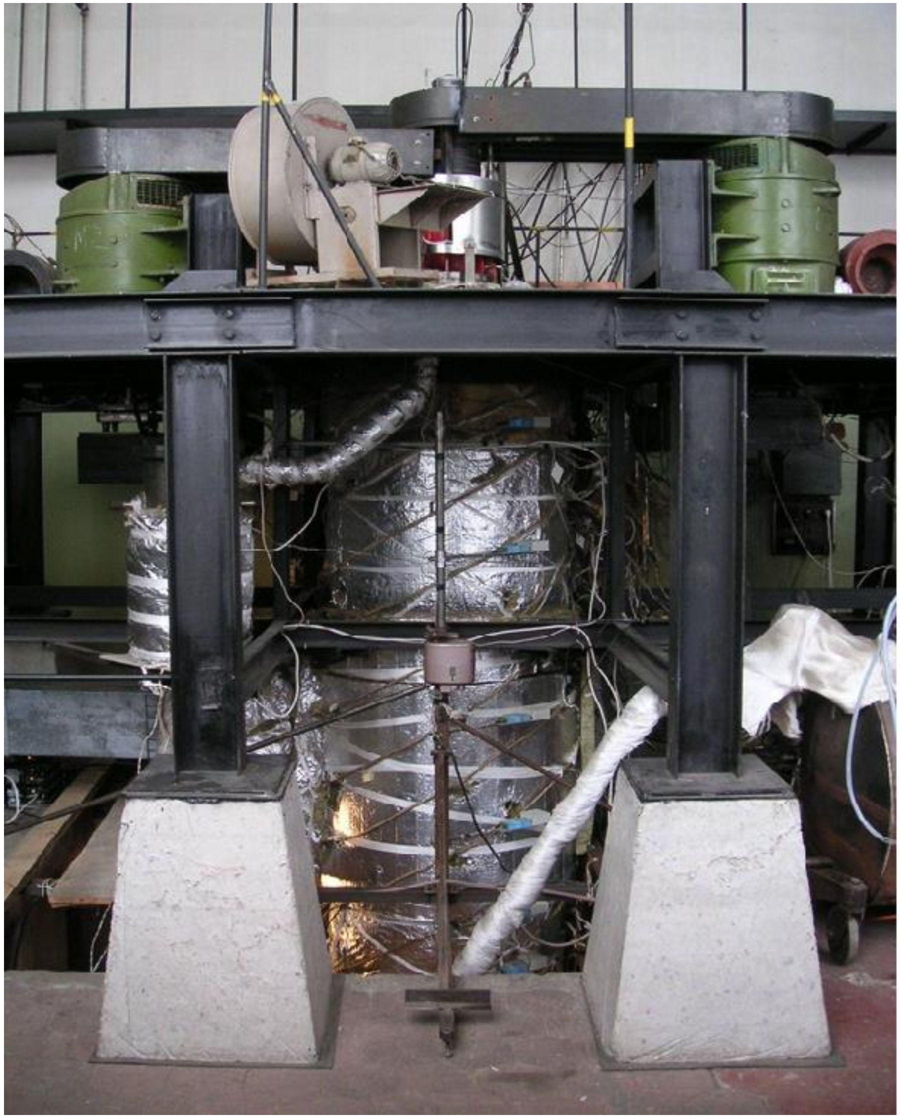
Karlsruhe

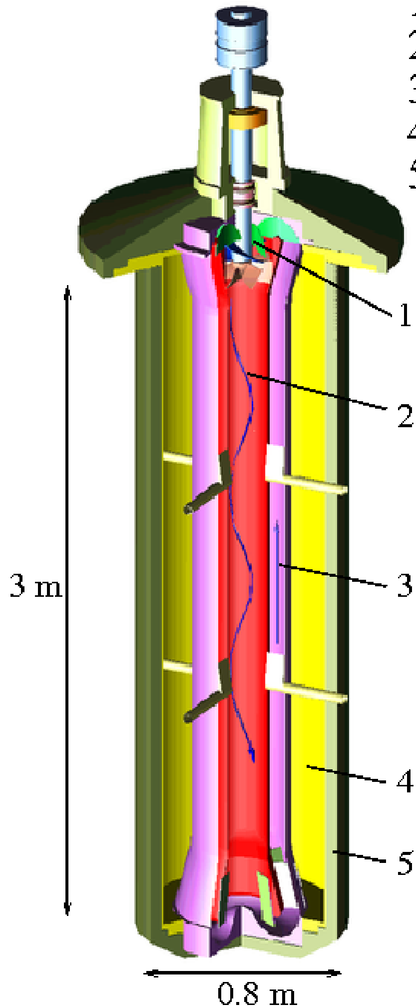
Dynamos

VKS

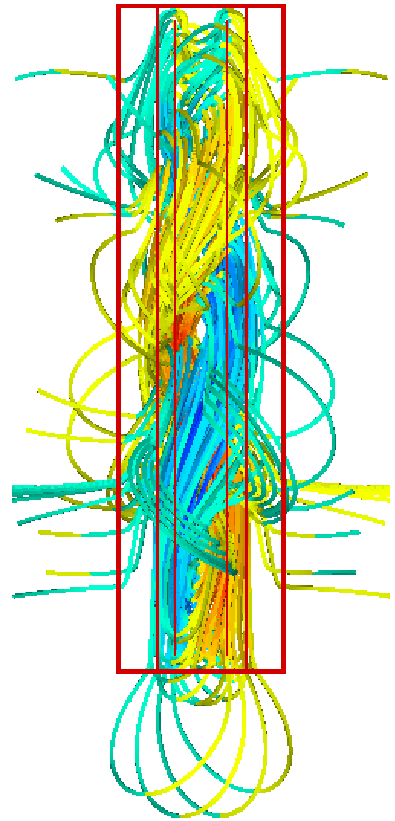
DRESDYN

Riga dynamo experiment





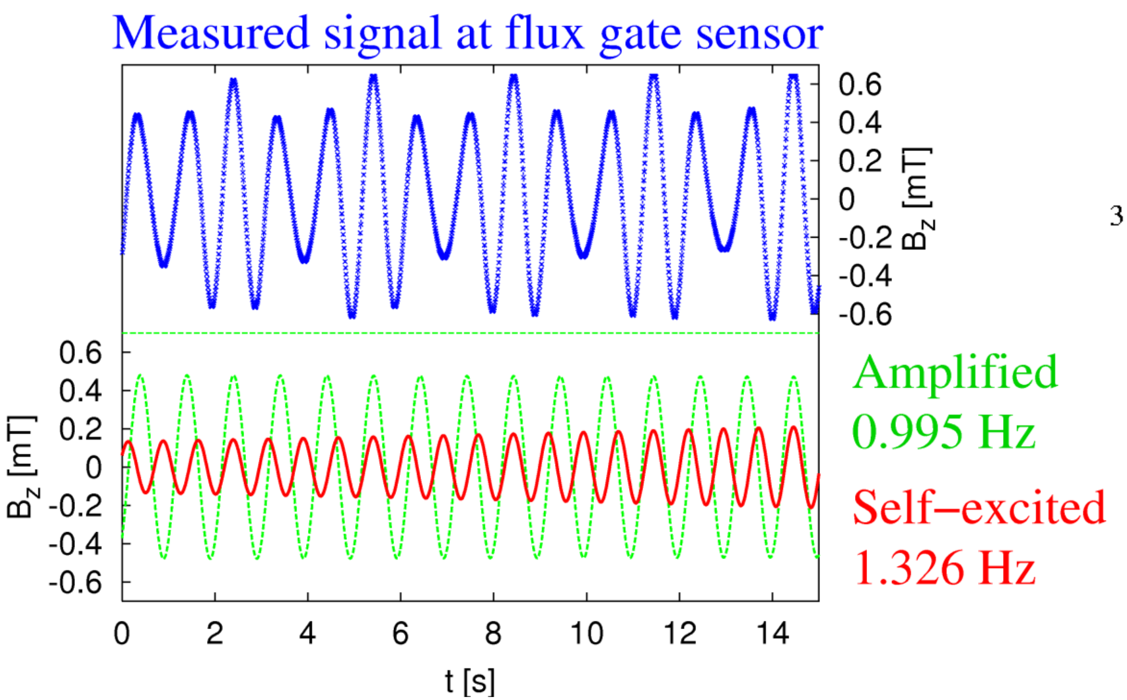
Dynamo module

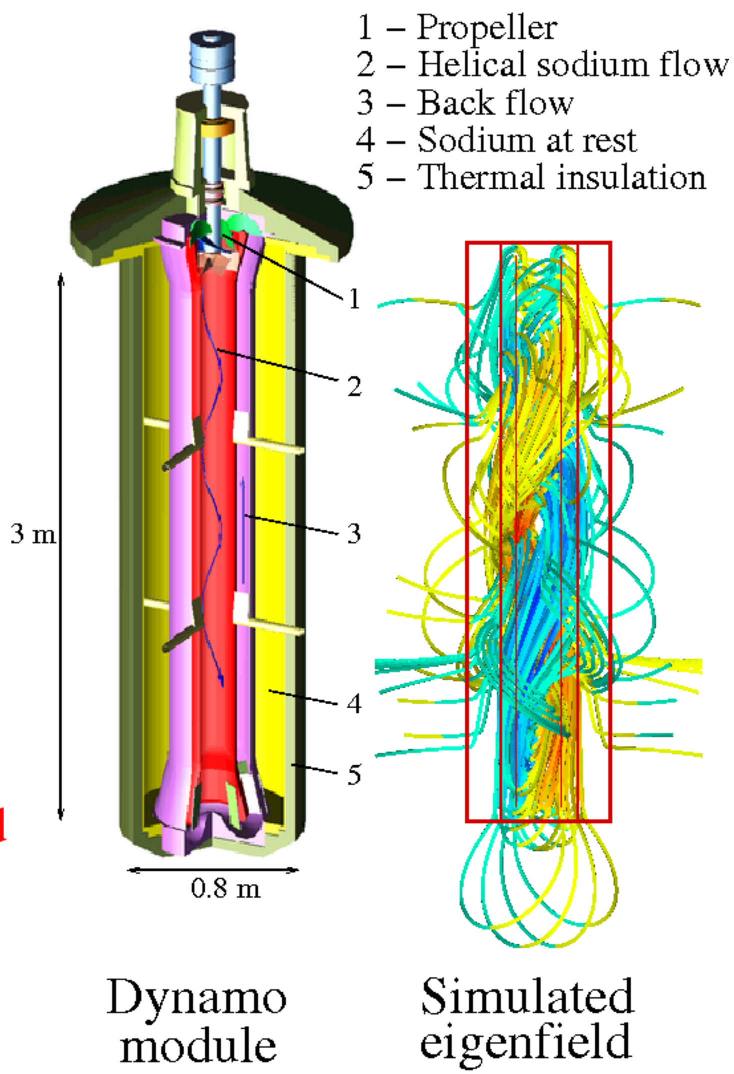


Simulated eigenfield

Riga dynamo experiment

First experimental realization of magnetic field self-excitation in a liquid metal flow (11 November 1999)



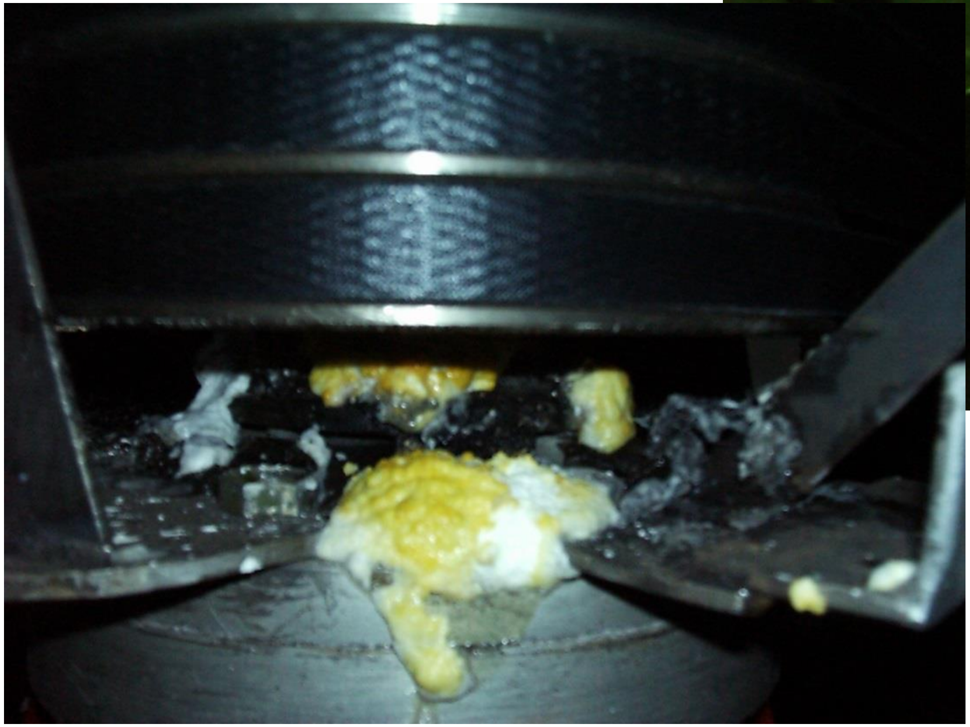


Gailitis et al., Phys. Rev. Lett. 84 (2000) 4365

DRESDEN concept HZDR

Come on baby light my SODIUM fire…

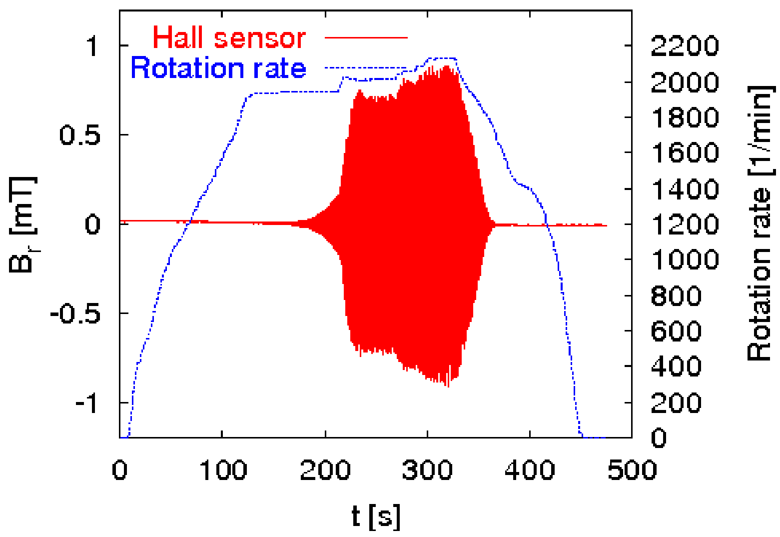
Evening of 11th November 1999



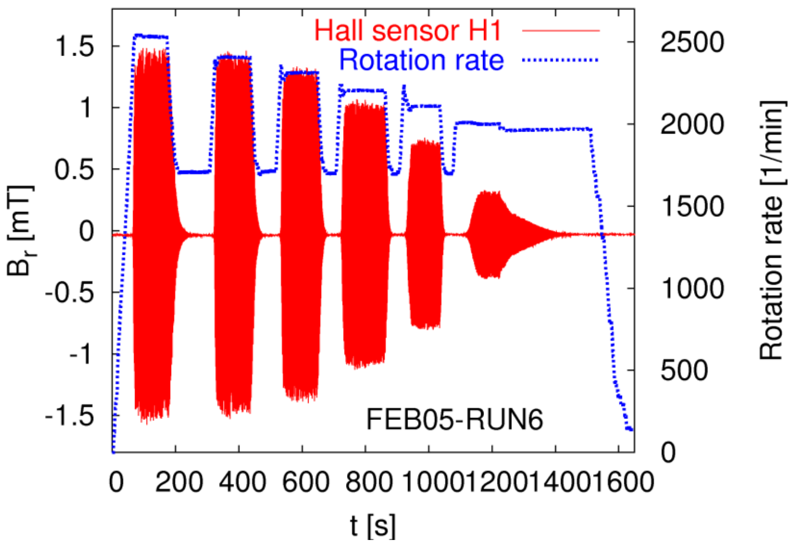
…and the day after…

Riga dynamo experiment

From the kinematic to the saturated regime (July 2000)



Switching the dynamo on and off (February 2005)

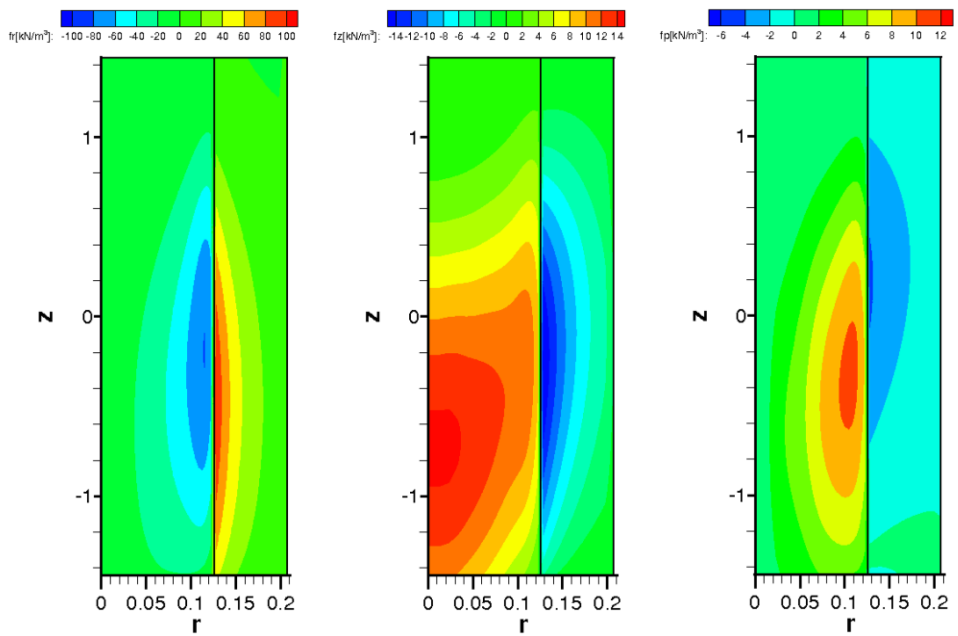


Gailitis et al., Phys. Rev. Lett. 84 (2000) 4365; Phys. Rev. Lett. 86 (2001) 3024; Rev. Mod. Phys. 74 (2002) 973 ; Phys. Plasmas 11 (2004) 2838; Compt. Rend. Phys. 9 (2008), 721; **J. Plasma Phys. 84, 735840301 (2018)**

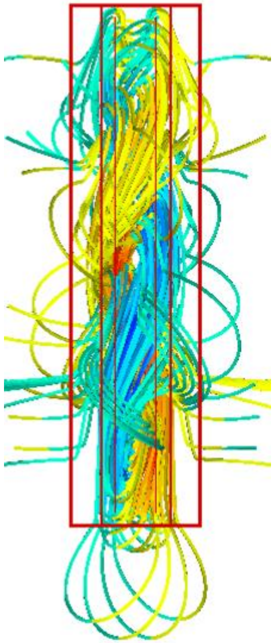
Riga dynamo experiment: Back-reaction illustrates Lenz´s rule

Lorentz force components resulting from self-excited eigenfield

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \frac{1}{\mu_0 \sigma} \Delta \mathbf{B}$$



$f_r(r,z)$ $f_z(r,z)$ $f_\varphi(r,z)$

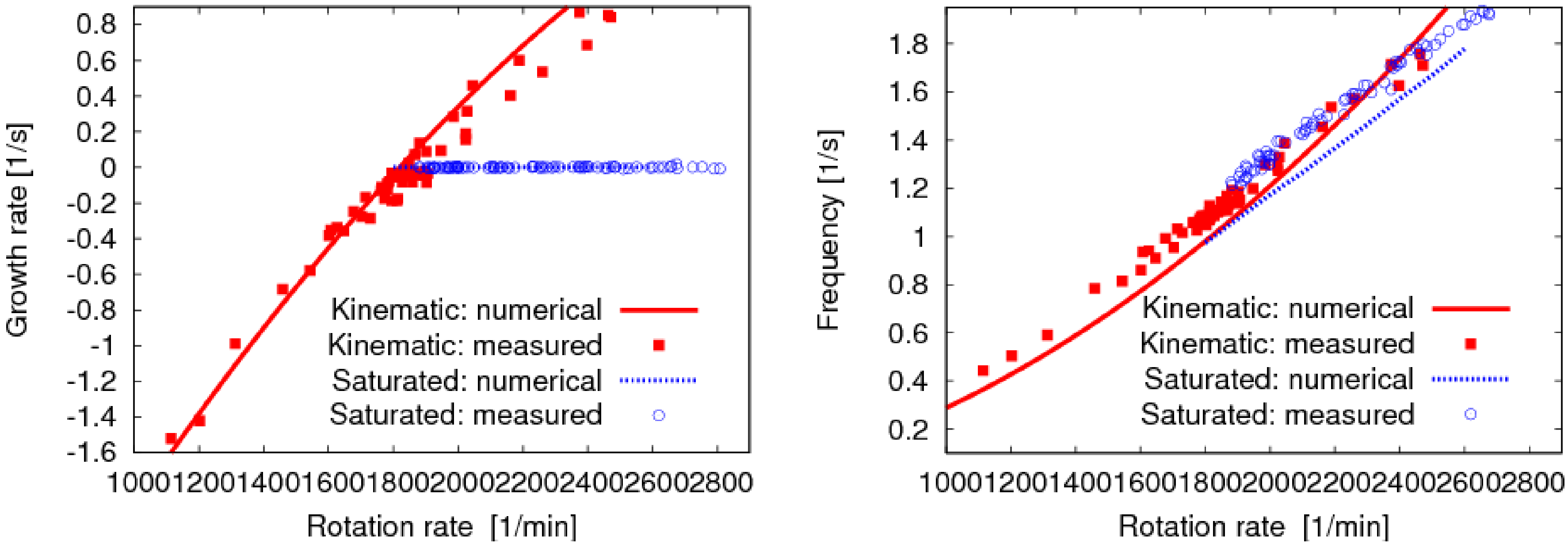


$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} = -\frac{\nabla p}{\rho} + \frac{1}{\mu_0 \rho}(\nabla \times \mathbf{B}) \times \mathbf{B} + \nu \Delta \mathbf{v} + \mathbf{f}_{extern}$$

DRESDEN concept

HZDR

Riga dynamo experiment: Growth rates and frequencies



Numerical predictions (with correct vacuum boundary conditions) of the kinematic dynamo were accurate to some 5 per cent

Simplified back-reaction model (Lorentz forces acting along streamlines) gives very reasonable field amplitudes and structures in the saturation regime

Gailitis et al. J. Plasma Phys. 84, 735840301 (2018)

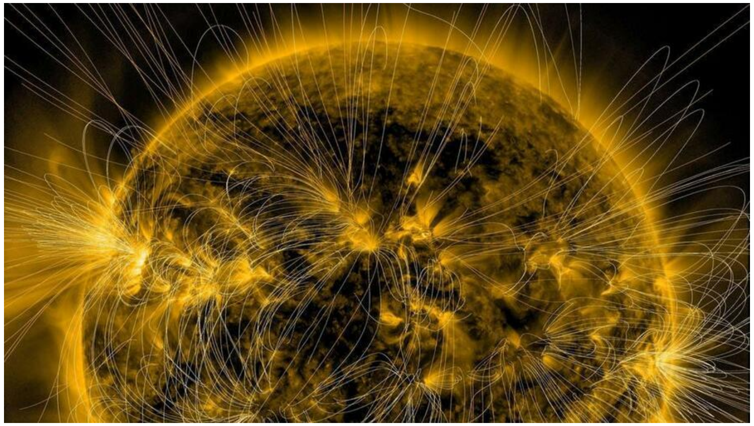
DRESDEN concept

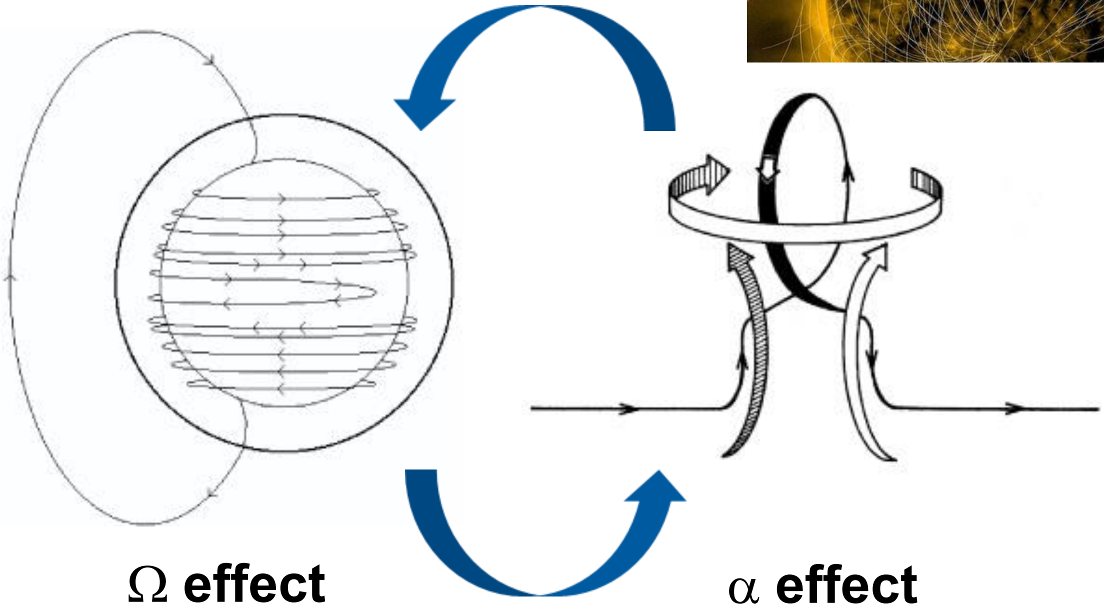
HZDR

A short diversion into theory: The solar dynamo

Any solar dynamo needs:

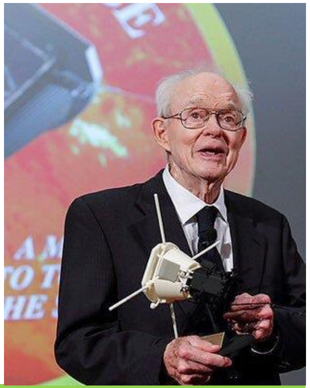
- some Ω effect to wind up toroidal field from poloidal field
- some α effect to regenerate poloidal field from toroidal field





Ω **effect**

α **effect**



Parker, Astrophys J. 122, 293 (1955)

DRESDEN concept

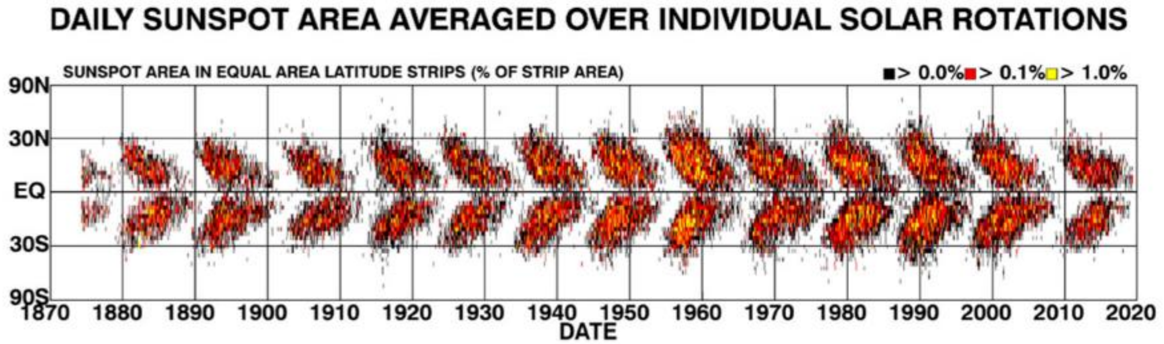
HZDR

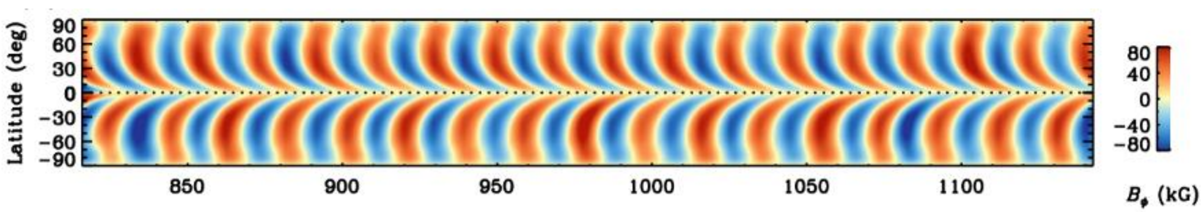
Solar dynamo: Conventional modelling

With appropriate models, (including meridional circulation), and some parameter fitting, one obtains

- a reasonable period of the Hale cycle (22 years)
- a reasonable shape of the butterfly diagram of sunspots

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

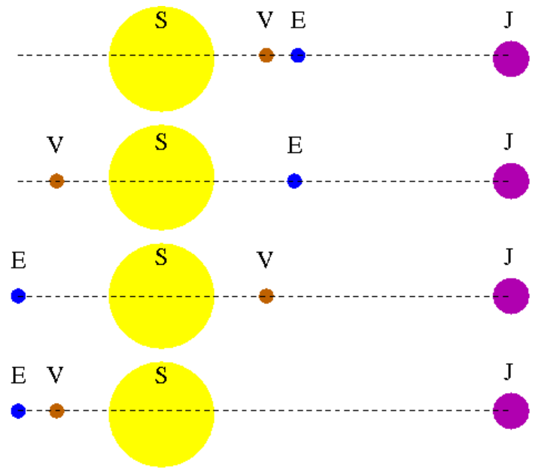




Karak, B.B., Miesch, M., ApJ 847 (2017), 69

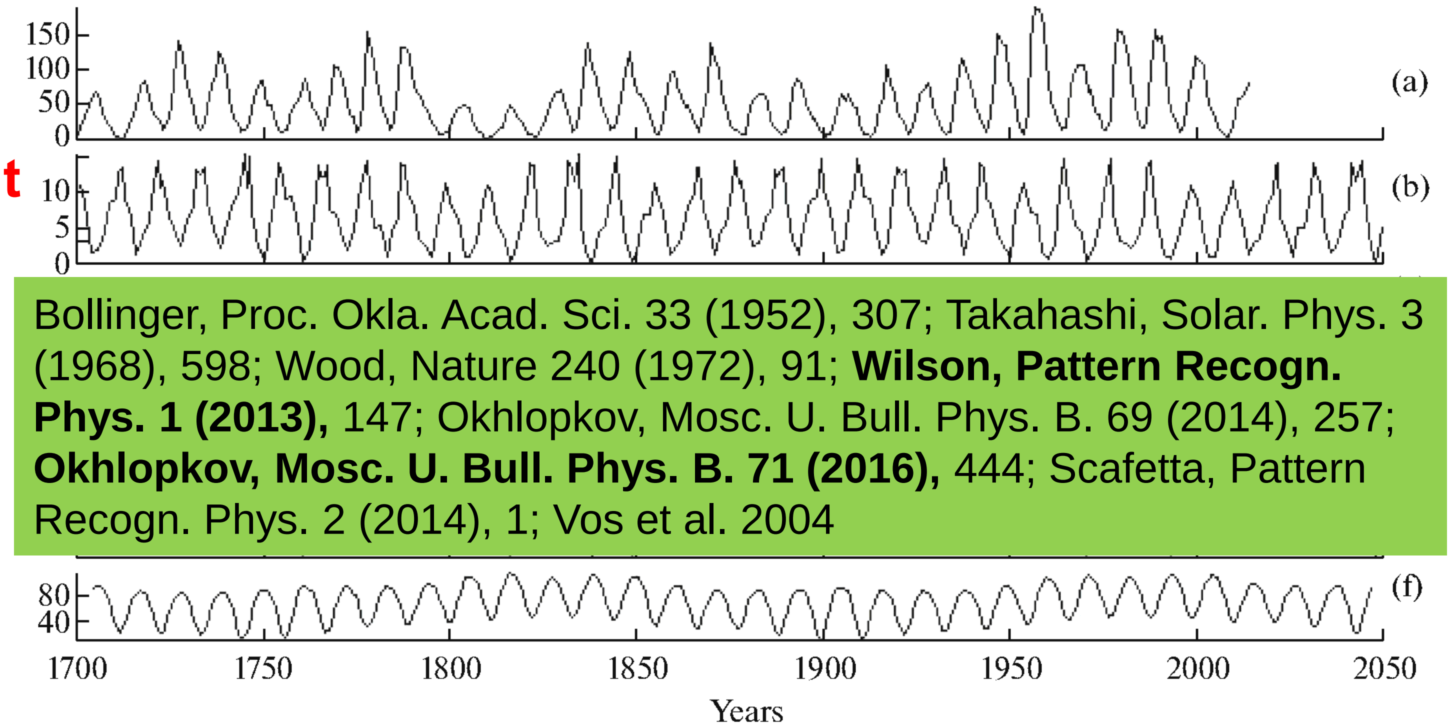
Is there a problem at all with the solar dynamo? Perhaps yes…

Conspicious synchronization of the solar Schwabe cycle with the 11.07-yr period of three-planet syzygies of the tidally dominant **Venus-Earth-Jupiter** system (despite weak tidal forces!)



Sunspots

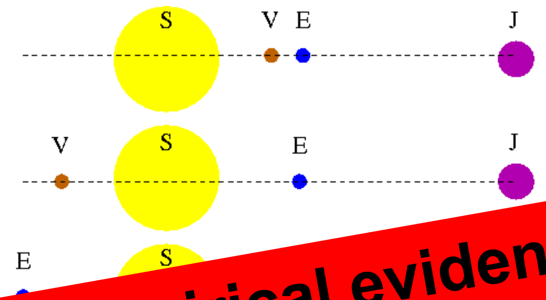
VEJ alignment index



Bollinger, Proc. Okla. Acad. Sci. 33 (1952), 307; Takahashi, Solar. Phys. 3 (1968), 598; Wood, Nature 240 (1972), 91; **Wilson, Pattern Recogn. Phys. 1 (2013),** 147; Okhlopkov, Mosc. U. Bull. Phys. B. 69 (2014), 257; **Okhlopkov, Mosc. U. Bull. Phys. B. 71 (2016),** 444; Scafetta, Pattern Recogn. Phys. 2 (2014), 1; Vos et al. 2004

Is there a problem at all with the solar dynamo? Perhaps yes…

Conspicious synchronization of the solar Schwabe cycle with the 11.07-yr period of three-planet syzygies of the tidally dominant **Venus-Earth-Jupiter** system (despite weak tidal forces!)



Heavy discussion about empirical evidence of phase-stability (and synchronization)

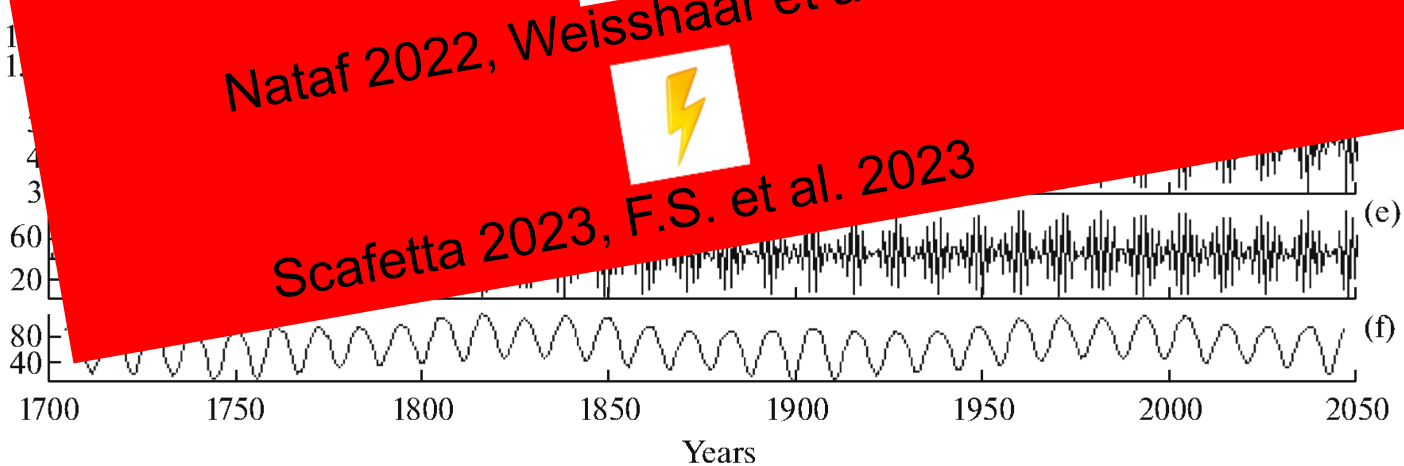
Dicke 1978, Schove 1983, F.S. et al. 2016, 2019, 2022

Nataf 2022, Weisshaar et al. 2023

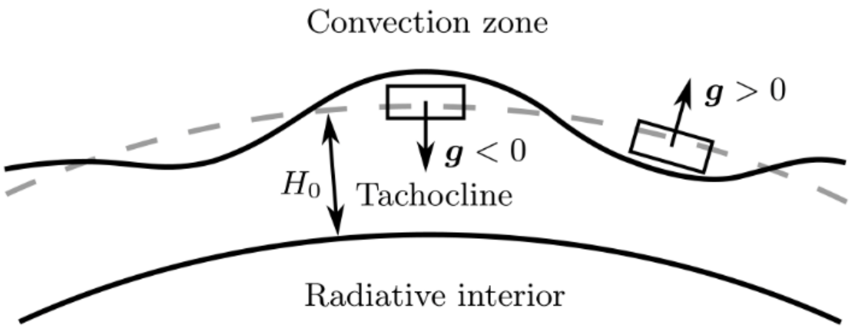
Scafetta 2023, F.S. et al. 2023

Sunspots

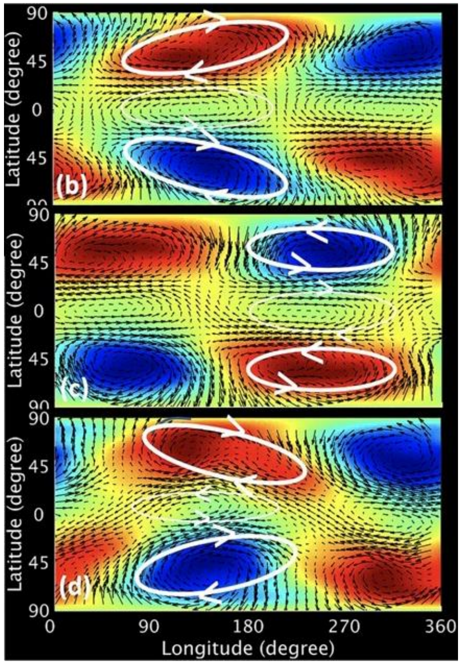
VEJ alignment index



New ansatz: Tidal synchronization of magneto-Rossby waves



magneto-Rossby waves



M. Dikpati, S.W. McIntosh, Space Weather 18 (2020), e2018SW002109

Shallow water approximation with azimuthal magnetic field under the influence of tidal forces

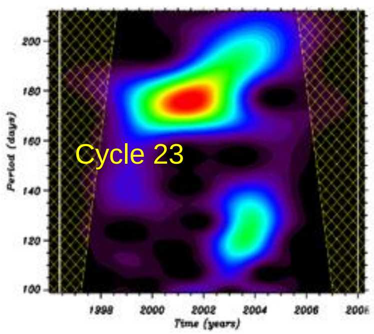
G. Horstmann et al., Astrophys. J. 944 (2023), 48; F.S. et al., Solar Physics 299 (2024), 51

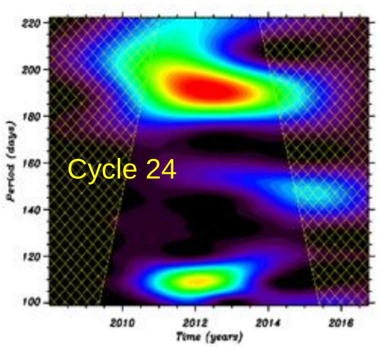
New ansatz: Tidal synchronization of magneto-Rossby waves

$$\Box^2_{v_A} v - C_0^2 \Box_{v_A}\Delta v + f_0^2 \frac{\partial^2 v}{\partial t^2} - C_0^2\beta \frac{\partial}{\partial x}\frac{\partial v}{\partial t} + 2\lambda\frac{\partial}{\partial t}\Box_{v_A} v - \lambda C_0^2 \Delta\frac{\partial v}{\partial t} + \lambda^2\frac{\partial^2 v}{\partial t^2} = f_0 \frac{\partial}{\partial x}\frac{\partial^2 V}{\partial t^2} - \lambda\frac{\partial}{\partial y}\frac{\partial^2 V}{\partial t^2} - \frac{\partial}{\partial t}\frac{\partial}{\partial y}\Box_{v_A} V$$

$$= \left[f_0\Omega + 2\Omega^2 - \frac{2v_A^2}{R_0^2} + \frac{2f_0\Omega}{R_0}y\right]\frac{4K\Omega}{R_0}\sin\left(\frac{2x}{R_0} - 2\Omega t\right) + \frac{4K\lambda\Omega^2}{R_0}\cos\left(\frac{2x}{R_0} - 2\Omega t\right)$$

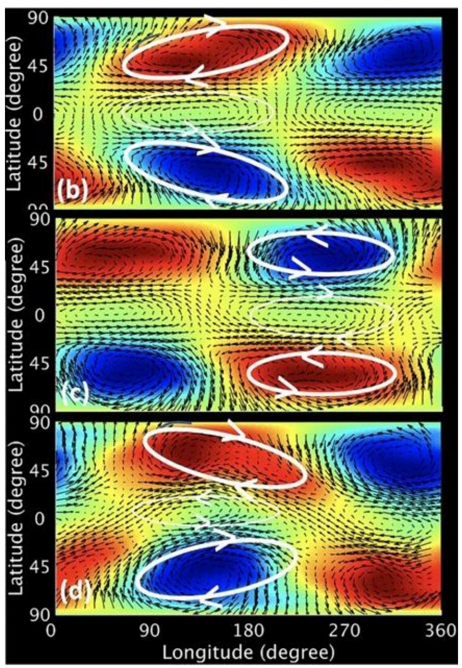
Rieger-type periods





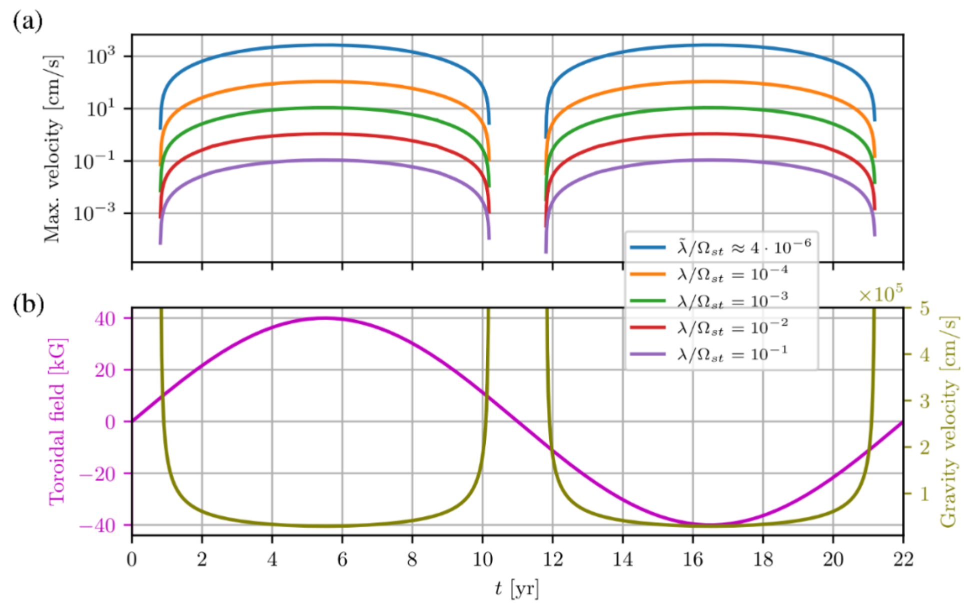
E. Gurgenashvili et al., A&A 653, A146 (2021)

magneto-Rossby waves



M. Dikpati, S.W. McIntosh, Space Weather 18 (2020), e2018SW002109

Analytical solution



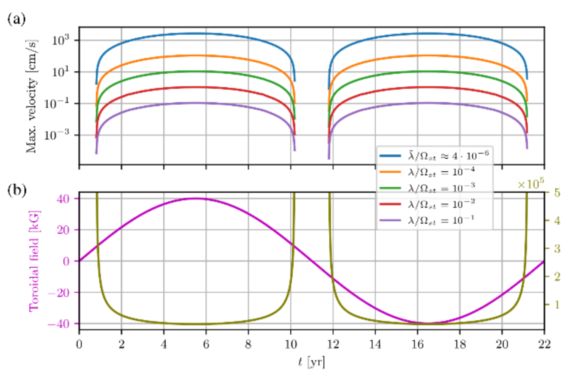
Example: Venus-Jupiter spring tide, period 118 days; wave **velocities of up to 1-100 m/s are possible** for realistic tides

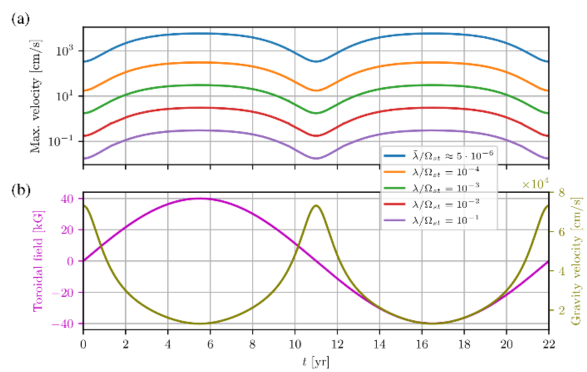
New ansatz: Tidal synchronization of magneto-Rossby waves

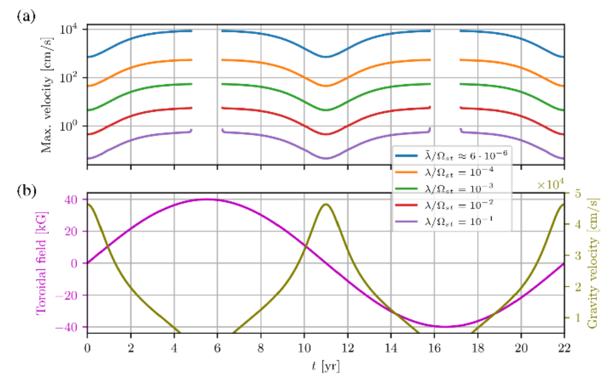
Venus-Jupiter spring tide with period 118 days

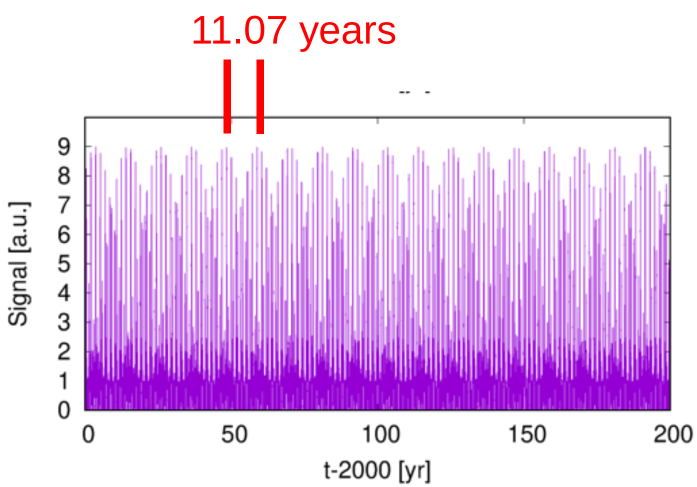
Earth-Jupiter spring tide with period 199 days

Venus-Earth spring tide with period 292 days









$$s(t) = \left[\cos\left(2\pi \cdot \frac{t - t_{\mathrm{VJ}}}{0.5 \cdot P_{\mathrm{VJ}}}\right) + \cos\left(2\pi \cdot \frac{t - t_{\mathrm{EJ}}}{0.5 \cdot P_{\mathrm{EJ}}}\right) + \cos\left(2\pi \cdot \frac{t - t_{\mathrm{VE}}}{0.5 \cdot P_{\mathrm{VE}}}\right)\right]^2$$

Any dynamo-relevant effect (helicity, α-effect, zonal flow, pressure…) will be a **quadratic functional** of the waves. This comprises a significant part with **11.07-year** period.

F.S. et al., Solar Physics 299 (2024), 51

A „realistic“ 2D α–Ω-dynamo model with meridional circulation…

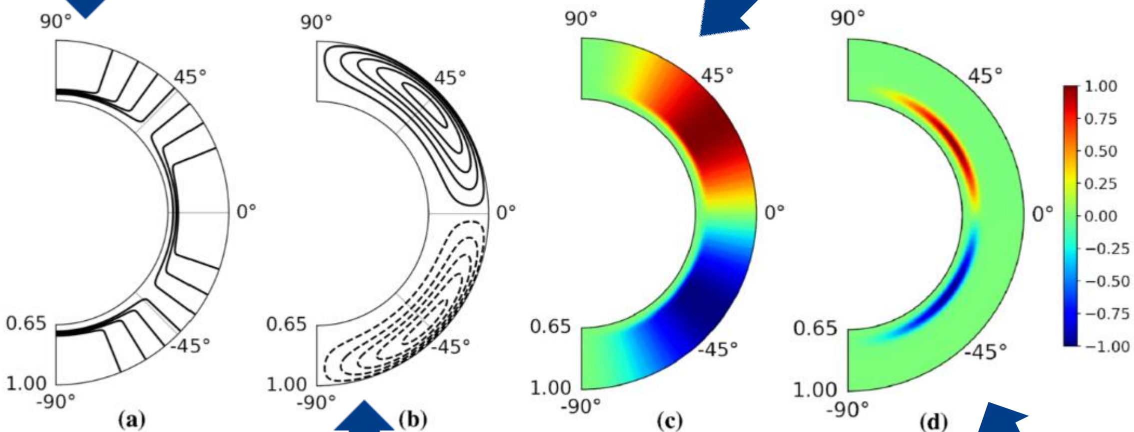
$$\frac{\partial B}{\partial t} = \tilde{\eta} D^2 B + \frac{1}{s}\frac{\partial (sB)}{\partial r}\frac{\partial \tilde{\eta}}{\partial r} - R_{\mathrm{m}} s \boldsymbol{u}_{\mathrm{p}} \cdot \nabla \left(\frac{B}{s}\right) + C_\Omega s (\nabla \times (A \boldsymbol{e}_\phi)) \cdot \nabla \Omega ,$$

$$\frac{\partial A}{\partial t} = \tilde{\eta} D^2 A - \frac{R_{\mathrm{m}}}{s} \boldsymbol{u}_{\mathrm{p}} \cdot \nabla (sA) + C_\alpha^{\mathrm{c}} \alpha^{\mathrm{c}} B + C_\alpha^{\mathrm{p}} \alpha^{\mathrm{p}} B ,$$

$$C_\Omega = \Omega_{\mathrm{eq}} \mathrm{R}_\odot^2 / \eta_{\mathrm{t}} ,$$
$$R_{\mathrm{m}} = u_0 \mathrm{R}_\odot / \eta_{\mathrm{t}} ,$$
$$C_\alpha^{\mathrm{c}} = \alpha_{\max}^{\mathrm{c}} \mathrm{R}_\odot / \eta_{\mathrm{t}} ,$$
$$C_\alpha^{\mathrm{p}} = \alpha_{\max}^{\mathrm{p}} \mathrm{R}_\odot / \eta_{\mathrm{t}} .$$

$$\Omega(r,\Theta) = C_\Omega \left\{ \Omega_{\mathrm{c}} + \frac{1}{2}\left[1 + \mathrm{erf}\left(\frac{r - r_{\mathrm{c}}}{d}\right)\right](1 - \Omega_{\mathrm{c}} - c_2 \cos^2\Theta) \right\}$$

$$\alpha^{\mathrm{c}}(r,\Theta,t) = C_\alpha^{\mathrm{c}} \frac{3\sqrt{3}}{4} \sin^2\Theta \cos\Theta \left[1 + \mathrm{erf}\left(\frac{r - r_{\mathrm{c}}}{d}\right)\right]\left[1 + \frac{|\boldsymbol{B}(r,\Theta,t)|^2}{B_0^2}\right]^{-1}$$



$$\alpha = \alpha^{\mathrm{c}} + \alpha^{\mathrm{p}}$$

Assumed to result from wave helicity

$$\boldsymbol{u}_{\mathrm{p}} = \nabla \times (\psi(r,\Theta) \boldsymbol{e}_\phi)$$

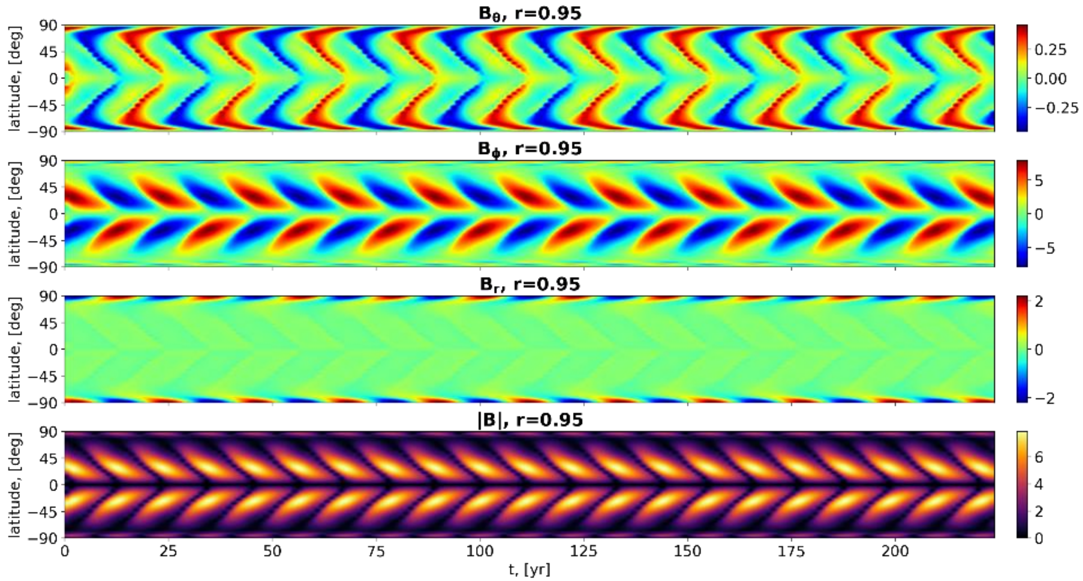
$$\psi(r,\Theta) = R_{\mathrm{m}} \left\{ -\frac{2}{\pi}\frac{(r - r_{\mathrm{b}})^2}{(1 - r_{\mathrm{b}})} \sin\left(\pi \frac{r - r_{\mathrm{b}}}{1 - r_{\mathrm{b}}}\right) \cos\Theta \sin\Theta \right\}$$

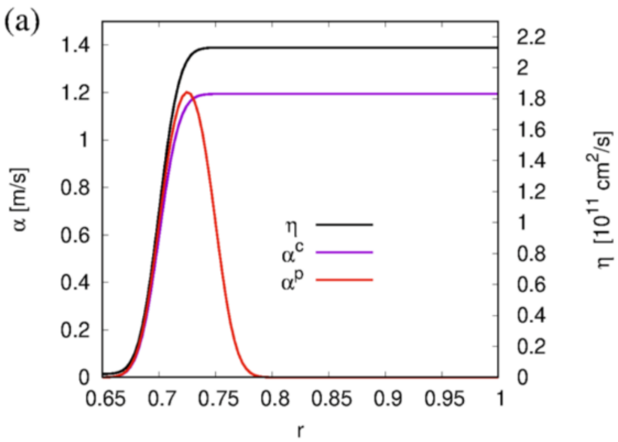
$$\alpha^{\mathrm{p}}(r,\Theta,t) = C_\alpha^{\mathrm{p}} \frac{1}{\sqrt{2}} \sin^2\Theta \cos\Theta \left[1 + \mathrm{erf}\left(\frac{r - r_{\mathrm{c}}}{d}\right)\right]\left[1 - \mathrm{erf}\left(\frac{r - r_{\mathrm{d}}}{d}\right)\right] \times \frac{2|\boldsymbol{B}(r,\Theta,t)|^2}{1 + |\boldsymbol{B}(r,\Theta,t)|^4} \sin(2\pi t / T_{\mathrm{f}}) ,$$

11.07 yr

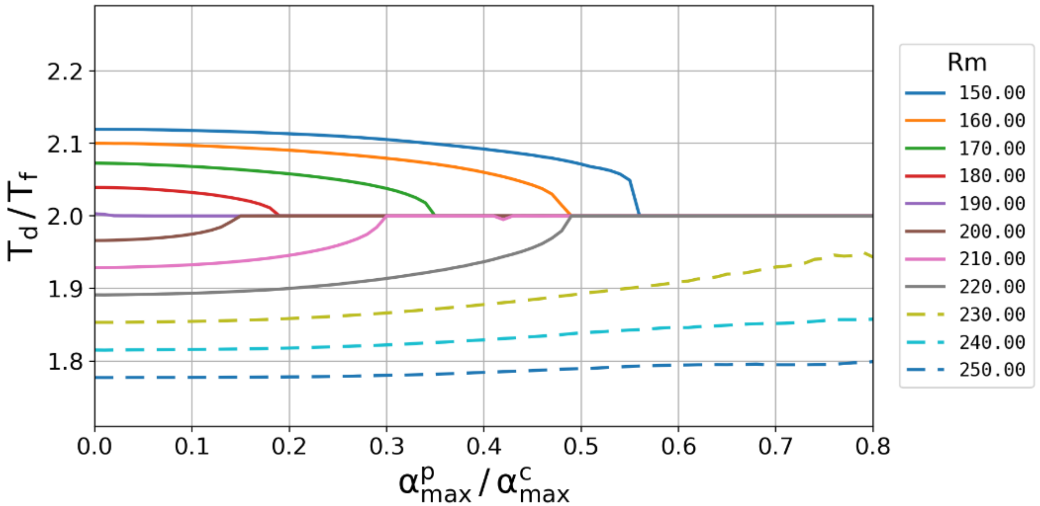
M. Klevs, F. Stefani., L. Jouve, Solar Phys. 298, 90 (2023)

…shows a nice parametric resonance



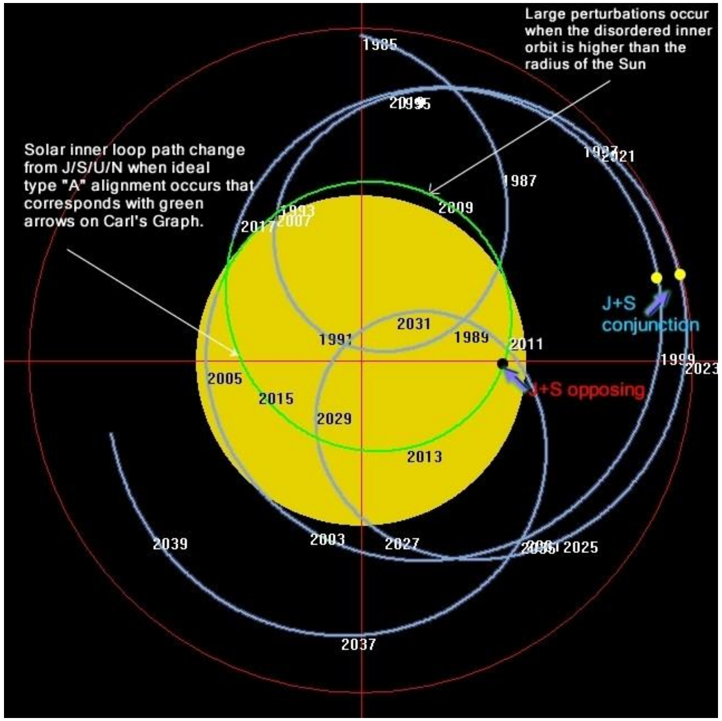


Much higher conductivity in the tachocline than in the convection zone



For a reasonable value α_0=1.3 m/s, we need just **some dm/s** for the synchronized α–term to entrain the entire dynamo

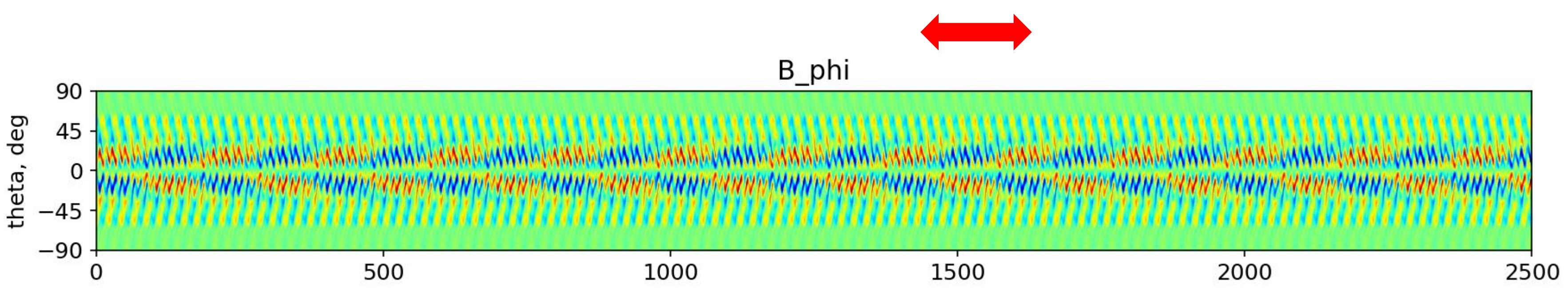
Suess/de Vries cycle: A beat period between 22.14 and 19.86 yr ?



Tidal forcing → **22.14 years**
Sun around barycenter → **19.86 years**
(with unclear spin-orbit coupling ← Vidal and Cebron; Shirley ?

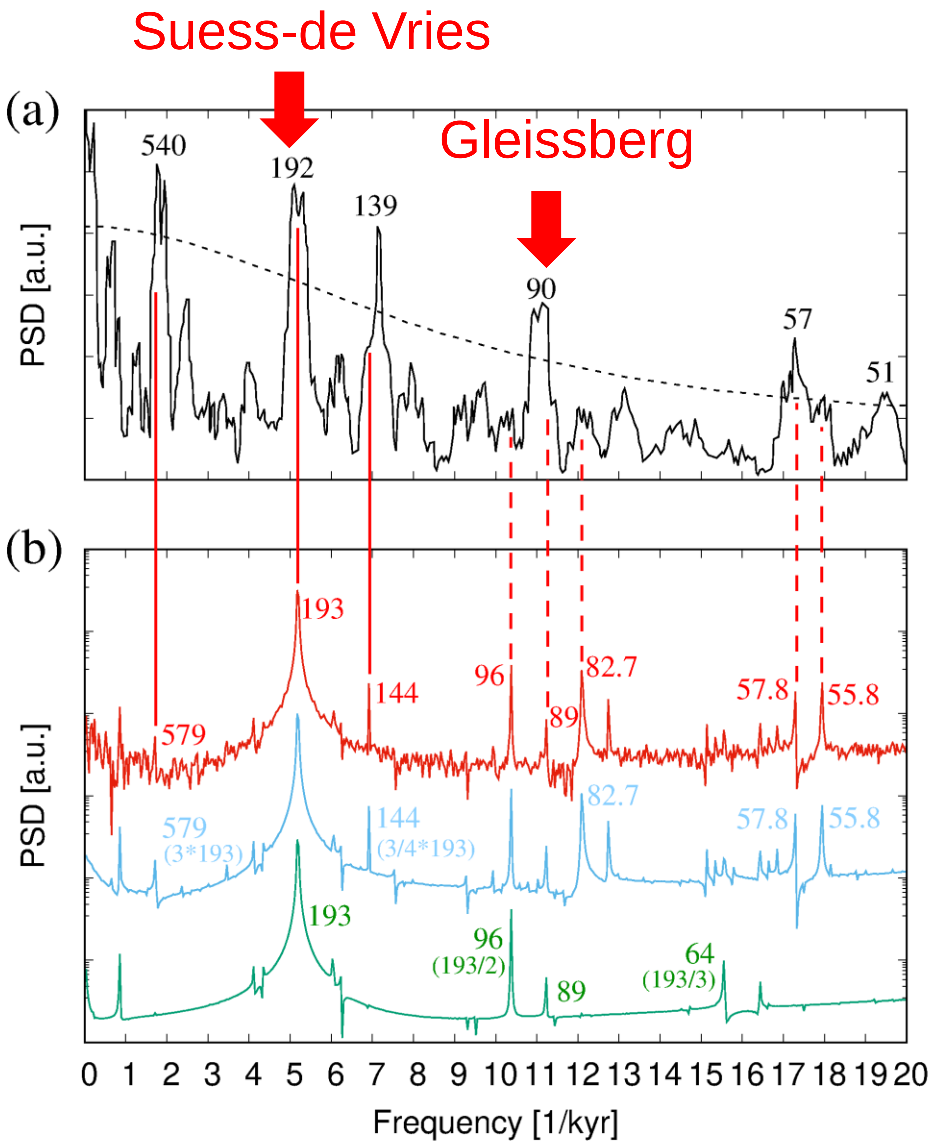
Beat period: **193 years**
19.86 x 22.14/(22.14-19.86)

193 years: Suess-de Vries cycle



DRESDEN concept HZDR

Comparison: numerical results - sediment data (Lake Lisan)



Yearly sediment thicknesses over 8500 years (climate archive)

S. Prasad et al., Geology 32, 581 (2004)

1D α–Ω-dynamo model

…with some noise

…all planets

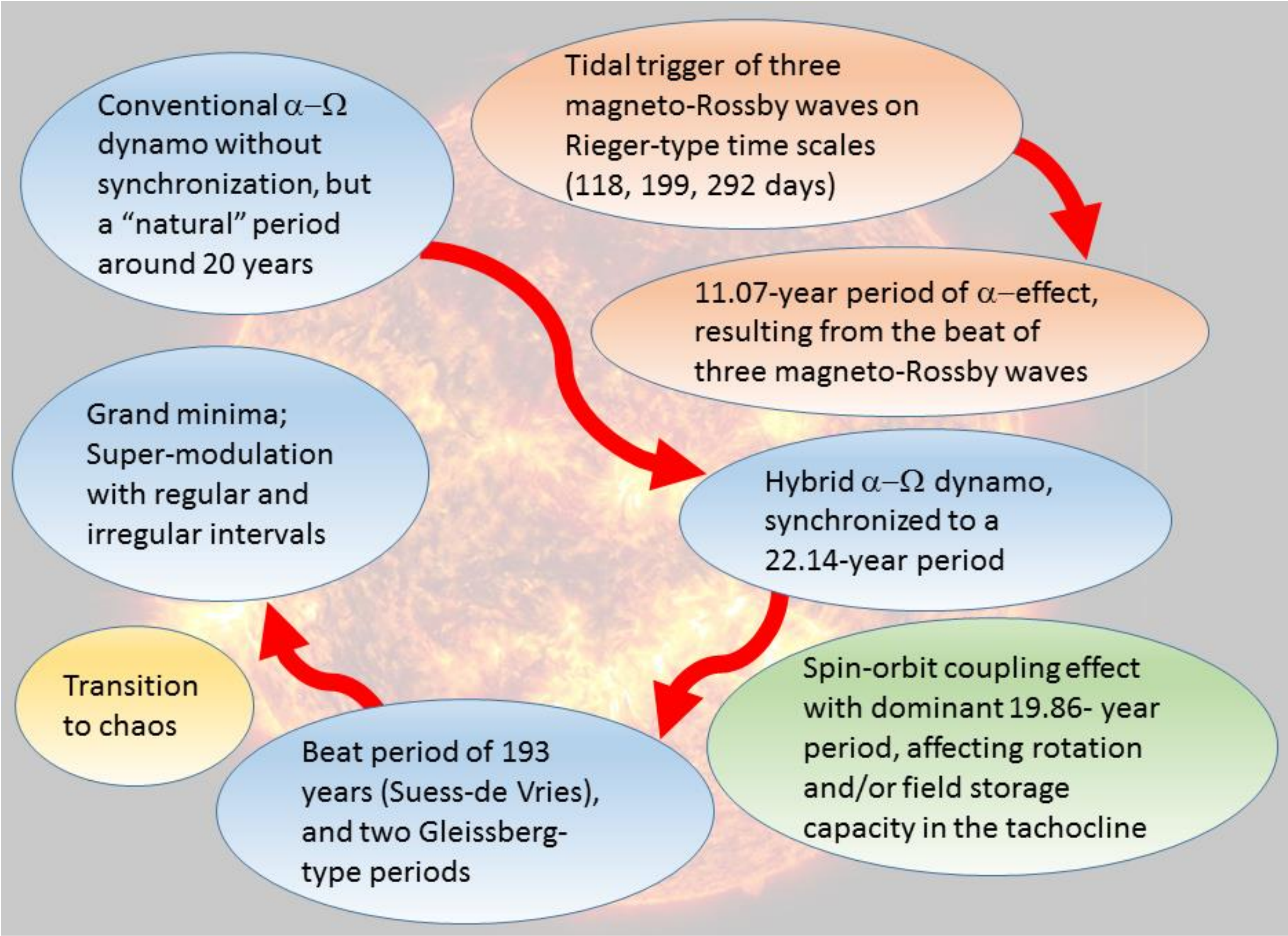
…only Jupiter and Saturn

F.S. et al., Solar Physics 296, 88 (2021); 299, 51 (2024)

Summary of our synchronized solar dynamo model

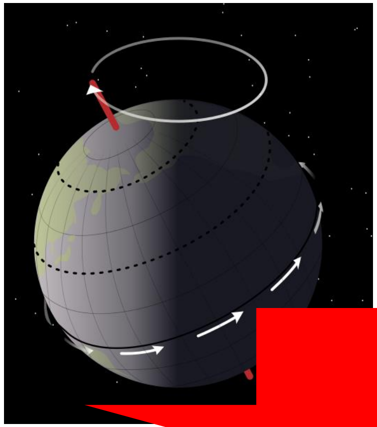
- General principle: Energy is „harvested“ on the shortest possible time-scales
- Various dynamo periods emerge as beat periods
- Three tidally triggered magneto-Rossby waves on Rieger-type time-scale → Schwabe/Hale
- Hale+Barycentric motion → Suess-de Vries (+Gleissberg)
- Self-consistency: The sharp Suess-de Vries peak at 193 years could hardly be explained without phase-stability of the primary Hale cycle at 22.14 years

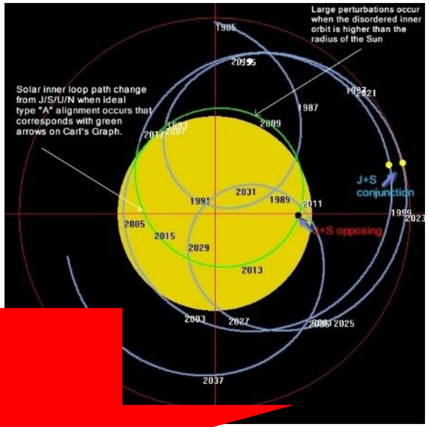
Summary of our synchronized solar dynamo model



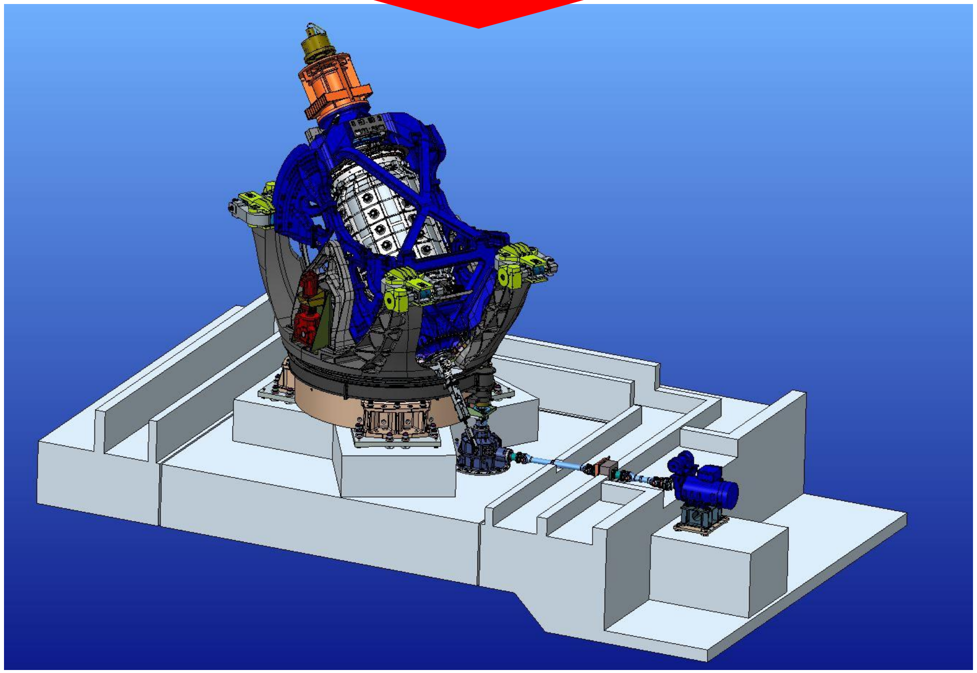
Precession driven DRESDYN dynamo: Two motivations

Influence of Milankovic cycles (precession, nutation, ellipticity) on the geodynamo





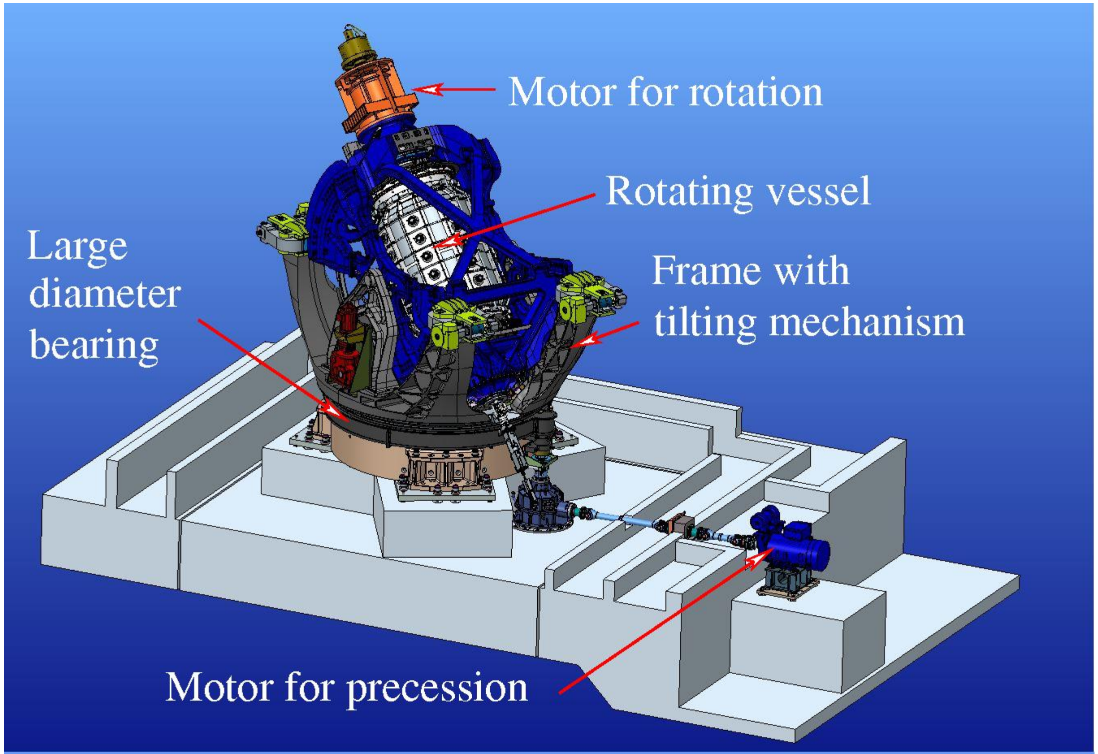
Influence of rosette-like motion on solar dynamo (spin-orbit coupling)

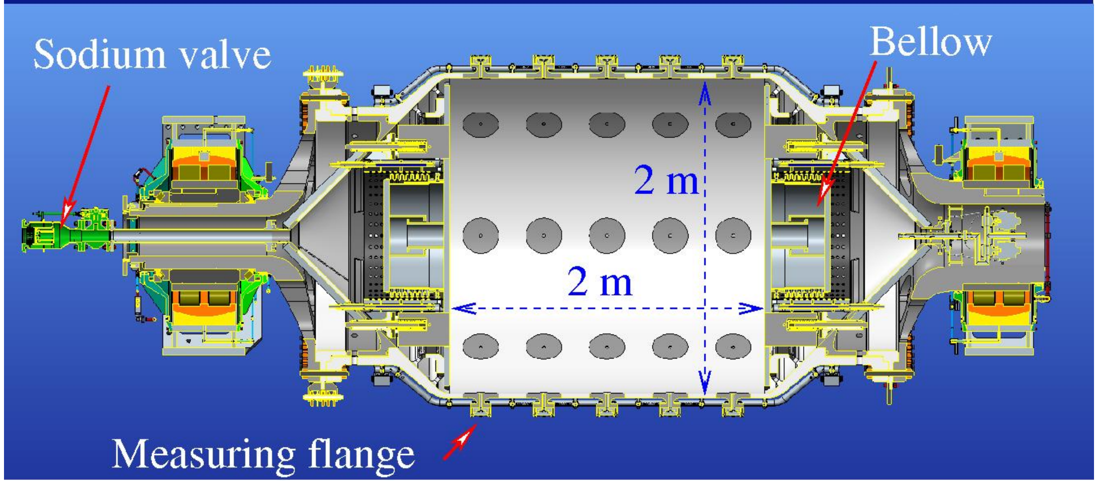


Precession driven dynamo within the DRESDYN project

Key parameters:

- Cylinder with 2 m diameter and 2 m height, 8 tons of liquid sodium
- Cylinder rotation: 10 Hz (will need some 800 kW motor power)
- Turntable rotation: 1 Hz
- Magnetic Reynolds number ~ 700
- Gyroscopic torque onto the basement: 8 MNm !





“Fundamental” problems due to huge gyroscopic torque

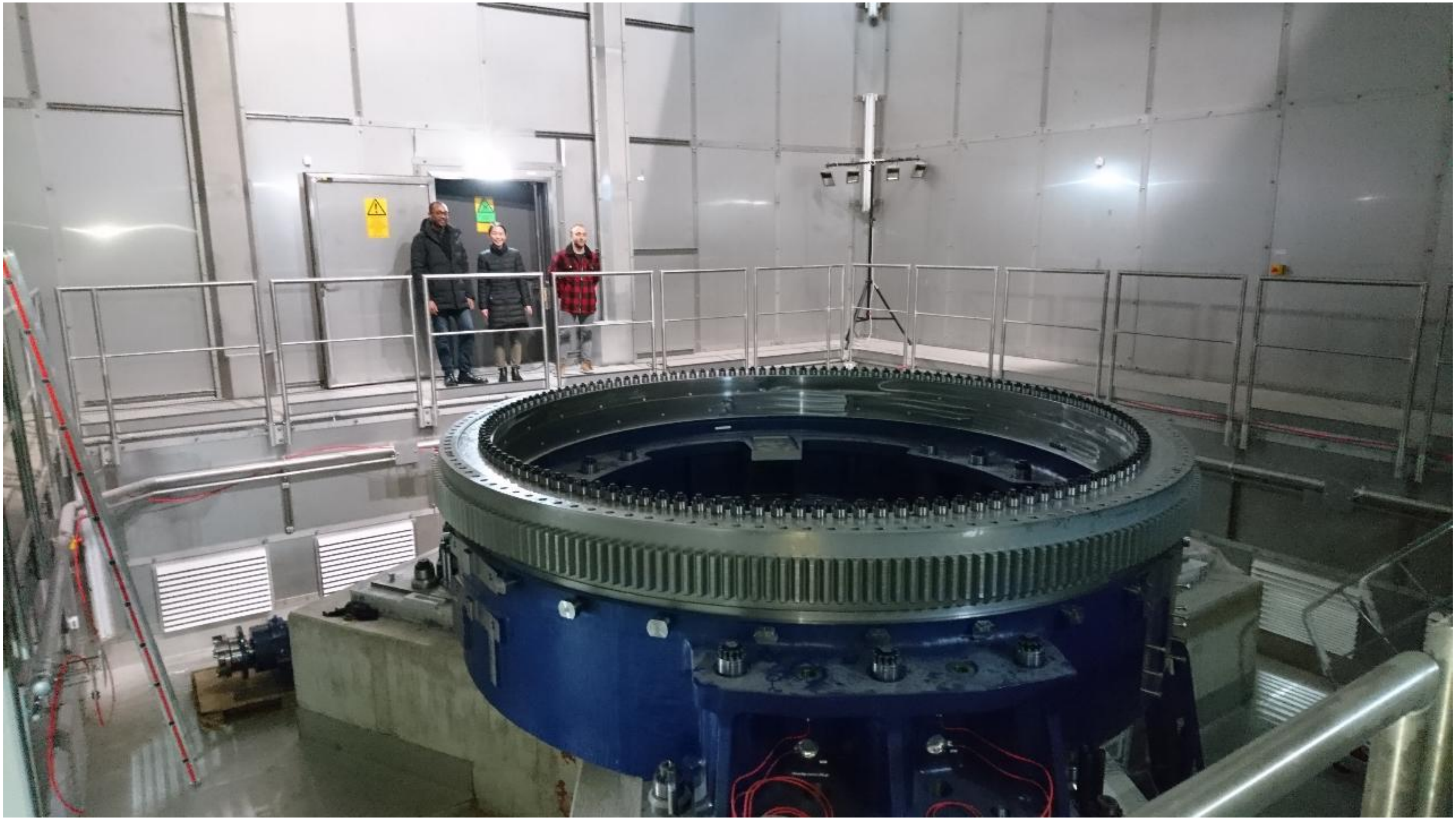
April 2013: drilling 7 holes (22 m deep)

July 2013: Constructing the ferroconcrete basement

May 2015: The tripod for the dynamo within the containment (with stainless steel “wallpaper”)

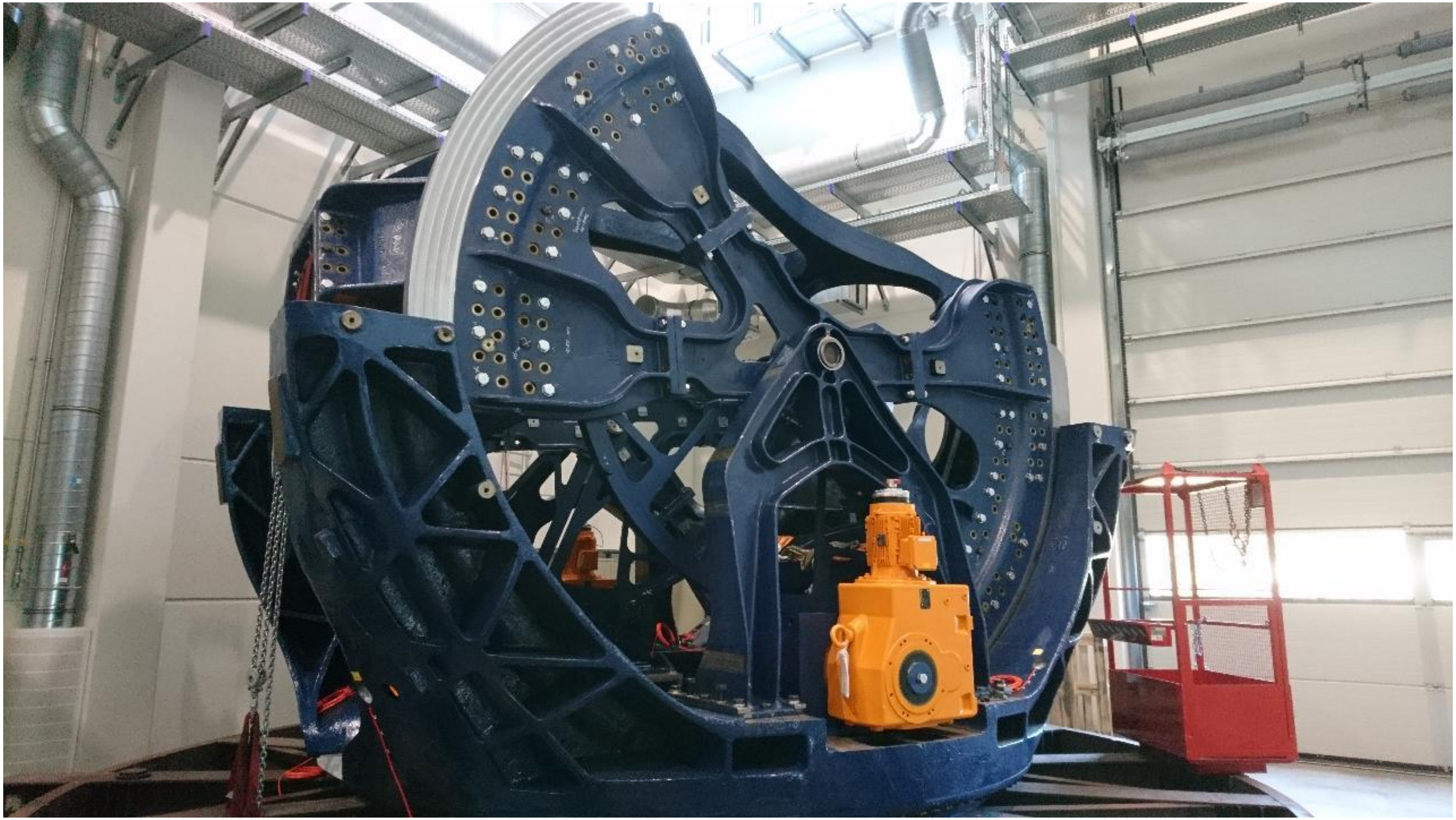
DRESDEN concept HZDR

Large ball bearing installed (12/2018)



Traverse and pylons (01/2019)

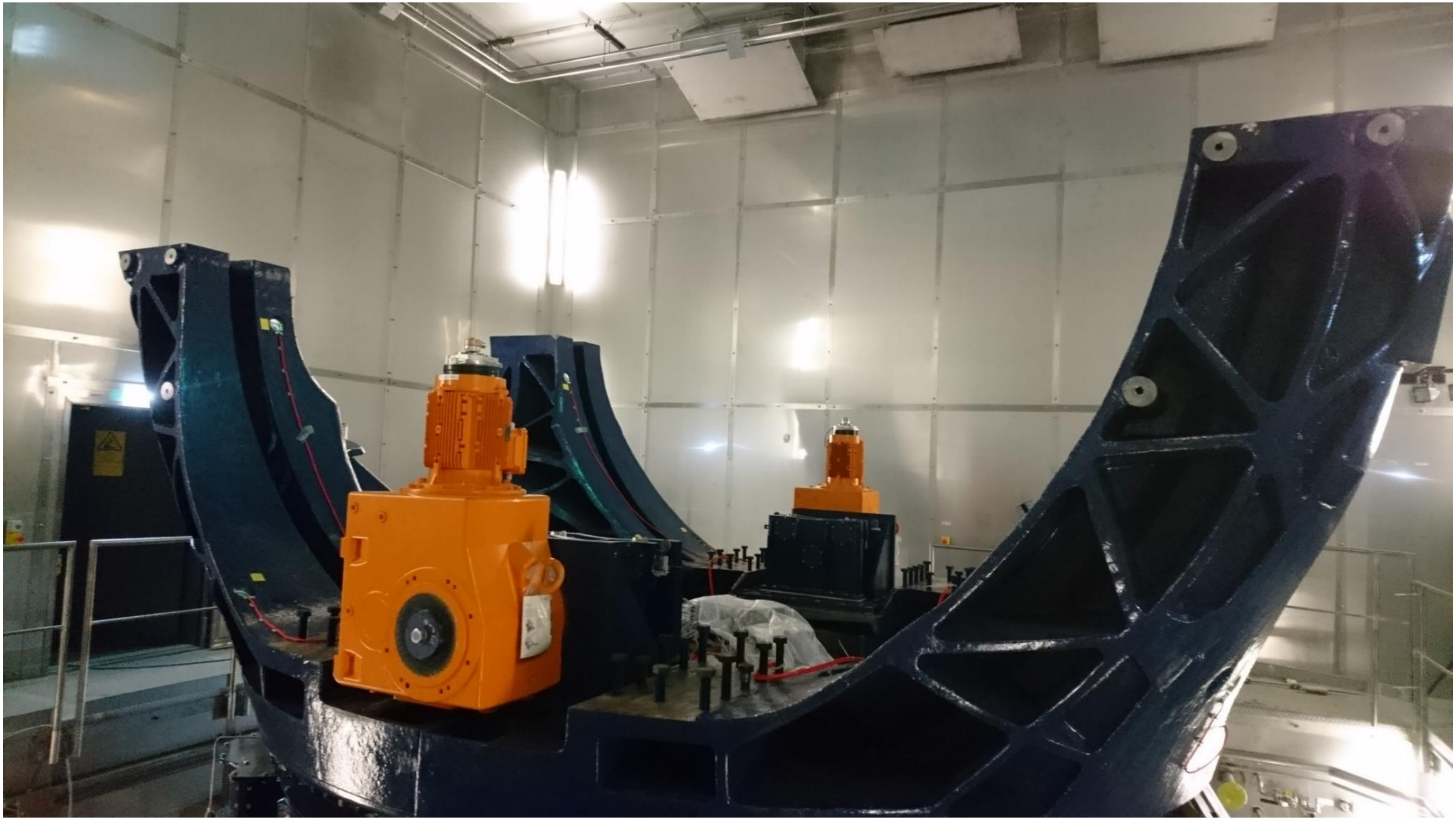
Test assembly of the tilting frame (07/2019)



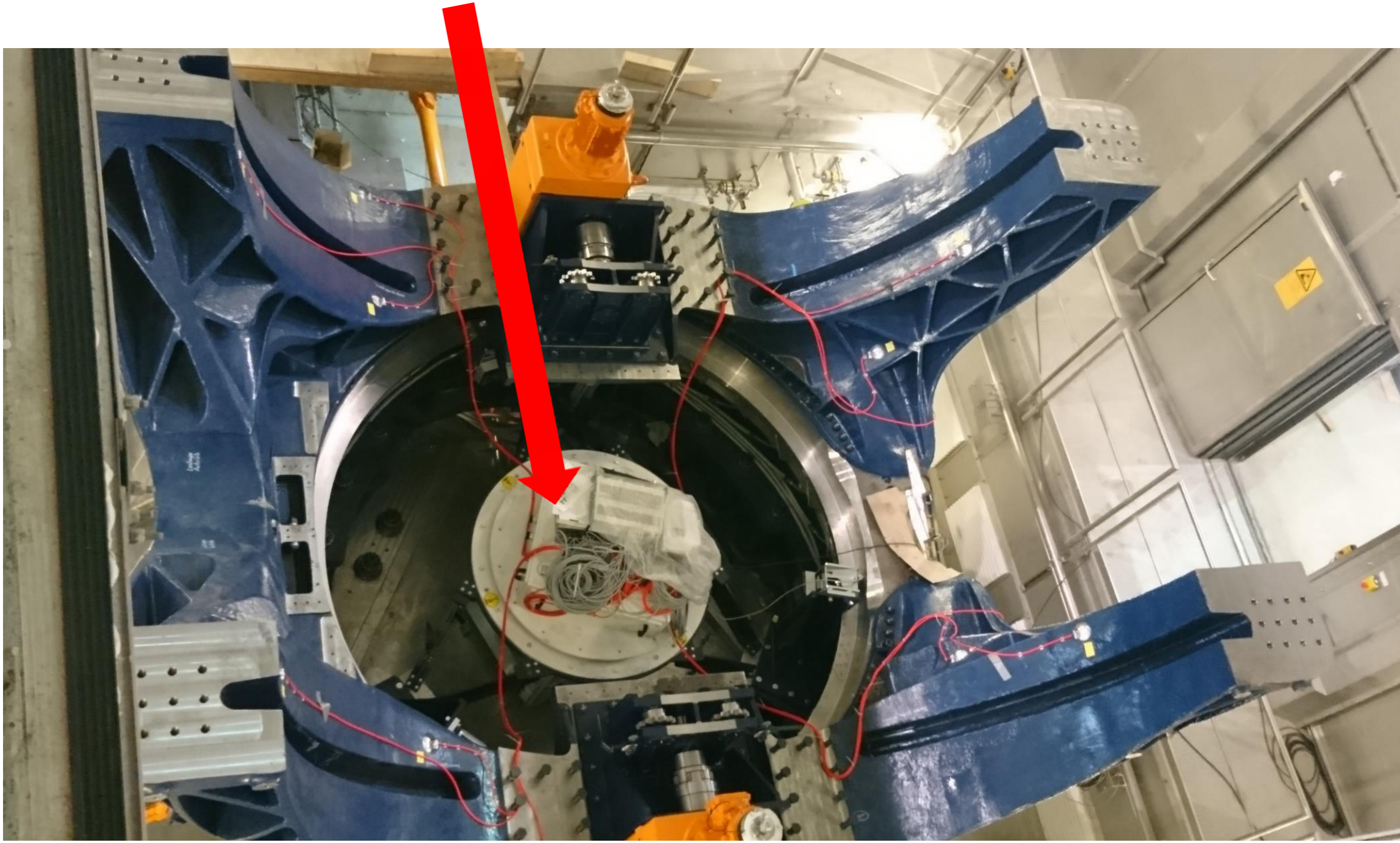
DRESDEN concept

HZDR

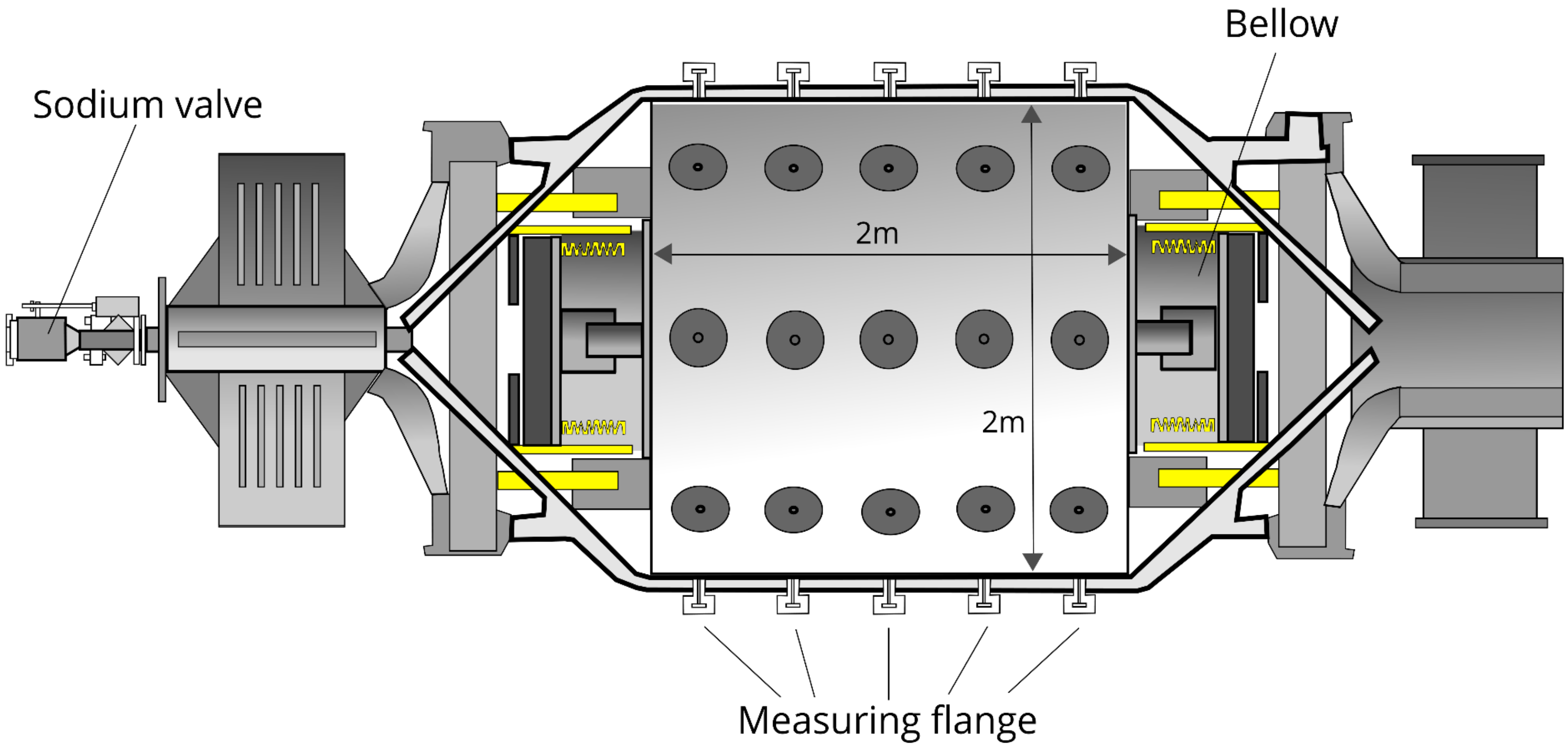
Pylons transferred to the containment (11/2019)



Pylons with central rotary connection (for 1 MW power and oil)



Rotation vessel with bearings

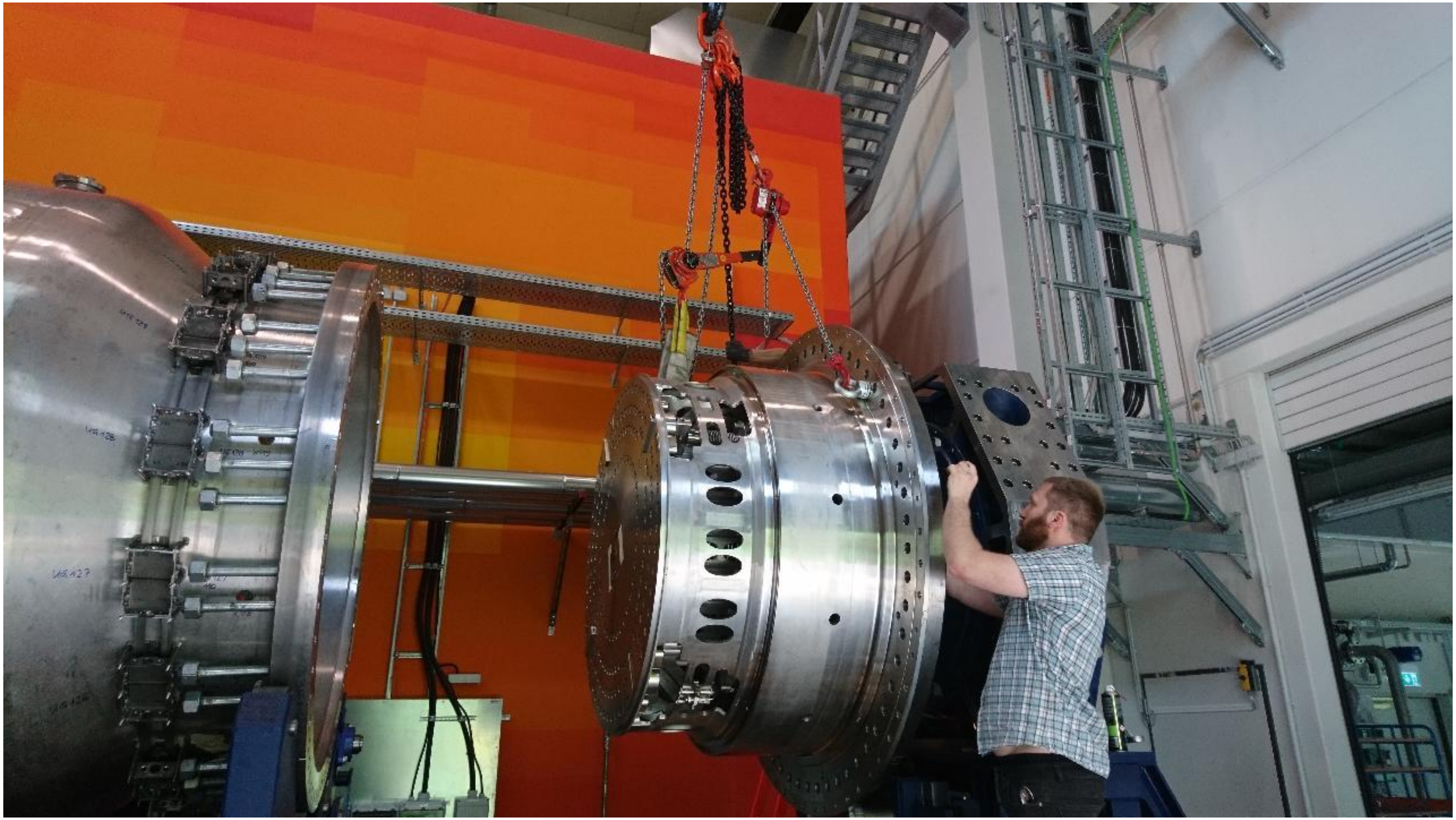


Pressure test (with 35 bar) of the rotation vessel (3/2019)

DRESDEN concept HZDR

The vessel arrives at HZDR (July 3, 2020)

Assembly of the first conical end and the bearing (May 2022)

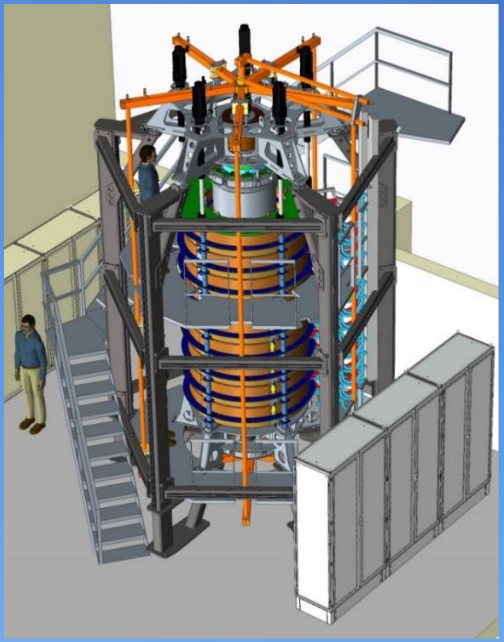


DRESDEN concept HZDR

January 17, 2024: “Wedding” of frame and vessel

June 18, 2024: First precession (though very slowly, 0.05 Hz…)

Thank you for your attention!



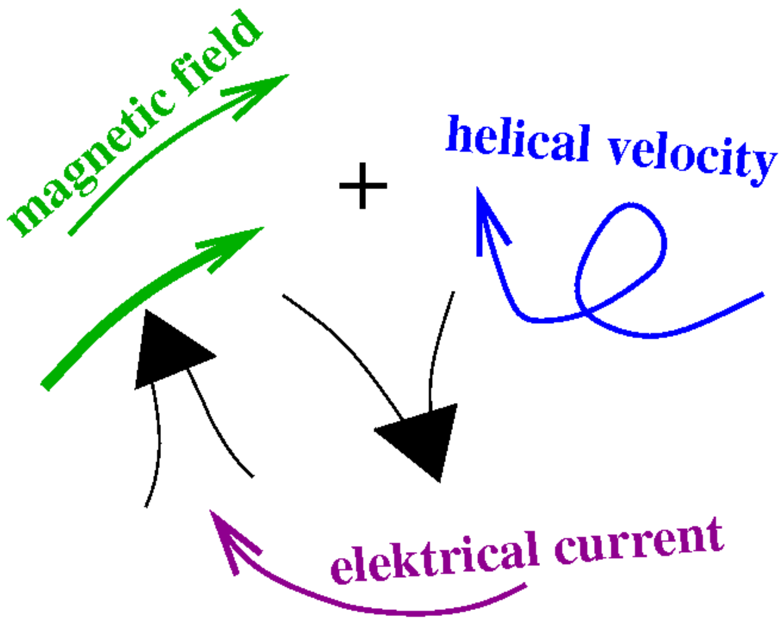
Geo- and astrophysical MHD: Basic mechanisms

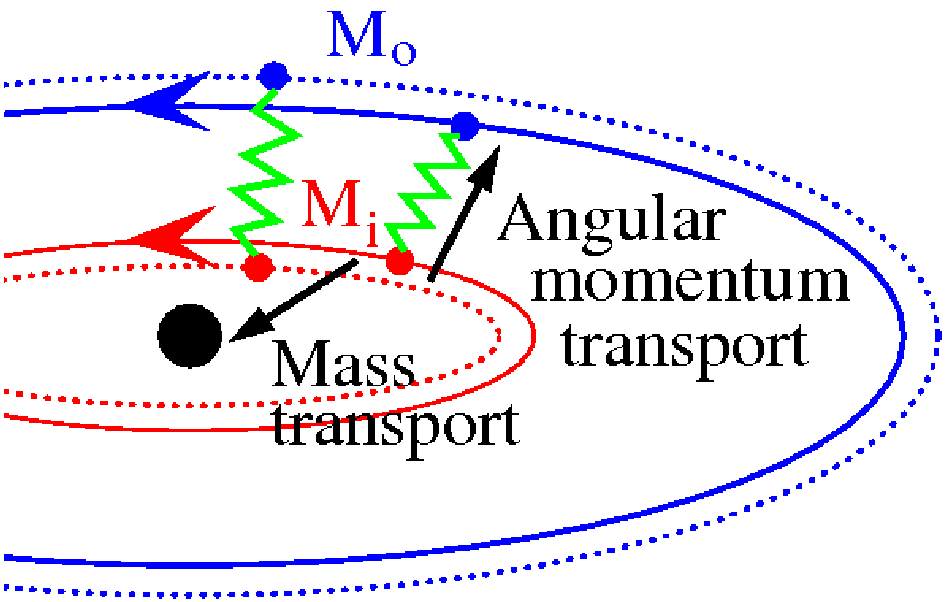
Homogeneous dynamo effect:

Self-excitation of magnetic fields in sufficiently strong, helical flows of conducting fluids

Magnetorotational instability (MRI):

Magnetic fields act like springs and trigger angular momentum transport in accretion disks around protostars or black holes

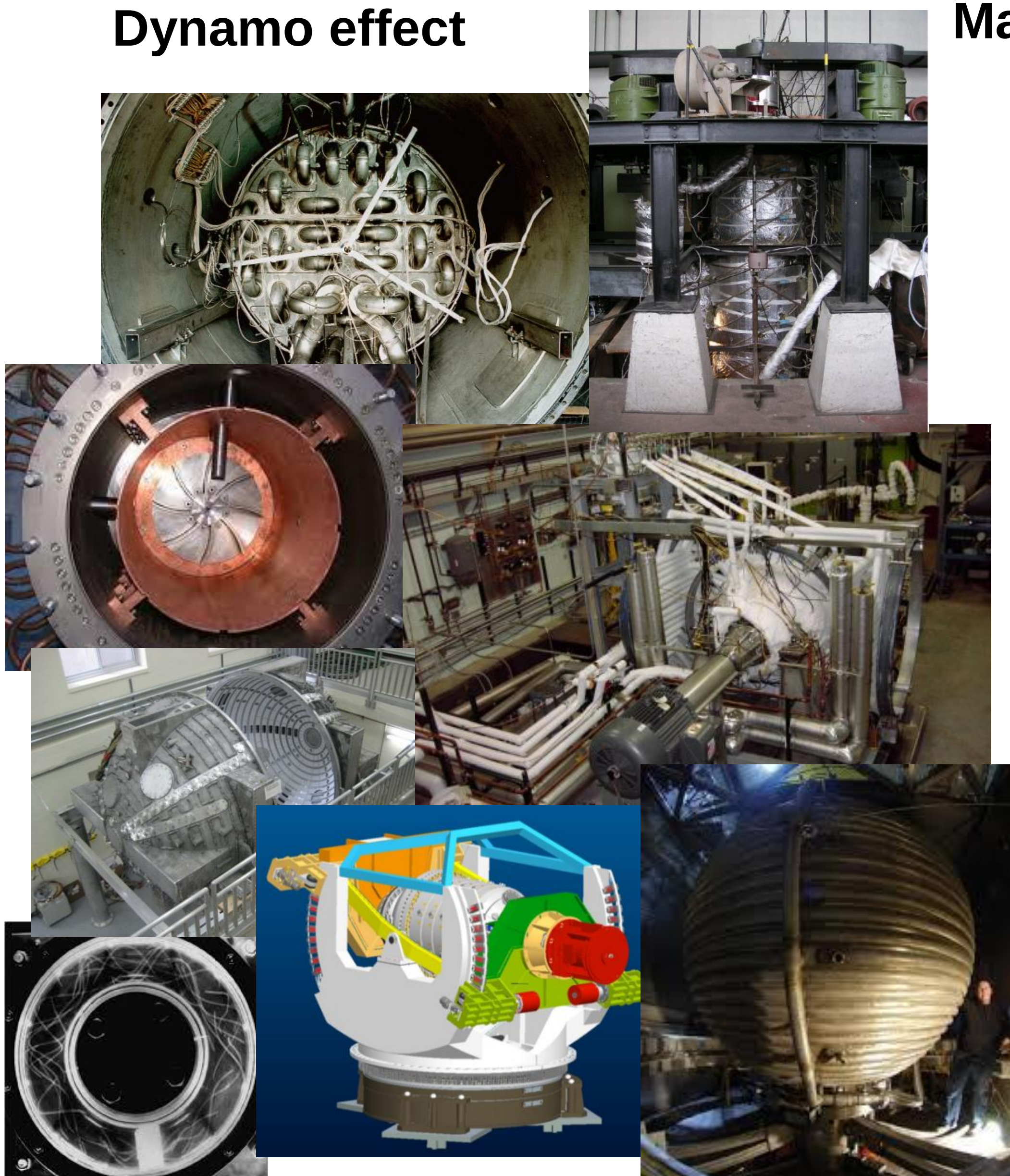




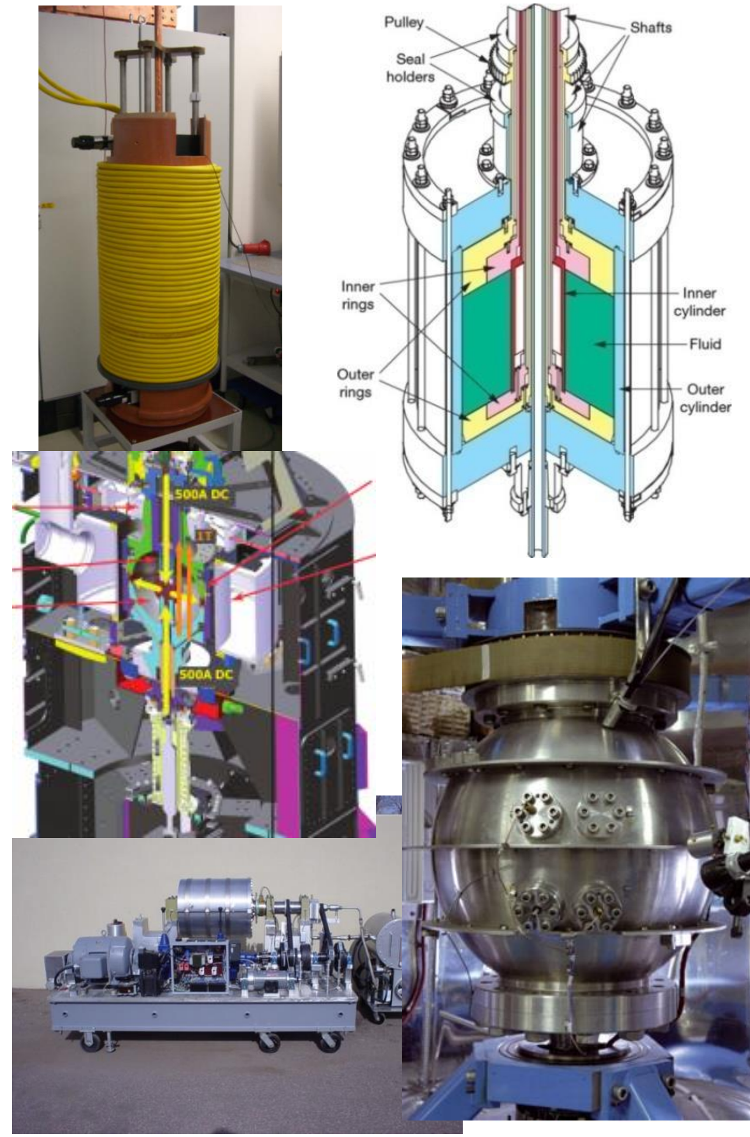
DRESDEN concept HZDR

Previous, present, and future experiments

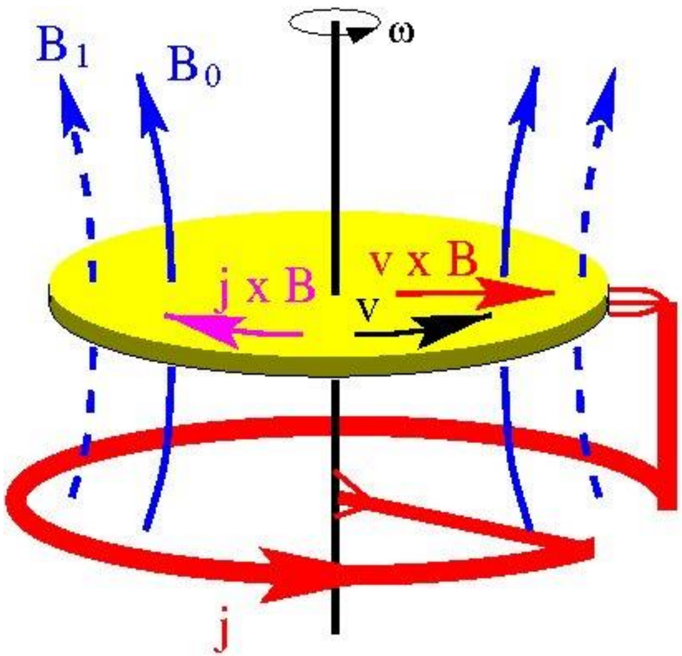
Dynamo effect

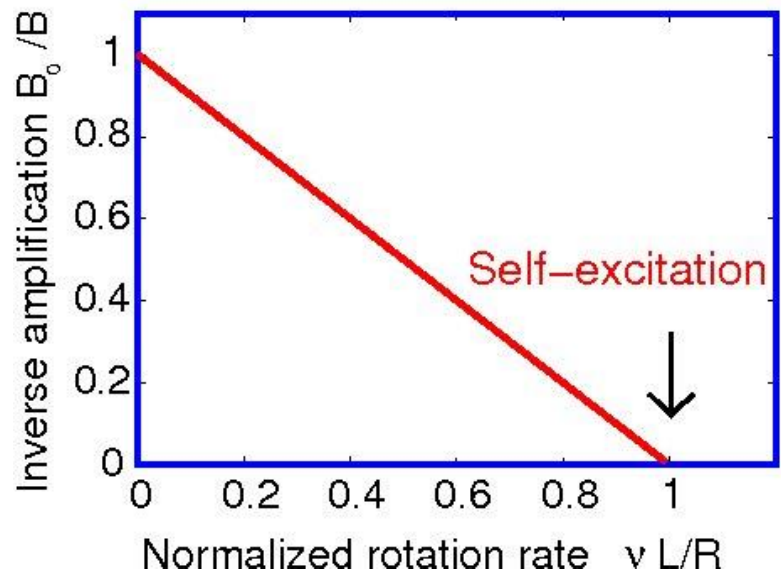


Magnetically triggered instabilities



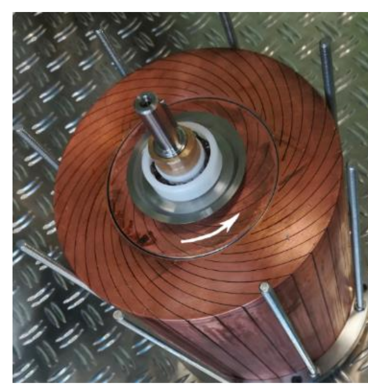
Principle of self-excitation: Illustrated at a disk dynamo model





Modified disk dynamos were recently built, and run, in Queretaro (Mexico) and in Grenoble

R. Avalos-Zúñiga, J. Priede, Proc. Royal Soc. A 479, 20220740 (2023)



T. Alboussière et al. Proc. Royal Soc. A 478, 20220374 (2023)

HZDR

Hydromagnetic dynamos: Dimensionless parameters

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \frac{1}{\mu_0 \sigma} \Delta \mathbf{B}$$

Governing parameter:
Magnetic Reynolds number

$$Rm = \mu_0 \sigma L V$$

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} = -\frac{\nabla p}{\rho} + \frac{1}{\mu_0 \rho}(\nabla \times \mathbf{B}) \times \mathbf{B} + \nu \Delta \mathbf{v} + \mathbf{f}_{extern}$$

Governing parameters:
Reynolds, Hartmann

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

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

Alternatively: Lundquist number

$$Lu = Pm^{1/2}\, Ha$$

…using the magnetic Prandtl number

$$Pm = \nu\, \mu_0\, \sigma$$

DRESDEN concept HZDR

Need for large-scale sodium facilities

Why sodium? Condition for magnetic self-excitation: Magnetic Reynolds number must be larger than ~10:

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

(μ - magnetic permeability, σ - conductivity, V - tyical velocity, L- typical size)

Sodium is the best liquid conductor with $\sigma \sim 10^7$ S/m → $VL \sim 1$ m²/s

Why so large? Necessary power scales with 1/L:

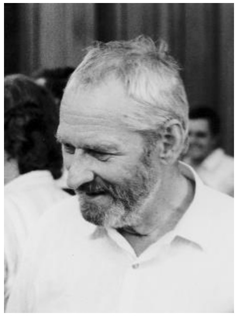
$$P \sim Rm^3 / L$$

Reasonable motor power (a few 100 kW) only with large facilities (~1 m)

DRESDEN concept HZDR

Karlsruhe dynamo experiment – Realizing an α^2 dynamo

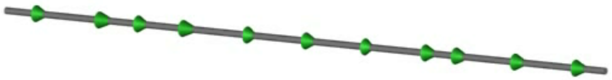
α-effect: Under the influence of a helical flow, electrical currents are induced which are directed PARALLEL to the magnetic field

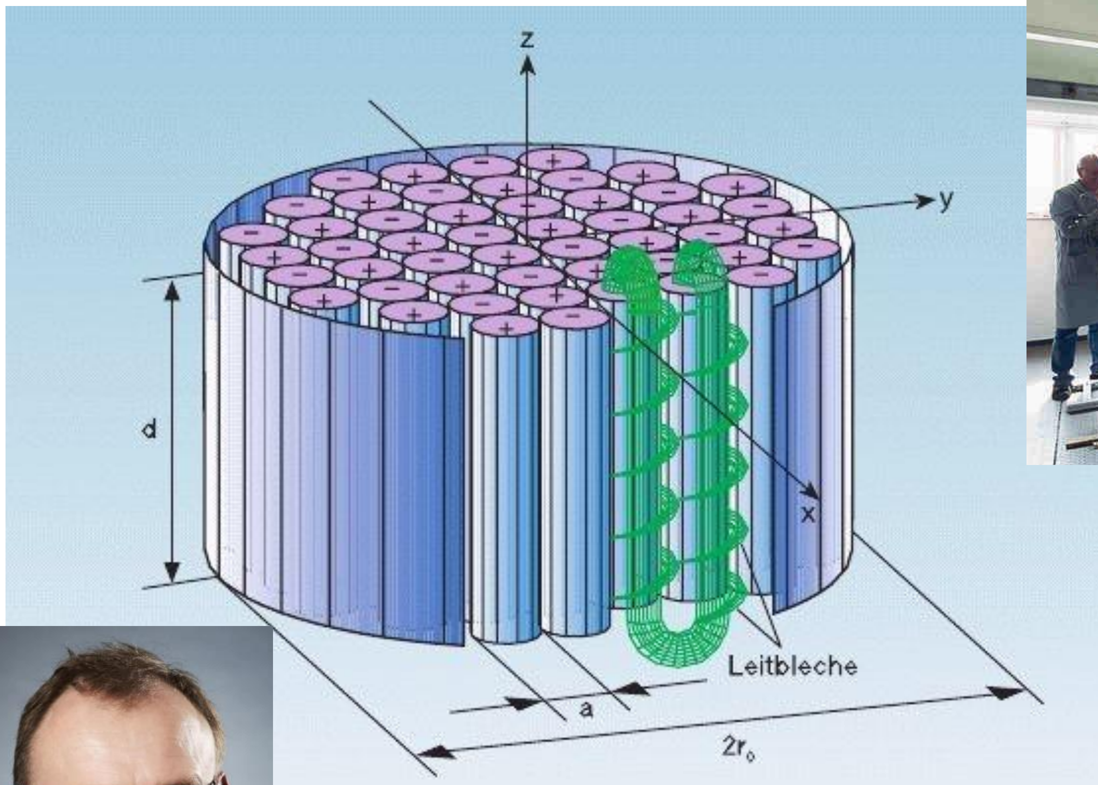

Max Steenbeck, Fritz Krause, Karl-Heinz Rädler:

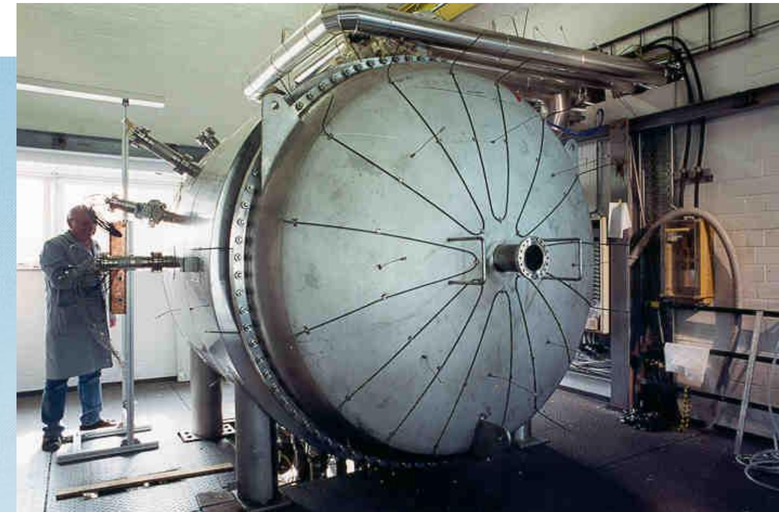
BERECHNUNG DER MITTLEREN LORENTZ-FELDSTÄRKE FÜR EIN ELEKTRISCH LEITENDES MEDIUM IN TURBULENTER, DURCH CORIOLIS-KRÄFTE BEEINFLUSSTER BEWEGUNG

Zeitschrift für Naturforschung 21a, 369 (1966)



Karlsruhe Dynamo Experiment

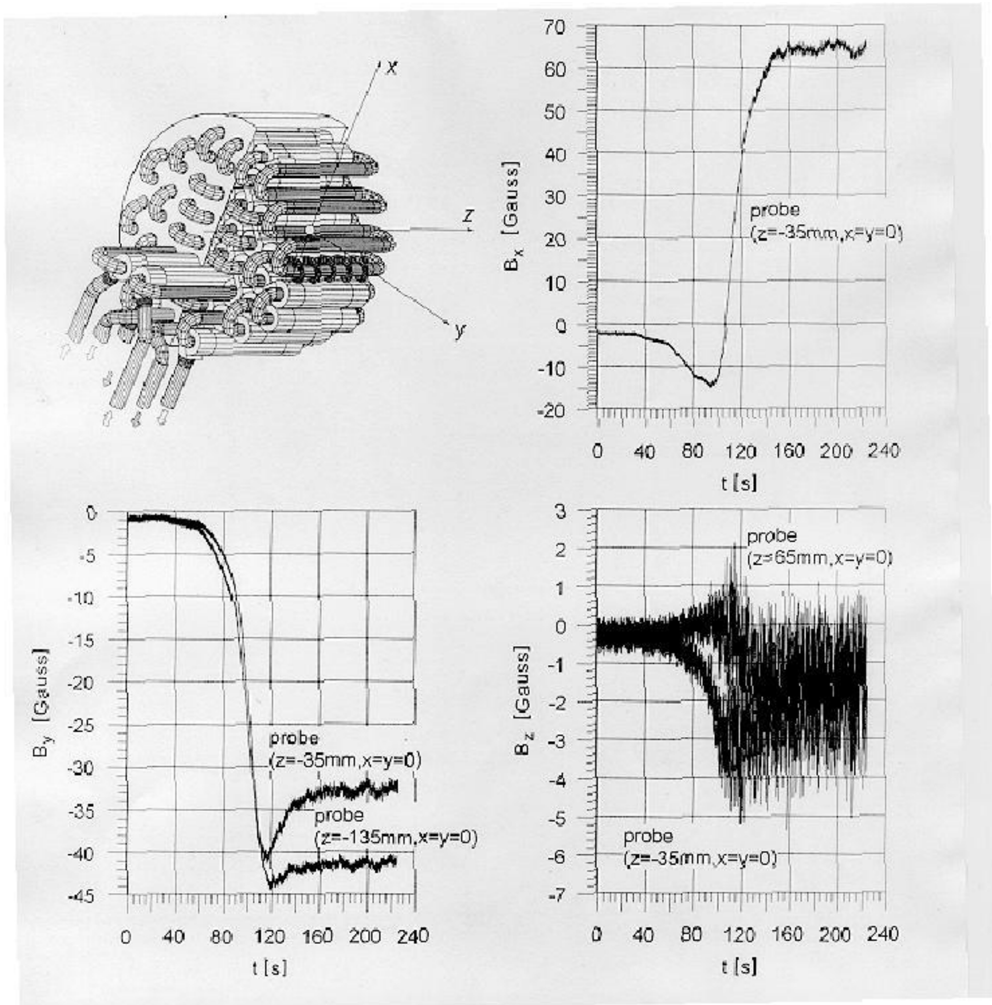




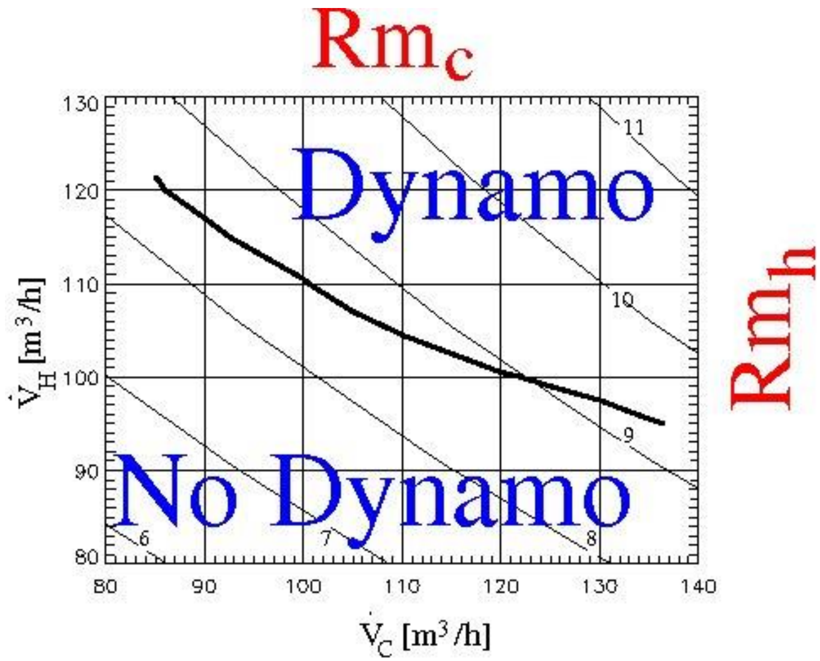
A two-scale, α^2 type dynamo (with anisotropic α) , realized by 52 spin-generators

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

Karlsruhe Dynamo Experiment



„Secret Fax“ from 19th December 1999, sent by Karl-Heinz Rädler



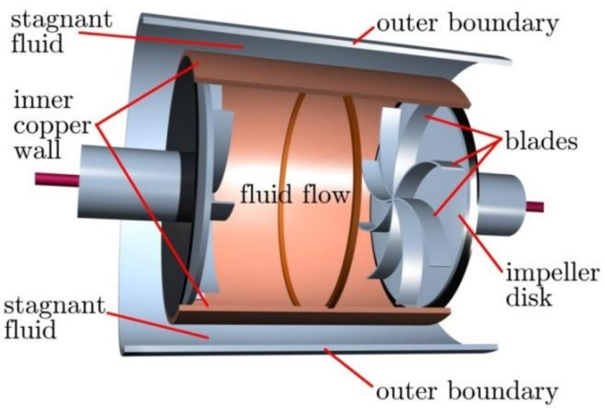
Again, very good agreement with numerical predictions

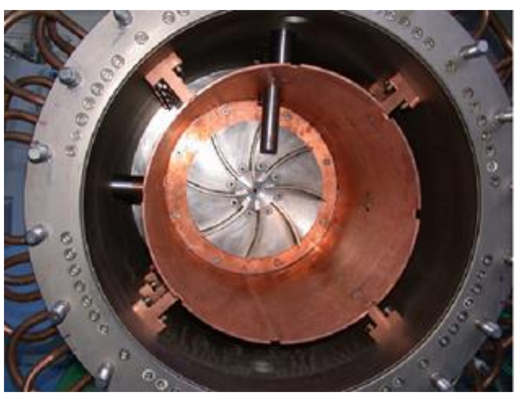
Rädler et al. Nonl. Proc. Geophys. 9, (2002), 171; Tilgner, Busse: Magnetohydrodynamics 38 (2002)

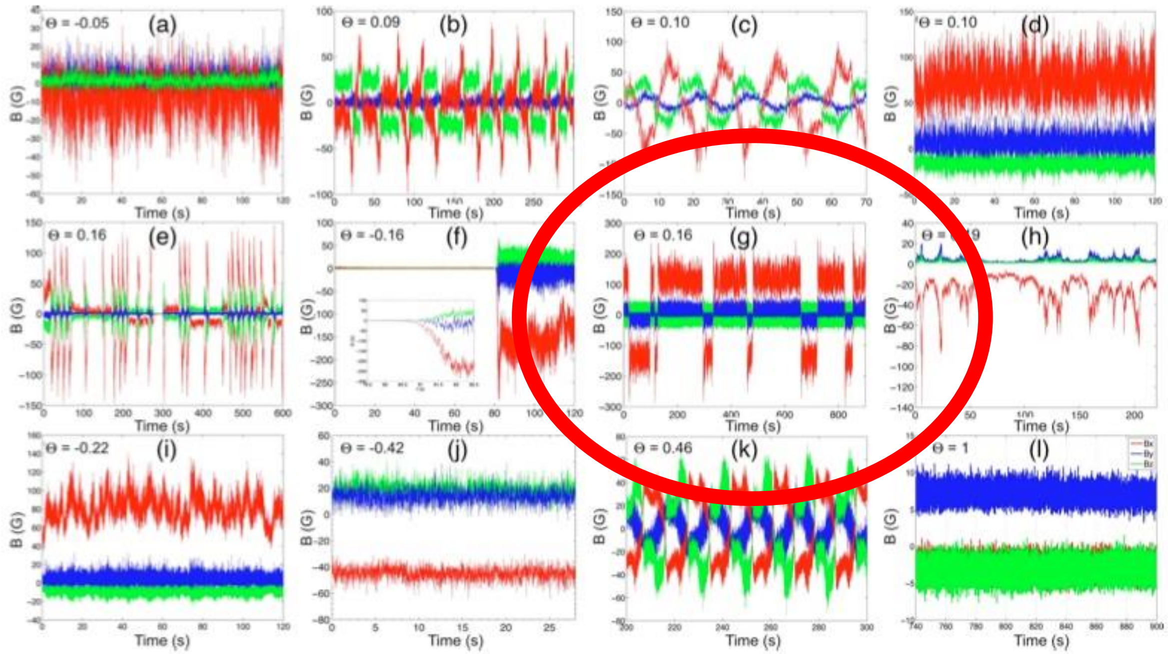
DRESDEN concept HZDR

von-Kármán-Sodium (VKS) Experiment in Cadarache

VKS has shown self-excitation and a wealth of wonderful dynamical effects, including oscillations, **reversals,** burst, localized fields….







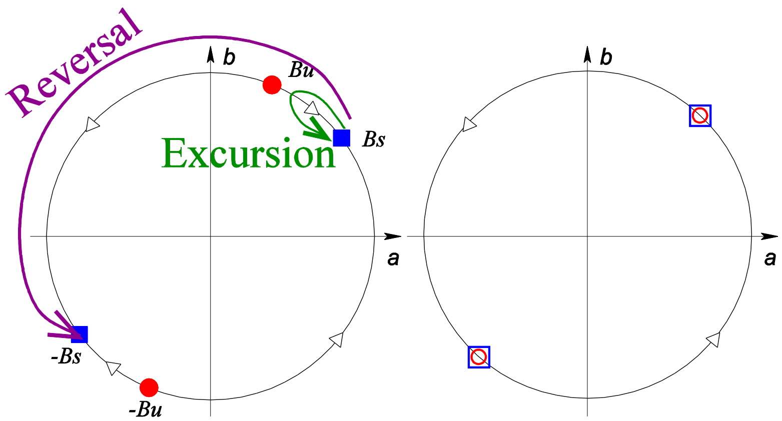
Monchaux et al., Phys. Fluids 21 (2009), 035108

However: The dynamo works only if magnetic material is used for the disks…

DRESDEN concept

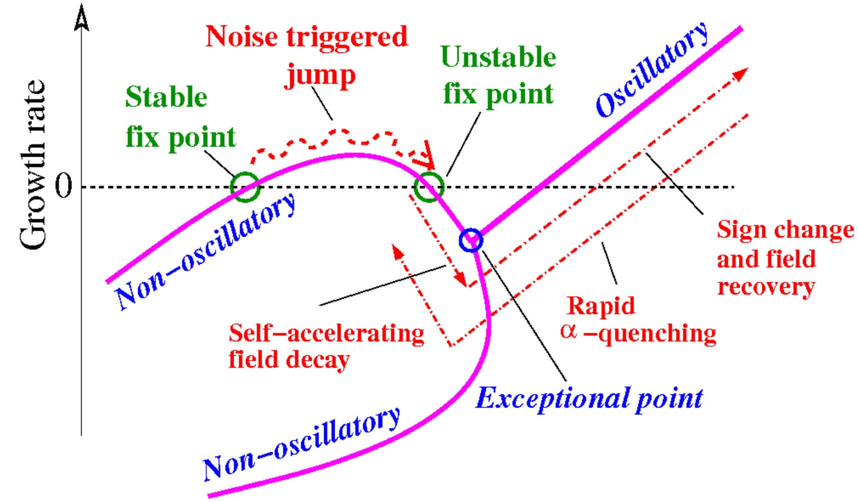
HZDR

Reversals: Two complementary pictures



Saddle-node bifurcation (Petrelis et al. 2008)

≙



Dynamical systems picture:

Saddle-node bifurcation

$$\frac{d\Theta}{dt} = \alpha_0 + \alpha_1 \sin(2\Theta) + \text{noise}$$

Petrelis et al., PRL 102 (2009), 144503

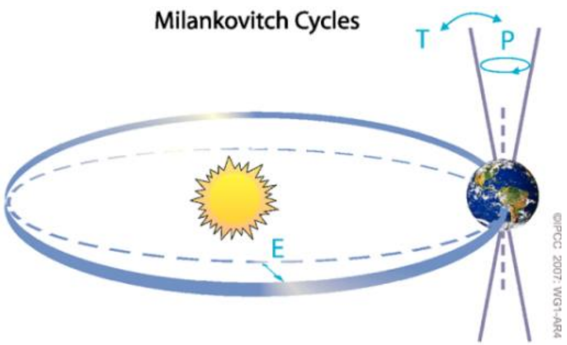
Spectral picture:

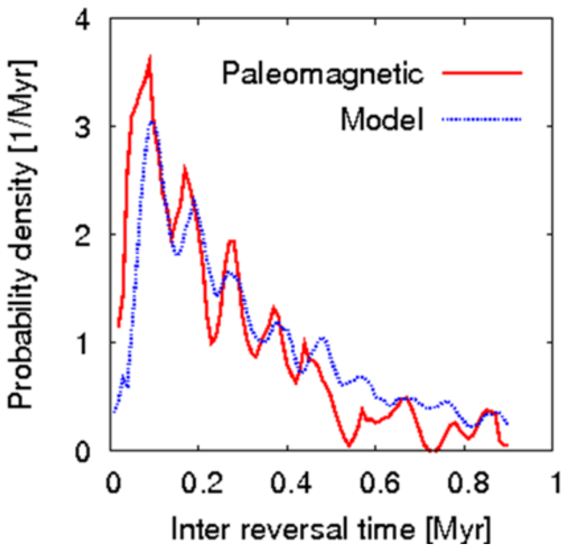
Noise triggered relaxation oscillations in the vicinity of spectral exceptional points of non-self-adjoint dynamo operators

F.S. et al., PRE 67 (2003), 027302; PRL 94 (2005) 184506; Earth Planet. Sci.Lett. 243 (2006), 828; GAFD 101 (2007) 227; Fischer et al., Inverse Probl. 25 (2008) 065011

Role of mechanical forcings for the geodynamo (Milankovic cycles)

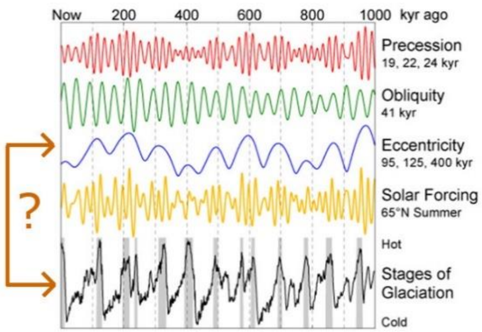
Strong indication for influence of variations of Earth´s orbit parameters (precession, obliquity, excentricity) on the statistics of the geodynamo





Probability density of inter-reversal times shows maxima at multiples of the Milankovic cycle of Earth's orbit eccentricity (95 ka)

Connection with climate??



Changing moment of inertia when a 120 m water column is concentrated in ice sheets

→ Change of Earth´s rotation period

→ Influence on geodynamo

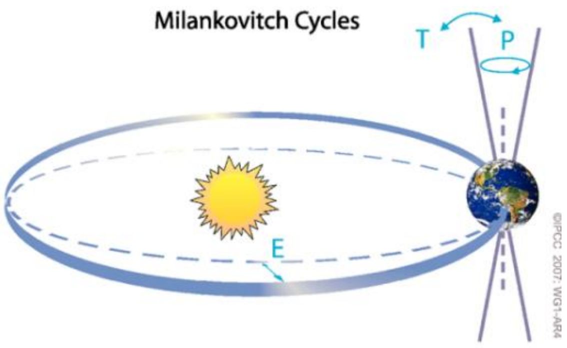
Consolini, De Michelis, Phys. Rev. Lett. 90 (2003), 058503

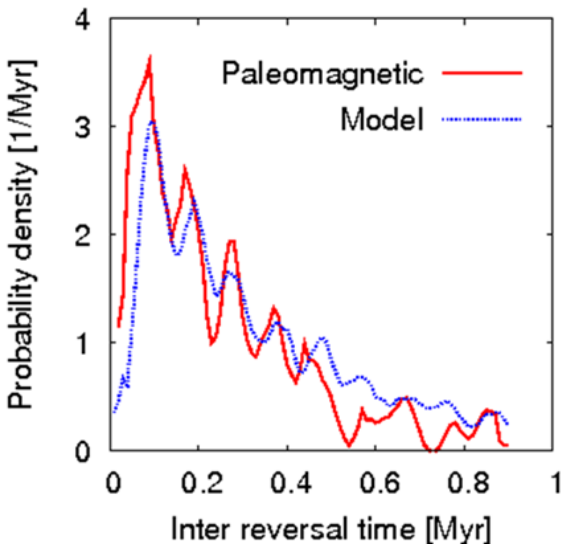
Stochastic resonance

C.S.M. Doake: A possible effect of ice ages on the Earth's magnetic field, Nature 267 (1977), 415

Role of mechanical forcings for the geodynamo (Milankovic cycles)

Strong indication for influence of variations of Earth´s orbit parameters (precession, obliquity, excentricity) on the statistics of the geodynamo





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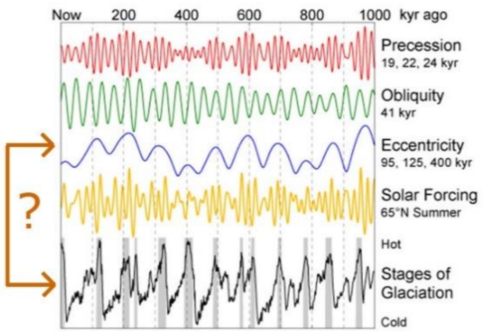
Connection with climate??



Consolini, De Michelis, Phys. Rev. Lett. 90 (2003), 058503

Stochastic resonance

Alternative: Effect of eccentric Kepler orbits

→ Fluid instabilities in ellipsoids

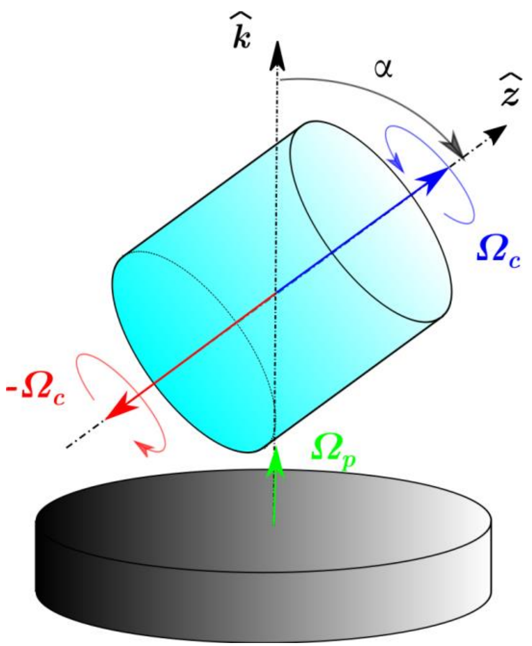
→ Orbit-spin coupling for the case of tilted rotation axis

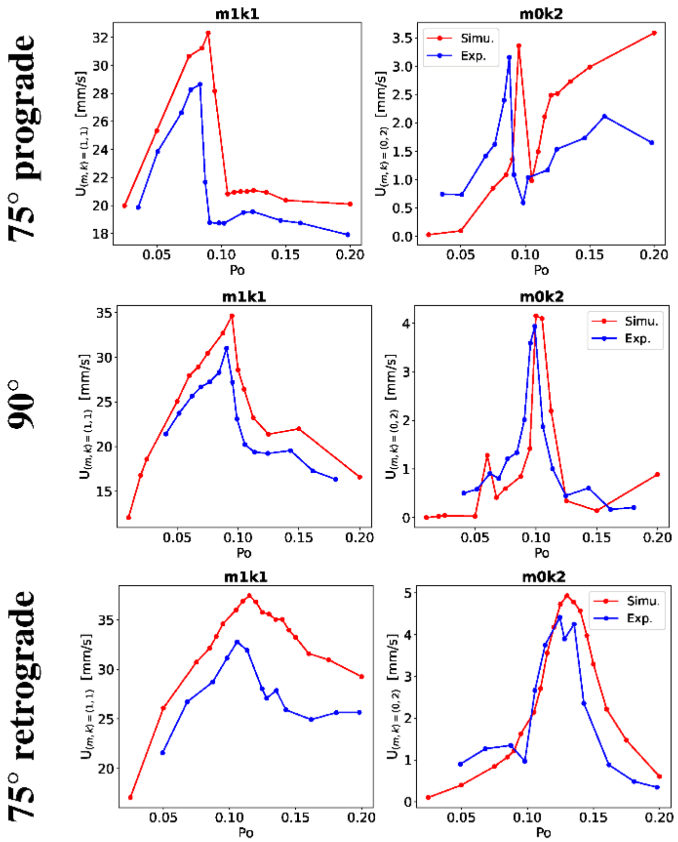
Vidal and Cebron, JFM 833 (2017), 469;

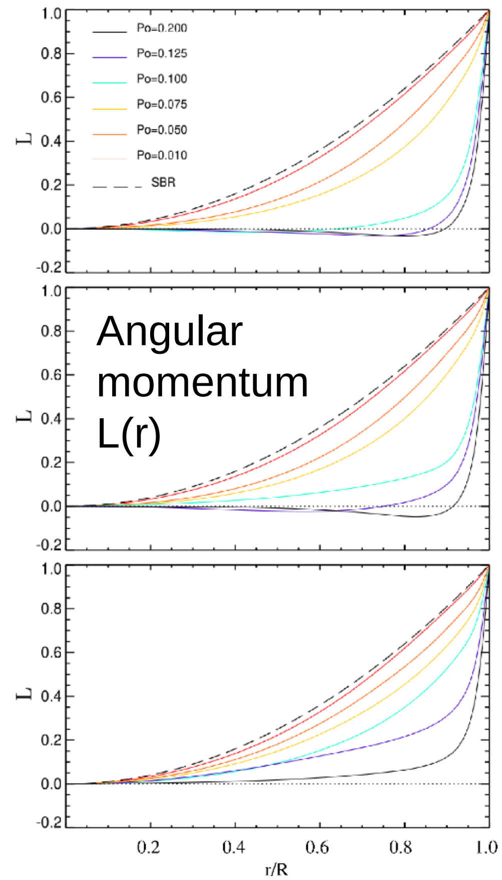
Shirley and Mischna, Planet. Space Science 139 (2017), 3; Shirley, arXiv:2309.13076

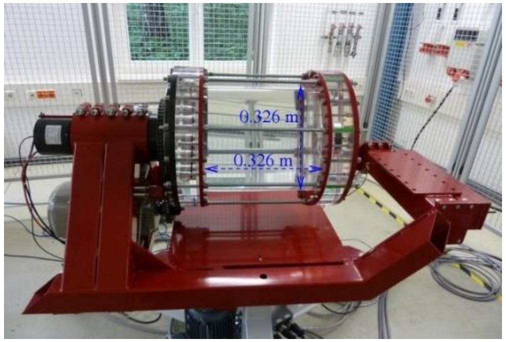
Precession driven dynamo: Prospects for self-excitation

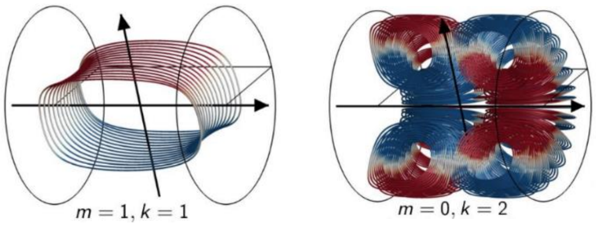
Good agreement of measured and simulated dynamo-relevant flow modes







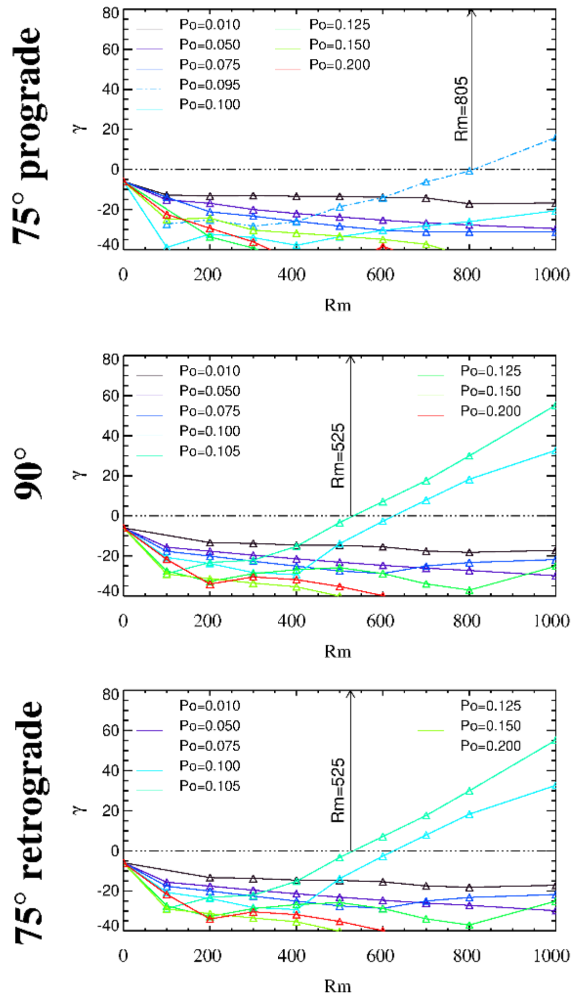


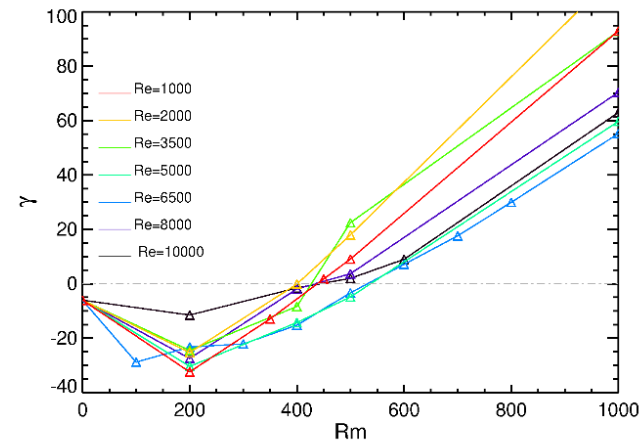


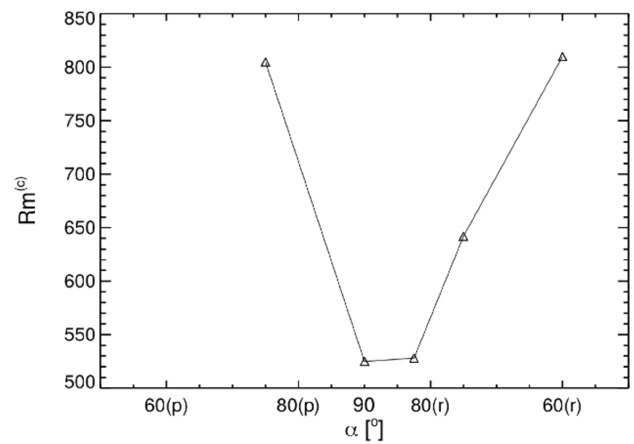
Kumar et al., Phys. Fluids 35 (2023), 014114

Precession driven dynamo: Prospects for self-excitation

In a narrow range of the precession ratio, **dynamo action is predicted for Rm~430** (Rm=700 is technically feasible)



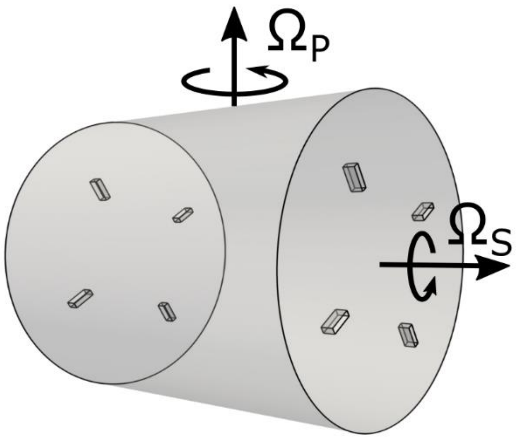


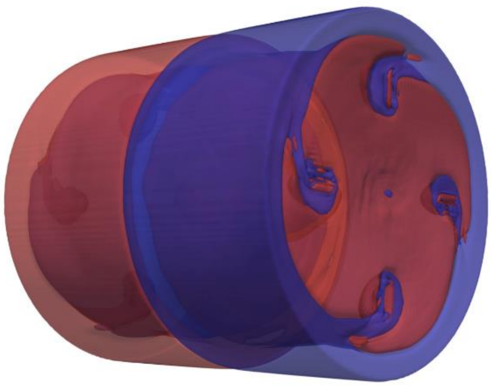


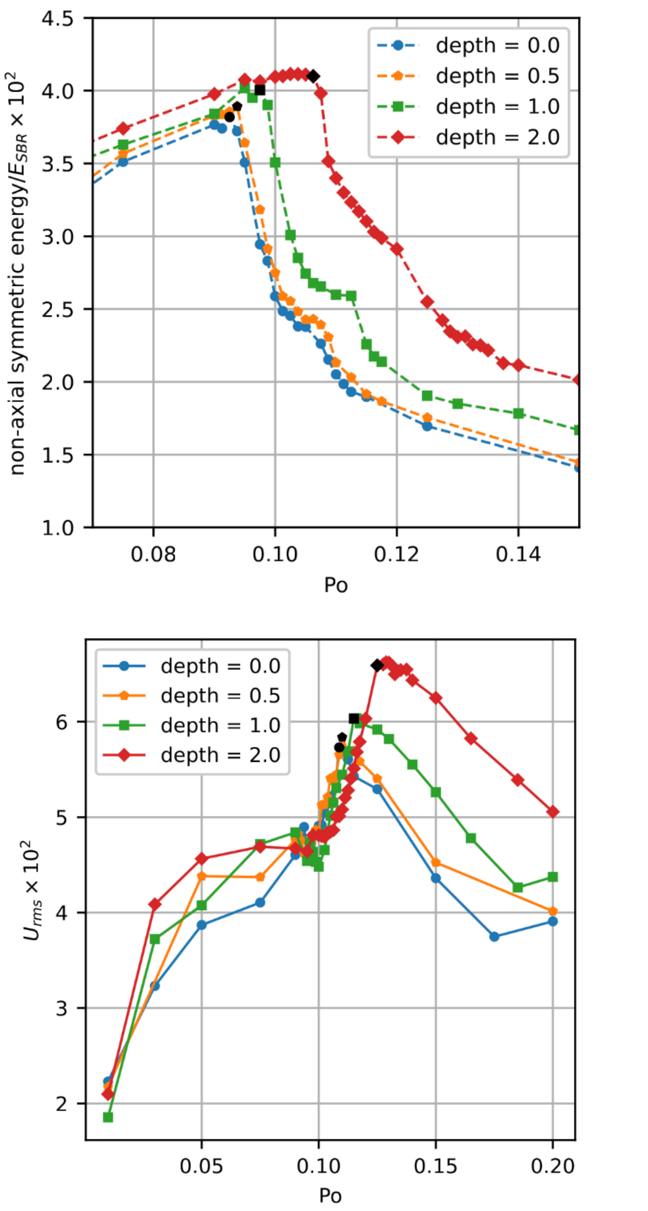
Giesecke et al., Phys. Rev. Lett. 120 (2018), 024502
Kumar et al., Phys. Fluids 35 (2023), 014114

DRESDEN concept HZDR

Role of inserted blades





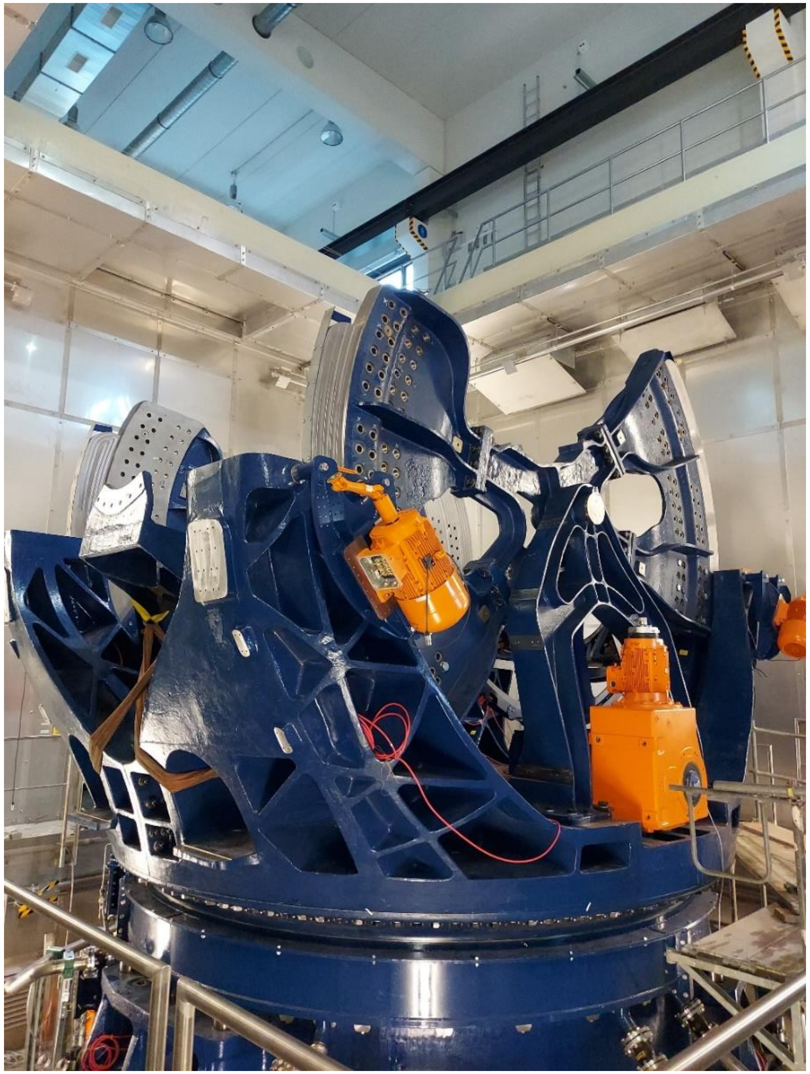


→ **Transition between laminar and turbulent flow can be shifted to higher precession ratios**

→ **Thereby, some 10-20 per cent more energy can be deposited into the dynamo-generating flow modes**

Wilbert, Giesecke, Grauer, Phys. Fluids, 34, 096607 (2022)

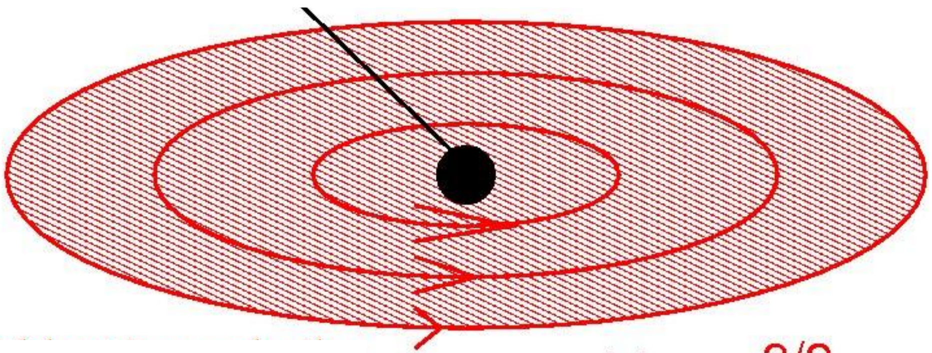
Tilting machine in containment and sodium system are ready



First experiments (with water) are planned for fall 2024

Magnetorotational instability: How do accretion discs work?

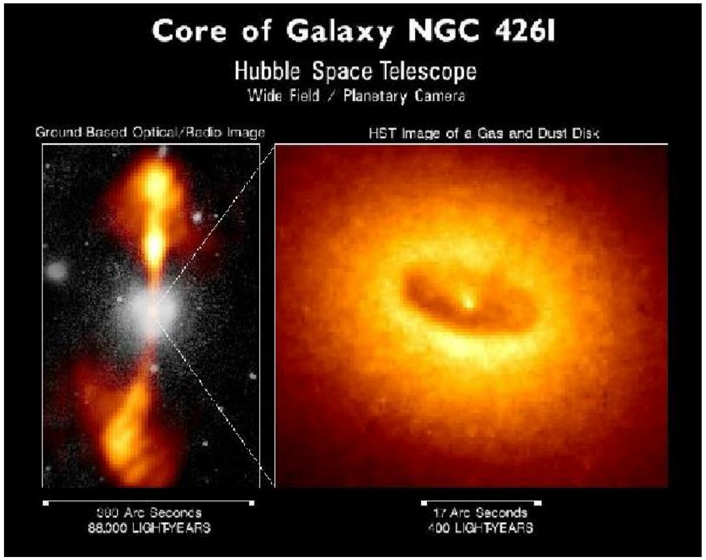
Central object (protostar, black hole)



Accretion disk

$\Omega(r) \sim r^{-3/2}$

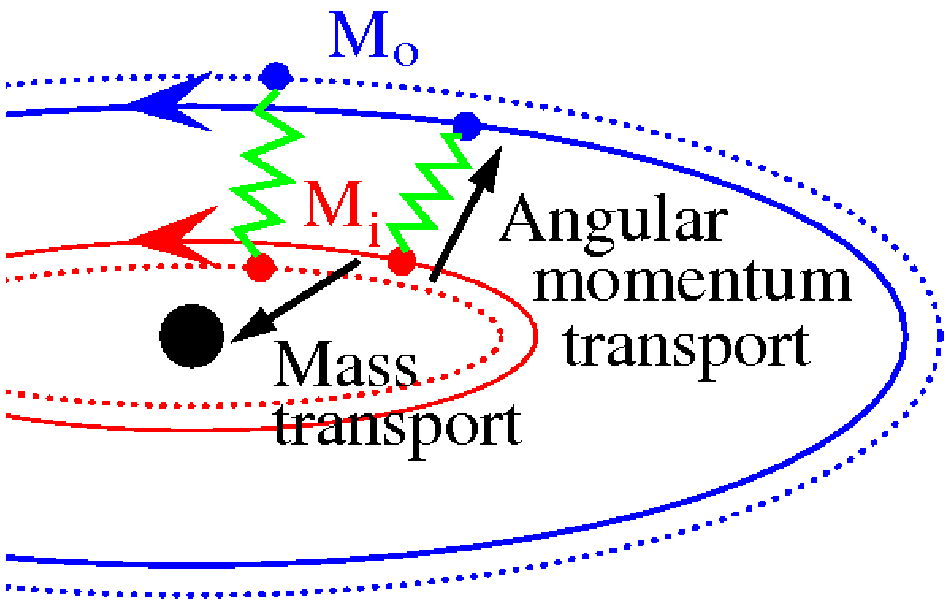
$\Omega(r) r^2 \sim r^{1/2}$

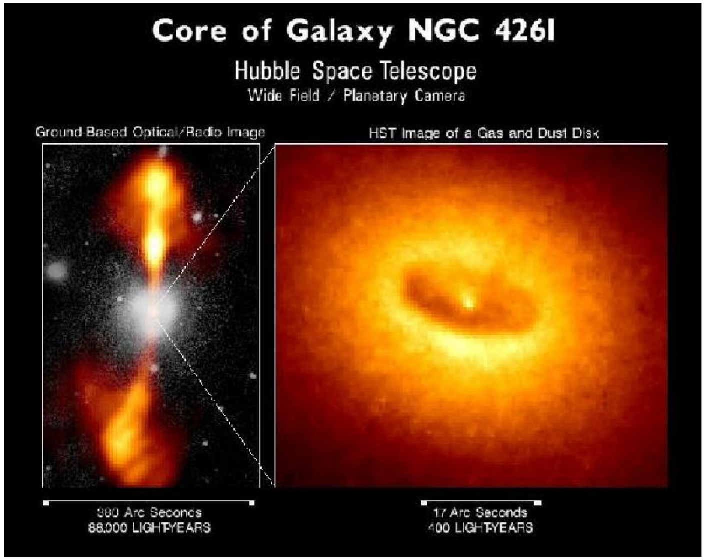


Problem: Outward angular momentum transport is not explainable by normal viscosity

Turbulence could help. But: Kepler rotation is hydrodynamically stable. Where does the turbulence come from?

Magnetorotational instability: How do accretion discs work?

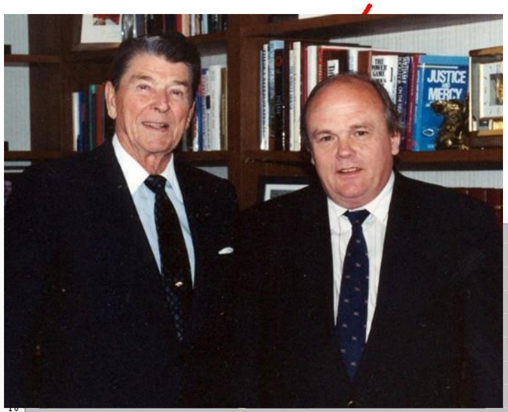




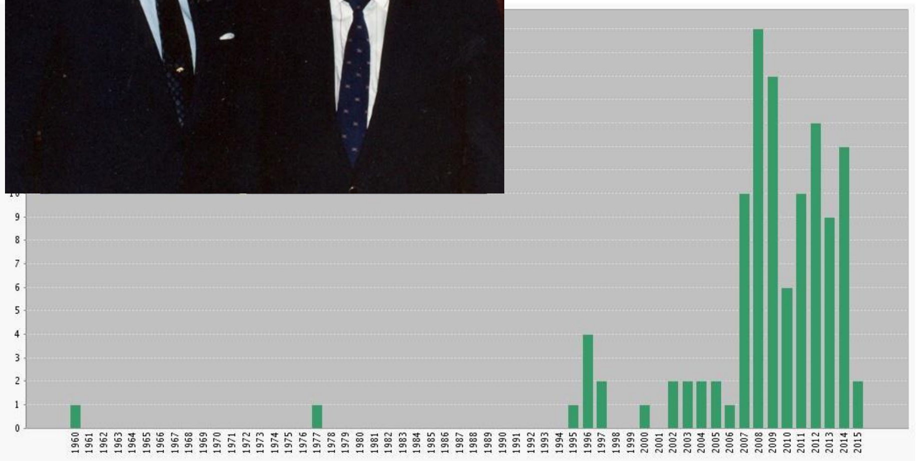
Solution: Magnetic fields act like springs and trigger angular momentum transport in accretion disks around protostars and black holes

(Citation) history of MRI

E.P. Velikhov



386 citations since 1959



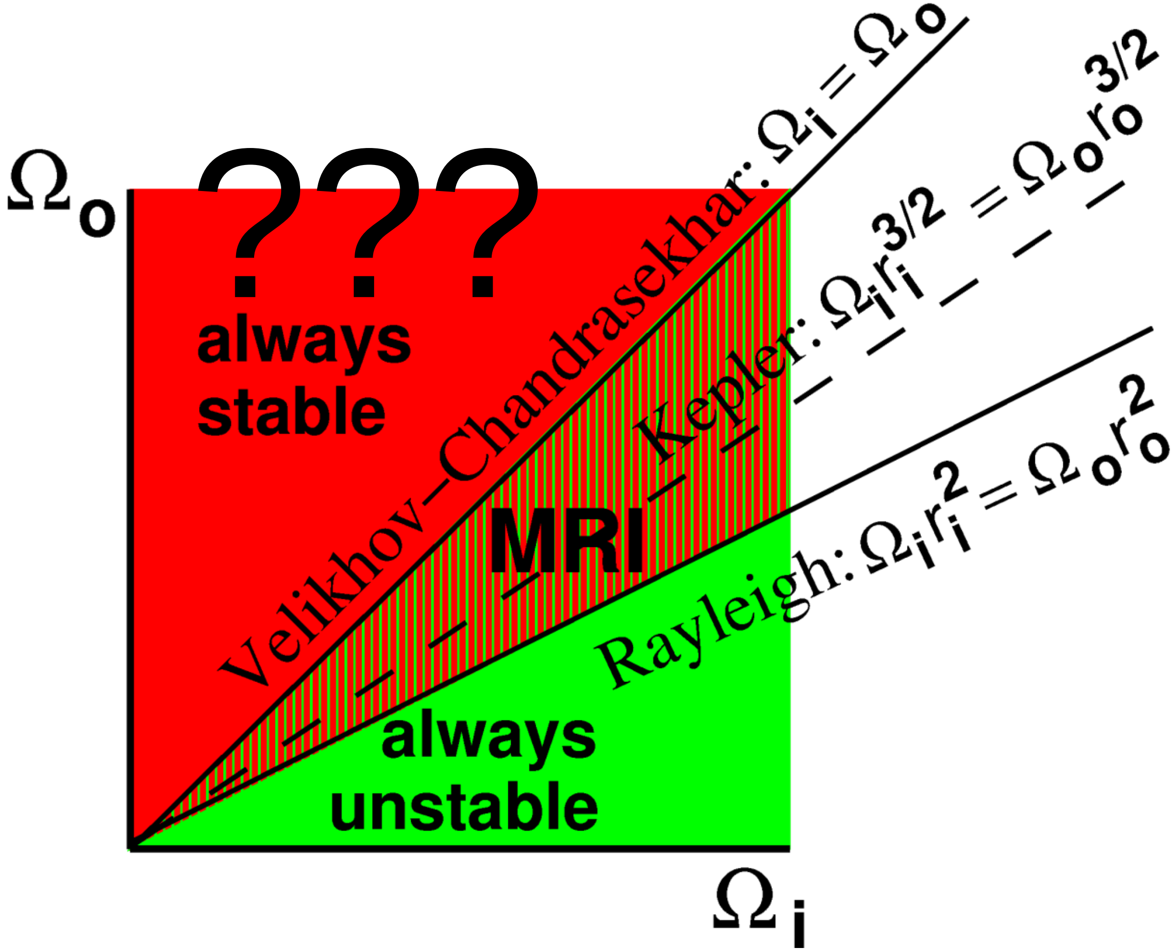
S.A. Balbus and J.F. Hawley

3470 citations since 1991

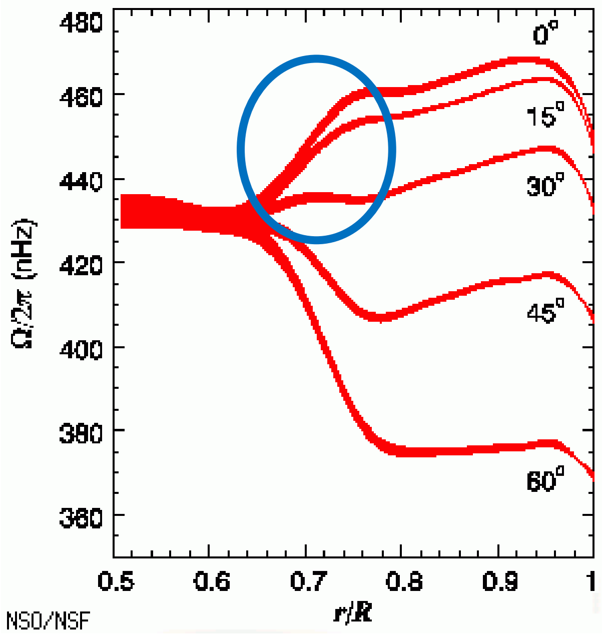
E.P. Velikhov: Sov. Phys. JETP 9 (1959), 995

S.A. Balbus and J.F. Hawley: ApJ 376 (1991), 214

Are rotational flows with positive shear always stable?



Possible relevance for the equator-near parts of the solar tachocline



MRI in the Maryland spherical Couette experiment ???

VOLUME 93, NUMBER 11 PHYSICAL REVIEW LETTERS week ending 10 SEPTEMBER 2004

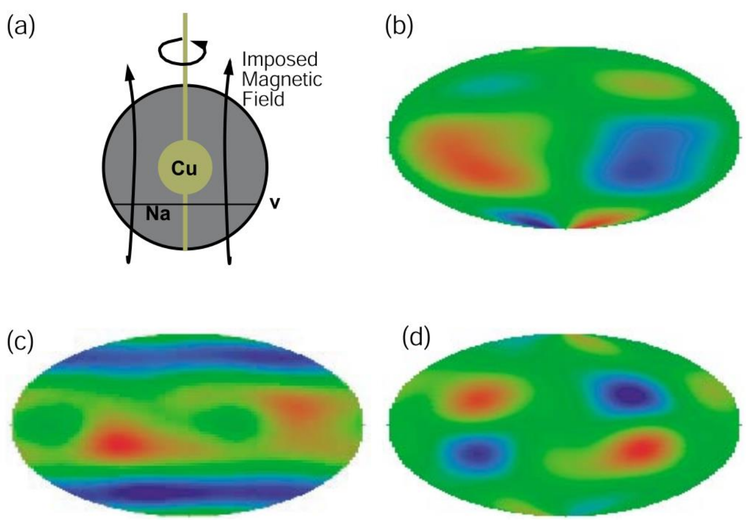
Experimental Observation and Characterization of the Magnetorotational Instability

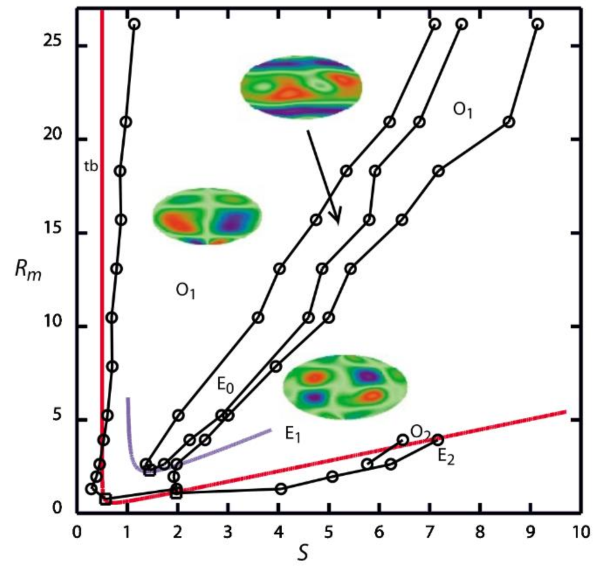
Daniel R. Sisan, Nicolás Mujica, W. Andrew Tillotson, Yi-Min Huang, William Dorland, Adil B. Hassam, Thomas M. Antonsen, and Daniel P. Lathrop*

Department of Physics, IREAP, IPST, University of Maryland, College Park, Maryland 20742, USA

(Received 25 February 2004; published 10 September 2004)

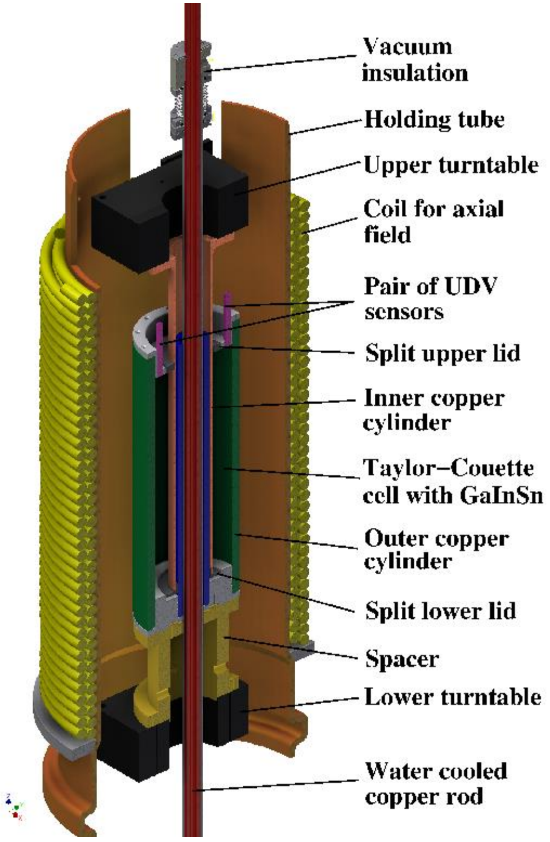
Differential rotation occurs in conducting flows in accretion disks and planetary cores. In such systems, the magnetorotational instability can arise from coupling Lorentz and centrifugal forces to cause large radial angular momentum fluxes. We present the first experimental observation of the magnetorotational instability. Our system consists of liquid sodium between differentially rotating spheres, with an imposed coaxial magnetic field. We characterize the observed patterns, dynamics, and torque increases, and establish that this instability can occur from a hydrodynamic turbulent background.

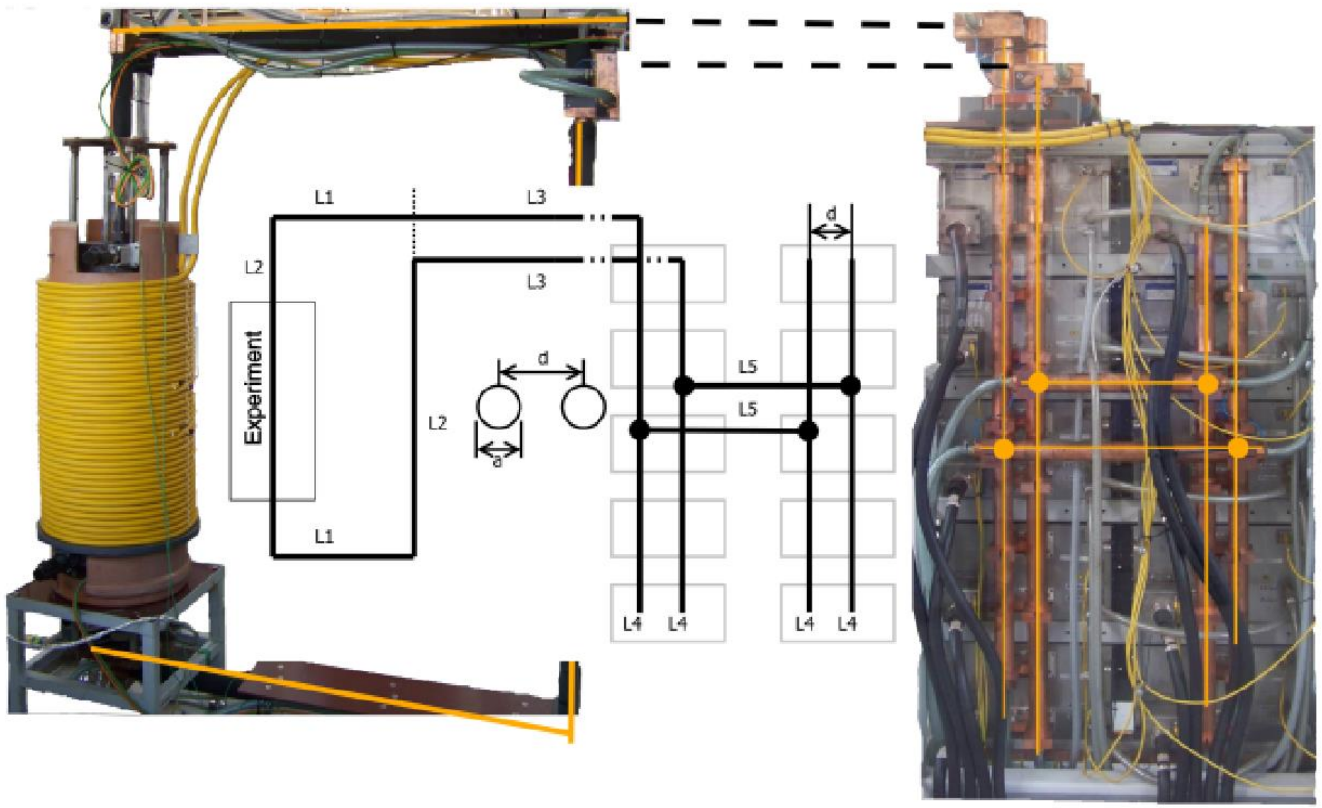




The azimuthal MRI (AMRI): m=1 mode under influence of (pure) B_φ

New power supply provides currents up to 20 kA





Very important: Simulation of the real geometry including the slight symmetry breaking of the applied magnetic field

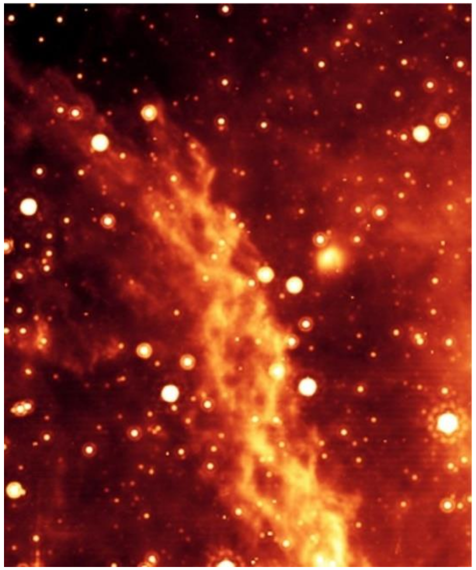
Kink-type Tayler instability (TI)

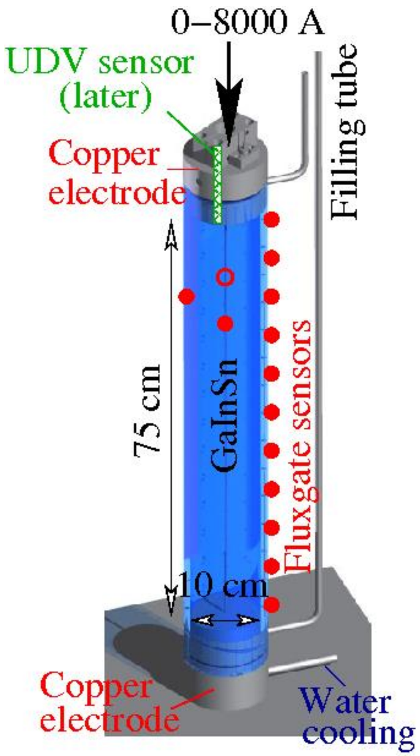
Astrophysical motivation:

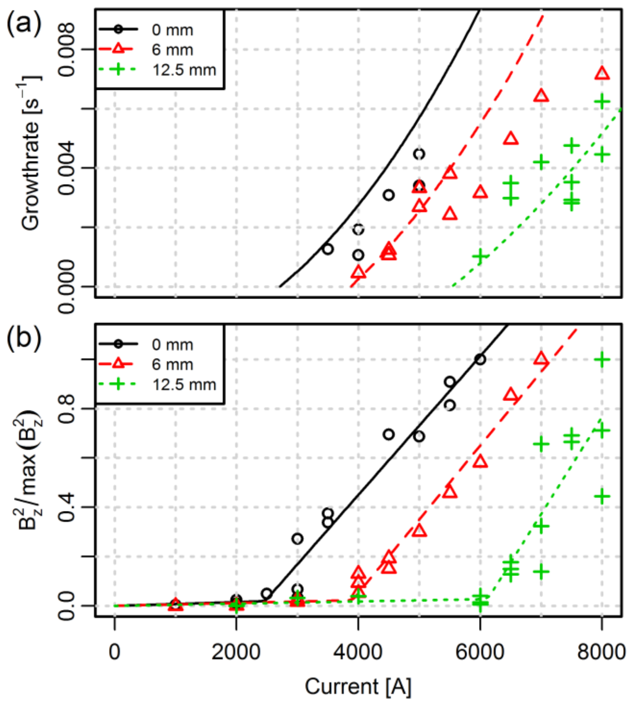
•Alternative mechanism of solar dynamo (Tayler-Spruit)

•Braking of neutron stars

•Instabilities in cosmic jets







First experiment at HZDR: Good correspondence of measured critical currents and growth rates of theTI with numerical simulations.

Seilmayer et al., PRL 108 (2012), 244501

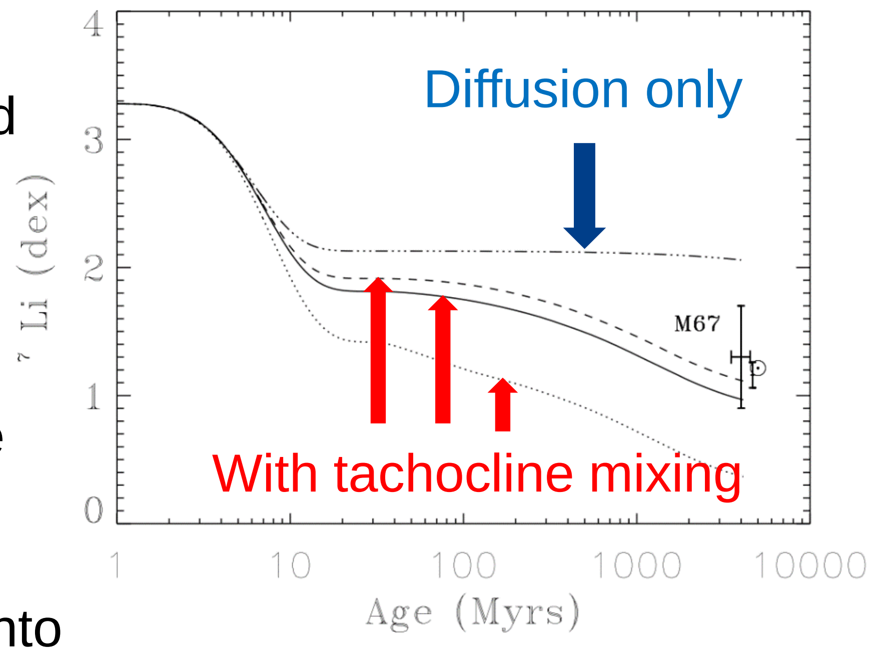
DRESDEN concept HZDR

This could solve Lithium depletion problem in the sun and stars

Lithium and Beryllium are destroyed by proton captures at very high temperatures (Li 2.5x10^{6} K).

These elements survive in outer (colder) convection zone of sun-like stars. Their observed continuous decrease suggests a transport process from the convection zone into the radiation zone, where they are destroyed.

Transport mechanism needs to be rather slow (compared to turbulent convective motion).

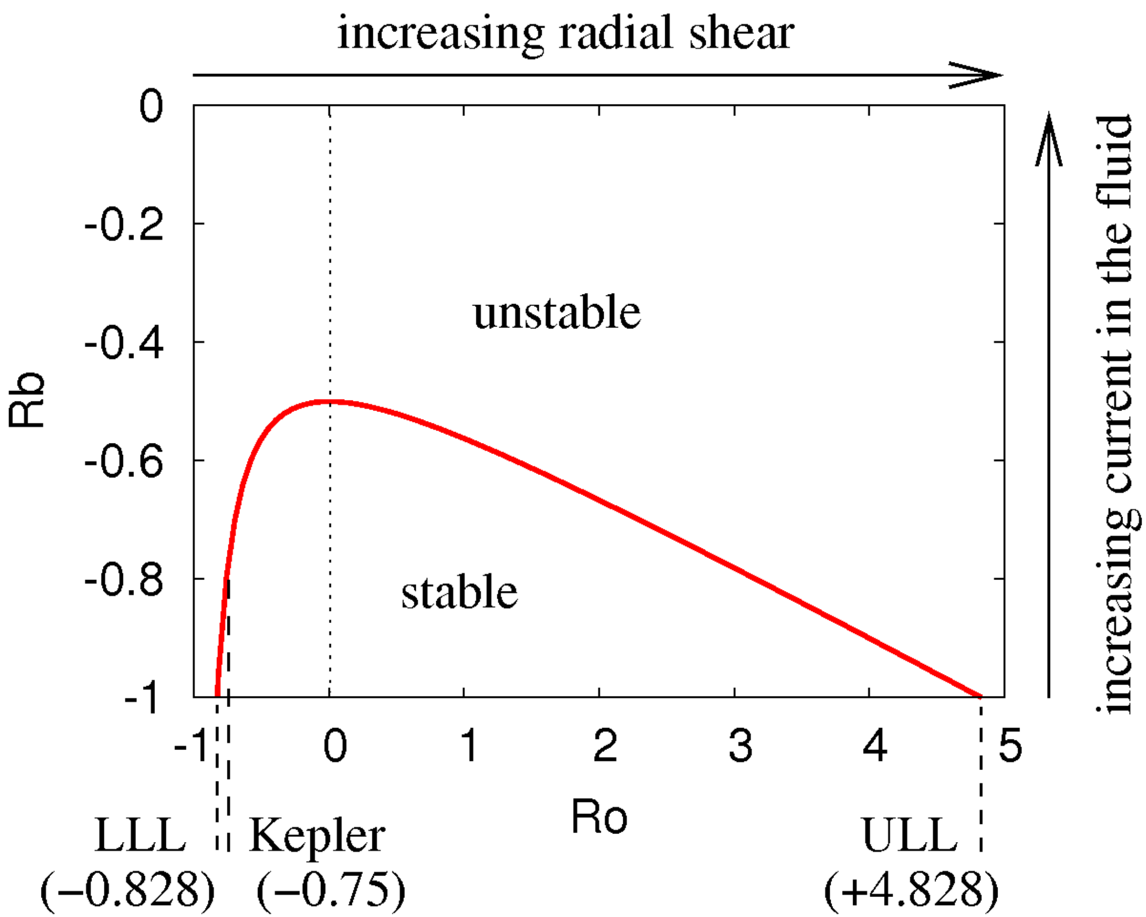


^{7}Li surface abundances in stars with solar mass and composition. Tachocline mixing with disk coupling time 10, 3, and 0.5 Myr, respectively. 5777 K at 4.6 Gyr

Piau and Turck-Chieze, ApJ 566, 419 (2002)
Rüdiger et al., MNRAS 399, 996 (2009)

DRESDEN concept HZDR

Can magnetic fields destabilize rotations with positive shear?



$$\mathrm{Ro} = \frac{r}{2\Omega}\frac{\partial \Omega}{\partial r}$$

$$\mathrm{Rb} = \frac{r}{2\omega_{A_\phi}}\frac{\partial \omega_{A_\phi}}{\partial r}$$

$$Rb = -\frac{1}{8}\frac{(Ro+2)^2}{Ro+1}$$

Lower Liu Limit (LLL)

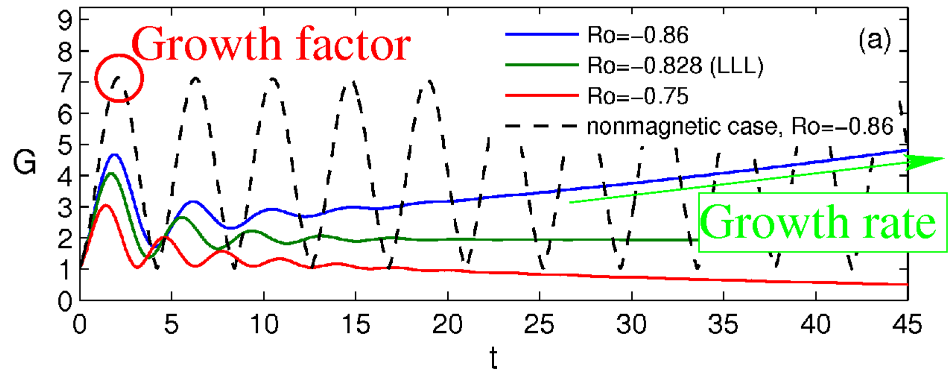
Upper Liu Limit (ULL)

Kirillov and F.S., Phys. Rev. Lett. 111 (2013), 061103; JFM 760 (2014), 591

Liu, Goodman, Herron, Ji, Phys. Rev. E 74 (2006), 056302

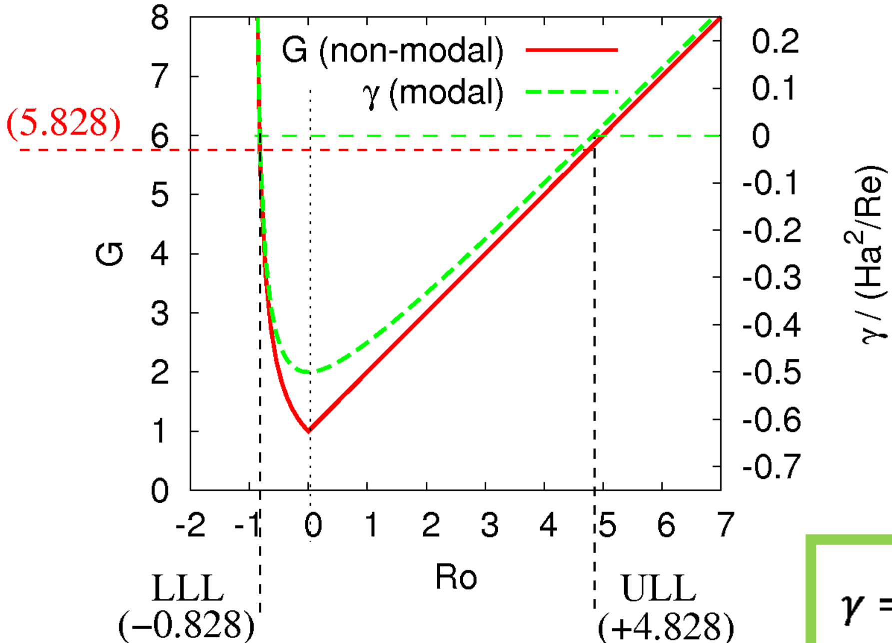
DRESDEN concept HZDR

Linking non-modal growth and dissipation-induced instabilities



Is there any physical reason behind LLL and ULL of the shear for the emergence of HMRI?

YES!



Analytical link between **non-modal growth factor G** of purely hydro-dynamic flows with **modal growth rate** γ of dissipation-induced HMRI

$$G_m = (1 + Ro)^{sgn(Ro)}$$

$$\gamma = \frac{Ha^2}{Re}\left[\frac{(Ro+2)^2}{8(1+Ro)} - 1\right] = \frac{Ha^2}{Re}\left[\frac{(G_m+1)^2}{8G_m} - 1\right]$$

Mamatsashvili and F.S., PRE 94, 051203 (R) (2016)

DRESDEN concept

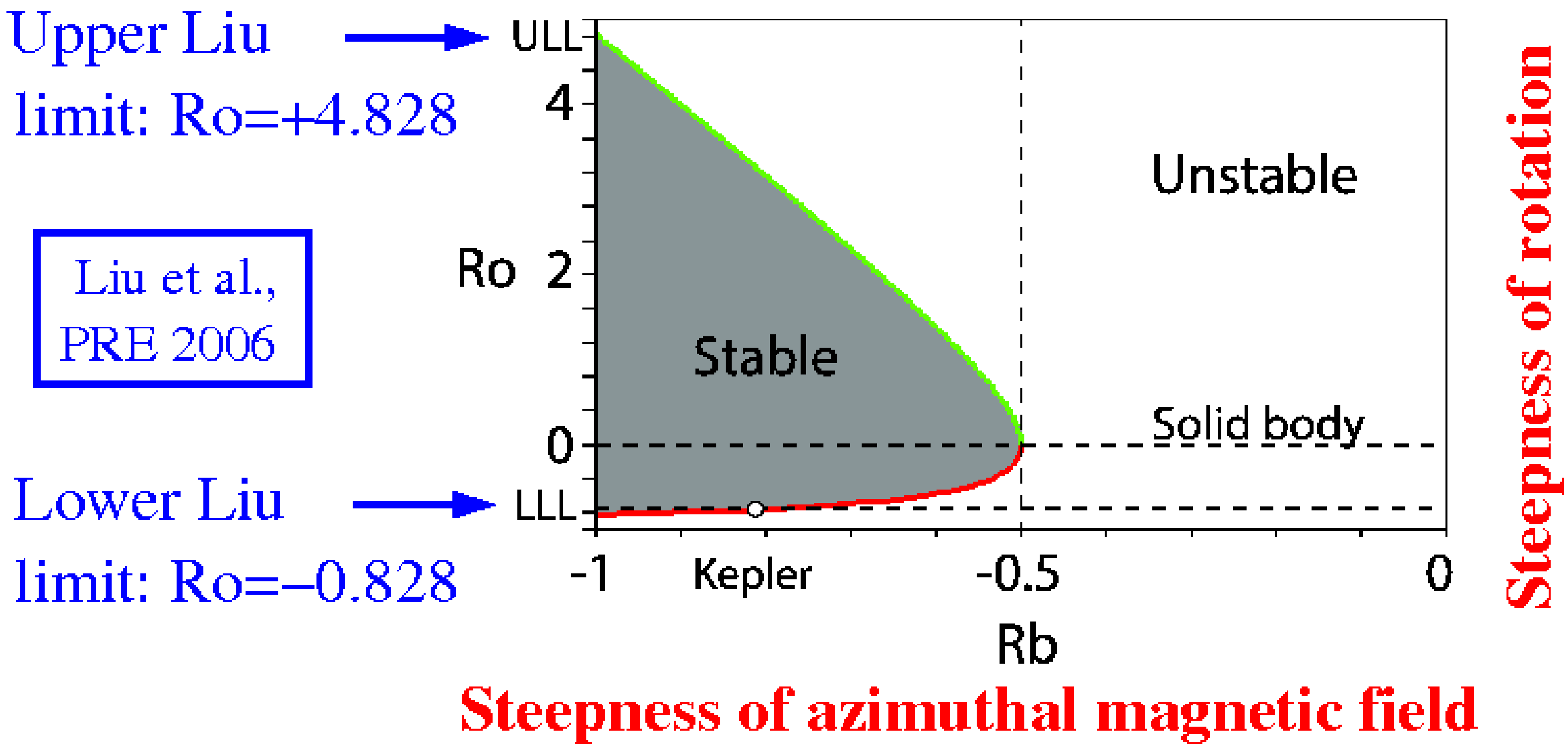
HZDR

Destabilizing Kepler flows with appropriate combination of MRI and TI

WKB-Analysis of the complete viscous and resistive MRI/TI problem for arbitrary azimuthal modes

Main results:

$$Rb = -\frac{1}{8}\frac{(Ro+2)^2}{Ro+1}$$

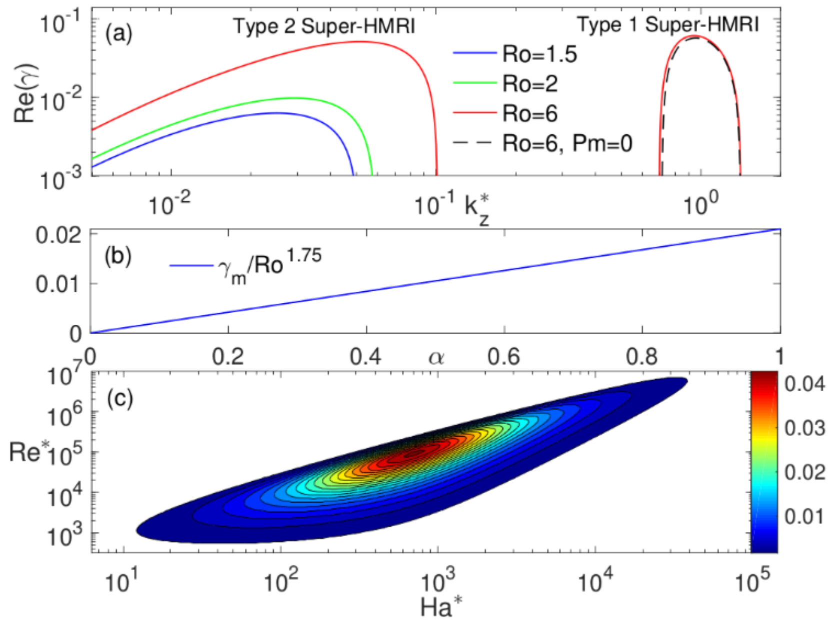


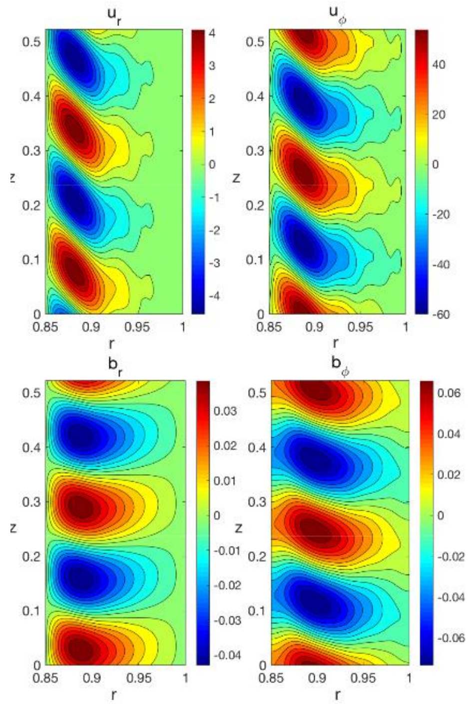
Kirillov and Stefani, Phys. Rev. Lett. 111 (2013), 061103; arXiv:1307.1576; arXiv:1401.8276

New instability for rotating flow with positive shear

Super-HMRI:

- Axi-symmetric: m=0
- Scales with Rm and Lundquist
- Requires B_φ and B_z
- Double-diffusive! Not for Pm=1
- Works for arbitrarily weak shear!





Mamatsashvili, F.S., Hollerbach, Rüdiger, Phys. Rev. Fluids 4 (2019), 103905

Super-HMRI should also be detectable in the new MRI/TI experiment…

…and seems also to work for the near-equator parts of the tachocline!

Planned experiment: Technical aspects

Parameters:

- 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

- Rm = 40
- Lu = 8